# Designing a HTEM system for mapping glaciolacustrine overburden thickness

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**Summary**

A helicopter-borne transient electromagnetic (HTEM) survey system is being designed with characteristics suitable to map glaciolacustrine overburden overlying Precambrian bedrock for the purpose of correcting airborne gravity measurements for lateral variations in overburden thickness. This paper discussed the optimization of two system parameters: transmitter moment and maximum duty time. A transmitter moment of 100 A and maximum duty time of 0.5 ms have been found to be a good compromise between generating enough energy to probe the complete thickness of the overburden while allowing very early time responses to be recorded and providing a high sounding frequency. Inversion of noise-free and noisy synthetic EM responses provide insight on the performance of the system to detect an overburden of thickness 5-60 m composed of up to 3 layers of clay, sand and till.

**Statement of the Problem**

Large areas of Precambrian bedrock in Canada, particularly in the Abitibi mining region, are covered by a thick glaciolacustrine overburden. The presence of this overburden complicates efforts in mineral exploration by covering the bedrock from exploration geologists thereby hiding geological information, and increasing the cost of drilling programs. Another undesirable effect of overburden topography is the creation of anomalies in potential field data that can be mistaken for a mineral deposit. In gravity data (Figure 1), these anomalies can be of a similar size and amplitude as a signal from a deeper target such as an ore body (Chen and Macnae, 1997). How can the contribution of the overburden, whose density varies laterally with thickness, independent of bedrock topography, be corrected for in remote areas where seismic surveying and boreholes are not an option?

Airborne electromagnetic methods (AEM) have been predominantly applied to mineral prospecting for bedrock-hosted deposits. These systems are generally configured with high magnetic moments of well over 100,000 A/m$^2$ in order to detect targets within the bedrock. More recently, lower power systems have been applied successfully to hydrogeological sounding. In Australia, the Tempest time-domain electromagnetic (TEM) system was used to measure the thickness of the overburden for the purpose of correcting gravity data. This approach relied on the presence of a conductive saprolite layer and assumed that areas of high conductivity and low density were associated to a thick overburden, and areas of low conductivity and high density were associated to a thin or absent overburden (Meyers et al., 2001).

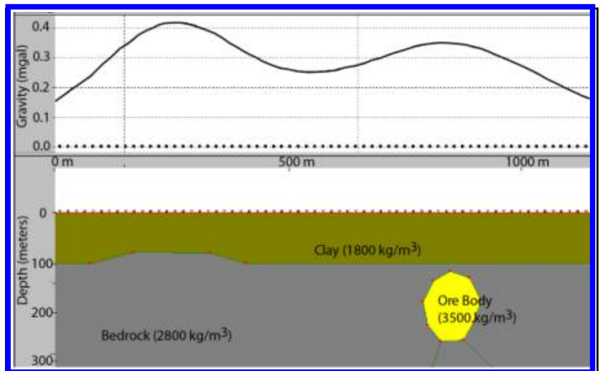


Figure 1: Simple two-layer subsurface model showing a dense ore body hosted in bedrock at a depth of ≈ 200 m. The gravity anomaly originating from the ore body has a similar amplitude and wavelength as that caused by a 20 m reduction in the thickness of the overburden.

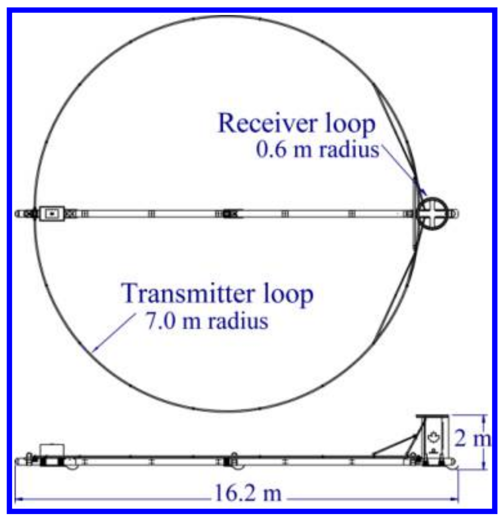


Figure 2: Concept drawing of the HTEM system currently under development. The transmitter is a single-turn 7 m radius loop with a moment of 15,400 A/m$^2$. The receiver location has not been finalized yet. It is shown here offset and slightly elevated from the transmitter.

