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Multi-layer inversion of freezing induced dispersive Ground Penetrating Radar data

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Seasonal freeze-thaw processes that take place in the shallow subsurface are important hydrological processes. Ground Penetrating Radar (GPR) is a powerful method for monitoring these processes due to its non-invasive character and sensitivity to the liquid water content in soil. These freeze-thaw processes can generate pronounced near-surface layering that significant impacts electromagnetic (EM) wave propagation. This layering can result in the formation of waveguides where multiple reflections of the EM waves within the waveguide produce frequency dispersion (i.e. frequency dependent phase velocity). In particular, the freezing process can generate a leaky waveguide where the EM wave velocity of the upper frozen zone is higher than the velocity of the underlying unfrozen substratum. Thawing processes can generate low-velocity waveguides, in which the EM wave velocity of the thawed waveguide is lower than the underlying (frozen) substratum. Due to the dispersive character of data acquired under these conditions, conventional travel time analysis cannot be used to infer the EM properties (i.e. dielectric permittivity) of the subsurface. Therefore, an inversion algorithm, similar to the inversion algorithm used in the seismic case for dispersed Rayleigh waves, is needed to estimate waveguide permittivity and thickness from the GPR data.

Subsequent freeze and thaw events can result in complicated layered systems. Therefore, the existing single-layer inversion algorithms for dispersive GPR data are not sufficient to invert correctly for the permittivity of the subsurface under these conditions. In this study, a new multi-layer leaky waveguide forward model for calculating dispersion curves was derived. This forward model was used to describe different permittivity distributions with depth, under which a two- and three-layer permittivity distribution and several gradients. These different permittivity distributions were implemented in the inversion algorithm and thus allowing to invert for different multi-layered subsurface models. The inversion algorithms were successfully tested on different synthetic datasets before applied to an experimental dataset (common mid-point gathers, 900 MHz) collected on a test site in Waterloo, Ontario, Canada. The use of the three-layer inversion algorithm resulted in the smallest misfit between the picked and the modelled dispersion curves, indicating that a three-layer model is best describing the data. Compared to the use of the single-layer inversion algorithm, the misfit was reduced by almost a factor three. Several synthetic datasets were generated with the model parameters resulting from the different inversions, confirming that a three layer model is best explaining the dispersive character of the experimental data set. However, not all characteristics of the experimental data were reproducible with our three-layer model indicating that we are dealing with a more complex reality.