To boldly go into a new dimension: 3D raypath interferometry issues

David C. Henley

CREWES, Geoscience Dept., Univ of Calgary

Summary

Raypath interferometry applies near-surface corrections to seismic reflection data in a raypath-consistent and wavefront-consistent manner. This enables nonstationary surface corrections, especially important for the S-wave leg of converted waves (PS). The method has been demonstrated on 2D seismic data sets, for both compressional wave (PP) and converted wave (PS) data. We recently devised a way to extend the technique to 3D 3C data and showed the first steps of its application to the vertical component (PP) of the Blackfoot 3D 3C survey. The work described here shows its application to the more difficult radial component (PS), and compares the Radial Trace and Tau-P transforms for moving seismic data to and from a 'common-raypath' domain, where the interferometry operation is performed. We anticipate a complete application of raypath interferometry to 3D data, including imaging, in the near future.

Introduction

Correcting land seismic reflection data for the effects of an irregular surface layer is a persistent problem in seismic data processing, and the problem is more difficult for shear-wave or converted-wave data. Fortunately, much seismic data can be corrected by the straightforward process of computing and applying time shifts to align reflection events on the individual traces before stacking them over common CMP or CCP. This process, known as residual statics correction, relies on the following two simplifying assumptions: the near-surface layer is much lower in velocity than underlying layers, enabling the 'surface consistency' approximation; and reflected (or converted) events arriving at the surface consist of a single arrival—no accompanying scattered or multi-path events. Henley (2012a) showed how surface consistency could be generalized to 'raypath consistency', with surface consistency as a special case; and he further showed how raypath consistency introduces nonstationary 'statics', or time shifts which can vary with transit time. Henley (2012a) also introduced the concept of surface effect removal by deconvolution of 'surface functions' from seismic traces rather than time-shifting the traces. Surface functions characterize not only the timing of a 'direct' arrival from a reflection, but also that of any multiples, scattered events, or multi-path events arising in the surface layer at specific locations. Furthermore, surface functions, with their inherent bandlimits, also capture the statistical time uncertainty of the event arrivals; hence the deconvolution of surface functions attempts to remove these various effects from the corresponding seismic traces, leaving a single consistent event arrival time and waveform from trace to trace. The detection and removal of surface functions by cross-correlation and deconvolution, and the adoption of raypath consistency are the two basic concepts embodied in raypath interferometry. The technique was first successfully applied to a set of 2D data from the Canadian Arctic in which surface-consistency and the single-arrival event assumption were both demonstrably violated (Henley, 2006, 2012a), then further demonstrated by application to other, more conventional data sets, including converted wave or PS data (Henley, 2012a, 2012b, 2014).

As has been convincingly shown by Cova et al (2013a, 2013b, 2014a, 2014b), most PS data violate the surface-consistent assumption for the shear-wave leg of the converted-wave travel path. They thus require nonstationary (time-varying) corrections, which makes a raypath-consistent approach the most appealing processing strategy for surface correction, regardless of whether interferometry is used as the mechanism to actually find and apply corrections.

Details

The common-raypath domain

The earliest implementation of raypath interferometry used the radial trace (RT) transform (Claerbout, 1975, 1983) to remap the X-T domain seismic traces to a raypath-dependent domain for computing and applying corrections. The reason for this transform choice is that the RT transform is relatively compact and exactly invertible, with no loss in data fidelity during a forward/inverse transform operation. Cova et al (2014b) have determined, however, that the Tau-P Transform is probably a superior pathway to the raypath domain, as long as the aperture for the transform is large enough to preserve most of the fidelity of the original data. The Tau-P transform has two further advantages: nothing need be known about the NMO velocities of events; and a commercial Tau-P transform and its inverse properly handle trace headers in both the X-T and Tau-P domains. Our CREWES-developed RT transform, however, only interpolates key headers linearly over an ensemble and forces the other headers to constant values, during transform inversion (Henley, 1999). This shortcut works well enough with 2D trace ensembles with nearly linear surface layout and regular surface station spacing, but fails with the irregular distributions of source-receiver offset values encountered in 3D trace ensembles.

The interferometry mechanism

There are many different applications of 'interferometry' described in the geophysical literature; but what they all have in common is cross-correlation of raw data traces either with each other or with summed raw traces, and the subsequent use of the cross-correlation functions to correct the raw data. Most applications, like the virtual source method (Bakulin and Calvert, 2006), use the summation of cross-correlations of one raw trace with a gather of similar traces to derive a Green's Function for the common trace, which can then be used to correct this trace to a datum. Our approach, however, uses the cross-correlation of a raw trace with the summation of raw traces within an aperture to estimate a 'surface function', which is then deconvolved from the original raw trace to correct the trace for the irregularity of its particular source or receiver surface point relative to the summed traces (Henley and Daley, 2007).

