

An Iterative Method To Measure Wellbore Azimuth While Drilling

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Abstract

An iterative method and algorithm is presented for measuring the azimuth angle of a borehole being drilled, the data for determining the azimuth angle is acquired from a previous standard (non-rotating) survey station and from data acquired while the drill-string is under rotation.

Introduction

Typical logging / measuring while drilling (L/MWD) technology utilizes the measurement of the x, y, and z components of the gravitational field (G) and magnetic field (H) while the drill-string is stationary in order to determine the inclination (I) and azimuth (A) of the wellbore. With the advent of rotary closed loop steerable (RCLS) technologies and subsequently the increasing complexity in well trajectories the need for accurate real-time while drilling azimuth and inclination data has magnified.

The iterative method introduced herein utilizes the known x, and y components (of G and H) from the last stationary survey point in concert with the z components (of G and H) acquired while rotating and drilling to solve for a new set of x and y magnetometer and accelerometer values.

The iterative method treats the x and y components (of G and H while rotating) as unknowns, and uses the fact that the z components (of G and H while rotating), the total field strength (of G and H), and the dip angle (the angle between the magnetic field and the plane tangent to the wellbores surface location) from the previous stationary survey point are known, to solve for the x and y components (of G and H while rotating). The result is a full set of tri-axial magnetometer and accelerometer data with preserved quality control measures of dip and total field strength which are then used to solve for the azimuth angle (A) while drilling. The crux of this method is that the orientation of the tools x and y measurement axis are treated as constant from the last stationary survey orientation (i.e. the “toolface” or “highside” remains the same) for the purpose of calculation of new x and y component values.

Related Work

Methods exist (Cobern et al.) to facilitate the determination of inclination and azimuth while the drill-string is being rotated, however their accuracy is limited due in part to: tool induced magnetic fields (from the internal circuitry and current flow needed to power components while drilling) which affect the measurement of the x, and y components of H while rotating, and drilling induced lateral vibrations which affect the measurement of the x, and y components of G while rotating. Additionally the method outlined by Cobern et al. requires both complex measurement and transmission of the “invariant” accelerometer and magnetometer components. The iterative method does not employ the

use of any x or y data obtained while rotating and thus both measurement and transmission are unnecessary. This reduces complexity, as well as design, maintenance, and repair costs.

Background

One begins with the raw values from the L/MWD tool being taken as a typical three-axis measurement system where the frame of reference is the wellbore and the z-axis is that of the wellbores path and that of the L/MWD tools rotation axis. The x and y axis are orthogonal to the z-axis and each other respectively.

Typically the raw accelerometer and magnetometer readings are transmitted via mud-pulse telemetry and calculations are performed at surface via computer. Surface calculations determine: total magnetic field strength (H_T), total gravitational field strength (G_T), the azimuth (A), inclination (I), and dip (D) based on the transmitted data. The “s” subscript denotes the data was acquired at a survey station.

$$(H_T) = \|H\| = \sqrt{H_{xs}^2 + H_{ys}^2 + H_{zs}^2} \dots\dots\dots (1)$$

$$(G_T) = \|G\| = \sqrt{G_{xs}^2 + G_{ys}^2 + G_{zs}^2} \dots\dots\dots (2)$$

$$(A) = \text{acosd} \left(\frac{G_{ys}(G_{ys}H_{zs} - G_{zs}H_{ys}) + G_{zs}(G_{xs}H_{zs} - G_{zs}H_{xs})}{\sqrt{(G_{ys}H_{zs} - G_{zs}H_{ys})^2 + (G_{xs}H_{zs} - G_{zs}H_{xs})^2 + (G_{xs}H_{ys} - G_{ys}H_{xs})^2}} \sqrt{G_{ys}^2 + G_{xs}^2}} \right) + \text{tac} \quad (3)$$

Where *tac* = total azimuth correction (i.e. local magnetic declination and grid convergence)

$$(I) = \text{acosd} \left(\frac{G_{zs}}{G_T} \right) \dots\dots\dots (4)$$

$$(D) = 90 - \text{acosd} \left(\frac{G_s \cdot H_s}{\|G_s\| \|H_s\|} \right) \dots\dots\dots (5)$$

Method

The iterative method begins with the raw x, y, and z component readings from the last stationary survey point: G_{xs} , G_{ys} , G_{zs} , H_{xs} , H_{ys} , and H_{zs} . It is imperative that this survey data passes the required quality control. The table 1 is comprised of actual survey data collected while drilling in the Gulf of Mexico.

