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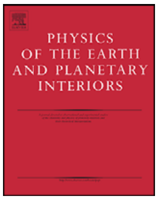

On the reported magnetic precursor of the 1989 Loma Prieta earthquake

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ABSTRACT

Among the most frequently cited reports in the science of earthquake prediction is that by Fraser-Smith et al. (1990) and Bernardi et al. (1991). They found anomalous enhancement of magnetic-field noise levels prior to the 18 October 1989 Loma Prieta earthquake in the ultra-low-frequency range (0.0110–10.001 Hz) from a ground-based sensor at Corralitos, CA, just 7 km from the earthquake epicenter. In this analysis, we re-examine all of the available Corralitos data (21 months from January 1989 to October 1990) and the logbook kept during this extended operational period. We also examine 1.0-Hz (1-s) data collected from Japan, 0.0167-Hz (1-min) data collected from the Fresno, CA magnetic observatory, and the global *Kp* magnetic-activity index. The Japanese data are of particular importance since their acquisition rate is sufficient to allow direct comparison with the lower-frequency bands of the Corralitos data. We identify numerous problems in the Corralitos data, evident from both straightforward examination of the Corralitos data on their own and by comparison with the Japanese and Fresno data sets. The most notable problems are changes in the baseline noise levels occurring during both the reported precursory period and at other times long before and after the earthquake. We conclude that the reported anomalous magnetic noise identified by Fraser-Smith et al. and Bernardi et al. is not related to the Loma Prieta earthquake but is an artifact of sensor-system malfunction.

1. Introduction

Reliable earthquake prediction is a worthwhile goal that, if ever attained, would reduce the loss of life and property. Unfortunately, it is not at all clear that earthquake prediction is either possible or practical, and the entire subject remains controversial (Geller, 1991; Normile, 1994; Campbell, 1998; Jordan, 2006). Still, some claims of success have been published, and among these are reports of anomalous magnetic-field activity detected by ground-based sensors prior to earthquake occurrence (Kopytenko et al., 1993; Hayakawa et al., 1996, 2000; Uyeda et al., 2002). By far the most prominent of such claims is that of Fraser-Smith et al. (1990), who identified enhancements of magnetic activity – 'noise' derived from an induction coil magnetometer – in discrete frequency bands across a total range of 0.0110–10.001 Hz before the 18 October 1989 M_s 7.1 Loma Prieta, CA, earthquake (for review of the earthquake itself: Stover and Coffman, 1993). A detailed analysis of the Loma Prieta magnetic-field data was subsequently provided by Bernardi et al. (1991), and together with the analysis of Fraser-Smith et al., these two publications constitute the most frequently cited report of the identification of a magnetic precursor of possible use for predicting earthquakes (as of November 2008 over 214 citations according to Google Scholar). The Loma Prieta magnetic precursor report has been extremely influential – helping to motivate new programs of large networks of ground-based instruments (Bleier and Freund, 2005; Bleier and Dunson, 2005) and even some satellite-based systems (Reichhardt, 2003; Parrot and Ouzounov, 2006; Zlotnicki et al., 2006).

Several physical mechanisms have been proposed to explain the reported Loma Prieta precursor, including electrokinetic (Fenoglio et al., 1995; Simpson and Taflove, 2005) and magnetohydrodynamic (Draganov et al., 1991) effects. Either of these might provide a local source of magnetic-field noise. Alternatively, stress-induced increase in local crustal conductivity (Merzer and Klemperer, 1997; Egbert, 2002) along the lines suggested by Fitterman (1976) might lead to a localized enhancement of normal ambient magnetic-field noise. For various reasons, none of the proposed physical mechanisms are completely satisfactory (Park et al., 1993; Johnston, 1997). In contrast to studies seeking natural explanations is the study of Campbell (unpublished manuscripts, 2005), who since at least 2004 has asserted, among other things, that the seeming detection of a precursor was actually just the result of a sensor suffering from a gain problem.

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Given the importance of the Corralitos data and the controversy that surrounds them, we were motivated to undertake our own analysis. The original papers of Fraser-Smith et al. and Bernardi et al. were focused on 2 months of data (September–October 1989), and only this relatively short time span has been generally considered in subsequent analyses of the Loma Prieta precursor report. Here, we examine 21 months of the Corralitos data, 9 months of data collected prior to the Loma Prieta earthquake and 12 months of data collected after the earthquake, and we examine the operational logbook kept during this period of time. In addition, we examine 1.0-Hz (1-s) magnetic-field data collected at the Kakioka magnetic observatory in Japan during the same 21-month period of time. The Japanese data overlap in frequency with the Corralitos data, thereby enabling direct, detailed, and quantitative comparison of magnetic-field data in discrete frequency bands thought to show precursive activity. Additional, but more qualitative, comparisons can be made with 0.0167-Hz (1-min) magnetic-field data collected at the magnetic observatory in Fresno, CA, and with the global 3-h magnetic-activity index *Kp*. All of this allows us to check the fidelity of the Corralitos data, and, in particular, to scrutinize the validity of what might be considered the most prominent reported detection of an earthquake precursor.

2. The Corralitos instrumentation and magnetic data 1989–1990

The data analyzed by Fraser-Smith et al. (1990) were collected by a single magnetic-induction coil sensor operated near Corralitos, CA and near the San Andreas fault. The sensor site was relatively free from artificial interference at 37.0°N, 121.8°W, magnetic latitude 42.7°N, about 7 km from the Loma Prieta earthquake epicenter and about 19 km from the hypocenter. The sensor consisted of horizontal coils oriented in the magnetic east–west direction (Bernardi, 1989; Bernardi et al., 1991). Small voltages induced by magnetic-field variations were amplified using a series of amplifiers. Magnetic-field amplitudes were estimated from raw, rate-of-change measurements by assuming that variation is sinusoidal in time (see Eq. (1) of Bernardi et al., 1989). This means that

