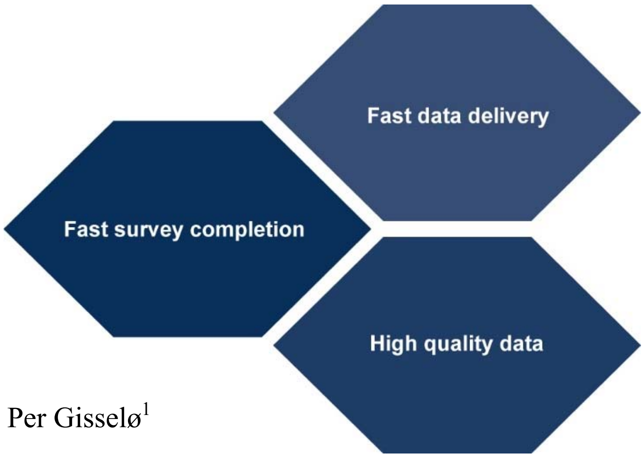

SkyTEM312 HP

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SUMMARY

The SkyTEM312 HP helicopter TEM system is engineered specifically for deep resource exploration and was introduced in 2017. Since the launch, the system has been used routinely for mineral exploration with great success. In part, this success can be attributed to its capability of offering 32 ms off-time data facilitated by employing a 12.5 Hz base frequency. Recently, B-field measurements have been added as a feature to further improve target characterization.

Key words: helicopter TEM, low base frequency, B-field measurements, deep exploration

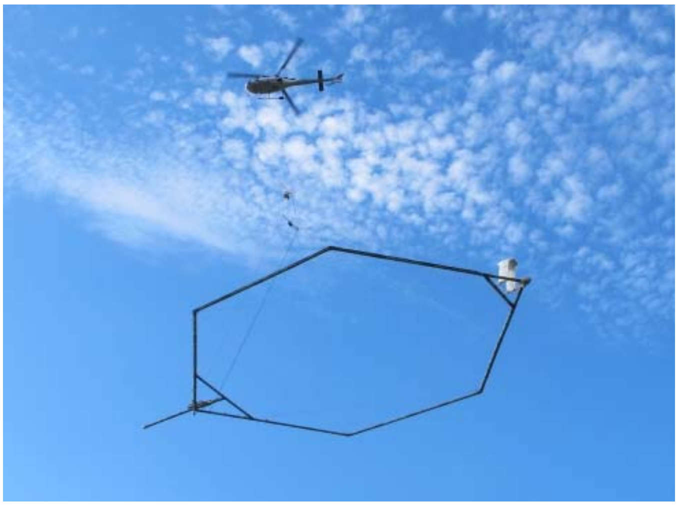

Figure 1: The SkyTEM312 HP system

INTRODUCTION

In many parts of the world, most shallow mineral deposits of economic value have already been discovered. Hence, there is an increasing emphasis on deeper mineral occurrences although such are more costly to explore and eventually also to mine. For this reason, many airborne geophysical companies have had a relentless focus on enhancing the depth of investigations ("DOI") of EM systems – particularly TEM systems. SkyTEM is no exception, and over the last 10 years the company has managed to increase the DOI of its SkyTEM helicopter TEM (HTEM) systems markedly. The most recent product of these efforts, SkyTEM312 HP, constitutes a giant leap in terms of performance of SkyTEM HTEM systems and currently appears to be the preeminent airborne TEM system when it comes to high DOI.

SKYTEM312 HP AT A GLANCE

The SkyTEM312 HP system is developed for maximum depth of investigation and enhanced characterization of mineral occurrences. The system leverages several key features:

- **Operate with a base frequency of 12.5 Hz** to allow better characterization of discrete conductors through 32 ms off-time data. This is enabled using a dipole-moment of 1,000,000 Am2 and a noise optimized induction coil suspension, resulting in an exceptionally high signal-to-noise ratio.

- **Measure B-field** data to allow better identification and characterization of discrete conductors than what is possible with dB/dt alone.
- **B-spline gates** to allow advanced post-processing and superior high-frequency noise suppression, including VLF transmitters.
- **Lightweight system** compared to other comparable systems on the market, offering high cost-efficiency, in-flight manoeuvrability, and range of operation with a Eurocopter B3 helicopter.

In the following, the technical details of SkyTEM312 HP are explained, and one real-world data example is shown.

THE RECEIVER TECHNOLOGY

The receiver technology is designed for a variety of different applications, ranging from shallow geotechnical pre-investigation to deep mineral exploration, and not specifically engineered for SkyTEM312 HP. Hence, the bandwidth of the signal path after the induction coil is 1 MHz (anti-aliasing filter) to accommodate the requirements to high-resolution surveys.

The signal path comprises the following steps:

1. The TEM signal is bandlimited by the induction coil that acts as a second order low-pass filter. The induction coils used together with SkyTEM312 HP has a bandwidth in the range from 30 to 40 kHz.
2. After the induction coil, the TEM signal passes through an anti-aliasing filter with a bandwidth of 1 MHz.
3. The bandlimited TEM signal is oversampled at 5 MHz employing a 36-bit ADC.
4. The 5 MHz data stream is densely gated in real-time using a B-spline approach which allows for post-acquisition gate adaptation.

Induction coil (step 1)

In the literature, it is well-documented that the earth's stationary magnetic field is a major noise source in airborne TEM systems that employ induction coils. Due to vibrations of the airborne system, the induction coil moves erratically in the magnetic field, which generates an electrical noise signal (motion-induced noise) superimposed on the TEM signal.

The motion-induced noise has a relatively broad spectrum, extending from DC to several hundreds of Hz. This poses a significant challenge because the TEM receiver system is sensitive at the applied base frequency, for example 12.5 Hz, and its odd harmonics. For this reason, an induction coil can pick up a substantial noise signal if its movements in the magnetic field are not dampened.

Airborne systems employ suspension of the induction coils to suppress the motion-induced noise. SkyTEM has introduced several generations of induction coil suspension systems and been able to vastly curtail the motion-induced noise contribution.