In the Abitibi mining region, the saprolite layer overlying Precambrian bedrock is either thin or absent as the bedrock was scoured by the last ice age (Palacky and Stephens, 1990), which also introduced a layer of till. Melting of the glaciers led to the creation of large lakes and river


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channels, which introduced layers of sand and clay sediment that can be either well or poorly sorted. The glaciers themselves also deposited sediment in the form of moraines, drumlins, and eskers that may have been subsequently buried by lake sediment from glacial melt water. Advances and retreats of the glacier also resulted locally in alternating layers of till and clay (Palacky, 1991). The overburden is therefore composed of till, sand, and clay that can vary in both thickness and conductivity. Any AEM method used to measure the thickness of the overburden will need the capability to either detect each individual layer of sediment, or accurately resolve the total depth of all of sediment layers above the bedrock.

**HTEM System Design**

A TEM system was chosen for its wide range of frequencies. A broadband system has a greater potential to induce currents in a larger portion of the overburden providing information on the variation of conductivity with depth (Spies and Frischknecht, 1991; Palacky and West, 1991). This system (Figure 2) is a single-turn in-loop or central-loop system where the transmitter and the receiver are in a horizontal plane. The transmitter emits a square waveform (Figure 3) to maximize the response of the overburden (Lui, 1998). The system is designed to be suspended 30m below the helicopter in order to reduce helicopter-generated EM interference and increase subsurface response.

**Optimizing System Parameters**

In this theoretical study done in support of the ongoing development of the system, two parameters were investigated in order to optimize the response of the shallow subsurface: transmitter moment and maximum duty time. For simplicity, concentric transmitter-receiver geometry has been assumed. Modelling was done using AirBeo of the P223F EM open source code suite developed by the Commonwealth Scientific and Industrial Research Organization (CSIRO). AirBeo computes and inverts EM responses for 1D layered-earth models (Chen and Raiche, 1998).

The transmitter moment was chosen by examining the forward modelled responses obtained using AirBeo over a suite of models based on the geology of the Abitibi mining region. Several moments were modelled corresponding to currents of 60 A, 100 A, and 200 A. Since the overburden-bedrock interface is the primary target of the EM system, and since the overburden information is found in the early time response, the transmitter turn-off time must be kept as short as possible. A large current induces a strong response that is desirable, but causes a long turn-off time that overshadows the early time response. On the other hand, a

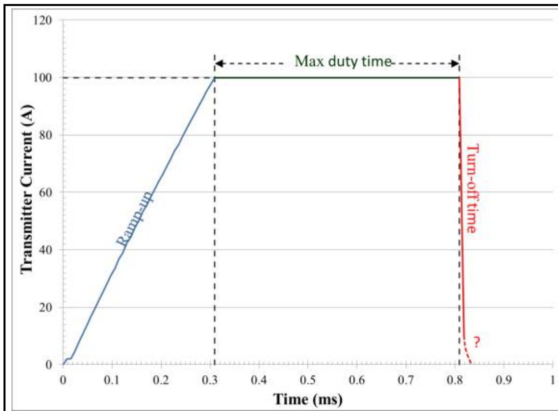


Figure 3: Transmitter waveform showing the ramp-up, maximum duty time, and turn-off times. Exact turn-off time is undetermined.

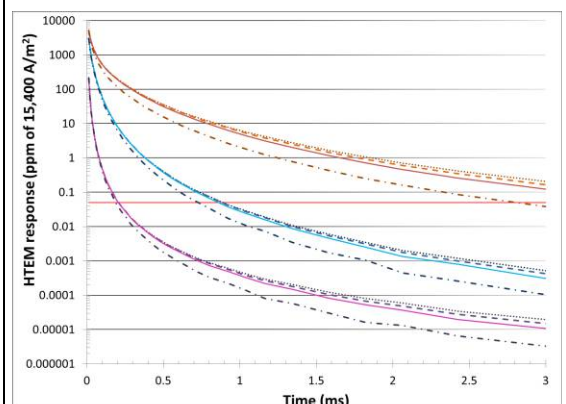


Figure 4: Comparison between responses for a transmitteer loop current of 100 A and different maximum duty times: 0 ms (dotted dashed lines), 0.5 ms (solid lines), 1.0 ms (dashed lines), and 2.0 ms (dotted lines). A simple model featuring a 20 m thick horizontal overburden layer over a highly resistive ($10^4$ Ω•m) half-space was analyzed. Plotted are the results for overburden resistivities of 5 (orange), 50 (blue) and 500 (purple) Ω•m. Red line indicates modelled noise level for the system.

small current induces a weak response. A current of 100 A was chosen as a compromise. The actual turn-off time of the system is a function of the physical characteristics of the transmitter. It is not known at present and will need to be measured experimentally.

