Geophys. J. Int. (2004) **157,** 141–146 doi: 10.1111/j.1365-246X.2004.02241.x

Three-hour activity index based on power spectra estimation

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Accepted 2004 January 14. Received 2003 October 13; in original form 2002 November 19

SUMMARY

We propose a new index of magnetic activity during three-hour intervals. The new index E is based on the energy spectra. As a result of the fact that energy is additive, we can use information from both horizontal components simultaneously. After calibration of the new index in relation to the commonly used K index, we made some numerical tests comparing both indices. The tests showed that the values of indices are similar (differences greater than ±1 occurred only in 0.1 per cent of cases). We also made calculation of correlation with some magnetospheric parameters. The new index seems to correlate slightly better than the old one. It is still an open question whether the new index can be treated as an improved version of the K index and create a prolongation of old series.

Key words: geomagnetic activity, geomagnetism, K indices, solar wind.

1 INTRODUCTION

The so-called K index introduced by Bartels *et al.* (1939) is most frequently used as a measure of magnetic activity. It is a measure of the level of disturbances in the Earth's magnetic field caused by the influence of the solar wind. It is derived from the maximum range in horizontal components X(H) or Y(D) of geomagnetic field variations recorded in the three-hour interval, after subtraction of the regular daily variations resulting from ionization of the ionosphere and its tides. This range is coded according to quasi-logarithmic scale to give K index an integer between 0 and 9. For this coding, the larger value of the two components is accepted. The K index depends on the recognition of the regular part of variations called S_R: this has been determined during many years by hand and depends on the observer's experience, which is subjective. When the day is quiet, the recognition of regular variation is comparatively easy, while during disturbed periods the S_R variation is negligible compared to the disturbances. The main difficulty is identifying S_R for a moderate disturbed day. The procedure used has been described by Bartels *et al.* (1939) and Mayaud (1980).

The series of K indices is now 60-yr long and is found useful for many analyses of various phenomena in such fields as radio communication, aurora, space weather and so on. It is still an open question as to what is the accuracy of the K-indices determination and the uniformity of series. Riddick & Stuart (1984) studied the differences between hand scaling by two observers of magnetograms from three UK observatories and found levels of agreement ranging between 82 and 91 per cent. Similar results were achieved by Menvielle *et al.* (1995). Loomer *et al.* (1983) showed that when two observers adjusted their scaling, they could achieve a 90 per cent level of agreement, which represents the best possible agreement. In the case of every observatory, there were no extensive studies, however, when there is a change of observer (because the observer retires or changes his activity) the differences in levels of agreement can be higher. This means that the whole long series cannot be assumed uniform and the level of its accuracy can be approximately 80 per cent (Clark 1992).

Let us return now to Bartels's definition of K indices. We may speculate why he recommended using the larger one of the two variations of horizontal components. We think that it was connected with analogue recording systems in the observatories. The processing of the analogue recording is very limited: for example, we cannot easily rotate the observational axis. The method of calculating activity basing on the larger one of the two components is quite ingenious because it is very simple, however, it is not accurate. The full vector length can differ up to 30 per cent, depending on the polarization of variations. Estimating a vector of length A, for example, by the greater value of the two components, results in the range from 0.7 to 1 A. Hence, the definition of the K index based on just one component is not precise because the index depends not only on amplitude but also on polarization. Fortunately, this dependence cannot drastically change the result of estimation. This does not mean that the values of indices cannot correlate with some physical phenomena: on the contrary, during 60 yr the indices were found useful for analyses of many various events. A possible geophysical meaning of K indices has been discussed by Menvielle (1979).

In the present paper, we propose a slightly different definition of the activity index based on the progress in the recording system and data processing.

