Advances in Airborne Time-Domain EM Technology

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ABSTRACT

The introduction of digital systems in the 1980s has resulted in the signal to noise ratios obtainable with airborne TEM systems being significantly enhanced. This results in a greater depth of penetration. The digital primary-field compensation algorithms mean that data collected in the transmitter pulse (in the transmitter on-time) can be used for geological mapping. This is particularly useful in resistive areas, where the conductivity can be mapped down to 25 μS/m. The on-time data can also be used to deconvolve for the shape of the waveform, allowing the measured data to be transformed into data which would have been collected if the system were transmitting another waveform. When the data is transformed to that which would be measured if the waveform were a square wave and the receiver a magnetometer, then the subsequent data can be used for calculating and mapping the conductivity as a function of depth.

The greater capability of the computers acquiring the digital data has allowed for larger volumes of data to be collected, so that multicomponent measurements are now standard. The extra components provide much more diagnostic information and make interpretation significantly easier. The fidelity of the data can also be improved by using all three components.

The systems have also been extended to operate at lower frequencies or longer time bases, allowing the response to be measured much later in time. This allows for more conductive bodies to be detected, or for bodies to be detected under thicker conductive overburden.

The ancillary magnetic data collected with EM systems has also improved, either by moving the sensor closer to the ground and/or closer spatial sampling of the data

The number of possible applications of airborne EM has increased, for example the polarizability of the ground can now be estimated from data acquired with an airborne TEM system. It has been found that the polarizability can only be measured when the ground is highly polarizable, but this occurs surprisingly frequently.

INTRODUCTION

This article reviews advances in airborne time-domain electromagnetic (TEM) technology since the review given at Exploration 87 by George Palacky (Palacky, 1989). An even more recent discussion of airborne electromagnetic (AEM) methods was presented by Palacky and West, 1991. The latter article is an excellent review of the history of airborne electromagnetic (EM) methods and contains an extensive tutorial on sources of noise, survey design, data display and interpretation techniques. Much of this information is still current, but significant changes in technology and interpretation procedure have taken place since 1991, so the present article will focus on these recent developments.

At the turn of the decade, the utilization of airborne TEM techniques was not great, but since 1993, there has been renewed demand for surveys and the number of commercially available aircraft has increased from 4 to 6. Scientific interest has also increased, with special workshops to discuss AEM technology and interpretation being organized by the USGS (Fitterman, 1990), and Ben Sternberg and Stan Ward of the University of Arizona (Smith, 1994).

There are three varieties of time-domain EM systems which are currently commercially available, the GEOTEM system (operated by Geoterrex-Dighem), and the SALTMAP and QUESTEM systems (both operated by World Geoscience Corporation). (The names GEOTEM and QUESTEM are trademarks of the respective operators). There is also a fourth system, SPECTREM, operated by Anglo American Corporation of South Africa (Klinkert *et al.*, 1996), which is a development of the PROSPECT I system (Annan, 1986). Although the SPECTREM system is not commercially available, we will discuss the system as it is interesting from a technical viewpoint. All these systems are fixed-wing towed bird systems.

Other airborne time-domain systems flown at some time during the past decade include an experimental system consisting of a SIROTEM system mounted on a blimp (Cull, 1989, 1991), and the Aerodat helicopter borne multigeometry system (Hogg, 1986), which is still in

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development. A hybrid system, designated FLAIRTEM (Elliot, 1995; 1996), is similar to the Turair system, in that it uses a ground based, large-loop transmitter and an airborne receiver. The FLAIRTEM system uses a Zonge GDP 32 as a receiver. Except for the papers cited above, there is not extensive discussion of these three systems in the literature, so they cannot be discussed in great detail.

There is a great commonality between the developments made with each of the four fixed-wing towed bird systems, so each system will be discussed in each of the sections which deal with specific technical advancements. A discussion of processing and interpretation techniques and new applications for airborne TEM is also included.

HARDWARE ADVANCES

Transmitter advances

Waveform—The GEOTEM and QUESTEM systems both utilize a half-sine current waveform, used so successfully by the Barringer INPUT system. The SPECTREM system has a full duty-cycle waveform, the shape is an *approximate* square wave, but the data are deconvolved in real-time to yield an equivalent step response. The SALTMAP waveform is a full-duty-cycle *modified* square wave (Duncan *et al.*, 1992).

