Azimuth determination by gyroscope, 50 years later, has anything changed?

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Abstract: **Hausmann presented the idea of using the gyroscope in the underground environment to German Mine Surveyors in 1914. Since the early 1950's various forms of gyro or meridian indicators were sporadically used in South African mines. However the first truly commercial gyroscope attachments developed by Rellensmann was introduced to and used on South African mines since 1965. Following an outline of these and other developments the question is asked: *"Given the improvements in instrumentation over the past 50 years, is there still a need for the use for gyroscopes underground and if so, what have we learnt since the original introduction of the gyroscope to the mining environment?"*
Based on 78 gyro-baseline determinations, performed over the past three years, a number of statistics and comparisons to the standards of accuracy required by the South African Mine Health and Safety Act (MHSA) and Corporate standards could be determined. Considering that under normal production conditions, observations are taken within one kilometre of the last baseline or from the shaft, the average error in cumulative azimuth for the number of baselines was found to be within the two minute minimum standard of accuracy prescribed by the MHSA (The South African Mine Health and Safety Act, 1996). It is considered that conventional check surveying can only verify the position of survey stations but cannot verify the true azimuth of the baseline. Although survey methods over the past 50 years have changed to include methods such as electronic distance measuring, electronic applications and sidewall station networks it is argued that the gyroscope, although considered "old technology", remains an essential tool to provide an accurate verification of azimuth in the underground environment. Some of the common misconceptions, errors in observation and calculation are highlighted for discussion.**

I. WHY WOULD YOU WANT TO USE A GYROSCOPE IN THE FIRST PLACE?

According to Livingstone-Blevins the fundamental difference between mine surveying and other branches of surveying is the "*mitigation of risk*", the gravity of the consequences of "*not getting it right*" may prove to be fatal (Livingstone-Blevins, 2010). The Mine Surveyor is responsible for accurately determining the position of all mining excavations relevant to surface infrastructure and boundaries as well as all other adjacent mining excavations. Young remarked that "*One of the most important phases of mine surveying and probably what requires most care is a survey for openings to connect two given or assumed points.*" (Young, 1904). Schofield differentiated between surface and underground surveying by stating "*the essential problem in underground surveying is that of orientating the underground surveys to the surface surveys...*" (Schofield W., 2007). The role of the Mine Surveyor in South Africa is regulated by the requirements of the Mine Health and Safety Act

(MHSA) and prescribes the minimum standards of accuracy, "limits of error", allowable for the accuracy of the position of mine surveying stations. It prescribes that all excavations must be accurately represented in relation to mining- and mineral rights boundaries, objects on the surface that require protection as well as any underground excavations that could pose a hazard including areas where there may be an accumulation of noxious gas, water or mud. (Grobler H. , 2015)

When transferring the network into a decline or spiral shaft system conventional underground surveying techniques can be used to ensure the accuracy of the network transfer. In the case of deep vertical shafts the surface survey network is transferred to a network of shaft wires that can be used to plumb the network to the required level. The accuracy of these plumb-lines are ensured by tape surveying methods and more recently by using freestation methods. Once the correct position for a level breakaway has been reached the survey is transferred from the plumb lines onto the station breakaway through the use of weisbach triangles or freestation positioning. Under ideal circumstances there should theoretically be no difference in alignment between the surface and underground network, but this cannot be correlated until a breakthrough is effected or a connection intersection with another independent survey is made. With most deep level vertical shafts having multiple levels breaking away towards the orebody it can be argued that each of these levels will be an independent survey network until a breakthrough and a closure can be made between the survey networks of the different levels. A check survey on any level can only verify the accuracy of the network carried forward from the shaft wire survey, but not the accurate direction thereof. The gyroscope remains the only means to independently verify this.

II. 1914 TO 1965 THE MERIDIAN WEISER TO THE GAK, 50 YEARS OF INTENSE DEVELOPMENT.

Hausmann from the University of Aachen presented the idea of using the gyroscope in the underground environment to German mine surveyors in 1914 after a prototype was developed by Lehman and Schuler in 1915. (Williams, Historical overview of the development and application of the gyroscope in surveying, 1981) During 1926-7 the Berg Akademie Clausthal constructed the "*Vermessungs Kreisel II*" which consisted of an improved Anschütz gyrocompass in collaboration with Breithaupt in Kassel.

By 1949, Jungwirth, at the mining university in Claustal Germany, developed the "Meridian Weiser MW1" (Meridian indicator) prototype. This instrument could provide accuracy up to 1 minute of arc but weighed in at a staggering 1 000 pounds. (Winiberg & Hooper, 1966) In

1951, Metcalfe discussed the correlation of surface and underground surveys through magnetic orientation *"...where an underground traverse is to be swung into a correct position..."* (Metcalfe, 1951) as a method of verifying the orientation of the underground network. The author goes on to define the permissible error in a survey as *"...not missing the holing or endangering life and safety or requiring straightening-out by additional mining."* (Metcalfe, 1951) Although the gyroscope is not mentioned by name, Metcalfe refers to special apparatus for the reduction of errors in correlation that has appeared but notes that the justification for purchasing such equipment for infrequent use is an open question. By 1953, a British coal mining textbook makes reference to a new Meridian Weiser being tested as an alternative to magnetic meridian observations in order to correlate underground workings but states that *"...tests of this instrument have not so far been entirely satisfactory..."* (Holland, Wardell, & Webster, 1951)

