Preparation of a Database for the Study of Scaling Phenomena in the Ionosphere

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Abstract. The correct forecast of the state of the ionosphere requires understanding of all the effects which influence its behaviour as well as the extent of the relationships in the system. A convenient way how to analyse large data sets and describe the coupling or disconnection at various time scales is to study the scaling phenomena. For the computations of scaling properties of the processes that influence the ionosphere dynamics we have prepared a database of several characteristics that describe the coupling processes in the solar-magnetosphere-ionosphere system. This data are of sufficient length and sampling density to verify the presence or absence of links between the processes under study.

1 Introduction

The ionosphere is significantly ionized part of the atmosphere which eminently influences radio propagation. It is a very variable system which is directly coupled to geomagnetic situation as well as to "space-weather" effects, mainly the solar activity and effects of neutral atmosphere (e.g., neutral atmosphere temperature, neutral wind velocity). Its time-scales vary from short periods (minutes – e.g., Travelling Ionospheric Disturbances) through medium (one-day, 27 days) to the long periods (one year, one solar cycle and even longer).

The study of coupling processes inside the solar-terrestrial system is generally very complicated task. However, identification of participating processes is possible using scaling analysis. Similar scaling characteristics (e.g., the fractal dimension of the processes) indicate close links between the processes in the system.

The aim of this paper is to describe the scaling analysis and the dataset which will be used. In Section 2 we will describe the scaling analysis. Section 3 defines the dataset, in Section 4 we will describe the data from ionospheric stations, Section 5 describes the geophysical and solar quantities. Section 6 contains brief discussion and conclusion.

2 Scaling analysis

Scaling analysis is a convenient way how to analyse the extent and time scales of coupling of many natural processes. Since the original data are problematic due to their nonstationarity or presence of various trends we will analyse the transformed data (wavelet coefficients) instead of original data. This way conserves the scaling properties of the original dataset.

Let $\{X(k), k \in R\}$ denote the studied time (or spatial) relation. The function $T_x(a,k)$ denotes the dependence of T_x on time (or length) k and corresponding scale a. If the expected value of $|T_x(a,k)|^q$ holds $E(|T_x(a,k)|^q) = c_q a^{\zeta(q)}$, where c_q is a constant we call the process $X(k)$ scale invariant. The scaling exponent $\zeta(q)$ is in general case a nonlinear function. In the case that $\zeta(q) = qH$ and the dependence is linear, we call the process selfsimilar, or monofractal which simply means it has one fractal dimension H. Otherwise, the process is multifractal, and the process has more than one dimension. Wavelet coefficients will be used as $T_x(a,k)$ in our analysis. This method has been supposed to be very convenient for analysis of geophysical data sets [*Venugopal et al.*, 2006] since the nonstationarity of the studied processes. A similar method that uses study of structure function instead of wavelet coefficients is described in [*Davis et al.*, 1994]. *Burlaga and Klein*, [1986] were among the first who used a simple scaling analysis in the solar–terrestrial research. They used a simple function T_x and found that the interplanetary magnetic field corresponds to Kolmogorov spectrum $f^{-5/3}$ (which describes inertial range turbulence in an incompressible fluid) and this equation holds over time scales from 20 s to $3 \cdot 10^5$ s. Many natural processes exhibit scaling behaviour and the existence of the scaling is not accidental but it reflects important properties of the system. We will compare the scaling exponent $\zeta(q)$ of different processes in our analysis. Processes which are linked together should have similar scaling exponent for time scales on which they are coupled. According to our results [e.g. Abry et al., 2002, Sauli et al., 2005] the critical frequencies exhibit mostly multifractal behaviour with the coefficient depending on the latitudal position of the measuring station.

Scaling analysis is used in many scientific disciplines (e.g., meteorology, physiology, hydrology, finance etc.). Although scaling analysis is widely used in geophysics [e.g. Consolini and Marcucci, 1996; Voros et al., 2002], its application to the ionosphere research is very rare [Dziri et al., 2003].

3 Data for the scaling analysis

The most used way how to describe the state of ionosphere is measuring of so-called critical frequencies foE, foF2 which directly reflect the maximum electron concentration in layers E and F2, respectively. The geomagnetic situation at different geomagnetic latitudes is described by various geomagnetic indices which differ in the location of measuring stations. The most common indices are Auroral electrojet index (AE), Kp index, and Dst index. The solar activity is described by the solar flux F10.7 and sunspot number. Scaling analysis requires convenient properties of the data sets. Since we study large range of scales we need time series as long as possible. Another important property is the continuous coverage of the given time series by the data. It may be problem mainly in case of critical frequencies (missing data due to shadowing sporadic E layer) and in case of AE index (two large data gaps due to drops-out of some geophysical stations mainly in Siberia). This question must be solved using special computation method. However, most of other data sets exhibit continuous sequence of measured quantities.

