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Probing the nature of low-frequency earthquakes through the deconvolution of tectonic tremor

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Abstract

Currently there are two end-member views of low-frequency earthquakes (LFEs). One is that they result from stick-slip behavior of Mxed brittle patches that are mechanically distinct from the surrounding, creeping, fault. The other is that they represent the high-frequency limit of stochastic accelerations and decelerations of slip on the fault, with boundaries that may vary with time. Among the many unknowns concerning LFEs are their physical dimensions, knowledge of which might place constraints on their underlying nature.

Estimates of LFE source sizes range from 100 m (if they have a stress drop similar to regular earthquakes) to more than 1 km (if they rupture at local shear wave speeds, given a ˜0.5-s duration). Our 4-s tremor catalogs have an estimated location uncertainty smaller than 1 km, and many consecutive and nearly consecutive detections are spaced closer than this. This suggests that if LFEs are close to the upper size limit, successive events are strongly overlapping, which seems more consistent with the stochastic acceleration and deceleration model of LFE generation. Moreover, many 4-s windows themselves contain multiple nearly co- located LFE-like arrivals. This encourages us to use LFE templates to deconvolve tremor seismograms, to obtain an LFE catalog with a temporal resolution conceivably as high as one event per LFE duration. Our preliminary catalog shows that many LFEs as close in time as 0.5 s are separated by less than 1 km. Figure 1 shows LFE detections from a 250-s window with an overall 2-km migration to the southeast. The median event has 75 other detections within 1 km. In the propagation direction, also the direction of low error, the median separation between consecutive events is 360 m. If LFEs are km-scale, possible explanations for the signiPcant overlap between events sometimes as close as 0.5 s in time (see the zoom) include reQected waves from boundaries of a low-velocity shear zone, or inertial vibrations at low normal stress (Im and Avouac, 2021). If, instead, LFEs are brittle asperities closer to 100 m in size, successive events need not overlap, but one must explain both their long duration and why, with so many sources in close proximity, nearly none are observed to grow larger in both duration and magnitude than is characteristic of LFEs.

