The Spatial Relationship Between Contemporaneous Tremor Detections in Relatively Low- and High-Frequency Bands

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Abstract

Although tremor is believed to consist of myriad Low-frequency Earthquakes (LFEs), it also contains longer-period signals of unknown origin. We investigate the source of some of the longer-period signals by locating tremor windows independently in relatively high-frequency ("HF", 1.25–6.5 Hz, containing typical LFEs) and low-frequency ("LF", 0.5–1.25 Hz) bands. We hypothesize that if tremor consists entirely of LFEs, such that the lower-frequency signals come from the non-uniform timing of higher-frequency ($\sim$2 Hz) LFEs, then contemporaneous LF and HF signals should be nearly co-located. Here we search for a systematic offset between the locations of contemporaneous LF and HF detections during rapid tremor migrations (RTMs). This first requires correcting for apparent offsets in location that arise simply from filtering in different passbands. To guard against possible errors in our empirical filtering effect corrections, we focus on a region of the subduction interface beneath southern Vancouver Island that hosts migrations propagating in nearly opposing directions. We find that the LF energy appears to occur roughly 500 m farther behind the propagating fronts of RTMs than the HF energy, whether those fronts propagate to the ENE or to the WSW. This separation is small compared to the location error of individual LF detections, but the result seems robust owing to the large number of detections. If this result stands, it suggests that tremor consists of more than just a collection of LFEs, with longer-period energy being generated farther behind the migrating fronts of RTMs, where slip speeds are presumably lower.
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Key Points:

\begin{itemize}
\item Coherent tremor signals are detected and located separately in relatively high-frequency (1.25-6.5 Hz) and low-frequency (0.5-1.25 Hz) bands
\item LF signals seem to consistently lag contemporaneous HF signals by \( \sim 500 \) m relative to the propagating fronts of rapid tremor migrations
\item Persistent offsets suggest that LF signals may have a source distinct from just the temporal overlapping of typical higher-frequency LFEs
\end{itemize}

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Abstract
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Plain Language Summary
Tectonic tremor is a poorly-understood seismic signal emanating from great depth along plate-bounding faults. It typically occurs in bursts of activity that correspond to “rapid tremor migrations”. Tremor contains myriad, sometimes impulsive arrivals termed Low-frequency Earthquakes (LFEs), but it also contains longer-period signals whose origin is debated. Investigating these longer-duration signals is hampered by their generally low signal-to-noise ratio, mostly due to the presence of the Earth’s microseismic noise band from ∼0.1–1 Hz. We find that beneath southern Vancouver Island the signal-to-noise ratio is often high enough to locate tremor in both the typical frequency band used for tremor and LFEs (≳2 Hz) and within the upper end of the microseismic band (down to 0.5 Hz). In this study we show that the lower-frequency signals appear to locate farther behind the propagating fronts of rapid tremor migrations, by about 500 m, than the higher-frequency signals containing typical LFEs. This spatial offset suggests that the longer-period signal in tremor does not arise simply from the clustering in time and space of more familiar higher-frequency LFEs. It also suggests that the same portion of the fault might produce energy of different frequencies at different times, depending upon the loading conditions.

1 Introduction
Nonvolcanic tremor, also known as tectonic tremor, was first detected occurring deep within subduction zones, at depths of ∼35 – 45 km along the subduction interface (Obara, 2002). Tremor is a low-amplitude, extended-duration signal often lacking clear impulsive arrivals, and is dominated by frequencies from 1–10 Hz (Beroza & Ide, 2011). Sometimes embedded within tremor are Low-frequency Earthquakes (LFEs), characterized by low dominant frequencies compared to regular earthquakes of similar magnitude, typically 1–2 (Katsumata & Kamaya, 2003). LFEs are sometimes impulsive enough to stand out above contemporaneous tremor (Katsumata & Kamaya, 2003); at other times or in other places they have been identified only by auto-correlation of seismograms across an entire seismic network (Brown et al., 2008; Shelly, 2010; Bostock et al., 2012). Varying slightly with tectonic setting, the dominant frequency band for detecting LFEs is generally similar to that of the contemporaneous tremor (e.g., Ide, Shelly, & Beroza, 2007;
Bostock et al., 2015; Thomas et al., 2016; Chestler & Creager, 2017). There are exceptions to the typical frequency range of ∼1–10 Hz; detection of both tremor and LFEs beneath Guerrero, Mexico, have been more successful in the 1–2 Hz passband, presumably because of a much narrower range of good signal-to-noise ratio (Frank et al., 2014; Peng & Rubin, 2017). Since the pioneering work of Shelly et al. (2006, 2007b), it has become well-accepted that tremor consists in large part of a swarm of LFEs, whose focal mechanisms are consistent with shear slip on the slab interface in the direction of plate motion (Shelly et al., 2006; Ide, Shelly, & Beroza, 2007; Wech & Creager, 2007; Brown et al., 2009). However, whether tremor consists entirely of LFEs, or includes longer-period sources distinct from LFEs, remains debated.

Regional studies show that LFEs tend to have a characteristic duration. Using in each case a 2–8 Hz passband, durations were found to be about 0.3 s in west Japan (Ide, Shelly, & Beroza, 2007), about 0.2 s in Parkfield (Thomas et al., 2016), and 0.25–0.4 s in Cascadia (Chestler & Creager, 2017). Bostock et al. (2012) used a somewhat wider passband of 1–8 Hz to detect LFEs beneath southern Vancouver Island; broadband stacks of nearly co-located LFEs (all the members of the same LFE family) still show a duration of only ∼0.3–0.5 s, a duration that moreover was found to be nearly independent of seismic moment $M_0$ (duration proportional to $\sim M_0^{0.1}$, over a range in $M_0$ of about one order of magnitude, with $M_0$ defined by the maximum of the displacement power spectrum between 0.5 and 1 Hz). In Guerrero, Farge et al. (2020) found similar durations (corner frequencies of $\sim$2 Hz) and moment-duration scaling, again over a range of about one order of magnitude in moment, although these LFEs were initially detected using a much narrower, 1–2 Hz passband. One question left unanswered by all these analyses is whether the observed clustering of durations is really an intrinsic feature of LFEs, or if it is biased by the narrow passband used to detect them.

The frequency band with a good signal-to-noise ratio for tremor detection is quite limited. The significantly reduced amplitude at high frequencies makes the upper limit no higher than 10 Hz. The lower limit is usually around 1 Hz because of the strong interference from the microseismic noise between 0.1 and 1 Hz (Beroza & Ide, 2011). Ide (2019) used a narrow-band template to detect “LFEs” in synthetic broadband random time sequences, and argued that what the community calls LFEs might just be an artifact of observing a broadband slow earthquake process over a narrow frequency band. He further showed that the broadband stacked templates of Bostock et al. (2015) actually include longer-period energy, up to periods of 4 s, in phase with the higher frequencies used to detect the LFEs, that are absent from the “LFEs” detected in his broadband random noise. However, the presence of this longer-period energy in the stacked templates from southern Vancouver Island does not by itself establish whether this longer-period energy reflects a longer-duration process associated with each LFE source; if it arises from the superposition of multiple LFEs, each relatively narrow-band, concentrated in time within a few seconds of the LFEs contributing to the stack; or if it is just a slightly longer-period part of a broadband process extending from “LFE” frequencies of a few Hz to much longer periods (Masuda et al., 2020).

Very Low-frequency Earthquakes (VLFs) have been observed on seismograms at frequencies below the microseismic band (e.g., 0.02–0.05 Hz) in both Japan and Cascadia (e.g., Obara & Ito, 2005; Ito & Obara, 2006; Ito et al., 2007; Ghosh et al., 2015). In Cascadia, Hutchison and Ghosh (2016) found VLFs during the 2014 ETS episode that occurred when and where there was no strong tremor, and suggested that VLFs and tremor may result from asperities of different sizes or characteristic behaviors. However, Gomberg et al. (2016) questioned the reliability of these VLF detections, and used synthetic seismograms to show that the distinguishing characteristics of VLFs could be produced just by a collection of temporally clustered LFEs. Thus, the question of whether VLFs represent an independent feature along the broadband “slow earthquake trend” (Ide, Beroza, et al., 2007), or just a superposition of LFEs, appears to remain open.
In contrast to studies of VLFs, relatively few studies have focused on the portion of the spectrum between LFEs and the microseism band. Kaneko et al. (2018) were the first to identify individual slow earthquakes in the 0.1–1 Hz passband between LFEs and VLFs. They found that although the locations of detections in the 0.1–1.0 Hz passband appeared to be shifted from those in the tremor band of 2–8 Hz by ∼20 km, the 20 events they found in the 0.1–1 Hz band were too few, and their location uncertainty too large (the semi-major axis of their 1σ error ellipse is ∼10 km), to confirm the spatial separation of the different sources above the 2σ significance level. Thus, their locations in the two passbands still permit the interpretation that tremor consists exclusively of LFEs, with the longer periods being due to the relative timing of those LFEs.

Data from the Canadian seismic network sometimes have sufficient signal-to-noise ratio to allow the detection of coherent tremor down to 0.5 Hz, near the upper limit of the microseismic band. Figure 1 shows some examples of tremor detected with a method similar to that of Rubin and Armbruster (2013), but using a passband of 0.5–1.25 Hz (referred as “LF” hereafter). These data come from the PGC-SSIB-SILB trio of stations focusing around LFE family 002 of Bostock et al. (2012) (see Appendix B for details of the detection procedure). The upper panel of each subplot shows the LF signal, and the lower panel shows the same time window using a more typical tremor passband (1.25–6.5 Hz; “HF” hereafter). Figures 1a and 1b show one kind of LF signal, where a relatively isolated pulse-like arrival is highly correlated between the three stations in both the LF and HF passbands (after alignment around that pulse). But more commonly, we see a different kind of signal, as in Figures 1c and 1d, where both the LF and HF passbands are less dominated by a single arrival, and where the maximum amplitudes in the HF band need not coincide with those in the LF band.

In this paper we detect and locate tremor in these separate LF and HF passbands. The goal is to place constraints on the origin of the longer-period signal in tremor; that is, signal that occurs at lower frequency than the standard tremor passband. If tremor consists exclusively of LFEs, i.e., if any contribution to the longer-period energy is just due to the timing of LFEs, then contemporaneous HF and LF detections should be almost co-located. In contrast, if LF and HF detections occupy clearly separate locations, it seems more likely that the LF energy has a source other than just the timing of LFEs.

In Section 2 we introduce the data processing steps and provide a brief summary of our analysis method. Then in Section 3 and the Supporting Information we describe how we use LFE templates to correct for the apparent differences in LF and HF source locations that arise just by virtue of filtering the data in the different passbands (what we call the “filtering effect” here).

On the time scale of Episodic Tremor and Slip (ETS) episodes, tremor in multiple subduction zones migrates along strike at speeds of 5–15 km/d over a period of weeks (e.g., Obara, 2002; Ito et al., 2007; Ghosh et al., 2009; Kao et al., 2009; Rubin & Armbruster, 2013). On shorter time scales, Rapid Tremor Reversals (RTRs) propagate several tens of kilometers back along strike over many hours (Houston et al., 2011). Rapid Tremor Migrations (RTMs) propagate 5–20 kilometers over periods of several minutes to a couple of hours (Rubin & Armbruster, 2013; Bostock et al., 2015; Peng et al., 2015). Both RTRs and RTMs usually start near the main tremor front and propagate either back along strike, or along the main front, at speeds tens to hundreds of times faster than that of the main front (e.g., Houston et al., 2011; Rubin & Armbruster, 2013; Peng et al., 2015), although in some regions, perhaps where tremor is more sparse, RTMs appear to initiate at greater distances behind a poorly-defined front (Shelly et al., 2007a; Peng & Rubin, 2017). In Section 4 we show that in general, the LF and HF sources come from roughly the same regions of the subduction interface, so in Sections 4 and 5 we next search for systematic offsets between the locations of contemporaneous LF and HF detections relative to the propagating fronts of RTMs. To guard against possible errors in our empirical filtering effect corrections, we focus on a region of the interface that hosts RTMs.
Figure 1. Examples of tremor detections in the LF (0.5–1.25 Hz) passband using the PGC-SSIB-SILB detector around LFE family 002 of Bostock et al. (2012). The upper panel of each subplot shows the detection in LF passband using a 16-s window. The velocity records at 3 stations are aligned with respect to the main station PGC, by the time offsets that maximize the cross-correlation coefficients. Station PGC is plotted in red, whereas SSIB is in blue and SILB is in black. The lower panel gives the records in HF (1.25–6.5 Hz) at the same time, but aligned independently. The numbers in blue and black are the differences in samples between LF and HF that are needed to align the records at station pairs PGC-SSIB and PGC-SILB, respectively. The black horizontal bars denote the frequency bands in terms of period. The vertical gray area indicates the time window $\delta t_{\text{min}}$ over which the arrival in LF has the most energy as defined in equation B1. (a) and (b) show one kind of LF signal, where a relatively isolated pulse-like arrival is highly correlated between the three stations in both the LF and HF passbands. The HF records are aligned based upon a 4-s segment around that pulse. (c) and (d) show a more common kind of signal, where both the LF and HF passbands are less dominated by a single arrival, and where the maximum amplitudes in the HF band need not coincide with those in the LF band. The HF records are aligned based upon the whole 16-s window.

propagating in nearly opposite directions. We find that the LF energy appears to occur roughly 0.5 km farther behind the propagating fronts of RTMs than the HF energy, whether those fronts propagate to the ENE or to the WSW. This distance is small compared to the location error of individual LF detections, but the result seems to be robust owing to the large number of detections. If this result stands, it suggests that tremor consists of more than just a collection of LFEs, with longer-period energy being produced farther behind the migrating fronts of RTMs, where slip speeds are presumably lower.
2 Data and Method

In this study we use continuous velocity records at permanent stations (3-digit code) and temporary POLARIS stations (4-digit code) from the Canadian National Seismograph Network (CNSN) located on southern Vancouver Island, Canada (Figure 2). Because most P arrivals are difficult to recognize, only horizontal north (N) and east (E) components are used. Data from the POLARIS project, which operated from 2003 to 2006, are down-sampled from 100 Hz to 40 Hz for consistency with the permanent stations. We carry out some pre-processing steps such as linear trend removal and tapering of the daily records, and instrument response removal. We examine 23 days including 3 major ETS periods: 1-5 March 2003, 12-21 July 2004 and 11-18 September 2005. Following Armbruster et al. (2014), we detect and locate tremor using groups of 3 stations. The trio we emphasize here, TWKB-LZB-MGCB (Peng et al., 2015), images the areas surrounding 13 LFE families identified by Bostock et al. (2012) (Figure 2). We also used the 3-station detector PGC-SSIB-SILB (Rubin & Armbruster, 2013) to image the area surrounding LFE family 002 of Bostock et al. (2012), but found too few LF detections using that trio for it to be useful.

