Full Waveform Seismic Tomography for geophysical velocity model in Canterbury region based on Adjoint-Wavefield method

Trung Dung (Andrei) Nguyen [1], Alan Juarez [2], Brendon Bradley [1], Robin Lee [1]

[1] University of Canterbury, [2] University of Southern California

andrei.nguyen@Canterbury.ac.nz

1. Introduction

In this poster, we present initial work to date applying Full Waveform Tomography (FWT) based on the Adjoint-Wavefield (AW) method to iteratively invert from a 3-D geophysical velocity model for the Canterbury, New Zealand region (Lee, 2017). The seismic wavefields were generated using numerical solution of the 3-D visco-elastodynamic equations for a domain of 65x65x40 cells with 2km grid-size. Simulation-to-observation misfit measurements based on 148 sources at 70 seismic stations in the Canterbury region were used in our inversion. Two types of FWT inversion runs at frequency band 0.05-0.1 Hz were implemented based on adjoint sources using broadband travel time delay and frequency-dependent GSDF measurements. The simulated seismograms computed from our inverted velocity model show an improved match with the observed seismograms.

2. 3D wave propagation and Adjoint-wavefield method

To set up the full waveform tomography problem, we solve the forward wave propagation problem using the Stress-Velocity formulation of 3D visco-elastic wave equations (Graves, 1996) in the software emod3d. We then define a misfit function between the observed data recorded at seismic stations for different events and the simulated data from our forward simulation using an inverted source and a given velocity model. From the defined misfit function, we construct the Frechet derivatives based on seismic data inversion theory (Tarantola, 1984). We then consider the adjoint-wavefield method, which back-propagates the data to attract information of the medium structure (Tromp, 2005). To construct the adjoint source for backward simulation, we implement two methods using: (1) the travel time shift of an isolated waveform estimated by maximizing the cross-correlation between observed and simulated data (Woodward, 1991); and (2) the waveform perturbation kernel (Chen, 2007) constructed from the generalized seismological data functional (GSDF) measurements (Gee & Jordan, 1992). We then express the Frechet derivatives calculated numerically in terms of our interested model parameters *Vs* and *Vp.*

3. Data processing and Flexwin segmentation

The earthquakes are densely located around Canterbury region. Observed data from 148 Earthquakes with Mw =3.5-5, recorded by 78 stations in the area were included in this study (as shown in Figure 2b). The observed seismograms were shifted and resampled to the simulation time step (dt=0.08s). The simulated data were generated as reference data using an inverted srf source for each event and a given 3D velocity model. Flexwin software (Maggi, 2009) was utilized for segmentation of the observed and reference simulated seismograms. The GSDF measurements and relative waveform misfit are performed on windowed sections of the seismograms only. By tuning parameters similar to tomographic scenarios of Southern California and using reference data from a 3D, we are able to pick up a window including the start time and end time. After segmentation, the normalized correlated coefficient and optimal time shift between windowed observed and simulated data were calculated as additional waveform selection criteria. Only seismograms with normalized correlated coefficient larger than 0.5 and maximum time shift less than 10s are used for inversion. The optimal time shift for the picked window could be used as measurement for the construction of the adjoint source. Figure 1b shows the example of Flexwin segmentation for a pair of observed and simulated data. Figure 1c shows the good windowed seismograms for inversion with their characteristics including: window length (under line), relative waveform misfist (rwm), broadband time delay (TauP), normalized correlalated coefficients (ncc).