A transportable version of the Meridian weiser MW2 was brought to South Africa in 1951 by Jungwirth (Lauf G. B., 1964) and used extensively in the new deep level gold mines by Prof Lauf. (Williams, 1981). These early instruments required at least two men to transport it underground and required compressed air, water and electricity in order to be operated. This meant that with the compressor and pump, the instrument weighed around 400 kilograms. According to papers from that time that an observation took around three hours to complete. (Benecke & Kalz, 2006). A later development of the Meridian Weiser was the MW3 from *"Ruhr Feinmechanik"* which became later *"WBK-Bochum"* which is today known as *"DMT-Essen"* (Heger, 2016)

Winniberg and Hooper describe how, by 1959, the Fennel KT1 gyro-theodolite was produced under the guidance of Prof O. Rellansman of Claustal and Dr J.I. McLennand. This instrument had an improved accuracy and weighed only 57kg but required a special tripod for mounting. A later development, the Fennel FT2 theodolite could be read directly to one second of arc. The gyroscope manufactured by Lear in the USA was suspended below the vertical axis on a Nivaflex tape that has about half the breaking strength of the weight of the gyro (Winiberg & Hooper, 1966). Instead of the read-out meter on earlier gyroscopes the instrument used an auto-collimated telescope to observe a fine projected line. The angle of the line of sight of the theodolite telescope, the auto collimation telescope and the axle of the gyroscope was defined as the calibration constant. The torsion constant of the tape was considered for the first time in this instrument. According to Lauf the instrument provided an average accuracy of 23 seconds in the survey of 11 underground lines. It can be agreed with Hooper *"such accuracy is readily acceptable to the mine surveyor..."*

III. 1965 TO 2015, 50 YEARS LATER.

The Precision Products Group of the British Aircraft Corporation designed an instrument called the Precision Indicator of Meridian or P.I.M. (Winiberg & Hooper, 1966). Although the date of this instrument design is not certain it seems to have been developed between 1959 and 1966. The entire unit weighed 60kg excluding batteries. The gyro unit

inside a hermetically sealed tube was suspended in a viscous fluid that required 10-15 minutes pre-heating to a temperature of 71 degrees Celsius to ensure neutral buoyancy (Thomas, 1967). Although the technology has changed significantly the pre-heating procedure is still advised in modern operator's manuals. The scale factor of the read-out meter *"... automatically corrects the readings to the latitude of the point of observation."* (Winiberg & Hooper, 1966). Winiberg refers to the "*built-in*" index error due to the displacement between the gyro axis and line of sight.

At this point the development of two distinct forms of gyroscope, namely the "gyro-theodolite" and the "gyro-attachment" can be observed. The term "gyro-theodolite" is used to describe the type of instrument where the gyroscope is located below the theodolite and normally inseparable from the instrument. *These early gyro-theodolites were extremely large and unpractical for the underground environment, although good results were achieved* (Williams, 1981)*. Due to the design of the gyro-theodolite, the accuracies obtained using this instrument was in the range of 5 seconds, but translated to a high cost per unit. The gyro-attachment, although only capable of around 20 seconds of accuracy, provided a lighter instrument at around 25% of the cost of the gyro-theodolite.*

Around 1959-60, Dr. Rellensmann developed one of the first truly portable commercial gyroscope attachment that was manufactured by Wild Heerbrugg from 1963. (Milestones in the story of Wild Heerbrugg, 2016). In this design, a gyroscope is attached to the top of a theodolite and referred to as a "gyro attachment". Lauf described the instrument in June of 1964, stating that the instrument was intended to be an *"ordinary everyday working instrument"* used every 1 000 metres or so in a development end, whereas the gyro-theodolite is intended to be used only on *"special occasions"* (Lauf G. B., 1964). The GAK attachment weighs only 1.8kg and is attached to a special bridge with three centring pins to ensure accurate positioning when mounted on a WILD theodolite. A double Mu[1] metal lining on the protective tube and housing was used to protect the gyro from magnetic influences. (Winiberg & Hooper, 1966) The instrument contains three spiral plate springs to dampen the gyro oscillations by friction when the clamping device is in a half open position. The gyro instrument consists of a gyro suspended on a thin alloy tape called *nivaflex* that is approximately *0.4mm* thick (Williams, Gyroscopic principles and the use of the Gyrotheodolite, 1981). According to Williams the GAK1 gyro attachment was first used in South Africa in early 1965. (Williams, 1981) The instrument was capable of providing an accurate geographic azimuth with a standard deviation of *20 seconds*. (Jones, 1977).