Transmitter moment—There has been a trend towards increasing the dipole moment of the transmitters. When the GEOTEM system was first introduced in 1985, the dipole moment was about 450 000 Am^2 at the peak of the transmitter waveform. However, recent changes to the GEOTEM transmitter allow pulse widths of two and four milliseconds, with increases in the dipole moment to 550 000 and 700 000 Am^2 respectively. The dipole moment of the QUESTEM system has historically been 280 000 Am^2. At the time of writing, a QUESTEM system capable of 450 000 Am^2 is in development. The SPECTREM system has an RMS dipole moment of 300 000 Am^2; with a planned increase to 600 000 Am^2. (Peak dipole moment can approximately be converted to RMS dipole moment by dividing by four).

Higher and lower base frequencies—The trend toward a greater variety of base frequencies will be discussed below under receiver advances.

Receiver advances

The most significant advance in time-domain EM technology has been the move to digital receivers (Thomson, 1987; Annan, 1990). The main benefit of this movement has been the ability to reduce the noise level. Having a digital system means that it is possible to identify noise sources with a coherent or other distinct characteristic and remove these digitally, rather than relying on brute force causal averaging to reduce the noise. Figure 1 (Smith, 1994) shows how the noise levels (in equivalent GEOTEM ppm units) have been reduced over the past thirty years, from 460 ppm in 1968 to 30 ppm in the early 1990s. On this diagram the INPUT noise levels have been converted to GEOTEM 150 Hz equivalent units. Data is no longer being routinely acquired with a base frequency of 150 Hz; however, the equivalent noise levels attainable at time of writing is about 10 ppm or less of the primary field. The reduced noise levels have resulted in significantly greater depths of exploration. For example, we define a large vertical conductor in free space as being detectable if the amplitude of the X component response at 0.71 ms (third gate or third largest curve on Figure 1) is above the noise level. With the noise level at 460 ppm, the conductor can only be detected at a depth of about 60 m. Reducing the noise to 80, 30 and then 10 ppm allows the conductor to be detected to 150, 200 and 275 m depth respectively. Of course, greater depths of detectability can be obtained if the conductor is flat-lying, or the Z component is also measured (see below).

A noise level quoted in ppm can be misleading, as the primary field (the derivative of the current waveform) normally decreases as the pulse width increases or the transmitter-receiver separation increases. Thus, the EM sensor and the receiver can have the same intrinsic noise levels, but by decreasing the pulse width, or the transmitter-receiver separation, the primary field can be increased substantially. In this case, the normalized noise level in ppm will decrease, but so will the normalized signal, meaning that the signal to noise level is essentially unchanged. For this

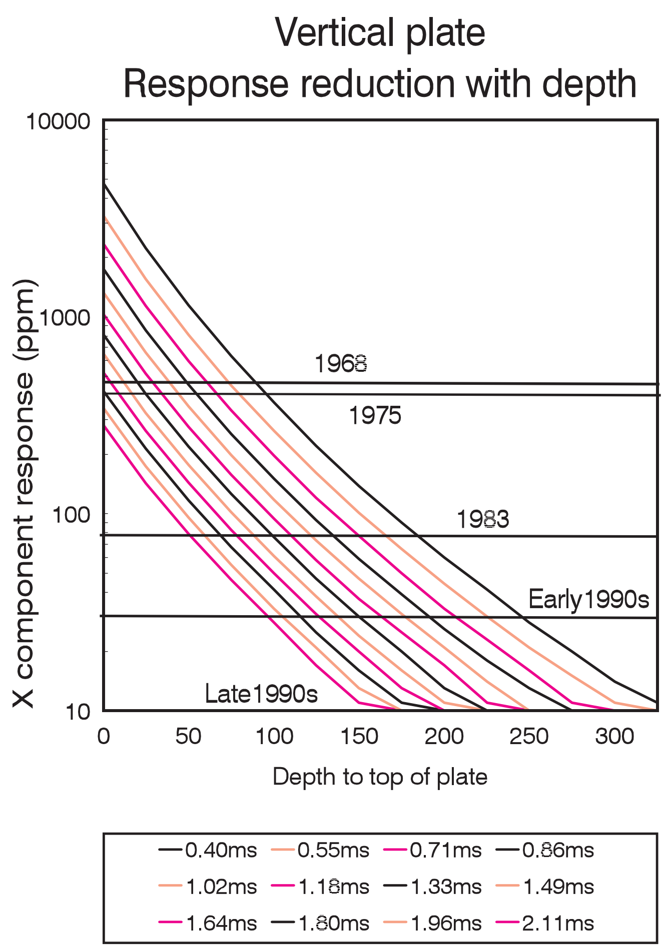

Figure 1: *The response of a thin vertical plate as the depth of the plate below the ground surface is increased. Each curve is the response measured in one of 12 contiguous windows 156 ms wide. The largest amplitude curve is the earliest gate centred 410 microseconds after cessation of the transmitter pulse. The horizontal lines are the noise levels (in equivalent 150 Hz GEOTEM ppm units) labelled with their respective dates. The first second and third windows are above the noise level when the conductor is at a depth of: 60 m (1968/75), 150 m (1983), 200 m (1990s), and 275 m (1997).*

reason, it makes more sense to quote noise levels in nV/m², as these are independent of the pulse width and transmitter-receiver separation.

