

STATISTICAL STUDY OF GEOMAGNETIC  
DISTURBANCES AT EUROPEAN AURORAL  
AND HIGH LATITUDES

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**Abstract**

Statistical studies allow probability statements about the frequency of certain events. The occurrence of magnetic substorms and their activity have been described with the help of extreme value distributions in the last few decades using the auroral electrojet indices AE, AL and AU. In this work we examined the distribution of the IL index, derived from observations at stations of the IMAGE magnetometer network. The distributions of magnetic disturbances, based on IL, were studied separately in the morning (3–9 MLT), day (9–15 MLT), evening (15–21 MLT), and night (21–3 MLT) sectors. In addition, we used the values of the IL index calculated from the meridional chains in the auroral zone (PPN-SOR) and from the chain of stations at high latitudes (BJN-NAL). The histograms, the empirical cumulative distributions and the occurrence rates were computed. It was shown that the empirical distributions could be well approximated with exponential distributions. The distribution parameters were determined from the occurrence rates. Three classes were discovered, which differ significantly by the respective distribution parameters. Structural changes in the distributions were found in the morning sector at both auroral and high latitudes. The relationship between the occurrence rate

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of magnetic disturbances with  $IL < -1000$  nT and the frequency of occurrence of geomagnetic induced currents was highlighted.

**Key words:** geomagnetic disturbances, extreme value statistics, occurrence rate

**Introduction.** It is well known that very strong geomagnetic storms provoke hazards as disruption of electrical power systems and communication systems, including navigation systems with all socio-economic consequences. Therefore in the last decades, such strong events were in the focus of statistical studies. They give answers to questions as the probability of occurrence of such events, their distribution over time intervals as seasons, years and dependencies on solar cycle. The occurrence of strong events was studied based on application of the extreme value theory using geomagnetic indices [1–7]. In these studies, indices as Dst, aa, AL, AU and AE describing the geomagnetic activity were examined. Geomagnetic disturbances related to substorms generate field variations observable on the Earth surface. From the magnetic field components measured at the Earth's surface, field variations are extracted and indices are determined that characterized geomagnetic activity. Most of them have global character. The IMAGE network includes European stations. The indices obtained on the basis of this network data are more appropriate for Europe than global indices. The aim of the investigations presented in this paper is the study of the distribution of IMAGE electrojet index IL, which to our knowledge has not been carried out so far. In addition, the occurrence rates are determined, which allows conclusions to be drawn about the frequency of the occurrence of geomagnetically induced currents (GIC).

**Data.** The IMAGE magnetometer network provides the auroral electrojets indices for different locations, for all stations located in Scandinavia and Fennoscandia (Scandinavia without Svalbard). Here we use the chain Polesie – Sørøya (PPN-SOR) from  $51.4^\circ$  ( $47.1^\circ$ ) to  $70.5^\circ$  ( $67.3^\circ$ ) geographical (geomagnetic) latitudes enclosing 12 stations, and the chain Bear Island – Ny Ålesund (BJN-NAL) enclosing four stations at Svalbard from  $74.5^\circ$  ( $71.4^\circ$ ) to  $78.9^\circ$  ( $75.2^\circ$ ) geographical (geomagnetic) latitudes. For these chains we have downloaded the IL index for the time interval from 2007 to 2020, centred over the 24 solar cycle ([https://space.fmi.fi/image/www/il\\_index\\_panel.php](https://space.fmi.fi/image/www/il_index_panel.php)). The perturbations in the horizontal magnetic X component relative to quiet magnetic conditions, are denoted by  $\delta X$ . During substorms, at auroral latitudes  $\delta X$  is strong negative and the IL-index is negative, too. The IL index is defined as the minimum of the disturbances  $\delta X$  registered in all stations considered at a certain point in time. The original IL indices were recorded every 10 s and are averages over these time intervals. By averaging over six consecutive values, we achieve a reduction in the amount of data and a time resolution of one minute. The daily time series were subdivided into four time sectors lasting 6 h: the midnight sector (called hereinafter for brevity night sector) (21–03 MLT) the morning sector (03–09 MLT),

the midday sector (for brevity called day sector) (09–15 MLT) and the evening sector (15–21 MLT). The noise in the IL time series was reduced by the application of a simple low-pass filter with a cut-off frequency corresponding to 5 min.

