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Angle-dependent Water Column Statics Correction through Sparse TauP Inversion

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SUMMARY

Water column statics caused by tidal variation and water velocity change during seismic surveys is one major source of noise in marine 4D projects. Correction of this statics effect is a key step in any marine 4D processing. Applying water column statics correction requires a good knowledge of the distance or surface take-off angle when waves travel through the water column, which conventional methods such as ray tracing are not able to obtain accurately when the subsurface velocity is complex.

We propose a new method to apply water column statics correction through progressive sparse TauP inversion. This method does not need prior inputs of subsurface velocity and reflector dips, as required for ray-tracing methods, and benefits from the progressive sparse TauP inversion engine that can properly handle spatially aliased marine seismic data and mitigate energy leakage in the TauP domain.

We demonstrate the effectiveness of this new method using synthetic ocean bottom seismometer (OBS) data derived from a SEAM velocity model and using real OBS data from 4D surveys over the Atlantis field in the Green Canyon area of the Gulf of Mexico (GOM).

Introduction

Water column statics, as a result of tidal variation and water velocity change, is one major source of noise in marine 4D projects. Residual water column statics often leak into 4D time-shift and amplitude attributes when the statics error is large, which can obscure 4D interpretation. Therefore, applying water column statics correction is a critical step in marine 4D processing.

A good water column statics correction starts with an accurate estimation of the time-variant water velocity and tidal changes that occur during seismic surveys. Much effort has been devoted to attaining a good estimation of these quantities, e.g., through traveltime inversion of seismic data (Udengaard and Kraft 2012), or direct measurements with innovative instrumentation (Wang *et al.* 2012). Water-column changes can be inverted for base and monitor surveys independently, or by estimating a relative statics change between base and monitor surveys by examining their relative time shifts across offsets (Lacombe *et al.* 2006). However, applying corrections for these static effects on seismic data is still rudimentary. Common practice is to use a zero-angle approximation, or apply angle-dependent corrections through an NMO approach that assumes a simple velocity and works on primary reflections only (Lacombe *et al.* 2006).

Applying an accurate water column statics correction requires a good knowledge of the distance or surface take-off angle when waves travel through the water column. Conventionally, this information is obtained through 1.5D ray tracing, which assumes flat reflectors and a simple 1D velocity model, or through target-specific 3D ray tracing on a geological horizon in a more realistic velocity model. In either case the problem is oversimplified, and when complexity exists in the overburden, e.g. salt bodies are present, the results obtained through ray tracing can be compromised.

Surface take-off or incident angles can be computed in the *f-k* or *f-p* transform of a common-receiver (OBS) or common shot (towed streamer) gather, respectively. However, direct *f-k* or *f-p* transforms cannot handle marine seismic data that is often sparsely acquired and thus exhibits spatial aliasing of the high-frequency content. Here we propose a new method to apply water column statics correction by obtaining the surface take-off angle through progressive sparse TauP inversion (Wang and Nimsaila 2014), which is equipped to handle data with strong spatial aliasing and mitigate energy leakage among different ray parameters. Furthermore, because large static shifts in the data can result in leakage in the TauP domain, we embed the static operator within the sparse TauP inversion instead of applying the static correction directly on the TauP representation of the input data. We demonstrate this method on synthetic OBS data with the SEAM model and on real OBS data from the Atlantis field in the Green Canyon area of the Gulf of Mexico.

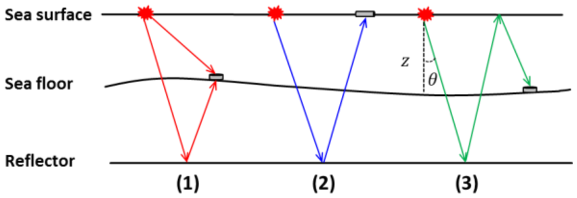

Figure 1 *Ray paths of different primary wavefields recorded in ocean bottom seismometer (OBS) and towed streamer. (1) OBS up-going wavefield and direct arrival with one trip, (2) wavefield recorded by towed streamer with two trips and (3) OBS down-going wavefield with three trips through the water column. Here* θ *denotes the shot-side surface take-off angle and* z *is the water bottom depth. Surface multiples not shown here will have more trips through the water column.*

