Water Column Corrections, Joint Water Velocity Inversion for 4D Marine Surveys

Didier Lecerf, Mathieu Lange, Andrew Oates, and Jyoti Kumar, PGS*

Summary

Water column variations are an important source of non-repeatability in time-lapse marine surveys. In a deep water context, the physical property variations within the water layers can generate significant time-shifts between repeated time-lapse seismic data.
We present a new methodology for estimating and correcting water velocity changes on 4D seismic datasets. Each sail line is migrated independently and Common Depth Point (CDP) gathers are output for the overburden along a subsurface strip for both vintages. The 4D approach consists of performing cross-correlations using collocated CDPs for each sail lines pair. It creates water bottom "cross-image CDP gathers". The cross-image CDP curvature along offsets is used to compute the water velocity difference between the two vintages. Once a water velocity is inverted for each sail line, the kinematic correction is performed on the pre-migrated datasets.

The main difference with conventional approaches is the simultaneous usage of both 4D datasets for estimating the water velocity changes and therefore minimizing the seismic difference in the overburden. The methodology is significantly beneficial for deep-water 4D acquisitions. The correction for such small environmental variations improves the time-lapse data repeatability and is part of the effort for providing high resolution 4D images.

Introduction

Water column variations, such as tidal elevation and/or water acoustic velocity changes, are an important source of non-repeatability in time-lapse marine surveys. In a deep water context, the physical property variations within the water layers can generate significant time-shifts between adjacent acquisition sail-lines (3D) and subsequently within repeated time-lapse seismic data (4D). It is important to handle properly these corrections during the data processing as the resulting 4D signal time-shifts can be improperly interpreted in the final 4D images.

The acoustic velocity of water is a function of physical properties such as temperature and salinity which can vary with time and depth due to the effects of oceanic currents. During a seismic marine acquisition, water velocity profiles can be measured to define the variations with water depth. If the water velocity measurement is performed continuously, it is common to observe some change in the velocity profiles within couple of hours. Because adjacent sail lines are acquired at different times, ranging from several hours or days apart, the spatial data consistency may be affected by a change in water velocity. These effects create lateral data jitters on crossline sections, characterized as "time striping" in common offset classes. Since the amount of timing adjustment is cumulative along the ray path, the correction can be more critical for deep water surveys.

Various methodologies have been proposed in the literature for estimating the water layer velocity variation and for correcting the seismic data. The tomographic approach using pre-migrated water bottom picks is commonly used to estimate the water velocity for each sail line. The data correction can be performed using dynamic time-shift correction by substituting the water layer velocity in the NMO/NMO-1 process (Lacombe et al., 2006) or applying residual wavefield propagation (Guerra et al., 2015). For diffracted and complex water bottom, an alternative approach in the image domain has been proposed for estimating the sail-line consistent water velocity (Kumar et al., 2015). The objective of these processes is to correct the pre-migration data and to be able to migrate the complete dataset with a laterally homogenous water layer within the velocity model.

Most of the authors who work on this problem mentioned the importance of the water column corrections for reservoir monitoring seismic campaigns. Despite the consensus on the critical impact on 4D data quality, the current methodologies attempt to solve the problem in a 3D sense. In other words, for reservoir monitoring studies, the water layer corrections are computed and applied independently for each vintage.

Methodology

Working in the image domain presents several advantages for estimating water velocities. The migration collapses the water bottom diffractions, particularly valuable when dealing with a rugose water bottom; additionally, the water velocity estimation is not biased by dip effects and cable feathering. In the proposed method, each sail line is migrated independently using a reference homogenous velocity function. Common Depth Point (CDP) gathers are produced for the overburden along a subsurface strip and for each sail lines and both vintages.

In a first step, the water velocity for the base is estimated using the Residual Move Out (RMO) approach at the water bottom level. Instead of repeating the process separately for the monitor, the second step consists of performing trace cross-correlations using collocated CDPs for each sail lines pair. This second step creates water bottom "cross-image CDP gathers", defined for a coupled sequence in a 4D sense. The cross-image CDP curvature along offsets is used to compute the water velocity difference between the two vintages, base and monitor.

