

MULTI-WELL 4D DAS VSP: A CASE STUDY AT MARS BASIN, GULF OF MEXICO

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Summary

We present a 4D case study of time-lapse multi-well Vertical Seismic Profiling (VSP) acquired with Distributed Acoustic Sensing (DAS) at the Mars field, deepwater Gulf of Mexico. In this work, we are able to obtain meaningful 4D signals from multi-well DAS VSPs by addressing various challenges that include weak 4D signals from a relatively short time interval (~1 year), an extremely noisy monitor survey, and poor repeatability between baseline and monitor acquisitions. 4D friendly pre-migration co-denoise was the key to attenuating the strong background noise in the monitor survey while preserving the potentially weak 4D signals. 4D shot co-selection and regularization effectively mitigated some of the acquisition differences between the baseline and monitor surveys. In addition, least-squares Kirchhoff (LS-Kir) migration compensated for the illumination variations and attenuated strong migration swings caused by irregular VSP acquisition geometry; it also improved the amplitude consistency between upgoing and downgoing wavefields within each well and among different wells. This facilitated the combination of three nearby wells with both upgoing and downgoing wavefields for 4D imaging and improved the coverage and S/N of the 4D results.

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Introduction

Vertical Seismic Profiling (VSP) surveys acquired with Distributed Acoustic Sensing (DAS) have been envisioned as good candidates for frequent, on-demand time-lapse (i.e., 4D) reservoir monitoring due to lower cost and less interruption to production. Recent reports of meaningful 4D signals from field data applications confirmed the viability of DAS VSP (Mateeva et al., 2017; Kiyashchenko et al., 2019). However, these studies so far have mostly focused on the upgoing wavefield from individual wells. As is known, VSP images are often limited to a small area close to the wellbore. As a result, many attempts have been made to expand the image coverage of VSP data, e.g., utilizing the downgoing wavefield. A recent study at the Mars field in the Gulf of Mexico (Zhan et al., 2020) shows that DAS VSP images from both upgoing and downgoing wavefields, as well as nearby wells, can be combined to improve the coverage and signal-to-noise ratio (S/N) of 3D images. However, combining upgoing, downgoing, and wavefields from multiple wells for 4D imaging is significantly more challenging, because 4D signals are more susceptible to noise and illumination variations from different wavefields of different wells. Here, we present a case study at the same Mars field to demonstrate that multi-well DAS VSP for 4D imaging is achievable and can provide the same benefits observed in the 3D imaging case.

The Mars field in the deepwater Gulf of Mexico started production in 1996 and is still undergoing active drilling and enhanced recovery. Several DAS VSP data sets have been acquired to monitor the oil and water movements from water flood at several key producing reservoirs. Among them, two surveys, acquired in 2018 and 2019, are the focus of this study. In general, DAS VSP data poses unique challenges for processing, compared to 3D surface seismic data, with less uniform and lower fold, poorer S/N, smaller data coverage, and larger illumination variations. In addition to these common issues, several specific challenges were met in this 4D work. Firstly, the acquisition configurations were not well repeated between the baseline and monitor surveys, as shown in Figure 1. The baseline survey was acquired by “eavesdropping” shots from a 2018 OBN survey with source spacing of 50 x 50 m and source volume of 2950 cu. in, while the monitor survey was acquired in 2019 with source spacing of 12.5 x 100 m and source volume of 2280 cu. in. Secondly, potential 4D signals are relatively weak from a time interval of only ~1 year. Thirdly, the baseline and monitor surveys have very different S/N (Figures 2a, 2b). The extremely strong noise from well activities in the monitor data (Figure 2b) makes it difficult to recover the 3D signals behind the noise and even more difficult to preserve the weak 4D signals during noise attenuation. Further, as these three wells have different paths and inclinations (Figure 1a), the illumination patterns of upgoing and downgoing wavefields at the same well and among different wells are all different. Achieving meaningful multi-well DAS VSP 4D imaging from this challenging data set requires properly addressing all of these challenges.

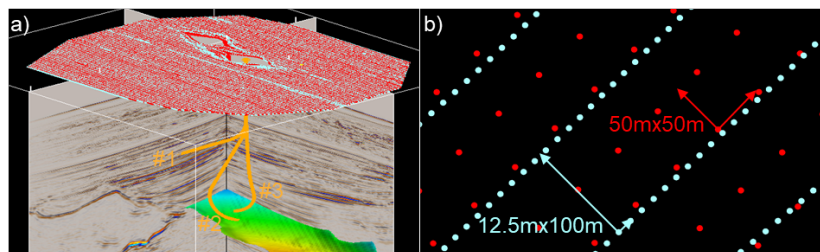


Figure 1 a) Legacy OBN RTM image in the background; red and light blue dots show shot maps of baseline (2018) and monitor (2019) DAS VSP surveys; orange curves are the trajectories of three wells. The map at the bottom of the wells shows one of the reservoir horizons. b) Zoomed-in view of baseline and monitor shots.

