Post-EAGE 2020 Comments on Full Waveform Inversion (FWI)

The recent virtual EAGE 2020 conference included an interesting discussion on 'High frequency FWI'. Whilst the short-term motivation is to deliver fast-track interpretation products with an abbreviated processing flow, the ambition of seismic inversion has always been to recover high-resolution elastic medium properties from the earth. After reviewing the traditional separation between low wavenumber background model building with FWI and high wavenumber reflectivity imaging, I consider the nature of the 'reflectivity' resolved by running traditional FWI to high frequencies. The issue of whether FWI is 'imaging multiples' by nature of being one form of a Least-Squares Reverse Time Migration (LS-RTM) is also considered. This discussion hopefully helps understood the products delivered by high frequency FWI.

Previous FWI Discussion

In previous industry insights newsletters this year I explained some basic elements of Full Waveform Inversion (FWI) and Least-Squares Migration (LSM). Regards FWI, content included the fundamental iterative data-fitting workflow (a gradient-based inversion that maps the misfit between modeled and recorded data to perturbations in the earth model), the fundamental challenges of cycle skipping, and the principles of adding regularization terms to the objective function.

It was noted that FWI uses elements of Reverse Time Migration (RTM); in that forward-propagated seismic wavefields from discrete source locations are correlated with back-propagated seismic wavefields from the associated receiver locations (the so-called 'adjoint sources'), and FWI is similar to Least-Squares RTM (LS-RTM); in that an initial model is iteratively updated until an objective function converges to a minimum value.

In principle, FWI is capable of recovering a complete earth model with a resolution dictated by the seismic experiment. In practice, and more than three decades after its conception, FWI is still evolving to deliver on that promise. The problem is not the theory itself, but most often a failure by many to recognize seismic inversion as a two-goal process. An earth model can be represented as a smoothly-varying (low wavenumber) background model onto which are superimposed sharp contrasts in acoustic properties (high wavenumber) associated with geological boundaries, expressed as reflectivity. The goals of seismic inversion are to both estimate the background model and predict the reflectivity without damaging either.

In the classical implementation of FWI, the model update produced for each shot correspondingly has an entirely different physical meaning to the seismic amplitudes recovered during RTM or LS-RTM. Nevertheless, the recent virtual EAGE conference held on 8-11 December 2020 included technical presentations that proposed running FWI to frequencies as high as 100 Hz (a 2D proof-of-concept), and using the final model as an interpretation product. It was argued that this approach has be considered as 'A form of LS-RTM that incorporates multiples and can be delivered within days of final shot of marine acquisition'. A new 'Hot Topics' panel discussion event titled 'FWI: Future perspectives without the hype' was also tested at the EAGE event, and a short audience poll indicated that 94% of respondents were interested in the concept of 'High frequency FWI'.

One form of 'FWI image' discussed at both the virtual SEG conference held in September and the EAGE conference was the application of a derivative to the FWI model to enhance local resolution. This principle is well known for the image processing of potential fields data, and in the form of Laplacian filtering has historically been used to dampen low wavenumber RTM artifacts. It is worth considering the nature of the features enhanced in FWI models—for both traditional low frequency models and for models with maximum frequency equivalent to that used in RTM imaging. Therefore, I will attempt to articulate a few relevant features of 'High frequency FWI'. Whilst there is no question that seismic inversion developments will advance significantly in coming years, it is useful to comment on what conventional FWI does and does not do.

The Classical View of Seismic Imaging

Low and high wavenumber models

Figure 1 presents a cartoon perspective of historical best-practice FWI and seismic migration, although I note that the continuous wavenumber spectrum incorrectly assumes a 'complete' acquisition experiment (unlimited offsets, very low frequency content, large source bandwidth, and the subsurface is uniformly illuminated and spatially sampled by all the recorded seismic wavefield):

- A nonlinear iterative inversion that updates a varying background velocity obtaining all wavenumbers that are resolvable by migration and tomography.
- A good initial 'very low wavenumber' model is normally required to ensure convergence to a global inverse solution.

