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Ultra Low Frequency (ULF) European multi station magnetic field analysis before and during the 2009 earthquake at L'Aquila regarding regional geotechnical information

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Abstract. This work presents ground based Ultra Low Frequency (ULF) magnetic field measurements in the frequency range from 10–15 mHz from 1 January 2008 to 14 April 2009. In this time period a strong earthquake series hit the Italian Abruzzo region around L'Aquila with the main stroke of magnitude $M = 6.3$ on 6 April 2009. In the frame of the South European Geomagnetic Array (SEGMA), a European collaboration runs ULF fluxgate instruments providing continuously magnetic field data recorded in mid- and south Europe. The main scientific objective is the investigation of signal variations due to seismic activity and the discrimination between other natural and human influences. The SEGMA station closest to the L'Aquila earthquake epicenter is L'Aquila observatory located in the epicenter region. For the scientific analysis we extract the nighttime period from 22:00–02:00 UT and determine the power spectral density (PSD) of the horizontal (H) and vertical (Z) magnetic field components and the standardized polarization ratio (Z) over (H). To discriminate local emissions from global geomagnetic effects, data from three SEGMA stations in distances up to 630 km from the epicenter region are analyzed and further compared to the independent global geomagnetic $\sum K_p$ index. Apart from indirect ionospheric effects, electromagnetic noise could be originated in the lithosphere due to tectonic mechanisms in the earthquake focus. To estimate the amplitude of assumed lithospheric electromagnetic noise emissions causing anomalies in the PSD of the (Z) component, we consider magnetotelluric calculations of the electric crust conductivity in the L'Aquila region. Results found at L'Aquila observatory are interpreted with respect to the lithosphere electrical conductivity in the local observatory region, the $\sum K_p$ index, and further in a multi station analysis. Possible seismic related ULF anomalies occur ∼2 weeks before the main stroke.

1 Introduction

Since two decades many authors have performed measurements over a wide frequency range and applied different signal processing methods and reported about electromagnetic effects related to earthquakes. Seismic ULF phenomena possibly related to earthquakes have been studied since Fraser-Smith et al. (1990). The polarization method based on the ratio of vertical and horizontal magnetic field intensity has been introduced by Hayakawa et al. (1996) and improved by Ida et al. (2008). The standardized polarization method was used by Masci et al. (2009) to investigate seismic events in the L'Aquila region. ULF anomalies related to seismic activity in a multi station approach have been investigated by Kopytenko et al. (1993) and Hayakawa et al. (2007).

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In the frame of the SEGMA network, the basic polarization method was applied in Prattes et al. (2008). Further, Villante et al. (2010) performed a classical polarization analysis with magnetic field data recorded before and during the L'Aquila earthquake series 2009. In the present work we show results obtained with the improved standardized polarization method applied on recorded data at several geomagnetic stations belonging to the SEGMA network spread over mid- and south Europe in a time period of 15 months, including the strong seismic active and further seismic weak time periods in the area of L'Aquila.

After a short performance summary of the SEGMA fluxgate magnetometer including a geographical overview of the SEGMA chain, we focus on the L'Aquila earthquake series 2009. Concerning signal processing the standardized polarization method is applied to four SEGMA stations. The improved standardized polarization method has justified that both the B_Z and the B_H components can be treated equally. Results in a first five months time period of weak seismic activity in the observatories local area show that data quality of the analyzed stations is comparable with regard to background noise and human influence. In a second period the station comparison is extended to the time span of the L'Aquila earthquake series with LAQ observatory being located in the main earthquake stroke region, whereas the SEGMA stations (CST, NCK) are located in (420 and 630) km distance to L'Aquila acting as comparison stations. This temporal splitting enables one to compare electromagnetic anomalies in the ULF range emitted in the local epicenter region.

According to theory there are three main sources of ULF noise emission: (i) geomagnetic effects, (ii) man-made noise, and finally (iii) seismic activity. Geomagnetic events are expected to be observed at all stations, and the $\sum K_p$ index gives an opportunity to compare the measurements to a planetary index. Experience shows that recorded data are less influenced by man-made noise during nighttime, so for the current analysis we extracted the four hour period from 22:00–02:00 UT. Instrumental housekeeping data has been used to eliminate days with data gaps or instrument dependent errors due to e.g. time synchronization.

To characterize magnetic field anomalies related to seismic activity in the ULF range we distinguish between two major effects:

(iii$_1$). The direct electromagnetic effect. A source of wideband electromagnetic noise is assumed in the earthquake focal zone. Higher frequency emissions are more attenuated due to a lower skin depth, while the lower frequencies, especially in the ULF range, can penetrate the Earth's lithosphere. This behavior leads to an increase of the polarization ratio due to an increase of B_Z. The ULF band from 10–50 mHz was found to be mainly affected, and authors report about ULF anomalies related to earthquakes around particular frequencies of 10 mHz. The measured ULF anomalies described in this work are possibly related to the direct electromagnetic effect. Observing several frequency sub bands from 10–500 mHz showed that anomalies turn out most significant in the sub band from 10–15 mHz. The source of emission is interpreted by Molchanov et al. (1998) due to microfracture electrification or the opening of an ensemble of cracks in the focal zone of the earthquake. Microfractures have sizes in the range from 10^{-4}–10^{-1} m^{-2}, and the number of cracks is estimated in the order of 10^6–10^7 m^{-3} generated on a time scale of approximately microseconds. The velocity of the opening is approximately 10^3 m s^{-1}, which is in the range of seismic waves. Electromagnetic ULF investigation related to lithosphere processes and earthquakes have been performed by Kopytenko et al. (1994).