The Royal School of Mines developed a modification of the GAK1 instrument to allow for the reading of the

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[1] *"Mu-metal is a nickel–iron soft magnetic alloy ... suitable for shielding sensitive electronic equipment against static or low-frequency magnetic fields." https://en.m.wikipedia.org/wiki/Mu-metal*

amplitude by means of a micrometer to one hundredth of a scale reading. The Amplitude method was developed by H.R. Schwendener in 1966 as a rough method to provide accuracy of 60 seconds. This method requires that turning points are read against the auxiliary scale for two settings of the theodolite approximately 1 degree east and west of true north. It is claimed that the method requires approximately three and a half minutes to observe and requires no timing. A variant of this method using the modified GAK with micrometer improved the accuracy of this method significantly. (Smith R. C., 1977) Smith described that the instrument was developed to improve the repeatability of observations rather than accuracy, writing *"the ability to achieve repeatability of a result is highly desirable"* (Smith R. C., 1983). This modified GAK was reported to be able to achieve a standard deviation in observations of 4 seconds of arc.

A later development by the Camborne School of Mines connected two time-data sensors to the eyepiece of the GAK1 gyro in order to automatically record the readings on the gyro. The two sensors were positioned to intersect the gyro tape image at known points and processing this information to calculate the position of True North. The data sensors remove the human element from the observation procedures. The main purpose of this development was to investigate the time sensor technology as an alternative to the gyro-theodolite technology available at the time. (Wetherhelt & Hunt, 2002)

In Hungary MOM[2] Gi-C2 and MOM Gi-D1 auto-tracking and recording gyro-theodolites were developed capable of a reported accuracy of 3 arc seconds. The MOM Gi-B2 replaced the auxiliary scale with a diaphragm that allowed for a reflected beam of light to provide automatic tracking. By 1971 the GYMO Gi-B1A incorporated electronic timing and digital print out. (Williams, 1981). This development heralded the first "automatic" method removing the operator from the actual observation and recording procedure. This development allowed for a greater level of consistent accuracy to be achieved. Gregerson describes testing the MOM B23 gyro-theodolite in 1981 and remarks upon the automatic following system comprising of a servomotor driven by two phototransistors to keep the suspension band torque to zero. (Gregerson, 1982). Gregerson describes the influence of *"heat shock"* during the spin-up of the gyro and states that it takes between 5-8 minutes for the effect thereof to dissipate.

The robust and accurate GP1 gyroscope attachment manufactured by Sokkisha was introduced in 1976. This instrument was exhibited in South Africa for the first time in 1978. (Williams, Historical overview of the development and application of the gyroscope in surveying, 1981). The Sokkia GPX gyro station was a combination of the GP1 gyro attachment and a SET total station. This instrument was equipped with on-board software to perform a true north determination by means of the Turning point or Reversal Point Methods.

From a review of papers produced in 1983 Caspary and Heister describes three problems that were under investigation in the early eighties. The investigations in the advancement of gyroscope technology were listed as the improvement of observation methods and the "mathematical models", the improvement of hardware coupled with automation to improve accuracy and speed of observation and the improvement of the mathematical model to convert the azimuth to a geodetic bearing. (Caspary & Heister, 1983) These authors investigated the problem of calculating the deflection from the vertical *"which are required for the reduction of gyroscope azimuth to the ellipsoid"* (Caspary & Heister, 1983).

A modern version of the gyro introduced to South Africa after the year 2000 features an *"air brake"* consisting of two small fans blowing air controlled by a Remote Control Unit in to the gyro to introduce stabilize the gyro oscillations through damping. Most modern gyro-attachments now offer a bluetooth connection between the total station and PDA for the purpose of recording readings during observations. These readings can be stored and downloaded, presenting a significant advantage over hand-written field notes that may be unclear or incomplete. It must be noted that these software solutions generally do not present a meridian convergence solution. In certain mining applications grid-convergence may not be necessary, but when auditing of an existing survey network on a grid system it essential to incorporate this in the azimuth calculations. A recent development incorporates a small video camera attachment that can be attached to the eyepiece of the instrument allowing the instrument to be used in cramped quarters such as in small diameter tunnels and in shipping applications.

The original Meridian Weiser instruments have undergone a number of improvements through the years ranging from the MW77 (1977) to the Gyromat (1978), Gyromat 2000 (1991), 3000 and 5000 (2014). These instruments are reported to have an accuracy of 3.2 seconds. The release and observation procedures in these instruments are completely automated, requiring minimal input from the operator and providing an accurate solution within 10 minutes. The size and weight of these instruments have been reduced to a point where the instrument can be transported underground with no inconvenience.

In the year 2013 Zhen et al. described new gyro suspension technologies including electrically suspended gyroscope, laser gyro and Magnetic Levitation (Maglev) technology. The paper by Zhen et al. describes the design of the GAT high precision maglev gyro using *"magnetic suspension technology"* coupled with advanced technology to produce a high accuracy instrument. It is stated that this instrument uses *"reverse torque measurement in static state"* that allows the instrument to be independent of swing observations. The instrument allows for the collection of large amounts of real-time data that can be post-processed and filtered for a highly accurate solution. (Zhen, Zhiqiang, & Zhang, 2013). At the 15th International ISM Congress in 2013 two papers on the application of filtering methods for the GAT gyro total station was presented by these authors. At the same conference Shamilov et al. describes the development of fibre optic sensors for *"gyro-compasses".* The abstract describes the development of a Fibre Optic survey Gyro Compass (FOGC-2) (Shamilov, Gordeev, Manyko, Badulin, Shestakov, & Shtykov, 2013). Unfortunately very little further information on these important developments is available.

