Systematic Search for Spontaneous Non-Volcanic Tremor in the Vicinity of the San Jacinto Fault, Southern California

Gregor Hillers and Jean-Paul Ampuero

California Institute of Technology, Seismological Laboratory, Pasadena, USA
gregor@gps.caltech.edu

Tremor bursts have been identified beneath the central section of the SAF over a time span of several years. Tremor swarms were also detected in southern California at different locations, triggered by the passage of surface waves from the 2002 Denali earthquake. These observations warrant a systematic search for tremor signals in southern California using continuous recordings by the available dense seismic network. Focusing on six-hour night time data segments from selected station subsets of the Southern California Seismic Network (CI), the Anza (AZ) network and selected Plate Boundary Observatory (PBO) borehole stations, we implemented a transient detection algorithm based on similarity across station clusters of seismogram envelopes in the 2 to 8 Hz frequency band. Processing data from the HRSN borehole stations that include tremor signals originating on the SAF, we test the algorithm by comparing results to higher resolution tremor detections by D. Shelly. This benchmarking warrants detections of similar signals at other places in southern California. We apply our strategy to a cluster of stations near the reported triggered tremor source in the vicinity of the San Jacinto fault. Signals that match the automated transient characteristics are individually inspected and selected for further analysis. Waveforms from these time periods are used in a low frequency earthquake (LFE) matched-filter high resolution detection algorithm, to confirm the tectonic origin of the low-resolution detections, and to facilitate the localization of the source region.

[1] Automatic Transient Detection Algorithm (critical algorithmic choices)

0 'Informed' station selection
1 Bandpass filter 6-hour night time seismograms in the frequency range 2-8 Hz
2 Compute envelope using down-sampling rate (1 – 30 sec), and averaging window (15 – 90 sec)
3 Choose cross correlation (cc) window size (5 – 30 min), and overlap (½ window size)
4 Cross correlate envelopes station-to-station; choose cc value threshold for the identification of 'correlated' pairs (0.85-ish)
5 Measure 'envelope transient duration' in each window by choosing amplitude threshold
6 Measure maximum-to-mean amplitude (abs filtered data) in each cc window to identify large-amplitude signals (e.g., earthquakes)

Identification of Potential Tremor Signals

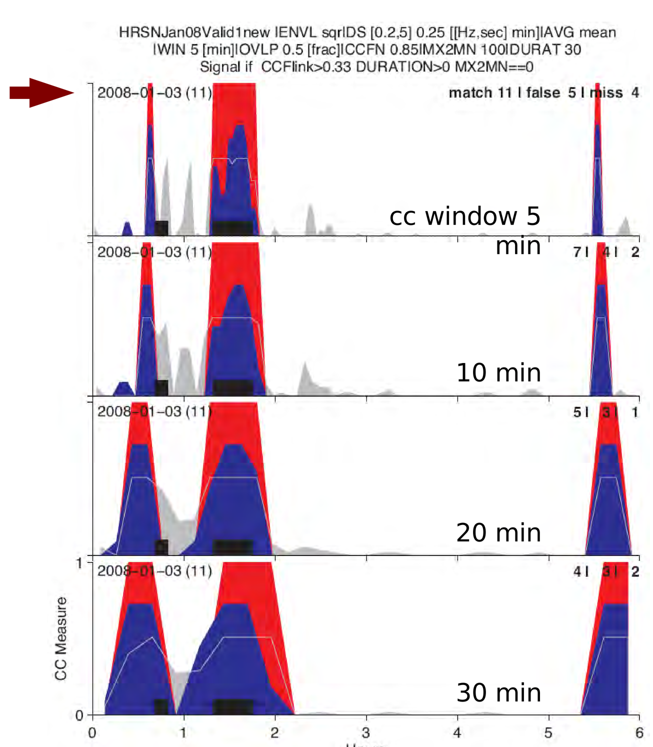
We identify potential tremor signals suitable for visual inspection by an analyst ...

