



A Gravity-Based Measurement-While-Drilling Technique Determines Borehole Azimuth From Toolface and Inclination Measurements

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Abstract

Gravity MWD™ is an innovative borehole surveying technique particularly operable in areas of high magnetic interference. In previous papers, the technique has been presented in general form. It allows for the determination of azimuth change using a pair of rigidly connected 3-axis accelerometers and does not require the use of magnetometers. Applications include determining well surveys in the presence of magnetic interference and the determination of the tool behavior in the lower portion of the bottom hole assembly. In these papers, the method was proved by experiment.

In this paper, a more theoretical basis of the concept is presented. It relies less on heuristic solutions to empirical data. This results in an improved, theoretically exact solution which is accurate over a large range of inclinations and of azimuth change. The two key assumptions in this method are that the two direction vectors of the tool at the two accelerometer locations are co-planar and that the tool and hole directions are the same. The azimuth change between the two accelerometer locations then depends only on the two inclinations and the toolface difference between the two accelerometers, both of which are determined solely by the accelerometer measurements.

It is also shown that the tool calibration may be accomplished at the surface. This calibration consists of a measurement of the relative orientation of the two accelerometer packages. The only remaining information needed to derive well surveys is a tie-in azimuth. The final theoretical result is an examination on the sources of error in the azimuth change determination and on various approximations that may be used.

Introduction

Traditional M/LWD surveying starts with the measurement of the inclination and azimuth (essentially a vector direction or unit-vector) at a discrete number of locations in the well bore, usually parameterized by the measured depth. The inclination is determined from a 3-axis accelerometer and the azimuth from a 3-axis

magnetometer. Care must be taken that the magnetometer is protected from magnetic interference through the use of an appropriate length of non-magnetic drill collars. A well trajectory type, typically a minimum curvature trajectory, is assumed connecting the surveys and allowing the evaluation of a continuous well path. A minimum curvature trajectory assumes that successive survey vectors are connected by the arc of a circle, tangent to both surveys, residing in a single plane, and with arc length equal to the course length between the two surveys.

An important assumption is that the tool vector measurement is an accurate reflection of the wellbore direction at each location. It may prove necessary to correct the individual measurements to account for the tool and the wellbore not being parallel. This type of correction, which is typically applied to the inclination only, is calculated in various manners and is attributed to the interaction of the tool elastic properties, gravity, and wellbore shape. It is generically known as a "sag" correction.

Proper survey design should take into account the assumed well shape. This is often not done. For example, Stockhausen and Lesso (2003) demonstrate that using a single minimum curvature assumption to evaluate a well path segment that encompasses a series of slide/rotate episodes leads to significant errors in the determination of the TVD of a typical well.

This paper presents Gravity MWD™, an alternate method of determining the inclination and azimuth without the use of a magnetometer. This is useful in those situations where the magnetometer values are suspect and for results near the bit (and motor) where magnetometers are inappropriate. Gravity MWD uses two rigidly connected 3-axis accelerometers embedded in a Bottom Hole Assembly (BHA) to simultaneously make 3-axis accelerometer measurements at two locations.

Toolface and Inclination

By limiting our instruments to accelerometers, two measurements may be made directly: inclination (hole

deviation) and gravity toolface (the angle between Top of Hole and a reference direction on the drill string e.g. Y-axis accelerometer). **Figure 1** shows a typical MWD sensor with the gravity based values shown. Inclination is shown as the angle the tool makes with the vertical gravity vector, G . The toolface is shown to be the rotation of the tool about its long axis with 0° the “high side” (vertical) direction.

This conventionally assigns pure build as 0° , a right turn to 90° , a left to -90° , and a pure drop as $\pm 180^\circ$. They are calculated using

$$\text{Inclination} = \tan^{-1} \left(\frac{G_z}{\sqrt{G_x^2 + G_y^2}} \right)$$

$$\text{Toolface} = \tan^{-1} \left(\frac{G_x}{G_y} \right)$$

where G_x , G_y , and G_z are the 3 accelerometer components, G_z being aligned parallel to the tool axis.

Toolface is used primarily during sliding using a bent sub and motor (when the drill string is not being rotated) or when using a 3-D rotary steering tool when controlling the force application to bend the tool in a controlled fashion. In the former case, the bent sub is aligned with the Y-axis accelerometer. During planning and drilling operations, the expectation is that orientation of the bend is aligned with the plane of the hole being drilled with the curvature being quantified as the dogleg severity.

This inclination and toolface are tool properties and are not, ipso facto, equal to the actual well path, especially when under load.

