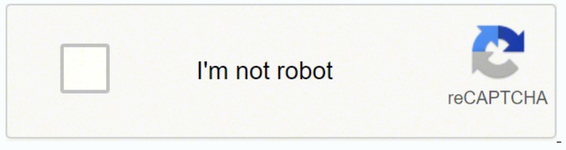

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Figs 2(c) and (d) show the adjoint sources calculated from eqs (18a) and (18b), again in natural time coordinates, as red lines, which are labeled ‘cc_dd’.Fig. 3 shows the misfit sensitivity kernels for both types of measurements. The maximum separation, however, depends on the wavelength λ and the path length L of the phases considered, the scale
length of the heterogeneity and the overall geometry of the illumination of the two stations by seismic sources. (2) in this example, the objective function is the sum of the squares of the individual time-shifts |$\chi _{\mathrm{cc}}=\frac{1}{2}([\Delta t_1]^2+[\Delta t_2]^2)=30.1$| s2. \end{equation} (10)Hence, from eqs (6a) and (10), the cross-
correlogram of the new seismograms |$\tilde{s}_i(t)$| and |$\tilde{s}_j(t)$| is, to first order in the perturbation, \begin{eqnarray} \tilde{\Gamma }_{ij}(\tau) &=& \int _0^T\tilde{s}_i(t+\tau)\tilde{s}_j(t)\mathrm{d}t\approx \Gamma _{ij}(\tau) + \int _0^T\delta s_i(t+\tau) s_j(t)\mathrm{d}t+ \int _0^Ts_i(t+\tau) \delta s_j(t)\mathrm{d}t= \Gamma
_{ij}(\tau) + \delta \Gamma _i(\tau) + \delta \Gamma _j(\tau) . The solid line is the multitaper estimate, with standard errors estimated using jackknifing. Subsequently, these sensitivity kernels need to be combined by weighting with the corresponding double-difference traveltime measurements, and summed up for all grouped kernels. The
observations (black) are in the checkerboard model and use the first derivative of the Gaussian function for a source wavelet. Cross-correlation traveltimes Δt1 = −0.42 s and Δt2 = −1.50 s. We propose two approaches to cluster analysis and regularization. These measurements are Δt1 = 4.08 s (d1 is advanced 4.08 s relative to s1) and Δt2 = 6.60 s
(d2 is advanced 6.60 s relative to s2). Figs 7(a) and (b) show the displacement synthetics. In this paper, we derive a constructive theory for the incorporation of generic ‘double-difference’ measurements into adjoint seismic tomography.The minimization of the difference of the difference between observations at distinct pairs of stations, and the
difference between synthetics at the same pairs, over all station pairs, requires explicit mathematical expressions for the adjoint sources that are necessary for the numerical computation of the corresponding misfit gradient functionals. \end{eqnarray} (A19)We shall associate the frequency-dependent partials that appear in eqs (A18) and (A19) with
the symbols \begin{eqnarray} p_{i|j}^k(\omega)= \frac{i}{2\omega }\frac{[s_j^k]^{\ast }}{S_{ij}} \qquad \mbox{and}\qquad p_{j|i}^k(\omega)= \frac{-i}{2\omega }\frac{[s_i^k]^{\ast }}{S_{ij}^{\ast }}, \end{eqnarray} (A20a) \begin{eqnarray} a_{i|j}^k(\omega)=\frac{1}{2}\frac{[s_j^k]^{\ast }}{S_{ij}} \qquad \mbox{and}\qquad
a_{j|i}^k(\omega)=\frac{1}{2}\frac{[s_i^k]^{\ast }}{S_{ij}^{\ast }}-\frac{[s_j^k]^{\ast }}{S_{jj}}, \end{eqnarray} (A20b)and their conjugates. \end{eqnarray} (11)We introduced the notation δΓi(τ) for the cross-correlogram of δsi(t) an sj(t), and δΓj(τ) for that between si(t) and δsj(t), noting that \begin{eqnarray} \delta \Gamma _i(\tau) &=&\int
_0^T\delta s_i(t+\tau)s_j(t)\mathrm{d}t= \int _0^Ts_j(t-\tau) \delta s_i(t)\mathrm{d}t\qquad \mbox{and}\qquad \delta \Gamma _j(\tau) = \int _0^Ts_i(t+\tau) \delta s_j(t)\mathrm{d}t. (b) Double-difference adjoint kernel |$K_\beta ^{\mathrm{dd}}(\mathbf {x})$| from the adjoint sources (red lines) in Figs 5(c) and (d). The predictions (green) use
the second derivative of the Gaussian, the ‘Ricker’ wavelet. In contrast, the double-difference cross-correlation traveltime S-wave speed adjoint misfit kernel Kddβ(x) shown in Fig. 3(b) displays a dominant sensitivity in the area in-between the two stations. A1 Multitaper measurements of differential phase and amplitude For notational convenience,
we distinguish time-domain functions such as s(t) or d(t) from their frequency-domain counterparts s(ω) and d(ω) only through their arguments t for time, and ω for angular frequency. Cross-correlation traveltimes Δt1 = −2.64 s and Δt2 = −3.72 s. Following eq. (4). Blue traces are for the conventional cross-correlation (‘cc’) adjoint source (4). (c) and
(d) Adjoint sources. Double-difference measurements |$\Delta t_{12}^{\mathrm{obs}}=-1.08$| s, |$\Delta t_{12}^{\mathrm{syn}}=0.00$| s, ΔΔt12 = 1.08 s. We have simultaneously extricated the tapers from their seismograms, |$\delta s_i^k(t)=\delta [s_i^k(t)]^{\ast }=h^{T\Omega }_k(t)\,\delta s_i(t)$|, and used the real-valuedness of the time-
series to arrive at the recognizable (see eq. 17) form \begin{eqnarray} \delta \chi ^{\mathrm{dd}}_\Phi &=& \int _0^T\left\{\sum\limits _{i} \left[4\pi \sum\limits _{j>i} \scr {S}_{i|j}(t)\right]\delta s_i(t)+\sum\limits _{j} \left[4\pi \sum\limits _{ii} \scr {A}_{i|j}(t)\right]\delta a_i(t)+\sum\limits _{j} \left[4\pi \sum\limits _{ii}\sum _\omega W_\Phi
(\omega)\big [\Delta \Delta t_{ij}(\omega)\big]^2, \end{eqnarray} (A13a) \begin{eqnarray} \chi _A^{\mathrm{dd}}=\frac{1}{2}\sum _{i}\sum _{j>i}\sum _\omega W_A(\omega)\big [\Delta \Delta \!\ln \!{A}_{ij}(\omega)\big]^2 , \end{eqnarray} (A13b)with |$W_\Phi (\omega)$| and WA(ω) appropriate weight functions. (6a) is unchanged if time
is globally shifted by some constant τ0: \begin{eqnarray} \arg \!\max _\tau \int _0^Ts_i(t+\tau -\tau _0) \: s_j(t-\tau _0) \mathrm{d}t= \arg \!\max _\tau \int _0^Ts_i(t+\tau)\; s_j(t) \mathrm{d}t=\Delta t_{ij}^{\mathrm{syn}}. On the other hand, from the differential cross-station traveltime measurements, we deduce that there is a 1.08 s advance in
the arrival of the observed waves at station 1 relative to station 2, but the synthetic records arrive at exactly the same time at both stations, based on the lag time of their cross-correlation maximum. For example, they can be relative times calculated from a catalogue of absolute arrival times (e.g. VanDecar & Crosson 1990); they may be relative
traveltime delays obtained from waveform cross-correlation analysis (e.g. Luo & Schuster 1991), or from the cross-correlation of their envelopes (e.g. Yuan et al.2015), and so on. The green traces labeled ‘synthetic’ are predictions in the homogeneous model of Fig. 1(b). \end{equation} (5)Positive cross-correlation traveltime differences Δti from eq.
