

1 **Empirical Green’s Function Retrieval using**
2 **Cross-correlation of Ambient Noise Correlations (C^2)**

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7 **Key Points:**

- 8 • An effective higher-order correlation technique is developed to extract the empir-
9 ical Green’s functions (EGFs) from asynchronous networks.
- 10 • Our technique cross-correlates the deterministic wavefield from virtual sources and
11 provides high-quality EGF estimates.
- 12 • Seismic tomography using asynchronous EGFs offers new constraints to areas under-
13 sampled by conventional ambient noise imaging methods.

Abstract

Empirical Green's function (EGF) retrieval commonly relies on cross-correlating the long-term ambient seismic wavefield that is simultaneously recorded at multiple stations. Recent studies have demonstrated observationally that cross-correlating the coda of ambient noise cross-correlation functions (C^3) enables reconstruction of the EGFs, regardless of the operating time of the stations. In this study, we develop a new technique to perform correlation of cross-correlation functions (C^2), thus permitting the reconstruction of asynchronous EGFs. Our approach exploits the deterministic wavefield rather than the diffusive codas that may be affected by incoherent energy under non-ideal (e.g., sparse, noisy and short-duration) network configurations. We demonstrate the robustness of C^2 by retrieving asynchronous EGFs between 1) nearby stations and 2) distant temporary arrays from southern Australia. The accuracy of the EGFs from C^2 are examined by analyzing seismic tomography of Rayleigh wave group velocities and benchmarking them with the results from conventional ambient noise imaging. The additional ray paths from asynchronous C^2 functions provide better illumination of small-scale crustal structures beneath the regional network. In the larger scale example, involving two asynchronous arrays, the implementation of the C^2 method offers new constraints to the sparsely sampled region of the southern Australian offshore. The resulting velocity model agrees well with the independent structural constraints from individual seismic array studies and sedimentary thickness measurements. This study demonstrates that C^2 is a promising tool for integrating transportable arrays deployed at different times and can greatly benefit the effort of improving seismic data coverage and resolution in crustal imaging.

Plain Language Summary

Seismic waves propagating between a pair of stations can be obtained by cross-correlating the long-term random (noisy-looking) signals simultaneously recorded at two stations. Earlier studies have shown that surface waves propagating between two stations, operated at different times (i.e., asynchronous), can also be obtained by cross-correlating the weak-amplitude coda waves trailing the strong surface waves in the correlation function. In this study, we develop a new method that directly utilizes the energetic surface waves, rather than just the codas, to extract the seismic waves between asynchronous stations. This method is more robust than the earlier proposed coda-wave based approach, espe-

cially when dealing with sparse, noisy and short-duration seismic networks. We apply
this new method at different length scales from nearby stations to two far apart, sep-
arated networks to demonstrate its superior performance to the traditional approach.
The new method can greatly improve data sampling and the resolution of seismic im-
age of subsurface structures.

1 Introduction

Seismic interferometry, commonly known as ambient noise cross-correlation in pas-
sive seismology, has been widely applied to probe the structure of the Earth’s interior
at various scales over the past two decades (e.g., Shapiro & Campillo, 2004; Yao et al.,
2006; Lin et al., 2007, 2008; Yang et al., 2007; Stehly et al., 2009; Saygin & Kennett, 2012;
Kao et al., 2013; Ward et al., 2013; Rawlinson et al., 2014; Porritt et al., 2016). Both
experimental and theoretical studies (e.g., Lobkis & Weaver, 2001; Weaver & Lobkis, 2001;
Shapiro & Campillo, 2004) have demonstrated that sufficient time-averaging of the cross-
correlation of diffuse wavefields recorded at two receivers effectively converge into the
interstation empirical Green’s function (hereafter EGF) (see Snieder & Larose, 2013; Campillo
et al., 2014; Boschi & Weemstra, 2015, for reviews). Conventionally, ambient noise cross-
correlation relies on the acquisition of equipartioned seismic wave energy from simulta-
neously acting sources (Wapenaar et al., 2010), which imposes a temporal constraint that
two stations need to operate simultaneously over a period of time. In recent years, meth-
ods have been proposed to reconstruct EGFs by cross-correlating the coda of the cor-
relation functions (hereafter C^3) extracted from the ambient noise (e.g., Stehly et al.,
2008; Froment et al., 2011; Ma & Beroza, 2012; Sheng et al., 2018). Such an approach
has been largely inspired by the earthquake coda interferometry that utilizes scattered
wave energy containing coherent information about the elastic response of the Earth (Campillo
& Paul, 2003). An underlying assumption of the C^3 approach is that the long-term stack-
ing of correlation functions produces stable, predominantly time-invariant coda waves
(Ma & Beroza, 2012), which permits extracting the EGFs between asynchronous stations
from the coherent coda energy acquired at different times. The additional ray paths from
the asynchronous EGFs enable improvement of the resolution of crustal imaging (Spica
et al., 2016; Ansaripour et al., 2019).

Aside from using diffuse wavefields, another branch of seismic interferometry takes
advantage of the deterministic signals from controlled (e.g., Schuster et al., 2004; Bakulin

77 & Calvert, 2006; Schuster, 2009) or earthquake sources (e.g., Curtis et al., 2009, 2012).
 78 This method generally integrates the correlation functions over the (known) distributed
 79 sources (Wapenaar et al., 2010). An intriguing implementation is source-receiver inter-
 80 ferometry (Curtis & Halliday, 2010) that retrieves the EGF between a source-receiver
 81 pair using the deterministic energy propagating from/to a set of surrounding receivers.
 82 Its application is not restricted to synchronous source-receiver pairs, thus, the virtual
 83 seismogram of an earthquake can be constructed on receivers deployed before or after
 84 the event, as long as the recordings are made using a few qualified backbone stations (Curtis
 85 et al., 2012).

86 Both the ambient noise coda-wave correlation (i.e., C^3) and source-receiver inter-
 87 ferometry techniques provide a form of temporal redatuming, whereby it is possible to
 88 reconstruct the EGFs between asynchronous station-station (earthquake) pairs. In this
 89 study, we extend beyond these two methods and examine the feasibility of reconstruct-
 90 ing EGFs from the deterministic wavefield extracted from ambient noise data. Specif-
 91 ically, we show that reliable EGF estimates are achievable from higher-order correlations
 92 that perform the cross-correlation of correlation functions (hereafter C^2) from surround-
 93 ing virtual sources (i.e., backbone stations). We demonstrate the effectiveness of the C^2
 94 technique using the data collected from two temporary networks deployed in southern
 95 Australia, operated five years apart and separated by a distance of approximately 1500
 96 km (Figure 1). We show that the C^2 method can robustly reconstruct the EGFs between
 97 nearby asynchronous stations and can easily be scaled up to achieve continental-scale
 98 applications involving distant temporary arrays. Benefiting from the asynchronous EGFs,
 99 the surface wave travel-time tomography offers new constraints to the southern Australian
 100 offshore, a region poorly resolved by conventional ambient-noise based methods.

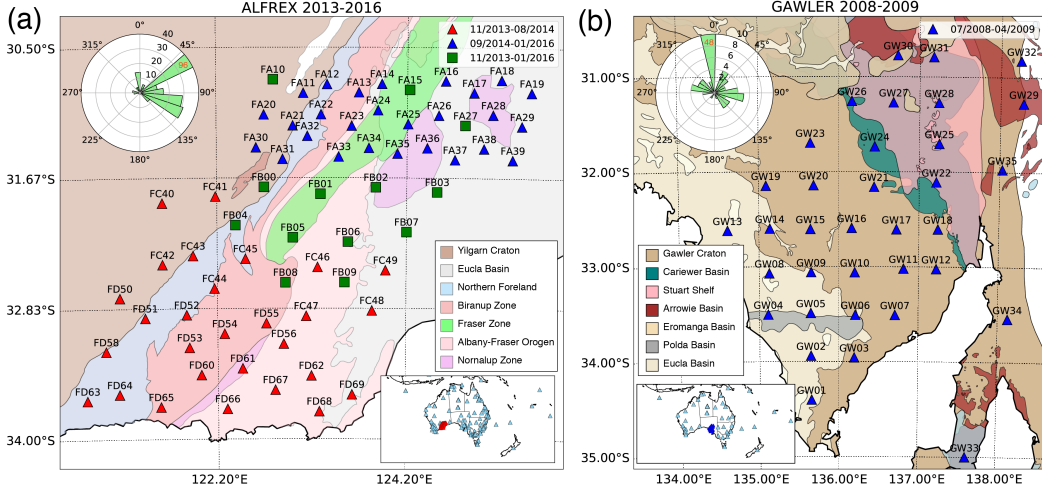


Figure 1. Spatiotemporal distribution of (a) ALFREX and (b) GAWLER seismic networks superimposed on regional geological maps of southern Australia. The crustal domains are colored to show the complex regional tectonic structures. The rose diagram shows the azimuthal distribution of virtual source stations used in the empirical Green’s function (C^2) retrieval in the respective test cases. The radial axis is clipped for a better illustration and the number of stations in the dominating direction are labeled on the bar. In the inset map, the locations of permanent seismic stations acting as virtual sources are marked with the cyan triangles and the ALFREX and GALWER networks are highlighted in red and blue.