To summarize the methodology, we are estimating, post-migration, the water velocities and correcting, pre-migration, the two 4D datasets using the following processes:

a) Estimate the residual baseline water velocity using the water bottom image: ΔVw base/ref

b) Estimate the residual water velocity between baseline and monitor using the water bottom cross-image: ΔVw mon/base

c) Calculate the water velocity in a sequence consistent manner along individual sail line and for both vintages:
Vw base = Vw ref + ΔVw base/ref
Vw mon = Vw ref +ΔVw base/ref + ΔVw mon/base

d) For each individual sail line, the data correction is applied in the pre-migration domain using water layer substitution method.

Methodology limitations and benefits

This method demands the acquisition spread to be wide enough for producing an optimal image of the water bottom and overburden. It requires also sufficient 4D sequences overlaps to ensure consistent sail lines cross-measurement. Typical modern 4D acquisition configurations tow from 10 to 14 cables with 50 to 100 m streamer separation, thus giving a minimum of 450 m of crossline image aperture. Such aperture is generally sufficient to define an accurate and consistent water bottom image. Short offsets are usually well overlapped between 4D marine acquisitions, however the degree of repeatability for the large offset should be adequate for having a meaningful cross-correlation function along the offset range. Therefore, the method may not be optimal for "non-4D friendly" acquisitions.

However, the cross-correlation function provides some useful attributes for assessing the quality of the residual velocity measurement. For example, the correlation coefficient defines the degree of the measurement consistency and may be used as quality assessment threshold. The zero offset lag specifies the optimum 4D statics values for minimizing the seismic stack difference. In addition, the cross-correlation is zero phase per definition and is not sensitive to water bottom signal distortion due to structural effects (assuming correct designature process).

Real data example

This 4D water velocity inversion method has been tested using real 4D deep water datasets with water depths going from 500 m to 1500 m. The 4D test acquisitions have a dedicated design for optimal reservoir monitoring purpose which includes repeated source positioning within 5 m and similar streamer configurations with feathering control. The corresponding acquisition sail line map, for both baseline and monitor surveys, are displayed in figure 1 with colour coded sequence numbers. This information is used for pairing the repeated sail lines according to the common sub-surface location. The subsequent cross-corelated data define the cross-image CDP gathers input to the joint 4D water velocity estimation.

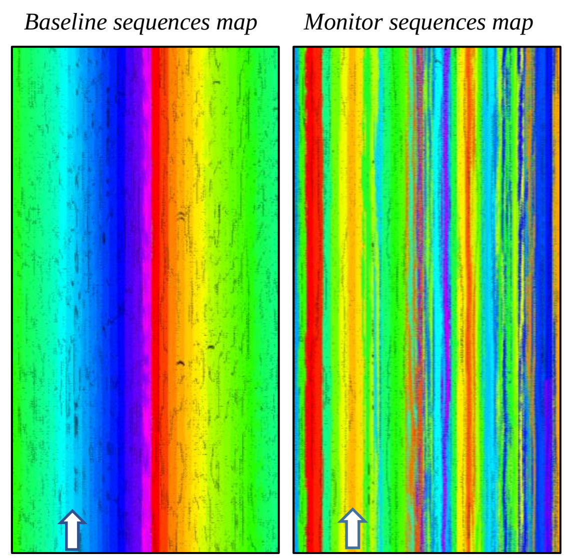

Figure 1*: Color coded sequence number maps for the baseline (left) and monitor (right). Co-located sequence number for base and monitor are used to pair 4D CDPs for the cross-correlation process. Example: Arrows indicate two sequences to be cross-correlated.*

