Radial trace filtering revisited: current practice and enhancements

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ABSTRACT

Filtering seismic data in the radial trace (R-T) domain is an effective technique for attenuating coherent noise on ensembles of seismic traces. In some applications R-T filtering can be more effective than more established methods like K-F filtering. Operational experience with radial trace filtering over the past three years has led to the implementation of a new interpolation option in the radial trace transform and to the identification of a particular attenuation method which works well in a variety of situations. The new interpolation scheme enables more effective removal of coherent noise that is mildly spatially aliased, in some instances, while the most generally effective R-T filtering method now appears to be that of modelling the noise in the R-T domain and subtracting the modelled noise from the original data in the X-T domain. Revisiting the 1998 Shaganappi high-resolution data set illustrates the increased effectiveness of both the new interpolation technique and the noise modelling/subtraction technique. A comparison to K-F filtering on these data is also shown, in which radial trace filtering is clearly superior.

INTRODUCTION

Techniques for attenuating coherent noise in seismic data were introduced by Henley (1999) and further elaborated by Henley (2000), based on earlier work by Claerbout (1975; 1983), who introduced the radial trace transform primarily for use in migration and related imaging algorithms. R-T coherent noise techniques rely on the fact that separation of linear noise from reflections can be achieved in the radial trace domain by aligning the transform coordinate trajectories with the linear noise wavefronts in the X-T domain. This causes linear noises which spread across all the traces of an X-T gather to be isolated into small groups of radial traces. In addition, the apparent frequencies of these events are shifted from the seismic band to much lower frequencies (Henley, 1999) by the geometric distortion of the transform.

It has been shown that the details of the interpolation used in the R-T transform greatly influence the relative fidelity with which reflection-like events and linear noise are captured by the transform (Claerbout, 1983), (Brown and Claerbout, 2000). In particular, interpolation in the X-direction favours reflections but not coherent noise, particularly noise that is spatially aliased. Interpolation along the R-T trajectories (V-interpolation), however, favours the coherent noise aligned with the trajectories but aliases reflections. At first consideration, it would seem that the V-interpolation would have limited application. However, when it is desired to extract or 'model' the linear noise, this mode of interpolation may actually perform better than the more usual X-interpolation. The reason for this is that linear noise that is aliased in the X-direction may not be aliased along a radial trace trajectory (the V-direction).

Among the different filtering options allowed by the radial trace filtering module in ProMAX are: the ability to filter either in frequency or time; to apply low-cut, low-pass, or bandpass filters; and to model the noise with a low-pass filter in the R-T domain before subtracting its inverse R-T transform from the original unfiltered ensemble. In general, it has been found better to use the frequency domain filter application and to use the model and subtract technique.

V-INTERPOLATION

Interpolation is the means by which radial trace sample values corresponding to R-T grid points which fall between X-T grid points are evaluated from nearby X-T sample values. The choice of X-T sample values that contribute to a given R-T sample can profoundly influence which seismic events are best preserved or enhanced in the transform, as shown by Claerbout (1983). In general, it is desirable to preferentially preserve horizontal or reflection-like events, so interpolation is usually done horizontally (X-direction). However, to provide the capability to preserve non-horizontal linear events, which are often aliased, the V-interpolation option has been implemented in the ProMAX radial trace modules.

Figure 1 shows the operational difference between X-interpolation and V-interpolation. In Figure 1a, values are required for a radial trace at sample points which fall between two traces in the X-T domain. The samples are evaluated at the same times as samples on the original X-T traces. The new sample values are determined in this case using an (unspecified) interpolation between the two nearest X-T trace sample values at the same travel times. This constitutes X-interpolation. Figure 1b, on the other hand, illustrates the two step process used to obtain the same R-T samples by interpolation along the R-T trace direction (V-interpolation). First, the points at which the R-T trajectory crosses the two nearest X-T traces are determined. On each X-T trace, the value at the R-T intersection is determined by linear interpolation between the nearest X-T trace samples above and below the intersection. These two values then become the endpoints of a segment of the R-T trace. Next, the actual R-T sample values lying on this segment are evaluated by linear interpolation from the endpoint values to the sample positions determined by the intersections of the R-T trajectory with the time grid.

Figure 2 shows the difference between the two interpolation methods as applied to a shot gather from Blackfoot (Figure 2a.). Figure 2b shows the X-interpolated R-T transform, while Figure 2c shows the V-interpolated R-T transform for the same shot gather. The differences are readily apparent. The low-pass filtered and inverse transformed gather (the ‘modelled’ linear noise) is shown in Figure 3 for both interpolation methods. Notice that the low-velocity region of the wavefield where spatial aliasing becomes apparent (labelled X-aliasing on Figure 3a) is where V-interpolation becomes most effective (Figure 3b). On the other hand, a new form of aliasing (V-aliasing) appears at higher velocities on the V-interpolated image. At higher velocities still, as the V-interpolation direction approaches that of X-interpolation, aliasing disappears.

CURRENT FILTER PRACTICE

The most straightforward R-T filter to design and apply for coherent noise attenuation is a simple low-cut filter applied to the X-interpolated R-T transform. Most of the early processing results using R-T filtering were, in fact, obtained with this type of filter. In theory, subtracting a low-pass R-T filtered gather from the original should yield identical results. In practice, however, due to algorithmic limitations, clear differences can often be seen between results for the two different methods. It now appears that the low-pass subtraction method is preferable on most data. The low-pass filter parameters needed to accurately model linear noise on any given gather can usually be significantly lower in frequency than the comparable low-cut filter parameters required for directly attenuating coherent noise in the R-T domain, thus potentially extending the lower limit of the usable seismic band. Subtraction of low-pass modelled noise also appears less likely to remove high spatial frequencies of geological significance or to smear other lateral discontinuities like statics.