Method and Theory

Assuming the tidal variation dz, relative to the mean sea level, and the water velocity change dv, relative to a reference velocity v_0 (usually water velocity in the migration model), are both known, the change of traveltime in the water layer can be expressed as follows:

$$dt = n\left(\frac{dz\cos\theta}{v_0} - \frac{zdv}{v_0^2\cos\theta}\right) \qquad \text{... (1)}$$

where z is the water bottom depth relative to the mean sea level, θ is the surface take-off angle and n denotes the total number of legs of the wavefield passing through the water column (Figure 1). In the sparse TauP domain, $\cos\theta$ can be expressed as the function of ray parameters p_x and p_y as $\cos\theta = \sqrt{1 - v^2 p_x^2 - v^2 p_y^2}$. When n > 1, we assume all the legs in the water column travel at this same angle.

One possible approach to apply water column statics correction in the TauP domain is to apply the statics correction operator on the TauP representation of the input data, and then reverse transform the corrected TauP model to obtain the statics-free data as described in **Method 1**:

1. Obtain TauP representation of the input data
$$D(f; x, y) = L(f; p_x, p_y; x, y) P_s(f; p_x, p_y) \qquad \ldots (2)$$
2. Apply reverse statics operator and reverse TauP to obtain the statics-free output data
$$O(f; x, y) = L(f; p_x, p_y; x, y) S^*(f; p_x, p_y; x, y) P_s(f; p_x, p_y) \qquad \ldots (3)$$

Here D is the input data with statics error, P_s is the TauP model with statics, L is the reverse TauP operator, $S^* = e^{-i2\pi f \cdot dt}$ is the statics correction operator with dt defined by equation (1), and O is the statics-free output data. One potential problem with this direct approach is that large statics errors can cause energy leakage in the TauP model and lead to inaccurate statics corrections.

To overcome this problem, we propose to include the statics operator $S = e^{i2\pi f \cdot dt}$ in the TauP inversion and solve for a statics-free TauP model P as described in **Method 2**:

1. Obtain statics-free TauP representation of the input data
$$D(f; x, y) = L(f; p_x, p_y; x, y) S(f; p_x, p_y; x, y) P(f; p_x, p_y) \qquad \ldots (4)$$
2. Apply reverse TauP to obtain the statics-free output data
$$O(f; x, y) = L(f; p_x, p_y; x, y) P(f; p_x, p_y) \qquad \ldots (5)$$

Combining the statics operator in the inversion can better explain the input data and avoid any errors in deriving the TauP model that may be caused by large statics shifts. We observed this approach to be effective in handling data with relatively large statics errors.

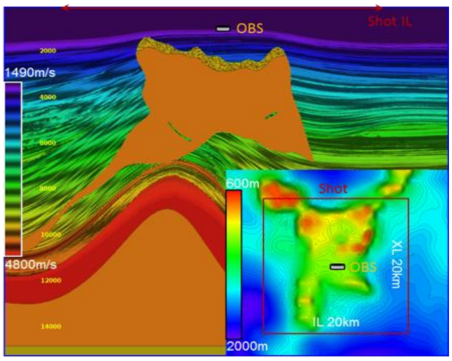

Figure 2 *OBS receiver location and shot coverage area overlayed with SEAM velocity model and water bottom depth map (inset). The synthetic OBS down-going wavefield is generated at a location with a rugose water bottom and a complex subsurface that includes shallow carapace and salt.*

Synthetic OBS Data Example

We validated this method with synthetic OBS data using the SEAM velocity model. The node sits on the water bottom at a depth of 1060 m and above a complex shallow carapace and salt body (Figure 2). The shot coverage extends 20 km in both inline and crossline directions, covering an area with a rugose water bottom that varies from 600 m to 1800 m. We generate three sets of down-going wavefields in mirror velocity models with constant water velocities at 1485, 1490, and 1495 m/s, respectively. All the synthetic data has a maximum frequency of 30 Hz and a shot spacing of 40x40 m without ghost or surface multiples.

We then picked every three shot lines from each synthetic data set with different water velocities, and put them together to form an input data with a repeated pattern of velocity errors at -5, 0, and 5 m/s, as shown in Figure 3a. We can see abundant diffraction and refraction energy related to the complex subsurface in both the crossline and time-slice views as well as jitters related to the velocity errors. This type of high-frequency velocity variation across shot lines is not typically seen in real acquisition, but it serves well to illustrate the difficulty Method 1 may encounter. Many artefacts are generated and lots of jitters still remain after applying the Method 1 water column statics correction (Figure 3b). In contrast, the Method 2 correction (Figure 3c) removes most of the jitters without generating artefacts and gives a result very similar to the ideal output - the synthetic data with a constant water velocity at 1490 m/s (Figure 3d). It is worthwhile to note that static errors on the refraction energy, highlighted by the arrows in Figure 3, are removed reasonably well with Method 2, whereas conventional ray tracing methods would fail due to their difficulty at handling rays beyond the critical angle.