Actual well path, Holeplane, and Holeface

This distinction between prospective tool derived properties used during planning and drilling the well and actual well path derived retrospective properties dealing with the actual well path properties is an important one and one that is often confused. The result of well planning involving significant changes in azimuth is often presented as a series of desired surveys. In actuality, desired hole curvature (know as dogleg severity) and the orientation of the tool during sliding (toolface) are estimated by the directional driller and used in determining the tool parameters (weight on bit, tool bend, etc.) and orientation (toolface) for drilling operations.

As the well is drilled, it is important to determine the actual (retrospective) well path as distinct from the desired or planned well path. Inclination is measured in the same manner as discussed above though the measurement is usually made with the tool unloaded (in tension). This is to encourage better alignment of the

tool with the well. Even here, it is often still required to include the “sag” corrections mentioned in the introduction.

Making use of the toolface measurement to characterize the actual well path is much more problematic. The toolface is not connected in any manner to the well path and will vary as the tool is rotated. It is not possible to identify the apparent measured toolface directly with a well path property.

In the calculation of the actual wellpath, each section of the well path, delineated by successive surveys, is assumed to be a minimum curvature segment. Each segment resides on a plane. This is defined as the holeplane of that segment. Also under this minimum curvature assumption, it is possible to calculate a quantity from the surveys which is conventionally called a toolface (Sawaryn and Thorogood, 2003). It is desirable to distinguish this “computed toolface” from one that identifies the orientation of a tool. Thus the term “holeface” is introduced to emphasize that it is calculated from the well path.

Toolface and Holeface

What is the connection between toolface, which is measured, and holeface, which is calculated from successive surveys? The toolface will equal the holeface when the “scribe” line (reflecting the accelerometer Y-axis) is aligned with the holeplane. This is the identification assumed when planning and/or drilling with a bentsub-motor or 3-D rotary tool. In fact, this a priori identity is only an approximation; if it were exact there would be little need for surveying while sliding.

In fact, the actual holeplane is seldom so easily defined. When rotating, there is no a priori means of connecting the toolface and holeplane. It should, in fact, be assumed that the toolface and holeplane are not correlated.

Recall that the BHA design being proposed consists of two sets of rigidly connected 3-axis accelerometers, each capable of determining toolface. This arrangement is schematically shown in **figure 2**. The figure sketches two views of the assembly. The upper sketch emphasizes the inclination measurement; the lower the direction (azimuth) measurement. In both figures, the orientations of the gravity vector and accelerometer components are shown.

Ideally, while at rest (under no external stress) the X and Y components of each of the two accelerometers are perfectly aligned. In practice, they are not. This misalignment (the rotational correction) may be measured and used to correct the differential toolface. Rigidly connected accelerometers that have the rotational correction applied are considered aligned. As it is required that the rotational correction be fixed during a BHA run as well, it is important that the BHA be properly assembled.

A consequence of being “rigidly connected and

aligned” is that if the toolface and holeface at one accelerometer are identical, they will also be identical at the second location. This is not to say that the values are the same at both locations. In fact, a consequence of the minimum curvature path is that toolface/holeface varies along a wellpath. For example, in **table 1** a prospective wellpath is calculated with a 5° dogleg severity and an initial toolface of 45°. After only 100 ft, the toolface has changed to 39.58°.

More generally, if the toolface and holeface at one location of two rigidly connected and aligned accelerometers are different by some amount, the difference between the toolface and holeface at the second location will be different by the same amount.

This means that given two properly aligned and rigidly connected accelerometers, the change in toolface between the two locations is identical to the change in holeface between the same two locations.

Thus, available for use from two rigidly connected aligned 3-axis accelerometers are a course length, two inclination values, and a holeface difference (from the toolface difference). It turns out that this is sufficient to calculate the change in azimuth between the two locations. This contrasts with the standard methods where the azimuths are determined directly.

To summarize, the Gravity MWD tool consists of two rigidly connected 3-axis accelerometers with a fixed and measurable relative orientation. While the toolface measured is variable due to the random orientation of the tool, the difference in the toolface measured at the accelerometers, corrected using the rotational correction, will be independent of the tool’s rotation and is identical to the change in holeface.

Calculation of Azimuth Change

The Gravity MWD calculation problem is to use the change in holeface and two inclinations to determine an azimuth change.

It is important to remember that the minimum curvature segment between the two successive surveys is on a single plane. This plane is characterized by a maximum dip and the direction of maximum dip. For this calculation, the dip is important.