Fifty years have passed since the introduction of the first truly transportable gyro in 1965 and one hundred years since the original concept was considered. It seems that the

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[2] *Hungarian Optical Works*

development of new technologies and ever improving computing power in the past five years may finally provide a lower cost, high accuracy solution for north-seeking mine surveys.

A. A review of two common observation methods

There appears to be at least six different techniques of observation according to Thomas 1982 (Thomas Survey review vol26 January 1982). Schofield refers to four of these methods, namely the Reversal Point Method, the Transit Method, the Transit method using the modified GAK1 attachment and the Amplitude method. (Schofield, 1984). The two most common manual methods of observation and calculation are briefly reviewed in the following sections.

1) Reversal Point method (RPM)

This method makes use of a continuous tracking of the gyroscope and booking the turning points of the oscillations of the gyroscope. This method was originally introduced by Schuler and is still commonly referred to as the *"Schuler method"* in South Africa. The method requires an instrument with continuous drive or an instrument with an extended horizontal motion screw that has been centred in order to track oscillation properly. When the oscillation of the gyroscope is followed correctly, it means that the tape is free of torsion and hence the torsion effect is eliminated from the oscillations. (Winiberg & Hooper, 1966) The oscillations follow the form of a sinusoidal curve with the speed at the greatest in the middle of the curve (when crossing the meridian line) and noticeably slower at the turning points. Using this method the earth's rotation torque is the only element controlling the swing time. The decrease in amplitude is normally so small that it can be treated as a linear function. (Winiberg & Hooper, 1966) The method is considered by some as a less accurate method of azimuth determination, this perception was probably encouraged by comments such as one by Williams who stated that *"Tracking methods are of little but historical interest now and should not be used if the best accuracy performance is desired..."* (Williams, 1981). The continuous tracking and concentration, that is required by the method, is considered by many surveyors as a less-ideal.

Irregular and incorrect following-up procedures can lead to a damping of the gyroscope disturbing the natural oscillation rhythm. Such disturbances cannot be quantified numerically. An error in booking of the horizontal circle reading at the turning point is likely if great care is not taken, as the time to identify the turning point, observe the horizontal circle reading and returning to following up the gyroscope movement is limited to around two seconds of time. The Gyro Indicated North determined by the tracking method is calculated using the following formula:

$$N = \left\{ \frac{\frac{a_1 + a_3}{2} + a_2}{2} + \frac{\frac{a_2 + a_4}{2} + a_3}{2} + ... + \frac{\frac{a_{n-2} + a_n}{2} + a_{n-1}}{2} \right\} * \frac{1}{n-2} \qquad (1)$$

Most of the gyro-attachment type instruments can, according to their manufacturers, achieve an average accuracy of ± *20 seconds* using the turning point method. Critics of this method of observation argue that it is less accurate than the Pass Through Method as the continuous

motion creates a damping effect on the gyro. In contrast the Reversal Point Method reduces tape torque to a minimum as the gyro is continuously tracked in the "zero-position". A recent development in gyro technology is the ability to record the horizontal circle reading a number of times per second through a Bluetooth connection to a PDA. A graph of the horizontal readings can be reproduced as an MS Excel graph and the accuracy of readings can be graphically observed. In the figure below, the irregular shape of the curve indicates the hesitancy of the observer in following the gyro oscillation exactly. In the graph the flattening and jagged bottoms of the curve indicate where the operator hesitated or doubted the direction that the gyro was moving at that specific point in time. This graph provides an excellent teaching and analysis opportunity for operators. In this case where 6 turning points were observed a total of 2480 horizontal circle readings or approximately 137 readings per minute, were recorded.
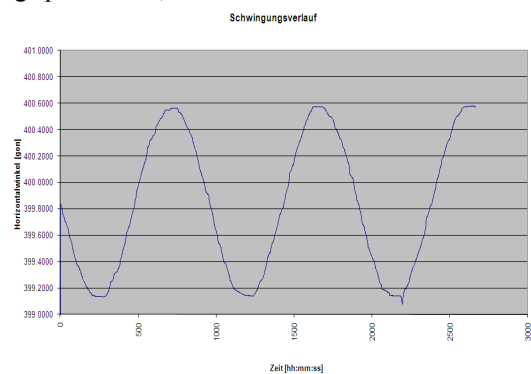

Figure 12. Actual observations using the RPM method.

2) Pass Through Method (PTM)

According to Lauf, H.R. Schwendener introduced this method in 1966 as a rough method to provide accuracy of 60 seconds (Lauf G. B., 1980). The method observes the movement of the gyro over the graduation scale while timing the observations with a stopwatch. When the method was originally developed, trailing hand stopwatches were used. The method was limited by the achievable accuracy of the analogue stopwatch used. Modern stopwatches are able to make up to one hundred readings accurate to a hundredth of a second. With the introduction of smart phone applications, accurate lap times can be now be e-mailed to the user as a backup.

The PTM method is a refinement of the Schwendener's method and is able to provide very accurate results. The method does not require the equipment to be manipulated during observation and as a result the oscillation rhythm is not damped in any way. The three to five minute period between observations allows the observer to monitor the progress of the observations and evaluate the measurements made. (Winiberg & Hooper, 1966) A distinct advantage of this method is that the recorded observations can be used to determine the *"c"* factor and Calibration constant *"E"* of the instrument at the same time.

