Towards full waveform inversion: A torturous path

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ABSTRACT

Full waveform inversion (FWI) can be viewed as an iterative cycle involving forward modelling, pre-stack migration, impedance inversion and velocity model updating. At each stage of the process there are many factors affecting the outcome. Among the most important are the type of modelling (acoustic versus elastic), derivation of the initial velocity model, the inherent differences between field data and numerically modelled data, and the conditioning of the field seismic data to be inverted.

Our attempts to derive an initial velocity model suggest that the integration of a refraction tomography velocity model with well log data provides a better initial velocity model than well log data alone as the sub-weathering velocities need to be included to help make a match between the first breaks of the field and modelled data. Initial comparisons of field and modelled shot gathers confirms that conditioning of the field seismic data plays a large role in the successful matching of field and modelled data.

INTRODUCTION

Full waveform inversion (FWI) is not a new concept in seismic imaging, having been proposed by Lailly (1983) and Tarantola (1984). The concept was to perform a sequence of pre-stack migrations, iteratively improving the velocity model with each migration. Although FWI has been studied and improved since the 1980's, and has been of more interest of late, it is not routinely used as a seismic exploration tool.

Margrave et al. (2010) review the development of FWI and propose that FWI can be viewed as an iterative cycle involving forward modelling, pre-stack migration, impedance inversion, and velocity model updating in each iteration (Figure 1). Stated simplistically, their procedure involves the generation of synthetic seismic data from a very smooth initial velocity model, calculation of the difference between the real and modelled data, pre-stack time migration and stack of this residual, calibration of the migrated residual to produce a velocity perturbation, and addition of the perturbation to the initial velocity model to create the next velocity model. The cycle is iterated until some convergence criteria are met. This method requires well control for calibration of the velocity residual, which is the difference between the well and migration velocities. The iterations start at the lowest frequencies and progress to higher frequencies as the velocity model is updated and becomes more complex (Pratt, 1999). The lower the frequencies in the real seismic data, the simpler the initial velocity model can be. Virieux and Operto (2009) warn that for FWI methods based upon the local least-squares optimization formulation, in which the misfit between the real and modelled data is minimized in the time or frequency domain, it remains very difficult to obtain reliable results without very low frequencies (<1 Hz). However, Vigh et al. (2011) reported successful waveform inversions in three different geological environments using frequency ranges of 2.2-7 Hz, 3-8 Hz and 4-8 Hz.

In September, 2011, CREWES, with the assistance of sponsoring companies, acquired low-frequency data at Hussar with a view to testing FWI methodology and requirements, and investigating optimal source-receiver combinations. We intend to use this dataset in our quest to learn the practical implementation of FWI.

