Bulletin of the Seismological Society of America, Vol. 86, No. 1A, pp. 255–258, February 1996

Short Notes

Continuous Monitoring of Seismic Energy Release Associated with the 1994 Northridge Earthquake and the 1992 Landers Earthquake

by Sharon Kedar and Hiroo Kanamori

Abstract We have developed a method to detect long-period precursors for large earthquakes observed in southern California, if they occur. The method allows us to continuously monitor seismic energy radiation over a wide frequency band to investigate slow deformation in the crust (e.g., slow earthquakes), especially before large earthquakes. We used the long-period records (1 sample/sec) from TERRAscope, a broadband seismic network in southern California. The method consists of dividing the record into a series of overlapping 30-min-long windows, computing the spectra over a frequency band of 0.00055 to 0.1 Hz, and plotting them in the form of a time-frequency diagram called spectrogram. This procedure is repeated daily over a day-long record. We have analyzed the 17 January 1994 Northridge earthquake (M_w = 6.7), and the 28 June 1992 Landers earthquake (M_w = 7.3). No slow precursor with spectral amplitude measured over a duration of 30 min larger than that of a magnitude 3.7 was detected prior to either event. In other words, there was no precursor whose moment was larger than ~0.003% of the mainshock.

Introduction

The initiation of an earthquake is generally considered abrupt. However, some precursory slow slip has been reported for the 1960 Chilean earthquake (Kanamori and Cipar, 1974; Kanamori and Anderson, 1975; Cifuentes and Silver, 1989), the 1944 Tonankai earthquake (Sato, 1970, 1977; Mogi, 1984), the 1983 Japan Sea earthquake (Linde *et al.*, 1988), and the 1989 Macquarie Ridge earthquake (Ihmle *et al.*, 1993). In particular, the leveling data before the Tonankai earthquake suggest a precursory tilt as large as 30% of that of the mainshock for a few hours prior to it. Unfortunately, data are very limited for both the Chilean earthquake and the Tonankai earthquake. Also, Kedar *et al.* (1994) saw no direct evidence for the precursor for the Macquarie Ridge earthquake. Hence, whether or not slow precursory deformations occur under certain circumstances is not presently resolved.

In contrast, several recent studies (mainly of California earthquakes) demonstrated that if a slow precursory slip occurs, it is probably less than 1% of the mainshock in terms of seismic moment (Johnston *et al.*, 1994, 1990, 1987; Agnew and Wyatt, 1989; Linde and Johnston, 1989). Also, modeling studies using velocity-weakening constitutive relations predict that such precursory changes on time scales of minutes are less than 1% of the mainshock moment (Lorenzetti and Tullis, 1989).

An example of slow deformation detection is that of Beroza and Jordan (1990) who used spectral amplitudes of the Earth's normal modes to identify slow earthquakes otherwise undetected. We have developed a method for continuously monitoring the long-period (1 sample/sec) record from TERRAscope, the Caltech/USGS Southern California Broadband seismic network. We report here the results from two recent large earthquakes in southern California: the 1994 Northridge earthquake and the 1992 Landers earthquake.

Method

The long-period part of the spectrum was analyzed by means of a frequency-time diagram or "spectrogram." The spectrograms were constructed and fine-tuned particularly for analysis of TERRAscope data over a frequency band 0.00055 to 0.1 Hz. The computation is done by taking the frequency spectrum of a 30-min-long time window (hence the low-frequency end 1/1800 sec = 0.00055 Hz), advancing the window by 10 min, and repeating the computation. The cutoff amplitude for the spectrogram was determined for each station to emphasize signals that are slightly above noise level. This analysis is performed automatically every day for the Pasadena station (PAS).

