Ultra low frequency geomagnetic field measurements during earthquake activity in Italy (September-October 1997)

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Abstract
Different methods with different results have been proposed in the scientific literature to identify the possible occurrence of weak seismo-magnetic ULF emissions. In September-October, 1997 Central Italy was struck by repeated seismic activity ($M_L < 5.8$). A simple amplitude analysis of the geomagnetic field variations (horizontal components, in the frequency range 4-100 mHz) at a geomagnetic facility located ≈ 65-85 km from epicenters of major earthquakes does not reveal in this case any clear evidence for possible ULF emissions.

Key words *ULF emissions – earthquake precursors*

1. Introduction

Although electromagnetic signals associated with earthquakes have been discussed in a wide frequency range, from megahertz to quasi-dc (Stacey,1964; Gokhberg *et al.*, 1982; Ogawa *et al.*, 1984; Park, 1991; Serebryakova *et al.*, 1992), few papers so far have investigated the possible occurrence of ULF signatures associated with seismic events (Fraser-Smith *et al.*, 1990, 1994; Molchanov *et al.*, 1992; Park *et al.*, 1993; Park, 1994; Kopytenko *et al.*, 1994; Dea *et al.*, 1994; Hayakawa *et al.*, 1996, 2000; Dea and Boerner, 1999).

Interesting results in this sense have been provided by Fraser-Smith *et al.* (1990) who examined half hourly power indexes of the geomagnetic field variations (0.01-10 Hz), and proposed a precursor ULF activity at a site located ~ 7 km from the epicenter of the Loma Pietra earthquake (M = 7.1). At these close distances they first identified a narrow band signal (50-200 mHz) which appeared approximately one month before the earthquake and persisted until the appearance of a substantial increase in the background noise in almost the entire ULF band; they then identified an anomalous dip in the background noise (0.2-5 Hz), starting one day before the shock, and finally an exceptionally high level of activity (10-500 mHz) starting approximately three hours before the earthquake. A similar investigation was conducted for the Northridge earthquake (M = 6.7): the absence in this case of clear ULF activity from two monitoring systems located ~ 80 km and ~ 200 km, respectively from the epicenter led Fraser-Smith *et al.* (1994) to conclude that a network of detectors spaced less than 100 km apart would be required to detect ULF fluctuations prior to earthquakes with magnitudes greater than 7. In conflict with their conclusions, Dea and Boerner (1999), who examined ULF data recorded at ≈ 160 km from

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the epicenter of the same earthquake, found a rise in the overall power level (100-500 mHz) for about two weeks preceding earthquake, together with an additional anomalous emission at higher frequencies (0.5 Hz - 1 Hz) one week before the earthquake. They proposed a possible interpretation of the discrepancy with Fraser- Smith *et al.*'s (1994) conclusions in terms of the different orientation of the sensor axes: indeed, while Fraser-Smith *et al.* (1994) examined the NS component, they detected major anomalous signals along the EW component. On the other hand, Dea *et al.* (1994) also proposed a three month elevation of the magnetic power (1-5 Hz) and impulsive wave train ≈ 15 s before the Big Bear quake (April 22, 1992, $M = 6.0$), about 150 km south of the epicenter. Molchanov *et al.* (1992), who analyzed ULF measurements at Dusheti (~ 28 km from the epicenter of the Spitak earthquake, $M = 6.9$), concluded that the intensity of the ULF activity started growing three to five days before the earthquake with a substantial ULF emission burst starting four hours before the main shock. Hayakawa *et al.* (1996) proposed a more sophisticated analysis of the ULF activity at a site located ~ 65 km from the epicenter of the Guam earthquake ($M = 7.1$). In particular, they considered the Z/H ratio in the midnight interval (22-02 LT) an important parameter for discriminating between possible seismic origin emissions and space plasma waves and proposed that the occurrence of a broad maximum of this ratio about one month before the earthquake could be interpreted in terms of ULF geomagnetic precursors of the seismic event. Pilipenko *et al.* (1999) proposed a comparative analysis between hypothetical electromagnetic disturbances produced by a lithospheric source and common electromagnetic noise of external origin. They applied their criteria for the detection of anomalous ULF activity before the destructive Kobe earthquake (January 17, 1995, $M = 7.2$) and concluded that no evident effects were revealed, possibly due to the large separation distance (~ 400 km) between the observation site and the earthquake epicenter. Recently, Hayakawa *et al.* (2000) examined ULF signals before a strong earthquake ($M = 8.2$, at Biak Islands: although the magnetic field intensity at two stations (1200 km apart) was found to be closely correlated with the K_p index, a detailed examination of the difference between the H and Z component, together with a polarization analysis of the experimental observations led them to conclude in favor of a local precursory emission (5-30 mHz) with amplitude of the order of 0.2-0.3 nT about 1-1.5 months before the quake.

