Application of 4D FWI to the Usan 4D Streamer Surveys

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Summary

In recent years industry has seen a paradigm shift with the advent of Full Waveform Inversion (FWI) imaging in 3D seismic data processing projects. Fundamentally this is a directional derivative of a velocity model, the resolution of which is controlled by the maximum frequency of the FWI and of course the subsurface properties.

FWI was first proposed by Tarantola (1984), due to the lack of cost-effective computers the uptake was limited. Sirgue et al (2010) published an example that accelerated development when FWI was run to 7Hz, to provide a significant uplift in imaging underneath a gas cloud. For many years FWI was run to 7Hz or 10Hz. Shen et al (2018) demonstrated the importance to subsalt imaging by extending beyond these traditional FWI frequencies, whilst Wei et al (2023) published a series of examples to demonstrate the value in 3D of extending FWI to frequencies in excess of 100Hz.

FWI has several potential advantages over conventional imaging, it is an iterative least squares solution of the full wavefield and thus has the ability to provide cleaner attributes as a result of the least squares nature of the process. As FWI uses the full wavefield (primary and multiples) it is possible to generate an image over a larger area relative to area obtained from single iteration, primary only RTM. FWI imaging has also enabled turnaround time for projects to be significantly reduced.

Despite the progress made, there are still very few published examples of using FWI imaging in 4D. In this paper we show the application of 4D FWI technology to show a towed streamer example offshore Nigeria. We will share examples of parallel 4D FWI (run FWI on each 3D and subtracting) versus a joint 4D FWI scheme, which produces equivalent results, but requires only around half the number of total iterations per frequency band relative to the parallel approach and has the advantage of using the 4D signal within the update. We then compare the results of the 4D FWI with a conventional 4D processing workflow, discuss the advantages and disadvantages of each and highlight future considerations.

Method

Dynamic Matching (DM) FWI uses both diving waves and reflections simultaneously to derive an accurate velocity field. DM FWI is insensitive to cycle skipping and robust to data with low S/N with proven success to produce a structurally conformable update to the velocity model (Mao, et al., 2020. DM FWI updates the velocity models by maximizing the similarity between the observed data d(t) and the synthetic data u(t) that is measured by the following objective function:

$$E(m) = \sum_{s,r,j} c(s,r,j) \qquad (1)$$

where c(s,r,j) is the local cross-correlation of an observed data d(t) and a dynamically matched version of the synthetic data u(t) simulated using model m, through local amplitude normalization, thus making the data matching less sensitive to amplitude discrepancies due to noises, etc

The proposed 4DFWI algorithm (Gao et al, 2024) that jointly inverts baseline and monitor datasets intends to minimize the following objective function:

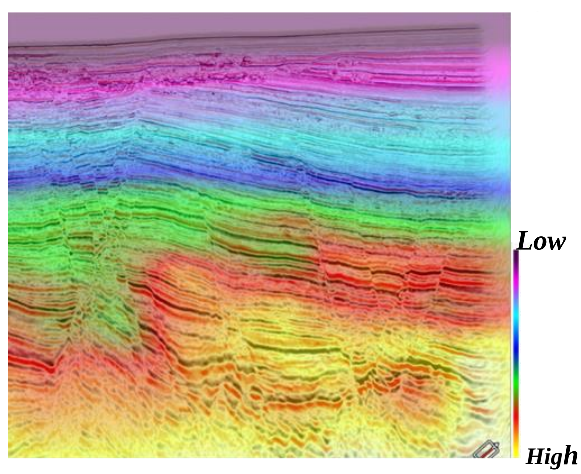
$$
\begin{aligned}
E(m_{base}, m_{monitor}) &= \sum_{s,r,j}\left[\frac{1}{2}-\frac{1}{2}c_{base}(s,r,j)\right] \\
&+ \sum_{s,r,j}\left[\frac{1}{2}-\frac{1}{2}c_{monitor}(s,r,j)\right] \\
&+ \alpha\left|\left|R(m_{base} - m_{monitor})\right|\right|^{p} \quad (2)
\end{aligned}
$$

The third term of Equation 2 is 4D coupling or regularization term that penalizes, or in some cases, promotes, certain relationships between base and monitor models. Where R is a regularization function which can constrain the function, α is the damping coefficient which defines the relative weight of the third term. and p is either 1 or 2, the norm of the 4D model. Minimizing the first and second term on the right-hand side of Equation (2) is equivalent to maximizing the 3D DM FWI objective function defined in Equation (1) using either dataset respectively, and the choice of ½ is to normalize the terms numerically within [0,1] for convenience. The final baseline and monitor models are the models with minimum difference between them (measured in L1 or L2 norm), yet each predicts the respective dataset well. One of the advantages of our 4D joint inversion is that the two datasets do not have to be repeated perfectly, although it is assumed that the two acquisition geometries are relatively near each other spatially.