Figure 2. Distribution of station detectors on and LFE families beneath southern Vancouver Island that are used in this study. Triangles with a 3-digit code represent permanent stations and squares with a 4-digit code represent POLARIS stations. Stations within the PGC-SSIB-SILB detector are filled in red, those in the TWKB-LZB-MGCB trio are filled in black, whereas unused stations are left open. Blue circles and corresponding numbers are the 13 LFE families identified by Bostock et al. (2012) that were utilized in this study. Their locations are determined via the same method as tremor detections, by inverting the relative arrival times obtained via cross-correlation (in this case of the stacked LFE templates) at three stations using Hypoinverse (Klein, 2002), while forcing the families to be on the slab interface. Dark gray lines contour the slab interface geometry from McCrory et al. (2012) with a 5-km interval. The inset at the bottom right gives an overview of the study region (plate boundary from Bird (2003)).
As in Peng et al. (2015), we rotate the horizontal components at each station into the dominant particle motion direction, after correcting for shear-wave splitting. The splitting parameters and particle motion directions are determined from preliminary LFE templates, made by stacking the broadband N and E records at each station using time windows determined from the LFE catalog of Bostock et al. (2012) (see Appendix A for details). We then refine the templates by cross-correlating the individual LFEs, already corrected for shear wave splitting and rotated into the particle motion direction, prior to stacking (Appendix A). Hereafter, by “template” we mean these split-corrected, rotated, and refined stacks. We use these templates to correct for the apparent differences in travel time from one LFE source to the different stations that arise from the different passbands used (see next section). Data are filtered using the passbands 1.25–6.5 Hz and 0.5–1.25 Hz; we refer to these as the HF (high-frequency) and LF (low-frequency) bands hereafter. Tremor in the vicinity of each LFE family is detected using seismograms that are processed with the splitting parameters and particle motion directions determined from the templates for that particular family, and subsequently filtered into the HF and LF passbands.

To make the detections we employ a sliding time window with a fixed length (4 s for HF; 16 s for LF) and sliding step (1 s for HF; 8 s for LF) to cross-correlate the 3 station pairs (Rubin & Armbruster, 2013) (see Appendix B for details). To determine the general time offsets between stations for each LFE family we first cross-correlate the LFE templates of that family at the 3 stations, and we enforce a maximum possible lag around that expectation when cross-correlating the processed daily seismograms. A successful detection requires the maximum normalized cross-correlation (CC) coefficient, averaged over the 3 station pairs, to be higher than a threshold value (0.4 in HF; 0.35 in LF), and the circuit of three time offsets between the station pairs that achieve this maximum average CC coefficient to be small enough (absolute value less than 1.5 samples at 40 Hz in HF and 4 samples at 20 Hz in LF). Given a successful detection, we then force the circuit of time offsets to be zero, and choose the two independent time offsets that maximize the average CC coefficient for the 3 station pairs (that must again be higher than the same threshold value).

Assuming that tremor is located on or near the plate interface (e.g., Shelly et al., 2006; Wech & Creager, 2007; Brown et al., 2009; La Rocca et al., 2009, 2010; Armbruster et al., 2014), these two independent time offsets are sufficient to determine the source location. To do so we use Hypoinverse (Klein, 2002) with the regional velocity model “Puget Sound P3” (Crosson, 1976), and iteratively force the source to locate at the depth of the plate interface according to the slab model Slab1.0 (McCrary et al., 2012). Because we expect the splitting parameters and dominant particle motion directions to vary spatially, HF detections more than 8 km and LF detections more than 12 km away from their parent LFE family are discarded. Even enforcing this criterion, some detections are connected to 2 or more parent LFE families; in such cases we adopt the single detection with the highest CC value. The catalog that results from merging those based on the 13 LFE families contains 51057 HF detections and 18491 LF detections. Most of the detections occur in spatially and temporally clustered bursts that correspond to rapid tremor migrations (RTMs); however, some detections are isolated temporally or spatially and are likely false positives, while some that occur during RTMs may be mislocated because of cycle skipping.

To analyze the spatial offset between HF and LF tremor detections relative to the propagating fronts of RTMs, we first identify dominant RTMs that have a simple unidirectional migrating pattern using the HF catalog, which has more and more accurately located detections. By projecting both HF and LF detections onto the propagation direction of each migration, as determined by the HF catalog, we are able to analyze the average spatial relationship between contemporaneous HF and LF detections within a
3 Empirical Filtering Effect Correction

Because we are locating tremor detections in different frequency bands, we need to account for the possibility that apparent differences in source location may arise from the different frequency bands used, independent of any actual differences in location. We refer to this as the “filtering effect” in this paper. The filtering effect potentially contains multiple sources of perturbations to the travel time along any source-station path as measured in different passbands. These could include near-source reflections that change the shape of the arriving pulse (e.g., Nowack & Bostock, 2013), physical dispersion caused by intrinsic attenuation in which seismic waves of different frequencies travel at distinct speeds, or other factors we have not thought of. The time offsets we measure by cross-correlation potentially include this filtering effect.

To obtain tremor locations using a single passband, we rely on cross-correlation measurements of the differential travel time between two stations (two such independent measurements from two pairs of stations are required for location). Therefore, to correct for apparent location differences when using two different passbands, we are concerned with the difference of this differential travel time between the two passbands, rather than with the differential travel time between the two passbands at any one station. To estimate this “differential” filtering effect, we assume that the LFE template includes relatively low- and high-frequency energy coming from the same physical location, at least when averaged over many LFEs by stacking. We then filter the template at each station in the LF and HF passbands, to obtain $\Delta t_{ij}^{LF-hf}$, the difference in cross-correlation time offsets between the LFE templates at stations $i$ and $j$ in the LF and HF passbands. To increase precision, for these high signal-to-noise-ratio templates the data are temporarily up-sampled to 80 Hz. Just as when we locate each of our fixed-window-length detections, we cross-correlate the filtered templates at each station pair, and then obtain the time offsets that maximize the average CC coefficient while forcing the circuit of three time offsets $(\Delta t_{12} + \Delta t_{23} + \Delta t_{31})$ to be zero. The filtering and cross-correlation are done separately for the HF and LF passbands. The difference in time offsets for the different passbands represents the empirical filtering effect correction we are seeking.

Figure 3 illustrates this procedure using family 043. Figure 3a shows the normalized 10-s broadband velocity templates stacked according to the timings of LFEs in family 043 at stations TWKB, LZB, and MGCB. Applying a 2-pole, 2-pass Butterworth band-pass filter to those templates using the appropriate corner frequencies results in the HF-filtered (Figure 3b) and LF-filtered (Figure 3c) templates. Figures 3d and 3e show the cross-correlation functions for the 3 station pairs in the two passbands. The open symbols mark the time offsets which maximize the individual CC coefficients (e.g., $\Delta t_{12}$). However, under the constraint $\Delta t_{12} + \Delta t_{23} + \Delta t_{31} = 0$, the accepted offsets, denoted by the closed symbols that maximize the summed cross-correlation of all three station pairs, are not necessarily the same as those from the individual CC measurements. The differences in the constrained offsets at station pairs TWKB-LZB and TWKB-MGCB between LF and HF are $\Delta t_{12}^{LF-hf} = -7$ and $\Delta t_{13}^{LF-hf} = -10$, respectively. This means that if one aligns the HF signals at the two stations, the LF signal arrives 7 samples later at station LZB than TWKB, and 10 samples later at station MGCB than TWKB, at the sampling rate of 80 Hz.

We determine the filtering effect, $\Delta t_{12}^{LF-hf}$ and $\Delta t_{13}^{LF-hf}$, for each of the 13 families using the stacked LFE templates from that family via the same procedure. These $\Delta t_{ij}^{LF-hf}$ are then used to correct the measured LF time offsets for any LF detection tied to the family in question. That is, we adopt the measured delay times in the HF passband without alteration, but subtract $\Delta t_{12}^{LF-hf}$ and $\Delta t_{13}^{LF-hf}$ from the measured CC time offsets.
Figure 3. Filtering effect for detections tied to LFE family 043 using the TWKB-LZB-MGCB detector. (a) shows the stacked broadband velocity templates (sampled at 80 Hz). (b) and (c) are the filtered templates for the frequency bands 1.25–6.5 Hz (HF) and 0.5–1.25 Hz (LF), respectively. (d) and (e) are the normalized cross-correlation functions for the corresponding passbands. The open symbols mark the time offsets which maximize the individual CC coefficients between each of the three station pairs. The closed symbols mark the time offsets that maximize the summed cross-correlation of all station pairs under the constraint $\Delta t_{12} + \Delta t_{23} + \Delta t_{31} = 0$. 
between station pairs, i.e., TWKB-LZB and TWKB-MGCB, for detections made in the LF passband. We find that the filtering effect correction is not sensitive to the length of the window used when cross-correlating the templates (Supplementary Figure S1), suggesting that the cross-correlation functions are dominated by the main S-wave arrival rather than the coda. But for consistency, we adopt the same window length used when detecting and locating tremor (4-s for HF and 16-s for LF), centered roughly at the main arrival. The median of the circuits of the three individual time offsets for the 9 LFE families of primary interest, located in the northwestern portion of our study region (inset to Figure 4), is about 0.25 sample at HF and 1 sample at LF, at the sampling rate of 80 Hz. The filtering effect corrections determined from the same families are typically larger than 5 samples. If we adopt the median circuit of the individual time offsets as a crude empirical measure of the uncertainty in our filtering effect correction, then this uncertainty amounts to only one-fifth of the filtering effect. We note finally that for the 9 LFE families of primary interest, the difference between the median time offsets of contemporaneous HF and (corrected) LF detections tied to that family are often small, compared to the corrections themselves (Supplementary Figures S2 and S3). This is despite the vast majority of these detections do not contribute to the stacks used to determine the filtering effect corrections.

To visualize these time offsets in terms of a spatial offset in the vicinity of each LFE family, we assume there is a HF detection denoted by offsets (0,0), i.e. at the HF location of that family, and then convert the differential offsets $\Delta t_{12}^{hf-hf}$ and $\Delta t_{13}^{hf-hf}$ into absolute locations using Hypoinverse (Klein, 2002), as if they represent a LF detection. The resulting spatial offsets for the TWKB trio are shown in Figure 4. One end of each gray bar (black dot) is the HF location of the LFE family, while the other end is where the LF detection would plot if the filtering effect were not corrected for. The first point to note is that these offsets are quite large – typically more than 5 km for the 9 LFE families in the northwestern portion of the imaged region. This is an order of magnitude larger than the systematic spatial offset we find between the LF and HF detections after correcting for the filtering effect, raising the possibility that modest errors in our empirical filtering effect corrections could significantly influence the results. For this reason, in the analysis to follow we focus on regions of the subduction interface that host RTMs propagating in nearly opposite directions. That is, if the apparent LF–HF offset from the same portion of the fault varies systematically with respect to the fronts of RTMs propagating in opposite directions, it cannot be ascribed to errors in our filtering effect corrections. The second point to note is that the filtering effect corrections are regionally consistent, in that the corrections for nearby families are similar in amplitude and direction. This gives us some confidence that, whatever the source of the filtering effect, our approach to determining it is robust, and, importantly, that the LF–HF offsets of sources that lie between LFE families will not be heavily dependent on which family is used to correct for the filtering effect. We test this assertion more systematically in Section 5.

In the Supporting Information we show that the filtering effect we see cannot be explained by physical dispersion due to spatially uniform, frequency-independent attenuation alone. A uniform shear-wave quality factor $Q_s$ of 200 (Gomberg et al., 2012) results in a filtering effect roughly an order of magnitude smaller than we observe (a few tenths of a sample at the sampling rate of 80 Hz, compared to the observed amplitude of a few samples). Amplitudes of a few samples would require values of $Q_s$ closer to 20, unreasonably low for a path-averaged value. Moreover, in a uniformly-attenuating body LF energy will lag HF energy by an amount that increases monotonically with propagation distance, which is inconsistent with our observations. The phase lag as a function of frequency, as determined from the phase of the cross-spectrum between LFE templates, does not simply manifest as a constant time offset between the different frequency ranges (Supplementary Figures S4 and S5). Therefore the filtering effect measured by cross-correlating the templates in the time domain is likely an average offset between the
Figure 4. Apparent spatial offsets between LF and HF detections due to filtering in the two distinct passbands, plotted for all LFE families. One end of each gray bar (black dot) is the HF location of the LFE family as seen by the TWKB trio, while the other end is where the LF detection would plot if the filtering effect was not corrected for. Symbols for the LFE families and station trios remain the same as those in Figure 2. The tiny blue bar denotes the location difference estimated using the PGC trio for family 002. The long and short axes of the red cross denote the location errors resulting from an error of ±2 samples at 40 Hz in the differential travel time between the station pairs TWKB-MGCB and TWKB-LZB, respectively, for LFE family 043 (black circle plotting at the origin). The bottom right inset plots the components of the filtering effect along the ENE-WSW direction for the 9 LFE families in the northwestern portion of the imaged region.