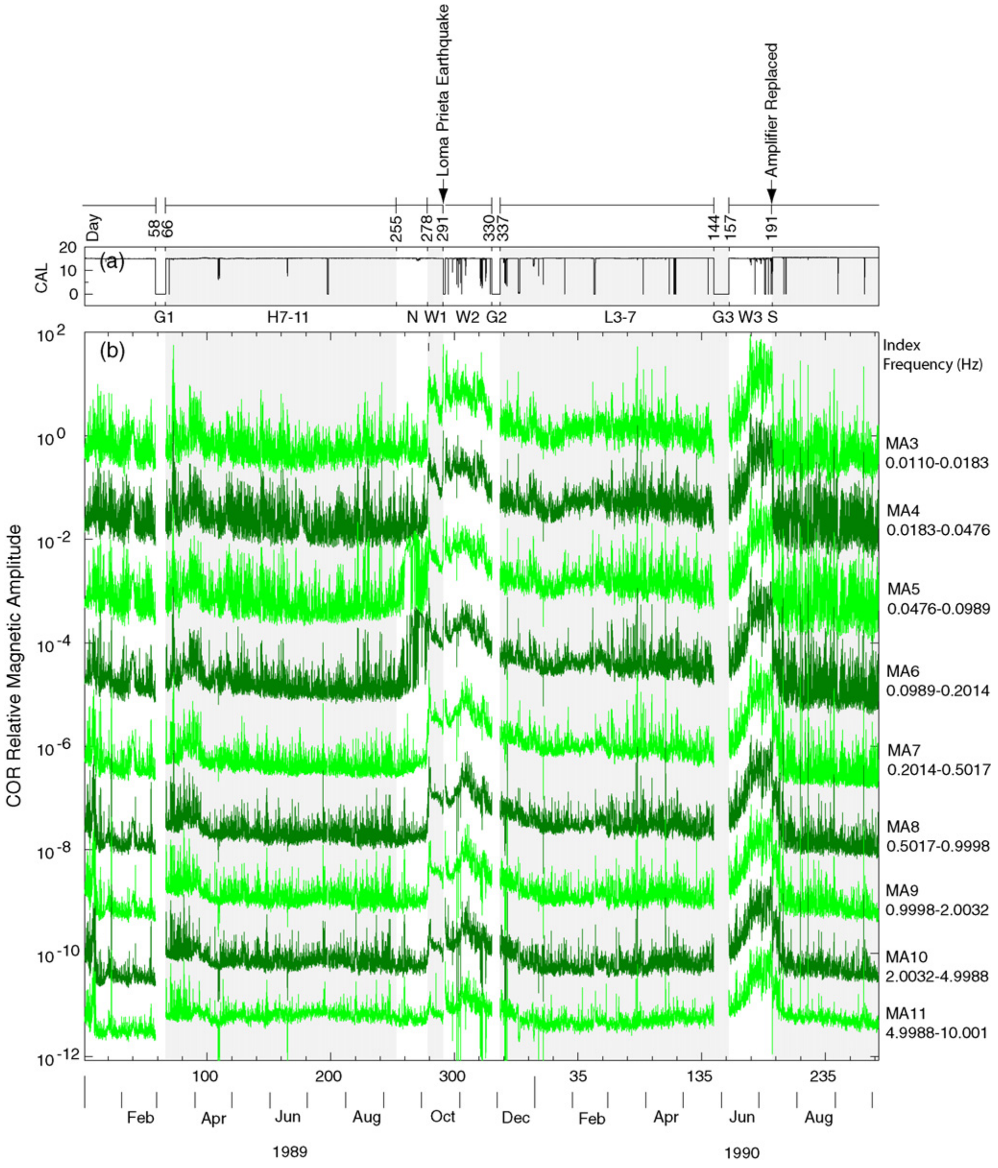
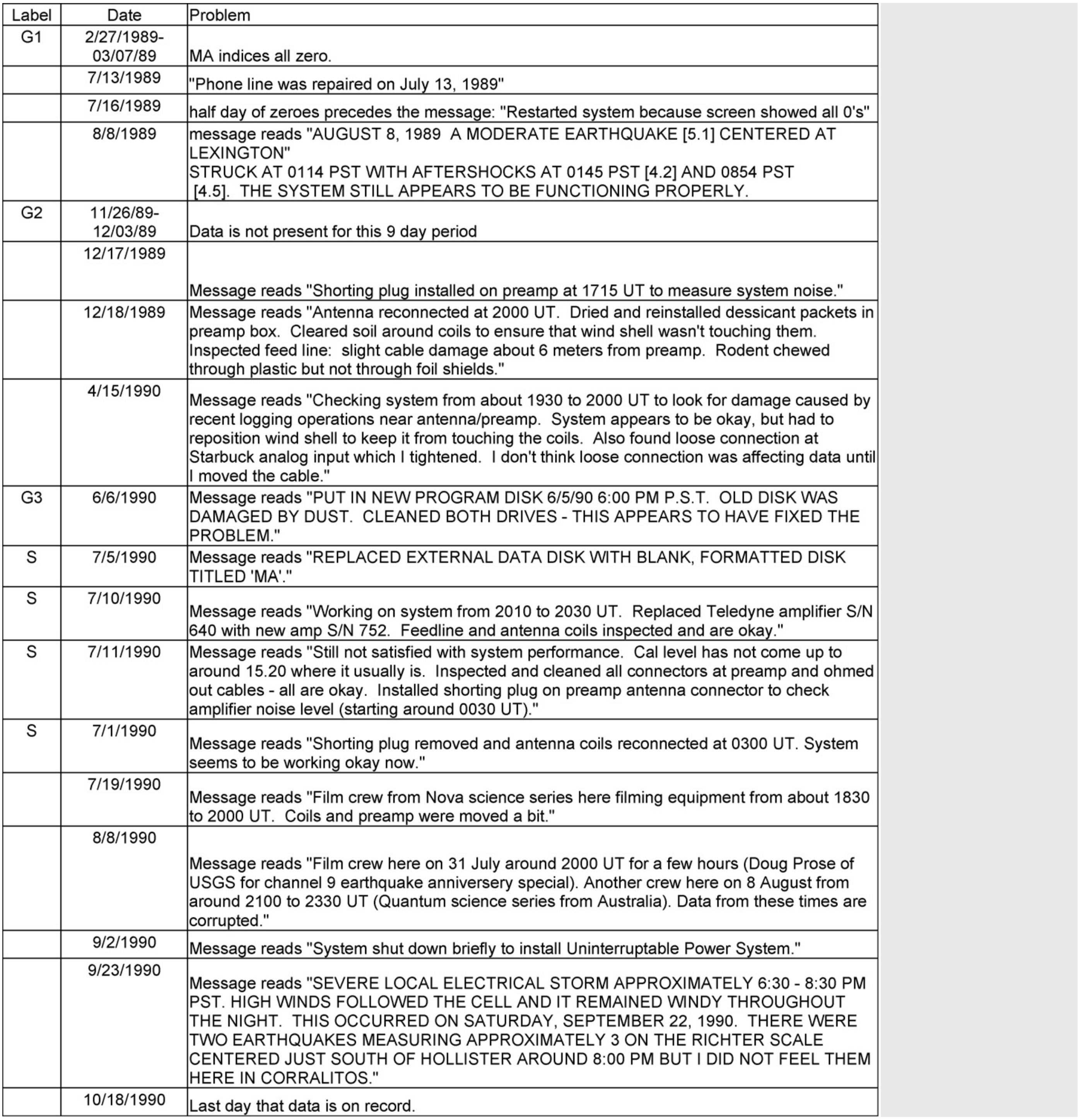


Fig. 1. Corralitos (a) calibration CAL index and (b) COR magnetic indices MA3-11 indices covering the frequency range 0.0110–10.001 Hz for the 21-month period of time (1 January 1989–5 October. 1990); specific frequency ranges are given in the right margin. Index amplitudes are in nT/(Hz)$^{1/2}$, but multiplicative separation factors have been applied for presentation clarity. Data gaps are indicated by G1, G2, and G3, equipment servicing S. The shaded regions highlight different periods of baseline offset: high-frequency indices (H7-11), low-frequency indices (L3-7), narrow-band noise (N), and wide-band across all indices (W1, W2, W3).

