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LOW-FREQUENCY MAGNETIC FIELD MEASUREMENTS NEAR THE EPICENTER OF THE M_S 7.1 LOMA PRIETA EARTHQUAKE

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Abstract. We report the results of measurements of low frequency magnetic noise by two independent monitoring systems prior to the occurrence of the M_S 7.1 Loma Prieta earthquake of 17 October 1989. Our measurements cover 25 narrow frequency bands in the more than six-decade frequency range 0.01 Hz–32 kHz, with a time resolution varying from a half hour in the ULF range (0.01–10 Hz) to one second in the ELF/VLF range (10 Hz–32 kHz). The ULF system is located near Corralitos, about 7 km from the epicenter. The ELF/VLF system is located on the Stanford campus, about 52 km from the epicenter. Analysis of the ELF/VLF data has revealed no precursor activity that we can identify at this time. However, the ULF data have some distinctive and anomalous features. First, a narrow-band signal appeared in the range 0.05–0.2 Hz around September 12 and persisted until the appearance of the second anomalous feature, which consisted of a substantial increase in the noise background starting on 5 October and covering almost the entire frequency range of the ULF system. Third, there was an anomalous dip in the noise background in the range 0.2–5 Hz, starting one day ahead of the earthquake. Finally, and perhaps most compelling, there was an increase to an exceptionally high level of activity in the range 0.01–0.5 Hz starting approximately three hours before the earthquake. There do not appear to have been any magnetic field fluctuations originating in the upper atmosphere that can account for this increase. Further, while our systems are sensitive to motion, seismic measurements indicate that there were no significant shocks preceding the quake. Thus, the various anomalous features in our data, and in particular the large-amplitude increase in activity starting three hours before the quake, may have been magnetic precursors.

Introduction

On October 17, 1989, at 15.24 seconds after 5:04 p.m. PDT, *i.e.*, at 0004:15.24 UT on October 18, a moderately-large M_S 7.1 earthquake occurred "suddenly and without foreshock activity" in Northern California [*USGS Staff*, 1990]. Its epicenter (37.039° N, 121.879° W) was located near Mt. Loma Prieta in the California Coast Range, just south of the San Francisco Bay area. At the time, we were operating two independent electromagnetic noise monitoring systems at locations relatively close to the epicenter, in continuation of a long-term program of low-frequency radio noise measurements that had started over two years previously. Taken together, the two systems provided complete coverage of magnetic field changes in the more than six decade frequency range 0.01 Hz to 32 kHz. One of these systems (the ultra-low frequency (ULF) system; frequencies 0.01–10 Hz) was located at Corralitos, California (37.015° N, 121.806° W), only 7 km from the epicenter, and the other (the extremely-low/very-low frequency (ELF/VLF) system; frequencies 10 Hz–32 kHz) was located on the Stanford campus (37.43° N, 122.18° W), about 52 km from the epicenter.

Since there have been numerous reports in recent years of possible electromagnetic precursors to earthquakes, some of which have involved frequencies covered by our ELF/VLF monitoring system [e.g., *Gokhberg et al.*, 1981, 1982; *Oike and Ogawa*, 1982; *Parrot and Mogilevsky*, 1989; *Tate and Daily*, 1989; *Larkina et al.*, 1989], we began processing our Stanford ELF/VLF data as soon as possible after the earthquaketo see whether any precursor activity could be detected. Somewhat later, we also retrieved and began processing our ULF data. We had less reason to expect electromagnetic precursors in these latter data, because previous reports of precursor signals at frequencies below the ELF/VLF range have, with few exceptions, involved frequencies either below or predominantly below our ULF range of operation [e.g., *Rikitake*, 1976; *Varotsos and Alexopoulos*, 1987; *Johnston*, 1989]. As we will now describe, the Stanford ELF/VLF data do not appear to show precursor activity, whereas the Corralitos ULF data contain a number of anomalous features that may prove to be precursors.

ELF/VLF Measurements

The Stanford ELF/VLF electromagnetic noise monitoring system is one of eight identical instruments that have been installed around the world and which have been described in detail elsewhere [*Fraser-Smith and Helliwell*, 1985]. Crossed-loop antennas are used to measure the magnetic component of the noise. The system records both analog and digital data, and it computes a variety of statistical quantities that define the characteristics of the ELF/VLF noise and which can be further processed to provide additional statistical measures of the noise. The data of immediate interest to us are the average amplitudes that are computed at the end of every minute from 600 amplitude measurements made at a rate of 10 per second on the envelope of the signal emerging from 16 narrow-band (5% bandwidth) filters. The center frequencies of the filters are at 10, 30, 80, 135, 275, 380, 500, and 750 Hz, and 1.0, 1.5, 2.0, 3.0, 4.0, 8.0, 10.2, and 32.0 kHz.