In the mid-1980s, when more and more observatories were introducing digital systems of magnetic field recording, several methods for computer derivation of K indices were developed. There was a long lasting discussion concerning how to separate the regular part of variations. Four methods were accepted by the International Association of Geomagnetism and Aeronomy (during the XX General Assembly of the International Union of Geodesy and Geophysics in

Vienna in 1991). The main criterion for evaluating these methods was the fit of the K indices derived by a computer to the hand-scaled ones. The computer methods accepted by IAGA are based on the hitherto existing definition, i.e. on the search for the maximum amplitude of irregular variation of horizontal components X(H) or Y(D). We believe that these indices are superior in the sense that the series in individual observatories do not depend on change of observer, but still, the methods used have the following two drawbacks:

(i) The K index is determined from the maximum amplitude of irregular variations of just one component: the K index is the same when, for example, $K_X = 3$ and $K_Y = 0$, and $K_X = 3$ and $K_Y = 3$.

(ii) The K index does not depend on the number of occurrences of natural disturbances in the three-hour interval: it is the same if the disturbance of certain amplitude occurred once or several times.

It seems that the magnetic activity index should be proportional to the energy of the field. This idea has a long history: it had already been mentioned in Janowski's handbook (Janowski 1958). The problem of relationships between the power spectra and K indices was also considered by Lanzerotti & Surkan (1974). However, these works have not led to any suggestion of a new definition of the K index.

2 ENERGETIC DEFINITION OF THE GEOMAGNETIC ACTIVITY INDEX AND SELECTION OF CRITERIA TO BE SATISFIED

We propose to base the magnetic activity index definition on the power spectra calculation. A new definition should be free of the drawbacks discussed above. The indices derived by the new method should be close enough to the already existing ones to form with them a satisfactorily uniform data series. This is very important for analysing the activity over long periods of time. We also hope that the new definition will be more useful for the diagnosis of solar wind parameters.

We will denote the new index by the letter E. Its proposed definition is as follows: the E index is a digit from the interval 0–9 proportional to the logarithm of energy of two horizontal components variations in the interval of 3 hr. The number is normalized so that the observatories situated in moderate geomagnetic latitudes have similar activity indices and the new indices are similar to the K indices.

3 THE PROCEDURE OF DETERMINING THE E INDEX FROM THE RECORDED POWER SPECTRA

The first step in the E index determination procedure is to eliminate the regular variations S_R. This can be done by any of the four methods recommended by IAGA. We used the adaptive smoothing method (ASm) (Nowożyński *et al.* 1991). Then we calculate power spectra for three-hour time intervals: the calculations are made for horizontal components only. The vertical component Z is neglected because at moderate geomagnetic latitudes its variations are smaller than those of horizontal components and the major part of their energy is produced by induction currents in upper layers of the Earth's crust.

To compute the energy contained in irregular variations of geomagnetic field one has to calculate the integral of the power spectra of the horizontal components X(H) and Y(D). The integration range, i.e. the lower frequency f_1 and upper frequency f_2, should be selected so that the integrated spectrum be free of regular variations S_R: on the other hand, we should also take into account the time interval between the samples of horizontal components of the geomagnetic field. Hence, the formula is

$$P_I = \int_{f_1}^{f_2} P_I(f)\, df, \qquad (1)$$

where P_I is the power spectrum P_X or P_Y (P_H or P_D, respectively): f_1 corresponds to a period of 3 hr and f_2 corresponds to Nyquist's frequency (for data in the Intermagnet format, $1/f_2 = 2$ min).

Because both horizontal components, X(H) and Y(D), decide upon the activity index of the field, the energy in the three-hour interval must be calculated from the formula:

$$P = P_X + P_Y \quad \text{or} \quad P = P_H + P_D. \qquad (2)$$

Then we calculate the E indices on the basis of the previously calculated energy P. In this stage, we made a calibration of the calculated values of energy P so as to obtain the E indices as close as possible to the K indices. In this manner we wanted to find out whether the E indices could be used as a continuation of the K indices. In the calculation with the least-squares method, the calibration procedure consisted of coefficients A and B in the formula:

$$K = A \log(P) + B. \qquad (3)$$

The calibration coefficients A and B and E indices were calculated for approximately 7.5 yr for data from the four observatories: Belsk (BEL), Wingst (WNG), Lerwick (LER) and Canberra (CAN). In place of K we were putting the activity indices calculated with the ASm in place of P, the mean energy values corresponding to them. The results are listed in Table 1.

