APPLICATION OF DFA METHOD TO MAGNETIC FIELD DATA FROM SEGMA ARRAY

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Abstract. We apply DFA method to magnetic field data from SEGMA array for the period August 2004 - February 2005. The SEGMA meridional array is a set of stations mainly localized in the Adriatic region (at a longitude of about 10-16° E) and devoted to magnetic field measurements in the ULF frequency range. We study the fluctuation function and the corresponding DFA scaling exponent which characterize the long-range correlations in magnetic field data series recorded by Italy and Hungary stations. For each station we consider both the similarity and the differences in the DFA index behavior. The similarity in the DFA trends is markedly associated with the global geomagnetic activity. Changes in the strength of the long-range correlations in different time scales 2-180 s and 2-900 s are reported. The disparities consist in the variable level of the DFA index value from different stations and an emergence of specific decreases of the DFA index (intervals of a lost of long-range correlations) at an individual station that last at least one day. The probable origin of such DFA index features might be related to local processes of selfsimilar characteristics either in the atmosphere/ionosphere system or in the lithosphere.

Key words: geomagnetic activity, DFA method, fluctuation function, SEGMA array.

Introduction

Recently, both fractal and multifractal analyses of ULF geomagnetic field data have been applied (Hayakawa et al, 1999; Gotoh et al, 2003; Telesca and Lapena, 2005.;, etc.). There are different methods of fractal analysis. The simplest way of fractal analysis is by studying the ULF emission spectrum slope (obtained by the FFT method) and its time evolution. The spectrum slope β is obtained from the straight line that is the best fit to the ULF spectrum given in the log-log form. The corresponding fractal dimension can be calculated using the Berry's equation: D_o = (5-β)/2 (Berry, 1979; Turcotte, 1992). Lately, the Higuchi method (Higuchi, 1988), Burlaga-Klein approach (Burlaga and Klein, 1986) and detrended fluctuation analysis (DFA) (Kantelhardt et al., 2002) were applied for studying the fractal dimension evolution of time series. Fractals and multifractal analyses to extract possible changes of scaling characteristics of the ULF geomagnetic field data both prior several strong earthquakes (Japan) and an earthquake swarm (Japan) have been applied (Hayakawa et al., 1999; Hayakawa et al., 2000; Gotoh et al., 2003). Gotoh et al. (2003) revealed a decrease of the spectrum slopes and corresponding increase of fractal dimensions of the ULF time series a few days before EQ swarm. Fractal analysis of ULF data associated with the Guam earthquake on August 8, 1993 revealed that the *relative short period* variations of the slope *(β)* can be attributed to more variable environmental conditions, such as solar activity, etc. The alternative gradual decrease in β ($\beta \sim 1$) that is characterized by a *longer scale* alteration can be associated with changes in the integrated ULF emission sources involving probably a formation of fractal conductor-dielectric structure in the Earth's crust (Hayakawa et al., 1999). It has been found that the fractals dimension increase appears at frequencies $f > 0.02$ Hz and is most pronounced in the higher frequency end of the ULF range, i.e. around 0.1 Hz.

In this study we continue our efforts to identify ULF signatures of series of earthquakes occurred in the Adriatic region in the period August 2004 – February 2005. ULF magnetic field measurements are provided by the SEGMA array. SEGMA is a low-latitude magnetometer array in South Europe which consists of three stations in Italy and one in Hungary, latitudinally equispaced between L=1.57 - 1.89 *(L* is Mcllwain parameter). Each station is equipped with high sensitivity (~10 pT) triaxial fluxgate magnetometers recording northward *(H),* eastward (D) and vertically (Z) components of the geomagnetic field variations. An automatic acquisition system collects the data at 1 seconds with timing provided via GPS. Coordinates of all stations are given in Villante et al. (2006).

DFA method

Detrended fluctuation analysis (DFA) to data set from August 2004 – February 2005 is applied. DFA is a well-established method for determining data scaling behavior in the presence of possible trends without knowing their origin and shape (Kantelhardt et al, 2001). In difference to conventional methods, e.g. power spectrum analysis, the DFA permits detection of intrinsic dynamical features, e.g. long-range correlations, embedded in non-stationary time series and avoids spurious detection of apparent scaling, which may be an artifact of non-stationary time series (Buldyrev et al., 1995). For long-range correlated signals the power spectral density P would behave as a power-law of the frequency f, thus its slope should be constant and usually denoted by β index.

