Raypath interferometry: statics in difficult places
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Summary
Successful seismic imaging relies not only on adequate sampling of the seismic reflection wavefield during data acquisition, but on the use of appropriate processing techniques to compensate the data for various effects introduced by the particular environment in which they were collected. We demonstrate here a technique designed to remove some of the distorting effects of the near-surface layer of the earth on the reflection wavefield. It differs from previous methods in that it does not assume surface-consistency or stationarity, as do most ‘statics correction’ methods, and it uses interferometric principles to apply corrections along raypath directions, rather than vertically.

Introduction
Among the earliest processing tools devised to help form seismic data into usable images of the subsurface are the so-called ‘statics-correction’ methods, which attempt to detect and remove time delays in seismic traces attributed to the transit of the recorded seismic energy through the relatively slow and highly variable material of the earth’s near surface. These methods have generally been very successful, except in certain regions, where near-surface conditions deviate from those assumed by the statics correction model.

When the near-surface consists of material lower in velocity than underlying layers, with local variations in thickness and/or velocity, deep seismic reflection energy travels nearly vertically through this region and is affected mainly by being delayed in proportion to the local variation of velocity or thickness. In this case, application of appropriate time shifts to seismic traces adequately removes the effects of near-surface irregularity. When the velocity of the near-surface is significantly higher than the underlying materials, however, as in Arctic permafrost regions (and some carbonate overthrust or surface volcanic flow areas); and if the near-surface layer is also irregular, reflection energy propagation becomes much more complex, and near-surface effects can no longer be adequately corrected by trace time shifts. Furthermore, conventional static corrections methods usually rely on ‘surface consistency’, due to assumed near-vertical seismic energy propagation, to solve for discrete time shifts for each source and receiver location on a seismic line. Representative early work on the statics correction problem can be found in Taner et al (1974) and Wiggins et al (1976), while later approaches are described in, for example, Rothman (1984a, 1984b, 1986) and Wilson et al (1994). The method we describe below neither requires surface consistency, nor is restricted to applying only one discrete time shift to each seismic trace. By transforming the data to a domain where the surface energy propagation angle is one of the principle coordinates, we provide a more natural environment for capturing variations in travel time along particular raypath directions in the near-surface, while, at the same time, providing a mechanism for what are, effectively, non-stationary (time-varying) corrections. Also, by using interferometric methods, we can correct for not only the single time delay of a main event arrival, but for multi-path arrivals as well, including short-period multiples and other portions of a seismic reflection scattered out of the direct raypath in the near-surface.

Method
We begin by transforming all the shot (or receiver) gathers into the radial trace domain (Claerbout, 1983), where each radial trace represents the seismic energy transmitted into the earth at a single injection angle (or received at a single angle, if you begin with a receiver gather). We then sort all the shot (receiver) radial traces by apparent velocity (which equates to injection or reception angle) and surface location, similar to creating common-offset gathers from conventional shot (receiver) gathers. The resulting gathers we call constant-angle gathers, and each one contains reflections sampled by energy propagating at a particular angle at the surface. Gatherers representing high apparent velocity (shallow propagation angle) capture mostly shallow reflections, since the raypaths don’t penetrate deeply before returning to the surface. Gatherers with low apparent velocity (steep propagation angle), on the other hand, can contain both shallow and deep reflections. Constant-angle gatherers are the primary processing media for our method. Appendix I shows a representative example of an angle gather.

In earlier work (Henley, 2006a), we presented a method which we termed ‘statics deconvolution’ for removing near-surface effects from seismic traces. Recently, we have acknowledged the relationship between that technique and the emerging field of seismic interferometry, in which trace cross-correlations are used for match filtering raw seismic traces (for example, Bakulin and Calvert, 2006). In brief, our earlier work described estimating ‘statics distribution functions’ embedded in raw seismic traces by cross-correlating these traces with ‘pilot traces’ consisting of stacked raw input traces. The ‘statics distribution functions’, were then used to derive match filters or inverse filters to remove their effects from the traces in which they were embedded. In recognition of the similarity of our technique to some of those in seismic interferometry, and because we apply it in the constant-angle domain, we term our method ‘raypath interferometry’.
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After obtaining a full set of constant-angle gathers, we create corresponding pilot trace gathers, one for each constant-angle gather. In early efforts, we merely applied a broad trace mix to each constant-angle gather to obtain its corresponding pilot trace panel. When seismic reflections are relatively flat-lying, this works well enough; but for structural areas, a more sophisticated approach is required. Our method involves selecting and picking two or three key reflections from the brute stack of the raw data to create horizon time files, which are used to separately flatten their corresponding windowed reflection events on each of the constant-angle gathers. We mix each of the windowed, flattened reflection trace segments, then remove the flattening corrections. Appending these mixed, windowed segments (in travel time) to form complete traces, we create composite constant-angle pilot trace panels. Although we pick the key reflection events only once, on the brute stack, we create a discrete pilot trace panel for each constant angle gather. An example of a composite pilot trace panel is shown in Appendix I.

The next step in our procedure is to cross-correlate the traces in each constant-angle gather with their corresponding pilot traces over a broad range of time shifts (typically +/- 200 ms). The resulting functions contain information from any and all correlations of reflections on the raw traces with their respective pilot traces. Typically, the shallow angle (high apparent velocity) constant-angle panel correlations represent mostly shallow reflections, while the high angle correlations contain more information from deeper events.