Table 1. The calculated coefficients A and B.

	Belsk (BEL)	Wingst (WNG)	Lerwick (LER)	Canberra (CNB)
Coefficient A	0.4831	0.4937	0.5082	0.5194
Coefficient B	0.4674	0.4228	0.2734	0.3596

4 COMPARISON OF K TO E INDICES AND THEIR STATISTICAL CORRELATIONS WITH SOLAR WIND PARAMETERS

To examine the properties of the E indices we made their statistical comparison to the K indices. We used data for 1994–2001 from the four observatories situated at different geomagnetic latitudes: Belsk, Canberra, Lerwick and Wingst. The total length of data available simultaneously for all these observatories was approximately 7.5 yr. The results of the comparison are shown as histograms in Fig. 1. The full agreement between the two indices ranged from 64 per cent for Belsk to 77 per cent for Lerwick. The number of cases in which the differences amounted to 2 ranged from 0.06 per cent at Canberra to 0.19 per cent at Belsk. There was only one case out of $80 \cdot 10^3$ calculated indices in which the difference amounted to 3.

In Figs 2 and 3 we present six examples in which the difference $|E - K|$ was 2. Fig. 2 represents cases when E was lower than K by 2. There is a similarity of situations for all these cases. In the intervals of our interest, the field was generally quiet with individual disturbances usually of one component. These disturbances usually occurred at the beginning or end of the three-hour interval and were related to the adjacent interval. Because of these disturbances, the

