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The elusive flying Squids: Interim results from recent tests with a heli-borne EM Low Temperature SQUID system.

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ABSTRACT

Following the positive outcomes and successful application of Low Temperature SQUIDs (LTS) as ground TEM B-field sensors, a research and development program was launched to try and realize similar benefits in airborne EM applications. The AeroTEM III helicopter-slung bird had been selected as the prototype platform for the integration of the IPHT / Supracon LTS EM SQUID sensor technology with a new generation experimental airborne EM system. A number of ground-based and two airborne flight tests were conducted, first in December 2007 with a 100% duty cycle Spectrem ("on-time") waveform and then in September 2008 with an AeroTEM triangular "off-time" waveform.

Some hardware development problems are recounted here and test results are analysed. While testing some novel concepts, like fast SQUID resetting, the inevitable developmental mistakes were made and valuable lessons learnt. Characteristics of various system components were discovered that only manifest when measuring B-fields with these ultra-sensitive, extremely broadband sensors. These include the extreme sensitivity of the on-time primary field bucking, DC transmitter current leakage in the off-time, very high frequency transmitter switching noise and secondary responses from parts of the SQUID cryostat that extend into poorly bucked regions of the strong transmitter field. Although the successful implementation of LT SQUIDs in an airborne EM system ("flying EM SQUIDs") still eludes us, insight was gained into more favourable configurations and parameters for future successful development and application of airborne EM SQUID systems.

Key words: TDEM, LTS SQUID, Airborne EM,

INTRODUCTION

Low-temperature superconductor (LTS) SQUIDs (superconducting quantum interference devices) have been developed and deployed successfully in ground transient electro-magnetic (TEM) geophysical surveys for Anglo American over the past five years. These LTS SQUIDs are essentially very sensitive detectors of magnetic flux with a very low noise floor.

Comparative tests (Leslie, et al, 2008) and Le Roux & Macnae, 2007) have shown that LTS SQUID sensors have significantly better sensitivity and noise floors in the frequency range used in ground TEM exploration than HTS (high temperature superconductor) SQUIDs and fluxgate B-field sensors. They also out-perform most TEM coil sensors in the late times required for detection of good to perfect conductors under conductive cover. HTS SQUID sensors are now being used regularly in ground TEM surveys world wide by contractors like Crone, Outer Rim and JOGMEC.

A number of successful TEM exploration surveys for base metal sulphide targets have been carried out for Anglo American using the ground TEM LTS SQUID system developed by the Institute for Photonic Technology (IPHT) in Jena, Germany and manufactured by Supracon, Jena under an exclusivity agreement with Anglo American Plc.. These results are usually confidential, but some results and case histories have been presented at international conferences recently (Le Roux, 2007; Webb & Corsadden, 2009; Smit, 2009).

The advantages of measuring or calculating B-fields for airborne electromagnetic (AEM) surveys have been studied and proclaimed by many leading geophysicists such as Macnae (2007) and Smith & Annan (1998). In theory these advantages include better resolution of highly conductive targets such as nickel sulphides especially in the presence of conductive cover, data that is easier to interpret, better conductor discrimination and less dynamic range required.

However, coil sensors measuring the rate of change of the magnetic field (dB/dt) have been doing a great job for many years and their intrinsic sensor noise levels are not the limiting factor for achieving these results. The B-field response is now being calculated routinely from dB/dt AEM survey data via different schemes that go a long way toward yielding many of these B-field advantages (Smith & Annan 2000).

The question arises whether there is any distinct advantage to measuring the B-field directly in airborne EM using LTS SQUID sensors over calculating them from dB/dt (coil) data.

Certainly, measuring the B-field from a moving airborne platform is more cumbersome and it brings with it additional problems and pitfalls as we will proceed to illustrate.

THE PROTO-TYPE TEST SYSTEM

The design of the "AeroTEM-SQUID" EM system needed to consider the following important SQUID sensor characteristics:

1. SQUID sensors have limited slew rate or tolerance for the rate of magnetic field change. Strong ambient signals and noise are known to cause SQUID sensors to exceed their slew rate tolerances resulting in flux jumps, rendering data poor or unusable. The IPHT LTS SQUID sensors are particularly robust and the current ground TEM models very seldom exhibit any of these effects in the field. IPHT developed SQUID sensors for the airborne EM applications that have an exceptionally high 20mT/s slew rate tolerance.

