Cable extrapolation in the frequency domain using sharpened k_x-k_y transforms

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Summary

The limited extent of spatial aperture in the cross-line direction that exists in marine streamers has recently been overcome by advances in marine acquisition technology. Among such advances are wide azimuth surveys that either utilize shooting vessels laterally offset or circle shooting acquisition. Some years ago, before such advances in the field took place, we wanted to see if we could extend the lateral aperture of the streamer geometry by extrapolating new cables on each side of the existing ones in the F-K_xK_y domain. The method developed and described in this paper seems to perform well on synthetic data but the real data results are less than satisfactory. Perhaps future modifications to the algorithm will bring the uplift that we were seeking and can be used in the reprocessing of narrow azimuth (NAZ) data.

Introduction

Many algorithms in seismic data processing are limited by the spatial extent (aperture) of the data that they have to work with. The resolution decreases in such processes as aperture get smaller. Prior state of the technology in marine acquisition was to have a few parallel streamers with equal distances between them which were generally between 100m and 200m providing an aperture in the order of 1km at the most while the streamer themselves were about 10km long. This technology is known today as narrow azimuth (NAZ) acquisition. With NAZ data it is common to do trace interpolation via F-XY (Spitz, 1991), or, F-K_xK_y domain (Gulunay, 2003) interpolators to lessen aliasing issues that the coarse trace increment causes between traces in the cross-line direction (traces on the common channel). Interpolation does not change the aspect ratio of NAZ data. This ratio is around ten. Therefore we might attempt to extrapolate new traces (cables) in the cross-line direction to emulate recording with wider crossline apertures. Such an attempt was first done by Chambers and Gulunay (2001) using an F-XY domain approach. There, one new cable at a time was obtained by placing the F-XY filter at the outer edge of the original cables to predict one sample ahead (in outward direction) version of the data and the process was repeated for each new outer cable using the previously generated ones in the space gate. Here I present also a frequency domain method but I operate strictly in the K_x-K_y domain to do the extrapolation.

Although the method to be described did not succeed to be part of the processing sequence for various reasons I think it is worth describing the principles, and pointing out its shortcomings. Perhaps this might inspire development of better algorithms in the future. In this paper I use words “cable” and “streamer” interchangeably.

Geometry Extrapolation

First thing to do in any such algorithm is to determine where to output extrapolated data. To do that we first specify how many new cables we would like to add to each side of the existing cables. A cartoon of such geometry extrapolation is given in Figure 1. As real data often has feathering as well as missing data due to editing (noisy portions) real data geometry may look like the one shown in Figure 2. In this method it is important that trace numbers on the original shots are present and traces to use for cross-line interpolation are hence predictable. Although feathering exists on real data it does not prohibit us from predicting where the extrapolated cables could be. By using coordinates of the existing traces at the same channel on different cables and assuming that the cables are equidistant on this common channel (Figure 2) we can predict where new traces (cables) should be on this channel.

Data Extrapolation

The general concept of the method can be illustrated well with the cartoons given in Figures 3-6. For these cartoons I chose a truncated but otherwise constant function. A truncated data along x (shown schematically in Figure 3) has a ringing response (sync function) in the wavenumber domain as shown in Figure 4. If this response can be converted into a spike (as in Figure 5) then the inverse transform will provide extrapolated data all the way at both ends as shown in Figure 6.

This is exactly what I do with the two space directional field data. I first calculate the K_x-K_y response of the original data (N_xN_y samples) by forward Fast Fourier Transform and also a sharper version (along K_x-K_y direction) of the same data derived from prediction error filter. I then use this as a mask function to sharpen the response of the original data using point-by-point multiplication. Finally I do inverse Fast Fourier transform to 2D space domain to obtain the extrapolated samples.

It is common to use frequency domain approaches and spatial and temporal windowing (with some post blending) to interpolate seismic data. I similarly use frequency domain of small time windows to implement the extrapolation problem: I also use small space gates (~20 traces) sliding with 50 percent overlap along the x-direction (along the cables). So spatial size of the elementary data is N_x traces along each cable, and N_y traces across the cables.

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N_y is same with the number of the existing streamers. Then the challenge for the algorithm is to bring in N_xN_y samples at a frequency slice and extrapolate them to their desired positions on both sides and end up with N_x (N_y+2L) samples.

