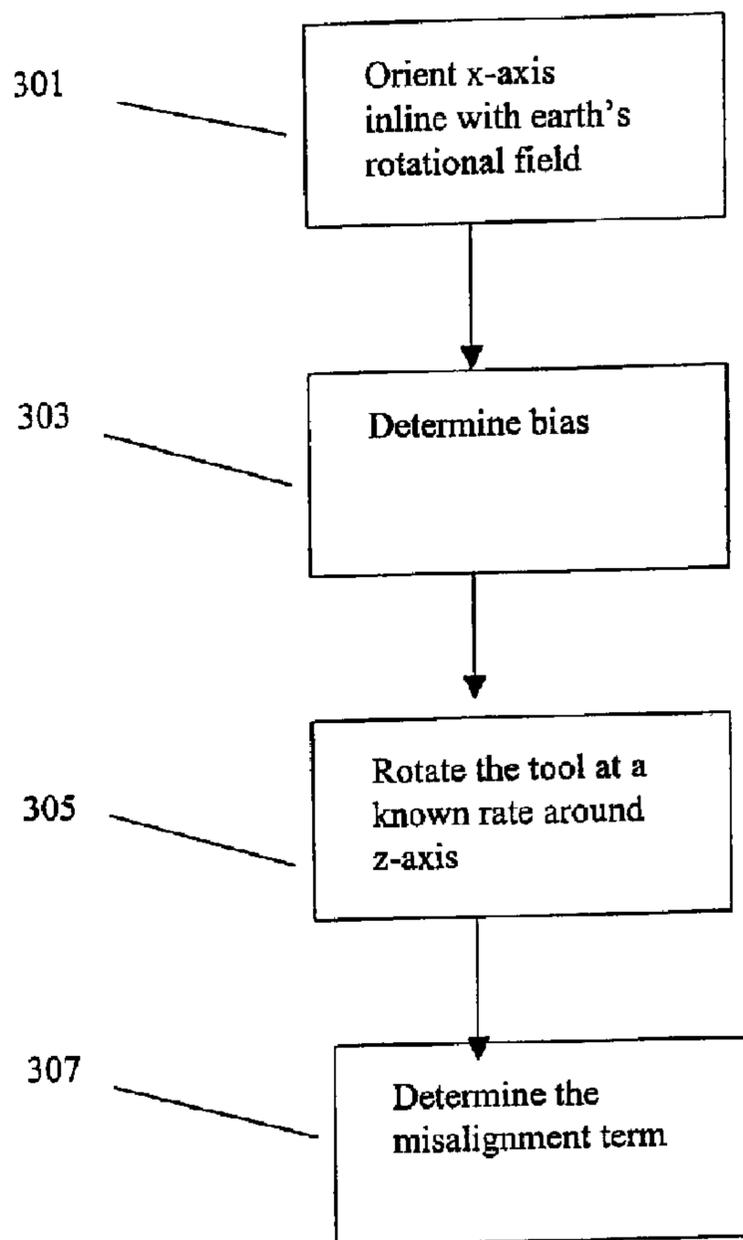




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(57) Abrégé/Abstract:

A method of using a two-axis gyroscope on a housing for determining a rate of rotation of the housing about a third axis is provided. The two axes of the two-axis gyroscope are substantially orthogonal to each other, wherein the third axis has a small deviation from orthogonality relative to at least one of the two axis.



**ABSTRACT**

A method of using a two-axis gyroscope on a housing for determining a rate of rotation of the housing about a third axis is provided. The two axes of the two-axis gyroscope are substantially orthogonal to each other, wherein the third axis  
5 has a small deviation from orthogonality relative to at least one of the two axis.

## **METHOD OF USING A TWO-AXIS GYROSCOPIC**

### **FIELD OF THE INVENTION**

This invention relates generally to bottom hole assemblies for drilling  
5 oilfield wellbores and more particularly to the use of gyroscopic and other sensors to  
determine wellbore and drilling tool direction during the drilling of the wellbores and  
to the correction of data from such sensors.

### **BACKGROUND OF THE INVENTION**

10 To obtain hydrocarbons such as oil and gas, wellbores (also referred to  
as the boreholes) are drilled by rotating a drill bit attached at the end of a drilling  
assembly generally referred to as the "bottom hole assembly" (BHA) or the "drilling  
assembly." A large portion of the current drilling activity involves drilling highly  
deviated and substantially horizontal wellbores to increase the hydrocarbon  
15 production and/or to withdraw additional hydrocarbons from the earth's formations.  
The wellbore path of such wells is carefully planned prior to drilling such wellbores  
utilizing seismic maps of the earth's subsurface and well data from previously drilled  
wellbores in the associated oil fields. Due to the very high cost of drilling such  
wellbores and the need to precisely place such wellbores in the reservoirs, it is  
20 essential to frequently determine the position and direction of the drilling assembly  
and thus the drill bit during drilling of the wellbores. Such information is utilized,  
among other things, to monitor and adjust the drilling direction of the wellbores. It  
should be noted that the terms "wellbore" and "borehole" are used interchangeably in  
the present document.

25 In the commonly used drilling assemblies, the directional package  
commonly includes a set of accelerometers and a set of magnetometers, which  
respectively measure the earth's gravity and magnetic fields. The drilling assembly is  
held stationary during the taking of the measurements from the accelerometers and the  
magnetometers. The toolface and the inclination angle are determined from the  
30 accelerometer measurements. The azimuth is then determined from the  
magnetometer measurements in conjunction with the tool face and inclination angle.  
As used herein, the term "toolface" means the orientation angle of the bent housing or  
sub in the borehole with respect to a reference such as high side of the borehole

which indicates the direction in which the borehole will be curving. The inclination angle is the angle between the borehole axis and the vertical (direction of the gravity field). The azimuth is the angle between the horizontal projection of the borehole axis and a reference direction such as magnetic north or absolute north.

5           The earth's magnetic field varies from day to day, which causes corresponding changes in the magnetic azimuth. The varying magnetic azimuth compromises the accuracy of the position measurements when magnetometers are used. Additionally, it is not feasible to measure the earth's magnetic field in the presence of ferrous or ferromagnetic materials, such as casing and drill pipe.

10          Gyroscopes measure the rate of the earth's rotation, which does not change with time nor are the gyroscopes adversely affected by the presence of ferrous materials. Thus, in the presence of ferrous materials the gyroscopic measurements can provide more accurate azimuth measurements than the magnetometer measurements.

          United States Patent 5,432,699 of *Hache* et al. discloses a method and  
15          apparatus measuring motion signals of gyroscopes in downhole instruments used to determine the heading of a borehole. Accelerometer and magnetometer data along three orthogonal axes of a measurement sub are used to obtain unit gravitational and magnetic vectors. The gyroscope measurements are used to correct the magnetic and gravity measurements made by the magnetometer and the accelerometer respectively.  
20          The calculations performed in the correction process by this, and other prior art optimization schemes based upon least squares methods, are valid when the measurements are corrupted by random additive noise. As would be known to those versed in the art, in the presence of systematic measurement errors, such least-squares optimization methods are unreliable.

25               Commercially available gyroscopes contain systematic errors or biases that can severely deteriorate accuracy of a gyroscope's measurements and thus the azimuth. Gyroscopes have been utilized in wireline survey applications but have not found commercial acceptance in the measurement-while-drilling (MWD) tools used in bottomhole assemblies.

30               In wireline applications, the survey tool is conveyed into the wellbore after the wellbore has been drilled, in contrast to the MWD tools wherein the measurements are made during the drilling of the wellbores. Wireline methods are

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not practical in determining the drilling assembly position and direction during the drilling of the wellbores. In wireline applications, the gyroscopes are used either in a continuous mode or at discrete survey intervals. Wireline survey methods often make it unnecessary to employ techniques to compensate for the present-value of the

5 gyroscopes. In wireline applications, the gyroscope can be powered-up at the surface and allowed to stabilize (thermally and dynamically) for a relatively long time period. Typically a warm-up period of ten (10) minutes or more is taken. The power to the gyroscope is continuously applied from the beginning at the surface, through the actual wellbore survey and through the final check of the survey tool at the surface

10 at the end of the survey. Therefore, reference alignments can be made at the surface prior to commencing the wellbore survey to adjust the drift in a gimballed gyroscope or verify the alignment accuracy of a north-seeking gyroscope. The initial independent reference can then be used at the end of the wireline survey. Any bias in the gyroscope in a wireline tool can be measured at the surface by taking the

15 difference in the alignments at the beginning and the end of the survey runs. Furthermore, the wireline tool carrying the north-seeking gyroscope can easily be rotated at the surface to several different toolface (roll angle) positions to determine the bias present on either of the transverse gyroscopes (i.e., along the x and y axis of the tool) when the tool is at the surface. This bias can be used to verify the accuracy

20 or to correct the gyroscope measurements.