If the vector of interest has an inclination equal to 90° minus maximum dip, the vector direction is in the down dip direction and the inclination is the minimum inclination or this plane. Consideration shows that for any other inclination value, there are two directions possible, one for a left and one for a right handed curve.

The holeface at the part of the hole at the minimum inclination is always ±90°. Extending the curve to an inclination of ±90°, the holeface is equal to ±dip. Thus, knowing the dip of the plane and the two inclinations not only specifies that azimuth change between two inclinations but also the change in holeface. It turns out the combination of two inclinations and holeface change uniquely determines the dip of the plane which in term

allows for the determination of two azimuths and hence an azimuth change.

In practice, the azimuth change is solved directly from the two inclinations and holeface change. This is carried out numerically by calculating the holeface change from the two inclinations and an assumed azimuth change. The numerical method essentially adjusts the azimuth change until the calculated holeface change matches the observed holeface change.

To enhance understanding, it is often useful to graphically demonstrate this relationship. Three contour plots were chosen as exemplars.

Figure 3 shows the contours of change in azimuth for the case where the inclination at the upper accelerometer is 30°, the inclination at the lower accelerometer varies from 5° to 90° (the X axis) and the change in holeface (the measured change in toolface) ranges from -180° to 180° (the Y axis). Figure 3 is used to demonstrate that the primary dependence of azimuth change, at moderate inclinations, is on the holeface change with the lower inclination playing a subsidiary role.

Figure 4 shows contours of total dogleg calculated for the same conditions used for figure 3. It serves to emphasize that net changes between the two accelerometers are being determined. To derive the “rate” properties (dogleg severity, build rate, walk rate), it is necessary to divide the appropriate value by the distance (course length) between the two accelerometers. In addition, a characterization of the average near bit behavior may be achieved using this method. Another application is the creation of infill actual surveys.

Figure 5 is used to directly address the issue of sensitivity of the azimuth change measurement to the holeface change over a wide range of inclinations. Contours of the sensitivity, defined as

$$Sensitivity = - \frac{\Delta Azimuth}{\Delta Holeface}$$

are displayed. Note that the contour spacing changes for values greater than 3. For this display, the change in inclination is set at 1°. The upper inclination (X axis) varies from 5° to 85°. The holeface change (Y axis) is allowed to vary from -180° to 180° as in figure 3 and 4. Over a wide range of near vertical inclinations, the sensitivity to inclination is minor and the error in determination of holeface is equal to the azimuth error. As the well becomes more horizontal, this sensitivity increases as does the azimuth error.

Examination of the limitations of the method

This method only determines a change in azimuth. This is, in fact, a weakness of the method when compared with traditional MWD surveying. Whereas the

traditional measurements will apparently average out errors in the azimuth measurement, Gravity MWD is dependent on having an accurate tie-in for the azimuth.

1) Tie in Azimuth Reference Errors

The quality of the original survey (or tie-in data) is an important factor that can produce azimuth errors that are carried through to each additional survey. An error model has been developed to determine the quality of the tie-in data allowing Gravity MWD to absorb the errors and complete the planned well. The error model is used when planning the well and running anti-collision surveys for the well plan. As the reference survey represents the start point for subsequent Gravity MWD surveys, a reasonable level of confidence must be gained in the reference surveys before executing the method.

2) Chaining error Azimuth / Inclination errors

The Gravity MWD azimuth measurement technique uses the results of a previous survey as a reference for the next, with the consequence that errors may accumulate over many survey points. Although this is only thought to be a significant problem in long sections of well, a practical limit of 1000 ft of survey section is in current use.

Inclination errors are the same as those made using than standard MWD survey methods. In addition, the inclinations from each accelerometer are independently determined. As the surveying methodology often calls for occupying the same well location with each of the accelerometers, the presence of independent measurements of the inclination increases confidence in the result.

3) Tool Configuration.

Gravity MWD requires an MWD tool with two rigidly connected tri-axial accelerometers spaced a known distance apart. The X and Y axis of both accelerometers must be aligned perfectly before applying the technique. Both accelerometers are operated simultaneously and the data are transmitted to the surface in pairs.

4) Error Analysis in the Well Planning Stage.

Determination of azimuth at low inclination can be very error-prone. Therefore, it is often difficult to determine an accurate azimuth tie-in when kicking off at low inclination. At inclinations below 5° there can be large azimuth errors that appear to be unacceptable until they are translated to positional uncertainties in a well plan. Planning the well using the maximum amount of error (from the error model mentioned above) translates these errors into positional uncertainties that provide a clearer picture of the well plan error tolerance. The result is typically that what may appear to be a large error in azimuth translates to a very small amount of displacement uncertainty. These errors are small because the inclination is low and the uncertainty does

not grow until either the inclination increases or the Gravity MWD technique is carried out for 1000ft of net footage.