(c) and (d) Adjoint sources. The conventional cross-correlation kernel, in Fig. 10(a), are clearly affected by the timing error, while the double-difference ones, in Fig. 10(b), are not biased at all by any such inaccuracies. Open in new tabDownload slideMisfit sensitivity kernel for the (a) double difference of cross-correlation traveltimes and for the
(b) double difference of multitaper phase measurements. \end{eqnarray} (7)A positive ΔΔtij indicates that the advancement of sj over si is larger than that of dj over di. Open in new tabDownload slideExperiment III: inversion results. (a) and (b) Displacement seismograms at stations 1 and 2. Instead, we find from eqs (A6) and (A7) that
|$T_{ij}T_{ji}=\gamma ^2_{ij}$|, suggesting that the required symmetry prevails only at frequencies at which the waveforms are highly coherent. \end{equation} (A7)Switching to polar coordinates, we write the estimate of the transfer function in terms of its ‘gain factor’ and ‘phase angle’ contributions, \begin{equation} T_{ij}^{\mathrm{syn}}
(\omega)=\big |T_{ij}^{\mathrm{syn}}(\omega)\big |e^{-i\phi _{ij}^{\mathrm{syn}}(\omega)} , \end{equation} (A8)where \begin{equation} \big |T_{ij}^{\mathrm{syn}}(\omega)\big |= \left(\big \{{\rm Im}\big [T_{ij}^{\mathrm{syn}}(\omega)\big]\big \} ^2+ \big \{{\rm Re}\big [T_{ij}^{\mathrm{syn}}(\omega)\big]\big \}
^2\right)^{1/2} \qquad \mbox{and}\qquad \phi _{ij}^{\mathrm{syn}}(\omega)=-\mbox{atan}\left\{\frac{{\rm Im}\big [T_{ij}^{\mathrm{syn}}(\omega)\big]}{{\rm Re}\big [T_{ij}^{\mathrm{syn}}(\omega)\big]} \right\} . For its part, eq. Open in new tabDownload slideExperiment IIC: data and synthetics. We envision a wide range of
promising applications in seismic array analysis, especially in areas where the use of active sources is restricted. (2007). (5) to involve the density and elastic moduli ρ(x), κ(x) and μ(x), or the density and the elastic wave speeds ρ(x), α(x) and β(x), and so on. Seismic tomography—in seeking to maximize the agreement between simulations and
observations from all sources at all recording stations—is at risk of mapping errors of this kind into estimates of wave speed variations (Schaeffer & Lebedev 2013). The Associate Editor, Jean Virieux, Carl Tape, and one other, anonymous, reviewer are thanked for their thoughtful and constructive comments, which improved our manuscript. A
comprehensive recent overview is by Luo et al. The utility of eq. We uniformly discretize each dimension using 40 elements of individual length 12 km. In this section, we discuss its application to the double-difference framework. And of course, the double-difference multitaper method could follow any number of prior inversions designed to bring the
starting model closer to the target; in this context we mention our own work on wavelet multiscale waveform-difference, envelope-difference and envelope-cross-correlation adjoint techniques (Yuan & Simons 2014; Yuan et al.2015). \end{equation} (A9)Uncertainties on the phase angle, gain factor and coherence estimates are approximately (Bendat
& Piersol 2000; Simons et al.2003) \begin{equation} \mbox{var}\{\phi _{ij}^{\mathrm{syn}}(\omega)\} \approx \frac{1-\gamma ^2_{ij}(\omega)}{2K\gamma ^2_{ij}(\omega)} ,\qquad \mbox{var}\big \{|T_{ij}^{\mathrm{syn}}|\big \} \approx \frac{1-\gamma ^2_{ij}(\omega)}{2K\gamma ^2_{ij}(\omega)}\big |T_{ij}^{\mathrm{syn}}\big |^2
\qquad \mbox{and}\qquad \mbox{var}\big \{\gamma ^2_{ij}(\omega)\} \approx \frac{\big [1-\gamma ^2_{ij}(\omega)\big]^2}{K/2}\gamma ^2_{ij}(\omega), \end{equation} (A10)where we have silently subscribed to the established practice of confusing the estimated (on the left-hand side of the expressions) from the ‘true’ quantities (on the
right). The adjoint sources necessary for the numerical gradient calculations are obtained by summing up contributions from all pairs, which are simultaneously backpropagated to calculate the differential misfit kernels using just one adjoint simulation per iteration.YOY expresses her thanks to Min Chen, Paula Koelemeijer, Guust Nolet and Youyi
Ruan for discussions. Structural inversions under the conventional formalism, unless actively ‘re’- or ‘pre’-conditioned to avoid doing so (Curtis & Snieder 1997; Spakman & Bijwaard 2001; Fichtner & Trampert 2011; Luo et al.2015), tend to overemphasize areas with high-density ray path coverage relative to poorly sampled parts of the model. The
first of these is |$\Delta t_{12}^{\mathrm{syn}}=-32.34$| s (s2 is delayed 32.34 s relative to s1) and the second |$\Delta t_{12}^{\mathrm{obs}}=-29.76$| s (d2 is delayed 29.76 s relative to d1). (2) requires a mechanism to relate a change in Earth properties (density and elastic constants or wave speeds) to a change in the seismogram, δsi(t). The
opposite kernel direction required for model update is to slow down along the path from the source to station 1, and to speed up towards station 2. We thank Carl Tape and Vala Hjörleifsdóttir for sharing unpublished notes related to their published work which we cite. With a more realistic geometry on the sphere, we would expect to recover
structure in the polar regions and at longitude 180°, as well as gain slight improvements for the interior structure. (b) Result after inversion with the conventional cross-correlation traveltime adjoint method (16 iterations). Since we linearly combine adjoint sources rather than combining individual adjoint kernels for each data ensemble, only one
