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PARAMETRIC INVERSION OF WATER COLUMN VELOCITY FOR COLD WATER STATICS CORRECTION IN OCEAN BOTTOM SEISMIC SURVEYS

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Summary

The abstract describes a methodology to compute time-varying, depth-dependent water column interval velocity profiles from Ocean bottom seismic data. The objective is to use these profiles to correct for cold water statics. They are inverted over time slots using direct arrival picks. The inversion is an integrated part of a flow that jointly inverts also for the nodes' positions and their clock drift. The main innovation in this work is the use of a second order polynomial approximation to model the velocity profile as function of depth. The rationale is to relax the need for an accurate initial velocity profile which is required by the standard methods and to improve the fitting for a more accurate velocity estimation. The parameters of the polynomial model are constrained to give a physically sensible velocity profile. The method is tested on synthetic and real data in comparison with a standard method. It performs quite well in terms of fitting the direct arrival picks and gives an overall better velocity estimation in terms of accuracy and time resolution. For the real data, the most visible uplift was for the far offsets (outer lines), where the standard method is known to produce biased velocity values

Introduction

In recent years, the seismic industry has seen a surge in Ocean Bottom Seismic (OBS) processing, mostly due to the focus on 4D for reservoir monitoring. One of the main challenges of OBS 4D processing is the issue of cold water statics. It manifests itself as jitter in the seismic cross-line section, which can lead to stack deterioration. The jitter correlates with changes in the acquisition sequence and therefore has a time stamp. The statics problem is caused by variation in the water column velocity due to seasonal changes in temperature/salinity of the water, and in some areas due to ocean currents.

The first step in the solution of cold water statics is to estimate the water column velocity profile. Most of the methods in the literature use the direct arrival (DA) picks for this purpose. They jointly invert for the water velocity and the node (x, y, z) position, as accurate node positioning can sometimes be difficult. In early studies, the proposed model for the velocity profile was a depth-invariant (constant) RMS velocity $V_{rms}(t)$ that varied for every acquisition sequence or group of shots (Lecerf et al., 2011). The time stamp t corresponds to an average time of acquisition for the data used in the inversion. The velocity model was then refined to handle more realistic ocean water interval velocity profiles that vary with depth as empirically reported in (Advocate and Hood, 1998). In this context, ray-tracing is used to model the DA times. Rather than inverting for a complete depth-variant velocity profile $V(z,t)$, which results in a highly ill-conditioned inverse problem, many papers proposed to invert for a scalar perturbation $\alpha(t)$ of a base velocity profile, i.e., $V(z,t) = \alpha(t)V_0(z)$ (Zietal and Haacke, 2016). The base velocity profile $V_0(z)$ is derived empirically from temperature-salinity measurements (TS Dips) or from a scaled Hood function (Advocate and Hood, 1998).

In this paper we propose to use a second order polynomial approximation to model the velocity profile as a function of depth, i.e., $V(z,t) = a_t z^2 + b_t z + c_t$. The motivation is to relax the need for an accurate base velocity profile. This is quite useful for surveys with little or no TS-dips measurements. The velocity is inverted as an integrated part of a flow that also jointly inverts for the nodes' positions and their clock drift (Figure 1). The data (i.e. DA picks with offset below a threshold) are partitioned into constant-time interval slots (typically between 3 to 7 hours), where the inversion for the velocity is performed. For time slots with insufficient data coverage (e.g., outer lines), the velocity profile is interpolated from adjacent slots. The parameters (a_t, b_t, c_t) are obtained by minimizing a robust cost function and they are constrained such that the resulting velocity is physically sensible.