... if the transient duration of the correlated envelopes is coherent for a number of stations and if the number of correlated station-to-station pairs is above a fraction of possible pairs and if (most) maximum to mean ratios are below a threshold (eliminate earthquake signals).

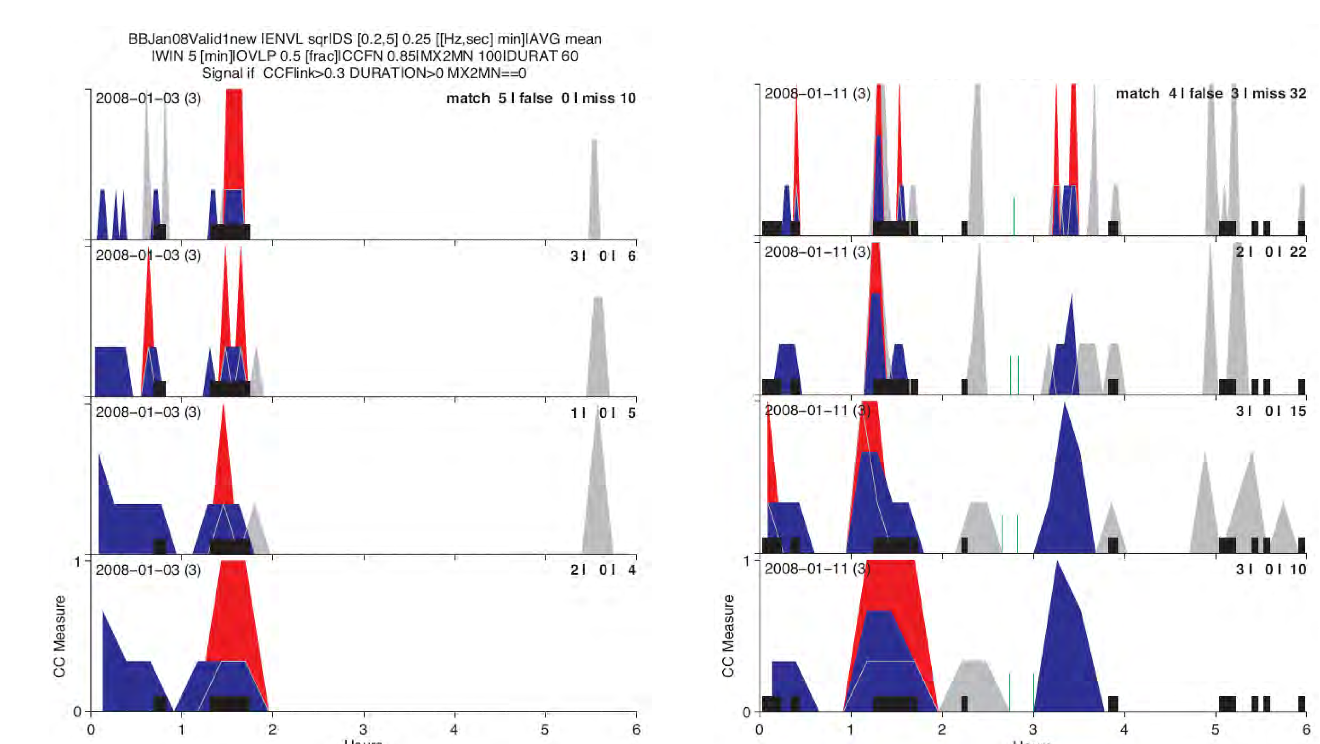
We benchmark the algorithm using data that include known spontaneous tremor signals originating in the SAF Parkfield/Cholame region. We analyze one month of data from the HRSN stations and collocated surface stations. The pattern below compares 6 hours from 2 days, using four different cc window lengths.

