Possible electromagnetic earthquake precursors in two years of ELF-VLF monitoring in the atmosphere

A. Nardi[1], M. Caputo[2, 3] and C. Chiarabba[4]

[1] *Dipartimento di Scienze della Terra, Univ. La Sapienza, Roma, Italy*
[2] *Dipartimento di Fisica, Università La Sapienza, Roma, Italy*
[3] *Department of Geology and Geophysics, Texas A&M University, College Station, Texas, U.S.A.*
[4] *Istituto Nazionale di Geofisica e Vulcanologia, Roma, Italy*

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ABSTRACT In this study we show that ELF-VLF emissions occurred during the fracturing of rocks in laboratory experiments and during rock extraction in a cave, and that such emissions have also been recorded by 3 ELF-VLF stations installed in the central Apennines before earthquakes . The electric field emission is composed of two types of signals that are related to the evolution of micro-fractures within the rocks. In two years of monitoring, from August 2003 to September 2005, we recorded three signals, which all have frequency bands and characteristics similar to the signal recorded during the fracturing of rocks in the laboratory and during the extraction of rocks. All these signals appeared a few days before the occurrence of $M \geq 4.5$ earthquakes in the surrounding region (100-300 km). May EM emissions be are precursors of the earthquakes ?

1. Introduction

The investigation of natural emissions and the modification of physical parameters during the stressing of rocks is fundamental for earthquake forecasting. Among several parameters indicated as potential seismic precursors, electromagnetic EM emissions are receiving wider attention.

The first information on EM emission related to earthquakes goes back to the 16th century, to the city of Ferrara, for the series of earthquakes occurring from 1550 through 1577 (Caputo, 1987). A more complete and detailed list of EM phenomena related to earthquakes is found in Galli (1910); in 52 cases the phenomenon occurred before the earthquake, in 37 cases they occurred during the earthquakes and in 20 cases after.

Several studies have confirmed that accumulation and release of tectonic stress may generate EM emissions (Eftaxias *et al.,* 2003). Following the 1980 Sugadaira event ($M = 7.0$), EM signals associated with large earthquakes started being documented, mostly in the ULF band (see Table 1).

An IASPEI commission examined the possibility that ground noise in the LF, VLF and ELF bands could be useful in earthquake forecasting (Yoshino, 1997), they concluded that the data collected until then did not allow them to reach any firm conclusion, but EM emission from rock fracturing is still a promising field.

In past years, Bella *et al*. (1993) measured electric, magnetic, and seismo - acoustic signals in relation to pre-seismic stress. A few days before the June 4, 1993 ($M = 4.3$) earthquake, an

