J Geophys (1988) 62: 175–179

Journal of Geophysics

Numerical methods for *K*-scaling from digital data, applied to records from Wingst Observatory

Jürgen Wendt

Institut für Geophysik der Universität Göttingen, Herzberger Landstraße 180, Postfach 2341, D-3400 Göttingen, Federal Republic of Germany

Abstract. Digital recordings obtained by Wingst Observatory for the year 1981 are investigated by methods which are essentially based on the application of numerical filters, in order to derive the non-*K*-variations and to estimate the *K*-values of terrestrial magnetism. The best result of the methods presented in this paper is an 81.8% agreement between the *K*-values estimated from digital recordings and the *K*-values estimated by an observer using analog recordings of the same time interval. At the same time the derivation of the non-*K*-variations by this method is attempted in a reasonable way.

Key words: *K*-values – *K*-scaling – Handscaled *K*-values – Digital *K*-values – *K*-variations – Non-*K*-variations

Introduction

The *K*-index was introduced by Bartels (1938). It should measure the intensity of solar particle (*P*) radiation effects (called *K*-variations) at any station for each of the intervals 00–03, 03–06, ..., 21–24 h UT (Bartels, 1957).

Originally the solar particle radiation was not considered to be responsible for a regular variation of the magnetic field. However, after the discovery of the continuous solar wind a regular variation caused by solar particle radiation was found (e.g. Mead, 1964). Therefore, *K*-variations are defined as the irregular disturbances due to solar particle radiation (Siebert, 1971).

Each station has a *K*-scale of 10 grades, $K=0$–9, chosen once and for all from a limited number of standard scales. This choice is governed, in general, by the geomagnetic latitude of the station (Bartels, 1957).

In practice, a major difficulty of *K*-scaling is the elimination of the solar wave (*W*) radiation effects (called non-*K*-variations). The non-*K*-variations can be directly observed in the magnetograms, solely on quiet days. Furthermore, they not only vary with season and sunspot cycle (as well as with the lunar phase), but they may also vary irregularly from day to day, in which case irregular and systematic variations can be of the same order of magnitude (Siebert, 1971). For the derivation of the non-*K*-variations, an observer is required to make a subjective judgement based on special knowledge of their local shape. Riddick and Stuart (1984) showed that trained observers only reached an 85% agreement, measuring independently over a 6-month period, using the same records.

A practical procedure for estimating the *K*-index is "to plot on the magnetogram, for a particular field component and for the 3-h interval considered, two parallel smooth curves representing the non-*K*-variation, the one touching the actual trace from below, the other one touching it from above: the vertical distance of these two smooth curves, multiplied by the scale-value, gives the range for that field component" (Bartels, 1957). The larger of the two ranges found for the components *H* and *D* (or *X* and *Y*) is used nowadays to decide on the index *K*-by means of a quasi-logarithmical scale which is well defined for each observatory. In recent years digital data acquisition has come more and more into use and is now supplementing or replacing the old standard photographic systems at most of the observatories. In connection with that change, certain questions arise. How precisely can the *K*-values of terrestrial magnetism be estimated when digital data acquisition is used? Can these estimations, which are based on numerical algorithms, be made by computers?

At some digital observatories *K*-indices are handscaled from digital data (Loomer et al., 1984). Computer methods for obtaining digital *K*-are described by several authors (Alldredge, 1960; Alldredge and Saldukas, 1964; Rangarajan and Murty, 1980). Some methods were tested at UK observatories (Riddick and Stuart, 1984). In the following sections, results of *K*-scaling and deriving non-*K*-variations for Wingst Observatory are presented and discussed. They have been reached by the max-min method, by numerical filters or by methods which chose the most appropriate filter considering the activity, the season and the eight intervals of the day.

