Radial filtering 3D data

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ABSTRACT

3D seismic data present a challenge for processors attempting to attenuate coherent noise, because the spatial sampling of coherent noise wavefronts by 3D field geometry is non-uniform. This means that attenuation processes which rely on regular sampling, like f-k domain techniques, require the data to be interpolated prior to filtering. One method which does not require regularization of the data before application is radial trace filtering. Since this method is based on an interpolated mapping of the original data traces to the radial trace domain, the source-receiver offset values of the original traces need not be regular. It has been found that receiver line gathers provide the best sampling of coherent noise, and therefore provide the best domain for attenuating this noise. A simple trace header preparation step is required to ready such gathers for radial filtering. A ProMAX module, **rad3d**, has been written to do the required trace header preparation and is demonstrated in this report.

INTRODUCTION

When 3D seismic data contain significant amounts of coherent noise, they present a unique challenge to processors. Sometimes the fold of the data is insufficient to guarantee sufficient noise attenuation by stacking; and the geometry of the acquisition layout means that obtaining ensembles of data which are uniformly spatially sampled for application of such procedures as f-k filtering is difficult and usually involves data interpolation of some kind.

The geometry of noise

At first consideration, it might seem that having a 3D assemblage of seismic data would enable a number of possible arrangements of seismic traces, which would facilitate application of standard noise attenuation processes. In actual fact, however, the typical 3D acquisition geometry used on land can generally be arranged in only one useful way to provide good filtering results on coherent noise. The difficulty is a consequence of the fact that 3D geometry, which usually consists of relatively widely spaced parallel receiver lines with closely spaced receivers, is designed to properly sample the surfaces of upcoming 3D reflection wavefronts, not coherent noise, which propagates as 2D wavefronts along the earth's surface, moving perpendicularly to most reflection energy. Figure 1 shows a typical 3D field geometry arrangement with coherent noise wavefronts (circles) superimposed. Figure 2 shows what the arrival pattern from a coherent noise wavefront would look like as recorded on each receiver line shown in Figure 1. Note that only for a receiver line which includes the shot location are the traces uniformly distributed in space. All other receiver lines have their traces distributed hyperbolically in source-receiver offset.

Sampling noise with trace gathers

There are many possible ways to organize the traces in a 3D data set to attempt to optimally capture coherent noise for attenuation. First, experience has shown that source-generated noise varies considerably in its characteristics from shot to shot, so that gathering traces from more than one shot provides no benefit, and can lead to disruption of the noise coherence. Within a single 3D shot gather, however, several possible ways to arrange the traces for coherent noise capture are:

- In order of increasing annular distance from the shot point
- In azimuthal 'wedge' ensembles, traces ordered by increasing annular distance from the shot point within each wedge
- In receiver line ensembles, traces ordered by increasing absolute source-receiver offset
- In receiver line ensembles, traces ordered by surface location number (as recorded)

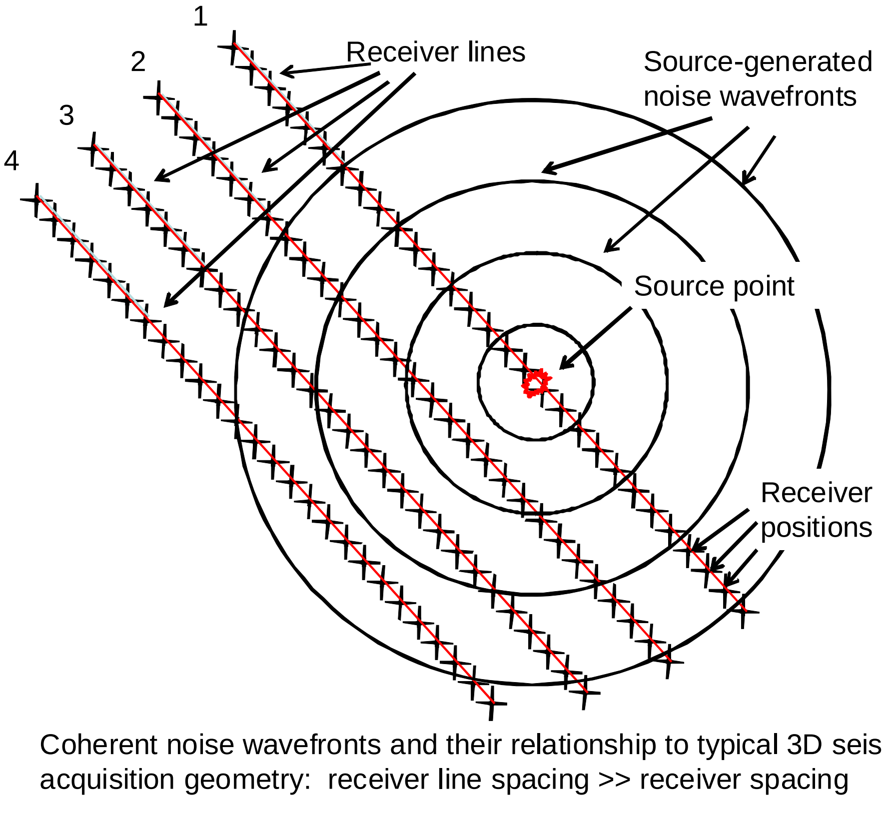
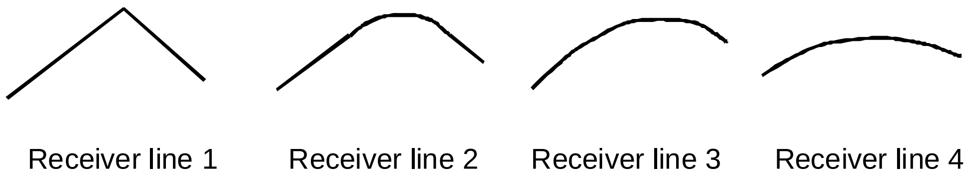


FIG. 1. Schematic showing how coherent noise wavefronts impinge upon receiver lines in a typical 3D seismic acquisition geometry arrangement. Source-generated coherent noise propagates either along the surface or parallel to it, so its wavefronts are circles centred on the source position.

