Derivation, Meaning, and Use of Geomagnetic Indices

P. N. Mayaud

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P. N. MAYAUD

American Geophysical Union
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To the Observers,
without the careful and continuous work of whom
geomagnetic indices could not be derived

Acknowledgements

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22 **Derivation, Meaning, and Use of Geomagnetic Indices,** P. N. Mayaud

Contents

Foreword

Indices have evolved in fields where there are massive data ensembles to be digested and interrelated. Usually, an index will be formed from one specific variable that tends to characterize the whole. Thus we have indices such as the Gross National Product, the Consumer Price Index, sunspot numbers, and birth and death rates. Geomagnetic indices have enjoyed a long history that dates back to the days when observers would watch through a magnifying glass the oscillatory motions of the end of a long compass needle. Geomagnetic indices have been particularly successful because they can characterize the state of affairs of the entire magnetosphere as well as that of the surrounding interplanetary medium. Furthermore, of all the relevant parameters that might be used to form an index, geomagnetic variations have one of the longest histories, and they are supported by one of the oldest and best-established worldwide networks of observatories.

The gathering of data with which to form a geomagnetic index is relatively inexpensive. The data are available year after year on a global basis from instruments whose absolute calibration can be verified frequently. Their long history, reliability, and relatively low cost make geomagnetic indices (along with sunspot numbers) virtually the only indices with a long data base that indicate something of the state of the magnetosphere and interplanetary medium.

Optical and corpuscular radiation from the sun interacts with the earth's ionosphere and magnetic field to produce or to influence a bewildering array of phenomena. Examples that might be mentioned are auroral displays, ionospheric changes, ULF emissions, ring currents, and changes in spatial distributions and physical properties of plasmas surrounding the earth. These various phenomena usually vary in concert with one another in a way that indicates a complex interrelationship. Geomagnetic indices are often used to study these interrelationships and to determine causal sequences. Furthermore, when a solar/interplanetary-medium/geomagnetic effect is sought, it is often a geomagnetic index that is used to test for a correlation with the suspected but apparently unrelated phenomenon. Thus we see in the scientific literature correlations reported between some geomagnetic indices and weather, crime, health, morbidity, and even seismic activity.

Although geomagnetic data are readily available from a global network, their formulation into a geomagnetic index is not an easy task. Dozens of indices have been suggested, and some of these have found widespread distribution and use. The indices have evolved so that some of the less popular indices are no longer in use, while new ones have been developed to take their place. Without the dedicated effort of scientists such as Dr. Mayaud, we would not have available to us the reliable geomagnetic indices that we so often take for granted.

While I served as an Editor of *Reviews of Geophysics and Space Physics*, I urged Dr. Mayaud to write a review paper on geomagnetic indices. I am pleased that the present volume is the result. It presents more than I had in mind, but as one looks through this book it becomes obvious that a complete review of geomagnetic indices is beyond the scope of a standard review paper. Also, this book will surely be recognized in the years to come as a classic. It is the capstone on the career of one who has contributed much to the development of the modern geomagnetic indices that are in wide use today. Scientists in diverse fields of research will find that this monograph contains all that they need to know about any of the geomagnetic indices that may interest them.

ALEXANDER J. DESSLER

1. Introduction

Within the frame of the International Association of Geomagnetism and Aeronomy (IAGA) or of its predecessors (Commission, Section, or Association of Terrestrial Magnetism and Electricity (IATME); see *Harradon* [1939, pp. 682–683], for the historical background), geomagneticians are entrusted with a particular and difficult task: to derive geomagnetic indices for the whole scientific community investigating geophysical phenomena in the earth's environment. The cause of this apparently privileged responsibility is not the fact that geomagneticians succeeded before others in obtaining continuous records but the fact that geomagnetic variations have two special features, as is stated by *Rostoker* [1972*b*]: 'they are unaffected by meteorological conditions, and are observable at great distances from the source current system in the upper atmosphere and magnetosphere.' Furthermore, geomagnetic indices are not only a reference for other geophysical disciplines, but they are of importance for solar terrestrial relationships. Although new techniques have improved the continuous monitoring of the sun in the last decades (for instance records of the solar flux emission by radioastronomy techniques, indirect observations of the X and extreme UV emission in the ionosphere), some of the transient geomagnetic variations are caused by other solar emissions which cannot be observed from earth's surface.

Geomagnetic indices have been reviewed by various authors [*Chapman and Bartels,* 1940, chap. 11; *Chernosky,* 1960; *Lincoln,* 1967; *Siebert,* 1971; *Rostoker,* 1972*b*]. Recently, *Lincoln* [1977*a*] compiled a useful list of geomagnetic and other indices. In this work we first try to answer the question, what is a geomagnetic index? Then, we make a historical review of the main indices used in the past, and we describe the three classes of indices officially recognized by IAGA at present: range indices (K, R, Q), planetary indices derived from them (Kp, am, aa), and AE and Dst indices. We also review the important problem of the international classification of days. When setting forth the meaning and the use of these indices or of the classification of days, we take the risk of critically evaluating them. This represents our own understanding and is proposed as being an eventual stimulation for further discussions.

We aim neither at reviewing all the properties of the geomagnetic variations as they can be deduced from the indices nor at relating their behavior to the theoretical mechanisms presently proposed. The domain of interest we plan to cover is much narrower. It consists of helping workers to use the geomagnetic indices; this requires that they have an understanding of their meaning and of the way in which they are derived. But one cannot understand the meaning of an index without knowing something about the geomagnetic variations that it monitors, and one cannot use it as a reference without knowing something about the statistical modulations it undergoes (for instance, daily, annual, or other modulations). Concerning the first point, we assume that the reader has already some knowledge of the geomagnetic variations. If not, he can refer to the review of *Nagata and Fukushima* [1971] on the morphology of magnetic disturbances or to the reviews of *Rostoker* [1972*a*] or *Fukushima and Kamide* [1973] restricted to particular geomagnetic variations. However, if the reader is not familiar with the theoretical developments contained in these works, he can look at a recent paper by *Mayaud* [1978*a*] (see also Appendix A) in which the author took a more limited scope and tried only to answer the following questions: how to recognize the various types of variations occurring in the records and how each type varies with latitude or with time. Concerning the second point, we shall systematically describe the main statistical modulations to which the indices are submitted, as far as they are presently known, and we shall do that only to the extent to which workers need to know them when using the indices. We shall mention theoretical mechanisms as little as possible. We shall not enter the very wide domain of the relationships of the geomagnetic variations with the phenomena of the interplanetary medium. The review of *Siebert* [1971] is probably the last and the most comprehensive one on this topic, while the problem of the indices is set forth more briefly in his work. *Svalgaard* [1975*c*] sets forth a unified overview of present knowledge for the geomagnetic response to the dynamic solar wind. Recent analyses of *Svalgaard* [1978], *Maezawa* [1978], and *Berthelier* [1979] on the relationship between indices and parameters of the interplanetary medium would be a source for other references on this topic.

We shall refer very often to the *IATME* or *IAGA Bulletins,* which are available from the International Union of Geodesy and Geophysics (IUGG) Publication Office. Some of these bulletins contain the transactions of the meetings of the international association, and others are concerned with particular topics of interest for the association. Each bulletin is identified by a number. Two series of these bulletins, numbered *12* and *32* followed by a letter, are entitled 'Geomagnetic Indices' and from issue *121* 'Geomagnetic Data.' They are to some extent publications similar to the yearbooks of observatories and can be considered as yearly bulletins in which most of the planetary indices officially recognized by IAGA are tabulated. Series number *12* covers the years 1940–1969, and series number *32* begins in 1970; some of these issues also contain appendices dealing with a special study on geomagnetic data. Three supplementary issues, numbered *18, 33,* and *39,* give collected or new geomagnetic data for past years. are deposited in the World Data Center (WDC) on magnetic tape and can be obtained on request in digital form.

In this work we shall use the centered dipole coordinate system and the corrected geomagnetic coördinate system. The former [*Schmidt,* 1918] is obtained by approximating the main field of the earth by a centered dipole (that is, the first term of a spherical harmonic analysis of this field); it is suitable when analyzing the ground effects of remote field sources such as the equatorial ring current variations. A use of the second system [*Hakura,* 1965] becomes necessary when one deals with auroral and polar cap phenomena; it differs from the first by taking the higher-order spherical harmonic terms of the main field into account. Both of them allow for the use of a geomagnetic time as introduced by *Vegard* [1917], that is the angle between the geomagnetic meridian through the station and the one opposite that one through the sun. Appendix B contains the coordinates of the observatories referred to in this work.

2. What Is a Geomagnetic Index?

An index is a very common concept widely used in many domains (for instance, price, or financial, indices exist). Basically, an index aims at giving summarized information in a continuous way concerning a more or less complex phenomenon which varies with time; this means that an index is made up of a set of discrete values, and each of them characterizes the phenomenon under consideration over a certain constant time interval. Let us note that no index must imply too many theoretical assumptions because they may always be submitted to possible modifications. Also an index must not be too sophisticated because it is not a substitute for the original data but aims at being a summary of them.

A given index can be used by two categories of people: (1) those who study the phenomenon itself and (2) those who need it as a reference in studying related phenomena. Obviously, some of the possible errors arising from the use of the geomagnetic indices, as is stated by *Rostoker* [1972*b*], concern only the first category. Thus the time of the onset of substorm activity cannot be identified by the *Kp* index, for which the constant time interval is 3 h. Similarly, an index which aims at being a planetary index should not be sensitive to any small-scale disturbance. For instance, if the index does not vary when a disturbance is observed at a given place, it means that this disturbance is very localized. The main role of an index is certainly to be such a reference for both of the above categories of people (in particular, for selecting time intervals corresponding to a given intensity level of the phenomenon). Another use, however, must not be neglected: if one can be sure that the index series is homogeneous in time and is significantly representative of the phenomenon, it becomes a tool for statistical studies concerning the time variations of the phenomenon or its relationship with other phenomena.