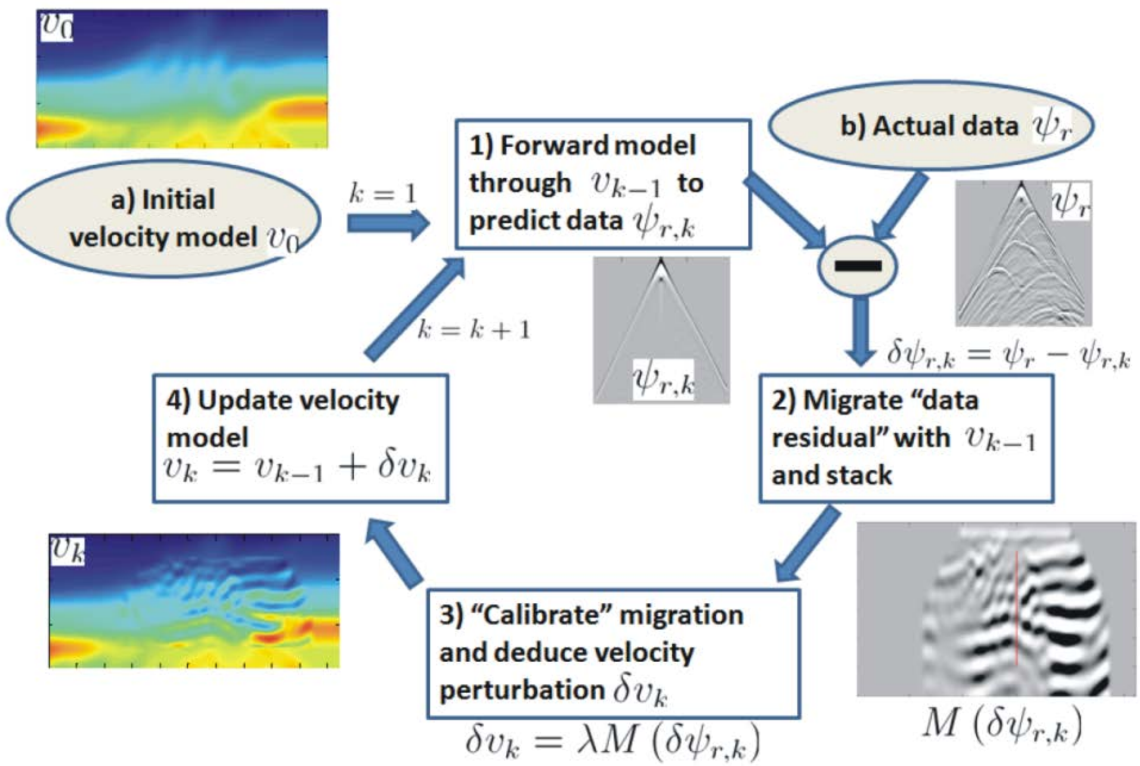

FIG. 1: The cycle of acoustic FWI. Data inputs are a) the initial velocity model and b) the real seismic data. Counter k increments from 1 to N when some defined stopping criterion is met. The velocity model v_{k-1} is used to predict synthetic seismic data with the same acquisition geometry as the real data. The data residual (real data - synthetic) is then pre-stack migrated and stacked. The pre-stack migration is used to estimate a velocity perturbation δv_k, which is added to the velocity model to estimate v_k.

METHOD

Initial velocity model

The initial velocity model should be very smooth but be close enough to the real world velocity to converge to a solution. Virieux and Operto (2009) caution that for short-offset acquisition the seismic wavefield is rather insensitive to intermediate wavelengths, so the waveform-fitting optimization cannot adequately reconstruct the true velocity structure through iterative updates unless the initial model is sufficiently accurate. The use of long-offset seismic data overcomes this issue. These authors also suggest that an initial model may be derived from first-arrival traveltime tomography, stereotomography or Laplace domain inversion (Shin and Cha, 2008). However, they warn that a drawback of first-arrival traveltime tomography is that the method is unsuitable when low-velocity zones exist because these create shadow zones and reliable picking of first-arrival times is also difficult. Results reported by Brenders and Pratt (2007a, 2007b, 2007c) suggest that very low frequencies and very large offsets are required to obtain reliable FWI results when the starting model is built by first-arrival traveltime tomography. Kamei et al (2011) used arrival traveltime tomography to generate a starting model for their successful FWI of a long-offset Canadian Foothills dataset.

How smooth is smooth enough and how close is close enough are questions we would like to answer. As we progress though FWI analysis we may experiment with different initial velocity models and observe the results. We propose using well sonic data where available. If well log data are not available, all we have are the velocities obtained through seismic data processing and these may not be accurate enough unless derived through PSDM velocity analysis. To use the method of Margrave et al. (2010), well data are necessary.

Conditioning of field seismic data

Kamei et al (2011) used data with muted first breaks, deconvolution and amplitude scaling (to avoid amplitude errors in acoustic modelling). Generally we find that published authors do not say much about the processing of the seismic data they are using in FWI. We consider that the data should have groundroll and as much noise as possible removed and stationary deconvolution applied. Refraction statics should be applied to remove the static effects of the thin weathering layer. Having first breaks in the data allows us to compare them with the first breaks of the modelled gathers to assess the veracity of the near-surface velocity in the model.

