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Extracting three component magnetic data from down hole surveys
or
Survey for nothing and your mag for free
(with apologies to Dire Straits)

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Most drill holes deeper that 100 m are now routinely surveyed using some form of down hole survey tool in order to recover the true hole path. If the survey tool relies on the earth's gravitational and magnetic field to recover azimuth and dip then it generally also provides three component magnetic data. These data are currently underutilised, principally because users are either unaware that the data exist, or do not have the software tools to easily convert the data into an interpretable format. This short note aims to address both these hurdles.

Magnetic survey tools contain a three component fluxgate to measure the magnetic field and a three component accelerometer to measure gravity as shown schematically in Figure 1.

Before anyone goes off on a tangent, NO, these accelerometers are not of sufficient accuracy to be used as gravity meters! In Figure 1 the components are labelled with x, y and z subscripts using a right hand rule in order to match the trigonometry that follows, however different tool manufacturers have different right hands and all that can be assumed with real data is that the three components are orthogonal and that the gravity and magnetic components are parallel and will occasionally have opposite signs. Remember that convention has both the magnetic field and gravity field as positive down.

The software provided with the survey tool, or firmware within it, use these six readings to derive the magnetic azimuth of the hole and its dip, which is why the tool was used by the driller in the first place. The driller passes the data on to the geologist and generally the data stop there. However, the majority of survey tools can also provide either the raw data for the six measurements, or a processed version of them that can be used by a geophysicist to create a three component down hole magnetic survey – free data!

We'll quickly work through the trigonometry required to recover the data but, in essence, if the two radial accelerometers are used to determine the tool roll, R, the ratio between the total radial and axial accelerometers then provides Dip. The tool roll computed from the accelerometers can then be applied to the magnetometers to recover total radial magnetic field, which using the hole dip and axial magnetic field can then be rotated to provide horizontal and vertical magnetic fields. The horizontal field is assumed to be pointing to magnetic north and the rotation between it and the vector normal to the hole, in the vertical plane through the hole, is the magnetic azimuth. Local disturbances in declination away from the regional can be mapped if we either have an independent non-magnetic measure of azimuth, for example from a gyro tool, or assume that long wavelength variations in the azimuth are due to hole deviation and short wavelength variations are due to local magnetic sources and apply a low pass filter to the azimuth to approximate what we hope is the hole azimuth. Armed with both the hole and the apparent magnetic azimuths we can separate the horizontal magnetic field into its east and north components.

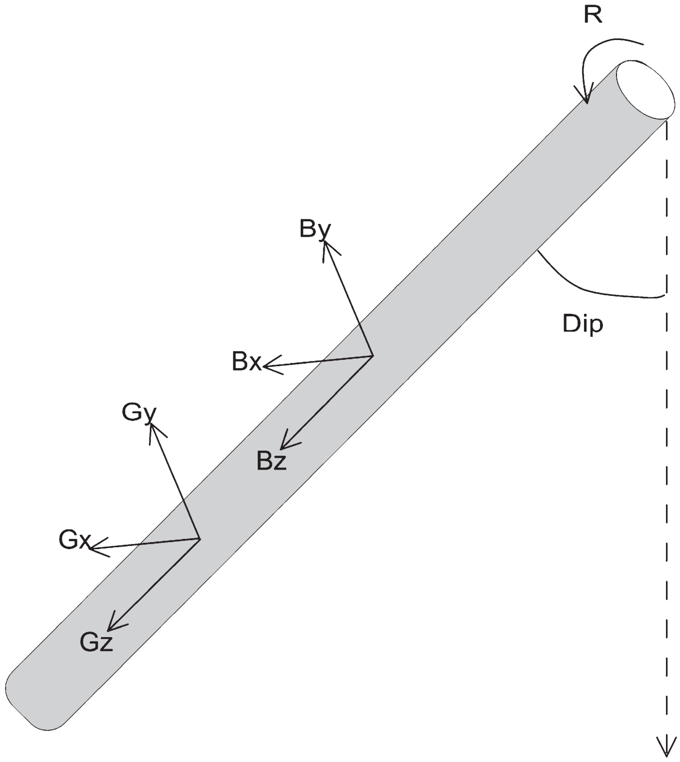

Figure 1. *Component labelling notation.*

Here is the same thing algebraically.

First, assume that the gravitational field is vertical and use the accelerometers to derive inclination and tool roll.

$$G_r = \sqrt{(G_x^2 + G_y^2)}$$

$$R = \Pi - \mathrm{Atan}(G_y/G_x)$$

$$\mathrm{Dip} = \mathrm{Atan}(G_r/G_z)$$

Mineral exploration convention has dip negative down from horizontal so to convert this dip to something more familiar to a minerals explorer we need to subtract 90° from it. The Dip used in the following equations is the Dip in the equation above not the typical mineral dip.