In the MWD environment, the above-noted advantages of the wireline systems are not present. The MWD surveys are usually taken during drill pipe connection times during the drilling of the wellbore, which intervals are relatively short - generally one to four minutes. Power in the MWD tools is generated

25 downhole and/or provided by batteries. To conserve the power, it is desirable to switch off the gyroscopes when not in use because the gyroscopes consume considerable power. For MWD tools utilizing turbine-alternator, the power is generated by flow of the drilling fluid ("mud") which is interrupted at each pipe connection. Even if the power could be applied continuously, the difference in the

30 bias measured at the surface prior to the drilling and post drilling is not considered an accurate measure due to the very long time between drilling assembly trips, which are typically between 20 and 200 hours.

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Earlier 2-axis (X-Y) gyro tools could be used for North-Seeking gyrocompass operations when the tool is vertical up to about 60 degrees inclination. This is a static operation, which is done during pipe connections while there is no motion of the drillstring. Gyroscopic steering of oilfield drilling assemblies is typically accomplished by the addition of a 3rd (Z-axis) gyro which is oriented to measure the rotation of the toolface along the long axis of the drillstring. An example of such a device is disclosed in US Patent 6347282 and US Patent 6529834 to *Estes et al*, having the same assignee. With slim (1-3/4" OD) tools, there is very little room to accommodate a 3rd gyro axis mounted crosswise to the X and Y axes, which are often realized in a single, 2-axis rate gyroscope.

Prior art devices have added a smaller, less accurate rate gyro in the Z-axis to allow direct measurements of the angular rotation rate in the Z-axis (toolface). By integrating this Z-axis rate, these tools can track changes in the toolface angular orientation as the drilling motor and deviation device (bent sub) are sliding down the borehole. However, the resultant accuracy leaves a lot to be desired.

Attempts by the applicant to track toolface using only the Rate-X and Rate-Y measurements have been made using a modification of the original gyrocompassing technique. On the theory that there may be some time periods when the BHA is still enough to allow using the conventional North-seeking operation to work, a "Fast Intermittent Gyrocompassing" technique was tested. Laboratory tests showed that the extreme difference between earth rate (15 deg/hr) and toolface changes during typical drilling (~45 deg/sec or ~ 162,000 deg/hr) caused detection problems. There is no guarantee the platform will ever be stable, and no independent indicator of a sufficiently stable condition. Even minuscule drillstring relaxation after a drilling period is likely to introduce large rate errors in trying to measure the earth's rotation.

It is desirable to be able to track toolface changes during steering, using only an (X-Y) 2-axis rate gyro sensor. The present invention satisfies this need.

### SUMMARY OF THE INVENTION

Accordingly, in one aspect there is provided a method of using a two-axis gyroscope on a housing for determining a rate of rotation of said housing about a third axis, said two axes of the two-axis gyroscope being substantially orthogonal to each other, wherein  
 5 said third axis has a small deviation from orthogonality relative to at least one of said two axes, said method comprising:

measuring an output of said two-axis gyroscope along said at least one of said two axes in response to said rotation about said third axis; and

determining from said output and a misalignment term, an estimate of said rate  
 10 of rotation about said third axis using a relation of the form:

$$R_x = \frac{S_x}{F_x} - B_x - B_{xg} - M_x R_z$$

where  $R_x$  is the rotation rate of said housing about said third axis,  $S_x$  is said output of said gyroscope corresponding to said at least one axis,  $F_x$  is a calibration scale factor for said at least one axis,  $B_x$  is a bias for the at least one axis,  $B_{xg}$  is a bias term for said at least one axis  
 15 that is gravity related,  $M_x$  is said misalignment term, and  $R_z$  is the z-axis rotation rate.

Under these conditions, the misaligned gyro has a sensitivity to rotation about the third axis. This makes it possible to determine the toolface angle of a drilling assembly with only a two-axis gyro. Using calibration procedures, the major temperature-dependent errors within the gyros are removed. Using prior art indexing procedures, residual bias  
 20 values for each of the two axes are determined and removed. By rotating the assembly at a known rate about the third axis, the cross-sensitivity can be determined, in the laboratory or downhole, and then subsequently used for determining rotation about the z- axis of the drilling assembly.

The gyro may be conveyed downhole on a drilling tubular or on a wireline.  
 25 When used in conjunction with a drilling tubular, the method of the present invention is particularly useful in directional drilling operations.

### BRIEF DESCRIPTION OF THE DRAWINGS

For detailed understanding of the present invention, references should be made  
 30 to the following detailed description of the preferred embodiment, taken in conjunction with the accompanying drawings, in which like elements have been given like numerals, wherein:

FIG. 1 shows a schematic diagram of a drilling system that employs the apparatus of the current invention in a measurement-while-drilling embodiment;

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FIG. 2 shows a schematic diagram of a portion of the bottomhole assembly with a set of gyroscopes and a corresponding set of accelerometers according to a preferred embodiment of the present invention;

FIG. 3 is a flow chart illustrating a method for determining a deviation from orthogonality between a gyro axis and an axis of rotation intended to be orthogonal to the gyro axis;

FIG. 4 illustrates the method of the present invention for use in controlling drilling operations;

FIGS. 5a-5c illustrate the survey mode of FIG. 4;

FIG. 6 illustrates a method of correcting downhole measurements using laboratory derived calibrations;

FIG. 7 illustrates the steering mode of FIG. 4;

FIG. 8 illustrates the effect of temperature drift on gyroscope measurements;

FIG. 9 shows the results of a sinusoidal curve fitting to measurements affected by temperature drift;

FIG. 10 shows residuals from Fig. 9 as a function of nominal temperature; and

FIG. 11 shows bias determination correcting for the effects of temperature drift.

### **DETAILED DESCRIPTION OF THE INVENTION**

**FIG. 1** (prior art) shows a schematic diagram of a drilling system **10** having a bottom hole assembly (BHA) or drilling assembly **90** that includes gyroscope(s) according to the present invention. The BHA **90** is conveyed in a borehole **26**. The drilling system **10** includes a conventional derrick **11** erected on a floor **12** which supports a rotary table **14** that is rotated by a prime mover such as an electric motor (not shown) at a desired rotational speed. The drill string **20** includes a tubing (drill pipe or coiled-tubing) **22** extending downward from the surface into the borehole **26**. A drill bit **50**, attached to the drill string **20** end, disintegrates the geological formations when it is rotated to drill the borehole **26**. The drill string **20** is coupled to a drawworks **30** via a kelly joint **21**, swivel **28** and line **29** through a pulley

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(not shown). Drawworks **30** is operated to control the weight on bit (“WOB”), which is an important parameter that affects the rate of penetration (“ROP”). A tubing injector **14a** and a reel (not shown) are used as instead of the rotary table **14** to inject the BHA into the wellbore when a coiled-tubing is used as the conveying member **22**.  
5 The operations of the drawworks **30** and the tubing injector **14a** are known in the art and are thus not described in detail herein.

During drilling, a suitable drilling fluid **31** from a mud pit (source) **32** is circulated under pressure through the drill string **20** by a mud pump **34**. The drilling fluid passes from the mud pump **34** into the drill string **20** via a desurger **36**  
10 and the fluid line **38**. The drilling fluid **31** discharges at the borehole bottom **51** through openings in the drill bit **50**. The drilling fluid **31** circulates uphole through the annular space **27** between the drill string **20** and the borehole **26** and returns to the mud pit **32** via a return line **35** and drill cutting screen **85** that removes the drill cuttings **86** from the returning drilling fluid **31b**. A sensor **S<sub>1</sub>** in line **38** provides  
15 information about the fluid flow rate. A surface torque sensor **S<sub>2</sub>** and a sensor **S<sub>3</sub>** associated with the drill string **20** respectively provide information about the torque and the rotational speed of the drill string **20**. Tubing injection speed is determined from the sensor **S<sub>5</sub>**, while the sensor **S<sub>6</sub>** provides the hook load of the drill string **20**.