Shortly, DFA approach consists in the following. DFA operates on a time series $x(i)$, where $i = 1,2,\ldots N$ and N is the length of series. Introducing x_{ave} where

$$x_{ave} = \frac{1}{N}\sum_{k=1}^{N} x(k)$$

the "profile" of series $x(i)$ is given by

$$y(i) = \sum_{k=1}^{i} [x(k) - x_{ave}]$$

Next, the integrated series is divided into N_s = int(N/s) non-overlapping segments of equal length s. Since the length N of the series is often not a multiple of the considered time scale s, a short part at the end of the profile $y(i)$ may remain. In order not to miss this part of the series, the same procedure is repeated starting from the opposite end. Thereby, 2 N_s segments are obtained altogether. The local trend for each of the 2 N_s segments is calculated by a least square fit of the series. Then we determine the variance

$$F^2(s,\nu) = \frac{1}{s} \sum_{i=1}^{s} \{y[(\nu-1)s+i] - y_\nu(i)\}^2$$

for each segment ν, $\nu = 1,\dots, N_s$ and

$$F^2(s,\nu) = \frac{1}{s} \sum_{i=1}^{s} \{y[N-(\nu-N_s)s+i] - y_\nu(i)\}^2$$

for ν, $\nu = N_s+1,\dots, 2\,N_s$. Here, $y_\nu(i)$ is the fitting line in segment ν. After averaging over all segments we derive the following fluctuation function:

$$F(s) = \frac{1}{2N_s} \sum_{\nu=1}^{2N_s} [F^2(s,\nu)]^{1/2}.$$

Repeating this procedure for several time scales, $F(s)$ will increase with increasing s. And analyzing log-log plots $F(s)$-s the scaling behavior of the fluctuation function will be determined. If the series $x(i)$ is long-range power –law correlated, the fluctuation function $F(s)$ will increase for large values of s as a power-law:

$$F(s) \approx s^\alpha.$$

By applying standard spectral analysis techniques to $x(i)$, the power spectra, i.e. the square of the Fourier transform amplitudes for $x(i)$, yields

$$S_x(f) \propto \frac{1}{f^\beta}$$

The exponent β is related to α by $\beta = 2\alpha - 1$. The value of α (i.e. the DFA scaling exponent) resulting from a least-square fit to a straight line, reveals the presence, or not, of long-range correlations. In particular, the case α = ½ represents the absence of long-range correlations.

Analysis and discussion

Data from all flux-gate magnetometers at SEGMA stations (AQU, RNC, CST, and NCK) are analyzed. Two intervals of one hour length: at midnight (00:01 UT) and at noon (11:12 UT) were chosen. At midnight the ionospheric activity is at its lowest level. This local time (LT=UT+1) interval is to the widest rate not modified by the ionospheric effects, i.e. the external influences on the ULF magnetic field variations are at their lowest level. Conventionally, this time interval is preferred for looking for ULF signals of lithospheric origin. At day hours (noon) the ionospheric activity, of course reaches its maximum. A comparison between noon and midnight data at one station would give some hints for possible impacts onto the fluctuation scaling parameter exerted from the ionosphere itself. The DFA scaling parameter α we studied was determined for two ranges of *s*: i) 2– 900 seconds and ii) 2– 180 seconds. Comparison of the DFA scaling parameter trends of the horizontal (*H*) and vertical (Z) components showed that α behaves very similarly at noon and midnight with close mean values. There are however differences. Comparing the variations of the DFA scaling index α of different magnetic field components, those of the Z component are of smallest amplitude, i.e. its standard deviation reaches minimum among all three components *(H, D,* and Z). In our further analysis we consider only the *H* and Z components. At noon the index is highly variable (with greater standard deviation), especially for the *H* component. At midnight, the variability is greatly reduced (smaller standard deviation). The scaling parameter behavior at midnight appears to be more readable when we look for longer time (daily and weekly) variations of the DFA index value. The mean values of the scaling parameter α however vary for different stations and are between 0.6 and 1.4. A specific peculiarity in the level of the DFA index *α* magnitude of both *H* and Z components was observed, as well. The DFA index magnitude of the *H* component at all stations was higher than that of the Z component except the results for the data set from the Ranchio station. The mean DFA index and its standard deviations of the Z component at midnight for SEGMA stations: Aquila (AQU), Ranchio (RNC), Castello Tesino (CST) and Nagycenk (NCK) are reported in Table 1. It is worth noting that different scaling parameter behavior is expected in different time scales. Table 1 illustrates this difference.

Table 1.

