CASE HISTORIES ILLUSTRATING THE CHARACTERISTICS OF THE HeliGEOTEM SYSTEM

Richard S Smith[1], Jean Lemieux[2] and Greg Hodges[3]*
Fugro Airborne Surveys, Ottawa, rsmith@fugroairborne.com[1], Fugro Airborne Surveys, Ottawa, jlemieux@fugroairborne.com[2] Fugro Airborne Surveys, ghodges@fugroairborne.com[3]

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INTRODUCTION

The HeliGEOTEM system was introduced in 2005 to provide greater operational flexibility and improved lateral resolution compared with a fixed-wing system (Fountain et al., 2005). The system, described in more detail by Fountain et al. (2005), is a vertical-axis dipole transmitter towed below and behind a helicopter. The receiver, also attached to the tow cable is about 15 m in front and 35 m above the transmitter. The system measures the response in the time domain when a half-sine current pulse excites the ground. The dB/dt and B-field responses are measured in the x, y and z orientations. The geometry of the system and the coordinate system are shown on Figure 1. Compared with fixed-wing systems, the helicopter systems have their transmitter / receiver closer to the ground surface, which is why the spatial resolution is greater (the response is much sharper); also, the response of shallow bodies is much larger. However, when the bodies are deeper, the responses are more comparable.

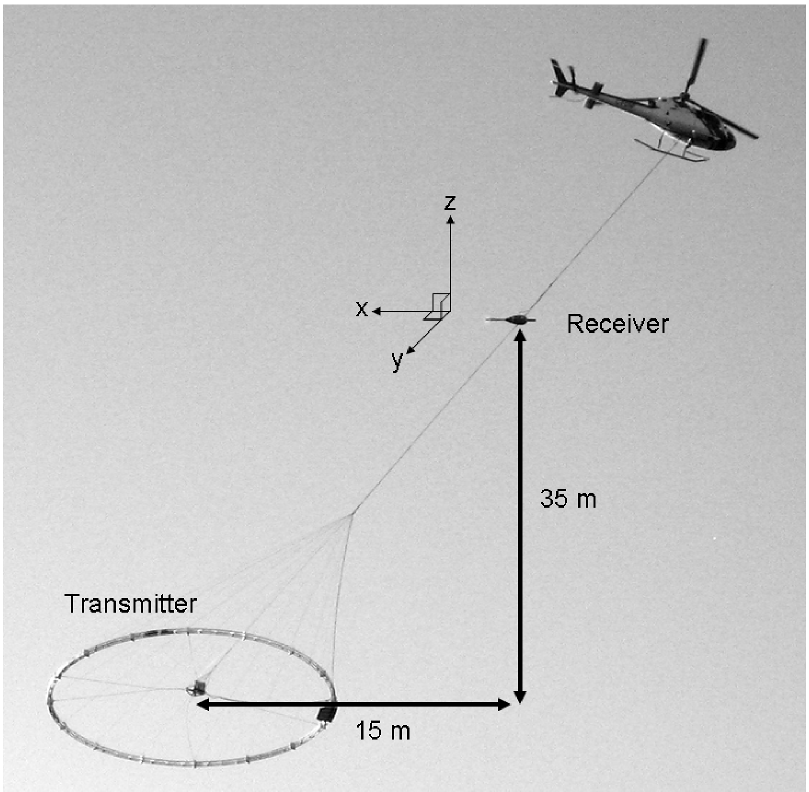

Figure 1: The HeliGEOTEM system with the transmitter receiver offsets labelled and the coordinate system shown.

Since its introduction, the HeliGEOTEM airborne electromagnetic (AEM) system has undergone a number of improvements. The introduction of broadband coils results in greater sensitivity to poor conductors. Increases in the dipole moment (signal level) and reductions in the noise level have improved the signal to noise ratio, allowing the response of deeper conductors to be detected. These characteristics are illustrated with case histories from the Sudbury and Timmins areas of Ontario, Canada and the Mattagami area of Quebec, Canada.

A comparison with data from the Dighem^V AEM system flown at Maimon, Dominican Republic, shows that the HeliGEOTEM is able to see deeper than Dighem^V, but does not have quite as good capability to resolve features close to the surface. Another comparison in an area of northern Alberta shows that the HeliGEOTEM has poorer resolution compared to the frequency-domain RESOLVE system, but better near-surface resolution that the fixed-wing GEOTEM system. This example is also used to illustrate the depth of penetration of the three systems in a conductive environment.

Also, interpretation and display tools developed for fixed-wing systems can also be applied to the HeliGEOTEM data.

COMPARISON OF HELICOPTER AND FIXED-WING SYSTEMS

The fact that the transmitter and receiver of the helicopter systems are closer to the ground surface means that the amplitude of shallow conductors will be larger and the anomalies will be sharper. This is illustrated using the following numerical example. The body is a 200 by 200 m dipping plate with its top just below the ground surface.