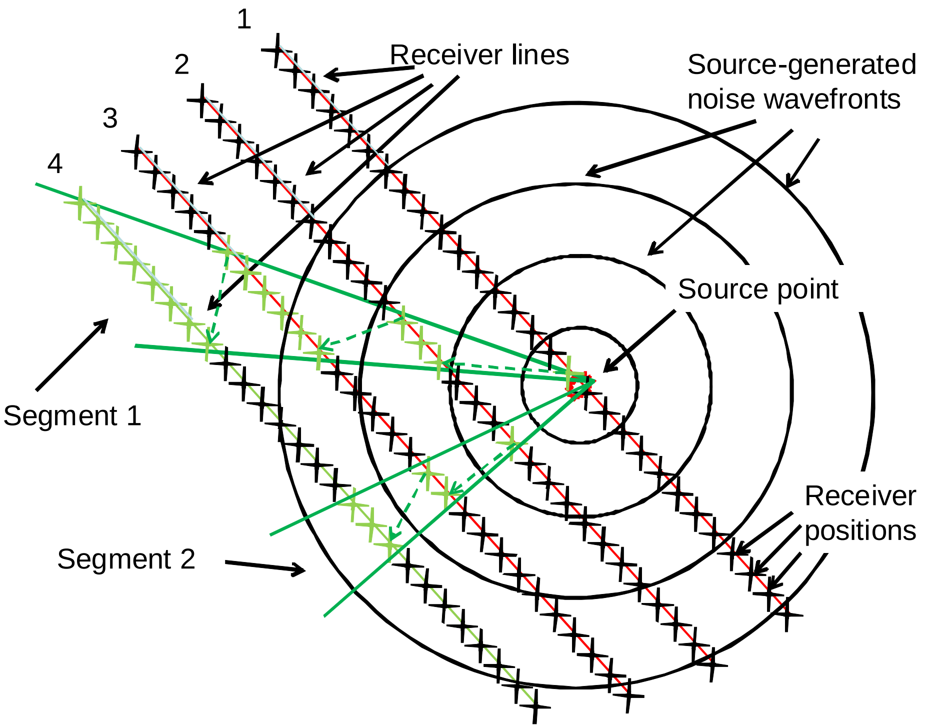


Wavefront arrival times as a function of receiver station (trace spacing) along each of the receiver lines in Figure 1. Only when the source point is on a receiver line will the arrivals be linear with trace spacing; but they are ***always*** linear with respect to ***source-receiver offset .***

FIG 2. Schematic showing typical coherent noise arrival patterns at each receiver line in Figure 1. Coherent source-generated noise is ***always*** linear with respect to source-receiver offset, regardless of its arrival pattern on receiver line gathers.

Experience has also shown that for most coherent noise, the event coherence (waveform shape and timing) is lost fairly quickly around the circumference of the wavefront, due to inhomogeneities in the earth's near-surface; so that only points on the wavefront in close proximity will be coherent enough to be useful for filtering purposes. The only one of the trace-gathering schemes described above which samples noise wavefronts at consistently closely-spaced intervals is the last. We have tried each of the others and found that because of their tendency to place in proximity in a gather traces which sample widely separated parts of a noise wavefront, the noise is simply not coherent enough with respect to source-receiver offset to filter effectively. While the azimuthal wedge ensemble might seem like a possibility, in that it restricts the portion of a noise wavefront to be sampled, Figure 3 illustrates the difficulty with this arrangement. For wedges perpendicular to the receiver lines, there will be groups of traces with nearly identical offset, but the gaps in offset *between* these groups will be large enough to alias any noise. For oblique wedges, on the other hand, receiver line segments within the wedge will sample coherent noise properly, but there will be coherence breaks between these segments where the part of the wavefront being sampled jumps from one boundary of the wedge to the other around the wavefront circumference.

Once we accept that receiver line gathers are the best domain in which to attenuate coherent noise, however, we still have to deal with the non-uniform distribution of source-receiver offset for any noise attenuation algorithm we use.



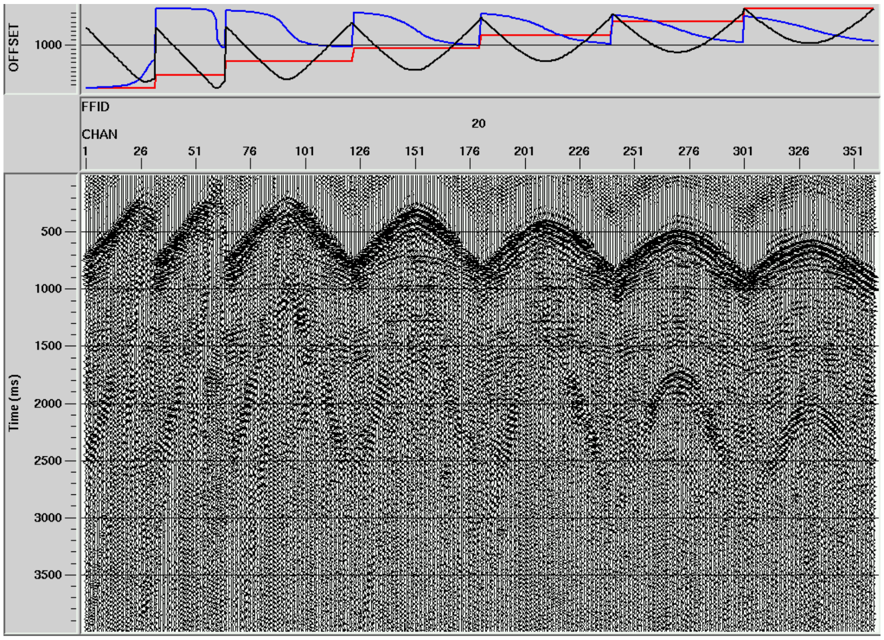
If traces are gathered by offset within angular wedges, either widely separated points on the wavefront are contiguous (segment 1), or offset distribution is too irregular to properly sample the wavefront (segment 2)

FIG. 3. Schematic showing a possible way to gather traces for coherent noise attenuation—sorted by ascending offset within a narrow angular segment (green wedges). For segments nearly perpendicular to receiver lines, however, large gaps in offset between the receiver lines mean that the coherent noise is badly aliased. For segments oblique to the receiver lines, the effective sampling of the coherent noise wavefronts shifts abruptly from one side of the wedge to the other (dashed arrows) as the segment boundaries intersect receiver lines, causing breaks in the coherency of the noise as viewed by the receivers. Individual receiver line gathers have the best-sampled and most coherent representations of the coherent noise, even though they are not ***uniformly*** sampled.

