Adaptive width filters for GEOTEM data.

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The measured signal from the GEOTEM airborne electromagnetic system (Annan and Lockwood, 1991; Annan et al, 1996) is a mixture of signal from conductive ground and noise. The noise is typically comprised of electronic noise, sensor noise, noise associated with the motion of the sensor in the earth's magnetic field, lightning discharges (spherics) and aircraft response to the transmitted pulse.

The noise from the aircraft response and the long wavelength coil movement are removed during the primary field compensation procedure (Annan, 1984; Smith, 2001). The large amplitude spheric noise is characterized as large one or two sample wide spikes and are removed by two separate non-linear filtering programs *SFERIC & SFERICFX* (O'Connell, 1985) that were designed solely for this purpose. The signature of the high frequency sensor motion noise is a series of low amplitude peaks and troughs that correlate with data from other coil orientations. This type of noise is removed by another specialty program, *GTMROCK*. Results from this algorithm are presented in Smith and Annan (1997).

The sources of the residual noise are now mainly due to low amplitude spherics, electronic sensor noise and small residuals after the original noise was imperfectly removed by the above procedures. This noise can have a range of wavelengths that span from 30 to 300+ metres and appear as a "hash" mixed with the ground response. Unfortunately, the longer wavelength hash overlaps with the wavelengths of the narrow near-surface geological anomalies that can be associated with zones of mineralization.

The GEOTEM ground response varies from about 150 metres (for the width of the near-surface anomalies) to several kilometers for layered-earth geology. This overlap precludes using frequency domain low-pass filters or fixed-width spatial domain filters (such as Hanning, running average etc.) as a single width of filter will not be successful at treating all the noise over the entire profile. Figure 1 is a typical trace of channel 9 data from the GEOTEM system after processing to remove the large spheric noise spikes and high frequency coil oscillations. The trace suggests four geological features. A, B and D could be attributed to changes in a stratified structure; feature C is one or two narrow conductive bodies that may be fault controlled. Figures 2 and 3 show the effects of two filters passed over the data from the trace in Figure 1. The upper trace in Figure 2 is the data after smoothing by a small three point triangular filter (Guillon and Naudy, 1981). The filter was able to improve the smoothness at C and keep the proper definition of the two peaks and the three troughs. It was also able to keep the definition of the shoulder at B. However, the filter did minimal smoothing over the rest of the profile as is evident in the lower trace of Figure 2, that is the 3 point filtered data minus the raw data. The upper trace in Figure 3 comes from a twenty-seven point triangular filter that was used to smooth the data. The filter does an excellent job at A and D, while at B the results are marginally acceptable. The filter has done a poor job at C, reducing the two peaks and the three troughs to a single broad peak. Again, this is evident in the lower profile of Figure 3 that is the filtered data minus the raw. The signal from the peaks at C can be seen to clearly leak through into the difference trace.

It is possible to generate various sets of traces by using different filter widths but no single data set would be adequate for all purposes. The required filter must give an almost hand-drawn look to the filtered trace. The algorithm in *ADPTFLT* functions by using a lower and an upper limit to the length of the filter. The program selects the width of the filter to give the best or “optimal” smoothing. It operates by first filtering the data with the widest filter and then by computing a smooth second difference of the profile. The smooth computed second difference is defined as:

$$\Delta_2(j) = \frac{2}{W_U - 1} \sum_{i=1}^{(W_u - 1)/2} 2d(j) - d(j+i) - d(j-i) \qquad (1)$$

Where W_U = Upper filter width, in samples
$d(j)$ = The j-th smoothed data value.
$\Delta_2(j)$ = The j-th smoothed computed second difference

This gives an estimate of the rate of change of the local gradients that reflect the amount of the variation in the ground response in the data. The absolute value of the second difference is at its maximum directly over narrow peaks/troughs and is essentially zero over broad, flat gradient zones. From the local value of the second difference, the program converts it to a filter width using a linear relationship between the lower and upper widths:

$$W_O(j) = W_U - (W_U - W_L)\left(\frac{|\Delta_2(j)|}{\Delta_T} - \frac{1}{2}\right) \qquad (2)$$

Where W_L = Lower filter width, in samples
Δ_T = Second difference threshold
W_O = The j-th optimal filter width.

The equation has a built-in-bias of -1/2 to produce wider filters than would otherwise be computed. The calculated filter width is bounded to be within the range of lower to upper filter widths.

The lower filter width, W_L is selected by determining the width of the filter that best preserves the amplitudes of the peaks and troughs of near-surface responses with adequate smoothing at location C. The value W_L is usually three for potentially rapidly varying data such as GEOTEM. The upper filter width, W_U, is selected by determining which filter gives the best smoothing at locations A and D.