Optimization of the maximum duty time (Figure 4) was conducted in order to achieve a balance between target response and signal repetition. Studies have shown that by increasing the maximum duty time of the transmitted waveform a higher amplitude response can be obtained from a conductive body (Becker et al., 1984). Conversely, if the target is not as conductive as an ore body, such as


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lacustrine clay, then the EM system does not require a large maximum duty time. The objective then is to increase the response of the target while maintaining a high repetition of soundings to increase the signal to noise ratio through stacking over the sampling distance.

Responses were calculated using AirBeo for a square 100 A waveform with maximum duty times of 0, 0.5, 1.0, and 2.0 ms and a simple model composed of a 20 m thick horizontal layer over a resistive half-space. The response was calculated over a range of overburden resistivities from 5 Ω•m to 500 Ω•m. Figure 4 shows that the maximum duty times of 0.5, 1.0 and 2.0 ms correspond to very similar decay curves, typically half a decade stronger that those associated with a 0 ms maximum duty time. The optimal choice is therefore 0.5 ms which energizes thoroughly the overburden while allowing for a higher sounding frequency. For example, an on-time of 0.8 ms (a ramp-up time of 0.3 ms followed by a duty time of 0.5 ms) and an off-time of 3 ms correspond to a sounding frequency of 250 Hz. A higher sounding frequency will not only lead to a higher signal to noise ratio through stacking, but will also provide increased versatility by alternating this transmitter waveform with other signals optimized for a deeper and/or more conductive target. This is the approach implemented in the SKYTEM system (e.g. Sorensen and Auken, 2004).

Acquisition will be conducted at the maximum sample rate allowed by the receiver (2 µs) during the transmitter off-time for a period of about 3 ms to ensure a complete capture of the overburden response. The sampled data can then be averaged into logarithmic gates to increase the signal to noise ratio.

Table 1 summarizes several parameters of the HTEM system under development.

**Overburden detectability study**

The next step in the study involved modelling the response of the HTEM system under development and inverting the results to check if the system could resolve overburden thickness and intra-overburden layering. The study was first performed with noise-free data, followed by data with different levels of Gaussian noise.

The scenarios (Figure 5) investigated included 2-layer, 3-layer, and 4-layer geological models. All of the models assumed that the glaciolacustrine sediment was deposited horizontally. The resistivities and thicknesses used (Figure 5) are based on the results of surveys conducted by the Geological Survey of Canada (GSC) near the town of Val Gagné, Ontario, in the Abitibi mining region. Ground-based horizontal-loop EM results conducted over boreholes during the surveys determined that the clay, sand, and till

| **HTEM System Specifications** | | | |
|---|---|---|---|
| | | **Waveform** | |
| Nominal altitude | 30 m | Shape | Square |
| Cable length | 30 m | Max duty-time | 0.5 ms |
| | | On-time | 0.8 ms |
| **Transmitter** | | Off-time | 3 ms |
| Type | Horizontal Loop | Sounding time | 4 ms |
| Tx moment | 15400 Am$^2$ | Frequency | 250 Hz |
| Tx current | 100 A | **Receiver** | |
| Tx turns | 1 turn | Vertical component, Horizontal Loop | |
| Tx radius | 7 m | Rx radius | 0.6 m |
| | | Sampling rate | 2 µs |

Table 1: Some parameters from an HTEM system designed to measure the depth to bedrock.

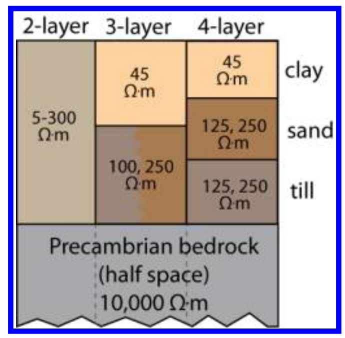


Figure 5: Subsurface models based on the geology of the Abitibi mining region. Glaciolacustrine sediment is typically deposited with till as the base followed by sand and/or clay.