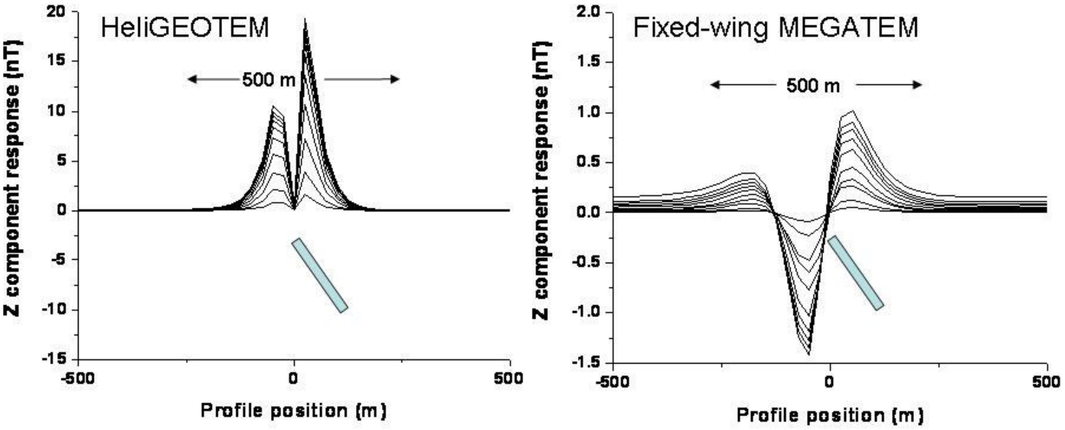

Figure 2: The response of a 200 by 200 m plate (blue) dipping at 70 degrees. The left panel is for a helicopter system (dipole moment 0.75 million Am^2) and the right panel is for a fixed-wing MEGATEM system (dipole moment 2 million Am^2). The waveform and measurement windows are identical for the two systems.

The width of the anomalous response of the helicopter system is less than 500 m, whereas the width of the anomaly from the fixed-wing system is about 500 m. Also, the amplitude of the deflections on the helicopter anomaly are about ten times larger that the variations on the fixed-wing anomaly. This example is for the case when the body is at surface. If the body is 100 metres deep, the amplitude difference is only a factor of two. For even deeper bodies, the larger moment fixed-wing systems will have a response larger than the helicopter systems (Macnae, 2008).

RECENT IMPROVEMENTS IN HeliGEOTEM

One of the most significant ways to increase the amplitude of the measured response is to increase the bandwidth of the system to provide large amplitude responses at early time. This is particularly true for poor conductors. In some cases, the very poor rapidly decaying responses can only be seen on the very early windows available with broad-band systems.

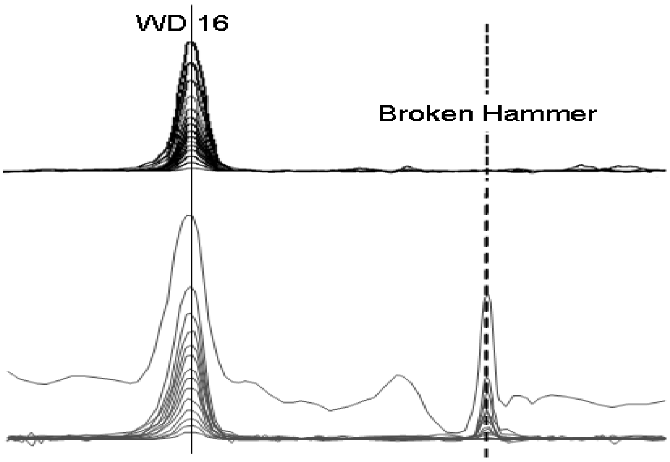

Figure 3: The z-component dB/dt response measured over the WD-16 and Broken Hammer prospects (Sudbury, Ontario, Canada); the approximate locations of the two bodies are indicated by the solid and dashed lines respectively. The top panel shows the narrowband profile, the bottom panel is the broadband profile.

The narrowband system (Figure 3, top) has a strong anomaly over the slowly decaying WD-16 prospect - a nickel-copper PGE-bearing massive sulphide, but no response at all over Broken Hammer which is a vein and vein-stockwork copper-PGE prospect. On the broadband data (Figure 3, bottom), the response over WD-16 is comparable, but the response over Broken Hammer is now evident as a rapidly decaying response in the early-time channels not available in the narrowband data.

Other improvements have resulted in the power of the HeliGEOTEM transmitter increasing from 235 000 Am^2 to 750 000 Am^2 (Figure 4, left). At the same time, the noise levels have been reduced by a factor of 2 (Figure 4, middle panel). This means that the signal-to-noise ratio of the system has improved by a factor of more than 6.4 since 2005.

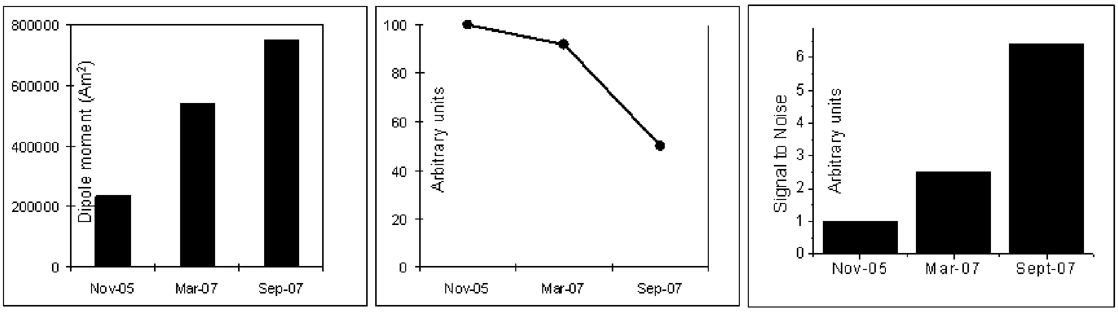

Figure 4: The increasing signal levels (left), the reducing noise levels (middle) result in the signal-to-noise ratio of the system increasing by more than a factor of 6 (right).