(iii$_2$). Indirect seismic effects: Strong seismic activity can lead to Atmospheric Gravity Waves (AGWs), leading to turbulence in the lower ionosphere. This process causes a depression of ULF waves going down from the magnetosphere and leads to a decrease of B_H on the Earth's surface.

2 Instrument, database, and seismic conditions

In this section we describe: (i) the magnetic field fluxgate instrument called CHIMAG, (ii) the SEGMA array with respect to the L'Aquila earthquake, and (iii) the strong seismic activity in the L'Aquila region 2009.

2.1 Instrument

SEGMA has heritage from the CHInese MAGnetometer (CHIMAG) fluxgate magnetometer chain with the primary goal to investigate magnetic pulsations in the ULF range. The vital parameters of the high temporal resolution 3-axes fluxgate magnetometer are the measurement range of ±512 nT, the compensation field of 60 000 nT in X and Z, and ±30 000 nT in Y direction. The accuracy is 8 pT at a temporal resolution of 1 Hz, the highest possible sampling frequency is 64 Hz. The 3-axes magnetometer measures in X (positive northward), Y (positive eastward), and Z (positive towards the centre of the Earth) direction. The horizontal components X and Y build up as described in Eq. (1),

$$H = \sqrt{X^2 + Y^2}. \qquad (1)$$

A detailed description of the instrument can be found in Magnes et al. (1999) and Schwingenschuh et al. (2000).

2.2 Database

Figure 1 shows a map of the SEGMA network with 5 operating stations. Indicated by yellow markers, the observatories

Fig. 1. Map of SEGMA ULF stations, Google Earth.

Castello Tesino (CST) and L'Aquila (LAQ), both located in Italy, and Nagycenk (NCK) in Hungary are evaluated in the frame of this work, contributing data for 2008 and 2009. The station Ranchio (RNC), Italy, indicated in green, contributes data only during 2008. The station Panagyurishte (PAG), Bulgaria, shown by a white marker, is not evaluated in the frame of this work but is introduced here for completeness as part of the SEGMA chain. SEGMA ULF data are available with high reliability during the last ten years. This multi station setup enables one to distinguish between seismic active and quiet time periods in that area.

Table 1 contains the SEGMA ULF stations with geographical coordinates, corrected geomagnetic coordinates, and the distances to the L'Aquila earthquake epicenter region.

2.3 The L'Aquila earthquake series 2009

From 30 March 2009 to 9 April 2009, US Geological Survey (USGS) recorded 25 earthquakes in the region around L'Aquila within a magnitude range from $3.6 \leq M \leq 6.3$. The main stroke was recorded on 6 April 2009, 01:32:39 UT in a depth of 10 km and geographical coordinates $42°33'$, $13°33'$. The disastrous earthquake series gives the opportunity to perform ULF investigations with the SEGMA chain related to seismic activity. The main stroke had the magnitude $M \geq 5$, and more than 25 earthquakes belonging to the series have been recorded in the local area of the L'Aquila ULF SEGMA station in a short time period. This condition is promising to observe ULF anomalies related to seismic activity.

Figure 2 and Table 2 show the magnitude-distance-depth distribution of the L'Aquila earthquake series.

In Table 2 all seismic events of the earthquake series with distances less than 10 km to L'Aquila earthquake epicenter and depth in the range from 5–18 km are summarized.

2.4 ULF analysis related to seismic activity

Basically, many physical processes are related to seismic activity. In this section we emphasize electromagnetic wave emission due to processes in the Earth's lithosphere. Pressure variations in the upper lithosphere lead to the generation of microfractures that are related to wideband electromagnetic emission in the earthquake focus zone. High frequency components are damped strong due to low skin depth (low pass filter function of the lithosphere). The lower frequencies can penetrate the Earth's crust without significant attenuation. So the chance to observe an electromagnetic earthquake signature is significantly increased in the ULF range than in other higher frequencies. An important requirement to study electromagnetic manifestations related to earthquakes is knowledge about the lithosphere pre-condition in the local area of the observation point. Main interest is on the electrical parameters and especially the electrical resistivity of ground layers. Palangio et al. (2007) reported a calculation of the ground resistivity profile for L'Aquila station by means of the single station magnetotelluric tensor evaluation. Several layers from 0–50 km depth show an increase of the electrical resistivity at $d \sim 2$ km depth from

Table 1. SEGMA ULF chain and distances to L'Aquila erathquake.