In some applications the drill bit **50** is rotated by only rotating the drill  
20 pipe **22**. However, in many other applications, a downhole motor **55** (mud motor) is disposed in the drilling assembly **90** to rotate the drill bit **50** and the drill pipe **22** is rotated usually to supplement the rotational power, if required, and to effect changes in the drilling direction. In either case, the ROP for a given BHA largely depends on the WOB or the thrust force on the drill bit **50** and its rotational speed.

25 The mud motor **55** is coupled to the drill bit **50** via a drive disposed in a bearing assembly **57**. The mud motor **55** rotates the drill bit **50** when the drilling fluid **31** passes through the mud motor **55** under pressure. The bearing assembly **57** supports the radial and axial forces of the drill bit **50**, the downthrust of the mud motor **55** and the reactive upward loading from the applied weight on bit. A lower  
30 stabilizer **58a** coupled to the bearing assembly **57** acts as a centralizer for the lowermost portion of the drill string **20**.

A surface control unit or processor **40** receives signals from the downhole sensors and devices via a sensor **43** placed in the fluid line **38** and signals from sensors **S<sub>1</sub>-S<sub>6</sub>** and other sensors used in the system **10** and processes such signals according to programmed instructions provided to the surface control unit **40**. The surface control unit **40** displays desired drilling parameters and other information on a display/monitor **42** that is utilized by an operator to control the drilling operations. The surface control unit **40** contains a computer, memory for storing data, recorder for recording data and other peripherals. The surface control unit **40** also includes a simulation model and processes data according to programmed instructions. The control unit **40** is preferably adapted to activate alarms **44** when certain unsafe or undesirable operating conditions occur.

The BHA may also contain formation evaluation sensors or devices for determining resistivity, density and porosity of the formations surrounding the BHA. A gamma ray device for measuring the natural gamma ray intensity and other nuclear and non-nuclear devices used as measurement-while-drilling devices are suitably included in the BHA **90**. As an example, **FIG. 1** shows a resistivity measuring device **64**. It provides signals from which resistivity of the formation near or in front of the drill bit **50** is determined. The resistivity device **64** has transmitting antennae **66a** and **66b** spaced from the receiving antennae **68a** and **68b**. In operation, the transmitted electromagnetic waves are perturbed as they propagate through the formation surrounding the resistivity device **64**. The receiving antennae **68a** and **68b** detect the perturbed waves. Formation resistivity is derived from the phase and amplitude of the detected signals. The detected signals are processed by a downhole computer **70** to determine the resistivity and dielectric values.

An inclinometer **74** and a gamma ray device **76** are suitably placed along the resistivity measuring device **64** for respectively determining the inclination of the portion of the drill string near the drill bit **50** and the formation gamma ray intensity. Any suitable inclinometer and gamma ray device, however, may be utilized for the purposes of this invention. In addition, position sensors, such as accelerometers, magnetometers or gyroscopic devices may be disposed in the BHA to determine the drill string azimuth, true coordinates and direction in the wellbore **26**. Such devices are known in the art and are not described in detail herein.

In the above-described configuration, the mud motor **55** transfers power to the drill bit **50** via one or more hollow shafts that run through the resistivity measuring device **64**. The hollow shaft enables the drilling fluid to pass from the mud motor **55** to the drill bit **50**. In an alternate embodiment of the drill string **20**, the mud motor **55** may be coupled below resistivity measuring device **64** or at any other suitable place. The above described resistivity device, gamma ray device and the inclinometer are preferably placed in a common housing that may be coupled to the motor. The devices for measuring formation porosity, permeability and density (collectively designated by numeral **78**) are preferably placed above the mud motor **55**. Such devices are known in the art and are thus not described in any detail.

As noted earlier, a large portion of the current drilling systems, especially for drilling highly deviated and horizontal wellbores, utilize coiled-tubing for conveying the drilling assembly downhole. In such application a thruster **71** is deployed in the drill string **90** to provide the required force on the drill bit. For the purpose of this invention, the term weight on bit is used to denote the force on the bit applied to the drill bit during the drilling operation, whether applied by adjusting the weight of the drill string or by thrusters. Also, when coiled-tubing is utilized the tubing is not rotated by a rotary table, instead it is injected into the wellbore by a suitable injector **14a** while the downhole motor **55** rotates the drill bit **50**.

A number of sensors are also placed in the various individual devices in the drilling assembly. For example, a variety of sensors are placed in the mud motor power section, bearing assembly, drill shaft, tubing and drill bit to determine the condition of such elements during drilling and to determine the borehole parameters. The preferred manner of deploying certain sensors in drill string **90** will now be described. The actual BHA utilized for a particular application may contain some or all of the above described sensors. For the purpose of this invention any such BHA could contain one or more gyroscopes and a set of accelerometers (collectively represented herein by numeral **88**) at a suitable location in the BHA **90**. A preferred configuration of such sensors is shown in **FIG. 2**.

**FIG. 2** is a schematic diagram showing a sensor section **200** containing a gyroscope **202** and a set of three accelerometers **204x**, **204y** and **204z** disposed at a suitable location in the bottomhole assembly (**90** in **FIG. 1**) according to one

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preferred embodiment of the present invention. The gyroscopes **202** may be a single axis gyroscope or a two-axis gyroscope. In vertical and low inclination wellbores, an x-axis and a y-axis gyroscope are deemed sufficient for determining the azimuth and toolface with respect to the true north. The configuration shown in **FIG. 2** utilizes a single two-axis (x-axis and y-axis) gyroscope that provides outputs corresponding to the earth's rate of rotation in the two axis (x-axis and y-axis) perpendicular to the borehole axis or the bottomhole assembly longitudinal axis, referred to herein as the z-axis. The sensor **202** thus measures the earth's rotation component in the x-axis and y-axis. The accelerometers **204x**, **204y** and **204z** measure the earth's gravity components respectively along the x, y, and z axes of the bottomhole assembly **90**.

The gyroscope **202** and accelerometers **204x-204z** are disposed in a rotating chassis **210** that rotates about the radial bearings **212a-212b** in a fixed or non-rotating housing **214**. An indexing drive motor **216** coupled to the rotating chassis **210** via a shaft **218** can rotate the chassis **210** in the bottomhole assembly **90** about the z-axis, thus rotating the gyroscopes **202** from one mechanical position to another position by any desired rotational angle. A stepper motor is preferred as the indexing drive motor **216** because stepper motors are precision devices and provide positive feedback about the amount of rotation. Any other mechanism, whether electrically-operated, hydraulically-operated or by any other desired manner, may be utilized to rotate the gyroscopes within the bottomhole assembly **90**. The gyroscope **202** may be rotated from an initial arbitrary position to a mechanical stop (not shown) in the tool or between two mechanical stops or from an initial peak measurement to a second position as described later. The rotational angle corresponding to a particular axis is selectable.

Although **FIG. 2** shows a single two axis gyroscope, a separate gyroscope may be utilized for each axis. A wiring harness **226** provides power to the gyroscope **202** and accelerometers **204x**, **204y**, **204z**. The wiring harness **226** transmits signals from the gyroscope and accelerometers to the processor in the bottomhole assembly **90**. Similarly, a suitable wiring harness **220** provides power and signal linkage to the stepper motor **216** and additional downhole equipment. A spring loaded torque limiter **240** may be used to prevent inertial loading caused by drillstring

rotation from damaging the gearbox of the stepper motor 216. Alternatively, a preset torque slip clutch may be used.

The present invention is based on the fact that in actual implementation of a two-axis gyroscope (designated herein as the  $x$ - and  $y$ - axes), the axes are not exactly orthogonal to each other. Recognizing the fact that the  $x$ - and  $y$ - axes of the rate gyro are not precisely orthogonal to the physical  $z$ -axis, then it is clear that there is some responsiveness of the  $x$ - and  $y$ - rate measurements to a rotation in the  $z$ - axis. This may be denoted by the equation:

$$R_x = \frac{S_x}{F_x} - B_x - B_{xg} - M_x R_z \quad (1)$$

where  $R_x$  is the  $x$ - axis rate,  $S_x$  is the output of the  $x$ - axis gyro,  $F_x$  is a calibration scale factor for the  $x$ - axis gyro,  $B_x$  is the bias in the  $x$ - axis gyro,  $B_{xg}$  is a bias term that is gravity related, i.e., it depends on the inclination of the tool,  $M_x$  is a misalignment term relating the  $z$ - axis rotation rate  $R_z$  to the  $x$ - axis gyro measured rate. If the  $x$ - axis is exactly orthogonal to the  $z$ - axis, this misalignment term is zero. This is the assumption that is made in prior art devices. A similar expression may be used for the  $y$ - axis rate  $R_y$ .

$$R_y = \frac{S_y}{F_y} - B_y - B_{yg} - M_y R_z \quad (2)$$

We digress briefly to distinguish the subject matter of the present invention from *Algrain*, "Determination of 3-D angular rates using two-axis measurements," SPIE Vol. 2468, pp 252-260. While the title is superficially similar to the subject of the present invention, *Algrain* addresses the problem of using perfectly aligned 2-axis gyros on an object in space (free of the gravity field of the earth) to determine a rotation rate about the third axis. The formulation of the problem is completely different from the present situation wherein imperfectly aligned 2-axis gyro measurements made in the earth's gravity field are used to estimate a rotation rate about the third axis.