MD ft	Degrees	Degrees	(m/s ²)	(m/s ²)	(m/s ²)	(nT)	(nT)	(nT)
Depth	Inclination	Azimuth	G_{xs}	G_{ys}	G_{zs}	H_{xs}	H_{ys}	H_{zs}
11580	17.3367	119.3685	1.31154	-2.60729	9.34936	29736	-11511	32735

Table 1 Raw survey station data and calculated inclination and azimuth (*TAC* = -1.56°).

Once rotation (and thus drilling) begins the L/MWD tool telemeters readings from the directional sonde namely G_z and H_z . The first step is to determine the change in inclination (ΔI), the difference between the survey station inclination and the current inclination as measured at the directional sonde.

$$(\Delta I) = I_s - \arccos\left(\frac{G_z}{G_{Ts}}\right) \dots\dots\dots (6)$$

Table 2 is comprised of actual data collected while drilling in the Gulf of Mexico. Column 1 is the depth that the rotating data in columns 2 and 3 was acquired. Columns 4 – 9 are the raw survey data as noted in columns 4 – 9 of table 1 from the prior survey station at 11580 feet measured depth (MD).

MD ft	(nT)	(m/s ²)	(m/s ²)	(m/s ²)	(m/s ²)	(nT)	(nT)	(nT)
Depth	H_z	G_z	G_{xs}	G_{ys}	G_{zs}	H_{xs}	H_{ys}	H_{zs}
11650	32820.6016	9.3441	1.31154	-2.60729	9.34936	29736	-11511	32735

Table 2 Raw survey station data from 11580 MD and Z-axis magnetometer / accelerometer readings from 11650 MD.

The next step is to rotate all of the raw survey station data about a line which is orthogonal to the gravity field (as measured by the tool) and which lies only in the xy plane of the tools measurement axis. This line can be computed as follows and the result can be proven as orthogonal by verifying the dot product between $\{G_{xs}, G_{ys}, G_{zs}\}$ and $\{u, v, w\} = 0$.

$$* \{u, v, w\} = \left\{ \frac{G_{ys}/G_{xs}}{\sqrt{1^2 + G_{ys}^2/G_{xs}^2}}, \frac{-1}{\sqrt{1^2 + G_{ys}^2/G_{xs}^2}}, 0 \right\} \dots\dots\dots (7)$$

**This equation varies slightly depending on the sign combination of the x and y accelerometer components, here the solution for both components being > 0 is shown.*

The rotation of the vector components is achieved via the rotation function defined as follows:

$$f(u, v, w, x, y, z, \Delta I) = \begin{bmatrix} u(ux+vy+wz)(1-\cos(\Delta I)) + x\cos(\Delta I) + (vz-wy)\sin(\Delta I) \\ v(ux+vy+wz)(1-\cos(\Delta I)) + y\cos(\Delta I) + (wx-uz)\sin(\Delta I) \\ w(ux+vy+wz)(1-\cos(\Delta I)) + z\cos(\Delta I) + (uy-vx)\sin(\Delta I) \end{bmatrix}^T \dots\dots\dots (8)$$

Where u , v , and w are defined by equation (7), the x , y , and z 's are the survey station components from the last stationary survey point: G_{xs} , G_{ys} , G_{zs} , H_{xs} , H_{ys} , H_{zs} . and ΔI is defined by equation (6).

Application of equation (6) using the data shown in table 2 yields: $\Delta I = -0.1030^\circ$.

Application of equation (7) using the data shown in table 2 yields: $\{u, v, w\} = \{-0.8933, -0.4494, 0\}$.