A greater signal-to-noise ratio means that the weaker responses associated with deeper conductors can be detected with an improved system. As an example of the capability of the improved system, we have an example showing the response of the Nighthawk graphite body near Timmins Ontario, Canada. This body is buried about 90 m below glacial overburden. A number of traverses were flown over the body, with increasing flying height. These types of height attenuation tests are didactic in resistive terrain, where the increase in flying height is analogous to the body being buried more deeply.

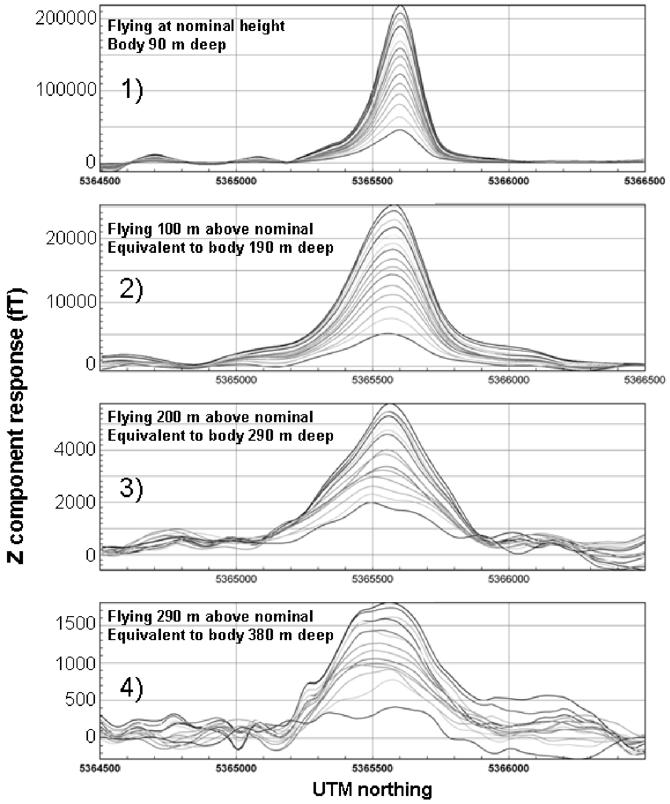

Figure 5: Z component B-field response over the Nighthawk body flown at four flying heights. Panel 1) is at the nominal height and panels 2), 3) and 4) are at heights 100, 200 and 290 m above nominal. A 90 Hz base frequency and a 2 ms pulse were used.

The response at the standard or nominal flying height is shown on panel (a) of Figure 5. Because the Nighthawk body is buried about 90 m below the ground surface, the case when the flying height is 100 m above nominal (panel 2), this is equivalent to the body being buried 190 m deep. For this case and for panel 3, which is equivalent to the body being buried 290 m below surface, the anomalous response is clearly well above the noise level. Panel 4 shows the case when the system is flying 290 m higher than nominal and in this case the anomalous response is close to, but still above the noise level. This demonstrates that the signal to noise of the system is such that bodies like Nighthawk could be identified when they are as deep as 380 m below surface. A similar height attenuation study has been done for the VTEM system (http://geotech.ca/images/stories/CaseStudies/VTEM%20exploration%20depth%20-%20Night%20Hawk%20Lake%20test%20range.pdf). A comparison of the two sets of results is shown plotted as a function of equivalent depth below surface on Figure 6. The results indicate that the two systems are very comparable for detecting good conductors such as the Nighthawk body.

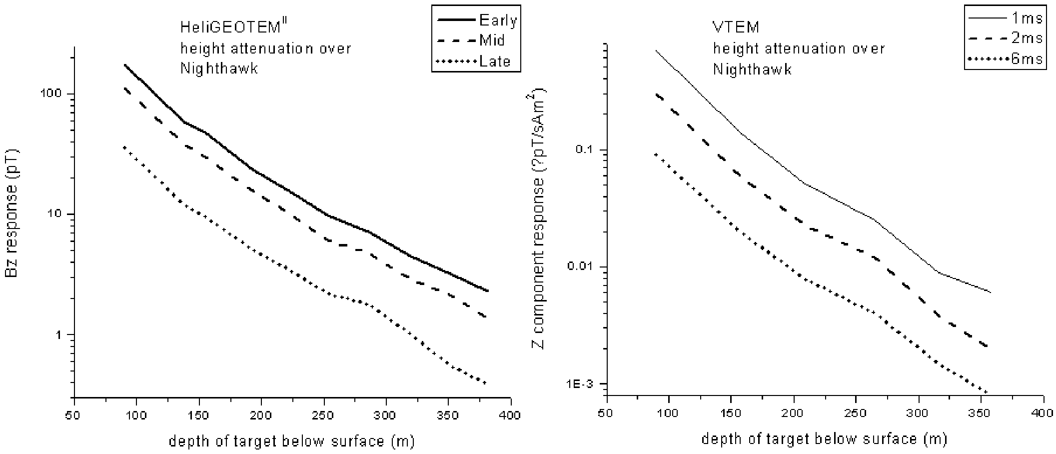

Figure 6: Z component response over the Nighthawk body as a function of equivalent depth below surface to the body. Panel a) shows the HeliGEOTEM B-field response and panel b) is the VTEM dB/dt response.

Another example of the improved signal-to-noise of the HeliGEOTEM system enabling the detection of a deep conductor is illustrated in Figure 7. In this case, the system was flown over the Caber body (in the Mattagami area of Quebec) which has a depth to top of 150 m and is both smaller than Nighthawk and steeply dipping, so the response is expected to be much smaller. A number of AEM systems are not able to see this difficult target. The HeliGEOTEM response at the nominal flying height is however, clearly evident.