Tailored Pre-processing Flow

A tailored pre-processing flow, designed on top of the regular 3D DAS VSP processing flow, contains two key steps: (1) iterative survey matching and pre-migration co-denoise (Peng et al., 2014) to attenuate the strong background noise in the monitor survey using the cleaner baseline survey as a reference and (2) shot regularization to mitigate the source position inconsistencies and reduce 4D coherent noise.

To mitigate the impact of acquisition discrepancy on 4D co-processing results, approximately one half of the baseline shots and one quarter of the monitor shots with close shot locations were kept after 4D trace selection at the early stage of processing. As a result of the extremely strong noise in the monitor data (Figure 2b), the 4D image difference (Figure 3c) from these co-selected shots is dominated by background noise, and no meaningful 4D signals could be observed. It is very difficult to attenuate such strong full-band noise (Figure 2e) effectively without primary damage using traditional noise attenuation methods as it is nearly impossible to differentiate noise from signal in the monitor data. By using the relatively clean baseline data as the reference, pre-migration co-denoise was able to identify and attenuate the strong noise in the monitor survey and preserve primaries (Figure 2c). As a result, the image of the denoised monitor data (Figure 3e) shows similar noise level as the baseline (Figure 3d), and potential 4D signals stand out better (green arrow in Figure 3f). However, we can still observe uncanceled migration swings in both baseline and monitor images (red arrows in Figures 3d-3e) as a result of irregular shot positions, as well as background 4D noise from non-repeating shot locations between the baseline and monitor surveys (red arrow in Figure 3f). Shot regularization through 3D sparse TauP inversion was performed to bring both baseline and monitor co-selected shots to the same locations in a regular grid. Consequently, swing noise was effectively attenuated (Figures 3g-3h) and the S/N of 4D signals was further improved (Figure 3i).

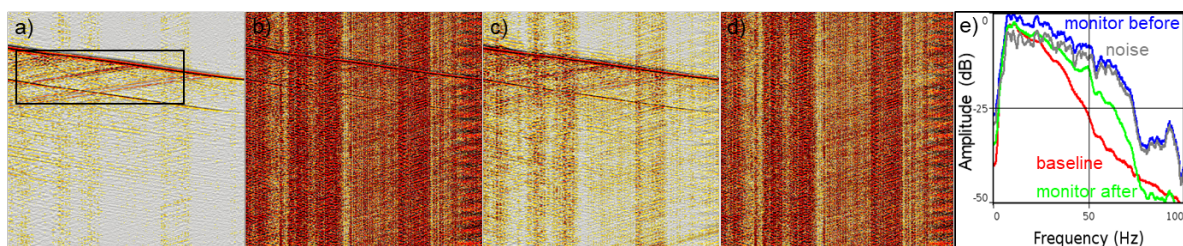


Figure 2 Example shot gathers from the a) baseline and b) monitor surveys; box in a) shows the window for the spectra measurement in e). c) Monitor shot gather after co-denoise; d) Strong noise attenuated by co-denoise; and e) The amplitude spectra of baseline, monitor before and after co-denoise, and the attenuated noise. Residual noise can still be observed in c) and e), though a significant portion of noise has been attenuated.

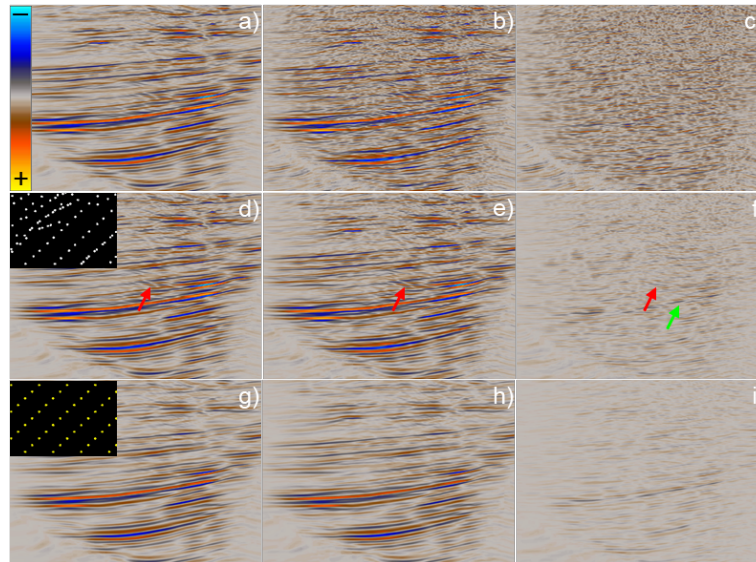


Figure 3 a) Baseline, b) monitor and c) 4D difference of Kirchhoff images from well #2 downgoing wavefield before co-denoise; d), e) and f) are the corresponding images after co-denoise; g), h) and i) are the corresponding images after shot regularization. The insets of d) and g) show the shot maps before and after shot regularization.