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The calibration scale factors  $F_x$  and  $F_y$  are determined using prior art methods— these calibration factors simply relate the output of the  $x$ - and  $y$ - gyros (which are typically in millivolts) to the  $x$ - and  $y$ - axis rotation rates. A simple way to determine the misalignment terms in a laboratory setting is first described next with  
5 reference to **FIG. 3**.

Initially, the tool is oriented with its ( $z$ ) axis inclined vertically so that the gravity terms  $B_{xg}$ ,  $B_{yg}$  are zero. This is not a limitation, as a calibration could be carried out with other orientations of the tool as well but would require the use of accelerometer measurements to zero out these terms and complete the calibration.  
10 Hence to simplify the discussion, it is assumed that the gravity terms are zero. The scale factors  $F_x$  and  $F_y$  are known quantities. Using prior art methods such as that described in either of the *Estes* patents, bias values are estimated for the  $x$ - and  $y$ - gyros **103**. At least two methods are described in the *Estes* patents. In one of them, gyro readings are taken with one toolface orientation of the tool, the housing is rotated  
15 by  $180^\circ$ , and a second gyro reading is taken. In the absence of a bias, readings spaced  $180^\circ$  apart should sum to zero. Any difference from zero of this sum is a measure of the bias in the gyro measurement. In a second method described in the *Estes* patents, the sensor housing is rotated (preferably using a stepper motor) and by fitting a sinusoid to the readings, bias can be determined.

20 In a laboratory setting, the misalignment term can be estimated by now rotating the housing at a known rate **105**. If the bias corrected  $x$ - and  $y$ - gyros give a value different from the expected values due to the presence of earth rate, then the misalignment terms are directly obtained as the ratio of the bias corrected measurements and the known rate of rotation about the  $z$ - axis **107**.

25 Once the misalignment term has been determined, the outputs of the  $x$ - and  $y$ - gyros can be used to determine a  $z$ - axis rotation rate when there is such actual rotation. This is because the bias terms are now known for the  $x$ - and  $y$ - gyros, and the gravity term is known from accelerometer and gyro measurements.

The same principle can be used in actual wellbore applications. Some  
30 important steps for this are discussed below. However, before discussing how such a method may be implemented in surveying and steering operations, a few comments about the  $z$ - axis rotation are in order.

The earth's rotation rate is approximately 15.1 deg/hr (approximately 264 milliradians per hour). The changes in borehole inclination and in borehole azimuth are typically of the same or lesser order of magnitude. In contrast, for a drillstring rotation speed of even 60 rpm, the change in tool face angle is 1,296,000 deg/hr, which is five orders of magnitude greater than the earth's rotation rate. Hence even if a z- axis gyro were mounted on the surveying tool, it would be difficult for such a z- axis gyro to maintain accuracy over such a large dynamic range. A typical misalignment for gyros is of the order of 10 milliradians. The effect of such a misalignment gives a resultant signal on the x- and y- gyros that is comparable in magnitude to measurements normally made by gyros on an MWD tool. Hence the present invention actually takes advantage of the misalignment to give reasonably accurate measurements of toolface angle.

Turning now to **FIG. 4**, the three major modes of operation are identified. The first is the surface calibration **401** wherein misalignment of the gyros is determined using methods discussed above with reference to **FIG. 3**. This step is not essential, but as described below, is helpful in what follows later in the wellbore. In the "survey mode" **403**, measurements are carried out at a substantially fixed position of the gyro assembly. The survey mode is followed by a "steering mode" **405** wherein the drillbit is actually making hole with the drillbit turning and powered by a mud motor. The survey mode is commonly used when additional sections of drillpipe are being added.

Turning now to **FIG. 5a**, some of the steps that could be carried out in the survey mode are discussed. It is to be noted that while these are described with reference to a flow chart, some of the "steps" identified need not necessarily be carried out in the sequence described. The only implication of a "sequence" of steps is if a particular operation requires the output of another operation. In all other cases, some of the operations could be carried out in parallel or even in a different order than that shown here. The "flow chart" is shown mainly as a matter of convenience to identify the different operations that could be carried out. A general guide to the operations is also given in a listing in the Appendix below. A static survey is initiated after a programmed delay **501**. The limits of mechanical travel of the housing carrying the sensors are determined **503** and a midpoint may be defined as the "zero"

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point **505**. Measurements are made with all the sensors on the survey assembly ( $x$ - and  $y$ - gyros,  $x$ -,  $y$ - and  $z$ - accelerometers and magnetometers if provided) at the “zero” position **507**. The indexing process is carried out as described in the *Estes* patents. In the indexing, measurements are made at the “zero” reading, and at  
 5  $\pm 20^{\circ}$ ,  $\pm 40^{\circ}$  and  $\pm 60^{\circ}$ , with a measurement taken at the “zero” mark each time **507**. It is not essential that these exact values be used, or even that such a number of measurements be made. Next, a polynomial fit is carried out to the measurements made by each of the plurality of sensors at the “zero” mark **511**. In an alternate embodiment of the invention, nine readings are taken  $40^{\circ}$  apart without repeating the  
 10 zero angle measurement.

The purpose of the polynomial fit is to determine any time dependent drift in the measurements made by the plurality of sensors. The cause of the drift may be temperature variation, though the cause of the drift is not important. This particular step merely identifies the drift if it exists. The order of the polynomial is less than or  
 15 equal to the number of points to which the polynomial is being fit. In an alternate embodiment of the invention, the sinusoidal fit and the drift compensation may be made simultaneously. A method of determining the correcting for the drift is discussed below with reference to **FIGS. 8-11**.

Having determined this drift as a function of time, it is then removed  
 20 from all the measurements made. This is indicated by **513** in **FIG. 5b**. Next, all the readings are corrected using laboratory determined model parameters **515**. This is discussed below with reference to **FIG. 6**.

Still referring to **FIG. 5b**, accelerometer based angular values are obtained for the static survey **517**. This includes a determination of high side tool face angle (HSTF), the inclination, and total gravity field (TGF). Next, a sinusoid is fit to  
 25 the measurements **519** using the corrected HSTF. The variables for the fit are the bias, Scale Factor, and phase. Gyro based angular values for the static survey are determined **521**. Bias values are calculated from sinusoidal fitting of the gyro measurements **523**). This is done separately for the  $x$ - and  $y$ - gyros. Next, the  $x$ - and  
 30  $y$ - rates are calculated at **527** in **FIG. 5c**. This is the end of the static survey **529**.

Turning now to **FIG. 6**, there is a further discussion of details of **515** in **FIG. 5b**. The operations involved include an application of a scale factor correction

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for the temperature at the final position **601**. A bias correction as obtained from the last survey is applied **603**. Misalignment corrections are applied **605** and gravity dependent bias corrections are applied to  $R_x$  and  $R_y$ .

Some details of the "steering" mode are next discussed with reference to **FIG. 7**. Sample readings are taken at a high rate, typically about 15Hz **701**. A moving average for the accelerometer raw readings is kept, typically over a one second time interval **703**. A new value of the  $R_z$  is determined for each sample **705**. These are done separately from the  $x$ - and  $y$ - gyros and the two values are averaged.

Still referring to **FIG. 7**, the  $R_z$  values are integrated with respect to time to find the change in the gyro toolface angle GTF **707**. The values derived for  $R_x$ ,  $R_y$ , and  $R_z$  by any method when the tool is at rest should read components of the earth's rotational field which always combine to produce the amplitude of the earth's known constant rotation rate of 15.04 degrees per hour. As a quality check, and to optimize results, the solutions can be iterated for the calibration terms and the multiple positions such that an optimal fit results in the minimum deviation from the ideal earth field values. This combined looping and iteration through the multiple positions and adjusting the calibration parameters to produce the optimum residual error in the earth field (gravity, magnetic, and/or rotational) follows the techniques disclosed in the SPE paper # 19546, by Estes & Walters, in 1989, and is commonly called "Total Field Calibration." This change in the gyro toolface angle (from the running integral) is added to original starting toolface **707** to give the current gyro toolface angle. A moving average for angular values is kept (typically over a 10 second interval) **709**. This is the "Steering Gyro TF" value that may be telemetered uphole for enabling steering decisions to be made. This is continued until timeout period has elapsed (~30 minutes) **711**, defining the end of the steering mode.