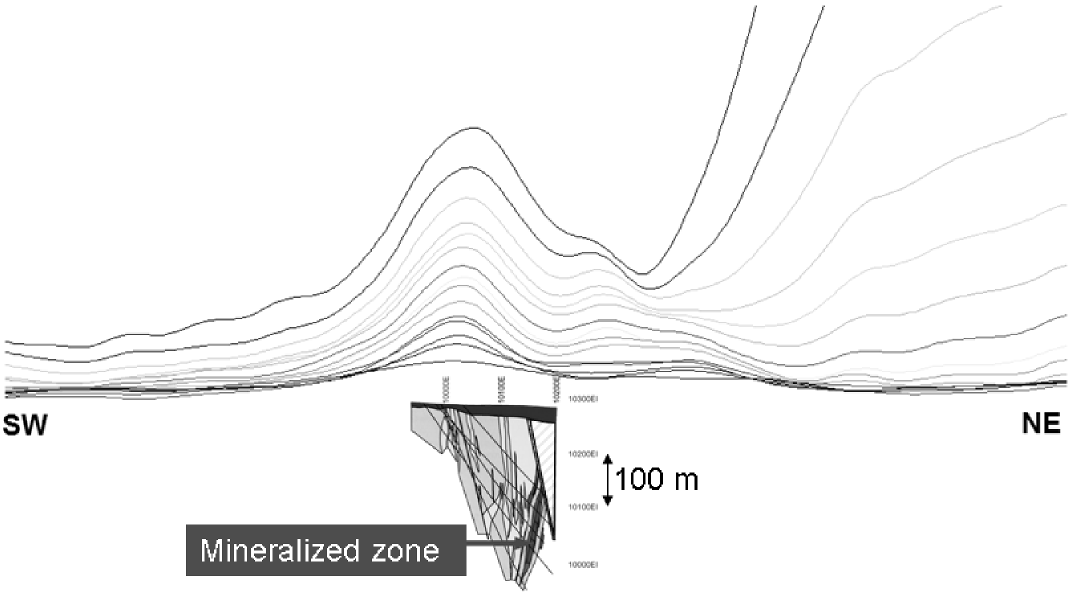

Figure 7: Z component HeliGEOTEM B-field response over the Caber body.

COMPARISON OF HeliGEOTEM WITH DIGHEM^V

The HeliGEOTEM system and the DIGHEM^V frequency-domain system were both flown over the Maimon deposit in the Dominican Republic. The deposit is a thin conductive massive sulphide body dipping at about 30 degrees (See panel c of Figure 8). The DIGHEM^V coplanar-coil (*z* transmitter and z receiver) response (Figure 8a) is very similar to the window 10 HeliGEOTEM *z*-component response (Figure 8b). The only significant differences are subtle, such as the feature at 369000E, which might be a deeper feature beyond the depth of penetration of the DIGHEM^V.

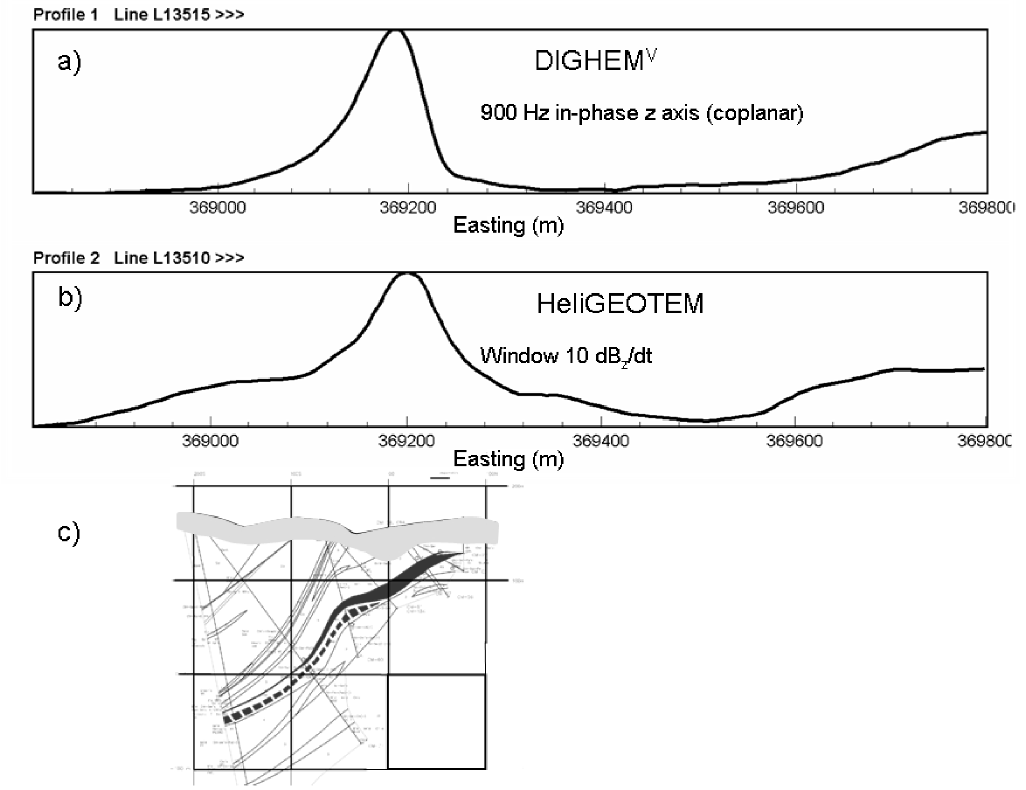

Figure 8: The coplanar coil DIGHEM^V response at 900 Hz (panel a) and the HeliGEOTEM window 10 z-component dB/dt response over the Maimon body (panel b). A geological cross section of the body is shown in panel c).