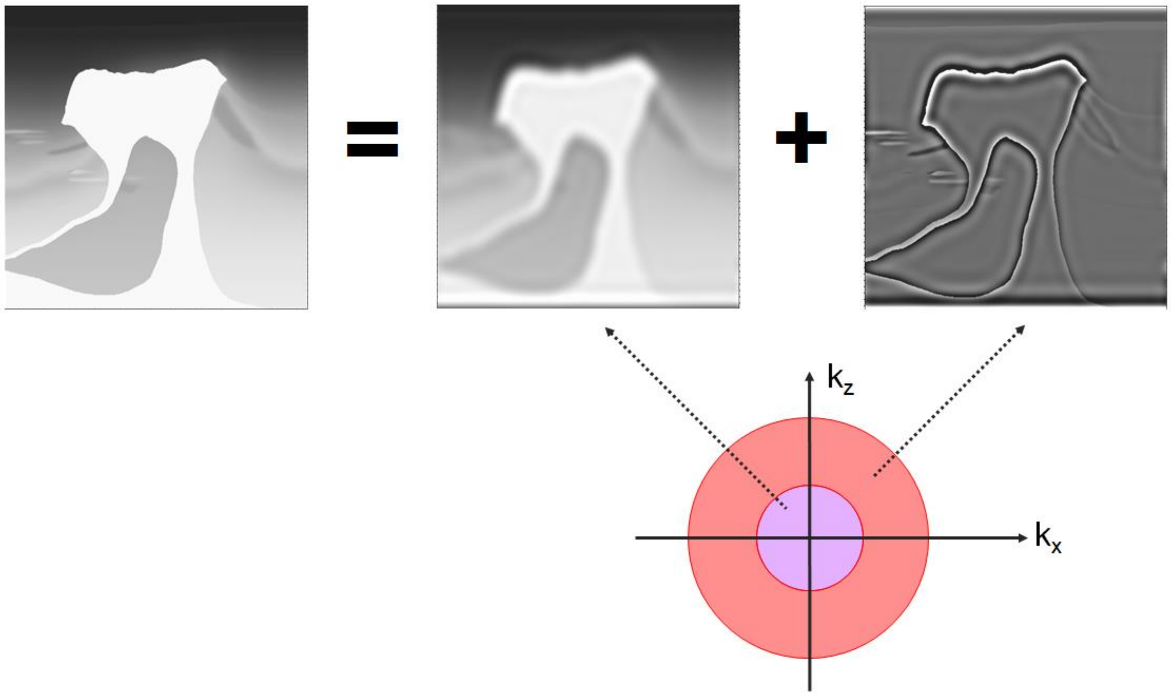

Figure 1. The 'true' earth model (left) can traditionally be regarded as the sum of the background model recovered by FWI (low wavenumbers: center) and the reflectivity recovered during imaging (high wavenumbers: right). The color wavenumber spectrum in the lower row assumes a perfect acquisition experiment.

In the 'traditional' approach, FWI is first run to recover the low wavenumber model of the velocity—with minimal contamination by reflectivity—and then this model is used within an RTM imaging step; which may subsequently feed an LS-RTM inversion step to yield the image of the earth with maximum spatial resolution. In such a workflow, the FWI step may incorporate multiples in the synthetic forward modeling steps when building the background velocity model, but the multiples contained in the data will be removed during a cascaded series of steps before the data is migrated.

Dealing with artifacts

Conventional FWI estimates the background velocity mainly relying upon refracted and diving waves that have limited penetration depth. The need to recover background velocities in the deep part of the model has triggered a demand for long offset acquisition that can provide diving waves that penetrate to the required depth. As an alternative, one can utilize reflections to recover background velocities in the deep part of the model. However, excluding the high wavenumbers when updating the reference model is a critical requirement on a reflection-inclusive FWI. Failure to build the correct background model leads to inversion results that resemble seismic images representing the reflectivity component of the model, but which can be contaminated with artifacts.

Figure 2 was originally relevant to advances by PGS in the application of RTM. Low-wavenumber artifacts common to RTM when a traditional cross-correlation imaging condition was applied were heuristically dampened by Laplacian filtering (a form of edge enhancement) of the RTM image. However, a new imaging condition based upon inverse scattering theory enabled the high-wavenumber migration isochrone to be summed without artifacts. To be specific, the 'rabbit ear' sensitivity kernel in the centre panel of Figure 2 no longer contributes to high-wavenumber RTM imaging. Note that it is increasingly common to hear claims that FWI run to higher-than-normal frequencies contains 'less artifacts' than traditional RTM images. A large part of such observations may be a failure to account for the aforementioned low-wavenumber artifacts in the RTM being used for comparison.

Figure 2 reconfigures the original mathematics of Tarantola (1984) that described the FWI gradient in terms of two 'sensitivity kernels' (or Fréchet derivatives) that recover bulk modulus and density properties of the earth. Instead, a dynamically-weighted 'velocity' sensitivity kernel computed with an inverse scattering imaging condition (ISIC: centre panel) recovers only background velocity model updates, and a dynamically-weighted 'impedance' sensitivity kernel (right panel) recovers high wavenumber reflectivity updates.