Use of on-time information — The development of digital primary field compensation algorithms means that the secondary response measured inside the transmitter pulse (on-time) can now be used. Annan *et al.* (1996) show how in resistive terrain the on-time response is directly proportional to the conductivity of the ground. In this type of terrain, the on-time response is orders of magnitude larger than the off-time response, so the response of very weakly conductive ground can be measured. Our experience is that features as weakly conductive as 25 μS/m (40 000 Ω m) can be reliably mapped. The old analogue systems were unable to generate any coherent signal in areas less conductive than 3 mS/m (300 Ω m), so the aperture of sensitivity to conductivity has been increased by two orders of magnitude at the resistive end. In conductive terrain, the on-time information can be used to deconvolve for the effects due to the shape of the transmitter pulse and produce a band-limited step or impulse response. This means that the system is much more sensitive to highly conductive bodies.

Variable frequencies

Prior to the 1980's, the typical base frequency or repetition rate used was about 144 Hz (the frequency of the INPUT system). When first introduced in 1985, the GEOTEM systems operated at comparable frequencies: 150 Hz (60 Hz power line areas) or 125 Hz (50 Hz power-line areas).

Higher base frequencies — The SALTMAP system, designed for mapping the conductivity of the groundwater in the top 50 m, requires data at high frequencies. The base frequency can therefore be set quite high, typically 500 Hz, and the upper limit of sampling is at about 50 000 Hz. This frequency range spans the VLF broadcast band positioned at about 20 000 Hz, so care has been taken to reduce this source of noise (Duncan *et al.*, 1992).

In areas were all the targets are weakly conductive, high frequencies can also be used for mineral exploration. The higher repetition rate allows more samples per stack and hence better signal to noise. A frequency of 270 Hz was used to explore for weakly conductive kimberlites in the Northwest Territories of Canada (Smith *et al.*, 1996).

Lower base frequencies — When the QUESTEM system was introduced in 1988/89, the base frequency was set as 75 (or 90) Hz, an option which QUESTOR surveys also offered with one of the latter versions of their INPUT system. Annan and Lockwood (1991) show the benefits of using a low frequency (75 Hz) with the GEOTEM system. In the early 1990s, an option for even lower base frequencies (37.5 or 45 Hz) was added to the QUESTEM system.

The use of low base frequencies (25 or 30 Hz) became more widespread in 1995, when the GEOTEM system was equipped with a high powered transmitter capable of transmitting a four millisecond pulse. Being able to excite the earth with a stronger transmitter and measuring the response out to significantly greater delay times means that the airborne systems are becoming comparable with ground TEM systems with moderately large transmitters (Liu and Asten, 1992). An early comparison of 90 Hz data and 30 Hz data is shown on Figure 2. At the later delay times available in the low frequency data, the response of the overburden to the right is suppressed, and the response of the discrete conductor to the left is enhanced. Figure 3 shows a plot of the decay rates for the overburden and the conductor. The response of the overburden (geological noise) is about the same for the 90 and 30 Hz systems; however, the response of the conductor in the 30 Hz data shows an enhanced signal and a response which (for this conductor) is greater than the noise level out to seven milliseconds after transmitter switch off. The ability to discriminate between conductors and overburden is considerably enhanced at these low frequencies.