2 Empirical Green’s function retrieval

The computation of C^2 is a two-stage process. The first step of our high-order cross-correlation scheme is to perform the conventional ambient noise cross-correlation (Figure 2a) that is mathematically expressed as

$$G(x, s, t) \simeq u(x, t) \otimes u(s, t), \quad (1)$$

where $G(x, s, t)$ is the EGF between stations x and s at time t , $u(x, t)$ and $u(s, t)$ are the corresponding wavefields recorded at two stations and \otimes represents the cross-correlation operator. This process turns station s into a virtual source (Figure 2b). Although equation (1) does not explicitly differentiate the source types (i.e., diffuse vs. deterministic) in the seismic recordings, ambient noise imaging usually utilizes the stochastic signals (e.g., noise) and removes the contaminating deterministic part (e.g., earthquakes) before cross-correlation (Bensen et al., 2007). Later, we show that this operation is not necessary for extracting EGFs using higher-order cross-correlations. To compute cross-correlation

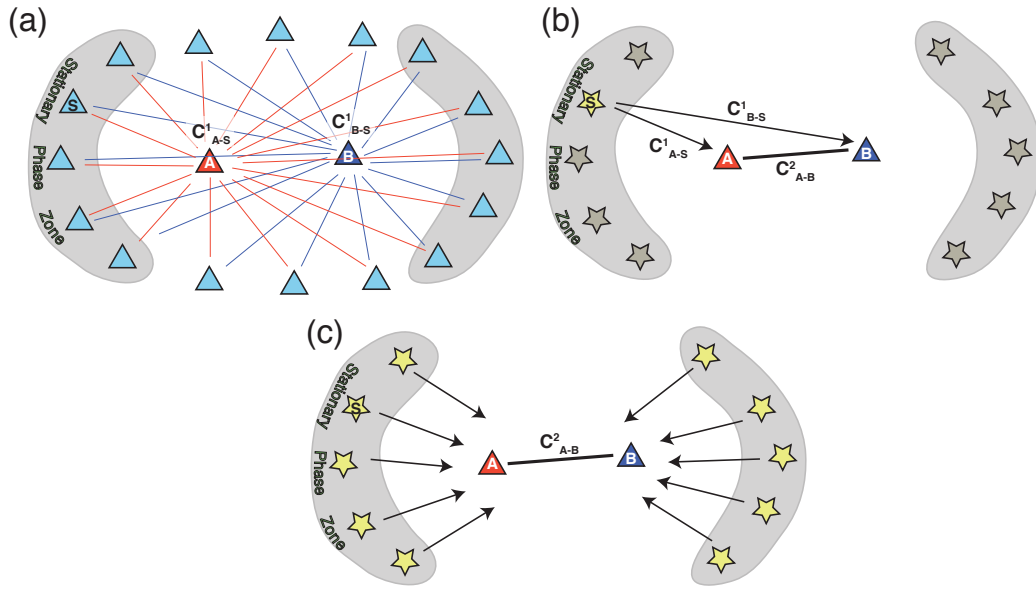


Figure 2. Cartoon illustrates the concept of C^2 . (a) Ambient noise correlations are performed between two temporary stations (A and B) and the surrounding permanent stations (S). This process turns the permanent stations into virtual sources. (b) The deterministic surface waves emitted from a virtual source station S (star) are recorded at stations A and B , which are then cross-correlated to obtain a C^2 function. (c) The cross-correlations are conducted for all virtual sources located within the stationary phase zone (shaded grey) that contribute constructively to the stacking.

113 functions (hereafter C^1) we cut the continuous seismic recordings into one hour segments
 114 with a 50% overlap between consecutive windows. After removing the mean and linear
 115 trend, we down-sample the data to 5 Hz and apply a bandpass filtering with corner fre-
 116 quencies at 150 sec and 0.5 sec. The processed (synchronous) time series from two sta-
 117 tions are cross-correlated and stacked to obtain the final C^1 estimate.

118 In the second step, we perform EGF retrieval by cross-correlating the correlation
 119 functions. This is formulated in the time domain as

$$G(x_B, x_A, t) \simeq \frac{1}{N} \sum_{i=1}^N G(x_B, s_i, t) \otimes G(x_A, s_i, t), \quad (2)$$

120 where $G(x_B, s_i, t)$ and $G(x_A, s_i, t)$ are the EGFs approximated using equation (1) be-
 121 tween temporary stations x_A or x_B and a virtual source station s_i , and the summation
 122 of correlation functions over N virtual sources produces $G(x_B, x_A, t)$, the EGF between
 123 x_A and x_B (Figure 2c). The two temporary stations (i.e., x_A and x_B) need not to be
 124 operating at the same time as long as the EGFs from a common virtual source (i.e., s_i)
 125 exist, which is typically one of the permanent stations from the backbone seismic net-
 126 work (Figure 1). Therefore, equation (2) provides a framework for reconstructing EGFs
 127 between asynchronous stations. In data processing, we select C^1 functions with at least
 128 three months of stacking to ensure the signal quality; no prior temporal or frequency nor-
 129 malizations are required. The C^1 functions are divided into causal and acausal signals,
 130 and cross-correlation is applied on each segment separately. The resulting two correla-
 131 tion functions (i.e., causal-causal and time reversed acausal-acausal correlations) are stacked
 132 to form a C^2 estimate. The final EGF between the two stations is obtained by stack-
 133 ing the normalized C^2 functions from all virtual sources.

134 **3 Data**

135 We apply the proposed higher-order cross-correlation method (C^2) to retrieve EGFs
 136 at two length scales 1) asynchronous station pairs within a regional array and 2) two dis-
 137 tant temporary networks with different operating periods (see Figure 1). The first ex-
 138 ample uses the recordings from the ALFREX network that consists of two subarrays, each
 139 sampling a part of the Albany-Fraser orogen in southwestern Australia at different time
 140 periods, as well as 13 semi-permanent stations operating throughout the acquisition pe-
 141 riod (Figure 1a). This network configuration is representative of a regional seismic sur-
 142 vey with a campaign-mode deployment (e.g., Transportable component of USArray). In

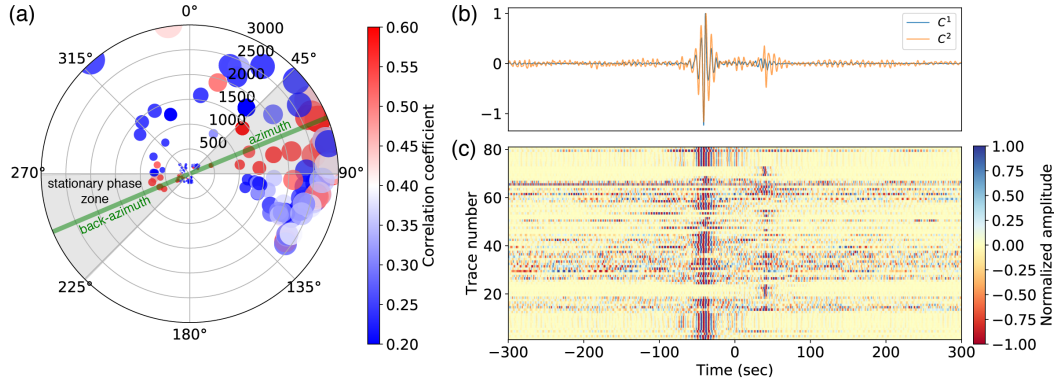


Figure 3. Comparison of the empirical Green’s functions retrieved from C^1 and C^2 approaches for the station pair FB07-FB08 within ALFREX. (a) Azimuthal and distance distribution of the correlation coefficient between C^1 and C^2 from individual virtual source. The green line indicates the directions of azimuth and back-azimuth of the selected station pair. The gray shades highlight the stationary phase zone that contributes constructively to the stacking. (b) Waveform comparison between C^1 (orange) and stacked C^2 (blue) using virtual sources within the stationary phase zone. The waveforms are filtered between 2 and 20 sec. (c) Normalized C^2 function from each virtual source contributes to the stack in (b).

