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A new approach to improve the stability and reliability of full-waveform crosshole GPR inversion

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Crosshole radar tomography is a non-invasive tool used in diverse geological, hydrogeological and engineering investigations. Conventional tomograms provided by standard ray-based techniques have limited resolution, primarily because only a fraction of the information contained in the radar data (i.e. the first-arrival times and maximum first-cycle amplitudes) is included in the inversion. Higher resolution radar tomograms can be derived by using full-waveform inversion schemes. However, despite the theoretical improvement in resolution, convergence problems can arise in the application of full-waveform schemes due to the ill-posed nature of the inverse problem and the highly non-linear nature of the forward problem.

Under the assumption of weak scattering and crosshole recording, it is possible to identify the area of spatial wavenumber coverage in the model space from a single frequency source. It is well known that the higher the frequency content of the source, the better the coverage in the spatial wavenumber domain. However, the assumption of weak scattering is rarely valid and more often, especially at the very early stages of inversion, instability may occur because of the large differences between the true and the current model, with the result that the inversion fails to converge to the true solution. This is often associated with cycle-skipping, in the sense that the time difference between the observed and the synthetics data is larger than half the period; it is obviously more severe for high frequencies than for low frequencies. Traditional time-domain, full-waveform inversion requires the minimization of a misfit norm between the observed and computed traces. A recently developed algorithm was based on a conjugate-gradient-type iterative scheme that for every iteration computed the cost function gradient and updated the model along it by a computed step length.

Here, we present a new approach to full-waveform inversion that combines the benefits of time domain analysis (simplicity of interpretation; ready availability of FDTD simulation tools) and frequency domain analysis (low frequency inversion conveys stability and avoids convergence to a local minimum; whereas high frequency inversion conveys resolution). In standard full-waveform inversion the entire frequency content of the data is used from the first iteration to update the model, but in our new approach we progressively increase the frequency content (starting at low frequency) as the iterations proceed. This involves band-pass filtering the original radargrams in gradual steps, and expanding the bandwidth. A somewhat similar approach is sometimes used in Gauss-Newton frequency-domain seismic inversion, but there only a small number of single frequencies is used. We perform our analysis in the time domain using a gradient algorithm. The key is to work with cumulative frequencies by starting at low frequency where stability is more likely, and gradually adding the higher frequency components to update the higher spatial frequencies of the model. The new inversion algorithm is compared to a traditional scheme that inverts the full bandwidth data set from the first inversion stages. Several synthetic results clearly demonstrate that the new scheme can markedly improve the quality of the inversion, avoiding local minima and strong artifacts in the images.