The Pass Through Method requires that two sets of observations that "bracket" the Grid North bearing by 10 minutes of arc. Therefore one set of observations are made at 179:50:00 and a further set of observations made at 180:10:00. In South Africa, the True North azimuth is 180 degrees. This creates some confusion when the surveyor is required to make observations in a system where the North

azimuth is at zero degrees. Some modern survey instruments no longer have a baseplate clamp fitted to the horizontal circle. The operator should therefore take care to ensure that if the instrument is set to a specific orientation such as for example 179:50:00, any "slippage" during the release and observation procedure be prevented or should it occur, be recorded as such.

From the observations, two equations are formed. Solving the two equations simultaneously, the *"c"* factor of the instrument can be determined and used to calculate the Gyro Indicated North.

$$TN_1 = N_1 + (c * \varDelta zt_1 * \tilde{a}_1) \qquad\qquad (2)$$
and
$$TN_2 = N_2 + (c * \varDelta zt_2 * \tilde{a}_2) \qquad\qquad (3)$$

The *"c"* value is expressed as "*n*" a*rc seconds per second of time.* Contrary to popular belief the *"c"* factor calculated does not remain constant and will change depending on the location of the baseline, internal conditions in the instrument and every time the tape is adjusted or replaced. Though personal observation it is common to see a printed *"c"* value attached permanently on the side of a gyroscope. Using the incorrect *"c"* value for a gyro calibration will lead to an inaccurate baseline bearing being determined. According to Lauf however the value of *"c"* *"may be regarded as constant for a latitude difference of up to 1 degree or about 100 kilometres."* (Lauf G. B., 1980)

3) Comparison in accuracy between the two common observation methods.

In order to compare the two different methods of observation, gyro instruments from two manufacturers were used as part of a quality assurance audit of the accuracy of the control network of a new shaft-sinking project. The two different instruments operated by two independent surveyors, one using the PTM and the other using the RPM methods revealed a difference of 0:00:06.3 in the final underground azimuth between the two methods. Such results support the argument that there is no difference between the different methods of azimuth determination.
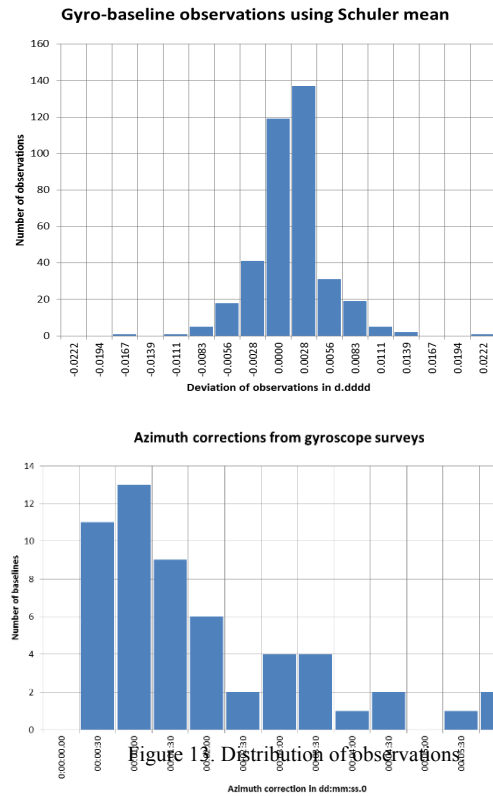
In a separate shaft surveying project a similar comparison using one instrument but two different methods yielded the following results:

TABLE 7. COMPARISON BETWEEN METHODS.

			Reversal Point Method 1	0:13:14.9
Pass Through Method 1	0:12:04.9		Reversal Point Method 2	0:12:26.9
Pass Through Method 2	0:13:08.0		Reversal Point Method 3	0:13:00.9
Average Bearing	0:12:36.5		Average Bearing	0:12:54.2
Difference between Readings	0:00:17.7			

Although there are discrepancies that may be larger than anticipated it should be considered that different observers made these last observations, while in training. As the skills of the observers improve, so should the accuracy. From these observations it can be seen that there are in this case only *20 seconds* different between the two methods of observation under non-ideal conditions. Under extreme conditions the Pass Through Method may be preferred over the Reversal Point Method when operator fatigue and operator comfort plays a role. According to Lauf the Reversal Point Method should be used in high latitudes

because the tape torque may be weaker or equal to the precessional forces. (Lauf G. B., 1980)

Gyro-baseline observations using Schuler mean

Azimuth corrections from gyroscope surveys

Figure 13. Distribution of observations

From 78 gyroscope baseline determinations, comprising of approximately 360 readings, performed over the past three years it has been observed that the standard deviation of a gyroscope is 13 seconds using a total station observing with a manufacturers accuracy of 7 seconds using the Reversal Point Method. On average the baseline determinations have indicated an average azimuth deviation of 1 minute 30 seconds. Considering that under normal production conditions, observations are taken within 1 km of the last baseline or from the shaft, the average error in cumulative azimuth for the number of baselines was found to be within the 2-minute level prescribed in the MHSA.