Station	Mean s = 2 – 900 s	Sd s = 2 – 900 s	Mean s = 2 – 180 s	Sd s = 2 – 180 s
AQU	0.786	0.105	0.707	0.092
RNC	1.187	0.117	1.304	0.103
CST	0.967	0.102	1.077	0.088
NCK	0.764	0.157	0.655	0.123

The results for scaling behavior of the Z component in night hours (00:01 LT) at different stations are illustrated in Figure 1 and Figure 2.

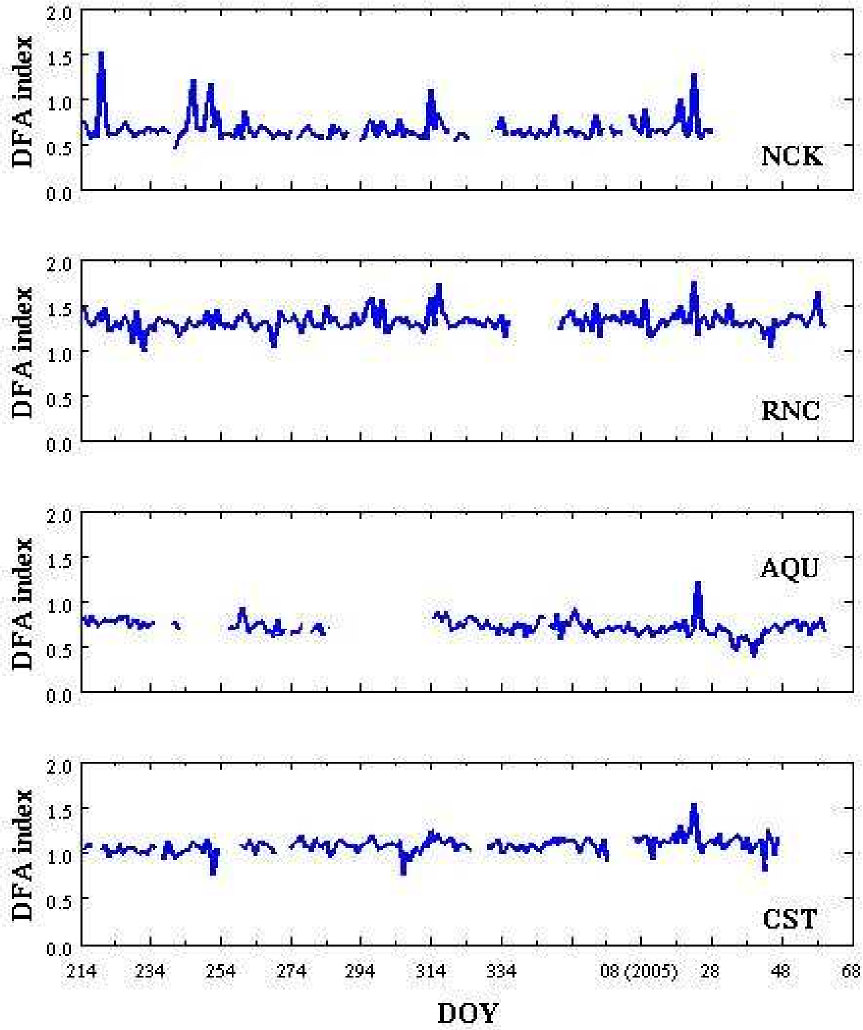

Fig. 1. Behavior of the DFA index at Ranchio, L'Aquila and Castello Tesino, s = 2-180 sec., from 00 till 01 UTC; Z component.