In the present paper, we discuss the ULF measurements obtained at L'Aquila (AQ, Abruzzo, Italy), during a time interval (September-October 1997) in which repeated seismic activity occurred in Central Italy. We are aware that confident measurements of the geomagnetic field variations in the horizontal plane at a single station and in a limited frequency band are not sufficient to draw firm conclusions on the ULF seismogenic appearance. Nevertheless, in order to provide additional experimental information on the important topic of the possible precursor ULF activity, we found it interesting to discuss the experimental observations in the period of interest.

Obviously, a clear identification (and removal) of signals of different origin is a fundamental task for this kind of investigation: so we focused our attention on the frequency range 4-100 mHz which has been extensively investigated at AQ. Here, geomagnetic field fluctuations in the ULF band (Villante and Vellante, 1997) are typically a $Pc3$ (20-100 mHz) daytime phenomenon which is characterized by the occurrence of two dominant oscillation modes which can be respectively interpreted in terms of external waves penetrating deep into the magnetosphere, and of resonant oscillations of local field line at the fundamental eigenfrequency. Through the solar cycle, due to the variable interplanetary and magnetospheric conditions, the two modes often become intermingled: however, the geomagnetic fluctuations related to upstream wave phenomena typically occur at lower frequencies (40-50 mHz) in both the horizontal components, while the resonant peak typically has a higher frequency (~ 80 mHz) and emerges much more sharply in the H component. During nighttime intervals, damped $Pi2$ fluctuations (6.6-25 mHz) can often be detected around local midnight.

2. Experimental observations

The geomagnetic facility is located at AQ, ≈ 10 km NW from the town (λ = 42°23′N, ϕ = 13°19′E, LT = UT + 1) where the geomagnetic field variations are continuously recorded by an induction magnetometer. The output signals, originally sampled at 16 Hz, are low pass filtered and stored at a sampling rate of 1 Hz. The power spectra of the geomagnetic field components were evaluated over consecutive 4 min intervals by means of the maximum entropy method with an autoregression order equal to 30. Power densities were then integrated in three adjacent frequency bands, namely 4-20 mHz, 20-50 mHz, 50-100 mHz. For short time intervals fluxgate measurements from the same station are also available.

As discussed by Amato *et al.* (1998), on September 3, 1997 (day 246, 2207 UT) a M_L = 4.5 earthquake occurred in the plain of Colfiorito (Umbria), triggering a long sequence of aftershocks which lasted for about three weeks. Then, on September 26 (269), at 0033 UT, Central Italy was struck by a strong earthquake (M_L = 5.6) which occurred about at the same location and at ≈ 7 km depth; it was followed by a stronger shock, approximately nine ours later (0940 UT, M_L = 5.8), ≈ 3 km WNW of the previous one. Four strong shocks (M_L between 5.0 and 5.5) occurred in the following 20 days (October 3, 276, 0855 UT; October 6, 279, 2324 UT; October 12, 285, 1108 UT; October 14, 287, 1523 UT), and more than 20 events exceeded M_L = 4. Some of the seismic events unfortunately occurred approximately one to two days after sudden geomagnetic storm commencements (September 2, 245, 2258 UT; October 1, 274, 0057 UT; October 10, 283, 1609 UT). In particular, the sudden commencement occurred on September 2 did not allow any peculiar, short-term analysis of the ULF activity preceding the initial earthquake of the whole sequence (September 3). Figure 1 shows the location of epicenters of the six major events (circles): they were located between ≈ 65 and ≈ 85 km from the geomagnetic station. Figure 1 also shows the epicenters (squares) of a sequence of much weaker events (October 25, 298, 1940-2002 UT, M_L = 2.1-2.6) which occurred much closer to the geomagnetic station at ≈ 11-15 km.

