On the Computer Generation of Geomagnetic *K*-Indices from Digital Data

P. A. HOPGOOD

*Bureau of Mineral Resources, Geology and Geophysics, G.P.O. Box 378, Canberra, A.C.T., 2601,
Australia*

(Received October 22, 1985; Revised May 28, 1986)

Since the advent of digitally recording magnetic variometers and the ready accessibility of computers, there has been a search for a technique to produce *K*-indices of geomagnetic activity by machine.

The principal difficulty in the determination of *K*-indices is the estimation of the regular solar diurnal variation (*SR*) for each day, which is used as a reference from which the *K*-Variations are scaled. A number of methods for the machine estimation of the daily *SR* are reviewed. These fall into two categories: (i) by use of neighbouring quiet days, or (ii) filtering out the high frequency harmonics. Of the techniques proposed to date, those which are data adaptive are considered preferable.

A data adaptive method which divides a magnetogram trace into high and low frequency harmonics is presented. It is found that there is no particular frequency below which can be considered all the *SR* variations and above which are all the *K*-variations.

The latitude dependence of the tolerance to differences between estimation of the *SR* by machine and that manually is also discussed.

1. Introduction

The *K*-index to classify the range of geomagnetic activity was proposed in 1939 by BARTELS *et al.* and was soon adopted internationally to become the most widely used of all geomagnetic indices. The index is derived from the largest range over each 3-hour U.T. interval, of the variations in *H* and *D* after removal of the regular variations. According to MAYAUD (1967): "the purpose of the *K*-index is to measure ... the effects of the solar corpuscular radiation on the terrestrial magnetic field, as distinct from the effects of the wave radiation and post-perturbation". Although the *K*-index is now recognized as poorly suited for this purpose, it still serves as a convenient indicator of geomagnetic activity.

The principal difficulty in the determination of *K*-indices is identification of the non-*K* variations, in particular the regular solar diurnal variation or *SR*, and much has been written on the subject e.g. BARTELS (1957), MAYAUD (1967), MAYAUD (1980). Many claims have been made that the manual scaling of *K*-indices introduces a component of subjectivity and that there is much to be said in favour of producing a *K*-index or a quasi-*K*-index by computer using an agreed upon algorithm. Since the

introduction and proliferation of digitally recording magnetic variometers and the ready accessibility of fast digital computers to most geomagnetic observatories, the trend towards machine produced indices has grown.

There are two schools of thought on the viability of scaling a geomagnetic '*K*-index' by computer. (The term in apostrophes is used to denote a machine produced index). The traditional view insists that the *K*-index, by definition, is scaled by hand by an experienced observer, thereby virtually eliminating subjectivity and resulting in as little as 5% variability between experienced observers (MENVIELLE, 1981). Although MAYAUD (1980) conceded that scaling *K*-indices by computer may eventually become possible, MENVIELLE (1981) states that any such attempt must follow the very same rules applied in hand scaling (to avoid a discontinuity in the *K*-index series).

The difficulty in producing machine '*K*-indices', as with the hand-scaling method, is the separation of the *K*-variations from the *SR*-variations. When hand-scaling is performed by an experienced observer, he draws upon his knowledge of the form of the quiet variations as well as the day to day and seasonal variability which can occur therein, at a station where he has had many years of experience. For a machine to yield an identical result it must apply the same rules to identify the *SR* as would the observer. The problem then is how to program into a machine the equivalent of the observer's experience!

Those who favour machine scaled '*K*-indices' would argue on the grounds of time savings, the elimination of the need for an experienced observer and the consistency and objectivity of such methods. Although conceding that machine methods to date have not followed the very same rules as for hand-scaling, it has been argued that this in itself is unimportant since the resulting consistency with hand-scaling is on a par with the consistency between two observers performing hand-scaling. Some would further argue that the machine produced '*K*-indices' be given another name to distinguish them from their hand-scaled predecessor. LUNDBACK (1984) has gone so far as to propose an alternative to the *K*-index called *aK*, which, although conforming to the *K*-index to some extent, does not attempt to remove the *SR* variation at all. Such a notion is abhorred by the traditionalists, drawing the response: "is science made for computers or computers for science?" (MAYAUD, 1980). But the notion is not without its merits. As well as eliminating the requirement of having to identify the *SR* variations exactly (it is debatable whether this can be achieved by any means) a definition could be proposed which is not only simple to perform and therefore easy to standardize, but the resulting index could be made to have a precise meaning, unlike the *K*-index which is a rather nebulous parameter in physical terms, (see MAYAUD, 1980).

2. Techniques for Computer Scaling

Over the past 25 years there have been a number of techniques suggested for the machine production of '*K*-indices'. In 1960 ALLDREDGE put forward the method of applying a running mean to estimate the *SR* variations, which was then subtracted

from the original data to leave the '*K*-variations'. MAYAUD (1980) raised the possibility of this method eliminating, at least to some extent, some of the longer period *K*-variations.