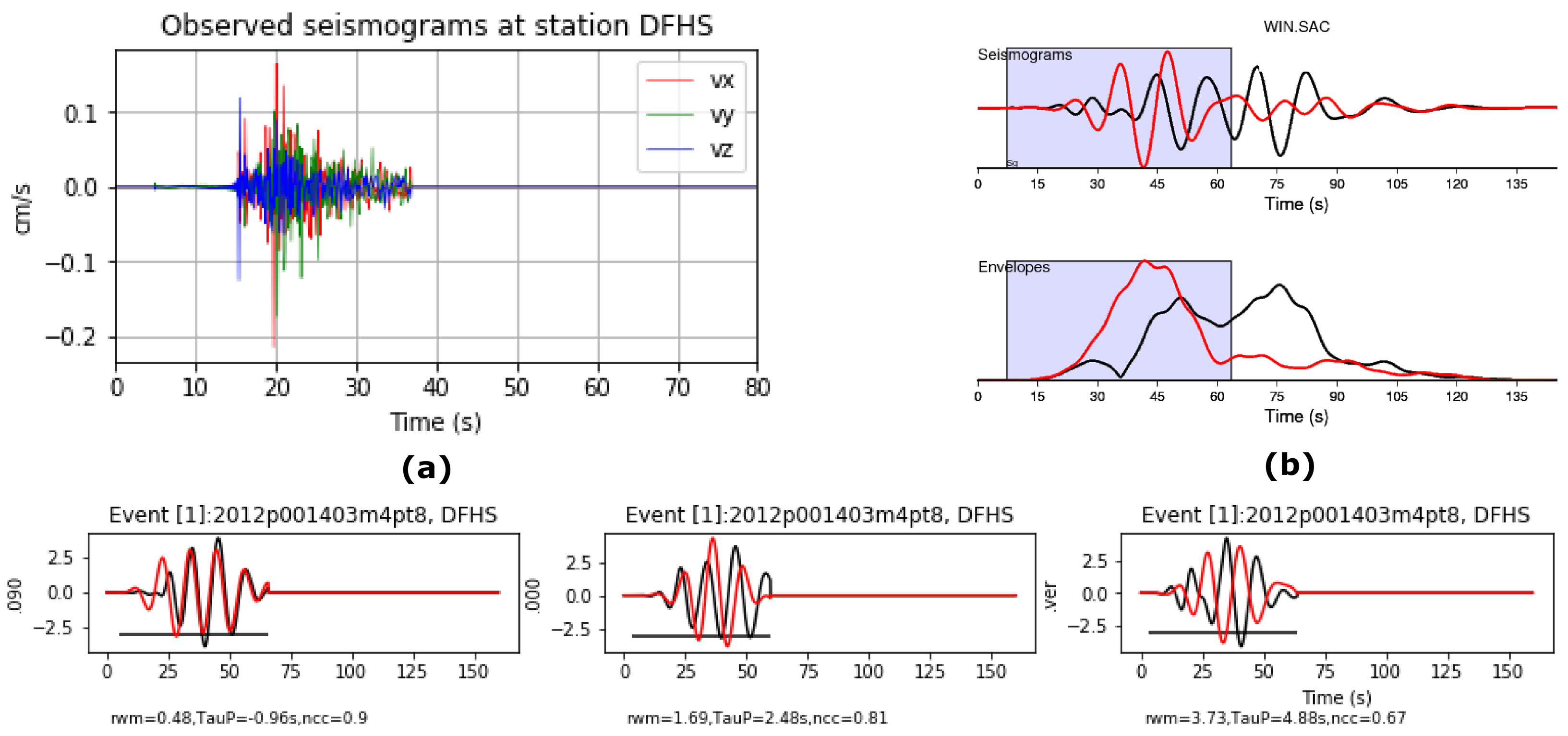

Figure 1: a) Observed data (unfiltered), b) Window picked by Flexwin for observed (black) and simulated (red) data filtered from 0.05-0.1Hz, c) 3 components of windowed seismograms at a station for inversion.

4. Automated simulation and computational demand

Simulation domains of 130x130x80 km are derived from a detailed velocity model of Lee et al. (2017) for the Canterbury region using 2km grid size (Figure 2a). The horizontal view of the *Vs* profile at 2km depth includes all sources and stations using for inversion (Figure 2b). The histograms of all relative waveform misfit and optimal time shift for windowed seismograms picked by Flexwin are shown in Figure 3. For each simulation, the recorded time is 160s and time step is 0.08s. For each event, a forward and a backward (adjoint) simulations are performed to extract strain wavefields for kernel calculation. These strain wavefields store strain components for every single cell in the domain and for every 10 time steps. For total 148 events, the computation was divided to an embarrassing parallel mode in Nesi's supercomputer (Maui). In addition to the kernels calculation, the optimal step length calculation for model updating also requires multiple forward modelling. One iteration of the inversion costs approximately 274 core hours. The workflow for our inversion process is present in Figure 4.