**The choice of events.** We have chosen the magnetic disturbance events by the following criteria:

1. IL falls below  $-2\sigma$ ;
2. the peak width at  $-\sigma$  is greater than 8 min;
3. a threshold of  $-\text{IL} > 50$  nT was applied for BJN-NAL, and for PPN-SOR a threshold of  $-\text{IL} > 100$  nT was used for the day sector on PPN-SOR, because below these thresholds only weak magnetic disturbances, similar to noise, were observed.

The minimal IL value of the negative bay of each of the chosen magnetic disturbance event was taken for further consideration.

**Determination of the distributions and observation rates of IL-index.** We constructed histograms, where the number of data were counted in successive, not overlapping equal intervals of 50 nT. Our histograms display the frequencies of numbers of magnetic disturbance events in every IL interval.  $\text{IL}(t)$  is defined as  $\min\{\delta X_i(t)\}$ , where  $i$  is the station number and the densities are expected to decrease as an exponential function. The empirical distribution density is easy to calculate from  $f_i = N_i/N$ , where  $N_i$  is the observed number of magnetic disturbance events in the  $i$ -th interval and  $N$  is the overall observation number in all classes. The theoretical distribution densities can be estimated with the help of an extreme value distribution, in our case the exponential distribution density is

$$(1) \quad f(x) = \lambda \exp(-\lambda x) \text{ with } x = -(\text{IL} + 50)nT,$$

the empirical cumulative distribution is given by  $F_i = \frac{1}{N} \sum_{j=1}^i N_j$  and the theoretical cumulative distribution for the exponential distribution density is

$$(2) \quad F(x) = P(X \leq x) = 1 - \exp(-\lambda x),$$

where  $P$  gives the probability that a random variable  $X$  is smaller than  $x$ . The survival function is defined as  $S(x) = P(X > x) = 1 - P(X \leq x) = 1 - F(x)$  [8]. In absolute counts the event observation number is  $N - NF_i$  and the occurrence rate per year is obtained by  $(N - NF_i)/(\text{number of years})$ . We note that the waiting time rate, used by some authors, is defined as the inverse of the occurrence rate [9]. It is easy to show, that the theoretical occurrence rate in the case of an exponential distribution is  $N \exp(-\lambda x)/(\text{number of years})$  and on a logarithmic scale it decreases linearly with  $-\text{IL}$ , with the slope equal to the parameter  $\lambda$  of

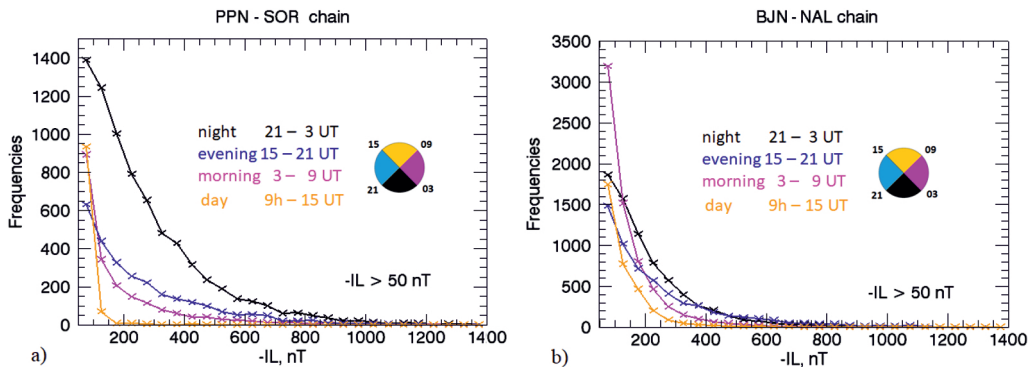


Fig. 1. Frequencies of the IL-index obtained in the four time sectors (shown in different colours) for IL-index calculated for the PPN-SOR chain (a) and for the BJN-NAL (b)

the exponential distribution, which can be determined by linear regression. The parameter  $\lambda$  could also be calculated from the expected mean  $E(f) = 1/\lambda$  for the exponential distribution. The results of both methods are not identical.  $E(f)$  is determined mostly by great values at the beginning of the distribution while by using linear regression, the tail of the distribution is better taken into account.