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Example tremor burst

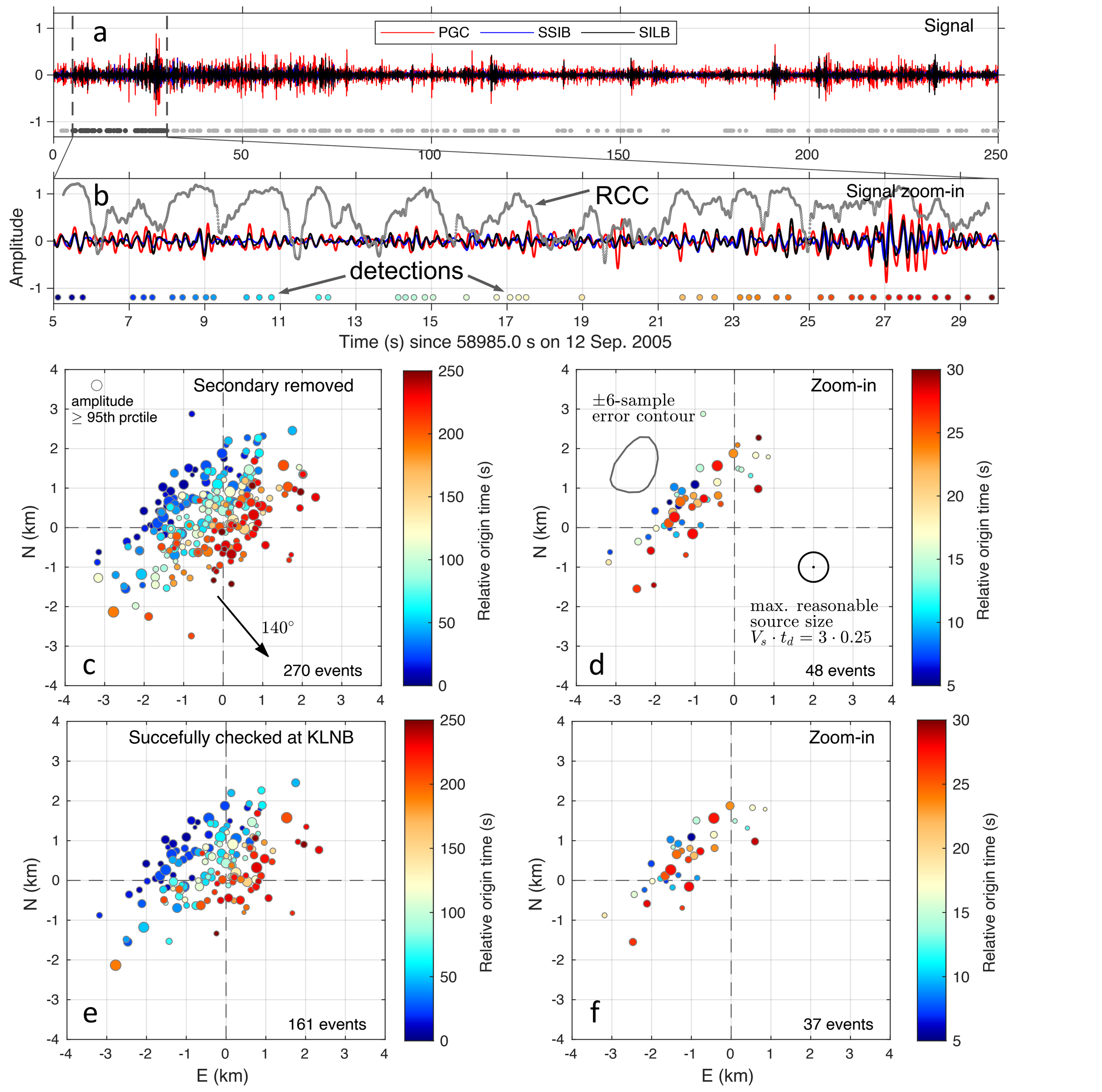


Fig. 1 Detected sources from deconvolution for an example tremor burst time window. (a) and (b) denote signals at stations PGC, SSIB and SILB, for the whole and zoom-in window, respectively. The gray line is the running cross-correlation RCC. (c) and (d) are map locations of deconvolved sources after the removal of secondary ones. (e) and (f) show sources whose predicted arrivals at KLNB can be matched with an independently deconvolved peak within an allowable range.

