Adding Value to Exploration Boreholes by Improving Trajectory Survey Accuracy

T G Sindle[1], I M Mason[1], J E Hargreaves[1] and J H Cloete[2]

ABSTRACT

The value of any information gleaned from exploration boreholes is increased enormously when this information can be accurately placed within the three-dimensional model of the mine site. It is not uncommon to find trajectory data to be out by tens of degrees causing compounding errors at the end of long holes. This misinformation can end up being extremely costly when mine plans and resource estimates are based upon it.

The aim of this paper is to investigate and explain many common areas for errors to occur in trajectory surveys and in the survey tools themselves. As magnetic-based survey tools are the most commonly used trajectory measuring tools the bulk of this paper is directed with these in mind.

INTRODUCTION

Boreholes are used to explore, delineate and sample orebodies, locate faults, and map mining hazards. The information taken from these costly holes effects resource estimates and mine design where position accuracy in the order of tens of metres makes a big difference. This is especially true with the kind of sparse pierce point resource delimitation done at most mine sites.

Besides producing core to be logged, these boreholes enable the deployment of geophysical survey tools such as borehole radar, which is used to delineate and image reefs, faults and other geological features in hard rock mines. Borehole radar range resolution of one metre or better can be attained. However, the accuracy with which borehole radar maps can be located in the 3D mine plan is clearly limited by the systematic errors associated with the borehole trajectory surveys. To this end, proprietary borehole survey tools, built from carefully selected electronic components, were developed and tested. Recently, orientation sensors have been integrated into borehole radars. Figure 1, is an example of a radar image from an orebody that needs accurate position survey information in order to be integrated into the mine plan.

Although drill contractors may claim that the boreholes drilled are straight and to plan, they often start off in slightly the wrong direction and tend to deviate. The deviation is caused by numerous factors including drill rod size, drill penetration rate, intersected rock interface types, and driller experience (Orpen, 2005). For instance, drillers pushing too hard to get metres per shift completed, often cause boreholes to deviate to the right in a corkscrew fashion due to the torque on the drill bit.

SURVEY TOOLS

The basic principle behind a borehole survey tool is that the azimuth (also called heading) and dip (vertical angle from the horizontal plane, sometimes referred to as pitch) of the borehole is measured at repeated stations along the hole. These survey stations are then linked to produce an interpolated path

1. Geophysical Imaging Laboratory, School of Geosciences, University of Sydney, Sydney NSW 2006.

2. Department of Electrical and Electronic Engineering, University of Stellenbosch, Private Bag X1, Stellenbosch, 7602, South Africa.

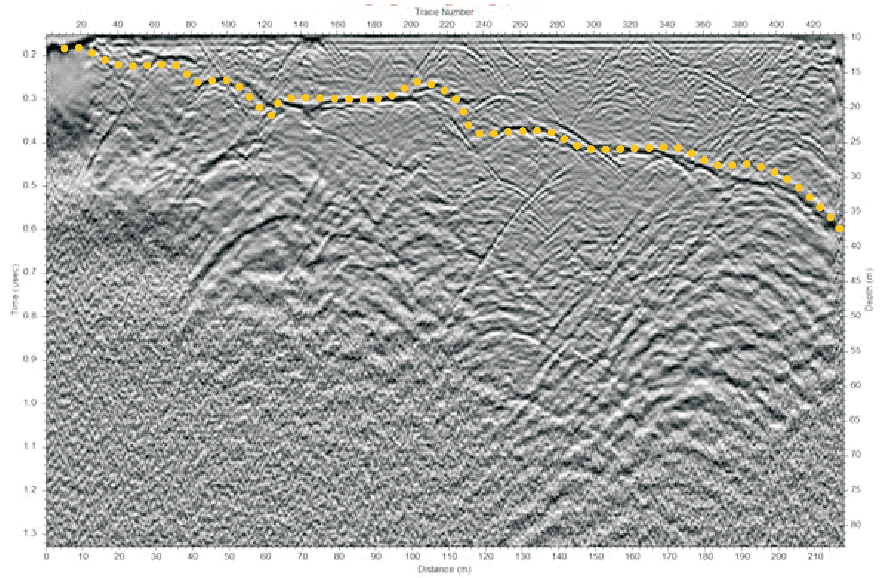

FIG 1 - Radar image of a reflection from an orebody.

