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Objective-function hybridization in adjoint seismic tomography

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Seismic tomography is at the threshold of a new era of massive data sets. Improving the resolution and accuracy of the estimated Earth structure by assimilating as much information as possible from every seismogram, remains a challenge. We propose the use of the "*exponentiated phase*", a type of measurement that robustly captures the information contained in the variation of phase with time in the seismogram. We explore its performance in both conventional and *double-difference* (Yuan, Simons & Tromp, *Geophys. J. Intern, 2016*) adjoint seismic tomography. We introduce a hybrid approach to combine different objective functions, taking advantage of both conventional and our new measurements. We initially focus on phase measurements in global tomography. *Cross-correlation* measurements are generally tailored by window selection algorithms, such as FLEXWIN, to balance amplitude differences between seismic phases. However, within selection windows, such measurements still favor the larger-amplitude phases. It is also difficult to select all usable portions of the seismogram in an optimal way, such that much information may be lost, particularly the scattered waves. Time-continuous phase measurements, which associate a time shift with each point in time, have the potential to extract information from every wiggle in the seismogram without cutting it into small pieces. One such type of measurement is the *instantaneous phase* (Bozdağ, Trampert & Tromp, *Geophys. J. Intern, 2011*), which thus far has not been implemented in realistic seismic-tomography experiments, given how difficult the computation of phase can sometimes be. The *exponentiated phase*, on the other hand, is computed on the basis of the normalized analytic signal, does not need an explicit measure of phase, and is thus much easier to implement, and more practical for real-world applications. Both types of measurements carry comparable structural information when direct measurements of the phase are not wrapped. To deal with cycle skips, we use the *exponentiated phase* to take into account relatively small-magnitude scattered waves at long periods, while using *cross-correlation* measurements on windows determined by FLEXWIN to select distinct body-wave arrivals without complicating measurements due to non-linearities at short periods. We present synthetic experiments to show how *exponentiated-phase*, *cross-correlation* measurements, and their *hybridization* affect tomographic results. We demonstrate the use of hybrid measurements on teleseismic seismograms, in which surface waves are prominent, for continental and global seismic imaging. It is clear that the *exponentiated-phase* measurements behave well and provide a better representation of the smaller phases in the adjoint sources required for the computation of the misfit gradient. The combination of two different types of phase measurements in a hybrid approach moves us towards using all of the available information in a data set, addressing data quality and measurement challenges simultaneously, while negligibly affecting computation time.