
Paper 60

Breaking Through the 25/30 Hz Barrier: Lowering the Base Frequency of the HELITEM Airborne EM System

Konieczny, G. [1], Miles, P. [1], Smiarowski, A. [1]

---

1. CGG, 2505 Meadowvale Boulevard, Mississauga, Ontario, Canada

ABSTRACT

Performance of airborne electromagnetic (AEM) systems has changed dramatically since the first helicopter time-domain systems were employed in the early 2000s. These systems have experienced dramatic improvements in transmitter power and system noise reduction, such that signal- to- noise has improved to a level that inductively induced polarization (airborne IP) and superparamagnetic effects are detectable. Lowering base frequency below 25 Hz has been a goal to improve discrimination of very conductive targets and to explore under conductive cover. Although easy to achieve in ground EM surveys, noise caused by receiver motion on airborne platforms has prevented this barrier from being surpassed. Here we discuss the technological innovations that led to and survey results from an AEM system capable of operating at a base frequency of 15 Hz. The noise level increase we observe using 15 Hz over operating the same system at 30 Hz is largely identical to the theoretically expected amount caused by decrease in data available for stacking. We show results from an area with very conductive and thick cover to highlight the extended measurement time of the 15 Hz base frequency.

INTRODUCTION

There are two main advantages to operating a system with a low base frequency: (1) long measurement time and (2) opportunity for a long excitation pulse. A number of authors have discussed these advantages of operating electromagnetic (EM) systems with a low base frequency. (Osmond et al. 2002; Witherly and Mackee, 2015).

Just as depth of exploration in frequency-domain is related to excitation frequency, ω, depth of penetration for time-domain systems is related to measurement time. The simplest estimate of depth of exploration is the diffusion depth of a plane wave in a full space (Ward and Hohmann, 1988), which gives depth of penetration as:

$$z = \sqrt{\frac{2t}{\mu\sigma}} \qquad (1)$$

where t is the measurement time, σ is conductivity, and μ is magnetic permeability. A long measurement time is particularly important in areas of conductive cover. Because conductive cover slows the diffusion of induced fields, the response from a target under cover is delayed, making late measurement times essential for target detection (Lamontagne, 1975; Raiche and Galagher, 1985).

A long excitation pulse provides greater sensitivity to conductive targets, in free space and in the presence of conductive cover. Liu (1998) calculated wire-loop responses for various pulse widths. Wire-loop targets with larger time constants are more effectively energized and produce larger responses with wider excitation pulses. For wire loops under conductive cover, Liu (1998) showed that the cover delays the response of the wire loop and that the maximum of the ratio of target to overburden response occurs earlier in time for longer duration pulses.

Receiver motion can introduce signals orders of magnitude greater than the secondary signal from Earth (Annan, 1983; Lane et al. 1998). Motion-induced noise has been identified as the main factor preventing useful acquisition of low base frequency data in airborne electromagnetic (AEM) systems (Buselli et al, 1998). A number of researchers have used estimates or measurements of the receiver motion in an attempt to correct for its' effect (Davis et al, 2006; Kratzer and Vrbancich, 2007; Smiarowski et al. 2010; Kratzer and Macnae, 2014) with at least some success at reducing receiver motion noise. To our knowledge, none of these methods have been employed on an AEM system to reduce base frequency.

AEM contractors have focused on designing suspension systems to reduce the frequency of receiver coil vibrations and rotations. Lower suspension frequencies allow operation at a lower base frequency. Reducing base frequency decreases the amount of data available for stacking, leading to an increase in the noise level in the case of 30 Hz to 15 Hz by an amount $\sqrt{2}=1.44$. While designing a transmitter to operate below 25 Hz is not difficult, reducing receiver coil motion and vibration to such an extent that noise increases by only a factor of $\sqrt{2}$ is very difficult. Previous efforts have acquired data at 15 Hz, but their absence from the marketplace suggests that the increase in noise levels overcame any advantage of long measurement times.

Here we describe a variation of the HELITEM system which has been designed to operate at frequencies below 25 Hz. A number of design changes allow operation at 15 Hz including a coincident transmitter-receiver geometry, an improved receiver suspension system and improved receiver electronics. By comparing the receiver power spectrum of the original to the new design, we observed a dramatic decrease in receiver coil motion which resulted in lower system noise and dramatically lower noise at operating frequencies below 30 Hz.

