LOTEM data processing for areas with high cultural noise levels

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Long Offset Transient Electromagnetic (LOTEM) soundings conducted in industrialized areas demand complex approaches to data processing for the removal of unwanted cultural noise. When sporadic, aperiodic noise (from pumps, electric fences, etc.) or periodic noise from power lines is present, as is the case in the F.R.G., standard data processing commonly applied to modern transients which are contaminated by the noise influence, and any processing done after stacking usually fail to improve the data resolution.

A new approach to the problem of periodic noise is to process each individual transient before averaging, which greatly improves the signal-to-noise ratio and provides a more detailed geoelectric image of the subsurface. An improved prestack, digital-recursive, time-amplitude model filter is applied to synthetic and real data. Sporadic noise is best handled with either a symmetric or antisymmetric inversion filter stack, whereas the signal amplitudes are selectively kept and the noise is statistically rejected. Data show that for LOTEM soundings the symmetry inversion algorithms improve the signal-to-noise ratio significantly.

After selective stacking, the system response is deconvolved and the data smoothed with digital recursive filters. The output transients are then converted to apparent resistivities and inverted to a horizontally layered Earth model. A comparison of prestack and poststack data processing for one profile shows that with prestack data processing the section correlates well with the known geology of the area, whereas poststack processing aspires an interpreted geoelectric section that is inconsistent with the geology.

1. Introduction

Long Offset Transient Electromagnetic (LOTEM) sounding (Sheriff, 1984) is a special type of Time-Domain Electromagnetic (TDEM) sounding where the offset between transmitter and receiver is approximately equal to or greater than the sounding depth, which depends on the resistivity-depth profile and the signal-to-noise ratio. The field set-up shown in Fig. 1 consists of a grounded wire transmitter — 1-2 km in length which represents a grounded dipole, and an induction loop receiver which records the temporal changes of the vertical magnetic field. The transmitter is kept fixed whereas the receiver may be moved about the survey area. Source-to-receiver offsets range between 4 and 20 km. A d.c. current of several hundred amperes is injected into the grounded dipole and abruptly reversed, inducing eddy currents which propagate downward and outward with increasing time. The resulting sec-
data, there is almost no visible difference between the filtered signal and the input synthetic signal without noise.

The left side of Fig. 4 shows a typical single transient of average quality from a test area in the F.R.G., contaminated by periodic 161 Hz railway noise. The right side of Fig. 4 shows the same transient after applying the digital recursive notch filter prestack. The signal information can now be clearly seen.

When this filter is applied prestack, there is almost no amplitude distortion and the periodic noise is clearly filtered out. Since the 161 Hz noise in Germany is not phase-stable over a long period of time, stacking smears the power line frequency and a digital notch filter applied poststack cannot eliminate all the noise. Therefore the filter must be applied before stacking. If the filtered transient is still strongly distorted, it may then be edited out.

2.3. Sporadic noise—selective stacking

Sporadic noise may be caused by many different cultural sources such as water pumps, electric fences, trains, factories, and/or vehicles passing by the receiver. Once this noise has been recorded and not recognized, it can severely distort the stacked results since its amplitude is either far above or far below the signal level. When acquiring transients with a short rise time, it is also difficult to integrate a spike detector in either analog or digital form.

A safe approach to eliminating this kind of noise by data processing is to consider the statistics of all signals and analyze their corresponding amplitude distributions, both of which becomes increasingly important when there are only a few transients and the sporadic noise is not cancelled in the stacking process. Here we discuss two selective stacking techniques which use different rejection criteria to suppress sporadic noise: symmetric and area-defined rejection. The symmetric selective stack, also known as alpha-trimmed mean (Watt and Bednarz, 1981; Naess and Bruland, 1985), is less frequently used because of computational expense.