Least-squares Migration and Multi-well 4D Imaging

In addition to 4D co-denoise and shot regularization, least-squares Kirchhoff (LS-Kir) migration was performed to further attenuate migration swings and improve S/N and, more importantly, to compensate for illumination variations of upgoing and downgoing wavefields at the same well and among different wells, which facilitated 4D imaging of multiple wells. Strong migration swings and artifacts are often observed on VSP gathers and stacks (Figures 4b, 4d) as a result of low fold and small imaging coverage.

The coherent and upwards curving energy on the gathers (Figure 4b) could be perceived as indication of a too-slow migration velocity. However, a synthetic study using the same model for demigration and remigration shows gathers of similar curvature (Figure 4a), which proves that this upwards curving energy on the gathers is not caused by velocity errors but rather uncancelled migration swings. Single-iteration LS-Kir (Wang et al., 2016) was applied in the surface-offset gather domain using a legacy OBN stack as the reflectivity model. LS-Kir effectively attenuated the migration swings and artifacts on the gathers and stack (Figures 4c, 4e). The corresponding 4D background noise (Figure 4f) was reduced, and potential 4D signals became clearer (Figure 4g). Furthermore, LS-Kir improved the amplitude consistency between upgoing and downgoing images of single wells, as well as images among different wells, by compensating for the illumination variations, which makes multi-well 4D imaging more straightforward.

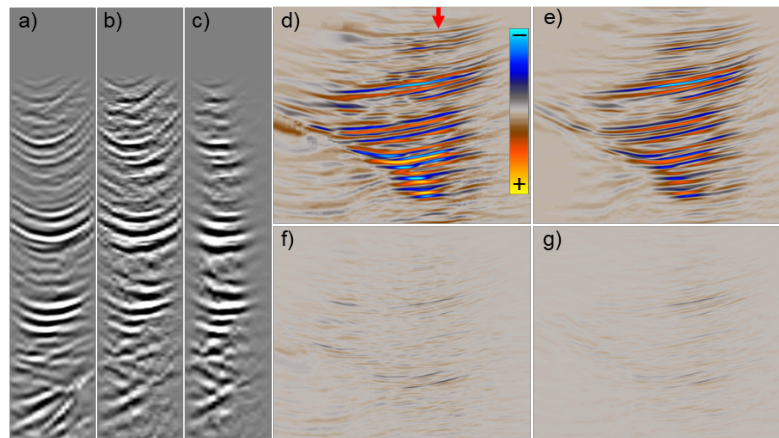


Figure 4 a) Synthetic Kirchhoff surface-offset gather and the corresponding gathers from well #2 upgoing monitor data b) before and c) after LS-Kir at the location marked by red arrow in d); 3D Kirchhoff upgoing images of monitor data d) before and e) after LS-Kir; 4D difference f) before and g) after LS-Kir.

With better balanced amplitudes after LS-Kir, three single-well upgoing images were merged by straight summation to form an upgoing three-well image. The downgoing three-well image was derived in the same way. Figure 5 shows the 4D amplitude extractions at the reservoir horizon shown in Figure 1 and the corresponding NRMS of upgoing images from the three single wells and the merged upgoing three-well image. The upgoing three-well image shows improved 4D S/N and reduced NRMS compared to the images of individual wells. The upgoing and downgoing three-well images were further combined, as shown in Figure 6. Though the shallower reservoirs (green arrows in Figure 6) are mostly imaged by the downgoing wavefield, the 4D signals at the deeper reservoirs (red arrows in Figure 6) are mainly provided by the upgoing wavefield. Due to their different ray paths and the stronger attenuation in the earth for the downgoing wavefield, imaging areas of good S/N only narrowly overlap in depth between upgoing and downgoing wavefields. Therefore, the primary benefit of combining upgoing and downgoing images is to expand the image coverage and to provide a single volume for interpretation. Compared to the 4D signals from legacy 2015-2018 OBN 4D (Figures 6d, 6h), the 4D signals from 2018-2019 DAS VSP show a clear water movement in the up-dip direction (Figures 6c, 6g) as expected from production, although DAS VSP 4D is obviously noisier and has a lower resolution.