ULF Stations		Geographic Coordinates		Corr. Geomagnetic Coordinates		Dist
Name	Code	Lat. (° N)	Long. (° E)	Lat. (° N)	Long. (° E)	(km)
Castello Tesino	CST	46.00	11.70	40.70	87.00	420
Nagycenk	NCK	47.60	16.70	42.60	91.70	630
Ranchio	RNC	43.97	12.08	38.22	86.71	200
L'Aquila	LAQ	42.23	13.19	36.30	87.35	5
Panagyurishte	PAG	42.51	24.18	36.98	97.21	890

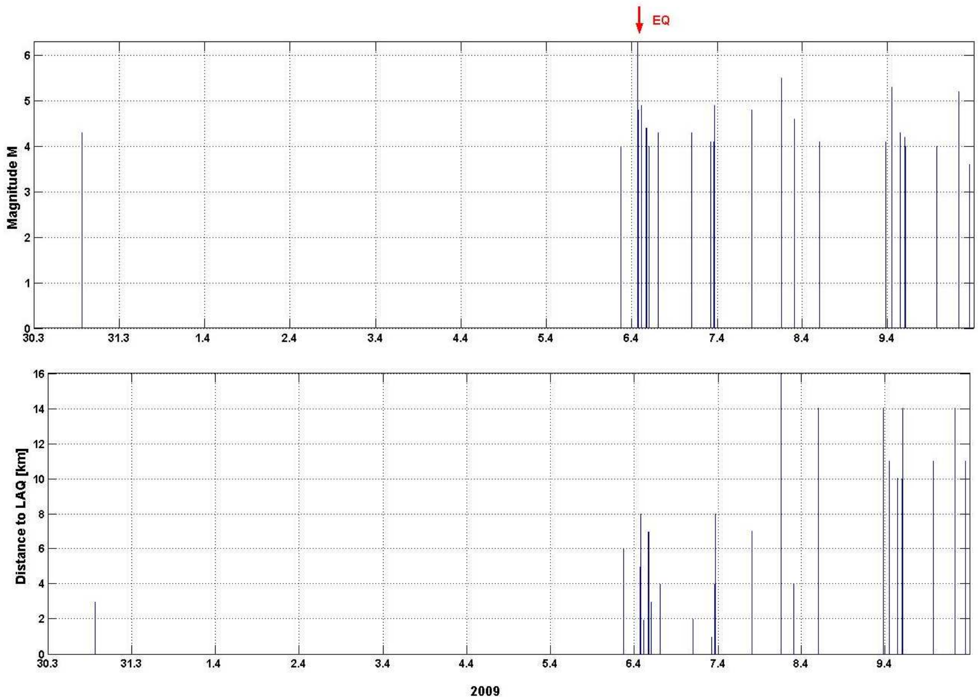

Fig. 2. Magnitude of seismic events (top panel) and distance to L'Aquila observatory during 30 March 2009 and 9 April 2009. The occurrence of the main stroke is indicated with an arrow. The magnitude of the seismic events is shown in the upper panel, the distances of earthquakes epicenters to L'Aquila in the lower panel.

$\sigma \sim 10$–$2000\,\Omega\,\mathrm{m}^{-1}$. The detailed geotechnical composition in the upper layer is reported in Monaco et al. (2009). The resistivity mean value from 0–10 km, which is the depth of the main earthquake, is $<\sigma> \sim 600\Omega\,\mathrm{m}^{-1}$. Examples for electrical conductivity, skin depths, and different materials at certain frequencies are summarized in Prattes et al. (2008). The skin depth δ for frequencies of our interest, i.e. in the range from 10–15 mHz with the above determined electrical resistivity of $600\,\Omega\,\mathrm{m}^{-1}$, is $\delta \sim 100$ km. Due to the high pressure variations in the vicinity of strong seismic activity, the electrical conductivity of the lithosphere is expected to show variations. If we assume realistically an electromagnetic wideband noise source emitting in the seismic focus region, L'Aquila observatory is in the ULF influence zone due to the high skin depth. The stations CST and NCK at wider distances to LAQ are located outside the zone of influence due to seismic ULF activity.

3 Signal processing methodology

We extracted the local midnight period from 22:00–02:00 UT for further analysis. This nighttime period is less influenced by man-made artificial noise than daytime periods. Each of these segments is subjected to a Fast Fourier Transform (FFT) analysis. The selected sampling frequency is f_S=1 Hz, which gives a Nyquist frequency of $f_{NY} = f_S/2 = 500$ mHz. The Fourier transformed horizontal and vertical magnetic field components were separated into

Table 2. Seismic events with less than 10 km distance to L'Aquila EQ extracted from USGS. The main stroke is indicated in bold letters.

Year.Mo.Day	HH.MM.SS	Magn	Depth (km)	Dist (km)
2009.03.30	13.38.40	4.3	5	3
2009.04.05	20.48.54	4.0	8	6
2009.04.06	**01.32.39**	**6.3**	**8**	**5**
2009.04.06	01.36.30	4.8	5	8
2009.04.06	02.27.46	4.2	10	1
2009.04.06	02.37.04	4.9	10	2
2009.04.06	03.56.45	4.4	10	7
2009.04.06	04.47.53	4.0	9	3
2009.04.06	07.17.10	4.3	9	4
2009.04.06	16.38.09	4.3	10	2
2009.04.06	21.56.53	4.1	9	1
2009.04.06	22.47.13	4.1	11	4
2009.04.06	23.15.37	4.9	8	8
2009.04.07	09.26.28	4.8	10	7
2009.04.07	21.34.29	4.6	7	4
2009.04.09	03.14.52	4.3	18	10
2009.04.09	04.32.44	4.2	8	10

sub bands to extract the frequency band $\Delta f = 10$–15 mHz. Further, the power spectral densities (PSD) of the individual component ($S_{H\mathrm{Day}}$, $S_{Z\mathrm{Day}}$, $S_{\sum H\mathrm{Day}}$, $S_{\sum Z\mathrm{Day}}$) in ($\mathrm{nT}^2\,\mathrm{Hz}^{-1}$) were determined as described in Eqs. (2) and (3).

