Augmenting 1D conductivity depth sections to include information pertaining to 2D/3D conductors

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SUMMARY

Conductivity depth data presentations derived using 1D approximations have become a very popular way to present airborne electromagnetic (AEM) data. While data profiles and a single error limit per station can accompany these presentations there are more information contained in data. This work proposes some ideas for augmenting 1D derived data presentations to highlight two and three-dimensional conductors as well as more detailed error level indication. The 1D conductivity depth algorithm used is an extended version of the S-layer differential transform. The depths calculated with the transform is used also present decay constant values corrected for conductive background responses. Fraser filtered X-component data are used to indicate structural complexity and data fit error levels are used to grey out areas on the depth section presentations where the results are less reliable. To demonstrate these ideas a line of Xcite data over the Abra deposit in Western Australia is analysed. The augmentations add valuable information to the conductivity depth section in the sense of drawing attention the where the 1D assumptions are not valid and should encourage interpreters to pursue 2D or 3D modelling techniques for successfully mapping the ore deposit.

Key words: CDI, inversion, decay constant, Xcite, Abra

INTRODUCTION

AEM surveys have become a standard geophysical tool applied in mineral and groundwater exploration. Parallel processing, cloud computing and hardware improvements greatly benefitted the interpretation of data and inversions (1D, 2D and 3D) are routinely performed on data sets. The layered earth assumption made in the 1D cases are well-known and understood, yet the 1D inversions (and CDI transforms) remain popular because these are still faster than the 2D and 3D options.

At the 7th International Workshop on Airborne Electromagnetics hosted in Denmark (2018) the popularity of conductivity-depth presentations to display AEM data was clearly evident. In some instances, data profiles and error levels were included, but most often only the depth sections were used to present the results of a survey to the audience. It is easy to understand the appeal of condensing AEM data to a single, visually attractive product for peers, colleagues and investors, yet if simplified too much we run the risk of missing valuable information contained in the data.

Firstly, in the case of popular central loop AEM systems, the X-component data are ignored when performing 1D operations as the theoretical response for a layered earth is always zero. Secondly, every conductor is assumed to be infinite in lateral extent, resulting in an inevitable discrimination against small, localized conductors. Apart from ignoring the information that could help define two- and three-dimensional conductors, the 1D layer properties that are calculated will be inherently inaccurate.

In this paper, I used an extended version of the S-layer differential transform to generate a basic 1D conductivity depth section over the Abra (lead-silver, gold-copper) ore deposit in Western Australia (Galena Mining Limited, 2018). I augmented the depth section with decay constant values corrected for overburden response, selected Fraser filtered X-component profiles and error/noise limits and show that these additions provide a better data presentation for highlighting the existence of the ore deposit. While I consider this an improved data presentation, many assumptions remain and true 2D or 3D modelling is still required to map the ore deposit in depth.

METHOD AND RESULTS

Adapted S-layer differential transform

The 1D conductivity-depth algorithm used for the examples in this paper is an adapted version of the S-layer differential transform (Tartaras et al., 2000; Combrinck, 2008). Additions to the transform include deconvolution of the system waveform (Macnae and Lamontagne, 1987; Stolz, and Macnae, 1998) to provide step current approximations for dBz/dt and Bz data, accounting for system filters and using analytical instead of numerical derivative calculations. Figure 1 shows an example of the original and adapted CDIs. The data were acquired over the Abra deposit in Western Australia using the NRG Xcite AEM system in 2017. Both versions of the CDI algorithm indicate a subtle anomaly at the ore deposit location, although it does not get highlighted as the most conductive feature on either of the sections. The adapted transform has much better continuity and detail especially on the shallower part of the section.

Decay constant (tau) depth images

Decay constant (tau) values is a well-known technique for identifying and classifying localized (3D) conductors. I have shown previously (Combrinck and Botha, 2011) that the ratio between Bz and dBz/dt data can be used to calculate the decay constant for a finite conductor using the equations for the late time, current step turn-off response:
\[ B_z = Ae^{-t/\tau} \]  \hspace{1cm} (1)

\[ \frac{\partial B_z}{\partial t} = -\frac{A}{\tau} e^{-t/\tau} \]  \hspace{1cm} (2)

where \( A \) is an amplitude based on the peak current, system and target geometry, \( t \) is time in seconds and \( \tau \) is the conductor decay constant in seconds.

Taking the ratio of equations 1 and 2, gives:

\[ \frac{B_z}{\frac{\partial B_z}{\partial t}} = -\tau \]  \hspace{1cm} (3)

Having applied this technique to AEM data (as with other tau calculations) I observed that the tau values consistently increase with increasing time. This is especially evident when working in a conductive background environment. Three assumptions that are not satisfied when calculating decay constants with this formula are:

• Airborne data rarely has a long enough off-time to be in theoretical late-time for which the equations are derived.
• The system current waveform is not a true step turn-off.
• The measured data is a combination of conductive background and confined conductor response.

The first factor is determined at acquisition and cannot be adjusted for in processing. Point two is addressed by deconvolving the system waveform from data and for point three I propose a correction based on the late-time approximations of a step current halfspace response (Ward and Hohmann, 1988):

\[ B_{z, HS} = \frac{l\sigma^{3/2}\mu_0^{3/2}a^2}{30\pi^{1/2}}t^{-3/2} \]  \hspace{1cm} (4)

\[ \frac{\partial B_{z, HS}}{\partial t} = -\frac{l\sigma^{3/2}\mu_0^{3/2}a^2}{20\pi^{1/2}}t^{-5/2} \]  \hspace{1cm} (5)

where \( l \) is peak current in ampere, \( \mu_0 \) is the magnetic permeability of free space in henry per meter, \( \sigma \) is conductivity of the halfspace in siemens, \( t \) is time in seconds and \( a \) is the radius of the transmitter loop in meters.