Table 1
Corralitos logbook entries verbatim from a spreadsheet supplied by D. Culp and S.L. Klemperer on 18 December 2007, but labels given here are original and used for reference in the text of this paper. The entry that reads 7/1/1990 is likely a typographical error and should read 7/11/1990.



Label	Date	Problem
G1	2/27/1989- 03/07/89	MA indices all zero.
	7/13/1989	"Phone line was repaired on July 13, 1989"
	7/16/1989	half day of zeroes precedes the message: "Restarted system because screen showed all 0's"
	8/8/1989	message reads "AUGUST 8, 1989 A MODERATE EARTHQUAKE [5.1] CENTERED AT LEXINGTON" STRUCK AT 0114 PST WITH AFTERSHOCKS AT 0145 PST [4.2] AND 0854 PST [4.5]. THE SYSTEM STILL APPEARS TO BE FUNCTIONING PROPERLY.
G2	11/26/89- 12/03/89	Data is not present for this 9 day period
	12/17/1989	Message reads "Shorting plug installed on preamp at 1715 UT to measure system noise."
	12/18/1989	Message reads "Antenna reconnected at 2000 UT. Dried and reinstalled dessicant packets in preamp box. Cleared soil around coils to ensure that wind shell wasn't touching them. Inspected feed line: slight cable damage about 6 meters from preamp. Rodent chewed through plastic but not through foil shields."
	4/15/1990	Message reads "Checking system from about 1930 to 2000 UT to look for damage caused by recent logging operations near antenna/preamp. System appears to be okay, but had to reposition wind shell to keep it from touching the coils. Also found loose connection at Starbuck analog input which I tightened. I don't think loose connection was affecting data until I moved the cable."
G3	6/6/1990	Message reads "PUT IN NEW PROGRAM DISK 6/5/90 6:00 PM P.S.T. OLD DISK WAS DAMAGED BY DUST. CLEANED BOTH DRIVES - THIS APPEARS TO HAVE FIXED THE PROBLEM."
S	7/5/1990	Message reads "REPLACED EXTERNAL DATA DISK WITH BLANK, FORMATTED DISK TITLED 'MA'."
S	7/10/1990	Message reads "Working on system from 2010 to 2030 UT. Replaced Teledyne amplifier S/N 640 with new amp S/N 752. Feedline and antenna coils inspected and are okay."
S	7/11/1990	Message reads "Still not satisfied with system performance. Cal level has not come up to around 15.20 where it usually is. Inspected and cleaned all connectors at preamp and ohmed out cables - all are okay. Installed shorting plug on preamp antenna connector to check amplifier noise level (starting around 0030 UT)."
S	7/1/1990	Message reads "Shorting plug removed and antenna coils reconnected at 0300 UT. System seems to be working okay now."
	7/19/1990	Message reads "Film crew from Nova science series here filming equipment from about 1830 to 2000 UT. Coils and preamp were moved a bit."
	8/8/1990	Message reads "Film crew here on 31 July around 2000 UT for a few hours (Doug Prose of USGS for channel 9 earthquake anniversery special). Another crew here on 8 August from around 2100 to 2330 UT (Quantum science series from Australia). Data from these times are corrupted."
	9/2/1990	Message reads "System shut down briefly to install Uninterruptable Power System."
	9/23/1990	Message reads "SEVERE LOCAL ELECTRICAL STORM APPROXIMATELY 6:30 - 8:30 PM PST. HIGH WINDS FOLLOWED THE CELL AND IT REMAINED WINDY THROUGHOUT THE NIGHT. THIS OCCURRED ON SATURDAY, SEPTEMBER 22, 1990. THERE WERE TWO EARTHQUAKES MEASURING APPROXIMATELY 3 ON THE RICHTER SCALE CENTERED JUST SOUTH OF HOLLISTER AROUND 8:00 PM BUT I DID NOT FEEL THEM HERE IN CORRALITOS."
	10/18/1990	Last day that data is on record.

the magnitude of the voltage across the coil is proportional to the magnitude of the magnetic field. These voltages were then digitized at a 30-Hz sampling rate in blocks of 136 s (4096 data points), but the voltage time series were not recorded due to operational limitations at the time (complete recording might be done today). The digitized data stream was smoothed by a Hamming window and then decomposed into harmonic amplitudes using a fast-Fourier transform. 30-min-average spectral-amplitudes were calculated using 13 or 14 of the 136-s data blocks. Nine different discrete frequency bands ('indices' labeled as MA3-11, see Fig. 1) covering 0.0110–10.001 Hz (Fraser-Smith et al., 1990; Bernardi, 1989; Bernardi et al., 1989, 1991) were recorded as time series (the only data values that were recorded). For indices in the frequency range 0.1–10 Hz, calibration was made prior to instrument deployment using a driven magnetic field signal, but for frequencies below 0.1 Hz the calibration was extrapolated using a theoretical response calculated from the magnetic permeability, the cross-sectional area, the number of turns, and the frequency of the magnetic field. To provide a check of the Corralitos sensor's calibration, a 12.5-Hz magnetic field with constant root-mean-square (RMS) amplitude was continuously generated during sensor-system operation. The recorded signal was reported as a separate (CAL) index having a value of 15 (arbitrary units) when the sensor was nominally operating and 0 when it was not. The other nine indices recording natural magnetic noise were expressed in units of pT/(Hz)$^{1/2}$.

The 21 months (1 January 1989–5 October 1990) of the original numerical index data and calibration data recorded at Corralitos (COR), together with a copy of the operational logbook (personal communication December 2007: A.C. Fraser-Smith through D. Culp and S.L. Klemperer), are shown in Fig. 1 and Table 1. These data include the 2-month period of time immediately preceding and following the Loma Prieta earthquake, and from which Fraser-Smith et al. (1990) identified anomalous magnetic-field activity. The long duration of these data provide a panoramic view of the operation of the Corralitos sensor for an extended period of time both before and after the earthquake. To our knowledge, the entirety of this time series has not been previously presented or discussed in detail in published journal form, but it were recently presented by Culp et al. (2007) at an American Geophysical Union meeting.