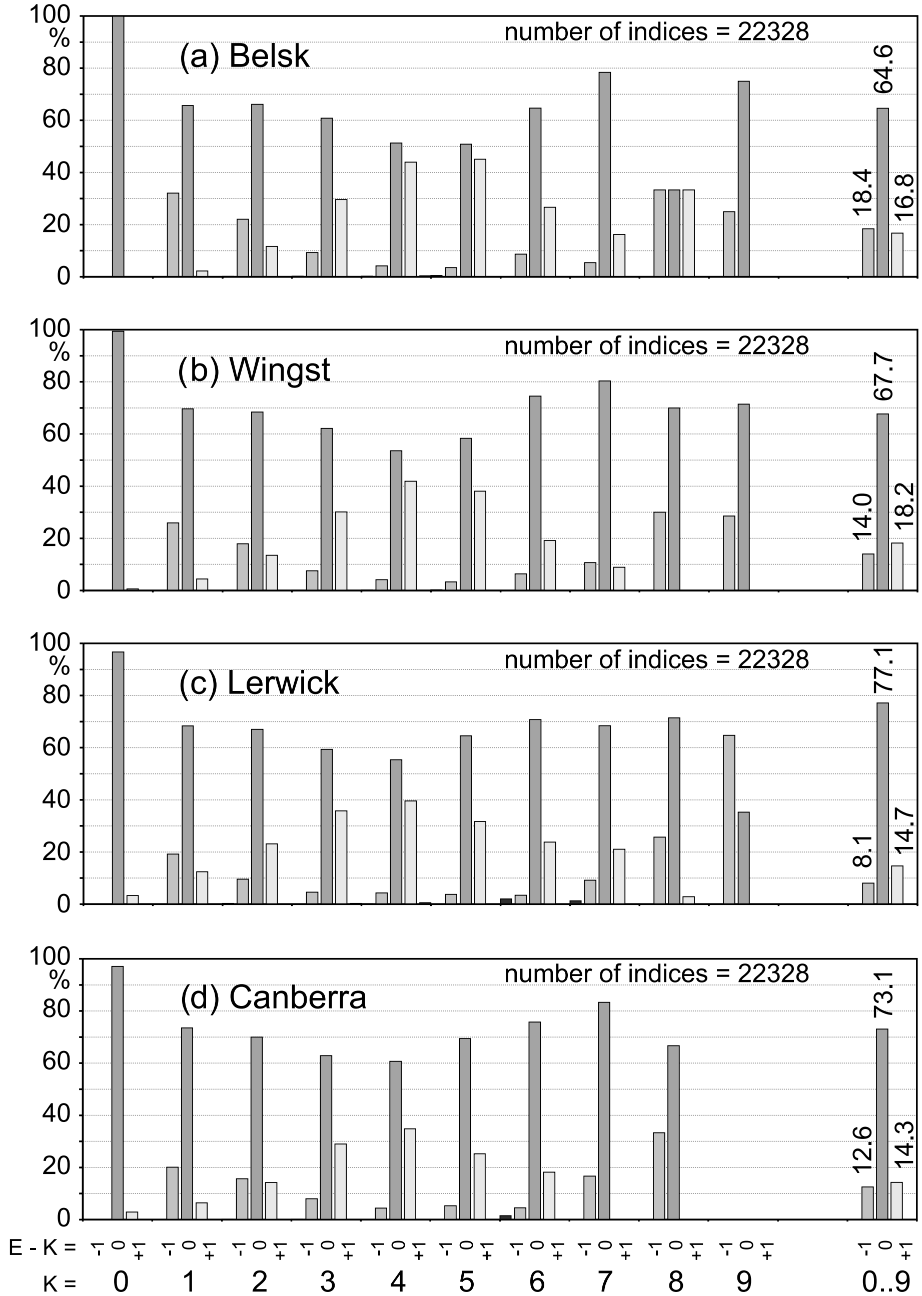

Figure 1. Comparison of indices E and K calculated over the period 1994–2001 for the observatories: (a) Belsk, (b) Wingst, (c) Lerwick, (d) Canberra.

indices calculated according to the ASm were relatively large. A characteristic example is the period from 12:00 to 15:00 hours on 1994 October 19, shown in Fig. 2(a). The disturbance by the end of the three-hour interval was mainly concerned with component X. For this case, the K index calculated with ASm was as high as 3, while that calculated from energy was 1. It seems to us that the $E = 1$ better characterizes the magnetic field activity in the analysed interval.

Fig. 3 presents three examples when E turned out to be greater than K by 2. We see that in all these cases the field activity was high and the amplitudes of irregular variations of both horizontal components were close to each other. Also, here we feel that the indices calculated from energy better represent the real state of the field activity, because they take into account variations of both components.

Because of the shortage of space we will not present all the cases when the difference between E and K was 2. Our analysis of these cases has given evidence in favour of the indices calculated from energy.

We believe that the indices calculated with the new method can be treated as a continuation of those determined from the former definition. A comparable perturbation in the K-index series had been associated with the transfer from hand-scaling to computer determination methods. Differences in the determination of indices have also occurred in the past, e.g. when a hand-scaling person has been changed.