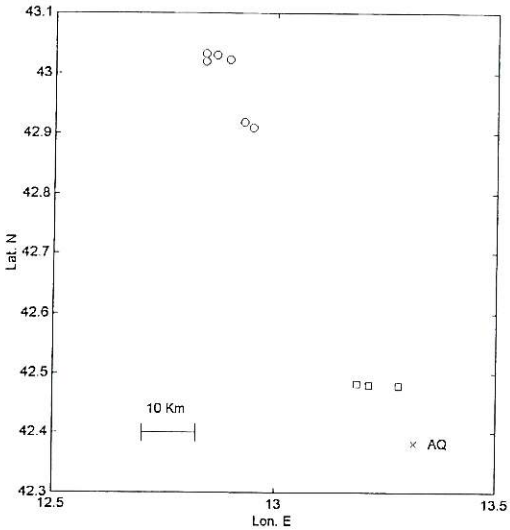

Fig. 1. The position of the epicenters of major (circles) and closer (squares) earthquakes with respect to the geomagnetic observatory.

Major seismic events were clearly accompanied by a coseismic shaking response of the induction magnetometer at AQ. As a matter of fact, the magnetometer response was typically much greater on the vertical component which more explicitly responds also to minor earthquakes. For this reason, in order to exclude any possible contamination by artificial effects, we focused our attention on the behavior of the horizontal components H and D, although this limitation does not allow a comparison with some results provided by previous investigations (Hayakawa *et al.*, 1996).

In order to identify the nighttime intervals less affected by ULF activity of external origin we conducted a preliminary analysis of the histograms and average values of the geomagnetic power over consecutive (and 1-h overlapping) 3 h intervals for the entire year 1997. As a matter of fact, we found in the highest (50-100 mHz) and intermediate (20-50 mHz) frequency band minimum power values for both components between 00-03 LT and 01-04 LT; in these