143 the larger scale implementation, we select a distant seismic network (GAWLER) deployed
 144 approximately 1500 km to the east of ALFREX near the Gawler craton in southern Aus-
 145 tralia (Figure 1b). Stations of the GALWER network were operated synchronously be-
 146 tween 2008-2009 but did not overlap in time with the ALFREX deployment (2013-2016).
 147 The large separation distance and asynchronous operations of the two arrays present great
 148 challenges when reconstructing the inter-array EGFs with conventional ambient noise
 149 or coda-wave based correlation methods. To implement C^2 , we incorporate all the avail-
 150 able permanent stations near the Australian continent as virtual sources (see Figure 1).

151 4 Results

152 4.1 Empirical Green’s function retrieval between asynchronous stations

153 We compute C^2 between all possible station pairs within the ALFREX network
 154 that include both synchronous and asynchronous setups. The synchronous EGFs are ex-
 155 tracted between subarrays and 13 semi-permanent stations for a direct comparison with
 156 the EGFs obtained from the ambient noise fields (i.e., C^1) (Figure 1a). We show a sam-

157 ple C^2 measurement between a pair of stations located in the center of the ALFREX ar-
 158 ray to ensure a balanced azimuthal coverage of the virtual sources (Figure 3). We com-
 159 pute the correlation coefficient of C^2 from each virtual source with C^1 as a function of
 160 distance and azimuth (Figure 3a). The distribution of the correlation coefficient shows
 161 a strong dependence on azimuth: higher values are observed in the directions of azimuth
 162 and back-azimuth of the selected station pair, while lower values are distributed perpen-
 163 dicular, consistent with the stationary phase approximation (Snieder, 2004; Snieder et
 164 al., 2008). By comparison, the dependency of the correlation coefficient on distance is
 165 weak, which may be affected by factors such as site condition, local structures and am-
 166 bient noise source distributions. We define the stationary phase zone as a 45-degree az-
 167 imuthal bin centering on the direction of inter-station line and perform stacking of C^2
 168 functions using only virtual sources within this regime. The stacked C^2 is highly con-
 169 sistent with the corresponding C^1 with a correlation coefficient of 0.86 (Figure 3b). Each
 170 individual C^2 from a contributing source shows a clear Rayleigh-type surface wave en-
 171 ergy on either a positive or negative time axis, depending on the direction of the source
 172 (Figure 3c).

173 We use stations from several long-operating networks distributed across the Aus-
 174 tralian continent, which provides approximately 180 virtual sources in C^2 calculation (Fig-
 175 ure 4a). The spatial distribution of virtual sources, particularly their azimuthal cover-
 176 age relative to the temporary stations, strongly affects the quality and reliability of the
 177 retrieved EGFs from C^2 (see Figure 3). Thus, we only select the virtual sources that sat-
 178 isfy the stationary phase constraint; on average 50 stations contribute to the stacking
 179 of C^2 . The resulting EGFs (C^2) show consistent surface wave arrivals characterized by
 180 1) a similar move-out velocity to that of the EGF estimates of C^1 (Figure 4b) and 2)
 181 a comparable waveform quality between synchronous and asynchronous station pairs at
 182 the overlapped distances (Figure 4c).

183 **4.2 Dispersion measurements and ambient noise tomography**

184 We examine the robustness of the EGFs from C^2 by computing the surface wave
 185 dispersion curve. The frequency-dependent Rayleigh wave travel times are determined
 186 by FTAN (e.g., Levshin & Ritzwoller, 2001). This method applies a series of narrow-band
 187 Gaussian filters with varying center frequencies to the analytical signal of the cross-correlation
 188 function. The amplitude of the filtered signal defines an envelope function of the sur-

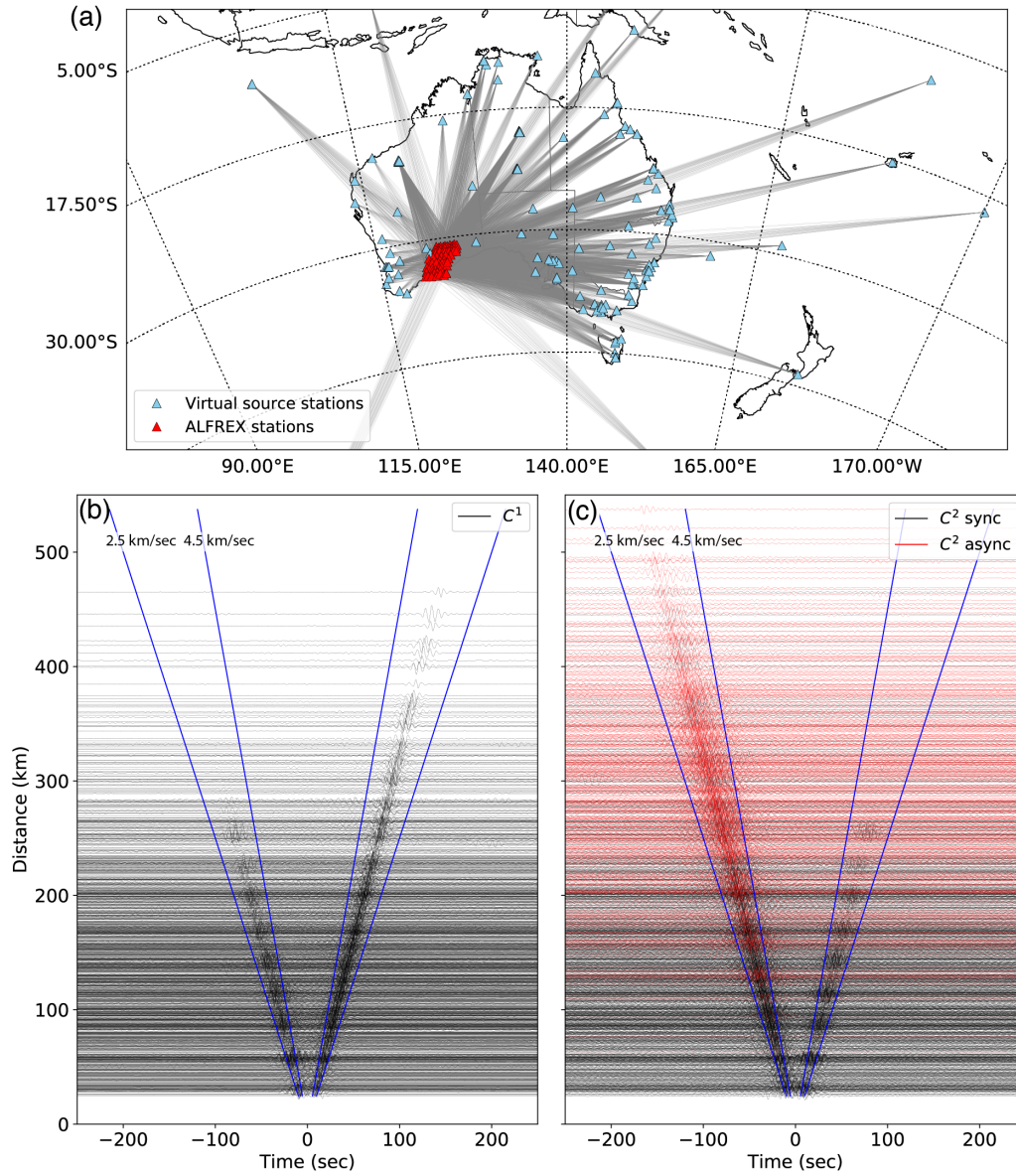


Figure 4. Empirical Green's functions (EGFs) of station pairs within the ALFREX network. (a) The ray-paths between virtual sources (cyan) and ALFREX stations (red) used in calculation of C^2 . (b) The EGFs extracted using the C^1 approach. The waveforms are normalized to unity and filtered between 5 and 20 sec. The blue lines mark the respective move-out velocities of 2.5 and 4.5 km/sec, corresponding to the expected range of speed for surface waves in southwestern Australia (Saygin & Kennett, 2012). (c) The EGFs between synchronous (black) and asynchronous (red) station pairs from C^2 .