The radial trace domain

Most of the algorithms which filter seismic data, since they are based on integral transforms, require that the input data panels be uniformly sampled, both in offset and time. The radial trace transform, however, since it is just a point-to-point mapping has no such requirement. In fact, it has its own internal interpolation, which, in effect, establishes a uniform grid of points in offset and transit time and extracts values for each point of the grid from the input traces. This makes radial trace filtering a natural process for removing coherent noise from 3D data (Henley 1999, 2003a, 2003b).

Ever since radial filtering was introduced, it has been possible to apply it to 3D data; but the details have been tedious, since our filtering module uses the signed source-receiver offset in the trace headers to properly transform the data and recover them. For most 3D data sets, this trace header needs modification to be used by the radial filtering module. Specifically, the radial trace transform requires traces to be presented in order of increasing source-receiver offset. For a normal split-spread 2D shot gather, with negative offsets on one side of the shot and positive on the other, the traces are automatically in the correct order for processing. The offset trace headers in a typical 3D receiver line gather, however, are unsigned, and normally decrease from one end of the gather, to the position on the receiver line closest to the shot, then increase beyond that point, as shown in Figure 4.



Raw shot gather before pass of rad3d to modify offset trace headers

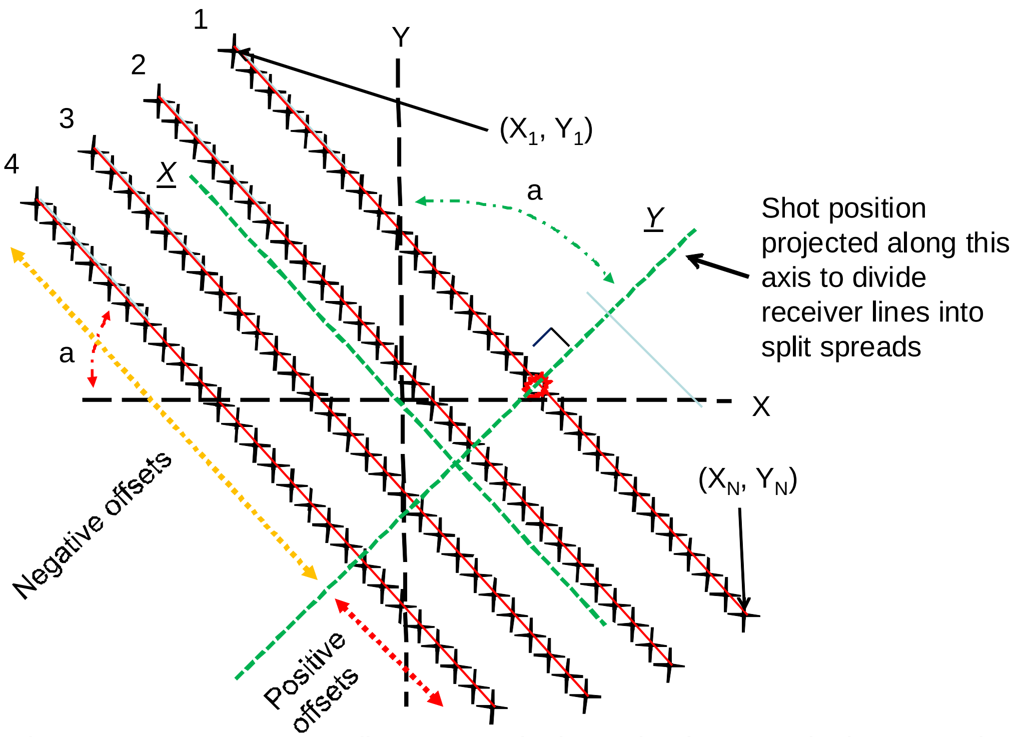
FIG. 4. Plot of a shot gather for a 3D survey. The black plot along the top of the gather is the source-receiver offset value (which is always positive by convention on 3D data). For each receiver line, the offset can be seen to decrease, then increase again beyond the receiver position nearest to the projected source position.

Furthermore, the receiver line stations nearest the shot often have almost the same offset value. Hence, any deviations from linearity of the receiver line itself can mean that offset values of these stations may not be in strictly monotonic order. Until recently, processors wishing to apply radial filtering to 3D data needed to set up various pre-processing schemes aimed at fixing the signed offset trace headers on the traces of receiver line gathers to make these gathers simulate split-spread shot gathers, and to ensure that these headers are in strictly monotonic increasing order. While this is not difficult to do, it can be tedious to anticipate all the circumstances which need to be addressed for a variety of receiver line gathers. To try to ease this burden for processors, we introduce here a ProMAX preprocessor module, **rad3d**, which will properly prepare most 3D land data sets for radial trace filtering by creating the appropriate signed offset trace headers, ensure that the data are segregated into receiver line ensembles with proper end-of-ensemble flags, and rearrange the order of nearest-offset traces, if necessary, to keep their offsets in strictly monotonic increasing order.