B. Common terminology and misconceptions clarified.

In the calculation of the calibration value of an instrument on a specific baseline, the value can be calculated using the formula:

$$E = N + \mu + \gamma - GIN \qquad\qquad (4)$$

The Gyro Indicated North (GIN) can be calculated using one of the observation methods discussed in the previous section. Assuming that the observer followed all the correct procedures it has been proven that regardless of the observation method used, the GIN can be calculated within 20 seconds of arc. The variables used in this formula are discussed in the following section.

1) Meridian convergence (γ)

According to the Mine Health and Safety Act, 1996 (Act No. 29 OF 1996) Chapter 17(4)(b) *"...all mine survey systems conform to the National Control Survey system…".* (DMR, 2011). All mine survey plans use Grid North (GN) is

defined by the US Geological survey as *"… the direction of a plane grid system, usually the grid associated with the map projection."* (US Geological Survey, 2016). The gyroscope indicates the True North as defined by the spinning axis of planet earth. True North (TN) or geographic north is defined by the US Geological survey *as "...the direction of the line of longitude ...lines converge to points at the north and south pole"* (US Geological Survey, 2016) The difference between Grid North and true North is the inherent effect of the transformation between the spherical surface of the earth (US Geological Survey, 2016) and the surface plane used for mine plans. The term therefore describes the convergence between True North and Grid North. A common misconception with modern gyro-theodolites and software is that the solution provided includes this conversion. It remains the surveyor's responsibility to ensure that the grid convergence has been included in all calculations.

2) *Instrument alignment*

Instrument alignment between optical center of the total station used for mounting and the axis alignment of the gyro. In newer gyroscopes the gyro is equipped with a telescope that is used for alignment, the instrument telescope is ignored, therefore the instrument acts as a mounting and horizontal circle reader only. The alignment based on the mounting is dependent on the torque and fitment of the instrument to the mounting brackets and will be subject to change every time the instrument is mounted on the total station mounting. A common mistake is to swing the telescope to vertical but that leads to the electronic angle compensator of the instrument adjusting the horizontal angle readings that will lead to an error in observation. Magnification on the gyro telescope is not as strong as the total station telescope, sighting in poor light conditions over long distances can present challenges and may introduce error within the observations. On one specific test instrument the average deviation between an observation to a target observed through the gyroscope telescope and the telescope of the total station on which it is mounted is 0:14:10 with a standard deviation of 0:03:21 and a maximum reading of 0:19:23 and a minimum reading of 0:09:10 over a period of three days of continuous surveying.

The fact that the total station telescope is not used during observations means that the deviations in mounting do not have any influence on the final readings of the instrument. However, the findings illustrate the importance of correct sighting procedures as well as demonstrating the need to check the instrument calibration value *(E)* before and after each set of underground observations.

The following photograph illustrates the alignment error over a short distance. The cross hairs of the total station are focused over the control beacon. It clearly illustrates the error in alignment between the optical centre of the total station and that of the gyro attachment.

Figure 14. The alignment error factor

3) *Non-spin check*

This test should be performed before and after every spinning gyro observation for two reasons. The first is to ensure that the tape is not broken or twisted by observing if the gyro oscillates freely on the suspension tape. Uneven releasing of the gyro can cause excessive wear on the suspension tape. (Heger, 2009) It is recommended that at least four consecutive turning points are observed. (Lauf G. B., 1980) The Schuler mean method of determining the mean reading can be used. Lauf mentions that a secondary reason for the non-spin observations is to ensure that there are no external electromagnetic influences on the instrument. Although the instrument is designed not to be influenced by magnetic influences, an instrument used in the mining environment may be exposed to far greater levels of interference. (Lauf G. B., 1980). The formula used to calculate the tolerance is:

$$T_m = \frac{(T_a - T_b)}{2} \leq 0.5 \text{ Increments} \qquad (5)$$

According to Lauf the mean of these values represents the torque free position of the suspension tape. (Lauf G. B., 1980). Authors do not agree on the acceptable value for this mean value, with Lauf quoting 2 divisions of scale (Lauf G. B., 1980) and Heger arguing for 0.5 division of scale

4) *"E" is for "Eichwert", not Error!*

Eichwert is the German term for "Calibration Value" (http://translation.babylon.com, 2015) for a Gyro instrument at a specific site using a specific theodolite and mountings on a specific beacon. The symbol *"E"* is commonly misinterpreted to represent the "error" of an instrument, when in fact the *"E"* value refers to the "calibration value" of the gyro. The value can be calculated using the formula:

$$E = N + \mu + \gamma - GIN \qquad (6)$$

Newer models of gyro instruments appear to have a larger *"E"* factor. (Grobler H. , 2015). In a specific case where a mine queried the adjustment of an instrument, an *"E"* factor of -0:08:40.8 was calculated on a calibrated baseline (Grobler H. , 2015). The larger than usual calibration value *"E"* for the instrument caused concern for the mine but in effect should not in any way affect the accuracy of underground observations. The *"E"* value is unique to each instrument and is a combination of the survey network alignment error on surface and the gyro instrument's unique alignment with the optical axis of the instrument. As this calculated calibration constant "E" is then transferred and used underground, the *"E"* remains constant and would not affect the final bearing calculation in any way. The author has noticed that the newer instruments have a larger *"E"* value than what can be expected from older instruments such as the Sokkia and Wild GAK instruments, this trend has been confirmed by Heger. (Grobler H. , 2015)

According to Williams the quantity of the *"E"* value can be determined by measuring the bearing of a line of which the astronomical azimuth is known (Williams, 1981). With the introduction of GPS technology this can now be done easily. Research into the results obtained in this manner should be conducted. Williams explains that a drift in the *"E"* value could be as a result of variables such as tape torque anomalies, uncompensated magnetic effects and minor mechanical state changes. (Williams, 1981) The *"E"* value will change when the tape is replaced.