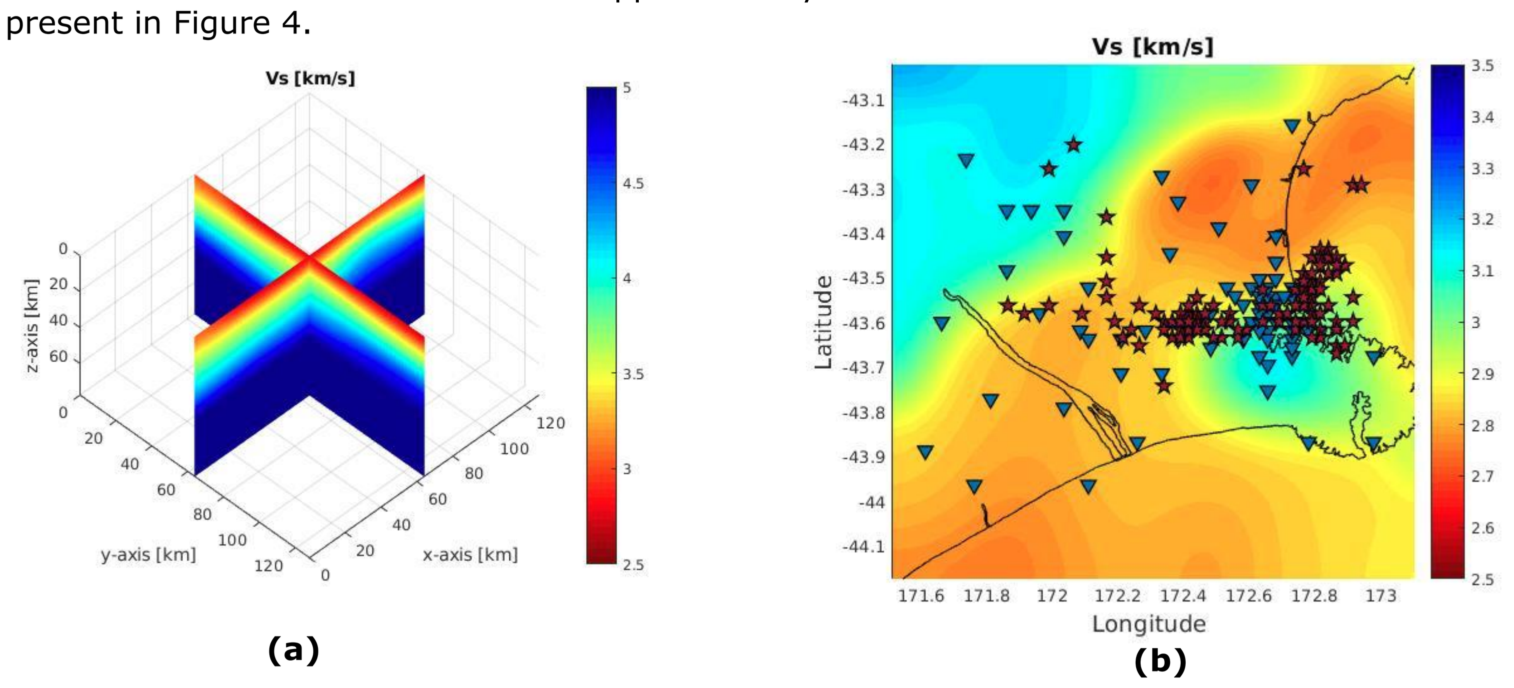

Figure 2: a) 3D velocity models *Vs* and *Vp* used for simulation, b) Plane view of *Vs* profile at 2km depth and source (star)/ station (triangle) locations in Canterbury region.

