Multiple attenuation using the space-time Radon transform and equivalent offset gathers

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Summary

The removal of multiple-energy from seismic data continues to be a serious problem for imaging the earth's subsurface. Numerous techniques exist with varying degrees of success, complexity, and runtimes. Our approach uses the time-space domain Radon transform method in which multiple-energy can be separated from the desired reflection energy, but rather than use the traditional common midpoint (CMP) gathers, we use equivalent offset (EO) gathers.

EO gathers are prestack migration gathers formed using an offset defined by the acquisition geometry. High resolution semblance plots of EO gathers illustrate their ability to focus and separate the primary reflection energy from multiple- and mode-converted energy.

Introduction

High Resolution Radon transforms

A process that uses the Radon transform will typically transforms data from the space-time domain (x, t) to the tau-p domain (τ, p) where it is modified and then transformed back to (x, t) space. The reverse transform is a direct and simple task. However the forward transform, (x, t) to (τ, p), is a difficult task and only approximations, with varying degree of accuracy, can be obtained.

High resolution transforms may be approximated in the space-frequency domain (x, ω) (Sacchi and Ulrych 1995 or Trad et al 2003), which produce reasonably accurate transforms that match the inverse transformed data with the original data.

The use of (x, ω) space allows conventional linear inversion techniques to be applied in the estimation process. These inversions are suitable for linear and parabolic radon transforms, but require time stretching of the (x, t) space (t to t^2) to accommodate hyperbolic or higher order polynomial approximations to the trajectories.

A paper by Hampson (1986) used the frequency domain approach to reduce multiple reflection energy from common midpoint (CMP) gathers. He used normal moveout (NMO) corrected data that left the "multiple energy" with little curvature that could be approximated with a parabolic curve. This multiple energy could then be estimated and removed using the parabolic Radon transform.

However, high resolution transforms to (τ, p) space can also be accomplished in (x, t) space without using the (x, ω) domain (Thorsen and Claerbout 1985 and Bradshaw and Ng 1987). A companion paper by Ng and Perz in this collection of abstracts describes this process in more detail.

We prefer this approach, in (x, t) space, because there are a number of advantages that are:

- The hyperbolic Radon transform can be estimated without time stretching.
- Non-linear and more complex rational functions that include anisotropy effects can be used.
- The weighting of multiple-energy can be time varying, rather than that of a frequency spectrum.
- Amplitude versus offset (AVO) effects may be simply incorporated for accurate focusing and identification in (τ, p) space.
- The spacing of the "p" increments can be variable. Smaller increments produce better separation at small "p" values that are close to the primary reflections, and larger values are more economical at larger "p" values where there is greater separation of primary and multiple energy.
- The run-time of the (x, t) approach is usually less than a corresponding (x, ω) method.
- The (x, t) approach produces superior results with model data; however the difference in real data appears to be negligible.

Common midpoint gathers

The removal of multiple-energy is usually performed on data in common midpoint (CMP) gathers. However, a basic assumption of processing CMP gathers is that the reflection energy comes from horizontal reflectors. Compensation for the moveout of energy from dipping reflectors is accomplished with a stacking velocity that is approximated by the RMS velocity divided by the cosine of the dip angle. This produces a smearing of energy along the dipping events. In addition, the stacking velocities obtained in this manner do not represent the RMS velocities, and are not suitable for model building or migration.

The fold in a CMP gather is usually quite low and will have missing traces. Consequently a number of CMP gathers will be combined to produce a super-CMP gather. This process also smears dipping energy that is located at different times in each of the individual CMP gathers

Diffraction energy in a CMP gather does not stack.

Multiple attenuation using EO gathers and Radon transforms

Equivalent offset gathers

The equivalent offset method (EOM) (Bancroft et al 1998) is a prestack migration process that maps the energy from all input traces into prestack migration gathers that are formed for each migrated trace. The offset of this energy is dependent on the location of the input trace relative to the location of the migrated trace. In essence, the double-square-root (DSR) equation that defines the geometry of the input trace is equated to a hyperbolic equation that contains a single equivalent offset (EO). Energy at a given time on an input trace is mapped to a prestack migration gather with the same time, and with an offset defined by the equivalent offset.