A last and fundamental point will now claim our attention. When reviewing the various geomagnetic indices used in the past, we shall see how it took time to understand that a given index must monitor a single class of geomagnetic variations. One of the great debts that geomagneticians owe to *Bartels* [1940*a*] is that he drew attention so strongly to the fundamental distinction between *W* variations (*W* for wave) and *P* variations (*P* for particles). We set it forth with a slightly different approach.

Variations of the terrestrial magnetic field can be classified into secular variations whose sources are internal and transient variations whose sources are external. The latter, however, induce internal effects which can be sensitive at some places to abnormal conductivity underground and localized layers. Such a fact may not be neglected when deriving indices: one is never sure that a given species of transient variations which one wishes to monitor is not more or less distorted at a given station. On the other hand, we shall see how the computation of the *Dst* index, one of the most significant geomagnetic indices, needs the elimination of the secular variation. The transient variations themselves do not constitute a single phenomenon. This is the origin of one of the main difficulties in deriving geomagnetic indices and is related to the feature mentioned in the introduction: geomagnetic variations, as they are observed at ground, are sensitive to any remote source of field. Now, the fundamental starting point of a classification of the transient variations is that some are due to permanent sources of field which cause the regular occurrence, every day, of a certain variation during certain local time hours at a given point of the earth. The others correspond to sources which do not permanently exist, and, hence, their occurrence is basically 'irregular.' They can be present, and they fluctuate more or less rapidly; they can be apparently completely absent, and one says that the geomagnetic field appears to be 'free of disturbance' [*Chapman and Bartels,* 1940, p. 194]. This last feature was recognized early when frequent eye observations, then continuous records, became available during the last century, and the workers began to use the terms calm or quiet and active or disturbed (in French, *'calme'* or *'tranquille'* and *'actif'* or *'troublé'*) for qualifying the periods during which such irregular variations are absent or present, respectively. Also the expression 'geomagnetic activity' began to cover all of the irregular transient variations. However, this does not mean that when the geomagnetic field is disturbed, the regular variations disappear. In other words, they are in no way a specific property of the quiet periods. The permanently existing sources of field which drive them do continue to cause their effects when irregular variations occur. Indeed, the present state of knowledge indicates that such sources are due to tidal movements within the daytime ionosphere in the presence of the permanent magnetic field of the earth. They induce vortices of electric currents whose positions are relatively stable with respect to the sun while the intensity of their currents varies little; hence you have the regular occurrence, every day, of a certain variation during certain local time hours, which *Mayaud* [1965*c*] proposed to call the regular daily magnetic variation S_R. Such a symbol is probably more suitable than the symbol S_q, which would tend to indicate that this phenomenon is a property of the quiet days only. We believe that this classification between the regular and irregular variations (see its limitations in *Mayaud* [1978*a*]) is better justified than the one proposed by *Bartels* [1940*a*]. Indeed, irregular variations such as the solar flare effects (sfe), which are disturbances of the geomagnetic field, are due to a component of the solar *W* radiation, while a part of the regular variations (the component which originates within the polar caps) cannot be attributed to the single *W* radiation, since it is still present during the polar night [*Mayaud,* 1965*c*]. But as was first recognized and emphasized by *Bartels* [1940*a*], any reliable geomagnetic index must be based on a choice by which one or the other of the species of transient variations is monitored. We shall see in the following chapters how difficult a proper discrimination between them is.

Furthermore, if one chooses to monitor the irregular variations, one has again to make some choice among the different phenomena which make up the magnetic activity. The wide domain of the pulsations will be neglected in the body of this work but will be mentioned in section 9.1 because valuable indices could be derived from the pulsations in order to monitor certain features of the magnetosphere. Concerning the other irregular variations, we note that the morphological classification proposed by *Mayaud* [1978*a*] is taken as a starting point. Two main classes are considered: the worldwide disturbances and the nonworldwide disturbances. In the first class, some variations have a zonal component (equatorial ring current effects, storm sudden commencements, sudden impulses, and fluctuations), and others have no zonal component (auroral variations and DP 2 variations). The second class includes the polar cap variations, the auroral PC 5 pulsations, and the solar flare effects (see also Appendix A). Let us note that special events such as the storm sudden commencements and solar flare effects are listed on an international basis in the yearly *IAGA Bulletins 32* (see the *IAGA Bulletin, 32g,* 1976, p. X, for the new method adopted for the final identification of the storm sudden commencements). Concerning the irregular variations, one may say that the most important phenomena are the auroral disturbances, the ring current effects, and the polar cap variations.

Any geomagnetic index should correspond, as much as possible, to a single and well-defined phenomenon and should be derived in such a manner that the data used (a given quantitative parameter, with a given sampling rate, observed at a given station or at several stations) be consistent with this phenomenon. Obviously, a series of problems arise. Is it possible to discriminate the phenomenon under consideration from the others in the records? Can one identify its zero level? And what is the suitable sampling rate in order to monitor properly its time variation? If the phenomenon varies with longitude and latitude, how does one select the network of stations in order to obtain a reliable result? What are the phenomena which are worth being monitored in themselves? Is it justified to answer a need for a characterization of all the disturbances as a whole? In the course of this work we shall see that the answers to these questions are not easy.

A last point is important. In order to solve some of the difficulties encountered, one can be tempted to use some standardization processes which are derived from statistical studies based on limited samples. We believe that a given index is all the more reliable as it is free of such intermediate inferences.

3. A Historical Review of Past Indices

In this review we mention not only the indices elaborated from data collected in several stations (or so-called 'planetary' indices) but also some which are derived from only one station. The latter will show how one has achieved little by litttle the building of the present indices. For this reason we describe them in chronological order.

3.1. Daily Range at a Given Observatory

The daily range, that is the difference between the highest and the lowest value recorded in a single element at a given station, constitutes probably the most immediate method of measuring the geomagnetic acitivity. It was also the first to be used for that purpose. Data for H and D were first published in the 1885 yearbook of the Greenwich Observatory. Other observatories included, with time, similar data in their yearbooks, and such a practice became the object of a recommendation in 1939 (*IATME Bulletin, 11,* 1939, p. 552, resolution 10). In 1963 the IAGA decided at its Berkeley meeting that 'the publication of the daily ranges may be discontinued' (*IATME Bulletin, 19,* 1963, p. 359, resolution 3) because of its misleading significance.

Chapman and Bartels [1940, pp. 195–196] indicate obvious reasons why daily ranges cannot be considered as numerical measures of the degree of disturbances. (1) They do not become zero on even the quietest day due to the nondiscrimination between regular and irregular variations. (2) Their statistical time variation is mainly due to that of the regular variations. (3) The range on some days may depend on a single brief variation in the field (any range index scaled over a certain time interval suffers from the same defect) and on the time of day when it occurs. A further point has to be added: the constant time interval, that is, 24 hours, is not suitable. It was chosen in the early days in view of a classification of days, especially for investigating the regular variations which have this period of occurrence. But disturbances, basically irregular in their occurrence and in their duration, are not at all characterized by such a time interval: it is much too long with respect to the morphology of the auroral variations, and it does not fit the duration of the main phase of the storms.

To some extent one can add a supplementary condition which any index of magnetic activity must satisfy: the constant time interval for which each quantitative measure is defined must be shorter in duration than 1 day. Daily, monthly, yearly, ... averages can be significant (with the restriction which we mention later on in section 6.2), but they will be significant only because the quantitative measurement scaled in the records is made over a constant time interval adapted to the morphology of the irregular variations.

3.2. Indices C and Ci (and C9)

The first step in defining a geomagnetic index at an international level was taken during the Innsbrück Conference of the Commission of Terrestrial Magnetism and Atmospheric Electricity in 1905. From this point of view it is of great historical interest (see *Terrestrial Magnetism and Atmospheric Electricity, 15,* 1910, p. 200, resolution 29).

As was recalled by *Chapman and Bartels* [1940,

p. 186], the primary object of the scheme when instituted was to distinguish adequately between the days of a single month, so that a proper choice of the 5 quietest days per month might be made; it should not be forgotten when considering the relatively long lifetime of this index and other uses made of it. Besides, the main idea of the scheme partly remedied some of the defects of the daily ranges: each observer has to assign a certain number to each constant time interval, the Greenwich day, by judging the relative degree of disturbance of the magnetogram. Thus regular and irregular variations could be rightly discriminated (however, see below a restriction to this fundamental point) and a brief and large disturbance would not be overweighted.

