Cleaning up first arrivals in the cross-spread domain

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Summary

It is standard practice in land seismic processing to correct for time delays caused by low-velocity weathered layers in the near surface. Typically the first step is to pick the first arrival times of the refracting energy. But first arrivals are often noisy due to, for example, wind on geophones, causing automatic pickers to produce poor results. I describe a novel method to remove random noise from the first arrivals by exploiting the "locally surface-consistent" property of cross spreads. This can produce faster and better first-arrival picking, and thus more accurate weathering correction, at a lower cost.

Introduction

Correcting for time delays caused by low-velocity near-surface weathered layers on land data is one of the oldest steps in seismic processing (e.g., Gardner, 1939). It is particularly vital in northern regions covered by glacial till and desert regions covered by sand dunes. And in all regions, river beds can cause significant statics problems. The standard approach is this:

- Pick the times of the first arrivals.
- Interpret the depth and velocity of the weathered layers from these picks.
- Apply statics to correct for the weathered layers, in effect turning the near-surface into a constant-velocity layer.

Picking first arrival – also called first break – times is mostly automated due to the massive amount of seismic data in modern seismic surveys. Often, though, it requires extensive and expensive human guidance and correction to ensure consistent results. A major cause of poor automatic picking is high-amplitude random noise caused by, for example, wind on geophones or poor penetration of seismic energy through the near surface. This might become worse in the future due to the adoption of high-density mini vibe shooting and single-point receivers.

Why do automated tools break down in the presence of such noise? As an example, one of the most useful tools for automated picking is the energy-ratio test (Coppens, 1985), where the amount of seismic energy immediately before and after a given time are compared. A surge in seismic energy suggests that the given time is near the first arrival. Such a test is useless for many of the traces at the left of Figure 2, as there is little increase in energy at the first arrival.

If random noise can be removed beforehand then automatic pickers will do a better job, resulting in faster throughput, reduced cost, and ultimately more accurate weathering correction. But this is a difficult problem given that first arrivals can have large and erratic time shifts even between adjacent traces which we need to preserve, and that the noise is often very strong, sometimes in excess of the first-arrival energy.

The literature on cleaning up first arrivals has been surprisingly sparse until recently. A powerline noise remover (e.g., Butler and Russel, 1993) is recommended, as is a short-length filter to remove high temporal frequencies from impulsive data. Souze et al. (2017) suggested an eigenimage filter similar to one designed for extracting coherent shot noise. It's difficult to know how well it preserves signal from the paper, but it's likely to smear out short-wavelength statics. Seismic interferometry has also been proposed (Place et al. (2019) and references therein).

Most modern 3D surveys are laid out along source and receiver lines, or as best as can be managed given local conditions. If we take all traces shot on a single source line and recorded on a single receiver line then we have a cross-spread gather. For this application, we need not restrict ourselves to source and receiver lines that are orthogonal to each other. They can be parallel as in SlimBin or MegaBin shooting, or even slanted. With this definition, an entire 2D survey can be considered a single cross spread.

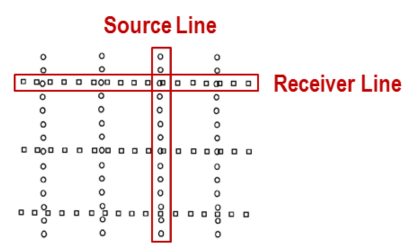

Figure 1: A cross-spread gather is a collection of all traces shot along a single source line and recorded along a single receiver line.

Cross-spreads gathers are well suited for many processing tasks (Vermeer, 2005). If we lay out the traces from a single cross spread on a grid where one axis represents common source and the other axis represents common receiver (known as a surface diagram), then traces that are near each other on the grid are also near each other by every conceivable metric: source location, receiver location, midpoint location, absolute offset, inline and crossline offset, and (except at zero offset) azimuth.

If we take a small region from a cross spread then we can model the first arrival time T_{ij} of a trace at the *i'th* source and *j'th* receiver as

$$T_{ij} \approx S_i + R_j + x_{ij} M$$

where S_i is a source-consistent static shift, R_j is a receiver-consistent shift, x_{ij} is the trace offset, and M is a linear moveout term. These parameters cannot be assumed to be the same for different regions of the cross-spread grid, as the first arrivals may represent different refractors. This paper shows how this "locally surface consistent" property of cross spreads can be exploited in a novel method to remove random noise from first arrivals.