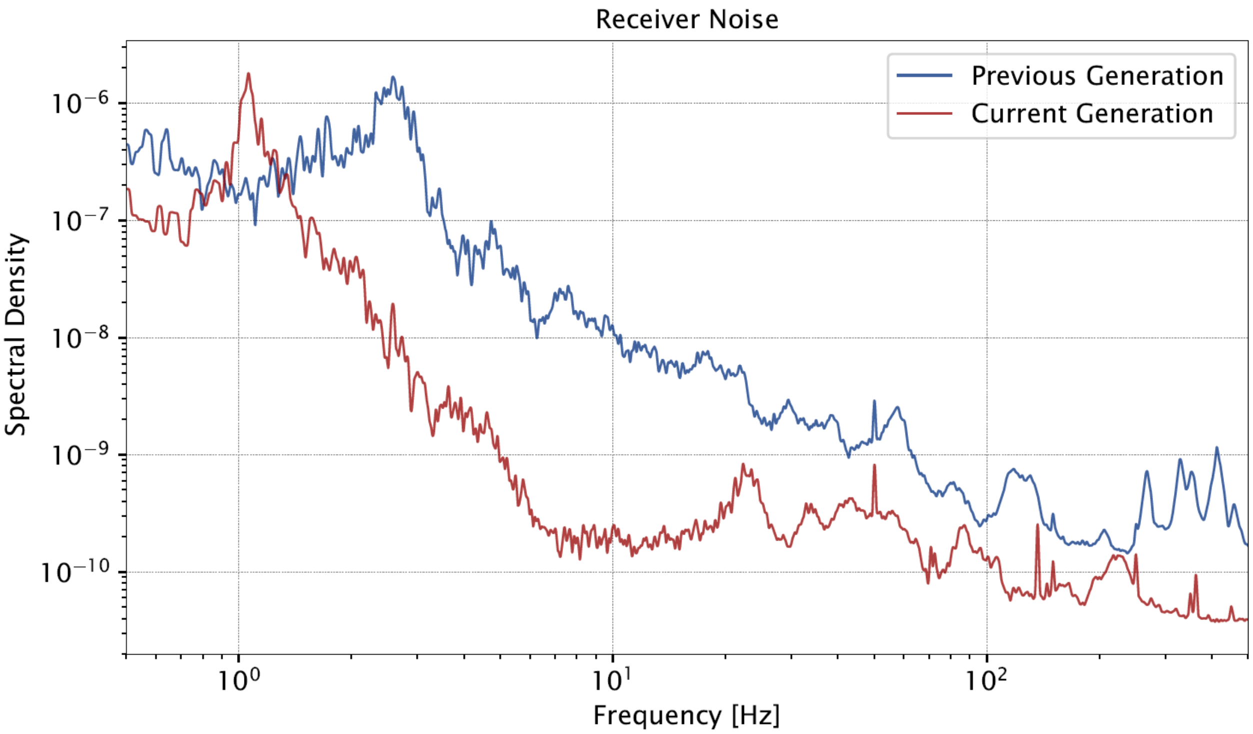

Figure 2: Spectral density of noise measured for the previous and current version of induction coil suspension.

Figure 2 shows that the spectral density of the noise has been significantly diminished with the most recent induction coil suspension, reflecting the said reduction of the motion-induced noise. Of particular significance is the large reduction near 12.5 Hz, which is the lowest frequency at which the TEM signal is susceptible to noise when using a 12.5 Hz base frequency.

Band-limitation and sampling (step 1-3)

Step 1 and 2 effectively bandlimit the analog signal well below 1 MHz, and aliasing is prevented by employing a sample rate of 5 MHz (step 3).

B-spline polynomial technique (step 4)

The TEM signal is stored using a B-spline technique to ensure a high level of post-processing freedom without material loss of information. Like conventional measuring methods, the TEM decay is recorded using a scheme of consecutive time channels (hereafter gates) whose length are tailored to the characteristics of the TEM signal. For each gate interval, three polynomial coefficients are computed from the input signal, $x[n]$, and stored, based on the equation

$$C_p = \sum_{n=0}^{N-1} x[n] \cdot n^p \quad where \;\; p \, \epsilon \, [0{:}\,2]$$

where:

- C_0 - equal weighting of all samples in sum
- C_1 - linear weighting function applied in summation
- C_2 - quadratic weighting function applied in summation

These three coefficients are used in the post-processing to create any gate shape that can be generated from the linear combination of these polynomial basis functions. The basis functions comprise constant (0^{th} order), linear (1^{st} order), and quadratic (2^{nd} order) functions, which together can form a variety of smooth second-order polynomial gate shapes as shown below.