One situation where the direct low-cut R-T filter option must still be used is the case where it is desired to also apply R-T domain normalisation or AGC in order to eliminate the amplitude contrast within a R-T gather between radial traces containing primarily signal and those dominated by noise. Applying R-T normalisation or AGC in the low-pass subtraction mode destroys the relative amplitudes of the modelled noise before subtraction and is therefore incorrect.

A bug in earlier versions of the ProMAX R-T filter module made the frequency domain filter application option less effective than the more time-consuming time domain option. The fault has been corrected, and frequency domain application is now preferable. In order to apply radial trace filtering in the frequency domain, the input ensemble must be conditioned by application of trace gain or AGC (in the mode which stores gain factors for later removal), so that large amplitude events at the beginning of the traces do not dominate the spectral amplitudes. If it is undesirable to apply gain or AGC, then R-T filtering should be applied in the time domain with a filter length significantly shorter than the trace length.

SHAGANAPPI THEN AND NOW

When R-T filtering was first introduced as a coherent noise attenuation technique in 1999, the Shaganappi high-resolution seismic data survey was used to illustrate the effectiveness of multiple passes of R-T filtering on very noisy data (Henley, 1999). Figure 4 shows representative raw shot gathers for the line, on which linear noise totally obscures any reflections. The image resulting from application of R-T techniques to the shot gathers was considered to be the best one obtained at that point in time (Figure 5). Since that time, the R-T filtering algorithm has improved, as has the understanding of how best to employ it. The earlier filtering was accomplished using the rather heavy-handed application of time domain low-cut R-T filters with relatively long filters to force steep attenuation curves. While this approach did, indeed, greatly attenuate the linear noise, it led to source gathers with a rather 'mixed' appearance, not unlike similar results from K-F filtering (Figure 6). For the new cycle of processing, the choice was made to model the noise and subtract, as well as to use the V-interpolation method when attenuating low velocity, spatially aliased coherent noise. As in the earlier processing, the coherent noise on the shot gathers was addressed one mode at a time, starting with the most prominent. Figure 7 shows the result of applying a V-interpolated R-T subtraction filter to the shot gathers shown in Figure 4, while Figure 8 shows the comparable X-interpolated result. It is clear that the 300 m/s air blast is significantly better attenuated on the V-interpolated result. This filter pass was only the first of six R-T noise subtraction filters applied to the gathers. Figure 9 shows a raw shot gather on the extreme left followed by the results of six successive passes of R-T subtraction filters. Note the emergence with successive filter passes of shallow hyperbolic events at 80 and 150 ms, as well as deeper flat events (650 and 950 ms) that are all likely reflections. Note, as well, that there is no 'mixed' look to the gather as it emerges from all these filter passes.

An attempt to accomplish the same result with K-F filtering is documented in Figure 10. Here, the raw shot gather on the left is followed by the R-T filtered version, then the K-F filtered version. The K-F filtered gather was obtained from the successive application of two different K-F filters, one to pass only velocities contained in reflection events, the other to reject velocities characteristic of the direct arrival and refractions that mask the shallow reflections. As can be seen, in spite of considerable effort to obtain the best possible K-F results, the R-T filtered results appear superior. The true test of coherent noise filtering, however, is whether the stack is improved by the filtering. Figure 11 shows the stack of unfiltered shot gathers for comparison, while Figures 12 and 13 are the stacks of R-T filtered and K-F filtered results, respectively. Most of the coherent event energy on the unfiltered stack is due to refraction events with nearly the same moveout at long offsets as the underlying hyperbolic events. The K-F filtered result in Figure 13 clearly retains more of the refracted energy than does the R-T filtered section in Figure 12. In addition, the R-T filtered section shows more detail, particularly in the shallow portion, and has a more "geologic" look to it, particularly near the centre of the section where some apparent diffractions can be seen. The point should be made, as well, that the NMO velocities used for all three sections were obtained from analysis of the R-T filtered data, since no reflections could be clearly identified on the raw data or the K-F filtered data.

CURRENT R-T SOFTWARE

Since the last release in 2001, the ProMAX R-T modules ('Radial filter' and 'Radial trace transform') have been modified in the following ways: bugs were located and corrected in the frequency domain filter application section; bugs were located and corrected in the trace normalisation and AGC subroutines; a new feature was implemented which mutes all output X-T traces above 'first live sample' as specified in the trace header (this only works if top mute times have been picked and applied prior to R-T filtering); and the V-interpolation option was implemented. In the case of the latter feature, the V-interpolation mode is activated by specifying the 'number of radial traces' parameter as an exact multiple of 3. This option is available in both the R-T filter module and the R-T transform module, while the other modifications mentioned above pertain only to the R-T filter module. In addition, the help files for both modules have changed to reflect the software changes, and the following parameter defaults have been changed: the default exponent for soft neighbour interpolation is now 4 instead of 2; the default filter domain is now ‘frequency’; and the default filter mode is now ‘subtract low pass in X-T’.

CONCLUSIONS

The practice of R-T filtering has been advanced by experience as well as software corrections and enhancements, including a new interpolation method for the R-T transform itself, that allows a better estimate of some linear noises, especially low-velocity partially aliased linear noise. Subtraction of noise modelled in the R-T domain appears to be the most generally applicable technique for coherent noise removal.