The correlation functions from the constant-angle gathers are ‘conditioned’ by raising them to an odd power to preserve sign and to whiten them without adding new peaks. The functions are then either used directly as match filters for their corresponding raw traces, or used to generate inverse filters to apply to the traces. The act of match-filtering or inverse filtering is the interferometric step which constitutes the ‘static correction’ procedure. Since we’re applying the procedure independently to every constant-angle gather, variation with raypath angle is properly compensated.

To complete the procedure, the match-filtered (or inverse-filtered) constant-angle gathers are sorted back into radial trace shot (receiver) gathers, and these gathers inverse transformed back to the X-T domain, resulting in corrected shot (receiver) gathers to be subsequently NMO corrected and stacked.

Example: MacKenzie Delta seismic line

Thanks to Shell Canada, for several years, we have had the use of a high resolution seismic data set from the MacKenzie Delta on which to test our methods. Unlike most other seismic surveys of the day, these data were recorded with single receivers, spaced 5m apart, and a moving spread 300m in length. The source was Vibroseis, so whenever the survey crossed ice-covered channels, abundant ice wave noise was generated. The channels were also associated with the worst ‘statics’ problems on the line, as is typical of the Arctic. The stack of this seismic line, after our best effort at coherent noise removal, is shown in Figure 1 (Henley 2006b).

In our first attempt to apply raypath-consistent statics, we used trace-mixed constant-angle panels for pilot traces, thus biasing results towards flat-lying layers. Figure 2 shows the result of using these pilot traces in the procedure described above. As can be seen, the obvious statics problems in the horizontal shallow layers, attributable to the unfrozen river channels, have been largely alleviated. However, the deeper structured layers have not been properly corrected by this procedure. Furthermore, there is an apparent statics ‘bust’ at the edge of the channel near the centre of the section.

Our next attempt selected an event located conformably within the obvious anticline on the stack of Figure 2. Its picked horizon times were applied to all constant-angle gathers as flattening corrections. Trace mixing was applied to the flattened constant-angle gathers; then the flattening corrections were removed to yield the pilot traces. The interferometry procedure was used to correct all the constant-angle gathers, whereupon the inverted and stacked seismic traces yielded an image (not shown) with good event continuity within the anticline, but with shallow events disrupted. It thus became obvious that statics functions derived to correct deep events were not appropriate to correct shallow ones, and vice versa.

Finally, we picked two separate reflection events, one above the unconformity, and one within the anticline and used each picked horizon to create its own set of pilot trace segments for each constant-angle gather. Shallow and deep pilot trace segments for each constant-angle gather were appended to create composite pilot traces representative of both shallow and deep events. Correlating these composite pilot traces with their respective constant-angle gather traces yielded match filters whose application to their corresponding traces corrected them for the significantly different effects seen by both shallow and deep raypaths.

Figure 3 illustrates the result of the full raypath interferometry method, using the two picked horizons. It is evident that this method allows different corrections to be applied to shallow and deep data, in such a way as to improve the image continuity of the entire section.

Discussion

When applying any method which uses interpreted horizons, care must be taken to honour the actual events and not to ‘phantom’ reflections through poor data zones, unless their continuity is strongly indicated by other evidence, such as the local geological setting.
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Figure 1: Brute stack of MacKenzie Delta seismic line; coherent noise attenuation and trace-by-trace deconvolution applied to shot gathers, no static corrections applied. Note major disruptions in structure and reflection continuity at all levels due to near-surface effects of three ice-covered river channels at the surface.

Figure 2: Stack of MacKenzie Delta seismic line; coherent noise attenuation, trace-by-trace deconvolution applied to shot gathers, raypath interferometry applied to constant-angle gathers before stack. Interferometry is based on simple horizontal horizon model for pilot traces. Note relative continuity of shallow reflections, but unresolved continuity/structural issues for deeper horizons. There is also a ‘static bust’ near the centre of the image, most evident at the level of the unconformity (about 300 ms).
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Figure 3: Stack of MacKenzie Delta seismic line; coherent noise attenuation and trace-by-trace deconvolution applied to shot gathers, Raypath interferometry applied to constant-angle gathers before stack. Interferometry is based on composite pilot traces created using two ‘picked’ events, one just above the unconformity, one following the anticlinal horizon whose crest is at about 800 ms.

Conclusions

We have demonstrated a method on real seismic data that effectively corrects the raw seismic traces for near-surface effects in a depth-varying manner. The key to the approach is analysis of the data in the radial trace domain; and the technique which allows simultaneous correction for all detected delays in the seismic reflections is a kind of interferometry.

Acknowledgements

We thank Shell Canada for the use of their high resolution arctic seismic line, and we gratefully acknowledge the support of CREWES sponsors and staff.

Appendix I

Below (Figure 1a) is an example of a constant-angle panel corresponding to the radial trace apparent velocity of -492 m/s. Note that for this injection angle, only the shallow reflections are manifested. A panel like this is created for every apparent velocity in the original radial trace transforms, and each is analyzed independently. Figure 1b is a representative composite pilot trace constant-angle panel, corresponding to the radial trace apparent velocity of -231 m/s.

Figure 1a: Constant-angle panel for -492 m/s apparent velocity

Figure 1b: Composite pilot trace panel for -231 m/s apparent velocity.