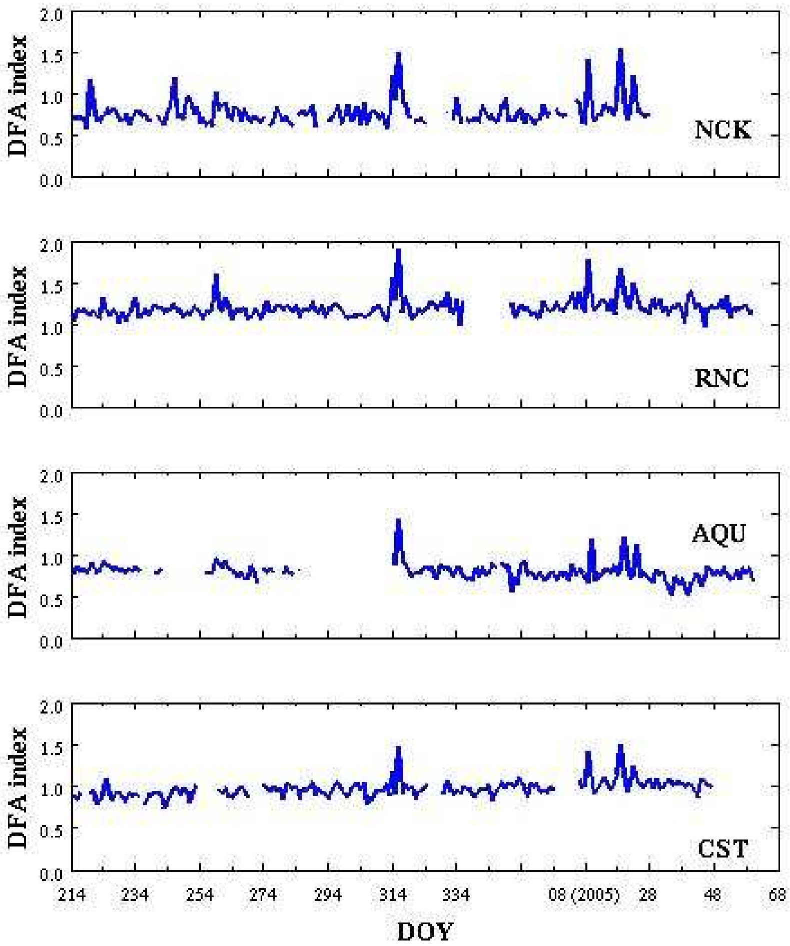

Fig. 2. Behavior of the DFA index at Nagycenk, Ranchio, L'Aquila and Castello Tesino, s = 2-900 sec., from 00 till 01 UTC; Z component.

Inspecting Figures 1 and 2 "anomalous" DFA index increases (i.e. those with deviations much above one standard deviation *Sd*) are sometimes observed. They are of short duration (up to 2-3 days) and usually observed simultaneously at all stations. This means that their source is not local, instead, the source of such strong long-range interactions should be related to non-local (global or regional) sources, most probably of solar-magnetosphere origin.