RAD3D

We constructed **rad3d** to make 3D receiver line gathers resemble 2D split-spread shot gathers. The usual convention with such gathers is for traces on the low-numbered side of the shot position to have negative offsets and traces on the high-numbered side to have positive offsets. Since most receiver line gathers do not include the source position, we adopt the convention of projecting the source position perpendicular to the receiver line and marking the intersection of this projection with the receiver line. Offsets to the low-numbered side of this mark are then made negative and offsets on the high-numbered side remain positive.

The arithmetic which accomplishes this projection and marking procedure is as follows: the azimuth of each receiver line with respect to the overall coordinate grid is determined using the Cartesian coordinates of stations near the endpoints of the receiver line. This azimuth is then used to rotate the coordinates of the source and receivers to make the receiver line parallel to the new coordinates; and these rotated coordinates are written to new trace headers. In this new system, the sign of the difference between source and receiver coordinates parallel to the receiver line determines the sign applied to the source-receiver offset headers. Figure 5 illustrates this procedure.



Rotation angle, a□for new coordinates $\underline{X}$, $\underline{Y}$ is determined from endpoints of each receiver line: $a = \text{atan}((X_N - X_1)/(Y_N - Y_1))$. In the new coordinates, receivers with negative $\underline{X}$ coordinates have their offsets negated, as well.

FIG. 5. Schematic showing the coordinate rotation procedure used by **rad3d**. For each receiver line, the angle between the line and the survey coordinate axes is determined. A new coordinate system is then constructed, in which one of the axes passes through the current source position perpendicular to the receiver line. The sign of the source-receiver coordinate difference along the receiver line then determines the sign of the source-receiver offset.

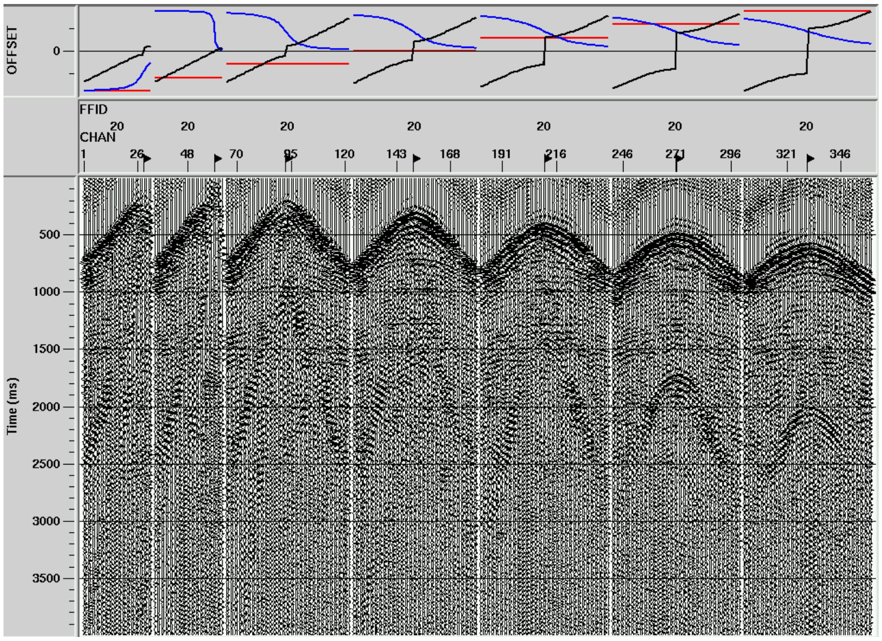
As a safeguard, **rad3d** also ensures that the input receiver line gathers are proper ensembles by flagging the last trace of each receiver line, using a new header, a second end-of-ensemble flag. For any processing subsequent to **rad3d**, the normal end_ens trace header can be set equal to the new end_ens2 flag using a 'Trace Header Math' process in ProMAX in order to ensure the integrity of the ensembles for those processes, like 'Radial Filter', which require well-organized trace groups.

DETAILS

Because we can't anticipate every possible configuration of data, the **rad3d** algorithm requires data to be presented either as discrete receiver line ensembles with proper end-of-ensemble flags, or as shot gather ensembles sorted by FFID or SOURCE, R_LINE, and CHAN. If, for some reason, the R_LINE trace header has not been created previously, data may be read in as a shot ensemble as long as it is sorted in receiver line order, and as long as each receiver line has the same number of channels. The appendix contains a copy of the documentation for **rad3d**, in which the various input possibilities are explained in more detail. The documentation also advocates following **rad3d** with an 'Inline Sort' operation as a final step to ensure that traces within receiver line ensembles are in strictly increasing offset order.

AN EXAMPLE

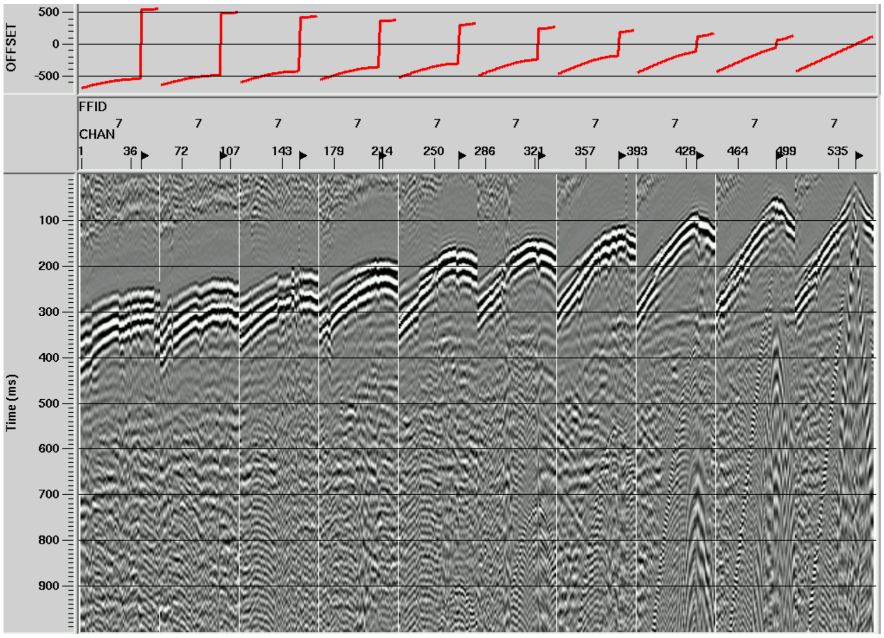
To illustrate the operation of **rad3d** on typical 3D data, Figure 4 shows a 3D shot organized in receiver line gathers. The trace header plot along the top of the figure shows the offsets as they originally occur in the trace headers, plotted against receiver line number, while Figure 6 shows the same shot after **rad3d**. Note the differences in the offset plot. The large discontinuities at the projected source position on each gather are normal, and do not affect radial filtering, since they simply mark the break between negative and positive offsets. Note that the 'Trace Display' used to create Figure 6 has posted shot location flags at the zero offset position of each receiver line ensemble, just as though they were split-spread shot gathers (albeit with rather odd receiver spacing).