$$
\begin{aligned}
S_{H\mathrm{Day}}(\omega) &= \frac{|B_H(\omega)|^2}{2\pi\cdot\Delta f} = \frac{|B_H(\omega)|^2}{2\pi\cdot 5\cdot 10^{-3}},\\
S_{Z\mathrm{Day}}(\omega) &= \frac{|B_Z(\omega)|^2}{2\pi\cdot\Delta f} = \frac{|B_Z(\omega)|^2}{2\pi\cdot 5\cdot 10^{-3}},
\end{aligned}
\tag{2}
$$

where $B_H(\omega)$ and $B_Z(\omega)$ are the Fourier transformed components in the sub band Δf. To get better statistics the PSDs are averaged as shown in Eq. (3).

$$
\begin{aligned}
S_{\Sigma H\mathrm{Day}} &= \sqrt{\frac{1}{N}\sum\left[S_{H\mathrm{Day}}(\omega)\right]^2},\\
S_{\Sigma Z\mathrm{Day}} &= \sqrt{\frac{1}{N}\sum\left[S_{Z\mathrm{Day}}(\omega)\right]^2},
\end{aligned}
\tag{3}
$$

where N indicates the sample size.

To obtain monthly PSD statistics (monthly mean and standard deviation), all $S_{H\mathrm{Day}}(\omega)$ and $S_{Z\mathrm{Day}}(\omega)$ spectra contributing to a month are processed (excluding days with bad data) and averaged similar to Eq. (3).

The improved polarization analysis normalizes each geomagnetic field component as described in Eq. (4):

$$
\begin{aligned}
H_{\mathrm{Day}} &= \frac{S_{\Sigma H\mathrm{Day}} - \mu_{\Sigma H\mathrm{Month}}}{\sigma_{\Sigma H\mathrm{Month}}},\\
Z_{\mathrm{Day}} &= \frac{S_{\Sigma Z\mathrm{Day}} - \mu_{\Sigma Z\mathrm{Month}}}{\sigma_{\Sigma Z\mathrm{Month}}},
\end{aligned}
\tag{4}
$$

where $\mu_{\sum H\mathrm{Month}}$ and $\mu_{\sum Z\mathrm{Month}}$ are the monthly mean PSD values and $\sigma_{\sum H\mathrm{Month}}$ and $\sigma_{\sum Z\mathrm{Month}}$ are the monthly standard deviation PSD values.

The standardized polarization is determined as follows:

$$
P_{\mathrm{Day}} = \frac{Z_{\mathrm{Day}}}{H_{\mathrm{Day}}}. \tag{5}
$$

The standardized polarization ratio increases if (i) the vertical magnetic PSD increases and/or (ii) the horizontal magnetic PSD decreases. Experience shows that polarization analysis results are robust if a significant variation of H_{Day} is observed and $H_{\mathrm{Day}} \geq 0.1$.

4 Standardized polarization analysis results

This section compares the four stations CST, RNC, NCK, and LAQ during a (i) seismic quiet time period of five months. Further, (ii) long term results for the entire 15 months and (iii) results focused on the L'Aquila seismic active period for the three stations CST, NCK, and LAQ are presented; and (iv) short term results for L'Aquila are discussed.

4.1 Station comparison during a seismic quiet time period from 1 August 2008 to 31 December 2008

Station comparison is of essential importance to (i) analyze global geomagnetic effects, (ii) evaluate the quality figure of observatories and man-made noise, and (iii) work out emission due to local effects. In Fig. 3 a station comparison of standardized horizontal H_{Day} and vertical Z_{Day} PSD for a five month time period is depicted. Data from the observatories CST, NCK, RNC, and LAQ are analyzed from 1 August 2008 to 31 December 2008. The upper panel shows the $\sum K_p$ geomagnetic index. The horizontal PSD is well correlated for CST, NCK, and RNC with the $\sum K_p$ index, with the exception of 8 November 2008 to 22 December 2008 for LAQ observatory. Global geomagnetic effects causing high PSD values are found in the horizontal PSD, e.g. during the period from 30 September 2008 to 5 October 2008.

Geomagnetic effects are not distinct in the vertical PSD except for the time periods 11 August 2008 to 14 August 2008, 2 September 2008 to 9 September 2008, and on 6 December 2008. The probability to observe locally emitted anomalies, e.g. artificial noise or effects in the lithosphere, is higher in the vertical PSD.

The single component results show that the vertical and horizontal PSDs are comparable in terms of background noise level.