Let us summarize the specific features in these data reported by Fraser-Smith et al. and identified as possibly associated with the 1989 Loma Prieta earthquake: (1) Narrow-band noise (N in Fig. 1) alternating between the adjacent MA5 (0.0476–0.0989 Hz) and MA6 (0.0989–0.2014 Hz) indices beginning on 12 September (day 255) and ending on 5 October (day 278), (2) wide-band noise enhancement (W1) in the MA3-11 indices beginning on 5 October (day 278) and lasting until the occurrence of the earthquake on 18 October (day 291), (3) a decrease in noise in the MA7-10 (0.2014–4.9988 Hz) indices during the day prior to the earthquake, and (4) a large jump in wide-band noise levels, on top of already heightened levels, starting 3 h before the earthquake. After the earthquake, the sensor was not operational for about 39 h, probably due to loss of power. For reference, it is the reported activity in the lowest frequency index MA3 (0.0110–0.0183 Hz) that has attracted most of the attention from the scientific community (e.g., Molchanov et al., 1992; Fenoglio et al., 1993; Park, 1996; Johnston, 1997; Karakelian et al., 2002; Barry and Phillips, 2003), and, indeed, in the original report by Fraser-Smith et al. (1990) the MA3 index is presented in a separate and prominent figure (see their Fig. 3).

It is important to recognize that the COR data shown in Fig. 1 display several shifts in baseline noise levels and several data gaps over the 21-month time span that are in addition to those reported by Fraser-Smith et al. for the 2-month period of time they considered. For example, the sensor was not operational, giving a data gap, during 27 February–7 March (days 58–66) 1989, which we indicate by G1 in the logbook (Table 1) and in Fig. 1. After this gap, the baselines of each index, but especially the high-frequency indices (H7-11 in Fig. 1), show obvious offsets from their pre-gap values. Subsequently, the baselines of the high-frequency indices remain at roughly constant levels up to and including the commencement of the narrow-band enhancements on 12 September (day 255, N) seen in indices MA5 and MA6. It is noteworthy that the apparent baseline changes occurring after G1 are not accompanied by any diagnostic indication of a problem in the calibration index CAL. The commencement of anomalous wide-band noise on 5 October (day 278, W1) prior to the earthquake and again about 39 h after the

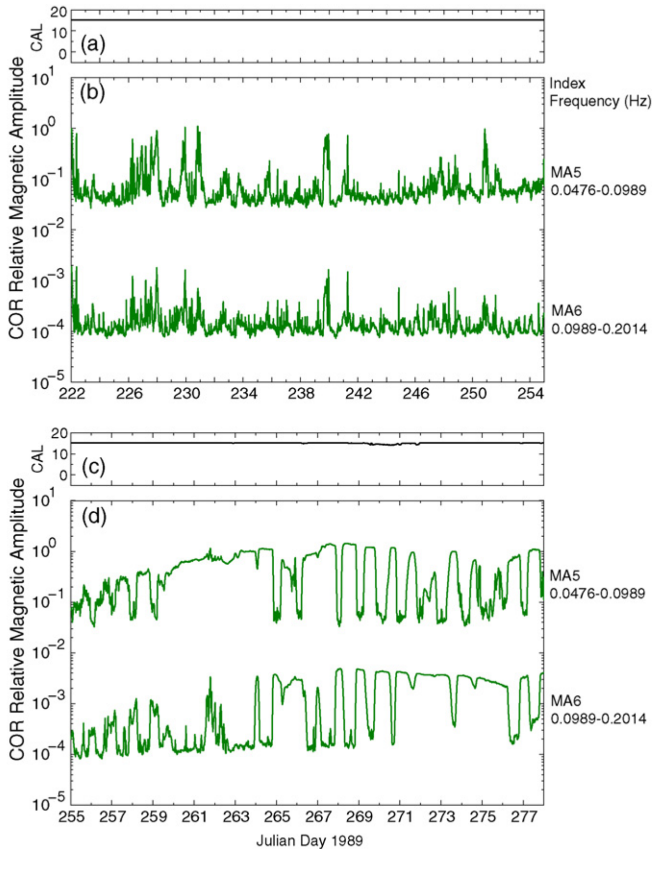


Fig. 2. Corralitos (a) calibration CAL index and (b) COR magnetic index data for the MA5 and MA6 indices during normal activity for 20 August–11 September (days 222–255). Corralitos (c) calibration CAL index and (d) COR magnetic index data for the MA5 and MA6 indices during the period of anomalous narrow-band noise (N) for 12 September–5 October (days 255–278). Index amplitudes are in nT/(Hz)$^{1/2}$, but multiplicative separation factors have been applied.

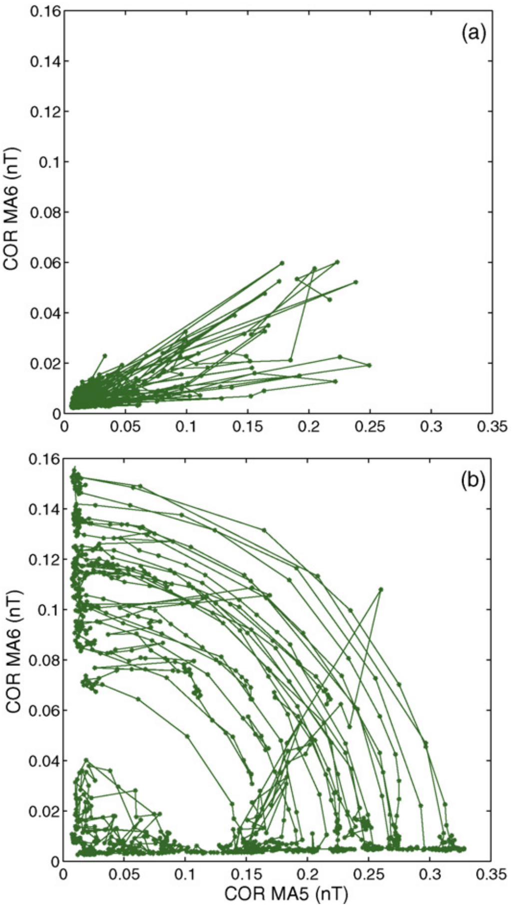


Fig. 3. (a) Corralitos COR MA5 versus 6 for 20 August–11 September (days 222–255). (b) Corralitos COR MA5 versus 6 for the period of anomalous narrow-band noise for 12 September–5 October (days 255–278).