The first step in both selective stacking schemes is to sort the data amplitudes in ascending order from all transients, at each time sample. Then, for the symmetric rejection, a determined percentage of the total number of transients is symmetrically rejected from both ends of the sorted amplitudes. From the remaining percentage of data, a preliminary amplitude average and standard deviation are calculated (Skoger, 1981). Those data points from the field data which lie within the standard deviation of the preliminary average are kept. This procedure is very robust with respect to changes in the symmetric cut-off percentage, which may be varied over a wide range (between 10 and 40%) where the low- and high-amplitude noise are removed.

For the area-defined rejection, amplitude frequency distributions are calculated by sliding overlapping windows over the sorted amplitude curves for each time sample of all transients. With this kind of rejection criterion, a percentage of the area under each distribution curve symmetric about the maximum is calculated, and all data points that fall within this area are kept.

An example of 20 individual transients distorted by sporadic noise is given in Fig. 5. These data build the database for the results shown in Fig. 6. The upper transient of Fig. 6 is the output of a straight average summation which did not cancel out the high- and low-energy noise. After calculating a preliminary amplitude average and standard deviation from all the field data, the data lying within two standard deviations of the average were then stacked. The lower transient of Fig. 6 is the result of this procedure. The high- and low-energy noise is now reduced and the signal-to-noise ratio improved.

Figure 7 shows a selectively stacked transient based on the symmetric rejection criterion, using a 20% cut-off at both ends of the amplitude distribution. The plots on the right show two examples of amplitude distributions for different samples. This transient displays an even higher signal-to-

![Fig. 4](image-url)  
Fig. 4. Digital recursive, time-amplitude, notch filter applied to transient data. The left curve shows the original field data and at the right the same data after filtering.

![Fig. 5](image-url)  
Fig. 5. Ten raw transients from the F.R.G. distorted by sporadic noise.

![Fig. 6](image-url)  
Fig. 6. Upper transient is the result of a straight average summation with poor signal-to-noise ratio. This stacking technique is improved by eliminating all amplitudes outside two standard deviations of the average from the selective stack as shown in the lower transient.

![Fig. 7](image-url)  
Fig. 7. Stacked data using the symmetric rejection selective stack technique with a cut-off of 20% at both ends of the sorted amplitudes. The shaded areas represent the amplitudes which are kept; all others are rejected.
ordinary field of induced currents is measured as a transient at the Earth's surface.

Depending upon signal-to-noise ratios, anywhere between 50 and 300 transients are digitally recorded and stored as time series at one receiver station. Because of the large quantity of raw data (10-50 MB/day), a ruggedized, desk-top-operated, digital data acquisition system is used which incorporates a 50 MB Winchester hard disc. It is essential that the data acquisition system be battery operated in order to reduce instrument noise.

2. Data processing

The LOTEM data-processing sequence shown in Fig. 2 consists of many different modules which may be applied before and after stacking. Most of these processing steps are now standardized (Steyer, 1981; Strack, 1984, 1985). Here we would like to discuss two new data-processing techniques which assist in removing the problem of periodic and sporadic noise, respectively: the improved, prestack digital recursive filter and the selective stack.

2.1. Periodic noise—prestack, digital recursive, true amplitude notch filter

The advantage of digital recursive filters is their small number of coefficients and thus speed in computation. Standard digital recursive filters (Shanks, 1977; Kuhlman, 1984) however, are not acceptable for processing LOTEM sounding data because they attenuate the signal amplitudes by at least several per cent. With the improved prestack filter, amplitude attenuation is eliminated when the position of the poles is chosen such that

\[
\frac{|Z_0 - 1|}{|Z_0 + 1|} = \frac{|Z_1 - 1|}{|Z_1 + 1|}
\]

(1)

yielding a recursion formula in the z-plane

\[
F(z) = \frac{Y(z)}{X(z)} = \frac{\eta (z - z_1)(z - z_2)}{(z - z_0)(z - z_2)}
\]

\[
= \eta \left( \frac{z^2 - 2a z + 1}{z^2 - 2a z + (2\eta - 1)} \right)
\]