4 Measurement of ionospheric properties, critical frequencies

Pruhonice digisonde

Pruhonice digisonde (digital ionosonde) DPS4 (geographic coordinates 50.0N, 14.6E) is a part of worldwide ionosonde network and works since year 2004 when it replaced classical ionosonde.

During the measurement the pulse is transmitted vertically upward. The signal propagates upward until its frequency equals to the ionospheric plasma frequency. The signal is reflected at this point and the time-of-flight of the signal is measured. As the plasma medium is not isotropic the pulse splits into two wave modes – the ordinary (o-mode) and extraordinary (x-mode). The frequency of x-mode is one half of the gyrofrequency higher ($\frac{1}{2} \cdot 1.4$ MHz $= 0.7$ MHz). The digital ionosondes, on the contrary of the old types of ionosondes, allow us distinguishing between these two modes as the polarisation of the received signal is measured. From measurement of the ordinary mode we obtain the plasma frequency at the height that corresponds to the time-of-flight of the signal. The plasma frequency is directly connected to the electron concentration by the equation

$$f_N^2 = \frac{N \cdot e^2}{\varepsilon_0 m \cdot 4\pi} \tag{1}$$

where f_N denotes plasma frequency, N denotes electron concentration, and e, ε_0, and m denote elementary charge, vacuum permittivity, and mass of electron, respectively. The frequency that equals to maximum plasma frequency of a layer is called critical frequency and it is indicated by letters fo (f as frequency, o as ordinary mode) and the name of the layer. Since the F-layer may

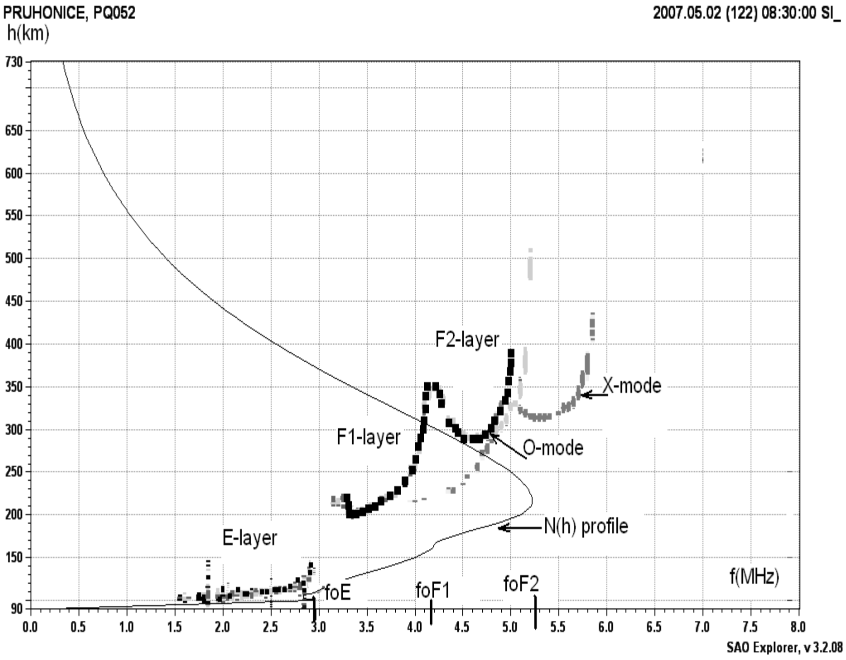

Figure 1. Typical daily ionogram from Pruhonice observatory. The usual step of measuring frequencies is 0.1 MHz. The daily E-layer is formed and F-layer is split into two layers – F1 and F2. The critical frequencies for each layer are drawn. The ionogram from digital ionosonde allows us distinguishing between ordinary (O) and extraordinary (X) wave mode (the different wave modes have different colors in the original ionogram). The electron concentration N(h) as a function of height is directly computed using Eq. (1).

be split during day time into F1-layer and F2-layer we use the foF2 values instead of foF. The electron concentration as a function of height is computed from the ionogram using standard methods (from the ordinary mode). Fig. 1 shows typical daily ionogram and the computed electron concentration profile.

The critical frequencies are relatively well defined quantities. Moreover, they have been measured for a long time and they are widely used to describe conditions and dynamics of the ionosphere. Problem is that the occasional existence of a shadowing sporadic Es layer may cause “invisibility” of a substantial part of the ionospheric layers and thus increase the inaccuracy or even cause the gaps in measured time series.