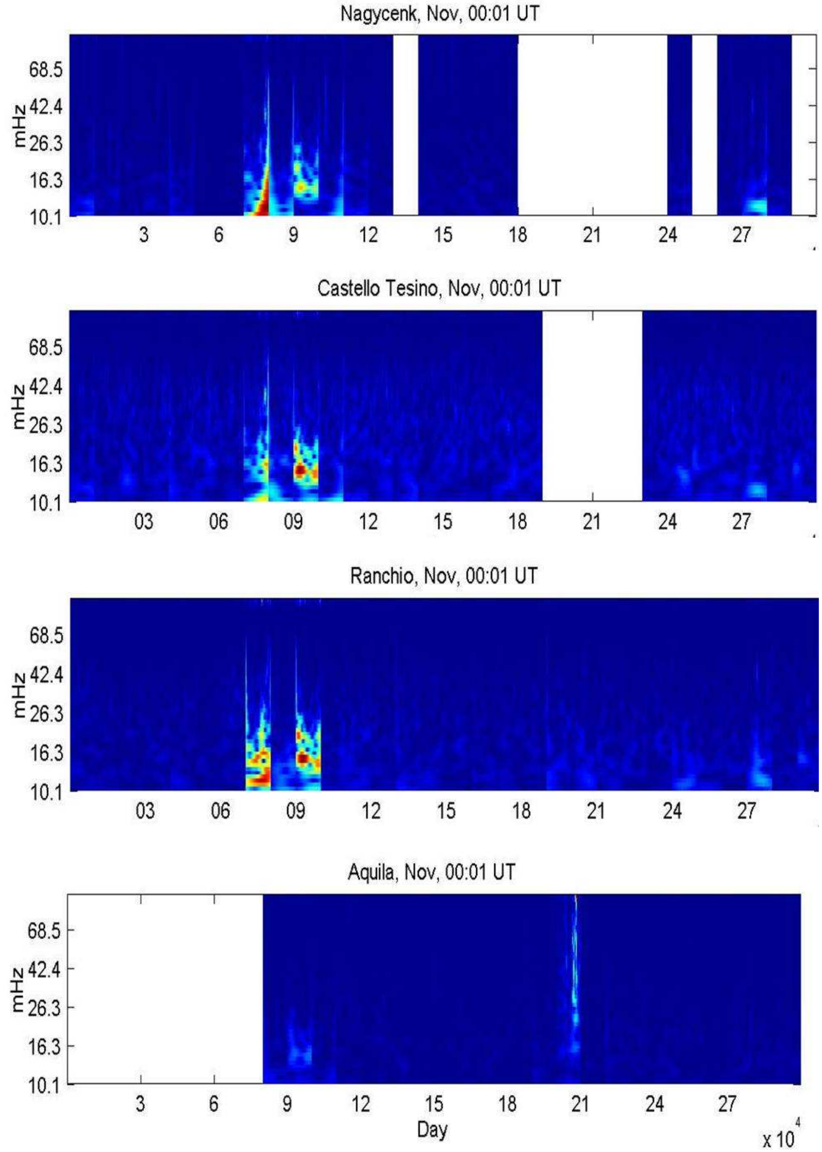

Fig. 3. Excerpt of the dynamic spectra of magnetospheric activity at midnight (of one hour length) for month November, 2004 at the stations: L'Aquila, Ranchio, Castello Tesino and Nagycenk is shown. Most disturbed are days 08 and 10 November 2004.

In order to check such an expectation, an overlook of the magnetospheric activity can be seen from the dynamic spectra made for month November, 2004 in midnight hours (00:01 UT interval) at the SEGMA stations: L'Aquila, Ranchio, Castello Tesino and Nagycenk. (Figure 3). The magnetospheric storm that occurred on 9-10 November (Kp ~ 8) is clearly indicated at all stations by a steep increase of the power density in the frequency interval 1-100 mHz. It is well known that the magnetospheric activity is quantified by the geomagnetic index Kp (Figure 4). It was most intense on 9-11 November 2004. It is seen also that all sharp peaks in the DFA index above its mean values (Figures 1 and 2) usually correspond to increases in the Kp index. This evidence is verified for all stations with one exception: the DFA index trend at the Castello Tesino station for short time intervals**,** i.e smaller than around 180 sec (see Figure 1). The DFA scaling index increase at CST is of weak amplitude. Therefore, during magnetospheric activity the DFA index usually increases.

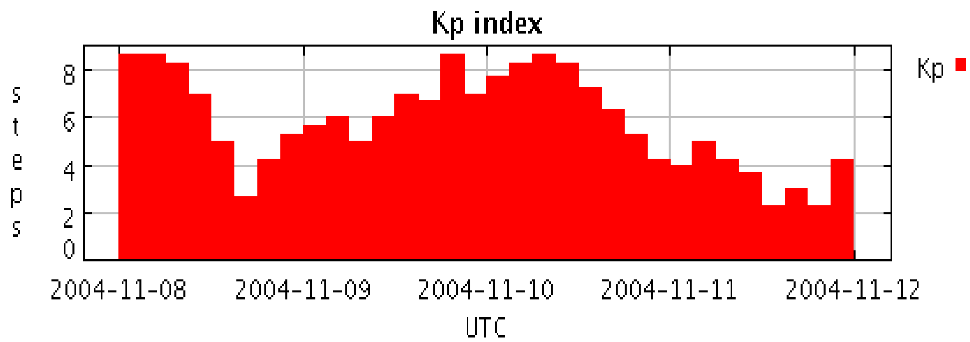

Fig. 4. Kp index for the period 8 till 12 November 2004. (http://spidr.ngdc.noaa.dov/spidr)

Let us examine in details the fluctuation function during such magnetospheric events. Figure 5 illustrates fluctuation functions $F(s)$-s on 09, 10 and 11 November 2004 at noon hours. We determined the fluctuation function $F(s)$ for three order time scales ($2 < t < 900$ sec). On days of high Kp we observed that a linear fit exists over all scales, i.e. this means that on days of high geomagnetic activity self-similarity (or fractality) over the scale 2 < t <900 sec is well present.