(2a)

where

\[
Z_0 - 1 = \eta
\]

\[
Z_1 - 1 = \eta
\]

\[
a = \frac{2 \eta}{\eta - 1} - (1 - x^2)
\]

(2b)

(2c)

\(F(z)\) is the filter function given by the ratio of the output function, \(Y(z)\), and the input function, \(X(z)\); and \(z_0\) and \(z_2\) are the positions of the zero and poles respectively; \(\eta\) is the proportionality factor which combines the real part of the pole, \(x\), with the real part of the zero, \(a\); and \(y\) is the imaginary part of the pole. To eliminate phase shifts the recursive filter is applied twice to the data: first in the forward, and then in the reverse direction.

In Fig. 3a-c, this recursive true amplitude notch filter has been applied to three different sets of synthetic data. For all curves in Fig. 3a-c, the superimposed solid line is the noise-free synthetic input signal. The top curves in Fig. 3a-c show this synthetic signal plus a 16 Hz periodic noise which is characteristic of the German railway. The middle curves in Fig. 3a-c have been filtered with a bandwidth (see eqn. 2a) of \(\eta = 1.02\), whereas the bottom curves have been filtered with a bandwidth of \(\eta = 1.08\).

For Fig. 3a, the synthetic signal is a sinusoid which starts abruptly and ends with a step. The filtered curves show that owing to the modest slope at the start of the sinusoid there are only minimal ringing effects. Ringing does occur at the step discontinuity, due to the Gibbs' phenomenon.

The ringing at the onset of the time series becomes less with increasing bandwidth and, at the step, the ringing becomes greater with increasing filter bandwidth. In this example, there is almost no amplitude distortion.

The synthetic input signal of Fig. 3b represents an ideal transient where the signal rises instantaneously to its maximum. As with the step discontinuity in Fig. 3a, the Gibbs' phenomenon causes ringing at the onset of the transient. The filtered sinusoids also show the same correlation of bandwidth to ringing as those in Fig. 3a. Again, there is no or minimal distortion.

Figure 3c shows a realistic transient obtained from convolving the synthetic input curve of Fig. 3b with the impulse response of the receiver and the transmitter current wave form from our field system. The ringing due to filtering at the rise of the transient is much less than in Fig. 3b since there is no longer a step discontinuity. For these
noise ratio than that shown at the bottom of Fig. 6. Similar results are obtained using the area-defined rejection selective stack with 60% of the area, as shown in Fig. 8. Amplitude frequency distribution curves are shown at the right, where the shaded part of the curve is 60% of the area kept.

Figures 6–8 show that both the symmetric rejection and the area-defined rejection selective stack significantly improve the signal-to-noise ratio compared with the summation process, which eliminated all data lying outside two standard deviations of the average. This is because the average is already corrupted by the outlying sporadic noise amplitudes which, for the selective stacking schemes, are rejected before the average is calculated. For LODEM soundings, our experience has been that the symmetric rejection stack gives us the best signal-to-noise ratios for the data from most survey areas.

2.3. Poststack data processing

After stacking the data, the transients are smoothed before deriving the output apparent resistivity curves. These processing steps include the deconvolution of the system response which accounts for the transmitter ramp and analog filters (Strack, 1985), and digital smoothing under the assumption that at early times the signal contains predominantly high frequencies and at late times mainly low frequencies. Based on this assumption, many different digital recursive smoothing filters can be developed using standard pole-zero filter design techniques (Shanks, 1967; Stoyan and Strack, 1984). To date, a new smoothing filter has been designed for almost every survey conducted in the F.R.G.