The DIGHEM^V profile for all frequencies and components is shown on Figure 9. The lower frequency in-phase coplanar coil responses (light green and light blue solid lines in panel a) both show a response that peaks to the west of the conductor's top edge (vertical dashed line). The highest frequency response is reflecting the conductivity of the overburden. The coplanar quadrature responses (dashed lines in the top panel) do not show an anomalous response over the body, indicating that the body can be interpreted as being highly conductive. However, the precise conductivity or conductance cannot be estimated, as the conductance of the Maimon body lies outside the aperture of sensitivity of the system.

The lower panel shows the coaxial response, where the transmitter and receiver are both in the *x* direction (along the profile). This coaxial response is very useful for identifying discrete conductors, as the response peaks directly over the top edge of the conductor.

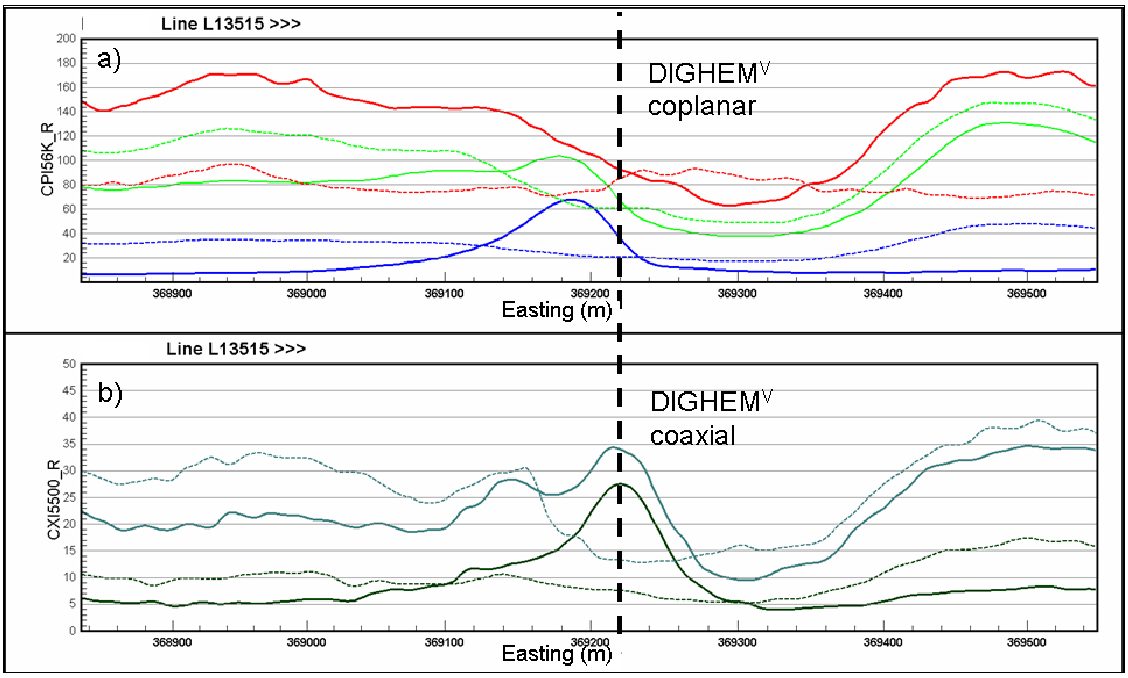

Figure 9: The DIGHEM^V *response over Maimon. Panel a) shows the coplanar response at 56 kHz (red), 7200 Hz (light green), and 900 Hz (light blue). Panel b) shows the coaxial coil response at 5500Hz (dark blue) and 1000 Hz (dark green). In both cases, the in-phase response is the solid curve and the dashed curves are the quadrature response. The vertical dashed line is the approximate location of the top edge of the body.*

The HeliGEOTEM B_z and B_x responses on the same profile line are shown on Figure 10. The top panel is the response measured by the z-oriented receiver and the bottom panel is the x-oriented receiver. As with Figure 8, the z-component response (panel a) is similar to the DIGHEM^V coplanar response. The amount that the amplitudes decrease in each subsequent measurement window is indicative of the decay rate of the conductor. If the body was more conductive, then the decay would be slower; conversely, a less conductive body would have a faster decay. The HeliGEOTEM is thus able to estimate the conductance of the Maimon body. A modelling exercise indicates that the conductance is 200 S. The x-component response is shown on Figure 10b. This response has a different shape to the DIGHEM coaxial response (Figure 9b), as the transmitter in the HeliGEOTEM case is z oriented, as opposed to an x-oriented transmitter in the DIGHEM^V coaxial case. Nevertheless, the x-component HeliGEOTEM response can be useful in some cases, as it helps to distinguish a thin conductor with a crossover from negative to positive (as shown) from that of a thick conductor, which has a crossover going from positive to negative (Fountain et al., 2005). Balch et al. (2003) also illustrates this reversal in the sense of the crossover; although their sign convention is reversed from Fugro's.