IV. RECOMMENDATIONS

Control surveys (check-surveys) are essential to the upgrading and maintenance of the accuracy and precision of an underground survey network. In the case where sidewall stations are used for the primary survey control network a "free-station" setup remains useful only for the time that the instrument occupies that specific position. It has been found that the accuracy of sidewall survey station networks tend to deteriorate in bearing faster than the conventional hanging wall network. As a result it is argued that sidewall station networks should be verified by gyroscope observations at regular intervals to ensure that error propagation is reduced to acceptable limits. It is recommended that a permanent hanging wall gyro baseline is established whenever an azimuth verification is performed. (Grobler H. , 2015).

"The use of the gyroscope to verify the accuracy of the underground survey network in relation to the surface survey network is therefore essential not only to check the error in bearing transfer underground but also the error propagation within the underground survey network itself." (Grobler H. , 2015) In order to ensure the continued accuracy of the underground workings, it is recommended that careful consideration should be made of the fundamental factors that may influence the accuracy of an azimuth determination. Some these factors are:

1. Ensuring that the gyro observations are not influenced by wind or vibration.
2. Ensuring that the gyro baseline is not placed near an area of high electromagnetic influence
3. Ensuring that the Automatic Target Recognition (ATR) is activated for accurate target alignment.
4. Ensuring correct instrument alignment under the survey stations by forced centering.

5. Ensuring that the check survey of the underground section is brought up to the gyro baseline(s) and verified by a closure.

It is of critical importance to understand the fundamentals and principles governing the design and operation of modern gyro-theodolites and gyro-attachments. Factors such as tape torsion, the regular servicing and calibration of the gyro-attachment and total station and the lifespan of batteries and components must form part of any check survey standard procedure. The lifespan of the gyro motor and servicing thereof is a critical aspect that is often neglected. Some manufacturers state that the gyro motor has a limited life span and should be overhauled between 1000 hours and 3000 hours of use. (Sokkia Topcon Co.Ltd., 2008)

V. 50 YEARS LATER, HAS ANYTHING CHANGED SIGNIFICANTLY?

The gyroscope provides an absolute azimuth, which provides an additional level of redundancy in an open traverse. (Anderson, 1982). In an answer to a question at a conference in 1964, Lauf stated that in the 1920's an accuracy of *"ten to fifteen minutes of arc"* could be obtained, by 1950 an accuracy of *"one minute"* could be obtained. In 1964 Lauf claimed an average error of 4 seconds over a twenty baseline surveys and stated that he had reason to believe that in a few years consistent accuracies of *"perhaps one second"* could be attained "every time" (Lauf G. B., 1964). Although Williams predicted that *"...by the year 2000 inertial navigation systems based on cryogenic nuclear resonance gyros will be in common use"* (Williams, 1981), the gyro-attachment has undergone virtually no internal improvement since 1960. Most developments have been made through various modifications that have enabled the observer to perform more accurate and repeatable surveys. The latest studies into the application of Maglev and fibre optic gyroscopes have led to several patents being registered and at least two "gyro total stations" developed as a result. At the time of this writing these instruments does not appear to be commercially available.

As South African mine surveyors become more exposed to work outside the national borders it is important to realize that a surveyor may perform work in high latitudes and in some cases perform work on both sides of the equator. In cases like these it is essential to have an excellent understanding of the various observation and calculation methodologies as well as co-ordinate systems in order to perform accurate work.

REFERENCES

Anderson, E. G. (1982). The impact of new gyrotheodolite technology on design of underground surveys. *Proceedings of the fourth canadian symposium on mining surveying and deformation measurements* (pp. 61-79). Banff, Alberta: The University if Calgary.

Benecke, N., & Kalz, U. (2006). A Company Presentation of Deutsche Montan Technologie GmbH & Co. KG. *Gyroscope Technology at DMT* . Deutsche Montan Technologie GmbH & Co.

Caspary, W., & Heister, H. (1983). Problems in precisazimuth determinations with gyrotheodolites. *XVII International Congress Federation Internationale des Geometres* (pp. 609.2.1-609.2.13). Sofia: Federation Internationale des Geometres.

DMR. (2011). Mine Health and Safety Act No 29 of 1996 Government Gazette 27 May 2011. Government Gazette Republic of South Africa.

Gregerson, L. F. (1982). Report from experiments with the MOM's B-23 gyroscopic theodolite. *Proceedings of the fourth canadian symposium on mining surveying and deformation measurements* (pp. 43-51). Banf. Alberta: Canadian Institute of surveying.

Grobler, H. (2013, June 10). Legend for annotating a check survey baseline.