Most conventional autostatics programs use cross-correlations between pairs of raw traces, or between raw traces and 'pilot' traces (usually summed raw traces), but they use only the picked delay times of the largest correlation peaks to compute 'statics' or time shifts to apply to the seismic traces whose cross-correlations were used in the computations. Nearly all the cross-correlation information is thus discarded. Interferometry differs, however, in that each cross-correlation function is used in its entirety to deconvolve its corresponding primary trace, which results not only in a net time shift of the trace, but also correction of phase disparity between the primary trace and its corresponding pilot trace.

Raypath interferometry

Deconvolution of surface functions estimated by cross-correlation of data transformed to the raypath domain constitutes the technique we call 'raypath interferometry'. We have demonstrated the success of the method on several examples of field data (Henley, 2006, 2012a, 2012b; and Cova et al, 2013a, 2013b, 2014a, 2014b), not only for vertical component (PP), but also for radial component (PS) data.

Moving from 2D to 3D

3D surface function coordinates

One way to extend raypath interferometry from 2D to 3D is to make the surface function, first described by Henley (2012a) a function of 3 variables rather than 2, then to determine and construct the ensembles of raw 3D traces that most readily allow estimation and removal of these 3D surface functions from the data (Henley, 2016). Figure 1 shows 1D (static shift) and 2D surface functions schematically, then illustrates the extension to 3D by introducing a new independent variable, azimuth. In this construction, a 3D surface function is a time series (wavelet) whose shape describes the distribution, timing, and phase of reflection arrivals at a specific surface location, raypath angle, and source-receiver azimuth.

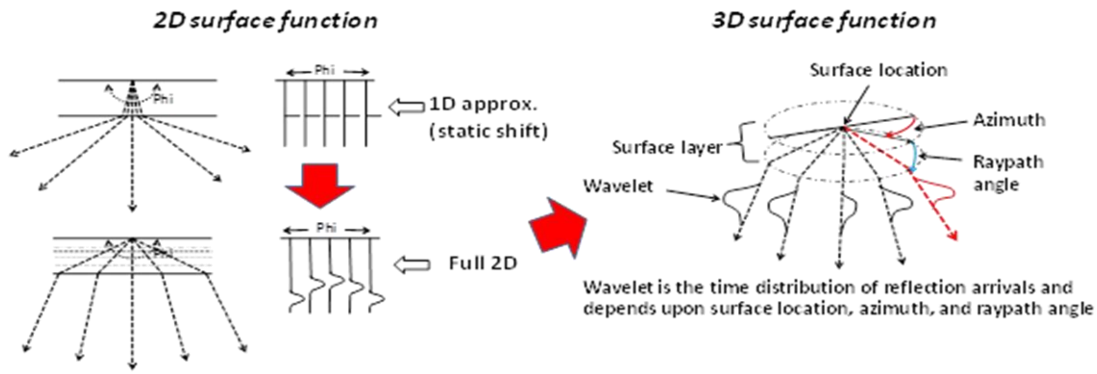

FIG.1. 3D surface function results from incorporating a new independent variable, azimuth, into 2D surface function.

Data coordinates

In order to extract and remove 3D surface functions from 3D seismic data, we must make the data compatible by introducing the source-receiver azimuth as a new dimension for seismic traces in a 3D survey. We can then extract ensembles of seismic traces whose raypath directions are reasonably coplanar, hence allowing us to map the data into a common-raypath domain, either via the Radial Trace (RT) Transform or the Tau-P Transform. Because 3D seismic surveys are usually laid out on a Cartesian grid, the main difficulty here is that of gathering the data into wedge-shaped azimuth bins where each common-azimuth ensemble is both well-populated and evenly sampled in source-receiver offset (Henley, 2016). For a thin azimuth wedge, where the trace raypaths are most nearly coplanar, the ensembles usually vary widely in the numbers of traces per ensemble, and the distribution of offsets is very irregular. A wide azimuth bin, on the other hand, while it leads to more uniform and regular trace distributions, departs from the 2D transform assumption that trace raypaths are coplanar within the ensemble.

Applying the method

The application of raypath interferometry to 3D data is quite straightforward, once the azimuth coordinate is introduced to the data set. Some experimentation with azimuth bin width may be necessary in order to optimize this parameter, as suggested above, but after the data are binned, the following steps constitute the application of raypath interferometry:

- Transform azimuth/offset-binned data to raypath domain (RT or Tau-P transform) and sort to common-ray-parameter ensembles
- Smooth common-ray-parameter ensembles in two dimensions to form reference wavefield ensembles
- Cross-correlate corresponding common-ray-parameter traces and reference wavefield traces
- Apply conditioned cross-correlation functions as match-filters to common-ray-parameter traces
- Sort common-ray-parameter ensembles back to Transform ensembles and invert the transform
- Form CMP or CCP image volume

The only way in which this differs from the 2D processing steps documented in previous work is in the 2D smoothing required for the reference wavefield ensembles.

Example-Blackfoot 3D 3C radial (PS) component

We show in Figure 2 a common-ray-parameter ensemble from the Blackfoot radial component data set. The uncorrected ensemble is shown on the left, while the corrected ensemble appears on the right. All 200 corrected ensembles like that on the right would next be sorted back to azimuth/ray-parameter ensembles and inverted to azimuth/offset ensembles. The RT transform was used in this demonstration.

