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# GPR full-waveform inversion using a combined frequency- and time-domain approach

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Full waveform inversion (FWI) can provide unprecedented high resolution images of the electromagnetic velocity and attenuation by minimizing the misfit between observed and modeled ground-penetrating radar (GPR) data. FWI can be implemented both in time- and frequency-domain that each have its own advantages and disadvantages. Compared to a time-domain implementation, the benefits of frequency-domain FWI (FD-FWI) are: 1) the forward modeling is more efficient in frequency domain than in time domain when many source locations are present, 2) frequency-dependent medium properties can be easily incorporated, 3) a wide range of misfit functions can be easily implemented in frequency domain 4) to reduce the non-linearity, low frequency data can be inverted first and higher frequencies can be included for increasing iterations easily. However, it is not straightforward to select the optimum frequencies to use for the inversion. Time-domain FWI (TD-FWI) does not have this disadvantage and can be more efficient when the number of unknowns is large such as for 3D applications.

Here, we introduce a combined frequency-and time-domain FWI (FD-TD-FWI) that combines both frequency- and time-domain inversion algorithms to benefit of the advantages of both approaches. The forward modeling use finite difference method in frequency- and time-domain respectively. The inversion algorithms in frequency and time domain simultaneously update the electromagnetic velocity and attenuation by calculating velocity and attenuation gradients and corresponding individual step lengths. A 2D high contrast synthetic data set and an experimental crosshole data set have been inverted using the FD-FWI, TD-FWI, and the novel combined FD-TD-FWI. Compared to TD-FWI that was implemented using a frequency-hopping technique and FD-FWI that started with one single frequency and progressively included higher frequencies, the final FD-TD-FWI inversion results returned the best inversion results with the smallest data misfit, model misfit, and the smallest remaining gradients while using the shortest computation time and smallest computational resources.