for the borehole. There are numerous survey tools available to choose from in the commercial and research arenas. The main types are optical, magnetic or gyroscopic based. Each having their own niche market segment – the optical and gyroscope-based systems have the benefit of being able to survey in magnetically active or screened areas but are normally more expensive and bulkier systems than the magnetic based ones, thus limiting their deployment. The magnetic-based sensors work by sampling Earth's gravitational and magnetic field. These two vectors are then used to calculate the orientation in 3D space of the instrument. They are often referred to as electronic multi-shot systems (EMS) meaning they are electronic tools that take multiple station readings as they are deployed down the borehole. The remainder of this paper will concentrate on issues involved with the more common magnetic-based EMS systems.

A HISTORY OF INACCURACIES

Whilst there are many borehole surveys being conducted every day, and some mines have even recently started to survey every hole drilled, the question often arises – but how accurate are the survey data? This has been investigated by numerous studies including surveys of one hole with multiple instruments at Finch Diamond mine (Wolmarans, 2005), and also in a survey conducted by the Geological Survey Society of Canada (Kileen *et al*, 1995). An important 'test survey' was conducted in 2005 at the Voorspoed site near Kroonstad in South Africa (Orpen, 2005). Here a 370 m long surface borehole made of PVC pipe, was laid out and then surveyed by seven EMS tools, one optical and one gyro survey instrument. The predicted trajectories recorded were then compared with conventional surface survey data. The various survey instruments recorded ellipsoids of uncertainty of between 0.2 and 13 per cent at the far end of the borehole. Figure 2, shows a photograph of the test site (left) and the surveyed as well as the actual hole path in 3D space (right). The ellipsoids of uncertainty associated with three EMS tools and the gyro tool are also shown. The gyro tool was accurate to within a metre of the target end of hole. The three EMS tools were off by between 2.3 and 48 m, and the optical tools between 63 and 72 m.

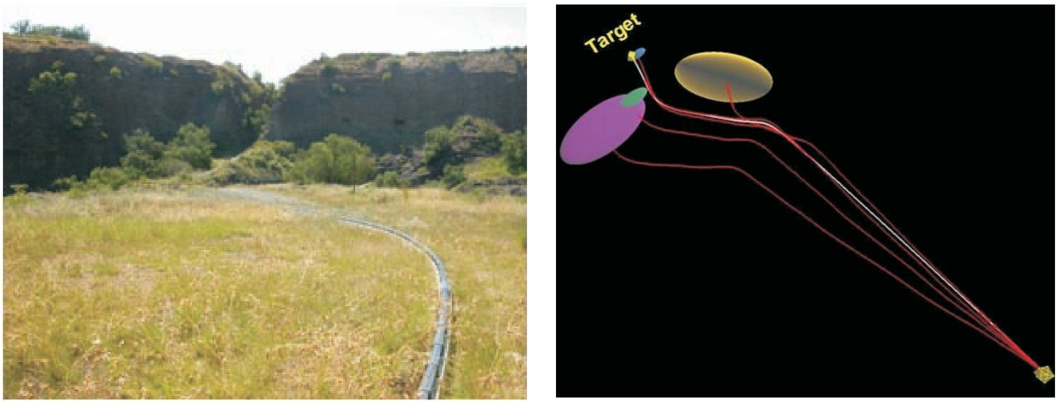

FIG 2 - The Voorspoed site: Photograph (left) and mapped 3D path (right). Right image shows the actual (white) and predicted paths (red) of the 370 m long pipe. Ellipsoids of uncertainty for each tool are also shown (modified from Wolmarans, 2005).

ISSUES PERTAINING TO SURVEY ACCURACY

Calibration

Perhaps most important of all, the initial calibration of the tool is crucial to survey accuracy. For EMS sensors two tri-axial modules need independent calibration, the magnetic sensor and the gravity sensor. The gravity sensor is calibrated by finding the maxima and minima for each of the axes – by placing it on a precise flat surface. The magnetic sensor is calibrated by placing it in a Helmholtz coil and effectively nullifying the Earth's magnetic field then applying an artificial magnetic field in various directions to calculate the calibration coefficients (van Brakel *et al*, 2005).