Raw shot gather after pass of rad3d to modify offset trace headers

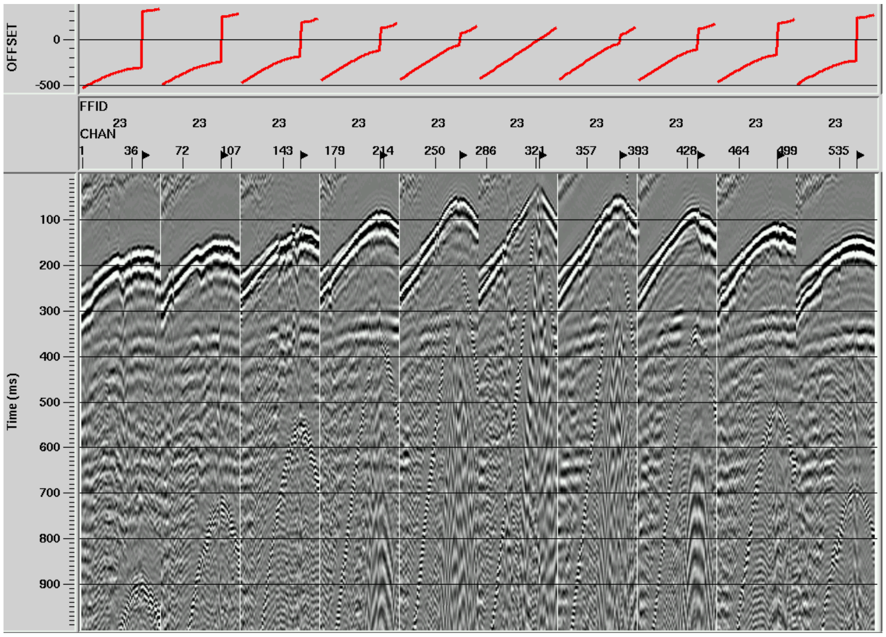
FIG. 6. 3D shot gather from Figure 4 after a pass of **rad3d**. The offset values for each receiver line are now monotonically increasing from negative values on one side of the projected shot position to positive values on the other. Also, since the gather has been broken into receiver line ensembles, the ensemble breaks are visible in the data.

To show the effectiveness of this header preparation, Figures 7 and 8 show two different shot gathers from a 3D survey, after their headers have been modified by **rad3d**, but before any filtering.



Raw shot gather after pass of rad3d to modify offset trace headers

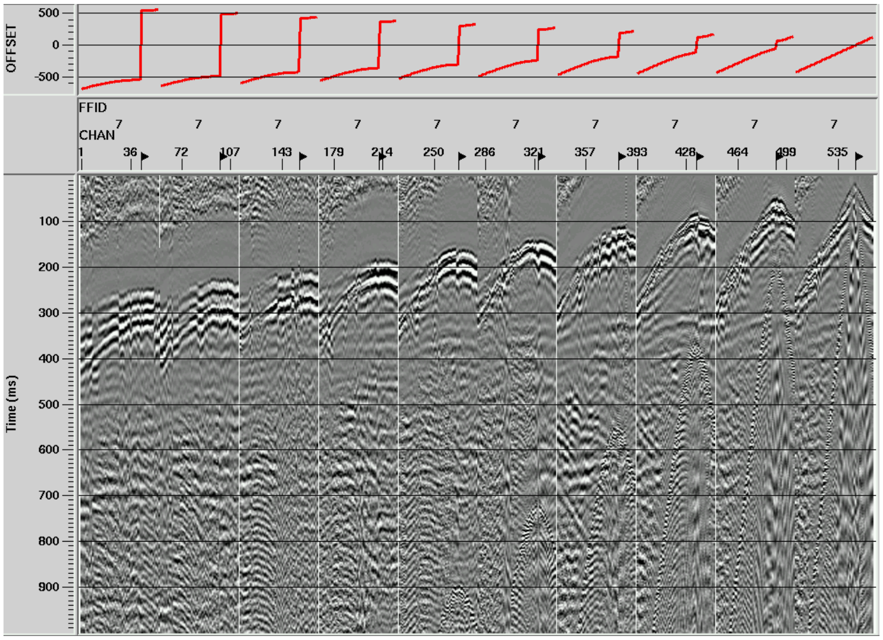
FIG. 7. 3D shot gather after header preparation in rad3d