Data sampling

At Wingst magnetic observatory, the components *H*, *D* and *Z* are recorded in analog form and, simultaneously, *X*, *Y* and *Z* are recorded digitally. The digital data have a sampling rate of 1 min; variations with a range of 1000 nT can be recorded with a remaining uncertainty of ± 1 nT (Schulz, 1983). The methods represented were applied to digital records obtained from 349 days of the year 1981. Before applying a method, the digital *X* and *Y* values were converted into *H* and *D* values. For 14 days no *K*-values were estimated, as on those days 180 or more minute values were not recorded. The K-scaling for the first and the last day of 1981, which is possible to a certain degree, has been omitted.

Criteria for the quality of a method

The K-indices which have been estimated by a method are compared to the K-values an observer has found using respective analog records (usual estimation). The agreement reached by a method $U(K)$ for a certain K-value (e.g. $K=3$) is the ratio of the number $A_D(K)$ of correctly estimated values ($K=3$) based on digital records and the number $A_N(K)$ of values ($K=3$) estimated in the usual way:

$$U(K)=\frac{A_D(K)}{A_N(K)}.$$

The total agreement reached by a method for all K-values is defined by

$$\sum U(K)=\frac{\sum_{K=0}^{9} A_D(K)}{\sum_{K=0}^{9} A_N(K)}.$$

$U(K)$ and $\sum U(K)$ can both be taken as a measure of agreement. Which one is meant can easily be seen from the context.

A scale for the quality $\sum U(K)$ of a method is the 85% agreement which Riddick and Stuart (1984) discovered analysing values estimated in the usual way by two observers. As a result of the underestimation of the peaks by digital records, the frequency distribution of the digital K-indices should be shifted to smaller values in comparison with the frequency distribution of analog K-values. Besides, the trace of the non-K-variations found numerically should not differ too much from the trace found in the visual way.

Application of the maximum-minimum method

The max-min method has already been applied to UK observatory records (Riddick and Stuart, 1984). Using the max-min method, the maxima and minima of the records are determined for every 3-h interval. The K-values are then estimated from the differences between the maxima and minima of the most disturbed component (Fig. 1). When the max-min method is applied the non-K-variations are not eliminated, so that the K-values estimated this way are higher than handscaled values. Figure 2 shows that K-values higher than 3 can be well estimated by the max-min method. Actually, in the case of very strong magnetic disturbances, the observatories refrain from deriving non-K-variations, which corresponds to an application of the max-min method.

In 1981 a 55.4% agreement was reached for Wingst with the max-min method. Table 1 shows that in the 3-h intervals E3 and E4, when the S_q trace is particularly strong, the agreement is bad; whereas in the intervals E1 and E8, an agreement of more than 80% is reached.

Application of numerical filters

In this paper low-pass trapezoidal filters are used to determine the non-K-variations. The ideal frequency response

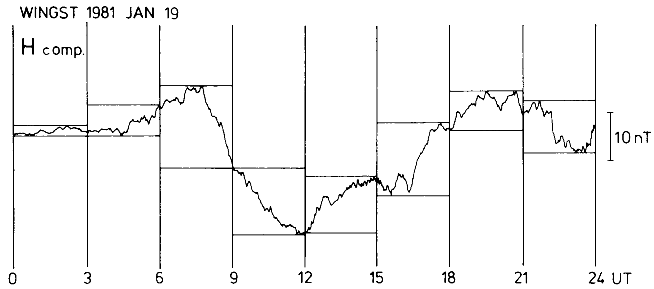

Fig. 1. Application of the max-min method to a recording of the H component

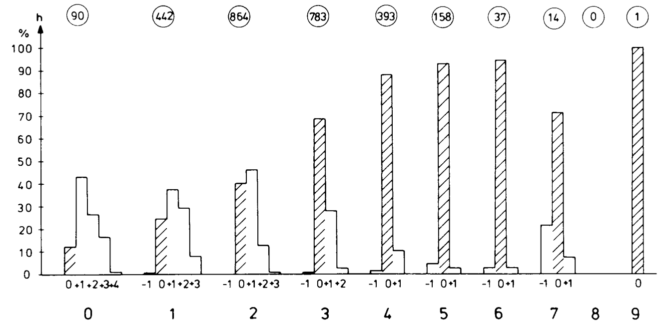

Fig. 2. Comparison between indices found by the max-min method and handscaled K-indices for 2782 3-h intervals in 1981. The *numbers in circles* are the absolute frequencies of the handscaled values. h shows the relative frequencies with which the numerically scaled values are estimated correctly (0), too small (-1, -2, ...) or too large ($+1$, $+2$, ...)