Following the October 17 earthquake, we prepared and examined plots of the one-minute average noise amplitudes for the preceding month. Taking into account the normal variations in the ELF/VLF noise data, no unusual changes in the amplitudes could be distinguished at any time pre-

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ceding the earthquake. To illustrate the form of the data, in Figure 1 we show simultaneous plots of the one-minute averages for 10 Hz, 500 Hz, 2 kHz, and 8 kHz, for the 8 day interval 13–20 October, 1989. The only obvious features are the well-defined diurnal variations that persist essentially unchanged throughout the interval.

Except for the fact that it was obtained for such a large earthquake, this negative result was not completely unexpected. On three earlier occasions we have searched for precursor signals in the Stanford ELF/VLF noise data following the occurrence of local earthquakes with magnitudes close to 5 (Alum Rock, 13 June 1988, $M_L = 5.3$; Lake Ellsman 1, 27 June 1988, $M_L = 5.0$; Lake Ellsman 2, 8 August 1989, $M_L = 5.2$) without detecting any obvious precursor signals. This latest observation sets a new upper limit on the magnitudes of the local earthquakes for which earthquake-related ELF/VLF radio noise has not been detected.

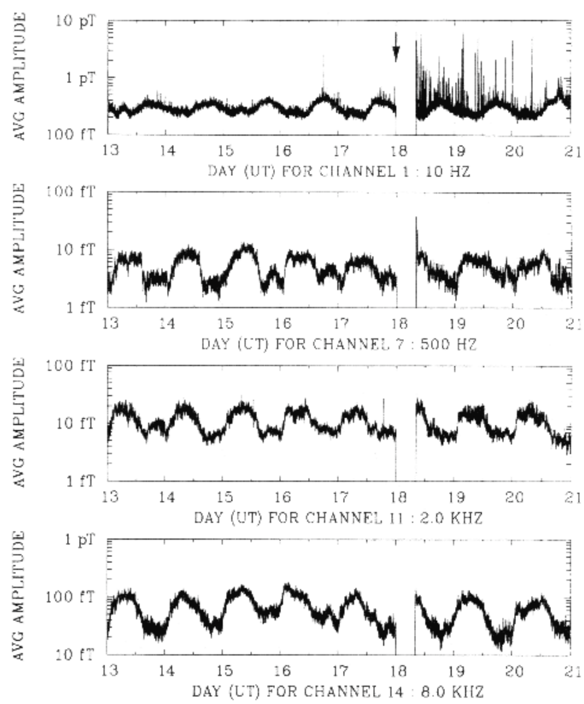

Fig. 1. Variation over the 8 day interval 13–20 October 1989 of the one-minute average ELF/VLF noise amplitudes measured at Stanford University for the four representative frequencies 10 Hz, 500 Hz, 2 kHz, and 8 kHz. The earthquake occurred just after 0004 UT on October 18 (arrow); it was followed immediately by an 8-hour power failure. Shaking of the antennas by aftershocks generated the many transients that can be seen in the 10 Hz data after the measurements recommenced. Note the different amplitude scales.

ULF Measurements

In addition to the ELF/VLF monitoring systems, we have also developed a geomagnetic activity index generator that can be used to characterize and monitor the state of natural geomagnetic activity in the ULF range 0.01–10 Hz [*Bernardi*, 1989]. Two of these systems have been built; one is now located at Grafton, New Hampshire, and the other is located at Corralitos. They are conventional in many of their technical details, including their use of solenoidal coils as sensors. However, they differ significantly from previous systems used by our Laboratory and by others for measurements of ULF geomagnetic field changes through their use of a small computer as an integral part of the measurement system and through an emphasis on the real-time computation of digital measures of the noise power. As described in greater detail by *Bernardi et al.* [1989], the basic output of each index generation system is a set of logarithms to the base two of the half-hourly averages of the power in nine frequency bands covering the overall range 0.01–10 Hz. These logarithms comprise our magnetic activity (MA) indices, which are stored permanently on a magnetic disk and which are continuously available via telephone line (the raw samples are discarded, due to limitations in storage capacity). Table 1 lists the nine frequency bands, their center frequencies, and conversion factors that enable the indices in each band to be converted to units of $pT/\sqrt{Hz}$.