Mine sites are often inhospitable locations not just for humans but for survey tools as well. In particular temperature variations can cause wildly varying calibrations factors for the magnetic and gravity sensors. If the survey tool has not been calibrated for a range of temperatures, data at the extremes will be inaccurate. As an example, recorded temperatures at diamond mines in north western Canada have been recorded as zero degrees Celsius, and at deep goldmines in South Africa, 60 degrees rock temperature is also commonplace. Figure 3 shows how the grouping of pitch values, for a number of surveys in the same hole, improves after temperature post processing for a set of EMS survey probes.

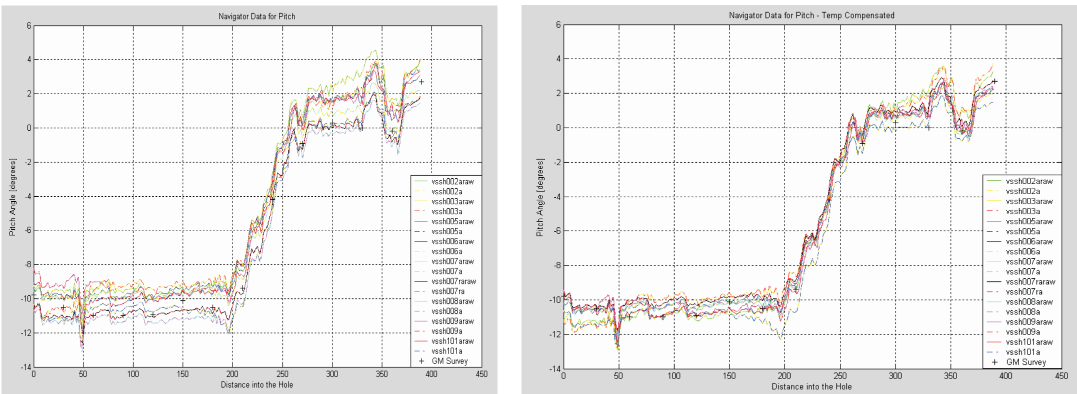

FIG 3 - Measured pitch reading before and after temperature compensation (Van Brakel, 2005).

In addition to calibrating the actual sensor, the entire probe should be checked for accuracy as wires carrying current and influences of metallic objects (like batteries) may influence the magnetic readings. Figure 4 shows how the apparent azimuth changes as a 60 cm stack of 12 NiCad batteries are axially moved progressively closer to an orientation sensor.

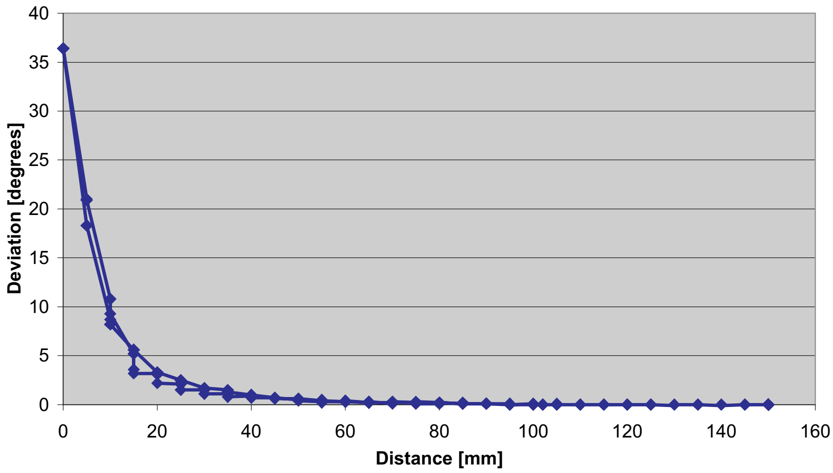

FIG 4 - Azimuth deviation caused by battery distance from sensor.

A good way to check the total calibration of a survey instrument is to point it in a defined direction and rotate it about its own axis. The azimuth should stay constant, to within the specification of the device. Another check is to lay the probe on a flat surface and rotate it in the horizontal plane, while logging the magnetic vector strengths in the X and Y horizontal plane. If this is plotted in an x-y graph, it should appear as a circle centred at zero, as shown in Figure 5.