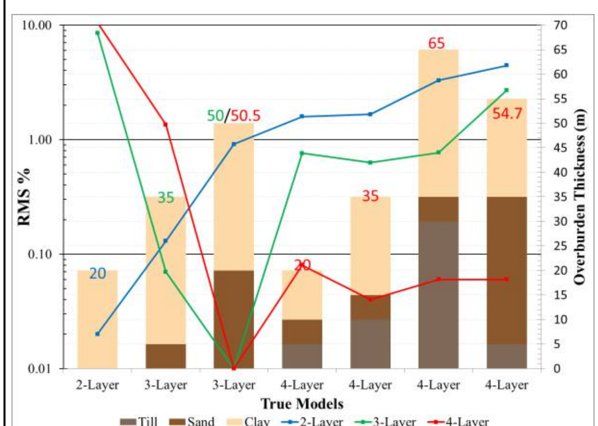


Figure 6: Inversion of noise-free data for 2-4 layer models. Half-space representing the bedrock is not shown. The mean absolute percentage error (RMS%) is plotted on a logarithmic scale in order to illustrate its wide range. A RMS% below 0.1 (black solid line) is considered a good fit. The inversion result, total depth to bedrock, is the number above each column. Colour corresponds to the result with the lowest RMS%. Inversions are a perfect match except for the far right 4-layer case (off by 0.3 m from 55 m), and the 4-layer inversion of the right-most 3-layer case (off by 0.5 m from 50 m).



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have an average resistivity of 47.3 ± 6.7 Ω•m, 251 ± 70 Ω•m, and 123 ± 35 Ω•m, respectively (Palacky, 1992). Lab tests of samples collected from nearby boreholes returned slightly different values for clay at 28.4 ± 9.8 Ω•m and till at 83.1 ± 26.8 Ω•m (Palacky and Stephens, 1990). The resistivity of the bedrock was kept constant at 10,000 Ω•m as work published by Palacky and Stephens (1990) showed that this resistivity is high enough to make any contribution from the basement to the response negligible.

Noise-free forward modelling and inversion were conducted using AirBeo. The process begins with the simplest 2-layer case. The inversion returns thickness $\mathbf{h_1}$ and resistivity $\boldsymbol{\rho_1}$ of the shallowest layer. The goodness of fit is expressed as the root mean square of the symmetric mean absolute percentage error (RMS %). If this parameter is less than 0.1 %, indicative of a good fit, then the process continues to the inversion of a 3-layer case where the starting model has a thickness $\mathbf{h_1}$ and resistivity $\boldsymbol{\rho_1}$ for its first layer adopted from the previous 2-layer inversion. The second layer $\mathbf{h_2}$ has loose constraints of a thickness of 5-40 m, and a loose constraint on the resistivity of 100-300 Ω•m. In the event that the 3-layer inversion has a RMS% below 0.1%, a 4-layer inversion is conducted using a starting model that features a first layer thickness $\mathbf{h_1}$ and resistivity $\boldsymbol{\rho_1}$. Loose constraints on $\mathbf{h_2}$, $\boldsymbol{\rho_2}$ and $\boldsymbol{\rho_3}$ are 5-40 m, 200-300 Ω•m, and 100-200 Ω•m respectively. The $\mathbf{h_3}$ constraints are identical to $\mathbf{h_2}$.

Forward modelling and inversion of noisy data were also conducted using AirBeo. Different sources of noise were added to the EM responses following the method outlined in Auken et al. (2008) which models the effect of different sources of noise as they affect the early, middle, and late decay measurements. Gaussian white noise with a mean of 0 and a standard deviation of 1 was added to model sferic sources of noise. A db/dt uniform noise of 2% was added to model instrument and other non-specified sources of noise along with an additional term that models radio transmitter noise and other background sources of noise (Auken et al., 2008).

The inversion methodology is the same as outlined for the noise-free inversion. A typical RMS % is now approximately less than 1% for a 2-layer case, 1.5% for a 3-layer case, and 1.5-2.3% for a 4-layer case. Several examples are shown in Figure 7 where the largest discrepancy between the model and the inversion occurs in the far-right 4-layer case. The RMS % match is 2.28, which results in a difference of 4.4 m in the overall overburden thickness. This is a 7.4 % mismatch between the inversion and the model.