Note that the large apparent spatial offset between HF and LF sources in Figure 4 can be explained by the small aperture of the TWKB trio in the NW-SE direction (a few km). Figure 4 shows the filtering effect for LFE family 002 using both the TWKB (gray bar) and PGC (blue bar) trios. The difference in differential travel times are comparable (for PGC trio, $\Delta t_{12}^{LF-hf} = -1$ and $\Delta t_{13}^{LF-hf} = -3$; for TWKB trio, $\Delta t_{12}^{LF-hf} = 2$ and $\Delta t_{13}^{LF-hf} = -3$), but the smaller station spacing of the TWKB trio in the NW-SE direction transforms this comparable time difference into a much larger location difference (see also Figure S6 of Peng et al. (2015)). The long axis of the red cross in Figure 4 shows the location error due to an error of ±2 samples at 40 Hz in the differential travel time between the station pair TWKB-MGCB for LFE family 043 (located at [0,0] in the plot), whereas the short axis shows the location error from the same differential timing error between the station pair TWKB-MGCB. Given the location error ellipse, the major orientation of the filtering effects mainly comes from the small aperture of the TWKB-LZB-MGCB trio in the NW-SE direction, rather than a large difference between the two time offsets from the two station pairs, $\Delta t_{12}^{LF-hf}$ and $\Delta t_{13}^{LF-hf}$. 

Different passbands used. The theoretical prediction from physical dispersion also fails to explain the observed phase lag as a function of frequency. Values of $\Delta t_{ij}^{LF-hf}$ of a few samples are more likely due to subtle variations in the shape of the pulse-like arrival, due perhaps to near-source velocity structure.
4 RTM Propagation Directions

The bulk of the detections in our “standard” tremor catalog (HF, in the notation of this study) occur during tremor bursts that, after detection and location, manifest as rapid tremor migrations. The tremor sources occupy patchy regions on the fault, with the same regions being activated by numerous RTMs within each ETS episode (Rubin & Armbruster, 2013; Peng et al., 2015). In both passbands, there are detections that are isolated in space and time; these seem likely to be false positives. For those detections that are clustered in space and time, and therefore likely to be real seismic sources, we find that the LF detections occur at roughly the same time and (after applying the filtering effect corrections) at roughly the same location as contemporaneous HF detections. We find that very few RTMs are visible in the 0.5–1.25 Hz (LF) catalog in 2003, probably because this was the only one of the 3 ETS events to occur during winter (March) when the noise level in the microseismic band is typically higher. From the cumulative density map of the HF and LF tremor catalogs from the ETS episodes in 2004 and 2005 (Figure 5), it seems that regions that generate most HF and LF energy are generally the same. This need not be the case; for example, one could imagine that LF detections might be concentrated in regions adjacent to HF tremor patches, or that RTMs seen in the HF catalog are preceded or followed by LF detections. Although there are a few regions in Figure 5 where there are a relatively larger number of LF detections compared to HF (e.g., a N-S band centered near -2 km E and -5 km N) or vice-versa (e.g., a NNW-SSE band centered near the origin), we do not highlight these regions here for several reasons. These include the larger location error in the LF catalog, possible errors in the filtering effect corrections in regions between the 13 LFE families used to determine them (e.g., the N-S band centered near -2 km E and -5 km N is between the family 043 and 010 whose filtering effect corrections are quite different), and the distortion of locations at distances far away from the TWKB detector (e.g., in the far SE quadrants of these maps). Establishing that these modest variations in location reflect source processes requires additional investigation of the space-time history of both the detections and the overall seismic energy of the two passbands that is beyond the scope of this paper. Here we test the hypothesis that the LF and HF detections have systematic offsets relative to the propagating fronts of RTMs, even while the regions of the fault that produce HF and LF energy are strongly overlapping.

We identify RTMs using the HF catalog because the signal-to-noise ratio is higher within this passband, and because its wider range of frequencies and higher-frequency content permit more accurate relative arrival time measurements (and hence relative locations) even for the same signal-to-noise ratio. We focus on migrations that have a simple unidirectional propagation direction. First, we sequentially group the HF detections that occur less than a threshold time $t_{thr} = 1 \times 10^{-3}$ days after the preceding detection into a tremor burst (Supplementary Figures S6 and S7). Only bursts that have at least $n_{thr} = 15$ detections in both the HF and LF catalogs are included. This automatic temporal clustering algorithm (Wu et al., 2015; Peng & Rubin, 2017) does not ensure that the detected tremor bursts are also clustered in space with a unidirectional pattern. To ensure that this is the case, we examine all the detected bursts in map and space-time plots, and modify the automatically-detected time ranges for $\sim 25\%$ of the bursts (additional details are given in the Supporting Information and some examples are shown in Supplementary Figures S8-S10). Many of these bursts propagate in a well-defined direction for distances that range from 5 to 20 km.

To determine these propagation directions and apply some additional quality-control measures, for each burst we next carry out a regression analysis, which we describe with the help of one migration on 16 July 2004 shown in Figure 6. First, we search over a series of trial propagation directions, onto which all HF detections that occur less than a threshold time $t_{thr} = 1 \times 10^{-3}$ days after the preceding detection into a tremor burst (Supplementary Figures S6 and S7). Only bursts that have at least $n_{thr} = 15$ detections in both the HF and LF catalogs are included. This automatic temporal clustering algorithm (Wu et al., 2015; Peng & Rubin, 2017) does not ensure that the detected tremor bursts are also clustered in space with a unidirectional pattern. To ensure that this is the case, we examine all the detected bursts in map and space-time plots, and modify the automatically-detected time ranges for $\sim 25\%$ of the bursts (additional details are given in the Supporting Information and some examples are shown in Supplementary Figures S8-S10). Many of these bursts propagate in a well-defined direction for distances that range from 5 to 20 km.
Figure 5. Cumulative density map of the HF and LF tremor catalogs from the ETS episodes 2004 and 2005 identified using the TWKB trio. (a) and (b) are the density maps for the HF and LF detections, respectively. A distance cutoff of 12 km from their parent family is used for both LF and HF detections here. Each 200 m $\times$ 200 m (HF) or 500 m $\times$ 500 m (LF) bin is color-coded by the logarithmic number of detections within it. Unfilled bins mean there is only 1 detection inside. The total number of detections is given at the top.

We adopt the minimum-RMSE direction as our default propagation direction because, given the long axis of the location error ellipse, the minimum-RMSE direction is the best option for measuring a reliable spatial offset between the projections of LF and HF detections onto the estimated propagation direction. The HF and LF detections in any RTM would be subject to location errors with the same orientation but different magnitudes, and be skewed more towards the long axis of the error ellipse, regardless of the true propagation direction. For the example in Figure 6a, the minimum-RMSE direction is nearly perpendicular to the long axis of the error ellipse (red cross), with the possible implication that this direction is biased by that location error (the true propagation direction might be more nearly east-west, for example). For this particular migration that does not appear to be the case, however, in that the overall width of the propagating front in the orthogonal direction (the direction of the gray dashed arrow) is larger than the distribution of locations in narrow time windows (orange and darker blue dots, for example, which give a better sense of the upper bound on the location error in that direction). For this example the propagation direction happens to be roughly in the di-
Figure 6. Regression analysis of the RTM detected using the TWKB trio that occurred from 23.4 to 24 hr on 16 July, 2004, labelled as I in Figure 8a. We extend the automatically-determined window to 23.2 hr, to show earlier LF detections which are spatiotemporally consistent with the later ones. (a) and (b) are the RTM in the HF and LF catalogs, color-coded by time. Solid black and dashed gray arrows indicate the propagation direction and its orthogonal. The long and short axes of the red cross show the location errors due to an error of ±1 sample at 40 Hz (a) or 20 Hz (b) in the differential travel time between the station pairs TWKB-MGCB and TWKB-LZB, respectively, for the representative LFE family 043. (c), the projections of HF (gray circles) and LF (cyan circles) detections onto the propagation direction. The gray line is the best-fitting line for HF projections, in which both the slope (propagation speed) and intercept are inverted for. Assuming the LF detections have the same propagation direction and speed, we invert for only the intercept of the cyan line. SE: Standard error of the slope of the HF fitting. Pearson: Pearson correlation coefficient of the HF fitting. SE_{LF}: Standard error of the slope of fitting the LF detections. LF–HF: Difference between the vertical intercepts of the fitted lines. (d), the variation of the resulting weighted root mean squared error (RMSE) and the propagation speed from the regression using each trial direction. The black and blue dashed lines mark the minimum-RMSE and maximum-speed directions, respectively, one of which is bold if chosen as the propagation direction. In most cases the minimum-RMSE direction is preferred, as is the case here.

rection of the short axis of the location error ellipse. This is common; the main tremor front in these slow slip episodes propagates more-or-less along the strike of the subduction zone, and many RTMs propagate along the main tremor front; i.e., close to the dip direction (Peng et al., 2015); which because of the mostly along-dip design of the PO-LARIS array is roughly parallel to the short axis of the error ellipse.
One can imagine scenarios in which the minimum-RMSE direction could lead one astray. For example, if there is a narrow, linear migration of sources (e.g., from east to west) in which the distribution of sources in any small time window is more elongate in the propagation (E-W) direction than the orthogonal (N-S) direction, even after the addition of location errors, then the minimum-RMSE direction will be oriented N-S, perpendicular to the true direction. None of the migrations in our catalog have this character; however, as an additional check for robustness, for each tremor burst we also consider the trial propagation direction that maximizes the slope of the best-fitting line to the projected HF locations; this maximizes the propagation speed (maximum-speed direction hereafter), and it would capture the proper direction in the above hypothetical scenario. In Figure 6d the minimum-RMSE and maximum-speed directions differ by roughly 45°. Using the maximum-speed direction (blue dashed line in Figure 6d) would lead to a LF–HF offset of −1.8 km rather than −1.2 km. Although the “true” propagation direction might be somewhere between the two, if the location errors in the direction of the long axis of the error ellipse are as small as those suggested by the detections with similar colors in Figure 6a, the maximum-speed direction is spurious and the resulting LF–HF offset when projected onto that direction is more prone to errors. In this example the default, minimum-RMSE direction (dashed black line in Figure 6d) is adopted as the propagation direction (black arrow in Figure 6a).

Based on examination of all the HF migrations, we adopt the minimum-RMSE direction as the propagation direction unless the Pearson correlation is increased by at least 0.05 using the maximum-speed direction. This occurs only 5 times in total; one example is shown in Figure C4. There is one exceptional case (Supplementary Figure S11) for which the adopted propagation direction is the minimum-RMSE direction obtained from fitting the LF migration, because neither of the two options based on the HF detections appeared satisfactory. More discussion concerning the selection of eligible migrations and their propagation directions, as well as how the measured LF–HF offset varies with the choice of propagation direction of each migration, is given in the Supporting Information. We also discuss the effect of the choice of propagation direction on the average LF–HF offset in Section 5.

Ultimately we preserve 52 migrations out of the initial 158 tremor bursts determined automatically using the TWKB trio. We order all the 52 migrations spanning the ETS episodes 2004 and 2005 chronologically and refer to them by their sequential numbers. Note that though one RTM in the vicinity of LFE family 002 passes all quality measures, we do not trust it because this region is generally not imaged well due to the possible distortion of locations (e.g., Figure S2 of Peng et al. (2015) and Supplementary Figures S12 and S13 here).

As the LF detections (Figure 6b) are generally fewer in number and have larger location errors, we assume that they have the same propagation direction (black arrow in Figure 6b) and propagation speed (slope of the cyan line in Figure 6c) as was determined for the HF detections. This means that the sole parameter we invert for using the LF locations with the bisquare weighting is the intercept of the cyan line in Figure 6c, and that the vertical separation between the gray and cyan lines reflects the average separation between the LF and HF detections in the RTM propagation direction. This separation is taken to be the difference between the vertical intercepts LF–HF of the fitted lines in Figure 6c, with negative values meaning that on average the LF detections lag the HF detections (the LF detections occur later at a given location, or at a given time are located behind the RTM front as determined by the HF detections).

Note that the migration plotted in Figure 6 includes a 0.2-hr period of time prior to the automatically-determined time window from 23.4 to 24 hr, because the LF detections start earlier than the HF detections in this particular migration (this is seen most clearly in Figure 6c). The earlier LF detections are spatiotemporally consistent with the later LF and HF detections such that they are unlikely to be false positives. The ear-
lier LF energy from 0 to 5 km N also seems to come from a region where there is a relative deficit of HF energy compared to LF (Figure 5). But due to the several reasons mentioned previously, we are not yet willing to conclude that this region produces LF energy only. Another possibility is that when this portion of the fault is active it is active over a larger region, such that longer-period energy correlates better than shorter-period energy, or that because of path effects longer periods correlate better between the 3 stations. Nevertheless, the automated window succeeds in capturing the period with roughy contemporaneous HF and LF detections that should be included in the regressions. For the migration in Figure 6 we use the automated time window (shown by the gray and cyan lines in panel c); we show the longer window only for illustration.