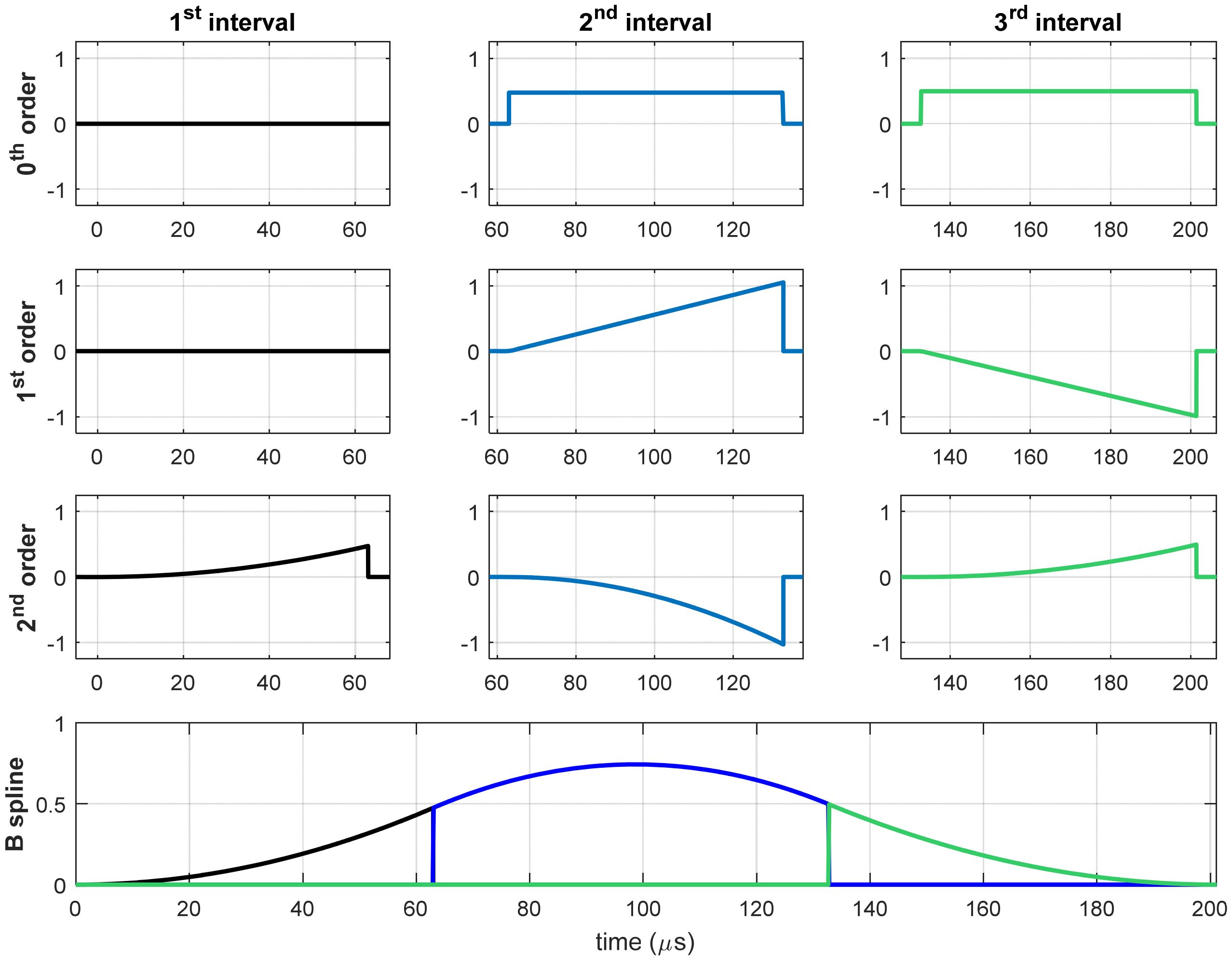

Figure 3: Illustrating how the B-spline gate (bottom panel) is constructed from the building blocks encompassing constant (0th order), linear (1st order), and quadratic (2nd order) elements.

A B-spline gate with the desired shape and filter response can be generated using 3 adjacent gates as shown in Figure 3.

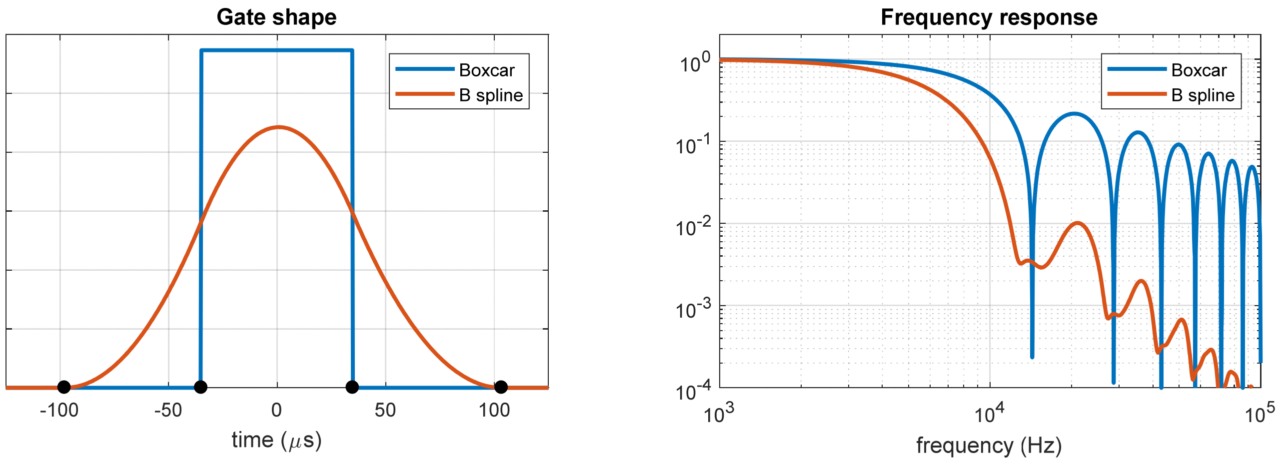

Figure 4: The left-hand panel shows a boxcar and a soft B-spline gate. The right-hand panel shows the frequency response for gate shapes to left.

In comparison with traditional boxcar gates, the B-spline gates have the advantage that high-frequency noise sources can be suppressed efficiently as shown in Figure 4. This means that VLF transmitters, which represent a considerable noise source in certain areas, can be efficiently curtailed in the post-processing. The same principle applies to other high-frequency noise sources such as radio transmitters.

Low base frequency measurements

With the recent suspension system introduced in late 2017, the noise has been reduced to such a low level that standard operation with base frequencies of 12.5 Hz and 6.25 Hz (50 Hz power grid) is enabled. The application of base frequencies below 25 Hz (low base frequencies) is advantageous in those cases where long off-time data is required (see Table 1).

Base frequency (Hz)	Pulse width (ms)	Length of off-time (ms)
25	5	15
12.5	8	32
6.25*	16	64

*Table 1: Different combinations of base frequencies, pulse widths and length of off-time data that can be realized with SkyTEM312 HP. *) 6.25 Hz has been successfully tested in the Smartexploration project but is currently not offered commercially.*

As the table shows, the low base frequencies offer much longer off-time data, potentially leading to much improved characterization of mineral targets. The panel to the right in Figure 5 shows a decay curve over an anomaly averaged over the time window indicated with the blue box in the gate plot in the left panel. The figure illustrates the benefit of the extra 17 ms of off-time data, which is available at 12.5 Hz base frequency as opposed to 25.0 Hz, because in this example even the last time channel at 28 ms is considerably above the noise level.