Another technique of approximating the *SR* variations was suggested by VAN WIJK and NAGTEGAAL (1977), involving the selection of 7 nearby quiet days which were smoothed by eliminating all harmonics with periods less than 6 hours and comparing each in turn with the day to be scaled. The smoothed quiet day which most closely matched, was deemed to be the *SR* for the day, and the '*K*-indices' scaled from that reference. The difficulty with this method as pointed out by MAYAUD (1980) is the limited number of quiet days from which the appropriate *SR* is selected. The probability of having an entirely appropriate *SR* in the nearby quiet days is small. This may be contrasted with the knowledge of the experienced observer who has an appreciation of the day to day variability and limits of the *SR* variations.

RANGARAJAN and MURTY (1980) described a method of scaling *K*-indices claimed to eliminate all subjectivity which is inherent in hand-scaling. Their technique used the 'Method of Orthogonal Natural Components' to identify the mean diurnal variations from a set of selected quiet days in a month. From an harmonic analysis of this mean diurnal variation the first six harmonics were used to synthesize the average *Sq*, the deviations from which were regarded as *K*-variations and scaled accordingly. This method was criticised by MENVIELLE (1981) who noted that subjectivity existed in the choice of quiet days and condemned the method as a failure. He further stated the method was not consistent with the definition of the *K*-index, having reverted to "iron-curve" method as coined by BARTELS (1957).

A comparison of various techniques for deriving "quasi-*K*-indices" by computer by RIDDICK and STUART (1984) concluded that it does not seem possible to derive an algorithm to accommodate the *Sq* variations at all latitudes. A comparison was made between hand scaled and machine generated *K*-indices from both analogue La Cour magnetographs and digitally produced magnetograms. Various automatic methods were used including: a simple min-max technique where no attempt is made to remove the diurnal variations; approximation of the diurnal variation by a straight line; and estimation of the diurnal variation from a selection of quiet days during the month by taking either their mean or the first 4 harmonics of the mean. The extent of agreement between hand-scaled analogue magnetograms and hand-scaled digital magnetograms was found to be 80%–90%. This would serve to demonstrate that care must be taken when dealing at all with discrete digital data, as pointed out by LOOMER *et al.* (1984). However these authors concluded that, at least for Ottawa, digital data recorded at 30 seconds or shorter intervals are adequate for the derivation of *K*-indices by hand.

Of the methods of producing *K*-indices by computer investigated by RIDDICK and STUART (1984), the method of harmonically synthesizing the diurnal variations from quiet days was only marginally better than the direct min-max method, when compared to hand scaling the same record. All their methods yielded an agreement around 75% compared to hand scaling.

3. Discussion of Methods

The methods of estimating the *SR* which have been proposed to date (with the exception of approximating it with a least-squares straight line) fall into two categories:

- 1) Use of a selection of neighbouring quiet days to give a mean *SR*;
 - 2) Filtering out the high frequency variations (4–6 hour periods);
- Or a combination of both methods.

Although the various methods proposed for machine scaling are all only moderately successful, achieving about the same degree of agreement with hand-scaling of the same magnetogram traces of 70%–80%, the methods utilizing neighbouring quiet days seem, in principle, the less satisfactory; bringing with them vestiges of the “iron curve” method. Nor can these methods take into account the full range of variability that the form of the *SR* may take. Furthermore, the element of subjectivity which ideally should be eliminated by machine scaling, is introduced via the selection of quiet days for use in the analysis.

On the other hand, the technique of filtering the data on the particular day to be scaled and retaining the first 4–6 harmonics to estimate the *SR*, while not ‘gaining experience’ from nearby quiet days, is not misled by them either. Neither is there any element of subjectivity in the method. With the filtering or harmonic analysis method, it does not matter what form the *SR* variations may take, nor whether they are anomalous, nor whether nearby quiet days have a similar form (or even if there are any nearby quiet days!). The method does implicitly assume that the frequency spectra of the *SR* and *K*-variations do not overlap. Methods which do not rely on a limited selection of nearby quiet days with which to estimate the *SR*, seem to have more potential to eliminate subjectivity in machine scaling.

The importance of the precision to which the *SR* must be identified is inversely proportional to magnetic activity (MAYAUD, 1980). If a machine method is to work well, on a very quiet day it must be able to identify virtually all the variations as *SR*. To this end any proposed algorithm for the machine production of *K*-indices must obey the (hand-scaling) rules at least as well as an experienced observer scaling by hand, and therefore estimate the *SR* from only the data of the day being scaled.