5 Spatial Offsets Between LF and HF Detections

The offset between the LF and HF detections in Figure 6, about -1.2 km, is larger than average. Most offsets are on the order of a few hundred meters, which is smaller than both the estimated location errors of the LF detections in Figure 6b, and the size of the filtering effect corrections in Figure 4. The former difficulty can be surmounted by averaging over enough detections from several migrations, and to a large extent this is the philosophy behind using simple linear fits to the projected tremor locations vs. time in each migration (e.g., Figure 6c). However, averaging many locations will not compensate for any systematic errors in the empirical filtering effect corrections. That these corrections appear spatially coherent (Figure 4) gives us some confidence that they are smoothly varying and reasonably well determined; however, they are large enough that it is not difficult to imagine that modest errors in these corrections could bias the LF–HF offsets in multiple migrations.

To circumvent this potential difficulty, we search for regions of the subduction interface that host migrations propagating in different, and ideally nearly opposite, directions. Our reasoning is that if (for example) LF detections are apparently consistently located to the SW of HF detections for migrations that propagate to the NE, but NE of migrations in the same region that propagate to the SW, then these apparent offsets cannot be ascribed to time-independent errors in the filtering effect corrections, as the same corrections are being applied in both cases.

We examine in map view the propagation direction and areal extent of all 52 recognized migrations as seen in the HF catalog (Supplementary Figure S14a) in order to find regions that host the opposing migrations. The highest density of nearly-oppositely-propagating migrations is located in the northwestern part of our study area, and hence we focus our attention here. The propagation direction of most of these opposing RTMs is close to perpendicular to the orientation of the filtering effect corrections (Figure 4), which fortunately means that the errors in the filtering effect corrections in this direction are the smallest. As the orientation of the filtering effect corrections is (not coincidentally) close to parallel to the long axis of the location error ellipse, the location errors are also the smallest in this direction. We don’t trust the remaining opposing migrations (one SE-NW pair and one SSW-NNE pair; Supplementary Figure S14) since their propagation directions are more nearly parallel to the filtering effect corrections and the long axis of the location error ellipse.

Ultimately, we are concerned with the systematic location offset LF–HF between the HF and LF detections as projected onto the propagation direction of the RTM, so ideally this offset would be relatively insensitive to the choice of propagation direction. However, for many RTMs this is not the case. This is not necessarily problematic; as discussed earlier, for many RTMs we have strong reasons for preferring the minimum-RMSE direction. Nonetheless, in some sense the sensitivity of the measured LF–HF offset to propagation direction is a measure of the robustness of our method. In some cases, large differences in offset result from large differences in the two potential propagation direc-
tions (Supplementary Figure S15); in some cases they come from relatively poor fits to scattered LF detections. If the fit to the LF detections is poor and the difference in LF–HF offset between the two potential propagation directions is small, keeping that migration would not bias the offset estimate; but if the difference in offset is large, we might want to throw that migration out even if we trust one of the potential propagation directions more than the other. To guard against the least robust of our measurements, we discard from the nearly-oppositely-propagating migrations those for which the difference in offset between the two possible directions is larger than 1 km, and for which the standard error of the slope of the linear fitting to the LF detections ($SE_{LF}$) is simultaneously higher than 3 (determined empirically). We recognize that this somewhat arbitrary choice could be a source of bias in the following spatial offset analysis, so later in this section we explore how varying the threshold for discarding migrations based on the difference in LF–HF offset between the two possible propagation directions influences our results.

Eventually, we find 27 eligible RTMs that propagate in the northwestern portion of the study area in nearly opposite directions, and we separate them into WSW-propagating and ENE-propagating groups, with respectively 20 and 7 members. The chosen migrations are illustrated in Figure 7a, where the arrows represent the propagation direction and extent of the HF migrations in the WSW-propagating group (gray) and ENE-propagating group (black). Each solid circle represents the median location of the HF detections, color-coded by the sequential number of that migration. As an additional check, Figure C5 plots the cumulative density map of the HF and LF detections belonging to the migrations in each of the ENE- and WSW-propagating groups. To a large extent these opposing migrations occupy the same portion of the fault, so any errors in the filtering effect corrections should affect the LF–HF offsets of the WSW- and ENE-propagating groups similarly.

Within each group, the statistics of the migrations are combined as follows. For each RTM, we take the vertical distance from each LF detection to the fitted HF line (see Figure 6c) as the spatial offset (LF–HF) in the propagation direction. To place the offsets from the two different groups into the same geographical coordinate frame, we need to assign a common sign convention to these offsets. We define an offset to be positive if the LF detection is located ENE of the linear fit to the HF detections at that time, so that (for example) if on average the LF detections lag the HF detections, the average offset would be positive for migrations to the WSW, as in Figure 6c, and negative for migrations to the ENE. We then combine all the offsets for each of the WSW- and ENE-propagating groups into a single histogram for that group. Each datum (that is, each distance measurement from an LF detection to the fitted HF line for that RTM) contributes to the histogram by an amount equal to its weight (0–1) assigned by the bisquare regression for the intercept of the LF migration.

The resulting histograms for the two groups are shown in the lower panel of Figure 7b, with the number of measurements for each group indicated. The height of each histogram is normalized to its probability density function (PDF) estimate. The vertical dashed lines represent the (bisquare-weighted) sample means of the offsets for the WSW- and ENE-propagating groups, which are about 570 m and −350 m, respectively. The error bar centered at the sample mean is the 99% confidence interval of the mean, which is computed following equation 4.46b of Bendat and Piersol (2011). The upper panel of Figure 7b shows a zoom of these non-overlapping confidence intervals. We do not interpret the width of these distributions because we suspect that this width is dominated by the LF location errors (a Gaussian fit to the data gives a weighted standard deviation $\sigma$ of $\sim$ 2 km). However, if one treats the samples in these histograms as independent (a point we return to below), it is clear that the average location difference between the LF and HF detections is significant. Moreover, since these opposing migrations occupy roughly the same portion of the fault (Figure C5), any error in the empir-
ical filtering effect corrections would impart the same shift to both distributions in Figure 7b. Consequently, even if the mean offset of either group is subject to uncertainty larger than the indicated confidence intervals, the difference between the two means is largely independent of any error in the filtering effect correction.

Figure 7. Significance of the difference between the mean (LF–HF) offsets of the WSW- and ENE-propagating migration groups in the northwestern portion of our study area. (a) shows the selected RTMs, where the black and gray arrows represent the propagation direction and extent of the migrations in the ENE-propagating group and WSW-propagating group, respectively. Each solid circle represents the median location of the HF detections, color-coded by the sequential number of that migration. The lower panel of (b) plots the histograms of the LF–HF offsets for the WSW- (cyan) and ENE-propagating (orange) groups. The height of the histogram is normalized to its PDF estimate. The vertical dashed lines represent the (bisquare-weighted) sample means of the offsets for the two groups, which are about 570 m and −350 m, making a difference of 920 m. The error bar centered at the sample mean is the 99% confidence interval of the mean. The upper panel of (b) shows a zoom of these non-overlapping confidence intervals.

To further quantify the significance of the non-overlapping confidence intervals in Figure 7b, we carry out a Student’s t-test (Press et al., 2007) on the two distributions assuming the true population variances are unknown (although they appear to be quite similar). The probability (p-value) of the null hypothesis that the two distributions have equal means, so that the current difference in means arises just by chance (again assuming independent measurements), is $1.7 \times 10^{-15}$. We also design a random sampling test of the data, under the assumption that the current data PDFs closely resemble the true PDFs of the underlying populations. For each of the ENE- and WSW-propagating groups, we draw an integer number of samples equal to the effective (that is, bisquare-weighted) number of data samples from that group. These samples are drawn randomly both from Gaussian fits to the data distributions, and from the data PDFs themselves. In each case we shift the distributions such that their means are zero. The resulting difference in the means of the two random sample distributions are noted, and we repeat this process 1000 times, to see how often the difference from the random sampling is at least as large as
that of the original data. As expected, the resulting frequency is 0 for both the Gaussian-fitted data PDF case and the direct data PDF case.

A summary of the spatial offset (LF–HF) from the linear regression to each RTM is given in Figure 8. The migrations in Figure 7, chosen because they occupy essentially the same portion of the fault but with opposing propagation directions, are illustrated in Figure 8a. Each offset is denoted by a circle indicating the mean value (difference in intercepts between the LF and HF detections), bounded by the error estimate representing the 95% confidence interval from the residual distribution of the regression to the LF detections. The number of detections in both the HF and LF passbands (HF:LF) are given on the right, with more detections providing more constraints to the regression. As can be seen, the offsets of most individual migrations in the same group (ENE or WSW) have the same sign as the mean offset of the combined detections.

Although we only include temporally overlapping windows in each of our HF or LF catalogs if the two windows don’t share the same strongest arrival, these catalogs nonetheless include some detections from windows that are half-overlapping. Because the confidence interval, Student’s t-test and random sampling test all assume the underlying measurements to be independent random variables, we next apply the same analysis to catalogs that include only non-overlapping windows. The corresponding distributions of the WSW- and ENE-propagating groups and the difference in the mean LF–HF offsets between the two groups are shown in Figure 9. It reveals that using independent detections changes the difference in means only slightly, from about 920 m in Figure 7b to 970 m in Figure 9b. Though the width of each confidence interval increases due to the smaller sample size, the two confidence intervals are still well separated. In terms of the significance of the difference, the $p$-value from the t-test is $1.8 \times 10^{-10}$ and the frequency from the random sampling test is still 0.

The largest source of inter-dependence of our LF–HF measurements comes from the choice of propagation direction. For example, choosing 2 directions that differ by 180 degrees flips the sign of every leading or lagging measurement for that migration. One could imagine that choosing the maximum-speed direction over the minimum-RMSE direction (determined from the HF detections) as the propagation direction for 5 migrations (e.g., Figure C4) could influence the separation of the confidence intervals in Figure 7b. To test this possibility, we re-select the nearly-oppositely-propagating RTMs after adopting the minimum-RMSE direction (determined from the HF detections) as the propagation direction for all 52 migrations. This results in 5 migrations in the ENE-propagating group and 18 in the WSW-propagating group, and increases the separation of the 99% confidence intervals by $\sim 300$ m (Supplementary Figure S16). We also note from Figures 7b and 9b that LF sources lag the HF sources for both the ENE- and WSW-propagating RTMs by $\sim 500$ m. Therefore, the aforementioned 1-km threshold for the absolute difference in offset we use to decide which migrations should be considered separately may be too high. In Supplementary Figure S17 we show histograms that use only opposing migrations for which the absolute difference in the spatial offset LF–HF between the minimum-RMSE and maximum-speed directions is smaller than 500 m (Supplementary Figure S18). This set includes 5 migrations in the ENE-propagating group and 11 in the WSW-propagating group, and decreases the separation of two means by $\sim 200$ m, but the 99% confidence intervals of the means remain separated.

The inset to Figure 4 shows that although the ENE-WSW component of the filtering effect corrections are largely consistent across the region of opposing ENE-WSW migrations, families 017, 043, 068, and 099 differ from the “consensus” of $\sim 400–600$ m by roughly $\pm 500$ m. This is a significant fraction of the difference between the mean LF–HF offsets of the WSW- and ENE-propagating groups. If any of these corrections is spurious, and the associated LFE family contributes many more detections to either the ENE- or WSW-propagating migrations than to the other, it could potentially bias the difference in mean LF–HF offsets between the two groups. We find that this is not
Figure 8. Summary of the spatial offset (LF–HF) from the linear regression to each RTM identified using the TWKB trio. (a) includes the chosen migrations with nearly opposite propagation directions contributing to the histograms in Figure 7. Each offset is denoted by a circle indicating the mean value, bounded by the error estimate representing the 95% confidence interval from the residual distribution of the LF regression. Migrations are filled in different colors by their propagation directions. The number of detections in both the HF and LF passbands (HF;LF) are given on the right. (b) summarizes the unused RTMs. Since SE-propagating and NW-propagating RTMs also exist, the sign of the offset is set to be negative if on average the LF detections lag the HF detections in the propagation direction. Note that migration #40 has an unrealistic mean offset of 15 km and an error of ±7 km, which results from the scattered LF detections. Migration #24 has an extreme error of ±5 km for the same reason. The migration marked I is shown in Figure 6 and migrations II, III, IV are shown in Figures C1-C3 in Appendix C.

The case. First, plots of the proportion of detections in every migration tied to a particular LFE family (one plot for each family) show that there is no LFE family that contributes much more to one of the ENE- or WSW-propagating groups than the other (Supplementary Figure S19). Second, plots of the average spatial offset (LF–HF) of every migration vs. the proportion of detections in that migration tied to a particular LFE family (one plot for each family) show no strong correlation, except for family 068 (Supplementary Figure S20). However, roughly the same positive correlation applies to both the ENE- and WSW-propagating groups for this family, which means that the mean LF–HF offsets from both groups would increase as the proportion increases, but the difference in offsets between the two groups would persist. Finally, we re-run our detection...
Figure 9. Same as Figure 7, but only the LF detections from non-overlapping detecting windows are involved.

and location procedure while eliminating (one at a time) each of the possibly anomalous LFE families 017, 043, 068 and 099. This reduces the number of detections in each migration only slightly, because detections seen by one family are often seen by at least one other. We find that the mean LF–HF offsets are essentially unaffected by this procedure (Supplementary Figures S21-S24).