Raw shot gather after pass of rad3d to modify offset trace headers

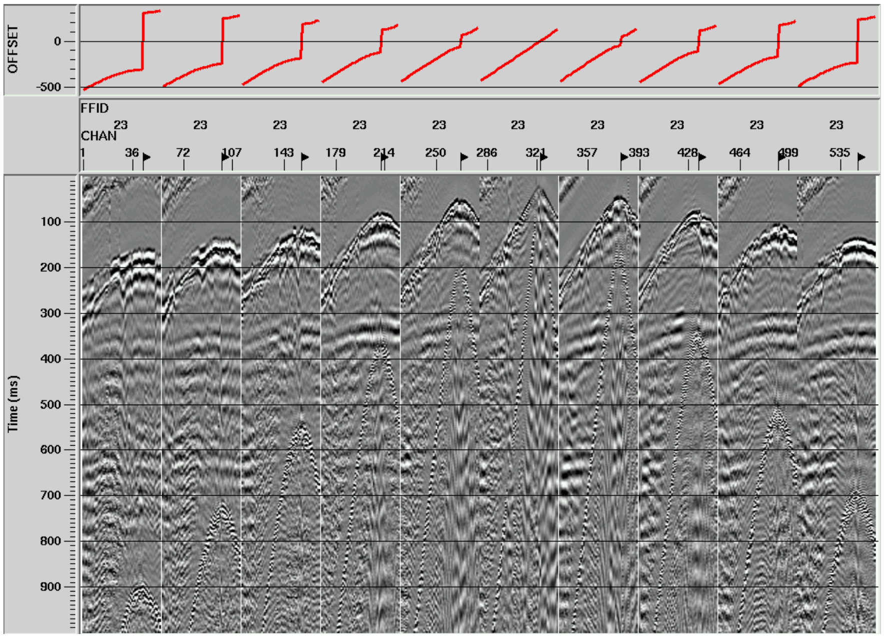
FIG. 8. 3D shot gather after header preparation in rad3d.

These gathers show fairly strong initial arrival noise and some relatively weak ground roll; but the acquisition parameters have led to aliasing of the ground roll. Figure 9 shows the data of Figure 7 after one pass of radial fan filtering, and Figure 10 shows the data in Figure 8 after the same pass of radial fan filtering.



Shot gather after pass of radfilt to attenuate coherent noise

FIG. 9. Shot gather from Figure 7 after a radial fan filter. First arrival noise has been somewhat attenuated; ground roll not much affected.

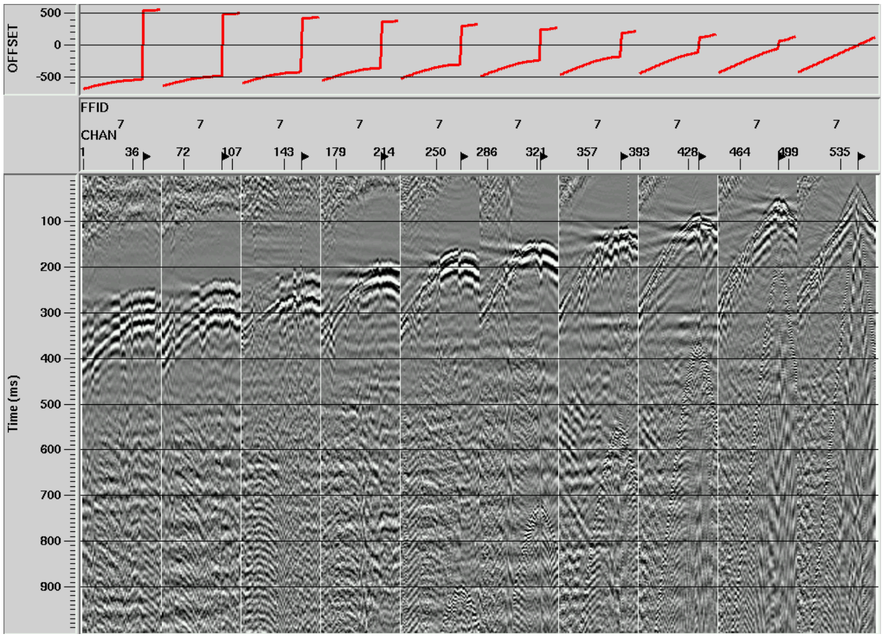


Shot gather after pass of radfilt to attenuate coherent noise

FIG. 10. Shot gather of Figure 8 after one pass of radial fan filter. First arrival noise has been attenuated significantly.

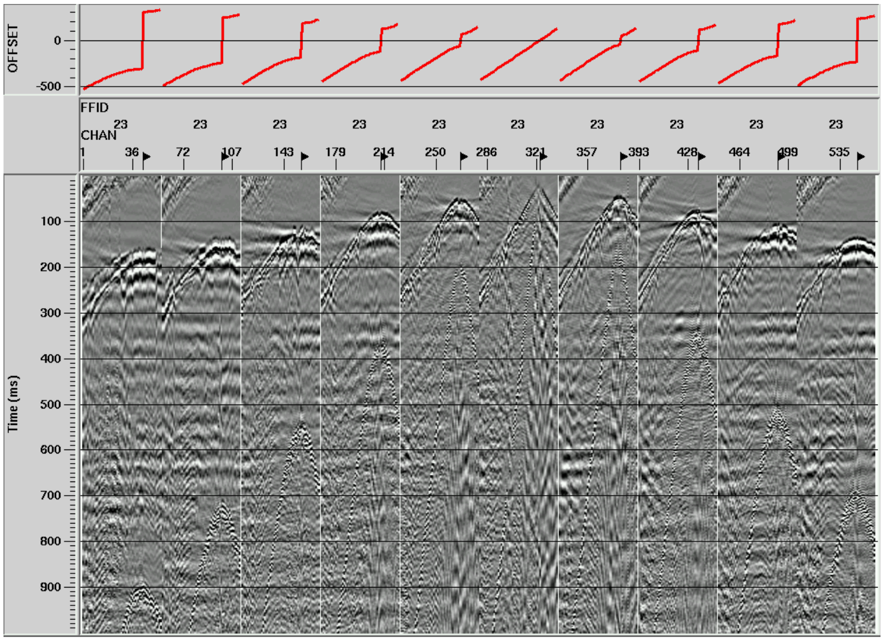
To show the effectiveness of further passes of radial filtering on these data, Figures 11 and 12 show the data in Figures 9 and 10, respectively, after a further four passes of radial filtering, this time with dip filters, each specifically designed to attenuate noise of a particular linear dip.