To do this I assume that lateral separations of these N_xN_y traces are uniform in the inline and crossline directions and calculate high resolution (edge effect free) spatial (X-Y) prediction error filters. Accompanying prediction filters for these prediction error filters were described by Gulunay and Pattberg (2001) in connection with residual noise suppression after seismic interference noise removal. These spatial filters are indeed short and are designed edge effect free in the sense that when prediction equations are formed the prediction filter never runs out of the data (Marple, 1987). As there are two lateral directions across the cables to consider two separate filters, each running along cross cable direction in opposite directions, are considered. In any case, once prediction error filters at a given frequency are calculated then their K_x-K_y response, $E(K_x,K_y)$, can also be calculated and a sharp normalized spectrum is obtained as

$$m(k_x,k_y)=\frac{\varepsilon}{\varepsilon+|E(k_x,k_y)|}$$

where epsilon is a small variable. This function goes to one at wavenumbers that have significant signal energy (i.e. where prediction error, E, is close to zero) and to zero at points away from such locations and can be used as a mask. This mask function is then applied to the K_x-K_y response of the original data and the result is inverse transformed to yield data at extrapolated (as well as original) positions.

Synthetics data examples

We tested the algorithm first on a two event model shown in Figures 7 and 8. We used real data headers to build two linear events on data that had 7 cables, each with 360 traces. Dip on the first event was 3 samples per trace in the inline direction (along cables), and 1 sample per trace in the crossline (across cables) direction. The dip on the second event was 1 sample per trace in the inline and 2 samples per trace in crossline directions. Sample interval of the data was 4ms. Figure 8 (only 24 traces are shown) illustrates that the result of the extrapolation is satisfactory.

Another synthetic that we tested the algorithm on was single shot record from BP's Mad Dog 2.5D model data which was indeed built to check multiple attenuation algorithms, and, hence contained primaries and multiples. It had a low frequency content (maximum frequency was about 25 Hz). As we wanted to use our extrapolation algorithm to increase the crossline aperture to see if it will help solve multiple attenuation algorithms it was natural to use such a model to check if extrapolation worked on it. It contained 7 cables, each with 155 traces. Shot lines ran from NW to SE at 45 degree to produce variations from cable to cable and from shot to shot. I extrapolated 2 more cables on each side of the existing 7 cables. The result (after NMO) is shown in Figure 9. Zooms (images in Figures 10 and 11) made to the left hand side of Figure 9 show in the shallow and in the deep how the nearby extrapolated cables compare to the nearest original cables. We found results satisfactory. Indeed extrapolated data are cleaner than in the input, showing that some spatial resolution was lost during extrapolation.

Field data example

We first tested the algorithm on a five cable marine recording by adding one cable on each side of the original cables. Figure 12 shows the result (with NMO application). Figure 13 shows the zoom on one of the outer cables. Dead traces there are the edited ones. Figure 14 shows the cable extrapolated successfully to the location next to it.

One can test the accuracy of such algorithms by dropping existing outer cable from the many cable shot records and compare the extrapolated cable at the same locations with the original cables. In real data situation there is no way of knowing where the actual locations of the new cables should be and our algorithm extrapolates those locations as mentioned previously. These locations will not in general agree with actual locations of the cable. So we don't expect perfect reconstruction. Nevertheless we performed this test on a different survey where there were actually more cables recorded. Figure 15 shows two outer cables of an 8 cable marine shot record after NMO. Note that NMO stretch at far offset is present, as well as multiples. The challenge is whether we will be able to reconstruct primaries as well as multiples accurately with the extrapolation algorithm described. Figure 16 shows the same cables after they were dropped from the original data and were extrapolated. Figure 17 is the difference between original data (at original locations) and extrapolated data (at extrapolated locations). Close inspection shows that errors in the extrapolation algorithm which are not as small as they are in cable interpolation algorithms. These errors could come from a)-the assumption that cables are uniformly separated, b)-the differences in the location of the actual cable that was dropped and the predicted location of this cable by the algorithm.

Conclusions

I have presented a cable extrapolation algorithm for 3D streamer data. The algorithm was developed especially for NAZ data to increase the cross line aperture. I presented results showing that although the algorithm seems to perform well on synthetic data the real data results are less than satisfactory. This may be due to the assumption made in the algorithm that the original cables are equally spaced. This is done during computation of prediction error filters as well as by use of FFT instead of non-uniform DFT during data reconstruction.

Acknowledgements

I thank CGGVeritas for allowing me to present this paper, BP for proving Mad Dog 2.5D data, and, my colleagues at CGGVeritas for their rigorous testing of the algorithm on real data.

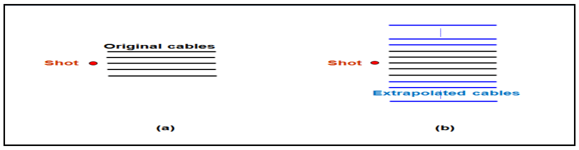

Figure 1: A cartoon describing the geometry cable extrapolation. Cables in (a) are extrapolated on each side to add more cables.