function of a low-pass trapezoidal filter with a cut-off frequency $f_0=(f_1+f_2)/2$ is

$$\tilde{w}(f)=\begin{cases} 1 & |f|\le f_1 \\ (f_2-f)/(f_2-f_1) & f_1\le|f|\le f_2 \\ 0 & |f|\ge f_2 \end{cases} \quad (1)$$

The filtering procedure is undertaken in the time domain, the length of the filter being $\tau=2N\cdot\Delta t$, where Δt is the sampling rate and $N+1$ is the number of filter coefficients. As the filter length is finite, the frequency response function will generally deviate from the ideal shape described by Eq. (1), especially $\tilde{w}(0)\neq 1$.

Using the additional condition $\tilde{w}(0)=1$, Schmucker (1978) calculates special filter coefficients which produce trapezoidal filters of almost ideal shape. These filters have a length $\tau=q/f_0$, where q is a positive integer. The quality of the filters is improved with increasing q which, on the other hand, affords a large number of filter coefficients.

The choice of filter parameters f_0 and q depends on the estimated influence of the first four solar and lunar harmonics on the analysis. The amplitudes of these harmonics have already been found by Gupta and Chapman (1968).

Trapezoidal filters of quality $q=5$ and with cut-off periods of 3–7 h yielded agreements between 70.3% and 80.9% during the seasons JFND, MASO, MJJA and for 1981 (Fig. 3). In all four cases, the best results are obtained with a filter with a cut-off period of $T_0=5$ h. However, agreements reached by a filter method differ from season to season, influenced by seasonal changes of activity.

Whereas small values are well estimated by a filter with cut-off period $T_0=3$ h, the filter with $T_0=5$ h is better for finding large values (Fig. 4). One can generally say that K-

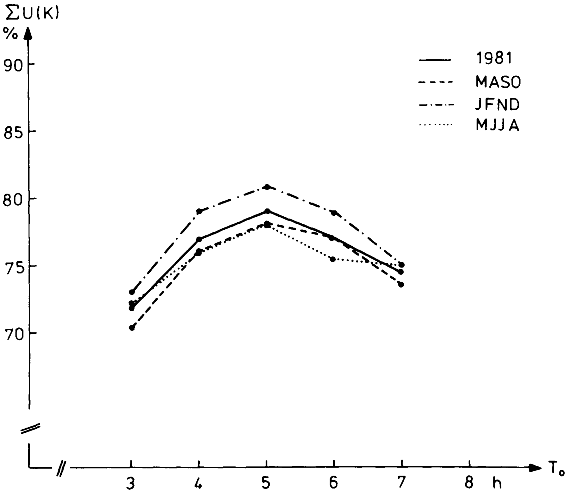

Fig. 3. Agreement between K-values estimated by filters with cut-off periods of 3–7 h and handscaled values for JFND, MASO, MJJA and 1981

