Spectral Tremor Detection Method

We stack unfiltered, daylong, east-component seismograms for all the available stations within the network and normalize for the number of operating stations and daily mean energy across all frequencies. We produce daily spectrograms with ~82 s windows and 50% overlap. Peaks of energy are identified within certain bands: the tremor band is chosen as 2-7 Hz and the earthquake/noise band 7-15 Hz. The spectrograms for the entire duration of the dataset (2006-2009) are computed and a baseline threshold established above which detections are defined. Because we want to allow positive tremor or earthquake/noise detections when power in a significant portion of the defined frequency bands exceed the baseline threshold, we establish a required percentage of the frequency band that must exceed the baseline threshold (termed the threshold percentage) for a positive detection. Our algorithm scans the entire dataset and for each time window determines the percentage of signal within the tremor and earthquake/noise bands, that falls above the baseline threshold. All time windows where this percentage exceeds the tremor and/or earthquake/noise threshold percentage are considered a positive tremor and/or earthquake detection. Time windows that contain only a tremor detection are retained, if an earthquake/noise-band detection occurs within the same window as a tremor detection, that tremor detection is negated.

In order to determine threshold percentages for tremor and earthquake/noise detections, we generated 10,201 tremor detection catalogs using data for several weeks surrounding the May 2007 slow slip event and different percentages between 0% and 100%, in 1% increments. We then compared these detection catalogs with an analyst-determined hand counted tremor catalog for the same time period [*Outerbridge et al.*, 2010]. The visually determined tremor catalog indicated that tremor started abruptly on Julian Day (JD) 136, continued at a high level through

JD 142, and tapered off by JD 146. The ten days preceding tremor initiation were virtually devoid of tremor activity. We tuned the threshold percentages to best fit this pattern by calculating the ratio of tremor detections between JD 136-146 to JD 125-135 for each of the 10,201 tremor catalogs and chose the threshold percentages that maximized this ratio. The highest ratio attained for the computed catalogs was 16.5, corresponding to tremor and earthquake percentage thresholds of 46% and 28%, respectively. These values are likely network and region specific. A combination of the high microseismicity and cultural noise for the Nicoya region likely determines the best values. This threshold percentage method could be easily tailored for use in other tectonic environments.

Comparison of Automatic Detection to Visually Determined Catalog of Tremor

The visually determined tremor catalog for 2007 presented in *Outerbridge et al.* [2010] counts the number of tremor episodes that occur within each hour lasting at least four minutes and computes tremor durations for the entirety of each episode. Because tremor episodes often consist of several tremor bursts separated by quiet intervals, this catalog overestimates tremor durations. Both the handpicked and automated tremor catalogs identify peak tremor activity in 2007 on JD 137. On this day the hand-picked catalog contains 36 tremor episodes totaling almost 400 minutes, while the automated detection algorithm described here finds 22 events with a total estimated duration of only 30 minutes. The spectrogram for this day displays an unusually high level of noise during both local daylight and night-time hours that unfortunately obscures a lot of the tremor activity. Automatic tremor detection methods developed for use in Mexico [*Husker et al.*, 2010] and Cascadia [*Wech and Creager*, 2008] also suffer from reduced tremor counts compared to handpicked determinations of tremor. These researchers have attributed this to storm activity and cultural noise, which both reduce automated detection compared to visual inspection. *Brudzinski and Allen* [2007] recognized the difficulty of detecting tremor in the presence of cultural noise and only searched for tremor during the twelve, quiet night-time hours. Because automated tremor detection algorithms consistently underestimate tremor when compared with visual inspection, we consider our tremor catalog to provide a lower bound estimate of tremor activity.

Tremor Location Method

Tremor events are located using an envelope cross-correlation method to determine the phase lag across the network similar to *Obara* [2002]. Daylong seismograms for each station are band-passed at 2-7 Hz, smoothed, decimated to a 2 Hz sample rate, and converted to single-sided functions or envelopes. Subtracting the mean and dividing by the standard deviation normalizes the envelopes for each station. We determine time lags for the maximum cross-correlation coefficient relative to one of the stations and exclude stations that do not have a correlation coefficient greater than 0.65. With the phase lag, we locate the tremor events with HYPOINVERSE [*Klein*, 1978], using a one-dimensional S-wave model determined for this region [*DeShon et al.,* 2006].

References

Brudzinski, M. R., and R. M. Allen (2007), Segmentation in episodic tremor and slip all along Cascadia, *Geology*, *35*, 907-910.

DeShon, H.R., S.Y. Schwartz, A.V. Newman, V. Gonzalez, J.M. Protti, L.M. Dorman, T. Dixon, E. Norabuena, and E. Flueh (2006), Seismogenic zone structure beneath the Nicoya Peninsula, Costa Rica, from 3D local earthquake P- and S- wave tomography*,* *Geophys. J. Int*., 164, 109-124.

Husker, A., S. Peyrat, N. Shapiro, and V. Kostoglodov, (2010), Automatic non-volcanic tremor detection in the Mexican subduction zone, *Geofisica Internacional* 49 (1), 17-25.

Klein, F.W. (1978), Hypocenter location program HYPOINVERSE, U.S. Geological Survey Open-File Report 78-694, 113 pp.

Obara, K. (2002), Nonvolcanic deep tremor associated with subduction in southwest Japan, *Science*, 296: 1679-1681.

Outerbridge, K. C., T. H. Dixon, S. Y. Schwartz, J. I. Walter, M. Protti, V. Gonzalez, J. Biggs, M. Thorwart, and W. Rabbel (2010), A Tremor and Slip Event on the Cocos-Caribbean Subduction zone as measured by a GPS and Seismic Network on the Nicoya Peninsula, Costa Rica, *J. Geophy. Res.*, doi:10.1029/2009JB006845

Wech, A. G., and K. C. Creager (2008), Automated detection and location of Cascadia tremor, *Geophys. Res. Lett*., 35, L20302, doi:10.1029/2008GL035458.

92

93