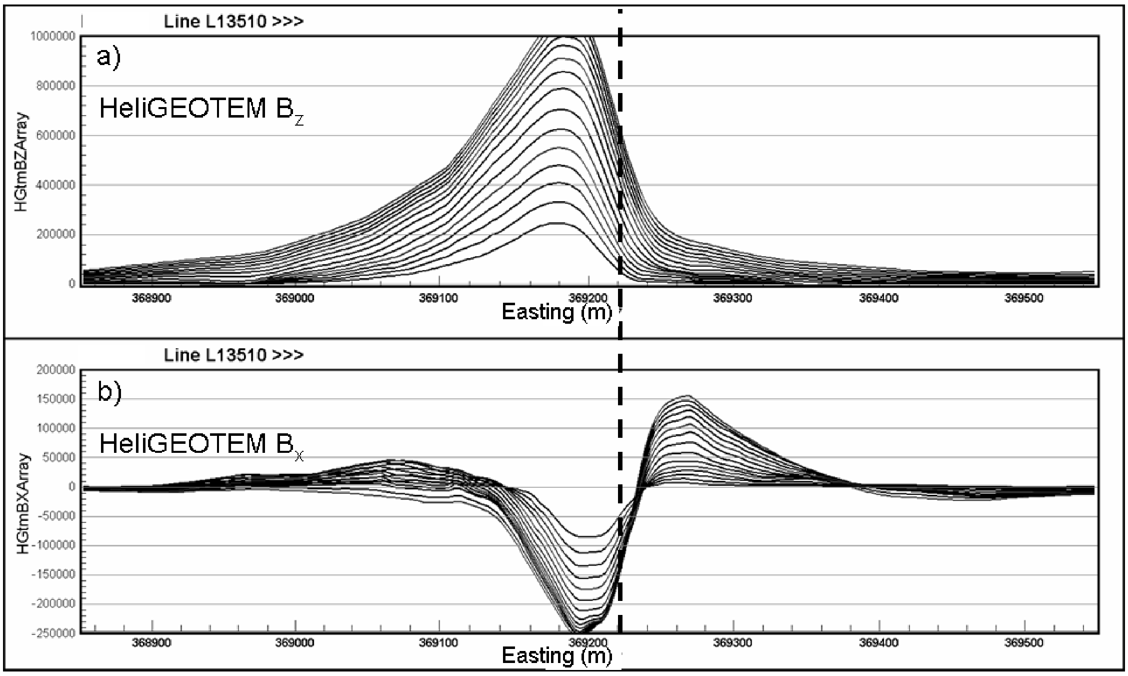

Figure 10: The HeliGEOTEM response over Maimon. Panel a) shows the z-component B field response and panel b) shows the x-component response. The vertical dashed line is the approximate location of the top edge of the body.

COMPARISON OF HeliGEOTEM WITH RESOLVE AND GEOTEM.

The HeliGEOTEM has been flown over an area where the RESOLVE and GEOTEM systems have been used to acquire data. RESOLVE is a frequency-domain system like DIGHEM^V, but all five coil pairs are coplanar, so RESOLVE is useful for mapping conductivity as a function of depth. The GEOTEM is a fixed-wing system with comparable power to HeliGEOTEM.

The RESOLVE data has been converted to a resistivity-depth image (RDI) on Figure 11a. It shows a resistive (orange) feature labelled “aquifer”. There is another similar but smaller feature on the far right of the section. Elsewhere the section is more conductive (purple), with the most conductive feature being blue on the extreme left. At this location, the depth of penetration of the RESOLVE is about 100m. The HeliGEOTEM data have been converted to an RDI on Figure 11b. The larger aquifer is seen as an orange feature, but the smaller one is not. The material surrounding the aquifer is brown, having a resistivity between 30 and 50 Ωm. Interestingly, this brown layer has a flat bottom and below that the more conductive shale has been mapped as a purple layer about 100 m thick. The HeliGEOTEM has mapped a resistive rock unit below the shale, particularly on the left-hand side. The bottom panel (Figure 11c) is the GEOTEM data, converted to an RDI. On this display, the results are very similar to the HeliGEOTEM section, except the section is not as laterally uniform. The GEOTEM has also penetrated into the resistive rock unit, although the estimated resistivity is less than on the HeliGEOTEM section.