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FIGURES

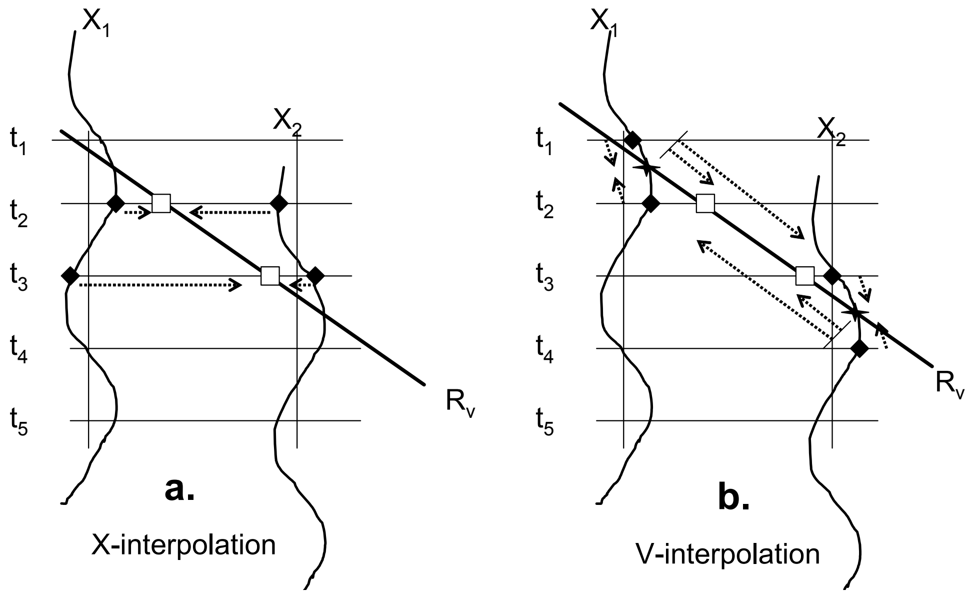
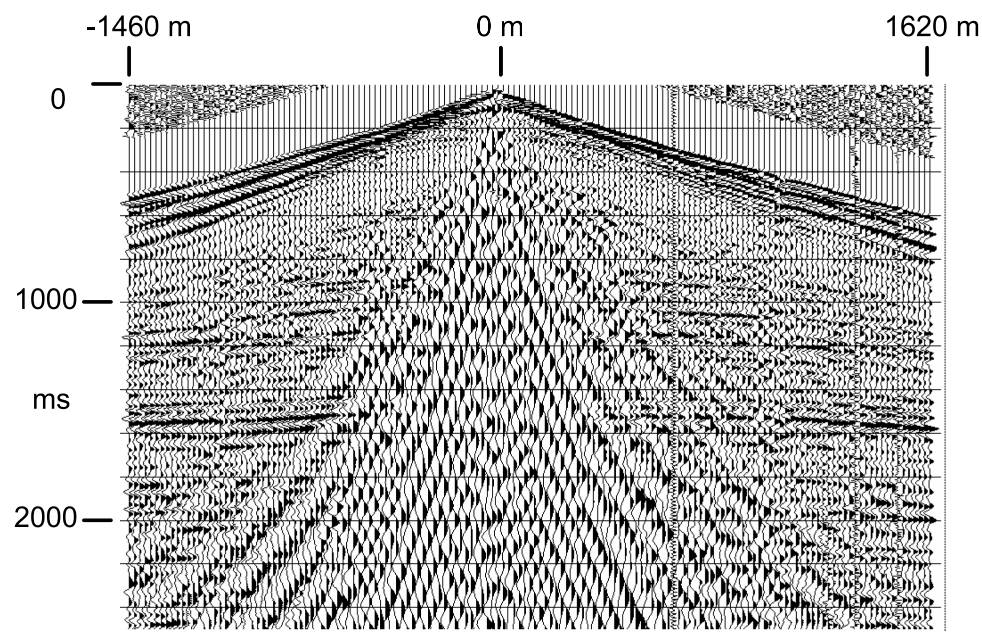
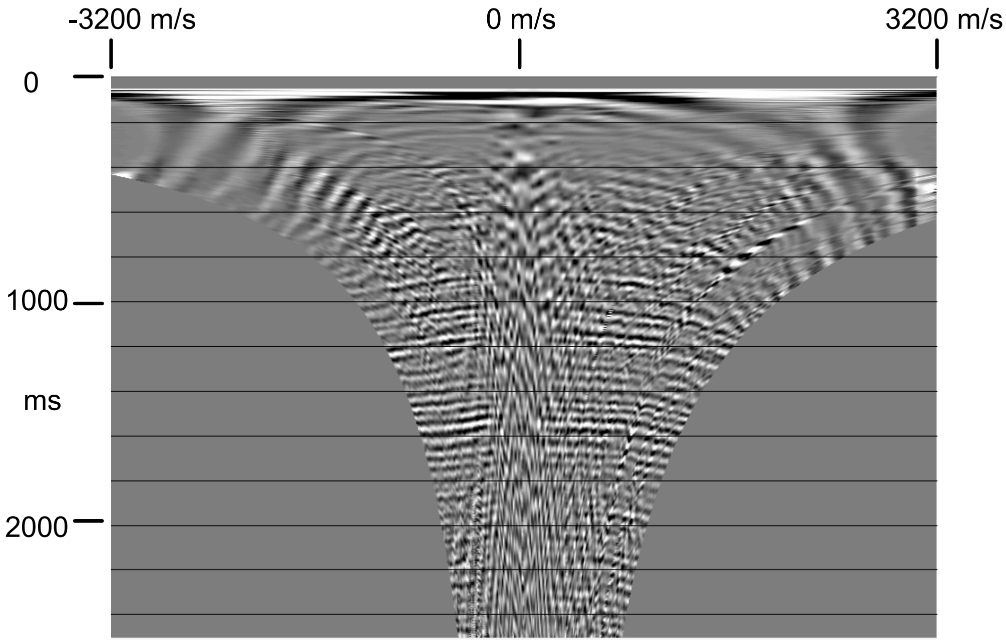