6 Discussion

We have shown that LF detections seem to consistently locate differently from HF detections, relative to the propagating fronts of RTMs, but whether LF detections lag or lead HF detections needs more discussion. In both Figures 7b and 9b, LF detections seem to lag HF detections on average by anywhere from 350 to 600 m. Thus a 500-m error in the filtering effect correction would imply that for RTMs propagating in one direction the LF sources would be roughly coincident with the HF sources, while for those propagating in the other they would lag by ~1 km. A 1-km error would imply that the LF sources would lead the HF by roughly 0.5 km in one propagation direction, but lag by 1.5 km in the other. It seems hard to rationalize such behavior, and given the magnitudes and consistency of the filtering effect corrections among the different families in the inset to Figure 4, we prefer the interpretation that the LF sources lag the HF sources in the propagation direction for both the ENE- and WSW-propagating RTMs by ~500 m. This would require an error in the filtering effect corrections of ~100 m, which seems reasonable given the consistency of the corrections in Figure 4. However, we note that the individual migrations in the two groups differ in spatial extent, time duration, number of detections, propagation (and perhaps slip) velocity, etc., so the mean offsets of the two groups are not necessarily the same. But for modest errors in the filtering effect corrections the LF signals would always lag the HF signals in both propagation directions.

Figure 8b shows the spatial offset (LF–HF) for the other unused RTMs. As this group contains RTMs propagating in various directions, we set the sign of the offset to be negative if on average the LF detections lag the HF detections in the RTM propa-
vation direction. Generating a histogram for this set (Figure C6), as was done in Figure 7b, indicates that on average the LF detections lead the HF detections by about 280 m. However, as we do not have oppositely-propagating migrations in this set, the results could be made consistent with those of Figure 7 if the filtering effect corrections for these migrations are in error by 780 m. This necessary error is several times larger than that required to make Figure 7b symmetric, but as this set mostly includes migrations more parallel to the filtering effect corrections, which can be 10 times larger than the component in the ENE-WSW direction (Figure 4), it is reasonable that filtering effect correction errors would be larger for this set.

If one accepts that lower-frequency tremor signals lag the higher-frequency signals in the propagation direction of RTMs, the simplest interpretation is that the seismic signal emanating from regions closer to the propagating slip front is enriched in high frequencies relative to regions farther behind. In a Barenblatt cohesive zone crack model (Barenblatt, 1962), slip speeds rapidly reach a maximum close to the rupture front and decay more slowly behind. Thus any process in which the frequency of velocity fluctuations increases with slip speed could account for a decrease in source frequency behind the rupture front.

The main goal of this research has been to investigate the source of the coherent LF signals in tremor. We hypothesize that if the lower-frequency signals come from the overlapping of higher-frequency LFEs that are randomly distributed in time, then the LF and HF signals would be nearly co-located. Alternatively, if the lower-frequency signals are generated from longer-period sources other than higher-frequency LFEs, this could manifest as a spatial offset between the two. The statistical tests described above support the consistent difference in average spatial location between contemporaneous LF and HF detections (LF–LF) during rapid tremor migrations. This seems unlikely to arise from higher-frequency LFEs that are distributed randomly in time and space, in the moving reference frame of a propagating RTM front. However, it remains to be established whether some non-uniform distribution of higher-frequency LFEs behind the RTM front could give rise to an apparent offset between contemporaneous HF and LF sources (for example, stronger but more temporally isolated higher-frequency LFEs near the front, simultaneously with temporally-overlapping but weaker LFEs farther behind the front). This possibility could be explored with synthetic seismograms made up of non-uniformly distributed LFE templates in future work. Barring this possibility, our results suggest that the LF (0.5–1.25 Hz) signals have a source which is indeed distinct from just the temporal overlapping of typical higher-frequency (1.25–6.5 Hz) LFEs. One possibility is that the frequency of seismic radiation produced at a given location is not fixed by time-invariant fault-zone properties, but that the same location is capable of producing signals of varying frequency, depending (e.g.) upon the current average or background slip speed. An alternative is that spatially distinct LF and HF sources are interspersed on the subduction interface. Given the strongly overlapping distribution of LF and HF sources in Figure 5, this would require mixing of these discrete regions on a finer scale than our location error, and on average the LF sources would have to be triggered farther behind the propagating RTM front (requiring greater total slip, perhaps).

7 Conclusions

In this paper we detect and locate tremor signals beneath southern Vancouver Island separately in relatively high-frequency (1.25–6.5 Hz; HF) and low-frequency (0.5–1.25 Hz; LF) bands, focusing on the three-station detector TWKB-LZB-MGCB. We hypothesize that if tremor consists entirely of LFEs, so that the lower-frequency signal in tremor comes just from the non-uniform timing of higher-frequency (∼2 Hz) LFEs, contemporaneous LF and HF signals would be nearly co-located. Alternatively, if the LF signals have a source distinct from overlapping higher-frequency LFEs, a spatial offset between the two sources might be present. Overall, we find some subtle differences in
source locations between the HF and LF catalogs (Figure 5). However, owing to uncertainty in our empirical filtering effect corrections (differences in relative arrival times obtained by cross-correlation that arise just because of the different passbands applied), and to possible spatial variability in the coherence of HF and LF seismograms between the various stations (due to either source-station path effects or to spatial variability in the typical spatial extent of source regions active at one time), we think it is premature to interpret these differences in terms of different fixed locations for HF and LF sources.

Instead, we identify 27 rapid tremor migrations in the northwestern portion of our study region that propagate in nearly opposite directions (20 to the WSW and 7 to the ENE), and examine the locations of LF and HF sources relative to the propagating front. Focusing on oppositely-propagating migrations greatly reduces the influence of any errors in our filtering effect corrections. The ENE-WSW trend also has the smallest location errors and filtering effect corrections (this is not due to chance alone – the oppositely-propagating RTMs migrate mostly along the main slow slip front, which is oriented roughly parallel to the dip direction of the subduction zone, as was the POLARIS array). We find that LF detections consistently lag HF detections, by about 500-600 m for migrations propagating to the ENE and about 300-400 m for migrations propagating to the WSW. Although this LF–HF offset is smaller than the location errors of our LF catalog, given the more than 1000 LF detections the result appears to be robust. Our preferred interpretation is that the LF sources lag the HF sources in both propagation directions by roughly the same amount (∼500 m), which would require a ∼100-m error in the ENE-WSW component of our filtering effect correction.

This persistent spatial offset suggests that the LF (0.5–1.25 Hz) signals have a source distinct from just the temporal overlapping of typical higher-frequency (1.25–6.5 Hz) LFEs. One interpretation is that a given location on the subduction interface, rather than generating a signal of fixed frequency tied to time-invariant fault-zone properties, instead radiates seismic energy at a frequency that depends upon the loading conditions (e.g., that decreases as the local average sliding speed decreases). Such a process seems consistent with so-called LFEs and tremor being manifestations of the same broadband stochastic process, as suggested by (Ide, 2008). Alternatively, relatively high-frequency and low-frequency sources can be mixed in the fault zone at a scale finer than our spatial resolution, with the lower-frequency sources being triggered farther behind the propagating front of tremor migrations.

Appendix A Shear-wave Splitting Corrections

As demonstrated by Bostock and Christensen (2012), there is significant crustal anisotropy beneath southern Vancouver Island, resulting in spatially-varying shear-wave splitting and polarization. Using a method similar to that of Peng et al. (2015), we empirically calculate the split times and fast polarization directions for each LFE family, and assume that these are representative of the splitting parameters in the surrounding region. These splitting parameters are determined via a grid search to maximize the cross-correlation (CC) coefficient between the fast and slow components of the LFE templates. For every LFE family at each station, we first obtain a preliminary stack of the broadband N and E component seismograms using time windows determined from the LFE catalog of Bostock et al. (2012). To maintain consistency with our detection/location method, we then filter these broadband stacks from 0.5–6.5 Hz. Next, we rotate and cross-correlate these N and E templates from 0–175 degrees, in 5-degree increments, to find the angle that maximizes the maximum CC coefficient at that station. We note this angle as the slow or fast direction, depending on the sign of the differential travel time between the rotated N and E templates, and the differential travel time resulting from that angle as the split time. For this cross-correlation we use only the 1.5-s segment containing the main dipole arrival to reduce interference from the S-wave coda. We recognize
the shear splitting as significant only if the split time is at least 2 samples at 40 Hz (0.05 s).

Figure A1 shows the obtained split times and fast wave directions for all LFE families using the TWKB detector. The result seems reliable, in that the split times and fast wave directions for different families at the same station vary smoothly in space. Moreover, the variation of these parameters at different stations for the same family is small. Although the adopted families are not exactly the same and locations of some families have been updated, our result is consistent with that in Figure S3 of Peng et al. (2015). We correct for the shear-wave splitting by aligning the fast and slow components using the split time and rotating them back to N and E.

Next, we determine the optimal shear-wave particle motion directions. We again rotate these (now split-corrected) N and E templates from 0–175 degrees in increments of 5 degrees, and compute the ratio of energy (sum of the squared amplitude) between the two components and find the angle at which this ratio reaches its maximum. At this angle we refer to the direction of maximum energy as the “optimal” orientation; this is the inferred shear-wave particle motion direction. We refer to the corresponding direction of minimum energy as the “orthogonal” orientation. Following this procedure, we are able to transform the raw N and E seismograms at each station into one optimal trace for each LFE family, where the shear-wave splitting is corrected for and most of the shear energy is concentrated. For the same LFE family, we then stack the optimal traces to obtain a preliminary template using time windows determined from the LFE catalog of Bostock et al. (2012). Because the member LFEs do not all have the same hypocenter, we refine the template by shifting each LFE by up to ±10 samples at 40 Hz (0.25 s) to maximize the CC coefficient with the preliminary stack, and then re-stack those slightly time-shifted LFEs. To determine the approximate travel-time offsets between the different stations for sources located in the vicinity of each LFE family, we cross-correlate the split-corrected optimal templates at stations with that at the reference station (e.g., TWKB for the TWKB detector).

Figure A1. Split times and fast wave directions determined at each station of the TWKB-LZB-MGCB detector for the 13 LFE families (dark gray dots) used. The orientation and length of each light gray bar denote the fast shear-wave direction and the split time between the fast and slow components. Triangles denote permanent stations and squares denote temporary stations. Each examined station is filled in black.

Appendix B Tremor Detection in HF and LF passbands

Many studies have employed a “cross-time” method to locate LFEs and tremor, meaning that the fundamental correlation measurement is between two different time
windows at one station. The cross-correlation can be between the target time window
and either a nearby previously-identified LFE (Shelly et al., 2007b), or a stack of many
nearly co-located LFEs (e.g., Brown et al., 2009; Shelly, 2010; Bostock et al., 2012). However,
this method will result in detected time windows that are highly coherent with the
template. As we are wondering if there are any other signals besides the 0.5-s LFEs in
tremor, prescribing any template for detection may miss longer-period signals. In con-
trast, a “cross-station” method, first proposed by Armbruster and Kim (2010) and fur-
ther developed in Rubin and Armbruster (2013), Armbruster et al. (2014) and Peng et
al. (2015), compares waveforms of the same time window (after accounting for travel-
time differences) at two widely separated stations, by taking advantage of the coherence
in tremor records across stations. Cross-station methods perform well when the response
to an impulsive source at each contributing station is dominated by the direct S-wave
arrival rather than its coda or any converted phases. In such cases the method effectively
cross-correlates the source-time function in each time window, provided the sources are
nearly co-located so that the differential travel times to the various stations are roughly
constant.

As in Peng et al. (2015), we obtain trial tremor catalogs associated with each adopted
LFE family by rotating the N and E component waveforms at each station to obtain a
single-component seismogram, that represents our best guess for the shear-wave parti-
cle motion direction after correcting for shear-wave splitting. These directions and splitt-
ing parameters are determined for each LFE family-station pair as described in Appendix
A, using the passband 0.5–6.5 Hz. Consistent with the generally small differences be-
tween nearby families, we assume that these parameters vary slowly over the fault, so
that they are useful for sources located within several kilometers of the associated LFE
family. The seismograms are then filtered using the passbands 1.25–6.5 Hz (HF) and 0.5–
1.25 Hz (LF).

To make detections, we employ a sliding time window with a fixed length (4 s for
HF; 16 s for LF) and sliding step (1 s for HF; 8 s for LF) to cross-correlate the three sta-
tion pairs (Rubin & Armbruster, 2013). With the general time offsets between stations
for signal coming from the vicinity of each LFE family as determined in Appendix A,
we enforce a maximum possible lag around that expectation when cross-correlating the
processed daily seismograms. The maximum allowed time lag is ±14 samples (0.35 s)
for the HF catalog using the TWKB trio.

For the HF catalog, a successful detection requires the maximum cross-correlation
(CC) coefficient, averaged over the three station pairs, to be higher than 0.4, and the cir-
cuit of three time offsets between the station pairs that achieve this maximum \( \text{OFF}_{\text{max}} \)
to be less than 1.5 samples (0.0375 s) in magnitude. Both thresholds were set by trial
and error. In principle, they should be strict enough to avoid those presumed “false pos-
itives” that are spatially or temporally isolated, without reducing much the total num-
ber of clustered detections, which are likely to be real seismic sources. Given a success-
ful detection, we interpolate the offsets to a quarter sample and then force the circuit
of time offsets to be zero, and choose the two independent time offsets that maximize
the average CC coefficient for the 3 station pairs (that must again be higher than 0.4).