Each input trace is now "stacked" into the prestack migration gather at the corresponding offset. The total number of input traces to each gather is equal to the number of prestack traces within the migration aperture. These input traces are spread over all offsets, creating very high folds in each of the offset traces.

Energy from reflectors below the migration location is focused to hyperbolic paths, while energy from neighbouring reflection points cancels. The RMS velocities at this location can be accurately identified from the hyperbolic moveout. The prestack migration is completed with moveout correction and scaling.

We refer to these prestack migration gathers as equivalent offset (EO) gathers (formally as common scatterpoint CSP gathers). These gathers may be formed for a prestack time migration using the RMS velocity assumptions as described above, or formed using raytracing or traveltime mapping for a prestack depth migration.

Anisotropic traveltime equations that incorporate higher order anisotropic approximations may be included in the DSR equation when estimating the equivalent offset. This process will still map the anisotropic data to hyperbolic paths on the EO gathers. In addition, EO gathers may be formed directly from data acquired on a rugged surface, in bore holes, or vertical marine cables. The acquired data may even be in any mode, including converted waves.

The maximum equivalent offset is not limited by the maximum source receiver offset, but by the size of the migration aperture. For example, a zero offset trace, distant from the migration location would be placed at a large offset in the EO gather as it may contain diffraction or dipping energy. Consequently, the EO gather can contain offsets that are much larger than a CMP gather, which is limited to the maximum source-receiver offset.

A prestack migration is more sensitive to velocities and is therefore more discriminating when summing the energy, providing a better attenuation of multiple-energy than a poststack migration. This becomes evident in the ability of EO gathers to separate multiple and primary energy, especially when viewing high resolution semblance plots.

The EO method is based on Kirchhoff migration principles and contains the benefits of arbitrary input geometry, and arbitrary output geometry. Each migrated trace can be computed separately and independently of all other traces. The method is much faster than comparable techniques as moveout correction, scaling, and antialiasing filters are postponed until after the gathers have been formed

Method

The energy of the primaries and multiples lie on hyperbolic paths in EO gathers, suitable for a hyperbolic Radon transform. It is this property that allows the hyperbolic Radon transform to focus the respective energy into more isolated locations for easier detection, identification, and separation. High resolution Radon transforms produce accurate semblance plots that are used for accurate velocity analysis. These accurate velocities are then used for moveout correction where the reflection energy becomes horizontal, especially when anisotropic properties are used in the formation of the gathers.

Multiple-removal can be accomplished before or after moveout correction. When applied before moveout the hyperbolic transform is required (without time stretching). After moveout correction is applied, the unflattened energy from primaries, multiples, or mode conversions is still hyperbolic. The small amount of moveout may be approximated by a parabolic trajectory for smaller offsets, typical of land data, but the longer offset with marine data may require that a hyperbolic transform be used.

Examples of EO gathers

Figure 1 contains a comparison between a CMP and an EO gather to illustrate the difference in coherent energy. It shows three panels of trace gathers at the same CMP location from land data over a sedimentary basin with a reasonably flat geology. The first panel (a) contains a CMP gather with the traces ordered with offset. The second panel (b) contains the same traces as (a), but the traces are now located at the source-receiver offset. Note that there are many missing traces making velocity analysis difficult. A super-gather of neighbouring CMP gathers could be formed to help fill in the missing traces, but that will only be of benefit for horizontal reflectors as the energy from dipping reflectors or diffractions would be smeared and attenuated. Figure 1c contains an EO gather. This EO gather has been formed from all the prestack traces within the prestack migration aperture of this CMP location. The input traces have been added into bins of the EO gather at their equivalent offset. Therefore, each trace in the EO gather is the sum of all traces falling in its bin, causing a reinforcement of the reflection energy that improves the signal to noise ratio. Energy in neighbouring EO gathers will have similar input traces, but they will have a slightly different geometry that reinforces the reflection energy at its own location.

Note that the hyperbolic nature of the move out is more evident in the EO gather than either of the CMP gathers and that more reflections are identifiable. Especially note the discrimination of events at shallower times.

Figure 2 illustrates the property of EO gathers that contain larger offset than a CMP gather. This figure uses data from a crustal study that extends to eleven seconds and the Moho is expected to be close to the bottom of the data.