A transmitter current of 60 A would provide better resolution in the near-surface (< 5 m), by collecting data at

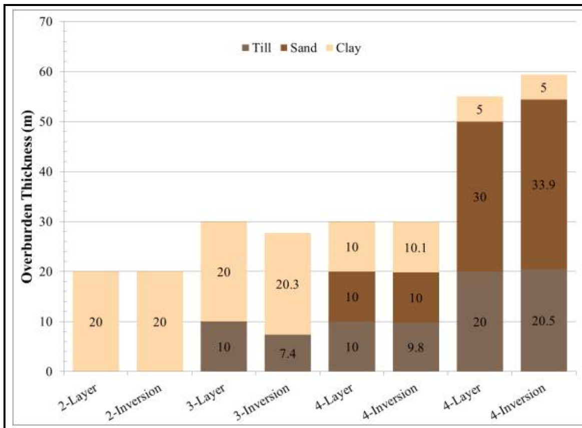


Figure 7: Inversion of noisy data for several 2-layer, 3-layer, and 4-layer scenarios. The half-space representing the bedrock is not shown. Despite noise added to the responses, the inversions are still able to identify the thickness and conductivity of individual layers as well as the overall depth to the bedrock.

an earlier time, but would also result in a larger loss of data from sources of noise, while a 200 A current would result in a loss of resolution in the near-surface but provide better results with regard to deeper responses.

## Conclusion

Two key parameters – transmitter moment and maximum duty time – of a new HTEM system being designed to measure the thickness of a glaciolacustrine overburden over a Precambrian bedrock have been investigated in this study. A transmitter moment of 100 A and maximum duty time of 0.5 ms have been found to be a good compromise between generating enough energy to probe the complete thickness of the overburden while allowing very early time responses to be recorded and providing a high sounding frequency.

The EM responses of a hypothetical HTEM system with these characteristics have been modelled and inverted with and without noise to evaluate its performance to detect the overall overburden thickness and the presence of layers of clay, sand and till within the overburden. For simple 1D models including up to 4 layers, results have shown that the system is able to measure the thickness of a glaciolacustrine overburden within 10% of the modelled response with noise added. These encouraging results should be considered as first-order crude estimates. Several factors, such as complex geology, time-varying noise, irregularities in flight path, will complicate data inversion in practice. They will need to be revisited as the system undergoes its first flight tests.



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**EDITED REFERENCES**

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**REFERENCES**

Auken, E., A. V. Christiansen, L. H. Jacobsen, and K. I. Sorensen, 2008, A resolution study of buried valleys using laterally constrained inversion of TEM Data: Journal of Applied Geophysics, **65**, no., 1, 10–20.

Becker, A., R. DeCarle, and P. G. Lazenby, 1984, Simplified prediction of transient electromagnetic response: Geophysics, **49**, 913–917.

Chen, J., and J. C. Macnae, 1997, Terrain corrections are critical for airborne gravity gradiometer data: Exploration Geophysics, **28**, no. 2, 21–25.

Chen, J., and A. Raiche, 1998, Inverting AEM data using a damped Eigen parameter method: Exploration Geophysics, **29**, no. 2, 128–132.

Lui, G., 1998, Effect of transmitter current waveform on airborne TEM response: Exploration Geophysics, **29**, no. 2, 35–41.

Meyers, J. B., L. Worrall, R. Lane, and B. Bell, 2001, Exploring through cover — The integrated interpretation of high-resolution aeromagnetic, airborne electromagnetic and ground gravity data from the Grant's Patch area, Eastern Goldfields Province, Archean Yilgarn Craton: Part C: Combining geophysical methods for a holistic exploration model: Exploration Geophysics, **32**, no. 4, 198–202.

Palacky, G., and L. Stephens, 1990, Mapping of quaternary sediments in northeastern Ontario using ground electromagnetic methods: Geophysics, **55**, 1596–1604.

Palacky, G. J., 1991, Resistivity characteristics of geological targets in electromagnetic methods in applied geophysics: SEG.

Palacky, G. J., 1992, Inversion of horizontal-loop electromagnetic field data: Case histories from Ontario and Northwest territories, Canada: 72nd Annual International Meeting, SEG, Expanded Abstracts, 457–460.

Palacky, G. J., and G. F. West, 1991, Airborne electromagnetic methods in electromagnetic methods in applied geophysics: SEG.

Sorensen, K. I., and E. Auken, 2004, SkyTEM — A new high-resolution helicopter transient electromagnetic system: Exploration Geophysics, **35**, no. 3, 191–199.

Spies, B., and F. Frischknecht, 1991, Electromagnetic sounding in electromagnetic methods in applied geophysics: SEG.