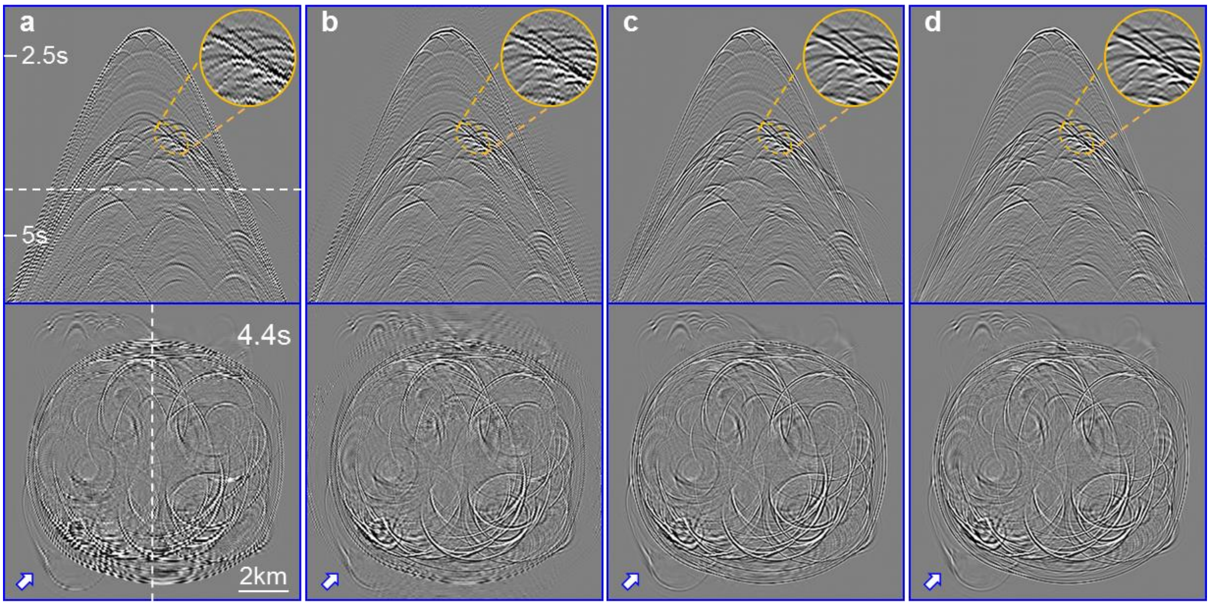

Figure 3 *30 Hz synthetic OBS down-going wavefield. Top row: crossline view. Bottom row: time slice at 4.4 s (a) with 5,0, -5 m/s velocity variation across shot lines, (b) after Method 1 correction, (c) after Method 2 correction and (d) ideal output with a constant water velocity at 1490 m/s. The direct arrival with only one trip through the water column has been removed. Method 2 handles the large statics error better and gives a result very close to the ideal output.*

Application on Atlantis 4D OBS Datasets

The Atlantis field is located in Green Canyon, GOM, beneath the Sigsbee escarpment. This area has a large water bottom depth variation of ~3000 ft and is near a complex salt body with multiple shallow salt fingers. The base and monitor OBS surveys were acquired in 2005 and 2009, respectively. Large water column statics were observed and recognized as one of the major challenges in previous 4D processing (van Gestel *et al.* 2013).

The raw 4D difference of the down-going wavefield without depth alignment and any post-processing (Figure 4b) has almost the same amplitude range as the 3D image (Figure 4a), indicating a strong water column statics effect. After water column statics correction with zero-angle approximation, 4D noise is significantly reduced (Figure 4c). Applying angle-dependent water column statics correction with Method 2 further reduces the 4D noise, best observed near the water bottom but still noticeable at the deeper section at ~12000 ft. Here the water velocity changes and tidal variations were obtained through direct arrival traveltime inversion for base and monitor surveys independently.

