A DETERMINISTIC 4D PROCESSING FLOW TO SUPPRESS ACQUISITION-RELATED NOISE AT DALIA AND ROSA FIELDS

N. Salaun[1], M. Pouget[1], Z. Yu[1], C. Beigbeder[1], A. Rivet[1], S. Dega[1], M. Peiro[1], A. Lafram[2], A. Grandi[2], E. Jungo[3]

[1] CGG; [2] TOTAL E&P; [3] TOTAL E&P Angola

Summary

Time-lapse seismic is now being used more frequently to assist reservoir development, prevent infrastructure damage or monitor geological storage. To better reveal true 4D signals while suppressing acquisition-related noise as a result of, for example, water velocity changes, source positioning errors etc., a new processing flow which focusses on correcting each noise-contributing factor based on its physical characteristics, has been developed to replace the conventional non-deterministic correction approach based on cross-survey matching. Our proposed flow is based on using common water bottom and the water-bottom travel time to invert each factor and correct for it, which allows for processing of each monitor survey independently and the possible acceleration of standard 4D processing timelines. We applied this workflow on two fields offshore Angola, one with strong subsidence and one without, and showed the superiority of this new approach to reveal the true 4D information. The subsidence effect, observable from the reservoir up to the water bottom, now better matches with the model of pressure changes in the new 4D results compared to legacy results. Even for field experiencing no subsidence effect, the time shift and NRMS maps obtained at the reservoir level are cleaner and easier to interpret from new flow.

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Introduction

Time-lapse (4D) seismic monitoring and imaging has been used with great success for two decades over the Angolan deepwater blocks (Pluchery et al., 2013). During 4D processing, being able to minimize all of the non-geological changes between two monitors is crucial for obtaining accurate 4D signals for interpretation. The non-geological changes here refer to changes in acquisition configuration and/or environmental conditions between two monitor surveys, such as source position and water velocity. A conventional method to correct for such changes aims at matching time, phase and amplitude differences between two monitors with the assumption of no geological changes in the referenced shallow overburden area (Rickett and Lumley, 1998). This method, that we will call cross-equalization, though showing great success over many fields, is limited by the lack of physical reasons supporting the corrections. Its application also fails when the whole survey area is affected by non-geological changes, for example, when subsidence affects the subsurface up to the water bottom.

To overcome the above-mentioned limits, a new 4D processing flow has been developed, which relies on deterministic and independent processing of each monitor to correct for the non-repeatable factors during acquisition, such as tide, source position and water velocity. The proposed method was applied over the Dalia field where 4D seismic information was used to both improve the hydrocarbon recovery and monitor the strong subsidence associated with the potential stress arching effect (Rodriguez-Herrera et al., 2015). This new method was also applied on a neighboring field, Rosa, which is free of any observable subsidence.

Deterministic correction to reduce 4D noise

Non-geological 4D differences, also called 4D noise, are linked to many non-repeatable factors. These factors can be split into two categories – changes related to seismic acquisition configuration and environmental conditions. Despite all of the special care taken during seismic acquisition to maximize the repeatability, source and/or receiver position and characteristics cannot be identical between two monitors. Moreover, in the marine environment, the water layer is varying with time and it is impossible to get repeatability in terms of water temperature, salinity, tide or wave height. The standard 4D processing flow relies on cross-survey matching to correct for these non-repeatable factors, in which the overburden is considered as not being affected by reservoir changes and is used to both align the timing and match the spectra between two monitors. With this method one monitor is chosen to be the reference and remains uncorrected. An alternative and better method would be to identify, as much as possible, the physical reasons of individual acquisition-related non-repeatable factors within each monitor and correct for them correspondingly. The benefits of this deterministic approach is especially obvious in the case of subsidence, where the overburden properties change between two monitors, so that it cannot be used as the reference for cross-survey matching. Over the Dalia field, to mitigate for the lack of a stable overburden, the vintage processing solution was to exclude the subsidence areas, leaving only some limited areas, prior to performing cross-equalization calculations. While effective, this method needs a-priori knowledge of the subsidence areas and needs an interpolation of the derived corrections to these exclusion zones. Moreover, the a-priori information used to define the areas of exclusion may contains biases which are difficult to overcome.