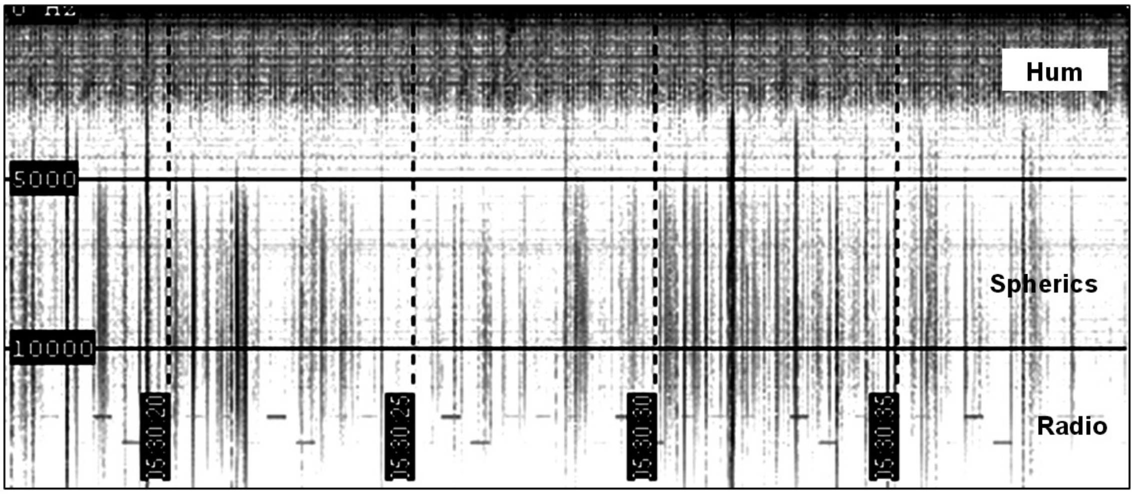

Fig. 1 - Spectrum of the noise of VLF. The frequency scale is in Hz on the y axis. The intensity of the signal is given by the intensity of the gray along the spectra. The time is in the x axis marked every 5 minutes. It shows the noise essentially generated by the harmonics of the 50 Hz of the electric power network (hum), some signals of natural atmospheric phenomena as lightnings and spherics and some VLF stations characterized by the typical intermittent radio-signal.

attenuation of 20 dB in the recordings of the long waves of Radio Montacarlo were observed (Bella *et al*., 1998).

Mognaschi (1997) studied the signals observed by a radio - amateur before the earthquake of May 12, 1997 in central Italy; he investigated the dynamics of the phenomenon that interests a wide frequency band. Mognaschi and Zezza (2000) recorded EM impulses during, and sometimes before, the fracture of a gneiss sample under uniaxial compression, by using a radio receiver of the medium frequency band (AM).

Table 1 - Examples of earthquakes appearing in the literature with a study of the EM emission prior to the earthquake. They are all strong earthquakes.

year	band	Associate event	bibliography
1988	ULF	Spitak, Armenia, 12.07.88, M=6.9	Molchanov *et al.*, 2003
1989	ULF	Loma Prieta, California, 17.10.89, M=7,1	Fraser-Smith *et al.*, 1990
1993	ULF	Guam, Giappone, 08.08.93, M=8,0	Smirnova *et al.*, 2001
1995	ULF-VHF	Kobe, Giappone, 17.01.95, M=7,2	Nagao *et. al.*, 2002
1995	VLF, VHF	Kozani, Grecia, 13.05.95, M=6,6	Eftaxias *et. al.*, 2003
1998	ULF	S.J. Bautista, California, 12.08.98, M=5,1	Karakelian *et. al.*, 2000b
1999	VLF	Atene, Grecia, 07.08.99, M=5,9	Eftaxias *et. al.*, 2003
1999	ULF-ELF	Chi-Chi, Taiwan, 21.09.99, M=7,6	Ohta *et. al.*, 2001 Akinaga *et al.*, 2001
1999	ULF	Hector Mine, California, 16.10.99, M=7,1	Karakelian *et. al.*, 2000a
2000	ULF	Izu, Giappone, 27.06.2000, M=6.4	Ismaguilov *et. al.*, 2002

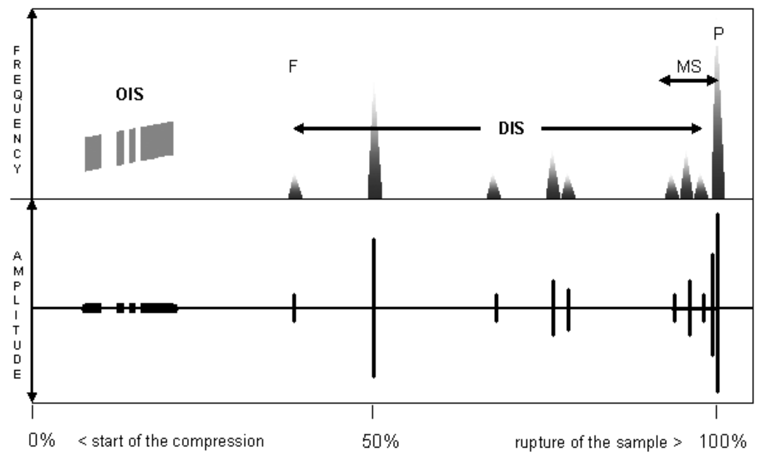

Fig. 2 - Schematic representation of the radioacoustic emission in the uniaxial compression and fracture of rock samples. At the top: the spectrum; below: the oscillogram. The y scale is the frequency in the band 20 Hz –20 kHz; with dynamic amplification of 60 dB. The time is in the x axis as percent of the time from the beginning of the constant rate compression to the fracture of the sample. We note two different types of impulsive sequences: the OIS is a orderly succession of impulses, the DIS is a disordered sequence of impulses. C is an impulse regularly appearing at about 50% of the time to fracture. SP is the concentrated sequence preceding the fracture.

