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Cancellation of Natural Geomagnetic Field Fluctuations: An Opportunity for New Discoveries in the Earth Sciences using Superconducting Magnetic Field Gradiometers

by

Antony C. Fraser-Smith

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Abstract

Recent measurements with an array of induction loop magnetometers in California by the author's research group have provided fresh evidence for the high spatial uniformity of ultra low-frequency (ULF; frequencies less than 5 Hz) magnetic field fluctuations produced by sources in the upper atmosphere. The measurements were made at Parkfield, in Central California, at two stations in Southern California, and at Corralitos in Northern California, and they show that the fluctuations remain very nearly identical over distances at least as large as 400 miles (650 km). By taking one measurement site as a remote reference and subtracting its measurements from those at other sites (within the indicated range of distances), it is possible to largely eliminate the upper atmosphere signals at each site. Once this differencing, or cancellation, process has been carried out, the measurements at each site become much more sensitive to locally-generated ULF magnetic field fluctuations.

These observations of the spatial coherence of ULF magnetic field fluctuations are important because other measurements by the author's research group, combined with other similar recent measurements by Russian scientists (and by a scattering of other earlier investigators), suggest that ULF magnetic field fluctuations may also propagate out from within the earth's crust under special circumstances: primarily before and during earthquakes, and certain other geophysical events (for example, those associated with volcanism). This possibility enhances the relevance of techniques to cancel ULF magnetic field fluctuations originating in the upper atmosphere, since they could facilitate studies of the crust and possibly also the upper mantle of the earth, and potentially lead to a method of short-term earthquake prediction.

The measurements also suggest that observations with superconducting magnetic field gradiometer (preferably a three-axis gradiometer) would automate the cancellation process described above and, because of the combination of a greatly reduced upper-atmospheric noise background with the much greater sensitivity of the superconducting instrumentation, potentially provide an opportunity for a breakthough in the search for ULF magnetic field fluctuations originating in the earth.

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1. Introduction

The author has had a broad interest in ultra-low frequency (ULF; frequencies less than 5 Hz) fluctuations of the Earth's magnetic field for many years. As an Office of Naval Research (ONR) contractor and grantee, this interest has included the use of ULF electromagnetic fields for the detection of, and communication with, submarines and other submersibles, and the research conducted by his group at Stanford University has included extensive computations of the penetration of electromagnetic fields into, and out of, electrically conducting media [e.g., *Fraser-Smith and Bubenik*, 1980, 1984]. The medium of primary interest, of course, was sea water, but the computations were carried out in parametric form, with the electrical conductivity of the medium as a parameter, with the result that all the computed numerical data apply just as well to the solid conducting layers of the earth.

By assuming known (i.e., measured) electrical conductivities for typical damp earth, or dry rock, these computations show that at ULF frequencies there is a 'window' for electromagnetic wave propagation into and out of the earth. Admittedly, at frequencies in the upper part of the ULF range, the electromagnetic waves can only propagate for distances of a few kilometers to a few tens of kilometers before they are absorbed, but these are useful distances for many purposes. As the frequency decreases, the range increases (there is an inverse relation with frequency), and at 0.1 Hz and an electrical conductivity of 0.01 S/m the waves can penetrate about 16 km before being reduced to one-third of their original amplitude; at 0.001 Hz the equivalent distance is 50 km.

In parallel with this theoretical work, the author's group has been involved in a variety of measurement programs involving low-frequency electromagnetic fields. It is relevant that one of these programs was one of the first uses of a superconducting magnetometer to measure the natural ULF fluctuations of the Earth's magnetic field [*Buxton and Fraser-Smith*, 1974; *Fraser-Smith and Buxton*, 1975]. More recently, the author's group developed a simple and rugged system for characterizing the ULF fluctuations of the Earth's magnetic field on a longer-term basis than usual: the system computes half-hour indices for nine narrow frequency bands in the overall range 0.01-10 Hz [*Bernardi et al.*, 1985, 1989]. One of these latter systems was built and, in 1987, installed at Corralitos, a semi-rural location south of the San Francisco Bay area, in order to avoid the large-amplitude ULF magnetic fields being produced by the Bay area's BART rapid transit system [*Fraser-Smith and Coates*, 1978; *Ho et al.*, 1979; *Samadani et al.*, 1981]. This was a classic example of "jumping from the frying pan into the fire," because in October 1989 the M7.1 Loma Prieta earthquake took place and its epicenter was only 7 km from the Corralitos measurement system [*Fraser-Smith et al.*, 1990; *Bernardi et al.*, 1991; *Fraser-Smith et al.*, 1993].

Following the Loma Prieta earthquake, the author was provided funds by the U.S. Geological Survey to install ULF magnetic field measurement systems at various locations in California in the hope of obtaining additional observations similar to those obtained at Corralitos.