Turning now to **FIG. 8**, a method of correcting for temperature drift is discussed. Although all significant error terms are corrected by application of a lab-derived thermal model prior to the fitting of a sinusoid for computation of angular values, this model correction process is not complete. There are still residual errors that distort the ideal sinusoidal shape of the rate measurements vs the indexed positions. This is largely due to the practice of acquiring lab calibration data after thermal stabilization has occurred, while downhole operation at a survey station often

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occurs during thermally unstable conditions. It is desirable to save battery power, thus the survey station operation is often initiated after a period during which the gyro is turned off, and is now increasing in temperature. Usually, during rapid temperature rise, the gyro exhibits errors which are a function of temperature, although the  
5 temperature sensor has not yet reached the corresponding amplitude.

This method assumes that the measured gyro output signal, after applying the temperature correction factors, is a composite of a sine wave from the actual earth rate felt on the sensitive axis during indexing and a residual bias shift that responds linearly with temperature. The response is assumed to be near linear due to  
10 the small magnitude of temperature change over the indexing time period. These residual temperature-dependent errors are assumed to be primarily bias errors, since the majority of the other temperature-dependent errors have been compensated already by the thermal model coefficients. The gyroscope is known to have very large bias errors, which dominate the other errors. It is reasonable to assume that the  
15 errors left over are bias errors, and over a short temperature excursion that they are a linear function of temperature. A source of error is the fact that the gyro has a much smaller time constant than the temperature sensor, so that the gyro is responding to a temperature that is different from that indicated by the temperature sensor. Unlike all other temperature correction factors, scale factor and mass balances terms, for  
20 example, this temperature dependent bias is problematic to determine in laboratory calibrations over such a small temperature span and also reasonably straightforward to correct during the survey station computation.

**FIG. 8** shows the 'true rate' signal **801** that represents the ideal sinusoid which will always be the characteristic of the resulting rate applied to the gyro when  
25 the sensor housing is indexed. This is true in all cases when the gyro sensitive axis is not null to the earth rate. Additionally, it shows the 'temp drift', the temperature change **803** over the time required to position the housing. Due to the linear relationship of temperature change and bias shift, the characteristics of the 'temp drift' waveform are shared by the bias shift as well. Finally, 'total rate' (measured rate) is  
30 the composite **805** of the true sine gyro signal and the gyro bias shift as a result of temperature change.

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After acquiring the signal and applying the laboratory determined temperature correction factors, it is the 'total signal' that is actually measured. The present invention uses an iterative process that will progressively break apart the two components to extract the true sine portion of the signal. **FIG. 9** shows the measured 'rate' signal **821** and a sine wave **823** fitted to it using motor position as the x-axis. The fit error **825** is calculated and passed onto the next portion of the method. **FIG. 10** shows the same sine fit error **825** now plotted using the nominal temperature change measured by the temperature sensor as the x-axis. This error is now fitted with a linear fit **843**, using temperature change as the x-axis. This linear fit of the sine fit error is an approximation of the residual bias shift due to temperature change in the original signal and will be subtracted from the original signal during the next iteration of the method. The process is repeated if necessary, and the final result is shown in **FIG. 11** with the corrected gyro readings **851** as a function of angular position and the bias **853**.

The bias correction has been described above with reference to gyroscopic measurements. The bias correction method is equally applicable to other types of survey measurements, such as those made by accelerometers, that are also affected by bias and a temperature dependent bias. A downhole processor then controls the drilling direction based on the corrected gyroscope and accelerometer measurements.

Steering a drilling assembly during drilling operations often results in wild angular toolface swings as the bit slips and grabs the stratified rock formations. This results in turn rates on the z-axis with wide dynamic range. In typical operations, a misalignment of less than 1 milliradian results in the x- or y- axis signal being too small for detection of normal rates of rotation about the z- axis. An upper bound on the misalignment is set by the fact that with values greater than 100 milliradians, the x- or y- output signals may exceed the operating range of the A/D converter. A preferred range for use of the method of the invention is between 5 and 20 milliradians.

The invention has been described above with reference to surveying operations and drill-steering applications. The methodology described above may also be used for wireline applications, or for slickline survey instruments. For

wireline applications, the survey mode could be entered at any desired time rather than being limited to time periods when drilling is suspended, since drilling operations are not involved. It can also be used in a memory-based "gyro drop shot" configuration.

5                   While the foregoing disclosure is directed to the preferred embodiments of the invention, various modifications will be apparent to those skilled in the art. It is intended that all variations within the scope and spirit of the appended claims be embraced by the foregoing disclosure.

**What is claimed is:**

1. A method of using a two-axis gyroscope on a housing for determining a rate of rotation of said housing about a third axis, said two axes of the two-axis gyroscope being substantially orthogonal to each other, wherein said third axis has a small deviation from orthogonality relative to at least one of said two axes, said method comprising:

measuring an output of said two-axis gyroscope along said at least one of said two axes in response to said rotation about said third axis; and

determining from said output and a misalignment term, an estimate of said rate of rotation about said third axis using a relation of the form:

$$R_x = \frac{S_x}{F_x} - B_x - B_{xg} - M_x R_z$$

where  $R_x$  is the rotation rate of said housing about said third axis,  $S_x$  is said output of said gyroscope corresponding to said at least one axis,  $F_x$  is a calibration scale factor for said at least one axis,  $B_x$  is a bias for the at least one axis,  $B_{xg}$  is a bias term for said at least one axis that is gravity related,  $M_x$  is said misalignment term, and  $R_z$  is the z-axis rotation rate.

2. The method of claim 1 wherein said at least one of said two axes comprises both of said two axes, the method further comprising determining said rate of rotation by averaging measurements made by two components of said two-axis gyroscope in response to said rotation.

3. The method of claim 1 or 2 further comprising determining said misalignment term from measurements outside a borehole.

4. The method of any one of claims 1 to 3 further comprising correcting said measurements for a bias.

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Figures: -2- et 8 à 11

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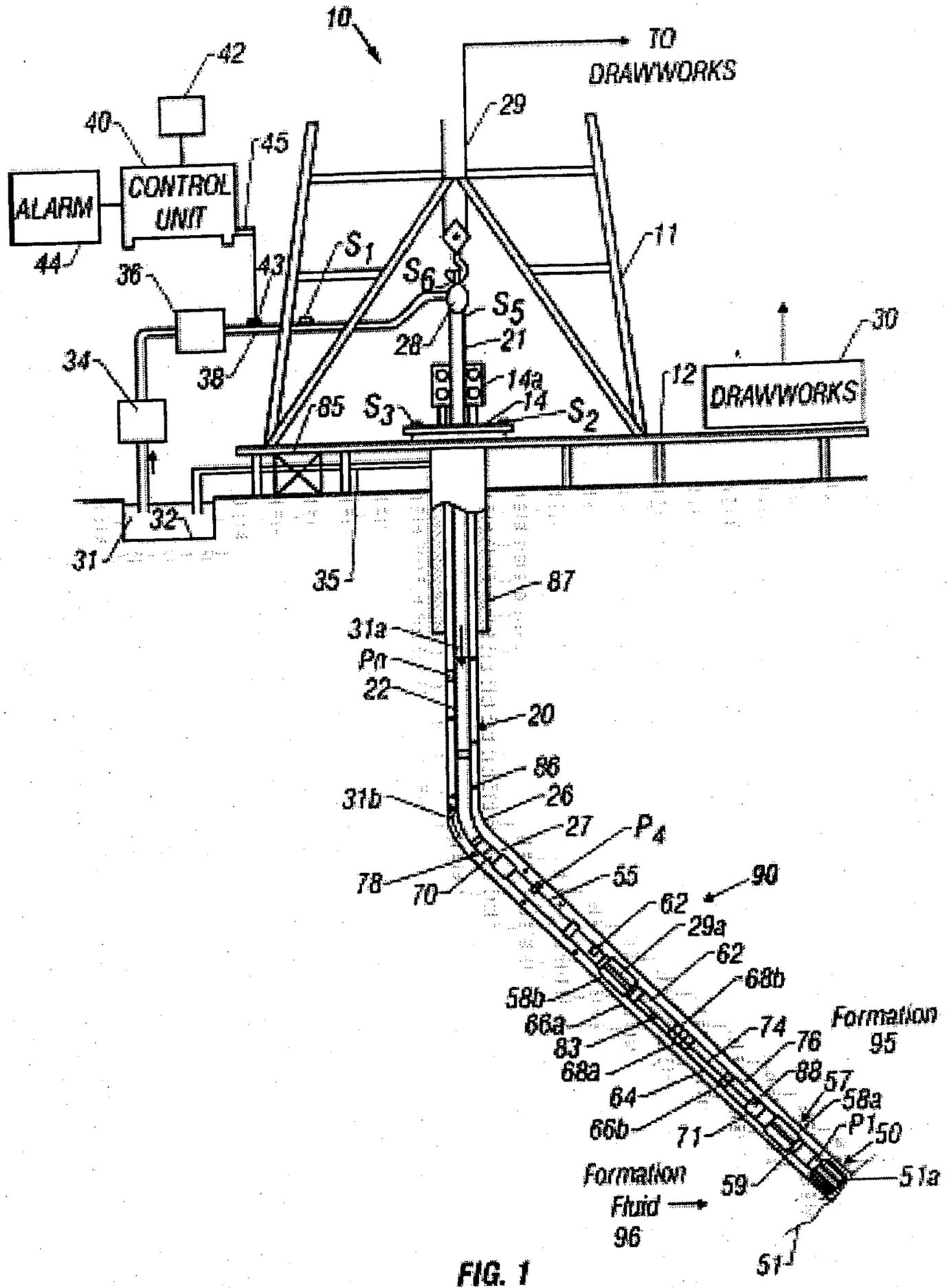