Records from other ionosondes

Critical frequencies measured at the other stations of different geomagnetic latitude allow us to study the differences between the time scales at which the critical frequencies are coupled to the other characteristics. Today, we have records of foE and foF2 from 42 observatories (e.g., Roma, Juliusruh, Sodankyla, Alma-Ata etc.) of the northern hemisphere.

5 Geomagnetic indices and solar activity

There is not one index describing state of geomagnetic field around the globe, hence we have to involve more geomagnetic indices.

AE index

The AE index is an auroral electrojet index obtained from selected (10–13) stations that are placed in northern auroral zone. Auroral electrojet is a strong horizontal current in the lower ionosphere (E region). Both conductivity and horizontal electric field of the auroral ionosphere

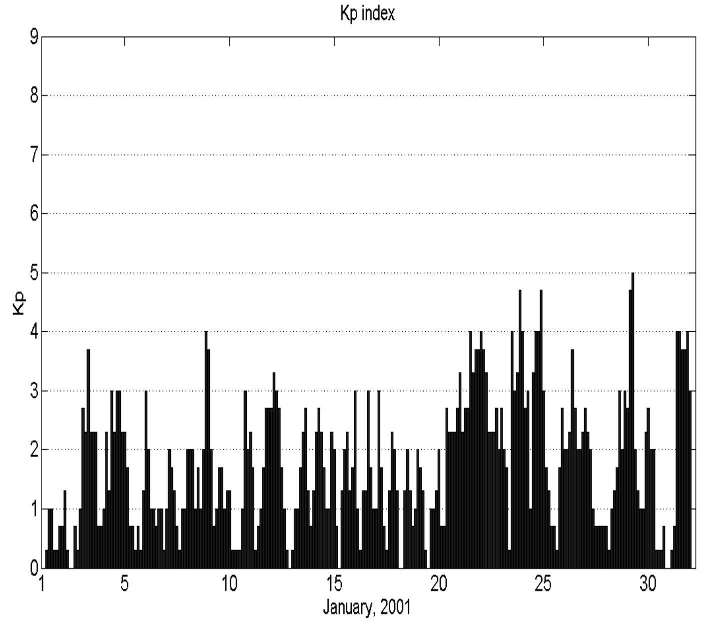

Figure 2. One month of 3-hours Kp indices. The situation varies from quiet (Kp 0–1) to active (Kp 3–4) with a peak of minor storm (Kp 5).

are larger than those of ionosphere located at lower geomagnetic latitude. That is the reason why is the auroral current so strong. Under geomagnetic quiet conditions the auroral electrojet is located close to the auroral oval. During geomagnetic storm the current is much stronger and extends to both higher and lower altitudes. A North-South value of horizontal component of magnetic field is recorded and normalised by subtracting of mean of five most quiet days of the month. The superposition of all records then forms a band with minimum (lower) AL and maximum (upper) AU index. AE is simply the difference: $AE = AU - AL$.

K, Kp, ap indices

The K indices are computed at 13 mid-latitude, or subauroral, stations. K index is a number that represents maximum disturbances of horizontal components of geomagnetic field caused by solar particle radiation related to the quiet day. Its range is 0–1 (quiet situation), 2 (unsettled), 3–4 (active), 5 (minor storm), 6 (major storm), 7 (severe storm), 8–9 (very major storm) and the highest value of 3-hour's period is used. The conversion between absolute value of the field in nT and K index at each station is roughly logarithmic and differs for each station to ensure similar statistical distribution of K-indices. For example, the same index at a station located at a higher geomagnetic latitude corresponds to higher activity than at the station located at a lower geomagnetic latitude. The planetary Kp index (from German “planetarische Kennziffer”) is a weighted average of all K – indices at a given time. One month of Kp is shown in fig 2.

The ap index is derived directly from Kp. It is a linear equivalent of quasilogarithmic Kp. Although the ap index is more convenient for the computations than Kp index it seems to be less used. We will use both the ap and Kp indices for our analysis.

Dst index

The hourly Dst (Disturbance storm time) index is derived from a network of stations near the magnetic equator (but sufficiently far from it to avoid the effects of equatorial electrojet). Dst index describes the variation of the ring current and it is used to quantify the strength of