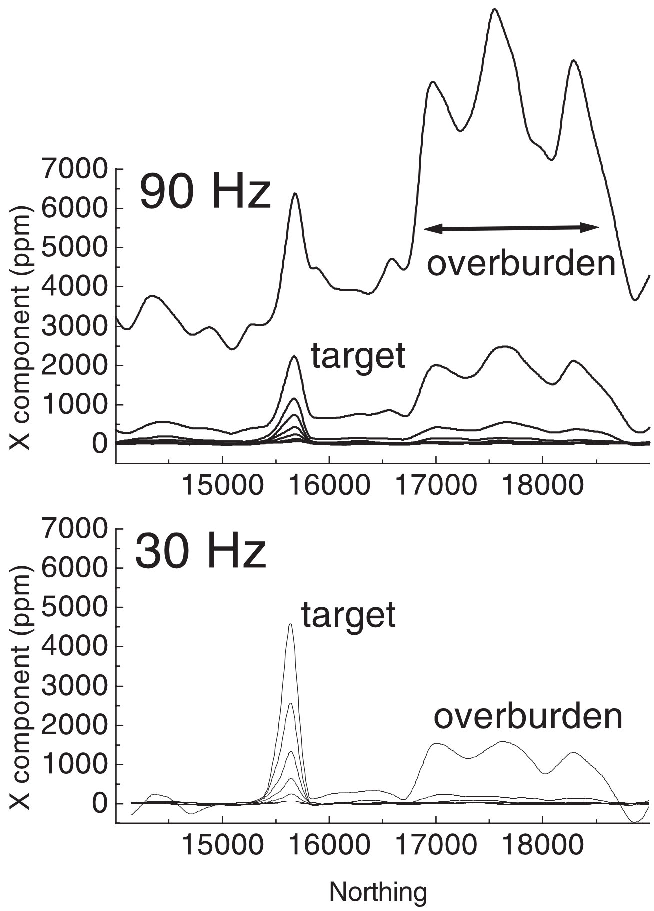

Figure 2: *A response profile over a conductor (left) and overburden (right) as measured with the GEOTEM system operating at 90 Hz (top). The bottom panel if the same profile line flown with a 30 Hz operating frequency. Note that the conductor response is much more apparent at 30 Hz and the overburden response is suppressed.*

Multicomponent measurements

The high-speed digital computers used to collect and process the EM data are capable of collecting multiple channels of high bandwidth information. Whereas the analogue INPUT system only collected a single component (the horizontal in-line or X component), the SPECTREM system (introduced in 1989) collected X and Z (vertical) component data on its first surveys. Macnae *et al.* show an example of X

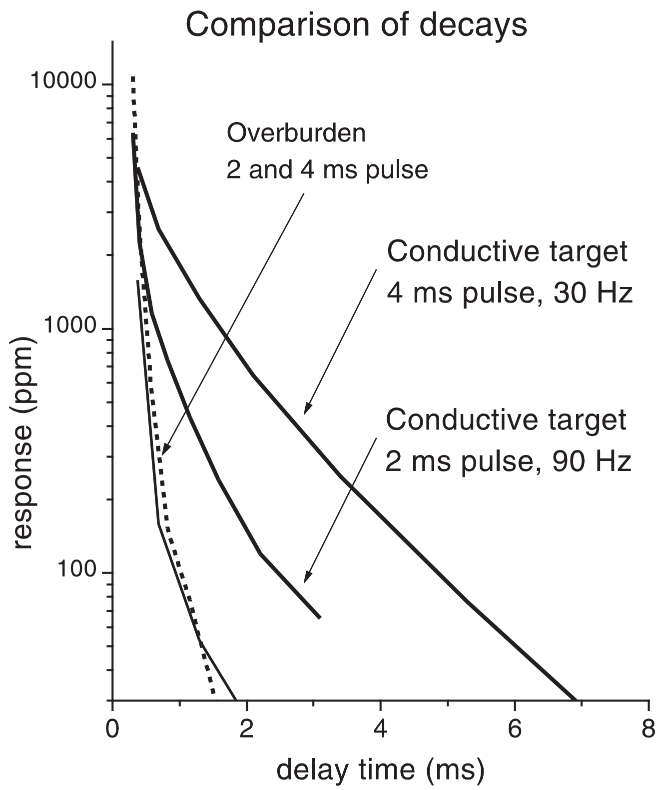

Figure 3: *The decay plot of the conductor and the overburden when measured with a 90 Hz base frequency and a 2 ms pulse, and a 30 Hz base frequency and a 4 ms pulse. The relative size of the conductor response compared with the overburden response is significantly increased when measured at 30 Hz.*