The algorithm is realized by alternative updates between the baseline and monitor models by deriving gradient with respect to either of them at a time. After one model is updated for n iterations, it will be used and fixed inside the 3rd term on the right hand of Equation (2) for the next alternation. In this case study, Acoustic FWI was selected as the velocity changes were expected to be small and thus minimal uplift was expected from Elastic FWI

Results

Initially we focused on generating a velocity model that is suitable for migrating all vintages used in the 4D processing. For early (low) frequency bands, we used data with minimal processing applied. However, as we moved to the frequency bands in excess of 16 Hz, we used data with a more rigorous processing applied (including demultiple). Throughout the inversion process, stringent Quality Control (QC) measures were implemented, ensuring convergence in both the data and image domains. Quantitative assessment in the data domain scrutinized the mismatch between forward-modelled shot gathers and input shot gathers, while multiple image domain QC methods, including the evaluation of the flatness of common image gathers, were employed. Directional derivatives were applied to the FWI velocity model, producing FWI Imaging after each frequency band, which was then compared against the corresponding Pre-Stack Depth Migration (PSDM) stack image. The output from the 3D model building was a very geologically consistent model and is shown in both figure 1 with reservoir intervals clearly identified by the FWI process.



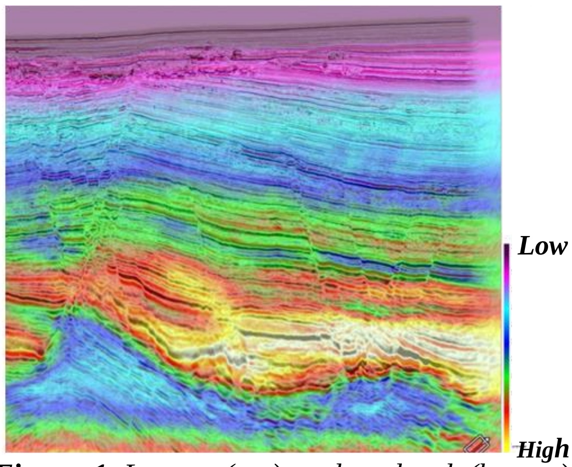


Figure 1 *Legacy (top) and updated (bottom) velocity models*

During the conventional processing of the 4D data using a single velocity model, 4D time-shifts were observed at the reservoir level and we embarked on a test to evaluate whether it was possible for FWI to also observe these changes.

As proof of concept, we took the penultimate band from the 3D FWI (16Hz) from the 3D velocity model build and re-ran the 20Hz band on a limited area (11 sail line swath) on both the base and monitor datasets. This provided a result that was very encouraging. We recognized the deficiencies in this very quick proof of concept test and set about testing in a more robust way.

Given the success of the initial test, we decided to use our 4D Joint Inversion FWI on a larger portion of the 4D area. Prior to running the inversion, we performed some basic 4D processing on the data to ensure we were inverting for the changes in the subsurface rather than geometrical issues in the various acquisitions. Much like in conventional 4D processing, where 4D binning is performed on CMPs, we perform a pseudo 4D binning on shots to ensure we are inverting for similar data.