This particular 3D survey would not be a prime candidate for radial filtering because of its relatively high S/N; and improvement of the data by radial filter methods is not dramatic.



Shot gather after five passes of radfilt to attenuate coherent noise

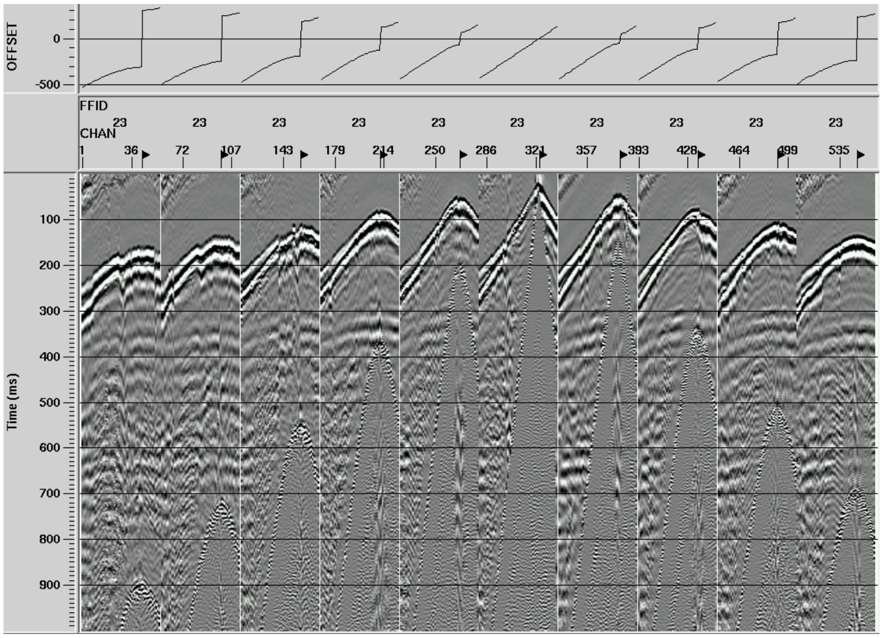
FIG. 11. Shot gather from Figure 9 after two additional pass of pairs of radial trace dip filters to attenuate specific linear noises.



Shot gather after five passes of radfilt to attenuate coherent noise

FIG. 12. Shot gather from Figure 10 after two additional passes of pairs of radial dip filters to attenuate specific linear noises.

A possible approach toward filtering ground roll in the radial domain is to apply a narrow fan filter in which the filter parameters within the fan strongly attenuate energy over a broad low-frequency band. This is a last resort, however, and is somewhat better than muting all the energy within this fan. Figure 13 shows this principle applied to the shot gather in Figure 8.



Shot gather after one pass of radfilt to attenuate noise in cone

FIG. 13. 3D shot gather in Figure 8 after application of broadband low-cut filter in the radial trace domain to a low-velocity fan (cone) in the centre of the gather.

CONCLUSIONS

We have advocated radial trace filtering as a viable method for removing coherent noise from 3D seismic data, and we have introduced a new ProMAX module to ease the burden of data preparation for filtering. Using simple arithmetic involving trace header values, the module, **rad3d**, prepares 3D receiver line gathers for the radial trace algorithms by fixing the offset trace headers to emulate split-spread 2D shot gathers.

ACKNOWLEDGEMENTS

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Henley, D.C., 2003, Coherent noise attenuation in the radial trace domain: Geophysics, **68**, No. 4, pp 1408-1416.

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APPENDIX

3D radial filter preparation—ProMAX documentation

This module is intended to be used in the data preparation for radial filtering of 3D land data organized as receiver line ensembles or shot ensembles. Its purpose is to create signed offset trace header values that allow the individual receiver line gathers to be processed by the radial trace filter module, or the radial trace transform module as if they were split spread shot gathers.

Theory

Attenuating source-generated noise on 3D seismic data is complicated by the typical irregularity of the acquisition geometry. For the most common 3D survey, each shot is recorded into a family of receiver lines. Since the spacing of geophone stations on a typical receiver line is smaller than the distance between receiver lines, a receiver line gather usually has the most coherent and least-aliased representation of the source-generated noise. For this reason, receiver line ensembles are usually the best environment in which to apply coherent noise attenuation.

Our standard radial trace modules, the radial trace transform (**radtran**) and the radial trace filter (**radfilt**), expect the traces in the input ensembles to be arranged by increasing source-receiver offset. For 2D trace ensembles (usually shot or receiver gathers), negative offset values denote traces on the lower-numbered side of the source (receiver) station, while positive values denote traces on the higher-numbered side. The algebraic sign attached to the offsets then ensures that the distances are in strictly increasing order over the whole spread.

With receiver line gathers from 3D surveys, however, there is no such convention, since most receiver lines are offset some distance laterally from the source position. In the usual 3D convention, the source-receiver offset header reflects just the magnitude of the offset and has no sign associated with it. These receiver line gathers can still be processed by radial trace modules, but the offset trace headers must first be modified to make the receiver line gathers emulate split-spread 2D source gathers. To accomplish this, the source position is projected perpendicular to each receiver line. All offsets on the low-numbered side of this projected position are negated, and all offsets on the high-numbered side remain positive.

If receiver lines are oriented exactly perpendicular to one or the other of the coordinate axes of the survey, offset values can be negated simply by comparing the inline coordinate differences between the source and each receiver. Negative differences mean negative offset values, and so forth.

Things are more complicated when receiver lines are oriented at an angle to the coordinate axes. If we can detect the angle, however, we can rotate the coordinate axes by that angle and once again use them to determine whether a given receiver position on any receiver line should be assigned a positive or negative offset value.

The 3d **radfilt** prep (**rad3d**) algorithm reads each receiver line gather, determines the angle with which it must be rotated to be perpendicular to the native coordinate system (by using the coordinates of two different stations near the ends of each receiver line), and applies simple trigonometric rotation to the source and receiver coordinates of the receiver line, creating new trace header values for the rotated coordinates. These rotated coordinates are then used to compare source and receiver positions to decide whether to assign positive or negative values to the offsets.