FIG. 1. Schematic showing the relationship between X-interpolation and V-interpolation as implemented in the radial trace transform. In Figure 1a, values (white squares) to be supplied at sample times t_2 and t_3 on the radial trace trajectory, R_v ,are extracted by interpolating in offset (X) the sample values (black diamonds) from seismic traces at offsets X_1 and X_2 to the intermediate offset values at which the R-T trajectory intersects the sample times. In Figure 1b, the R-T sample values (white squares) are extracted by interpolating in time between intermediate sample values (black stars) on the R-T trajectory which are the intersections of the trajectory with seismic traces at offsets X_1 and X_2. These values are themselves interpolated from the trace sample values at the nearest sample times (t_1 and t_2 for the trace at X_1 and t_3 and t_4 for the trace at X_2).



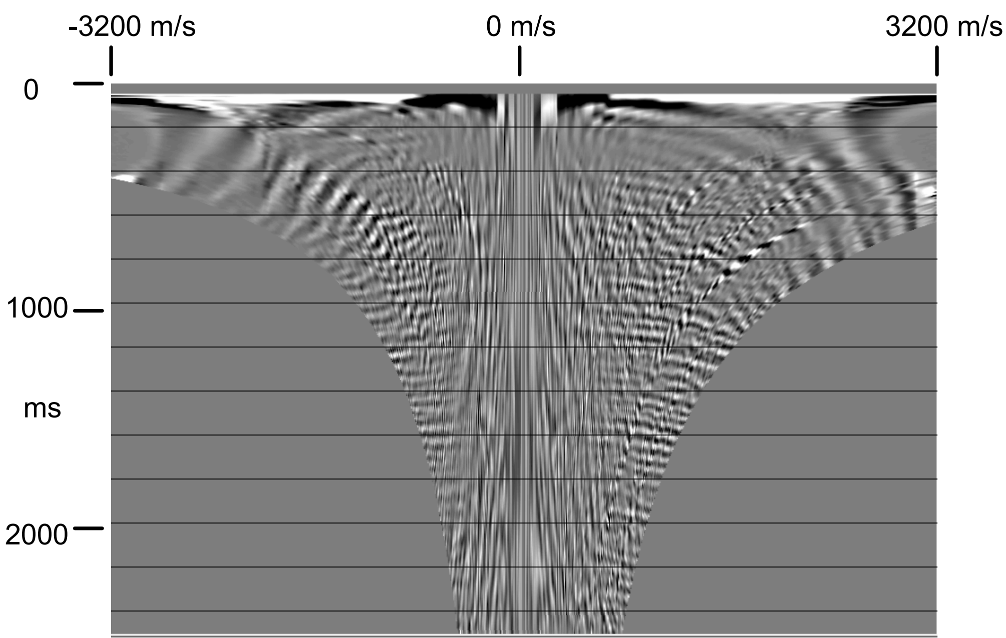
a.

FIG. 2a. Raw shot gather from the Blackfoot seismic survey



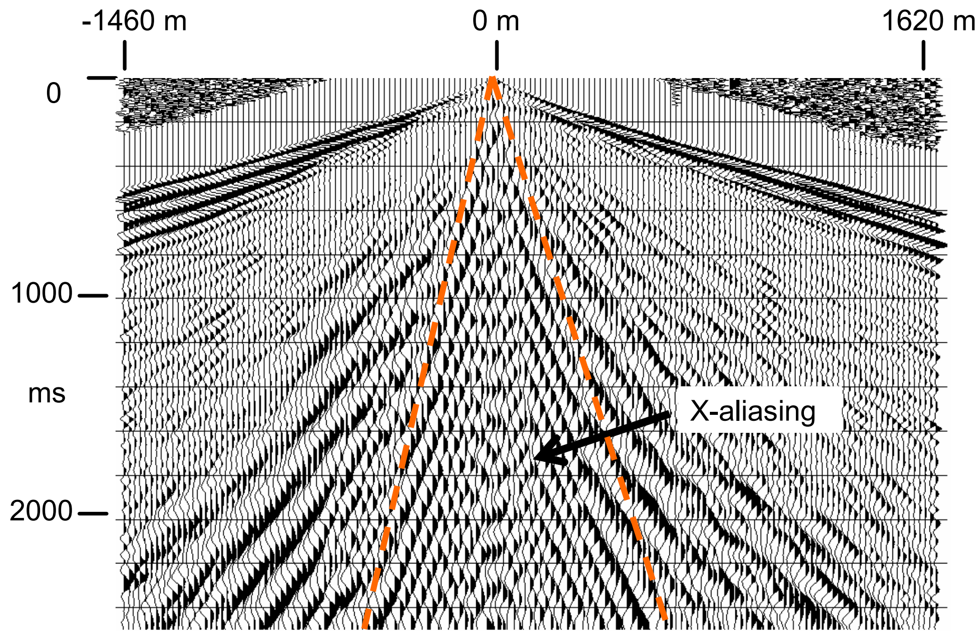
b.

FIG. 2b. Radial trace transform of Blackfoot shot gather using X-interpolation.