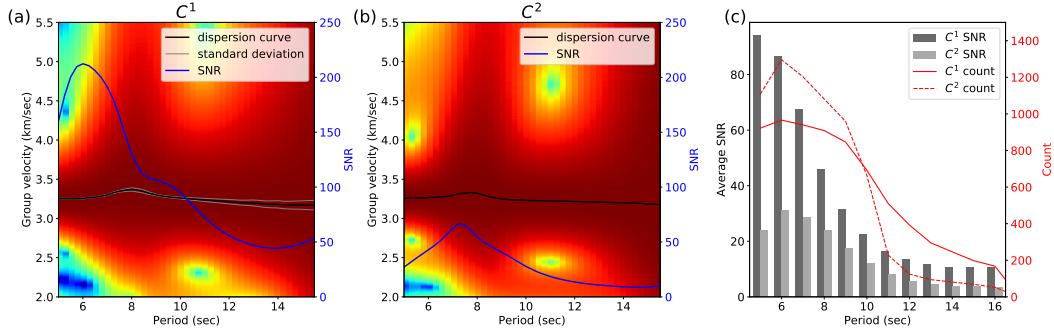


Figure 5. Group velocity measurements of (a) C^1 and (b) synchronous C^2 functions between the station pair FA10-FA15. The black line shows the dispersion curve and the blue line shows the signal-to-noise ratio (SNR) of the cross-correlation function. The uncertainty of the dispersion curve of C^1 is determined by the standard deviation of the measurements on the three-month stacking of C^1 functions (e.g., January-March, February-April etc.). (c) The histogram of average SNR of C^1 (dark grey) and C^2 (light grey) functions at each period. The red solid line shows the number of dispersion measurements of C^1 with $\text{SNR} > 10$ and the corresponding result for C^2 is indicated by the dashed line.

189 face wave, from which the dispersion curve can be retrieved by tracking the peak loca-
 190 tion of the envelope at each period. The dispersion curves of C^1 and C^2 functions be-
 191 tween a sample station pair (FA10-FA15) are highly consistent within the frequency band
 192 of interest (4-16 sec) (Figure 5). The average discrepancy is 0.01 km/sec, which is well
 193 below the uncertainty range (0.02 km/sec) of the dispersion measurement of C^1 that re-
 194 sults from the temporal variation in the EGF (Figures 5a). We further assess the qual-
 195 ity of dispersion measurements based on the signal-to-noise ratio (SNR). We define the
 196 SNR as the ratio between the maximum absolute amplitude of the surface wave and the
 197 standard deviation of the noise in a 500 sec window that starts 500 sec after the surface
 198 wave arrival. For the selected station pair, the SNRs of the C^1 and C^2 functions both
 199 peak at short periods (7 sec) and decrease rapidly towards longer periods (Figures 5a
 200 and 5b). The SNR value of the C^1 function is significantly higher than that of C^2 at all
 201 periods, which is expected when C^1 emerges from a sufficiently-averaged ambient noise
 202 field. The average SNR of dispersion measurements of all station pairs shows a similar
 203 decaying pattern (Figure 5c). For both C^1 and C^2 functions, the majority of high-quality
 204 measurements ($\text{SNR} > 10$) are concentrated between 5-9 sec, which approximately coin-
 205 cides with the frequency band of the primary microseism (Campillo et al., 2014), and

206 the number decreases with increasing period (Figure 5c). The inclusion of asynchronous
 207 station pairs leads to a greater number of measurements of C^2 at periods below 10 sec,
 208 beyond which the number decreases quickly to about half of the C^1 results (Figure 5c).
 209 The sharp decrease of C^2 measurements at 10 sec is limited mainly by the instrument
 210 type of the ALFREX stations, the majority of which are equipped with short-period (1
 211 Hz) sensors. The cross-correlation involving a short-period station produces incoherent
 212 signals at longer periods. This effect is amplified in the C^2 function because of the mul-
 213 tiple (two-times) cross-correlations of narrow band signals.

214 **4.3 Ambient noise tomography with EGFs from C^2**

215 We perform ambient seismic tomography (ANT) to verify that the EGFs from C^2
 216 are indeed composed of physical signals carrying information on the Earth’s structure
 217 and are not processing artifacts. We conduct four groups of inversions considering the
 218 distinctive ray-path constraints of C^1 and C^2 functions (Figure 6). The C^1 function mainly
 219 offers short-distance EGFs between nearby stations (Figure 6a) with the majority of inter-
 220 station distances being less than 250 km (see Figure 4b). The C^2 approach enables re-
 221 construction of the EGFs between both synchronous and asynchronous station pairs. The
 222 former possesses a similar ray-path coverage to that of C^1 with a slightly lower sampling
 223 density (Figure 6b), whereas the asynchronous case provides primarily long-distance (200-
 224 450 km) EGFs connecting the two subarrays (Figure 6c). Thus, the combined ray-paths
 225 from C^1 and asynchronous C^2 provide complementary (short vs. long wavelength) con-
 226 straints to the subsurface structures (Figure 6d).

227 We invert the 5-sec dispersion measurements for group velocities based on an it-
 228 erative non-linear inversion scheme that applies the fast-matching method for wavefront
 229 tracking (Rawlinson & Kennett, 2004). To ensure the accuracy of the dispersion mea-
 230 surement, travel times that deviate largely from the linear trend (i.e., more than two stan-
 231 dard deviation) of the time-distance relationship are considered to be outliers and dis-
 232 carded from the subsequent inversion (supplementary Figure S3). The study area is pa-
 233 rameterized into a regular grid of 31×31 nodes, which approximates to a cell size of 20
 234 km in both directions. A constant velocity of 3.24 km/sec is assigned to each node lo-
 235 cation as the initial value. We follow the damping and smoothing criteria from Sippl et
 236 al. (2017) for the inversions of C^1 , synchronous C^2 and the joint C^1 and asynchronous
 237 C^2 functions considering a similar ray-path coverage (Figure 6). Lower values are adopted