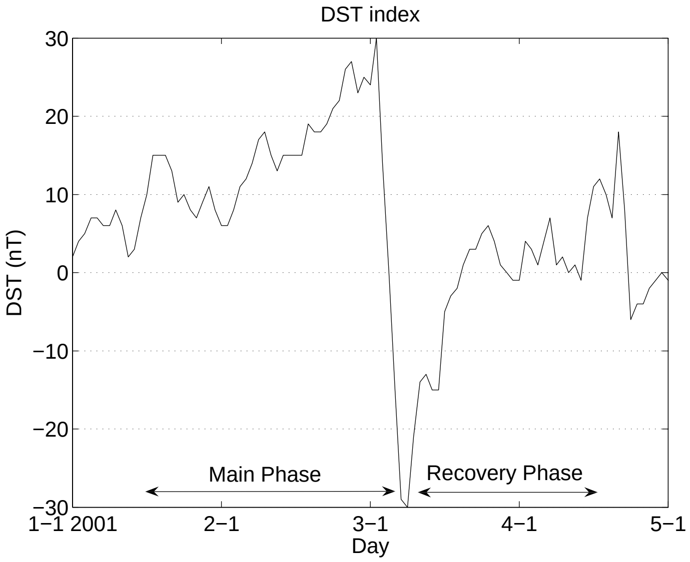

Figure 3. Evolution of the DST index during a geomagnetic storm.

magnetic storm. Typical evolution of the Dst index during the geomagnetic storm is shown in Fig. 3. For instance, value -30 nT (moderate storm) corresponds to a current of 10^6 A at a geocentric distance of 4.5 R_e [Hargreaves, 1992].

Sunspot number and solar flux

The number of sunspots is the oldest quantitative parameter describing the solar activity. The sunspot number is computed using the formula $R = k(10g + s)$, where R is the sunspot number, g is the number of sunspot groups, s is the total number of all individual sunspots and k is a coefficient that includes observing conditions and type of the telescope. Today, two datasets of sunspot numbers are used: the Boulder sunspot number, and the International sunspot number. For both numbers the same methodics of computation is used but the observatories are different. The International sunspot number will be used in our analysis.

The solar flux is more objective indicator of solar activity than the sunspot number. It is measured at the wavelength 10.7 cm (2800 MHz) and its unit sfu is defined as sfu $= 10^{-22}\mathrm{Wm}^{-2}\mathrm{Hz}^{-1}$. There are two definitions of this characteristics. The so-called “observed” value is a quantity that is detected by the radio telescope without compensation of the Earth position. It is used for terrestrial studies and it is also used for our analysis. The second, “adjusted” value is corrected for the variable distance of the Earth from the Sun and it is used for solar research.

6 Discussion and conclusion

Our database consists of geophysical indices, solar activity indices, and 42 long-term foF2 and foE records. Most of the ionospheric stations which provide us with the data started their operation in the International Geophysical Year 1957 or before. Approximately one-third of the stations used for our analysis started their operation later, mainly between 1960 and 1965. Only five stations have been working since 1970s and 1980’s. As an example, Fig. 4 shows variability of foF2 in the record from Pruhonice observatory.

For our analysis, we need to have data that simultanously cover the maximum possible time interval. The limiting factor is the length of the ionospheric data because all the geomagnetic indices and solar activity indices were measured long time before 1957. Since most of the

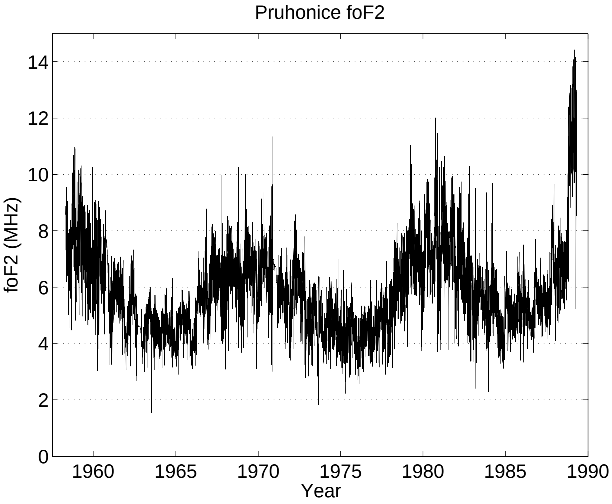

Figure 4. The foF2 critical frequency record from Pruhonice observatory.

available ionospheric data are from 1957 to approximately 2000 (data after 2000 are often unavailable) we have more than 40 years of data. This is sufficient for a study up to scales comparable with one solar cycle length (on the average 11 years). The time resolution of the data is mostly one hour but some data only have one-day resolution. The one-day resolution will be initially used for our analysis. Most of the data are without large gaps. However, in the case of the AE index there are two large gaps in the time series: years 1976 and 1977 are missing as well as part of 1989. This was caused by the absence of measuring at the Siberian stations which are essential to compute the AE index. The data from ionosondes have fewer problems. Missing critical frequencies were not measured because the shadowing sporadic E-layer was present or because of the short-term technical problems of the stations. The occurrence of missing data is not negligible but the gaps last for only a few hours.

We have prepared a consistent set of ionospheric data, geomagnetic indices and solar activity parameters for scaling analysis. The first results will be published as soon as the scaling analysis is finished.

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