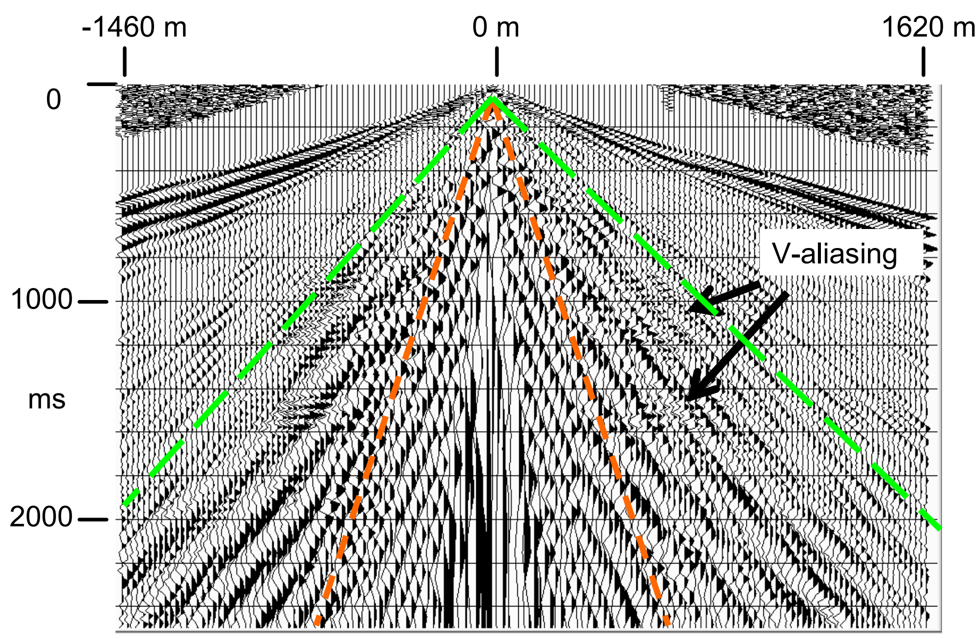
c.

FIG. 2c. Radial trace transform of Blackfoot shot gather using V-interpolation



a.

FIG. 3a. Linear noise estimated from the Blackfoot shot gather using X-interpolation. Spatial aliasing occurs inside low velocity wedge.



b.

FIG. 3b. Linear noise estimated from the Blackfoot shot gather using V-interpolation. Aliasing occurs outside low velocity wedge, but inside higher velocity wedge. Aliasing disappears for highest velocities, as V-interpolation direction approaches that of X-interpolation.

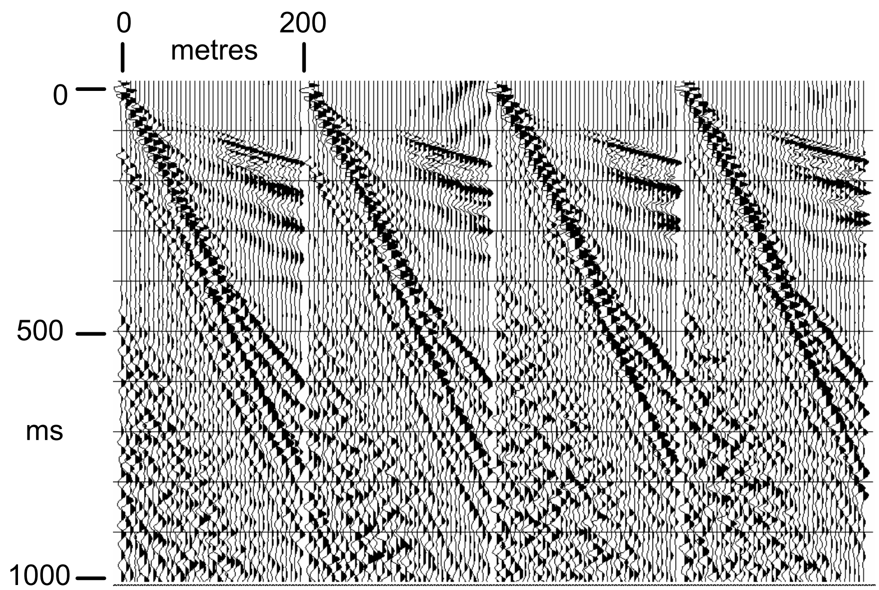


FIG. 4. Raw shot records from the Shaganappi high-resolution survey.

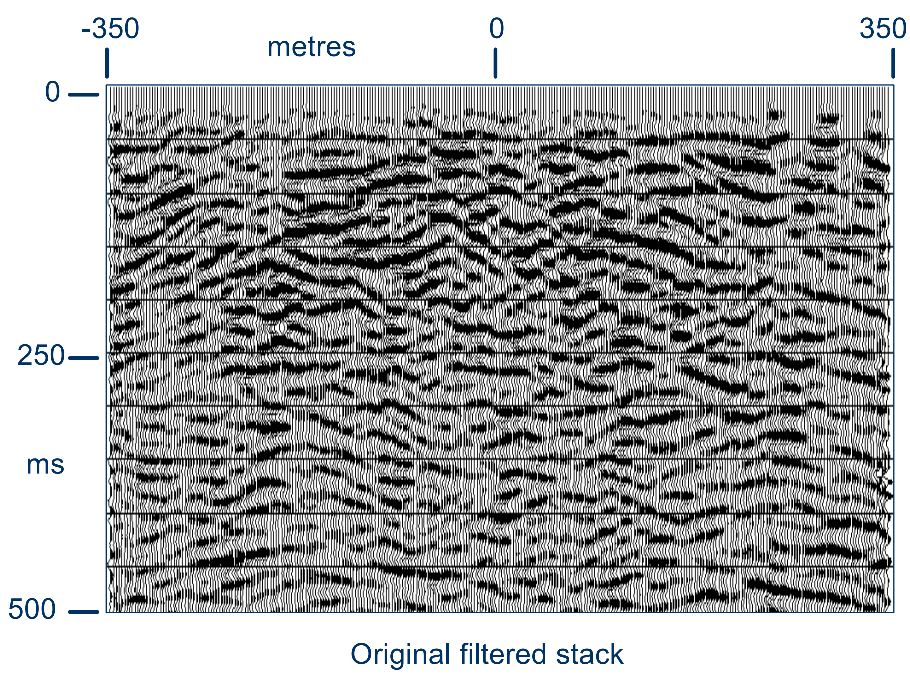


FIG. 5. Stack of Shaganappi shot gathers filtered using cascaded "old" R-T filters.