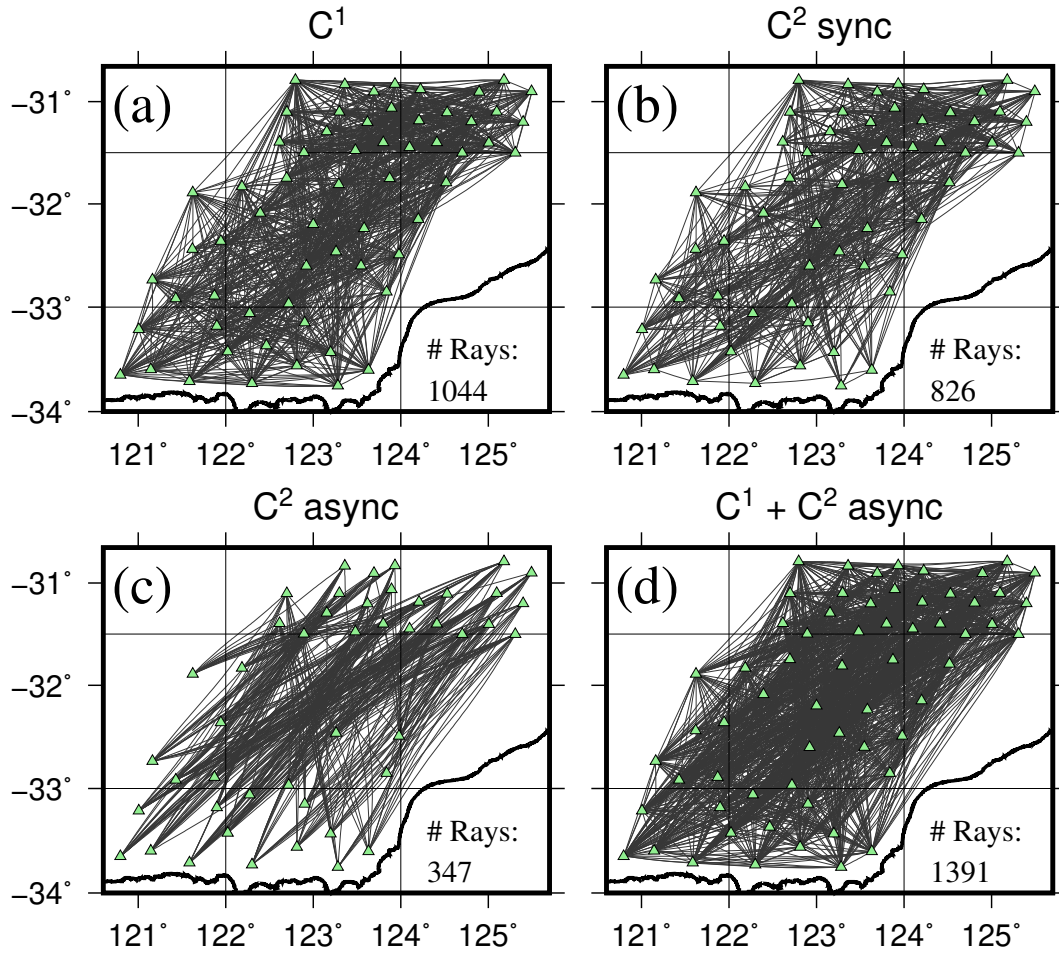


Figure 6. The ray-path coverages at 5 sec of (a) C^1 , (b) synchronous C^2 , (c) asynchronous C^2 and (d) C^1 and asynchronous C^2 functions from ALFREX. Only ray paths with robust travel-time measurements (i.e., within one standard deviation of the linear regression of time-distance curve) are preserved.

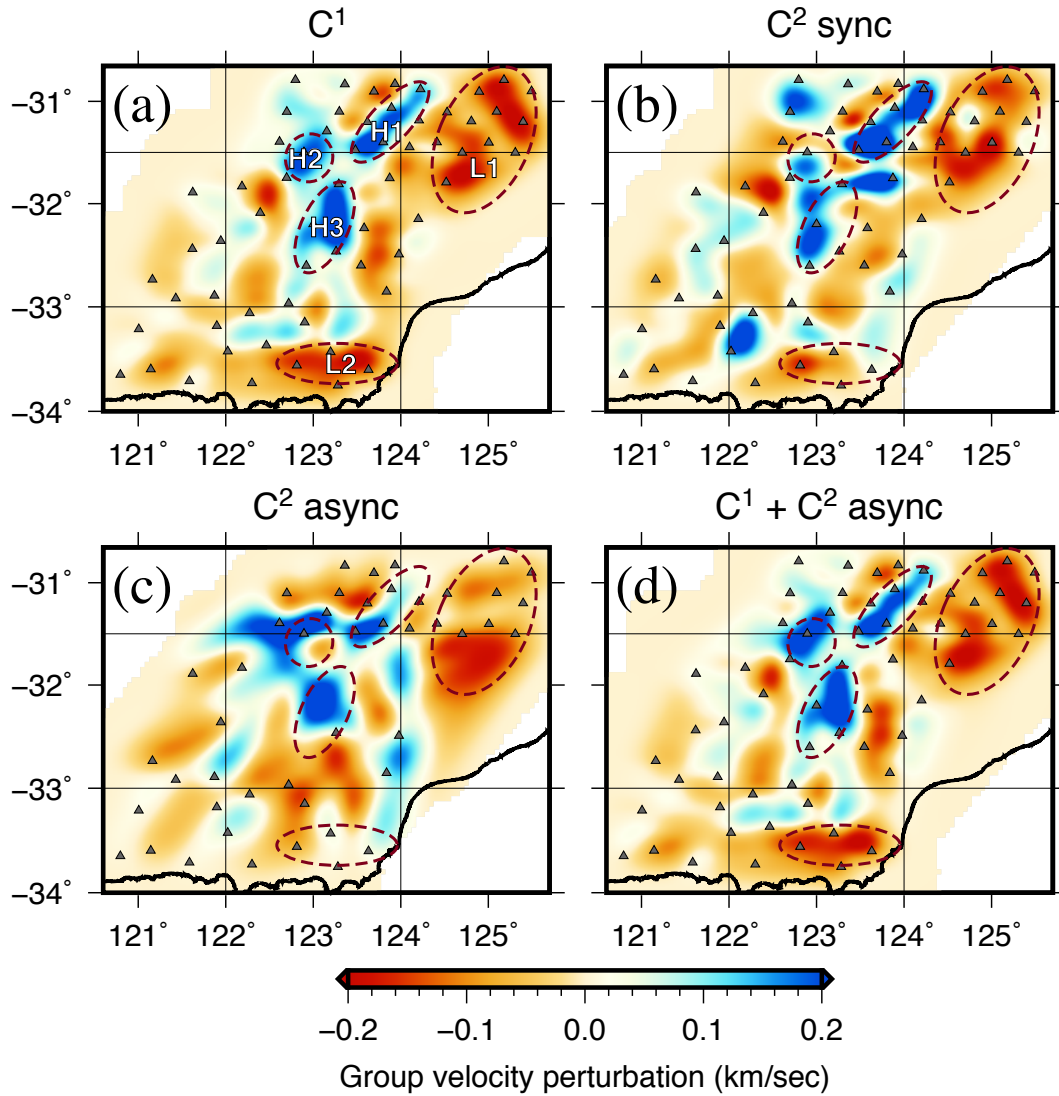


Figure 7. Group velocities at 5 sec beneath the ALFREX network inverted using (a) C^1 , (b) synchronous C^2 , (c) asynchronous C^2 and (d) C^1 and asynchronous C^2 functions. The velocities are plotted in perturbation relative to the regional mean of 3.24 km/sec. The circled areas highlight the major high (H1-H3) and low (L1-L2) velocity structures discussed in the text.

238 for the inversion of asynchronous C^2 functions to account for the intrinsic smoothing ef-
 239 fect imposed by the long-distance ray-paths (Figure 6c). The resulting C^1 tomogram shows
 240 a dominating NE-SW striking high-velocity structure with three distinctive clusters (H1-
 241 H3) that are bound by a broad low-velocity zone (L1) to the east and a smaller low-velocity
 242 zone (L2) to the south (Figure 7a), consistent with the observations from the study by
 243 Sippl et al. (2017). The inversion of synchronous C^2 functions largely confirms the ve-
 244 locity pattern observed in the C^1 result. However, the shape of high-velocity structures
 245 (H2 and H3) are less-well constrained and the smaller low-velocity zone (L2) is recov-
 246 ered at a lower amplitude because of reduced ray-path density in these regions (Figure
 247 7b). The asynchronous result successfully captures the large-scale structural variation
 248 of the juxtaposed high and low velocities. The recovery of three high-velocity structures
 249 is in reasonable agreement with the C^1 result (Figure 7c). The larger low-velocity zone
 250 (L1) is generally well resolved, except at the northern tip. In contrast, the smaller-scale
 251 low velocity anomaly L2 is characterized by close to average wave speeds, which poten-
 252 tially represents an inversion artifact arising from a lack of crisscrossing ray-paths in that
 253 region (Figure 6c). The combined dataset that consists of the C^1 and asynchronous C^2
 254 functions leads to 1) more crisscrossing ray-paths in the center of the network and 2) an
 255 increased number of rays sampling the eastern and western flanks of the model (com-
 256 pare Figures 6a and 6d). The overall improvement is subtle as there is a dominating con-
 257 tribution from C^1 functions, yet the resulting model exhibits a better recovery of small-
 258 scale anomalies (e.g., H2) and more distinct velocity variation across the array (e.g., shaper
 259 contrast between H3 and surrounding regions) (Figure 7d).