**Results. Histograms.** The histograms of the event numbers are presented by polygons for both station chains PPN-SOR and BJN-NAL for each time sector (Fig. 1). The frequencies decrease like exponential functions as it was expected from the definition of IL as  $\min\{\delta X_i(t)\}$ . Only in the day sector for the PPN-SOR chain a very strong decrease is obtained from the value of the first interval from 50–100 nT to the value of the second one 100–150 nT. The high event number in the first interval is caused by very weak magnetic disturbances like these in the  $0 < -IL < 50$  nT interval. For that reason the first interval ( $50 < -IL < 100$  nT) for the day sector of the PPN-SOR chain was excluded from further consideration. The greatest number of magnetic disturbances is observed in the morning sector at the BJN-NAL stations (Fig. 1b). Probably it is associated with polar substorms, usually observed at high latitudes [10]. These substorms are usually characterized by small intensity and observed under quiet geomagnetic conditions (low solar wind velocity, small negative or positive values of Bz IMF) [13]. It should be noted that at these latitudes not only polar substorms, but also expanded (high-latitude) substorms and other magnetic disturbances are observed [11–14].

**Cumulative distributions.** By the PPN-SOR chain the greatest event numbers were obtained in the night sector independently from the IL-index level. This also applies for the BJN-NAL chain except for  $-IL < 200$  nT. Here the observed event numbers in the morning sector are greater than in the night sector. The cumulative event counts at the BJN-NAL chain and at the PPN-SOR chain are very different. Most magnetic disturbances, over 8000, were observed at the BJN-NAL stations. It is well known that substorms occur mostly at auroral



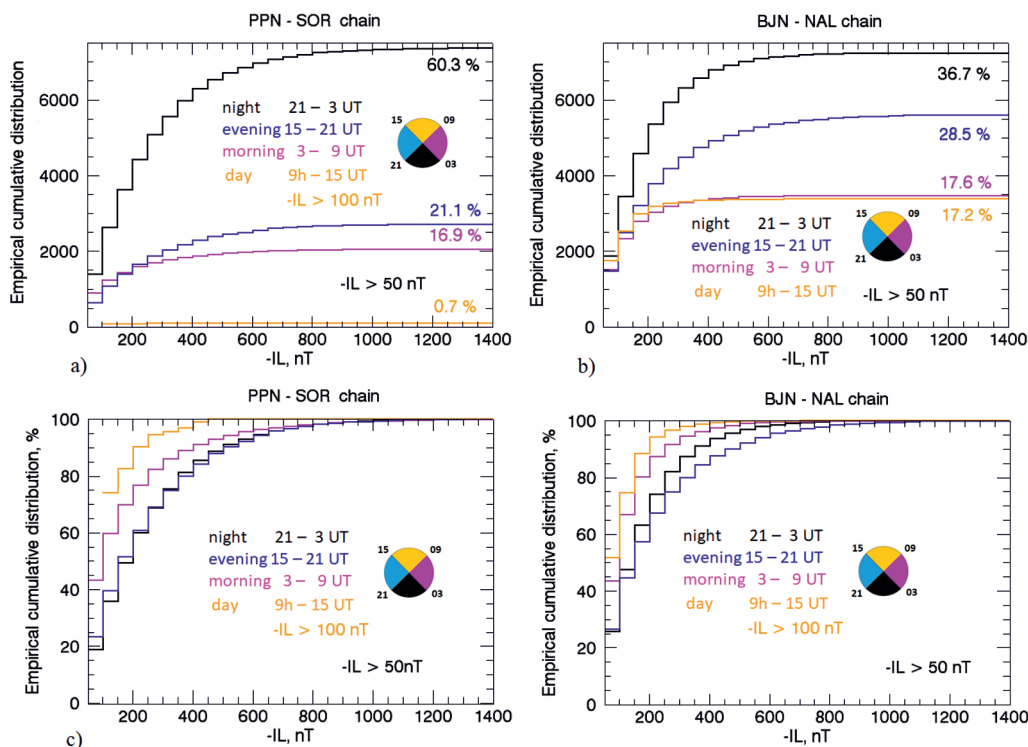


Fig. 2. Absolute empirical cumulative distributions of the IL-index for the night, evening, morning and day sectors in different colours: a) for the PPN-SOR chain; b) for the BJJ-NAL chain; Relative empirical cumulative distributions c) for the PPN-SOR chain; d) for the BJJ-NAL chain