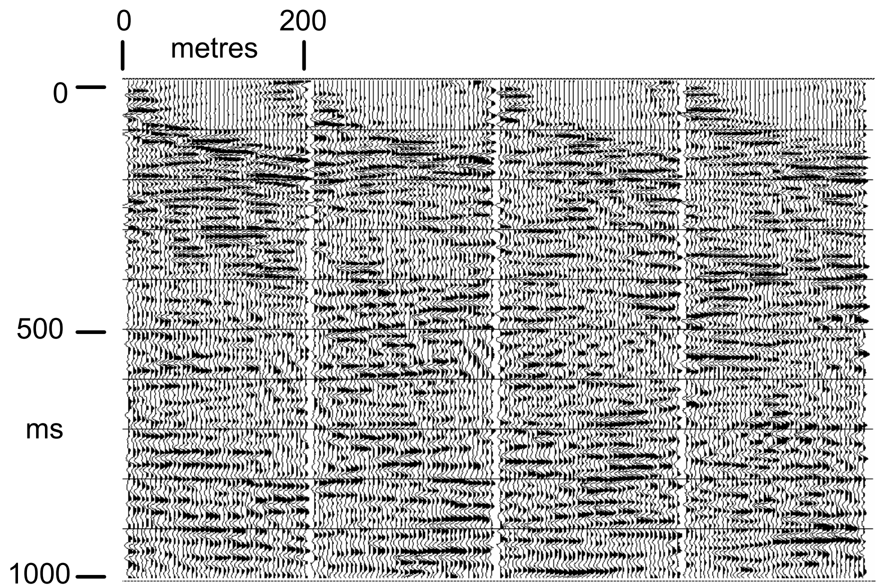


FIG. 6. Shaganappi shot gathers filtered using a cascade of “old” R-T filter passes.

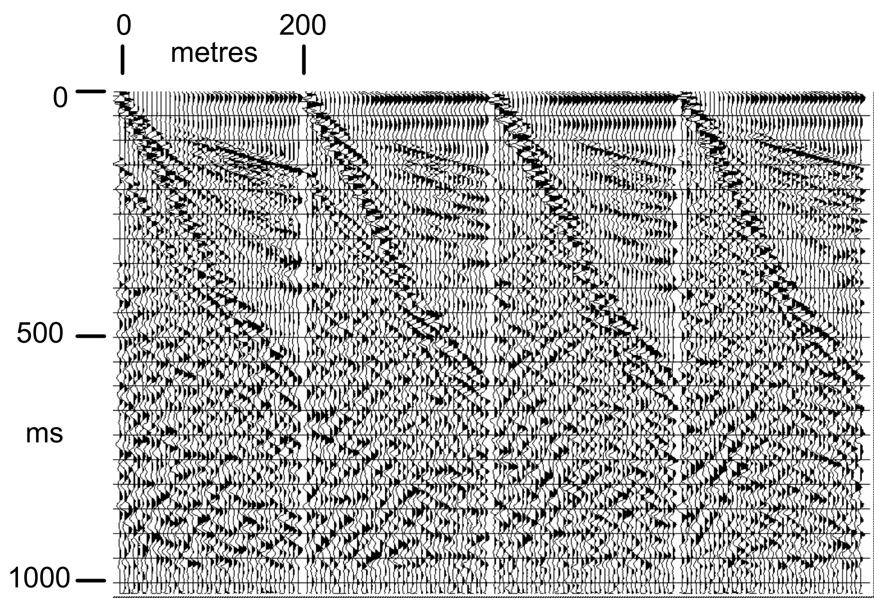


FIG. 7. Shaganappi shot records filtered with V-interpolated R-T filter

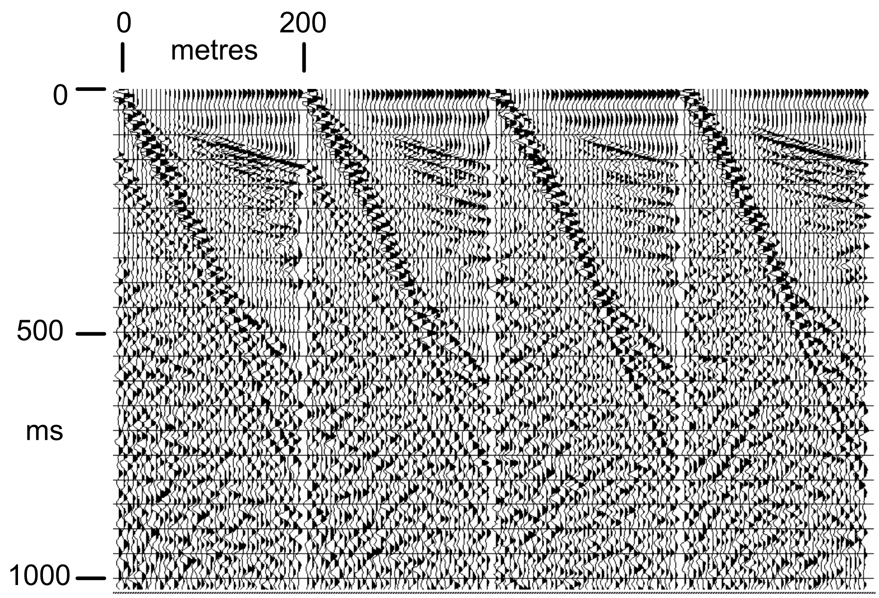


FIG. 8. Shaganappi shot records filtered with X-interpolated R-T filter.

