The impact of estimated temporal and spatial variability of water layer velocity on the correction of OBS data
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Summary
Corrections for source and receiver positioning and clock-drift errors are early steps in the processing of ocean bottom seismic (OBS) data. We have implemented an optimization process to correct jointly for these 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. The main novel parts in the process are using a non-linear clock-drift correction term, using a higher-order polynomial model for the vertical profile of water-velocity and an enhanced data pre-conditioning for optimization. A real data example confirms the success of the approach.

Introduction
Ocean bottom seismics is becoming an increasingly accessible method to provide superior seismic data for imaging complex geologies as well as reservoir monitoring. However, there are some difficulties in the acquisition method that need to be addressed through appropriate extra processing steps.

One of the main issues is the positioning of the receivers on the ocean bottom, as it cannot rely on direct accurate GPS measurements. Therefore, the receiver locations should be estimated more accurately during the processing of seismic data, surpassing the accuracy of the current methods provided at deployment. This process is referred to as receiver relocation. The position of the sources also need correction, due to GPS inaccuracy and some other factors such as wind and current. Another challenge arises from the variability in water velocity, which changes not only by location but also over time. These changes are caused by temperature and salinity variations occurring during long-duration surveys. Seasonal changes, tides and ocean currents further contribute to altering the water velocity, leading to time-shifts in seismic events. This is especially important for time-lapse data processing as the water-velocity profile is noticeably different for different vintages of data. To counteract these effects, we employ cold water statics to compensate for the small time-variations, necessitating an estimate of water velocity in both time and space. Furthermore, the inaccuracy of the receivers’ internal clocks, unable to rely on accurate GPS atomic clocks, presents another obstacle. To address this, clock-drift estimation and clock-drift removal are carried out to establish the proper timing of the recordings.

All these compensation processes are interconnected, and their successful implementation ensures the generation of high-quality seismic data for subsurface imaging and reservoir monitoring. Receiver relocation, the estimation of the correct receiver coordinates, is usually carried out by utilizing the direct wave arrival picks of the recorded data. Knowledge of the OBS geometry allows modelling of direct wave arrival times, and the high density of carpet shooting gives the redundancy required to invert for water velocity and receiver positioning. There are different possibilities to carry out the joint inversion. The simplest methods use depth-invariant velocities, while more elaborate ones use depth-dependent ones. The velocity profile estimation method described by Bekara et al. (2021) applies a second-degree polynomial approximation to model the velocity profile, \( V(z_i) = a z_i^2 + b z_i + c \), with constrains for minimum and maximum velocities which stabilize the inversion for time- and depth-dependent water velocity. The depth dependent velocity profile provides a more precise model of the water layer, which results in a better fit to picked traveltimes at long offsets (greater than twice the water depth).

Nowadays, the internal clocks of ocean bottom nodes are considerably accurate, and the bulk of the clock drift can be approximated by a linear trend. This trend can be estimated by synchronizing the clock at the time of deployment and retrieval with an accurate GPS time. Rentsch et al. (2023) conducted a study using a controlled experiment with 100 nodes, which demonstrated that residuals from a linear correction can be mainly attributed to aging as the dominant effect. Furthermore, their data showed no indication of chaotic behavior. In large-scale OBS observation systems designed for monitoring earthquakes, the analysis of clock drift problems commonly involves using the ambient noise cross-correlation function (NCCF) from continuously recorded waveforms. This approach can overcome the lack of frequent events, such as earthquakes. These methods rely on the time symmetry of NCCF between two nearby receivers when their clock behaviors match (Gouedard et al., 2014). Conversely, clock inaccuracies lead to broken symmetry of the NCCFs. In their study, NCCFs are calculated from recorded data in short time slots and then stacked over several days to enhance the signal-to-noise ratio (SNR). In the case of active seismic measurements, the direct wave arrivals can be employed to establish clock drift parameters for each node, given the availability of very dense shooting over an extended period of time.
The impact of estimated temporal and spatial variability of water layer velocity

Utilizing direct waves

In this work, our primary objective is to correct for the receiver and source positioning errors, along with the clock drift of the ocean bottom nodes. Additionally, we aim to derive time- and depth-dependent velocities for the water layer, which can significantly improve the subsequent processing and generate more accurate seismic data. Our observations using densely sampled shot carpets provide valuable data redundancy that can be utilized in an inversion algorithm when estimating positioning and clock-drift errors using direct waves. This requires accurate water velocity estimates, which can also be jointly inverted for.

In our implemented method, the main forward modeling of the inversion engine involves estimating the direct arrival time from the source to the receiver using a set of parameters. These parameters include source and receiver coordinates, the time-space dependent velocity model for the water layer, clock-drift, and tidal height measurements.