2. Earthquake-Related Measurements

The Stanford measurements before and after the moderately-large Loma Prieta earthquake have been extensively reported [*Fraser-Smith et al.*, 1990; *Bernardi et al.*, 1991; *Fraser-Smith et al.*, 1993]. They showed some unusual changes occurring over a month before the earthquake, but the greatest change was an increase by about a factor of 30 in the amplitude of the lowest frequency fluctuations (i.e., at 0.01 Hz) starting 12 days before the earthquake and continuing with a slight decline in strength until three hours before the earthquake, at which time there was a further increase in amplitude by a factor of about 30. The overall increase just before the earthquake was close to 300 times above the normal natural background level – clearly an extraordinary increase, which had never been seen before the earthquake and which has never been seen since.

It is probably of considerable relevance that the largest increase of the ULF magnetic fields at Corralitos took place at the lowest frequency being monitored (0.01 Hz). The increase was seen at all frequencies, but it was comparatively quite small at the highest frequency (10 Hz). This kind of variation is consistent with a source in the earth, and it is relevant that the depth at which the Loma Prieta earthquake took place was 17.6 km as compared with a skin depth (distance over which and electromagnetic wave is reduced in amplitude to 1/e, or roughly one-third, of its original amplitude) of 15.9 km for a 0.01 Hz electromagnetic wave propagating through typical earth materials (electrical conductivity 0.1 S/m). The equivalent skin depth for a 10 Hz electromagnetic wave is 0.50 km. These results do not prove that the Loma Prieta ULF magnetic fields came from a source within the earth, but they are clearly consistent with a source located close to the point in the Earth where the earthquake took place.

Using the results of the research conducted earlier for ONR on the ULF magnetic fields produced above a conducting layer by submerged (or buried) magnetic and electric dipole sources, the author derived a range on the surface of about 100 km for the Loma Prieta signals [*Fraser-Smith et al.*, 1993]. It is of crucial importance, from the point of view of this communication, to realize that this range computation is based on the decline of the ULF magnetic fields from the buried dipole sources to a level where they can no longer be distinguished from the natural background noise, i.e., the range of detection is dependent upon the natural ULF magnetic background noise level, and it can be increased if the natural background noise level can be reduced in the measuring instruments.

The earth science community has no trouble accepting the existence of sources of electromagnetic fields within the earth. It has long been known that many crystalline materials in the earth are piezoelectric, and there are also materials that are piezomagnetic, and it was suggested some years ago that there could be co-seismic magnetic field changes, which have been observed [*Johnston*, 1989]. It was also suggested that seismomagnetic changes resulting from the piezomagnetic properties of rock might also take place before earthquakes [e.g., *Stacey*, 1964], but unfortunately such precursory changes were not observed. In retrospect, the author suggests that the measurements were made at frequencies that were too low, and with instruments of too low sensitivity, but this is necessarily a controversial issue.

Although piezoelectric and piezomagnetic generation mechanisms are acceptable to the earth science community, the most favored mechanism for earthquake-related electromagnetic field generation is one involving what are referred to as streaming potentials, or, equivalently, the electrokinetic effect [e.g., *Mizutani et al.*, 1976; *Fitterman*, 1979]. Here the electrokinetic effect refers to the charge separation that occurs at the interface between a rock and a fluid (electrons adhere to the surface, leaving positive ions in the adjacent fluid), and the streaming potential is the potential produced when the fluid flows, carrying some of the positive ions along with it.

Following observation of the Loma Prieta ULF magnetic fields, the author collaborated with a Russian group on a paper describing very similar ULF magnetic fields that the Russian group observed before the M6.9 earthquake that took place at Spitak in Armenia in 1988 [*Molchanov et al.*, 1992]. The Stanford measurements are not therefore unique and there has been some corroboration. In addition, there are numerous hints in the earlier literature of other similar ULF magnetic field changes before earthquakes that appear to have been ignored and which will not be detailed here. If the reader is interested, one of these earlier papers describes a burst of ULF magnetic fluctuations just prior to the very large earthquake ($M > 8.0$) that took place near Anchorage, Alaska, on March 27, 1964 [*Moore*, 1964].

To end this discussion of earthquake-related ULF electromagnetic field changes, reference must now be made to the new measurement systems installed by the author's group in central California (two systems) and in Southern California (an additional two systems) following the Loma Prieta earthquake. Support for the construction and installation of these systems was provided by the U.S. Geological Survey (USGS) , and the USGS is currently providing maintenance level support to keep them running and to have their data inspected at regular intervals. They are all installed along the San Andreas fault and the two at Parkfield are particularly relevant because of the prediction that a moderately large earthquake should occur soon at that location [*Bakun and Lindh*, 1985]. As a result of this prediction, Parkfield is heavily instrumented with a great variety of different kinds of measurement systems, which together provide uniquely complete information about the groundwater and gaseous emissions in the area, as well as its seismic state, the stress and strain in the crustal rocks, and electromagnetic fields. Our two ULF measurement systems are spaced about 5 km apart, on either side of the little town of Parkfield, at locations referred to as Varian and Haliburton (Figure 1). In Southern California, our two systems are located at Table Mountain and at Piñon Flat, which are also shown in Figure 1.