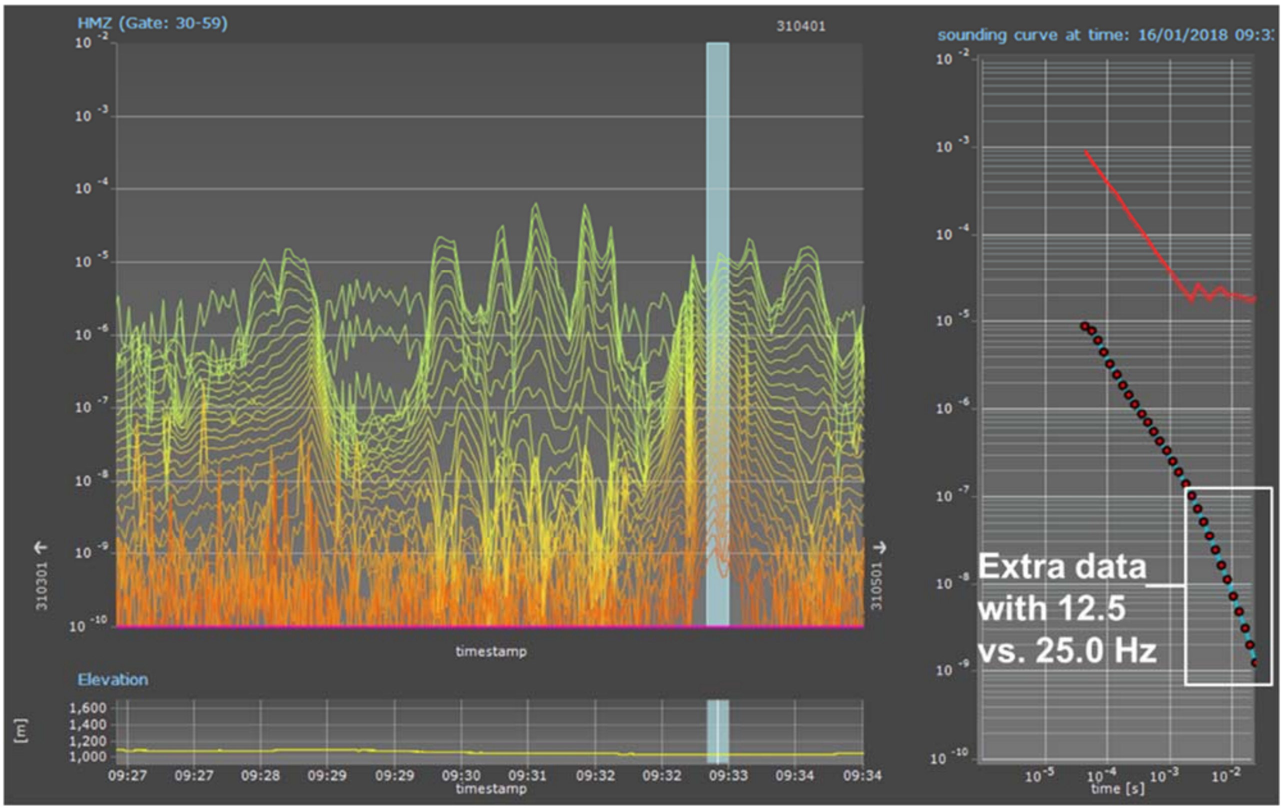

Figure 5: Example of 12.5 Hz data shown over a discrete conductor. The off-time data extends to 32 ms and has a high SNR to the last gate.

Measurement of B-field

The B-field earth response is measured utilizing the same induction coil as for dB/dt data. The B-field measurement is performed as follows:

- The bandlimited dB/dt is oversampled employing a 5 MHz sample rate during both on- and off-times.
- The sampled dB/dt signal represents a continuous function with no loss of information.
- The B-field data is calculated in real-time based on the full-waveform dB/dt readings and stored in-flight.

The accuracy of the B-field measurements was examined employing a controlled discrete target consisting of a wire loop with a well-defined time-constant (see Figure 6).

Figure 6: A B-field target consisting of a 521 m^2 wire loop (black cable bundle) was employed for testing the B-field measurements.

The wire loop comprised an approximate square with an area of 521 m^2 with a measured time-constant, $\tau = L/R$, of 47.5 ms.

The tests with the wire loop were performed at the Danish national test site where the resistivity model is well-known. The wire loop on the ground was overflown in 30, 50, 70, and 90 metres above the ground along four profile lines as shown in Figure 7.

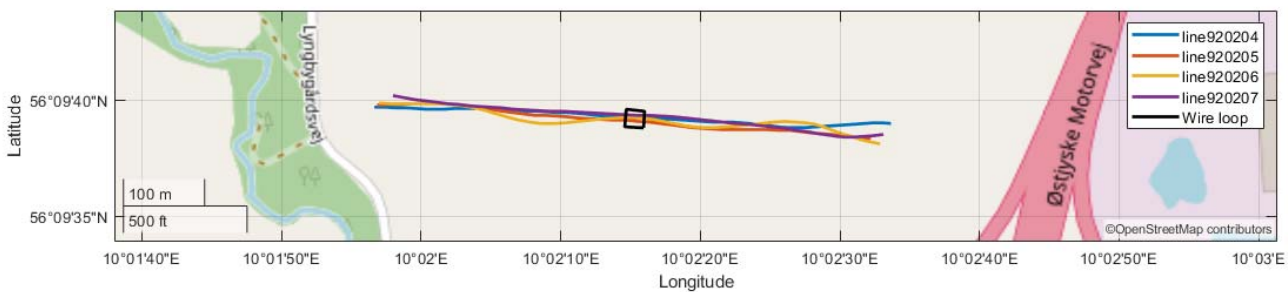

Figure 7: Location of the four profile lines and the wire loop test target. The time-constant of the wire loop target was determined independently of the TEM measurements.