With the purpose of better characterizing the subsidence effect over Dalia field, reprocessing was carried out by considering all monitors independently. To correct for the source difference, in the absence of a near field hydrophone, the far-field source signature was extracted from the data for each monitor and then matched to a target wavelet free of bubble. This designature step allowed the removal of the bubble energy and homogenized the spectrum between all monitors. To avoid different ghost effects due to the difference in source or receiver depth, a provisional deghosting was applied prior to far-field signature extraction. This step also allowed for a better estimation of the low frequency bubble energy.

To correct for the other non-repeatable factors between monitors, a water layer inversion (WLI) was performed within each monitor survey after the application of deterministic tidal correction based on measurements from nearby tide stations. In WLI, five acquisition- and environment-related parameters are inverted for each shot by minimizing the difference between the modeled travel time and the recorded one for the water bottom reflection and its first multiple (Dega et al., 2021). In this method, the reference information is the bathymetry, so each monitor will have corrections inverted and applied based on a common water bottom location.

The first two parameters, *dhx*, *dhy*, represent the geometrical corrections of the source position. Indeed, the source position is supposed to be the theoretical barycenter of all the guns present in the source array. This barycenter may however be wrongly located, especially when the gun array is in motion, and a constant offset error needs to be estimated to correct for it. As the source configuration and the source motion is mostly constant over a survey, the *dhx* correction is similar for the entire monitor. The *dhy* can also be linked to the source barycenter but its value is more strongly affected by the feathering, varying throughout the survey. Due to the instability of this inversion, *dhy* was set to zero, assuming no errors on the y location. The next parameter, *dt*, is linked to the gun delay and is constant for a given monitor. To reduce the crosstalk among different parameters during the inversion, the medians of the above three parameters are calculated and applied to the data prior to inverting the last two parameters. The water velocity variation, *dv*, is mainly influenced by the water temperature and the salinity. The different monitors over the Dalia were all acquired in winter, therefore the average water velocity is not expected to change much between monitors. However, with an acquisition running over a month, water temperature during the survey is also expected to vary. Figure 1 shows the inverted *dv*, for each sequence of a single monitor. Both monthly and daily (day/night temperature cycle) variations can be observed. Monitor surveys over the Rosa field, located nearby, were also acquired during the same acquisition campaign and the *dv* estimation for this field shows good agreement with the Dalia values. The strong correlation between inverted parameters can be well illustrated with the push-reversed example. To infill acquisition holes coming from the presence of the floating production storage and offloading (FPSO) vessel in the middle of the shooting area, some of the undershoot sequences were acquired in a push-reversed configuration. In this configuration, the source boat is near the tail buoy, at the end of the streamer. When applying similar *dhx* correction as regular lines on these sequences, WLI output a larger velocity correction, which is difficult to explain. However, when applying a dedicated *dhx* correction compensating for the erroneous location of the tail buoy, the inverted velocity values are better aligned with those from the other sail-lines.