In "Proceedings of Exploration 17: Sixth Decennial International Conference on Mineral Exploration" edited by V. Tschirhart and M.D. Thomas, 2017, p. 767–771

The system modifications allow collection of AEM data at frequencies below the standard 30 Hz. However, low base frequencies reduce the number of samples available for averaging by stacking resulting in increased noise levels. We observed noise levels approximately 1.8 times higher with 15 Hz operation compared to 30 Hz operation, in line with the expected √2 increase. In order to demonstrate the system performance at 15 Hz, we present two data examples from testing performed thus far. One survey was flown over an area with very conductive cover in the Sudbury region, but no discrete commercial target; response is above noise level for the entire 25 ms of off-time and conductivity-depth sections show a deeper penetration depth than a 30 Hz system. In the second data example, we compare results from 15 and 30 Hz system over the Caber deposit in Quebec, where 15 Hz data is not essential. This example shows that the noise level has increased by close to the theoretically expected amount of √2 compared to a 30 Hz configuration.

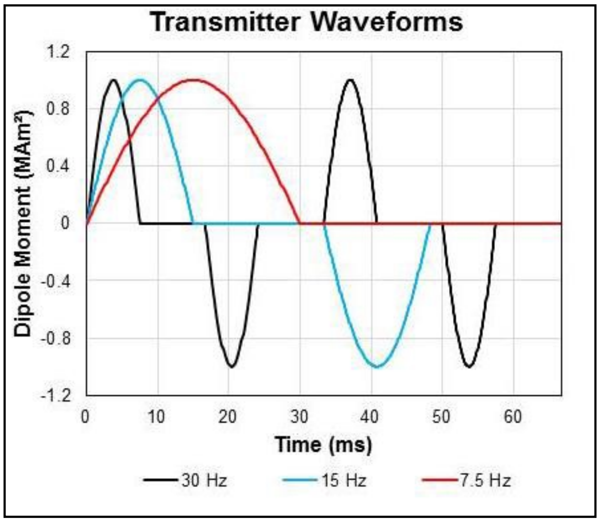

Figure 1: The transmitter waveforms used for calculations and the field surveys. The black line shows a 4 ms half-sine pulse operated at 30 Hz. The blue line shows an 8 ms half-sine pulse operated with a 15 Hz base frequency. Notice that the off-time is considerably longer using the 15 Hz base frequency even though the pulse width has been doubled.

THEORY

Design of an electromagnetic exploration system requires various trade-offs in terms of the electronic components. The current in a large transmitter loop of a high-powered system cannot be turned off as quickly as a small amount of current in a small loop; the system trades high-frequency resolution for moment and depth of exploration. Comparing an ideal step-off response to a half-sine excitation is useful to understand the relative merits of each waveform, but to evaluate performance in an exploration setting, one must consider what is practically achievable from an electronics perspective and realize that the moment of these two waveforms will be quite different.

Here, we contrast synthetic 15 Hz and 30 Hz waveforms using power (and noise) levels actually observed in the field. The transmitter pulses are shown in Figure 1; the black line shows a 4 ms wide half-sine pulse operated at 30 Hz with a moment of 0.8 MAm^2 (12.6 ms off-time) and an 8 ms wide half-sine pulse operated at 15 Hz with a moment of 1.1 MAm^2 (26 ms of off-time); the longer repetition time allows the moment to be increased.

Figure 2 shows the wire-loop nomogram calculated for a concentric loop system employing these waveforms. The waveform using a 15 Hz base frequency is able to place channels further after the end of the pulse; two of these possible channels are shown with the dotted blue lines. The figure shows that the narrow pulse generates higher signals for more resistive (shorter time constant) wire-loop models. The wider pulse generates significantly higher (> 2.5 times) signals for very conductive wire-loop targets. Importantly, the long pulse generates higher signals for conductive loops and smaller signals for resistive loops.

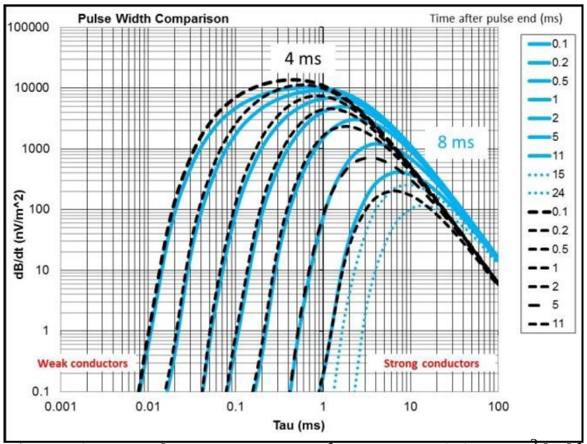

Figure 2: Wire-loop nomogram for a 4 ms 0.8 Mam^2 half-sine pulse (black) operated at 30 Hz and an 8 ms 1.1 Mam^2 pulse (blue) at 15 Hz. The blue dotted lines show the response that can be measured utilizing the extra off-time afforded by the slower repetition rate.