earthquake (W2) can both be appropriately described, in part, as changes of noise-level baseline. The sensor was again not operational during 26 November–3 December (days 330–337, G2) 1989. Until the next data gap that starts on 24 May (day 144, G3) 1990, the noise-level baselines are now evidently lower than for the period prior to G2; this is most easily seen for the low-frequency indices (L3-7). Again, none of these baseline differences come with any indication of a problem in the calibration index. The last long duration data gap occurs during 24 May–6 June (days 144–157, G3) 1990. The logbook does not mention this data gap, but it does record that a program disk was replaced on 6 June. After G3 and until the sensor was serviced on 10–11 July (days 191–192, S), all indices show a rising noise level (W3). Just prior to sensor-system servicing, all indices reach a maximum noise level for the 21-month period, but this happens, as before, without any diagnostic indication in the calibration index of a problem. The logbook records that an amplifier was changed on 10 July, after which the noise levels in all indices return to levels more typical of early 1989. After servicing (S), the calibration index shows a small increase from about 15.2 to 15.5. In summary, it is apparent that the seemingly anomalous enhancements of magnetic noise reported by Fraser-Smith et al. as occurring prior to the Loma Prieta earthquake were not particularly unusual. Baseline changes of noise level in the COR data occurred both long before the earthquake and long afterwards.

The adjacent indices MA5 and MA6 exhibit some unusual characteristics during the 12 September–5 October (days 255–278) 1989 period of narrow-band noise enhancement (N). Anomalous noise levels alternate between these two indices on a nearly diurnal schedule, something that is only visually discernable upon close inspection of the figures in the original reports (Fig. 2 of Fraser-Smith et al., 1990, Fig. 5 of Bernardi et al., 1991). To make this more clear, in Fig. 2 we plot the calibration index CAL and the MA5 and MA6 amplitudes during a normal period preceding narrow-band enhancement (20 August–11 September, days 222–255) and during the anomalous narrow-band noise period itself. Diurnal variation in the MA5 and MA6 amplitudes are almost exactly 12 h out of phase, and yet throughout this period of time CAL remains essentially constant. In Fig. 3 we plot MA5 versus MA6, where the regular transition in noise between these two indices during N is evident. Bernardi et al. argued that some of this behavior could be explained by narrow-band magnetic-field activity with a center frequency that drifts between the frequency bands encompassed by the adjacent MA5 and MA6 indices (see Eq. (7) of Bernardi et al., 1991). To us the functional relationship and the 12-h transitional schedule between MA5 and MA6 during narrow-band enhancement is so tightly anti-correlated that we suspect it to be artificial. But since we were not, ourselves, involved with the operation of the Corralitos sensor, we do not have any specific explanation for this odd behavior.

3. Comparisons with data from Kakioka and Fresno

Next, to better characterize the Corralitos data, we compare them with data collected from other sites. This is, of course, a common-sense means of assessing the fidelity of an unusual data set, and we are not the first to make inter-comparisons for inspection of the COR data. Mueller and Johnston (1990), using 10-min data recorded at sites just 3 km from the Corralitos sensor from 1972 to 1986 and just after the Loma Prieta earthquake in 1989, found no evidence of anomalous noise which might have been aliased from higher frequency ULF variations. Bernardi et al. (1991) compared the COR data with the 3-h *Kp* index, which is based on data from a global distribution of magnetic observatories. They concluded that the anomalous noise reported by Fraser-Smith et al. (1990) was not due to global magnetic activity. Campbell (2005, unpublished manuscripts) inspected 1-min data from several U.S. Geological Survey (USGS) observatories and concluded that a gain change can explain the wide-band noise enhancement reported by Fraser-Smith et al. Although valuable, in none of these cases were direct and detailed comparisons with the COR data possible, since none of the comparison data sets were acquired with sufficiently high sampling rates. The 1-min observatory data considered by Campbell come close to the frequencies of the lowest (MA3) index presented by Fraser-Smith et al. But given that some of the observations of Fraser-Smith et al. concerned anomalous noise occurring in very narrow frequency bands, the USGS observatory data alone are not sufficient to conduct a quantitative comparison with confidence.

In 1989, a dedicated 1.0-Hz optical-pumping magnetometer system was continuously operated at the Kakioka, Japan, observatory (KAK, magnetic latitude 28.9°N, 8284-km great-circle distance from the Loma Prieta epicenter). At the time (and before then) this was very unusual, and we know of no other standard magnetic observatory that operated a dedicated 1-Hz acquisition system. Since the Kakioka sampling rate was sufficiently high to permit direct comparison with the lowest-frequency COR indices, we have obtained 21 months of data that are simultaneous with those from Corralitos. We estimated the magnetic east–west component of the KAK data by using the reported horizontal intensity and magnetic declination measurements, thus obtaining a data time series in a coordinate system like that of Corralitos. We filtered these data using a 4-pole Butterworth filter and computed 30-min averages of the magnitude of magnetic variation to construct two frequency bands like the first two Corralitos indices (MA3: 0.0110–0.0183 Hz, MA4: 0.0183–0.0476 Hz).[1]

As we did with the Japanese data, we estimated an east–west magnetic-component time series from 1-min fluxgate data collected at the USGS Fresno, CA, observatory (FRN, magnetic latitude 43.2°N, 201 km from the epicenter). We band-pass filtered the FRN data at 0.0010–0.0083 Hz, which is of the same bandwidth as the COR data, but because of the 1-min acquisition rate of the FRN data, the frequencies are slightly below the lowest-frequency COR index MA3. Despite this technical difference we will, hereafter, refer to the filtered FRN data as MA3; we acknowledge, of course, the subtle difference between the FRN MA3 and those of COR and KAK. We also note that our treatment of the FRN data is different from that of Campbell (2005, unpublished manuscripts); he used simple first-differences of 1-min data, instead of a band-pass filter, and he analyzed horizontal intensity data (magnetic north-south), a component that is essentially orthogonal to the orientation of the Corralitos sensor.

In Fig. 4 we show MA3 for COR, KAK, and FRN and MA4 for COR and KAK, each for the same 21-month period of time shown in Fig. 1, and together, again, with the calibration data (CAL). Fig. 4 also contains the 3-h *Kp* index, providing a succinct measure of global magnetic-field activity (e.g., Mayaud, 1980). Fourier analysis (not shown) of the COR, KAK, and FRN data reveals significant diurnal modulation of magnetic noise levels, a well-known phenomenon caused by solar–terrestrial interaction that is far removed from and unrelated to earthquakes. Since the phase and amplitude of the diurnal noise modulation are a function of local time and geographic location (Bloom and Singer, 1995), in order to make comparisons between data collected from different sites, it is sensible to remove the diurnal signal. This is most easily done by simple smoothing, which we accomplish by the convolution of each data set with a 2-day-wide triangle filter. The *Kp* index does not have a

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[1] The amplitude resolution of the KAK data (0.1 nT) makes them insufficient to allow meaningful noise measurements with the three higher frequency COR indices (MA5-7: up to 0.5 Hz); the four highest-frequency indices (MA8-11: >0.5 Hz) are beyond the frequency resolution of the KAK data.

strong diurnal variation, but applying the same 2-day-wide filter facilitates comparison with the other magnetic indices.