2. Although B-field measurements require lower dynamic range than dB/dt (Macnae, 2007), a major constraint in TDEM data acquisition remains the limited dynamic range of the combined receiver system (sensor, amplifiers and analogue-to-digital converters (ADC)). Tiny secondary EM signals (10pT) have to be measured and resolved in the presence of very large primary fields (290,000–500,000nT), i.e. 0.02ppm.

3. Another characteristic of SQUID sensors, which is both a blessing and a curse, is their extreme broad-band flat response. This enhances detection of low frequency signals, but also enhances motion noise and 50/60 Hz noise, as well as rendering the sensors sensitive to noise at very high frequencies (RF & HF). While high-pass filters such as fast SQUID resets just below the pass band can be employed, no analogue low-pass filters can be used with the SQUID electronics and HF noise must be avoided by using physical metal screening.

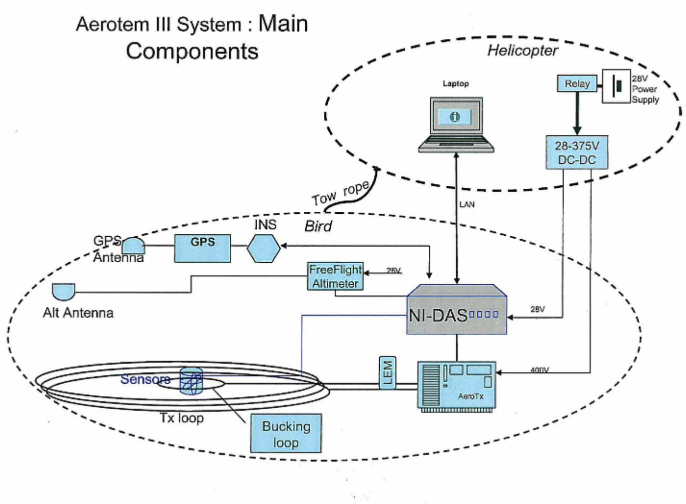


Figure 1. The "AeroTEM-SQUID" heli-borne system

An experimental prototype system shown in figure 1 was built and tested to take the above characteristics into account and also to capitalize on the available Spectrem Air and AeroQuest technology and expertise.

The platform is the rigid AeroTEM III 9.2m diameter bird which is slung typically 40m below a helicopter. The first prototype development and flight tests in December 2007 employed a 100% duty cycle Spectrem transmitter. In 2008 a standard AeroTEM III transmitter with triangular on-time waveform was used to facilitate measurements during the off-time and thus avoid transmitter on-time complications.

The data acquisition unit (DAS) is an off-the-shelf National Instrument PXI unit with a 4-channel 24-bit ADC board, counter card (to produce the transmitter control signals) and standard CPU all accurately synchronized via a common backplane.

Because of the complications of measuring B-fields while moving through the earth's magnetic field a GPS, radar altimeter and tactical Inertial Navigation System (INS) employing Applanix and Novatel technologies, were added to measure the exact position, rotation and movement of the bird. These signals together with the 3-channel output from the EM sensors and LEM transmitter current monitor are digitized on the bird and monitored in the helicopter via a LAN connection. Custom operator QC and data logging software was developed based on the Spectrem SpecDAS system.

TEST RESULTS AND DISCUSSION

SQUID and ADC noise levels as measured by IPHT inside a three-layer mu-metal cylinder are shown in figure 2. Low frequency ambient noise is still seen to penetrate the mu-metal cylinder, but the sensor white noise limit is shown to be 15 fT/√Hz.

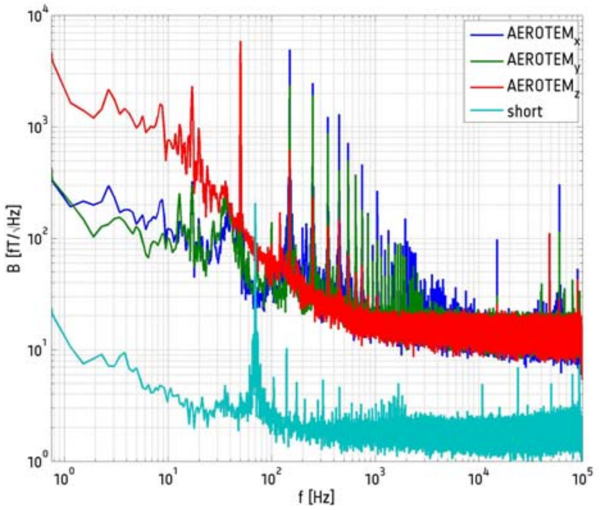


Figure 2. SQUID system noise spectra from IPHT showing white noise levels of 15 fT/√Hz in a shielded cylinder.