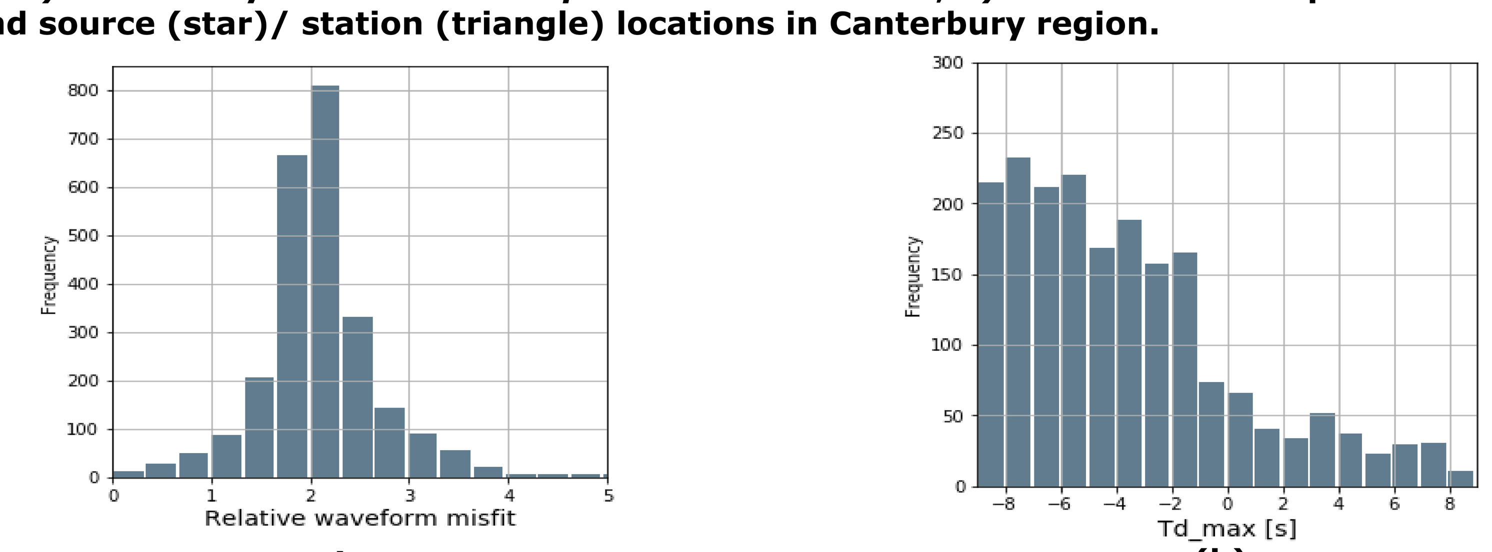

Figure 3: a) Histograms of initial reference simulations: (a) Relative waveform misfit, (b) Broadband time delay.

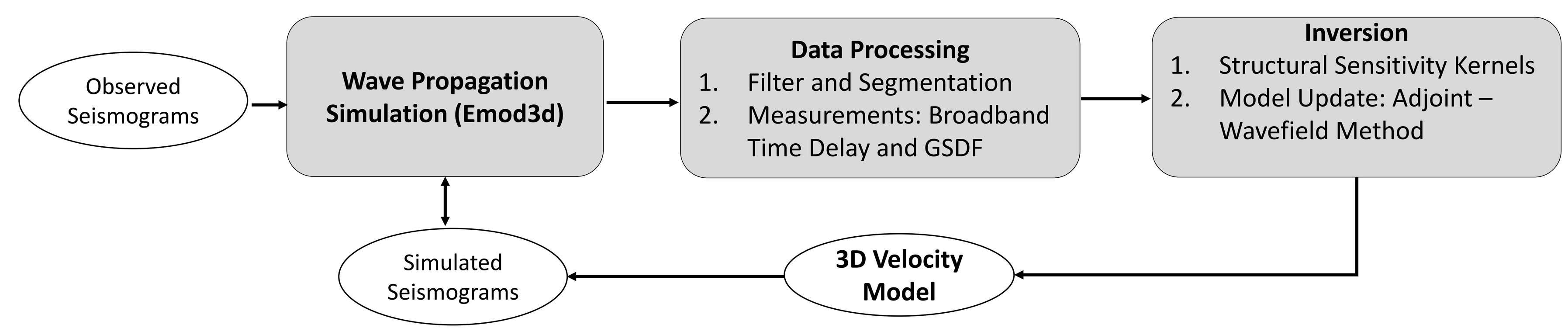

Figure 4: Computational workflow of Full Waveform Inversion (FWI)