The figure 2 shows the analysis of the water bottom image CDP gathers and the cross-image CDP gathers computed for repeated sail lines. The figure 2a) and 2b) displays the baseline migrated CDPs at the water bottom level, respectively, before and after the water layer correction using ΔVw base/reference. The equivalent cross-image CDPs are shown in figure 2c) and 2d) using the ΔVw base/monitor estimation. The two ΔVwaters are inverted such as the seismic event representing the water bottom becomes flat along the offsets. It can be noted that the

ΔVwater which flattens the cross-image CDP is the one which minimizes the 4D difference directly.
The figure panels 2b) and 2d), showing the CDPs after RMO applied, are processed for QC purpose only. In fact, the effective data correction is performed on pre-migrated datasets.

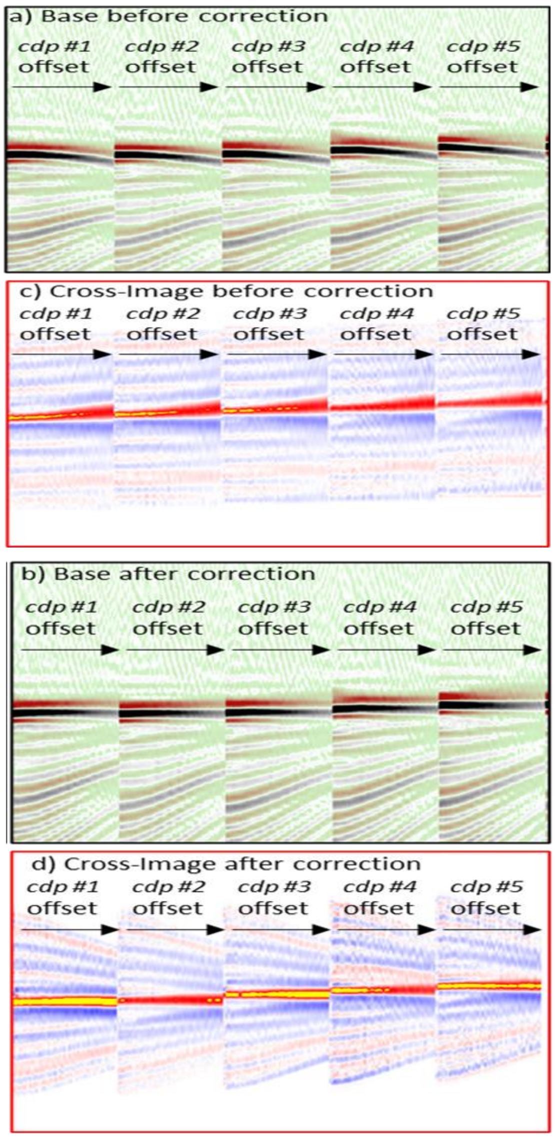

***Figure 2**: Sail line CDPs before and after water layer correction.*
a) and b) for the baseline water bottom CDP gathers
c) and d) for the cross-image CDP gathers using 4D paired sail lines.

The water column correction is performed during the early pre-processing stages on the non-migrated datasets, prior to 4D binning. After the 4D binning, the data are organized in such a way that we can calculate one-to-one trace 4D attributes for the different offset classes. Figure 3 shows 4D time-shift attributes computed within an overburden window for two offset classes without and with the water layer correction applied (includes common NMO). In our test, a