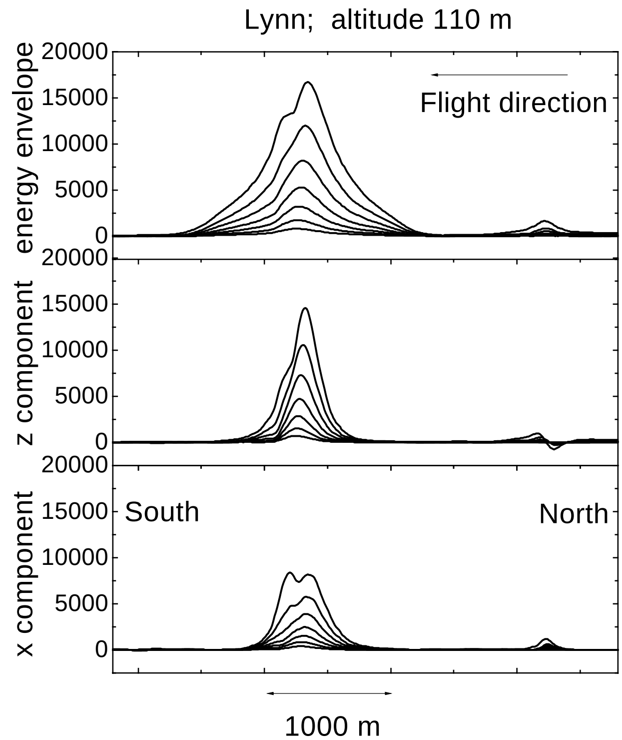

Figure 4: *The GEOTEM response over the Lynn deposit (Wisconsin) measured at a flying height of 110m. Note that the X and Z component response have a roughly comparable magnitude. The data can be explained by a thin plate model 600 m in strike extent, 180 m in depth extent having a conductance of 33 S, dipping at 26° to the north and having a depth to top of 30 m.*

and Z component SPECTREM data. The SALTMAP system (Duncan *et al.*, 1992) was designed to collect three component data, although no examples have been published.

Smith and Keating (1996) describe how multicomponent information is useful. The Z component data can be used to resolve horizontal layers at great depth and for detecting discrete and extensive conductors at much greater depths than was previously possible with old single component systems. Figure 4 shows the X and Z component response of the Lynn deposit in Wisconsin, at an aircraft altitude of 110 m. The deposit is a small plate-like conductor dipping shallowly to the north. The surrounding country rock is comparable in resistivity to the air, so flying at a greater altitude above the deposit is equivalent to the deposit being deeper. The response measured when the body is effectively 220 m below the ground (aircraft altitude of 330 m) is shown on Figure 5. The X component response is almost at the noise level, while the Z component response is well above the noise. Hence, the Z component response can be used to easily detect a small conductor such as this 220 m below the ground surface.

The Z component allows easy determination of the depth and dip of discrete conductors and the asymmetric aspects of a conductor (a non-normal strike and an offset from the flight line) can be determined with the Y component. Figure 6 shows the X, Y and Z component response of a conductor in northern Canada. Note that the Y component response is similar in shape, but opposite in sign to the Z component. This implies that the conductor is offset to the starboard of the aircraft. Using the rules of thumb given in Smith and Keating (1996), the conductor is determined to be 100 metres deep, have a dip of 60° to the right and be offset to the starboard of the profile line by 115 m.

The three component response can also be used to correct for the receiver sensors not being oriented in the nominal direction. Figure 7 shows how changes in orientation of the receiver modulate the response, an effect which is most evident in conductive areas such as Arizona, where this data was collected. Part of the digital primary field compensation process involves estimating the primary field for each component. This primary field data can be used to predict the roll, pitch and yaw of the receiver (Figure 8), which subsequently can be used to correct the measured secondary response (Figure 9).

The herringbone pattern which previously plagued airborne EM maps can be greatly reduced when multicomponent data is acquired and processed, either by displaying the energy envelope of the response (Smith and Keating, 1996), or by using grid-based de-herringbone filters.

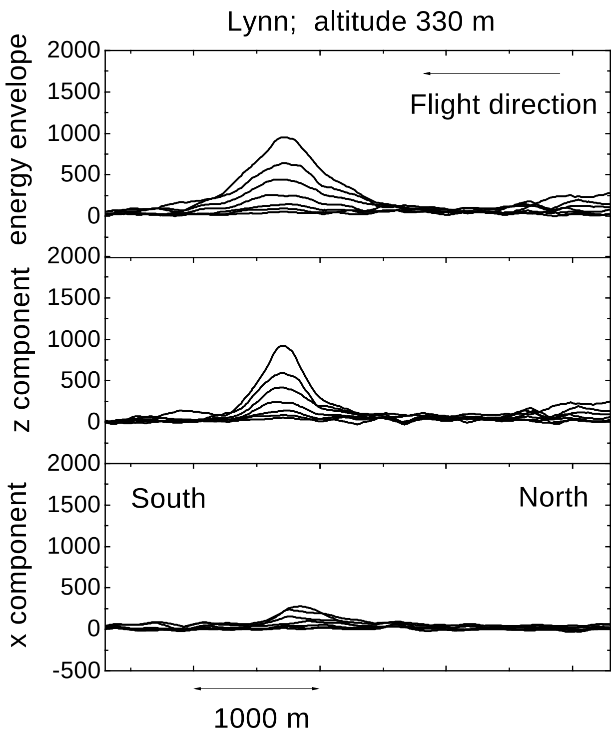

Figure 5: *The GEOTEM response over the Lynn deposit measured at a flying height of 330 m. Because the ground is resistive, this is comparable to the conductor being 220 m below the ground at the normal flying height. This shows that a conductor 220 m deep can be detected easily on the Z component, but the response is near the noise level on the X component.*