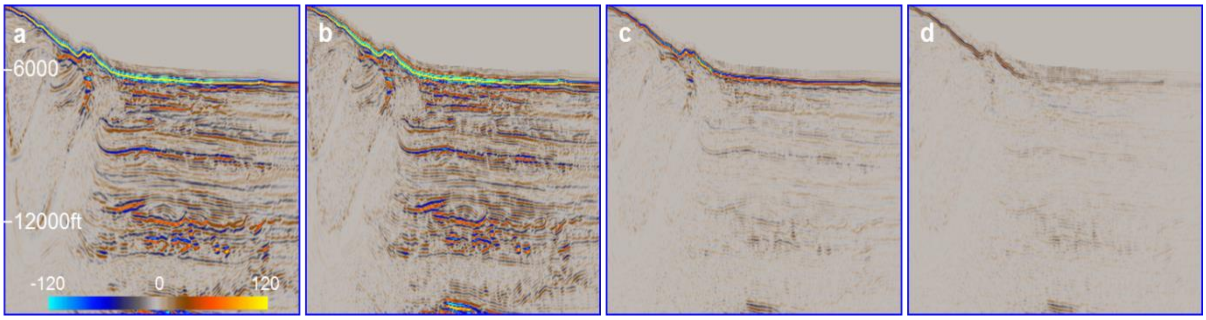

Figure 4 *Inline view of the shallow overburden above the reservoir (a) Atlantis 2005 OBS down-going wavefield image, (b) 4D difference (2009 vs. 2005) without water column statics correction, (c) 4D difference with zero-angle approximation of water column statics correction and (d) 4D difference with angle-dependent water column statics correction.*

Further QC on the water bottom NRMS maps shows the global reduction of 4D noise in the whole survey area after applying Method 2 angle-dependent water column statics correction (Figure 5). The peak NRMS value was reduced from 100 % to 29 % after zero-angle water column statics correction (Figures 5a and 5b), and was further reduced to 9 % after angle-dependent water column statics correction as shown in Figure 5c.

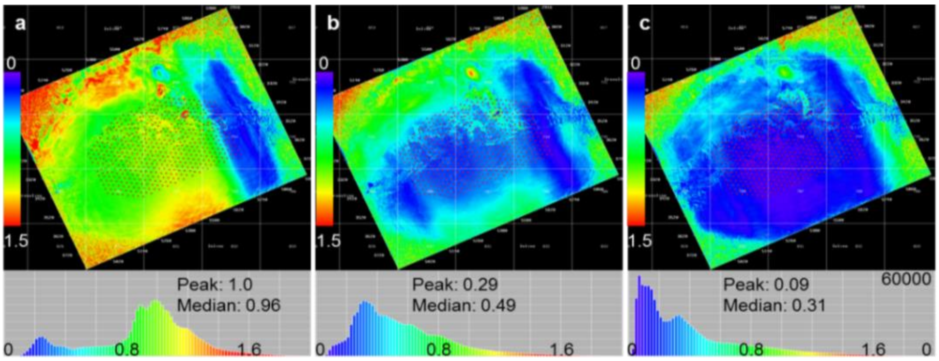

***Figure 5** Atlantis 2005 and 2009 OBS 4D NRMS map at the water bottom (a) without water column statics correction, (b) with zero-angle approximation of water column statics correction, and (d) with angle-dependent water column statics correction. The NRMS is computed within the window of WB-300 ft and WB+1200 ft. Red dots indicate the 4D node locations.*

Conclusions and Discussions

We devised a method to apply accurate water column statics correction through sparse TauP inversion. This method does not require inputs of subsurface velocity and reflector dips, thereby better overcoming the geology-related challenges that exist for ray tracing-based methods. It also benefits from the progressive sparse TauP inversion algorithm that can properly handle spatially aliased marine seismic data and reduce energy leakage in the TauP domain. Both synthetic and real data examples demonstrate the effectiveness of this method. Examples show the method to be an important component for achieving good 4D repeatability in the Atlantis area.

Our proposed method is theoretically accurate for the OBS up-going wavefield that travels through the water column only once. For streamer data or the OBS down-going wavefield passing through the water column more than once, we assume that the extra legs travel at the same angle as the first leg, which is only valid for flat reflectors in a 1D velocity model. However, we find this assumption works reasonably well on the down-going wavefield as shown here in both synthetic and real data examples, where the subsurface velocity and structures are quite complex.

Acknowledgements

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