Figure 2a contains a CMP gather and its semblance plot. Note that the velocities are only interpretable in the upper twenty five percent as multiples dominate the gather. That is not really obvious until we compare the results with the EO gather in part (b) of this figure. The EO gather has a much larger maximum offset and allows us to observe hyperbolic energy that is not obscured by the multiples. Especially note the hyperbolic energy towards the bottom of the EO gather below the black arrow. This high velocity event is well defined in the semblance plot of the EO gather, but is barely visible in the semblance plot of the CMP gather where it would have been considered to be noise. We believe that this reflection energy is from the Moho. It is the improved separation of the primary reflection energy from the multiple-energy in an EO gather that makes it more suitable for use in multiple-attenuation using the hyperbolic Radon transform.

High resolution semblance plots are illustrated in Figure 3 that contains a super-CMP gather and an EO gather with their semblance plots. The land data is in an area with horizontal reflectors where dipping reflection energy does not harm the super-CMP gather. Note the presence of multiple- and mode-converted energy on both semblance plots, especially the multiple-energy near the surface. We believe that the primary reflecting energy is more identifiable and separable in the EO gather than the super-CMP gather and is therefore more suitable for multiple-attenuation.

Figure 4 contains a CMP and EO gather at the same location from a marine line, illustrating the improved resolution of the EO gather.

Conclusions

A high resolution (τ, p) transform may be computed directly from the time domain without the need for converting to the frequency domain. There are many advantages of using the time domain that may make it a preferred choice for the identification and removal of multiple and mode converted energy.

The equivalent offset (EO) gather provides a data set that is superior to a CMP or super-CMP gather. The EO gathers provide a better signal to noise ratio, larger offsets, better resolution of the reflection energy, and velocities that are independent of dip. These features provide a better separation of the primary reflection energy, allowing a more effective attenuation of the multiple-energy.

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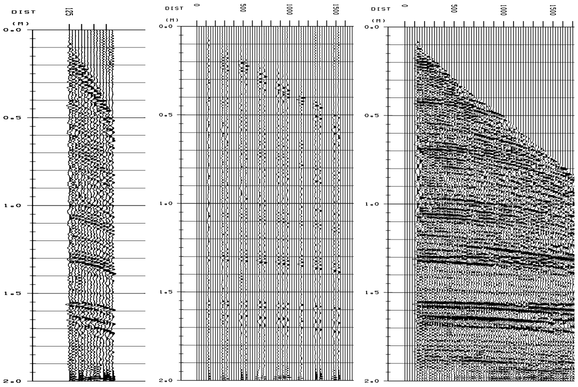
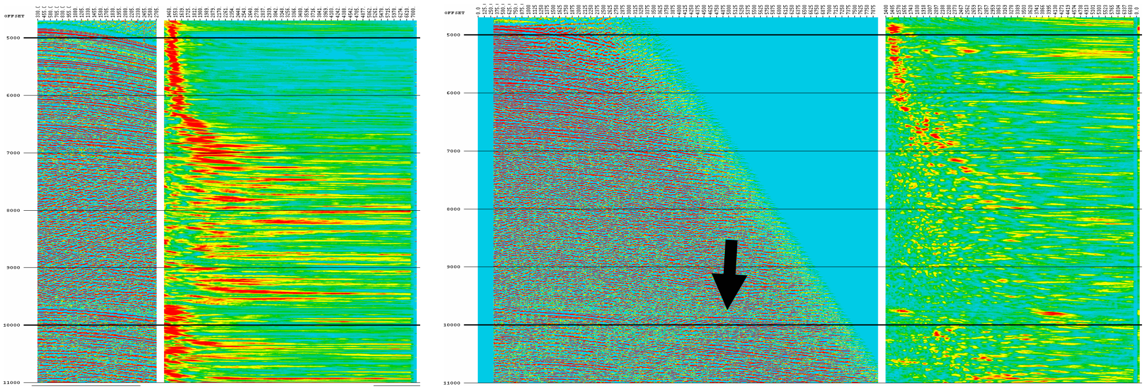