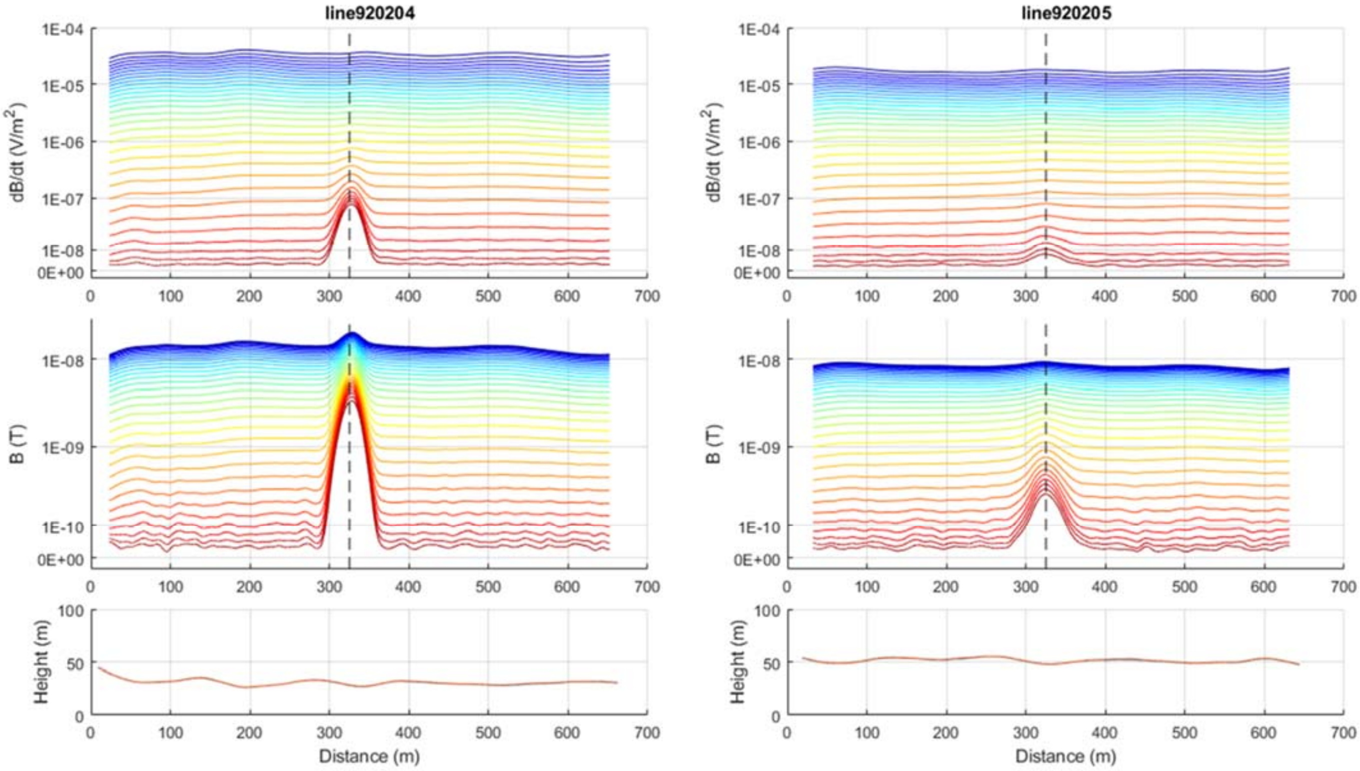

Figure 8: The left-hand and right-hand panels represent the wire loop target responses in 30 m and 50 m height above the target. The target responses are collected on profile lines 920204 and 920205 displayed in Figure 7.

Figure 8 illustrates the significance of measuring the B-field that has a more pronounced response compared to dB/dt. In 50 m, the B-field response is still clearly identifiable as compared to the dB/dt response in this height.

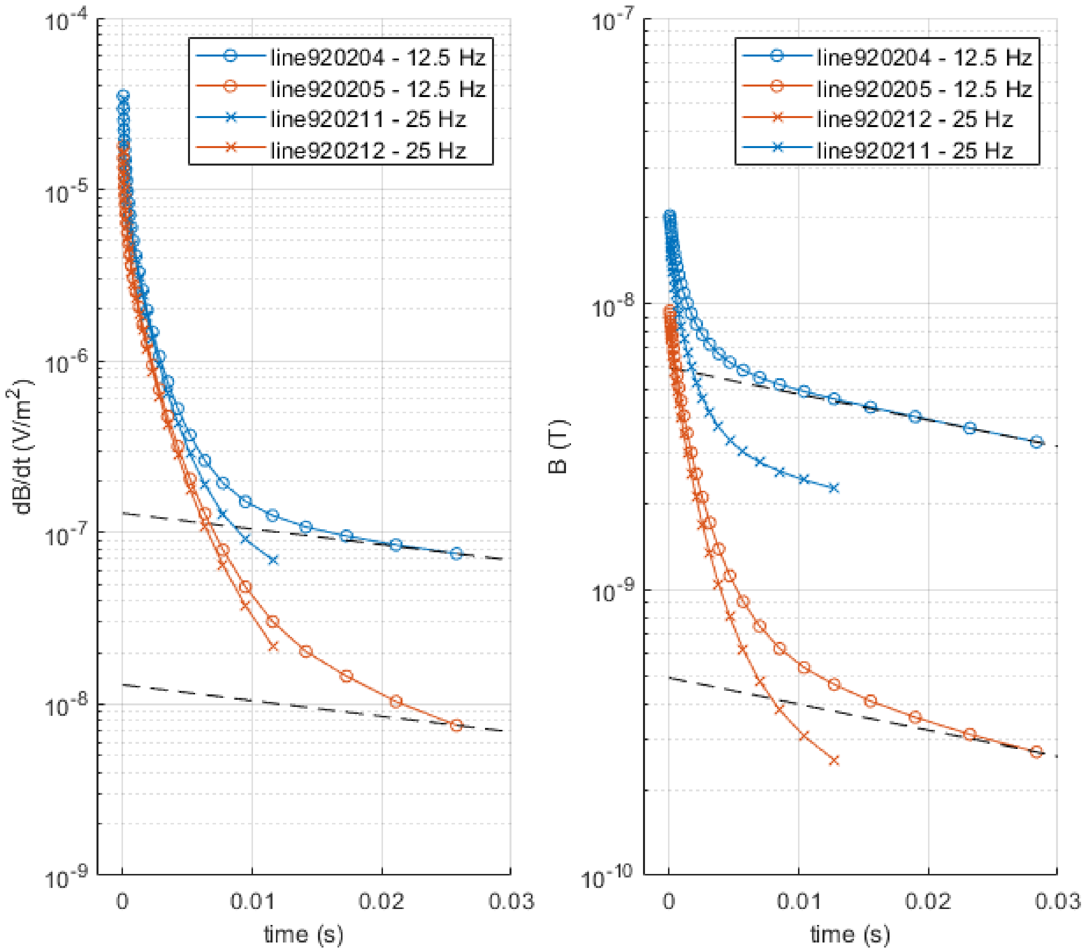

Figure 9: dB/dt and B-field responses measured over the wire loop target in 30 m (blue curves) and 50 m (red curves) with both 12.5 Hz and 25 Hz base frequencies. The dashed lines represent exponential functions with a time-constant of 47.5 ms.

Figure 9 shows that TEM data collected over the wire loop target can be fitted by an exponential function with the known time-constant of 47.5 ms. However, the plot also demonstrates that for large time-constants, in this case 47.5 ms, long off-time data (12.5 Hz base frequency) is required to obtain a suitable estimation of the time-constant. Furthermore, B-field measurements lead to better characterization of the time-constant because they asymptotically approach the exponential decay at earlier off-times in comparison with dB/dt measurements.

THE TRANSMITTER TECHNOLOGY

The current waveform

The transmitted current waveform is shown in Figure 10.

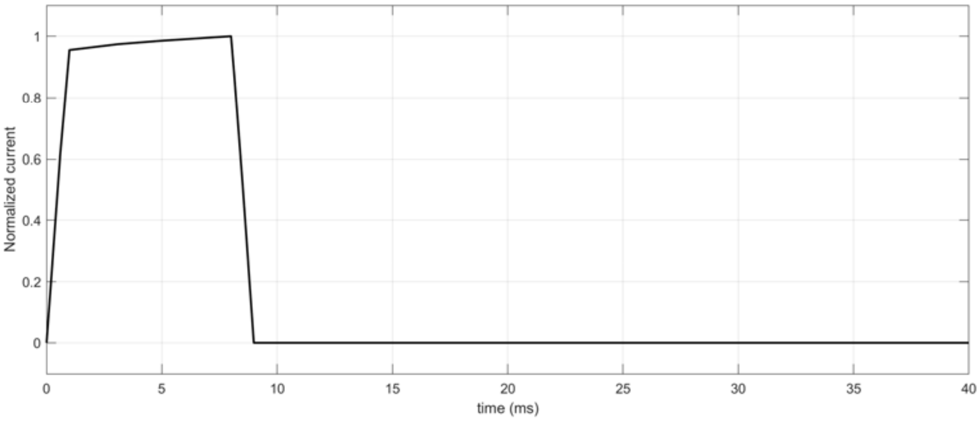

Figure 10: The normalized SkyTEM312 HP current waveform.