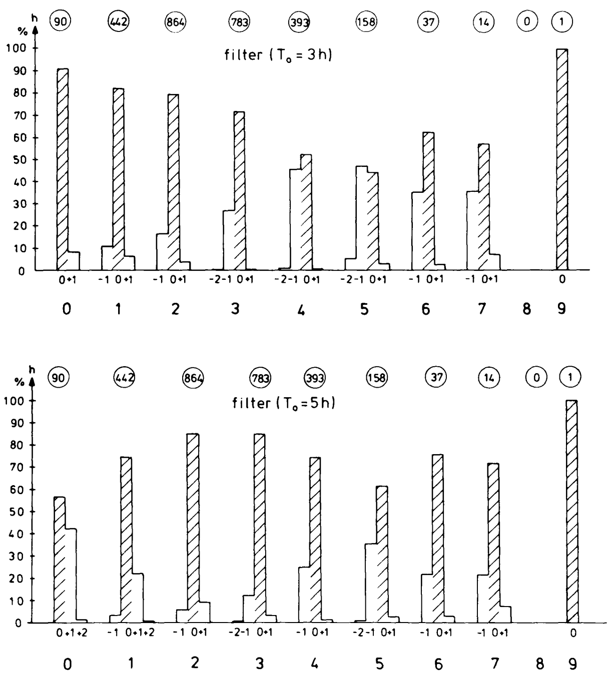

Fig. 4. Results of comparisons between digitally derived indices using a filter with cut-off period $T_0 = 3$ h, and a filter with cut-off period $T_0 = 5$ h, and the handscaled indices for 2782 3-h intervals in 1981

values < 2, found in the usual way with filters with cut-off periods from $T_0 = 3$ h to $T_0 = 7$ h, are estimated correctly more often if a lower cut-off period is chosen. For K-values > 2, this is true for larger cut-off periods. The usually scaled values $K = 2$ are found most correctly with a filter with cut-off period $T_0 = 5$ h. Table 1 shows the agreements in the different 3-h intervals which were reached using different filters. The max-min method is understood as a filter with a cut-off period $T_0 \gg 12$ h.

When the activity is low, the filter with cut-off period $T_0 = 3$ h is the best for deriving the non-K-variations (Fig. 5a). For higher activity this is no longer the case (Fig. 5b). The disturbances in the intervals E 6, E 7 and E 8 (there is a loss of data in E 5 and at the beginning of E 6) are much too closely approached by the trace of the non-K-variations which have been found by the filter. In the process of filtering, both disturbed and undisturbed values are used and, due to the low-pass filter, a smoothing of the record takes place. As long as the parts of the K-variations above and below the trace to be eliminated are approximately the same, a filtering process offers reasonable results. When disturbances occur, e.g. as in interval E 8 or especially with bay disturbances, one finds the above-mentioned disagreements between the digitally derived trace and the actual trace of non-K-variations. So the digital method leads to values which are smaller than the real ones.

With longer cut-off periods, the undesired approach is considerably less pronounced (Fig. 6); now one finds a vertical shift between the whole derived trace and the actual trace of the non-K-variations. The shape of the two traces, however, is approximately the same, which is solely decisive for the scaling of K-values.

This means that for the actual derivation: although the phenomenon of the undesired approach cannot be avoided, its effect can be diminished by choosing an appropriate filter. Therefore, the effect of the systematic scaling errors, which is connected with the filtering procedure, depends on the choice of cut-off period. For every activity there can be found an appropriate cut-off period. Therefore, filter methods can be used for K-scaling.

Combination of different filters depending on the time of day or the activity

As filters with different cut-off periods yield variable results for different times of day and with altering activity, one can try to improve the result of the filtering ($\sum U(K) = 79\%$ for 1981, $T_0 = 5$ h) by a skilful combination of several filters. If one uses for each 3-h interval the filter which is empirically found to have the most suitable cut-off period for that time (Table 1), one reaches an 80.4% agreement for 1981. If in

Table 1. Agreements $\sum U(K)$ in the day's eight 3-h intervals reached by several methods in the year 1981 (in %)

Method	T_0 [h]	E_1	E_2	E_3	E_4	E_5	E_6	E_7	E_8
Filter	3	68.2	73.9	76.5	72.5	71.1	66.8	69.3	76.2
Filter	4	75.6	78.2	76.8	75.9	77.9	73.4	75.6	82.5
Filter	5	77.1	79.1	77.1	79.4	77.7	77.9	79.4	84.5
Filter	6	75.9	75.1	70.2	76.2	79.4	80.5	75.6	84.8
Filter	7	75.4	71.3	63.6	74.5	73.9	75.1	78.8	84.2
Max-min	$\gg 12$	82.8	52.7	26.6	17.8	45.8	57.0	75.6	85.1