Once free of magnetic interference the hole is usually at a higher inclination. At this point the MWD tool lies more solidly against one side of the borehole wall giving a more accurate representation of the holes direction and inclination. It is standard practice to re-reference the Gravity MWD displacement points to the magnetic (vector measurement) survey at this point. The azimuth so determine becomes a tie-in for a reverse azimuth calculation, including a fresh determination of the initial azimuth. The result is a more accurate determination of the well path.

5) Random errors

Random errors are generally not critical, as they tend to even out across multiple surveys. Traditional surveying quality control procedures will detect random events such as tool movement during acquisition and mud pulse signal detection problems. Some of these methods include monitoring the total gravity measured and reviewing the raw data for each axis results. Potentially more serious error types are offset errors as they are accumulative. As mentioned above, unlike surveying with magnetometers or gyros, the Gravity MWD survey is derived from delta azimuth increments where the starting point is a known vector position. It is therefore very important to reduce any source of offset errors such as tool alignment, or tie-in errors as discussed above.

6) Sag Error Correction

Sag does not consider the accuracy of the survey instrument itself. Instead it is concerned with evaluating how the instrument is positioned geometrically in the borehole and how that position relates to the borehole inclination. Typically the structure and stiffness of the BHA are accounted for by calculating the effect of stabilizers at a number of different inclination angles. Because the Gravity MWD technique applies the use of two inclinometers which are a known distance apart and are placed at difference locations in the BHA, it is possible to gain a better understanding of how each inclinometer is oriented in the borehole. Given that each accelerometer will often be placed in the same borehole location as the other during the progress of the survey method, sag correction calculations can be reinforced with actual measured data from Gravity MWD. Results can then be more accurately calculated and applied to surveys.

Conclusions

Gravity MWD™ is a technique for evaluating azimuth variation using standard accelerometers in regimes where magnetometers are not useful. An indication of the mathematical basis of this technique has been given

with a discussion of the limitations and errors inherent in this procedure. Configuring the tool with two rigidly connected tri-axial accelerometers has removed the risk of alignment errors. Finally by examining the practical limitations of executing the method, procedures to mitigate systematic errors such as reference errors, sag errors, and tie-in errors have been developed. The Gravity MWD procedure has been applied in the field to more than 50 wells, providing a reliable method of positioning a well bore in the vicinity of casing where timely information on the near bit behavior of a BHA is required.

Nomenclature

TVD = true vertical depth

M/LWD = Measurement/Logging While Drilling

References

1. Stockhausen, E.J., and Lesso, W.G.: "Continuous Direction and Inclination Measurements Lead to an Improvement in Wellbore Positioning", paper SPE/IADC 79917 presented at SPE/IADC Drilling Conference held in Amsterdam, The Netherlands, 19–21 February 2003.
2. Sawaryn, S.J. and Thorogood, J.L.: "A Compendium of Directional Calculations Based on the Minimum Curvature Method", paper SPE 84246, presented at SPE Annual Technical Conference and Exhibition held in Denver, Colorado, 5-8 October, 2003.

Measured Depth (ft)	Inclination Dir. (deg.)	Azimuth (deg.)	Toolface (deg.)
1000	30.00	0.00	45.00
1010	30.36	0.70	44.40
1020	30.71	1.38	43.81
1030	31.08	2.05	43.23
1040	31.44	2.71	42.67
1050	31.81	3.35	42.12
1060	32.18	3.98	41.59
1070	32.56	4.60	41.07
1080	32.94	5.20	40.56
1090	33.32	5.80	40.06
1100	33.70	6.38	39.58

Table 1- Typical variation in Toolface for a 5° dogleg severity and an initial holeface of 45°.