adjoint simulation is required to numerically evaluate the gradient of the double-difference misfit function, and once again we obtain an expression of the type in eq. An incorrect source model was used in the latter case (different source-time function but the same origin time and dominant periods). Figs 5(c) and (d) show the adjoint sources for this
model setup. These are small and almost identical as the ray paths sample almost equal path lengths of slow and fast wave speed anomalies. An alternative derivation is through the lens of wave-equation-constrained functional minimization (Liu & Tromp 2006). The source wavelet used is the first derivative of a Gaussian function with a dominant
period of 12 s. (a) and (b) Displacement seismograms, computed in the target model (black) and in the initial model (green). Fortunately, the double-difference measurement approach yields relatively consistent adjoint kernels, based on the comparison of the kernel shown in in Fig. 8(b) with the one using exact source signature in Fig. 6(b).
Furthermore, the differential measurements themselves can be composed from any of the types used in conventional tomography. Following Laske & Masters (1996), we begin by multiplying each of the individual time-domain records si(t) and di(t) by one of a small set of K orthogonal data windows denoted |$h^{T\Omega }_k(t)$| (here, the prolate
spheroidal functions of Slepian 1978), designed for a particular record length T and for a desired resolution angular-frequency half-bandwidth Ω (Mullis & Scharf 1991; Simons & Plattner 2015), and Fourier-transforming the result to yield the sets \begin{equation} s_i^k(\omega), s_j^k(\omega)\qquad \mbox{and}\qquad d_i^k(\omega),
d_j^k(\omega)\quad \mbox{where}\quad k=1,\ldots ,\left\lfloor \frac{T\Omega }{\pi } \right\rfloor -1 . (c) and (d) Adjoint sources, (c) at station i = 1 and (d) at station j = 2. The latter two are nearly identical, which is indicative of desirable robustness in the inversion.In Experiment IIC, we next consider the scenario of having an incorrect origin time,
an advance of 0.96 s expressed by the synthetics. 3.3 Misfit gradient The derivative of the differential objective function in eq. \end{eqnarray} (14)The solution then yields the cross-correlation traveltime perturbation |$\delta \Delta t_{ij}^{\mathrm{syn}}$| due to the model perturbation, namely \begin{eqnarray} \delta \Delta
t_{ij}^{\mathrm{syn}}&=&-\frac{\displaystyle {\partial _\tau \delta \Gamma _i(\Delta t_{ij}^{\mathrm{syn}}) + \partial _\tau \delta \Gamma _j(\Delta t_{ij}^{\mathrm{syn}})}}{\displaystyle {\partial ^2_\tau \Gamma _{ij}(\Delta t_{ij}^{\mathrm{syn}})}} = \frac{\int _0^T\partial _t s_j(t-\Delta t_{ij}^{\mathrm{syn}})\,\delta s_i(t)\mathrm{d}t-
\int _0^T\partial _t s_i(t+\Delta t_{ij}^{\mathrm{syn}})\,\delta s_j(t)\mathrm{d}t}{\int _0^T\partial ^2_t s_i(t+\Delta t_{ij}^{\mathrm{syn}}) s_j(t)\mathrm{d}t}. All existing individual measurements are simply paired up, and only the construction of the adjoint sources requires modification. 5 NUMERICAL EXPERIMENTS Three types of validation
experiments are conducted here. (8) proceeds until model perturbations no longer produce meaningful adjustments |$\delta \Delta t_{ij}^{\mathrm{syn}}$| in the differential measurement on the synthetics |$\Delta t_{ij}^{\mathrm{syn}}$|, in which case δχccdd effectively vanishes and a minimum χccdd is reached. The correct source-time function
and origin time are used. We derive those and show in numerical experiments that the gradients of the new misfit functional with respect to structural perturbations are relatively insensitive to an incorrect source signature and timing errors. The black traces are the ‘data’, computed in the target model shown in Fig. 1(a). Figs 5(a) and (b) show the
displacement seismograms recorded at both stations, with the checkerboard-model traces in black and the homogeneous-model traces in green. Open in new tabDownload slideExperiment I: data and synthetics. \end{eqnarray} (A1b)We define the differential frequency-dependent ‘phase’ (compare with eqs 6) and ‘logarithmic amplitude’ anomalies as
\begin{eqnarray} \Delta t_{ij}^{\mathrm{syn}}(\omega)&=& t_i^{\mathrm{syn}}(\omega)-t_j^{\mathrm{syn}}(\omega)\qquad \mbox{and}\qquad \Delta \!\ln \!{A}_{ij}^{\mathrm{syn}}(\omega)= \ln \left[\frac{A_i^{\mathrm{syn}}(\omega)}{A_j^{\mathrm{syn}}(\omega)}\right] , \end{eqnarray} (A2a) \begin{eqnarray} \Delta
t_{ij}^{\mathrm{obs}}(\omega)= t_i^{\mathrm{obs}}(\omega)-t_j^{\mathrm{obs}}(\omega)\qquad \mbox{and}\qquad \Delta \!\ln \!{A}_{ij}^{\mathrm{obs}}(\omega)= \ln \left[\frac{A_i^{\mathrm{obs}}(\omega)}{A_j^{\mathrm{obs}}(\omega)}\right] . Considering all possible such pairs i and j, we write the adjoint sources explicitly as
\begin{eqnarray} f_i^{\dagger }(\mathbf {x},t) &=&+\sum _{j>i} \frac{\Delta \Delta t_{ij}}{N_{ij}}\, \partial _t s_j \big (T-[t-\Delta t_{ij}^{\mathrm{syn}}] \big) \delta (\mathbf {x}-\mathbf {x}_i) , \end{eqnarray} (18a) \begin{eqnarray} f_j^{\dagger }(\mathbf {x},t) &=&-\sum _{i i and ∑j∑i < j that appear in the expressions above by a common
∑ij.With these expressions, we are finally able to define the multitaper misfit sensitivity kernels along the same lines as eqs (5) and (19), one for the phase and one for the amplitude measurements, both in terms of the velocity perturbation—we are (yet) not concerned with variations in intrinsic attenuation (e.g. Tian et al.2009, 2011; Zhu et al.2013).