The first step in the process is a joint optimization of the receiver coordinates and a spatially varying velocity field for the water. Once we have established more accurate receiver locations and obtained the first estimate of the water velocity field, we further refine the velocity field by calculating depth- and time-dependent velocities for the water column. To ensure a stable inversion, we employ a polynomial with a user-specifiable degree to approximate the velocity profile. We find that for shallower water, a second-degree polynomial can provide a very good fit to a real velocity profile, as depicted in Figure 1a. However, for locations in deeper waters, a second-degree polynomial may not produce an overall good fit, as shown in Figure 1b. In such cases, a fifth-degree polynomial offers a more reasonable fit (Figure 1c). Of course, with increasing degrees, more parameters need to be solved for. To obtain a more robust solution, we impose constraints on the polynomial coefficients, which can be derived from expected velocity ranges based on direct measurements at sparse locations using specialized equipment such as PIES. To account for velocity changes within the water layer, we use a ray-tracing method to calculate the arrival times of the direct waves through the water column.

Having obtained reliable receiver coordinates and a refined velocity field, we can proceed with calculating the source lay-back correction. Here, we have a few options to choose from: one is a global solution, which involves a single correction distance in the sail-line direction (field geometry error in the source position caused by drag on the source during towing), or we can opt for a solution that is sail-line dependent, or we can correct each shot position separately.

Figure 1: Examples of using polynomial models for water-velocity inversion compared to measured (TS-dips based) interval velocity profiles at different locations. (a) second-degree gives good match, (b) second-degree gives poor result, (c) fifth-degree gives good fitting to the same measurement where second-degree fails.
The impact of estimated temporal and spatial variability of water layer velocity

The final step involves updating the clock-drift parameters. The clock-drift can be approximated either by a linear or a quadratic function (Rentsch et al., 2023), depending on the duration of acquisition, and it can take into account synchronization time data.

Example

We have tested our approach on a portion of the Gorgon OBN data where we used 580 out of the 3100 receivers in the whole survey distributed over an area of 100km², located offshore Western Australia and the full shot carpet covers 980km². The water depth varies in the range of 100 – 900m. The receivers are placed on a staggered 375m grid. The staggered shot interval is 37.5m and the source line separation is 37.5m. We have applied a limited offset range of 600m to pick the direct wave arrivals. For constraining the depth-dependent velocity solutions we used a single TS-dips measurement on the area to define the range of tolerance. As we pointed in Figure 1 the shallower water depth allows us to approximate the measured velocity profile by a polynomial of second-degree (the velocity profile in Figure 1a guided our solutions in this project).

We conducted a joint inversion process to simultaneously solve for the receiver coordinates and an initial spatial velocity field. Subsequently, we refined the velocity field by optimizing the results, incorporating depth and time dependencies. The time slot length for this optimization was set to 3 hours. Two more steps were undertaken in the process. Firstly, we addressed the correction for source layback. We chose the “whole survey shift” option to account for a global sail-line direction-dependent source position correction. Secondly, we estimated and corrected the clock-drift, approximating it using a quadratic function.

Figure 2 illustrates the misfit between the model and the picked direct arrival time in disc maps. Each data point in these maps represents a shot point around the node location, in a compressed form. Figure 2a demonstrates the initial error based on raw geometry information and an average velocity. At certain nodes, the deviation is notably higher than for others due to positioning errors. However, in Figure 2b, we observe the results after correcting the shot and receiver coordinate errors while considering the jointly estimated spatial velocity field (disc maps are displayed on the original pre-plot locations in all figures). As seen, the error between our model and the picked arrival times has significantly reduced, and the positions of the receivers are now well resolved.

Despite the improvements, some striping is still noticeable in the disc maps, particularly evident in the zoomed-in portion of the survey shown on the left of Figure 3. The striping observed in the disc maps (Figure 2b) is a result of

Figure 2: Reduction in error between modelled and measured direct wave arrival times as seen in disc maps of the nodes with, (a) no correction applied, (b) source and receiver coordinates corrected and (c) including time- and depth-dependent water velocity variations together with clock drift corrections. Red rectangles highlight the area for close-up in Figure 3.
The impact of estimated temporal and spatial variability of water layer velocity

the variation in water velocity over time, as the survey was conducted over several days. To address this issue comprehensively, Figure 2c presents the best-fit results, taking into account both the temporal and spatial variation of water velocity, along with source lay-back correction and clock-drift correction using a quadratic time-dependency. The incorporation of temporal and spatial variations in water velocity is crucial to achieving notably improved results (Figure 2c), especially in the presence of variable water depth.

Figure 3 provides a close-up view of a small portion of the survey to illustrate how the corrections have reduced the error between the improved model and the direct arrival pick times. On the left side of the figure, the results show the effect of receiver relocation and spatially-variant velocity variation, while on the right side, time and depth-dependent velocity functions are taken into account along with clock-drift corrections. As evident, most of the stripes have been eliminated, and the error level between the model and the direct arrival picked times has significantly decreased.

In Figure 4, we observe the variation of RMS velocity at the water bottom with respect to space and time. The colors in the figure represent the velocity displayed at each shot point. As each shot has a specific timing, this velocity map enables us to analyze the time and space variations of the velocity field in a comprehensive manner.

Conclusions

The process of correcting the mis-positioning of source and receivers and clock-drift issues of OBS data is an essential step in their effective processing and subsequent subsurface imaging. We show that estimating temporal and spatial variations of water column velocity is critical for high quality corrections. Such velocity profile becomes even more important in the time-lapse processing and imaging context where different vintages of the data are acquired in different years and seasons with much greater navigation and environmental changes.

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