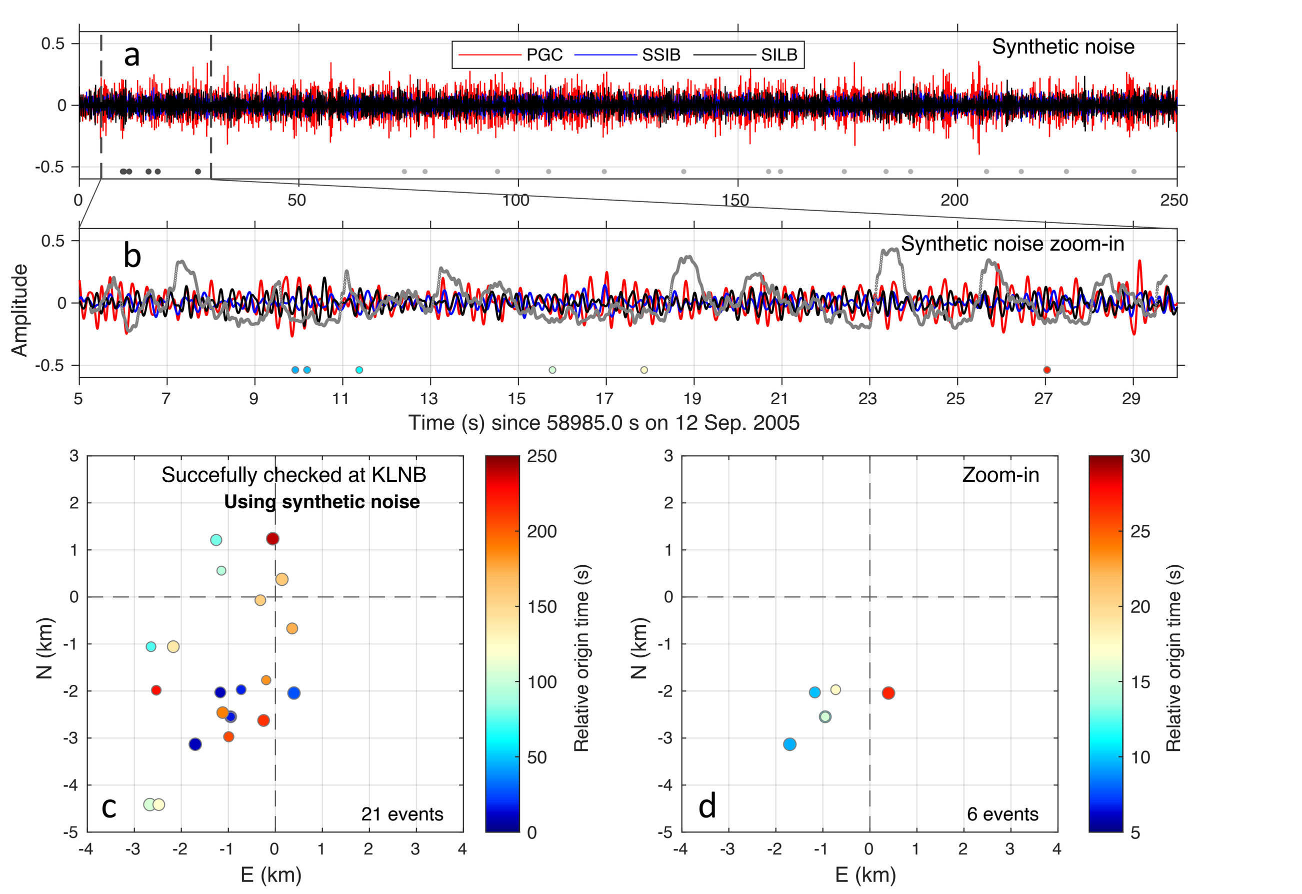
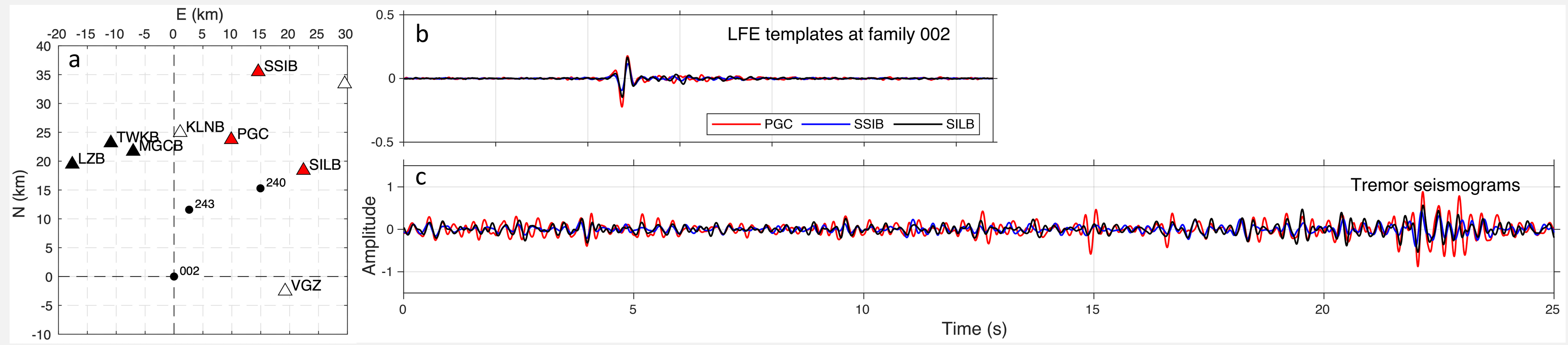


Fig 2. Synthetic noise experiment to assess what fraction of detections in Fig. 1e and 1f are reliable. (a) and (b) denote the synthetic noise, which is made by the amplitude spectrum of data plus a uniformly random phase spectrum. (c) and (d) show the resulting sources that pass the check at KLNB, for the whole and zoom-in window, respectively.

References

[1]. Shelly, D. R., Beroza, G. C., & Ide, S. (2007). Non-volcanic tremor and low-frequency earthquake swarms. *Nature, 446*(7133), 305-307.
[2]. Kikuchi, M., & Kanamori, H. (1982). Inversion of complex body waves. *Bulletin of the Seismological Society of America, 72*(2), 491-506.
[3]. Ohta, K., & Ide, S. (2017). Resolving the detailed spatiotemporal slip evolution of deep tremor in western Japan. *Journal of Geophysical Research: Solid Earth, 122*(12), 10-009.

