A multiple transmitter and receiver electromagnetic system for improved target detection

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Summary

In inductive electromagnetic (EM) geophysics, repeating measurement stations using multiple transmitter positions and summing these datasets into a single dataset can drastically improve the signal-to-noise (S/N) ratio from targets, especially deeper ones. The manner in which these datasets (one dataset per transmitter location) are summed depends on the target location and orientation. A simple method to estimate the target location and orientation is to compare the summed responses with a lookup table of known locations and orientations. Once the location and orientation is known, a new dataset can be created which will enhance the S/N ratio for that particular target. If multiple large moment transmitters are used (such as airborne transmitters) then S/N ratios significantly larger than large ground horizontal loops are possible. In a test ground time-domain EM survey, 25 transmitter positions were used and the location and orientation of a shallow target could be determined. The resultant summed profile had a larger S/N ratio and, as such, was easier to interpret.

Introduction

With the continual depletion of mineral resources, exploration for deeper ore bodies will be essential in sustaining current production levels. From an electromagnetic geophysical exploration point of view, deeper ore bodies present technical challenges as the response (secondary magnetic fields) of these bodies may be smaller than the background noise levels. The main strategy to overcome this issue has been to use large high powered transmitters with large magnetic moments. These large transmitters increase the depth of penetration by producing larger fields at greater depths (Nabighian and Macnae, 1991). However, the logistical issues associated with using transmitter loops several kilometers in length and transmitters that are very large and cumbersome are often costly (Zhdanov, 2010). Furthermore, even though large transmitter loops will increase the depth of penetration, if the transmitter loop is not positioned properly and the primary field does not couple well to the target, then the secondary fields of the target body may not be adequately increased to allow for an acceptable S/N ratio. It is common practice to move the transmitter loop to one or more other locations to ensure adequate coupling, which can be logistically challenging (Nabighian and Macnae, 1991). In airborne EM, this coupling issue is less prevalent due to the moving transmitter loop but the size of the transmitter, and thus the depth of penetration of the system, is limited as the transmitter loop is restricted by the size and power of the aircraft (Palacky and West, 1991). In both the ground and airborne situation, longer recording times are preferable as the waveform stacking process increases the S/N ratio. However, a longer stacking time results in decreased production in ground surveys (Zhdanov, 2010) and is limited by the speed of the aircraft in airborne surveys.

An alternative strategy, presented in Lymburner and Smith (2012), which aims to address the issues of depth of penetration and good coupling (larger S/N ratios) for deeper ore bodies, is to repeat the profile or grid with many smaller transmitters. The data associated with each transmitter can then be summed into a single profile or grid to produce a large equivalent transmitter moment. Furthermore, by using many transmitter locations, the probability of strong coupling to the target is dramatically increased. The optimal manner in which the data is summed will depend on the target location and orientation and thus, the data can be summed in different ways in order to identify different targets.

In this paper we discuss the summation process of the multiple transmitter data and how it can increase the S/N ratio from deeper targets compared with traditional methods. With synthetic studies, we present a simple imaging procedure which can identify the depth and orientation of the target(s) which then allows for profiles and grids with the largest S/N ratio to be produced. This method is also tested on the field data of Lymburner and Smith (2012) which was collected over a shallow conductor on Wallbridge Mining property in the East range of the Sudbury Basin in Ontario, Canada.

Method

When multiple transmitter locations are used, the responses are generally not combined. Each transmitter will couple differently to the target(s), may possess different information and will have a different S/N ratio. The goal of the method presented here is to sum the different transmitter responses in such a way so as to maximally enhance the response from a certain target in order to achieve a larger S/N ratio. One way of summing the transmitters it to apply weights that are proportional to how well the transmitters coupled to the target (Lymburner and Smith, 2012). In order to calculate the coupling between the transmitter and the target, we use a dipole approximation for both the transmitter and the target. Figure 1 displays the normalized coupling coefficients for vertical dipole transmitters (spaced 50 m apart) and a target

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with varying dip located in the center of the profile at a depth of 500 m. These normalized coefficients seen on the y-axes would be the weighting factors applied to the corresponding data associated with the transmitter at that location. This ensures that the data associated with transmitters that coupled well to the target (high S/N ratio) are enhanced and those that did not couple well (low S/N ratio) are reduced. However, the weights vary for different target locations and orientations, and as such, the target orientation and location must be estimated in order to apply the appropriate weights so as to enhance the response.