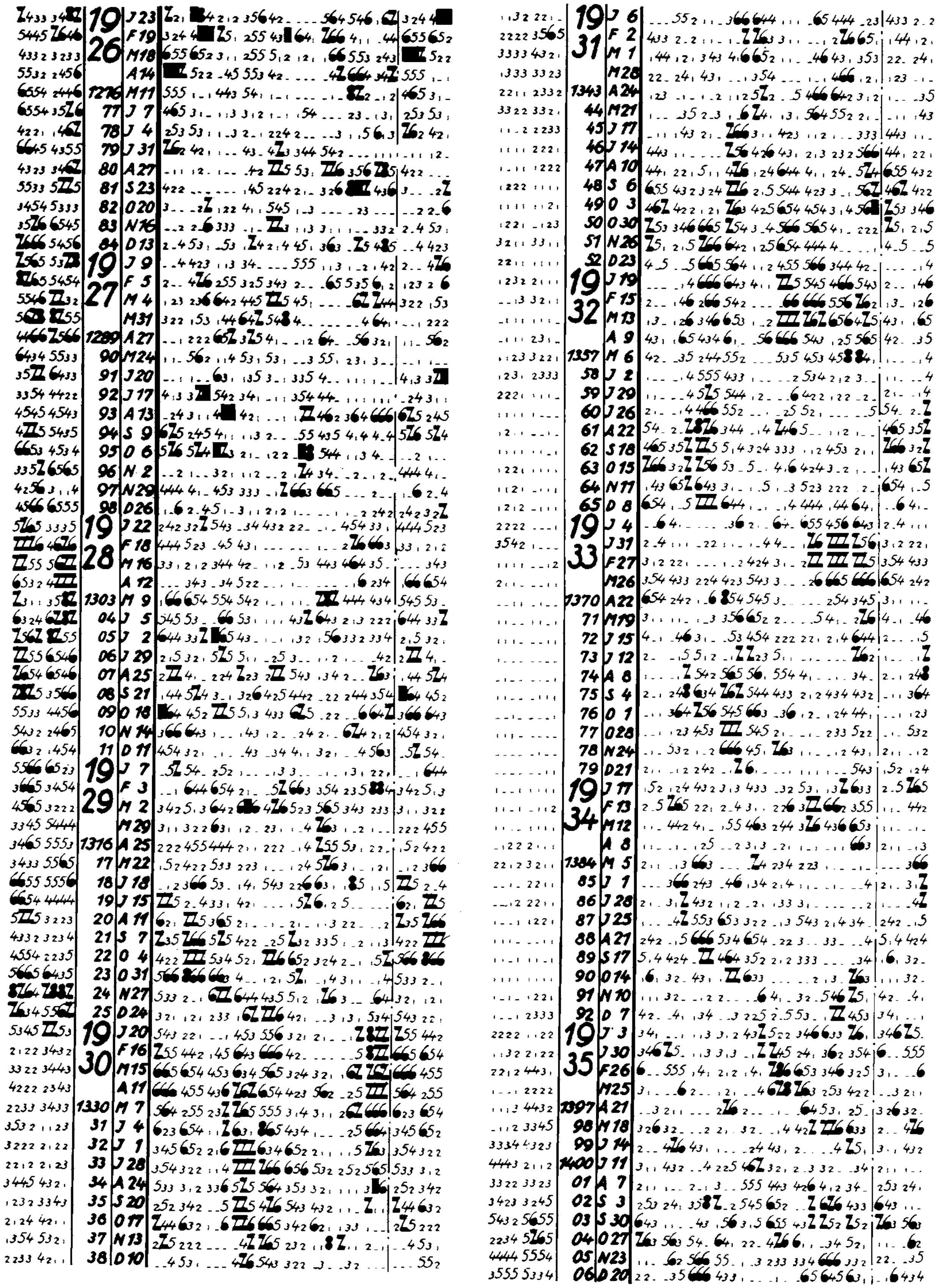
At the time of the definition of the index, several observatories already used this procedure, but the number of degrees of disturbances varied: only 3 at Kew (England), 5 at Potsdam (Germany), and 8 at Saint-Maur-des-Fossés (France). The simplest one and the apparently most crude prevailed and became the character C (the letter C means character here) with possible values equal to 0, 1, and 2 (respectively, quiet, moderately disturbed, and disturbed). It is important to note that the Executive Bureau of the commission refused to give any criteria and particularly any quantitative criteria to the observers for the distinction between the three steps. A complete freedom was left to each institution; the advice of Schmidt, Secretary of the bureau, was predominant on that point [see *Bartels,* 1932, p. 3]. In particular, Schmidt felt that any quantitative criterion could introduce some bias. When reading the introduction to the first *C* bulletins published on behalf of the commission by the Institut Météorologique Royal des Pays-Bas at De Bilt, one sees that his advice was not always followed. Even more, the circular sent to its observatory network by a national agency mentioned that any important change in the amplitude of the daily variation should be considered as a disturbance; obviously, this criterion was a misconception of the day-to-day variability of the regular variations.

The planetary or international magnetic character figure *Ci* was defined as the mean of the figures supplied to the Central Bureau at De Bilt by all the cooperating observatories. These figures provide a more delicate classification of days, since there are 21 classes, corresponding to the numbers 0.0, 0.1, ..., and 2.0. The number of contributing observatories has greatly varied in the course of time; from 15 in 1906 (with 11 European stations) it increased rapidly to about 40 at the end of the first decade of the century, became about 100 at the time of the International Geophysical Year, but decreased later to about 40 (see *IAGA Bulletin, 12t1,* 1968, pp. IV–V) in order to speed up its monthly computation. The series was extended backward to 1890 by van Dijk, then to 1884 by Bartels; a few stations contributed in these early years, but their distribution was truly worldwide. IAGA decided to discontinue the computation of the *Ci* index during its Grenoble Assembly in 1975 (*IAGA Bulletin, 37,* 1975, p. 128, resolution 3), because of the existence of a new series, the *aa* indices, which is truly quantitative and homogeneous and began sooner (1868 onward). We describe it in section 5.3.

Daily values of the *Ci* index can be found in the work of *Bartels* [1940*b*] for 1884–1889, in the work of *van Dijk* [1938] for 1890–1905, in the yearly bulletins of the Institut Royal Météorologique des Pays-Bas for 1906–1939, and in the *IATME-IAGA Bulletins 12* (1940–1969) and *32* (1970–1975).

The *C9* daily indices, with their 10 steps from 0 to 9, were derived by *Bartels* [1951*b*] from the *Ci* indices in order to display, in a simple graphical way, the 27-day solar recurrences in the magnetic activity and their relationship or rather their absence of relationship with the solar activity, as measured by the sunspot numbers. Figure 1 shows an example of that fact. However, from 1932 onward, Bartels used the *Cp* index (see section 5.1.3), derived from the *Kp* index, for the computation of the *C9*. The *C9* were never published in tables; they can easily be derived by anybody from the *Ci* or the *Cp* tables. Let us note the solar rotations used in this figure were introduced by *Bartels* [1934*a*] and adopted by IATME at Brussels (*IATME Bulletin, 14,* 1954, p. 320, resolution 9). They are shorter than the Carrington rotations [see *Chapman and Bartels,* 1940, p. 169] by 0.275 day because they are made up of a whole number of days. They were thus defined by Bartels at a time where only daily indices were available. The rotation, numbered 1001, began on January 17, 1906.

The *Ci* figures were extensively used for about 60 years and fulfilled the goal for which they were conceived, that is, an international classification of days within each month according to their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degree of disturbance (see section 3.3). Examples of fine studies and results obtained from *C* figures can be taken from the works of *Chree* [1915] or *Stagg* [1926], who also determined such indices for a constant time interval of 1 hour. *Bartels* [1932] identified the now classical *M* regions (active regions of the sun) from the 27-day graphs of *Ci* indices. One would find in *Chernosky* [1966] another typical work based on the long series of *Ci* indices.

In spite of the irreplaceable services provided to the scientific community by the *Ci* index, its insufficiency is clear. In this respect, it is noteworthy that from the beginning the transactions of the international meetings contained criticisms of its too qualitative aspects. It has the great merit of fully allowing for the distinction between regular and irregular variations. But one must set forth the following limitations. (1) The practice in assigning the figures 0, 1, and 2 may vary from one month or year to another at the same observatory; in that sense, the *Ci* index cannot be considered to be a quantitative characterization of the magnetic activity. The series suffers basically from inhomogeneities, which sometimes become greater (see, for instance, the controversy between *van Dijk* [1935] or *Howe* [1950] and *Bartels* [1935*a*, 1950] which is set forth again by *Bartels* [1951*a*]). (2) The series suffers also from inhomogeneities because of the varying number of observatories contributing to the project; its planetary aspect is certainly questionable because of the too large number of European stations. (3) As is true with the daily ranges, the constant time interval on which the index is defined is not well adapted to the magnetic activity. (4) In some respects the rigid choice of the Greenwich day for the time interval does not permit workers to classify 24-hour periods corresponding to local days at longitudes different from that of Greenwich. (5) Auroral and subauroral stations contributing to the *Ci* index are chiefly sensitive to auroral variations while low-latitude stations are chiefly sensitive to ring current variations; hence it is difficult to say of which species of variations the index is mainly representative. Since the number of the contributing stations has varied, it is a supplementary source of inhomogeneity from this point of view.

Fig. 1. (opposite) Example of a *C*9 diagram. Years are indicated in large figures, while the other figures refer to the numbers of Bartels' solar rotations (see text). Letters and figures in the next column indicate the month and the date of the first day of each rotation. The 27 *C*9 of each rotation are displayed on the right-hand side and are followed by the first six *C*9 of the subsequent rotation; a hyphen stands for *C*9 = 0, and a solid rectangle for *C*9 = 9. On the left-hand side, sunspot numbers are displayed in a more contracted way for each solar rotation and with a similar scale of 0–9. The year 1930 is remarkable for two sets of 27-day recurrent stormy periods, which occur after the solar maximum; they are outstanding examples of the effects of two *M* regions in the sun. Other such recurrent stormy periods occur in the following years (1931–1933) at a time when the solar activity is very weak. Around the solar maximum, in 1928, sunspots are recurrent, but the geomagnetic activity does not appear to be so. Note also the contrast between rotations 1323–1326 with high sunspot numbers and the following rotations 1327–1331: the correlation with the geomagnetic activity appears to be very poor. Compare also rotations 1302 and 1376 [after *Bartels*, 1951*b*].

3.3. *Classification of Days*

The classification of days is a very important topic: geomagneticians as well as workers from other disciplines make very wide and frequent use of the days internationally classified.