Motivation

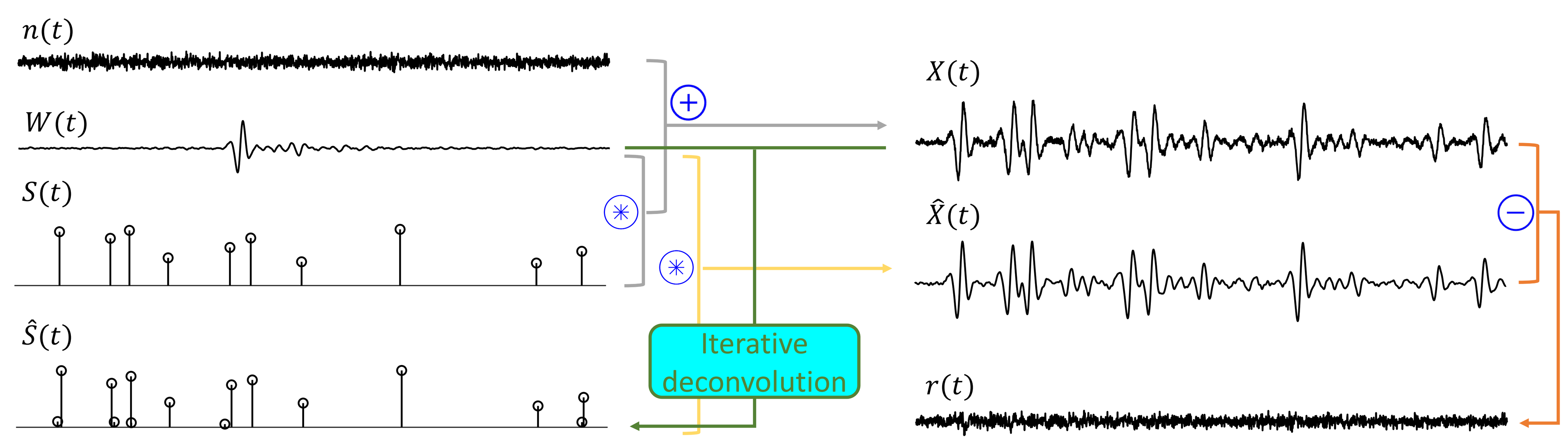


Facts
- Research exploiting matched-filter techniques[1] found that tremor likely contains myriad low-frequency earthquakes (LFEs)
- Consecutive template-like arrivals possess a persistent high coherence between waveforms at nearby stations, where the real number may be countless

Assumptions
- Tremor signal is entirely composed of LFEs plus noise
- There is no significant change in focal mechanism during the target time period or location

Questions
- Can we do a formal deconvolution to reveal the minimum number $[S(t)]$ of LFE templates $[W(t)]$ that is required to explain the tremor record $[X(t)]$?
- Given the distribution of these events, what is the size of region generating them? How does their spatial separation compare to the maximum reasonable source size ($V_s \cdot t_d$)? Can this be used to distinguish between candidate physical models for the source of tremor?

Workflow



Method brief

○ **Time domain iterative deconvolution[2, 3] at each station**

For the 1st source, its arrival time t_1 and amplitude m_1

$$\arg\min_{m_1,t_1}\{\,\Delta_1 = \int_0^{\infty}[X(t)-m_1W(t-t_1)]^2dt\,\} \xrightarrow{\text{rewrite}} \arg\min_{m_1,t_1}\{\,\Delta_1 = R_x(0) - 2R_{wx}(t_1)m_1 + R_w(0)m_1^2\,\}$$

Auto-correlation: $R_x(0)$, $R_w(0)$; Cross-correlation: $R_{wx}(t_1)$

$$\arg\max_{t_1}\{\,RCC(t_1)\cdot R_{wx}^2(t_1)\,\},\quad m_1 = R_{wx}(t_1)/R_w(0)$$

$RCC(t)$ is the cross-correlation over a running 0.5-s window averaged at 3 station pairs, so that the deconvolution order is guided by both the waveform coherence and amplitude of $R_{wx}(t)$

Similarly, the 2nd source is derived from the residual: $X'(t) = X(t) - m_1W(t-t_1)$

Iteration stops when the final residual is small enough: $r(t) = X(t) - \sum_{i=1}^{N_s} m_iW(t-t_i)$

○ **Grouping of sources**

Impulses $W(t)$ are independently deconvolved at each of 3 stations. A trio of detections are grouped as coming from a single source when they occur with a maximum allowable arrival time difference. The order of grouping is the same as that in deconvolution, so that more "significant" sources are grouped first.

○ **Removal of secondary sources**

Secondary arrivals might result if the duration of waveform peaks differs from that of templates. Given we are interested in the **minimum** number of sources, we keep only the largest peak when multiple detections are associated with the same waveform peak.