In order to eliminate motion noise that is much lower in frequency than the transmitter frequency, IPHT developed internal control electronics that allowed the SQUIDs to be reset to zero within a few microseconds at any specified time to effectively act as a high-pass filter.

As no analogue low-pass filters can be used with the SQUID electronics, the SQUID sensors detected strong high frequency noise signals that are emitted by the transmitter (figure 3). This noise does not affect coil measurements as severely, as coils are naturally band limited due to their peaked frequency response characteristics which renders them relatively insensitive to these high frequencies.

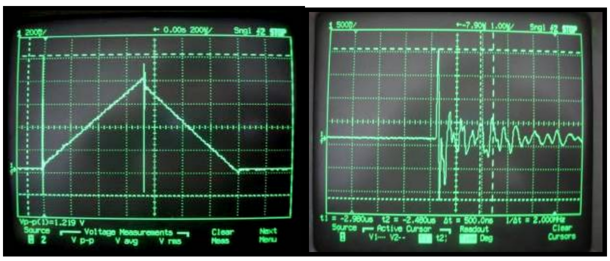


Figure 3: High frequency (2Mhz+) transmitter switching noise as seen on an oscilloscope.

This high frequency noise caused the SQUIDs to lose lock resulting in flux jumps in the data (figure 4).

Another previously unknown phenomena that manifested in the broad-band SQUID B-field test results is a leaked DC current flowing in the transmitter loop during the transmitter off-time (figure 4). As this is DC, coils measuring dB/dt show a zero reading in the off-time, but together with the flux jumps of unknown amplitude, these changing "zero" levels messed up the standard stacking process for SQUID B-fields.

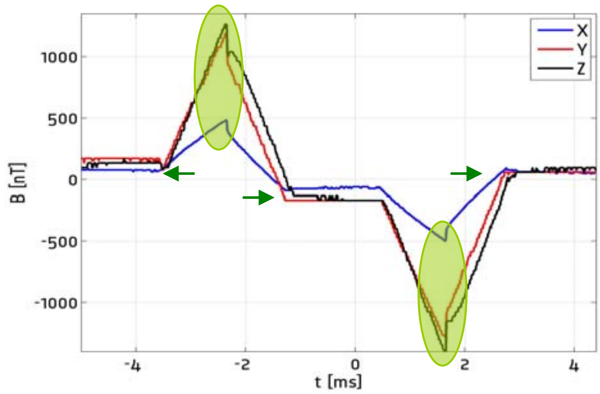


Figure 4: SQUID sensor flux jumps (shading) in the data from switching too fast or HF noise and off-time DC current all causing unknown zero-level offsets (arrows).

The system design deliberately used an AeroTEM III frame to benefit from the rigidity and proven primary field bucking technology of AeroQuest Ltd. However, because the SQUID cryostat have thin foil around the cryostat to screen out radio frequency noise, the foil screen acted as a conductor in the strong primary field where the cryostat extended vertically outside of the bucked region, which had been designed for the AeroTEM Z-coil in the plane of the transmitter. This is illustrated in figure 5 that shows modelled B_z amplitudes for the AeroTEM III transmitter and bucking loop geometry.

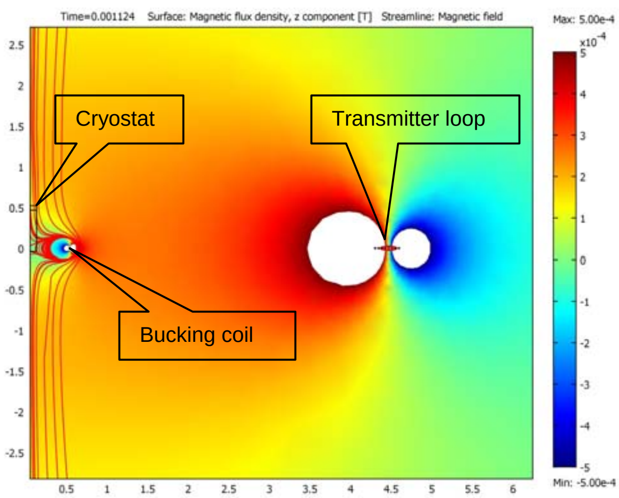


Figure 5: Modelled B_z primary field amplitude in cross section through the transmitter and bucking loops showing the significant field amplitude at the top of the cryostat.