Now, rotate the magnetic components into horizontal and vertical fields.

$M^{`}_{x} = M_x \mathrm{Cos}(R) - M_y \mathrm{Sin}(R)$

$M^{`}_{y} = M_x \mathrm{Sin}(R) + M_y \mathrm{Cos}(R)$

$M^{``}_{x} = M^{`}_{x} \mathrm{Cos}(Dip) + M_z \mathrm{Sin}(Dip)$

$B_v = -M^{`}_{x} \mathrm{Sin}(Dip) + M_z \mathrm{Cos}(Dip)$

$B_h = \sqrt{}(M^{``2}_{x} + M^{`2}_{y})$

Now, compute the apparent magnetic azimuth, total field and magnetic inclination

$\mathrm{Azimuth} = \mathrm{Atan}(M^{`}_{y} / M^{``}_{x})$

$B_t = \sqrt{}(M_x^2 + M_y^2 + M_z^2)$

$B_i = \mathrm{Atan}(B_v/B_h)$

Because we are dealing with three component data it is a powerful interpretation aid to be able to display these as vectors in 3D. However, in nearly all cases, the anomaly of interest is only a small fraction of the earth's field and the vectors of B_v and B_h are so dominated by the earth's field that the anomaly is lost. A background or regional is therefore subtracted from the data to produce residual components. The choice of background is entirely up to the user and will depend on the target being sought. Because drillholes are generally relatively short, compared to comparable ground or airborne survey lines, most workers start by subtracting a constant from the data as removal of a varying value automatically involves interpretation and we need to see the data before interpreting it. A typical background value can be derived from looking at B_t and B_i and trying to pick an non anomalous part of the profile, although some workers use the IGRF values for the area. The latter approach assumes that all tools are well calibrated and clear of all magnetic interference, a courageous assumption.

From the Total Field and inclination background values we can compute background values for the horizontal and vertical fields (B_{hr} and B_{vr}) and thus derive anomalous north and down component fields

$B_n = B_h - B_{hr}$

$B_d = B_v - B_{vr}$

The east component of the magnetic field at this stage is zero as the anomalous field is assumed to have the same declination as the earth's field. If, however, we now introduce a new version of the magnetic azimuth that is free from local magnetic effects, (we will call this the hole Azimuth) we can break the horizontal field into its two components using simple trigonometry.

$B_e = B_n \mathrm{Sin}(\text{hole Azimuth} - \text{apparent Azimuth})$

$B_n = B_n \mathrm{Cos}(\text{hole Azimuth} - \text{apparent Azimuth})$

Remember that at this stage everything has been referred to magnetic north, in order to use the data in a 3D package it will need to be rotated to true north or local grid north if not using UTM co-ords.

$B_{ge} = B_e \mathrm{Cos}(Decl) + B_n \mathrm{Sin}(Decl)$

$B_{gn} = B_n \mathrm{Cos}(Decl) - B_e \mathrm{Sin}(Decl)$

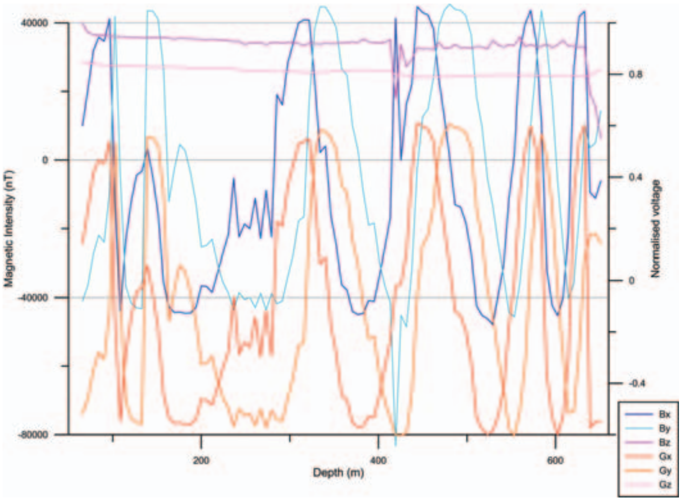

Figure 2. *Plot of raw data against depth down hole.*

Where Decl is the declination between grid and magnetic north, positive east.

In the absence of purpose written magnetic reduction software these calculations are easily performed in a spreadsheet. As noted above, some manufacturers output all six raw components, others output B_t and B_i, and yet others output B_h and B_v. The latter two data types also require azimuth and dip from the same tool, but these are nearly always provided in the same file.