Grobler, H. (2015). *Report on Gyromax 128*. Johannesburg.

Grobler, H. (2015, April 24). Spatial positioning of Sidewall stations in a narrow tunnel environment. A safe alternative to traditional mine survey practice. *PhD thesis* . Johannesburg: University of the Witwatersrand.

Heger, W. (2008, May 15). *Manual Gyromax AK-2M Gyromax Control* . Wulkenzin, Germany: Geo MessTechnik Heger.

Heger, W. (2009). *Gyro attachment AK2M user's manual.* Wulkenzin, Germany: GMT GeoMess Technik.

Heger, W. (2016, February 14). information on old gyros at Wits University. (H. Grobler, Interviewer)

Holland, J. L., Wardell, K., & Webster, A. G. (1951). *Surveying, Coal mining series, Volume 2.* London: Virtue and Company Limited.

http://translation.babylon.com. (2015, J). From translation.babylon: http://translation.babylon.com/german/to-english/Eichwert/

Jones, T. P. (1977, September). An introduction to the Wild GAK 1 Gyro attachment. *The Ontario Land surveyor* , pp. 4-10.

Lauf, G. B. (1980). *Notes on Gyroscopic methods of surveying.* Johannesburg: Chamber of Mines of South Africa.

Lauf, G. B. (1964). The gyro-theodolite as a precision instrument for the determination of direction in a mine. *The proceedings of the second national conference of South African surveyors* (pp. 494-509). Cape Town: Institute of Land Surveyors of the Cape Province.

Livingstone-Blevins, M. (2010). Getting it right saves lives and mitigates risk. *PositionIT* .

Metcalfe, J. E. (1951). *A Mining engineer's survey Manual.* London: Mine and Quarry Engineering.

Milestones in the story of Wild Heerbrugg. (2016, February 07). From Virtual webpage of Wild Heerbrugg: http://www.wild-heerbrugg.com/milestones_in_the_story.htm

Pretorius, C. (2016, February 16). Gyromat 2000 used at Lonmin mine. (H. Grobler, Interviewer)

Schofield W., B. M. (2007). *Engineering Surveying, Sixth Edition.* Elesevier, Butterworth Heineman, ISBN 13 978-0-7506-6949-8.

Schofield, W. (1984). *Engineering surveying 1, Third edition.* London: Butterworths.

Shamilov, L. N., Gordeev, V. A., Manyko, N. G., Badulin, A. P., Shestakov, G. V., & Shtykov, A. N. (2013). Development and experimental studies of highly sensitive fibre-optic sensors for gyro-compasses. *XV International ISM Congress 2013* (pp. 98-102). Aachen, Germany: International Society of Mine Sureying.

Smith, R. C. (1977, January 01). A MODIFIED G.A.K.l GYRO ATTACHMENT. *Survey Review* , pp. Volume 24, Issue 183 pp. 3-24,.

Smith, R. C. (1983). Engineering and the suspended gyrotheodolite. *XVII Federation Internationale des Geometres Commission 6* (pp. 606.2.1 - 606.2.10). Sofia: Federation Internationale des Geometres Commission 6.

Sokkia Topcon Co.Ltd. (2008). *Sokkia GP1X gyro station operators manual.* Kanagawa, Japan: Sokkia Topcon Co.Ltd.

Thomas, T. L. (1967). The Precision Indicator of the Meridian: Theory and Application. *Third South African National Survey Conference*, (pp. 39-59). Johannesburg.

US Geological Survey. (2016, January 31). *http://www.usgs.gov/faq/categories/10482/3019%20*. From US Geological Survey: http://www.usgs.gov/faq/categories/10482/3019%20

Wetherhelt, A., & Hunt, P. (2002). Underground Azimuth Determinations Using an Adapted Wild GAK1. *FIG XXII International Congress.* Washington.

WILD Heerbrugg. (1971). *WILD GAK1 Gyro Attachment "Rellensmann system" Instructions for use.* Heerbrugg, Switserland: WILD Heerbrugg.

Williams, H. S. (1981). *Gyroscopic principles and the use of the Gyrotheodolite.* Johannesburg: Chamber of Mines of South Africa.

Williams, H. S. (1981). Historical overview of the development and application of the gyroscope in surveying. In *Advanced Surveying Course.* Johannesburg: Chamber of Mines with the University of the Witwatersrand.

Williams, H. S. (1981). Reduction of gyrotheodolite observations. In C. o. Africa, *Gyroscopic Principles an the use of the gyro-theodolite* (p. 8). Johannesburg: University of the Witwatersrand.

Williams, H. S. (1981). *The gyroscope and methodological considerations.* Johannesburg: University of the Witwatersrand under the auspices of the Chamber of Mines.

Winiberg, F., & Hooper, R. C. (1966). *Metaliferous Mine Surveying, 5th Edition.* London: Salisbury House.

Young, E. M. (1904). *A Study of Mine Surveying Methods And Their Applications to Mining Engineering.* Golden, Colorado: THE IOWA ENGINEER.

Zhen, S., Zhiqiang, Y., & Zhang, Z. (2013). Study on automatic north-seeking key technologies of Maglev gyroscope. *The open Mechanical Engineering journal* , 83-89.