As a third quality-control measure to help weed out false positives, we require that
the ratio of energy on the optimal component to that on the orthogonal component, \( R_{o/o} \),
be larger than 3 at the time of the strongest “arrival” in the window (Peng et al., 2015).
To identify this arrival, we first multiply the aligned seismogram pairs in each window
point-wise, and average over the three pairs. For velocity seismograms this is a proxy
for the coherent radiated energy rate in the analyzed passband, and we denote it as \( \dot{E}' \)
(Rubin & Armbruster, 2013):

\[
\dot{E}'(t) = \frac{S_1(t)S_2(t_2') + S_1(t)S_3(t_3') + S_2(t_2')S_3(t_3')}{3},
\] (B1)
where the subscripts 1, 2 and 3 denote the stations TWKB, LZB and MGCB in the TWKB trio, $S(t)$ is the seismogram, and $t'$ represents the time offset between the arrival at station 2 or 3 and station 1. The time that reaches the maximum $\dot{E}'$ is noted as the most energetic arrival of the detected window. We determine $R_{o/o}$ over a time window that extends over $\pm \delta t_{\text{min}}$ from this most energetic arrival, via

$$
R_{o/o} = \frac{\sum_{2 \delta t_{\text{min}}} \left( S_{1 \text{opt}}(t) + S_{2 \text{opt}}(t') + S_{3 \text{opt}}(t') \right)}{\sum_{2 \delta t_{\text{min}}} \left( S_{1 \text{ort}}(t) + S_{2 \text{ort}}(t') + S_{3 \text{ort}}(t') \right)},
$$

(B2)

where the subscripts “opt” and “ort” denote the optimal and orthogonal components, respectively. We take $\delta t_{\text{min}}$ to be the approximate duration of the dipole in the stacked templates, 0.5 s in HF (e.g., Figure 3b).

To avoid double-counting of the same event because of the overlapping detecting windows, we do not preserve all detected windows. We accept both of two overlapping windows only if their most energetic arrivals are separated at least by $\delta t_{\text{min}}$, otherwise we only preserve the one with a larger average CC coefficient. This may admit two sources separated more than 0.5 s, or a single source twice if it radiates longer than 0.5 s.

As the LF detections invariably have a lower location resolution due to the widening of the waveform, we down-sample the seismograms from 40 Hz to 20 Hz. Due to a generally lower signal-to-noise ratio and a narrower passband (a factor of 2.5 between the high and low frequency limits rather than the factor of 5.2 for the HF band), the LF catalog is also more prone to cycle skipping. To guard against the possibility that LF sources lie outside our maximum allowable time lag but, via a cycle skip, have a secondary CC maximum that places them within our region of interest, we increase the time lag over which we search for the maximum CC value to $\pm 34$ samples, but retain in the catalog only those detections with lags up to $\pm 14$ samples. The difference of 20 samples is approximately the expectation for a single cycle skip. For 16-s windows, threshold values of $CC_{\text{min}} = 0.35$ and $OFF_{\text{max}} = \pm 4$ samples at 20 Hz were deemed suitable. As the width of the dipole-like arrival is larger at lower frequencies, (e.g., Figure 3c), $\delta t_{\text{min}}$ is set to be 1.1 s. For the LF catalog, $R_{o/o}$ must exceed 1.5.

Because the splitting parameters and dominant particle motion directions appear to vary smoothly in space, HF detections up to 8 km and LF detections up to 12 km from their parent LFE family are permitted. Adopting this criterion, some detections are common to 2 or more LFE families. The final HF and LF catalogs are made by merging the detections tied to each LFE family. In the event that a detected window is common to more than one family (meaning more than one set of splitting and rotation parameters), we choose the one that gave rise to the largest CC value. As station TWKB is the reference station for all LFE families, the time limits of all windows for the catalogs tied to all LFE families are identical at TWKB, which makes identifying duplicate detections straightforward. The catalog that results from merging those based on all the 13 LFE families using the TWKB detector contains 51057 HF detections and 18491 LF detections (23 days, 1-5 March 2003, 12-21 July 2004 and 11-18 September 2005).

Appendix C  More RTM Examples

In the main text, we showed one migration detected using the TWKB trio to demonstrate the regression analysis. Here we show 2 more examples (Figures C1-C2) from the WSW-propagating group and 1 example (Figure C3) from the ENE-propagating group, that are labelled in Figure 8a. We also show one migration (Figure C4) from the ENE-propagating group in Figure 8a where we choose the maximum-speed direction (in HF) as the propagation direction, rather than the default minimum-RMSE direction. All the other oppositely-propagating migrations included in Figure 8a are shown in Supplementary Figures S26-S46.
In Figure C5 we plot cumulative density maps of the HF and LF detections belonging to the migrations of the ENE-propagating and WSW-propagating groups in Figure 8a. These maps show that to a large extent the migrations of the ENE- and WSW-propagating groups occupy the same portion of the fault. In Figures C5b and C5d, a few tens of LF detections from the WSW-propagating group are located in the vicinity of LFE family 002. LF detections in this area are nearly absent from the ENE-propagating group. These detections are from migrations (e.g., migration III in Figure C2) whose majority lie in the northwestern portion of the study region. Excluding the spatial offset (LF–HF) measurements tied to those LF detections from the histograms in 7b does not substantially alter the mean offsets and their difference (see Supplementary Figure S25) because the number of LF detections in this vicinity is very small compared to the majority.

Finally, we show in Figure C6 a single histogram of the spatial offset (LF–HF) measurements from the unused RTMs in Figure 8b. As this group contains RTMs propagating in various directions, we set the sign of the offset to be negative if on average the LF detections lag the HF detections in the RTM propagation direction. The result indicates that on average the LF detections lead the HF detections by about 280 m. However, as discussed in the main text, it is likely that the filtering effect corrections are significantly less accurate for these migrations, and as they are not migrating in nearly opposite directions, for these RTMs we have no means of circumventing such errors.

**Figure C1.** One RTM occurring from 21.2 to 21.7 hr on 13 September, 2005 from the WSW-propagating group detected using the TWKB trio. Symbols are the same as in Figure 6.

**Acknowledgments**

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Figure C2. One RTM occurring from 20.4 to 22 hr on 14 September, 2005 from the WSW-propagating group detected using the TWKB trio. Symbols are the same as in Figure 6.

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Figure C3. One RTM occurring from 14.9 to 16.1 hr on 16 July, 2004 from the ENE-propagating group detected using the TWKB trio. Symbols are the same as in Figure 6.


Figure C4. One RTM occurring from 10.3 to 10.7 hr on 13 September, 2005 from the ENE-propagating group detected using the TWKB trio. For this RTM we use the maximum-speed direction as the propagation direction, because the Pearson correlation of the fit to HF detections using this direction is higher by 0.15 than that using the default minimum-RMSE direction, which is nearly N-S, and the maximum-speed direction also is visually better. Symbols are the same as in Figure 6.


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Figure C5. Cumulative density map for the HF and LF detections belonging to the migrations in each of the ENE- and WSW-propagating groups in Figure 8a. (a) and (b) are the density maps for the HF and LF detections in the ENE-propagating group, respectively. (c) and (d) are the density maps for the HF and LF detections in the WSW-propagating group, respectively. Symbols are the same as in Figure 5.


Figure C6. Histogram of the spatial offset (LF–HF) measurements from the LF detections of the unused RTMs in Figure 8b. (a) shows the propagation direction and extent of these migrations. Symbols are the same as in Figure 7a. The lower panel of (b) plots the histogram of the LF–HF offsets. The vertical dashed line represents the (bisquare-weighted) sample mean of the offsets, which is about 280 m. The error bar centered at the sample mean is the 99% confidence interval of the mean. The upper panel of (b) shows a zoom of the confidence interval.


Supporting Information for “The Spatial Relationship Between Contemporaneous Tremor Detections in Relatively Low- and High-Frequency Bands”

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1. Texts S1 to S2
2. Figures S1 to S46

Introduction

This supporting information contains two sections in detail on the filtering effect caused by physical dispersion and the identification of rapid tremor migrations that are referred to in the main text, and 46 supplementary figures.

Figure S1 shows the variation of differential travel time with the length of the window used, at different station pairs, when cross-correlating the templates of each LFE family filtered under the LF passband (0.5–1.25 Hz). Figure S2-S3 shows the median difference in detected time offsets, after correcting for the filtering effect, for station pairs TWKB-LZB (12) and TWKB-MGCB (13), between contemporaneous LF and HF detections from all migrations, or only the WSW- and ENE-propagating migrations, that are tied to each of

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the 9 LFE families of our primary interest. Figures S4-S5 show the phase lag (normalized by $\pi$) as a function of frequency, as determined from the phase of the cross-spectrum between LFE templates at the three station pairs that are pre-aligned in the HF (1.25–6.5 Hz) passband, for LFE families 002 and 144. Figure S6 shows the separation in time between each HF detection and its preceding detection in each ETS episode. Figure S7 shows the tremor bursts determined automatically in each ETS episode. Figures S8-S10 show tremor burst examples whose time range is modified. Figure S11 shows the only migration for which neither the minimum-RMSE direction nor the maximum-speed direction from the linear regression to the projected HF detections seem satisfactory, but the linear regression to the LF detections appears to give a satisfactory estimate.

Figures S12-S13 show an example of a migration detected by both the TWKB and PGC trios that reveals the distortion of locations in the vicinity of LFE family 002, the far SE corner of our study region, when using the TWKB trio. Figure S14 shows the propagation direction and extent of all the 52 recognized migrations in HF detected using the TWKB trio. Figure S15 shows the absolute difference in the resulting spatial offset (LF–HF) between the minimum-RMSE and maximum-speed directions, vs. the absolute difference (in degrees) between the two directions, for the 52 migrations identified. Figure S16 shows the significance of the difference between the mean LF–HF offsets of the WSW- and ENE-propagating migration groups when the minimum-RMSE direction (fitting HF detections) is adopted as the propagation direction for all 52 migrations. Figure S17 shows the significance of the difference between the mean LF–HF offsets of the WSW- and ENE-propagating migration groups, when we adopt only the migrations for which the absolute difference in the resulting LF–HF offset between the minimum-RMSE and
maximum-speed directions is less than 500 m. Figure S18 shows the absolute difference in the resulting spatial offset (LF–HF) between the minimum-RMSE and maximum-speed directions, vs. the absolute difference between the two directions, for the 27 migrations that propagate in the nearly opposite directions in Figure 8a of the main text.

Figure S19 shows the proportion of detections in every migration tied to a particular LFE family. Figure S20 shows the average LF–HF offset in every migration vs. the proportion of detections in that migration tied to a particular LFE family. Figures S21-S24 show the significance of the difference between the mean LF–HF offsets of the WSW- and ENE-propagating migration groups when eliminating (one at a time) each of the possibly anomalous LFE families 017, 043, 068 and 099. Figure S25 shows the significance of the difference between the mean LF–HF offsets of the WSW- and ENE-propagating migration groups when the few tens of LF detections from the WSW-propagating group in the vicinity of family 002 are excluded. Figures S26-S41 show the rest of migrations in the WSW-propagating group in Figure 8a that are not presented in the main text or appendices. Figures S42-S46 show the rest of migrations in the ENE-propagating group in Figure 8a that are not presented in the main text or appendices.
Text S1. Filtering Effect Caused by Physical Dispersion

Because physical dispersion due to intrinsic attenuation causes seismic waves of different frequencies to travel at different speeds, we want to evaluate the difference in travel time between two stations that arises from the different passbands used. Here we adopt a simplified attenuation model. Assuming the attenuation along the ray path of tremor is frequency-independent (constant S-wave quality factor $Q_s$) in a homogeneous half-space, we wish to determine if attenuation alone can explain most of the filtering effect we see. Azimi’s attenuation law gives a physical dispersion relation for phase velocity as a function of frequency if $Q_s$ is constant (Aki & Richards, 2002):

$$c(\omega) = c_0 \left[ 1 + \frac{1}{\pi Q_s} \ln \left( \frac{\omega}{\omega_0} \right) \right],$$  \hspace{1cm} (1)

where $c(\omega)$ and $c_0$ are phase velocities at the angular frequency $\omega$ and the reference frequency $\omega_0$, respectively. This equation is valid when $|\ln(\omega/\omega_0)/(\pi Q_s)| \ll 1$, which is satisfied for the frequency bands we use and a typical $Q_s$ of 200–500 (Beroza & Ide, 2011). Thus we can simply substitute for $\omega$ to find that the ratio between the phase velocity at angular frequency $\omega_{hf}$ and $\omega_{lf}$ is

$$\frac{c_{hf}}{c_{lf}} = 1 + \frac{1}{\pi Q_s} \ln \left( \frac{\omega_{hf}}{\omega_{lf}} \right).$$ \hspace{1cm} (2)

Equation 2 implies that the LF signal always arrives later than the HF signal at any given station. Rather than the differential travel time (of a signal from the tremor source; here we take the LFE family location as the source) due to the frequency bands at one station $i$ or $j$, we care about the difference in this differential travel time between the station pair $i$ and $j$, i.e., the differential travel time due to the passbands at station $j$
relative to that at station $i$,

$$\Delta t_{ij}^{lf-hf} = (D_j - D_i) \frac{1}{\pi Q_s c_{hf}} \ln \left( \frac{\omega_{hf}}{\omega_{lf}} \right), \quad (3)$$

where $D_j$ and $D_i$ are the travel distances from the LFE family location to stations $j$ and $i$, respectively. In addition to the LF signal arriving later at each station, equation 3 further shows that this differential travel time increases as the distance from the LFE family to the station increases.