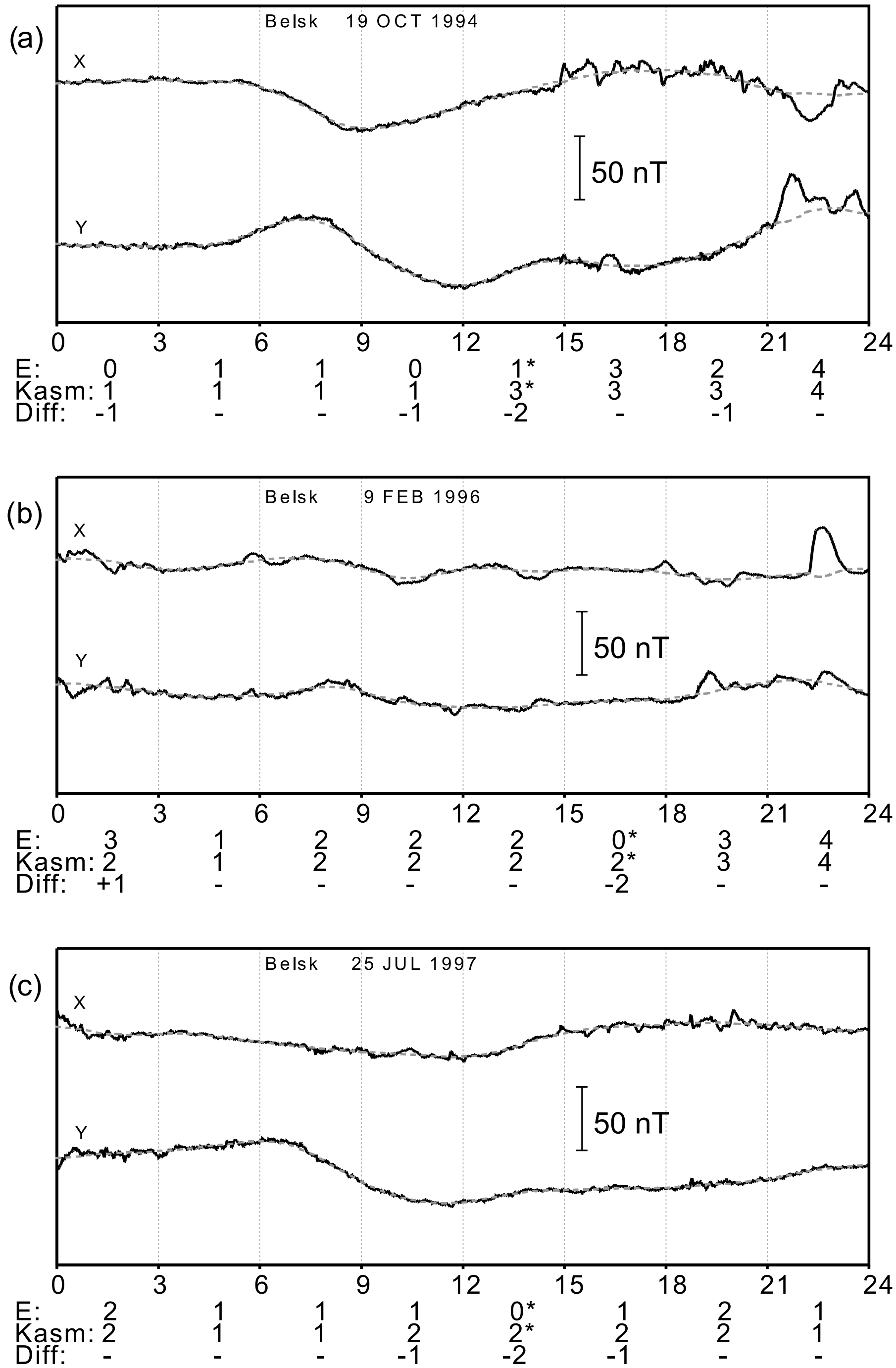

Figure 2. Examples of situations when index *E* was lower than *K* by 2: (a) 1994 October 19, 12:00–15:00 hours UT, (b) 1996 February 9, 15:00–18:00 hours UT, (c) 1997 July 25, 12:00–15:00 hours UT.

In order to find out how the new indices correlate with the solar wind parameters, we took into account three parameters:

(i) vertical component *Bz*, i.e. component Z of the interplanetary magnetic field (IMF) in the geocentric solar magnetospheric coordinates (GSM);

(ii) plasma temperature *Tp*;

(iii) solar wind speed *V*.