The pulse duration is 9 ms in total, consisting of 1 ms ramp-up, a 7 ms period of nearly constant level, and 1 ms ramp-down. Effectively, the waveform functions as a square pulse with 8 ms pulse duration. This waveform shape has been designed to achieve a high earth response and thereby large DOI.

When it comes to DOI, the pulse duration affects the generated signal level as shown below.

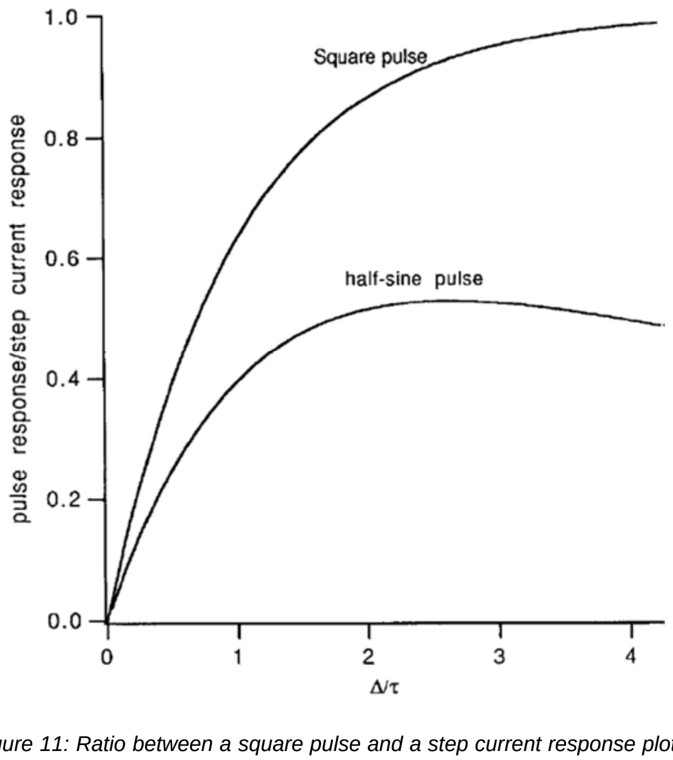

Figure 11: Ratio between a square pulse and a step current response plotted against varying ratios (first axis) of pulse duration, Δ, and the time constant, τ, of the discrete conductor (Liu 1998). The same plot is shown for a half-sine pulse.

Δ is the pulse duration and τ is the time constant of the discrete conductor. The plot shows the ratio between a square pulse and a step current response and the same ratio for a half-sine pulse. Provided the same peak level of the pulses, the square pulse always exceeds the signal level generated by the half-sine pulse. Moreover, the earth response elicited by a square pulse asymptotically approaches the ideal step current response with increasing pulse duration. Conversely, the half-sine response has a maximum at a Δ/τ ratio close to 2. For the square pulse, an increasingly higher signal level is generated with increasing pulse width for a given τ value.

Figure 9 also illustrates the above-mentioned relationship between pulse width and signal level. The signal elicited using a 25 Hz base frequency involves a 5 ms pulse duration whereas the 12.5 Hz base frequency involves a 8 ms pulse duration (see Table 1). As seen, the 8 ms pulse generates a markedly higher late-time response in all cases.

Against this backdrop, the practically square waveform employed by SkyTEM312 HP and the large pulse duration of 8 ms are advantageous compared to other systems on the market in relation to DOI.

Segmented transmitter

The patented transmitter is composed of 6 TX-blocks that are each connected with 2 transmitter loop turns, which in total provide 12 TX-loop turns. Because each TX-block only has to handle 2 TX-loop turns, the current can be turned-off much faster in comparison with a configuration in which one TX-block must cope with all TX-loop turns. Combining this with a high TX current of 250A, we have enabled a small TX-loop of merely 342 m^2 area to transmit 1,000,000 Am^2 while maintaining a quick current turn-off. Conventional one-block transmitter systems comprise an area typically exceeding 900 m^2 and employ fewer TX-loop turns to achieve an acceptable turn-off time and dipole-moment. The drawbacks of these large systems include larger footprints and diminished in-flight manoeuvrability as compared to the compact 342 m^2 TX-loop of SkyTEM312 HP.

The system configuration

System weight has a considerable influence on survey costs, and SkyTEM has, therefore, strived to significantly curtail the weight of SkyTEM312 HP. This endeavour has had the following positive effects:

- By reducing the system size from 540 m^2 (previous generation system) to 340 m2 and switching from composite to carbon fibre reinforced material, the system weight has dropped 100 kg.
- It is economically feasible to operate SkyTEM312 HP with a Eurocopter B3 helicopter under most conditions except in high altitudes and hot weather above 35 C. Eurocopter B3 is a highly cost-efficient helicopter widely available around the world as opposed to less cost-efficient and accessible helicopter alternatives.
- The reduced system weight has increased the amount of fuel that can be carried by 100 kg, thereby increasing flight duration around 45 minutes.

DATA EXAMPLE

VMS and Ni-Cu exploration

The SkyTEM312 HP system was employed for exploration of VMS and Ni-Cu occurrences for Orion Minerals ("Orion") in the highly prospective Areachap Belt (Baile et al. 2010), South Africa (see Figure 12) in 2017.

Figure 12: Location of the Areachap Belt (red star)

Orion wanted to fast-track their planned exploration programme and leverage modern exploration techniques. For these reasons, a staged process was applied encompassing the following steps: (1) pre-modelling of selected well-known deposits for selecting the appropriate helicopter TEM ("HTEM") system, (2) execution of a HTEM survey over the entire survey block using a high power system with a large DOI capability, (3) modelling of anomalies identified in the HTEM survey, (4) ground follow up on identified anomalies.

Orion commissioned SkyTEM to carry out the survey with the SkyTEM312 HP system. This HTEM system was chosen because it offers a high DOI owing to its large dipole-moment of 1,000,000 Am^2, low noise level, and off-times up to 32 ms facilitated by the 12.5 Hz repetition frequency.