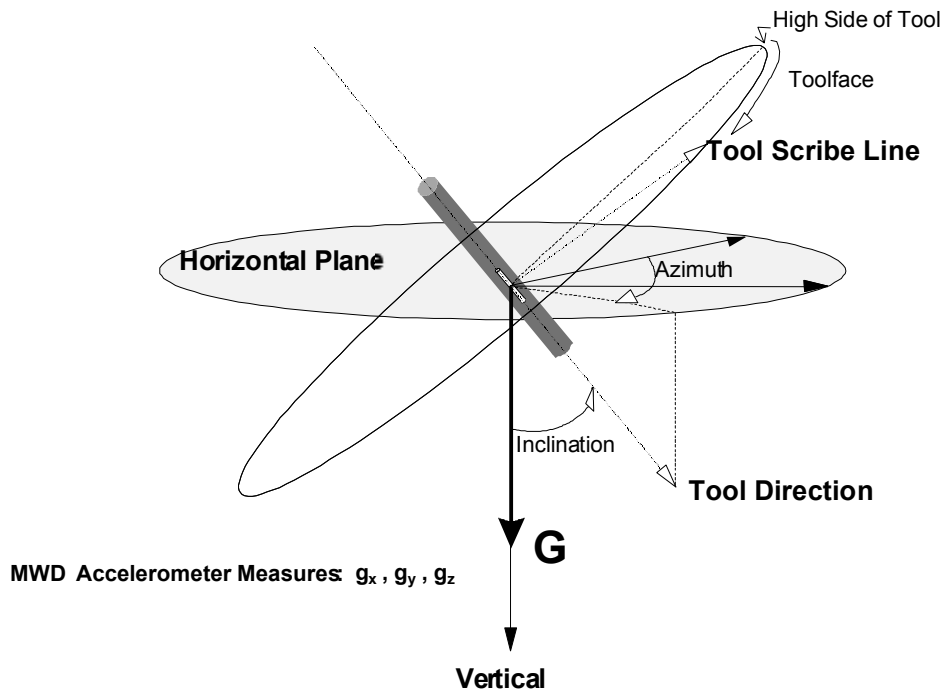


Figure 1 - The figure above shows an MWD sensor package within a drill collar, relative to the gravity field (G). The sensor measures three components of the G field along the tool's internal X, Y, and Z-axes. These components are then used to calculate tool inclination and rotation (toolface) angle.