17 January 1994 Northridge Earthquake

Figure 1 shows the spectrogram for the mainshock of the 1994 Northridge earthquake and its aftershock sequence

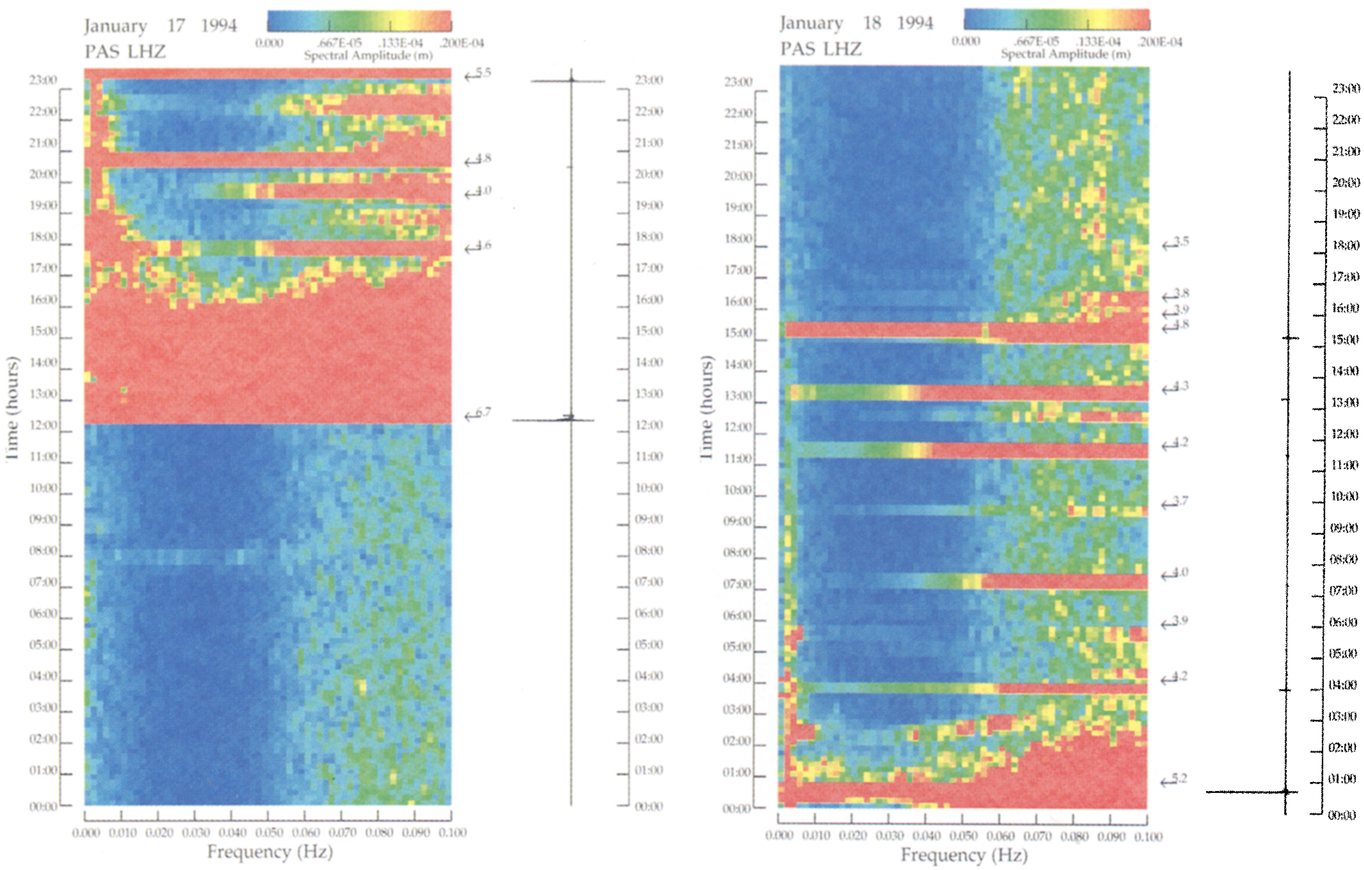

Figure 1. (a) Spectrogram for 17 January and (b) 18 January 1994 recorded on the long-period vertical component of the Pasadena TERRAscope station. The corresponding time series is shown in the boxes on the right-hand side of the spectrograms. The mainshock and some of the observed aftershocks are marked by magnitude on the spectrogram.