Synthetic data modelling

Which type of forward modelling should we use? Seismic amplitudes of a spherical wavefront decay as they travel through the medium and further amplitude loss is caused by absorption and transmission loss. The effect of spherical divergence is that energy density in a constant velocity medium declines by $1/r^2$ and amplitude by $1/r$ (where r is the distance of the wavefront from the assumed point source). For the real heterogeneous earth the effect is more complex. Other factors that may affect seismic amplitudes are source strength, source coupling, tuning and AVO effects (Sheriff, 1975; Henry, 2004). The recorded amplitude is also a function of receiver coupling and directional sensitivity (Liner, 2010). These equipment and earth effects are not accounted for in 2D forward modelling. Thus the modelled seismic data will never match the recorded seismic data. However, we can try to mitigate this as much as possible in our pre-processing of the field data or scaling of the modelled data. Some authors have trace-normalized the data thus eliminating the effect of AVO (Dessa et al., 2004; Operto et al., 2004; Ravaut et al., 2004). Phase-only inversion (Bednar et al., 2007), which ignores waveform amplitudes, was discussed and tested successfully by Kamei et al (2011). The pre-processing of their seismic data included deconvolution, bandpass filtering for low frequency content only, first break muting and amplitude scaling.

Acoustic modelling, although less computationally expensive than elastic modelling, does not model correctly seismic amplitudes or modes other than P-wave, such as shear-wave arrivals and converted-waves (Barnes and Charara, 2008; Virieux and Operto, 2009). Barnes and Charara (2008) compared FWI results obtained with acoustic versus elastic 1D modelling and concluded that (1) when S-phases are present in marine data, acoustic inversion cannot provide reliable results; (2) when S-phases are not present but when the AVO effect due to S conversions is significant, acoustic inversion can lead to reliable results only when near offsets are used; (3) for regions with a smooth S-wave velocity profile, acoustic inversion can provide reliable results. However, this is not a realistic case and the convergence to the “true” model is better when using full elastic inversion.

Brenders and Pratt (2007b) discussed the seismic amplitude disparity caused by the inelastic attenuation factors in the true model compared to those in the acoustic wave-equation solution. To invert data from all offset ranges they found it essential to scale the amplitudes of the real data to match those of the forward-modelled synthetic data. They also windowed the real data to exclude shear-wave arrivals and mode-conversions.

Acoustic modelling involves only P-wave velocities (assuming constant density) whereas elastic modelling must also include S-wave velocities, which are often not well known. Acoustic-wave modelling usually resolves the acoustic-wave equation in pressure therefore the particle-velocity synthetic wavefield might not be computed (Hustedt et al., 2004). If the receivers are geophones, the physical measurements collected in the field (particle velocities) are not the same as those computed by seismic modelling (pressure). A match between the vertical geophone data and the synthetic pressure data can be performed by exploiting the reciprocity of the Green’s functions if the sources are explosions (Operto et al., 2006). In contrast, if the sources and receivers are directional, the pressure wavefield cannot account for the directivity of the sources and receivers, and amplitude corrections must be applied before inversion (Virieux and Operto, 2009). Thus it appears that we may have to adjust the amplitudes of the real and/or modelled seismic data prior to comparing the two data sets so that the misfits can be attributed to errors in the velocity model rather than being caused by inappropriate amplitudes generated by the forward modelling.

We have several software packages that can perform finite difference modelling. CREWES has its own two codes, developed independently by Gary Margrave and Peter Manning for use in Matlab. Dr Margrave’s acoustic FD code does not handle elevation variations at present so is of limited use for land seismic data. Dr Manning’s elastic FD code can handle a varied topography. ProMAX has acoustic FD modelling from topography. We will be testing these FD modelling packages and any others that we acquire or develop.

Inversion

FWI can be implemented in the time (Tarantola, 1984) or the frequency domain (Pratt and Worthington, 1990; Pratt, 1990; Pratt 1999). Kamei et al (2011) found that the phase-only approach (Bednar et al., 2007) resulted in a greater effective aperture, a wider band of recovered wavenumbers and an enhanced imaging quality of the overall subsurface structure.