4.2 Shift invariance The time-shift calculated by maximizing the cross-correlogram in eq. (7), between all station pairs: \begin{eqnarray} \chi _{\mathrm{cc}}^{\mathrm{dd}}&=&\frac{1}{2}\sum _{i}\sum _{j>i}[\Delta \Delta t_{ij}]^2 . (2007), Fichtner et al. A3 Double-difference multitaper adjoint sources By taking perturbations to the formula in
(A4a) in its estimated (italicized) form, we have \begin{eqnarray} \delta T_{ij}^{\mathrm{syn}}(\omega)&=& T_{ij}^{\mathrm{syn}}(\omega)\big [\delta \Delta \!\ln \!{A}^{\mathrm{syn}}_{ij}(\omega)- i\omega\, \delta \Delta t^{\mathrm{syn}}_{ij}(\omega)\big]. This research was partially supported by NSF grants EAR-1150145 to FJS and
EAR-1112906 to JT, and by a Charlotte Elizabeth Procter Fellowship from Princeton University to YOY. (b) Double-difference cross-correlation traveltime misfit sensitivity kernel |$K_m^{\mathrm{dd}}(\mathbf {x})$|, as in eq. With these techniques, it is now possible to incorporate essentially any type of seismic ‘measurement’ (absolute, relative, or
differential) into global inversions for seismic wave speed, boundary perturbations and source parameters. The differential cross-correlation traveltimes, between stations, for the synthetic and the observation pairs are, respectively, \begin{eqnarray} \Delta t_{ij}^{\mathrm{syn}}&=&\arg \!\max _\tau \int _0^Ts_i(t+\tau)s_j(t) \mathrm{d}t, \qquad
\mbox{and we define} \qquad \Gamma _{ij}(\tau)= \int _0^Ts_i(t+\tau)s_j(t) \mathrm{d}t, \end{eqnarray} (6a) \begin{eqnarray} \Delta t_{ij}^{\mathrm{obs}}&=&\arg \!\max _\tau \int _0^Td_i(t+\tau)d_j(t) \mathrm{d}t, \qquad \mbox{and we define} \qquad \Lambda _{ij}(\tau)= \int _0^Td_i(t+\tau)d_j(t) \mathrm{d}t. The blue traces marked
‘cc’ are calculated via eq. Our derivations borrow heavily from Hjörleifsdóttir (2007). (A6) from seismic records si(t), sj(t) and di(t), dj(t) multitapered by the Slepian window set |$h^{T\Omega }_k(t)$|, k = 1, ..., ⌊TΩ/π⌋ − 1. In this paper, we bring double-difference inversions to full-waveform adjoint seismic tomography. \end{eqnarray} (15)We
introduce a notation for the denominator, \begin{equation} N_{ij}=\int _0^T\partial ^2_t s_i(t+\Delta t_{ij}^{\mathrm{syn}}) s_j(t)\mathrm{d}t, \end{equation} (16)and rewrite eq. The target model of interest is a 480 km × 480 km checkerboard expressed as four circular S-wave speed anomalies of alternating sign, shown in Fig. 1(a).
\end{eqnarray} (A11b)Error propagation will turn eqs (A10) into the relevant uncertainties on the differential phase and amplitude measurements in eqs (A11).The logarithmic amplitude measurements in eqs (A11) are not skew-symmetric under a change of the station indices, since eq. The similarity criterion can be used alone, or in combination
with the relative physical proximity of the stations. When the waveform similarity exceeds a certain threshold, the pair of stations is integrated in the double-difference group, and the relative contributions to the misfit function from all qualifying station pairs are weighted by their similarity.We demonstrate how to make double-difference
measurements, and how to use them for adjoint tomography. A2 Double-difference multitaper measurements, misfit functions and their gradients Making differential measurements between stations resolves the intrinsic ambiguity in the attribution of the phase and amplitude behaviour of individual seismic records to source-related, structure-induced
or instrumental factors (Kennett 2002), and for this reason has been the classical approach for many decades (Dziewoński et al.1969; Dziewoński & Hales 1972). Open in new tabDownload slideExperiment V: model and inversion results. The ‘double’ differencing of the traveltime metrics between the distinct stations cancels out much of the sensitivity
common to both ray paths, the area between the source and station 1 in this case. (a) Conventional kernel Kβ(x) and (b) double-difference kernel |$K_\beta ^{\mathrm{dd}}(\mathbf {x})$| from the adjoint sources in Figs 9(c) and (d). The interaction of the adjoint with the forward-propagating wavefield then produces the gradients of the objective
function in eq. The comparison need not be between the same phase observed at two distinct stations; it can involve different phases recorded on the same trace, or signals recorded at the same station but originating from two different events. (a) The 2-D target model, inspired by Trampert & Woodhouse (1995). All of these factors introduce intrinsic
errors into synthetic modeling, even when accurate information on structure is available. Tape et al. In contrast, our eqs (18) are proper generalizations of the differential traveltime adjoint sources of Tromp et al. (a) Target model. \end{eqnarray} (21)The scale invariance directly removes any sensitivity to incorrect seismic moment estimates. The
reverse-time synthetics generated at each of the stations from the corresponding adjoint sources in eq. (19) computed using the adjoint sources shown by the red lines in Figs 2(c) and (d). 3.2 Misfit function The misfit that we minimize is the sum of squares of the double-difference traveltime measurements, from eq. The sampling rate is 0.06 s and the
total recording length is 4.8 s. (1): \begin{eqnarray} \chi _{\mathrm{cc}}^{\mathrm{dd}}&=&\frac{1}{2}\sum _i [\Delta t_i]^2 . We show how to implement the double-difference concept in adjoint tomography, both theoretically and practically. It is for the terms δΔtsynij(ω) and δΔln Asynij(ω) that we will construct expressions leading to a new set of adjoint
sources. The objective function to be minimized by ‘least-squares’ is the sum over all measurements of the squared traveltime shifts in eq. Combining eqs (A15) and (A16) and using eq (A6) again, we then obtain the perturbations \begin{eqnarray} \delta \Delta t^{\mathrm{syn}}_{ij}(\omega)&=&\frac{i}{2\omega } \sum _k^K\frac{[s_j^k]^{\ast }}