latitudes ( $65\text{--}70^\circ\text{N}$ ) during the night, but at polar latitudes may be registered also polar substorms observed only at high latitudes (above  $70^\circ$  MLAT). The night and morning events account for over 90% at the PPN-NAL stations and about 65% at the BJJ-NAL stations (Fig. 2a, b). During the night the recorded event numbers at the BJJ-NAL stations are of the same order as for the PPN-SOR chain (see Fig. 2a, b), but their ratio to the general event counts is about 52% at auroral latitudes and only 32% at high latitudes. In the evening and day sectors at the BJJ-NAL stations about 35% of the events were observed, but in the evening sector at the PPN-SOR only about 5%, and in the day sector only 2% of the general event numbers occur. In absolute numbers: during both the evening and at the dayside at PPN-SOR about 870 magnetic disturbances were observed, and at BJJ-NAL more than 8200 events were registered – ten times more than at PPN-SOR in the same time sectors. In Fig. 2c, d the relative empirical cumulative distributions of the IL-index for both chains are presented. A much faster saturation is observed on the BJJ-NAL chain. For example, up to  $-IL < 300$  nT, at the PPN-SOR chain we have observed about 70% of all events

in the morning sector against 88% at the BJN-NAL stations and about 65% of the events in the night sector against 75% at the BJN-NAL stations for the same intervals (Fig. 2c, d).

**Occurrence rates and parameters of the exponential distributions.**

The computed empirical and theoretical occurrence rates for the examined time sectors are shown in Fig. 3. As it is well known the magnetic disturbances in the night, morning and evening sector are often associated with substorms. The obtained occurrence rate distributions of the magnetic disturbances registered at the PPN-SOR chain in these sectors and at the BJN-NAL chain in the evening sector and for  $-IL > 1025/nT$  in the morning sector are grouped in the interval of the parameters of the exponential distribution between about  $0.004/nT$  and  $0.005/nT$ . In the night sector for the BJN-NAL chain the exponential distribution decreases faster than the one for the PPN-SOR chain, with  $0.0067/nT$  (Fig. 3a). The sources of the disturbances observed during night at PPN-SOR and at BJN-NAL are probably different. The occurrence rate in the morning BJN-NAL sector decrease faster up to  $-IL = 1025 nT$  with a slope of about  $0.0065/nT$ , and after

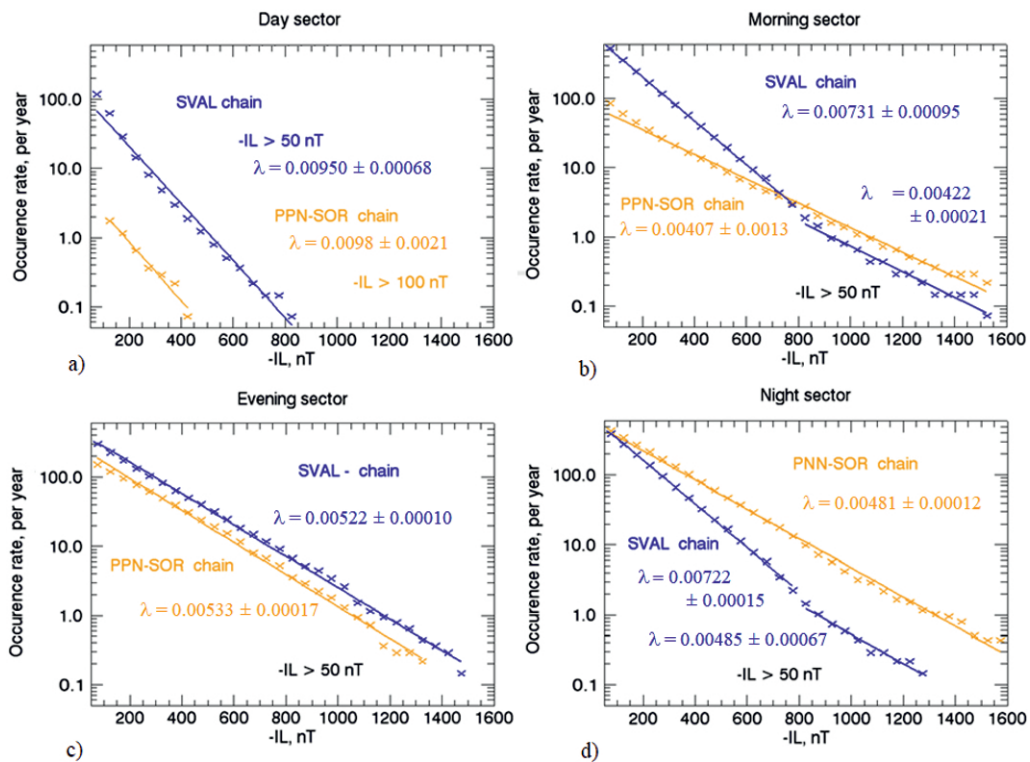


Fig. 3. Occurrence rate of IL-index calculated for PPN-SOR (orange colour) and for BJN-NAL (blue colour) for all time sectors. The empirical rates are shown by crosses. The theoretical rates, estimated with the help of exponential functions, are drawn by continuous lines. The values of the  $\lambda$  parameters and their confidence intervals are noted

