Using ray-path domain interferometry to address non-stationary S-wave statics
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SUMMARY

When the velocity change between the near surface and the medium underneath is relatively small, the vertical raypath assumption that supports the surface consistent approach for computing statics may be violated. This results in non-stationary statics that must be addressed. In this work the radial-trace (R-T) transform is used to move the data to a raypath consistent framework where the statics were showed to be approximately stationary. In this domain traveltimes interferometry was applied to retrieve the delays caused by the near surface. Cross-correlation of the delayed traces with a model trace free of statics was showed to return a cross-correlation function that carries the statics information. The analysis of the trend of the cross-correlation functions for different receiver locations showed that there is a link between the delays captured by these functions in the R-T domain and the traveltimes in the near surface at different raypath angles. Such information could be used in an inversion algorithm to retrieve a velocity model for the near surface.

INTRODUCTION

Computation of receiver statics for converted-wave processing is still an important concern. The solutions for P-wave statics that are used conventionally are not directly transferable to the S-wave statics problem. Difficulties in picking S-wave refracted waves generated from P-wave sources makes it difficult to use refraction-based statics solutions to solve the problem.

Henley (2012) introduced what may be classified as a reflection-coherency based method, since first break picks are not needed for removing the statics. This method is based on the concepts of interferometry and raypath consistency. Application of this approach has been demonstrated to be successful on field data for both for P- and S-wave statics. However, there has been found evidence on field data of non-stationary statics in the processing of converted-wave data (Henley, 2014 and personal communication, submitted SEG abstract, 2014)

In this work we show the robustness of “raypath interferometry” for addressing the non-stationarity of S-wave statics. Furthermore, we show how the delay times captured by the cross correlation function are linked to the structure of the near surface. This sets the stage for future characterization of the near-surface by inversion methods.

S-WAVE STATICS NON-STATIONARITY

Most of the traditional approaches for statics solution rely on the assumption of nearly-vertical ray-paths in the near surface. However, the low velocity of S-waves magnifies the delays produced by the violation of the vertical-raypath assumption.

Assuming a low velocity layer (LVL) with 100 m thickness and S-wave velocity $V_s=500$ m/s we get a vertical ray-path travel time of 200 ms. However, for a ray arriving with a deviation of 30° we get an additional delay of 30 ms. This delay is of the same order of magnitude as P-wave refraction statics and since it is not surface consistent, will not be solved with residual statics methods.

In Figure 1 (right) are shown the travel times for a PS ray tracing using the velocity model at the left. Notice that no P-wave velocity contrast was included in the near surface in order to avoid P-wave statics. Results show that reflection times with the same transmission angle in the LVL, i.e. the same static, are not located at the same offset. Furthermore, for the same offset, reflections coming from different depths show different transmission angles, hence they should receive different static correction. This imprints a non-stationary character to the S-wave statics problem.

To address the issue of a structurally complex LVL, elastic finite difference modelling was used to compute synthetic PS-wave shot records. Figure 2 shows the S-wave velocity model used for computing the synthetic data. As in the ray tracing, no changes in P-wave velocity were included in the LVL in order to avoid P-wave statics.

In Figure 3 is shown a raw radial component shot-gather with the most important events identified on the record. Around the 350m offset it is possible to see that the quasi-hyperbolic shape of the PS-event has been clearly deformed by the geometry of the near surface.

Figure 4 shows a zoom of the receiver gather located just above the statics anomaly seen in Figure 3. On this display traces were sorted by absolute offset so negative and positive offsets are mixed. In Figure 4 (top-left) there is a difference of about 22 ms between the reflection travel times for the 250m positive and negative offsets. On the other hand in Figure 4 (bottom-left) the deep reflector has just a 9 ms delay for the same offset values. Applying a constant shift to all the traces of this re-
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Figure 2: S-wave velocity model used for computing synthetic data by elastic finite-difference modelling.

Figure 3: Raw radial-component gather showing the most important features on the record.

If the receiver gather, honoring surface consistency, will result in poor stacking power and low resolution for these events. Hence, methods relying on the stack of common receiver gathers will produce suboptimal results if the non-stationary character of the statics is not addressed.

STATIONARITY IN THE RADIAL TRACE DOMAIN

The radial-trace (R-T) transform has the effect of approximately simulating seismic data recorded along straight raypaths, each of which has an associated ray parameter (Claerbout, 1975, 1983, 1985). Hence, statics may be computed in the common-ray-parameter domain in order to properly account for changes in the structure and in the transmission angle in the LVL. To study the consistency of the statics with the ray-path angles, receiver gathers were NMO-corrected and transformed to the R-T domain.

In Figure 4 (top-right) is shown a zoom around the ray parameter 500 m/s for the two PS events. The term “ray parameter” in this context, makes reference to the apparent velocity of the remapping done by the R-T transform. The shifts between consecutive traces, for both reflectors, now display a very similar value ($\Delta t_{R1} = 22$ ms and $\Delta t_{R2} = 20$ ms). This result is an evidence that in the ray parameter domain the static value for two different events is very close. The ability of the R-T transform to gather arrivals with a similar ray parameter leads to a better consistency in the static problem. The small residual shift may be due to the assumption of straight rays made in the application of the R-T transform.