Despite the abundance of information on emission phenomena, rigorous scientific experiments on the VLF emissions are still lacking. Recent laboratory experiments revealed VLF emissions during the fracturing of rock samples with different lithologies (Nardi, 2001). VLF emissions occurred during the entire loading of the rock sample and culminated at the final sample rupture. Similar VLF signals were observed during the collapsing of the walls for the extraction of rocks in a cave (Nardi, 2001; Nardi *et al.*, 2003).

2. Laboratory experiments

We ran a series of experiments in the Laboratorio Terre of Istituto Sperimentale della Ferrovie dello Stato (Nardi and Caputo, 2006) by using a 500-ton hydraulic press. A constant rate uniaxial pressure is applied to 36 wide rock samples with different lithologies. The fracture was obtained within 3 - 8 minutes, depending on the rock lithology.

The EM signals, recorded during the loading and at rock fracture, are formed by a sequence of micro-impulses. The band of emission of these signals is about 3 kHz wide, the centre of the band is from 6 to 11 kHz, with a tendency to drift towards the radio-frequency band spectrum but always remaining in the band 0.5 -11 kHz, as shown in Figs. 1 and 2. These electric emissions are, possibly, associated to in pre-seismic signals.

We observed EM in 36 of the 42 compression and fracture tests which cover all the 14 different lithologies examined (massive limestone, clay sandstone, metamorphic rocks and also beton). We recorded two different subsequent types of signals evolving during the compression and the fracturing of the samples: Orderly Impulsive Sequence (OIS) and Disorderly Impulsive

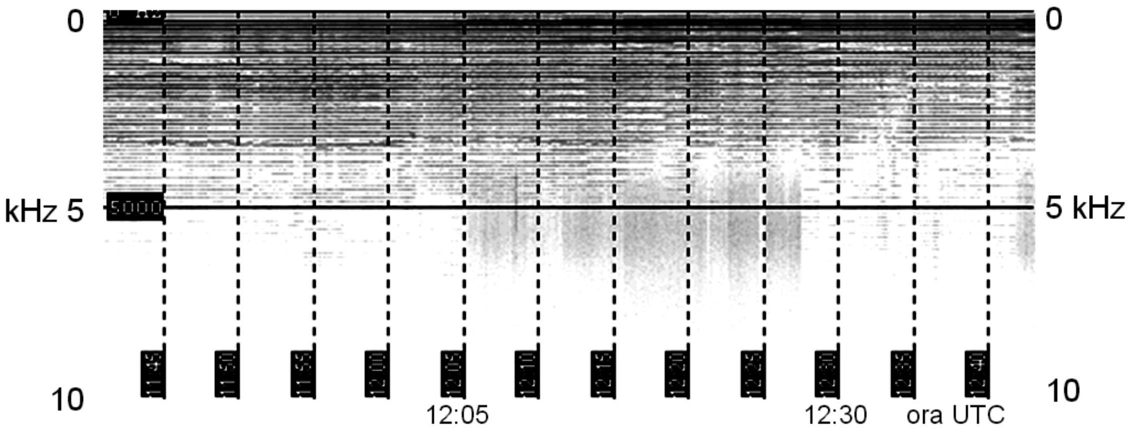

Fig. 3 - Spectrum of the EM signal associated to the (M = 5.0) earthquake occurring in the Emilian Apennine on September 14, 2003. The OIS signal was recorded on September 10. The hours in UTC are on the x axis, the frequency in kHz is in the y axis. The amplitude of the spectrum is expressed by means of the intensity of the gray color. The OIS signal covers a band of about 3 kHz centered at about 5 kHz.

Sequence (DIS) (Fig. 2).