All of our measurement systems, including the one at Corralitos, were operating during the moderately-large Northridge earthquake that occurred on 17 January 1994 in Southern California. Unfortunately, this earthquake was not located on the San Andreas fault and its epicenter was more distant from our two closest measurement systems than was desirable for detection according to the criteria we are gradually developing: it was 81 km from the nearest system, at Table Mountain (Figure 1), and over 200 km from Piñon Flat. Since it was a smaller earthquake (M6.7) than the Loma Prieta, our lack of observation of any precursory

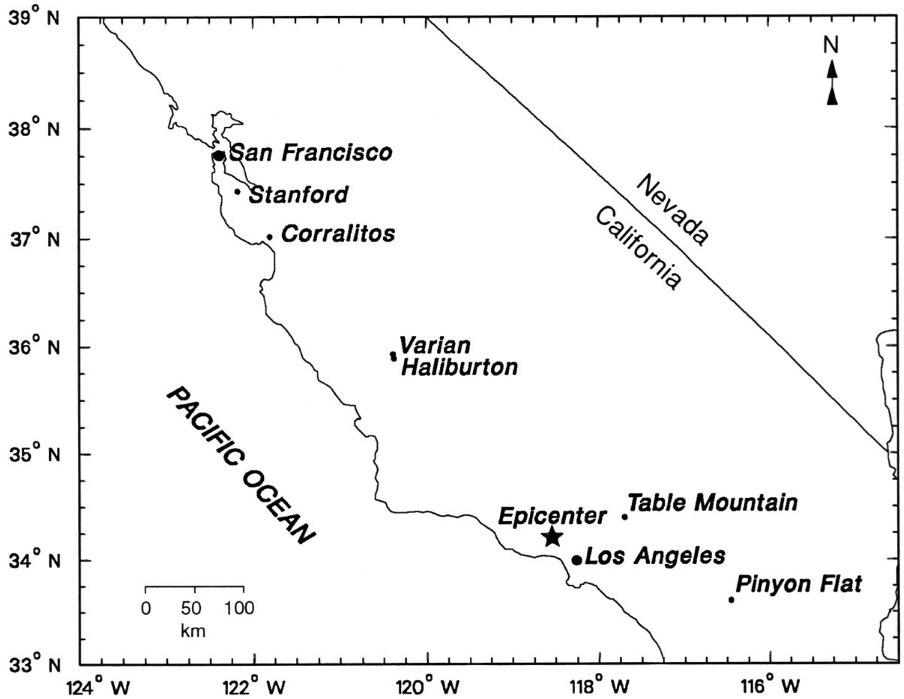

Figure 1. Map of California showing the relative locations of the five Stanford University ULF magnetic field measuring systems (small dots) and the location of the epicenter of the Northridge earthquake of January 17, 1994.

ULF magnetic field changes is consistent with our earlier published estimate of a range of about 100 km for a M7.1 earthquake. The Northridge results have since been published [*Fraser-Smith et al.*, 1994]. However, what is of most relevance to this communication are the data recorded simultaneously at each site during the month of January, which appear in the paper. I will now show these results and discuss their implications.

3. ULF Magnetic Field Measurements during January 1994

Given the publication by *Fraser-Smith et al.* [1994] describing the measurements made during the Northridge earthquake, the discussion in this section will concentrate on the form of the data and the reader is referred to the paper for additional details. The data are shown in Figures 2, 3, and 4, recorded respectively at Table Mountain (81 km from the epicenter), Piñon Flat (206 km from the epicenter), and Corralitos (428 km from the epicenter). Although the distances from the epicenter are of interest, the point to be emphasized in this section is the great similarity between the measurements at the three locations, which are separated by as much as 616 km, or 383 miles (the distance between Corralitos and Piñon Flat).

If the reader compares the data in Figures 2, 3, and 4, very little difference will be seen between the measurements (values are plotted for every half-hour). Unfortunately, due to funding limitations, the Corralitos system is not completely identical to the other systems in our network, and its calibration is necessarily somewhat different. This is the reason for the different baseline noise levels in each frequency channel as compared with those for Table Mountain and Piñon Flat. Nevertheless, its measurements can hardly be distinguished from those at the two Southern California sites. There is evidently very substantial coherence in the ULF magnetic field fluctuations at each location.

Further evidence for this coherence is given by the data in Figure 5, which shows the result obtained when the Piñon Flat half-hour measurements are subtracted from the corresponding measurements at Table Mountain, which is 145 km to the north of Piñon Flat. The data in Figure 5 show almost no features of interest, and very clearly almost all the naturally occurring ULF fluctuations have been canceled out.

The use of Piñon Flat as remote reference, and the differencing technique used to produce the display in Figure 5, is illustrative of an anti-submarine warfare (ASW) technique much discussed in the Navy: the data from a reference measurement system is used to eliminate the ever-present natural ULF noise from the system being used to search for submarines, or other magnetic anomalies, thus making the search system more sensitive to the magnetic fields of any nearby magnetic anomalies. Perhaps more importantly, the differencing technique removes a highly variable and confusing noise signal from the measurements, thus eliminating a major source of difficulty for operators of the detection systems, who typically will not be experts on the upper atmosphere signals. In the earth sciences, the use of remote reference and differencing techniques to improve the sensitivity of magnetic field measurements to locally-generated fluctuations is well established [e.g., *Smith and Johnston*, 1976; *Nichols et al.*, 1988].