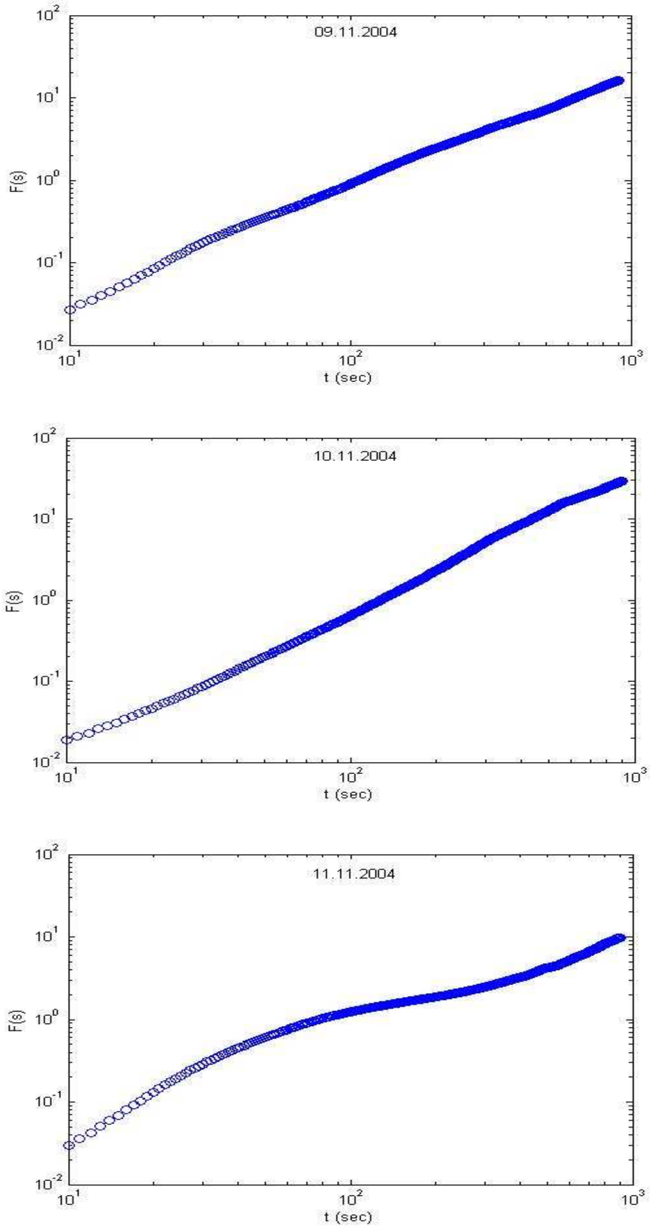

Fig. 5. Fluctuation functions *F*(*s*)-s of the H component at CST on 09, 10 and 11 November 2004 at 11 and 12 UT. On 09 and 10 November 2004 one power law dependence is applicable, with $\alpha = 0.99$ and $\alpha = 1.28$, respectively. On 11 November 2004 regions of different slopes (different scales) emerge.

Short time DFA index decreases at all stations were also observed but their amplitude variations rarely exceed one standard deviation (Figures 1, 2 and Table 1). Besides, long time DFA index decreases of ~ a week, up to two weeks duration were observed. The specifics of these DFA index decreases is that their amplitude variations exceeded one standard deviation, i.e. they are anomalous and are clearly observed at one station only. It is worthy to note that such long time decreases are observed only for short times, i.e. for time interval smaller than 180 sec (Figure 1).

During the period August 2004–February 2005 a few long time decreases of the DFA index were observed at Castello Tesino and at Aquila. At Castello Tesino such anomalous picks of DFA index decreases were observed on two days, on 07 September 2004 (lasting ~ 4 days), 31 October 2004 (~10 days).

For longer time intervals, up to 900 sec (Figure 2), no long time DFA index decreases are observed during the same August 2004–February 2005 period. One can see that due to the effect of the DFA index decrease on 31 October 2004, the DFA index increase event (with a maximum on day 314 corresponding to the magnetospheric storm on 09 November) is partly suppressed. A DFA scaling index trend with shorter time intervals 10–90 s and 90–450 s of the same ULF data set reveals similar properties (Nenovski et al., 2007). The emergence of such long time anomalous DFA index decreases at one station and their absence at other ones could be related to ULF emission sources of local origin. Following the relation Do = 3–α, the DFA index decrease corresponds to fractal dimension increase, i.e. Do increases. Thus, our results are consistent with the earlier findings by Hayakawa et al. (1999), Varotsos et al. (2002) and Gotoh et al. (2003). The fractal dimension of ULF geomagnetic data is found to be variable in the range of D_o = 1.2–2.1 with tendency to increase prior to quake (Hayakawa et al. 1999). Gotoh et al. (2003) have revealed an increase of fractal dimensions of the ULF time series at Izu peninsula in relation to nearby EQ swarm. The fractal dimension increase has been most pronounced at highest frequency band (f = 0.1–0.2 Hz). In analyzing telluric data and especially the dynamics of seismic electric signals (SES) that precede rupture (the SES signals are of frequency < 1 Hz, thus they are belonging to the ULF range), Varotsos et al (2002) have derived two different long-range interactions, i.e. the DFA scaling behavior is different for short times ($10 < t < \sim 30$ sec) and long times ($\sim 30 < t < 200$ sec). Their results for the DFA index magnitudes are α= 1.19 and α = 0.88 respectively. Our finding that long time anomalous DFA index decreases of ~0.8 are observed only for short times (< 180 sec) and not observed for longer times is in consonance with the Varotsos et al's conclusion about an emergence of different long-range interactions at different time scales. Indeed, our finding of different DFA scaling index values suggests another long range interaction for longer times (i.e. $180 < t < 900$ sec). Therefore, the process of DFA scaling index decreases does not possess self-similarity property at all.