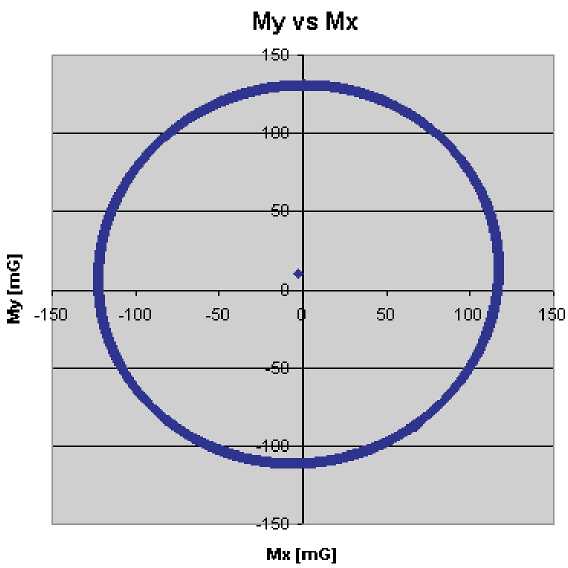

FIG 5 - A full circle calibration, showing the offsets (Sindle, 2002).

Survey technique and station spacing

There are two main techniques for surveying a borehole. The first is to rig up some form of pulley system to pull the survey probe into and then back out of the borehole. The probe is stopped at various stations, each a predefined distance apart to take readings. The other method is used when there is still a drill rig on site. The survey probe is pumped down the inside of the drill string, until it passes through and protrudes out of the drill bit. As the rods are retracted the survey is conducted.

A borehole navigator is most accurate if it is stationary while taking the readings for each station. This is because bumping along the borehole causes small accelerations which add noise to the reading of the gravity vector. It is thus essential, for maximum accuracy, that the probe is stationary at each station. This is particularly important in partially filled water boreholes where the probe may float around for a while before settling. In probes where access to the continually sampled data is available, eg in Figure 6, the tool rattling within the hole can be clearly seen.

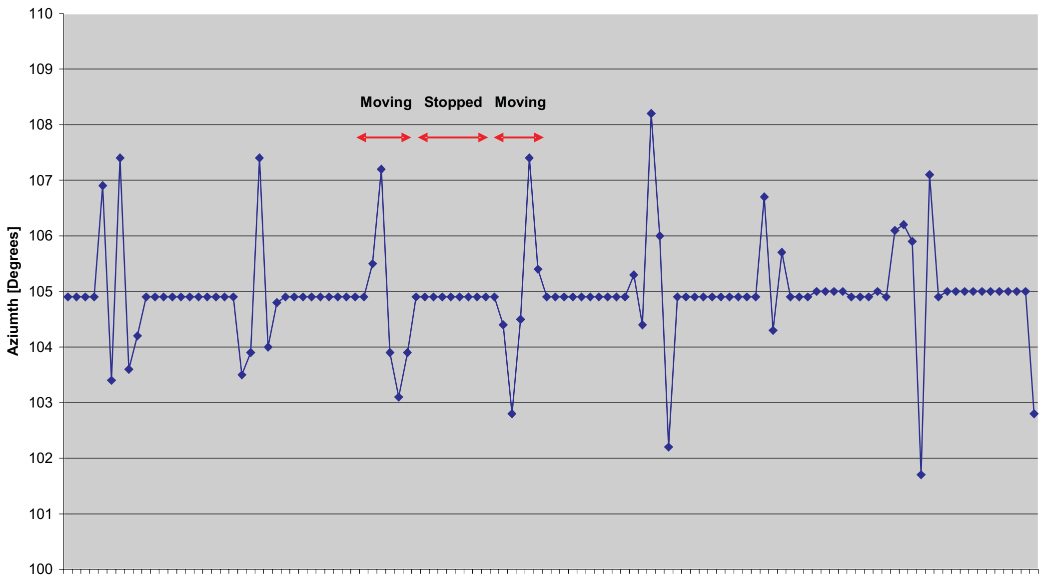

FIG 6 - Graphic of continually sampled azimuth when probe is moving and stopped.