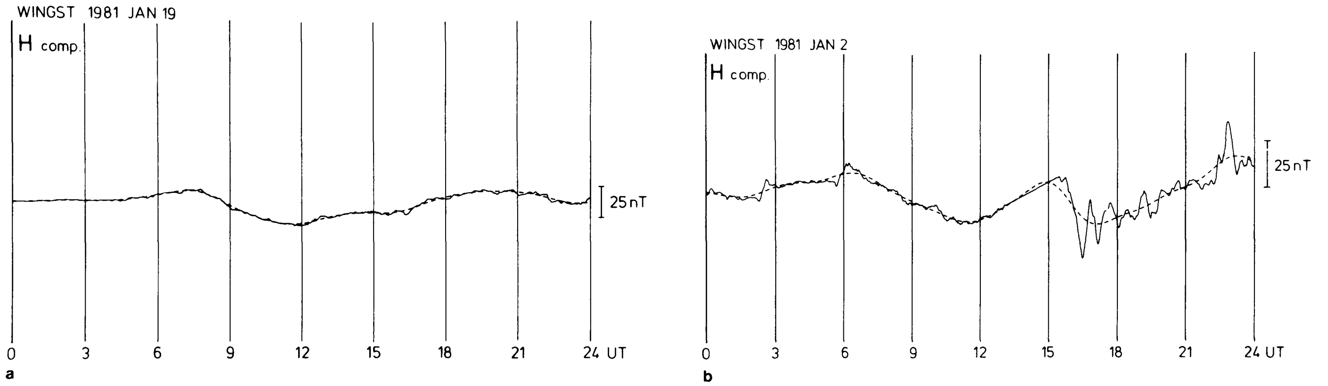

Fig. 5a and b. Application of a filter ($T_0 = 3$ h) to recordings of the H component. The *dashed lines* show the traces of the non-K-variations which have been found by the filter. **a** The non-K variations are well derived when the activity is low. **b** For higher activity, this is no longer the case

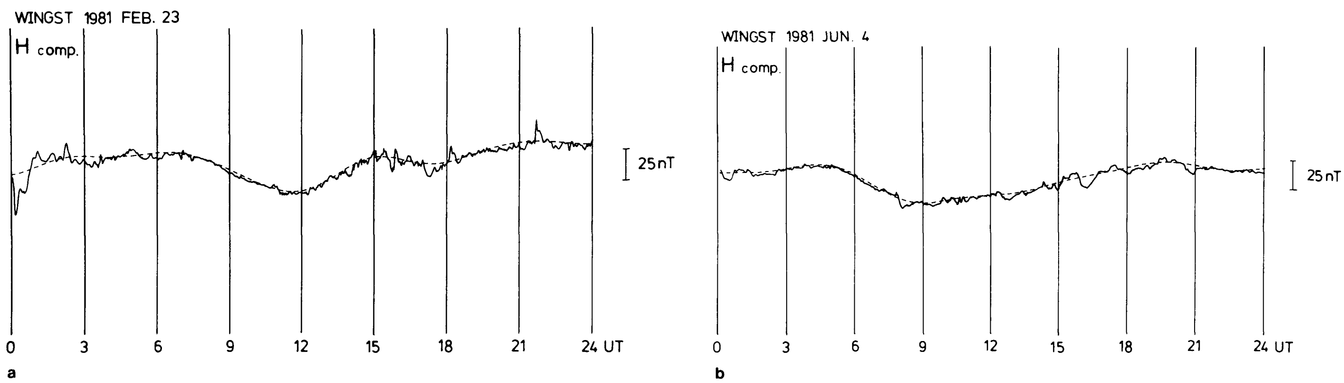

Fig. 6a and b. Application of a filter ($T_0 = 5$ h) to recordings of the H component. There exists a very good correlation between the derived and actual traces of the non-K-variations, except for a shift of the basis

addition to that one takes the season into account, deciding upon the most appropriate cut-off period, one reaches agreements of 80.5% for JFND, 83.5% for MASO, 79.8% for MJJA, and thus an 81.8% agreement for the year 1981.

