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Full Waveform Inversion (FWI) for glaciological seismic data –Improving the seismic characterisation of glacier firn

Emma Pearce[1], Adam Booth[1], Sebastian Rost[1], Paul Sava[2], Alex Brisbourne[3], Ian Jones[5], and Bryn Hubbard[4]
[1]School of Earth and Environment, University of Leeds, UK
[2]Center for Wave Phenomena, Colorado School of Mines, Colorado, USA
[3]Britsih Antarctic Survey, Cambridge, UK
[4]Aberystwyth University, Wales, UK
[5]ION Geophysical, Chertsey, UK

Full Waveform Inversion (FWI) is a well-established seismic imaging technique used in the exploration industry to acquire high resolution, high precision velocity models of the subsurface from seismic data. Although FWI is computationally expensive and requires customized data acquisition, the technique has the potential to improve subsurface glaciological imaging.

Firn is formed as an intermediate material (of density ~400 – 810 kg m^{-3}) as snow is compressed into ice (~810 – 917 kg m^{-3}). Variations in surface conditions and periods of surface melting commonly lead to the presence of discrete layers and lenses of refrozen ('infiltration') ice within the firn column; layers that can be from millimetres to several tens of metres thick. Therefore, firn characteristics provide a tool for reconstructing climate conditions relating to the amount of snow accumulation, melt, temperature conditions and subsequent snow preservation. Given the complexity of these relationships, it has not been possible to develop a theoretical model that predicts accurately variations in firn properties or density with depth. Consequently, seismic techniques, which are logistically less demanding than extracting firn cores, are typically used to reconstruct these physical properties of the firn column.

Firn seismic velocity is often derived from seismic data using the Herglotz-Wiechert (HW) inversion. A velocity trend would be expected to increase from ~400 m s^{-1} in snow through to ~3,800 m s^{-1} in ice. Thus, the presence of infiltration ice within the firn column results in anomalously high velocity intervals at shallow depths. HW inversion can be limited by the accuracy of first-break picking (specifically in the near offset, where a small error in the travel time pick gives the greatest variability to the HW velocity output), and it cannot recover the velocity inversion below a refrozen ice layer without elastodynamic redatumming. Importantly, FWI has the capacity to mitigate issues such as these, and thereby potentially offers a new standard for glaciological seismic modelling.

Using seismic datasets obtained from Pine Island Glacier, Antarctica, and synthetic data that simulate firn columns that include substantial thicknesses of infiltration ice ('ice slabs', up to 100 m thick and from 5-80 m deep), we show how FWI improves on current seismic techniques in terms

of identifying the velocity variations associated with both included ice layers and the firn underlying them. We present a best practice methodology for the use of FWI with glaciological data, including (i) the extraction of a source wavelet from the data for the use with modelling, (ii) the steps needed to ensure a consistent waveform, (iii) the appropriate offset-to-depth ratio, and (iv) the requirement of a constraint for the uppermost part of the velocity model. Finally, we evaluate the robustness of the FWI approach by comparing it with well-established HW methods for building velocity models.