We chose these parameters because they are relatively well correlated with planetary indices *Kp*. Parameters *Bz* and *V* are used by researchers for developing methods of geomagnetic activity predictions (Boberg *et al.* 2000). A statistical analysis was made for the whole year in 1999 (except for the gaps in the data). The source of data on solar wind parameters was the http server of the NSSDC (National Space Science Data Center, ftp://nssdcftp.gsfc.nasa.gov/spacecraft_data/omni/).

To find out whether the E indices better correlate with *Bz*, *Tp* and *V*, we made an analysis for such cases in which they differed from K indices. For calculating correlations, we used a_K indices obtained from *K* and *E* indices. We did so because the indices *K* and *E* are only codes. According to Mayaud (1980), it is more reliable to use the amplitude of perturbations expressed in nT, i.e. to re-convert each K

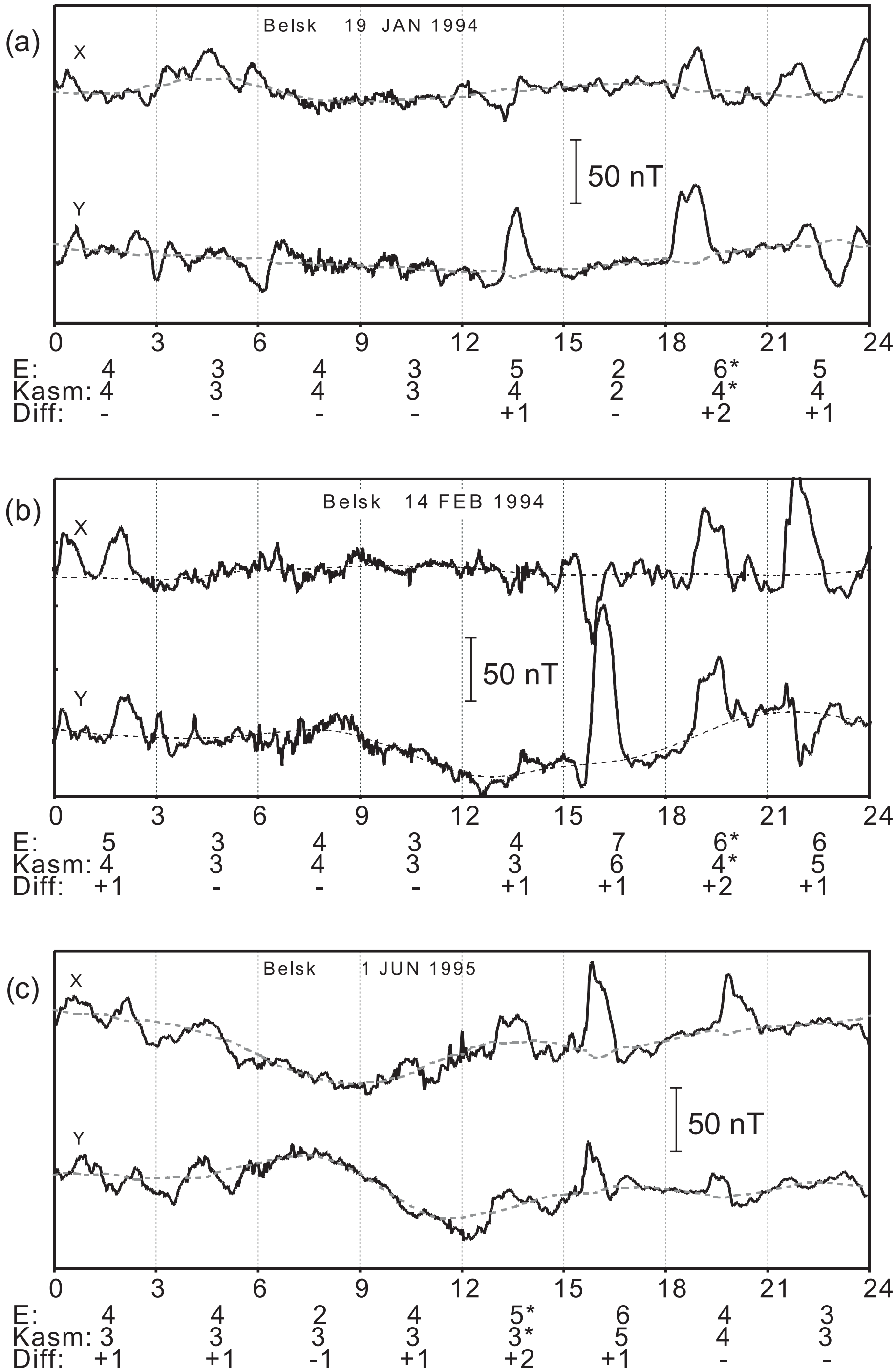

Figure 3. Examples of situations when index *E* was greater than *K* by 2: (a) 1994 January 19, 18:00–21:00 hours UT, (b) 1994 February 14, 18:00–21:00 hours UT, (c) 1995 June 1, 12:00–15:00 hours UT.

index into an equivalent range, a_K, which is about the centre of the limiting ranges for a given grade of K. The results of computation of correlations are shown in Table 2.

We see from Table 2 that the correlation of the E index with the solar wind parameters was better than that of *K*. It turned out that the correlations thus obtained are another, even stronger argument in favour of the indices calculated from energy. Hence, the correlation of *Bz* with a_K indices calculated from the E index was as much as 18.3 per cent better than that with the indices obtained using the ASm method. With regard to the parameters *V* and *Tp*, the improvement amounted to 11.6 and, more over, 7.6 per cent, respectively.

Table 2. Correlation of a_K indices obtained from *K* and *E* with solar wind parameters *Bz*, *Tp* and *V* over the period 1994–1999.

	Bz		*Tp*		*V*	
	K	*E*	*K*	*E*	*K*	*E*
BEL	0.376	0.425	0.450	0.458	0.495	0.519
WNG	0.350	0.408	0.453	0.459	0.463	0.504
LER	0.276	0.339	0.230	0.295	0.264	0.348