This suggests that the wider pulse will have a greater target-to-overburden ratio. This is particularly evident for the last time channels of the 15 Hz pulse repetition (24 ms after the pulse end) compared to the last channel of the 30 Hz base frequency (11 ms); the signal due to resistive wire loop targets is significantly smaller than the 30 Hz case but the response from conductive wire-loops is higher.

The plane wave depth of penetration estimate provided in equation (1) does not include the effect of the pulse shape. We can estimate the depth of investigation using the frequency domain skin depth equation by first calculating the effective frequency using the geobandwidth (Hodges and Chen, 2015) concept. Grant and West (1965) showed that the quadrature component of a frequency domain system peaks when $\tau=1/2\pi f$. Using the calculated wire-loop response, we locate for each

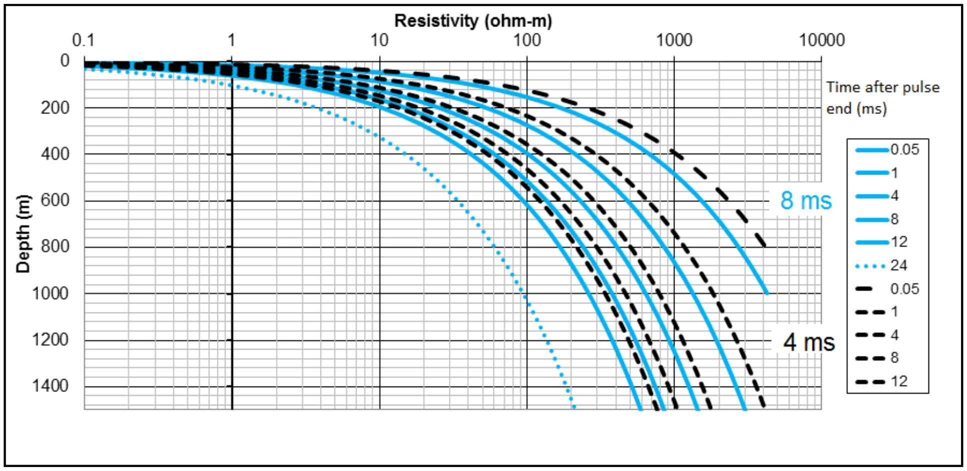

Figure 3: Exploration depth of selected channels (time after end of pulse) for an 8 ms half-sine pulse (blue) with a 15 Hz base frequency and a 4 ms half-sine (black) operated at 30 Hz. Depth is estimated as 55% of the frequency domain skin-depth, calculated by using the effective frequency (found from the wire-loop response nomogram for the particular pulse and channel time).

channel the time constant which results in a signal peak and obtain the "effective frequency" of that channel. We then estimate the depth of penetration of that channel for a range of half-space resistivity values as depth=0.55 $\delta = 0.55\,(2\rho/\mu\omega)^{1/2}$. The result is shown in Figure 3; notice that for channels with the same time after the end of the pulse, the effective frequency is lower for the longer transmitter pulse, leading to a greater depth of investigation. The extra off-time available when operating at a 15 Hz base frequency allows for additional measurement channels and a considerably greater depth of investigation (and ensures sufficient off-time when a wide pulse is used); for conductive areas where signal is able to persist above late-time noise levels the depth increase is about 1.8 times.

FIELD EXAMPLES

To date airborne EM systems have not been able to acquire data with satisfactory signal-to-noise ratios at base frequencies below 25 Hz. As the towed receiver moves and rotates in the earth's static field, noise signals orders of magnitude greater than the earth's response are induced. The challenge has been to remove these unwanted signals by either suppressing motion or by signal processing.

We have conducted a number of surveys using a modified version of the HELITEM system. These changes include a concentric loop transmitter-receiver design, a patented receiver suspension system and updated receiver electronics. Through a combination of noise suppression and signal processing, we have been able to decrease motion noise at low frequencies.