The activity is a further criterion for the selection of the method to use. The best results for 1981 in the range $K \leq 1$ were reached by a filter with cut-off period $T_0 = 4$ h, in the range $3 \leq K \leq 4$ by a filter with $T_0 = 6$ h and in the range $K \geq 6$ by the max-min method. The first method is used for estimating the values $K = 0$ and $K = 1$, the second one for the values $K = 3$ and $K = 4$ and the third method for values $K > 5$. This way, however, there remain some intervals of no particular K-value. They get either the index $K = 2$ or $K = 5$; K shall equal 2 if the second method has estimated a value $K < 3$ for that interval, and K shall equal 5 if the second method has estimated a value $K > 4$. If there are several indices for one interval, that index is chosen which has been estimated by the second method.

With this combination one reaches an agreement of $\sum U(K) = 80.1\%$ for 1981. The computing time of this combination is approximately 3 times longer than that of a filter with cut-off period $T_0 = 5$ h.

A second procedure takes the activity into account and chooses the method according to the terrestrial magnetic activity in that interval for which the K-value shall be estimated and also in its surrounding intervals. First of all, the filter with $T_0 = 5$ h is applied. For each interval a sum of five K-values (SK) is formed, consisting of the interval's K-value and the K-values of the two preceding and the two following intervals. Then, depending on SK, the method of index determination for intervals is chosen. By applying a filter with cut-off period $T_0 = 4$ h for $SK \leq 11$ and $T_0 = 6$ h for $11 < SK < 22$ and the max-min method for $SK \geq 22$, an agreement of 80.3% for 1981 has been reached. The computing time of this combination is twice as much as that of a filter with cut-off period $T_0 = 5$ h.

Discussion and conclusions

The max-min method and numerical filters were applied to digital registrations of Wingst Observatory in order to derive the index K. The use of a filter with a cut-off period of $T_0 = 5$ h provided the best result; namely a 79% agreement with the usual handscaled values for 1981.

It has been shown that for higher activity the non-K-variations and thus the indices can be derived in a better way by filters with longer cut-off periods because K-variations and non-K-variations cannot be distinguished well when using filters with lower cut-off periods. In the case of lower activity, the non-K-variations and the indices can be found in a better way with filters with lower cut-off periods. This is probably due to the influence of higher solar harmonics which are not suppressed by filters with longer cut-off periods; their existence, however, may – in spite of the low amplitudes – lead to incorrectly estimated values in the case of lower activity. The different results which were reached when methods were used for different times of the day and for changing activity implied the use of criter-

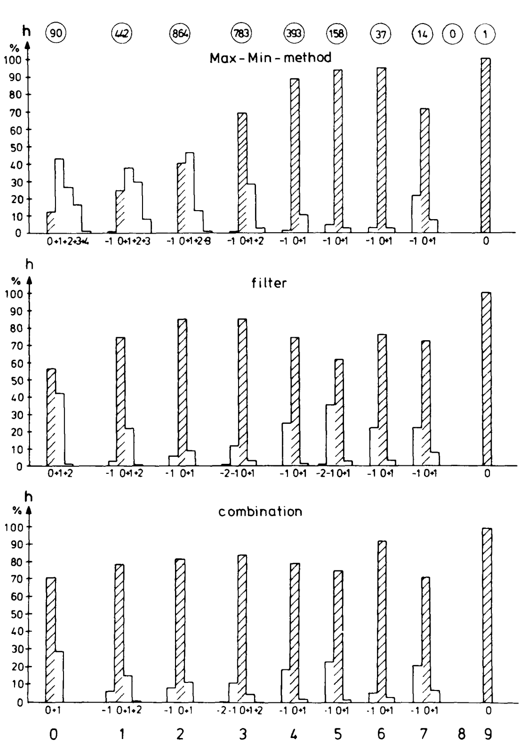

Fig. 7. Results of comparisons between digitally derived indices using the max-min method, the best filter ($T_0 = 5$ h) and one combination (activity) and the handscaled indices for 2782 3-h intervals in 1981