5. Adjoint-wavefield method realisation and optimization

In the synthetic study of the Adjoint-wavefield method, we can demonstrate the calculation of the adjoint sources using two different methods. Figure 5 shows the sensitivity kernel for an arrival phase of the seismograms for a simple case with a source and stations embedded in homogeneous mediums based on broadband time delay measurement. We are also able to implement the frequency dependence GSDF measurements for a pair of windowed observed and simulated seismograms to construct the adjoint source (Figure 6).

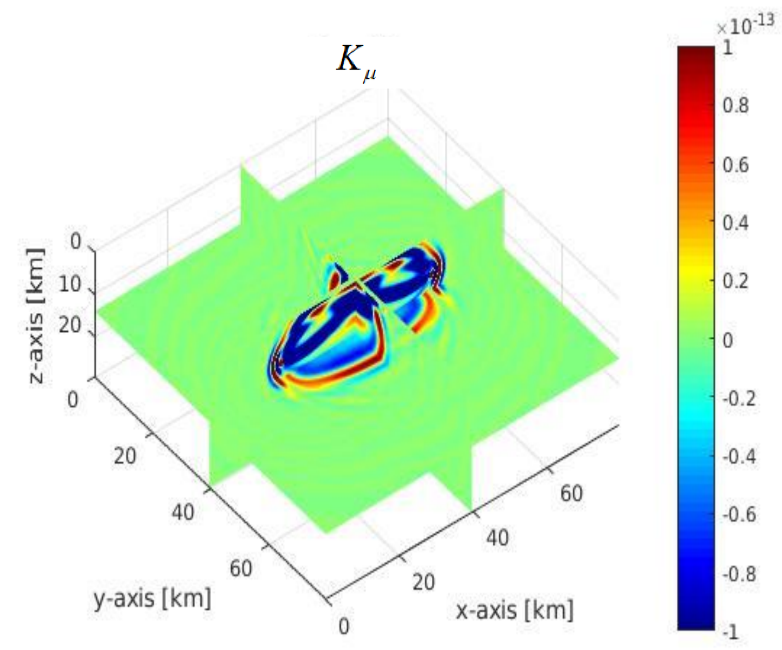

Figure 5: Kernel *μ* for a broadband time delay adjoint source

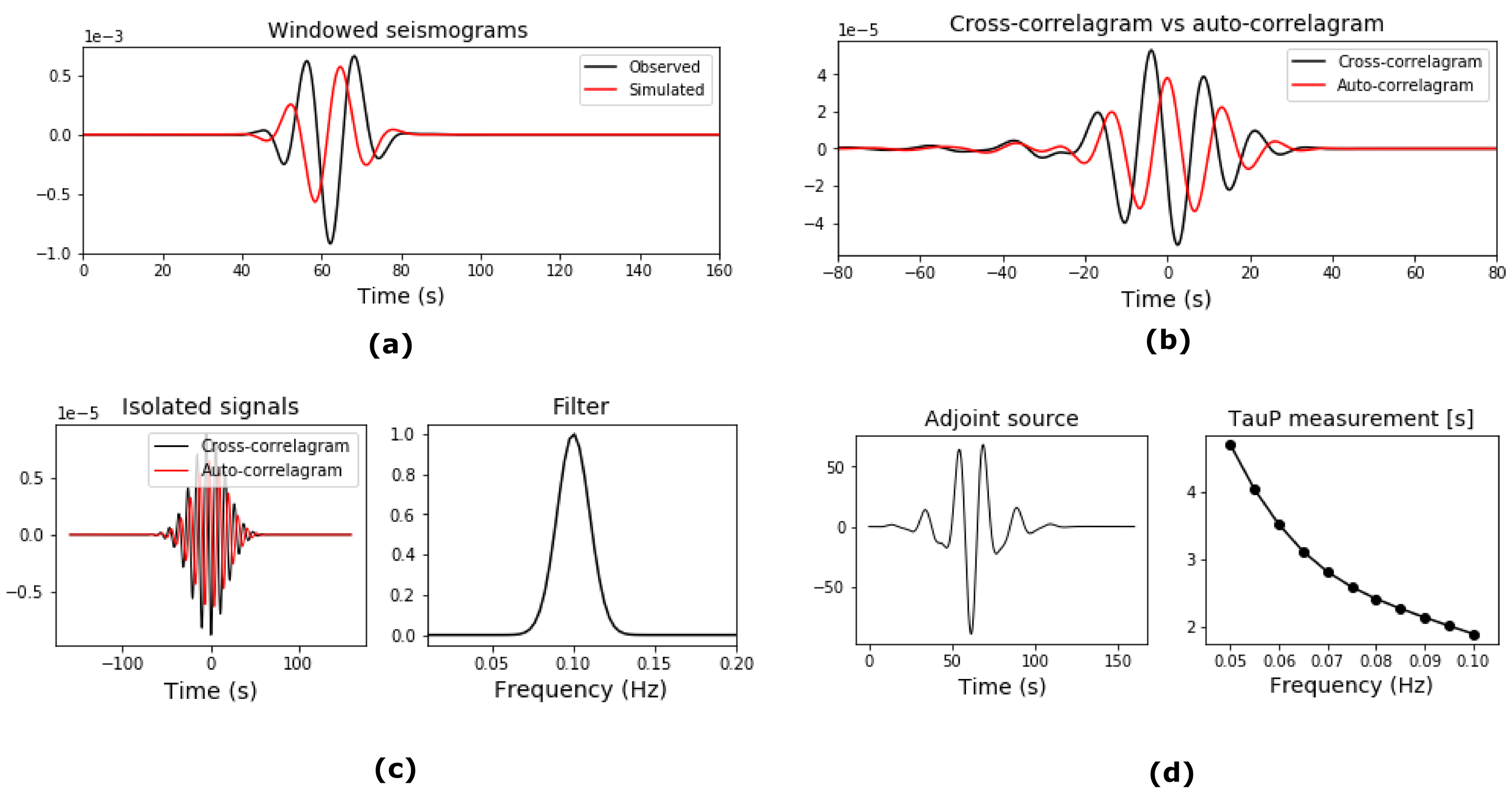

Figure 6: a) Windowed observed and simulated data, b) Cross- correlagram between observed data and isolation filter (windowed simulated seismogram), and Auto- correlagram for simulated data, c) Narrow-band filter of the correlagrams at 0.1Hz, d) Constructed adjoint source and Time delay measurements at frequencies from 0.05-0.1Hz.

To optimize the inversion, we implemented a geometrical correlation matrix for all recorded seismograms based on the source and station locations (Li & Romanowicz, 1996). We also considered preconditioning the kernels (Gaussian filtering in spatial domain), implementing conjugate-gradient algorithm (Fletcher & Reeves, 1964) for the update direction and calculating the update step length by line search algorithm (Nocedal, 2000). The Vs and Vp models are updated dependently at the early stage of inversion. The update is constrained by 10% maximum of the current *Vp* at an iteration or minimum value of *Vs*.

6. Preliminary inversion result

In earlier iterations, the synthetics were poorly aligned with the observed waveforms. We therefore restrict the inverted data to the broadband delay times from the earthquake seismograms. The waveform fitting in general has been improved (Figure 7b) with total misfit for reference events reducing by 8% (Figure 7a). This is a good indication of the improvement in characterizing the 3D crustal velocity model for Canterbury region.