Let us now make a close inspection of Fig. 4. Consider first the MA3 indices for KAK and FRN (Fig. 4b) and the MA4 index for KAK (Fig. 4c). Each of these indices is virtually continuous, with very few data gaps in the time series. The KAK and FRN indices show noise-level variation having periods of hours, days, and weeks, but over longer periods of time, variation occurs about relatively stable baselines. This is a typical characteristic of data collected from magnetic sensor systems that are operated under stable and carefully controlled conditions. In contrast, the noise-level baseline shifts exhibited by the COR data, and about which we have already remarked, are especially obvious when compared with the KAK and FRN data. The COR noise-level baseline shifts that occur around the time of the Loma Prieta earthquake are not seen in either the KAK or FRN data. If these were the only unusual features in the COR data then it might be reasonable to associate them with the earthquake. But let us also take note of other differences between the COR data and those of KAK and FRN. Compare the COR MA 3 and 4 baseline levels for the long H7-11 period (7 March–12 September 1989, days 66–255) after data gap G1 and before the earthquake with the long L3-7 period (3 December 1989, day 337 to 24 May 1990, day 144) after data gap G2 and after the earthquake; such data gaps and shifts in baseline levels are not seen in either the KAK or FRN data. The prominent wide-band (W3) anomalous noise levels (6 June–10 July 1990, days 157–191), coming after the data gap G3 and persisting until the Corralitos sensor-system was serviced (S) and an amplifier was replaced, are not seen in the KAK or FRN data. Furthermore, features similar to the wide-band noise jump during the day prior to the earthquake are also seen uniquely in the Corralitos data on several other occasions, most notably around 25 March 1990 (day 84).

Much of the magnetic activity shown in Fig. 4 is global in scale. This can be verified through detailed visual inspection of the smoothed COR, KAK, and FRN data, and the *Kp* index, where good correlation persists for periods of time lasting up to several months. This fact is, perhaps, most especially appreciated through the identification of magnetic storms. Note, for example, the recording across all indices of the large (*Kp* = 9) magnetic storm for 13–14 March 1989 (days 72–73), or, similarly, the recording of the (*Kp* = 8)

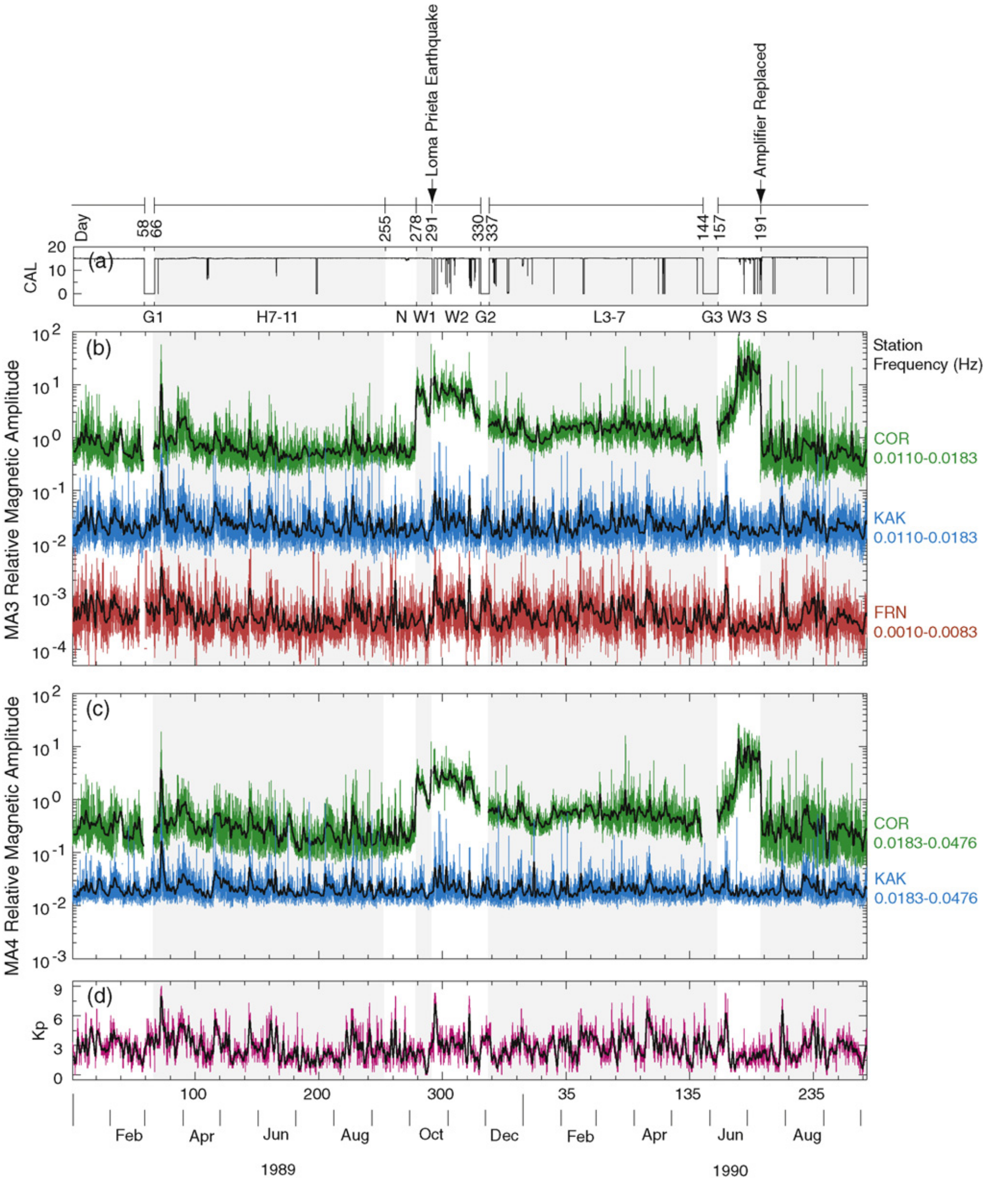

Fig. 4. (a) Corralitos calibration CAL index, (b) the MA3 indices for COR and Kakioka (KAK) and for Fresno (FRN), (c) MA4 magnetic indices for COR and KAK, and (d) *Kp* index. Black lines show smoothing using a two-day triangle filter. Index amplitudes are in nT/(Hz)$^{1/2}$, but multiplicative separation factors have been applied.