Application of equation (8) on G_{xs} , G_{ys} , G_{zs} , H_{xs} , H_{ys} , and H_{zs} . using $\Delta I = -0.1030^\circ$, and with $\{u, v, w\} = \{-0.8933, -0.4494, 0\}$ yields:

(m/s ²)	(m/s ²)	(m/s ²)	(nT)	(nT)	(nT)
G'_{xs}	G'_{ys}	G'_{zs}	H'_{xs}	H'_{ys}	H'_{zs}
1.3191	-2.6223	9.3441	29762	-11564	32692

Table 3 Survey data that has been rotated by ΔI about $\{u, v, w\}$ by the application of equation (8).

It should be noted that the z component of the rotated survey station gravity vector G'_{zs} is equal to the rotating G_z that was acquired at 11650 MD. This confirms we have rotated the vectors by ΔI , and the G_z value has been converged upon.

The next step is to iteratively rotate the vectors (G' and H') about the tool axis (i.e. the gravity vector) until the H_z value has been converged upon. During this process none of the G (gravity vector) components will change due to the fact that we will be rotating about the axis of the tool in the reference frame of the gravity field. This line can be computed as follows and the result is easily shown to be parallel to the tools axis.

$$\{q, r, s\} = \frac{\{G'_{xs}, G'_{ys}, G'_{zs}\}}{\|G'_{ts}\|} \dots\dots\dots (9)$$

This step relies on the same rotation function with the new function inputs $\{q, r, s\}$ and rotation angle θ . The iteration can be handled in a manner that the algorithm loops until the absolute value of the difference between H_z and H''_{zs} is significantly small, in other words we have iteratively rotated each vector until the z component of the rotated survey data converges upon the measured H_z .

$$f(q, r, s, x, y, z, \theta) = \begin{bmatrix} q(qx+ry+sz)(1-\cos(\theta)) + x\cos(\theta) + (rz-sy)\sin(\theta) \\ r(qx+ry+sz)(1-\cos(\theta)) + y\cos(\theta) + (sx-qz)\sin(\theta) \\ s(qx+ry+sz)(1-\cos(\theta)) + z\cos(\theta) + (qy-rx)\sin(\theta) \end{bmatrix}^T \dots\dots\dots (10)$$

Where q, r , and s are defined by equation (9), the x, y , and z 's are the rotated survey station components: $G'_{xs}, G'_{ys}, G'_{zs}, H'_{xs}, H'_{ys}, H'_{zs}$, and θ is the desired rotation increment ($\pm 0.1^\circ$).

Table 4 shows the resulting H''_{zs} converges on the measured value of H_z . As shown below the function was called 12 times and the resulting azimuth was found to be 118.28° . It should be noted that the looping criteria (the absolute value of the difference between H_z and H''_{zs}) was set at ± 10.0 nT.

#	(nT)	(nT)	Degrees	Degrees
Iteration	H_z	H''_z	Azimuth (Rotating)	Dip
1	32821	32703	119.28	56.927
2	32821	32713	119.19	56.927
3	32821	32723	119.10	56.927
4	32821	32733	119.00	56.927
5	32821	32743	118.91	56.927
6	32821	32754	118.82	56.927
7	32821	32764	118.73	56.927
8	32821	32774	118.64	56.927
9	32821	32784	118.55	56.927
10	32821	32795	118.46	56.927
11	32821	32805	118.37	56.927
12	32821	32815	118.28	56.927

Table 4 Enumerated results of iterative call to equation (10) where $\theta = \pm 0.10^\circ$ with rotation about $\{q, r, s\}$ defined by equation (9).

Table 5 is comprised of the original survey components, the final components of the rotated vectors after convergence on the z components of G and H, and the next set of survey components at 11713.

MD ft	Degrees	Degrees	(m/s ²)	(m/s ²)	(m/s ²)	(nT)	(nT)	(nT)
Depth	Inclination	Azimuth	G _{xs}	G _{ys}	G _{zs}	H _{xs}	H _{ys}	H _{zs}
11580	17.3367	119.3685	1.3115	-2.6073	9.3494	29736	-11511	32735
Depth	Inclination	Azimuth	G'' _{xs}	G'' _{ys}	G'' _{zs}	H'' _{xs}	H'' _{ys}	H'' _{zs}
11650	17.4396	118.28	1.3191	-2.6223	9.3441	29801	-11106	32815
Depth	Inclination	Azimuth	G _{xs}	G _{ys}	G _{zs}	H _{xs}	H _{ys}	H _{zs}
11713	17.4323	119.86	2.1280	2.0226	9.3441	2628	31935	32678

Table 5 Comparison of survey station data vector components to components acquired via iterative method.