Another issue is spatial under-sampling. As with any mathematical curve, if it is under sampled, an accurate recreation of the hole path cannot be made. Due to cost cutting some miners are tempted to space their samples 20 - 30 m apart even when stations spacing of three to five meters are required for reasonable accuracy (Orpen, 2005).

If surveying is done using the pump-down method, an aluminium or other non-magnetic spacer rod must be used to position the probe 4 - 6 m away from the drill string. This moves the probe out of the area of distorted magnetic fields. Similarly, care must be taken to ignore the survey stations too close to the metallic collar of the hole. It is also good practice to get the mine surveyors to check the actual start dip and azimuth of the hole when they survey the collar's position.

Magnetic field issues

Magnetic clutter

Surveying in a magnetically active area presents additional problems. Although some believe that a gyro or optical-based tool should be used in magnetically active areas, it is frequently possible to get accurate EMS survey data from a borehole that lies within a magnetically active area, if it is just small areas of intrusion that pull Earth's magnetic field. The total magnetic field should be observed for every station reading and if this is different to the rest of the survey then this outlier can be cropped. Reliable outlier cropping obviously requires a short or even continuous sampling interval. This can seen in Figure 7, where the magnetic clutter caused by geological formation intersection, and the collar influences are present in this continuous survey log.

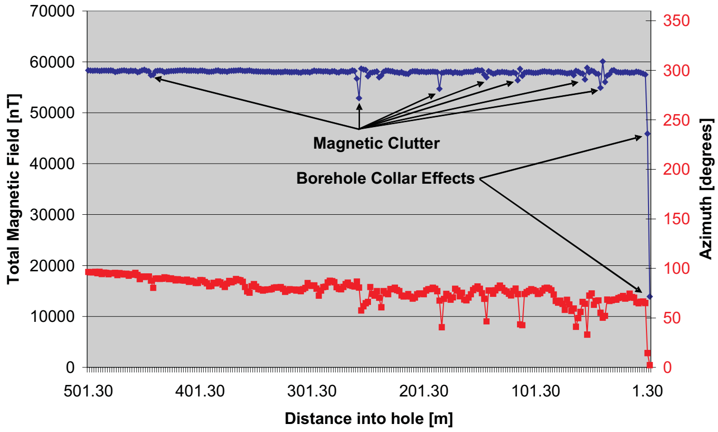

FIG 7 - Total magnetic field and azimuth log. The clutter is associated with borehole fault intersections.

Magnetic deviation

EMS tools measure Earth's magnetic field or in other words the direction to the magnetic North Pole. The problem with this is that the magnetic North Pole is drifting at an increasing rate from the true North Pole. There are models and magnetic observatories around the world that calculate these and the deviation for any position on the earth can be read from internet websites† for the date of the survey. Alternatively the national magnetic observation station for the country can be contacted. Additionally the magnetic declination varies on a minutely basis, particularly at high latitudes, due to solar flares and other space weather effects. Figure 8 shows how the magnetic declination and inclination can vary, with changes over half a degree on this survey day in Northern Canada. Using this information the declination can be dynamically adjusted for the precise duration of the survey that is shown in Figure 9.

Aero-magnetic surveys

On a local scale the entire magnetic field for a mine site can be rotated by a few degrees as a result of the geological rock formations. Aero-magnetic surveys can be used to check and correct for this. At the Voorspoed test survey it was found that all magnetic survey instruments were off by three degrees (Wolmarans, 2005). An aero-magnetic survey confirmed this fact, with the likely cause being the dominant kimberlitic pipe.

† <http://www.ngdc.noaa.gov/seg/geomag/jsp/Declination.jsp> – USA National Geophysical Data Centre.