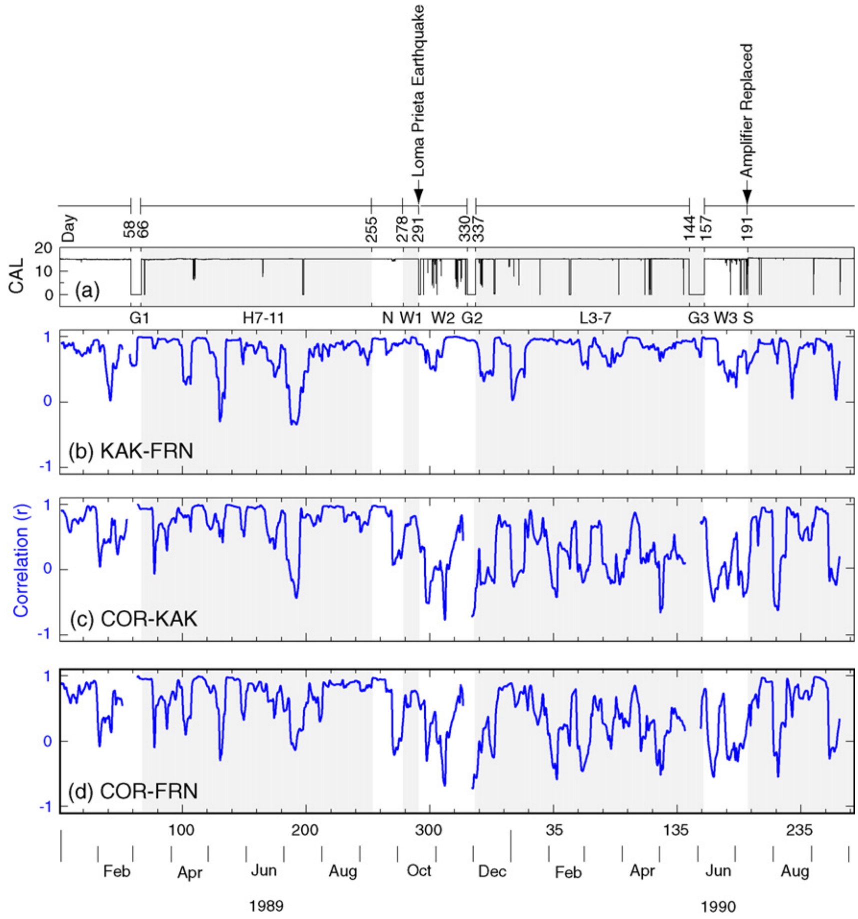

Fig. 5. (a) Corralitos calibration CAL index and linear correlation (r) for the smoothed (b) KAK-FRN, (c) COR-KAK, and (d) COR-FRN data pairs. Each value of r was calculated using a running window 10.7 days in width that includes up to 512 30-min data points. Because of data gaps in the COR time series we did not calculate the correlation unless there were at least 256 30-min data points in the 10.7-day wide averaging window. As is standard, values for r range continuously from +1 meaning perfect correlation to −1 meaning perfect anti-correlation (see for example Bulmer, 1979).

magnetic storm for 17–19 November 1989 (days 321–323). It is important to recognize that the registration of these magnetic storms, and other correlated features in the COR, KAK, and FRN data, comes despite the factor of ∼9 noise-level baseline offsets exhibited by the COR data. How can this be possible? One explanation is that least part of the source of the anomalous noise exhibited in the COR data was caused by a faulty sensor-system amplifier, perhaps the one which was ultimately replaced on 10 July 1990 (day 191). This amplifier could have been intermittently giving incorrect amplification of ambient magnetic-field variation and at other times simply been giving corrupted data.

Aspects of these observations are quantitatively verified in Fig. 5, where we show the linear correlation coefficient r over time between MA3 indices from the various sites for all 21 months. The correlation between KAK and FRN (Fig. 5(b)) is almost always rather high, something which can be attributed to global geophysical phenomena. On the other hand, the situation with the data from Corralitos is more complicated. In Fig. 5(c) and (d) the COR data are generally well correlated with both the KAK and FRN data until the commencement of the period of wide-band noise enhancement (5 October 1989, day 278, W1) identified by Fraser-Smith et al. (1990) just prior to the Loma Prieta earthquake. After day 278 and for a protracted period of time after the earthquake, the correlations of the COR data with the KAK and FRN data are sometimes high and at other times low. This might, at first, seem to be surprising, given that we have also identified baseline shifts in the COR data prior to the earthquake. Recall that the correlation coefficient r is independent of baseline level, but it is sensitive to changes in baseline. After the earthquake (18 October 1989, day 291) and until the logbook indicates the Corralitos sensor was serviced (11 July 1990, day 192, S), the COR data are only intermittently well correlated with the KAK and FRN data. However, immediately after servicing (S) and replacement of the amplifier, correlation improves for a while. These observations are consistent with our earlier interpretation that the Corralitos acquisition system was suffering from a faulty amplifier.

A more detailed presentation of MA3 correlations during the narrow-band (N) and wide-band (W1) enhancement period is made in Fig. 6. Starting at 12 September (day 255) the correlations between data from all three sites (COR, FRN, and KAK) is high, but decreases to about 0 starting at about 26 September (day 269) just prior to the commencement of wide-band noise (5 October, day 278). Afterwards, and prior to the earthquake on 18 October (day 291) the correlations between the COR data and those from FRN and KAK returns to high levels (which we have verified to be statistically significant with a confidence level exceeding 99%). Again, these specific observations are consistent with a faulty amplifier in the Corralitos system delivering data that are occasionally little more than an amplification of natural global-scale magnetic activity.

4. Discussion and conclusions

The magnetic-field sensor system in operation near Corralitos, CA, at the time of the Loma Prieta earthquake that produced the data analyzed by Fraser-Smith et al. (1990) and Bernardi et al. (1991) was apparently suffering from a malfunctioning amplifier. Since all spectral indices were calculated from a single analog signal, this could account for noise-level baseline instability across multiple indices, first seen, for example, in the high-frequency indices (H7-11) starting in 7 March 1989 (day 66), later on in the low-frequency indices (L3-7) starting on 3 December 1989 (day 337), and, finally, across all indices (W3) starting on 6 June (day 157) and continuing until the logbook records that an amplifier was finally replaced (S) on 10 July 1990 (day 191). Some sort of amplifier malfunction might also account for the seemingly anomalous magnetic activity detected prior to the Loma Prieta earthquake and first seen as an odd narrow-band phenomenon (N) starting on 12 September 1989 and, subsequently, as a wide-band phenomenon (W1) starting on 5 October (day 278). Indeed, comparison of the COR data with those from other sites, but especially those from Japan (KAK) in Fig. 6, indicates that the anomalous noise seen in the COR data during the wide-band period (W1) is essentially an anomalous amplification of normal ambient magnetic activity occurring on a global scale. In this respect we agree with Campbell (2005, unpublished manuscripts): at least part of the anomalous precursory noise levels in COR data appear to be the manifestation of a sensor-system gain problem. None of these noise-level shifts were accompanied by significant changes in the calibration (CAL) index, including the W3 wide-band anomalous noise increase that preceded the replacement of an amplifier (as recorded in the logbook). The lack of change in the CAL index during this obviously problematic period demonstrates that the CAL index is not a reliable diagnostic of defective data. Thus, it is understandable that the Corralitos sensor system might have been thought to be properly operating, even when it was not. In our collective experience working with data acquisition systems and observing the results of their occasional malfunctioning, we would not find any of these operational difficulties to be particularly surprising.

