Signature-related time shift adjustment of direct wave arrival times for correction of OBS data

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Summary

Ocean bottom seismics (OBS) is crucial for seismic imaging and reservoir monitoring but faces challenges due to positioning errors, water velocity variations, and clock drift. These issues impact data accuracy and require correction methods very early in the data processing sequence, when de-signatured seismic traces are not available. This study introduces a method to correct picked direct wave arrival times of raw seismic data, by addressing source signature directional effects. The approach involves two steps: estimating a bulk time shift and calculating angle-dependent corrections from the data itself. The method was tested on synthetic and real data from the Gorgon OBN survey in Western Australia. Results show that applying these corrections improves the accuracy by enhancing model fitting.

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Introduction

Ocean bottom seismics (OBS) is increasingly being used as an effective method to obtain high-quality seismic data for imaging complex geological structures and monitoring reservoirs. However, challenges associated with the acquisition itself must be addressed through additional processing steps to enhance data accuracy.

The primary challenge is the positioning of the receivers on the ocean floor, as precise GPS measurements cannot be directly used in this setting due to the water layer. Therefore, it is essential to improve the estimation of the receiver positions during seismic data processing, exceeding the accuracy provided by the acquisition contractor. Additionally, the positioning of the sources must also be corrected due to GPS inaccuracies and other influencing factors, such as wind and ocean currents. Another complication stems from the variability in water velocity, which differs by location and can change over time, influenced by factors such as sea temperature, salinity, and long-duration survey conditions. Seasonal changes, tides, and ocean currents further alter water velocity, causing shifts in seismic event timings. This becomes particularly significant for time-lapse 4D data processing, as water-velocity profiles can differ significantly for different data vintages. To mitigate these effects, cold water statics are applied to account for minor time variations, requiring accurate estimates of water velocity in both time and space. Furthermore, the receivers' internal clocks, which do not have access to the precision of GPS atomic clocks, introduce another challenge. To overcome this, clock drift estimation and correction are performed to ensure proper timing in the data recordings.

These compensation procedures are interconnected, and their effective implementation ensures high-quality seismic data for subsurface imaging and reservoir monitoring. Receiver relocation, which involves determining the correct coordinates of the receivers, is typically achieved using the direct wave arrival picks from recorded data. Understanding the OBS geometry allows for the modelling of direct wave arrival times, and the dense coverage from carpet shooting provides the redundancy needed for inverting water velocity and receiver positioning. In Scholtz et al. (2023) we presented an optimization process to correct jointly for receiver coordinate errors while a water velocity model gets updated from an initial uniform estimate to a final time- and depth-dependent version at the node locations. One of the novel parts in the process is a higher-order polynomial model for the vertical profile of water-velocity, improving the fit to picked travel times.

In modern OBS systems, the internal clocks of the nodes are quite accurate, and most clock drift can be approximated as a linear trend estimated by synchronizing the clocks at deployment and retrieval with an accurate GPS time. Rentsch et al. (2023) show that residuals from a linear correction can largely be attributed to aging as the primary cause and can be approximated by a non-linear (quadratic) clock drift term as being employed in Scholtz et al. (ibid).

Method

The direct arrival times are key in the coordinate corrections, the water velocity estimation, and the clock drift calculations. To eliminate the source signature effects ideally the direct arrival picking should be carried out on de-signatured seismic recordings. When acting this way, we would not distort our arrival times by source array directionality (including source ghost). However, the de-signature step usually comes much later in the processing sequence than the very early requirement for the corrections to enhance the accuracy of the survey geometry and the timing of the seismic records. In the pre-processing phase we have only raw seismic data where all the source array signature-related effects are present. Also, a bulk shift is introduced into the arrival times if the picking is not exactly at the onset of the wavelet. It could be easier to pick the trough rather than the zero-crossing for greater robustness, adding a time shift to the arrival times.

In this work, we present a method where the raw picks are corrected for signature-related directional effects, including the source ghost, and a bulk shift introduced into the picking is also determined. Any other bulk statics intrinsic to the dataset would also be present in this term. This process is added in front of the other steps in estimating the OBS corrections (receiver coordinate, source coordinate, clock drift) and water velocities (Scholtz et. al, ibid).

If we analyse pick times of direct waves in raw OBS acquisition seismic recordings after LMO correction, we can observe a "Gull-Wing" effect. This is where the direct arrival times, after LMO, show a dip in the middle with raised flanks, appearing like a seagull in flight (Figure 1). The impact will vary depending on the severity of the source signature variations, the receiver depth and the maximum offset available. There is a potential risk for these deviations to leak through into the OBS correction solutions, typically into the water velocity trends, if not corrected for.