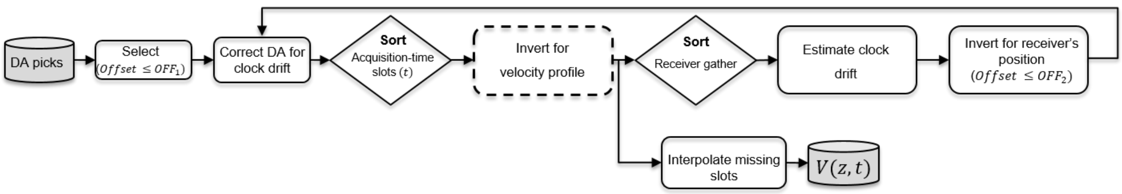

Figure 1 *Flowchart of joint estimation of velocity profile, node position and clock-drift. The choice of OFF_1 is dictated by the quality of DA picks and chosen to minimize the effect of wavelet distortion (< 5km). OFF_2 is selected to be smaller, i.e., about 1km ~ 2km to reduce sensitivity of the water velocity on the inversion of position.*

Parametric tomography

Let $T_n^{(t)}$ be the DA times picked from a trace with receiver position $\boldsymbol{r}_n$ and shot position $\boldsymbol{s}_n$ that was acquired in the time slot t. Using a velocity profile $V(z_i) = az_i^2 + bz_i + c$ for $0 \le z_i \le z_{max}$, a ray tracing table is constructed to model the source-receiver direct travel time including the refraction (post critical ray-paths). We assume also that for a given time slot t, we have N_t DA samples. The parameters $\{a_t, b_t, c_t\}$ are estimated by minimizing the following misfit function,

$$\{\hat{a}_t, \hat{b}_t, \hat{c}_t\} = \min_{a,b,c} \sum_{n=1}^{N_t} \left| T_n^{(t)} - da\_model(a,b,c; \boldsymbol{s}_n, \boldsymbol{r}_n) \right|^p \quad p \in [1,2] \qquad (1)$$

The use of a robust norm is important to reduce the influence of outliers (erratic picks). Furthermore, the model is constrained to ensure that the resulting velocity is feasible at all N_z depths locations, i.e.

$$V_i^{min} \le az_i^2 + bz_i + c \le V_i^{max}, for\ i = 1,2,\cdots,N_z \qquad (2)$$

The constraints are derived from a base model $V_0(z)$, when available, and/or from physically possible min/max values of the water velocity. This translates to $V_i^{min} = \max\big((1-\epsilon)V_0(z_i)\,, V_{min}\big)$ and $V_i^{max} = \min\big((1+\epsilon)V_0(z_i)\,, V_{max}\big)$. The value ϵ is a user-supplied parameter that controls the tightness of the constraints. The set of constraints in Eq. (2) construct a convex feasible region in the (abc) space that can be numerically computed.

The optimization problem in Eq. (1) is highly nonlinear with many local minima. The use of descent methods is not suitable due to the complexity in computing partial derivatives and the inclusion of the constraints. The best option here is to grid over the feasible region. This approach is CPU intensive if a good resolution is required. However, we found that for this problem the *locus of minima* of the cost function is an affine function, i.e. $c = f(a,b)$. So rather than gridding over the entire feasible region, a good resolution gridding is done only along the affine function and this reduces the computational requirements.

Data examples

1. *Synthetic data*

The synthetic example consists of a single receiver and a source line with 200 shot points (Figure 2-a). The water bottom is dipping up in the NW direction with a depth ranging from 1000 m to 1160 m. The true and the base interval velocities (TS-dip) are shown in Figure 2-b. The TS-dips span a larger depth as they are from a real survey taken at a deeper location. There are visible differences between the two velocities in the shallow part (below 200 m) but also around and below the water bottom (> 900 m). The true DA picks (Figure 2-c) were generated using ray-tracing with a 5 m step size. The proposed parametric method is used to invert for the velocity profile with a ± 1% corridor constraint around the base velocity in addition to a limitation of velocity in the interval [1480,1540] m/sec. Its performance is compared with the scalar-multiplier method (Zietal and Haacke, 2016).