The remaining unbucked primary field at the top of the cryostat caused strong secondary field decays, particularly in the SQUID Z-component (figure 6). The standard solution of cutting narrow slits in the outside foil screen managed to get rid of most of this eddy current flow, but caused the SQUIDs to become unstable due to high frequency noise now penetrating to the sensors.

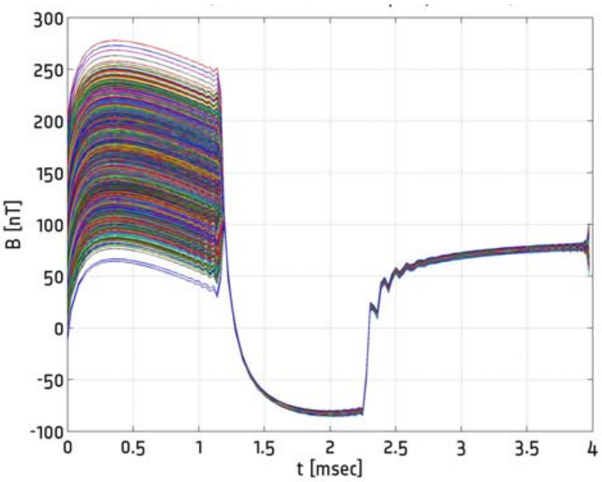


Figure 6: Measured z-component SQUID overlays with strong secondary response presumably from the cryostat RF screen.

In spite of all these problems anomaly simulations were recorded on the ground by moving a small coil past the system to see if we could detect the expected secondary response and to help identify the noise sources. By selecting a single off-time without a reset for each fid and adjusting the decay to the late time zero-level, sensible windowed TEM profiles could be produced without any stacking or filtering. Although the SQUID AEM system was stationary, the pseudo-profiles clearly show the artificial target "anomaly" above noise levels (figure 7). This result compared well with the modelled response.

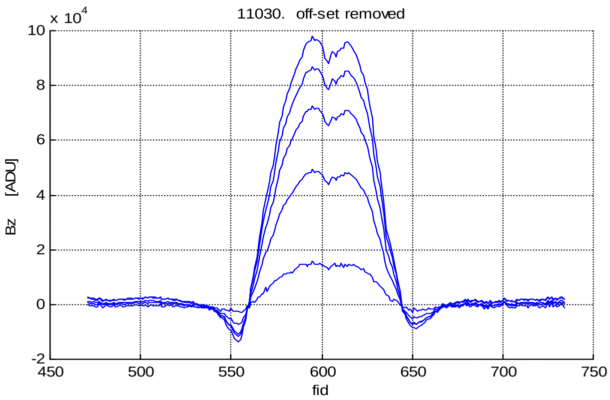
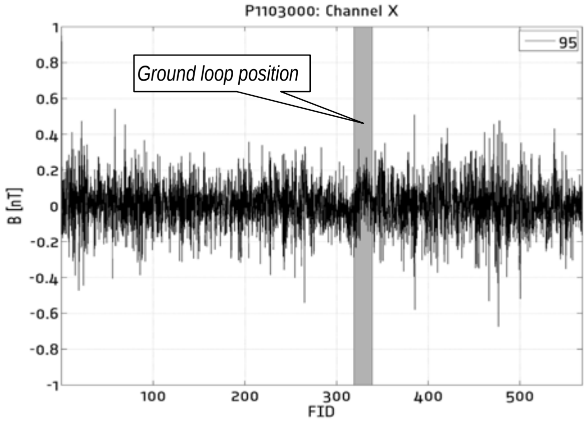


Figure 7: Measured response for a test coil being moved past the stationary AeroTEM-SQUID system.

Subsequently the system was flown over a 80m x 80m wire loop laid out on the ground to record its anomalous response. At the same time the current induced in the loop was recorded for comparison of the measured airborne TEM SQUID response with the theoretically calculated target response.