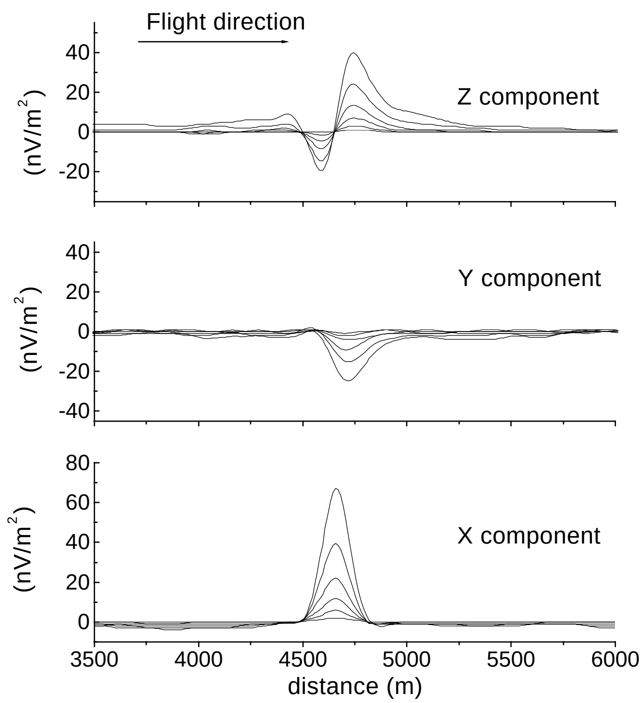

Figure 6: *The X, Y and Z component GEOTEM profile for a conductor in northern Canada. The positive Z component shoulders are 375 m apart, indicating a distance of 220 m to the conductor, and their amplitude ratio indicates a dip of 60°. The Y component response is similar in shape to the Z component, indicating the conductor is offset from the profile line, and the ratio of the Z and Y components indicates that the conductor is 32° to the starboard of the aircraft.*

Magnetic information

An important supplement to airborne EM data is the magnetic data which is invariably also acquired. In the last 10 years the quality of the magnetic data acquired by the QUESTEM system has improved by sampling the data twice a second (compared with once a second with the older INPUT system), and more recently five times a second. This QUESTEM data is acquired with a sensor mounted in the aircraft.

The quality of the magnetic data acquired with the GEOTEM and the SPECTREM systems has improved by increasing the sampling rate to 10 and 5 times a second (respectively) and by acquiring the data from a sensor inside a towed bird. Having the towed bird much closer to the magnetic material and a faster sample rate, results in much higher resolution data.

PROCESSING AND INTERPRETATION

A significant advance in the presentation of airborne TEM data is to convert the data to a conductivity-depth section. Macnae *et al.* (1991) took an approximate image solution previously used for converting ground EM data to conductivity-depth sections and modified it for use on airborne step-response (SPECTREM) data. The algorithm used a number of damping parameters judiciously selected to give a geologically reasonable answer. Leggart and Pendock (1993) found that they could get better results by finding the solution with maximum entropy. Wolfgram and Karlik (1995) extended the method to work with any time-domain AEM system by deconvolving the measured data to an equivalent step response. This step response data is then converted to a conductivity section using a method based on the approximation described by Macnae *et al* (1991).

This type of conductivity-depth presentation is designed for mapping the geology in quasi layered areas; however, the same data presentation technique is useful for enhancing the subtle responses due to non-horizontal conductors below or in an otherwise layered environment (Stolz *et al.*, 1995). One of the advantages of using such a display technique is that the approximate imaging algorithm takes care of the effect of a varying distance between the ground and the aircraft (and hence the transmitter and the receiver). These height variations can result in large changes in the response which have in the past been misinterpreted as conductive features. The conductivity-depth algorithms are designed to work on the total response, rather than individual components, as the total response is insensitive to variations in the receiver orientation, whereas the individual components are not (Macnae *et al.*, 1991).