Taking the ratio of equations 4 and 5, gives:

\[ \frac{B_{z, HS}}{\frac{\partial B_{z, HS}}{\partial t}} = -\frac{2}{3} \frac{1}{t} \]  \hspace{1cm} (6)

Equation 6 gives an explanation as to why tau values always increase with later times in conductive areas. Aware of the late time and geometry assumptions made in the derivation of these equations, I tested this relationship with Maxwell/Airbeo forward modelling simulating the Xcite system at 30 m instrument height. I modelled halfspace resistivities of 1, 10 and 1000 ohm.m as well as three-layered earth example of 1000, 10 and 1000 ohm.m. The modelling indicated that the slopes are dependent on the conductivity and the earlier times do not show an exact correlation, but there are definite linear trends visible between time and the \( B_z, HS / (dB_z, HS/dt) \) ratios (Figure 2).

![Ratio of Bz to dBz/dt](image)

**Figure 2. Ratio tau values as a function of time calculated with Maxwell/Airbeo for different layered earth models.**

In order to isolate the confined conductor tau values (defined in Equation 3) from the background values, I calculated an average value over the survey area and subtracted that from the ratio tau. Other options would be to fit a straight line, or average stations over areas with similar background signatures, but as this is an anomaly indicator and not intended to be numerically exact, the average is a sufficient approximation as long as it follows the linear background trend.

Once the residual tau values for each channel are calculated, they are linked to approximate depths using the channel-depth correlation found from the adapted S-layer differential transform algorithm. Any depth algorithm based on current distribution with time would suffice, but if it is closely related to the algorithm calculating the conductivity-depths, a better match of the anomalies can be expected.

A plot of tau-depths is shown in Figure 3. The uncorrected values are dominated by the background response, giving consistently higher values with depth. The background corrected, residual values are successful in highlighting the conductive Abra ore deposit and helps to distinguish between conductivities of localized, good conductors versus large, weaker conductors where the 1D depth section does not. My final presentation of residual taus is limited to values higher than 0.1 ms and shown as symbol plots at each channel depth rather than a gridded section (Figure 4). In this way I can overlay the data on the conductivity-depth section and also see on how many channels a tau anomaly is manifested.
X-component data

In order to present near-surface, 2D or 3D conductors I combined X-component data with the depth section. Fraser filtered profiles stacked over five channels are plotted at relative depths for later times. No depth calculations are done, the profiles are simply spaced out over the depth extent of the section. Positive values associated with sub-vertical features are plotted in black and negative values associated with limited extent horizontal features in grey. The Fraser filtered profiles thus give an indication of where vertical structures are mapped and warns of the potential failure of 1D techniques to accurately interpret the data in those locations.

Channel and depth linked error levels

Indicating error levels on depth sections is required to make decisions on the validity of the calculated parameters. The specific implementation will vary depending on the algorithm and how errors are calculated. In the adapted S-layer differential transform I determine an error estimate based on how well the measured data are matched by an approximation of the sum of exponential functions prior to the conductivity-depth conversion. As expected, noisier data will give larger errors.

Proper inversion routines present error values as a misfit between the measured and calculated data, but having only a single number per station reduces confidence in that station at all depths while it may mostly be caused by late time noise and still have high integrity in the shallower part of the model. Having an error estimate that can be linked to different channels or depths, allow us to still have confidence in results unaffected by large misfits at different depths. To integrate this information with the conductivity depth section I propose greying out regions where the misfits exceed a specified limit and where the input data falls below a specified noise level. Where inversion algorithms provide confidence levels on individual layer thicknesses and conductivities it can potentially be displayed in a similar manner.

Figure 4 is an example of the final augmented conductivity depth section. It combines the traditional conductivity-depth information with anomalous residual tau values, near surface structural information and error limits on the conductivity-depth values. Compared with the section shown in figure 1, the Abra ore deposit is highlighted more effectively, the noise levels indicate that while we are on the edge of detectability the anomaly is validated on at least five channels, and the lack of near-surface x-component signal indicates that the conductor is located at depth and not an artefact of near-surface interference. Note that the actual depth and conductivity is still undetermined. The result of data presentation is to highlight areas where 1D assumptions are not valid and encourage more suited modelling to properly define three-dimensional conductors.

CONCLUSIONS

Combining 1D conductivity-depth sections with decay constants, depth-based error limits and often neglected x-component data in a single image allows the user to present a more complete view of AEM data than a 1D conductivity-depth image alone. Augmented sections have the potential to highlight small, localized conductors, near-surface structural contributions and areas where the 1D assumption fails. Having this information allows us to make more informed, and justifiable decisions on when and where to implement the more extensive two- and three-dimensional interpretation methods.

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REFERENCES


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Figure 1. Standard (top) and adapted (bottom) S-layer differential transform CDI. The Abra ore deposit location is indicated with black arrows.

Figure 3. Tau values at channel S-layer depths, calculated from $B_Z$ to $dB_z/dt$ ratio (top) and with mean channel values removed (bottom) to compensate for layered earth response.
Figure 4. Tau values larger than 0.1 ms at channel S-layer depths as well as three dBx/dt stacked Fraser filtered profiles overlain on the basic conductivity depth section. The stacked Fraser filtered profiles are presented in black for positive values and grey for negative values and plotted at arbitrary intervals increasing with time, not calculated depths. The conductivity depth section is greyed out where errors exceed 20 % or input data values fall below the noise level of 0.01 pV/(Am^4).