{S_{ij}} \,\delta s_i^k-\frac{s_j^k}{S_{ij}^{\ast }} \,\delta [s_i^k]^{\ast } -\frac{[s_i^k]^{\ast }}{S_{ij}^{\ast }} \,\delta s_j^k+\frac{s_i^k}{S_{ij}}\,\delta [s_j^k]^{\ast } \end{eqnarray} (A18)through straightforward manipulation, and, likewise, \begin{eqnarray} \delta \Delta \!\ln \!{A}^{\mathrm{syn}}_{ij}(\omega)&=&\frac{1}{2}\sum
_k^K\frac{[s_j^k]^{\ast }}{S_{ij}} \,\delta s_i^k+\frac{s_j^k}{S_{ij}^{\ast }} \,\delta [s_i^k]^{\ast } +\left(\frac{[s_i^k]^{\ast }}{S_{ij}^{\ast }}-2\frac{[s_j^k]^{\ast }}{S_{jj}}\right) \delta s_j^k+\left(\frac{s_i^k}{S_{ij}}-2\frac{s_j^k}{S_{jj}}\right) \delta [s_j^k]^{\ast } . (A6) might thus be Tij/|γij|, as under this scenario a switch in the
indices would indeed lead to Δln Aji being equal to −Δln Aij under all circumstances of mutual coherence. Consequently, we may recognize eqs (A18) and (A19) as the (differential) frequency-dependent (narrow-band) multitaper generalization of the traveltime expressions (3) and (15), familiar from Dahlen et al. Now suppose waveforms of si(t) and
sj(t) are identical upon time-shifting, that is, they are of the ‘identical pulse shape’ type (perhaps achieved by pre-processing, e.g. to equate the Maslov indices of P and PP, or S and SS) as identified by Dahlen et al. The dashed line is the cross-correlation value. The traditional measurements provide absolute information on wave speed structure along
the ray paths, whereas the double-difference measurements are sensitive to relative structural variations. For an individual measurement of cross-correlation traveltime made at xi, the adjoint source \begin{eqnarray} f_i^{\dagger }(\mathbf {x},t)&=& \Delta t_i \frac{\partial _t s_i(T-t)}{\int _0^T\partial ^2_t s_i(t) \, s_i(t) \mathrm{d}t} \, \delta
(\mathbf {x}-\mathbf {x}_i) . In blue, for the traditional cross-correlation time-shift between predictions and observations, in red for the difference of the differential cross-correlation time-shifts between stations, where |$\Delta t_{12}^{\mathrm{syn}}=0.00$| s (as s1 and s2 arrive at the same time), |$\Delta t_{12}^{\mathrm{obs}}=-1.08$| s (as
d2 is delayed by 1.08 s relative to d1) and the ‘double’ difference ΔΔt12 = 1.08 s. The intrinsic sensitivity of differential measurements will make the double-difference technique ideal for the high-resolution investigation of well-instrumented areas with limited natural seismic activity, or where destructive sources are not an option. Of course here too,
to reduce the misfit (in eq. 8), the wave speed from the common source to station 1 should be made faster than that to station 2.In Experiment IIB, we treat the more realistic scenario where an incorrect source wavelet is used for the synthetic modeling. (A25), ultimately, is the double-difference multitaper generalization of the amplitude-tomography
adjoint source derived by, for example, Tromp et al. Let si(t) and sj(t) denote a pair of synthetic waveforms, and let di(t) and dj(t) be the corresponding pair of observations. The finite-frequency character of the measurements remains apparent from the ‘swallowtails’ visible in the area between the source and station 1. (c) and (d) Adjoint sources for
the conventional cross-correlation (blue) and for the double-difference cross-correlation (red). We evaluate the time-shift between the predictions and the observations at each of the stations via the conventional cross-correlation approach, as in eq. (c) Inversion result from the double-difference cross-correlation traveltime adjoint method
(13 iterations).We use the SPECFEM2D code to model the wavefield. (7) results in positive kernel values (19) along the path between the source and station j, and negative kernel values along the path towards station i. Open in new tabDownload slideExperiment IV: model and inversion results. A view of the target model with the source-station
geometry marked is shown in Fig. 14(a). The earthquake location community pioneered the concept of ‘double-difference’ inversions (Poupinet et al.1984; Got et al.1994), and a popular code, hypoDD, was introduced by Waldhauser & Ellsworth (2000) to improve the accuracy of source locations. (1). Figs 9(a) and (b) show the records, with the same
colour conventions as before. In addition to the works cited above, we must still mention Zhao et al. \end{eqnarray} (24)In other words, in the case of ‘identical’ waveforms, the Fréchet sensitivity kernel for their differential traveltime can be approximated by taking the difference of the individual Fréchet sensitivity kernels for each of the absolute
traveltimes, and the classical formalism of adjoint tomography can be used to perform double-difference adjoint tomography, albeit approximately. (19) is shown in Fig. 12(b). We do not make this choice (or indeed, any other of many possible options listed by, e.g. Knapp & Carter 1976) here, but we will revisit the issue of symmetry later in this
appendix.If the seismogram pairs had been pre-aligned and pre-scaled using conventional cross-correlation, perhaps to improve the stability of the frequency-dependent phase and amplitude expressions (A9), these time-domain, frequency-independent, measurements would need to be added to the traveltime and amplitude equations (A11). The open
circles represent 300 stations from the USArray network. In contrast, the double-difference method reveals substantial details of the local structure beneath the array, and the perturbations along the direct path are also reasonable. Estimated shear wave speed models with exact source-time function but different origin time. (b) Using double-
difference cross-correlation traveltime measurements (7 iterations).Our checkerboard synthetic experiments were designed to demonstrate the ease and power of the double-difference concept in adjoint tomography, from making the measurements to calculating the kernels, to inverting for the best-fitting models. (a) and (b) Data and synthetics.