Indeed, the step taken by the International Commission at the Innsbrück Conference in 1905 was extremely fruitful and cannot be overestimated: the classification of 5 international quiet days per month initiated a lot of studies in which workers used them and made direct comparisons of their results because the samples studied were made up of the same days. But soon a difficulty made its appearance. *Chapman and Bartels* [1940, p. 196] are careful of calling them the 5 quietest days of the month, as they were chosen from the beginning by taking the days with the five lowest values of the *Ci* index. It appears, however, that an error of terminology was made in the first yearly bulletin for 1906: the expression 'cinq jours calmes' was used and it becomes later 'five quiet days' in the *IAGA Bulletins 12.* This is highly misleading because some workers, particularly from other disciplines, can infer from such an expression that such days are truly quiet. *Mayaud* [1969] made an investigation of that subject, and some of the conclusions were adopted by IAGA (see section 6.1 in which we describe the present method used for the classification). Figure 2 gives an idea of the very unequal distribution of the truly quiet days during a very low activity period and a high activity one.

The success of the classification of quiet days was such that it was soon extended to the

1902

	JAN.				FEB.				MAR.			
	N	S	M		N	S	M		N	S	M	
1	3	3	2	4QCC	4	5	4	6 CC	3	7	6	4 CC
2	2	5	4	3 CC	4	4	5	3 CC	3	3	4	3 CC
3	7	13	12	8 CC	4	7	4	7 CC	2	2	2	2 CC
4	4	8	4	7 CC	4	6	6	3 CC	2	2	2	2QCC
5	3	4	4	3 CC	5	6	5	6 CC	4	3	2	4 CC
6	5	4	4	5 CC	3	7	4	6 CC	5	7	4	9 CC
7	4	5	5	5 CC	19	27	11	35	3	4	4	3 CC
8	4	6	4	5 CC	19	16	16	20	10	10	11	10 CC
9	4	6	5	5 CC	9	10	9	11 CK	2	4	4	3 CC
10	6	3	6	3 CC	7	8	7	7 CC	2	3	3	2 CC
11	2	4	4	2 CC	7	5	4	8 CC	15	10	3	22 KK
12	2	2	2	2QCC	8	11	11	8 CC	15	10	18	7 KK
13	2	5	4	3 CC	7	6	6	7 CC	6	7	6	6 CC
14	4	4	4	4QCC	4	8	8	4 CC	2	2	2	2QCC
15	21	17	3	35	3	5	5	3QCC	5	6	6	5 CC
16	35	17	39	13	7	12	8	11 CC	2	5	4	4 CC
17	11	12	17	6 KK	3	4	4	3 CC	6	7	4	10 CC
18	6	7	6	7 CC	3	3	3	4QCC	2	3	4	2 CC
19	3	4	4	3 CC	4	2	2	4QCC	3	3	2	4QCC
20	2	6	3	5 CC	13	14	6	22 KK	4	4	4	4QCC
21	2	3	2	3QCC	11	14	14	11 KK	4	6	4	6 CC
22	3	5	4	3QCC	4	3	3	4 CK	3	5	5	3 CC
23	3	2	3	2 CC	4	3	4	3 CC	6	4	3	7 CK
24	12	14	6	21 KK	6	7	2	11 KK	31	29	25	34
25	4	6	7	3 CK	28	20	24	24	26	17	28	16
26	7	12	11	9 CC	8	8	9	7 CK	4	9	9	4 CC
27	5	5	4	7 CC	5	2	5	2QCC	2	3	4	2 CC
28	4	3	2	5 CC	3	3	3	3QCC	3	3	3	4QCC
29	4	7	6	5 CC					3	3	2	4 CC
30	6	5	5	6 CC					3	3	3	3 CC
31	3	3	4	3 CC					4	3	2	5 CC
	5.8	6.5	6.1		7.2	8.0	7.6		6.0	6.1	5.9	

	APR.				MAY				JUNE			
	N	S	M		N	S	M		N	S	M	
1	7	10	10	8 CC	4	4	2	6 CC	12	7	13	7 CC
2	3	4	3	4 CC	3	5	3	4 CC	2	2	2	2QCC
3	8	8	6	10 CC	3	3	3	3QCC	3	3	3	3QCC
4	6	7	5	8 CC	4	5	4	5 CC	5	3	3	6 CC
5	4	5	4	5 CC	5	4	3	6 CC	5	3	3	5 CC
6	4	5	3	6 CC	2	3	4	2 CC	6	6	5	8 CC
7	4	3	2	5QCC	5	5	3	7 CC	2	3	2	3 CC
8	12	10	8	15 CC	15	15	4	26	4	2	4	2QCC
9	12	10	10	13 CC	27	35	21	42	3	2	2	3 CC
10	20	13	8	25	8	10	13	5 K	5	3	2	5 CC
11	51	54	63	42	2	2	2	2QCC	12	8	8	13 CC
12	5	7	9	3 C	2	3	3	2QCC	8	8	9	8 CC
13	5	5	4	6 CC	5	3	2	6 CC	4	5	6	3 CC
14	3	3	3	3 CC	6	6	5	7 CC	6	6	7	5 CC
15	2	3	3	2QCC	6	3	5	4 CC	14	9	6	17 KK
16	3	5	3	5 CC	2	3	3	3QCC	4	3	5	2 CK
17	6	6	8	4 CC	4	3	2	4 CC	5	3	2	6 CC
18	5	3	4	4 CC	7	7	9	6 CC	4	2	2	4 CC
19	5	5	3	7 CC	7	5	5	7 CC	2	3	3	2 CC
20	24	22	12	33	5	5	6	4 CC	3	3	2	4QCC
21	21	17	15	24	3	3	3	3 CC	7	5	3	9 CC
22	5	6	6	6 CK	2	3	4	2QCC	9	6	6	9 CC
23	4	5	4	6 CC	3	3	3	3 CC	2	2	2	2QCC
24	4	5	6	2 CC	5	3	2	5 CC	10	6	5	11 CC
25	2	2	2	2QCC	4	2	3	3 CC	6	4	5	5 CC
26	2	2	2	2QCC	5	5	5	5 CC	8	6	7	7 CC
27	2	2	2	2QCC	6	3	3	6 CC	4	5	6	4 CC
28	4	2	2	4 CC	5	3	3	4 CC	6	6	4	8 CC
29	4	2	3	3 CC	8	6	4	11 CC	16	9	7	18 KC
30	4	6	6	4 CC	9	8	12	5 CC	8	10	10	9 CC
31					9	4	3	10 CC				
	8.0	8.0	7.9		5.8	5.6	5.6		6.2	4.7	5.4	

1958

	JAN.				FEB.				MAR.			
	N	S	M		N	S	M		N	S	M	
1	61	37	55	43	16	18	18	17	15	9	16	9QK
2	27	34	42	19	14	18	20	13	12	11	15	7QCK
3	10	7	10	8QCC	11	14	11	16QK	35	27	15	47
4	9	9	9	9QCK	31	31	17	45	45	44	48	41
5	12	19	22	9Q K	56	56	44	67	44	59	67	36
6	13	15	13	16	43	50	44	49	50	49	53	47
7	11	17	17	12Q	42	36	34	43	35	32	36	31
8	11	13	10	14QKK	45	42	48	39	28	21	31	19
9	22	25	13	34	32	32	23	41	33	29	38	25
10	20	16	21	16	46	34	29	51	31	37	30	38
11	28	23	24	27	276	320	422	175	47	34	23	58
12	24	30	32	22	76	118	128	67	61	54	72	43
13	32	30	31	32	33	28	21	41	43	61	53	51
14	30	30	20	41	38	33	41	30	31	18	11	39
15	24	35	28	31	22	12	12	23Q	29	49	50	29
16	20	38	24	34	28	26	19	36	27	16	29	15Q
17	36	41	32	45	40	56	39	56	43	36	37	42
18	50	43	57	37	38	41	41	38	41	45	32	55
19	20	22	21	22	40	41	41	39	62	50	45	69
20	32	41	25	48	45	45	36	55	64	34	43	55
21	43	31	59	16	45	41	34	51	52	47	43	57
22	30	40	40	30	40	37	38	39	44	20	42	22
23	32	45	38	39	35	33	46	22	43	28	36	36
24	17	24	17	24	14	14	16	12Q	48	33	25	57
25	30	39	28	41	11	9	15	5QCK	50	42	39	53
26	26	22	29	19	15	16	21	11Q K	38	32	27	43
27	15	13	12	17	23	11	13	21	25	18	22	22
28	14	20	21	13	21	30	27	24	29	18	20	28Q
29	29	20	27	23					26	9	16	19Q
30	17	23	25	15					44	41	30	55
31	14	12	13	14 C					30	23	28	26
	24.6	26.3	25.5		42.0	44.3	43.2		38.9	33.1	36.1	