Figure 4 shows decays collected during surveys in conductive terrain near the Sudbury area. Two systems were flown; one using a 6 ms 30 Hz waveform (0.9 MAm^2) and the other flown with an 8 ms 15 Hz waveform (as depicted in Figure 1). The dashed lines show time constants fitted over a span of four channels, at mid and late time (5-8 ms after the end of each pulse and 18-24 ms after the 15 Hz waveform pulse). The late-time channels of the 30 Hz waveform have the same decay constant as the mid-channels of the 15 Hz waveform. The decay constant at late time of the 15 Hz waveform has been estimated to be 7.8 ms, about two times as long as the mid-channel estimate.

We then performed tests over a known deposit in the Matagami area, Quebec. This was flown with a 5.5 ms pulse width at 30 Hz and an 8 ms pulse width at 15 Hz and 7.5 Hz. A comparison of the measured dB/dt data and calculated B-field data is shown in Figure 5. The short pulse has higher response from the overburden; this is because the short pulse generates relatively more high-frequency energy than the longer pulse width, resulting in more signal from weaker targets (here, the thin overburden). The longer pulse width generates more low-frequency energy and better energizes the target. Figure 6 shows this in more detail; we have extracted the measured response from above the target and above the overburden, and shown the time-decay of the signal. This figure shows the decreased overburden response with a longer pulse width (note that the 15 Hz and 7.5 Hz both employ an 8 ms pulse and they have similar early time responses) and higher response from the conductive target. Note that the 7.5 Hz base frequency also provides for a longer measurement time (not useful here), but which is useful in areas with conductive cover or very conductive targets.

CONCLUSIONS

Reducing the operating frequency of AEM systems has long been a goal to increase depth of exploration and allow better resolution of very conductive targets. Here we have studied a synthetic 15 Hz waveform and showed that by increasing the pulse width and utilizing the extra measurement time, the depth of exploration can be increased by about a factor of 1.8.

We have used a concentric-loop HELITEM system to acquire data with base frequencies below 30 Hz (15 Hz and 7.5 Hz data have been collected). Special attention was paid to reduce motion-induced noise through data processing and system design. Data collected from a conductive area in the vicinity of Sudbury showed that the late time channels of the 15 Hz waveform were able to detect longer time constants than 30 Hz data. Field data also showed the advantage of a longer pulse width in reducing the response from weakly conductive overburden, made possible by a low base frequency. The system modifications made to the HELITEM system make low base frequency operation a reality.

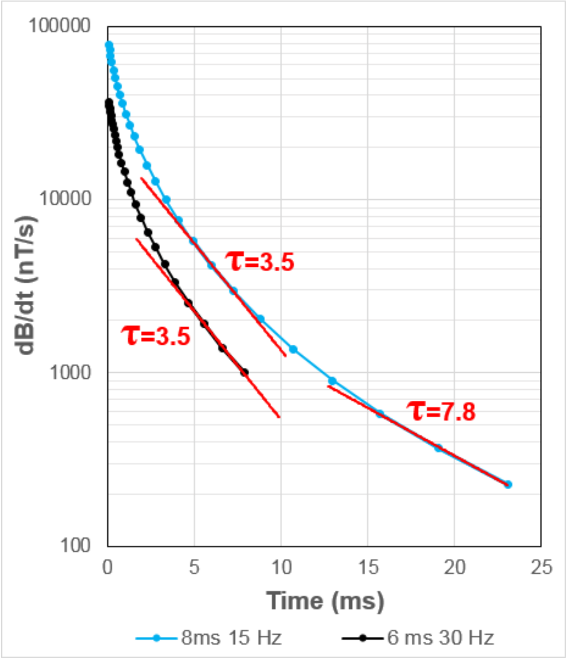

Figure 4: Measured decays from the 6 ms 30 Hz system (black) and the 8 ms 15 Hz system. We have calculated decay constants (shown as the red lines) for the channels 5–8 ms after the end of each pulse, as well as 18–24 ms after the 15 Hz waveform.