Conclusions and Discussions

In this study, we were able to address various challenges and obtain meaningful 4D signals from very noisy multi-well DAS VSP data. Due to strong noise in the 2019 monitor survey, good pre-migration noise attenuation through 4D co-denoise was essential for achieving the final results. In addition, LS-Kir is an important step to attenuate migration swings and balance illumination in DAS VSP surveys, and thus facilitate multi-well 4D imaging to improve the imaging coverage and/or 4D S/N. However, a relatively clean survey is needed for co-denoise to work, which may not always be available. Also, caution needs to be taken during LS-Kir so that areas in single-well images of very low illumination and poor S/N are not over boosted, contaminating the final multi-well image. Although 4D co-denoise, shot regularization, and LS-Kir could reduce the 4D noise to some extent, good repeatability of 4D surveys would still be critical for 4D imaging, especially for the low-fold DAS data. If the monitor survey comes with a more repeatable acquisition configuration and a more normal noise level, it would

be more feasible to achieve better 4D results of higher S/N and broader bandwidth. Therefore, besides improving the repeatability of 4D surveys, optimizing the DAS VSP acquisition to reduce the background noise and/or improve signal strength, e.g., increasing the fiber sensitivity, remains one of the key elements to further reduce the uncertainty of DAS VSP 4D results.

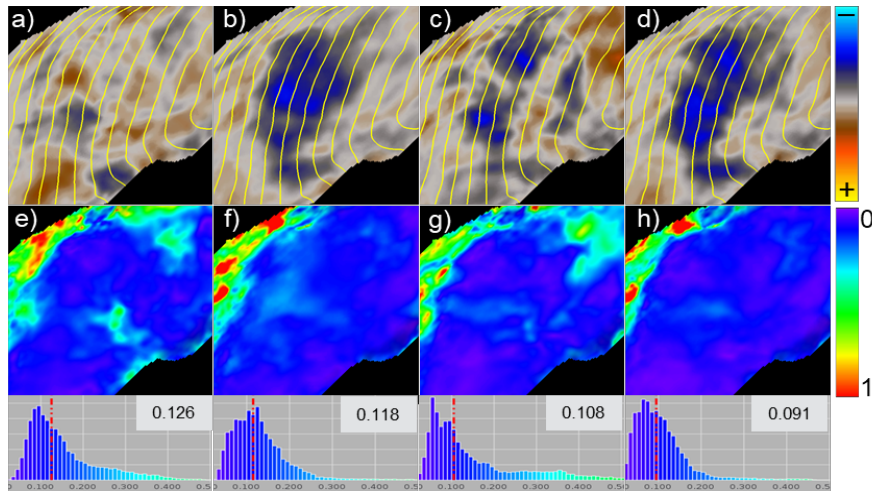


Figure 5 a), b) and c) 4D amplitude extractions from upgoing images of wells #1, #2 and #3, respectively; d) 4D amplitude extractions of the merged upgoing three-well image; e), f), g) and h) the corresponding NRMS and histograms.

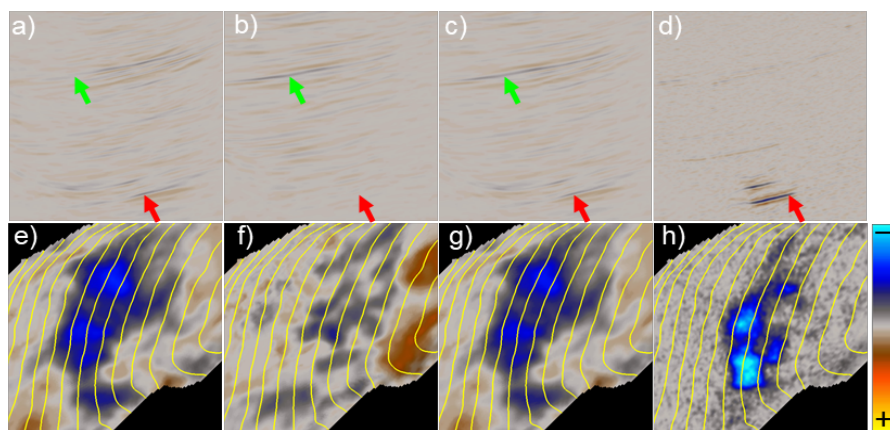


Figure 6 4D difference of a) upgoing three-well, b) downgoing three-well and c) merged three-well images; d) legacy 2015-2018 OBN RTM 4D difference; e), f), g) and h) are the corresponding 4D amplitude extractions for a deep reservoir (red arrows). Red arrows point to the location with water movement after 2018. Green arrows mark a shallow reservoir with 4D signals better imaged by the downgoing wavefield.

Acknowledgements

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