Statistics

Example burst

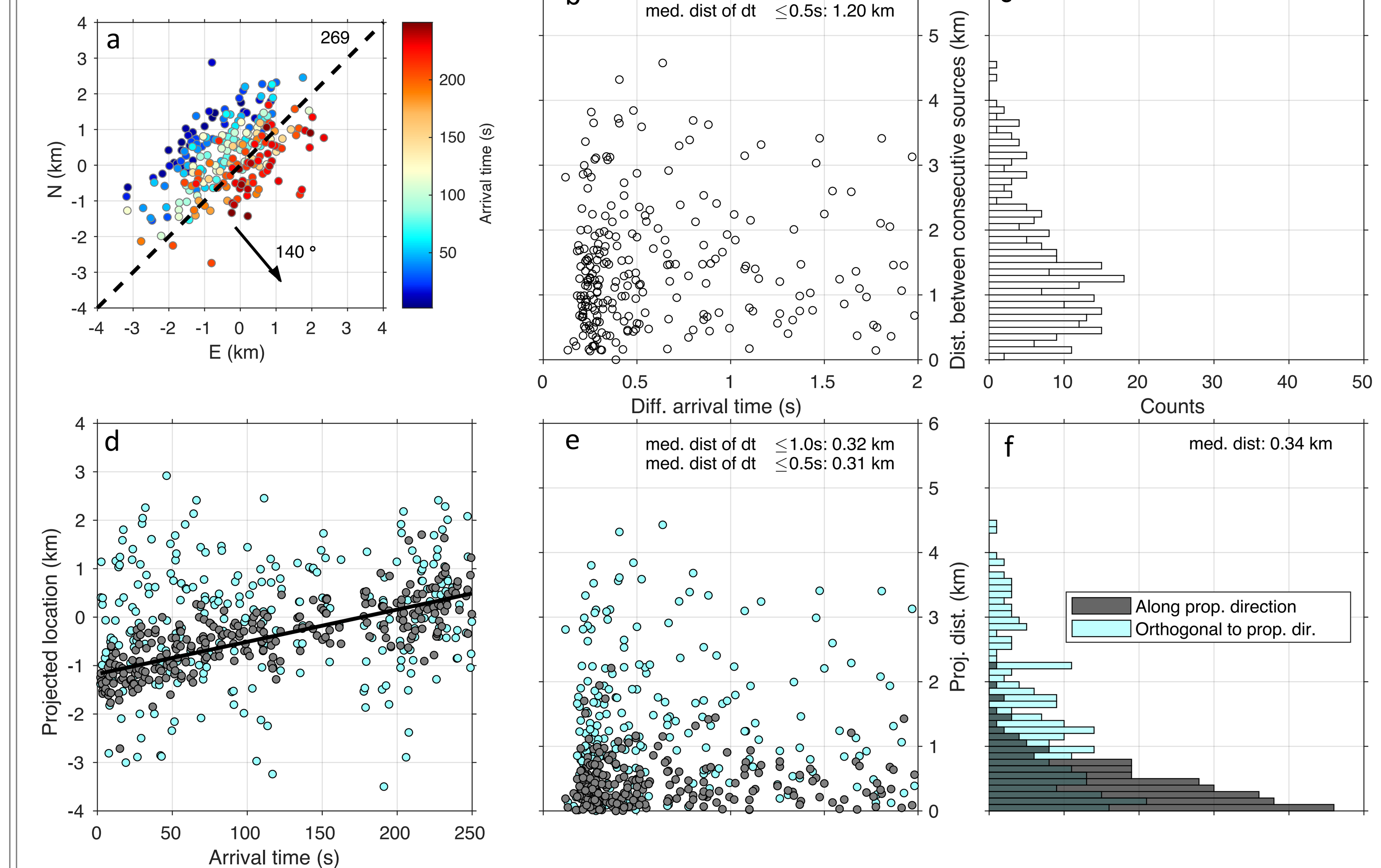


Fig. 3 Separation in arrival time and distance between consecutive sources. (b) scatters the absolute distance vs. time separation. (c) shows the histogram of distance. Given a clear migrating pattern for this burst, we determine its propagating direction and obtain the consecutive separation distance along this direction and its orthogonal direction. The median along-propagation separation is ~3 times smaller than the absolute one.