CNB	0.339	0.414	0.384	0.420	0.459	0.505
Avg	0.335	0.396	0.379	0.408	0.420	0.469

5 CONCLUSIONS

Recent progress in the technology of recording and processing magnetic field variations allows for slightly different methods of determination of the activity index. In this paper, we describe a new index, which, in our opinion, has some advantages over the classical K index. These advantages are as follows:

(i) The activity measure is based on the energy estimation (strictly speaking, the volume density of energy). Such an approach seems to be more natural and is common in physics.

(ii) The activity measure is based on the behaviour of variations of both horizontal components simultaneously.

(iii) The activity measure is rotation invariant. One can get the same results using components X and Y, or H and D.

(iv) The correlation of the E index with the solar wind parameters is slightly better than that of K index.

Numerical tests showed that the values of the new index are not much different from those of the old one. The differences are not large but clearly visible. It seems to us that it is worth discussing whether it is reasonable to change the method of deriving the activity measure. The question should be answered by users of the data. There is also a question of whether the new index can be treated as a modified K index. In the past, the K-indices series for individual observatories were never homogeneous. The numerical test shows that the difference between the old and new index is greater than 1 in only 0.1 per cent of cases. We believe that IAGA division *V* should organize discussion on the subject.

ACKNOWLEDGMENTS

This work was supported by State Committee Scientific Research (Komitet Badań Naukowych), grant 5 12B 007 22.

We used the geomagnetic data from the Canberra, Lerwick, Wingst and Belsk observatories available on CD-ROMs issued by Intermagnet.

The magnetospheric data were taken from the http server NSSDC (National Space Science Data Center, ftp://nssdcftp.gsfc.nasa.gov/spacecraft_data/omni/).

The authors wish to thank Mrs Anna Dziembowska for useful remarks and translation.

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