Now we insert some values to compare the prediction of equation 3 to the empirical filtering effect we obtain from cross-correlating the LFE templates. Take LFE family 002 and the PGC trio as an example. The central frequencies of the passbands we use (0.5–1.25 Hz and 1.25–6.5 Hz) differ by a factor of $\sim 4.4$. Assuming that $c_{hf}$ is equal to the average S-wave velocity $V_s = 3.84$ km/s of the model we use, and a frequency-independent and path-averaged $Q_s$ of 200 (Gomberg et al., 2012), equation 3 yields $\Delta t_{12}^{lf-hf} \approx 0.4$ sample, and $\Delta t_{13}^{lf-hf} \approx 0.1$ sample at a sampling rate of 80 Hz. This means that if one aligns the seismograms according to the HF signals at the two stations, the LF signal arrives 0.4 samples later at station SSIB than station PGC, and 0.1 sample later at station SILB than PGC. Compared to the empirical filtering effect, the absolute magnitudes from equation 3 are too small. Moreover, the relative magnitudes of the differential filtering effects predicted by equation 3, $\Delta t_{12}^{lf-hf}/\Delta t_{13}^{lf-hf} = 4$, are far different from the value of $1/3$ we estimated empirically via cross-correlation of the templates (that is, the empirical differential correction is several times larger for the station pair with the much shorter path difference, rather than several times smaller). It has been suggested that tremor is generated in a region of very high attenuation (Gomberg et al., 2012; Bostock et al., 2017). A much lower $Q_s$ (at least as low as $\sim 20$) is needed to fit the absolute magnitudes, but
this will not change their ratios (nor is it a reasonable path-averaged value). There are several other observations that equation 3 fails to explain as well. It predicts that the sign and magnitude of the difference of differential travel time for a given station pair depend on the differential travel distance from the LFE family to that station pair. For example, the sign of $\Delta t_{12}^{f-hf}$ and $\Delta t_{13}^{f-hf}$ from family 002 to the TWKB trio according to equation 3 would be opposite to that from family 144, due to the TWKB-LZB-MGCB geometry. However, Figure 4 of the main text shows that the signs for these two families are actually the same. In addition to this inconsistency in sign, the empirically-determined filtering effects show that the absolute relative magnitude $|\Delta t_{13}^{f-hf}/\Delta t_{12}^{f-hf}| \geq 1$ applies to almost all LFE families, which again contradicts the expectation from equation 3.

Next, we show the phase lag as a function of frequency, as determined from the phase of the cross-spectrum between LFE templates that are pre-aligned in the HF passband for families 002 and 144 in Figures S4 and S5. It seems that the phase lag does not simply indicate a constant time offset between different frequency ranges that are separated near our dividing frequency 1.25 Hz. Therefore the filtering effect measured by cross-correlating the templates in the time domain is likely just an average offset between different passbands. We then overlay the theoretical prediction of the phase lag according to equation 3 by aligning the S-wave arrivals at a station pair with respect to a specific frequency using a $Q_s$ of 20. As can be seen, even if a unreasonably low $Q_s$ could fit the general magnitude and trend of the observed phase lag as a function of frequency, there is a clear sign inconsistency between the prediction and observation at the station pair TWKB-LZB for family 144. This similar sign inconsistency could be found for family 010, 068 and 125 as well. Another caveat is, the prediction fails to explain the observed
non-zero phase lag within the LF passband, which seems unlikely to be the noise as it persists for different families.

Based on these lines of evidence, a simple model of a frequency-independent and spatially invariant $Q_s$ cannot capture the filtering effect we see. The uniformity of the corrections in Figure 4 of the main text imply that other more important factors than attenuation cause the filtering effect, e.g., the change in shape of the arriving pulse because of near-source reflections (Nowack & Bostock, 2013). Cross-correlating the LFE templates seems like an appropriate way of determining the combined influence of all contributions to the filtering effect, whatever their source, which we can then correct (subtract) from our raw cross-correlation measurements of tremor.
Text S2. Identification of Rapid Tremor Migrations

To test the hypothesis that there are systematic spatial offsets between contemporaneous high-frequency (HF) and low-frequency (LF) tremor sources relative to the propagating fronts of rapid tremor migrations (RTMs), we need to identify the migrations that have a relatively simple and unidirectional migrating pattern. The process we adopt relies mainly on the HF catalog because its signal-to-noise ratio is higher, and because its wider range of frequencies and higher-frequency content permit more accurate relative arrival time measurements even for the same signal-to-noise ratio.

First, we employ an automatic algorithm to identify tremor bursts that have HF detections clustered in time (Wu et al., 2015; Peng & Rubin, 2017). We obtain the separation in time between each HF detection and its preceding detection (Figure S6), then for each ETS episode we sequentially group all HF detections that occur less than a threshold time $t_{thr} = 1 \times 10^{-3}$ days after the preceding detection into a tremor burst. Only the bursts that have at least $n_{thr} = 15$ detections in both the HF and LF catalogs are kept (using the same time window for the LF catalog that was determined using the HF catalog). On the one hand, it is meaningless to define a migration with too few or sporadic HF detections. On the other hand, as the LF detections are generally fewer in number due to their lower signal-to-noise ratio, setting a minimum number of LF detections reduces the influence of false positives. In total, 1 burst in 2003, 80 bursts in 2004, and 77 bursts in 2005 pass the thresholds (Figure S7). The total number of detections included in these bursts accounts for $\sim 53\%$ of the entire HF catalog.

This automatic temporal clustering algorithm does not ensure that the detected tremor bursts are also clustered in space with a unidirectional pattern. To ensure that
this is the case, we examine all the detected bursts in map and space-time plots. We
found that some bursts contain several spatial clusters which could also be well separated
in time (e.g., Figure S8); some temporally neighbouring bursts are continuous in space
such that they should be combined (e.g., Figure S9); and some have to be truncated in
time to maintain a simple pattern (e.g., Figure S10). Accordingly, 17 bursts (21% of the
total) in 2004 are modified in time, 9 of which are combined into 4 bursts, 3 of which are
separated into 7 bursts, and 5 of which are truncated. Similarly, 23 bursts (30% of the
total) in 2005 are modified in time, 2 of which are combined into 1 burst, 4 of which are
separated into 9 bursts, and 17 of which are truncated. Many of these bursts propagate
in a well-defined direction for distances that range from 5 to 20 km.

To determine these propagation directions and apply some additional quality-control
measures for unidirectionality, for the updated bursts (1 from 2003; 79 from 2004; 81
from 2005) we next carry out a regression analysis as shown in Figure 6 of the main
text. We start by using the HF catalog to determine the propagation direction for each
burst. First, we search over a series of trial propagation directions from 0–355 degrees,
in 5-degree increments, onto which all HF detections are projected, and consider these
projected locations as a function of time. We then implement a robust least-squares
regression that minimizes the weighted distances of these projected HF locations to a
best-fitting line (i.e., the weighted root mean squared error, RMSE), using a bisquare
weighting scheme (e.g., Holland & Welsch, 1977). To choose which migrations should be
kept for analysis we need some measures for the quality of the determined propagation
direction and the unidirectionality of the migration. The first measure is the standard
error (SE) of the estimated slope of the linear fit to the projected HF detections vs. time.
Mathematically, the RMSE is related to the SE of the slope:

\[ SE_\beta = \frac{RMSE}{\sqrt{\sum_{i=1}^{n} (x_i - \bar{x})^2}}, \tag{4} \]

where \( \hat{\beta} \) is the estimated HF slope, \( n \) is the number of detections involved in the regression, \( x_i \) is the time of each detection and \( \bar{x} \) is the arithmetic mean. As the denominator, which represents the time spanned by the burst with respect to its mean, is constant for the same migration however the trial propagation direction changes, minimizing the SE of the slope is equivalent to minimizing the RMSE among all trial directions. However, the SE of the slope is a better indicator of the overall reliability of the measurement. For example, a migration with a moderately low RMSE can still be suspect if its time span is too short. An empirical maximum of 3 is set for the SE of the HF slope.

The second quality-control measure is the Pearson correlation coefficient (ranging from -1 to 1) between the along-propagation distance of the projected HF detections and time. This coefficient quantifies the strength of linear association between two variables (e.g., Benesty et al., 2009), which is useful to check if it is rational to approximate the propagation as linear. The minimum Pearson correlation allowed is set as 0.5. Two types of trial directions among all are considered as candidates for the propagation direction, one that (globally) minimizes the RMSE, and one that (globally) maximizes the slope of the linear fit (i.e., the propagating speed). For the sake of robustness, we require the bursts to pass the thresholds for the fit to HF detections projected onto both candidate directions, otherwise it would imply that the fitting quality is too sensitive to the used direction so that the direction estimate might be unstable. The above criteria result in 25 eligible migrations in the 2004 ETS episode and 27 in 2005. The only burst in 2003 was discarded due to the large spatial scatter of the LF detections.
Finally, for the remaining migrations, we have to decide which of the two candidate propagation directions is a better estimate of the true propagation direction. As explained in the main text, we adopt the minimum-RMSE direction as our default propagation direction because, given the long axis of the location error ellipse, the minimum-RMSE direction is the best option for measuring a reliable spatial offset between the LF and HF detections after projection onto the estimated propagation direction. As an additional check for robustness, for each tremor burst we also consider the maximum-speed direction. Based on examination of all the HF migrations, we adopt the minimum-RMSE direction as the propagation direction unless the Pearson correlation is increased by at least 0.05 using the maximum-speed direction, which occurs only 5 times in total (one example shown in Figure C4). Figure S11 shows the one exceptional case for which the adopted propagation direction is the minimum-RMSE direction obtained from fitting the LF detections, because neither of the two options based on the HF detections appeared satisfactory. In this manner, we manage to identify 52 migrations that have a relatively simple and unidirectional pattern and have their propagation directions determined at the same time.

In the vicinity of LFE family 002, in the SE corner of our study region, we found some additional tremor bursts. This region is at the far limit of what can be detected by the TWKB trio, presumably because more distant sources generate surface-converted phases that do not correlate between the stations. The locations here appear somewhat distorted, in that there is a very non-linear relationship between the relative timing delays at the TWKB-MGCB and TWKB-LZB station pairs, and the resulting relative locations determined by Hypoinverse (this can be seen in Figure S2 of Peng, Rubin, Bostock, and
Armbruster (2015), which compares the same migration as seen by the TWKB and PGC trios). The distortion would make the algorithm-determined propagation directions of these migrations questionable, because the minimum-RMSE and maximum-speed direction differ substantially, although the maximum-speed direction usually seems better in this region when using the TWKB trio. Most of these bursts therefore fail to pass all the quality-control measures. Only one migration was qualified, but nonetheless we do not trust it. This migration and the corresponding version detected by the PGC trio, showing the unreliable propagation direction due to the distortion of locations, is given in Figures S12 and S13. Although at higher frequency the region surrounding family 002 is imaged much better by the PGC trio than by the TWKB trio, we found that the PGC trio did not provide enough LF detections from this region to be useful for this study.