For receiver lines which are offset significantly from the source point, the source-receiver offset values for the several receivers nearest the source may be nearly equal. Due to local irregularities in the geometry, however, the offset values, even when the correct sign has been attached by the rotation operation above, may not be in strictly increasing order.

Such a condition leads to failure of radial trace algorithms, so a subsequent pass of the data through an 'Inline Sort' operation is recommended, to rearrange traces into strictly increasing order of signed offset.

Because **rad3d** operates exclusively on receiver line gathers, input traces must be organized either as receiver line ensembles, complete with the proper 'end-of-ensemble' flag in the trace headers, or as shot ensembles with the traces sorted internally into receiver line gathers. In the latter case, **rad3d** will break the shot gather into discrete receiver line ensembles using one of two methods: If the trace headers contain the receiver line number header, R_LINE, this header is used to find the ensemble breaks for the receiver line gathers. If this trace header isabsent, however, and all receiver lines have the same number of stations, the number of receivers per receiver line can be entered as a parameter, and **rad3d** will subdivide the shot gather into receiver line ensembles of equal numbers of traces.

Usage

Because we can't foresee all geometry conditions, the onus is on the user of **rad3d** to ensure that his input data accurately conform to one of the following cases:

Case 1: Traces are arranged in receiver line ensembles, sorted by receiver line, R_LINE, and channel number, CHAN, with proper end-of-ensemble flags in the trace headers.

Case 2: Traces are arranged in shot ensembles, sorted by field file, FFID, (or source, SOURCE), receiver line, R_LINE, and channel number, CHAN.

Case 3: Traces are arranged in shot ensembles, sorted by receiver lines, and each receiver line has the same number of stations.

Input data organized as in case 1 are the least likely to encounter problem with irregularities in geometry, but if there are known "wiggles" in the receiver lines due to avoidance of surface obstacles, **rad3d** should be followed by an 'Inline Sort' operation, sorting on R_LINE and OFFSET (ascending).

Case 2 is a common form of input, but **rad3d** must properly locate the ends of all receiver lines so that it can generate END_ENS flags for creating receiver line ensembles; so trace headers within the shot ensembles must be completely accurate, or problems can occur in **rad3d**.

Case 3 is a relatively uncommon occurrence. With this geometry, any deviation from trace count within the ensemble or within receiver lines will cause problems.

For cases 2 and 3, **rad3d** must be followed by a 'Trace Header Math' operation in which the formula is END_ENS = END_ENS2. This will complete the process of converting the receiver line gathers to separate trace ensembles. If there are significant wiggles in any of the receiver lines, or if there is a chance that R_LINE headers may be inaccurate in any way, an 'Inline Sort' operation (sorting on FFID, R_LINE, and OFFSET) should replace the 'Trace Header Math'. IN THIS 'Inline Sort', THE SECONDARY HEADER, R_LINE, SHOULD BE CHOSEN AS THE SORT KEY TO DETERMINE THE END OF ENSEMBLE. AS WELL, THE NUMBER OF TRACES IN BUFFER SHOULD BE EQUAL TO THE MAX TRACES PER SHOT GATHER, THOUGH THE NUMBER OF TRACES PER OUTPUT ENSEMBLE CAN BE THE MAX NUMBER OF TRACES EXPECTED IN A RECEIVER LINE.

BECAUSE DATA ALREADY ORGANIZED AS RECEIVER LINE ENSEMBLES ARE THE LEAST LIKELY TO ENCOUNTER PROBLEMS IN RAD3D, WE URGE PROCESSORS TO TAKE THE EXTRA STEP TO CREATE THESE ENSEMBLES.

After filtering the resulting receiver line ensembles with one or more passes of '**radfilt**' the offset headers should be reset to their initial values. This can be done with a 'Trace Header Math' operation using the equation 'OFFSET = AOFFSET'. The equation 'OFFSET = ABS(OFFSET)' should NOT be used, since some of the near-source offset values may have been adjusted to make the signed-offset values strictly increasing for input to '**radfilt**'. If, for some reason, the trace headers of the input data do not contain 'AOFFSET', then a 'Trace Header Math' statement with the equation 'AOFFSET = OFFSET' should precede the '**rad3d**' operation.

Caution:

The user should be aware that the 'radial trace transform' (**radtran**) operation destroys all trace headers in the forward transform, then stores a skeleton set of trace headers for the inverse transform. It regenerates the 'offset' headers by interpolation between 'minimum' and 'maximum' offset values stored in the radial trace headers. Since it uses either a linear or quadratic formula for regenerating offsets, it cannot recreate offset values which depart from linearity, the way that those in receiver line gathers do (hyperbolic).

For this reason, although **rad3d** will prepare 3D receiver line gathers which are acceptable for '**radtran**' in the forward transform mode, the inverse transform mode of '**radtran**' cannot recover the original receiver line gather offset values, and hence cannot invert the transform properly. Hence, '**radtran**' should be used only for radial trace diagnostics on 3D receiver line gathers, *never* for inverting previously transformed 3D receiver line gathers.

Parameters

There are two parameters for this process:

Number of stations in each receiver line -- As described above, if the input data have been arranged in ensembles which correspond to receiver line gathers, this parameter should be defaulted to 1. If the input consists of complete shot gather ensembles, however, but with receiver lines all having the same number of stations per line, that number should be entered into this parameter.

Flag to indicate the presence of the R_LINE trace header in the input data. If this flag defaults, **rad3d** assumes that the R_LINE trace header is present in the input data and uses the header to flag the ends of the receiver lines to form ensembles. If this parameter defaults, it forces the previous parameter to a value of 1. If the parameter is switched to 'R_LINE trace header absent', however, the value of the above parameter is used to locate the ends of receiver lines in order to flag them.

References

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