The selection of the second difference threshold, Δ_T, is more difficult. If Δ_T is too small (eg. Δ_T =100), then the computed filter widths would be too narrow to properly smooth the flatter regions A, B and D but the performance would be adequate at C. When Δ_T is too large (eg. Δ_T =12000), then the computed widths would now be too wide. Locations A and D would be fine but B would be marginal and C would be too smooth as some of signal from C would be removed.

The program, *ADPTFLT*, will compute an estimate of Δ_T when the user has to filter data with new noise characteristics. The program iteratively adjusts the estimate of Δ_T to an "optimal" value, defined such that the average filter length used to smooth the data, is:

$$W_{AVE} = \frac{W_U + W_L}{2} \tag{3}$$

The results in Figure 4 were obtained using the program-estimated value of Δ_T =1152 and are overlain on top of the raw data for comparison purposes. The results are clearly superior to fixed-width filters. The locations at A, B and D are properly smoothed. The smoothed profile follows the original raw data quite accurately. The peak/trough amplitudes at C are fully preserved. This preservation permits useful data inversions for such products as layered earth (CDT's) and finite conductors (plate/sphere models), all using the same data input. The lower trace in Figure 4 is the optimally smoothed data minus the raw data. This trace does not contain any signal leaked from the surface conductors nor does it have any signs of distortion being introduced in the final results. The "optimal" value that is computed by *ADPTFLT*, may not necessarily the best estimate of Δ_T for all data profiles. The present data example might be better with a Δ_T that would produce smoother data as the majority of the data are from the layered structure. Figure 5 shows the width of the smoothing filter used at each point along the profile. The narrowest filter widths are at location C and the widest widths are to the right of A where the data have zero gradients. The algorithm will switch to wide filters on the sides of steep gradients as the second difference there is essentially zero and the data still requires a wide filter to properly smooth them.

This filter is simple and robust. The lower and upper limits of the algorithm are easily found by using a simple filtering program or by merely defining the values from theoretical consideration. Its results do closely match that of a hand-drawn profile. It is possible to use other filters such as a Hanning or a running average rather than the triangular filters demonstrated above.

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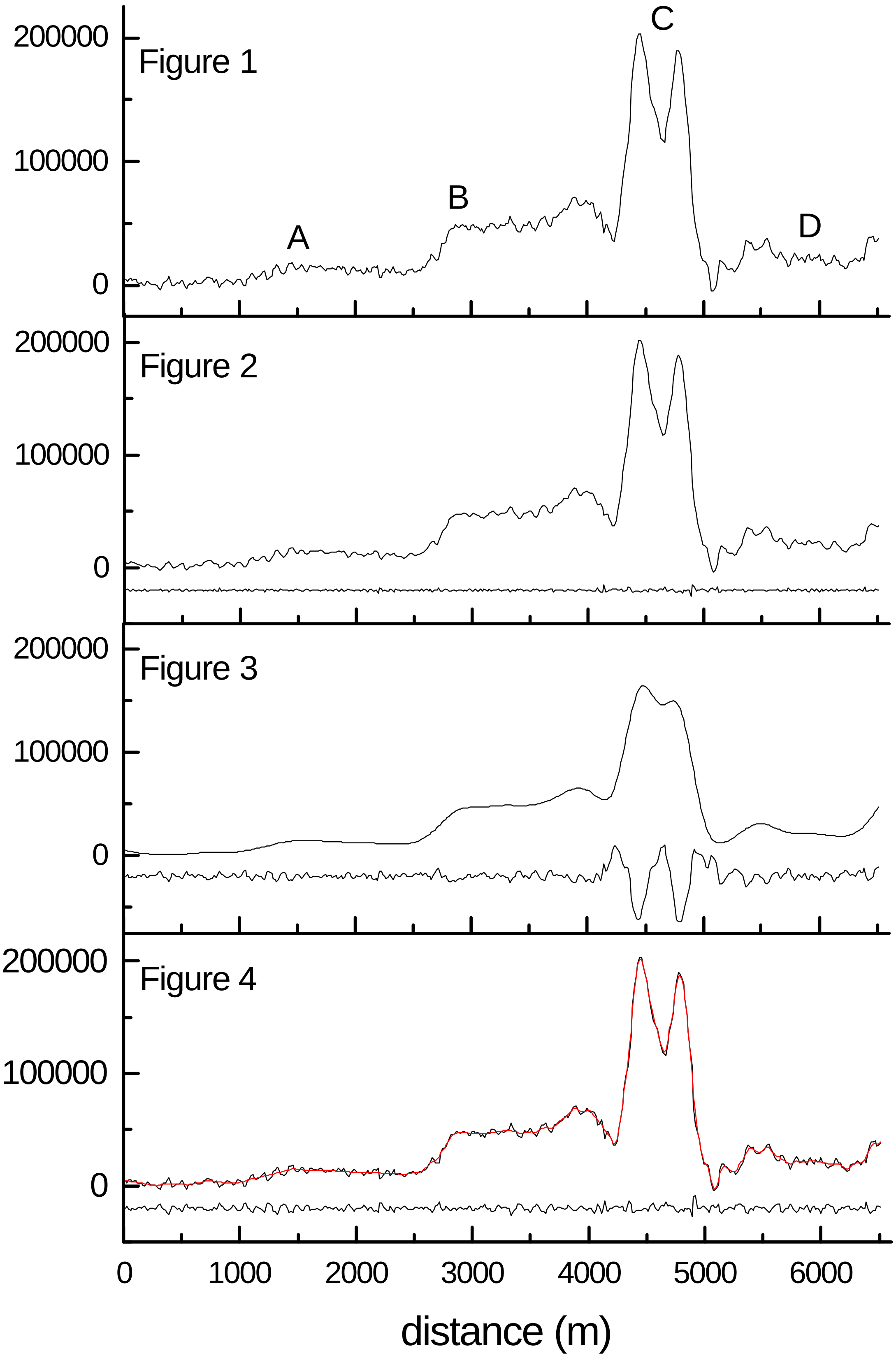
Figure 1
Figure 2
Figure 3
Figure 4
A
B
C
D
200000
100000
0
0
1000
2000
3000
4000
5000
6000
distance (m)