observed on the long-period velocity channel at Pasadena ($\Delta = 35$ km). The window position is adjusted so that the origin time of the mainshock is at the beginning of the 30-min-long time window, which includes the mainshock. Note that the first window to include the mainshock starts 20 min prior to it, resulting in high amplitude of the spectrogram prior to the appearance of the mainshock on the time trace.

To determine the detection threshold of slow events, we used the spectra of the aftershocks. Figure 1b shows that the aftershocks with $M \geqq 3.7$ can clearly be identified over the entire frequency band, but the aftershock with magnitude $M = 3.5$ is not obvious at long period. Thus, a slow event with a seismic moment comparable to that of $M \geqq 3.7$ events would be detected over the long-period band (left-hand side) of the spectrogram. The window length used in our analysis is 30 min. Therefore, if the duration of the slow event is longer than 30 min, then its moment increase in that time period must be larger than the moment of an $M = 3.7$ earthquake for it to be detected on the spectrogram.

Immediately before the mainshock, no long-period event can be detected. A long-period signal is observed at 8:00 a.m. at the frequency band of 0.01 to 0.05 Hz. Although the lack of short-period energy associated with this signal could suggest a local slow event, a further look across the array reveals a long-period wave train coming from the northwest with a group velocity of ~4 km/sec (Fig. 2). We conclude that this signal is caused by a Rayleigh wave from a small teleseismic event and not by any local slow event.

Figure 1 shows no slow precursory event whose long-period spectral amplitude measured over a period of 30 min is larger than that of $M = 3.7$ during the 12-hr period prior to the 1994 Northridge earthquake.

28 June 1992 Landers Earthquake

Figure 3 displays the spectrogram for the 1992 Landers earthquake and its aftershock sequence, which includes the Big Bear earthquake ($M_w = 6.5$). The records are taken from the east–west component of the Piñon Flat (PFO) station. Several events appear prior to the mainshock. A magnitude 3.6 local earthquake is observed at 5:55 a.m., and a teleseismic Rayleigh-wave packet arrives after 6:00 a.m.

The spectrogram begins with a long-period (0.005 to 0.02 Hz) signal, which dies out by 3:00 a.m. Examination

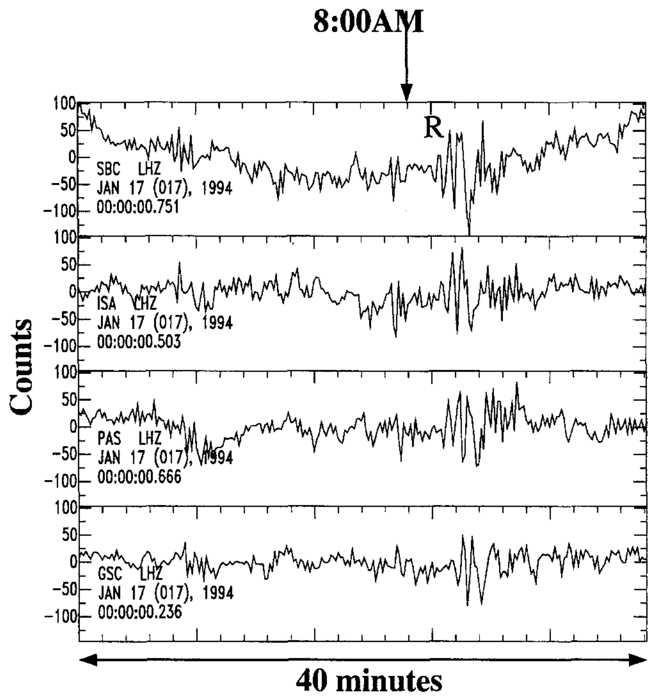

Figure 2. A 40-min-long window around 8:00 a.m. on 17 January 1994, at several TERRAscope stations. The questionable signal observed on the spectrogram at Pasadena has the appearance of a teleseismic Rayleigh wave propagating from the northwest.