	APR.				MAY				JUNE			
	N	S	M		N	S	M		N	S	M	
1	33	28	24	38	38	21	24	36	68	35	67	36
2	54	38	48	44	23	11	21	13	41	35	48	29
3	38	18	27	30	16	7	10	13 CC	11	8	8	12QC
4	52	39	29	62	19	10	17	12 C	12	6	13	5QCC
5	36	30	40	27	25	11	10	27	18	6	9	17 KK
6	34	22	27	30	19	6	17	8 K	29	11	14	26
7	26	21	22	26	14	4	9	9QCC	69	75	111	33
8	22	8	11	19	21	15	15	22	25	10	8	29
9	16	6	11	12 CC	21	17	25	13	54	32	31	55
10	10	5	7	9QCC	38	21	27	32	38	47	41	45
11	18	11	15	14Q C	19	16	18	17	32	21	26	28
12	10	7	7	11QCC	28	21	7	43	31	23	30	25
13	10	8	10	8QCK	40	35	24	51	21	10	15	16
14	33	28	22	39	48	50	48	51	32	11	11	32
15	41	32	46	27	43	25	27	41	31	30	44	17
16	42	34	31	45	26	27	21	33	22	14	20	16
17	64	49	46	67	36	28	29	36	9	4	8	5QCC
18	62	64	65	62	36	23	27	33	16	7	4	19QKC
19	34	36	30	39	26	21	29	18	20	11	9	23
20	29	20	21	29	12	8	10	11QC	13	7	7	14QC
21	24	20	19	26	15	9	17	7 KK	85	76	67	94
22	10	11	15	6QCK	11	5	6	11QCC	55	60	77	39
23	21	13	6	28	7	4	6	5QCC	22	17	22	18
24	26	16	24	19	5	4	4	5QCC	30	30	31	29
25	21	8	21	9 K	29	8	10	27	38	18	27	29
26	26	12	4	35	48	33	34	48	18	8	12	14 C
27	21	13	10	25	40	33	27	46	16	8	12	12 C
28	35	32	29	38	33	19	27	26	76	36	28	84
29	45	50	43	53	64	72	78	58	85	75	106	53
30	42	32	38	36	23	20	22	22	18	10	12	16
31					92	56	23	125				
	31.2	23.8	27.6		29.5	20.7	25.2		34.5	24.7	29.7	

Fig. 2. Example of the unequal distribution of the quiet and disturbed days for months belonging to years when the average activity level is very different. The figures are a tabulation of average values derived from the *aa* indices (see section 5.3.3). The five international quietest days are noted by the letter *Q*. Letters *C* or *K* of the first subsequent column in each month identify the Greenwich days which are truly quiet (*C*) or approximately quiet (*K*). Similar letters in the following column identify the 48-h periods, centered on the Greenwich noon, whose characterization is similar (see section 6.1.2 for the quantitative definition by which such days are identified). The contrast between June 1902 and March 1958 is extremely large: all the days of June 1902 are truly quiet (except, maybe, the June 15 and 29), but only one day in March 1958 is truly quiet.

preceding years when the *Ci* index became available for them (more precisely, the *Ci* was computed backward primarily for that aim). Besides, it led in the 1920's to a classification of disturbed days; the decision was taken by the Commission of Terrestrial Magnetism and Atmospheric Electricity at Utrecht in 1923; paradoxically, this commission, depending on the International Meteorological Organization, continued to work after the establishment of the corresponding section within the International Union of Geodesy and Geophysics. Note that the same error of terminology was made, in publishing the days classified under the label '5 disturbed days' instead of the 5 most disturbed days (curiously, however, the expression 'cinq jours les plus troublés' is used in the yearly bulletins during 1923–1926).

One could find in *Mayaud* [1969] the different methods used from the beginning for classifying the international days of both kinds. We do not believe that such changes introduce very significant differences. The more or less good quality of the various planetary indices used (*Ci, Kw,* and *Kp*) is of greater importance; in particular, too great a weight is given to European stations in these indices, and this could introduce a bias in the choice of international days.

A further remark is of importance: if the concept of a quiet day is valid, the one of a disturbed day could be misleading. Suppose that one tries to define and classify only the days which are truly quiet. This is of significance because it means that the regular variation occurring on such days is truly (or almost truly) free of disturbance and may be studied in itself; the time interval chosen, that is, 24 h, is a suitable one, since such regular variations last less than 24 h (however, the whole 24 h are indispensable for the determination of a correct zero level). On the contrary, the concept of a disturbed day is very ambiguous. Indeed, the duration of a given disturbance (or storm) is not at all related to any 24-h period; that disturbance may begin or end at any time of the period classified (ordinarily, the Greenwich day), and its intensity may greatly vary in the course of the 24-h period classified. Furthermore, if one remembers that some of the international disturbed days are less disturbed than some of the international quiet days [see *Mayaud,* 1969], it is obvious how much one has to be prudent in using them (see other remarks in section 6.1).

However, an extensive use of both series of such international days has been made in the past within most of the geophysical disciplines, and it would be futile to assert that the results thus obtained are not at all reliable. In the geomagnetic domain, the definitions of the *Sq* and *Sd* daily variations were based upon the average of the hourly values recorded during international quiet and disturbed days, respectively (the *SD* variation being obtained from the difference *Sd* − *Sq*). The first discovery of what are now called the auroral electrojets comes from the *SD* studies of Chapman. However, the ambiguity of both the *Sq* and *SD* concepts is that their basis is purely statistical. With the former, one would have to be sure that the days used are truly free of disturbance and contain regular variations only. With the latter, the statistical variation obtained is a pure artifact (it is the average of irregular variations lasting only a few hours but whose direction and intensity vary systematically with local time) whose zero level is very difficult if not impossible to determine [*Mayaud,* 1978*a*].

Note that a full list (since 1884) of the 5 international quietest days of each month is given in the yearly tables of the *aa* index contained in the *IAGA Bulletins 33* and *39.*

3.4. Declination Ranges at Greenwich

When *Chapman* [1925] extensively studied the geomagnetic lunar variation at Greenwich, he needed a quantitative index for classifying the days. Because he was using data going back to 1848, he had to build it himself and chose the declination daily range R_D'. It differs from the daily range described in section 3.1 because it is the range during the day in the hourly differences in component *D* obtained by subtracting the monthly mean solar daily variation from the corresponding hourly values. The very large number of days used (68 years) permitted *Chapman* [1941] to point out various statistical properties of the magnetic activity (6- and 12-month variations, 11-year solar cycle, ...).

The index, thus defined, accounts roughly for a separation between regular and irregular variations and is mainly sensitive to the latter. Among them, given the subauroral latitude of Greenwich and the field component chosen, the index is certainly only slightly sensitive to the ring current variations and mainly to the auroral variations; we shall show later on how component *D* is particularly suitable for monitoring auroral variations at subauroral latitudes (see section 4.5). However, the constant time interval (24 h) is too long. More basically, the way of eliminating the regular variations is too crude: it does not allow for the great day-to-day variability in amplitude and phase of the variations S_R. Because of that, a part of the 12-month variation displayed by this index is due to the regular variations (the larger amplitude of the S_R in summer at this station must induce within a month a larger scattering of the ranges), and the too strict relationship with the sunspot numbers is also due to a remainder of these variations (the latter are strongly related to the sunspots while the irregular variations are not).

In spite of these limitations the main interest of this index is to be the first attempt at a quantitative measurement of the intensity of disturbances including a tentative elimination of the regular variations.

3.5. The Numerical Magnetic Character

The numerical magnetic character is probably the best illustration of the numerous gropings of the geomagneticians in deriving a quantitative index. Before its adoption at the IATME meeting of 1930 (*IATME Bulletin, 8,* 1930, pp. 206, 466) it was a subject of discussions whose transactions of the international meetings always give the trace for 20 years under the item 'magnetic characterization of the days'; they are very interesting from a historical point of view. The main paradox is that although it was designed to take the place of the *Ci* index, its lifetime was much shorter: its publication, stopped by World War II, was never resumed because the *K* index itself practically took its place.

Among the various proposals made for characterizing the energy variation of the geomagnetic field (it was a very fashionable idea at that time after the suggestion of Bidlingmaier: any reliable index should characterize such a quantity), the expression put forward by Crichton Mitchell was retained, $X_0R_X + Y_0R_Y + Z_0R_Z$, where X_0, Y_0, and Z_0 are the mean values of the field components and R_X, R_Y, and R_Z are the absolute ranges (that is, the differences between the highest and the lowest values of the components) in the course of a Greenwich day at a given station. Such data were compiled and published for about 30 stations from 1930 to 1939 on behalf of the Association of Terrestrial Magnetism and Electricity by the Institut Météorologique Royal des Pays-Bas (in a series of 32 booklets entitled 'Caractère Magnétique Numérique des Jours'), but no attempt at deriving a planetary index from them was ever made.

The best review of attempts to derive an energy variation index is given by *Chree* [1923]. Briefly, if $\mathbf{F}$ is the vectorial intensity of the geomagnetic field, and $\Delta\mathbf{F}$ is its variation over a given time interval, the energy variation is proportionate to the volume integral of $(\Delta\mathbf{F})^2$ throughout the whole space. It already appears that observations hardly permit one to compute the integral at the earth's surface if we assume that the density of observations is sufficient; furthermore, Chree makes fine remarks concerning the relative contribution of the various components with latitude. Anyway, it was rapidly noticed that the quadratic term in $(\Delta\mathbf{F})^2$ is negligible with respect to the term $\mathbf{F} \cdot \Delta\mathbf{F}$, and this was the reason why the latter was the only one to be kept in the expression chosen by the association. But as *Bartels* [1932, p. 12] remarked very soon afterward, the expression is 'deceptive, since the extreme values of X, with range R_X, occur generally at other times than the extreme values of Y and Z.' Finally, such an expression does not discriminate between regular and irregular variations; hence the sets of values obtained at each station displayed a seasonal change mainly related to that of the S_R variation and a year-to-year change also which mainly depends on this variation. In all these ways the numerical magnetic character was a failure.

3.6 The Norwegian 'Storminess' Index

The storminess index of activity was introduced for the Tromso Observatory by *Harang et al.* [1933]; its idea was derived from the famous work of *Birkeland* [1908, 1913] on the auroral variations.

The aim of the index is to monitor the single auroral variations. In view of this, one determines a zero level for each local hour of a given month by choosing not the average of the international 5 quietest days but the average of quiet hours identified during that month. Differences of the observed hourly values from these quiet hourly values give the intensity of the disturbance, or storminess, which are given in the tables with their sign for each component.

These values were regularly published in the Tromso yearbooks up to 1960 (inclusive). They were extended to the Dombas Observatory for some years. The index never reached a planetary level.