An alternate approach for generating conductance or conductivity depth sections is described by Liu and Asten (1993). This technique uses

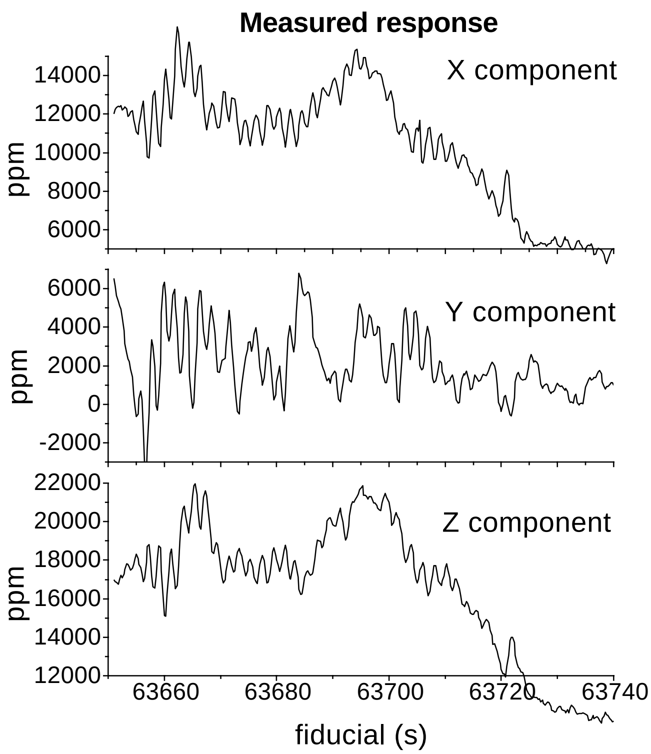

Figure 7: *The X, Y and Z component GEOTEM response measured in a conductive part of Arizona. The modulation seen on the profiles is attributed to the orientation of the receiver changing over a period of about 2 seconds.*

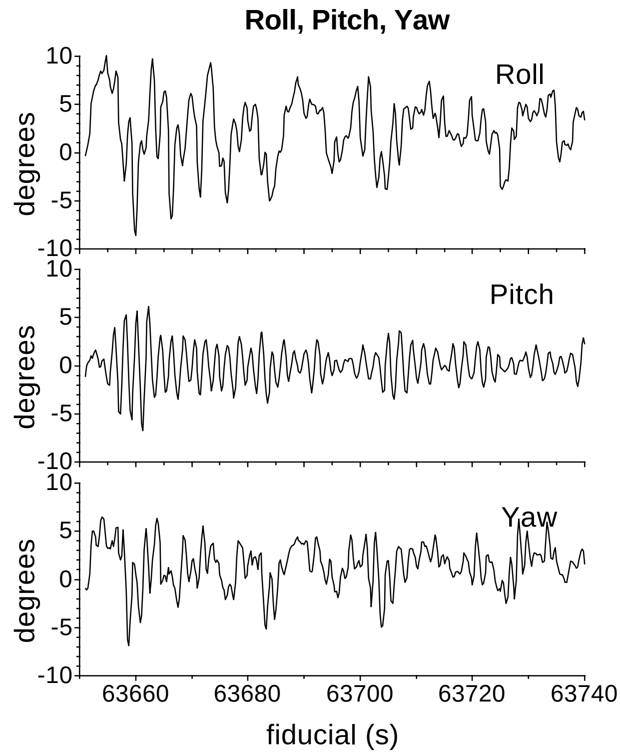

Figure 8: *The roll, pitch and yaw of the receiver, as determined from the primary field measurements. Note that the significant modulation seen in Figure 7 is the consequence of orientation changes of about 5°.*

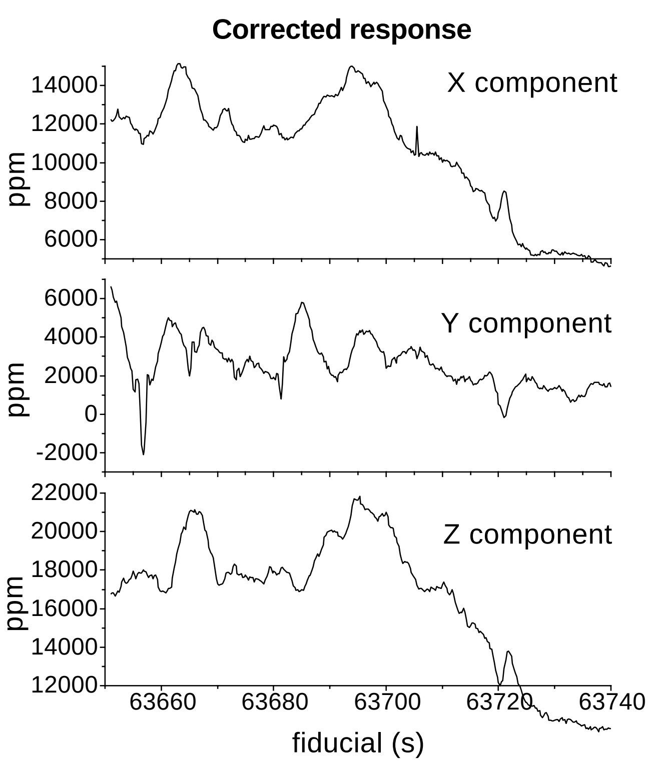

Figure 9: *The response profiles of Figure 8 corrected for roll, pitch, and yaw. No modulation is apparent and anomalous features barely evident in Figure 7 are now obvious.*