We acknowledge that, at first inspection, the anomalous magnetic noise recorded by the Corralitos sensor, and perhaps especially the rise in noise level just 3 h prior to the earthquake, might appear to be so coincidental in time that despite evident operational prob-

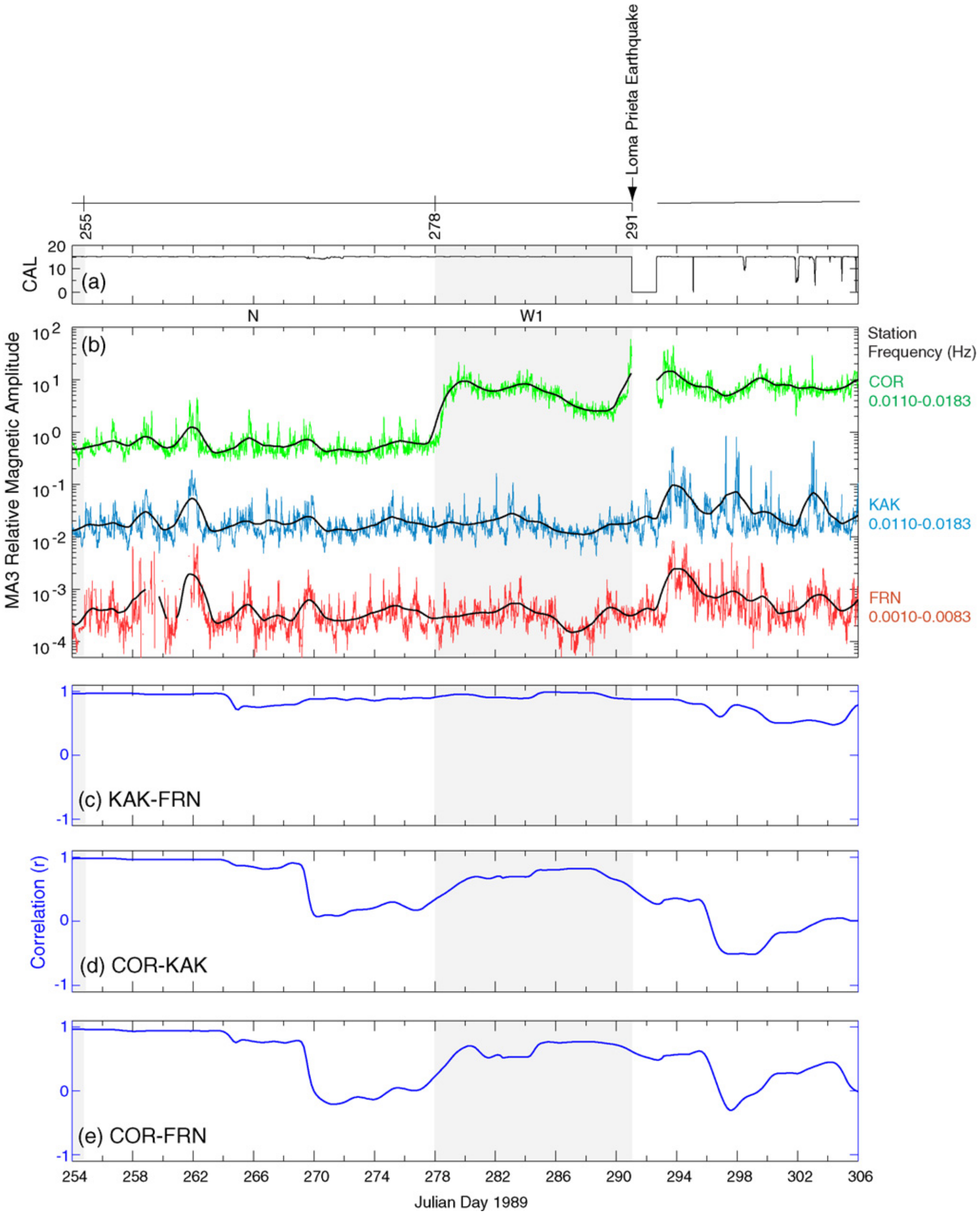

Fig. 6. (a) Corralitos calibration CAL index, (b) the MA3 indices for COR and Kakioka (KAK) and for Fresno (FRN), and linear correlation (r) for the smoothed (c) KAK-FRN, (d) COR-KAK, and (e) COR-FRN data pairs for 11 September–2 November 1989 (days 254–306).

lems a natural causal explanation is still almost required. In our opinion, some of this expectation stems from the fact that the original report of Fraser-Smith et al. (1990) was focused on a brief 2-month period of time around the time of the Loma Prieta earthquake. When a longer period of time is considered, like the 21 months of COR data analyzed here, the temporal coincidence seems much less remarkable. The Corralitos sensor was producing anomalous data long before the earthquake, and it continued to produce anomalous data long after the earthquake, so the fact that an earthquake did occur is probably irrelevant to any particular anomalous magnetic signal. Looked at from an inverse perspective, if the COR time series are to be trusted and the narrow-band (N) and wide-band (W1) anomalous periods are to be legitimately associated with the earthquake, then shouldn't the high-frequency anomalous period (H7-11) or the wide-band anomalous period (W3), neither of which have been previously associated with the earthquake, be considered to be false precursory signals?

Successful earthquake prediction requires clearly identifiable indicators of the imminent occurrence of earthquakes and their magnitude, and these must be reliably provided in a real-time setting (e.g., Jordan, 2006). But these are not the indicators that have been reported for the Loma Prieta earthquake. The magnetic precursory report of Fraser-Smith et al. (1990) and Bernardi et al. (1991) is what is sometimes called a 'post-diction'—it came after the earthquake occurred. We find it difficult to imagine how the Corralitos data, with all of their apparent problems, could have ever been used to predict the Loma Prieta earthquake before it actually occurred.

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