Color coding of detection pattern below

Number of 'correlated' cc window pairs scaled by the number of possible pairs [0 1] (Alternatively: number of stations involved in any correlated pair)
Fraction of transients per cc window with duration larger than threshold [0 1] (Alternatively: number of stations where transient duration larger than threshold)
Large amplitude detection: at least one fourth (or any other fraction) of the cc windows contain large amplitudes (not to scale) (*exclude* these time windows)
Automatically identified potential tremor signal [no 0 yes 1]
6-sec tremor template identified by D. Shelly (not to scale)



12 HRSN borehole stations



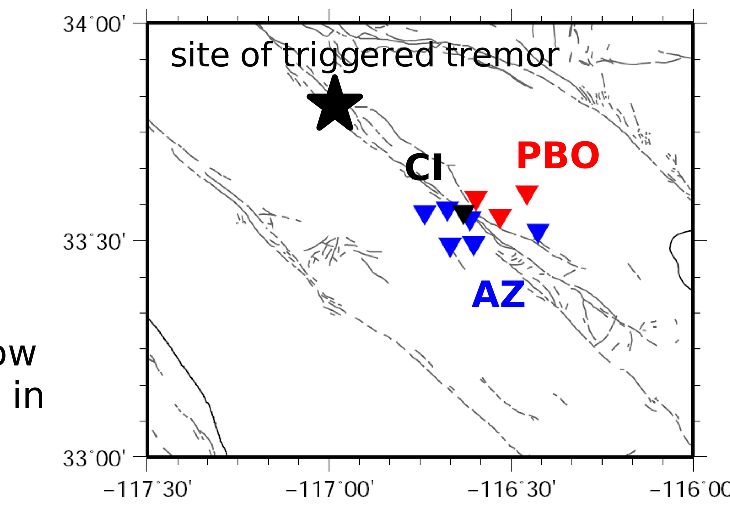
3 surface broadband stations

Transients with durations larger than about a minute are still identified by the three relatively widely spaced surface broadband stations.

We apply the transient detection algorithm [1] to the target area in the vicinity of the San Jacinto fault using data only from the PBO borehole stations, after learning that amplitudes associated with potential tremor signals in this area are weaker compared to signals from the SAF central section. To confirm the tectonic origin of the analyst-reviewed automatically selected signals, we use waveforms from these highlighted time periods as initial templates in a low frequency earthquake (LFE) matched-filter approach:

[2] LFE Matched-Filter Detection (critical algorithmic choices)

0 Use data from limited time periods identified by [1] using exclusively PBO stations as initial templates to facilitate computational progress
1 Compute summed auto correlation values between equal-lag correlation windows (5 sec) and continuous waveforms from PBO, CI, and AZ stations in the target area
2 Select template/matched waveforms that show statistically significant auto correlations at all stations (3 components)
3 Group waveforms depending on similarity in windows around initial detection window (10 sec) (assumption: detect similar waveforms associated with near repeats of LFE's in a confined source region)
4 Construct stacked master templates for repeated, robust LFE verification, using larger thresholds
5 Use highest-similarity templates to adjust for P and S arrival on vertical and horizontal components; Perform grid search to determine most likely source location using these measurements