These final values (with the double prime notation) are then used as inputs to equations (1-5) to verify the validity as well as the results of the iterative method. Table 6 compares the results of the stationary survey with the results of the iterative method.

Comparison Data	11580 Survey (G _s & H _s)	11650 Rotated (G'' H'')	11713 Survey (G _s & H _s)
H _T (nT)	45698	45698	45767
G _T (m/s ²)	9.7943	9.7943	9.7944
Azimuth (Degrees)	119.368	118.268	119.86
Inclination (Degrees)	17.337	17.44	17.43
Magnetic Dip (Degrees)	56.927	56.927	56.902

Table 6 Quality control comparison on survey station data vector components and components acquired via iterative method. Advantage AZRB at 11650 ft MD = 118.2356°.

Performance Experiments

To properly compare the iterative method versus the current methods, sets of data with specific qualities must be analyzed. The method must be able to perform in situations that pose difficulty, for example the areas such as drilling due magnetic north or south inclined within +/- 5° of parallel to the magnetic field (the “no go” zone), and 3 dimensional well paths where simultaneous changes in inclination and azimuth occur. The goal is to be as accurate as possible over a wide array of wellbores. The scope of the performance experiments includes the following data sets.

- A moderate 3-D well, drilled in the Gulf of Mexico spring 2015.
- A 3593 - foot interval calculated using a single stationary survey point.
- A “no go” zone well, drilled in the Gulf of Mexico winter 2015.

Figure 1 below overlays the current rotating azimuth (AZRB i.e. Rotaz) and the azimuth obtained via the iterative method (New Rotaz) as well as survey data at stationary survey points. The moderate 3-D well was drilled in the Gulf of Mexico in spring of 2015.

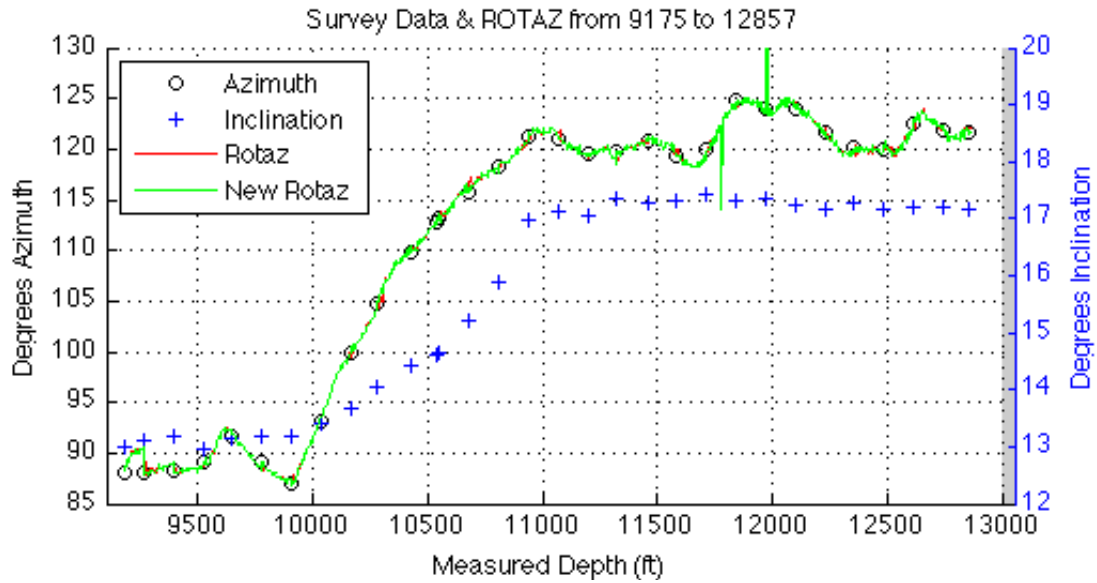


Figure 1 Survey data and Rotaz comparison plot where New Rotaz is Iterative method.