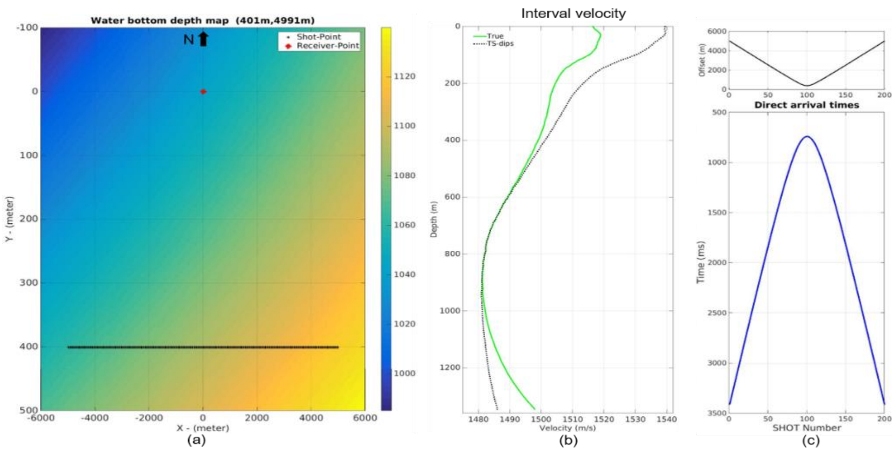

Figure 2 *(a) Layout of the synthetic example: a single receiver-point and 200 shot-points, (b) Corresponding true and base interval velocities used in the simulation. (c) Generated direct arrival picks and their associated offset values.*

Compared to the inverted velocity with a scalar-multiplier, the parametric velocity is closer to the true velocity overall depths (Figure 3-a). The fitting of the DA picks is consistently much better (lower residual) across all offsets (Figure 3-c). The fitting of the scalar-multiplier method starts to deteriorate from an offset of about 3 km. When we inspect the RMS velocities (Figure 3-b), we understand better why the parametric inversion fits the DA picks better. Both RMS velocities (true and parametric inversion) are very close around a depth range that covers the water bottom. At the end, it is the RMS velocity at the receiver depth that will determine the amount of statics correction to apply to the seismic data.

2. *Real data*

The proposed method was tested on a real OBS 4D dataset from offshore Brazil. The survey consists of a relatively small receiver spread (712 receivers) and 564 sail-lines. Small positioning errors on some receivers were expected but no clock drift. A few TS-dips interval velocity profiles were available at different points during the survey, and they were averaged to create the base velocity profile. Standard

OBS processing was applied that included: noise attenuation, P-Z summation to derive the up and down going wave-fields and 1D designature. DA picks were obtained from the down going wave-fields. A maximum offset of 3 km was restricted for the picks used in the velocity inversion to limit the effect of wavelet distortion at far offsets. The water column interval velocity profiles were then inverted jointly with the receiver positions over slots of time of about 7.5 hours. The proposed parametric method was run with a ± 0.1% corridor constraint around the base velocity. For comparison, the scalar-multiplier method was also tested in the same setup.

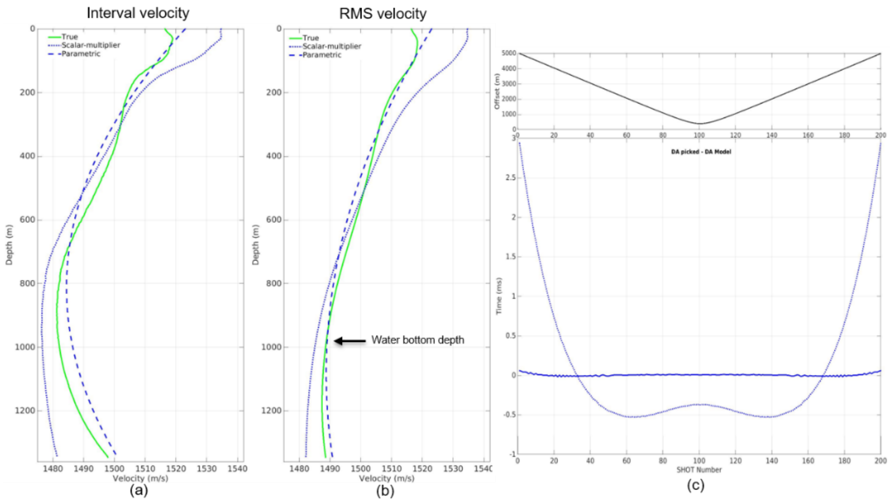

Figure 3 *(a) True and inverted interval velocities. (b) True and inverted RMS velocities. (c) Residual direct arrival picks (data-model) and their associated offset values.*