4. Earlier Studies of Coherence

The author has been involved in Navy studies of magnetic anomaly detection (MAD) at

ULF frequencies for well over a decade. Throughout this interval he has been involved in numerous discussions and Navy-sponsored meetings in which the desirability of coherence measurements on natural ULF magnetic noise was clearly expressed. However, published reports of such studies are largely lacking. To the best of the author's knowledge, there have been only two relatively recent studies, one involving an analysis of data from a long-baseline array of seven magnetometers set up across the continental U.S. and operated some years ago by the Air Force Geophysics Laboratory (AFGL) [*Bubenik et al.*, 1983], and the other involving measurements made simultaneously on two aircraft over the deep ocean and separated by distances in the range 1.6–4600 km [*Ochadlick*, 1990]. Both these studies provide valuable data, but they are limited in various ways, as will now be described.

The *Ochadlick* [1990] study found that there was a high correlation between the measurements made on the two aircraft (frequencies in the range 0.04–0.5 Hz) for separation distances of up to about 150 km, but for distances greater than about 150 km the similarity of the magnetic signals rapidly declined. This result is in disagreement with the results I report here and in *Fraser-Smith et al.* [1994] for much longer observational intervals, and it is also in disagreement with the results of the pioneering early study of coherence by *Orange and Bostick* [1965] and with the results reported by *Bubenik et al.* [1983]. Clearly further studies using the Navy's MAD aircraft are desirable, but they involve practical difficulties that are best avoided at this stage of development of the study of the coherence of natural ULF magnetic noise.

As pointed out in their report, the *Bubenik et al.* [1983] study found statistically significant levels of coherence in the two horizontal magnetic field components at all frequencies below 125 mHz between all pairs of the measurement stations, which were distributed across the continental U.S. The report concluded with some suggestions for further work and with the following positive statement (p. 56): "This study is the first look at geomagnetic coherence levels over long baselines at relatively low frequencies. The results are encouraging and should be pursued in a more extensive study." A number of the suggestions for further work are covered in the following description of how our present measurements could be expanded to provide definitive new information on the coherence of natural ULF magnetic field fluctuations. This new information would obviously be relevant to Navy MAD interests, given the discussion above, but it would in addition provide a better basis for the detection of ULF electromagnetic fields emerging from the earth's crust, with application to the detection of electromagnetic fields associated with earthquakes, volcanism, and other processes in the crust.

5. Expansion of the Coherence Measurements

To provide the desired "definitive" new information on coherence, the present array of measurement systems in California needs to be expanded, both in the range of distances covered and in the capability of the individual measurement systems. This may sound like an ambitious undertaking, and in scientific terms that is an accurate description, but in terms of cost and the manpower required the expansion is straightforward and not particularly demanding, since a number of measurement sites have already been established. The following are the changes we would suggest:

(1) The first change is the installation of GPS receivers at each site to provide both accurate and consistent (i.e., synchronized) timing. At the present time we have accurate but not necessarily consistent timing at each site—the crystal standards are not tied to each other and differences in timing can occur as the standards drift. The cost of GPS receivers has been dropping dramatically over the last few years and inexpensive systems are now widely available.

(2) The second suggested change is the installation of a full suite of component measurements at each site. At the present time, due to funding limitations, we still have mostly single component (magnetic N-S) measurement sytems at each site ; while this is adequate (barely) for earthquake monitoring purposes, it is inadequate for the desired "definitive" study of coherence. Fortunately, adding more component measurements (for the vertical and the magnetic E-W components) is not a major expense.

(3) The third change is the provision of higher speed data links between the individual measurement sites and our data processing facilities at Stanford. We currently use modems to access the computers and their data at three of our five measurement sites (via telephone). The USGS has installed satellite data links for some of their remote seismometer sites, and this would also be an option for us, but at increased cost. Internet access is becoming a

viable option: the JPL Table Mountain Facility has recently had an ethernet LAN installed, which could provide internet access at that site.

(4) The fourth change is the addition of up to several extra three-component measurement systems to the present array to extend its baseline beyond the present 400 miles, which runs from Southern California to the San Francisco Bay area, and to make simultaneous measurements in a direction perpendicular to the baseline.

(5) The fifth change we would suggest does not involve equipment but an important difference in procedure – a difference made possible by the GPS time receivers at each site. Instead of merely subtracting magnetic indices from the separate sites, as was done to prepare the difference plot shown in Figure 5, we would carry out a full coherence analysis using the original sampled data from each site. We have available our own DEC alpha computer, which would facilitate these computations.

Although it would not be the point of the proposed coherence study to detect ULF magnetic fields originating in the earth, the measurements will enable the natural ULF magnetic field fluctuations originating in the upper atmosphere to be canceled to an unprecedented level over the full extent of the expanded array. This would provide an opportunity to observe possible ULF magnetic field changes originating in the earth. This would be a significant discovery, and it would be facilitated by the present location of several of the measurement systems at premier geophysical measurement sites (as pointed out above, the Parkfield area is heavily instrumented by geophysicists; Piñon Flat is also heavily instrumented). As a result, we have close cooperation from a variety of geophysicists making measurements at these sites, and, through data sharing arrangements, we have access to much of their data.