4. Application of an Harmonic Analysis Method

In view of the considered superior features of data adaptive computer scaling techniques described in the previous section, an harmonic analysis method has been applied to both magnetically quiet and disturbed conditions at the new digital magnetic observatory at Charters Towers, Australia (CTA): geographic co-ordinates 20° 05'.3 S, 146° 15'.2 E. The procedure to produce ‘*K*-indices’ for a day was to:

- 1) Make the data up to 2048 values by adding 304 values to the beginning and end of the day’s data (1440 minutes) from the previous and next days’ data respectively.

- 2) Fill any gaps in the data by interpolation using a cubic polynomial.
- 3) Detrend the data by removal of the least-squares straight line of best fit and taper the data by the application of a split cosine bell affecting 15% of the data at each end.
- 4) Apply a radix-2 FFT algorithm to the data, set to zero those harmonics with periods greater than the desired cut-off (of the order of 300 minutes), and then perform an inverse FFT.
- 5) The resulting high passed data are divided into 3-hour U.T. intervals and the range of the variations within each interval compared with the appropriate quasi-logarithmic scale and an index allotted.
- 6) The ' K -index' is the larger of the individual H and D indices.

Figure 1 shows the power spectra of the H and D components on a magnetically quiet day. Clearly there is little power in any harmonic with period less than 293 minutes in either spectrum. This period may thus serve as convenient cut-off, above and including which may be defined as the SR variation spectrum. Figure 2 shows the magnetogram of the same day decomposed into ' SR ' and ' K ' variations using the above criterion. Of course the estimated SR very closely approaches the total variations although the fit is not as close in some places as perhaps an 'experienced observer' would choose.

The spectra of a disturbed day are shown in Fig. 3. Inspection of the magnetogram filtered at 293 minutes (Fig. 4) clearly indicates that the SR estimated no longer resembles the SR on a quiet day nor that which would be estimated by an 'experienced' observer. Removal of the long period harmonics clearly distorts the K -variations and so leads to incorrect ' K -indices'.

The method has also been applied to a wide selection of days using values of the cut-off period ranging from 180 minutes to 400 minutes. The results were similar to those cited above.

Clearly it is not satisfactory to simply apply a sharp filter to a magnetogram trace and to expect all the SR to be contained in harmonics with periods longer than some cut-off value and all the K -variations to be contained in the shorter period harmonics which remain. The foregoing examples are sufficient to demonstrate that the SR and K -variations may have overlapping spectra. It is therefore obvious that the method described is too simplistic to be applied to any magnetogram and expect to derive ' K -indices' which always agree with true, hand-scaled K -indices.

Being at a low latitude, the lower limit for a K -index of 9 at Charters Towers is low. Indeed, at 300 nT no station has one lower. It follows that at this station any discrepancy between a machine identification of the SR and that determined manually will result in the greatest possible discrepancy between respective K -indices. At the U.K. stations which RIDDICK and STUART (1984) used to test their algorithms, the K_9 low limits range between 500–1000 nT, giving a tolerance of around 2–3 times that at Charters Towers. Inspection of the mean quiet day horizontal intensity magnetogram traces presented for the U.K. stations show that no 3-hour K -index scaling interval has a range of more than about 40 nT which is similar for the quiet behaviour at Charters Towers. It follows that the ratio of the range of the SR in any 3

Fig. 1. Power spectra for *H* and *D* on a magnetically quiet day, 09 March 1985 at Charters Towers.

hour interval to the *K*9 low limit is relatively small for the U.K. stations. It is therefore not surprising that at the U.K. stations the simple maximum-minimum method taking no account of the *SR* yielded results only marginally worse than the harmonic method.

5. Discussion

The limitation in even the manual scaling of *K*-indices is the impossibility of identification of the *SR* at all times, especially during magnetically disturbed periods. Although the larger *K*-indices are more tolerant of improper *SR* identification, when

Fig. 2. Magnetogram for *H* and *D* on 09 March 1985 shown both raw and filtered at 293 minutes.

the rule “interpretation ... should always be the simplest and least speculative” (MAYAUD, 1976) is applied, i.e. no interpretation at all in which case the *SR* is implicitly assumed to be zero, the resulting *K*-indices will frequently be erroneous. This limitation was noted by Mayaud, who recognised that the *SR* must be present every day even though it could not always be identified.

That the *SR* is present every day regardless of magnetic disturbance has recently been highlighted by HIBBERD (1981). By choosing pairs of stations having similar longitudes but on opposite sides of the latitude of the path of the *Sq* focus, Hibberd was able to identify a composite *Sq* variation, which was found to be more regular and uniform than the *H* variations at either station. The analyses of Hibberd gives some justification once again to the “iron curve” method of gaining *K*-indices. Without

CHARTERS TOWERS

13 July 1984

Fig. 3. Power spectra for *H* and *D* on a magnetically active day, 13 July 1985 at Charters Towers.

condoning the technique for all days, it is suggested that it may be useful on days when the *SR* cannot be estimated in any other way!