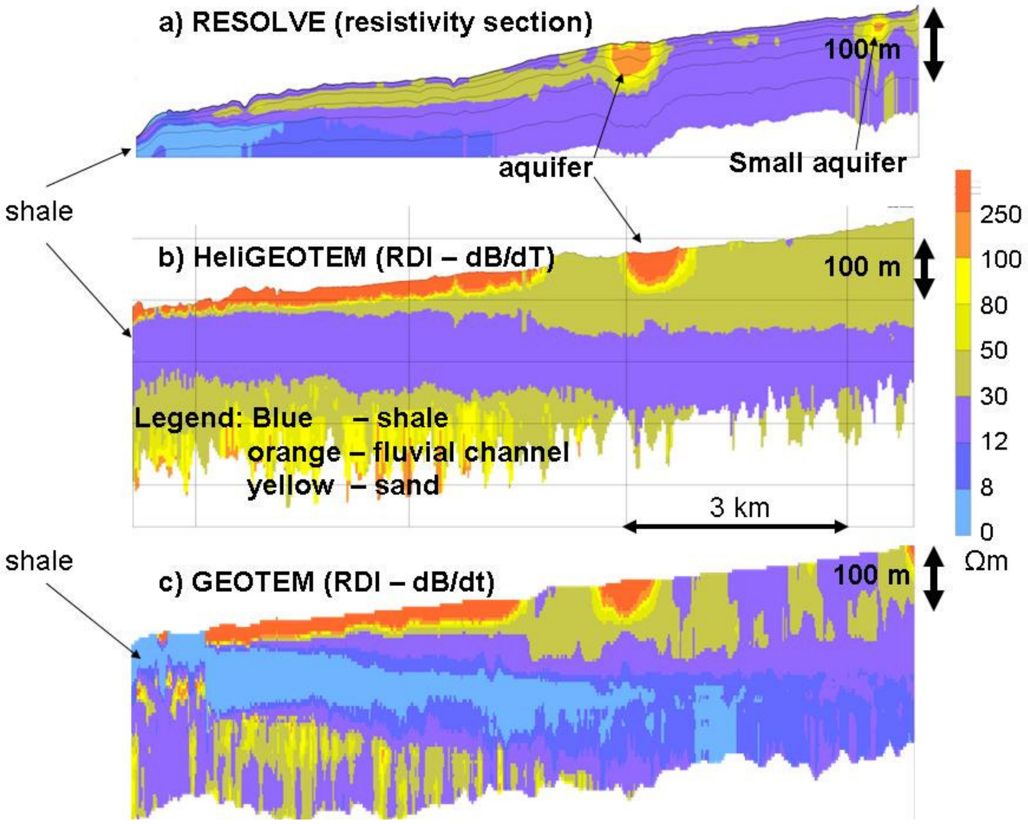

Figure 11: A comparison of resistivity depth images (RDI) derived from RESOLVE data (a), HeliGEOTEM data (b) and GEOTEM data (c). The resistivity colour bar used for all images is on the right-hand side of the figure.

INTERPRETATION AND DISPLAY TOOLS

The tools developed for the display and interpretation of fixed-wing GEOTEM data have been adapted for use on HeliGEOTEM data. The conductivity-depth-transform approach advocated for GEOTEM (Wolfgram and Karlik, 1996) has been implemented for HeliGEOTEM using the algorithms of Smith et al. (1994). Figure 12 shows the Maimon data of Figure 10a converted to a conductivity-depth image. This conductivity-depth imaging approach assumes that the earth is comprised of horizontal layers at each location. As the Maimon body is relatively shallow and dipping at 30 degrees, this is not a bad approximation, so the more conductive (maroon colour) zone to the left corresponds approximately to the body location (black outline). However, there is also a maroon zone to the right that does not correspond to a conductor. A conductive "arch effect" is often seen when discrete conductors are imaged with an assumed layered model.

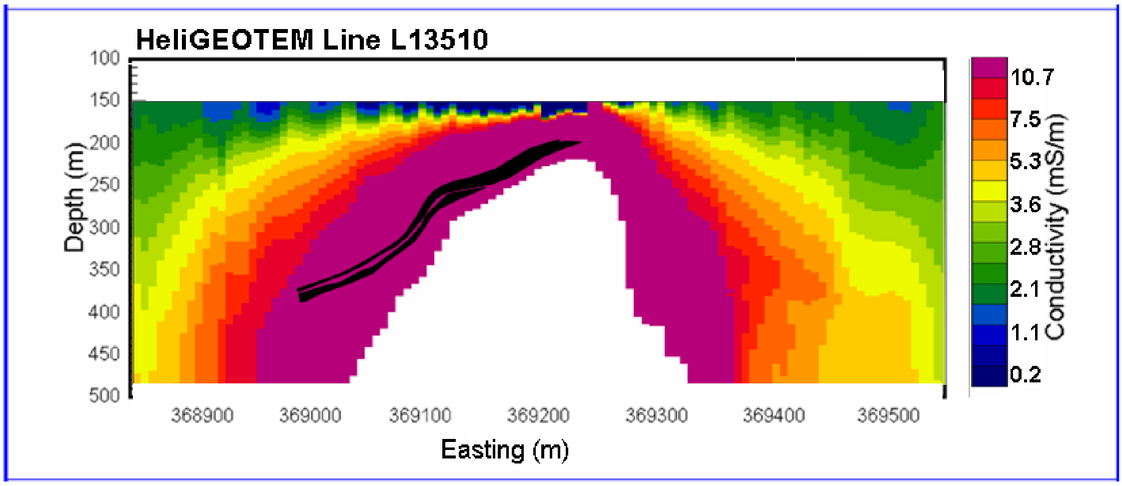

Figure 12: The data of Figure 10a converted to a conductivity-depth image. The colour bar for the conductivity is on the right hand side. The outline of the ore body is shown on the section in black.

An alternate approach is to assume a discrete conductor model and explain the data with this model (Smith and Salem, 2007). Figure 13 shows the discrete conductor transform of the HeliGEOTEM data. In this case, a dipolar conductor model is assumed. The location of the dipole capable of best explaining the data is at 369200E, at a depth that is close to the top edge of the body. The estimated conductivity-radius-squared of the sphere is 26000 Sm (Figure 13a). The best model has currents flowing at a dip that can be estimated from the brightest colour on the section in Figure 13b. In this case, red corresponds to a dip of 30 degrees, which is close to the true dip.