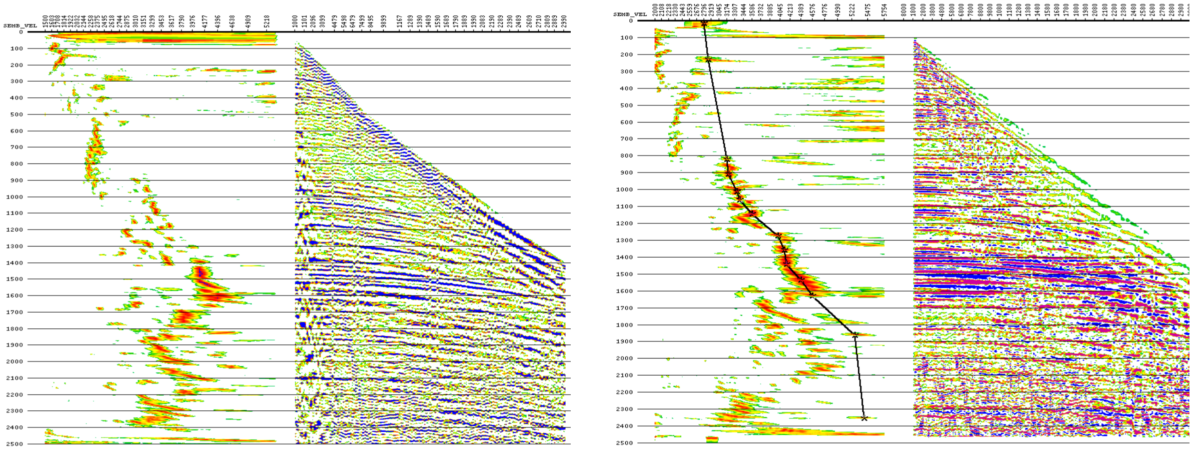
a) b) c)

Figure 1. Gathers at the same location with a) a CMP gather, traces ordered by offset, b) the same CMP gather, traces located at the source-receiver offset, and c) an EO prestack migration gather.



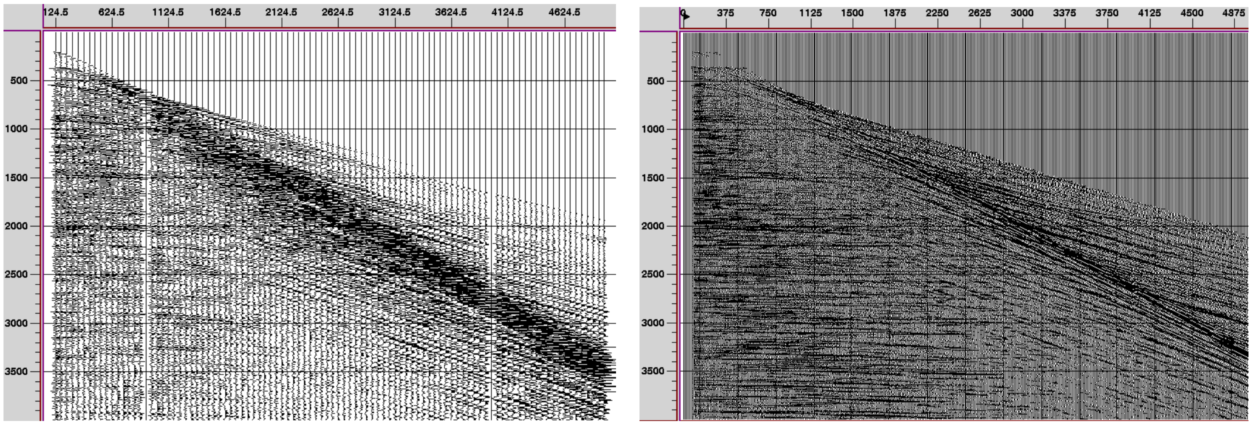
a) b)

Figure 2. Crustal data illustrating the offset differences between a) a super-CMP gather with its semblance plot and b) an EO gather with its semblance plot.



a b)

Figure 3. The differences in high-resolution semblance plots for a) a super-CMP gather and b) an EO gather.



a) b)

Figure 4. a) A CMP gather from a noisy marine line, and b) an EO gather at the same location.