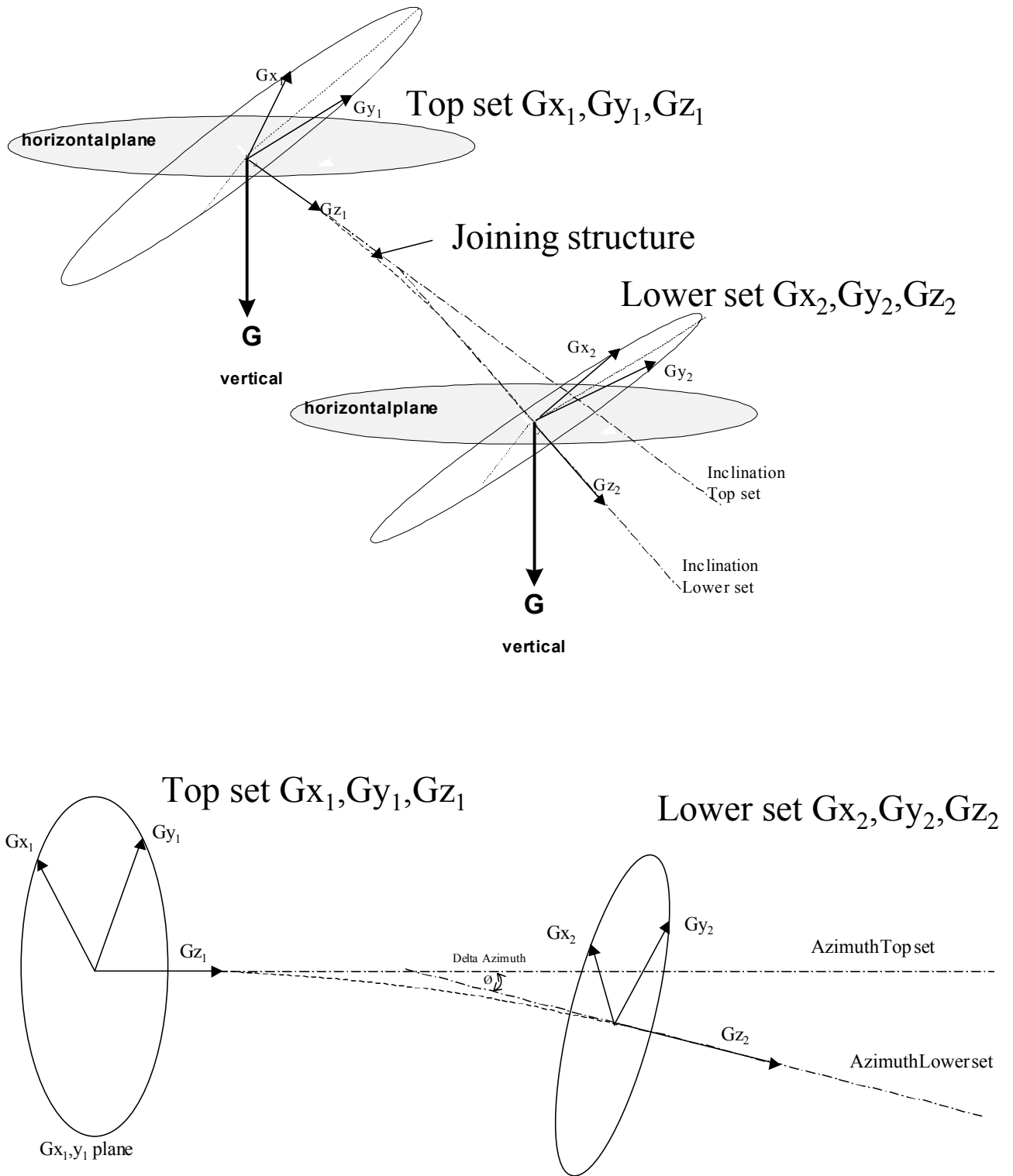


Figure 2 - Geometry of the dual accelerometer BHA used in the Gravity MWD procedure.