So what does this data look like? Figure 2 shows a plot of the raw data from the 6 components for a hole in the northern hemisphere.

The axial components are generally easy to spot as they are relatively well behaved. The radial components, on the other hand, can be seen to change wildly as the tool rolls in the hole. Note that the two X components are in phase as are the two Y components. In the southern hemisphere, because the regional magnetic field is pointing up, matching components will generally be 180 degrees out of phase. Clearly in this state the data are not particularly useful as an interpretation aid, although there are obvious magnetic anomalies around 430 m down hole and at the end of this hole. Note, however, that the anomaly at around 430 m coincides with a flexure in G_z indicating a change in dip. It is likely that the magnetic anomaly here is due to a metal wedge, information that is not always passed on with the data. The anomaly at the bottom of the hole is also accompanied by a change in G_z, possibly due to the tool twisting sideways in the hole. While for most surveys picking the axial component is relatively easy, it is not generally possible to tell which pair is X and which is Y. A new tool type therefore requires a trial and error calculation, swapping components and signs until a calculation using the formulae given here derives a dip and apparent azimuth in agreement with those provided by the tool's software. Note the signs of the gravity and magnetic sensors on the axial component as these may also need to be flipped. Table 1 lists tools and adjustments required for some of the tools used by the author.

Having established which component is which, it is a simple matter to compute apparent azimuth, dip, total magnetic field, magnetic inclination and the horizontal and vertical component of the field. A background value can then be subtracted from these to provide the north and down magnetic residuals.

Table 1. Tools and adjustments required for some of the tools used by the author

Tool	Adjustment
Champ	None
TBS Russel – Subsurface Systems	Swap X and Y
Scintex Auslog	Swap X and Z
Reflex EZ Track	Swap X and Y
Flexit	Swap X and Y
Direct Systems DMU	Swap X and Y Mag is in µT
Geoscience Televiewer	Does not output G_z. Calculate using $G_z = (1 - \sqrt{(G_x^2 + G_y^2)})$ Mag is in µT and multiply B_z by −1
Crone Rad Tool	Swap X and Z
Globaltech Pathfinder	Swap X and Y and multiply all G by −1
EMIT Atlantis Analogue	Multiply all mags by −1
EMIT Digi-Atlantis	Outputs magnetic data in standard EM U, V and A convention so rotate using azimuth and dip only

Figure 3 shows vector plots of the B_h and B_v on the left and the residuals B_n and B_d on the right. The hole has a roughly southerly azimuth and is also in the northern hemisphere at a place where the regional inclination is about 73° as is evident from the left hand plot. Clearly the removal of a background value makes the data more interpretable. Can you guess where the magnetic body is?

Remember that at the moment we have assumed the east component of the magnetic field is zero. Because the holes were drilled towards a strongly magnetic target they were also surveyed with a gyro tool, which only relies on an assumption that gravity is vertical down and that the driller has entered the correct starting azimuth and dip for the tool. North seeking gyros go a step further to remove the driller uncertainty, relying instead on a gyrocompass to compute a rotation axis of the earth and then determine which is the north and south rotational pole relative to the survey point. Figure 4 shows a comparison plot for the apparent magnetic azimuth computed from the multishot survey tool and the magnetic azimuth generated from by gyro, assuming the regional value for magnetic declination. The magnetic field here is clearly very variable and has strong local anomalies affecting the east component with local declination anomalies of over 15°.

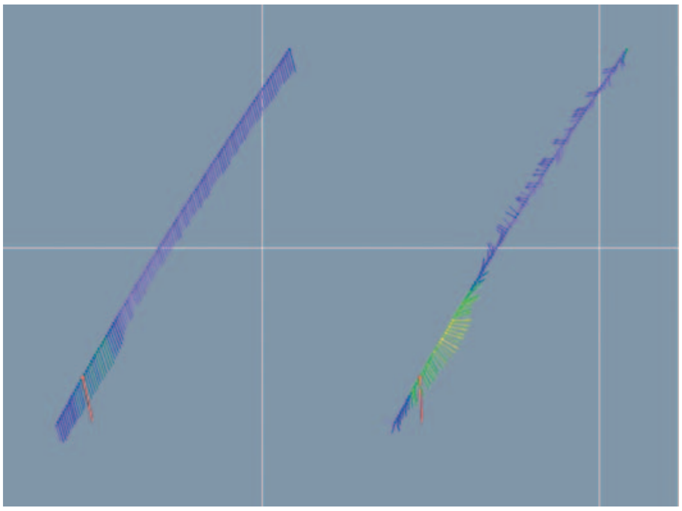

Figure 3. *Comparison between a vector plot of B_h and B_v on the left and the residuals B_n and B_d on the right.*