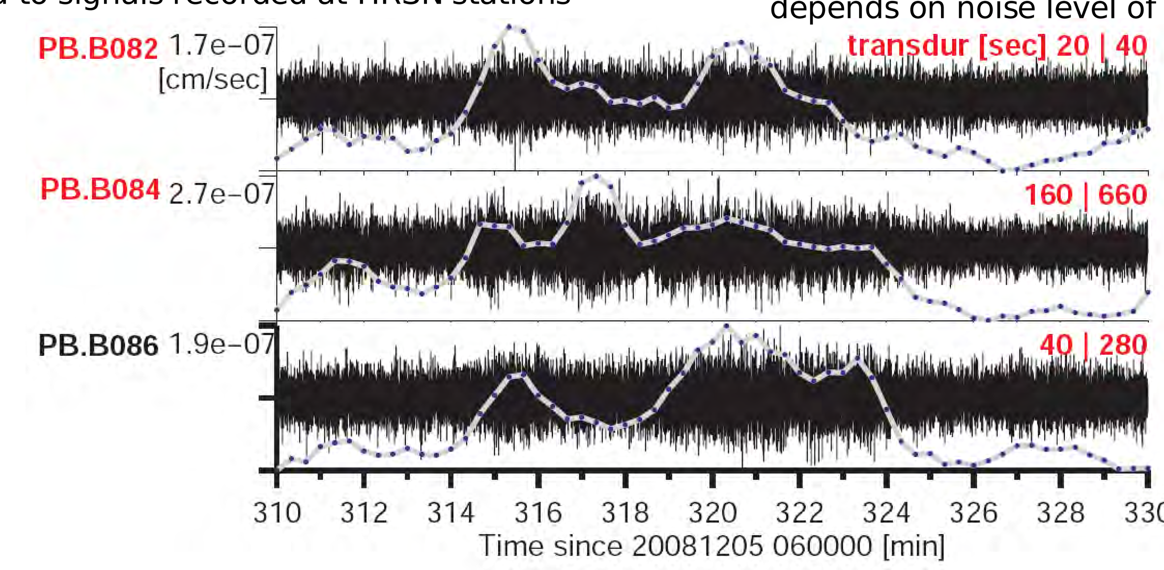


[2]0 Identification of Potential Tremor Transients Using [1]

The opposite figure shows 20 minutes of 2-8 Hz filtered horizontal components from the PBO borehole stations. The envelopes (grey/blue-dotted) are cross correlated and checked for similarity (established for 1 and 2); In addition, the duration of amplitude values above a threshold is measured to select times that contain transients associated with tremor signals.

maximum tremor amplitudes are smaller compared to signals recorded at HRSN stations

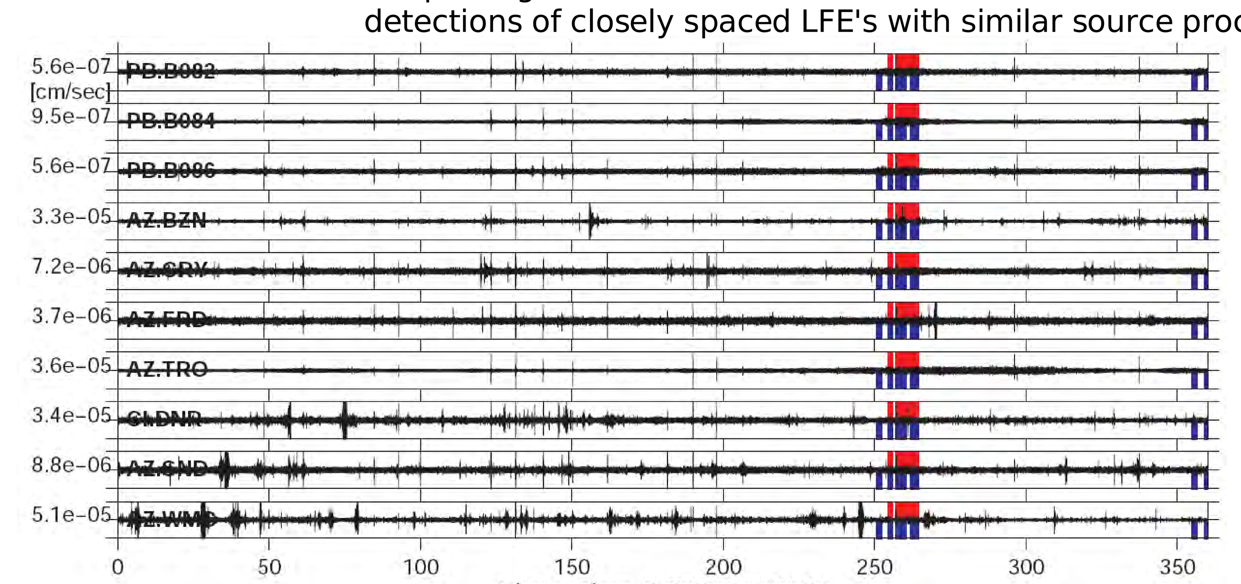
transient duration (min|max) depends on noise level of station



