**Improved PP- and PS imaging using Full Waveform Inversion; Tommeliten OBC case study**

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**Introduction**

Full Waveform Inversion (FWI) is currently a topic of great interest in the oil and gas industry. The promise is to produce high-quality, high-resolution velocity models, not only to benefit the imaging of complex geological structures, but also to provide an interpretable product in itself. Spurred on by advances in computing power, there has been renewed work in this area in the past few years. This has resulted in a number of publications demonstrating spectacular applications of FWI to various synthetic datasets (see Virieux and Operto, 2009 and references therein). Real data examples have proved more challenging, although noticeably impressive success stories exist, for example, Sirgue et al. (2009).

In this paper we apply FWI to a North Sea OBC data set with wide azimuths and more than 10 km long offsets over the Tommeliten field. We discuss the methodology used and the associated practical issues. In Ratcliffe et al. (2011) we demonstrated that this velocity update improves the imaging of the deeper structures for PP PSDM. In this paper we also show improvement in imaging of converted-wave (i.e. PS) PSDM.

**Real Data OBC Example**

We apply FWI to multicomponent data from the Tommeliten Alpha area in the Norwegian North Sea (Block 1/9). Tommeliten Alpha is a gas condensate discovery located 25km South-West of the Ekofisk field. The reservoir consists of two fractured chalk formations (Ekofisk and Tor) situated at approximately 3000 m depth. A large part of the reservoir is located in a seismic obscured area (SOA) caused by gas in thin silt and sandstone layers of the middle Pliocene (920 m). In 2005, a high-density, full azimuth, OBC survey was acquired in an attempt to improve imaging in the SOA. This objective was partly achieved, mainly thanks to pre-stack depth migration of PS data. The present objective of using our latest version of FWI is to improve the P-velocity definition of the shallow, thin, gas-charged layers to improve the PS imaging.

**Methodology**

We use the FWI implementation described in Warner et al. (2010) and Ratcliffe et al. (2011). This is a 3D, acoustic, finite difference, time domain method that updates the P-wave velocity in a VTI- or TTI model using a linearised least squares inversion process.

Our FWI is driven by the inversion of transmitted energy (e.g. diving- and head waves). Therefore, the pre-processing of the real data is geared towards preserving and enhancing this energy on the field records. At present, all other energies are seen as “noise” and subsequently attenuated. In the future, as our technology develops further, using additional elements of the wave-field should be advantageous, aiding the inversion process and improving the final result.

Our data pre-processing steps complement this strategy and consist of: de-bubbling, low-pass filter and inner/outer muting. This leaves a real dataset that still contains ghosts and multiples. For the modelling we start from the shot de-ghosted gun signature wavelet and propagate in a model with a free surface. The aim of this workflow is to give comparable real and modelled datasets for the FWI. These choices are discussed in the next section.
Practicalities

FWI involves a wiggle for wiggle comparison between the real seismic data and the modelled field records. In order for this differencing to work effectively we need a consistency between the real and modelled data. Hence, we try to include as much real physical phenomena as is practical in the modelling. At present we concentrate on inverting the pressure wave-field only. As is often the case, the devil is in the detail, and it was the complete workflow that produced a significant result.

- In the time domain the source wavelet is a critical aspect of FWI. We could estimate this from the field data itself by picking and processing the first breaks, but this is a non-trivial and time consuming task. We have found that a simpler, and perhaps safer, route is to use the gun signature. Of course, this is a valid approach only if the gun signature is a good representation of the real data wavelet at the frequencies of interest.
- Ghosts and other multiples are a complicating factor in the raw P-wave data that we use in the inversion. Rather than try to address these effects in the real data, we include them in our modelling through the use of a free surface.
- Because our FWI is driven by transmitted energy, we can only expect a sensible update to the velocity model in areas where this energy has penetrated. The critical factor is the size of the longest offsets in the real data. The larger the offset, the deeper the penetration of the transmitted energy. Offsets exceeding 10 km were acquired in the real data example shown here. Based on the combination of a simple modelling exercise and careful examination of the FWI results we find that sensible updates can be obtained down to ~2 km depth.
- Strong Vertical Transverse Isotropy (VTI) is known in the Tommeliten area, as high as 20% in some layers. This causes a significant change in travel-times of the modelled events. Consequently, a key factor in producing reliable results was having an FWI algorithm that honours this behaviour.
- Even though we use a time domain algorithm we are not immune to the local vs. global minima convergence problem and so we only invert the low frequencies in the seismic data. New acquisition and processing techniques that aim to extend the seismic bandwidth (Soubaras 2010), especially at the low frequencies, will prove valuable in this regard. In Ratcliffe et. al. (2011) we ran FWI on the Tommeliten data with frequencies up to 4.25 Hz, but in the current example we perform the inversion up to 7.5Hz achieving sharper results.
- The starting (VTI) velocity model needs to be close enough to reality such that the modelled field records are not cycle skipped with respect to the real data. In the current paper this starting model comes from a traditional PSDM velocity model building and covers a ~220 km² area to a depth of 4.6 km.