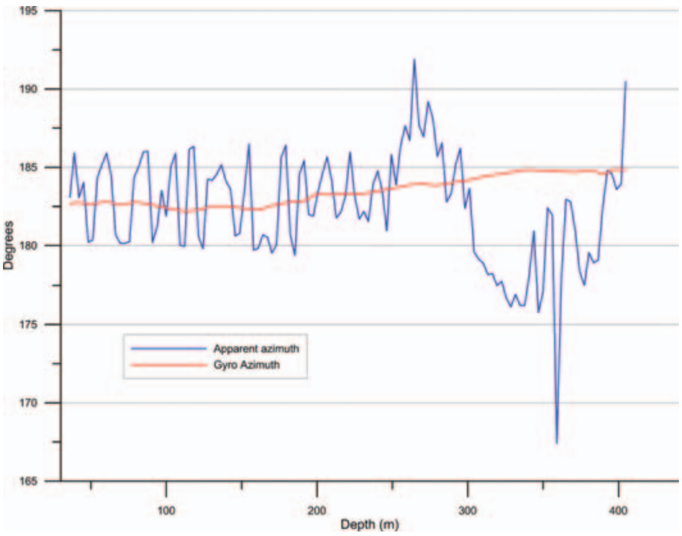

Figure 4. *Comparison of the magnetic azimuths computed by the multishot tool (blue) and gyro (red).*

We don't always have a gyro or other non-magnetic survey to determine the hole azimuth and in these cases we have to assume that long wavelength changes in azimuth are due to hole deviation while short wavelength changes reflect local magnetic anomalies. While clearly a flawed assumption, it is often the best we can do.

Using the angle between the hole azimuth and the apparent azimuth we can separate the east and north components to recover full three component data.

Interpreting a single hole of three component data is similar to interpreting a single line of ground magnetic data, you have a lot of room to move! In the absence of evidence from surface magnetic surveys we start by assuming the anomalous field is induced rather than dominated by remanence. However, even in cases of remanence, the vectors can be used to visualise where the body is. If we go back to the hole shown in Figure 3 and add its scissor pair the interpretation becomes even easier. Figure 5 shows the residual magnetic vectors with a schematic bar magnet aligned parallel to the earth's field overlain to simplify the interpretation even further.

As a confirmation of the interpretation above, Figure 6 shows a section through the ore shells of the deposit computed from all drilling.

The surveys shown above were acquired at 6 m intervals and taken at rod breaks on the final trip out from the hole. The core barrel is removed, the tool attached to a non-magnetic sub and pumped to the bottom of the drill stem, through the diamond bit, and set to take readings at a fixed interval. The driller then ensures that whenever the magnetic 'camera' is taking a shot that the rods are stationary. This occurs during rod breaks and so the survey just requires the driller to be able to synchronise the trip out with the stop watch marking 'camera' shots. Single shot surveys are also taken as the hole is drilled, generally at 30–50 m intervals. If the hole is long enough these too are a

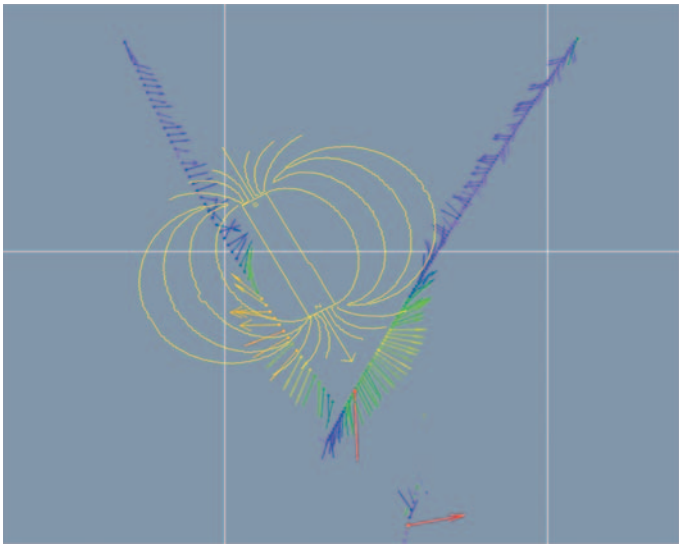

Figure 5. *Anomalous magnetic field plotted for two scissor holes with a schematic bar magnet field overlain as an interpretational aid.*

valuable source of magnetic data, although the coarse sample interval allows for a lot of aliasing.

