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The devil's checkerboard: why cross-correlation delay times require a finite frequency interpretation

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We present the first complete test of finite frequency tomography with banana-doughnut kernels, from the generation of seismograms in a 3D model to the final inversion, and are able to lay to rest all of the so-called 'controversies' that have slowed down its adoption. Onset times follow a minimum time trajectory and must therefore be interpreted with ray theory. Cross-correlation delay times are influenced by energy arriving in a time window that includes later arrivals, either scattered from, or diffracted around lateral heterogeneities. Cross-correlation times are often much more precise than onset picks, certainly in the presence of noise, but for such delays only finite-frequency interpretations offer the correct theoretical approach. A long lasting controversy has revolved around questions whether the difference between the two approaches warrants the extra effort, whether first-order scattering (or Born) theory is adequate to derive the sensitivity (or banana-doughnut) kernels used in finite-frequency theory, or even whether the kernels - with a zero sensitivity "doughnut"-like hole coinciding with the ray trajectory - are correct. We present here the results of a 3D test in which we generate 1716 seismograms using the spectral element method in a cross-borehole experiment conducted in a checkerboard box. Delays are determined for the broadband signals as well as for five frequency bands (each one octave apart) by cross-correlating seismograms for a homogeneous pattern with those for a checkerboard. The large (10%) velocity contrast and the regularity of the checkerboard pattern causes severe reverberations that arrive late in the cross-correlation window. Data errors are estimated by comparing linearity between delays measured for a model with 10% velocity contrast with those with a 4% contrast. Sensitivity kernels are efficiently computed with ray theory using the 'banana-doughnut' kernels from Dahlen et al. (GJI 141:157,2000). The model resulting from the inversion with a data fit with reduced $\chi^2_{red} = 1$ shows an excellent correspondence with the input model and allows for a complete validation of the theory. Amplitudes in the (well resolved) top part of the model are close to the input amplitudes. Comparing a model derived from one band only shows the power of using multiple frequency bands in resolving detail - essentially the observed dispersion captures some of the waveform information. Finite frequency theory also allows us to image the checkerboard at some distance from the borehole plane. Most disconcertingly for advocates of ray theory are the results obtained when we interpret cross-correlation delays with ray theory. We shall present an extreme case of the devil's checkerboard (the term is from Jacobsen and Sigloch), in which the sign of the anomalies in the checkerboard is reversed in the ray-theoretical solution, a clear demonstration of the reality of effects of the doughnut hole. We conclude that the test fully validates 'banana-doughnut' theory, and disqualifies ray theoretical inversions of cross-correlation delays.