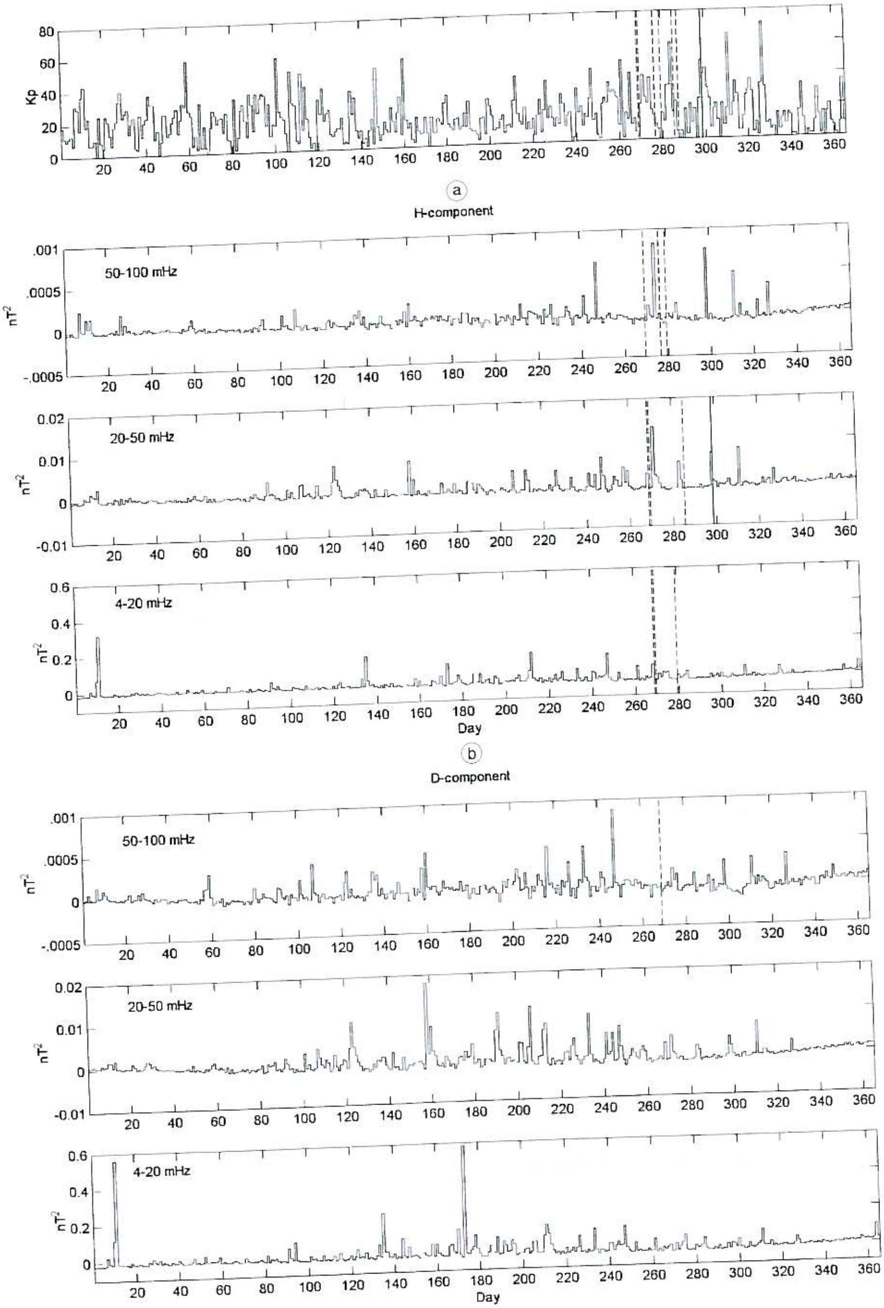

Fig. 2a,b. The daily average values (0200-0500 UT) of the integrated power of geomagnetic field fluctuations in different frequency bands. Data are referred to the average value for the whole of 1997. In the top plot the K_p index. Dotted vertical lines identify the occurrence of major earthquakes; solid lines identify the occurrence of the local earthquakes. a) *H* component; b) *D* component.

intervals, the average power level is ≈ 60% of that detected around local midnight (22-02 LT). In the following, however, we will mainly focus our attention on the time interval 03-06 LT (02-05 UT) which, in addition to a low power level in the higher frequency bands also shows a minimum energy content in the lowest frequency band (4-20 mHz) since long period phenomena, such as *Pi*2's, are less frequent. However, we also paid attention to major power enhancements detected in other 3 h intervals.

Figure 2a,b shows on daily time scale and for the entire year 1997 the behavior of the integrated power of the *H* and *D* component. As we said, in this long-term analysis, in order to minimize the effects of natural signals of external origin, we only considered for each day the average power in the time interval 02-05 UT. On the top plot we also show the daily average values of the geomagnetic activity index K_p. Sharp peaks of power are occasionally observed in fig. 2a,b, both in the lowest (for example on days 11, 135, 173, etc.) and in the higher frequency bands. As can be seen in several cases, the power enhancements in the *D* component are as explicit as (or greater than) those in the *H* component (for example, day 173, 4-20 mHz band). As shown in fig. 3a, the lower frequency peaks can be typically interpreted in terms of *Pi*2 pulsations associated with bays which occurred in the postmidnight sector. In particular, the results of fig. 3a (see also fig. 3b,c) confirm that these events cannot be simply interpreted as *H*-polarized phenomena (Saito, 1969; Hayakawa *et al.*, 1996) in that the *D* perturbation might well be as important as in the *H* component.

Higher frequency power enhancements deserve more attention in that some of them are detected close to the earthquake occurrence (obviously, the power peaks detected on day 274 are related with the geomagnetic storm). In this sense, we carefully examined also the power enhancements occurring close to weaker seismic events ($4 < M_L < 5$). For example, the power enhancements which appear on November 7 (311) in all the frequency bands and in both components might be interesting in that they might be related to a $M_L = 4.6$ earthquake (November 9, 1907 UT). Nevertheless, the experimental observations (fig. 3b) show that also in this case the power enhancements can be associated with a broadband pulsation activity which follows a sharp geomagnetic bay (November 6, ~ 2248 UT). We also paid careful attention to the time sequence of geomagnetic signals for a 24 h interval preceding the weak earthquake sequence occurring close to the geomagnetic station (298). These events occurred during a period characterized by a persistent ULF activity of external origin (note the power peaks and the high K_p values in fig. 2a,b) which makes it hard to identify possible geomagnetic signals associated with earthquakes. In particular, we detected at ~ 0109 UT a sharp *Pi*2 event (fig. 3c); then, the experimental observations (fig. 3d) showed the ULF activity which is typically detected at our station in the daytime hours during active magnetospheric conditions.