The transients are then converted to early- and late-time apparent resistivity curves using the early- and late-time apparent resistivity formulae (Kaufmann and Keller, 1983)

\[ \rho_{ST} = \frac{2\rho_{1}^{2}}{M_{0}y} \frac{V(r)}{t} \]

\[ \rho_{LT} = \frac{M_{3}y}{4\pi y} \frac{V(r)}{t} \]

(3)

where \( \rho_{ST} \) is early-time apparent resistivity, \( \rho_{LT} \) is late-time apparent resistivity, \( M_{0} \) is the dipole moment (which equals the source current multiplied by the transmitter length), \( t \) is the receiver area, \( y \) and \( r \) are the coordinates of the receiver, \( V(r) \) is the measured voltage at the receiver.

An example output apparent resistivity curve is displayed in Fig. 9. The lower curve represents the early-time and the upper the late-time apparent resistivity curve. The vertical bars are the standard errors of the measurements obtained from the selective stacking algorithm. These errors are also used as filter weights for an interactive inversion scheme which uses the early- and late-time apparent resistivities as input (Vincent and Jupp, 1978; Stoyan, 1980). The results of interactive inversion are the resistivities and thicknesses of a horizontally layered earth model, as shown on the right side of Fig. 9. The inversion results are then used to generate geoelectric depth sections.

2.4. Comparison of poststack and prestack data processing

To compare the effect of poststack and prestack data processing on the final averaged transients and corresponding apparent resistivity...
curves, one typical station for the F.R.O. was selected which contained only 36 Hz periodic noise. In this case, the raw data are still visible in the noisy signals. First, the data were selectively stacked without any other data processing, as shown in the upper curve of Fig. 16, a by-pass stack of ~100 raw transients. Then the data were filtered with the digital recursive notch filter, but not true amplitude, using algorithms from Shanks (1967) and Stoeye (1981) (centre curve of Fig. 16). The output transient contains lower noise frequencies than 161 Hz. This is caused by the summation of noise and signal which are not phase-locked onto each other. The bottom curve in Fig. 10 is the selective stack output of data filtered with the digital recursive filter described in this paper. Note that it contains much less high-frequency noise than the poststack filtered curve. Thus the filter adequately removed unwanted periodic noise prestack and the summation then stacked out any extraneous sporadic noise.

The Fig. 11 apparent resistivity curves were obtained by converting the voltage transients from Fig. 10, smoothed with a time-varying Hanning window, to apparent resistivities using eqn. (3). The upper two plots display noisy curves whose standard errors become larger at later times. The apparent resistivity curve for the prestack filtered data (bottom curve of Fig. 11) is smoother and has smaller error bars.

Using the LOTEM data-processing techniques with the available options as discussed and shown in Fig. 2, one profile was processed in two different ways. First, the field data were selectively stacked in the field and then digitally filtered. A typical data-processing sequence prior to the availability of a ruggedized (old disk). The result of this is the inverse profile shown in Fig. 12.

The best-resolved model is a three-layer model with a conductor as the intermediate layer. In this case, the inversion output model strongly depended on the starting model, which gives unstable inversion results. Classified seismic data showed approximately horizontal layers and well-log data contained a resistivity contrast at ~ 600 m depth. This information could not be successfully integrated into the interpretation so that consistent inversion results were obtained. Thus the structural trend of the conductor was unrealistic.

Figure 13 displays the same section after the transients were prestack data processed. In this case, the inversion data were sufficiently resolved so that the thickness of the first layer could be fixed using well log information at the point of projection onto the profile. All other inversion parameters were left free. The results of the inversion were then further verified and the best-resolved model is a five-layer case. The conductive layer which appeared in Fig. 12 is still present as the fourth layer of this section. The overall structure of the geologic depth section correlates with the geology and the seismic information much better than the interpreted section in Fig. 12.

3. Conclusions

In areas with high cultural noise levels, LOTEM depth soundings can be best interpreted using prestack data-processing techniques. New LOTEM data-processing concepts have been introduced and applied to both synthetic and real data, illustrating their importance in processing data from noisy areas. The examples discussed show that even in the presence of cultural noise, such as periodic power line noise and sporadic noise due to machinery, prestack data processing yields more realistic geologic depth sections compared with stacking the signal directly and then processing.

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References