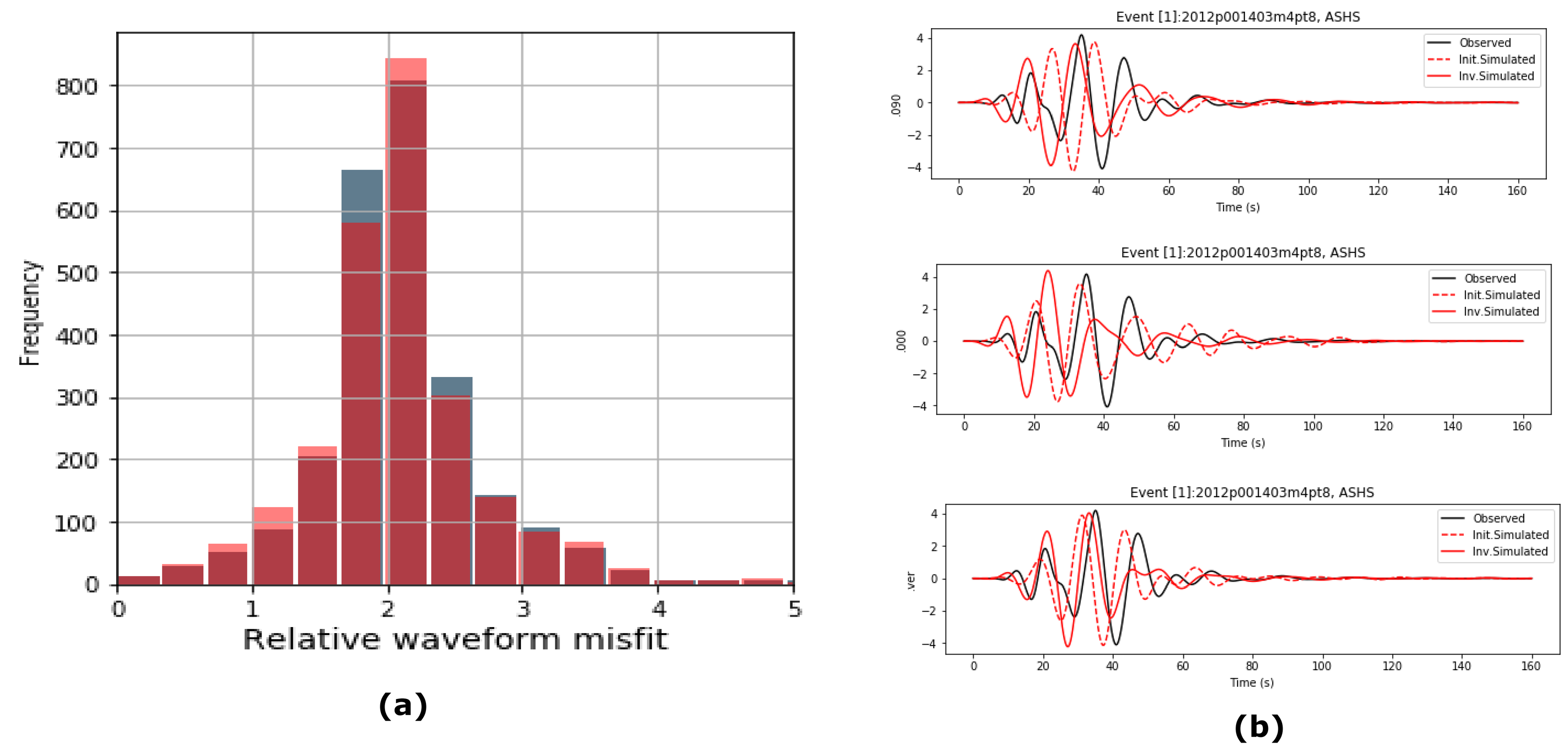

Figure 7: a) Histograms of relative waveform misfit for initial model (grey) and inverted model after the first iteration (red), b) Waveform comparison.

7. Future study

Further iteration runs are expected based on better window selection, introducing higher frequency data and more accurate frequency-dependent GSDF measurements. The inverted velocity model can be tested for earthquake data not included in the inversion process or for the ambient-noise collected in the area. A higher spatial resolution of the inversion will also be considered such as for a finer spatial grid of 0.4km. In the future, we expect the inverted crustal velocity model will be included to ground motion prediction of the Canterbury region. This will have a good impact on seismic hazard analysis and earthquake early warning for Canterbury region as well as New Zealand wide.