ia considering these influences to choose the most appropriate scaling method. A filter combination which takes the time of day into account had the best result of 81.8% agreement, and a combination which considers the activity reached an 80.3% agreement. Figure 7 shows a comparison between the result of the max-min method, the best result of the filtering procedures and the best result of a filter combination which takes activity into account. Values which are estimated by the max-min method and which are too large compared with handscaled values usually occur in the case of low activity, as there is no elimination *of non-K*-variations. The incorrectly estimated values of the filter with cut-off period $T_0 = 5$ h, however, are too small (exceptions are, naturally, those values estimated for intervals where a handscaled value yields $K = 0$) and are distributed among all ranges of activity, which is a basic requirement for an acceptable method. Compared to that filter, the combination of methods leads to an improvement in scaling, especially in the case of low ($K < 2$) and high ($K > 4$) activity. Besides, the combination can provide a satisfactory estimation of the non-K-variations.

The mere performance of a filtering procedure needs a lot of computing time. The combinations, which take activity into account, need 2 or 3 times as much computing time as a filtering procedure with a cut-off period $T_0 = 5$ h. Therefore, the practical application of those methods might exceed the capacity of small computers. However, as the described filters use every minute value for the derivation of the non-K-variations, a lot of computing time could be saved using every tenth minute value.

The methods introduced in this paper yield reasonable results, except the max-min method. It cannot be said which of them is the best. Firstly, the investigated time series was too short; secondly, the results derived for Wingst Observatory might not be reached when applying the methods to other stations. Therefore, for each station it is recommended to test the methods before using one of them for K-scaling.

Similar results can probably be expected by applying the scaling methods to observatories at middle latitudes which have similar amplitudes of solar and lunar harmonics as Wingst. Because of the increase of activity from the equator to the auroral zones, which is considered by a suitable value classification, respectable results can also be expected when filter methods are used at higher latitudes. In the case of larger amplitudes of the solar harmonics, the results for observatories at lower latitudes, however, will certainly be of poorer quality because of the narrow classification.

References

Alldredge, L.R.: A proposed automatic standard magnetic observatory. J. Geophys. Res. **65**, 3777–3786, 1960

Alldredge, L.R., Saldukas, I.: An automatic standard magnetic observatory. J. Geophys. Res. **69**, 1963–1970, 1964

Bartels, J.: Potsdamer erdmagnetische Kennziffern, 1. Mitteilung. Z. Geophys. **14**, 68–78, 1938

Bartels, J.: The technique of scaling indices K and Q of geomagnetic activity. Annals of the IGY **4**, 215–226, 1957

Gupta, J.C., Chapman, S.: Manual of the coefficients of the first four harmonics of the solar and lunar daily geomagnetic variations computed from IGY/C and certain other data. **98**, National Center Atmospheric Research, Boulder, Colorado, 1968

Loomer, E.I., Jansen Van Beek, G., Niblett, E.R.: Derivation of K-indices using magnetograms constructed from digital data. IAGA News **22**, 87–90, 1984

Mead, G.D.: Deformation of the geomagnetic field by the solar wind. J. Geophys. Res. **69**, 1181–1195, 1964

Rangarajan, G.K., Murty, A.V.S.: Scaling K without subjectivity. IAGA News **19**, 112–118, 1980

Riddick, J.C., Stuart, W.F.: The generation of K-indices from digitally recorded magnetic data. In: Geomagnetic observatory and survey practice, W.F. Stuart, ed.: pp. 439–456. Dordrecht, Boston 1984

Schmucker, U.: Auswerteverfahren Göttingen. Protokoll Kolloquium "Elektromagnetische Tiefenforschung", Neustadt/Weinstraße, 163–188, 1978

Schulz, G.: Experience with a digitally recording magnetometer system at Wingst Geomagnetic Observatory. Dt. Hydrogr. Z. **36**, 173–190, 1983

Siebert, M.: Maßzahlen der erdmagnetischen Aktivität. In Handb. der Phys., Bd. 49/3, S. Flügge, ed. Berlin-Heidelberg-New York: Springer-Verlag 1971

Received July 9, 1987; revised October 22, 1987
Accepted October 22, 1987