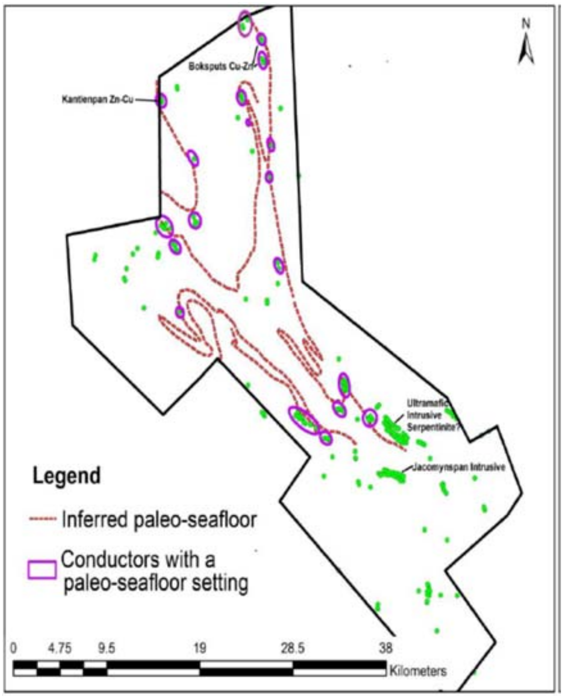

Figure 13: 19 high priority VMS targets (purple circles) identified in the SkyTEM survey. The green spots show identified anomalies.

As Figure 13 shows, 19 hitherto unknown VMS and Ni-Cu deposits were identified in the SkyTEM312 HP survey. The high detection rate can in part be attributed to the use of the 12.5 Hz repetition frequency and the associated 32 ms off-times.

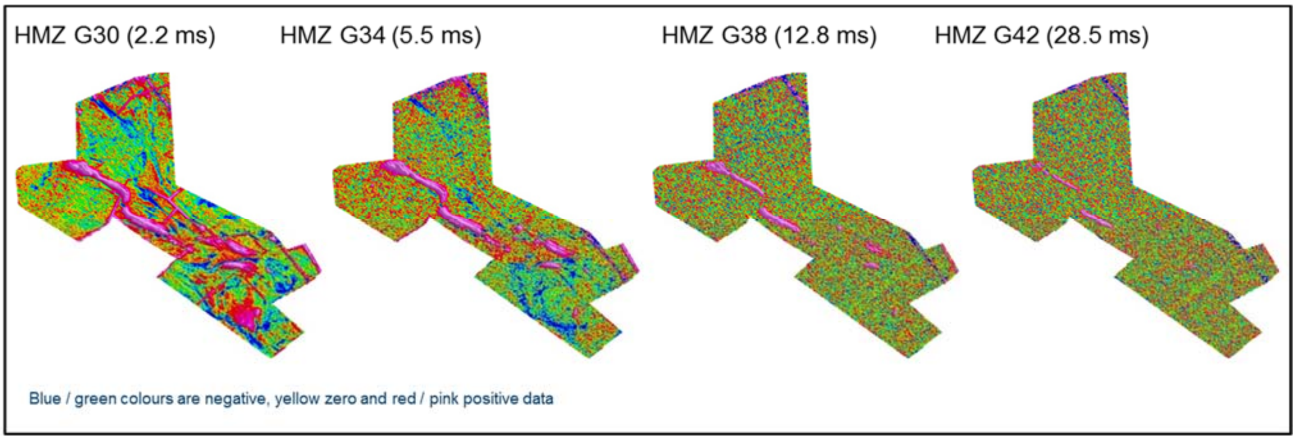

Figure 14: Four gate plots G30-G42 in plan view. Gates later than G38 are exclusively available employing a 12.5 Hz repetition frequency.

Figure 14 illustrates the value of the long off-time data. The panels G30-G42 are gate plots in plan view representing 4 gates in the off-time. Gates later than G38 are exclusively available employing a 12.5 Hz repetition frequency as opposed to 25 Hz. As seen, it is possible to identify strong conductors in the G42 gate plot. Hence, the long off-times afforded by the 12.5 Hz repetition frequency enable late time anomaly detection as well as contribute to an improved characterization of conductors otherwise not attainable using a conventional 25 Hz repetition frequency.

The high priority anomalies singled out in the SkyTEM survey were subsequently 2D plate modelled to guide the follow up on the targets with FLTEM.

The FLTEM system is a powerful ground-based TEM system offering an extremely high DOI effected by a dipole-moment of up to 120,000,000 Am^2 employing a peak current of 120-140A and large TEM loops of 1,000x1,000 m^2. The FLTEM soundings for each target were carried out utilising an optimal coupled loop along profile lines with orientations guided by the modelling of SkyTEM data (see Figure 15). Consistently, the FLTEM soundings confirmed the targets identified in the SkyTEM survey.