Combine multiple bursts

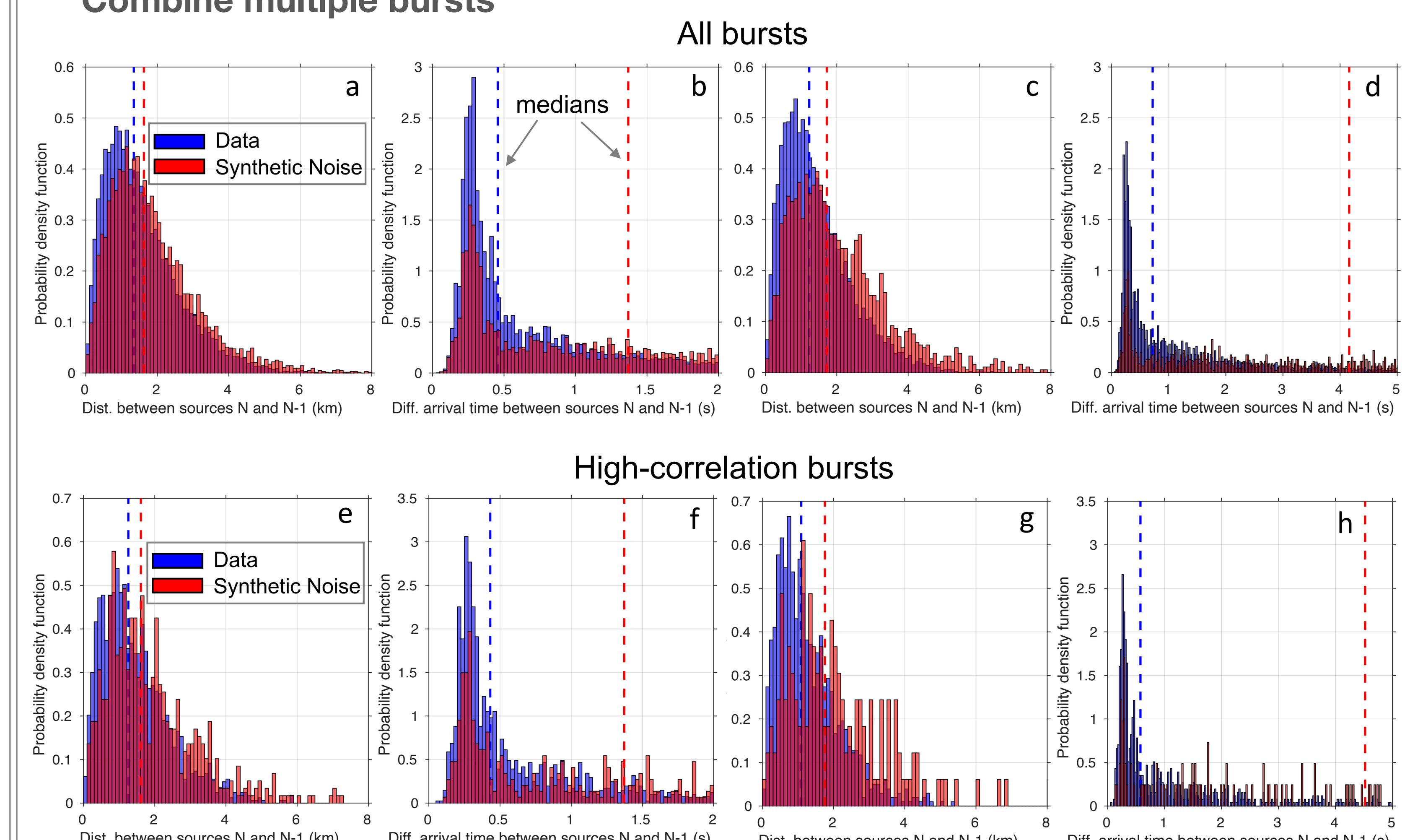


Fig. 4 Comparison between data and synthetic noise on the separation in arrival time and distance between consecutive sources, after combining all bursts. (a) and (b) show the histogram of distance and separation in arrival time, respectively. (c)-(d) show only the sources that pass the check at KLNB. (e)-(h) show a similar analysis for bursts when the average cross-correlation of envelopes between the trio stations are above the 75th percentile. The distribution of separation in time and space between sources detected from synthetic noise is clearly different from that from data, which is one reasonable indictor of the reliability of our detections. The check at a 4th station distinguishes the statistics between data and noise more, and a focus on the high-correlation bursts further amplifies their difference.