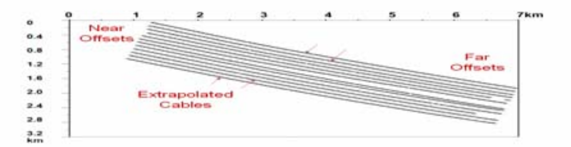

Figure 2: Geometry of extrapolated real marine streamer data with 8 original streamers. Headers are extrapolated to add two more cables on each side of the existing cables

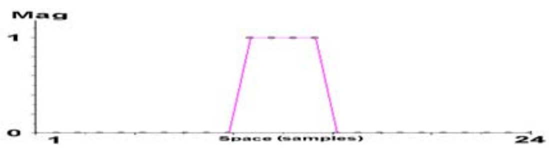

Figure 3: A function with 4 spatial samples (with same value to make the illustration simple) is placed in an all zeroes array. Zero valued data points are desired to be extrapolated...

Figure 4: Wavenumber response of the event given in Figure 3. This is a sync function.

Figure 5: Wavenumber response after sharpening . Here all samples except peak sample are simply zeroed to ilustrate the concept.

Figure 6: Space domain response after inverse Fourier transformation of Figure 5. Comparing with Figure 3 shows that desired samples are properly extrapolated.

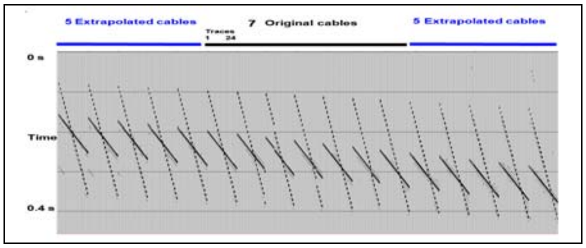

Figure 7: A seven cable recording is extrapolated with 5 cables at each side. Data is made of two linear events to check the algorithm on a model that was built on the geometry of some real data.

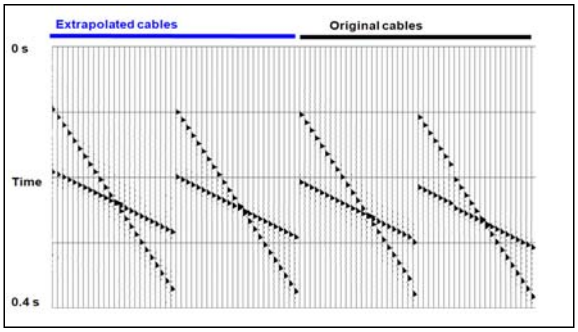

Figure 8: Zoom of the extrapolation on the left side of the image in Figure 7. Left two cable are the extrapolated ones. Note one trace gap (missing due to edited data) in the second original cable pointing to the fact that field geometry was used to build the linear events.

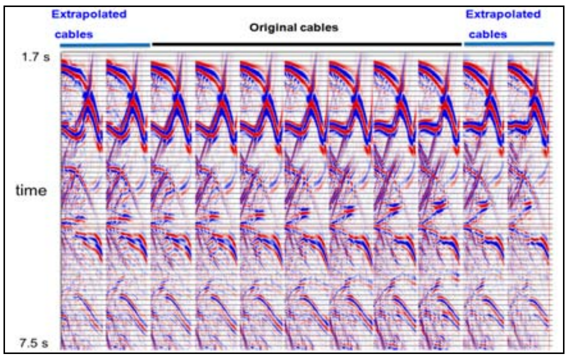

Figure 9: BP synthetic data extrapolated post NMO. Two cables are extrapolated on each side of the existing 7 cables.

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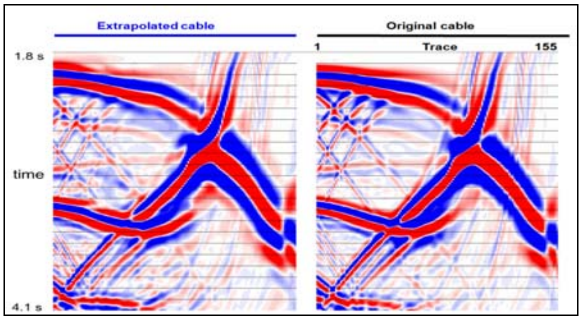

Figure 10 Zoom of shallow time zone of the left hand side of Figure 9. Note that extrapolated cable on the left seems very successful.

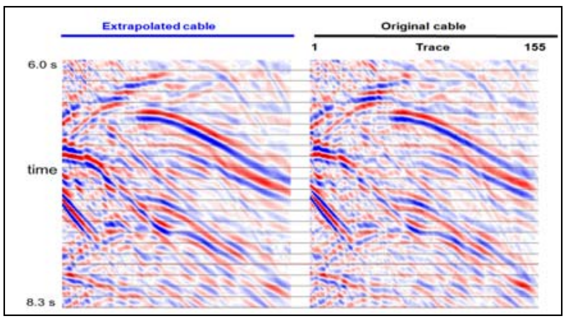

Figure 11 Zoom of deeper time zone of the left hand side of Figure 9.