INTERFEROMETRIC RAYPATH-CONSISTENT STATICS COMPUTATION

Figure 5 depicts the geometry of the converted-wave problem. One of the issues with converted wave processing is that of the asymmetry of the rays. Although the ray-path angles of the source leg and the receiver leg of a PS converted wave may differ, we assign a single ‘ray-parameter’ value for the combined path in the RT transform process. Tao and Sen (2013) proposed a mathematical framework for using seismic interferometry in the $\tau$-$p$ domain. The main idea they exposed is that cross correlation of raypaths with the same ray-parameter results in the cancellation of the shared paths.

Once the data are transformed to the R-T domain, cross correlation of statics-free data simulating the specular ray SOR in figure 5 with PS raw data may return the traveltime difference due to the delays caused by the near surface. Moreover, since the PP and PS raypaths share the same source-leg path which we assume is already free of statics (since we constructed it that way), the delays must be related to the receiver side statics. The process of retrieving traveltimes differences through the use of cross-correlation functions and removing them using convolution is an essential part of traveltime interferometry (Schuster, 2005; Bakulin and Calvert, 2006).

Figure 6 shows the workflow proposed for solving S-wave stat-
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![Sketch showing the geometry of the converted-wave static problem. Dashed paths represent a PS arrival affected by the LVL. The continuous path depicts the PS arrival we should get if there were no LVL.](image)

Figure 5: Sketch showing the geometry of the converted-wave static problem. Dashed paths represent a PS arrival affected by the LVL. The continuous path depicts the PS arrival we should get if there were no LVL.

ics in the R-T domain. This workflow was applied to synthetic data computed using the near surface S-wave velocity model shown in Figure 2 but including some structures in the reflectors. It is expected that under this condition raypath dependency is even more pronounced. This can be seen in Figure 7 (top), where we can see in the PS stack that the surface-consistent solution was not able to remove the statics from either event. Particularly in the zones where the LVL has larger dip, the right flank of the depressed feature in the shallow horizon can not be properly stacked. Moreover, the deep event is deformed, and although it is known to have a constant dip it shows some deformation imposed by the LVL.

Figure 7 (bottom) shows the ray-parameter-consistent PS stack. As we can see, the statics were effectively removed from both events. Both flanks of the depressed section on the shallow horizon are properly stacked and the deep event now shows the correct constant dip.

Cross-correlation analysis

In order to understand event timing information retrieved by the cross-correlation functions we compared them with the traveltimes computed for a given range of raypath angles in the LVL, at a fixed receiver location. In Figure 8 (top) we can see the ray-tracing done for a receiver located just above a flat segment of the LVL. Figure 8 (middle) shows the traveltimes for each one of the raypaths displayed in the ray-tracing. For a flat LVL, the variation of the traveltimes as a function of the raypath angles is in the form of \( t = (h/v)(1/\cos(\phi)) \), where \( h \) is the vertical thickness of the LVL, \( v \) is the velocity in the LVL and \( \phi \) is the raypath angle measured respect to the normal of the base of the LVL. The important result here is that the cross-correlation functions showed at the bottom of Figure 8 display a similar trend. However, these cross-correlation functions were computed in the R-T domain, hence each trace represents a slope in X-T and not a direct raypath angle. A relationship between these two variables must be derived in order to link the delay times captured by the cross-correlation functions in the R-T domain with actual raypath angle.

![Workflow for solving S-wave statics in the R-T domain using traveltime interferometry.](image)

Figure 6: Workflow for solving S-wave statics in the R-T domain using traveltime interferometry.

![Stacked PS sections using surface-consistent (top) and raypath-consistent (bottom) static corrections.](image)

Figure 7: Stacked PS sections using surface-consistent (top) and raypath-consistent (bottom) static corrections.
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In Figure 9 the same analysis is done but at a receiver location where the LVL is dipping. In this case we can still note that the new trend in the traveltimes imposed by the dip of the LVL is reproduced by the cross-correlation functions. For the case of a dipping LVL the traveltimes in the LVL as a function of the raypath angles can be computed as $t = (h/v)(\cos(\theta)/\cos(\phi + \theta))$, where $\theta$ is the dip at the base of the LVL. These results justify our continuing efforts to use such cross-correlation delays for characterizing the thickness, dip and velocity of the LVL.

CONCLUSIONS

Unlike some surface-consistent statics techniques, like refraction statics, which require time-consuming event picking, interferometric statics are derived and applied using only cross-correlation and convolution. Furthermore, for converted-wave data, the raypath consistent approach produces results superior to conventional surface-consistent statics when the LVL exhibits structural complexity, or the events beneath the LVL contain a structural component. Both situations lead to non-stationary statics, for which a raypath-consistent approach outperforms conventional surface-consistent statics.

The delays captured by the cross correlation functions in the R-T domain may be related to the travel times in the near surface at different raypath angles. Inversion of these delay times may lead to characterization of the thickness, dip and velocity of the near surface, in a way similar to refraction methods but without the time consuming and error-prone task of first breaks picking.

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