We observed two events of DFA index decrease (or fractal dimension increase) for time interval 2 - 180 sec (~0.01 – 0.5 Hz) the first one occurred on 07 September 2004 and the second one began on 31 October 2004, i.e. approximately two and half months and one month ahead the moderate M5.2 and M5.3 earthquakes on 24 and 25 November 2004 (Figure 1). In the same interval August 2004-February 2005, weak to moderate earthquakes with magnitudes up to M = 5.5 occurred in this region (Table 2). Two earthquakes with magnitudes M = 5.5 and M=5.3 struck the north-eastern part of Italy (45.63 Lat, 10.56 Long) on Nov. 24, 2004 and the central part of the Adriatic sea (34.17 Lat, 15.36 Long) on Nov 25, 2004. The DFA index decreases that were observed only at Castello Tesino might suggest an emergence of a local geophysical process associated to impending earthquake that occurred at distance ~ 90 km (45.63 Lat, 10.56 Long) on Nov. 24, 2004.

Table 2. (http://neic.usgs.gov/neis/epic/epic_rect.html)

Date(yy-mm-dd)	Time (UT)	LAT	LONG	Depth (km)	Magnitude
2004-11-24	22:59:40	45.63	10.56	17	5.5
2004-11-25	06:21:16	43.17	15.36	21	5.3
2004-11-25	07:26:13	43.07	15.74	10	4.5
2004-12-03	08:13:14	43.09	15.50	10	4.8
2004-12-04	02:16:11	43.08	15.46	10	4.5
2004-12-09	02:44:25	42.79	13.79	05	4.7
2004-12-18	09:12:48	40.89	10.15	10	5.1

According to Hayakawa et al. (1999) the decrease in the ULF spectrum slope is consistent with the appearance of small-scale fractal structures in the focal zone of impending earthquakes. Enhancements of small-scale fractal structures accompanied with ULF emissions of similar fractal structures might also be the cause of the observed DFA index decreases in the SEGMA data.

The obtained results suggest two possible explanations. The first one is that there is an enhancement of higher frequency fluctuations in the 0.01-0.5 Hz interval compared to the lower frequency components (< 0.01 Hz). The second one is that there is a relative suppression of the power density of lower frequency (< 0.01 Hz) components compared to the higher frequency ULF components (0.01-0.5 Hz). In order to answer to this question the power density distribution at SEGMA station Castello Tesino averaged in all Pc frequency ranges, Pc2, Pc3, Pc and Pc5 is examined (see Figure 6).