[2]1-2 Application of LFE Matched Filter Detection Using Transient Waveforms

From a limited time interval as identified by the above procedure, consecutive 5 second windows are cross correlated with all data, at all stations (including AZ and CI), using 3 components (red templates in the figure from 255-265 min matched any of the blue indicated waveforms). *The clustering of LFE detections suggests a tectonic origin of the increased amplitude levels visible only at the PBO stations.*

equal-lag auto correlations across a cluster of stations show detections of closely spaced LFE's with similar source processes

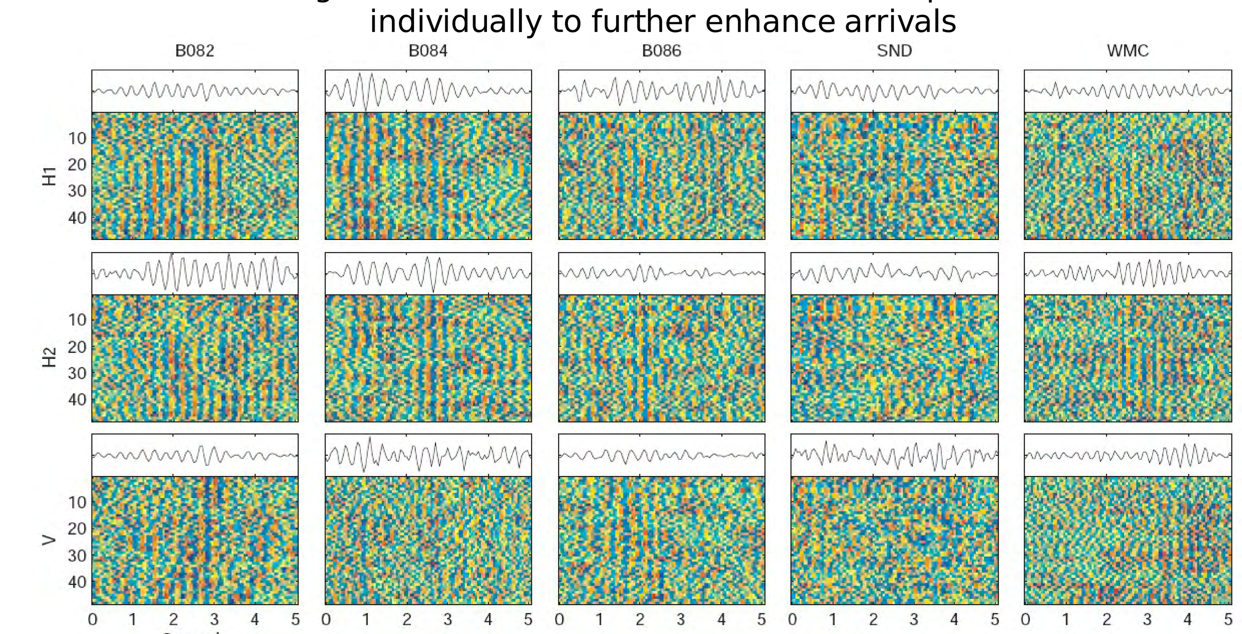


[2]3 Clustering of Similar Waveforms to Construct Stacked Templates

The similarity of 48 matching waveforms is exploited to construct stacked master templates of the type shown in the top traces of the figure. Groups of robust detections, now called verifications, using these master templates are then aligned on the horizontal and vertical components individually to enhance the P and S wave arrivals. In tandem with the moveouts measured across the network, this information will be used in a grid search to locate the most probable source volume.

Left to be done: Verify & Locate.

stacked waveforms enhance weak P and S arrivals; align traces on horizontal and vertical components individually to further enhance arrivals



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