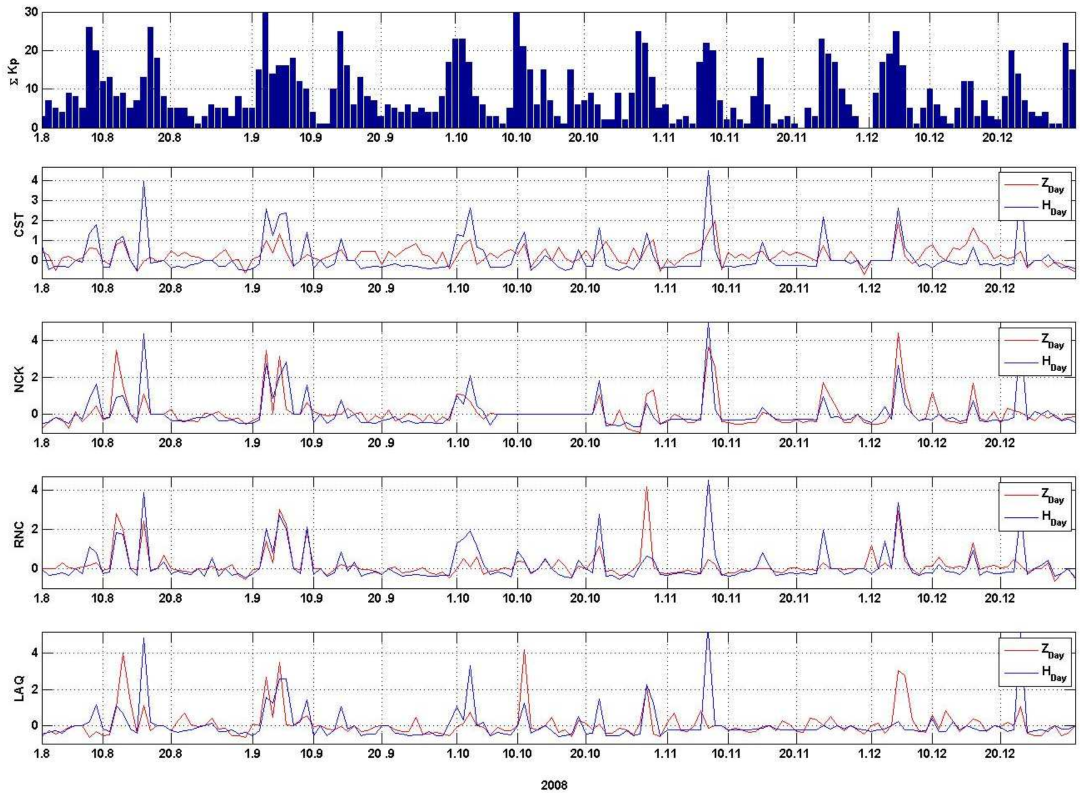

Fig. 3. $\sum K_p$ and standardized daily horizontal (blue) and vertical (red) PSD from 1 August 2008 to 31 December 2008 for CST, NCK, RNC, and LAQ station in a seismic quiet time period.

4.2 Long term station comparison from 1 January 2008 to 14 April 2009 including the L'Aquila Earthquake series

For the entire 15 month time period from 1 January 2008 to 14 April 2009, the three observatories CST, NCK and LAQ provide continuously high quality data. Figure 4 shows the five day running mean value of the $\sum K_p$ index in the upper panel. The second panel shows a summary of earthquakes in the area of L'Aquila by bars. During 2008, seven earthquakes have been recorded with magnitude $M \geq 3.0$ and distance $d \leq 90$ km to L'Aquila. The L'Aquila earthquake series 2009 starts on 30 March with the main stroke on 6 April 2009 indicated by an arrow. On days with more than one stroke the strongest earthquake was chosen and indicated in the panel. In the lower panel the five day running mean of standardized polarization P_{Day} for CST (green), NCK (blue), and LAQ (red) is depicted. Further, the polarization mean (μ) plus two standard deviation (σ) and μ-2σ is shown in dotted lines. Geomagnetic events commonly occurring in all observatories and compared to $\sum K_p$ index are eliminated. Further, days influenced by man-made noise and days containing data gaps are eliminated. Man-made noise generated in the local area of the particular SEGMA stations is characterized by Prattes (2007). The remaining local ULF events are probably due to seismic active sources. Except single days of anomalies the μ-2σ level for L'Aquila observatory located in the earthquake epicenter region is exceeded on five days in the entire period during 11 March 2009 to 20 March 2009. This period is eleven days prior the impending earthquake series. The stations CST and NCK in wider distance of the LAQ influence zone do not show abnormal variations of P_{Day} in this time span (yellow area).

4.3 Station comparison before and during the L'Aquila earthquake series from 1 January 2009 to 14 April 2009

In this section the analysis focuses on the time period 1 January 2009 to 14 April 2009, and results are shown for the standardized horizontal and vertical component as well as the polarization ratio.