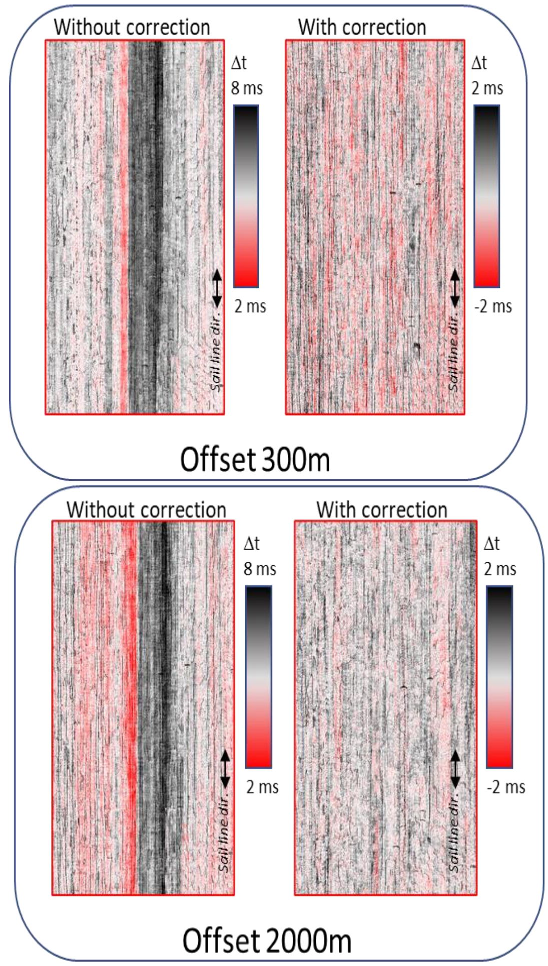

***Figure 3**: Pre-migration 4D time-shifts maps at the water bottom level for two common offsets gather. Note: for better visualization, the color-range has been reduced for the time-shift values after correction.*

water layer substitution approach has been employed to correct the shot gather kinematics. The attribute maps demonstrate the minimization of the time difference between the two vintages along offsets and the consistency of the correction, especially in crossline direction. The process works efficiently as a 4D time destriping, attenuating the effect of variations in the acquisition environment.

In this deep water case, the time-shift between the two datasets can reach 8 ms before the correction. After correction, the resolution is less than 0.5 ms with a mean value around +-0.1 ms. However, the resolution of such 4D methodology is dependent of the water depth and the offset range used for the water velocity inversion. A comparison with a conventional 2x3D approach has shown that the 4D joint methodology significantly improves the resolution of the water velocity variation estimation. With typical 4D acquisition designs and water depth around 1000 m, we can reasonably expect to estimate a rms water sound speed change less than 1 m/s. This value varies according to the condition of repeated acquisition, the water depth, the quality of the data, and the seismic bandwidth available.

Conclusion

We have presented a specific 4D methodology for correcting the effect of the water layer variability on time-lapse seismic datasets. The main difference with conventional approaches is the simultaneous usage of both vintage datasets for estimating the water velocity changes between the two surveys and therefore minimizing the seismic difference in the overburden. The 4D water velocity inversion is performed in the image domain using cross-image CDP gathers built from cross-correlations of acquisition sequences migrated data.

We have found that the methodology is significantly beneficial for deep water "4D friendly" acquisitions. Today, the demand for increasing the detectability resolution of the 4D signal is rising in reservoir monitoring studies. This objective goes with the capability to correct for small environmental variations affecting the time-lapse data repeatability and producing undesirable "4D noise". The presented 4D methodology is part of the effort to provide high resolution 4D images.

Acknowledgements
The authors would like to thank PGS for the permission to present the study.

REFERENCES

Guerra, C., J. Carbonesi, and G. Ritter, 2015, Dynamic correction for water-velocity and tidal variations: Presented at the 14th International Congress of the Brazilian Geophysical Society & EXPOGEF, Rio de Janeiro, Brazil, 3-6 August 2015, Expanded Abstracts, 1–4, doi: https://doi.org/10.1190/sbgf2015-268.

Kumar, J., G. Jangelme, and S. Barnes, 2015, A new way of compensating for water column variation by velocity estimation of sea layer: 77th Annual International Conference and Exhibition, EAGE, Extended Abstracts, Th N116 11, doi: https://doi.org/10.3997/2214-4609.201413322.

Lacombe, C., J. Schultzen, S. Butt, and D. Lecerf, 2006, Correction for water velocity variations and tidal statics: 76th Annual International Meeting, SEG, Extended Abstracts, 2881–2885, doi: https://doi.org/10.1190/1.2370124.