off-time data only, and hence does not need to deconvolve the data to a step response. The method has been incorporated into a proprietary data processing and display program called TEMPER, developed by BHP (Monks and Asten, 1994). The TEMPER program has been specifically developed for viewing and interpreting a large amount of AEM data, and can also be used for profile plotting, generating flight path maps and images, performing decay rate analysis, and forward modelling data using a model consisting of a plate below a horizontal thin sheet (Liu and Asten, 1993). Monks and Asten also point to work being done towards automatic inversion (using the same plate model) and automatic anomaly picking within the TEMPER package.

Other methods for interpreting time-domain EM data have been described in the literature. One method, used for determining the depth to a conductor, has been described by Bartel and Becker (1990). The method uses a line-current approximation, which will give good results for large shallow bodies, but will be less valid for deeper bodies. Other methods invert the measured data to find the best-fitting plate-like body (Keating, 1989; Keating and Crossley, 1990), or the best-fitting layered earth model (Keating and Vallée, 1986; Huang and Palacky, 1991).

One of the difficulties of inverting airborne TEM data is that there are very large number of potentially interesting anomalies which require modelling. Efficient methods are therefore required, and Stolz and Macnae (1996) describe one such method. They reduce many profiles at multiple delay times to two profiles depicting the inductive and resistive limit response. The two wire-loop circuits which best explains each of these two profiles is then determined. Determining two models is appropriate, as the current flow may have different geometric properties at early time (inductive limit) and late time (resistive limit). Another novel way of doing fast inversion is to find the best-fitting line current (Keating, 1991). The implementation described by Keating uses Werner deconvolution techniques and is extremely rapid.

CASE HISTORIES AND OTHER APPLICATIONS

There are a number of case histories of interest published in recent years, which well illustrate the application of the new hardware and interpretation/presentation technologies.

Anderson *et al.* (1993a), describes the use of image processing of QUESTEM data from an area which hosts the Lady Loretta and Lady Annie deposits. Shalley and Harvey (1992) and Webb and Rohrlach (1992) discuss the geophysical signatures of two Queensland deposits and at the same time give two examples of airborne EM responses over the bodies. A case history describing the discovery of a gold deposit in Ontario is given by Pedersen and Thomson (1990).

World Geoscience has published numerous examples showing how data acquired with an airborne TEM system (QUESTEM) can monitor salinity by mapping the conductivity of the top 50 m (Street, 1992; Anderson *et al.*, 1993b; Street and Anderson, 1993, Odins *et al.*, 1995).

A discussion of how the GEOTEM system can be optimized for the purposes of exploring for kimberlites in a relatively resistive area is discussed by Smith *et al.* (1996).

Another application of transient airborne EM technology is described by Zollinger *et al.* (1987). They describe the use of the INPUT system for mapping the depth of conductive seawater. This has generated interest from contractors as a potential new market area (Pearson and McConnell, 1995), but has far as we are aware, has not been widely used.

Another potential new market area being pursued by Geoterrex is the use of AEM for detecting alteration plumes (as conductivity anomalies) in the near-surface rocks above hydrocarbon traps (Rowe *et al.*, 1994; Smith and Rowe, 1997).

The use of AEM to geological mapping (as advocated by Palacky, 1987; 1989) has become more standard through the development of robust techniques for converting TEM data to apparent conductance or apparent conductivity (Anderson *et al.*, 1993a; Annan *et al.*, 1996). However, the primary purpose of the survey is normally still mineral exploration, with the conductivity map being of secondary use.

Other information which can be identified in EM data is an induced polarization signal (but only when the signal is stronger than the EM signal). This allows a further physical property to be mapped with airborne TEM systems (Smith and Klein, 1996).

CONCLUSION

The technology used to acquire, process and interpret time-domain AEM data over the past decade has improved significantly. Coupled with a renewed interest in base metal exploration, the number of line kilometres flown has increased significantly. The potential new applications, the flying of systems in new geoelectric terrains, and the greater expectations from geophysicists will stretch the capability of systems and pose new questions. With increased utilization, there will be more money available for continued research and development to answer or attempt to answer these questions, which augers well for future improvements in time-domain AEM technology.

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