In Fig. 5 the vertical PSD Z_{Day} and the horizontal PSD H_{Day} for 1 January 2009 to 14 April 2009 is illustrated for the three available stations CST, NCK, and LAQ. As described before, geomagnetic anomalies can be observed causing similar results in all stations, e.g. 26 January 2009, 15 February 2009, 12 March 2009, 9 to 10 April 2009, and another single event in LAQ on 29 January 2009. Local anomalies only occurring in the LAQ vertical PSD from 11 March 2009

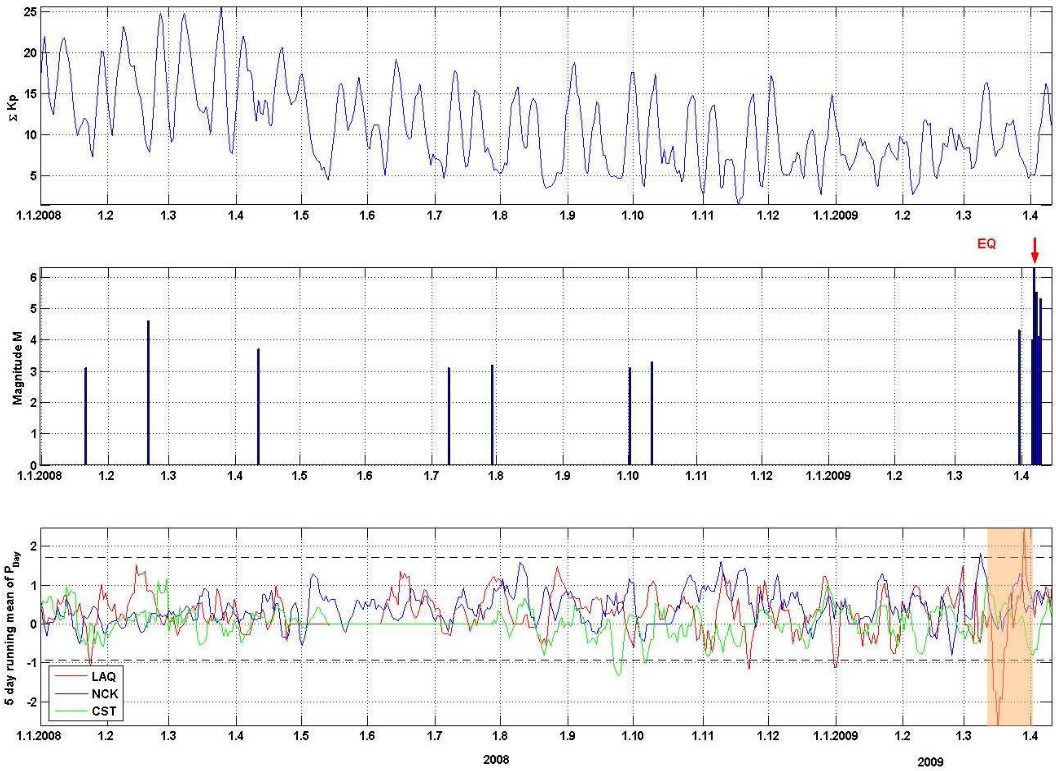

Fig. 4. Five day running mean of $\sum K_p$, magnitude of the seismic events with the earthquake swarm in April 2009, and standardized polarization from 1 January 2008 to 14 April 2009 for CST, NCK, and LAQ station. LAQ station shows anomalies above and below 2σ eleven days prior the impending earthquake series. The earthquake series main stroke is indicated with an arrow in the second panel.

to 20 March 2009 are probably related to the impending L'Aquila earthquake series causing polarization events (compare also in Fig. 4, bottom panel). The earthquake main stroke is indicated with an arrow. The colored time period contains days which are probably influenced by ULF anomalies due to disturbances in the lithosphere. The power spectral density $S_{Z\mathrm{Day}}$ details for LAQ observatory are shown in Fig. 7.

To complete the analysis for the zoomed time span 2009, Fig. 6 illustrates in the upper panels the $\sum K_p$ index and the seismic activity in the L'Aquila region. The L'Aquila earthquake is indicated with an arrow in the second panel. In panel three the standardized polarizations which are compared for CST (green), NCK (blue), and LAQ (red). ULF anomalies at LAQ during 11 March 2009 to 20 March 2009 are unique, as they are start approximately two weeks before the earthquake series and do not occur in NCK and CST. The lower panel depicts the 5 day running mean values showing that the $\mu \pm 2\sigma$ sigma levels are not exceeded from 1 January 2009 to 14 April 2009 in CST and NCK, in contrast to LAQ where excitations for five days and one single event occurred.

4.4 Short term L'Aquila results from 11 March 2009 to 20 March 2009

A sequence of vertical PSD spectra recorded at LAQ station $S_{Z\mathrm{Day}}$ for the time period of interest during 11 March 2009 to 20 March 2009 is shown in Fig. 7. These emissions are probably seismic related. The subplots show ULF noise in the frequency range from $\Delta f = 10$–15 mHz (red) exceeding the monthly mean $\mu_{Z\mathrm{Month}}$ plus two times sigma $\sigma_{Z\mathrm{Month}}$. The depicted spectra have intensities in the range of 35–40 pT in the 5 mHz frequency range. In the frequency range from 10–50 mHz the intensities are 50–60 pT, in the same range Hayakawa et al. (1996) reported about maximum intensities of $\sim$0.1 nT.