Building a PS model using FWI

Usually the P-velocities from FWI are used for two purposes; 1) direct interpretation of the velocities to find channels, fracture zones, high-pressure zones or gas, 2) as migration velocity in PP PSDM to improve the imaging. In this paper we will use the P-velocity from FWI for PS imaging. The PS PSDM model we have built is VTI and consists of:

- P-velocity field used for the P-wave propagation from the seismic sources close to the water surface.
- S-velocity used in the S-wave propagation from the receivers on the ocean-bottom.
- Thomsen δ, ν and ε parameters used in both P- and S-wave propagation.

In this study we use the radial component of the 4C OBC recording in the PS migrations.

The input model for FWI was built by state-of-the-art model building technique including layer-stripping and ray-based, 3D tomography. The Thomsen δ, ν and ε was found by the mismatch between the formation tops from wells and the near-offset migration stacks followed by joint PP/PS tomography.

Initial S-velocity was estimated from the P-velocity using a best-guess PS ratio, followed by a S-velocity update based on the mismatch between PP- and PS images.

Then FWI as described above was used to update the P-velocity model only, which was inserted into the PS velocity model. No subsequent changes were done to either the S-velocity or the Thomsen δ, ν and ε in the model.
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<tr>
<th>Image</th>
<th>Description</th>
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<tr>
<td>a)</td>
<td>Depth slice of initial P-velocity with RTM PP-image overlaid. The P-velocity model is from a conventional depth imaging VMB.</td>
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<tr>
<td>b)</td>
<td>Depth slice of P-velocity updated by FWI using frequencies up to 7.5 Hz. The RTM PP-image is overlaid.</td>
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<td>c)</td>
<td>PS Kirchhoff PSDM using model from standard VMB</td>
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<td>d)</td>
<td>PS Kirchhoff PSDM using model with P-velocity from FWI</td>
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<td>e)</td>
<td>PP RTM image using model from standard VMB</td>
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<td>f)</td>
<td>PP RTM image using model with P-velocity from FWI showing better imaging in the SOA.</td>
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Figure 1: a), c), e): Images and P-velocity before FWI. b), d), f): Images and velocity after FWI.
Results

In Figure 1, an depth slice through the starting P-velocity model, updated P-velocity model and Crossline/Inline sections of PP- and PS migrated stacks are shown. Notice the remarkable correspondence in Figure 1 b) between the fractures in the gas-charged area and the inverted velocity. This improves our confidence in the inversion. We have also noticed that the resolution is better when we run FWI up to 7.5 Hz compared to the 4.25 Hz in Ratcliffe et.al. (2011). However, a drawback is that we observe slightly more acquisition footprint when inverting with the higher frequencies.

The PS images in Figure 1 c) and d) were generated by Kirchhoff migration, while the PP images in Figure 1 e) and f) were generated by Reverse Time Migration (RTM). Figure 1 b) shows the locations of the Crossline for the PP images and the Inline for the PS images. (NOTE: We are waiting for the latest PS images from Thomas)

The PS Inline goes through the centre of the gas charged area and the effect of the gas is clearly visible in the SOA. Generally PS images are better in the SOA than the PP images. This is caused by less scattering by the S-waves than the P-waves in the gas. A further improvement is observed in the PS image in Figure 1 d) where the P-velocity has been updated by FWI. The image is more focused with more coherent events than the image from the original PS model. This is another indication that the P-velocity from FWI is more correct than the P-velocity from the conventional velocity model building.

Conclusions

This case study demonstrates the benefit of using FWI in velocity model building for both PP- and PS imaging in a North Sea OBC case. The update of P-velocity in the upper 2 km of the model improves the PP- and PS imaging in the deeper parts of the model down to around 4 km.

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References