The storminess, to some extent, was an early precursor of the *AE* index. It has the merit of being less contaminated by the regular variations than the *AE* index is (see Chapter 7.)

3.7. *The u Measure of Geomagnetic Activity*

The purpose of *Bartels* [1932] in deriving this index was to meet the 'need for establishing a homogeneous series for all the time since consistent terrestrial magnetic observations were begun.' And 'it will be sufficient, for the time being, to devise such a measure only as averages for intervals of months or years, since *C* is available for the relative characterization of days within a month.' In evaluating this index one has to keep in mind the intentions of the author: to establish a series as long as possible in order to provide reliable and quantitative information during long-term periods, which the single index available at that time was unable to give (remember that he was so fully aware of all the defects of the numerical character figure that he considered it to be of no value).

The basic quantity for the index is taken from the early works of *Moos* [1910] at Colaba in India. (It is interesting to note that Bartels received a stimulus for this work from Schmidt [*Bartels,* 1946*b*].) Moos defined the interdiurnal variability *U* of the horizontal intensity at a given station as the difference between the mean values for that day and for the preceding day taken without regard to sign. Two remarks may help one to understand this twofold choice. (1) To take the differences gives freedom from the base line problems often not well solved in the early records. (2) To take the absolute differences is necessary when the goal is the monthly averages; if not, any increase in the equatorial ring current intensity, obviously mainly sought in this quantity, would be canceled by the subsequent decrease.

The next step is to combine the *U* values from various observatories. Now, the interdiurnal variability *U* as conceived by Moos at a low-latitude observatory aims at monitoring these depressions of the geomagnetic field in *H* component, observed by him in the records of Colaba and later called the main phase and the recovery phase of a storm. They are due to the intensity variation of the equatorial ring current, a phenomenon already postulated at the time of Bartels' work on the *u* index. The obvious process in order to combine the *U* values would consequently consist in standardizing the value *U* observed at each observatory to the one which would be observed at the dipole equator by a correction factor $1/\sin\theta$ (where θ is the colatitude of the station in the dipole coordinate system). However, such an operation is applied only to Potsdam-Seddin, a subauroral station; all the other stations are calibrated with respect to this key station in order that the mean of the *U* values for the complete series at a given station is equal to that obtained at the key station. During the periods for which measurements from Postdam-Seddin are not available, Colaba is taken as a reference with the factor obtained for the period common with that of Potsdam-Seddin. This empirical standardization 'does not bias fluctuations of the average value from month to month between the various stations,' but it appears less logical than the theoretical standardization. Thus the Colaba Observatory got a correction factor of less than 1 unit, which seems abnormal for a standardization of the *U* value to the equator. Bartels adopted that process 'for guaranteeing the homogeneity of the series.' Indeed, the number of observatories and their latitudinal distribution vary with time from 1872 to 1930: (1) one subauroral station during the whole series (Greenwich, then Potsdam-Seddin), (2) at first one tropical station (Colaba), then two from 1884, and three from 1902, and (3) one mid-latitude station from 1902, and then two from 1919. Supplementary values for 1931–1949 are contained in *Landolt-Börnstein, Zahlenwerk and Funktionen, Band 3, Astronomie und Geophysik,* p. 761 (Berlin, 1952, Springer-Verlag), but we cannot identify what observatories were used for all years. However, see *Bartels* [1934*b*, 1935*b*, 1936, 1938*a*] for the years 1931–1936; but, for instance, the *u* values given for 1940–1945 by *Scott* [1946] are derived from Huancayo only and differ from those given in *Landolt-Börnstein.* Anyway the various changes which already intervened in the years 1872–1930 probably necessitated a standardization; it is difficult to estimate how it has worked (remember that any empirical calibration based on a limited sample of geophysical observations is dangerous).

The average of the standardized monthly values at each observatory gives the *u* index. It is expressed in tens of gammas 'in order to make the index of the order of magnitude 1, and therefore comparable with the *C* index.' Furthermore, a u_1 index is derived from *u* by an empirical formula made up ofa combination of linear and quadratic functions (four sets are used corresponding to *u* being less than 0.6, 1.6, and 3.6 or greater than 3.6). The aim of this other index is to attenuate the effect of exceptionally great disturbances. Functions were chosen so that the u_1 values had a frequency distribution similar to that of the sunspot numbers, at least for the high values. This last attempt corresponds to the constant concern of Bartels to correct the distortions caused in any geophysical average by positive conservation and abnormally large values (see section 6.2). But the very complex and empirical transformation of *u* into u_1 probably makes the latter less reliable.

Annual values were also computed for the years 1835–1871 by using the daily range of the *D* component at Greenwich (from 1835) and the summed ranges of the *H* component at Colaba (from 1847). Again a calibration was made through a comparison for the years 1872–1901. Such values, as said by *Bartels* [1932, p. 10] himself, are probably more for illustration than for actual use. This is obvious in Figure 3: the greater similitude between the *u* curves and the sunspot number curve before 1872 indicates that the former tends to become for this early period a pure measure of the regular variations (whose amplitude is strictly related to the latter), as it can be readily assumed according to the data used. Let us remark that it is always dangerous to try to derive indices in too early periods with imperfect data.

Some of the fundamental results obtained by Bartels with the *u* index prove its reliability. However, the *u* curve of Figure 3 (after 1872) cannot be directly compared with the curve illustrating the variation of the *aa* index (see Figure 4); this index is mainly sensitive to the auroral variations, the other to the ring current variations. Furthermore, the *u* index is probably less sensitive to the 27-day recurrent variations than is any auroral (or subauroral) index. The year 1930 is

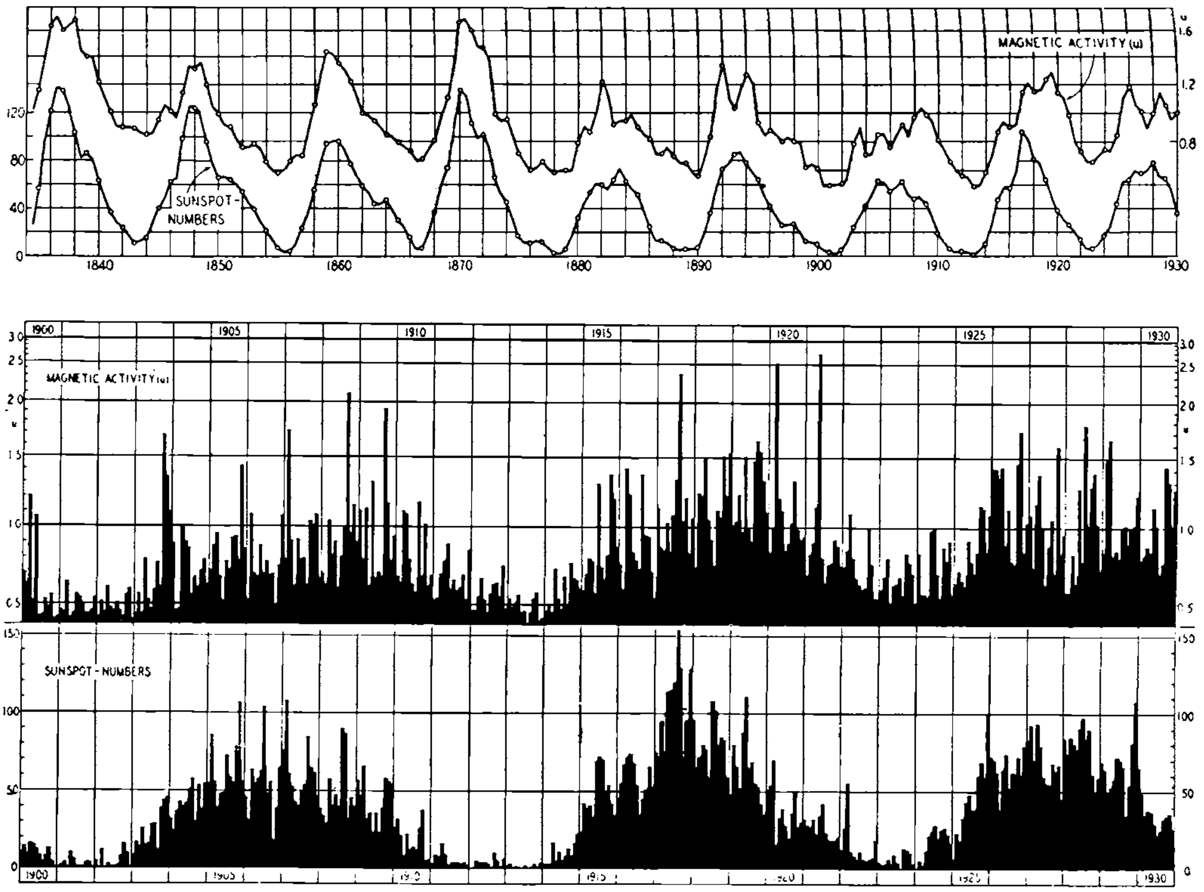


Fig. 3. (Top) Annual means of the geomagnetic activity (as measured by the *u* index) and of the solar sunspot number *R*. After 1872 the availability of the monthly values allows the drawing of two points per year: the circles correspond to the usual yearly mean for January–December. (Bottom) Monthly values of the *u* index and monthly averages of the solar sunspot number *R* [after *Bartels,* 1932].