Both velocity profiles capture the same low frequency variations of the sea-state (Figure 4). However, the parametric inversion gives more details that we claim are related to short-time variations of the sea-state. These high frequency details are important to properly correct for cold water statics. We consider a receiver node with an evident positioning error. The seismic traces were flattened using the modelled DA times, calculated by ray tracing from the each of inverted velocity profiles. A case with a constant velocity (1500 m/s) and no inversion of the receiver position was added to highlight the statics. Figure 5 shows a slice through the receiver gather at the reference alignment time for the three cases. Misalignment (white colour) at the near offsets for the case of the constant velocity profile is an indication of a position error (Figure 5-a). The alignment using the velocity obtained by parametric inversion (Figure 5-c) is better at the far offsets, compared the one obtained using the scalar multiplier method (Figure 5-b). Inspecting a subline section at the location indicated by the white arrow in Figure 5 shows clearly the jitter related to the water statics and the bias related to the position error (Figure 6-a).

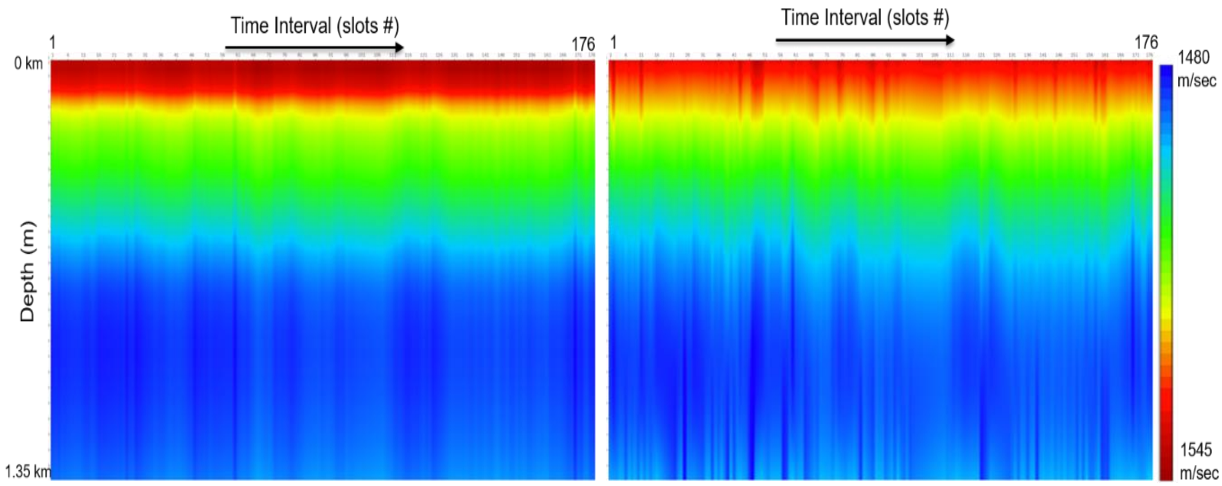

Figure 4 *Time varying Inverted velocity profiles using the (a) scalar-multiplier method, (b) parametric inversion.*

Joint inversion of the water velocity and the receiver position reduces dramatically the jitter and the bias (Figure 6-b, c). However, the parametric method performs slightly better at the far offsets. The remaining jitter is mainly due to the tidal statics.