Table 1. Table to convert MA indices to magnetic field units. To convert a particular MA index value, M, to a corresponding average magnetic field amplitude, a, in $pT/\sqrt{Hz}$, substitute M and the appropriate conversion factor C in the expression $a = \sqrt{2^M \times C}$ $pT/\sqrt{Hz}$.

MA Index	Frequency Band (Hz)	Center Frequency (Hz)	Conversion Factor (C)
MA3	0.01–0.02	0.015	$2.704 \times 10^{+2}$
MA4	0.02–0.05	0.033	$4.790 \times 10^{+1}$
MA5	0.05–0.10	0.073	$1.070 \times 10^{+1}$
MA6	0.10–0.20	0.150	2.645×10^{0}
MA7	0.20–0.50	0.352	4.992×10^{-1}
MA8	0.50–1.00	0.751	1.213×10^{-1}
MA9	1.00–2.00	1.502	3.698×10^{-2}
MA10	2.00–5.00	3.501	1.368×10^{-2}
MA11	5.00–10.0	7.500	7.129×10^{-3}

The Corralitos index generator has been in operation since October 1987. It was running during the Alum Rock and Lake Ellsman 2 earthquakes, but its measurements showed no evidence of precursor signals. As already noted, its location was fortuitously only 7 km away from the epicenter of the Loma Prieta earthquake. There was a 39-hour loss of power following the earthquake, after which, when power was restored, the system automatically recommenced operation. When the indices were inspected, it was clear that there had not only been major changes in the measurements in the few hours before the earthquake but also in the preceding weeks. We first suspected that the changes could have been caused either by seismic activity moving the coil sensor and producing spurious signals or by an extraordinarily lengthy interval of natural large-amplitude magnetic activity. Because of the half-hour averaging involved in their computation, the MA indices are not particularly sensitive to even moderately large ground motions of short duration (local earthquakes of magnitude ~ 5 have produced only small co-seismic increases in the indices), so the seismic activity required to produce the anomalous changes would have had to be either particularly persistent, very strong, or a combination of the two. However, we were able to establish that there had been no significant seismic activity before the earthquake [W. L. Ellsworth and M. J. S. Johnston, personal communications, 1989; *USGS Staff*, 1990]. In addition, the available geomagnetic activity indices did not show any evidence of magnetic storms or other increases in activity that could account for our measurements before the earthquake (The daily sum of Kp remained less than 27+ throughout the interval October 1–19; there was a moderately-large storm on October 20–21, during which time the sum of Kp reached 57). Unfortunately, the East coast index generator was not operating at the time.

The complete set of MA indices for the months of September and October 1989 are shown in Figure 2. Most of the fluctuations in the September indices are typical of those observed during earlier months and can be considered normal. However, around September 12 an anomalous signal began to appear in the data for the two adjacent frequency bands 0.05–0.1 Hz and 0.1–0.2 Hz and it grew until it was of comparatively large amplitude (the largest converted amplitude (Table 1) is roughly 1500 pT). The unusual alternation of the signal amplitude between the two frequency bands suggests that it has a narrow bandwidth centered on 0.1 Hz and that this center frequency drifts between the two bands. On October 5 the narrow band signal disappeared upon the occurrence of the second anomaly in the measurements: a large and sustained increase in the noise background covering all the frequencies of operation, but strongest at the lowest frequencies (~ 0.01 Hz), where the increase is to an amplitude roughly 30 times the inferred normal amplitude. This anomalous increase gradually declined in strength until the day before the earthquake. The third and fourth anomalous changes occurred on this latter day. The third is a distinctive drop and recovery in the noise background in the frequency range 0.2–5 Hz, and the fourth, confined to the frequency range 0.01–0.5 Hz, is an increase to an exceptionally large level of activity starting approximately three hours before the earthquake.

Figure 3 shows the changes that take place at 0.01 Hz in a different format. Absolute magnetic field units are used and it can be seen that the largest amplitudes exceed the normal background level by over 100 times (the amplitudes of these largest signals also exceed the dynamic range of our system, so their measured amplitudes are probably smaller than their true values). The aftershock data are also of particular interest, but their analysis is made difficult by the large number and variety of aftershocks, by the shaking response of our measurement system, and by the occurrence of the magnetic storm on October 20–21. No analysis of the aftershock data has been attempted at this time.