Figure 2 breaks the same data set into smaller intervals such that the data overlay can be viewed intensively. As shown in figure 2, the iterative method proves to be precise in terms of tracking AZRB, however the accuracy for both AZRB and the iterative method cannot be determined with certainty as the actual wellbore azimuth between survey stations is unknown. The plots highlight the performance of both calculations with respect to the definitive stationary survey stations.

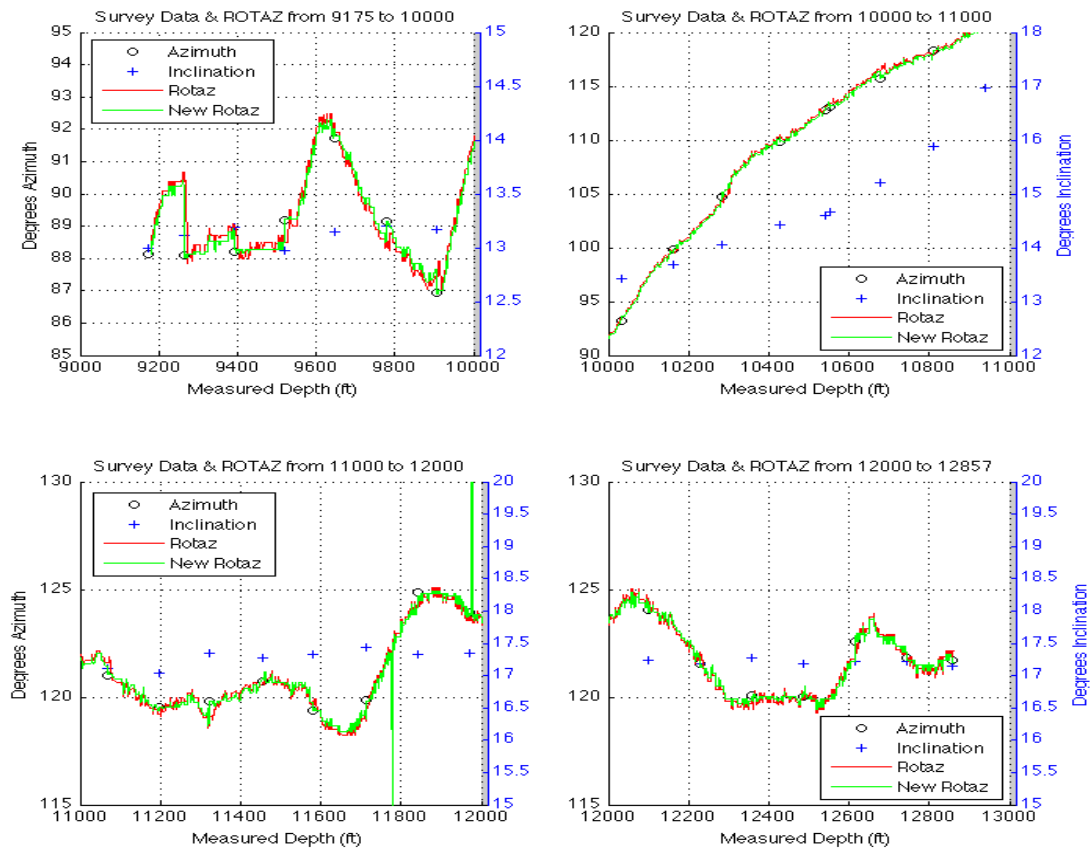


Figure 2 Survey data and Rotaz comparison plots where New Rotaz is Iterative method.

In effort to determine the amount of error as a function of depth (distance away from a stationary survey point) the iterative method was used to calculate an entire runs worth of azimuth data from an initial survey point. This experiment was performed using the same data set as figures 1 and 2. The survey point used was at 9264 feet MD and the calculation throughout (9264 – 12857 feet MD) was based solely on this singular stationary survey point.