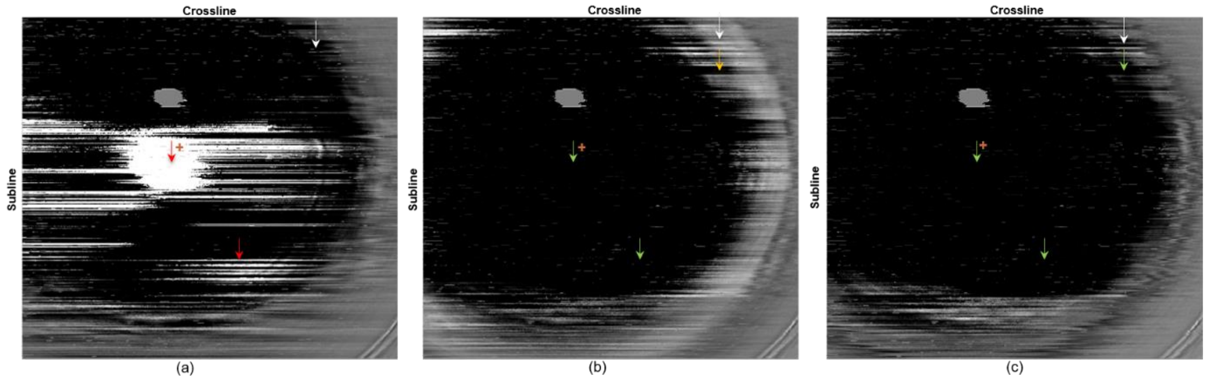

***Figure 5** Time slice through a receiver cube after aligning data using modelled DA times using (a) Constant velocity 1500 m/s velocity, Inverted by (b) the scalar-multiplier method, (c) the parametric method.*

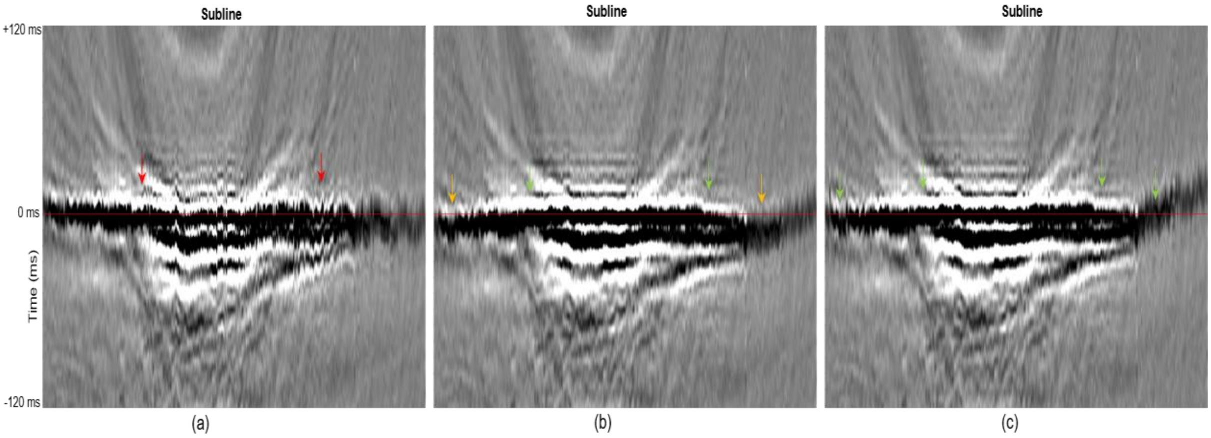

Figure 6 Crossline section of aligned data using modelled DA times using (a) Constant velocity 1500 m/s velocity *Inverted by (b) the scalar-multiplier method, (c) the parametric method.*

Conclusion

The proposed parametric approach to estimate the water column velocity profile performs better compared to the conventional scalar-multiplier method when the DA times are picked from far offset traces. This is the case for the outer lines, where water velocity estimation is always a challenge. The parametric method has more freedom to fit the DA time picks and hence can absorb some of the nonlinearities in the DA modelling and capture short term variation of the sea-sate. However, it is very important to constrain the parametric inversion with a-priori knowledge of a base velocity profile or physically expected velocity values to ensure sensible and realistic velocity profiles.

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