5 Summary and Outlook

The advanced standardized polarization analysis applied in this work shows a series of ULF polarization events in the frequency range from 10–15 mHz at L'Aquila observatory about 2 weeks before the Abruzzo 2009 earthquake series. The observed events are due to an increased B_Z PSD at L'Aquila observatory, while the stations CST and NCK show no anomalies in this time period. Multi point results during

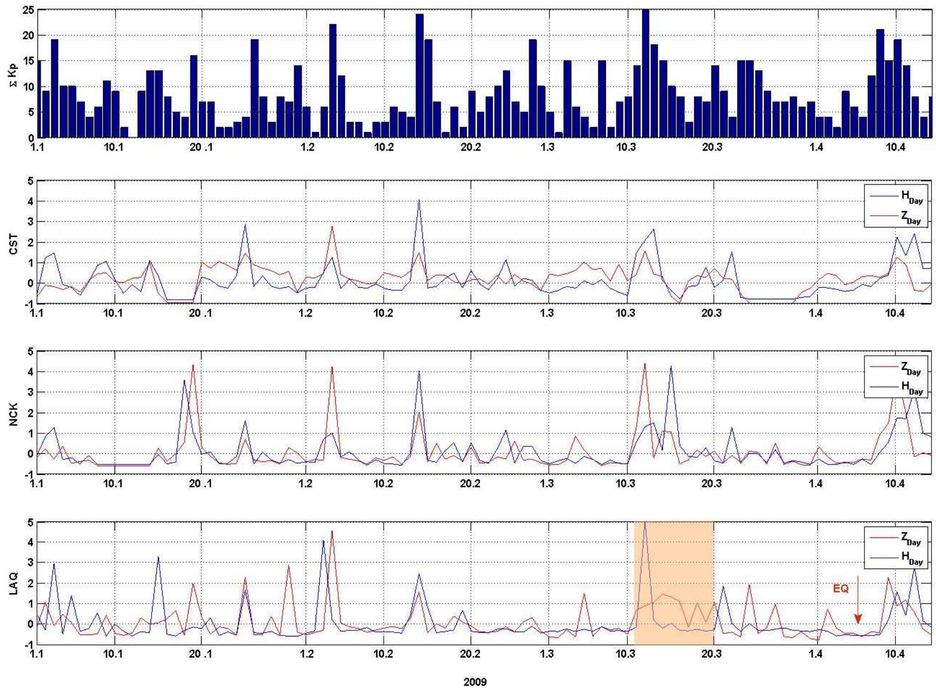

Fig. 5. $\sum K_p$ and standardized daily horizontal (blue) and vertical (red) PSD from 1 January 2009 to 14 April 2009 for CST, NCK, and LAQ station. Days in the colored shaded time period are probably influenced by ULF anomalies due to the impending seismic activity. The L'Aquila earthquake series main stroke is indicated with an arrow.

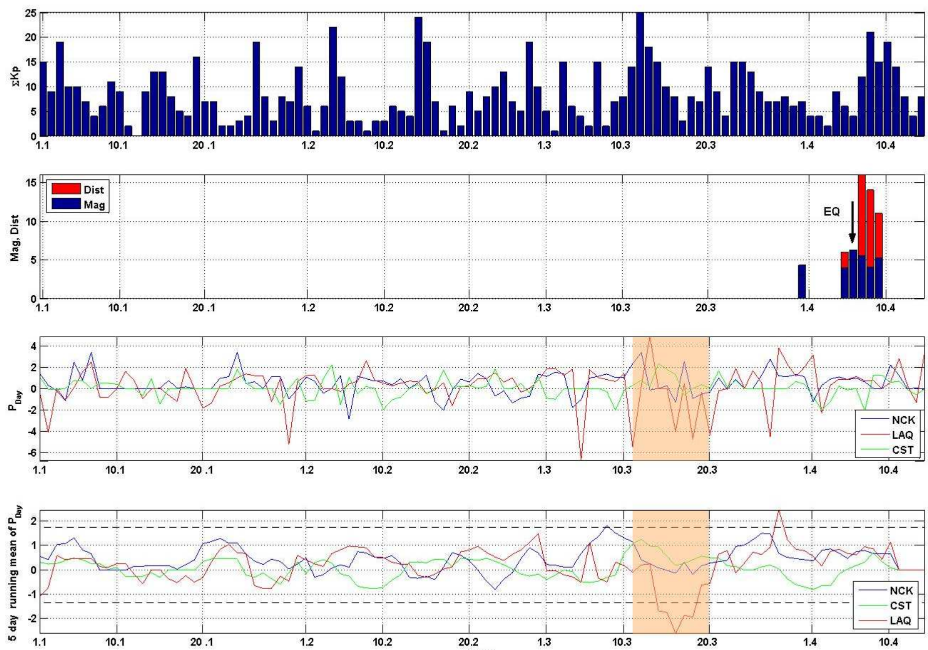

Fig. 6. Top $\sum K_p$, magnitude of seismic events and distance to L'Aquila, standardized polarization from 1 January 2009 to 14 April 2009 and 5 day running mean of standardized polarization for CST, NCK, and LAQ station. Time periods probably affected by ULF events due to seismic activity are color shaded.