MODEL BUILDING

We have attempted to derive an initial velocity model for FWI of the Hussar data. We extracted one shot gather with unmuted first breaks (Figure 2) and will model shot gathers with the same topography. We started with the sonic log for well 12-27-025-21W4M, which runs from 208 m to 1565 m KB. We attached sonic data from well 09-27-028-22W4M to extend the depth to 2424 m. For the top 216 m to seismic datum we projected the well log velocity on a linear path. A smooth velocity curve was created from the composite well log and a synthetic shot gather generated by acoustic FD modelling (Figure 3). We compared the first break picks of the model data to those of the field data, which had refraction statics applied that were derived through tomography. The average absolute difference between the modelled and actual picks is 21 ms so we modified the velocity model by inserting the near-surface model derived by CGGVeritas through traveltime tomography. After a few iterations of smoothing and editing this model to amend the modelled first break picks, the average absolute difference between the modelled and actual picks is reduced to 8 ms. This velocity model and the synthetic gather generated with it are shown in Figure 4. At this time we have not addressed the issues of amplitude or phase differences between the field and modelled seismic data.

We thought it interesting to compare the field and modelled data after bandpass filtering, since FWI starts with the lowest frequencies. We selected field data that had refraction statics and radial filters applied to remove groundroll. The field and modelled data were bandpass filtered to retain only frequencies of 2-5 Hz (Figure 5). Application of spiking deconvolution to the radial-filtered shot gather does not make a noticeable difference. The gathers in Figure 5 are discouragingly different and we would not want to start ascribing the difference between them to errors in the velocity model.

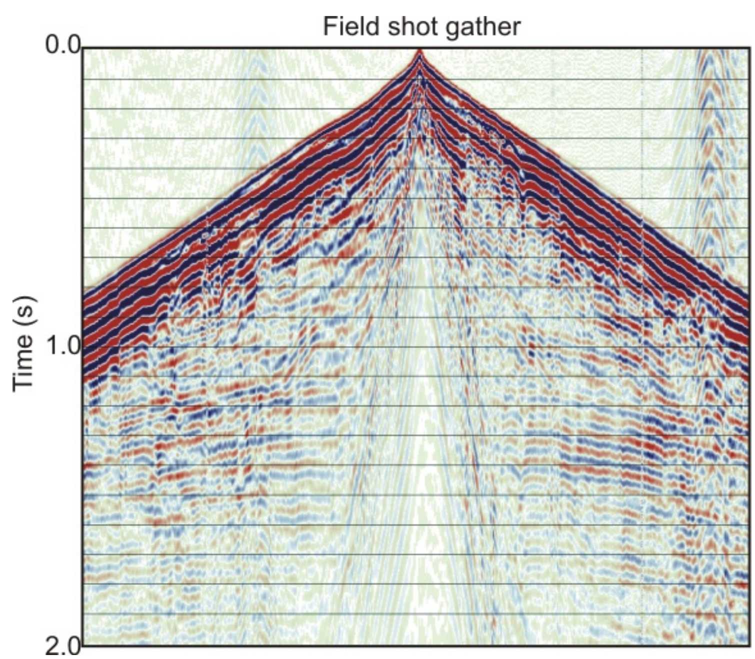

FIG. 2: Shot gather selected from the Hussar dynamite data recorded by the 10 Hz 3C geophones. Refraction statics have been applied.