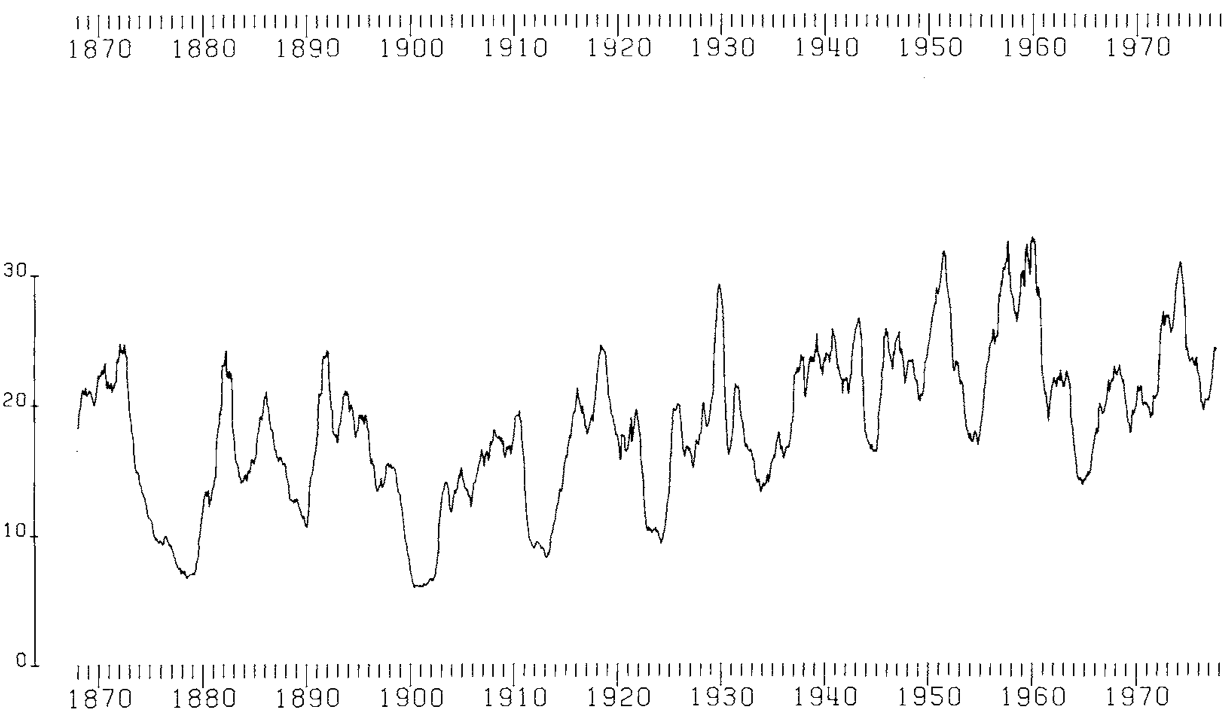


Fig. 4. Long-term variation of the geomagnetic activity as measured by the *aa* index (see section 5.3). The curve is made up of running yearly averages with 12 points per year; at the abscissa of a given year, the ordinate corresponds to the average from January to December of that year. Values after 1968 correspond to revised values as explained in section 5.3.4.

typical from this point of view. It appears less disturbed than the preceding years in its solar cycle with the *u* index, while it is most disturbed with the *aa* index (Figure 4); that year was characterized by recurrent and long stormy periods of great intensity (see Figure 1). The activity level in this year was probably the starting point of the Bartels-van Dijk controversy (see section 3.2), and Bartels may not have been right to criticize the high value of *Ci* in 1930. Both indices do not react in the same way to a given effect of the solar activity. (Let us note, however, that the comparison made by *Mayaud* [1972] between the *Ci* index and the *aa* index proves the insufficiency of the former.) In all these respects it seems that at the time of this original work on the *u* index, Bartels was too optimistic in considering that the *Ci* index and the *u* index could be considered to be readily comparable.

In fact, the *u* index is a precursor of the *Dst* index which monitors a particular species among the irregular variations, and one could ask if it is of historical interest only. It certainly suffers from intrinsic defects. (1) It does not give the intensity variation of the equatorial ring current but only that of the absolute first daily differences. (2) One may suspect a contamination by the regular variation S_R, since its day-to-day variability should contribute to the interdiurnal variability U defined. However, we tried to evaluate the importance of this contamination and were astonished at its relative smallness. For this test we chose a series of 35 consecutive days in July–August 1935, the first 22 of which are very quiet, and computed an interdiurnal variability U' at Alibag by using the first and last 6 local hours of each day instead of 24 h. Thus the daytime hours are eliminated, and most of the contribution of S_R should disappear. Average values of U' for these two series of 22 and 35 days are 0.38 and 0.48, respectively (in tens of gammas), while those of the classical U (with the 24 h) are 0.59 and 0.69, respectively. Then the S_R contributes about 2 gammas only to the *u* index at the time of a solar cycle minimum; the rest is due to fluctuations of the ring current intensity. At the time of a solar maximum the S_R contribution is probably higher. Besides, it is easy to check that the interdiurnal variability of the *Dst* index results in a value of about 4 gammas in quiet periods, which is consistent with the above values of U'. Then it appears that attempts could be made to compute U' values for some tropical observatories and to compare them with interdiurnal *Dst* values. If the comparison is significant, the series could be extended backward to early years and would be of value.

Note that *Chernosky* [1960], in his review on magnetic activity indices, classifies among them the delta indices which he computed from Huancayo. Although they are derived in an analogous way to the *u* indices (absolute differences in component *H*), they greatly differ from them because the second intrinsic defect mentioned above is accentuated. Indeed, he used daily averages of the hourly differences. Such a process makes the indices strongly sensitive to the regular variations, which are furthermore twice as large at this equatorial electrojet station as at an ordinary tropical station. In that sense, such indices do obviously miss the essential condition that we set forth in Chapter 2: to discriminate between regular and irregular variations.

3.8. The W Index

With this index, we move on to an attempt at monitoring the regular variations. Bartels was the main worker in this field, and the symbol used indicates that he planned to monitor the *W* radiation by it. In a first paper, *Bartels* [1940*a*] describes the broad features of its definition, while in a later paper [*Bartels,* 1946*a*], his first results are set forth.

The index *W* defined in the last paper is derived from the daily range of the hourly values in *H* component at Huancayo. The excess of the average *H* from 0900–1400 LT (over the average from 0000–0500 LT) is corrected for noncyclic change and for the lunar daily variation. Monthly values are computed by using the days with $Ci < 1.2$; daily values are also derived, but complex empirical corrections are introduced which make them probably less reliable. Tables of the index are given in this paper for the years 1922–1939, but the series was never extended further.

The choice of the time intervals 0900–1400 LT and 0000–0500 LT for defining the range is certainly the best: the first one corresponds to the average time at which the regular variation maximizes in *H*, while the second avoids the influence of the low-latitude negative disturbances in the evening. Bartels made an extensive study of the daily and monthly values. Two main results are obtained. (1) There exists a very high correlation between solar activity (sunspot numbers) and regular variations for averages over periods of months or years, and this correlation is much higher than the correlation between solar activity and magnetic activity, a fact which is often minimized or forgotten by many workers. (2) The fast variations in the solar activity, as are monitored by sunspot numbers, are accompanied by fast variations in the *W* index; the 27-day recurrence tendency in *W* is just as strong as that in the solar activity.

The first result has been known for a long time (for earlier results, see *Chapman and Bartels,* [1940, pp. 220–224]), but the second one does not seem to have been made the object of further studies. At least, it escaped our attention in the last years and does not seem to be mentioned in such classical reviews as those of *Matsushita* [1967] and *Nagata and Fukushima* [1971]. However, any studies along these lines would be of great interest for a better understanding of the day-to-day variability of the regular variation S_R. Furthermore, this variation S_R is probably one of the best tools for monitoring the wave radiations of the sun: hence any attempts at building an index monitoring the regular variations would be worthwhile.

Is the choice of the *H* component at Huancayo suitable for such an index? We now know that equatorial electrojet stations are submitted to very particular phenomena, which make the regular variations still more complex at equatorial dip latitudes than at other latitudes (see, for instance, the problems raised by the equatorial counterelectrojet in *Mayaud* [1977*b*]). At low latitudes the *H* component could be used, but the difficult problem of the night zero level has to be solved. Another solution is that proposed by *Bartels* [1940*a*]: the use of the *D* or the *Y* component at mid-latitudes. It presents several advantages. (1) The daily range, at least on quiet days, is a good estimate of the intensity of the vortex currents (for instance, *Price and Wilkins* [1963]). (2) The problem of the zero level does not interfere. (3) The daily range should be scaled by identifying the S_R itself in the trace, which is frequently possible at the focus latitudes; then the variations due to disturbances (see section 3.4) would be eliminated. (4) The latitude variation of this range on either side of the focus latitude is not large, and the effect of latitude shifts of the vortices is very small. (5) A suitable network of stations could be used in both hemispheres. (6) If the longitude density of the stations is sufficient, more than one value per day could be given. (A range, at a given station, corresponds to the average intensity of