6. Superconducting Gradiometers

Until now this report has concentrated on a discussion of how an array of conventional ULF magnetometers can be used to measure the spatial coherence of natural ULF magnetic noise and to cancel the noise at individual sites. However, an obvious implication of this discussion is the advantage of using superconducting magnetic field gradiometers for the measurements, since they can automatically cancel the upper atmospheric ULF noise without the need for reference measurements at other locations, thus leaving the gradiometer particularly sensitive to locally-generated ULF magnetic fields (it is pertinent that superconducting magnetic field gradiometers contain pairs of spaced magnetic field sensors whose outputs are subtracted and thus their operation does not differ in principle from the operation of conventional magnetometer systems with cancellation as described above (see *Fraser-Smith* [1983]). Furthermore, because of their extraordinarily low internal noise [*Gillespie et al.*, 1977], and the exceptional control over the layout and orientation of the superconducting loops used as sensors, superconducting magnetic field gradiometers could have advantages over arrays of conventional magnetometer arrays for the detection of the locally-generated fields. Their sensitivity, for example, could be greater by orders of magnitude (in a different context, not involving gradiometers, a pioneering study by *Nichols et al.* [1988] suggested that signal-to-noise improvements of 40–60 dB could be achieved by converting from conventional to superconducting magnetometers). Few superconducting magnetic field gradiometers have been built, but they are not particularly difficult to build. A three-axis magnetic field gradiometer would be bulky and probably should not be considered for an initial study, but single-axis systems can be constructed without great difficulty [J. Clarke, personal communication] and they would be more than adequate for a proof-of-concept measurement program. Given the discussion above, they would provide an opportunity for new discoveries in the earth sciences.

7. Conclusion

The high spatial uniformity of natural ULF magnetic field fluctuations leaves open the possibility of using the measurements from a reference magnetometer to cancel the natural fluctuations at other locations, thus increasing the sensitivity of the magnetometers at those other locations to locally generated ULF magnetic fields. This cancellation technique has application both to non-acoustic anti-submarine warfare (ASW) as used by the U. S. Navy (primarily by giving the magnetometers used for MAD greater sensitivity and range), and to the detection of ULF magnetic field fluctuations originating in the earth. It is not surprising that the cancellation of the ULF magnetic fields originating in the upper atmosphere has been discussed for many years within the Navy and the earth sciences community, but the measurements necessary to establish and fully exploit the technique have largely been lacking. This report describes how an already existing array of ULF magnetometers in California could be relatively inexpensively extended to provide "definitive" measurements of the spatial coherence of the naturally occurring ULF magnetic noise over distances of interest both to the Navy and in geophysical studies, and thus enable the cancellation technique to be assessed meaningfully with real data. These new coherence data would also be helpful to the detection of ULF magnetic fields originating in the earth.

Perhaps more importantly, the coherence measurements already made with conventional ULF magnetometers suggest the advantage of using superconducting magnetic field gradiometers to search for ULF magnetic field fluctuations originating in the earth, since they can automatically cancel the upper atmospheric ULF noise without the need for reference measurements at other locations, thus leaving the gradiometer particularly sensitive to locally-generated ULF magnetic fields. Measurements with conventional ULF magnetometers can add incrementally to our knowledge of these earth-crust ULF magnetic fields, but measurements with superconducting magnetic field gradiometers have the potential to provide breakthroughs in our knowledge of the fields and in our ability to make use of them.