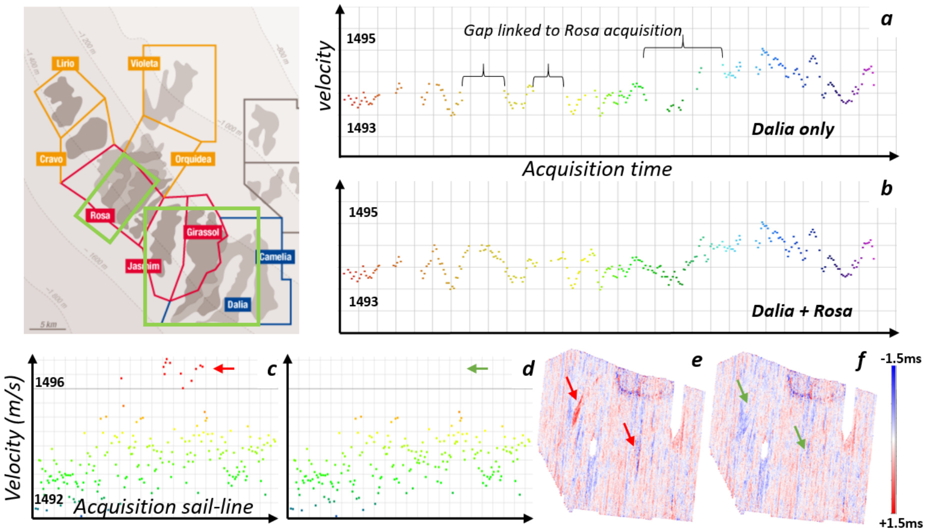

Figure 1: *Geographical map shows the location of Block 17 fields. For practical reasons, the same 4D acquisition campaigns cover the nearby Dalia and Rosa fields, boxed in green. When plotting the inverted water velocity against acquisition time for Dalia field (a) and combining it with Rosa (b), good continuation of velocity is observed despite a different reference bathymetry. Panel c shows the inverted velocity along sail-lines over Dalia only. On this graph outlier points, marked by the red arrow, correspond to push-reversed undershoot sequences. After dhx correction, the inverted velocity of undershoot sequences aligns with that of the other sail-lines (d). After applying these corrections, the clear imprint on the time shift map at the water bottom level of the push-reversed sequences (e) is well corrected (f).*

The last inverted parameter, *dz*, measures the variation of the sea surface and may compensate for possible inaccuracy in the provided reference water bottom. This parameter varies with acquisition time, similar to the tide. As it is the last parameter to be inverted it also includes residual effects of previous smoothed corrections (*dhx*, *dv*).The effect of these corrections on one monitor is summarized in Figure 2, where the application of the tidal static, *dv* and *dz* can be appreciated. Alignment between the sail-lines and between near and far offsets is improved, confirming the convergence of WLI.

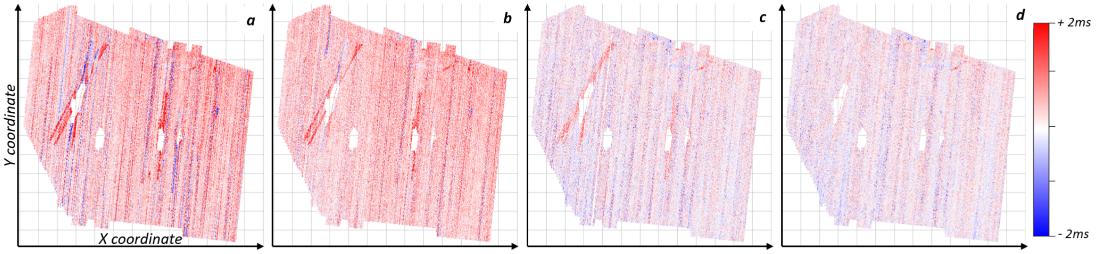

Figure 2*: Applying progressively each correction and cross-correlating NMO-corrected near and far offset of a single monitor allows assessment of the quality of inverted parameters. Time shift map at water bottom before any corrections (a) shows an obvious sequence-to-sequence striping pattern which is corrected by tidal application (b). After the application of dv (c) the time shift values reduce and approach zero. After applying dz correction (d) residual stripes between sail-lines are further corrected.*

Impact on 4D results

After the application of WLI corrections, conventional 4D binning was performed and followed by a pre-stack time migration to compare 4D results with the legacy. By looking at the calculated time-shift volume along the subline section (Figure 3a), new results show a stronger subsidence effect than the legacy with visible impact up to the water bottom. On a time slice crossing the overburden, more spots of subsidence can be identified, which are well correlated with the delta pressure model. These improved 4D responses are crucial to reconcile information from time-lapse seismic and reservoir engineering. For the time slice at the reservoir level, the result obtained with WLI shows a clearer delineation of the reservoir compartments.