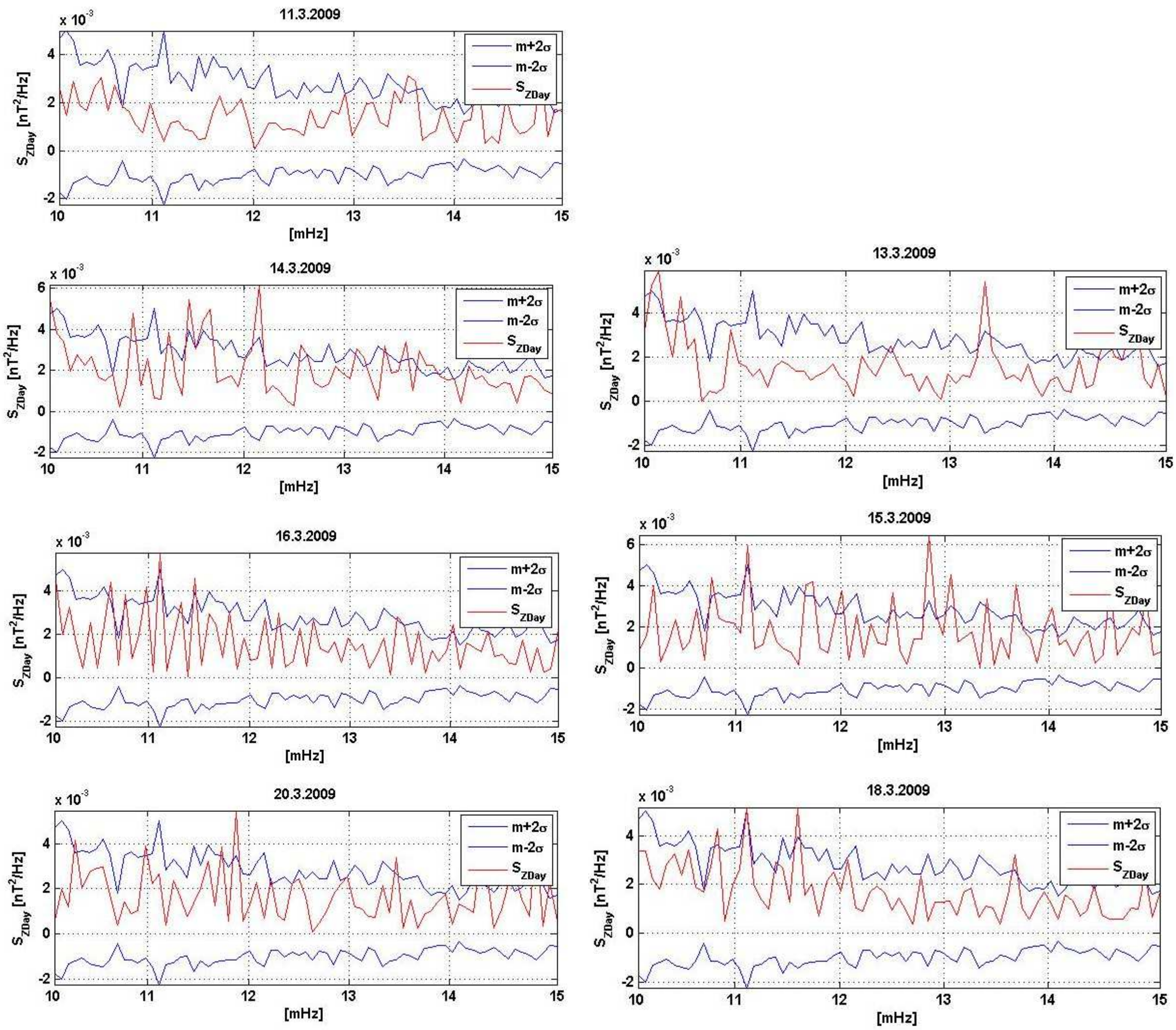

Fig. 7. Daily vertical PSD in the frequency range 10–15 mHz exceeding $\mu \pm 2\sigma$ from 11 March 2009 to 20 March 2009 (shaded area in Fig. 6).

seismic quiet periods do not show events like this, and further long term results indicate that these events are unique during the extended time span of 15 months. We conclude that the increased B_Z PSD at L'Aquila has a local source of emission and is possibly related to seismic activity in the region. The ground electrical resistivity profile has been used to estimate the skin depth for ULF variations, in particular for the 10–15 mHz range, and support an argument for ULF studies near the earthquake epicenter. The observed anomalies before the L'Aquila earthquake series lasted several days and were locally emitted in or near the L'Aquila region. They occurred during the seismic active period. The classical polarization method has not shown an evidence of polarization events in relation to seismicity reported in Villante et al. (2010). The SEGMA chain with multiple stations in various distances to L'Aquila gives the opportunity for further analysis. Apart from the direct electromagnetic effect described in this work, which could lead to ULF events related to earthquakes, the indirect seismic effect is suggested to be analyzed in the frame of SEGMA during the L'Aquila earthquake period. Further, the analyses are suggested to be extended and compared to a wider ULF frequency range up to 500 mHz and even higher frequencies, e.g. the Very Low Frequency (VLF) range (see Rozhnoi et al., 2009). Concerning ULF studies, a detailed analysis of the horizontal components X and Y (see Du et al. 2002) will be performed to find the direction of ULF emission. A more detailed background noise level and local ULF source of emission estimation could help to clarify if the emitted signals are of true seismic origin.

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