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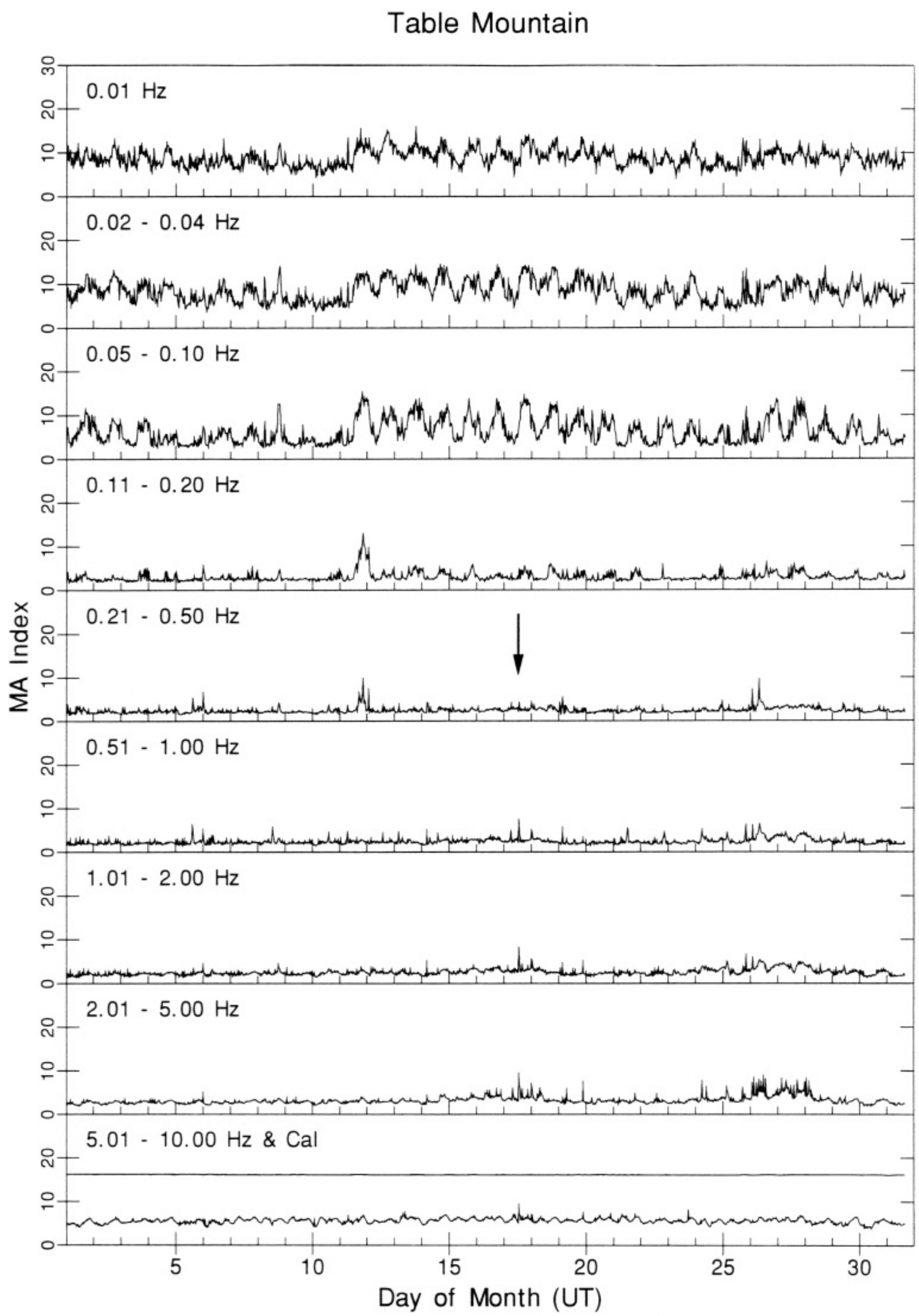

Figure 2. Variation of the magnetic activity indices measured during January 1994 at Table Mountain, California. The horizontal line in the 5.00–10.00 Hz panel is a calibration signal (12.5 Hz). It should be present and remain at a constant amplitude at all times for the index generator to be operating correctly. The Northridge earthquake took place at 1231 UT (arrow), and small co-seismic spikes can be seen in the corresponding higher frequency indices ($f > 0.5$ Hz).