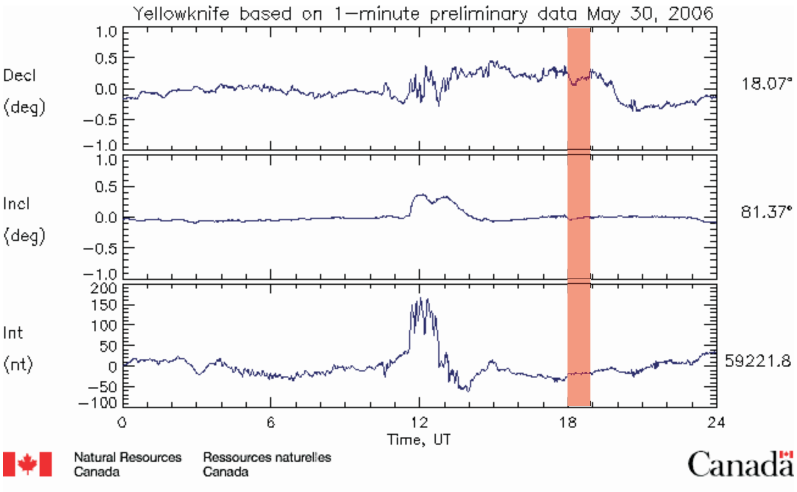

FIG 8 - Magnetic field variations over the 24 hour period (from Natural Resources Canada: http://www.geolab.nrcan.gc.ca), survey time is shaded.

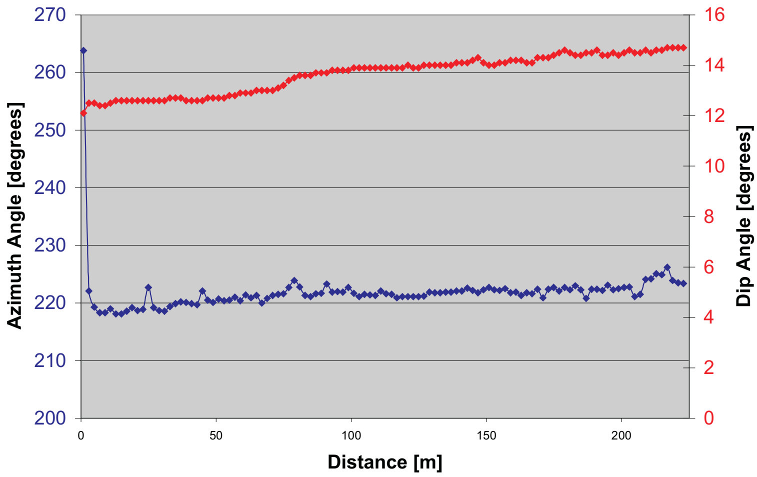

FIG 9 - Azimuth and dip survey data, during shaded interval in Figure 8.

Borehole position

Unfortunately not all boreholes in the world are created equal in terms of survey accuracy. Surveying at very high or low latitudes (towards the poles) may give less accurate azimuth readings. This is due to the inclination angle of the Earth's magnetic field lines shown in Figure 10. In Sydney at a latitude of 34 degrees south the magnetic inclination angle is 64 degrees, this means that the horizontal component of the Earth's magnetic field, from which azimuth is derived, is about 43 per cent of the total field. However, at a mine in Canada at 63 degrees north, the horizontal field makes up only 12 per cent with an inclination angle of 83 degrees. This causes small inaccuracies in calibration and system noise to result in large azimuth direction uncertainties.

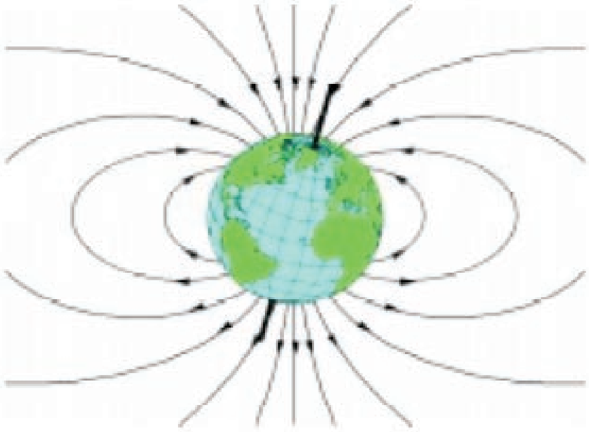

FIG 10 - World magnetic model illustration (Caruso, 1998).

Figure 11 (left) shows the expected azimuth errors for an orientation sensor where sensor errors of 1 mg for accelerometers and 50 nT for magnetometers are assumed (Goodman, 2006). These errors could be caused by measurement inaccuracy or sensor misalignment.