that the slope changes to about 0.0042/nT. For the PPN-SOR chain in the same sector it decreases with a slope of about 0.0052/nT up to  $-IL = 875$  nT, and after that the slope becomes about 0.0039. These changes in the occurrence rate in the morning sector for both chains are identified as structural changes with break points at the limits mentioned above (Fig. 3b) [15]. The significance of the breakpoints was tested for a Two Phase Regression model using an F-statistic [16] with  $F_{\max}$ -percentiles calculated by LUND and REEVES [17]. The breakpoints are significant at the level of 0.99. The segments after the break points for stronger magnetic disturbances show a smaller  $\lambda$  than the segments for weaker intensity of the magnetic disturbances. However, the occurrence of events in the morning sector with strong activities  $-IL > 1025$  nT (BJN-NAL) and  $-IL > 825$  nT (PPN-SOR) is only about 0.9 events per year and 4 events per year, respectively. That means that in general only approximately 13 events at BJN-NAL and 56 events at PPN-SOR during the studied here interval of 14 years were observed. We suppose that at BJN-NAL events are predominantly expanded substorms observed at auroral latitudes and at high latitudes at the same time.

The fastest saturations were observed in the cumulative frequencies in the day sectors of both chains. This is reflected in the rapid decrease of the respective frequencies in the histograms (see Fig. 1a, b) and in the occurrence rates, as well (see Fig. 3d), giving us the estimated parameters of the exponential distributions of 0.011/nT for the BJN-NAL chain and of 0.0075/nT for the PPN-SOR chain. During evening time usually the eastward electrojet is predominant but at the SOR chain negative IL can be observed for some configurations of the electrojet vortices.

***The relation of magnetic disturbances to geomagnetic induced currents.*** It is well known that intense magnetic disturbances can cause power outages and corrosion of petroleum and gas pipelines by geomagnetically induced currents (GICs). In a case study of observations of GICs in transformers in north-western Russia evidence of a good correlation between the appearance of GICs and the westward electrojet indices IL was provided [18]. Moreover, in the same study was found that magnetic substorms observed in Northern Europe, characterized by a westward electrojet with  $-IL > 1000$  nT, can induce currents in gas pipelines in excess of 10 A. By the calculated occurrence rate we found that in Scandinavia such events (totalled across all sectors) do occur about seven times a year. In contrast, such events are to be expected only half as often at Svalbard.

**Conclusions.** The occurrence rates of magnetic disturbances at the IMAGE chains PPN-SOR in the western part of Scandinavia and at the Svalbard stations obtained in the here presented paper clearly show three classes, which are characterized by different parameters  $\lambda$  of the exponential distributions.

The first class is the more extensive and is characterized by slopes in the  $\lambda$  interval of approximately 0.004/nT to 0.005/nT, and is typical for the exponential distributions at auroral latitudes. In the morning sector for both the PPN-SOR

and the BJN-NAL chain a structural change (with one break point) is observed, where the segments for stronger magnetic disturbances have a  $\lambda$  parameter, belongs to the first class. The second class with a  $\lambda$  of between about 0.0065 and 0.0075/nT is mainly observed at polar latitudes in the night sector and in the morning sector up to about  $-IL = 1025$  nT. At auroral latitudes it is observed only in the day sector. The third class comprises only a few events with  $\lambda$  of about 0.011/nT, typical for the occurrences of weak disturbances in the day sector at auroral latitudes. Besides it was found out that in Scandinavia events (totalled across all sectors) which could induce currents (GICs) in gas pipelines stronger than 10 A do occur about seven times a year. In contrast, such events are to be expected only half as often at Svalbard.

The present work examines planetary geomagnetic disturbances. Together with the corpuscular influences on the Earth environment, they represent the main factors in solar-terrestrial and space physics [1,19,20].

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