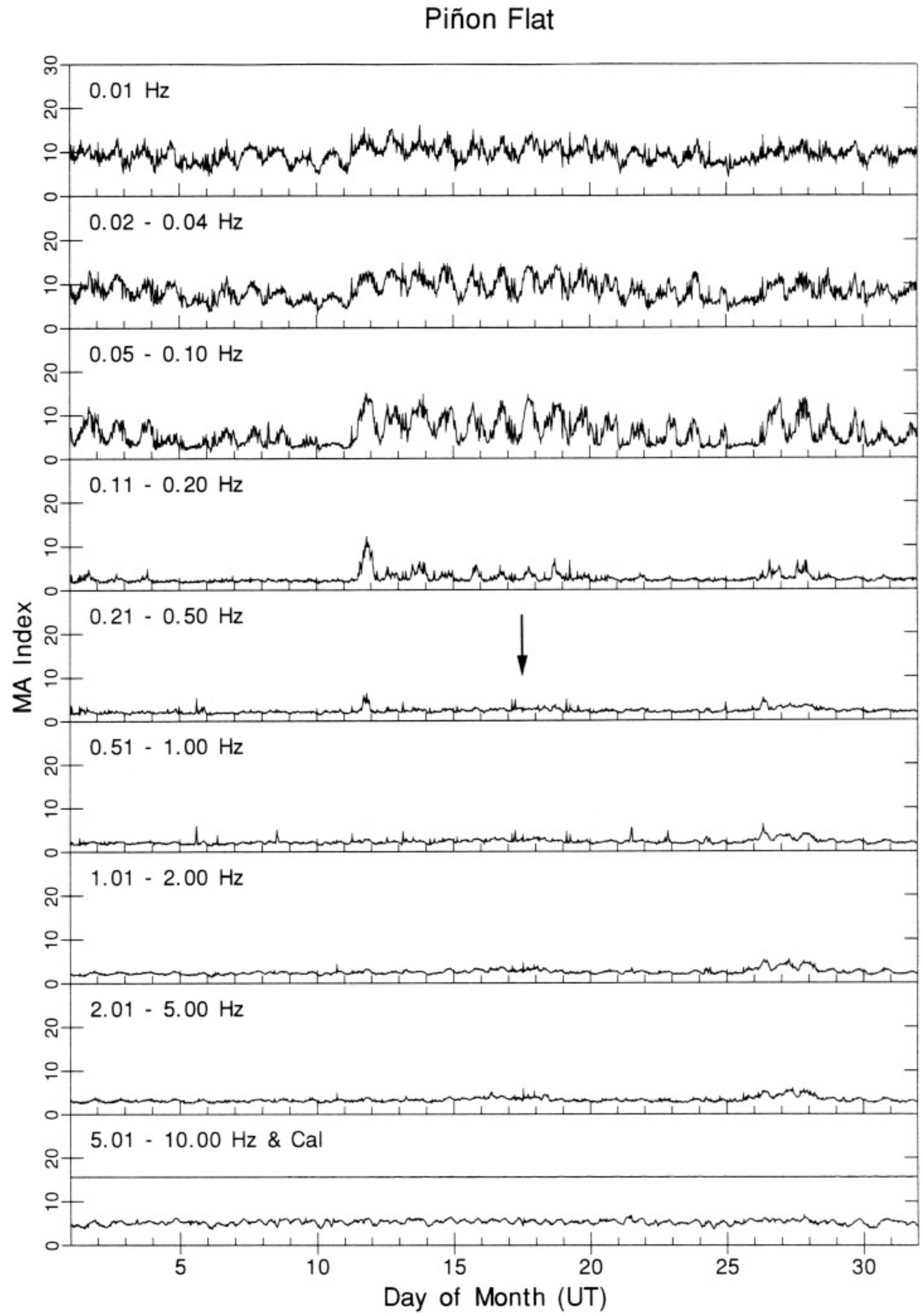

Figure 3. Variation of the magnetic activity indices measured during January 1994 at Piñon Flat, California. The Northridge earthquake took place at 1231 UT (arrow), and very small co-seismic spikes can be seen in the corresponding higher frequency indices ($f > 0.5$ Hz).