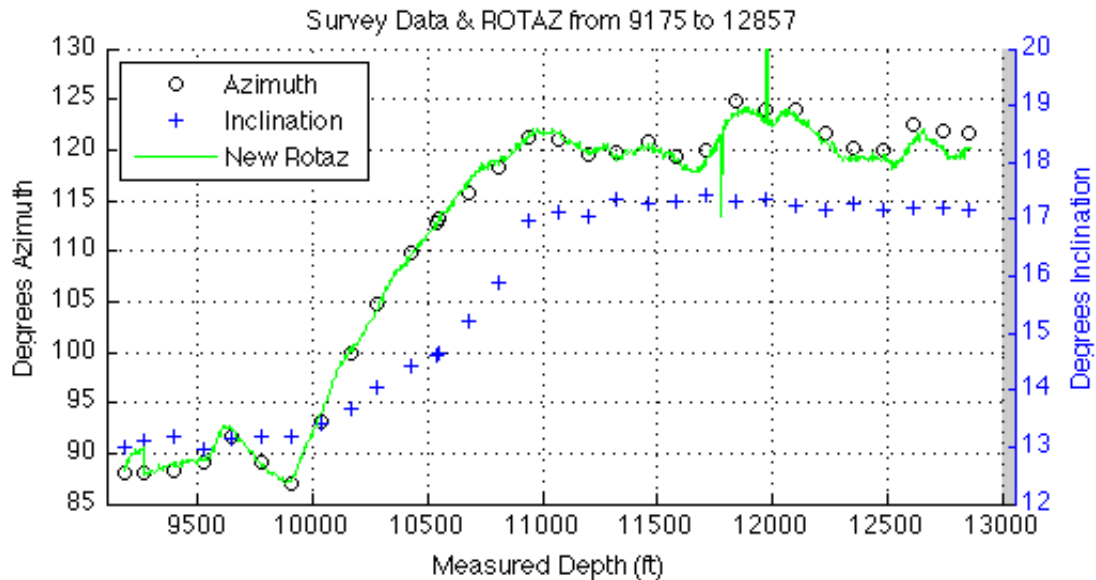


Figure 3 Survey data and Rotaz comparison plot where New Rotaz is Iterative method, and only the initial survey at 9264 feet MD was used until 12861 feet MD.

As seen in figure 3, the iterative method proves accurate over long intervals. After drilling 3593 feet (without an update to the stationary survey data) the difference between the survey station and the iterative methods calculated rotating azimuth at 12857 feet MD is $121.72^\circ - 120.25^\circ$ or 1.47° .

Furthermore the previous single survey experiment can be used to simulate the performance of the iterative method for rigorous 3-D well paths where simultaneous changes in inclination and azimuth occur. With that said it should be noted that over a single survey interval that was not 3500 feet (as above), the iterative method would likely prove much more accurate than 1.47° . This argument is given as an example only.

The final performance experiment performed was an analysis of the iterative method upon a data set obtained while drilling a well path that intersected the “no go” zone. This well was drilled in the Gulf of Mexico in winter 2015.

As shown in figure 4, the iterative method proves to be precise in terms of tracking AZRB, the accuracy however for both AZRB and the iterative method cannot be determined with certainty as the actual wellbore azimuth between survey stations is unknown. What is known is that the iterative method produced consistent results (with respects to AZRB and the actual survey data) throughout the “no go” zone.

Note that for over 60 ft (4918 – 4978 ft. MD) the current method used to determine the rotating azimuth (AZRB) failed to calculate a rotating azimuth, however the iterative method had no issues. This may be due to the fact that the “invariant” values needed for other methods approach zero as the tool orientation is parallel to the magnetic field. The iterative method simply converges on the correct z components of G and H and thus all components of G and H are known.