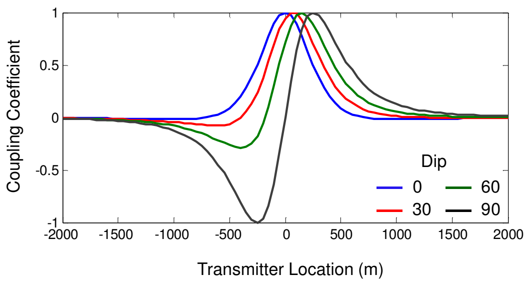

Figure 1. Normalized coupling coefficient between a vertical dipole transmitter and a body (dipole) of varying dip located in the center of the profile at a depth of 500 m.

The proposed method is to assume every possible target location and orientation, and to sum the transmitter datasets for each assumed location/orientation using the dipole coupling coefficients. When the assumed location and orientation matches the actual location and orientation, the summed data will maximally reinforce the signal from that particular target. This can be assessed quantitatively by a comparison of the shape of the profile with the shape from a theoretical body at that location (dipole table look-up). In this paper, the fit is determined using a difference of squares method from Smith and Salem (2007),

$$I_{(\theta,l)} = \left[1 - \frac{\sum\left(M_{(\theta,l)} - L_{(\theta,l)}\right)^2}{\sum\left(L_{(\theta,l)}\right)^2}\right]^2 \qquad (1)$$

where M is the summed transmitter data, L is the dipole look-up data, I is the degree of fit, and the subscripts Θ and l represent the orientation and location of the target, respectively. M and I are normalized to have a maximum amplitude of ± 1 on the profile. I is set to zero when negative. When multiple component data are available, I is the product of the fit for each of the measured components (i.e. for 3-component EM data, $I = I_x I_y I_z$). When the fit, I, is close to unity, there is a high likelihood that there is a target at that particular location (l) and orientation (Θ). From this, a map (or volume) of the likely locations and orientations of the target(s) can be produced. Subsequently, this information can be used to produce a new EM dataset for each identified target by summing the transmitter datasets using the appropriate weighting scheme for a target at a particular location and orientation (i.e. Figure 1). We call this the "optimal sum" as it will optimally enhance the S/N ratio for the desired target. Note that there will be different optimal sums if there are multiple targets (one for each target). These high S/N ratio datasets can then be used for further interpretation and/or improved data display.

Synthetic Example

The described survey methodology and logistics (i.e. repeating profiles with multiple transmitter positions) is best exploited with a hybrid airborne/ground EM system. With a typical airborne EM transmitter and a distributed ground receiver array system (such as the Geoferret distributed system, Golden et al., 2006), the survey time is drastically reduced as there is no moving ground EM transmitter. In the synthetic example, a hybrid airborne/ground frequency domain survey (100 Hz) is simulated in GeoTutor (PeTros EiKon) and, for simplicity, only the quadrature components were considered. The 2 million Am^2 dipole airborne transmitter is at a height of 120 m and the ground receiver stations are spaced every 100 m along a 3 km by 3 km grid. Due to computational limits, the transmitter locations are spaced every 200 m, resulting in a net total of 961 stations for each of the 256 transmitters. The top center of a 100 S plate is located at (0, 0, -500 m). The plate has a strike and dip of 40° and 150°, respectively, and has a strike length and down dip length of 300 m and 150 m, respectively. In addition to the hybrid airborne/ground survey, two other surveys were simulated for comparison purposes: a large horizontal 3 km by 1.5 km loop ground survey (100 million Am^2 moment) and an airborne survey (receiver is towed 130 m behind and 50 m below the airborne transmitter). The background medium was set to a resistivity of 10^8 ohm (essentially free space). Gaussian noise with a mean and standard deviation of 0 pT and 0.1 pT, respectively, was added to each dataset. An aerial view of the survey geometry can be seen in Figure 2.