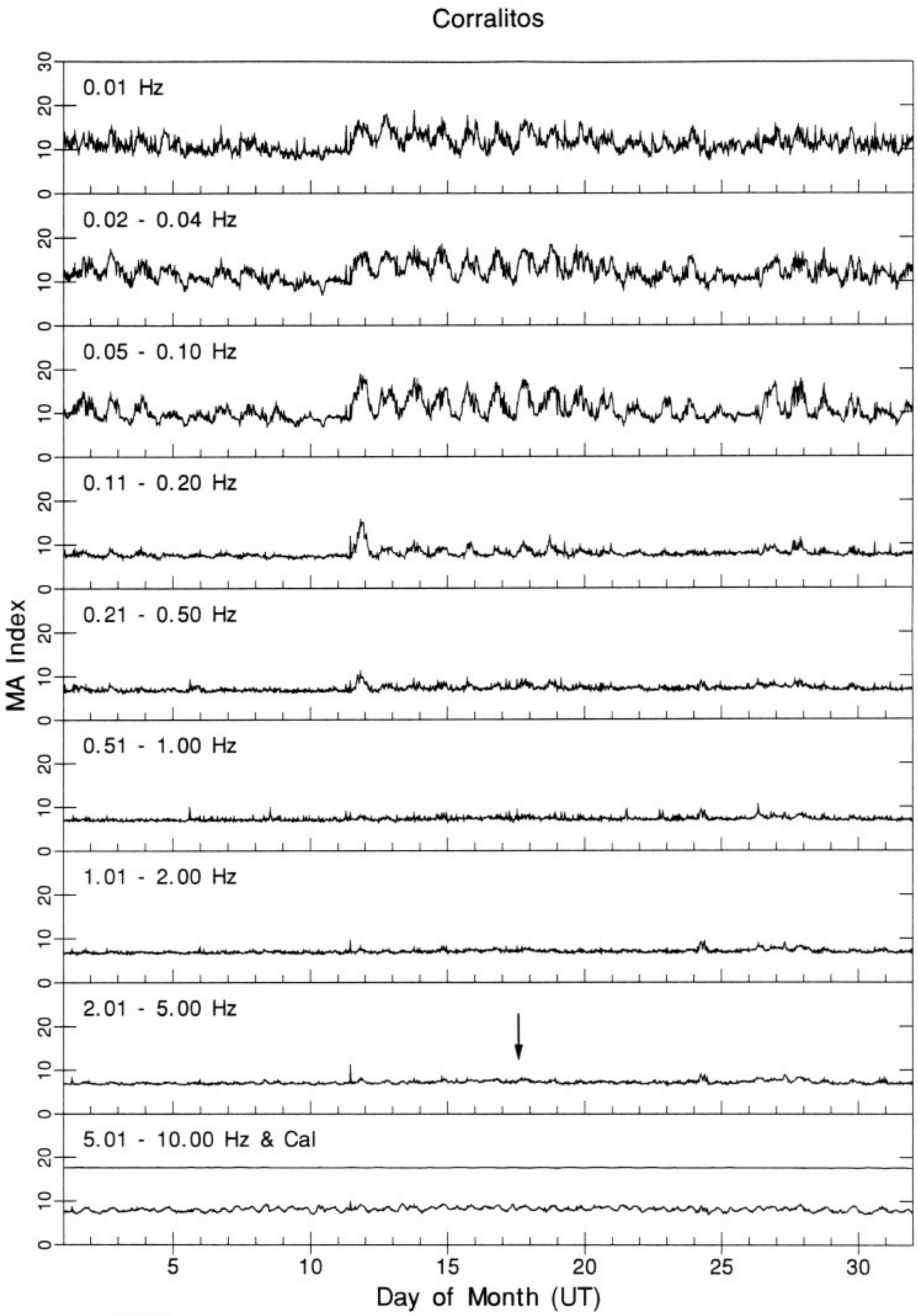

Figure 4. Variation of the magnetic activity indices measured during January 1994 at Corralitos, California. Corralitos is located 471 km to the north of Table Mountain. An arrow indicates the time of the Northridge earthquake.

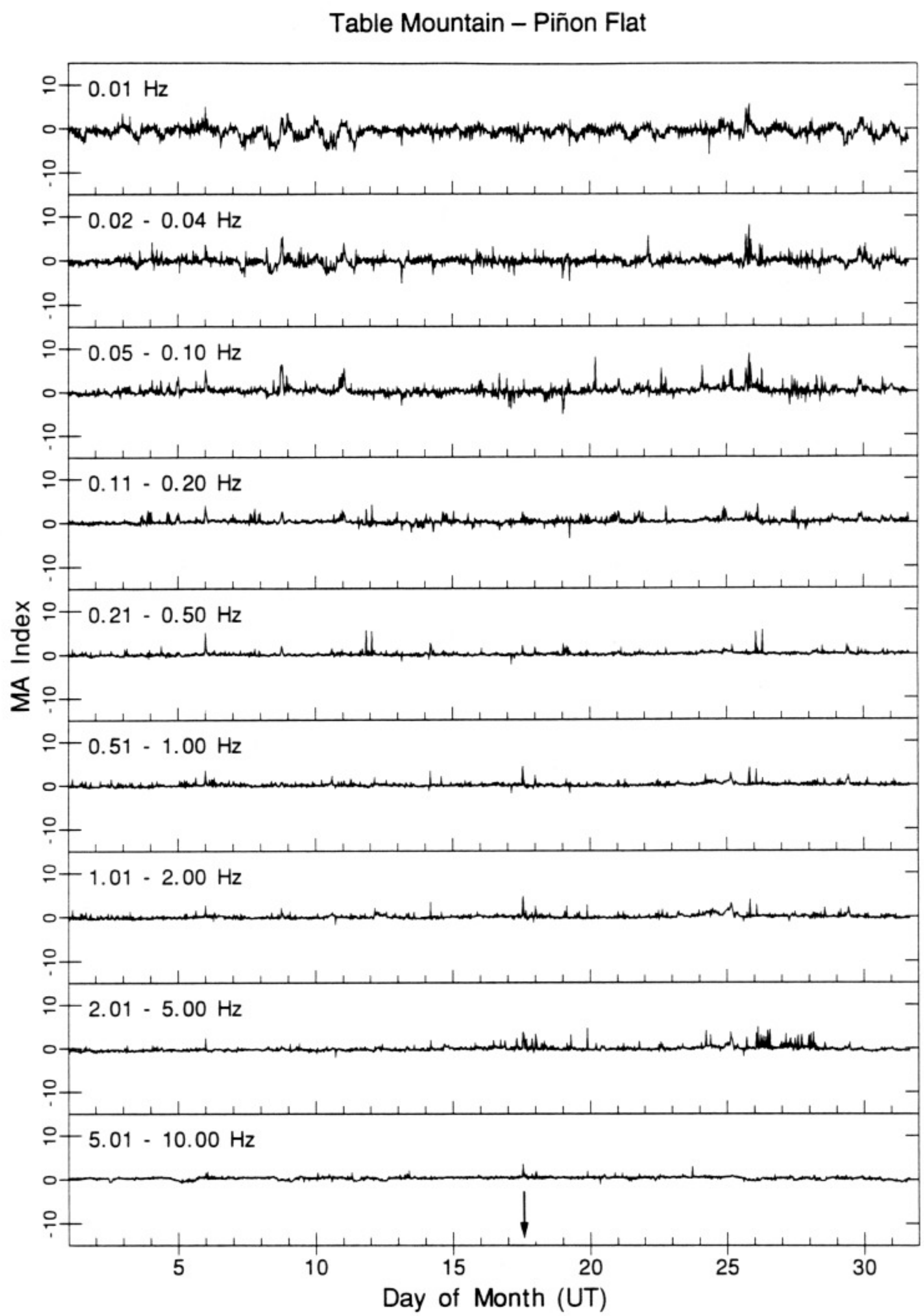

Figure 5. Variation of the difference between the magnetic activity indices measured during January 1994 at Table Mountain (Figure 2) and Piñon Flat (Figure 3). An arrow indicates the time of the Northridge earthquake.