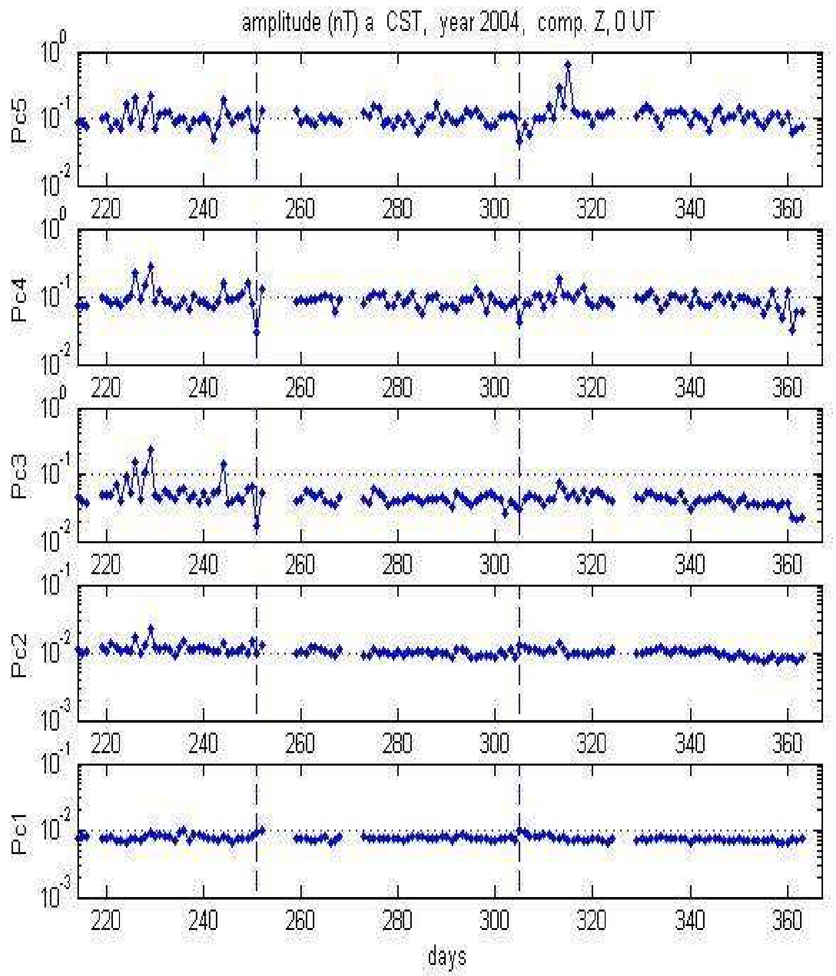

Fig. 6: Power density distribution in all Pc frequency ranges of the Z component at Castello Tesino during August-December 2004. Marked decrease in the power density in the Pc3, Pc4 and Pc5 ranges is observed at days indicated by dashed lines.

Days of interest, 07 September and 31 October, are marked with vertical (dash) lines. So, the suppression of the lower frequency ULF components is the probable cause of the DFA scaling index decrease at the mentioned days. Hence, there is no evidence for an appearance of higher frequency components as a signature of earthquake preparation processes. Thus, the origin of such a short time suppression in the ULF activity remains unclear. The sources of these ULF components need to be sought in alternative processes occurred at and/or near the Earth's surface occurred locally.

The seismic events mentioned here were taken into account as one of possible geophysical factors responsible for the observed features in the ULF signal behavior. Having in mind the above findings, as well as our previous results based on the polarization

(Z/H) analysis for the same period, it is not possible to ascertain that the features in the DFA scaling index of ULF magnetic field variations are closely related to earthquake preparation processes occurred nearby the closest station of SEGMA array.

Conclusion

In summary, the DFA approach applied to SEGMA array data set from August 2004–February 2005 that cover the ULF range, reveals the following characteristics:

First, the DFA index magnitude appears to possess averaged values that are different at different measurement points. Such a persistent difference in the DFA index trends suggest probably different impacts from the underneath geology on the fractal structures of ULF emission.

Second, the DFA index time evolution possesses regional and local characteristics that consist in: i) frequent appearance of short time anomalous increases in the DFA index magnitude observed simultaneously at all stations. These short time DFA index increases are usually associated to geomagnetic activity increases and the fluctuation function reveals self similarity; and ii) (rare) appearance of DFA scaling index decreases of day to week duration. The latter emerge locally, i.e. at one station. This seems to be consistent with local enhancements/suppression of higher/lower frequency ULF fluctuations.

These unexplained features in the ULF signal dynamics observed by our multipoint measurements by the SEGMA array might be related to geophysical or other processes of unknown origin near the measurement point (in the Earth's crust, or in the Earth's atmosphere).

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Прилагане на DFA метод върху данни за земното магнитно поле, получени от мрежата SEGMA.

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Резюме. Приложен е DFA метод за анализ на данни за стойностите на геомагнитното поле, получени от меридионалната мрежа SEGMA (South European GeoMagnetic Array). Мрежата включва станции, разположени в Адриатическият регион (Италия) и Централна Европа (Унгария) в географския интервал 10-16 градуса източна дължина. Основното предназначение на тази магнитометрична мрежа е измерването и наблюдението на земното магнитно поле в неговия нискочестотен спектър. Изследвана е флуктуационната функция и съответният DFA скейлинг индекс, като последният характеризира силата на далекодействащи корелации в данните за магнитното поле. За всяка станция са разглеждани паралелно приликите и разликите в поведението на DFA индекса. Забелязва се, че ходът на DFA скейлинг индекса следва поведението на глобалната геомагнитна активност. В хода на изследването са открити изменения в силата на далекодействащите корелации за различни времеви интервали: 2-180 сек. и 2-900сек. Разликите се състоят в промяната на DFA скейлинг индекса в различните станции и появяването на специфични понижения на този индекс (които индикират интервали с отслабване на силата на далекодействащи корелации), което продължава поне един ден. Такова поведение на DFA скейлинг индекса вероятно се дължи на локални процеси с характеристики на себеподобие, дължащи се на локален атмосферен/йоносферен или литосферен източник.