The OIS is a high frequency signal which may be mechanically associated with the crack formation and, independently from the scale of the phenomenon, may be subdivided in: impulses, sets of impulses with variable intervals in between. The impulses are rather similar and appear with a band width of about 3 kHz, whose center may vary from 4 to 8 kHz and sometimes may even drift during the phenomenon.

The DIS is more intense and characterized by a low frequency and it may be associated with the opening of the fractures. During this phase, the impulses are different and variably distributed in time, although they sometimes appear in clusters and are progressively more intense and dense, forming a sequence that culminates with the fracture of the sample.

In the recorded DIS, each single EM impulse corresponds to a mechanical impulse recorded acoustically. The phenomenology has been observed in all the tested lithologies with differences that depend on the style of deformation and structural homogeneity of samples rather than their mineralogy.

The OIS emission occurred during all the tests, at least during the last phase that culminates with the final fracture of the sample. The absence of emissions during only a few tests is due to

Table 2 - Earthquakes occurring in the 2 years of recording from August 2003 and September 2005 in the Apennines and the Thyrrenean Sea with magnitude ≥ 4.5 and corresponding SIO signals recorded by the field stations.

Epicenter of seismic event	**Date**	**Mag**	**Receiving station**	**(km)**	**Advance hours days**
Appennino Emiliano	14-09-03	5.0	Cascia (PG)	200	106 = 4,4
Costa calabra occid.	03-03-04	4.6	Frascati (RM)	270	62 = 2.6
Mare a largo di Anzio	22-08-05	4.5	Cascia (PG)	150	89 = 3,7

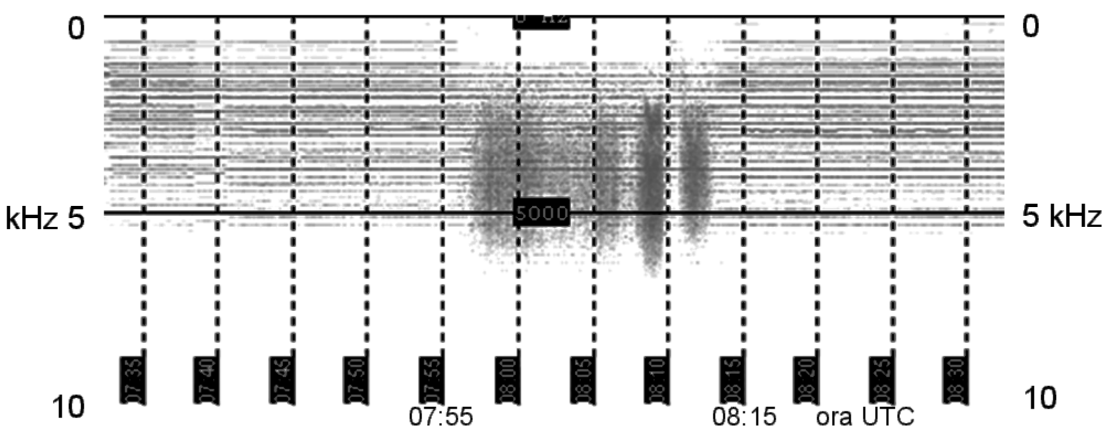

Fig. 4 - Spectrum of the EM signal associated to the (M = 4.6) earthquake occurring on the Calabrian coast on March 3, 2004. The OIS signal was recorded on March 1. The hours in UTC are on the x axis, the frequency in kHz is on the y axis. The amplitude of the spectrum is expressed by means of the intensity of the gray color. The OIS signal covers a band of about 3 kHz centered at about 4 kHz.

problems with the recordings apparatus or to the irregular shape of the samples.

3. Monitoring in the atmosphere

Three EM continuously recording stations have been installed in central Apennines. EM signal is recorded by a electric ELF-VLF antenna and digitized on a PC. Since the high sampling frequency (44100 Hz), only spectrograms are stored on the PC hard disk.

In the EM stations installed in the Apennines, we recognised OIS type signals (see Table 2). In all the three cases they are associated with magnitude ≥ 4.5 earthquakes, occurred 3~4 days later.