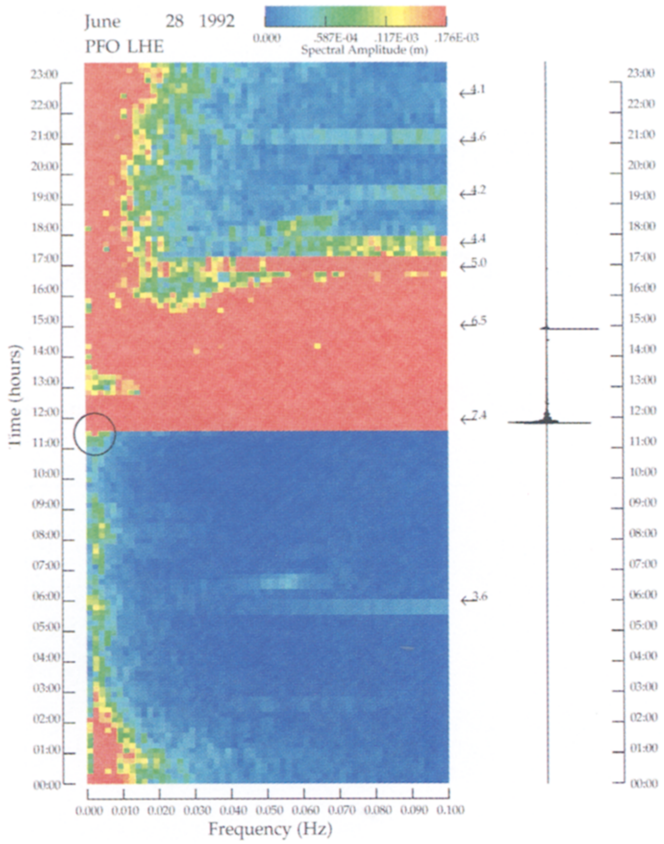

Figure 3. Spectrogram of the 28 June 1992 Landers earthquake and some of its aftershocks recorded on the east–west long-period component of the Piñon Flat TERRAscope station. Marked by a circle is a suspicious long-period event showing up right before the mainshock on the spectrogram.

of the three days prior to 28 June (Fig. 4) reveals a daily pattern of background noise whose tail end decays in the beginning of 28 June and is not associated with the Landers earthquake.

An intriguing signal on the spectrogram is the one marked by a circle in Figure 3. It appears during the last time window just before the mainshock. A closeup of the last 30 min before the mainshock (Fig. 5) reveals an ~6 min-long signal on the east–west component, slightly stronger than the background noise. This signal is equivalent to a tilt of $\sim 10^{-9}$ radians. However, examination of the Piñon Flat strainmeter records (Frank Wyatt, personal comm.) and the Punchbowl strainmeter records (Malcolm Johnston, personal comm.) show no east–west disturbance of the same order of magnitude during this time window, which leads to the conclusion that the signal in question is a site-related long-period noise.

Conclusion

We have introduced a convenient method for detection of long-period signals on the seismic record by computing daily spectrograms of the long-period data channel of TERRAscope stations. We have presented two cases of interest: the 1994 Northridge earthquake and the 1992 Landers earthquake. In both cases, some suspicious long-period events appeared on the spectrograms prior to the mainshock.