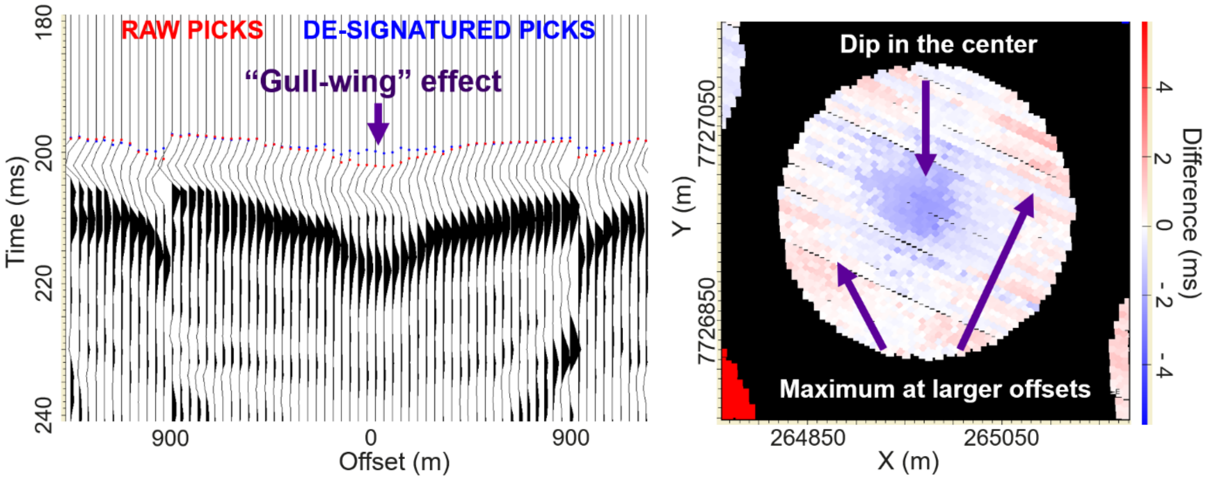

Figure 1 *An example of the "Gull-Wing" effect. The first break picks (red) are on the raw seismic traces, and the blue picks are copied from de-signature traces (left). We can observe the dip in the middle and the raised flanks in the difference disc map, where the survey geometry-based modelled arrival times are compared to the raw pick times (right).*

To estimate signature-related time shift corrections, we carry out a two-step process. First, we calculate a bulk time shift, which would correct for any deviation from the true onset of the wavelet. In this case, we are not constrained by picking the relatively less robust part of the direct arrival at the zero-crossing, but we can utilise the more robust picking made on the trough. To calculate the bulk shift, we estimate the mean velocities for each depth or depth range of the survey and invert for a best-fit bulk shift value based on the initial survey geometry.

The second step follows the bulk shift corrected direct arrival pick times: we generate source-receiver azimuth and source-receiver angle-of-incidence bins for all the available picks. Then, we calculate for each bin the deviation of the pick times (corrected by the bulk shift) from the arrival times determined from the survey geometry and the mean velocity for the appropriate depth (or depth range).

Example

We evaluated our method using a subset of the Gorgon OBN dataset, which involved 580 receivers out of the 3100 used in the entire survey. These receivers were arranged across a 100 km² area offshore Western Australia, with the full shot carpet covering 980 km². The water depth ranges from 100 to 900 meters. The receivers are spaced on a staggered grid with 375-meter intervals. The shot intervals are also staggered, with a separation of 37.5 meters between each source. To identify the direct wave arrivals, we restricted the offset range.

First, we test our method on synthetic data. We generated far-field signatures (including the source ghost) with the Gundalf modelling package covering the whole -180º - 180º azimuth and the 0º - 70º angle of incidence range for a gun-array arrangement used in the Gorgon project. We picked the positive maximum amplitudes to get the angle-dependent signature-related time shift data as a reference. Using these correction times, we produced synthetic direct arrival times for the acquisition geometry of the Gorgon project and applied our method to recover the source signature-related time shift data. In Figure 2, we show some far field signatures at different azimuths and angle of incidence (left) and the resulting source signature-related angle-dependent correction data calculated by our method (right).