The recording of the first episode (September 2003) allowed us to compare the characteristics of the signal with those of the OIS recorded in the laboratory. Both have the same spectral distribution and an analogous time distribution on the wide scale (see Figs. 3, 4, and 5) and show identical or almost equal distribution times, that is the impulsive sequences have a duration of 1.2 s and are separated by intervals of 3 - 3.6 s with a bandwidth of 3 kHz.

The analogy of the signals recorded in the atmosphere with those recorded in the laboratory may be due to the dimension of the micro-fractures in small samples (those in the laboratory) and in the large scale and in spite of the fact that in the laboratory the stress rate is much greater than in the crust of the Earth.

Considering the earthquake list, shown in Table 2 (with events with $M \geq 4.5$), it is interesting to note that, the three earthquakes for which the hypothetical precursors are observed are relatively large and close enough to the EM stations to be detected.

Based on this observation, we tentatively propose the hypothesis of a magnitude threshold related to the release of observable EM precursors remembering that the EM emissions have always been recorded during laboratory experiments.

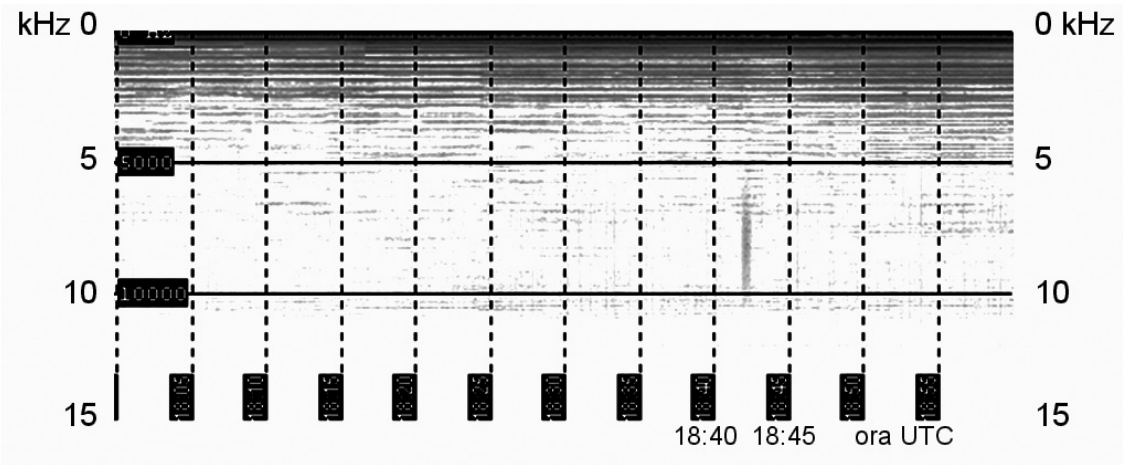

Fig. 5 - Spectrum of the EM signal associated to the ($M \geq 4.5$) earthquake occurring off the coast of Anzio (Latium) on August 22, 2005. The OIS signal was recorded on August 18. The hours in UTC are on the x axis, the frequency in kHz is on the y axis. The amplitude of the spectrum is expressed by means of the intensity of the gray color. The OIS signal covers a band of about 3 kHz centered at about 8 kHz.

We could not record the DIS signals using the automatic recording in the field, due to the limited resolution of the apparatus. However, a similar signal was observed during the explosions and collapsing of rocks in the cave of massive limestone (Nardi, 2001; Nardi *et al*., 2003; Nardi and Caputo, 2003, 2006).

4. Conclusions

The instruments and procedure used in this study allow us to identify possible EM precursors of earthquakes. We describe the EM emission as composed of two independent signals (SIO and SID) occurring during different stages of the stressing process. In two years of field observations, we recorded possible precursors for three earthquakes occurring in the area monitored by the instruments. We observe only SIO signals, while the presence of eventual SID signals is hampered by the automatic operation of the stations used in the field, whose time resolution is much lower than that of the apparatus used in the laboratory experiments. Although the number of cases is still limited, we did not record any false alarm and all the $M \geq 4.5$ earthquakes occurring close to the stations show presumed EM precursors that are very similar to OIS signals.