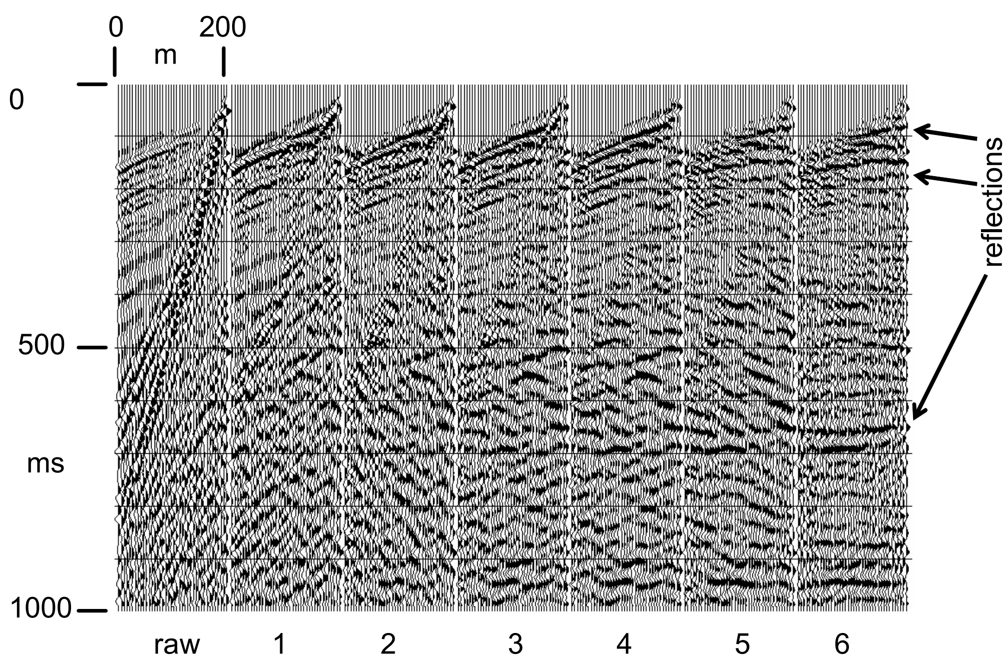


FIG. 9. Single Shaganappi shot gather showing successive passes of “new” R-T filters.

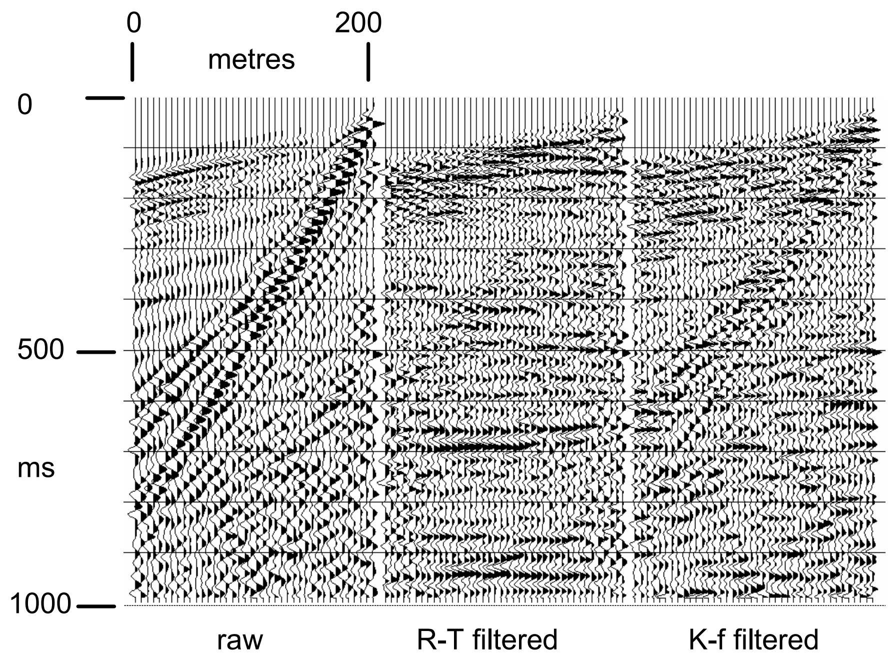


FIG. 10. Single Shaganappi shot gather showing comparison between R-T filtering and K-F filtering.