FIG. 1

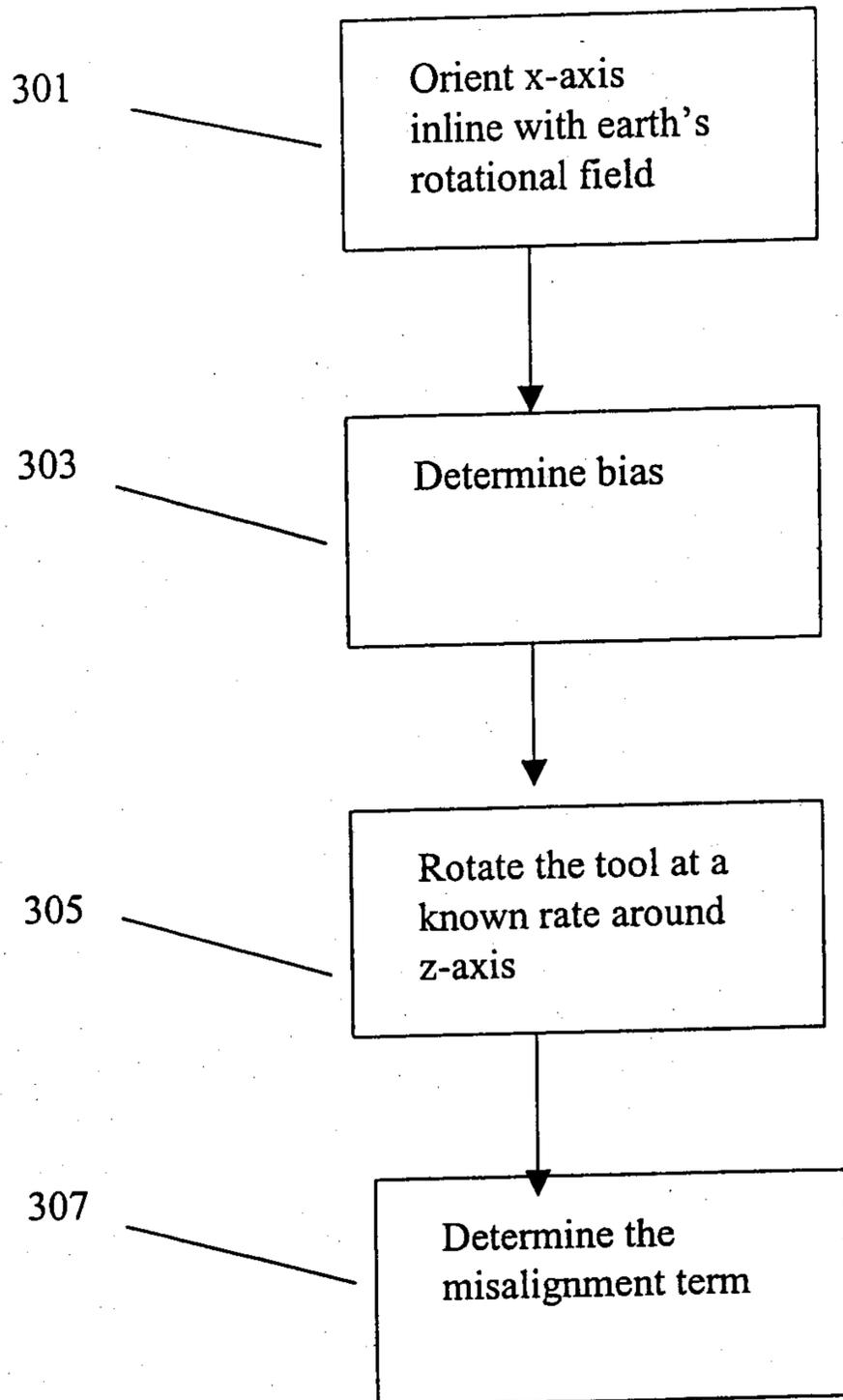


Figure 3

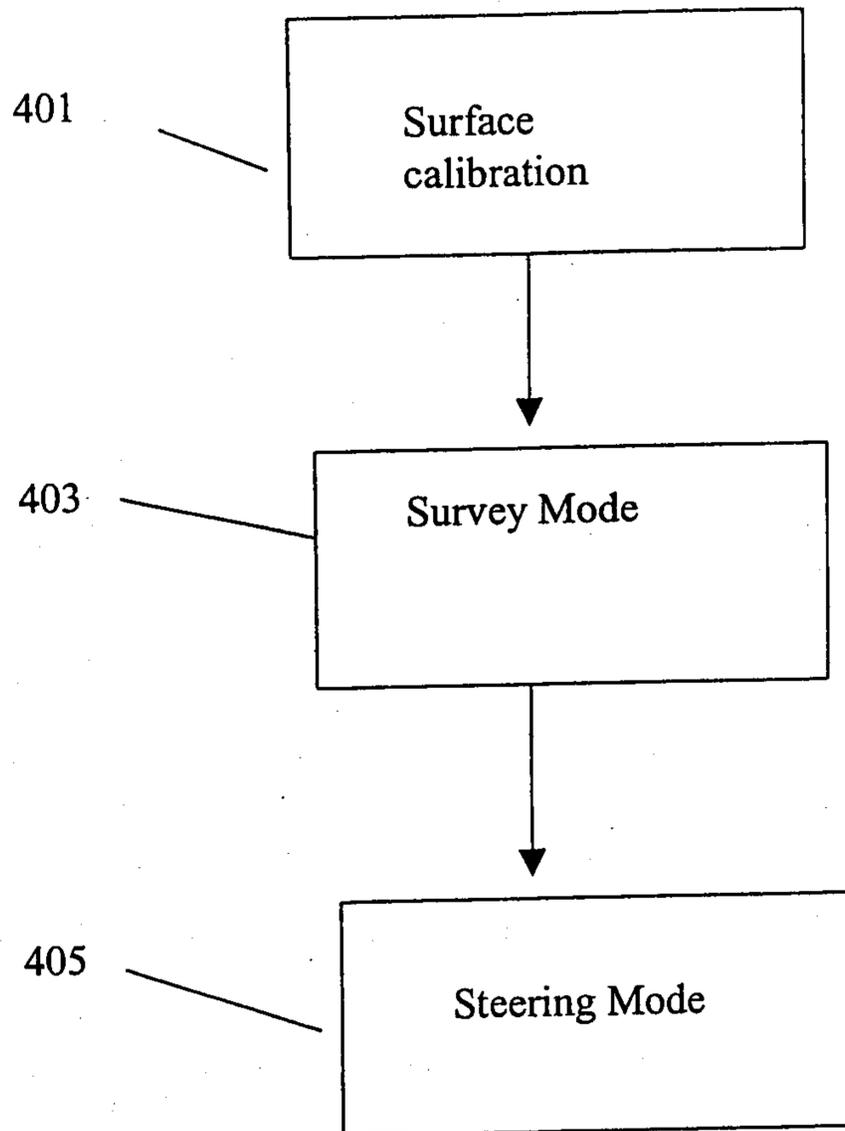


Figure 4

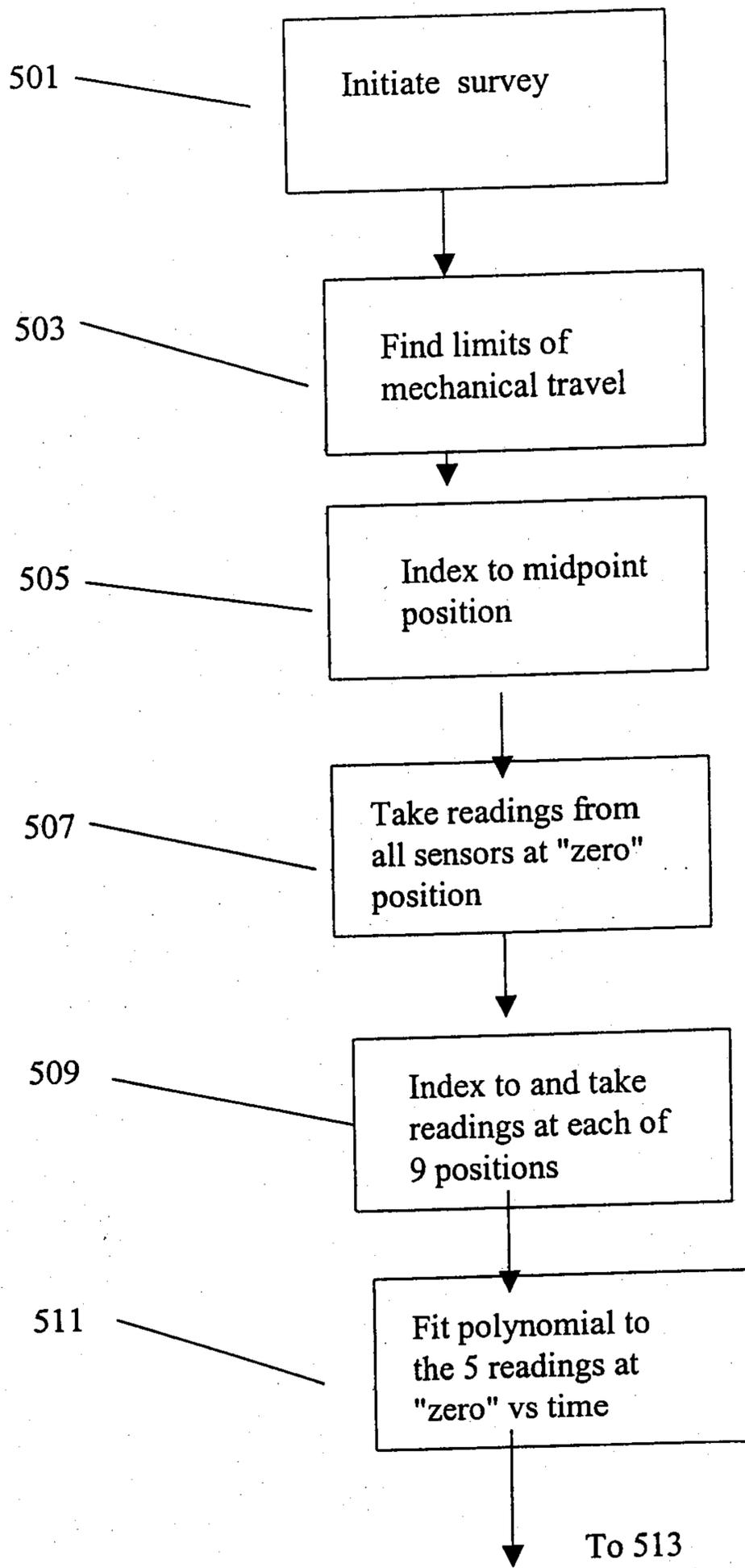


Fig. 5a

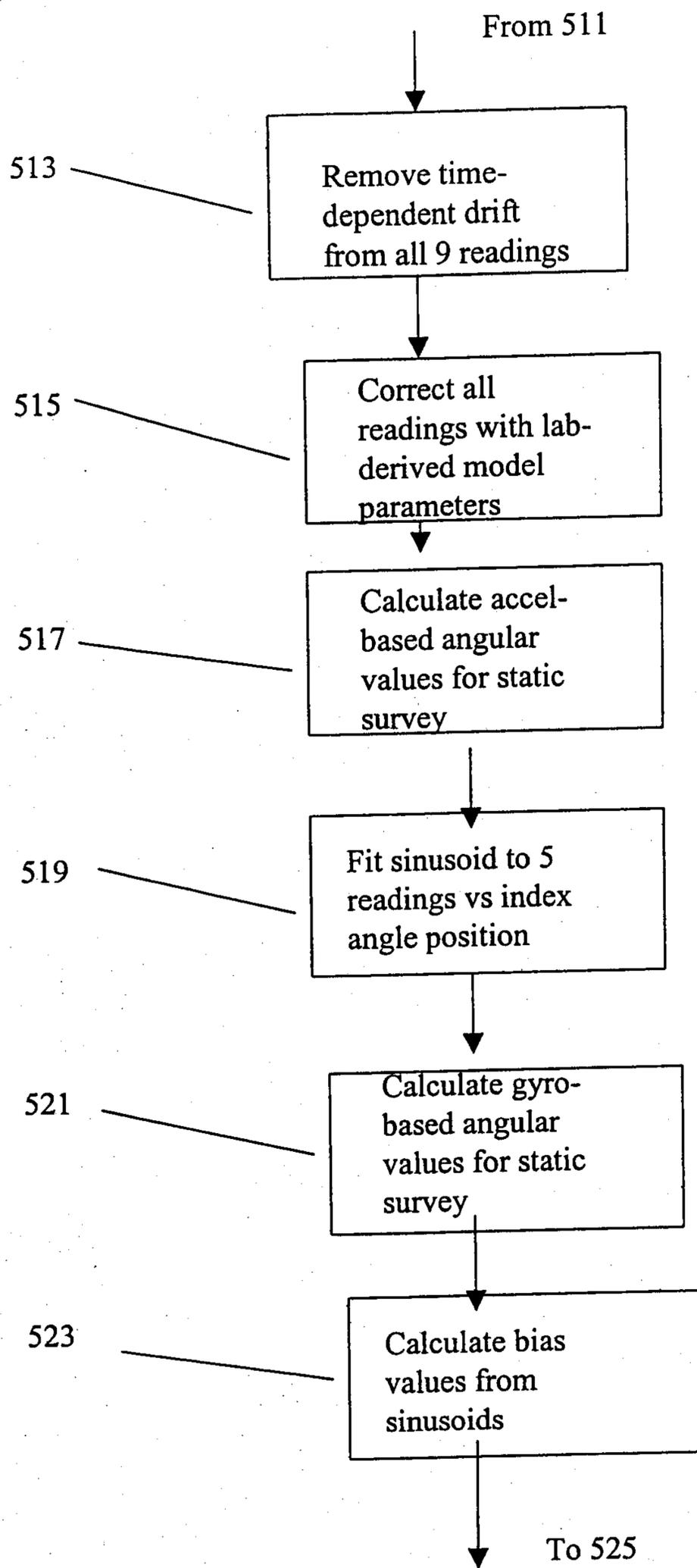