An examination of the 12-hr period prior to the main-

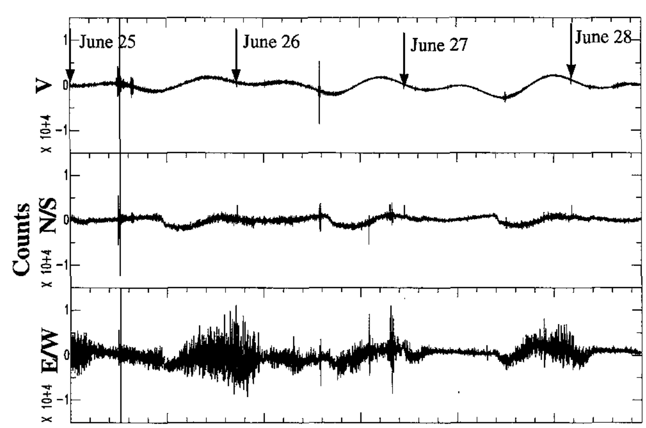

Figure 4. Three and a half days preceding the Landers earthquake at Piñon Flats. The horizontal-component noise shows a daily cyclic pattern. The noise level from 27 June decreases into the beginning of 28 June.

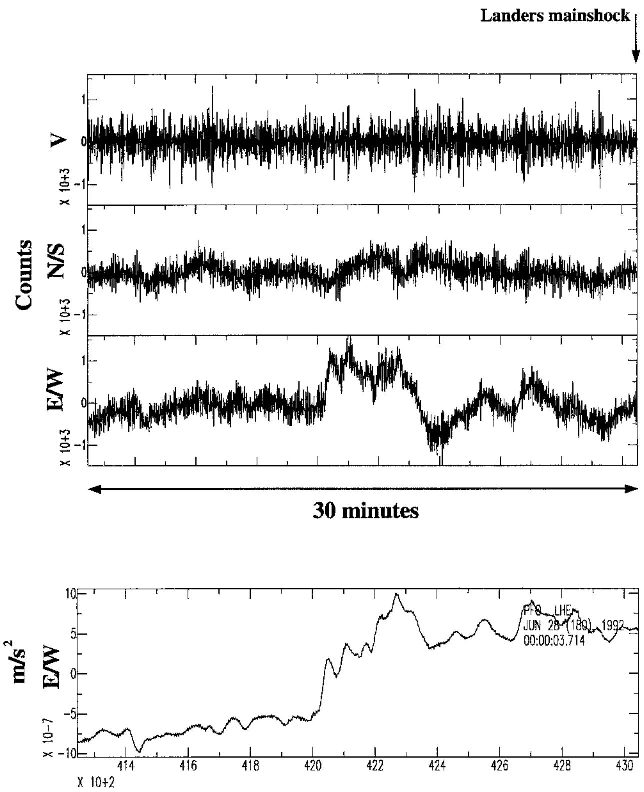

Figure 5. A closeup on the last half hour prior to the mainshock of the 1992 Landers earthquake. A long-period disturbance appears on the east–west component 10 min prior to the mainshock. The east–west component long-period acceleration is $\sim 1.5 \times 10^{-6}$ m/sec^2 or equivalently $\sim 1.5 \times 10^{-9}$ radians.

shock leads us to conclude that there was no slow precursory event whose long-period spectral amplitude measured over a duration of 30 min is larger than that of an $M = 3.7$ event during the 12-hr period prior to the 1994 Northridge earthquake. In other words, there was no precursor whose moment was larger than $\sim$0.003% of the mainshock. This result is consistent with the observation of Johnston (1994).

Similarly, no slow precursor with spectral amplitude larger than a magnitude 3.7 was detected in the 12 hr prior to the 1992 Landers earthquake. Again, this result agrees with the observation of Wyatt *et al.* (1994).

Acknowledgments

The authors wish to thank Robert Clayton from Caltech for his invaluable advice in constructing the spectrogram. We thank Frank Wyatt from UCSD and Malcolm Johnston from the USGS for sharing their tilt-meter records of the 1992 Landers earthquake. This study was supported by USGS Grant 1434-93-G-2305 and USGS Grant 1434-95-G-2554. Contribution Number 5561 of the Division of Geology and Planetary Sciences, California Institute of Technology.

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Manuscript received 3 July 1995.