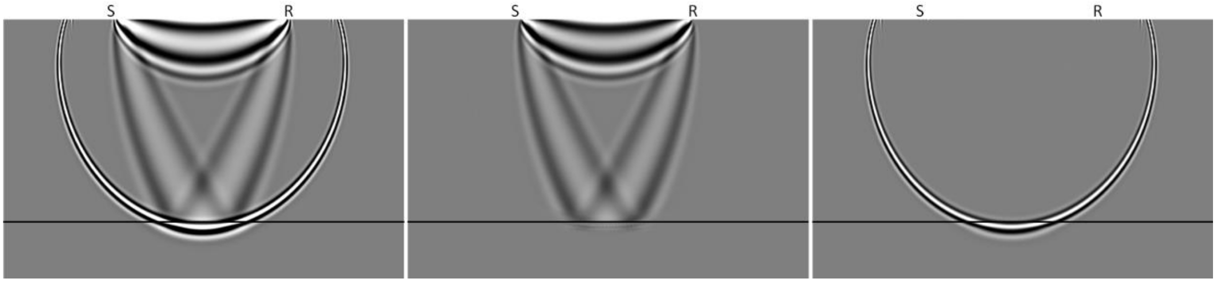

Figure 2. (left) Sensitivity kernels for full wavefield FWI, computed with a cross-correlation imaging condition and using a simple V(z) over a half-space velocity model for one offset; (centre) Banana (driving wave) and rabbit ear (reflection) sensitivity kernels computed with an Inverse Scattering Imaging Condition (ISIC) in a manner that updates the low wavenumber background model; and (right) Migration isochrone corresponding to the impedance kernel.

Stated alternatively, the different sensitivity kernels associated with the FWI can be separated into a tomography term (rabbit ears and banana donut) and a scattering term (migration isochrone). The low-wavenumber component (centre panel) is used to update the background velocity model, while the scattering term (right panel) is used to update the reflectivity. Separation of the two components allows the background velocity and the reflectivity to be independently updated while avoiding cross-talk between the two model updates.

How reflectivity affects the seismic wavefield contribution to each FWI sensitivity kernel

The historically most common FWI implementations relied only upon diving wave and refraction information; and used heavily-muted shot gathers isolating the first arrival events. Only the phase (i.e. travel time) information was useful (no 'full waveform' aspect), there is no useful reflectivity information, and this transmission FWI is a form of tomography. The head wave component of refractions require a velocity contrast to exist, and therefore the banana kernel will contribute reflectivity information into velocity model updates at high frequencies.

Deep model updates using the reflection component of the impedance kernel typically do not require very long offsets. In this context, FWI will likely only benefit from very long offsets during the initial low frequency model updates, and much shorter updates will suffice when pursuing high frequency reflection-inclusive updates.

Note that coupling between velocity and density can generally be detected (if you look for it) below about 10 Hz. If FWI is driven beyond 20-30 Hz, the velocity-density coupling is unavoidable, and the model will therefore represent higher frequency reflectivity. It is also important to note that reflections essential for the reconstruction of high-resolution interfaces are traditionally modeled with a simple empirical velocity-density assumption. In contrast, PGS has published how wave equation modeling using variable velocity and vector-reflectivity now eliminates any need to estimate a (simple) density model.

Finally, it must always be remembered that such considerations assume at all times that cycle-skipping can be avoided; that the numerical inversion is robust, accurate, and properly constrained; and that the computational cost is acceptable.

FWI is Not a Full Wavefield Migration (FWM)

FWI is not a form of 'imaging with multiples'; such as Full Wavefield Migration (FWM). If the free-surface condition is included in the forward modeling step of FWI, the synthetic shot gather will include both primary reflections and multiples. After some process is typically applied to reduce cycle-skipping, and starting at the lowest useful frequency, the residual wavefield computed by subtracting the synthetic shot from the recorded shot will better represent differences associated with errors in the velocity model than will be the case if the synthetic shot only modeled primary reflections. The ambition of including multiples in the forward modeling is therefore to yield model updates with less artifacts. FWM of both primaries and multiples uses up-going and down-going wavefields when applying the imaging condition, and should not be confused with any form of FWI.

The advantage of the FWI ambition discussed here is that with regards to multiples, a form of reflectivity image—implicitly assumed to be free of crosstalk artifacts not associated with legitimate impedance boundaries in the earth—can possibly be obtained without having to explicitly remove multiples prior to imaging. The reflectivity information within the multiples is **not** reconstructed to complement the final reflectivity model.

Correspondingly, one motivation today to run FWI to frequencies comparable to the maximum frequency used for traditional RTM or LS-RTM (60 Hz or higher) is to pursue an abbreviated processing flow that can deliver a fast-track interpretation product. This assumes that the computational demands are manageable for large 3D volumes, and that the assumptions discussed above are understood when the interpreters receive the data.

What is Next?

The future is more sophisticated inversions that simultaneously compute several FWI gradients. Example pursuits include elastic FWI, full wavenumber seismic inversions (acoustic and elastic), and so on.

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