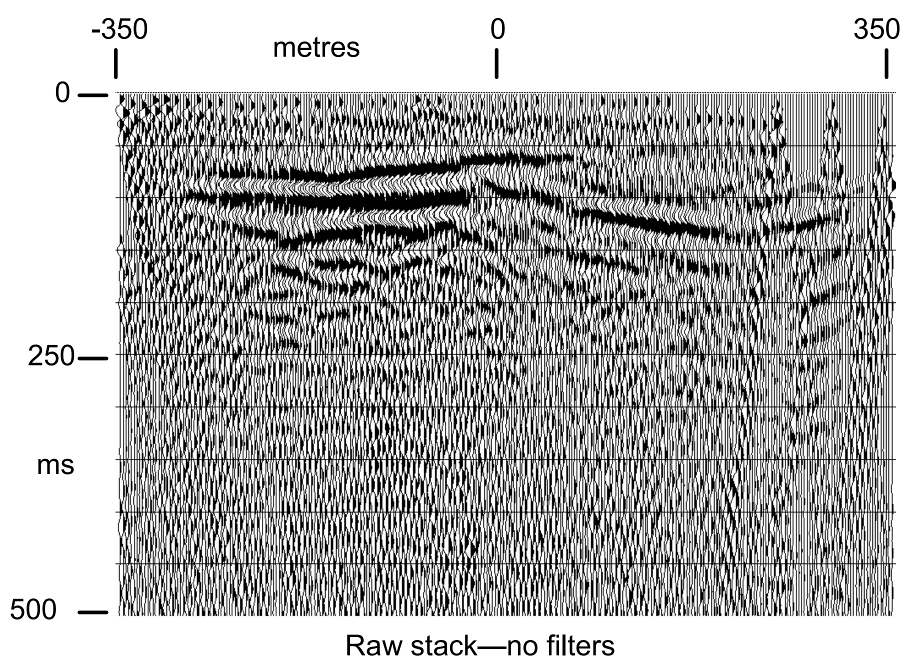


FIG. 11. Raw stack of Shaganappi seismic survey with no pre-stack filtering applied to shot gathers. Much of the visible coherent energy is fortuitously stacked refraction energy.

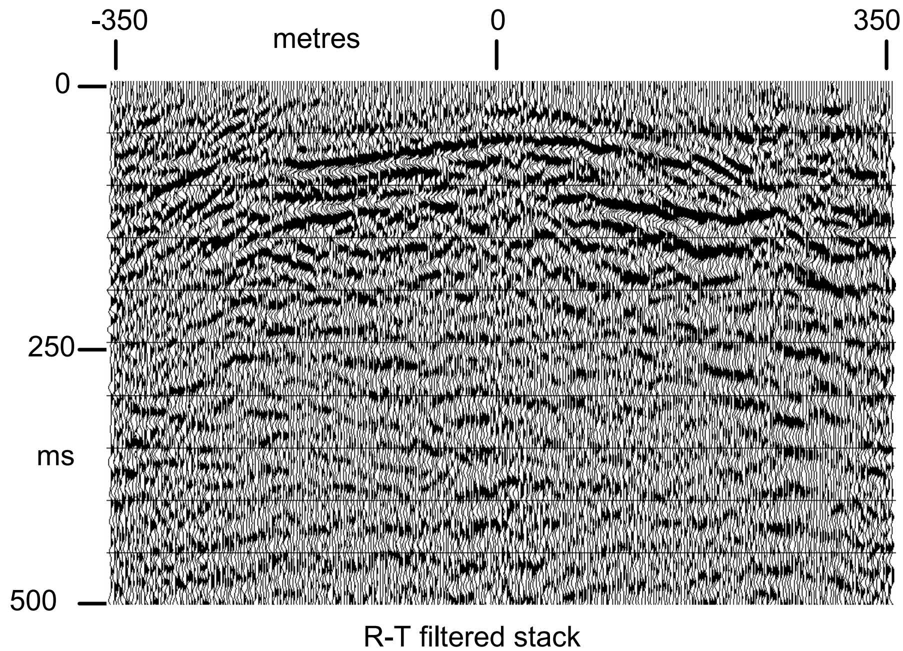


FIG. 12. Stack of Shaganappi shot gathers filtered with “new” R-T filters.

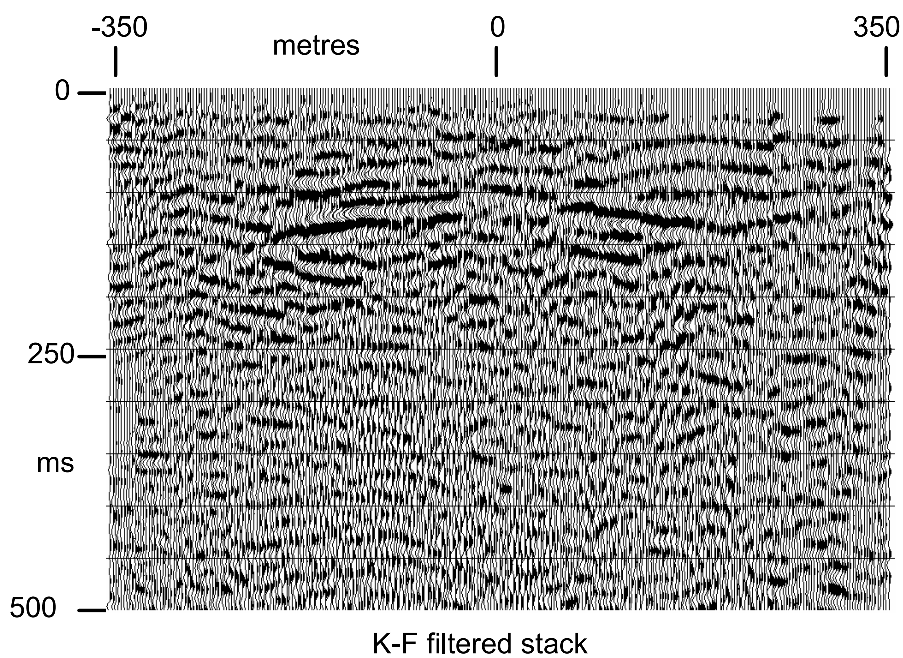


FIG. 13. Stack of Shaganappi shot gathers filtered in the K-F domain.