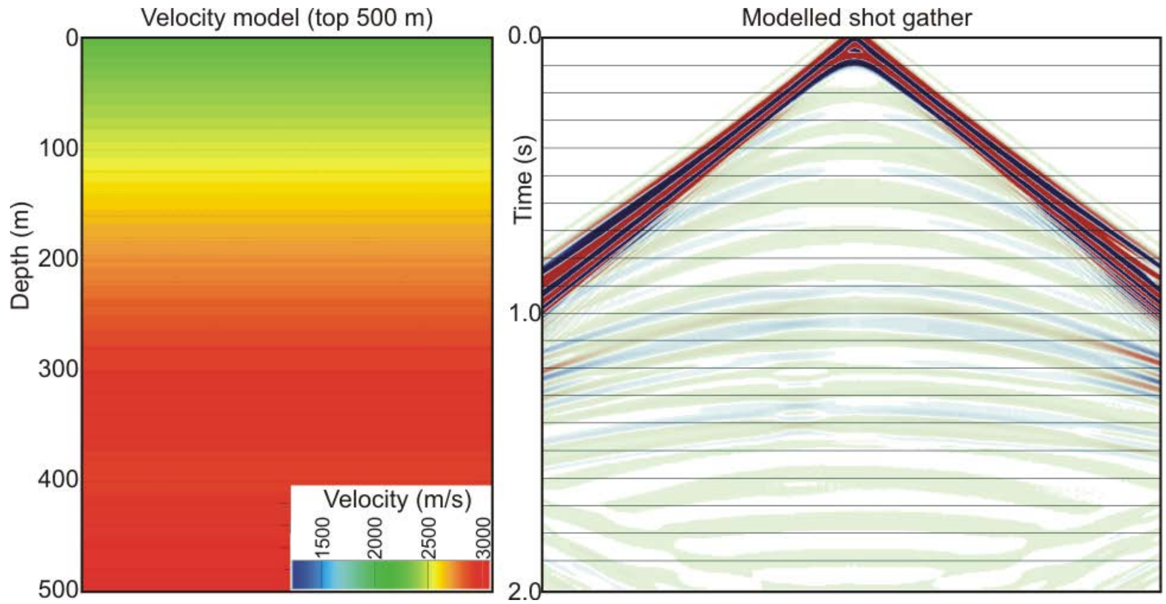

FIG. 3: Initial velocity model, created from the composite 12-27-025-21W4M-sonic log, and the modelled shot gather. Only the top 500 m of the velocity model is shown.

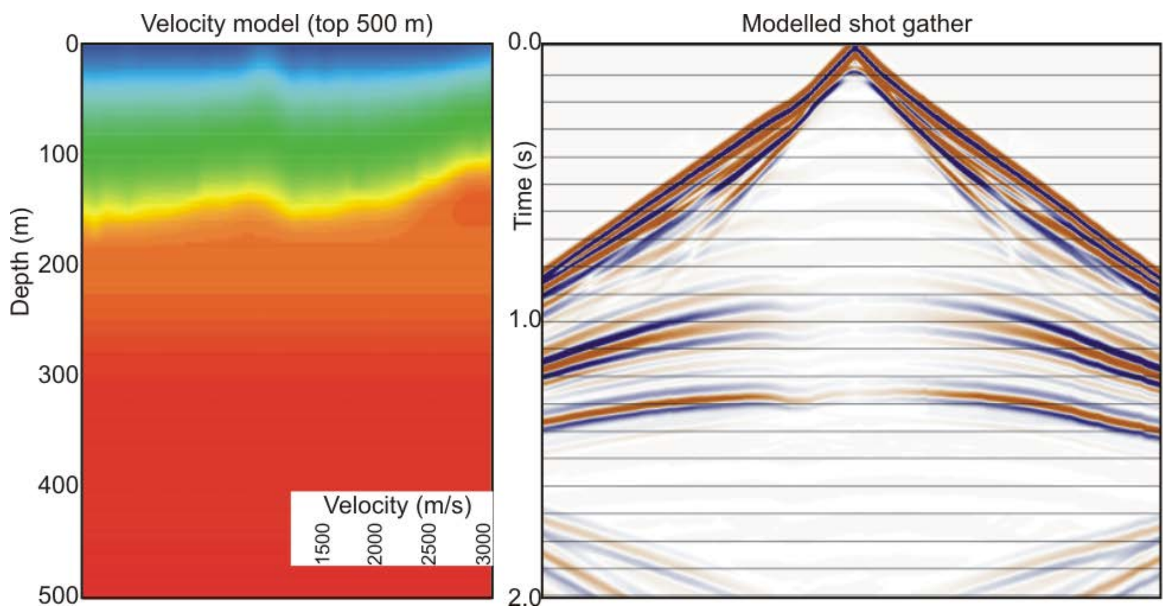

FIG. 4: Velocity model after integration of the refraction tomography model with the well data, and the modelled shot gather. Only the top 500 m of the velocity model is shown. The first breaks on this modelled shot gather match the actual picks in Figure 2 much better than do those of the first model in Figure 3.