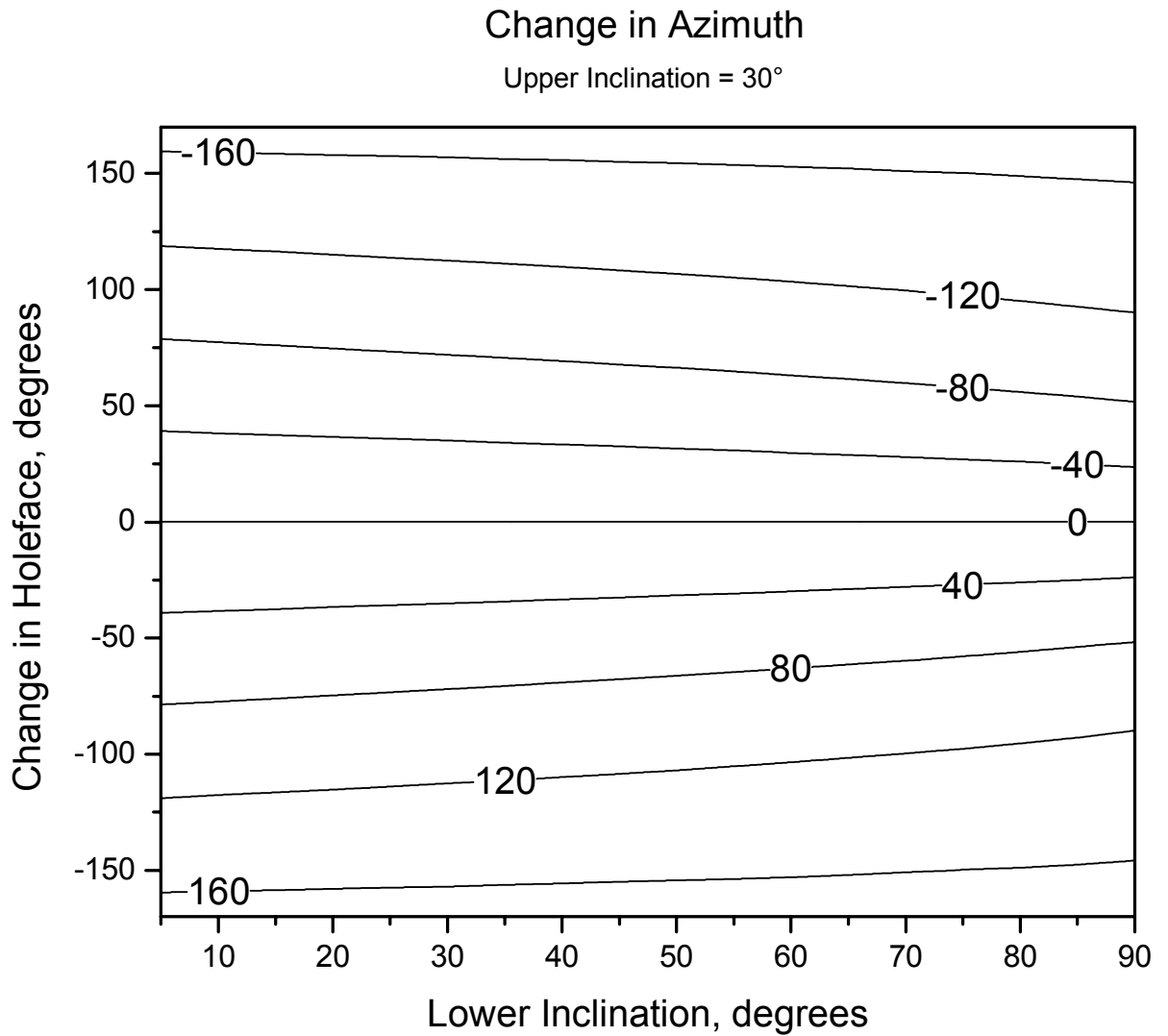


Figure 3 - Predicted change in Azimuth given an inclination at the upper accelerometer of 30° for a range of inclinations at the lower accelerometer and a range of holeface variation.

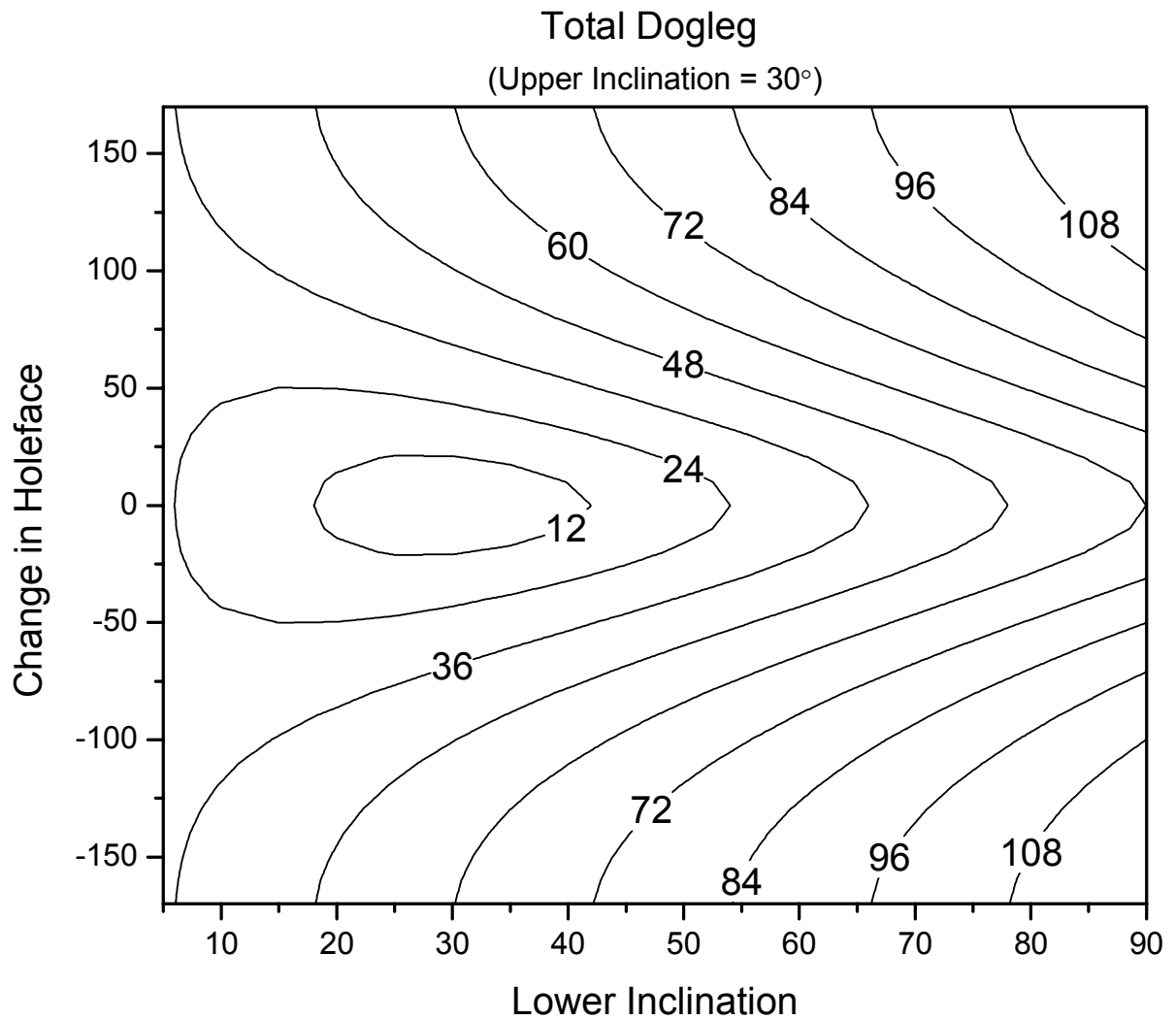


Figure 4 - Predicted Total Dogleg given an inclination at the upper accelerometer of 30° for a range of inclinations at the lower accelerometer and a range of holeface variation.