Figure 7 shows vectors from nearly 100 RC precollars that have been surveyed at 40 m intervals from an example in the southern hemisphere. Because the target was a magnetic ironstone and the geologist was unaware that the multishot could still provide useful information, the diamond tails were unfortunately only surveyed with a gyro. No attempt was made to try and clean up single point anomalies in these data and because of the large number of holes and small number of readings per hole a single average background constant has been removed, rather than trying to estimate a background from just a few points or in some cases just one point. Clearly the background used is not correct for several of the holes in the left of the figure. Nevertheless, from the curvature of the anomaly shown by the vectors, it is clear that the ironstone continues to greater depths than indicated by the ore reserve wire frame.

RC holes can be surveyed inside the rods if a long non magnetic sub is used and the tool pulled far enough away from the bit. In practice the results carry around 100 nT of noise so surveying inside RC rods is not ideal and only recommended where the target is very magnetic and expected to be close to the hole or if there is no other option.

One great advantage of these down hole magnetic data is that they are immediately available. They are available as the hole is being drilled and whilst the rig is still onsite. Decisions can be made to extend the hole before the rig moves, and decisions about follow up EM and the casing that may have to go down the hole can be made on the spot – potentially saving money or adding value depending on whether an EM survey had already been planned or not.

Hopefully this short note will result in data that are currently ignored by most geophysicists and geologists being used to guide drilling and add a touch of geophysical class to what might otherwise be labelled as a boring geochemical discovery!

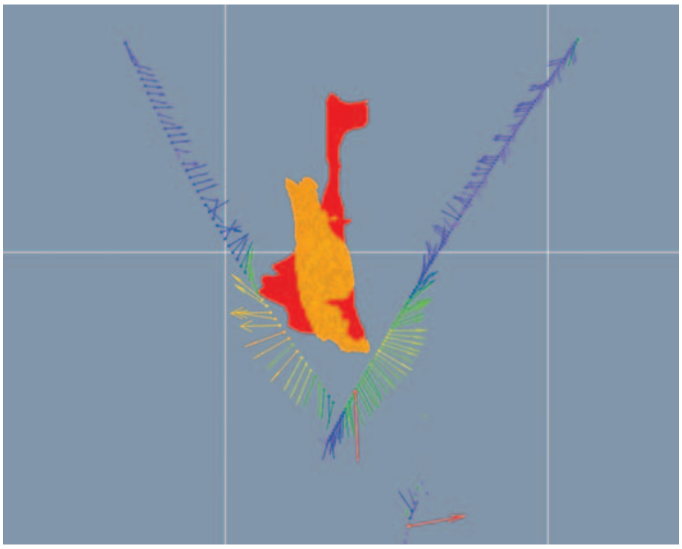

Figure 6. *Vector plot of anomalous magnetic field with ore shells in the same section overlain. Red = massive sulphide ore, orange = semi massive sulphide ore.*

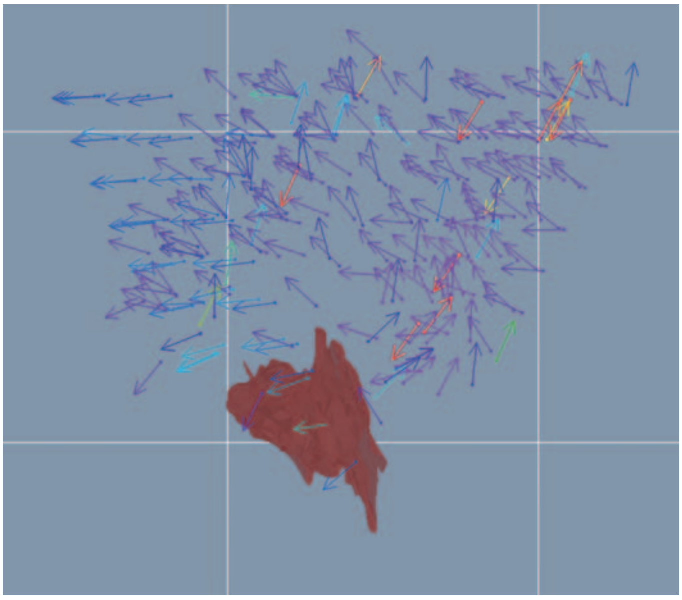

Figure 7. *Section looking west showing anomalous magnetic field vectors from around 100 RC pre-collars. Wire frame of ironstone from drilling shown in brown.*

Acknowledgements

Eagle Mine and Lundin Mining are thanked for permission to present the data for the northern hemisphere example shown here. The data were originally provided by Rio Tinto who are thanked for encouraging me to put this note together.