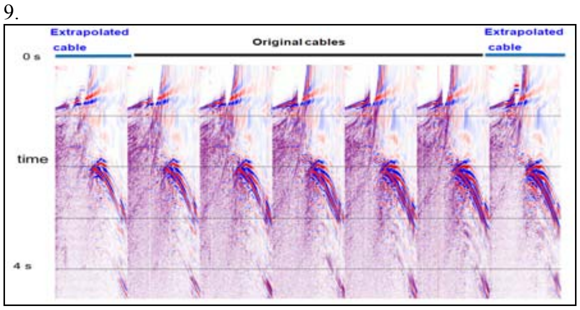

Figure 12 A five cable stramer data is extrapolated to become a 7 cable data by adding a cable on each side. Data has NMO applied.

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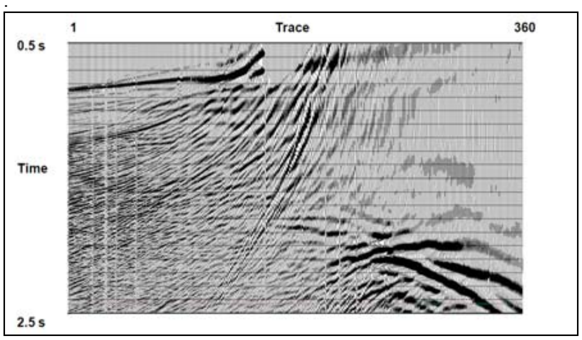

Figure 13 One of the outer cables of the original recording.Note the presence of edited channels. Data has NMO applied.

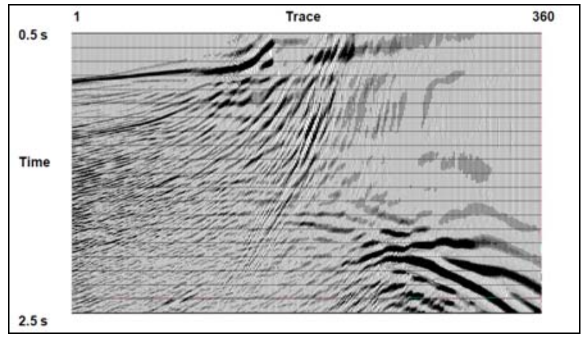

Figure 14 Extrapolated cable next to the outer cable shown in Figure 13.

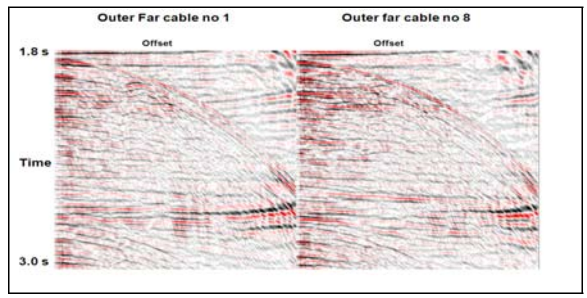

Figure 15 Original far cables of an 8-cable streamer recording (post NMO)

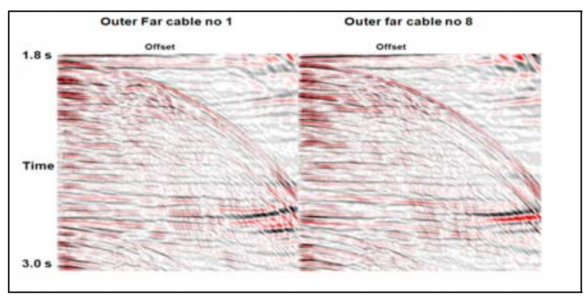

Figure 16 Same far cables in Figure 15 but after deleting them and extrapolating them from the remaining 6 inner cables.

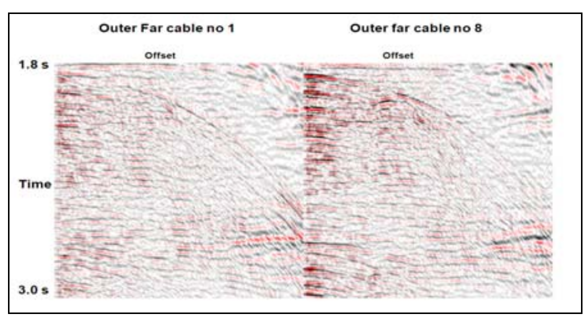

Figure 17 The difference between original cables in Figure 15 and extrapolated cables in Figure 16

EDITED REFERENCES

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