Previous investigations (Fraser-Smith *et al.*, 1990; Molchanov *et al.*, 1992) also suggested, in some cases, the onset of exceptionally high level of ULF activity starting 3-4 h prior to major earthquakes. The strong September 26 earthquake (0033 UT), which marked the onset of the major seismic activity, appears interesting in the sense that it occurred close to local midnight (*i.e.* when *Pc*3 pulsations of external origin should not be expected), and geomagnetic measurements cannot be affected by the aftershocks sequence of other major events. Fluxgate measurements in fig. 4a clearly show that in this case the earthquake (dotted line) rather occurred after several hours in which no ULF activity was detected, while the higher amplitude, longer term geomagnetic field variations (*i.e.* ~ 2115-22 UT) found correspondence in simultaneous measurements in other European Observatories (Vero, private communication). Similarly, the strongest seismic event occurring a few hours later (0940 UT) was not anticipated by any burst of ULF activity. In this case, the experimental observations provide evidence for a less frequent fluctuation which was detected less than 2 h before the shock (≈ 0756-0800 UT, fig. 4b): however, as for the previous case, a comparison with observations performed at different locations revealed the simultaneous occurrence of similar structures at distant sites.

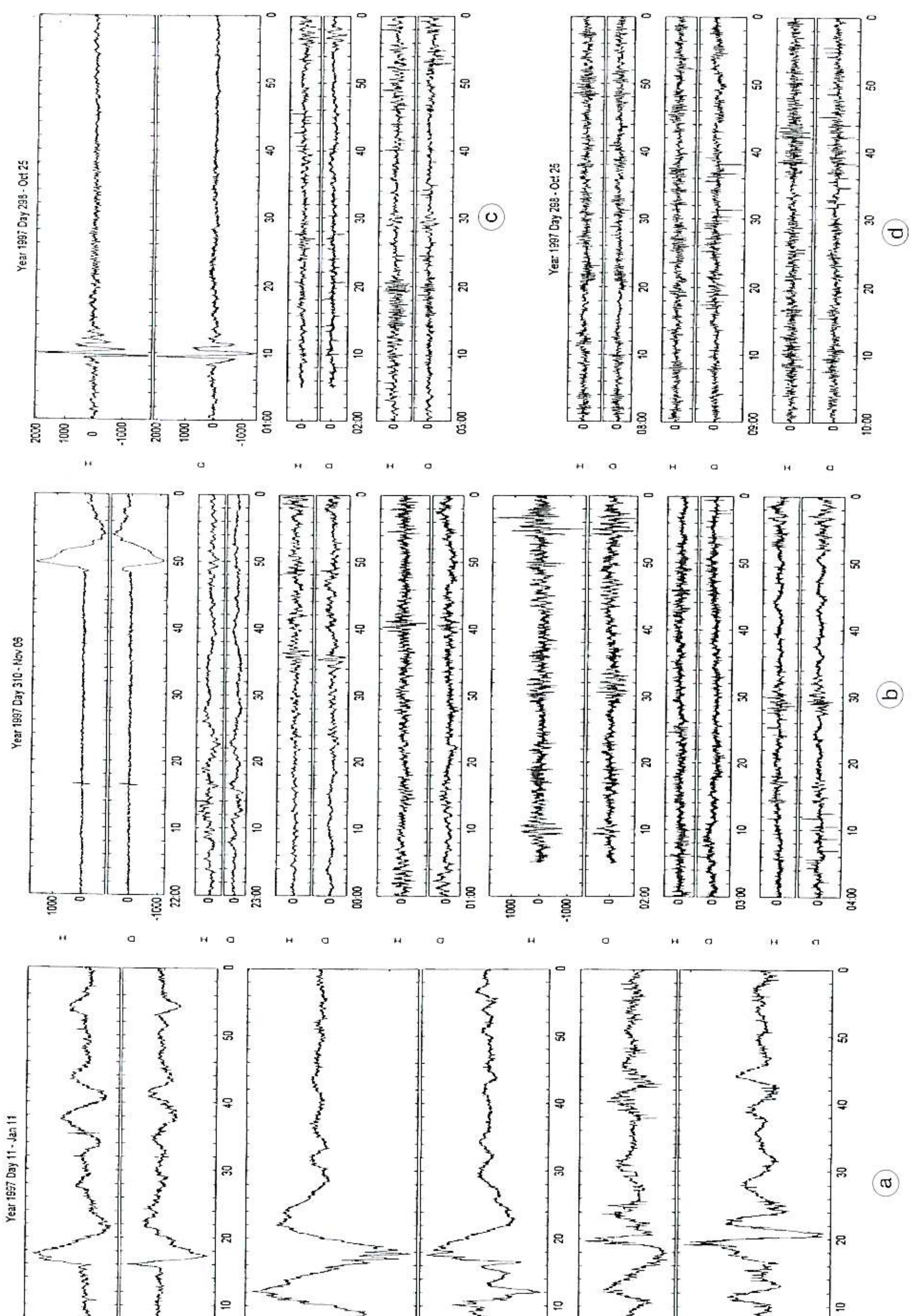

Fig. 3a-d. Search coil measurements of geomagnetic field variations.

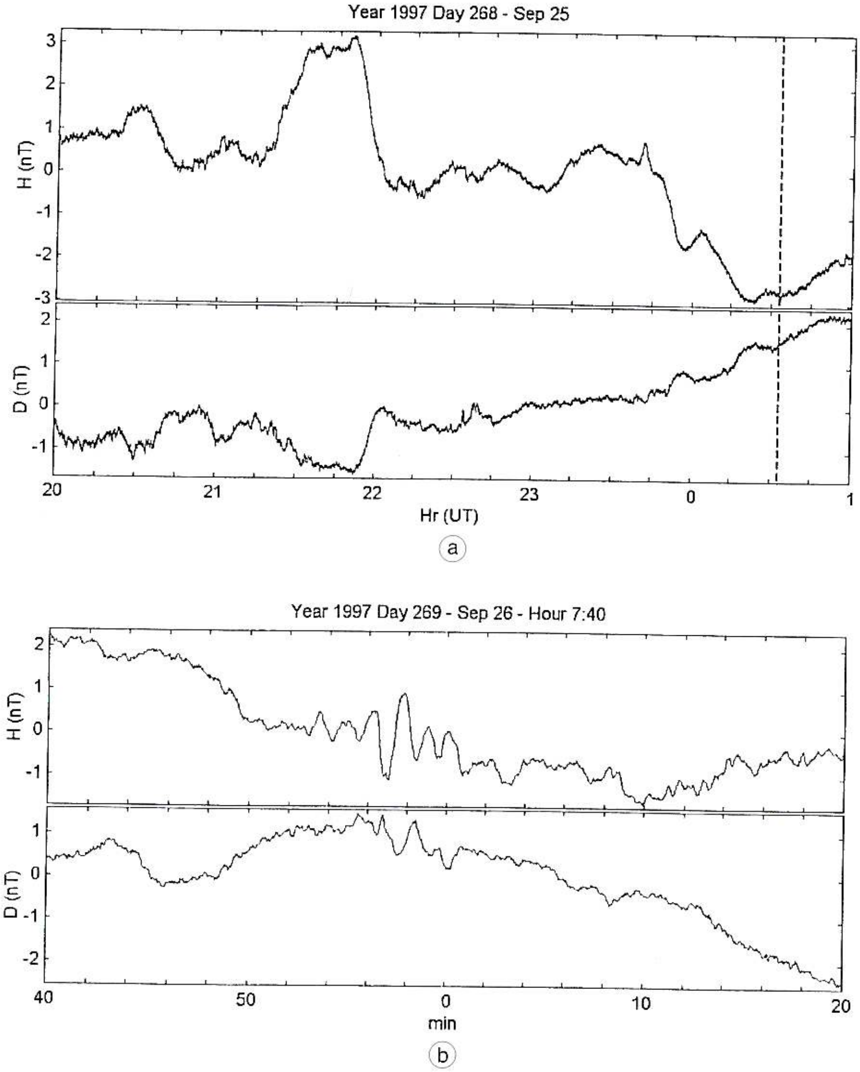

Fig. 4a,b. Fluxgate measurements of geomagnetic field variations.