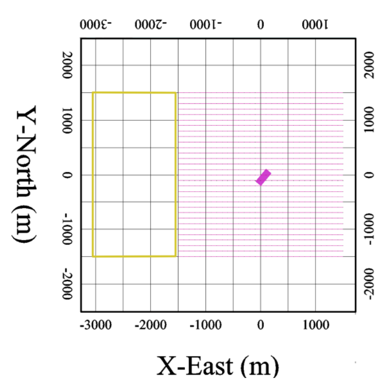

Figure 2. Survey geometry used in the synthetic example (GeoTutor). Yellow line indicates the ground loop, the pink lines represent the airborne transmitters and ground receivers spaced every 200 m and 100 m, respectively, and airborne receivers (70 m above the ground receivers). The purple plate represents the aerial view of the plate conductor.

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The imaging algorithm (equation 1) was run to produce Figure 3 where the color saturation corresponds to the fit value, *I*, scaled to be between 0 and 1 and the hue corresponds to the likely dip or strike (where $I < 0.5$, the color is set to white). As can be seen in Figure 3, the estimated location of the plate matches the actual location and the estimated dip and strike varied from 130° to 150° and from 30° to 60°, respectively. The fit which produced the maximum *I* value corresponded to a dipole at (0, 0, -550) with a dip and strike of 140° and 40°, respectively.

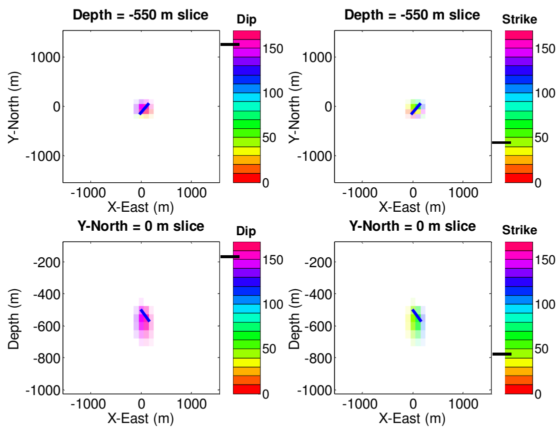

Figure 3. Horizontal slice at depth = -550 m (top row) and vertical slice at Y-North = 0 m (bottom row) with the dip (left column) and strike (right column) calculated using equation 1. The blue line corresponds to the actual location of the target and the black line indicates the color of the actual strike and dip of the target.

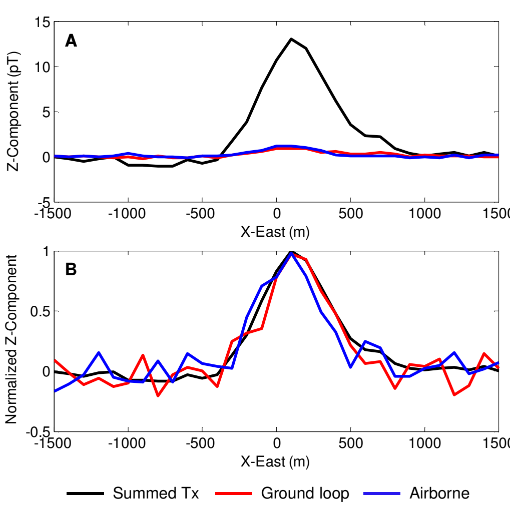

Figure 4. Comparison of the center profile (Y-North = 0 m) of the summed transmitter (black line), ground loop (red line) and airborne survey data (blue line) data. A. Comparison of the amplitudes of the responses. B. Comparison of the S/N ratio (data has been normalized to a max of 1).