Fig. 5b

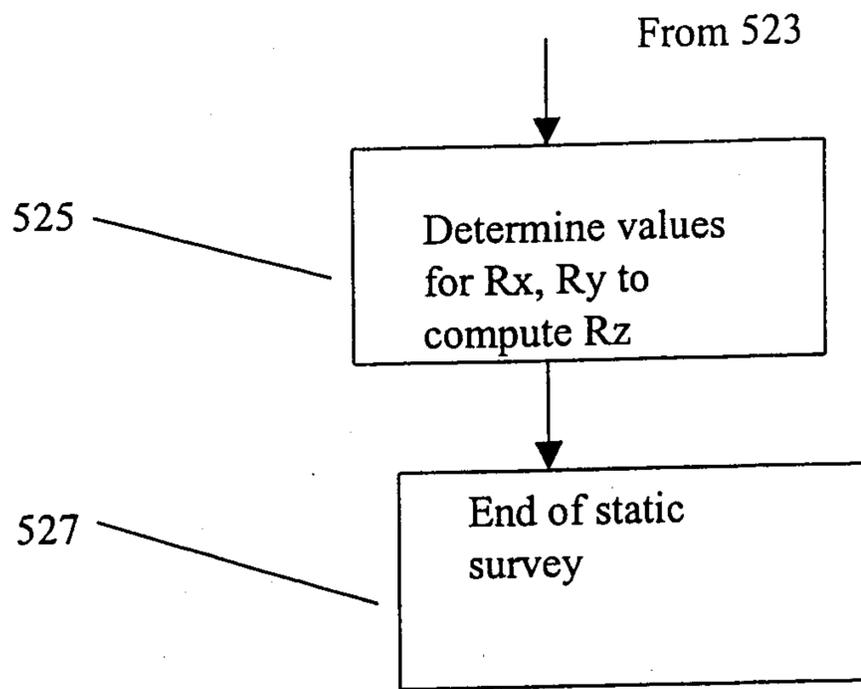


Figure 5c

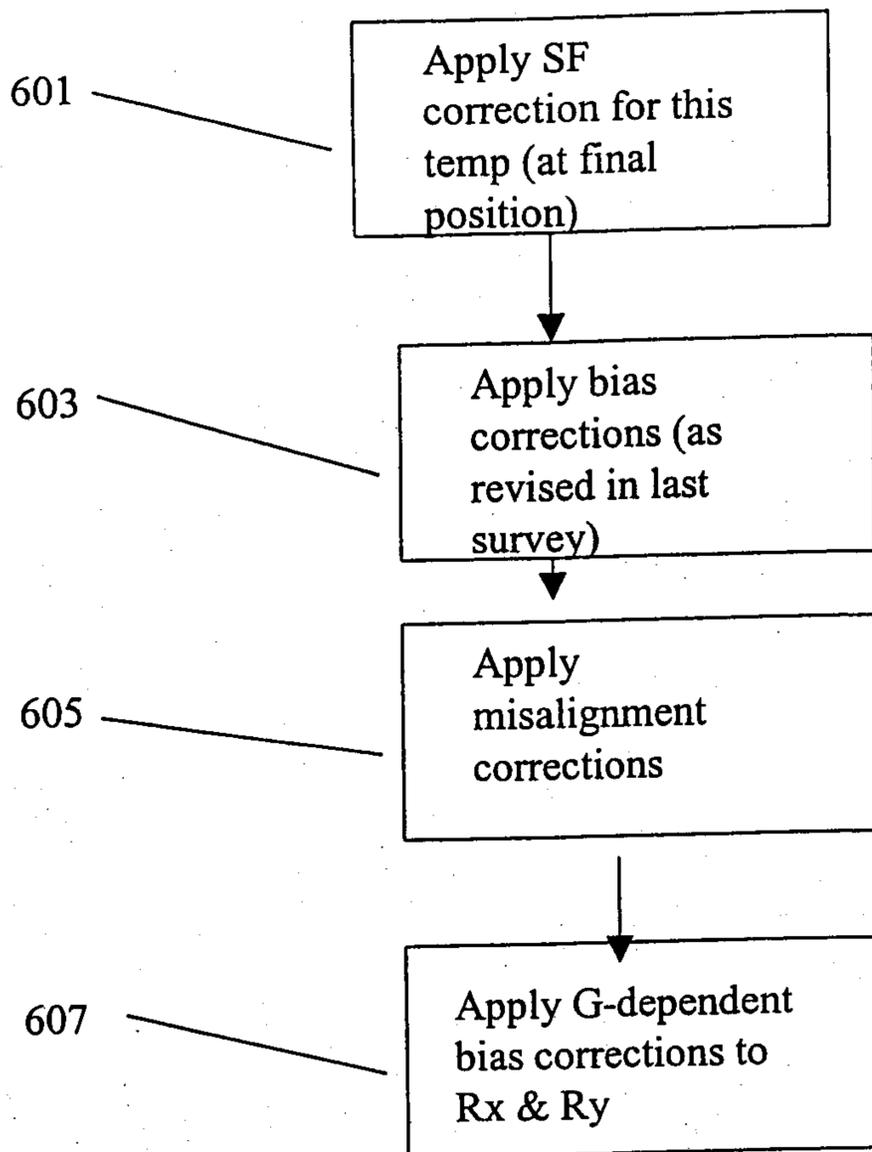


Fig. 6

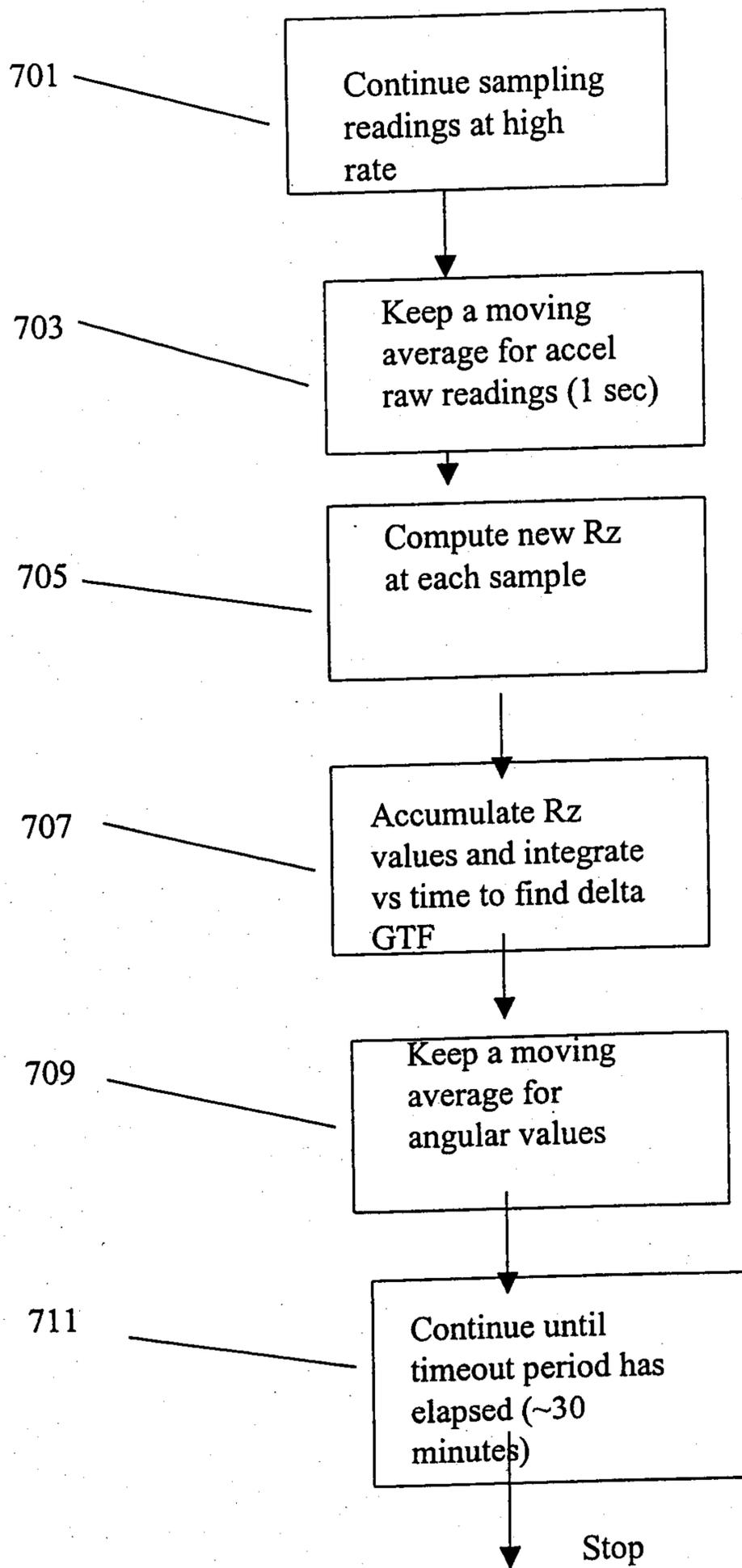


Fig. 7

301

**Orient x-axis  
inline with earth's  
rotational field**

303

**Determine bias**

305

**Rotate the tool at a  
known rate around  
z-axis**

307

**Determine the  
misalignment term**