260 **4.4 Empirical Green’s function retrieval between distant asynchronous** 261 **networks**

262 The example of ALFREX demonstrates the robustness of the C^2 method in retriev-
 263 ing EGFs within a regional-scale temporary network. A more challenging test is performed
 264 on two distant arrays (ALFREX and GAWLER), where the inter-array C^1 is not avail-
 265 able because of the non-overlapping deployment periods of the two temporary networks.
 266 The dominating east-west orientation of the ray-paths makes the permanent stations lo-
 267 cated along the eastern and western coasts of Australia the most useful virtual sources
 268 for constructing C^2 , on average 22 sites contribute to the EGF retrieval (Figure 8a). De-
 269 spite a significantly smaller number of virtual sources employed in the extractions com-

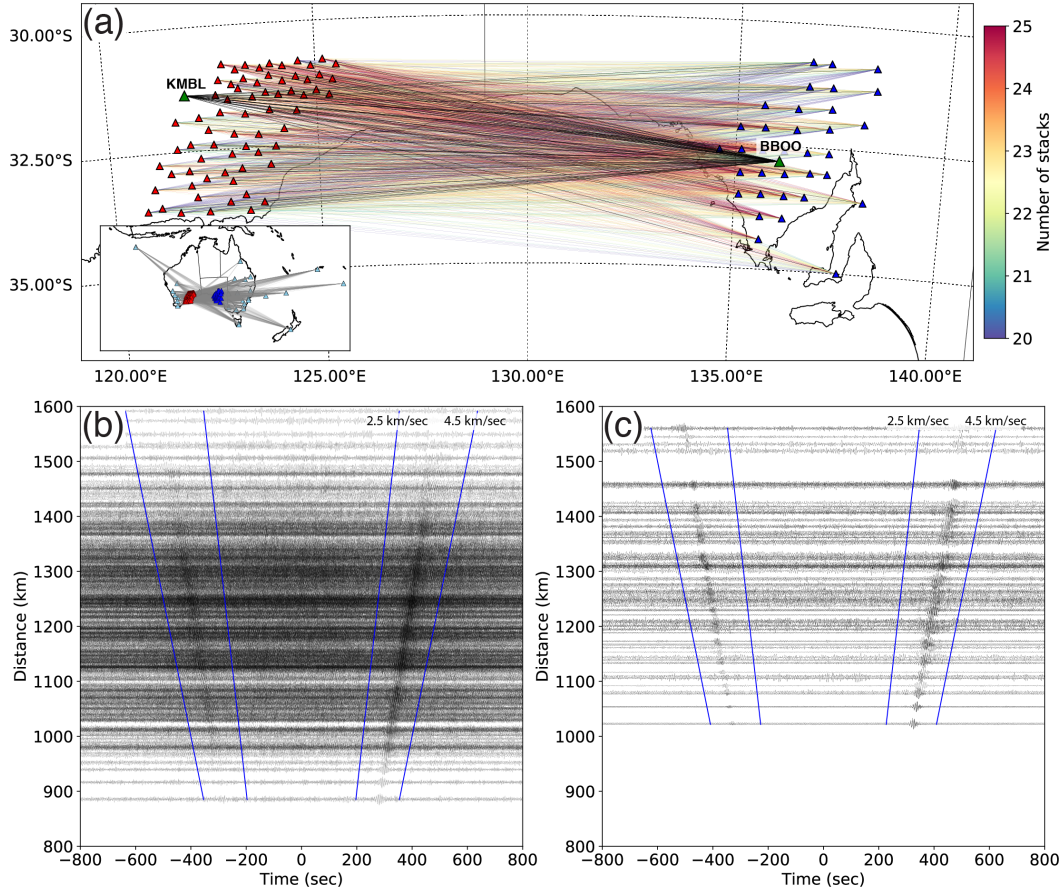


Figure 8. Empirical Green’s function (EGF) retrieval using two distant temporary networks of ALFREX and GAWLER. (a) The inter-array ray paths between stations from the two networks color-coded with the number of virtual sources used in the stack. The green triangles mark two nearby permanent stations (KMBL and BBOO) that are used to compute C^1 . The ray paths connecting the permanent station to the temporary stations in the opposite network are shown by the black lines. The inset map shows the distribution of virtual source stations (cyan triangles). (b) The inter-array EGFs retrieved using C^2 . (c) The EGFs retrieved using C^1 between the selected permanent stations and temporary arrays shown in (a). All waveforms are normalized and filtered between 2 and 20 sec.

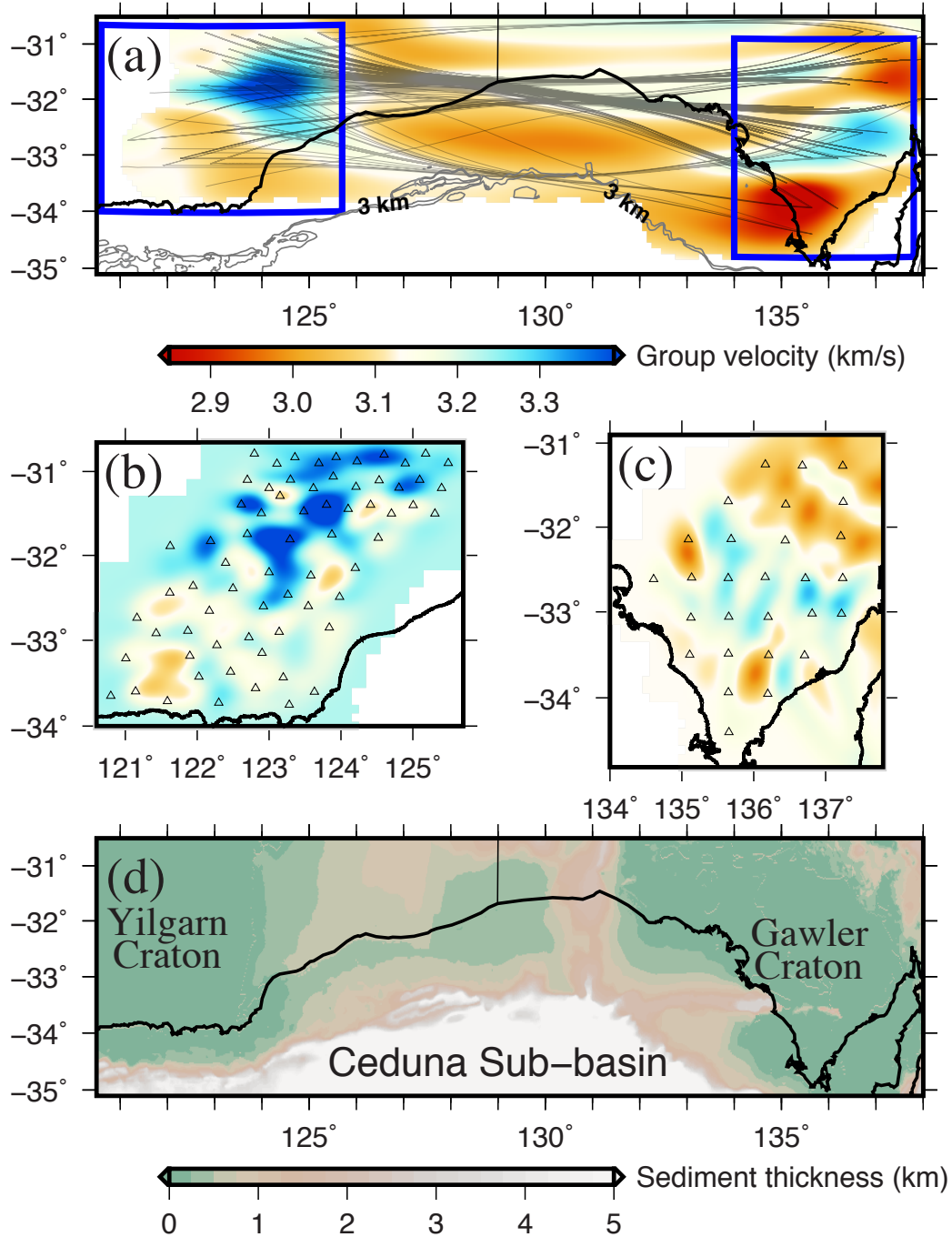


Figure 9. Tomographic inversion using the empirical Green's functions retrieved from C^1 and C^2 . (a) The group velocity tomograms at 8 sec constructed by inverting the group delays measured from the EGFs retrieved using C^2 between the two temporary arrays. The locations of ALFREX and GAWLER are highlighted with the blue rectangles. The grey lines indicate the sedimentary thickness contours. The velocities beneath (b) ALFREX and (c) GAWLER inverted using C^1 from the respective arrays. The station locations are indicated by the triangles. (d) The sedimentary thickness distribution near the southern Australian margins obtained from OZ Seebase model (<http://www.frogtech.com.au/ozseebase/>), providing constraints to shallow crustal structures.