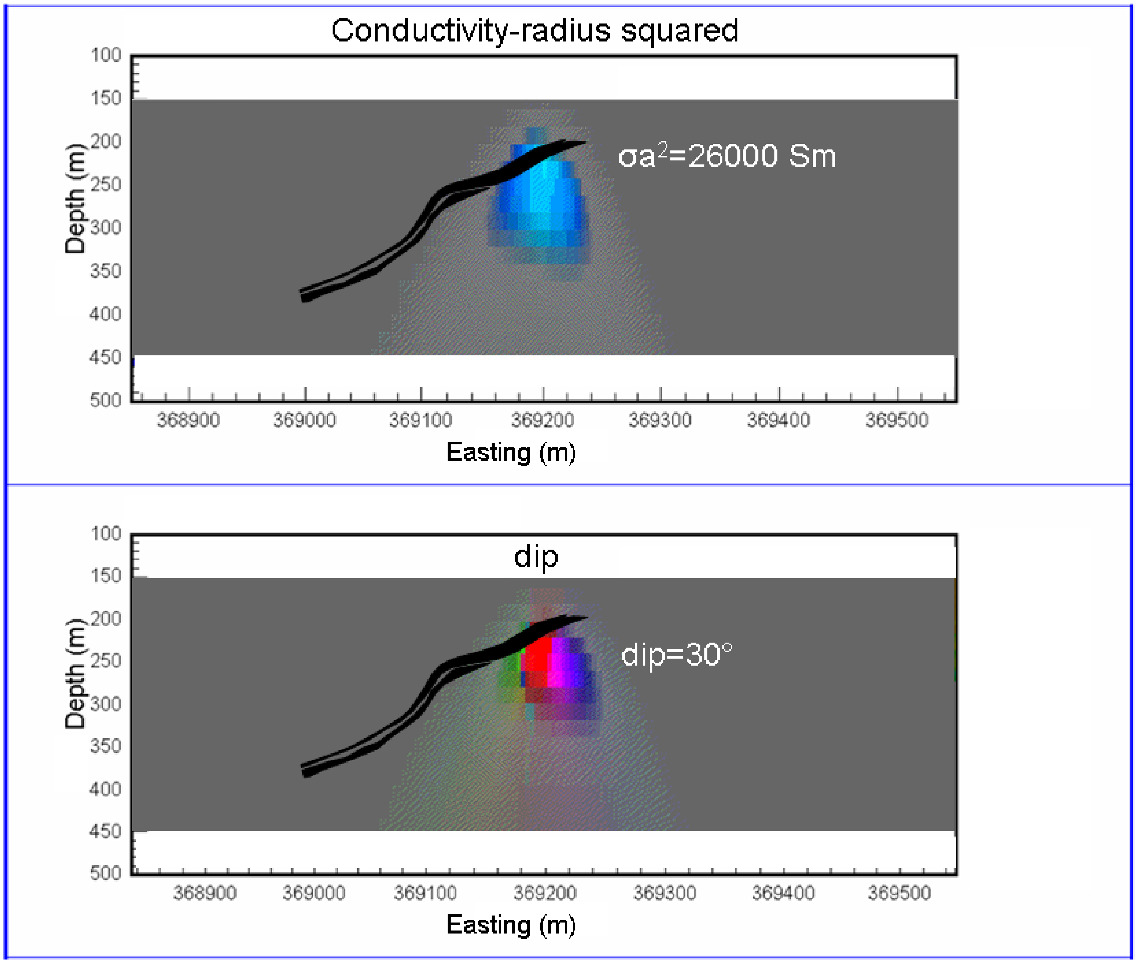

Figure 13: The data of Figure 10a converted to a discrete conductor transform. Panel a) shows the brightest colours where a dipolar conductor is consistent with the data. The hue of the colour corresponds to the estimated conductivity-radius squared. Panel b) is the dip that is most consistent with the data, with a red hue corresponding to a dip of about 30 degrees. The outline of the ore body is shown on the section in black and the thickest part appears to have a dip of about 30 degrees.

CONCLUSIONS

The benefit of greater operational flexibility, improved spatial resolution and larger responses from near-surface conductors induced Fugro to introduce the HeliGEOTEM system to compliment its line of fixed-wing EM systems.

Since first introduced in 2005, the HeliGEOTEM system has been significantly improved. The bandwidth of the system has increased, allowing information to be acquired at very early delay times. This means that rapidly decaying conductors such as Broken Hammer can now be detected. The signal levels have increased, as the dipole moment has increased from 235 000 to 750 000 Am^2, at the same time, the noise levels have been reduced by a factor of two, resulting in a signal-to-noise level improvement by a factor of 6.4. This improvement in signal-to-noise ratio means that the system is able to detect the small response from deep conductors. For example, a height attenuation survey suggests that if the Nighthawk conductor was buried at a depth of 380 m below surface, it might be detected. A traverse over the Caber prospect, which is a small and difficult target, shows that the deposit can be detected.

A comparison of the HeliGEOTEM data with DIGHEM^V at the Maimon deposit shows that the *z*-component and coplanar responses respectively are comparable in shape. The *x*-component HeliGEOTEM and the coaxial DIGHEM^V data are different: the former has a crossover near the top of the conductor, whereas the latter has a peak. In the case of the HeliGEOTEM the thickness of the conductor is indicated by the sense of the *x*-component crossover. (It is also possible to interpret the thickness of the conductor from the DIGHEM^V data.) The conductance of the body cannot be estimated from the DIGHEM^V data, as the quadrature anomaly is zero, but the HeliGEOTEM decay rate can be used to estimate a conductance of 200 S. There are some features on the HeliGEOTEM profiles that are not evident on the DIGHEM^V data, so it could be argued that the HeliGEOTEM might be detecting deeper features.

A comparison of HeliGEOTEM with RESOLVE and GEOTEM shows that the HeliGEOTEM does not have the ability to identify small shallow resistive features seen on the RESOLVE data. The HeliGEOTEM and GEOTEM systems can both map a conductive layer about 100 m thick and identify a resistive unit below the conductive layer.

Tools for the display and interpretation of the fixed-wing data have been modified to work with HeliGEOTEM data. If a layered earth model is appropriate, then conductivity-depth images can be produced. If an isolated conductive target is more appropriate, then the data can be used to generate a discrete-conductor-transform image. In this case, it is possible to estimate the location, depth, dip and conductivity-radius-squared of the body.

ACKNOWLEDGEMENTS

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