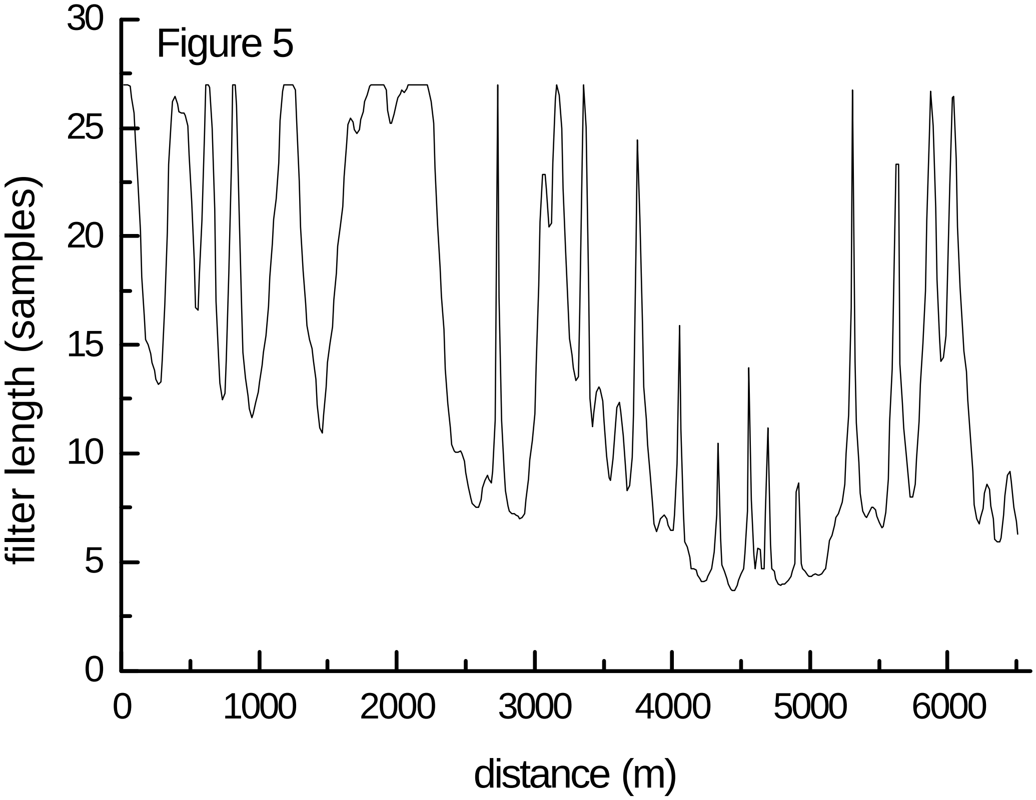
Figure 5
filter length (samples)
30
25
20
15
10
5
0
0
1000
2000
3000
4000
5000
6000
distance (m)