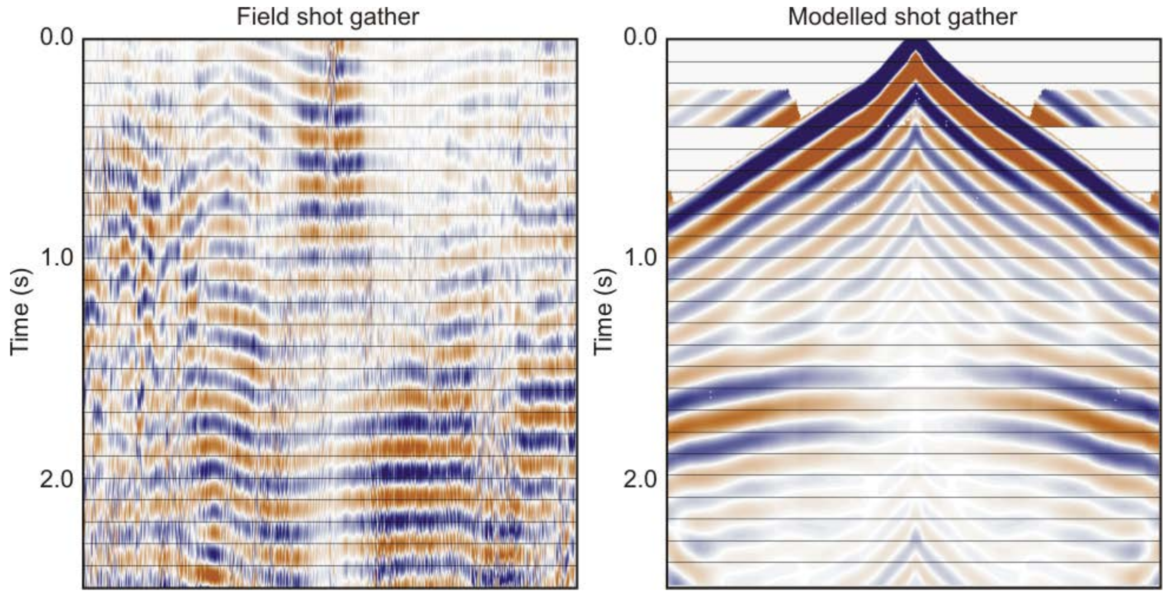

FIG. 5: Field and modelled shot gathers bandpass filtered to 2-5 Hz. The field gather has been processed to remove groundroll and other unwanted noise.

DISCUSSION

Practical implementation of FWI appears to be a difficult task. There are many factors to be taken into account. Amongst these are the question of acoustic versus elastic modelling, the modelling code, the determination of the initial velocity model, the inversion domain and the processing of the field seismic data.

Little of the published literature discusses the processing of field data, apart from advice to mute first breaks and apply deconvolution. We know there are many factors that affect the field data that cannot be accounted for in the numerical modelling, even if elastic modelling is used. Our future work will include analysis of data with different processing to assess the suitability of the processing for data intended for input into FWI.

The initial velocity model should be close enough to the true solution so that the inversion converges to a solution. We integrated well log data with a near-surface velocity model derived through refraction tomography and achieved a fair match between the field and modelled first breaks.

CREWES has access to several FD modelling codes and would like to test them all with the same velocity model to assess their applicability to FWI. We hope to experiment with shot gathers having different processing techniques applied to determine the optimum processing to apply.

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