These results stand in contrast to conventional tomography, which aims to minimize the difference between predictions and observations obtained from measurements made at individual stations.A seismic phase observed at two ‘nearby’ (relative to the average source–receiver distance) stations will have ‘similar’ (using robust metrics) waveforms and
‘sensitivities’ (misfit gradients) to Earth structure. In the double-difference approach, measurements made on pairs of stations that share a similar source and similar systematic effects are differenced to partially cancel out such consequences. Both of these mix contributions from both seismograms si and sj. (3), into a useful expression for the
perturbation of the misfit function in eq. The star is the source and the open circles depict two stations.Synthetics were computed used one point-source Ricker wavelet with 40 Hz dominant frequency located at 0.5 m depth, at a horizontal distance of 100 m from the left edge of the model. \end{eqnarray} (A15)Dropping the argument that captures
the dependence on frequency for notational convenience, we use the product and chain rules for differentiation to write the total derivative of eq. The cross-correlation time delays between two synthetic seismograms calculated with the wrong source information should be relatively robust as long as we can view the ‘wrong’ records as filtered, or
otherwise mostly linearly mapped, from what would be the ‘right’ seismograms. The double-difference methodology can be incorporated into the usual adjoint tomography workflow by simply pairing up all conventional measurements; the computational cost of the necessary adjoint simulations is largely unaffected. We note here for completeness that
the associated ‘coherence’ estimate is \begin{equation} \gamma ^2_{ij}(\omega)= \frac{\left|\sum _k^Ks_i^k(\omega)\big [s^k_j(\omega)\big]^{\ast }\right|^2}{\sum _k^Ks^k_i(\omega)\big [s^k_i(\omega)\big]^{\ast } \sum _l^Ks^l_j(\omega)\big [s^l_j(\omega)\big]^{\ast }} . (6). All the pairs of differential measurements are included in the
adjoint process, which is otherwise identical to that used in conventional adjoint tomography. Open in new tabDownload slideExperiment IIC: misfit sensitivity kernels. 2 ADJOINT TOMOGRAPHY: THE CLASSICAL APPROACH We briefly review the principles of ‘conventional’ adjoint tomography using ‘absolute’ cross-correlation traveltimes. (a) and
(b) Displacement records in the target (black) and in the initial model (green). The open circles represent 293 global network stations. We conduct tests with realistic network configurations, both on a global scale and at the scale of the North American continent, and for wave speed structures that are either checkerboard synthetics or plausible
Rayleigh-wave phase speed maps inspired by prior studies. 3.1 Measurement We consider the case of differential traveltimes calculated by cross-correlation of waveforms from a common source recorded at a pair of stations indexed i and j. This is the approach adopted by, among others, Hung et al. (A14) are now given by \begin{eqnarray} \delta \chi
^{\mathrm{dd}}_\Phi = \sum _{i}\sum _{j>i}\sum _k^K\sum _\omega W_\Phi (\omega)[\Delta \Delta t_{ij}(\omega)] \left\{p_{i|j}^k(\omega)\,\delta s_i^k(\omega)+[p_{i|j}^k(\omega)]^{\ast } \,\delta [s_i^k(\omega)]^{\ast } +p_{j|i}^k(\omega)\,\delta s_j^k(\omega)+[p_{j|i}^k(\omega)]^{\ast } \,\delta [s_j^k(\omega)]^{\ast } \right\} ,
\end{eqnarray} (A21a) \begin{eqnarray} \delta \chi ^{\mathrm{dd}}_A= \sum _{i}\sum _{j>i}\sum _k^K\sum _\omega W_A(\omega)[\Delta \Delta \!\ln \!{A}_{ij}(\omega)] \left\{a_{i|j}^k(\omega)\,\delta s_i^k(\omega)+[a_{i| j}^k(\omega)]^{\ast } \,\delta [s_i^k(\omega)]^{\ast } +a_{j|i}^k(\omega)\,\delta s_j^k(\omega)+[a_{j|i}^k(\omega
)]^{\ast } \,\delta [s_j^k(\omega)]^{\ast } \right\} . (7), yields ΔΔt12 = −2.58 s (the delay of s2 over s1 is 2.58 s larger than that of d2 over d1). Open in new tabDownload slideExperiment with multitaper phase and amplitude measurements. If we expand the perturbed cross-correlogram |$\tilde{\Gamma }_{ij}(\tau)$| in the vicinity of the
unperturbed cross-correlation maximum differential time |$\Delta t_{ij}^{\mathrm{syn}}$|, keeping terms up to second order, we obtain \begin{eqnarray} \tilde{\Gamma }_{ij}(\Delta t_{ij}^{\mathrm{syn}}+\delta \tau) &=& \Gamma _{ij}(\Delta t_{ij}^{\mathrm{syn}}) +\delta \Gamma _i(\Delta t_{ij}^{\mathrm{syn}}) +\delta \Gamma _j(\Delta
t_{ij}^{\mathrm{syn}}) +\delta \tau \, \partial _\tau \delta \Gamma _i(\Delta t_{ij}^{\mathrm{syn}}) +\delta \tau \, \partial _\tau \delta \Gamma _j(\Delta t_{ij}^{\mathrm{syn}}) +\frac{1}{2}\delta \tau ^2 \: \partial ^2_\tau \Gamma _{ij}(\Delta t_{ij}^{\mathrm{syn}}) . In conclusion, the misfit sensitivity for differential measurements for use in
double-difference adjoint tomography is best obtained, both theoretically and in practice, via the paired adjoint sources of eqs (18). (1), are Δt1 = 4.08 s and Δt2 = 6.60 s. (A10) lies in the interpretation that highly ‘coherent’ (in the sense of eq. A7) waveforms estimated from a relatively large number of multitapered Fourier-domain ‘projections’ will
be, quite generally, very precise.Through eqs (A4a) and (A8), finally, we arrive at our estimates for the frequency-dependent differential phase and amplitude measurements on the synthetic time-series si(t) and sj(t), namely \begin{eqnarray} \Delta t^{\mathrm{syn}}_{ij}(\omega)&=& \phi _{ij}^{\mathrm{syn}}(\omega)/\omega \qquad
\mbox{and}\qquad \Delta \!\ln \!{A}_{ij}^{\mathrm{syn}}(\omega)= \ln \big |{T_{ij}^{\mathrm{syn}}(\omega)}\big | . The second is based on waveform similarity, as evaluated by the maximum normalized cross-correlation between two waveforms. Furthermore, double-difference adjoint tomography is an efficient technique to resolve local