Discussion

The ULF measurements shown here obviously require much further analysis before any of their anomalous features can be said to be precursors to the Loma Prieta earthquake. However, the location of the Corralitos ULF index generator so close to the epicenter of the earthquake, and the timing of the occurrence of the anomalous features, particularly the increase to an exceptionally high level of activity starting three hours before the earthquake, are encouraging. The lack of similar anomalies in the ULF data obtained during two earlier local earthquakes of magnitude ~ 5 suggest that there is a threshold of magnitude below which the anomalies are not produced. We can only superficially describe all our ULF measurements here; their analysis is continuing and we hope to report in greater depth in a further publication [*Bernardi et al.*, manuscript in preparation, 1990]. In the long run, confirmation of the data will require measurements during further moderately-large to large earthquakes.

The lack of any clearly obvious precursor signals in the ELF/VLF data for four local earthquakes, including the Loma Prieta earthquake, is also of considerable interest, particularly in view of the earlier reports of such precursors. We cannot claim that this is a general result at this time because of the many differences in the geophysical

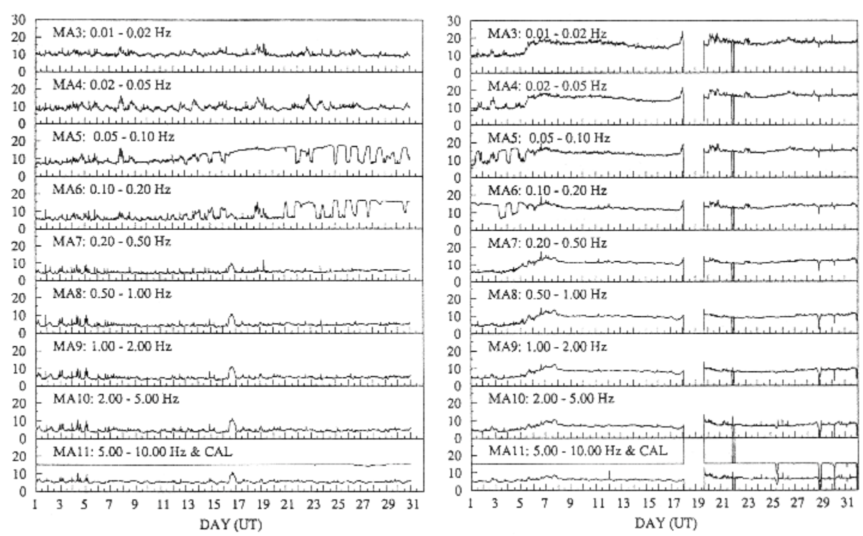

Fig. 2. Variation of the magnetic activity indices measured during the months of September (left panel) and October (right panel), 1989. The power failure caused by the Loma Prieta earthquake created the large gap in the October data. The horizontal line in the 5.00–10.00 Hz display is a calibration signal (12.5 Hz). It should be present and remain at a constant amplitude at all times for the index generator to be operating correctly.

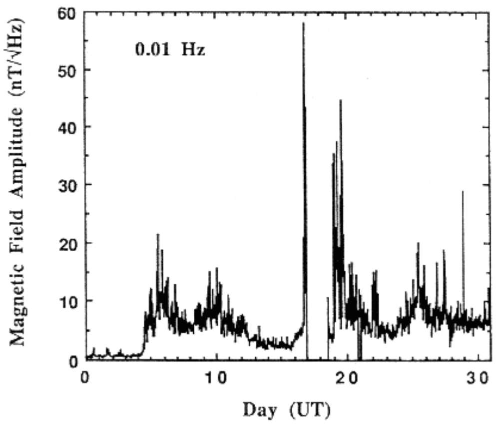

Fig. 3. Variation of the Corralitos 0.01 Hz magnetic field measurements during October 1989. The Loma Prieta earthquake started just after 0004 UT on October 18 and a power failure occurred almost immediately, whereupon the magnetic field measurements went to zero. The large peaks following the earthquake include many aftershocks as well as a magnetic storm that peaked October 20–21. The amplitudes can be converted to nT units (where 1 nT = 1000 pT) by multiplying by $\sqrt{0.00732}$, or 0.0855.

characteristics of earthquakes. In the case of the Loma Prieta earthquake, for example, the hypocenter was comparatively deep (for an earthquake along the Northern California section of the San Andreas fault) and the earthquake may not have produced any of the surface electrical effects, or other changes, which presumably are required to launch ELF/VLF signals into the atmosphere. On the other hand, some of the earlier reports of VLF signals from earthquakes have involved earthquakes at much greater depths and distances from the measurement systems [e.g., *Gokhberg et al.*, 1981, 1982]. Our lack of observation of precursor ELF/VLF noise so close to the epicenters of several moderate to moderately-large earthquakes shows that ELF/VLF noise need not be a strong nor an obvious feature of every earthquake.

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