As the location and orientation of the plate can now be estimated (maximum *I* value), the data from all of the transmitters can be summed into a single dataset. In Figure 4, the summed transmitter response, the ground horizontal loop and the airborne survey are plotted for comparison. The amplitude of the summed transmitter response is roughly 13 times larger than both the ground and airborne response profiles (Figure 4A). The S/N ratio is 43, 10 and 11 for the summed transmitter, ground loop and airborne data, respectively (best seen in Figure 4B). This example is also a conservative estimate of what the hybrid system could potentially achieve as, with typical aircraft speeds, the equivalent transmitter spacing would be roughly 15 m (as opposed to 200 m which is used in this example). This would have resulted in 24 times the number of transmitter locations which would have resulted in an S/N ratio of approximately 220.

Field example

While the synthetic example uses a hybrid airborne/ground survey, the methodology is general and can also be applied to a purely ground survey. A test time domain EM survey was conducted over a small, thin offset dyke in the North-East range of the Sudbury Basin and is discussed in more detail in Lymburner and Smith (2012). Based on previous geophysics work, drilling and geological information, the target is believed to be at a depth ranging from roughly 70 m to 130 m, trending at an azimuth of 33° and is vertical to subvertical. The test survey was conducted over a 1 km line with a station spacing of 25 m. The transmitters (20000 Am^2 moment), spaced every 25 m, occupied the inner 600 m of the line for a total of 25 transmitter positions. The stations in proximity to the transmitters were corrupted with high noise levels (± 75 m from the transmitter position) and were removed during the data editing stage

As with the synthetic example, a strike/dip display section can be generated using equation 1. Note that since there is only a single line of data, only a 2D depth section under this line can be generated. Due to high noise levels, it was preferable to first to use equation 1 with only the B_y component to find a reasonable range of strikes (30 to 60°) and then to fit the B_z and B_x components together constrained to that strike range (Figure 5). Using this approach, the largest fit value at early time was found at (-10, -100) with a strike and dip of 30° and 90°, respectively, which is consistent with the known information. The removal of stations in close proximity to the transmitter locations has an adverse effect on the methodology as some datasets had up to half of the target's response removed. The summation process (weighted sum of the transmitter datasets) did not take this effect into account and from synthetic studies, it was found that removing stations in a similar fashion produced slightly deeper targets (~20-30 m) with steeper dips (~10°). Had the data not been corrupted, Figure 5 may have suggested a slightly shallower and gentler dipping target. The effect is however not severe and thus Figure 5 is likely an acceptable interpretation.

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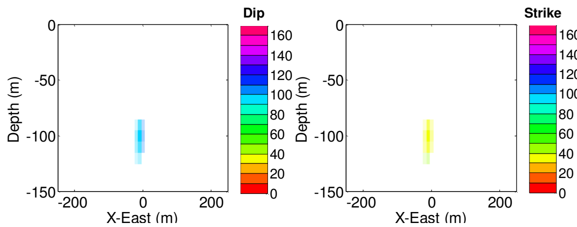

Figure 5. The estimated dip (left column) and strike (right column) using equation 1 on the measured B_z and B_x components at early time (off-time).

As with the synthetic example (Figure 4), once the location of the target is known, the optimally summed profile can be found (Figure 6). For comparison, the well-coupled single transmitter datasets on either side of the target are also shown. The S/N ratio is 250 and an average of 115 for the summed dataset and the two single transmitters, respectively, which is consistent with the findings in the synthetic example. Furthermore, note the difficulty of interpreting the single transmitter data as a large portion of the response was removed due to the high noise close to the transmitter.