270 compared to those used in the ALFREX example (see Figure 2b), clear surface wave arrivals
 271 can be identified from the resulting C^2 functions (Figure 8b). However, a direct assess-
 272 ment of the quality of inter-array C^2 is prohibited by the lack of C^1 functions from the
 273 same ray-paths. Thus, we select two permanent stations in the proximity of the respec-
 274 tive temporary networks (Figure 8a) to compute the EGFs using C^1 (Figure 8c). This
 275 ensures, as best as possible, a similar spatial sampling to the inter-array area as that of
 276 C^2 . Benefiting from a long-time (>1 year) averaging of ambient noise, the SNR of C^1
 277 is higher than that of C^2 which has been computed using a limited number of determin-
 278 istic sources. The consistency between the two sets of EGFs is encouraging in view of
 279 1) a similar move-out velocity of the surface waves and 2) the asymmetric waveforms with
 280 a decreasing amplitude at far offsets.

281 The retrieved EGFs between the ALFREX and GAWLER networks provide new
 282 seismic constraints to the subsurface structure of the inter-array area. This broad region
 283 marks the complex tectonic setting of the southern Australia continental margin, where
 284 the crustal domain transitions rapidly from the Archean Yilgarn craton in the west, through
 285 the Proterozoic Albany-Fraser orogen and the Paleozoic offshore basin, to the Archean
 286 Gawler craton in the east. Rayleigh wave travel times determined from C^2 functions are
 287 inverted with the fast-matching method on a regular grid with 31×31 nodes. The result-
 288 ing tomogram shows a strong lateral variation from the high group velocities beneath
 289 ALFREX and GAWLER networks to a broad intervening low-velocity zone (Figure 9a).
 290 The predominantly E-W orientated ray-paths lead to strong smearing, which prevents
 291 an accurate assessment of the lateral scale of the size of the velocity structures. In con-
 292 trast, the nominal resolution in the latitudinal direction is higher, delineating a sharp
 293 velocity transition from the continental to offshore areas. The majority of rays propa-
 294 gate along a high-velocity corridor along the continental margin (Figure 9a), a structure
 295 that has been reported in an earlier continental-scale model (Saygin & Kennett, 2012).
 296 We present independent constraints to the structures beneath the two arrays by invert-
 297 ing the C^1 from the respective network (i.e., intra-array EGFs). The ALFREX result
 298 shows a high-velocity zone extending from the center towards the NE (Figure 9b). The
 299 structure of GALWER is dominated by a core of scattered high velocities surrounded
 300 by reduced wave speeds (Figure 9c). Similar high-velocity structures are revealed by am-
 301 bient noise imaging using the C^1 technique conducted near the Albany-Fraser orogen (Sippl
 302 et al., 2017) and the Gawler craton (Pilia et al., 2015). The spatial distributions and rel-

303 active strength of the two high-velocity structures beneath the two arrays are highly cor-
 304 related with those from the tomographic model inverted using the asynchronous EGFs
 305 from C^2 (Figure 9a). This broad inter-array region constitutes the offshore of the south-
 306 ern Australian margins that has been sparsely sampled by earlier continental-scale stud-
 307 ies (Saygin & Kennett, 2010, 2012). Several offshore basins are covered by a thick Proterozoic-
 308 Mesozoic sedimentary sequence, varying from 2 km in the shallow marginal basin to over
 309 15 km in the depocentre of the Ceduna Sub-basin (OZ Seebase model). The propaga-
 310 tion of short-period (8 sec) surface waves are mainly sensitive to upper crustal hetero-
 311 geneities. As a result, the ray-path is strongly affected by the defocusing effect of the low-
 312 velocity structures, which generally follow the distribution of shallow (<3 km) sediment
 313 deposits in the offshore basins (Figure 9d).

314 5 Discussion

315 5.1 Controlling factors for the quality of C^2

316 The two examples at different scales demonstrate that the EGFs can be robustly
 317 retrieved from the deterministic wavefields between asynchronous stations (networks).
 318 We discuss a few key factors that can affect the performance of C^2 , including 1) the qual-
 319 ity of C^1 , 2) the azimuthal and distance distribution of the virtual sources and 3) the
 320 relative location between a pair of asynchronous stations. Since C^2 exploits the deter-
 321 ministic surface wave energy from C^1 , missing or low-quality signals in C^1 inevitably lead
 322 to poor EGF retrieval. Specifically, strong noise in C^1 functions often introduces inter-
 323 fering spurious arrivals with amplitudes comparable to that of the surface wave in C^2 ,
 324 which prevents an accurate determination of group/phase arrivals. As has been exten-
 325 sively discussed in earlier studies (e.g., Bensen et al., 2007; Sabra et al., 2005; Stehly et
 326 al., 2006; Yang & Ritzwoller, 2008), the quality of C^1 is predominately affected by the
 327 spatiotemporal distribution of the noise sources, and a long-term averaging of ambient
 328 noises is often required to obtain stable C^1 functions. Signal processing techniques such
 329 as Welch’s method (Seats et al., 2012) and phase weighted stacking (Schimmel & Paulssen,
 330 1997) can be applied to improve the convergence of C^1 functions.

331 The dominating factor for obtaining high-quality EGFs using C^2 is the spatial dis-
 332 tribution of virtual sources. Unlike C^1 that utilizes ambient noise without well-constrained
 333 source locations, C^2 functions are essentially constructed from a set of controlled (vir-

334 tual) sources that are collocated with the permanent stations (Figure 2). Thus, a biased
 335 azimuthal distribution of the virtual sources (see the rose diagram in Figure 1) can pre-
 336 clude a uniform wavefield illumination at the receiver pair of interest, a prerequisite for
 337 the constructive stacking of EGFs (Snieder et al., 2008). This criterion is relaxed by the
 338 stationary phase approximation, stating that only seismic sources distributed near the
 339 inter-station path dominantly contribute to the correct arrival times, hence the construc-
 340 tive stacking of seismic phases (Snieder, 2004; Snieder et al., 2008). In our test cases, the
 341 virtual sources that contribute the most to C^2 stacking are spatially confined within a
 342 45-deg bin centering on the line connecting two targeting receivers, whereas non-physical
 343 precursory energies emerge when all C^2 functions are stacked without carefully select-
 344 ing the azimuthal coverage (supplementary Figure S1). An inversion scheme that directly
 345 utilizes these biased correlation functions has been recently investigated by Fichtner et
 346 al. (2016). Compared to the azimuth, the effect of source-station distance on the qual-
 347 ity of individual C^2 is secondary (Figure 3). However, the far-field virtual sources are
 348 useful to ensure the constructive stacking of C^2 functions, since the stationary phase ap-
 349 proximation is more easily fulfilled by including distant virtual sources, the result of a
 350 wider aperture at far distances. Finally, another controlling factor is the relative loca-
 351 tion between a pair of temporary stations subject to EGFs retrieval. The C^2 achieves
 352 the best performance when the majority of virtual sources are well aligned with the tar-
 353 geting station pair. For example, the highest quality EGFs in the AFLREX network are
 354 characterized by the dominating NE-SW orientated ray-paths (Figure 6c), consistent with
 355 the direction of the densely distributed virtual sources in the NE quadrant (Figure 1a).

356 5.2 Comparison between C^2 and C^3 methods

357 In both test cases presented above, the C^3 approach based on cross-correlation of
 358 coda waves fails to extract consistent phase arrivals between asynchronous stations (sup-
 359plementary Figure S2). We attribute the performance difference (C^2 vs. C^3) to the un-
 360derlying assumptions of the seismic wavefield. The proposed C^2 method exploits the in-
 361formation carried by the deterministic part of the EGF, which is different from C^3 that
 362utilizes the diffuse coda wave energy. The application of C^3 typically succeeds when sta-
 363ble C^1 functions are available from a dense seismic network (e.g., Stehly et al., 2008; Fro-
 364ment et al., 2011; Ma & Beroza, 2012; Zhang & Yang, 2013; Spica et al., 2016, 2017; Sheng
 365et al., 2018). In such cases, the uniformity and diffusivity of the source illuminations of

366 C^1 can be enhanced through the presence of (near receiver) scatters (Boschi & Weem-
 367 stra, 2015), which produce a sufficiently diffuse scattering wavefield that is critical for
 368 the cancellation of the cross-terms in the correlation functions (Snieder et al., 2008). How-
 369 ever, in our study, the C^3 implementation is limited by the incoherent scattering energy
 370 in the codas that potentially arises from 1) insufficient recordings from the temporary
 371 deployments of networks, 2) a large separation distance between the virtual source and
 372 receiver, and/or 3) time-varying and/or a biased distribution of multiple scattering sources.
 373 Instead, the C^2 approach utilizes the deterministic energy flux (i.e., surface wave) from
 374 a distant source, approximating a plane wave that approaches the two nearby stations
 375 at nearly the same angle (azimuth). The accuracy of the travel-time measurements from
 376 correlations based on the plane wave assumption has been investigated in earlier stud-
 377 ies (Tsai, 2009; Yao & Van Der Hilst, 2009; Boschi et al., 2012) and is also demonstrated
 378 by our tomography examples (see Figures 7 and 9). We argue that the C^2 method is less
 379 affected by the high-level waveform fluctuations in C^1 codas and is more resistant to net-
 380 work irregularity, such that a few high-quality virtual sources within the stationary phase
 381 zone are generally sufficient to provide the unbiased EGF estimates (Figure 3).