structure with high resolution. The average station spacing is about 0.7°. The details of that procedure are relegated to the Appendix.Double-difference adjoint tomography relies on the assimilation of measurements, which we discuss how to group (e.g. via cluster analysis), and how to weight and stabilize (e.g. by regularization). Cross-correlation
traveltimes, computed via eq. Here, we follow Tromp et al. The simplest form of the weight function is thus |$W_\Phi (\omega)=W_A(\omega)=2\Omega$|, for a discrete set of angular frequencies ω = Ω, 3Ω, ... until the complete signal bandwidth is exhausted, tapering slightly at the edges of the frequency axis to smoothly contain the full bandwidth
of the seismograms. The 32 selected earthquakes are shown by red stars and white circles depict 293 station locations from the global networks. In the latter case, an incorrect source model had the same source-time function but a shifted origin time. (6b). (c) Inversion result using the double-difference method (6 iterations).The initial model is
homogeneous. Fig. A3 compares the misfit sensitivity kernel of the double-difference time-domain cross-correlation measurement to the misfit sensitivity kernel of the double-difference multitaper phase measurement, which shows some additional structure. 3.5 Cluster analysis and regularization From N individual measurements, a total of
|${{N}\atopwithdelims (){2}}=n(n-1)/2$| double-difference measurements can be created. 3 ADJOINT TOMOGRAPHY: THE DOUBLE-DIFFERENCE WAY We use the term ‘double-difference’ measurement for the difference (between synthetics and observations) of differential measurements (either between pairs of stations or between pairs of
events). The double-difference algorithm can be simply implemented into a conventional adjoint tomography scheme, by pairing up all regular measurements. The pairwise combination of seismic measurements should enable imaging local structures with high spatial resolution.In Experiment V, we continue the test of the synthetic model used in the
global-scale Experiment IV, but this time with stations located at the sites of the Transportable Array system in the United States. On the other hand, the double-difference approach, by joining all possible pairs of measurements, does cancel out much of the shared sensitivity and, instead, illuminates wave speed structure locally among station
clusters. The double-difference tomography code tomoDD (Zhang & Thurber 2003) produces high-resolution wave speed models simultaneously with accurate event locations. Those areas are often plagued by smearing artefacts in conventional tomography, especially when limited numbers of earthquakes are available nearby. In the next section,
these properties will be verified and illustrated by numerical experiments. (A6) as \begin{eqnarray} \delta T_{ij}^{\mathrm{syn}}&=&\frac{1}{S_{jj}}\sum _k^K\, [s_j^k]^{\ast } \,\delta s_i^k-T_{ij}^{\mathrm{syn}}[s_j^k]^{\ast } \,\delta s_j^k+\left(s_i^k-T_{ij}^{\mathrm{syn}}s_j^k\right) \,\delta [s_j^k]^{\ast } . Either route leads to a
paired set of adjoint sources, formulated with respect to the synthetic wavefields si and sj recorded at locations xi and xj. Most central to the development, \begin{equation} \delta \Delta t_i= \frac{\int _0^T\partial _t s_i(t)\, \delta s_i(t)\mathrm{d}t}{\int _0^T\partial ^2_t s_i(t) s_i(t) \mathrm{d}t} . Since the wrong source-time function was used, the
cross-correlation traveltime misfit kernel in (a) differs greatly from the one in Fig. 6(a), whereas the double-difference misfit kernel in (b) is almost identical to the one in Fig. 6(b).The effects of an incorrect source signature on the traditional cross-correlation measurements can be clearly seen by comparing the adjoint kernel in Fig. 8(a) with that
shown in Fig. 6(a). The cross-correlation traveltime S-wave speed adjoint misfit kernel Kβ(x) shown in Fig. 3(a) is most sensitive to the area of effective overlap of the ray paths from the source to either station. They should also be relatively robust to errors in the source's focal mechanism, unless incorrect assumptions should place one of the event-
station paths—but not both—on the wrong side of the nodal plane. The double-difference technique is expected to resolve scale lengths comparable to the station spacing, which is much smaller than the scale of structural variations in this model. (2009) and others, describe in detail how the forward and adjoint wavefields interact to produce the
various types of ‘misfit sensitivity kernels’ under different model parametrizations, and for the specific case considered in this section. For example, for a total number of N measurements, one only needs one adjoint simulation to numerically calculate the gradient of the differential misfit under |${{N}\atopwithdelims (){2}}$| possible combinations.
It comes as no surprise that the cross-correlation time-shifts between predictions and observations are biased. \end{eqnarray} (A12a)As in eq. The desired model update is in the negative kernel direction, increasing the wave speed to station 1 and to station 2. Open in new tabDownload slideExperiment IIB: data and synthetics. To enhance the
stability of the inverse problem and reduce the computational cost of the data pairings, we can regularize the problem via cluster analysis in which only pairs that are well linked to each other are included. The rescaling corresponds to dimensions of one metre per latitudinal degree (°) of the original. The kernels are very different from one another.