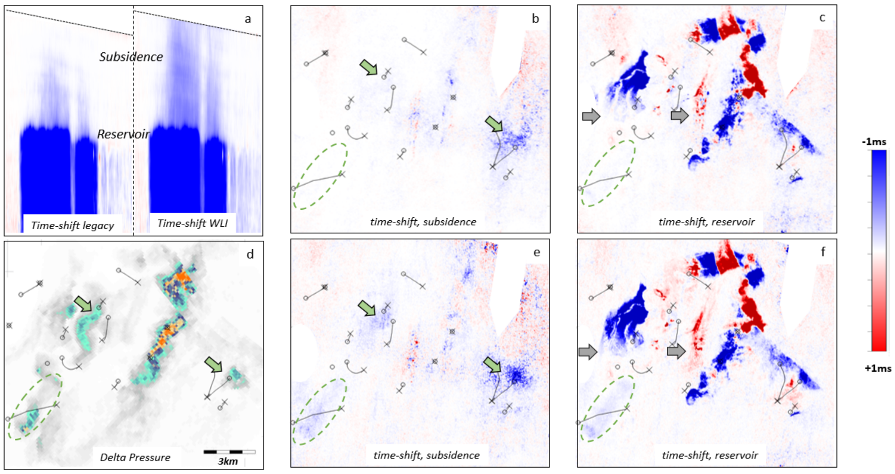

Figure 3*: Subline cross-section (a) of time-shift volume shows a stronger subsidence effect going up to the water bottom on the WLI processing than legacy. Overburden time slices of time-shift volume are compared between legacy (b) and new (e) 4D processing. Subsidence areas, highlighted by green arrows, are hardly visible on the legacy result, while they are better captured by the new result and match better with the delta pressure model (d). For the time-slice crossing the reservoir, the new result (f) shows an improved signal-to-noise ratio with clearer reservoir boundaries (grey arrows) over legacy (c).*

On the Dalia field, the benefits of our proposed flow, based on deterministic corrections, are quite noticeable both at the overburden and reservoir levels, when the conventional 4D processing flow has difficulty in handling the subsidence in the shallow overburden. On the Rosa field however, there is no observed subsidence and the cross-equalization can be potentially effective. As shown in Figure 4a, the time shift map at the water bottom from the conventional flow is nearly zero as expected from the cross-survey matching method. However the time shifts from the conventional flow at the reservoir level appear noisier (Figure 4b), partially obscuring the reservoir boundaries; whereas the time shifts from the new flow (Figure 4e) have less background noise and show better delineated reservoirs. This can also be observed from the NRMS maps (Figures 4c and 4f). Corrections from cross-survey matching are only 1D and cannot fully compensate for 3D effects related to source geometry errors or water velocity variations. Such corrections done to reduce the noise in the overburden may then introduce artefacts underneath, damaging the true 4D responses at the reservoir level.

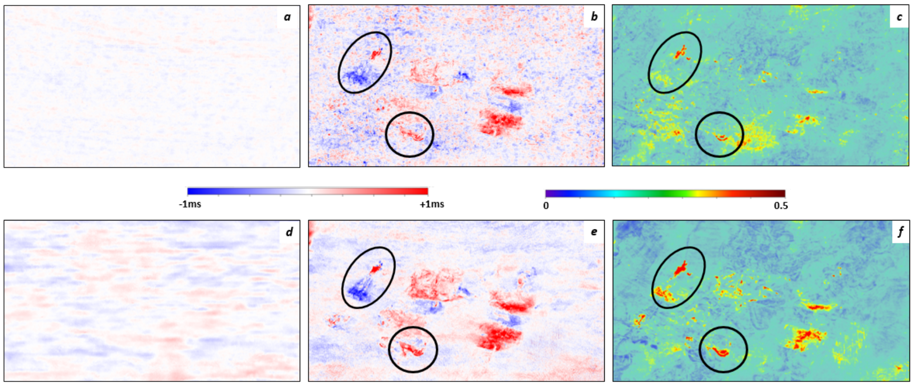

Figure 4*: Time-shift map computed at the water bottom level appears to be less stripy and with small values on the legacy (a) than the raw migration of new result (d). However, 4D signals are cleaner and more visible in both time-shift and NRMS maps in the new processing (e and f) than the legacy (b and c). Even in the case of stable overburden, performing harsh equalization between the two data sets does not guarantee to improve the 4D response at the reservoir level. Note that current results from the new flow can be further improved with mild residual 4D de-striping.*

Conclusions and Discussions

By independently processing each monitor and correcting for acquisition geometry difference, water velocity and water column height variations, this new deterministic method better preserves the true 4D signal while suppressing acquisition-related 4D noise. Its application on two Angolan fields, one with subsidence and one without, shows that the proposed method better reveals the 4D signals than the classical cross-equalization method. Subsidence information now better matches with the pressure model; time shift and NRMS maps at the reservoir level are cleaner and easier to interpret. This new workflow is particularly well suited for surveys in deep water settings as they allow accurate picking of the water bottom and multiple arrivals in a large offset range. However, when the subsidence effect is large at the water bottom, errors could be present in the current proposed workflow as a bathymetry survey is used as the common reference of water bottom for inversion and correction. Fortunately, the subsidence effect at the water bottom is normally small and negligible for WLI for most of the fields. Lastly, as each monitor is processed independently, the new flow may not require reprocessing of existing monitors when a new monitor is acquired in the future, thus having the potential to reduce the timeline of future 4D processing.

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