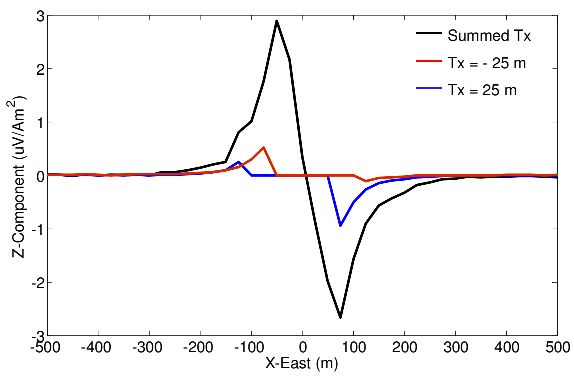

Figure 6. Comparison of the optimally summed transmitter and the single transmitter profiles (located on either side of the target) at an early time window. Note the large portion of removed data over the target response.

Conclusion

Using multiple transmitter locations has the advantage of ensuring adequate coupling between the transmitter and the target(s). Furthermore, if the independent transmitter datasets are summed into a single dataset, the S/N ratio can be drastically increased, allowing for deeper and more focused exploration. However, the optimal manner in which the data is summed depends on the target location and orientation. By assuming every possible target location and orientation, the true location and orientation can be found by calculating the best fitting summed data and look-up data pair. From a synthetic example, we show that this methodology is robust and can adequately locate the target and determine its orientation. Once this is known, the multiple transmitter datasets can be summed into a single large S/N dataset. In a ground time domain EM field test, 25 transmitter positions were used and a shallow target could be identified using the developed methodology. The produced summed dataset was considerably easier to interpret and had a considerably higher signal than any one single transmitter dataset.

This presents an alternative strategy for deeper exploration as rather than using very large magnetic moment ground loops, many smaller moment loops can be used and through summation become significantly larger than any ground loop (as was shown in the synthetic example). Logistically speaking, the optimum way to collect these types of datasets will be with a hybrid ground/airborne system; the ground receivers can be laid out and then an airborne transmitter is flown (or vice versa). One manner in which the amount of data collection can be reduced is through the use of reciprocity. In Lymburner and Smith (2012), it was shown that in the field example presented here, the data could be reduced by 28.75% by applying the principals of reciprocity.

One limitation of the methodology is the dipole approximation for the subsurface target. This approximation is generally adequate for smaller bodies but may produce misleading or incorrect results when this approximation is invalidated. Additionally, one missing piece of information is the conductivity of the target. This can be determined through decay rate analysis in the time domain (inphase/quadrature ratio in the frequency domain) or through various conductivity-depth-imaging algorithms. The high S/N ratio data provided by the developed methodology will improve these and other subsequent interpretation procedures.

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EDITED REFERENCES

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REFERENCES

Golden, H., T. Herbert, and A. Duncan, 2006, GEOFERRET: A new distributed system for deep-probing TEM surveys: 76th Annual International Meeting, SEG, Workshop on Geophysical Methods and Techniques Applied to Uranium Exploration.

Lymburner, J., and R. Smith, 2012, A multiple transmitter/receiver system: The advantage of summing responses from multiple transmitters: 82nd Annual International Meeting, SEG, Expanded Abstracts, http://dx.doi.org/10.1190/segam2012-0276.1.

Nabighian, M. N., and J. C. Macnae, 1991, Time domain electromagnetic prospecting methods, *in* M. N. Nabighian, ed., Electromagnetic methods in applied geophysics, vol. 2: SEG, 427–520.

Palacky, G. J., and G. F. West, 1991, Airborne electromagnetic methods, *in* M. N. Nabighian, ed., Electromagnetic methods in applied geophysics, vol. 2: SEG, 811–879.

Smith, R. S., and A. S. Salem, 2007, A discrete conductor transformation of airborne electromagnetic data: Near Surface Geophysics, **5**, no. 2, 87–95, doi: 10.3997/1873-0604.2006021.

Zhdanov, M. S., 2010, Electromagnetic geophysics: Notes from the past and the road ahead: Geophysics, **75**, no. 5, 75A49–75A66.