Method

Suppose we have a single cross-spread gather, with the traces laid out on a grid representing common source on one axis and common receiver on the other. Also suppose we have a rough estimate of the time of the first arrivals (accurate to within, say, 100 ms), a function which is smoothly changing in space. A method to remove noise from first arrivals is as follows:

> Divide the grid into small (e.g., 5 sources by 5 receivers) overlapping rectangular spatial tiles.
>
> For each tile…
> {
>
> **A**: For each trace, extract a small (e.g., 400 ms) window of samples centered on the estimate of the first-arrival time.
>
> **B**. Flatten the events in the windows by determining and applying surface-consistent source and receiver statics and a residual linear moveout term. These corrections are independently determined for each tile.
>
> **C**. Stack the flattened windows.
>
> **D**: Place the stack back into the windows, undoing the flattening static for each trace.
>
> **E**: Insert the noise-attenuated windows back into the full traces, tapering the window boundaries so there is no abrupt change.
>
> }
>
> Once all tiles are processed, merge them together to reform the full cross-spread gather.

A tile size between 3x3 and 7x7 traces gives reasonable results. The amount of noise attenuation increases with size, but so does the risk of distorting of the first arrivals.

Step B is a tiny residual-statics problem (Cox, 1999, chapter 7). There are many ways this can be solved, such as correlation with pilot traces followed by linear inversion (Taner et al., 1974) or stack energy maximization (Ronen and Claerbout, 1985). Here I suggest the following method inspired by Kirchheimer (1986):

First, determine the time lag L_{ijpq} between every pair of traces in the tile, where the source-receiver indices of the two traces are *(i,j)* and *(p,q)*. This can be done by finding the position of the maximum value of the cross-correlation of their window samples. Now form a linear system of equations

$$L_{ijpq} = S_i - S_p + R_j - R_q + (x_{ij} - x_{pq})\, M.$$

Why invoke the surface-consistent assumption rather than flattening each trace with its own trim static? The reason is that some of the traces may be so noisy that accurate time lags cannot be determined. The surface-consistent assumption extrapolates information from cleaner traces to very noisy traces.

This system is under-constrained. Specifically, it contains no information about the absolute time shifts of sources or receivers, so we are free to assume that one of the source and one of the receiver statics (chosen arbitrarily) are zero. This removes two columns of the matrix and two variables to be solved for with no deterioration in results, making the matrix well conditioned rather than rank deficient.

The system is also over-determined. For a 5x5 tile with no missing traces, for example, there are 300 rows (the number of pairs of traces) and 9 columns (4 source statics, 4 receiver statics, and a residual linear moveout term). This system should *not* be solved using least squares. The errors in relative times shifts can be erratic – that is, highly non-Gaussian – due to some of the traces being unusually noisy and due to cycle skipping (Cox, 1999, chapter 7). Rather a statistically robust regression is recommended, such as iteratively reweighted least squares using the Huber or biweight (bisquare) M estimators (Ji, 2011).

The final static to flatten each trace *(i,j)* is

$$-S_i - R_j - (x_{ij} - x^*)\, M$$

where x* is the offset of one of the central traces in the tile.

In step C, stacking the windows is also best done through robust statistics rather than the standard arithmetic mean

(Elston, 2005), as the noise levels can vary erratically between traces.

Step D can be accompanied by some mild match filtering. At a minimum, the scaling of the stack should be matched to the scaling of the original window data so as to minimize the difference between the original and filtered traces. When there is a serious misfit between an original and filtered trace, however, match filtering should not be done.

This method can be modified to handle the occasional reverse-polarity receiver. The goal should be to properly noise attenuate it while preserving the polarity. Without going into details, this involves identifying when a receiver correlates negatively with other receivers in step B.

Examples

Figure 2 shows part of a Vibroseis 3D shot record before and after cleaning up the first arrivals. The first arrivals are now much easier to pick, while the polarity of a reversed trace has been preserved.

Figure 3 shows traces from part of a shot in a Vibroseis 3D which have been flattened using a rough estimate of the first arrivals times. The top section is the raw data, the middle the filtered data, and the bottom the difference. Again the first arrivals are easier to pick.