The standard deviation of the airborne results over a quiet part of the profile turned out to be an average of 8 times larger than those of the stationary data. The best actual measured noise levels are 0.6nT$_{p-p}$ for B_x over the loop (figure 8a) and hence the loop response, which is modelled to peak at only 0.13nT in similar early off-times (figure 8b), cannot be identified in these noisy data. However, by eliminating some of the problems described above, using a more conductive target loop and further customized processing, future similar experiments are expected to produce better signal-to-noise ratios and more positive results.

(a) Measured B_x



(b) Modelled B_x

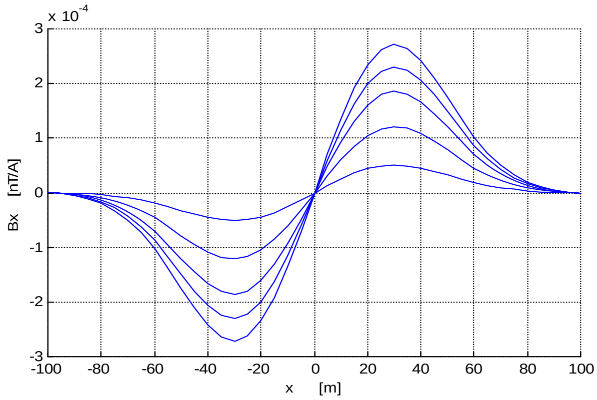


Figure 8. Comparison airborne profile and model data
(a) In-flight AeroTEM-SQUID X-component for a single off-time (~350us) over the ground loop (position shaded in grey), and (b) Modelled B_x ground loop anomaly for 60m flying altitude (in nT/A). Nominal tx current was 253A$_{0-p}$.

As part of our evaluation of the results we revisited the question of what real additional value direct B-field airborne TEM measurements would yield over conventional coils. It has become standard procedure to calculate B-fields from measured airborne dB/dt data and if the full dB/dt waveform (full cycle through on and off-time) is integrated many of the reported advantages of B-field data are realised (Macnae, 2007; Smith & Annan, 1998).

However, simultaneous tests of SQUIDs and Spectrem coils have confirmed that the SQUID sensors are more sensitive below about 1000 Hz (figure 9). It all then comes down to noise levels of the complete systems in the frequency band between the base frequency (typically 25 Hz) and 1000 Hz. In theory if similar noise levels can be achieved for the two systems and the coil sensor sensitivity is lower than the noise level at the low frequency end, then SQUIDs would have an advantage in detecting a select group of targets that have responses in this frequency range. Such a scenario is postulated and illustrated in figure 9.

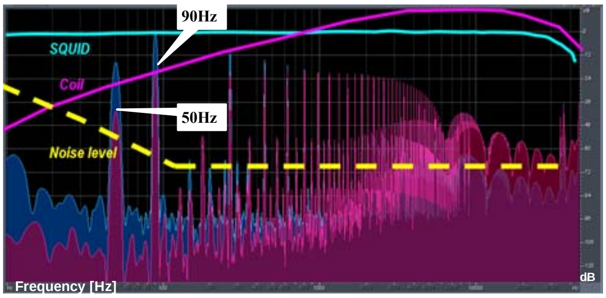


Figure 9: SQUID and Spectrem Coil Frequency Response Curves: Real measured response for 90Hz signal (thin lines), and Postulated smoothed frequency responses (thick curves)

CONCLUSIONS

In spite of the apparent negative results from the tests described here in the sense of "flying SQUIDs" still eluding us, there are indications that airborne TEM SQUID or direct B-field measurements are possible and could yield successful results.

The main hurdles to overcome are:

i. Avoiding the very strong primary fields of centre-loop HEM configurations by going to towed bird AEM systems and hence eliminating the emitted HF transmitter noise and need for both bucking and fast resetting of the SQUID sensors.
ii. Finding a solution for the SQUID RF screening to avoid secondary eddy current flow, yet still effectively screen out high frequency noise.
iii. Using a well-controlled on-time transmitter such as the Spectrem system and developing appropriate data processing methods that will correct for on-time primary field variations and motion.

No doubt LTS SQUID sensors are significantly more expensive to develop, purchase and run than conventional coils and there is still some argument as to the eventual cost benefit of employing them in the AEM mode.

These are however still early days of a challenging research effort to explore exactly this question and we believe there is much that can and should still be done to provide an adequate answer and to possibly realize their full potential to find mines that other systems would miss, particularly for special target - conductive cover scenarios.

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