Differential measurements, from the same seismic event to a pair of stations, are more robust to errors in the source wavelet than absolute ones. To alleviate the corresponding non-uniqueness in the inverse problem, we construct differential measurements between stations, thereby reducing the influence of the source signature and systematic
errors. (2004).Conditional statements of the kind that validated the applicability of eq. Three-dimensional models, oceans, rotation and self-gravitation Modeling of wave dispersion using continuous wavelet transforms Three-dimensional sensitivity kernels for finite-frequency travel times: the banana-doughnut paradox An efficient algorithm for
double-difference tomography and location in heterogeneous media, with an application to the Kilauea volcano Seismic waveform modelling in a 3-D Earth using the Born approximation: potential shortcomings and a remedy Using differential waveform data to retrieve local S velocity structure or path-averaged S velocity gradients The mixed discrete-
continuous inverse problem: application to the simultaneous determination of earthquake hypocenters and velocity structure Monitoring velocity variations in the crust using earthquake doublets: an application to the Calaveras fault, California Earthquake locations in southern California obtained using source specific station terms LLNL-G3Dv3:
global P wave tomography model for improved regional and teleseismic travel time prediction Spatiospectral localization of isostatic coherence anisotropy in Australia and its relation to seismic anisotropy: implications for lithospheric deformation Travel-time inversion for simultaneous earthquake location and velocity structure determination in
laterally varying media Finite-frequency tomography using adjoint methods—methodology and examples using membrane surface waves Structure of North American mantle constrained by simultaneous inversion of multiple-frequency SH, SS, and Love waves A double-difference earthquake location algorithm: method and application to the Northern
Hayward Fault, California Improving global shear wave traveltime tomography using three-dimensional ray tracing and iterative inversion Seismic attenuation beneath Europe and the North Atlantic: implications for water in the mantle APPENDIX: DOUBLE-DIFFERENCE MULTITAPER MEASUREMENTS In the main text, we focused on measuring
traveltime shifts via cross-correlation, a time-domain method that does not offer frequency resolution beyond what can be achieved using explicit filtering operations prior to analysis. (3) that \begin{eqnarray} \delta \Delta t_{ij}^{\mathrm{syn}}= \frac{\int _0^T\partial _t s_i(t)\delta s_i(t)\mathrm{d}t}{\int _0^T\partial ^2_t s_i(t)s_i(t)\mathrm{d}t}
- \frac{\int _0^T\partial _t s_j(t)\delta s_j(t)\mathrm{d}t}{\int _0^T\partial ^2_t s_j(t)s_j(t)\mathrm{d}t} = \delta \Delta t_i -\delta \Delta t_j . In this paper, we use common waveform cross-correlation traveltimes as examples of incorporating differential measurements into adjoint-based tomography. (2005) (their eq. 61) which do not suffer similar
such restrictions—save for the general adequacy of the Born approximation, which appears practically unavoidable though perhaps not theoretically unassailable (Hudson & Heritage 1981; Panning et al.2009; Wu & Zheng 2014).As a further point of note, it is computationally more efficient and algorithmically less complicated to evaluate the double-
difference adjoint kernel using eqs (18) than via eqs (4) and (24). From the new measurement, we construct a new misfit function and derive its Fréchet derivatives and adjoint sources. The cross-correlation time-shift measurements are now Δt1 = 0.54 s (d1 is advanced 0.54 s relative to s1) and Δt2 = −0.54 s (d2 is delayed 0.54 s relative to s2).
\end{eqnarray} (18b)The comparison of the expression for the adjoint sources of the classical case in eq. (2000) (compare our eq. 15 with their eq. 75). 4 THE ADVANTAGE OF DIFFERENTIAL MEASUREMENTS In this section, we briefly list some of the properties of differential traveltime measurements that make them good candidates for being less
affected by source uncertainties than traditional absolute measurements. (a) The 2-D target model, a portion of the model shown in Fig. 13(a). To reduce the misfit function (in eq. 2), the wave speed along the ray path from the source to station 1 should be increased, and the wave speed between the source and station 2 decreased. Open in new
tabDownload slideExperiment IIB: misfit sensitivity kernels. This behaviour is indeed explained by the nature of the kernel, which is obtained by summation of the individual adjoint kernels for each station. (A4a) can be estimated in the least-squares sense (Bendat & Piersol 2000, Ch. 9) as minimizing the linear-mapping ‘noise’ power associated with
eq. (5), computed using the adjoint sources shown by the blue lines in Figs 2(c) and (d). We randomly selected 300 stations from the USArray station pool for tomographic testing using membrane surface waves as in all prior experiments. Black traces are computed in the target model of Fig. 4(a). As in the classical case, however, the final adjoint
source for double-difference measurements is the sum of the contributions from all stations, which are thus backpropagated simultaneously to obtain the adjoint kernels of the objective function in eqs (8). (1) result in negative kernel values Km in eq. The typical isotropic situation would be for eq. The initial model is homogeneous. Both theoretically
and in numerical experiments, we have shown that the ‘double-difference’ approach produces reliable misfit kernels for adjoint tomography, despite potentially incorrect source wavelets, scale factors, or timings used in synthetic modeling. 4.1 Scaling invariance The cross-correlation measurement in eq. \end{eqnarray} (8)The summation avoids
double counting from the symmetry of the traveltime measurements, since |$\Delta t_{ji}^{\mathrm{syn}}= -\Delta t_{ij}^{\mathrm{syn}}$| and |$\Delta t_{ji}^{\mathrm{obs}}= -\Delta t_{ij}^{\mathrm{obs}}$|. The black traces marked ‘data’ are calculated in the checkerboard model of Fig. 1(a). In contrast, by using the approximation in eq.
The target and initial models and the station-receiver geometry are shown in Fig. 11. For dispersive waves, such as surface waves, differential frequency-dependent phase and amplitude measurements can be made using multitaper cross-spectral analysis. \end{eqnarray} (A23b)The multitaper phase and amplitude adjoint sources are thus
\begin{eqnarray} f_{\Phi ,i}^{\dagger }(t)= 4\pi \sum _{j>i} \scr {S}_{i|j}(T-t)\,\delta (\mathbf {x}-\mathbf {x}_i) \qquad \mbox{and}\qquad f_{\Phi ,j}^{\dagger }(t)= 4\pi \sum _{ii} \scr {A}_{i|j}(T-t)\,\delta (\mathbf {x}-\mathbf {x}_i) \qquad \mbox{and}\qquad f_{A,j}^{\dagger }(t)= 4\pi \sum _{ii} \frac{\Delta \Delta t_{ij}}{N_{ij}}\partial _t
s_j(t-\Delta t_{ij}^{\mathrm{syn}}) \right] \delta s_i(t) -\sum _{j} \left[\sum _{i

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