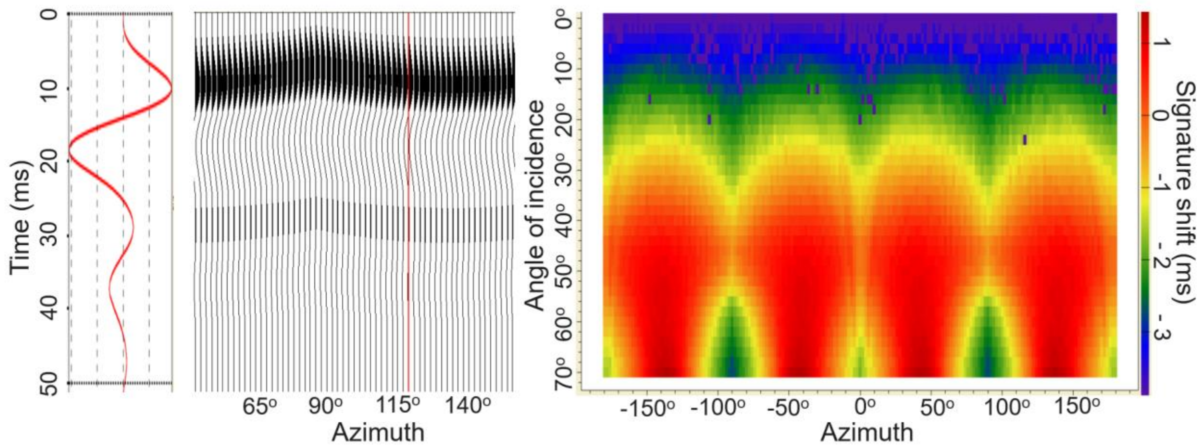

Figure 2 *A typical wavelet for the gun-array configuration of the Gorgon project where 36 guns are distributed along 3 sub-arrays (left). The modelling shows varying arrival times due to different source-receiver azimuths (middle). Signature-related angle-dependent time shift data calculated by our method for synthetic direct arrival times from the acquisition geometry of the Gorgon project (right).*

The next step is to perform a joint inversion to simultaneously determine the receiver coordinates, the velocity model (varying both temporally and spatially), and the clock drift on the actual direct arrival picks of the Gorgon dataset, having already calculated the source layback correction to account for global sail-line direction-dependent corrections to the source positions. Initially, we have not employed our method to correct for any source signature-related time shifts but have only used the raw pick data (Figure 3, centre). Using these results as a reference, we then re-run the process but now using our method to establish the correction for the source signature directional dependency (Figure 3, left) and modified the raw picks. The second set of results is an improvement on the outcome based on the raw picks alone. One of our quality indicators is the standard deviation of our model on the direct arrival times from the actual picks. The value decreased from 0.563 ms to 0.357 ms for the whole survey with our method.

As a further diagnostic, we show some disc maps before and after the raw pick corrections: in Figure 3, the disc maps show the misfit between the model and the observed direct arrival times. Each data point on these maps represents a shot point near the node location, displayed in a compressed format. The first disc map illustrates the initial error based on raw geometry and raw picks with bulk statics removed, where the dominant feature is the "Gull-Wing" effect, discussed earlier. However, after correcting for the source signature-related directional effects, the disc map on the right shows a substantial reduction in the error between the model and the observed arrival times, and the dominant feature became the receiver positioning error.

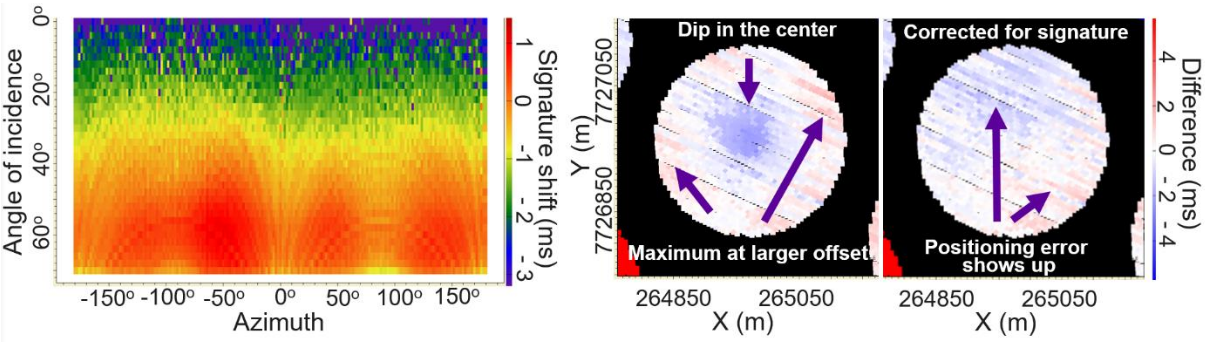

Figure 3 *Angle of incidence and azimuth-dependent signature-related time shift pattern for one of the gun arrays employed in the Gorgon project (left). In the disc maps (right), we can observe the signature-related "Gull-Wing" effect when the raw picks are displayed with bulk statics removed, but after the correction, the receiver positioning error appears as the dominant feature in the updated disc map on the right.*

Conclusions

Properly estimating source layback correction, receiver coordinates, and accounting for the temporal and spatial variations in water column velocity, along with clock drift adjustments, are key components in achieving high-quality OBS corrections. Our results demonstrate that it is possible to account for the directional dependency of the direct wave arrival times related to the source signature, even without performing de-signature on the seismic records, purely based on the picks themselves. Hence, we can increase the data accuracy early in the processing sequence. These factors become even more critical in time-lapse processing and imaging, where data are collected across different years and seasons, often subject to significant variations in navigation and environmental conditions.

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