Figure 4 shows three consecutive shots taken from a cross spread, flattened using a rough estimate of the first arrival times. Note that:

- Short-wavelength spatial statics are preserved.
- Coherent noise is removed so long as it's not surface consistent.
- Even severe noise can be tamed.

Final Comments

Removing noise from first arrivals is doable if one exploits local surface-consistency, robust statistics, and the special properties of cross spreads. In fact, the degree of noise attenuation possible is surprising.

But the proposed method has some limitations. There are some regions where this method does poorly, particularly where a first-arriving refractor is very low amplitude compared to slower refractors. The method can also break down in the presence of geometry errors. This is disappointing, as first arrival picks are often used to identify geometry problems such as mispositioned sources and receivers. In addition this method requires that acquisition be carried out along source and receiver lines. Such acquisition is typical today, but more random acquisition designs may be popular in the future in certain regions. Even on a conventional survey, source lines can be so crooked and erratic that application of this method is difficult.

As mentioned above, a 2D survey can be thought of as a single cross spread where the source and receiver lines are parallel. Unlike 3D cross spreads, however the source spacing is usually larger than the receiver spacing. This suggests using rectangular tiles, such as 3 sources by 7 receivers.

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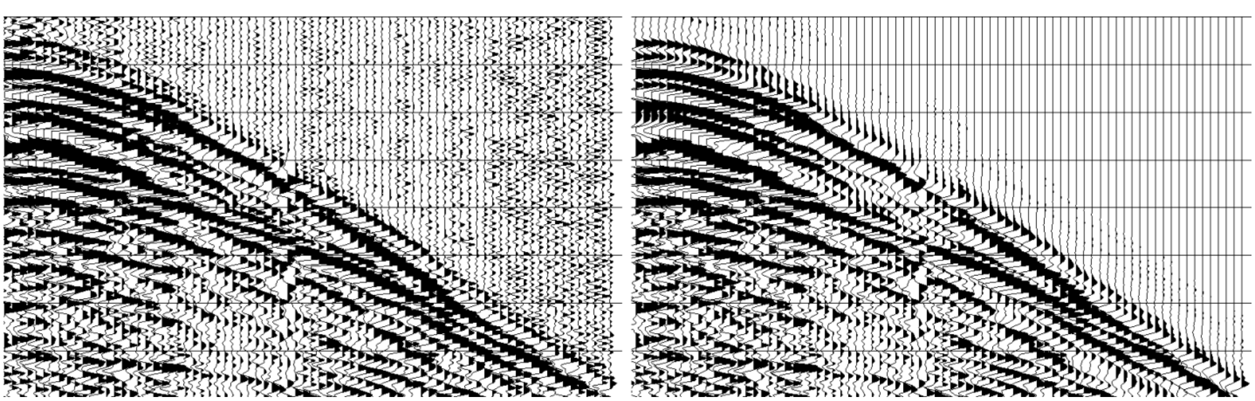

Figure 2: Part of a Vibroseis shot record before and after cleaning up the first arrivals. Data above the first arrival window (that is, data above about 200 ms of the first arrival) has been muted. Note the reverse trace, whose polarity has been preserved.