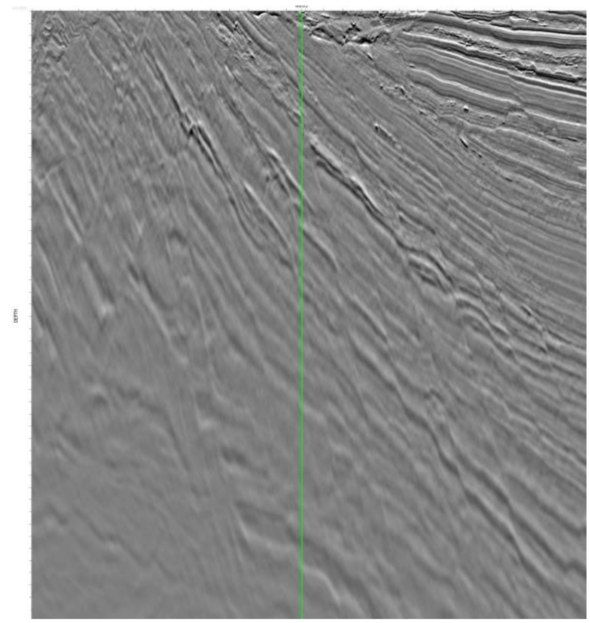


Figure 3 *3D reflectivity stack,*

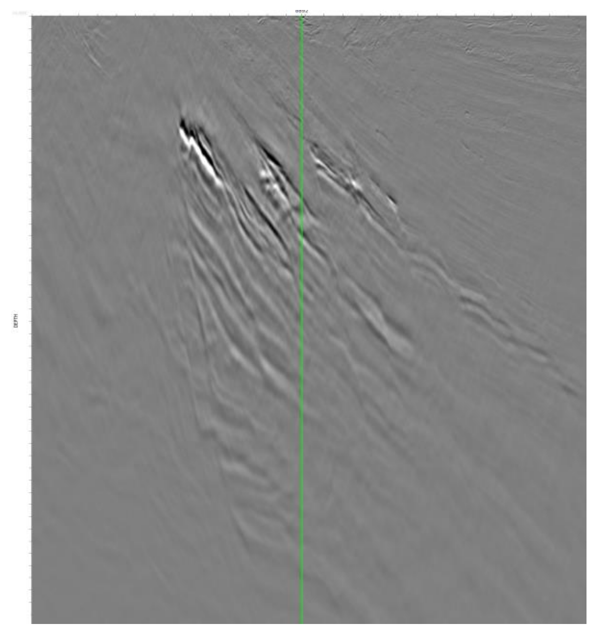


Figure 4 *4D reflectivity difference (single model)*

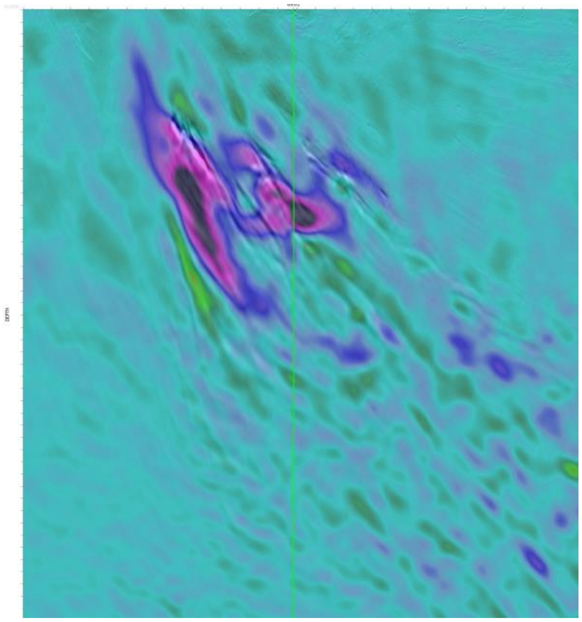


Figure 5 *4D reflectivity difference with 4D colour overlay*

We began the inversion process at the first frequency band and repeated the frequency bands of the 3D FWI model build. The use of the Joint inversion produced very similar, but sharper results relative to the parallel 3D FWI approach.

The advantage of this joint inversion is that it requires far fewer iterations than two independent 3D FWI runs and the use of the 4D within the inversion stabilizes the results. Inspection of the 3D stack, 4D difference, 4D dV and 4D FWI (figures 3-5) show excellent correlation of events which is a good validation of the reliability of the 4D FWI results.

Conclusions

We have found that our 4D FWI produces anomalies in coincident locations as 4D features on conventionally derived reflectivity images. This gives us confidence that FWI can produce reliable 4D signals but in a fraction of the time and effort.

The use of both the dual 3D approach and the joint 4D approach and the similarity of the results, resulting in greater confidence.

The correlation between the 3D reflectivity difference and the 4D FWI gives credence to the use of amplitudes from 3D FWI image for exploration purposes.

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References

Tarantola, A., Inversion of seismic reflection data in the acoustic approximation, GEOPHYSICS, August 1984

Shen, X., I. Ahmed, A. Brenders, J. Dellinger, J. Etgen, and S. Michell, 2018b, Full-waveform inversion: The next leap forward in subsalt imaging: The Leading Edge, 37,

Sirgue, L., Barkved,O., Dellinger,J., Etgen, J., Albertin, U., and Kommedal, J., First Break, Volume 28, Issue 4, April 2010

Wei, Z., Mei, J., Wu, Z., Zhang, Z. Haung, R., Wang, P., Pushing seismic resolution to the limit with FWI imaging, The Leading Edge , January 2023

Gao F., Cavalin D., Davies D,. Saxton L., Liu F., Calderon C., [2024] Time-lapse model by 4D dynamic matching joint inversion, SEG 4D Workshop

Mao, J., J. Sheng, Y. Huang, F. Hao and F. Liu, 2020, Multi-Channel dynamic matching full-waveform inversion, SEG Technical Program Expanded Abstracts.