Introduction

High resolution velocity models of the near surface are required to accurately image the deep subsurface (Keho and Kelamis, 2012). This is particularly true in arid environments where sand dunes, karsts and wadis further complicate seismic data processing and interpretation by obscuring deeper exploration targets.

Refraction tomography (Taner et al., 1998) is a widely utilized technique to obtain near-surface velocity models but lacks the capability of reconstructing velocity inversions, and has resolution limitations. Full waveform inversion (FWI) addresses these challenges (Virieux and Operto, 2009), but its accuracy depends on the initial velocity estimate, and requires extremely low frequencies in the data. FWI in the Laplace-Fourier domain (Shin and Ho Cha, 2009) provides a solution in the absence of these frequencies but falls short of being practical due to the computational cost and the low signal to noise ratio of conventional land seismic data.

In this paper we show a land data application of a recently developed, Laplace-Fourier FWI (Kontakis et al., 2020). Starting from the original 3D Laplace-Fourier FWI of Petrov and Newman (2014), this acoustic 1D FWI is able to recover, fast and accurately, a detailed model of the near surface.

Method

The near-surface velocity can be locally approximated with a 1D approach employing a specific CMP-offset sorting mechanism (Colombo et al., 2016a). Similarly to seismic first-break arrivals (FB) the full waveforms can be organized in a CMP-offset (XYO) hypercube in which the offset represents pseudo-depth. We further extend the previously developed 1.5D travel-time velocity modelling method to a 1.5D acoustic Laplace-Fourier FWI.

The XYO domain allows the generation of “virtual shot gathers”, which are made from the stacked traces within a column of the described hypercube (Colombo et al., 2016a). These gathers show higher signal to noise ratio and are located in the same surface position of the XY (midpoint) column. The reconstructed virtual midpoint gathers enable the application of the 1.5D FWI inversion.

Using the same sorting domain, surface-consistent residual statics and amplitude balancing can be automatically performed without the need to fully progress in the seismic processing workflow (Colombo et al., 2016a, 2019). The generation of residual static corrected, amplitude balanced, virtual shot gathers (figure 1) is what makes this inversion scheme so effective with land data.

Figure 1 Shot gathers including a) poor and (b) medium quality data with no pre-processing, and c) and d) pre-processed virtual shot gathers roughly corresponding to a) and b) respectively.
Land data application

We tested the new method in a complex wadi structure reported in Colombo et al. (2017). It contains a structure-controlled depression which is well-known for poor seismic imaging due to strong scattering, possibly triggered by numerous faults (Weijermars, 1998), severe velocity variations in the near surface and rough topography. Improvements to its imaging have occurred thanks to acquisition, processing and interpretation of different geophysical techniques (Colombo et al., 2016b and 2017). Previous efforts around this area present a unique opportunity to benchmark the recently developed 1D Laplace-Fourier FWI.

The workflow is simple and does not require sophisticated processing. FB are automatically picked from the seismic data with no pre-processing. FB are then sorted in a XYO hyper-cube to produce a monotonically increasing pseudo-3D velocity model. This model is used to calculate surface-consistent long wavelength statics. Then the full seismic waveforms are sorted, in the same fashion, to calculate surface-consistent refraction residual statics and amplitude balancing (Colombo et al., 2016c). These aligned and balanced traces are then stacked to produce the gathers we show in figure 1.

The number of virtual shot gathers generated in the previous step are at least two orders of magnitude less than the actual shot gathers, have higher signal to noise ratio and are easier to analyse to parametrise an inversion. We compare the different components of the Laplace-Fourier coefficients and we determine the range of frequency and damping we want to invert for. A central frequency and damping result of this analysis is shown in Figure 2 by plotting the real coefficients of the Laplace-Fourier transform at an offset of 1000m. The depth migration image and the Laplace-Fourier coefficient distributions show extremely similar features (Figure 2). Such visualizations can be used for QC purposes before initiating the FWI work.

![Figure 2 Field example showing a) a migrated depth section at 500m depth, and b) the normalized real component of the Laplace-Fourier coefficient at 1km offset and 12Hz with a damping of 10s\(^{-1}\).](image)

Virtual shot gathers, in the Laplace-Fourier domain, show the sharp boundaries of the wadi caused by strong velocity contrasts between unconsolidated sediments within the wadi and harder rocks outcropping on its surroundings. These near-surface features were previously characterized by a high resolution 3D multi-geophysics program comprising helicopter-borne transient electromagnetics, audio magnetotellurics and precision gravity (Colombo et al., 2016b). The high similarity between the data...
and these features are a good indication that a 1.5D Laplace-Fourier FWI can reconstruct a pseudo-3D velocity model of the near surface.

Starting from a smooth model (Figure 3a) we proceed to invert these data with the approach described in Kontakis et al. (2020). We start the inversion with the lowest significant frequency in our data (10Hz, from our analysis) and the largest damping showing desired features (15s$^{-1}$). Once convergence has been reached, the obtained model serves as initial estimate for a joint inversion between the first frequency and the largest damping, and a higher frequency with a smaller damping. We repeat these two steps until we utilize all the desired combinations of frequencies and damping values.

The data is characterized by narrow bandwidth, due to the near-surface complications present in the area. Three joint inversions increasing bandwidth (from 10 Hz to 14 Hz), and decreasing damping (from 15s$^{-1}$ to 5s$^{-1}$) were enough to recover a pseudo-3D velocity model with layering consistent with previous imaging for the delineation of the described wadi (Figure 3b).

This velocity model exceeds the depth needed to accurately calculate long-wavelength statics and can be used for either imaging or as an initial velocity model for a 3D FWI approach. The major obstacle to image the subsurface successfully utilizing land seismic data, is the accurate estimation of the near surface velocity distributions which, in our case, can be extend to more than 500m in depth.

Due to the presence of farms, access restriction limited data acquisition to record offsets larger than 50 meters within the wadi area. This makes it almost impossible to reconstruct the extremely shallow layer accurately. Nonetheless the inverted velocity model shows a low velocity trough in the center, surrounded by higher velocities. This is in agreement with the observation of a wadi filled with unconsolidated material and surrounding carbonate plateaus (Colombo et al., 2015).

**Figure 3** Migrated depth section, co-rendered with a) the initial velocity model, and b) results from Laplace-Fourier full waveform inversion.
Conclusions

Inversion results show a high resolution near-surface velocity model. This velocity model, unlike the ones generated from refraction tomography, shows the velocity inversions present in the shallow subsurface. Due to its 1D nature, the sorting mechanism and the pre-processing performed, we are able to obtain high resolution velocity models in a fraction of the time needed by a 3D FWI approach.

Data pre-processing improved the continuity of the seismic events, balanced their amplitudes and improved their signal to noise ratio. It also allowed us to QC the data and define the parameters for the inversion efficiently (i.e. frequency, damping).

The velocity model shows, as expected from the analysis of the data, strong correlation with the anisotropic depth migration previously performed. The observed features were characterized before by a 3D multi-geophysics campaign and have been further verified by recent drilling results.

References