Additionally, azimuth accuracy decreases as the sensor approaches a dip angle of 90 degrees (vertical). This is not the result of sensor performance, but is due to the coordinate system, which is singular at a dip of 90 degrees. Figure 11 (right) shows the uncertainties in azimuth, as a function of sensor dip angle. Close to vertical the error is dominated by systematic errors, such as imperfect calibration. It is assumed for this calculation that the accelerometers are accurate to 1 mg, the magnetometers are accurate to 50 nT, and the magnetic vector inclination angle is 60 degrees.

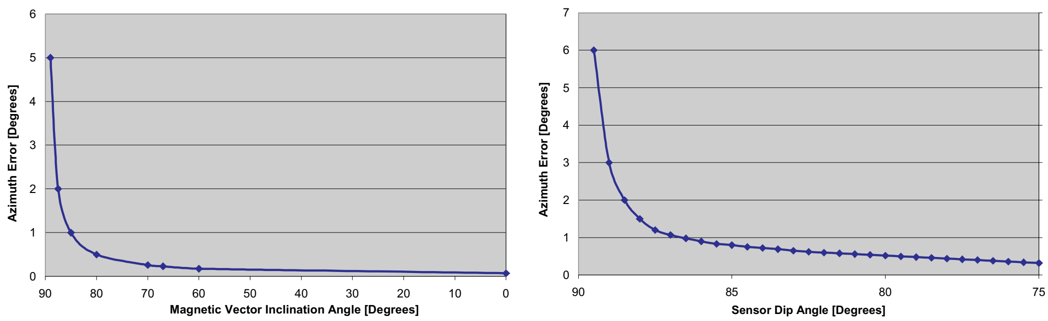

FIG 11 - Azimuth errors due to magnetic inclination angle, (left) and near vertical boreholes (right) (Goodman, 2006).

CONCLUSIONS

This paper has examined the need for improved borehole survey accuracy to give real value to information gleaned from exploration boreholes. Common causes of inaccuracies have been examined and some possible solutions have been presented. In point form these can be listed as:

- calibrate the entire survey device (not just the sensor part) regularly and at a range of temperatures;

- use good survey techniques, including short or continuous station spacing, and check that probe is stationary for each station measurement;
- use up to date magnetic declination data and check for solar magnetic activity;
- be on the look out for magnetic clutter – use the total magnetic field as a guide for this;
- if many surveys are being done in one area, like a mine site, consider finding out if there is a local magnetic anomaly there; and
- when surveying at high latitudes or vertical holes be aware of possible accuracy degradation.

ACKNOWLEDGEMENTS

The authors would like to express their thanks to Anton Wolmarans for his driving of the Voorspoed project. Valuable assistance and insight was also gained from Wessel van Brakel, Brian Woods, Wessel Croukamp, Keith Palmer, Philip Manning and Carina Simmat. The assistance of the geology team of DeBeers Canada is also gratefully acknowledged. Furthermore, the authors would like to extend their appreciation to CRC Mining, ARCO and the University of Sydney for their continued support of this work.

REFERENCES

Caruso, M J, 1998. Applications of magneto-resistive sensors in navigation systems, Honeywell Inc [online]. Available from: <http://www.ssec.honeywell.com/magnetic>.

Goodman, W L, 2006. *544 Orientation Sensor Manual*, Mountain View, CA, USA, April.

Killeen, P G, Bernius, G R and Mwenifumbo, C J, 1995. Surveying the path of boreholes: a review of orientation methods and experience, Geological Survey of Canada, Natural Resources Canada, Ottawa.

Orpen, J, 2005. Introducing the borehole surveying benchmarking project, Institute of Mine Surveyors of South Africa Colloquium, Voorspoed Mine, Belmont, Republic of South Africa, 5 to 6 May.

Sindle, T G, 2002. Design of an orientation sensor for borehole radar, BEng (E&E) Project, Stellenbosch University, South Africa, November.

van Brakel, W J A, Sindle, T G, Cloete, J H and Mason, I M, 2005. The effect of magnetometer and accelerometer errors on the predicted trajectories of boreholes surveyed by EMS instruments, SAGA Conference, Cape Town, Republic of South Africa.

Wolmarans, A V, 2005. Borehole orientation surveys benchmark study, Institute of Mine Surveyors of South Africa Colloquium, Belmont, Republic of South Africa, 5 to 6 May.