3. Summary and discussion

The possible occurrence of ULF emissions related with earthquakes is an interesting subject which has been so far discussed in a number of papers in the scientific literature and different methods analysis (as well as different frequency bands) have been proposed with some controversial results. In some cases (Fraser-Smith *et al.*, 1990; Molchanov *et al.*, 1992; Dea *et al.*, 1994; Dea and Boerner, 1999; Hayakawa *et al.*, 1996, 2000), the onset of ULF activity preceding earthquakes was proposed, while in others (Fraser-Smith *et al.*, 1994; Pilipenko *et al.*, 1999) the geomagnetic observations did not reveal any particular feature prior to the earthquake occurrence.

In the present paper we conducted a simple amplitude analysis of the ULF wave activity (horizontal components in the frequency band 4-100 mHz)) detected at AQ during a time interval (September-October, 1997) in which a repeated seismic activity occurred in Central Italy ($M_l < 5.8$). The geomagnetic facility was located between ≈ 65 and ≈ 85 km from epicenters of major earthquakes, while much weaker seismic events occurred at much closer distances (≈ 15 km).

Since a clear identification of signals of different origin is a fundamental task for this kind of investigation, we focused our attention on the time intervals which typically correspond to the quietest magnetospheric conditions. A preliminary long-term analysis in this sense showed that at our site the post-midnight sectors are less influenced by natural signals of external origin than the midnight sector examined in previous investigations (Hayakawa *et al.*, 1996). In particular, we mainly focused our attention on the time interval 03-06 LT during which *Pi*2 pulsations are less frequent. Nevertheless, we still found several sharp power enhancements which, without a careful analysis of the time series observations, might easily have been misinterpreted in terms of geomagnetic precursors of earthquake occurrence. It leads to underline that this kind of investigation requires in-depth knowledge of all the physical aspects of the geomagnetic activity of different origin at the observatory site. In addition, our results confirm that the natural signals of external origin occurring in the midnight and post-midnight sectors are not *H*-polarized phenomena in that in several cases the *D* perturbation is more explicit than the *H* perturbation. This argument should be taken into account for a better identification of those parameters (such as the ratio *Z*/*H*) which might be important for discriminating between seismic emissions and natural signals of external origin.

The coseismic shaking response of the vertical component (which is also more affected by man-made disturbances) prevented a more sophisticated analysis of the experimental observations proposed by previous investigations (Hayakawa *et al.*, 1996, 2000). However, within the limits of a simple amplitude analysis, the experimental results do not provide in this case any convincing evidence for a possible association between the amplitude of ULF emissions and earthquake occurrence. A similar conclusion was recently proposed by Pilipenko *et al.* (1999) from an analysis of the geomagnetic field variations detected at a much greater distance from the epicenter of a destructive earthquake. In this sense, our results can also be considered consistent with the conclusions drawn by Fraser-Smith *et al.* (1994) who examined ULF signals at two measuring systems located ~ 80 and ~ 200 km from the epicenter of a $M = 6.7$ earthquake and found that no evident feature could be associated with earthquakes. Nevertheless, as previously remarked, for the same event Dea and Boerner (1999) found some evidence for a precursor activity at distances of the order of 150 km, at frequencies higher than those examined in the present investigation. On the other hand, Molchanov *et al.* (1995) performed theoretical calculations on the electromagnetic fields (10^{-2}-10^{2} Hz) induced by stochastic microcurrent activity inside future seismic sources and predicted magnetic field signals of the order of 1-10 pT $Hz^{-1/2}$. As a matter of fact, in the present case, seismic events also have smaller magnitudes than those examined in previous investigations: so, assuming that ULF signals were produced, they were likely too small to be clearly identified at a distant site in our frequency band by an amplitude analysis of horizontal components. It is clear, however, that, on time intervals of 24 h, seismic events were not anticipated by any burst of activity in the ULF band.

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