References


Figure S1. Variation of differential travel time with the length of the window used, at different station pairs, when cross-correlating the templates of each LFE family filtered using the LF passband (0.5–1.25 Hz). The upper panel shows the variation of differential travel time (in samples, at 80 Hz) between the station pair TWKB-LZB, and the lower panel shows that between the station pair TWKB-MGCB. The variation with cross-correlation window length is within 1 sample for all families. Meanwhile, there is no variation of the differential travel time with the window length using the HF (1.25–6.5 Hz) passband, meaning that our filtering effect correction is not sensitive to the window length in template cross-correlations.
Figure S2. Median difference in detected time offsets, after correcting for the filtering effect, for station pairs TWKB-LZB (12) and TWKB-MGCB (13), between contemporaneous LF and HF detections from all migrations tied to each of the 9 LFE families of primary interest. In each panel, gray circles denote RTMs, shaded by the number of LF detections in that migration tied to the family of that panel (numbered in upper right corner). The upper-left-to-lower-right elongation of the offsets reflects the ENE-WSW elongation of most of the RTMs imaged. The black star represents the median (weighted by the number of LF detections) of all RTMs. The black square denotes the empirical filtering effect correction for that family, and shows that the median LF–HF offset is often but not always small compared to the filtering effect correction.
**Figure S3.** Same as Figure S2, but only the detections from the nearly-oppositely-propagating migrations are involved. Red and blue circles (shaded according to the number of LF detections) denote the WSW- and ENE-propagating RTMs, respectively. The elongation remains, but the scatter is slightly reduced. Orange and cyan stars represent the weighted medians of the two groups. Generally they have different magnitudes but not always different signs. The black star denotes the overall weighted median. The black square is the filtering effect correction. The overall median LF–HF offset (black star) is generally comparable to or slightly larger than that of Figure S2, and is not necessarily cancelled out by merging the two groups.
Figure S4. Phase lag (normalized by $\pi$) as a function of frequency, as determined from the phase of the cross-spectrum between LFE templates at the three station pairs that are pre-aligned in the HF passband for LFE family 002. The solid line denotes the observed phase lag. The theoretical prediction of the phase lag according to equation 3 by aligning the S-wave arrivals at a station pair with respect to a specific frequency using a $Q_s$ of 20 is overlaid. The dashed line is the prediction by aligning at 3.875 Hz, which is the arithmetic average of the two corners of the HF passband, whereas the dot-dash line is the prediction by aligning at 2.5 Hz, which is roughly the corner frequency of the power spectral density of the broadband templates. The gray dashed lines denote the corners of LF and HF passbands.
Figure S5. Phase lag (normalized by $\pi$) as a function of frequency, as determined from the phase of the cross-spectrum between LFE templates at the three station pairs that are pre-aligned in the HF passband for LFE family 144. Symbols are the same as in Figure S4.
Figure S6. The separation in time between each HF detection and its preceding detection for the ETS episodes 2003, 2004 and 2005. The dashed blue line denotes the threshold time $t_{thr} = 1 \times 10^{-3}$ days that is used to group all HF detections that occur less than $t_{thr}$ after the preceding detection into a tremor burst for each episode.
Figure S7. Tremor bursts determined automatically in which the separation in time between each HF detection and its preceding detection is less than $t_{thr} = 1 \times 10^{-3}$ days, and the number of detections is higher than $n_{thr} = 15$ in both HF and LF passbands for the ETS episodes 2003, 2004 and 2005. The blue curve shows the cumulative number of detections increasing with time. Bursts are shaded in gray. The percentages of HF detections (relative to all detections in each episode) that fall into the bursts are given on the left.
**Figure S8.** A tremor burst example that contains several clusters separated in space which could also be well separated in time. (a) is the original automatically-detected burst, which consists of 3 clusters. (b)-(d) are the 3 bursts separated from (a). These modified bursts, along with unchanged ones, would then enter the regression analysis.
Figure S9. Some temporally neighbouring tremor bursts that are spatially continuous such that they should be combined into one burst. (a)-(c) are the original automatically-detected bursts that are spatially continuous despite that the separation in time between them is longer than $t_{thr}$. (d) is the combined burst which enters the regression analysis. (e) is the linear regression to the projected detections onto the minimum-RMSE direction. From the SE of the slope and Pearson correlation, the fitting seems satisfactory.
Figure S10. A tremor burst example that is better to be truncated in time to maintain a simple pattern. (a) is the original automatically-detected burst where the later HF detections start to propagate bilaterally to both the SW and NE direction at $\sim 21.8$ hr. (b) is the modified burst from (a) where the time after 21.8 hr is truncated. It is necessary because the later detections are numerous, clustered and thus are likely to be real, the bisquare-weighting scheme would not be able to down-weight them properly such that the resulting spatial offset (LF–HF) could be biased. (c) and (d) are the linear regressions to the projected HF detections onto the minimum-RMSE direction for the original and modified bursts, respectively.
Figure S11. The only migration where neither the minimum-RMSE direction nor the maximum-speed direction from the linear fit to the projected HF detections seem satisfactory, but the linear fit to the LF detections appears to give a satisfactory estimate. Symbols are the same as in Figure 6 of the main text. In this case, the minimum-RMSE direction is 210°, whereas the maximum-speed direction is 280°. From the standard error of the slope of the best-fitting line to LF detections, $SE_{LF}$, the minimum-RMSE direction from LF, 255° seems better than the former two.
Figure S12. The version imaged by the TWKB trio of a migration example that reveals the distortion of locations in the vicinity of LFE family 002, in the SE corner of our study region. Symbols are the same as in Figure 6 of the main text. This region is at the far limit of what can be detected by the TWKB trio, presumably because more distant sources generate surface-converted phases that do not correlate between the stations. The locations here appear somewhat distorted, in that there is a very non-linear relationship between the relative timing delays at the TWKB-MGCB and TWKB-LZB station pairs, and the resulting relative locations determined by Hypoinverse (compare to Figure S13). In this particular migration, the maximum-speed direction is chosen as the propagation direction.
Figure S13. Same migration as that in Figure S12, but imaged by the PGC trio. Because of the greater station spacing in the PGC trio the location errors in both frequency bands are smaller, and because of the shorter distance to the imaged area the distortion is less. Therefore, the propagation direction is much more reliable than that determined using the TWKB trio. Although at high frequency the region surrounding family 002 is imaged much better by the PGC trio than by the TWKB trio, the PGC trio did not provide enough LF detections to be useful for this study.
Figure S14. Propagation direction and extent of all the 52 recognized migrations in HF detected using the TWKB trio. (a) shows all RTMs, where the gray arrows represent the propagation direction and extent of the HF migrations in the propagation direction. Each solid circle represents the median location of the HF detections, color-coded by the sequential number of that migration. The extent, i.e., the arrow length, is determined by the 2nd and 98th percentiles of the projected distances of HF detections along the propagation direction. (b) shows the distribution of the propagation directions of RTMs and the associated number of RTMs in each quadrant of azimuth. The peripheral numbers indicate the azimuth in degrees clockwise from the north.
Figure S15. The absolute difference in the resulting spatial offset (LF–HF) between the minimum-RMSE and maximum-speed directions, vs. the absolute difference (in degrees) between the two directions, for all the 52 migrations identified. Colored symbols represent the 27 migrations that propagate in the nearly opposite directions in Figure 8a of the main text. The ENE-propagating RTMs are filled in blue, whereas the WSW-propagating RTMs are filled in red. The other migrations in Figure 8b of the main text are denoted by open black symbols. Circles represent the RTMs that use the minimum-RMSE direction, and triangles represent the RTMs that use the minimum-speed direction as the propagation direction.
Figure S16. Significance of the difference between the mean LF–HF offsets of the WSW- and ENE-propagating migration groups when the minimum-RMSE direction (determined from the HF detections) is adopted as the propagation direction for all 52 migrations. This leads to a slight change in the qualified migrations that propagate in the nearly opposite directions in the northwestern portion of the study area. The WSW-propagating and ENE-propagating groups have respectively 18 and 5 members. The mean LF–HF offset of the WSW-propagating group decreases by $\sim 150$ m and the mean offset of the ENE-propagating group increases by $\sim 150$ m, which means that their difference increases by $\sim 300$ m, compared to Figure 7 of the main text. Symbols are the same as in Figure 7 of the main text.
Figure S17. Significance of the difference between the mean LF–HF offsets of the WSW- and ENE-propagating migration groups, when we adopt only the migrations for which the absolute difference in the resulting spatial offset (LF–HF) between the minimum-RMSE and maximum-speed directions is less than 500 m (see Figure S18). The difference in the two mean offsets decreases by $\sim 150$ m, compared to Figure 7 of the main text, but the two confidence intervals are still well separated. Symbols are the same as in Figure S16.
**Figure S18.** The absolute difference in the resulting spatial offset (LF–HF) between the minimum-RMSE and maximum-speed directions, vs. the absolute difference between the two directions, for the 27 migrations that propagate in the nearly opposite directions in Figure 8a of the main text. Everything is the same as Figure S18, except the dashed line at 500 m is the new threshold for discarding migrations to create Figure S17.
Figure S19. The proportion of detections in every migration tied to a particular LFE family (one plot for each family). The migrations in which the spatial offset (LF–HF) is on average negative are colored blue, while the ones in which the offset is positive are colored red. It seems that no LFE family contributes much more to one of the ENE- or WSW-propagating groups than the other.
**Figure S20.** The average spatial offset (LF–HF) in every migration vs. the proportion of detections in that migration tied to a particular LFE family (one plot for each family). The ENE- and WSW-propagating migrations are plotted as triangles and circles, respectively. The Spearman’s rank correlation coefficient, ranging from -1 to 1, is used to assess how well the relationship between two variables can be described using a monotonic function (e.g., Myers et al., 2010). The Kendall rank correlation coefficient, ranging from -1 to 1, is used to measure the similarity of the orderings of data when ranked by each of the quantities (Kendall, 1938). It seems that there is no strong correlation between the offset and proportion, except for family 068.
Figure S21. Significance of the difference between the mean LF–HF offsets of the WSW- and ENE-propagating migration groups when the LF–HF offset measurements from detections using the empirical filtering effect corrections (and other parameters) of family 017 are excluded. We try to re-obtain the propagation direction for each migration in the merged catalog without family 017, and select migrations for the histograms based on the same criteria described in Section 5 of the main text. The number of detections in each group changes only slightly, because detections seen by one family are often seen by at least one other. It shows that the mean LF–HF offset of the WSW-propagating group decreases by only $\sim 100$ m, such that the difference between the means of two groups is essentially unaffected (decreases by $\sim 100$ m), compared to Figure 7 of the main text. Symbols are the same as in Figure S16.
Figure S22. Significance of the difference between the mean LF–HF offsets of the WSW- and ENE-propagating migration groups when the LF–HF offset measurements using the parameters of family 043 are excluded. It shows that the mean LF–HF offset of the WSW-propagating group decreases by $\sim 50$ m and that of the ENE-propagating group decreases by $\sim 150$ m, such that the difference between the means of two groups is essentially unaffected (increases by $\sim 100$ m), compared to Figure 7 of the main text. Symbols are the same as in Figure S16.
Figure S23. Significance of the difference between the mean LF–HF offsets of the WSW- and ENE-propagating migration groups when the LF–HF offset measurements using the parameters of family 068 are excluded. It shows that the mean LF–HF offset of the WSW-propagating group increases by $\sim 150$ m and that of the ENE-propagating group increases by $\sim 50$ m, such that the difference between the means of two groups is essentially unaffected (increases by $\sim 100$ m), compared to Figure 7 of the main text. Symbols are the same as in Figure S16.
Figure S24. Significance of the difference between the mean LF–HF offsets of the WSW- and ENE-propagating migration groups when the LF–HF offset measurements using the parameters of family 099 are excluded. It shows that the mean LF–HF offset of only the ENE-propagating group decreases by $\sim 50$ m, such that the difference between the means of two groups is essentially unaffected (increases by $\sim 50$ m), compared to Figure 7 of the main text. Symbols are the same as in Figure S16.
Figure S25. Significance of the difference between the mean LF–HF offsets of the WSW- and ENE-propagating migration groups when the few tens of LF detections from the WSW-propagating group in the vicinity of family 002 are excluded. In the same region LF detections are nearly absent in the ENE-propagating group. To eliminate the contributions from these detections, we exclude the distance measurements from them in the histograms. The mean offset of the WSW-propagating group decreases by $\sim 50$ m, such that difference between the means of two groups is essentially unaffected (decreases by $\sim 50$ m), compared to Figure 7 of the main text. Symbols are the same as in Figure S16.
Figure S26. One RTM occurring from 23.2 to 23.6 hr on 15 July, 2004 from the WSW-propagating migration group detected by the TWKB trio. Symbols are the same as in Figure S11.
Figure S27. One RTM occurring from 23.7 to 24 hr on 15 July, 2004 from the WSW-propagating migration group detected by the TWKB trio. Symbols are the same as in Figure S11.
Figure S28. One RTM occurring from 1.7 to 2.7 hr on 16 July, 2004 from the WSW-propagating migration group detected by the TWKB trio. Symbols are the same as in Figure S11.
Figure S29. One RTM occurring from 11.85 to 12.15 hr on 16 July, 2004 from the WSW-propagating migration group detected by the TWKB trio. Symbols are the same as in Figure S11.
Figure S30. One RTM occurring from 20.4 to 21.1 hr on 16 July, 2004 from the WSW-propagating migration group detected by the TWKB trio. Symbols are the same as in Figure S11.
**Figure S31.** One RTM occurring from 11.90 to 12.04 hr on 17 July, 2004 from the WSW-propagating migration group detected by the TWKB trio. Symbols are the same as in Figure S11.
Figure S32. One RTM occurring from 5.30 to 5.55 hr on 18 July, 2004 from the WSW-propagating migration group detected by the TWKB trio. Symbols are the same as in Figure 5.
Figure S33. One RTM occurring from 13.36 to 13.52 hr on 18 July, 2004 from the WSW-propagating migration group detected by the TWKB trio. Symbols are the same as in Figure S11.
**Figure S34.** One RTM occurring from 23.4 to 23.8 hr on 12 September, 2005 from the WSW-propagating migration group detected by the TWKB trio. Symbols are the same as in Figure 5.
Figure S35. One RTM occurring from 9.66 to 9.79 hr on 13 September, 2005 from the WSW-propagating migration group detected by the TWKB trio. Symbols are the same as in Figure S11.
**Figure S36.** One RTM occurring from 14.45 to 14.61 hr on 13 September, 2005 from the WSW-propagating migration group detected by the TWKB trio. Symbols are the same as in Figure S11.
Figure S37. One RTM occurring from 20.2 to 20.5 hr on 13 September, 2005 from the WSW-propagating migration group detected by the TWKB trio. Symbols are the same as in Figure S11.
Figure S38. One RTM occurring from 5.8 to 7.0 hr on 14 September, 2005 from the WSW-propagating migration group detected by the TWKB trio. Symbols are the same as in Figure S11.
Figure S39. One RTM occurring from 17.1 to 17.8 hr on 14 September, 2005 from the WSW-propagating migration group detected by the TWKB trio. Symbols are the same as in Figure S11.
Figure S40. One RTM occurring from 1.00 to 1.25 hr on 17 September, 2005 from the WSW-propagating migration group detected by the TWKB trio. Symbols are the same as in Figure S11.
Figure S41. One RTM occurring from 15.6 to 16.2 hr on 17 September, 2005 from the WSW-propagating migration group detected by the TWKB trio. Symbols are the same as in Figure S11.
Figure S42. One RTM occurring from 22.45 to 22.80 hr on 17 July, 2004 from the ENE-propagating migration group detected by the TWKB trio. Symbols are the same as in Figure S11.
Figure S43. One RTM occurring from 4.40 to 4.75 hr on 18 July, 2004 from the ENE-propagating migration group detected by the TWKB trio. Symbols are the same as in Figure S11.
Figure S44. One RTM occurring from 3.7 to 4.0 hr on 13 September, 2005 from the ENE-propagating migration group detected by the TWKB trio. Symbols are the same as in Figure S11.
Figure S45. One RTM occurring from 9.7 to 10.2 hr on 15 September, 2005 from the ENE-propagating migration group detected by the TWKB trio. Symbols are the same as in Figure S11.
Figure S46. One RTM occurring from 10.2 to 10.6 hr on 15 September, 2005 from the ENE-propagating migration group detected by the TWKB trio. Symbols are the same as in Figure S11.