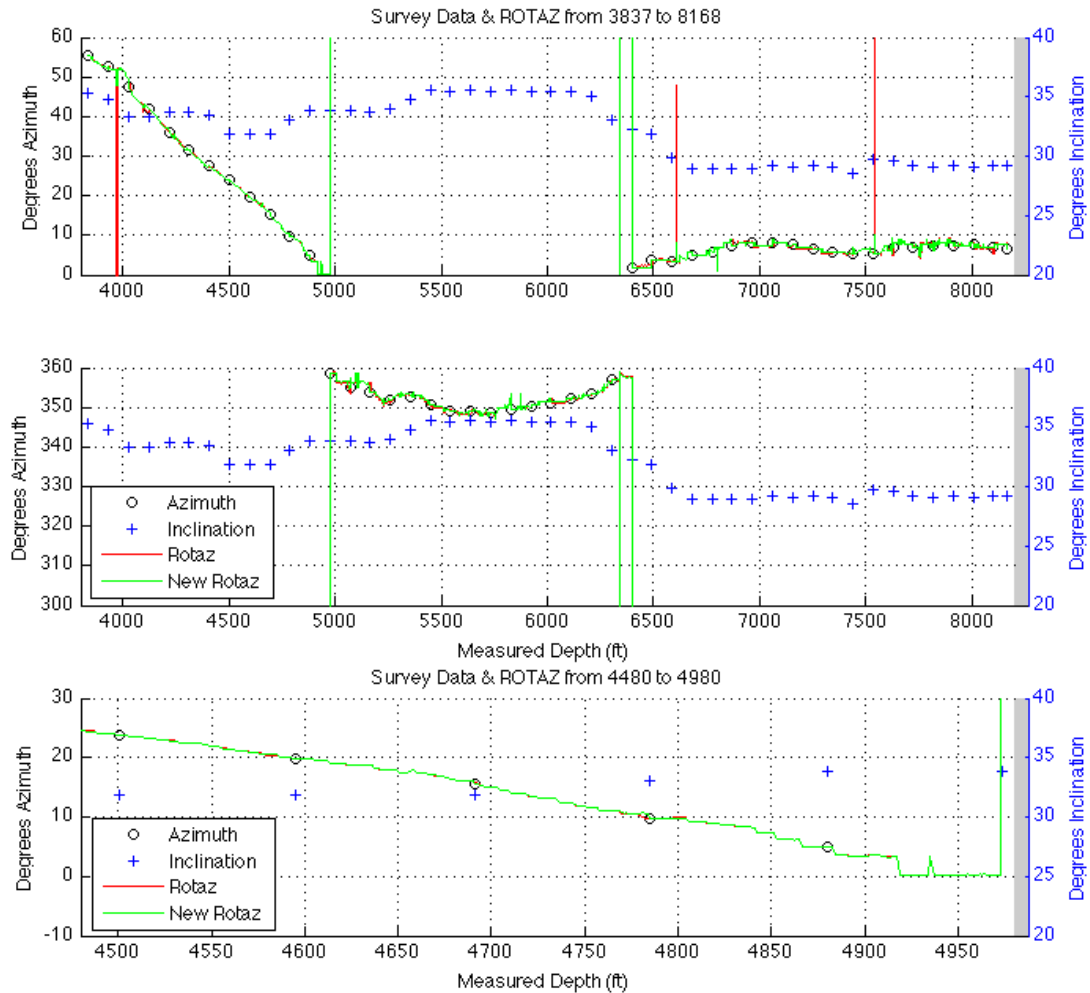


Figure 4 Survey data and Rotaz “no go” zone comparison plot where New Rotaz is Iterative method. The lowermost subplot covers the interval where AZRB fails and the iterative method converges.

Conclusions

It has been shown that the iterative method proves an effective and improved method for measuring the wellbore azimuth while rotating. This ability can be implemented in many ways, such as:

- Improvement of azimuths while drilling enables more precise control of RCLS system.
- Precise control has potential to improve wellbore as drilled trajectory vs. planned trajectory.
- Enables the ability to implement “target azimuth” command to RCLS system.
- Enables RCLS system to autonomously monitor performance.
- Potential to increase the distance between stationary surveys.
- Reduction of time spent stationary if interval between surveys is increased.

The mathematics behind the iterative method does not introduce error to the measurement or produce error in the calculation itself. The quality of the rotating azimuth calculation is a function of the quality of the initial stationary survey point and the rotating sensor measurements for the z components of G and H. If there are no gravitational or magnetic anomalies present in the formation, and the z component sensors remain functional then the iterative method holds valid over long drilling intervals (1000 feet +) between stationary surveys.

Implementing the iterative method would be cost effective, with the benefits far outweighing the costs. There are no known hardware re-design issues; the only capital needed would be to update computer code in the surface computers and tool firmware (in the AutoTrak and OnTrak units). This would provide an enhancement to services currently offered, and pave the way for an autonomous steering unit.

References

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