Statistical studies about different types of EM precursors observed in the ionosphere (Asada *et al*., 2001; Liu *et al*., 2004; Pulinets and Boyarchuck, 2004) shows advance times, distance from the epicenter and also one threshold of magnitude analogous to our observations.

The SID signals observed in laboratory experiments would also be important since they appear with a larger amplitude than the SIO signals and they last longer, culminating with the fracture of the samples.

Moreover, the one to one correspondence between the VLF impulses and the opening of the fractures in the samples observed acoustically suggests that these signals may potentially monitor the

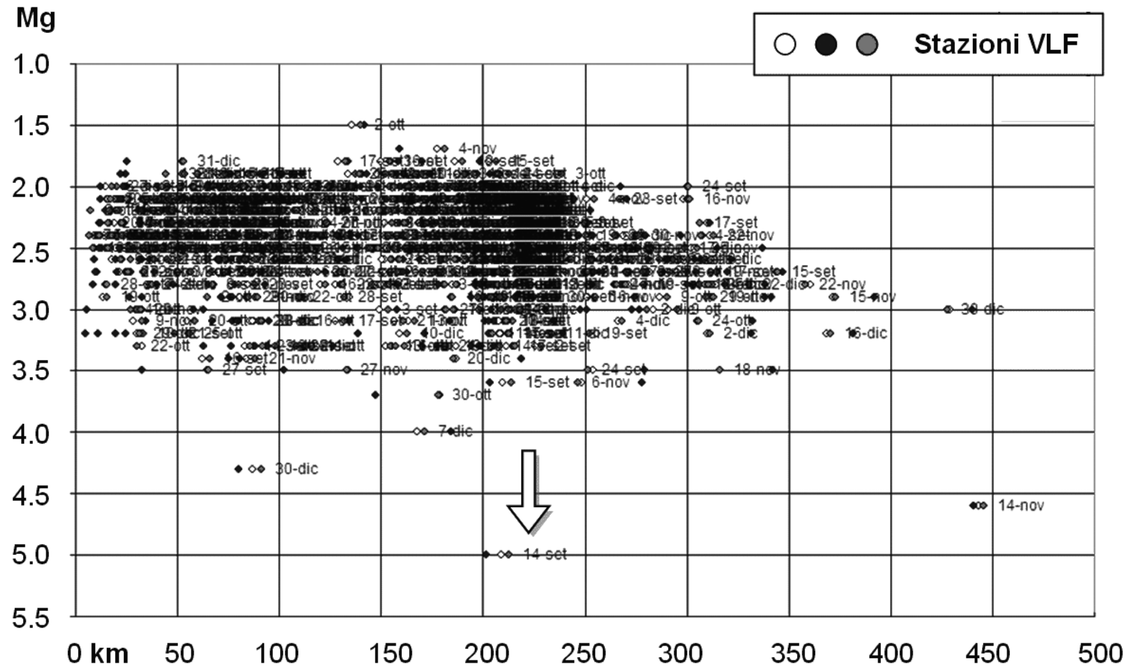

Fig. 6 - Distribution of the earthquakes recorded in the time interval September - December 2003 [retrieved from the INGV catalogue (www.ingv.it/~roma/reti/rms/bollettino/index.php)] plotted as function of decreasing magnitude (on the y axis) and of an increasing distance (on the x axis) from the VLF recording stations. The sets of 3 points for each epicenter indicate the relative distances from the 3 stations. The arrow indicates the earthquake of September 14, 2003 associated to the EM emission of September 10, shown in Fig. 3. This signal is the strongest and, at the same time, the closest to the associated earthquake.The 3 cases considered tentatively suggest the possible existence of a magnitude threshold (around 4.5) for the generation and recording of the EM emission.

phenomenon of dilatancy at distance.

Finally, the temporal relation tentatively inferred from the laboratory data may be related to the possibility of forecasting the time of occurrence of the earthquake.

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Corresponding author: Adriano Nardi
Istituto Nazionale di Geofisica e Vulcanologia, UTO-MAE
c/o Caserma Bulgarella
Viale Pinturicchio 23/e, 00196 Roma, Italy
e-mail: adriano.nardi@ingv.it