382 **5.3 Travel-time bias in EGFs from C^2**

383 Travel-time bias in cross-correlation function resulting from non-isotropic source
 384 distribution has been widely reported (e.g., Weaver et al., 2009; Tsai, 2009; Yao & Van
 385 Der Hilst, 2009; Froment et al., 2010). The effects of virtual source distribution on travel
 386 time are further investigated in our study. The amount of travel-time bias in the C^2 func-
 387 tion is determined by the time lag (δt) that leads to the maximum correlation coefficient
 388 between the surface waves of C^1 and C^2 functions from the same station pair (Figure
 389 10a) (Froment et al., 2010). To ensure a statistically robust result, we remove large out-
 390 liers with time lags greater than one standard deviation of the measurements, which typ-
 391 ically result from unreliable cross-correlation measurements caused by cycle skipping or
 392 noisy C^1/C^2 functions. The cleaned dataset retains 70-90% of the raw measurements,
 393 depending on the frequency. The resulting bias is small at shorter periods, which is on
 394 par with the sampling rate of the cross-correlation function (0.2 sec), and increases semi-
 395 linearly to about 0.5 sec at longer periods (Figure 10b). These travel-time biases are small
 396 compared to the total travel times (on average 45 sec) of surface wave, hence only in-
 397 troducing a maximum measurement uncertainty of less than 2%. For most of the mea-

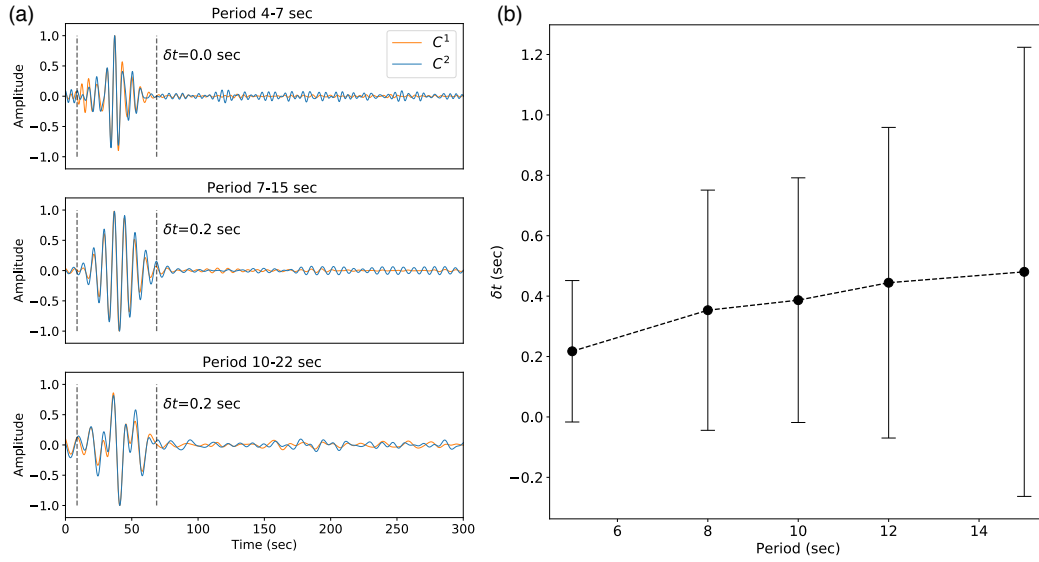


Figure 10. Figure 10 Measurement of the travel-time bias in C^2 functions. (a) A sample measurement for station pair FA30-FB02. The EGFs obtained from C^1 (orange) and C^2 functions (blue) are filtered in multi-frequency bands and their relative travel-time shift (δt) is labeled. The dashed lines indicate the time window of surface wave used in the analysis. (b) Travel-time bias as a function of period for all synchronous station pairs in the ALFREX network. The mean value is marked by the circle and the corresponding standard deviation is indicated by the error bar.

398 measurements, the mismatch between the C^1 and C^2 functions is minimal and excellent con-
399 sistency exists in surface waves and extends into the late codas (Figure 10a and supple-
400 mentary Figures S4-S11).

401 This frequency-dependent uncertainty is consistent with earlier theoretical inves-
402 tigations of the error in apparent travel-time in cross-correlation functions caused by far-
403 field anisotropic sources (Froment et al., 2010; Weaver et al., 2009). These have shown
404 that the predicted travel-time uncertainty decreases at shorter periods and larger inter-
405 station distances. In our study, we do not observe a clear dependency of travel-time bias
406 on distance, which may be caused by a relatively small variation in inter-station distance
407 (~ 100 km) compared to the length-scale of the far-field sources (in the order of thou-
408 sands of kilometers; Figure 1). Overall, the effect of non-isotropic wavefield intensity is
409 minimized by stacking the C^2 functions from virtual sources that fall within the station-
410 ary phase zone, as validated by our tomographic examples. This non-isotropic effect can
411 be further reduced by the C^3 method that takes advantage of the scattered wavefield (Froment
412 et al., 2010), which may lead to more accurate travel time estimates under an ideal net-
413 work configuration.

414 **5.4 Relationship to source-receiver interferometry**

415 The representation of C^2 is similar to source-receiver interferometry (Curtis & Hal-
416 liday, 2010; Curtis et al., 2012) that has been applied to reconstructing the virtual seis-
417 mograms between earthquake-earthquake (Curtis et al., 2009) or earthquake-station pairs
418 (Curtis et al., 2012; Entwistle et al., 2015). In these implementations, the actual earth-
419 quake response is projected to a receiver using the C^1 functions between the target re-
420 ceiver and the backbone stations. The C^2 method differs from source-receiver interfer-
421 ometry by replacing the earthquake with a collocated receiver that acts as a virtual source
422 with respect to the surrounding permanent (backbone) stations. This equivalence also
423 implies a change in source characteristics (depth and focal mechanism) from a complex
424 source-time function of an earthquake to an impulse surface response of the EGF (Denolle
425 et al., 2013). An earlier study extended the applicability of source-receiver interferom-
426 etry to inter-receiver distances over 2000 km (Entwistle et al., 2015), similar to the length-
427 scale investigated in our study.

6 Conclusion

This study presents the development of a new higher-order cross-correlation scheme (C^2) to extract the EGFs between seismic stations operated asynchronously through deterministic wavefields. Compared to the C^3 approach, the implementation of C^2 is less affected by irregular network configurations and only requires a relatively short recording period of the ambient noise wavefield, hence is ideal for bridging the spatiotemporal gaps between networks deployed at different times. The retrieved EGFs are inverted to obtain group velocities at two length scales, including a regional network with asynchronous station setup and two distant networks operating 5 years apart. The accuracy of the tomographic model derived from the C^2 functions is benchmarked with the results from conventional ambient noise imaging. The larger scale implementation offers new structural constraints to the previously largely undersampled offshore area of southern Australia. We conclude that C^2 is a feasible and promising method for exploiting the information of existing data and improving the resolution of seismic imaging. Our study shows that the current network topology of Australia, characterized by a set of asynchronous transportable arrays covering various parts of the continent and permanent stations mostly deployed along the coastlines, offers an ideal setting to implement the C^2 method. Furthermore, this technique is easily applicable to other continents. With improved data sampling, it is possible to further refine the regional and continental scale crustal models that will ultimately lead to a better understanding of the Earth's structure.

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