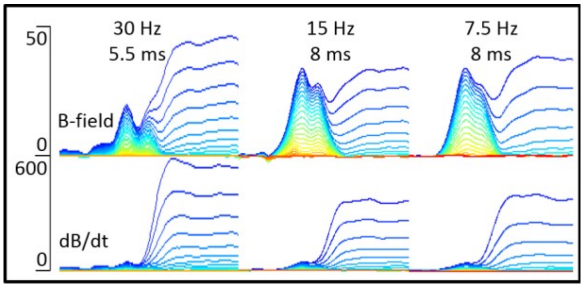

Figure 5: Data collected over the known Caber deposit, Quebec. Overburden is present on the right side of the lines. Panels show calculated B-field (top) and measured dB/dt signals. The system was flown with a 5.5 ms half-sine pulse width at 30 Hz and with an 8ms pulse at 15 Hz and 7.5 Hz.

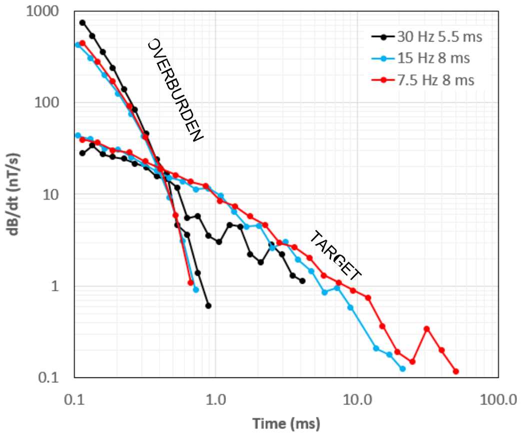

Figure 6: Display of the time-decay of the measured signal from over the target and over the thin overburden of Figure 5. The short pulse width (5.5 ms) has relatively higher amplitude overburden response and weaker response from the target. The 7.5 Hz base frequency allows for longer measurement times (which is not necessary for this particular geology but is useful in conductive terrains or for very conductive targets).

ACKNOWLEDGEMENTS

We would like to thank CGG for supporting this research effort and allowing us to present these results.

REFERENCES

Annan, A. P., 1984, Compensation of towed bird AEM system data for differential transmitter receiver motion: 54th Annual International Meeting, SEG, Expanded Abstracts, 80-81.

Buselli, G., H.S. Hwang, and J.P. Pik, 1998, AEM noise reduction with remote referencing: Exploration Geophysics, 29, 71-76.

Davis, A., J. Macnae, and T. Robb, 2006, Pendulum motion in airborne HEM systems: Exploration Geophysics, 37, 355–362.

Grant, F.S. and G.F. West, 1965, Interpretation theory in applied geophysics: McGraw-Hill.

Hodges, G. and T. Chen, 2015, Geobandwidth: comparing time domain electromagnetic waveforms with a wire loop mode: Exploration Geophysics, 46, 58-63.

Huang, H. and D. Fraser, 1996, The differential parameter method for multifrequency airborne resistivity mapping: Geophysics, 61, 1, 100-109.

Kratzer, T. and J. Macnae, 2014, Prediction and removal of rotation noise in airborne EM systems: Exploration Geophysics, 45, 147-153.

Kratzer, T. and J. Vrbancich, 2007, Real-time kinematic tracking of towed AEM birds: Exploration Geophysics, 38, 132-143.

Lamontagne, Y.L., 1975, Application of wideband, time-domain EM measurements in mineral exploration: PhD thesis, University of Toronto

Lane, R., C. Plunkett, A. Rice, A. Green, and Y. Hu, 1998, Streamed data- A source of insight and improvement for time domain airborne EM: Exploration Geophysics, 29, 16-23.

Liu, G., 1998, Effect of transmitter current waveform on airborne TEM response: Exploration Geophysics, 29, 35-41.

Osmond, R. T., A.H. Watts, W.R. Ravenhurst, C.P. Foley, and K.E. Leslie, 2002, Finding nickel from the B-field at Raglan – 'To B or not dB': CSEG Recorder, 27, 9.

Raiche, A.P. and R.G. Gallagher, 1985s Apparent resistivity and diffusion velocity: Geophysics, 50 (10), 1628-1633.

Smiarowski, A., J. Macnae, and R. Bailey, 2010, Predictive filter calculation of primary fields in a fixed-wing time-domain AEM system: Geophysics, 75, F97-F106.

Ward, S. H. and G.W. Hohmann, 1988, Electromagnetic theory for geophysical applications, in M.N. Nabighian, ed., Electromagnetic Methods in Applied Geophysics, Vol 1, Chapter 4, Society of Exploration Geophysicists.

Witherly, K. and G. Mackee, 2015, Geophysical responses over the Cannington Ag-Zn-Pb deposit-Queensland: ASEG Expanded Abstracts 2015.