In view of the problems encountered with the manual identification of the *SR* it is not surprising that hitherto it has not been achieved by machine methods.

Consider the harmonic method described in Section 4 when applied to magnetically quiet conditions. Although the form of the magnetogram trace can almost entirely be represented by the long period harmonics as seen in Fig. 1, the existence of virtually flat regions on the magnetogram traces during the night and the sharp variations, particularly in declination, during the day-time, necessitate the inclusion of shorter period harmonics to faithfully represent the *SR*. Almost

Fig. 4. Magnetogram for *H* and *D* on 13 July 1985 shown both raw and filtered at 293 minutes.

invariably the result is over-estimation of most of the resulting '*K*-indices' throughout the day.

This is in contrast to the success achieved by the similar technique applied to the U.K. data by RIDDICK and STUART (1984). As well as being more tolerant to errors in the identification of the *SR*, as shown earlier, the form of the *SR* at the U.K. stations was shown to be quite smoothly varying and so more faithfully represented by long period harmonics alone, in contrast to the *SR* form at Charters Towers.

Under magnetically disturbed conditions it is clear from Fig. 4. That *K*-variations can have long period components which overlap with the dominant harmonics in the spectrum of the *SR* under quiet conditions.

6. Conclusion

For a computer derivation of K -indices to work, without re-definition of the K -index, we must return more closely to the rules (MAYAUD, 1967) applied when manual scaling is performed by the 'experienced observer'. The question to be addressed is: how can a computer be given "experience" so as to identify the SR like the human eye? Although the filtering method goes some way towards this by recognising certain periods, there is not enough experience built in. No attention is given to amplitude or phase of the periods selected as the SR and so it is possible to come up with estimations of the SR which would never be obtained by hand scaling.

It is seen that the simple harmonic analysis method is inadequate to identify the SR sufficiently well during both magnetically quiet and disturbed conditions at Charters Towers. This is in contrast to the results of other workers at higher latitudes. This is sufficient to indicate the method is in general not suitable to use in the machine production of K -indices.

On the basis that even the traditional rules for the manual scaling of K -indices do not always adequately identify the SR , the production of a sophisticated algorithm to imitate these rules may not be well justified. We may well be better served by a quasi- K -index or an index which does not require the identification of the SR . It would seem the present time is appropriate for the introduction of such a machine produced index. This might be based on the range or variance, possibly of only certain spectral components or harmonics, within the same 3-hour intervals as the K -indices. Any new index should be simple to produce and ideally have a clear physical meaning. Harmonic analysis techniques achieve these goals as well as eliminating subjectivity.

This paper is published with the permission of the Director, Bureau of Mineral Resources, Geology & Geophysics, Canberra.

REFERENCES

- ALLDREDGE, L. R., A proposed automatic standard magnetic observatory, *J. Geophys. Res.*, **65**, 3777–3786, 1960.
- BARTELS, J., The technique of scaling indices K and Q of geomagnetic activity, *Ann. Int. Geophys. Year*, **4**, 215–226, 1957.
- BARTELS, J., N. H. HECK, and H. F. JOHNSTON, The three-hour-range index measuring geomagnetic activity, *Terr. Magn. Atmos. Elec.*, **44**, 411–454, 1939.
- HIBBERD, F. H., Day-to-day variability of the Sq geomagnetic field variation, *Aust. J. Phys.*, **34**, 81–89, 1981.
- LOOMER, E. I., G. JANSEN VAN BEEK, and E. R. NIBLETT, Derivation of K -indices using magnetograms constructed from digital data, *IGA News*, No. **22**, 87–90, IUGG, 1984.
- LUNDBACK, Asger, About digital alternative to the Kp index, *Geophysical Surveys*, **6**, 425–430, 1984.
- MAYAUD, P. N., Atlas of K -indices, *IGA Bull.*, No. **21**, 113 pp., IUGG Publication Office, Paris, 1967.
- MAYAUD, P. N., Derivation, meaning and use of geomagnetic indices, *Geophysical Monograph* **22**, 154 pp., AGU, Washington DC, 1980.
- MENVIELLE, M., About the scalings of K -indices, *IGA News*, No. **20**, 110–111, IUGG, 1981.

- RANGARAJAN, G. K. and A. V. S. MURTY, Scaling *K*-indices without subjectivity, *LAGA News*, No. **19**, 112–118, IUGG, 1980.
- RIDDICK, J. C. and W. F. STUART, Computer generated quasi *K*-indices, *LAGA News*, No. **22**, 91–97, IUGG, 1984.
- VAN WIJK, A. M. and T. NAGTEGAAL, *K* measurements by computer, *J. Atmos. Terr. Phys.*, **39**, 1447–1450, 1977.