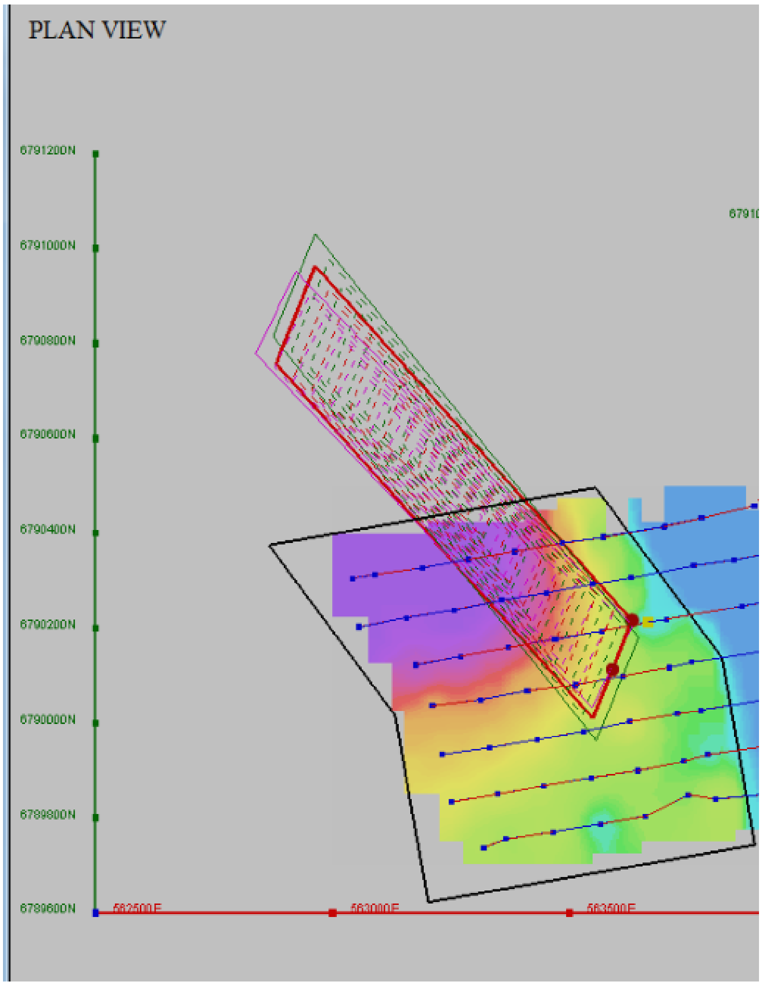

Figure 15: Modelled plates (with dashed lines) based on FLTEM data. Blue dots show FLTEM sounding locations spaced with 50-100 m and profile lines spaced with 100-200 m.

Afterwards, the acquired FLTEM data was 2D plate modelled to obtain a reliable characterisation of the target. This type of modelling, in comparison with the modelling of HTEM data, will often provide improved parameters for drilling targets. The reasons are (1) that FLTEM has a superior DOI compared to HTEM, (2) the profile lines can, based on the SkyTEM survey results, be orientated to provide the optimum coupling with the target, and (3) the line spacing is kept closer than what, due to budget considerations, are feasible for an HTEM survey.

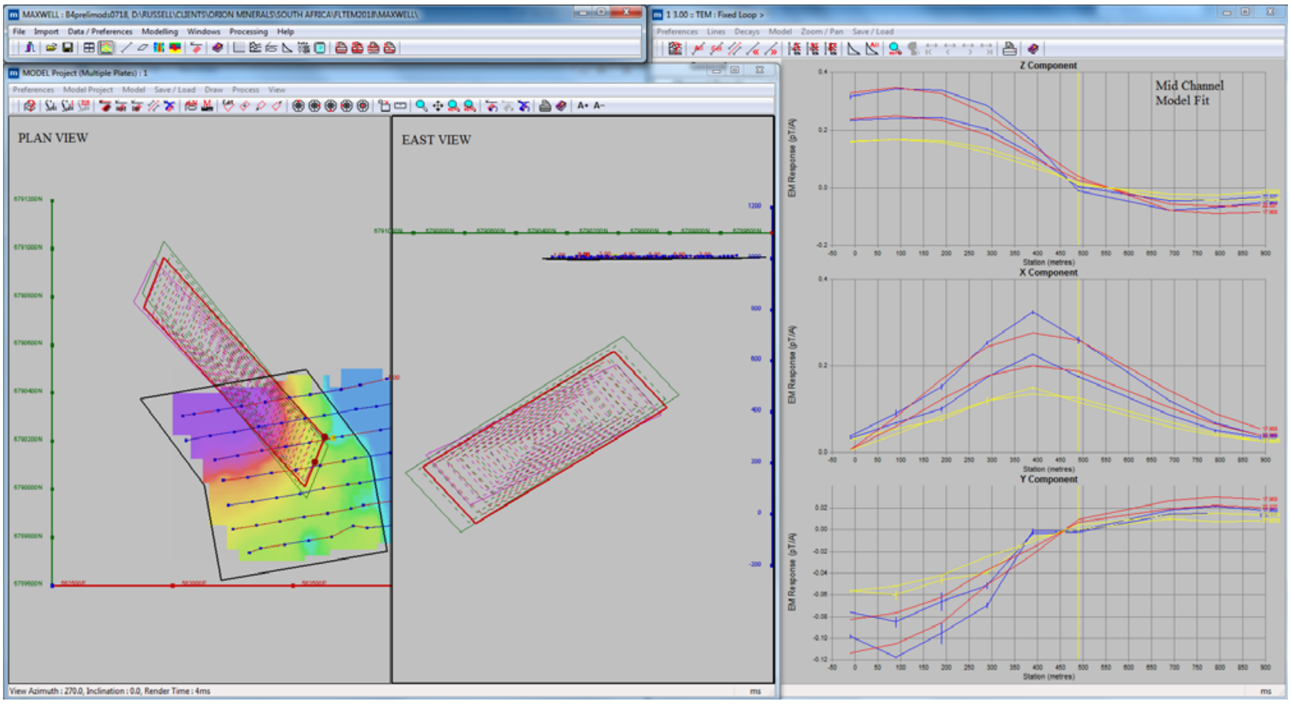

Figure 16: 2D plate modelling results for 3 of the 7 profile lines shown in Figure 15. In the right-hand panel, each curve represents a mid-channel gate along one profile line.

Figure 16 shows the data fit for a FLTEM mid-channel along the three of the seven profile lines shown in Figure 15. The data fit is satisfying for the X,Y,Z-components along all profile lines. Predicated on these modelling results, several drilling targets were established for a follow up drilling campaign. Drillings OROD001 confirmed the SkyTEM anomalies and FLTEM conductors and detected significant Ni-Cu mineralisations. Figure 17 shows the geochemical results from four intersections in drilling OROD001.

Drill Hole	Cut Off	From m	Width m	Ni Tenor wt%	Cu Tenor wt%
OROD001	0.2% Ni	201.05	8.99	3.80	2.58
OROD001	0.2% Ni	292.09	7.29	9.29	3.65
OROD001	0.3% Ni	297.44	1.94	10.22	3.86
OROD001	0.5% Ni	201.05	1.22	2.90	3.66

Figure 17: Drill holes OROD001 confirmed SkyTEM and FLTEM targets. Table shows the drilling results.

Conclusions

Orion carried out an integrated helicopter TEM and large fixed loop ground TEM exploration program to optimize and fast track the chances of finding VMS and Ni-CuS deposits of economic value and providing the optimal parameters for drilling of identified targets. The program was performed employing modern techniques comprising the SkyTEM312 HP system and a FLTEM system and both proved to be time and cost efficient. Within 6 months from the start of the program, 19 high primary VMS and Ni-CuS targets were identified, and a comprehensive drilling program was drawn up for follow up.

This case study suggests that, provided the mineral deposits of interests have a sufficient conductivity contrast to the host rock, this staged method can be highly cost-efficient, and it also optimizes the chances of a successful outcome both in terms of discoveries and lowering of the risks and costs.

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ACKNOWLEGDEMENTS

We thank Orion Minerals Ltd. for giving permission to share the results shown in the data example.