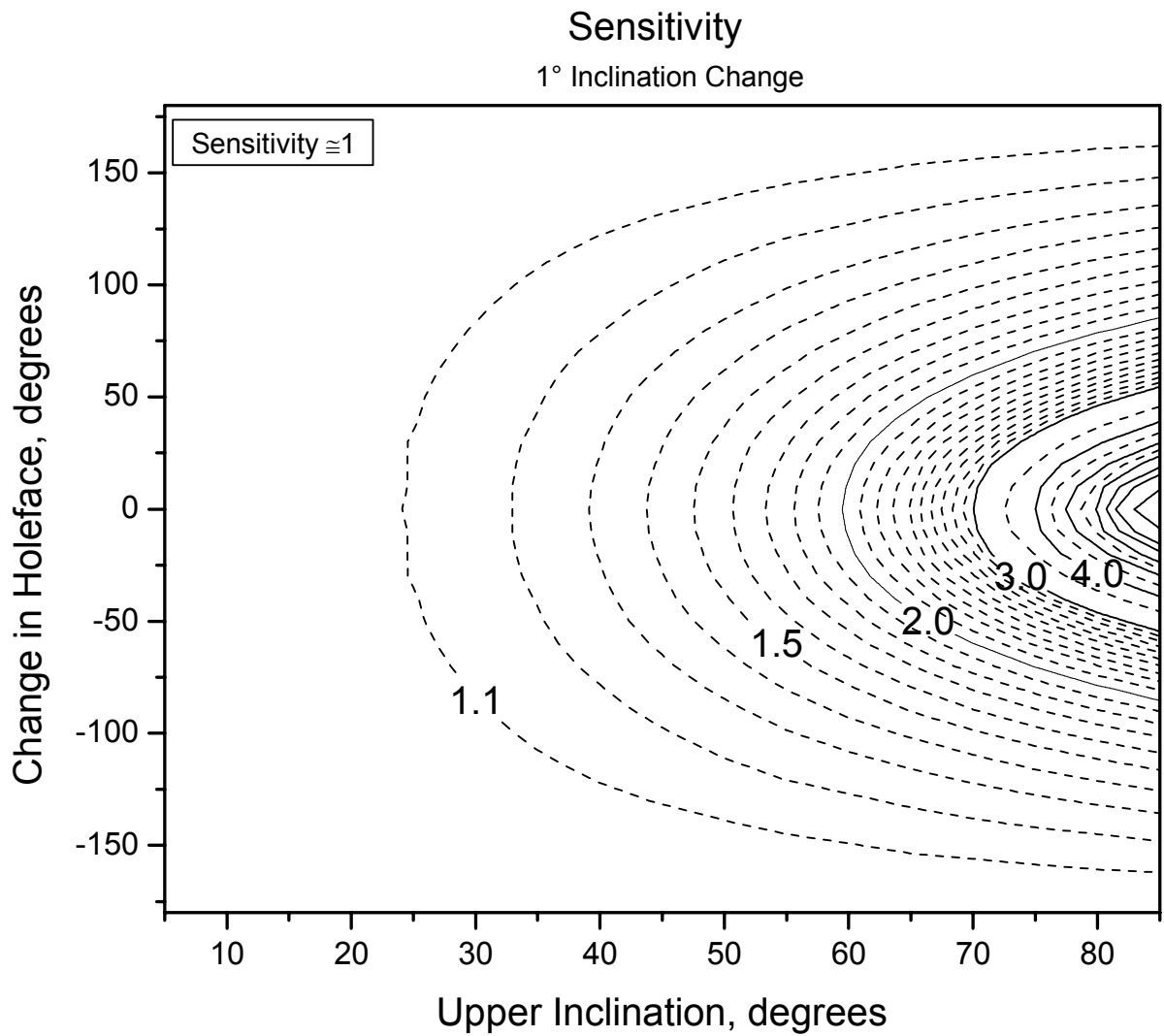


Figure 5 - Sensitivity (the ratio of azimuth to holeface change) of the determination of azimuth change for a range of upper accelerometer inclinations and holeface change for a 1° change in inclination.