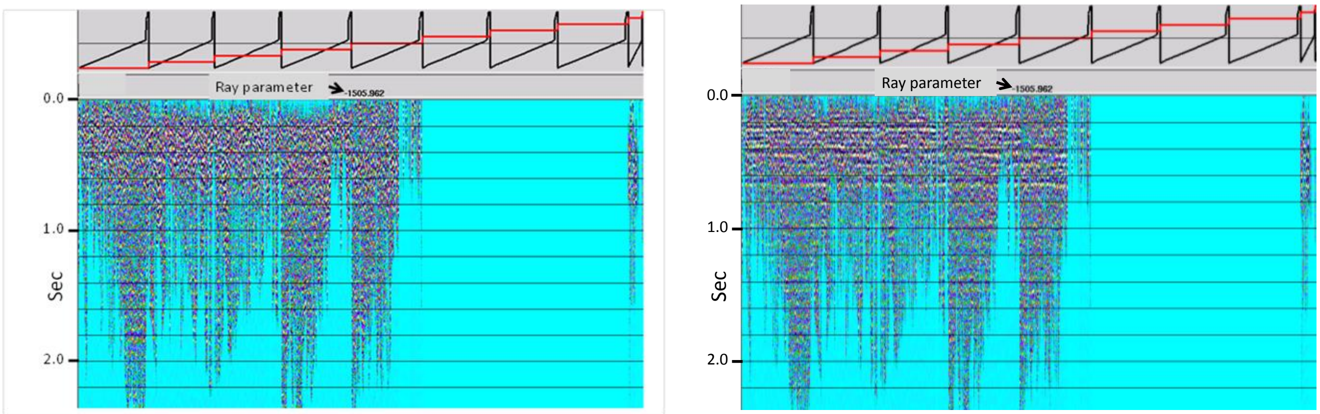

FIG. 2. Uncorrected common-ray-parameter ensemble on the left, interferometry-corrected ensemble on the right. Azimuth bins plotted in red, source station number plotted in black. There are about 70,000 traces in each ensemble. In the raypath domain, there are a total of 200 similar common-ray-parameter ensembles for the complete Blackfoot radial component data set.

Problems arising

In addition to the the azimuthal binning problem discussed earlier, the most significant difficulty for applying raypath interferometry to 3D data sets is the choice of 2D transform. The CREWES version of the RT transform, while relatively compact in terms of storage requirements, does not properly restore trace header information during inversion; but the Tau-P transform, while it restores proper headers, typically requires two orders of magnitude more storage for the transform, with appropriate resolution-preserving aperture parameters. Nevertheless, the Tau-P transform is likely the better choice for implementing raypath interferometry. Figure 3 (left) shows a typical azimuth/offset ensemble from the Blackfoot radial component data, while Figure 3 (centre) shows the result of a forward/inverse RT transform, and Figure 3 (right) shows the result of a forward/inverse Tau-P transform. The data distortions in Figure 3 (centre) are solely due to the improper trace header restoration in this algorithm, which would require a major rewrite to correct.

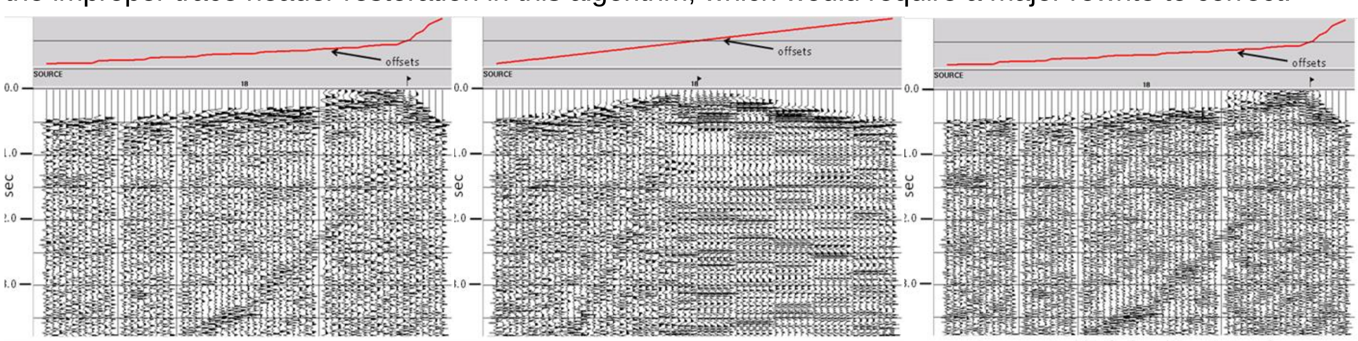

FIG. 3. Raw common-azimuth ensemble Forward/inverse RT transform Forward/inverse Tau-P transform

Conclusions

We have shown a viable approach for applying raypath interferometry to 3D data and expect to complete the inversion and imaging of both vertical and radial components of the Blackfoot 3D 3C survey in the near future, likely using the Tau-P transform, once data storage logistics are solved.

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