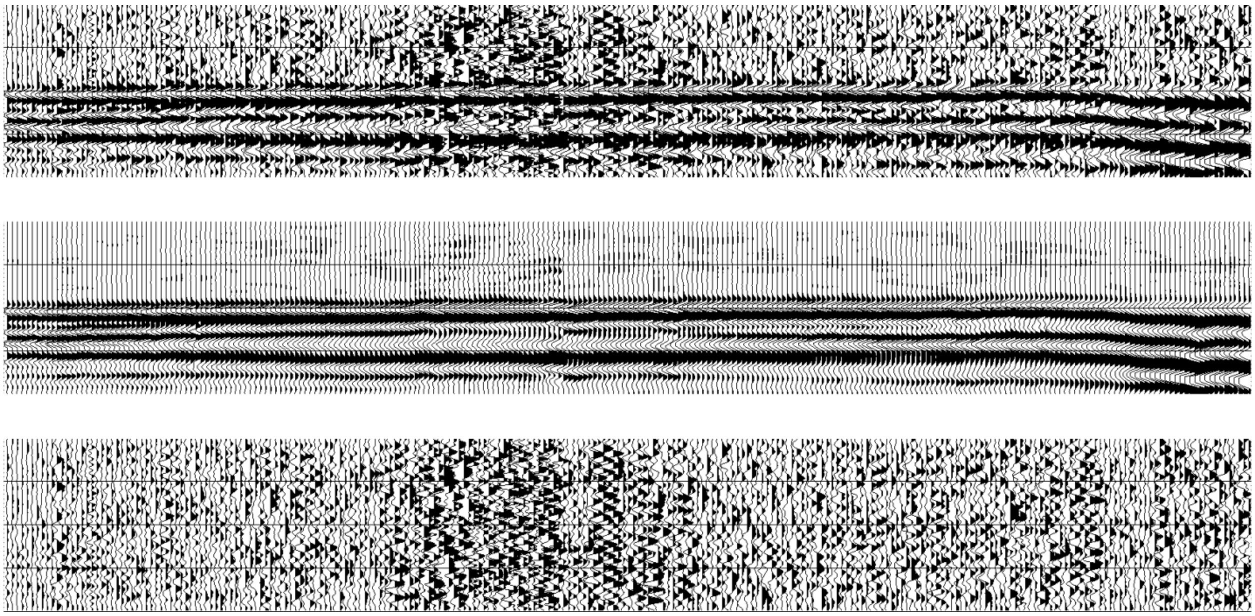

Figure 3: Part of a shot from a Vibroseis survey flattened by a rough estimate of the first arrival times. Top is the raw data, middle is the filtered data, and bottom is the difference. Data complements of Explor.

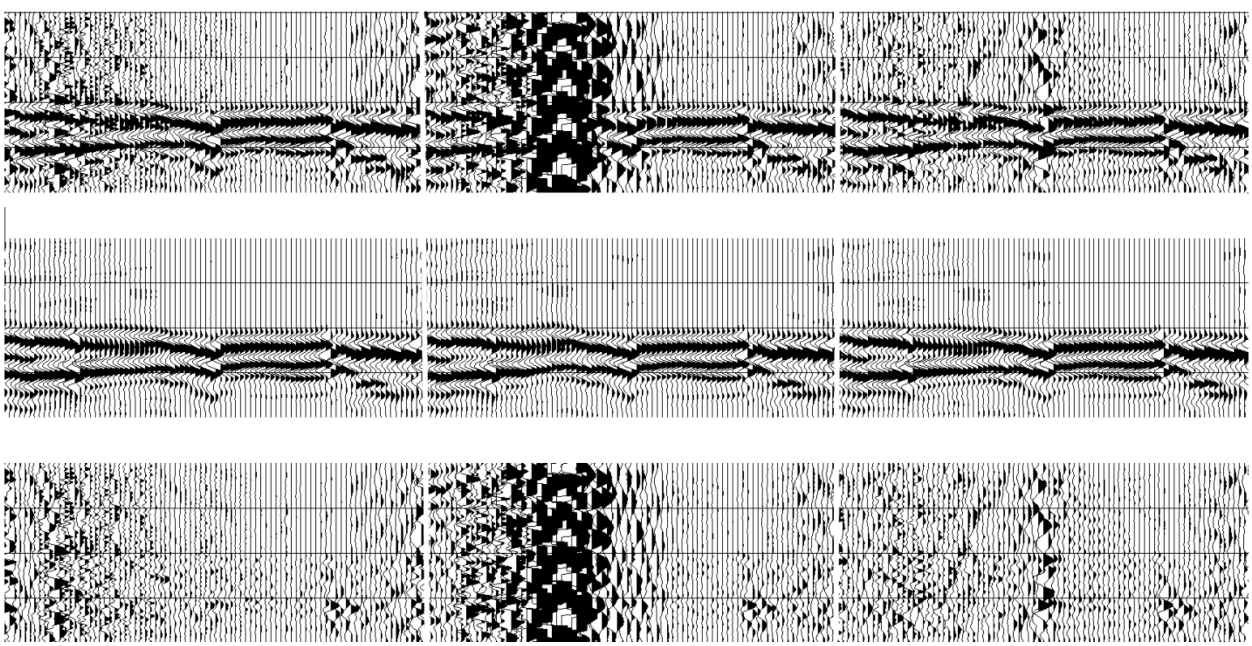

Figure 4: Three consecutive shots from a single cross spread, flattened by a rough estimate of the first arrival time. Top is the raw data, middle is the filtered data, and bottom is the difference. Data complements of Explor

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