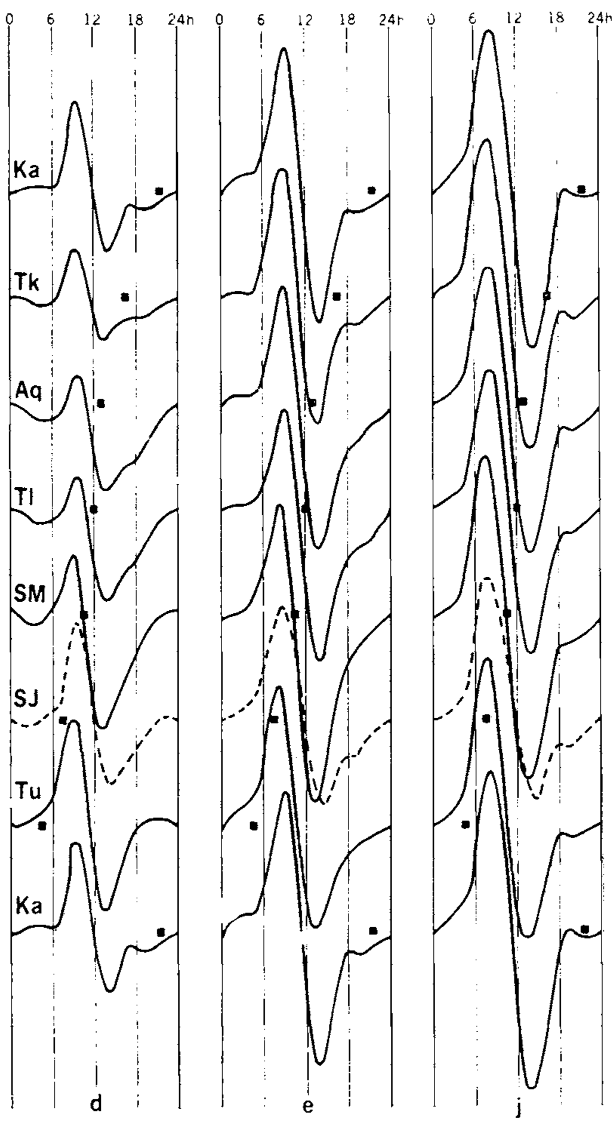


Fig. 5. *Sq* curves of the eastward component *Y* of the geomagnetic field for the three Lloyd seasons (*d* denotes December solstice; *e*, equinoxes; and *j*, June solstice) of the years 1958–1960 at seven stations of the northern hemisphere close to the northern focus vortex (Ka, Kakioka; Tk, Tashkent; Aq, Aquila; Tl, Toledo; SM, San Miguel; SJ, San Juan; and Tu, Tucson). The SJ curve is a dashed line because this station is not as close to the focus as the others. The square indicates 1200 UT at each station. The ordinate scale is 2 γ/h. Assuming that the range of the variation *Sq* is a good approximation of the current intensity in the vortex, no significant variation of this intensity appears, except in the wintertime (*d*): the range is twice as high at Tucson as it is at Tashkent. With respect to a zero-level chosen at local midnight, the extremal amplitudes of the variation *Sq* are symmetrical at Tucson, Kakioka, and Tashkent. They differ most at Aquila. The variation from the morning to the afternoon confirms that the vortex intensity is increasing from Tashkent to Tucson [after *Mayaud,* 1965*d*].

the vortex for about 6 to 8 h, that is, the average time interval between the extremes of the regular variation in *D*.)

However, if such an index may describe the day-to-day variability of the vortices intensity, it could not be directly related to the solar wave radiation (except for yearly averages) for several reasons. (1) The seasonal variation at the focus latitudes is a first factor. (2) The large variation with longitude of the northern vortex intensity during the December solstice (see Figure 5) would have to be taken into account, and one has to remember that the introduction of any empirical correction in an index is dangerous. (3) We recently had the opportunity of scaling *K* indices in the records of many stations. Our attention was again attracted by the enormous day-to-day variability of the range in the *D* component at southern stations in the December solstice (it can vary from one to three in 2 successive days). This can be related to an explanation proposed for the equatorial counterelectrojet (see *Mayaud* [1977*b*] and for the discussion of the invasion concept see *Mayaud* [1979*a*]): the existence of supplementary vortices with a reversed direction of currents (which could be as well the cause of the apparent anomaly described in the legend of Figure 5). If so, the range no longer represents the intensity of the vortices.

In spite of these difficulties, any regular variation index would be of great interest.

3.9. *From Past Indices to the Present IAGA Indices*

Among the past indices, the *Ci* index, in spite of its crude definition, was the most useful and widely recognized. The *u* index was the most reliable because of its quantitative character, but its definition, which used only a 1-month time interval, limited its interest. The Norwegian storminess had the advantage of a very clear geophysical meaning, but its nonplanetary character and the difficulty of its computation (especially the identification of the quiet hourly values) were a brake to its derivation in many other auroral observatories and to a wide use.

Over the decades which are reviewed in this chapter, experience in deriving geomagnetic indices was acquired along two paths. Bartels, with his criticisms of some of the indices, was probably the main initiator of these two paths: (1) any reliable index must discriminate between the regular and the irregular variations and (2) the constant time interval over which the index is defined must be clearly much smaller than 1 day. Furthermore, progress in knowledge of the transient variations also contributes to a better understanding of the indices needed.

The indices officially recognized by IAGA at present, which will be described in the next chapters, resemble the past indices, insofar as they aim at similar goals. Thus on the one hand, *Dst* or *AE* indices are analogous to the *u* or storminess indices, and on the other hand, range indices (either the local *K, R,* and *Q* indices or the planetary derivatives *Kp, am,* and *aa* from the *K* indices) are analogous to the *C* or *Ci* indices. These present indices constitute two greatly distinct families. The first family has a great advantage over the second, as was true with the past indices: they aim at monitoring a single and well-defined phenomenon (ring current variations or auroral variations). Two improvements will be made in this first family: a much better quantitative estimation of the intensity of the phenomenon and, thanks to their definition, the possibility of using any sampling rate. The only limitation will be the sampling rate of the data; the indices tend, to some extent, to be a record, and their physical meaning is clear. Indices of the second family, at the level of the planetary derivatives, meet the need felt during the first decades of this century: to have at one's disposal, as with the index *Ci*, an index characterizing the planetary level of the irregular variations as a whole without any discrimination between their different species. Two improvements will also be made: a much better choice for the constant time interval and the definition of a quantitative measurement instead of a qualitative estimation. However, such indices are still summarized information (a range) over an imposed and invariable constant time interval, and their physical meaning is far from being as clear as it is with indices of the first family. Conversely, a disadvantage of the first family is that the indices may be used only for studies of the phenomenon monitored or of the related phenomena. The second family may have a wider use.

We shall begin the review of the present indices by the second family for several reasons. (1) Indices of this family and some of their derivatives were conceived first. (2) From them, fundamental properties of the geomagnetic activity (see, for instance, the work of *McIntosh* [1959] concerning the universal time daily variation predicted by *Bartels* [1925]) have been discovered, and they are of use when discussing the true features of the indices of the first family. (3) The latter, in its derivation, uses a classification of days, which is derived from the former.

4. Range Indices (*K, R, Q*)

As we shall see in the next chapters, a number of significant physical results that the *AE* or *Dst* indices cannot display come from *K* indices through some of their planetary derivatives. Therefore it is important to develop fully an understanding of these indices. This is why we will describe them at length.

4.1. A Preliminary Description

The 3-h range index *K* was the first to be proposed at an international level and was adopted in 1939 (*IATME Bulletin, 11,* 1940, p. 550, resolution 2). It was one of the two 'Kennziffers' K_1 and K_2 (the use of the letter K comes from this German word which means character) introduced by *Bartels* [1938*b*] at the Niemegk Observatory. The index K_2, which deals with the nature of the variations, was not internationally extended. The index K_1 became the *K* index and rapidly spread in most of the observatories after the adoption of the above resolution and the publication of the paper of *Bartels et al.* [1939].

The conception of the index obviously originates in the previous attempts made for characterizing the magnetic activity, but it also takes advantage of the experience acquired. A first and brief description may be made as follows. (1) One began in the 1930's to feel that a daily index was insufficient. In particular, a strong request came from the International Union of Scientific Radiotelegraphy. Hence the choice of a 3-h interval as a constant time interval was judged suitable: 'Such intervals seem to be long enough to give a correct indication for such details as bays and other perturbations of only 1 h or 2 in duration: at the same time, it is short enough not to affect too much the day in cases where two successive intervals might be affected by disturbances as the bay, occurring centred on their common point' [*Bartels,* 1940*c*, p. 28]. Obviously, the beginning and the end of the time intervals are reckoned in universal time, that is, 0000–0300 UT, 0300–0600 UT, etc. (2) We saw that geomagneticians extensively used the daily ranges in the previous decades; it seemed suitable to use the same quantitative measure in the records. But very important progress was made. This range should be a measure of the single irregular variations and would consequently include the elimination of the regular variation S_R of the day. Thus the index satisfies the fundamental condition required for a magnetic activity index: to be sensitive to the irregular variations only. (3) How can one synthesize by a single number the irregular variations observed in the three components? At the birth place of the K index, Schmidt initiated for Potsdam in the 1920's an index defined by the sum of the daily ranges $R_X + R_Y + R_Z$, that is, 'the sum of the three sides of the rectangular space on which the movements of the end point of the magnetic field vector (supposed to be plotted from a fixed origin) could be enclosed' [*Chapman and Bartels,* 1940, p. 362]. An analogous image is used by *Bartels et al.* [1939] to describe the choice made for the K index: to retain the longest edge of the box, that is, the largest of the ranges scaled in the three components (we shall see later on why the Z component was excluded from the K scalings). (4) In view of the possibility of simplifying the index as much as possible, possibly through an imitation of the C index with its three steps symbolized by a single figure, and certainly for the reason which we shall largely comment on in section 4.6 although Bartels, to our knowledge, never stated that point, the scaling becomes that of a 'class' of ranges instead of being that of the range itself. Ten classes are defined which give the possibility of symbolizing the index by a single figure, varying from 0 to 9. We would like to emphasize that at a time when no computer was available and when any handling of many numbers was very taxing, synthetizing valuable information in such a condensed form was a remarkable achievement. (5) Given the large changes with latitude in the activity levels, classes of amplitudes have to be varied with the latitude of the station. This is made in such way that, as a principle, the frequency distribution of the indices has to be the same at any latitude.

The 1-hour index R was first introduced by Nikolsky for a polar cap station, Tikhaya Bay. It was extended to other polar cap or auroral stations at the time of Second Polar Year and was officially adopted by IAGA in 1963 (*IAGA Bulletin, 19,* 1969, p. 360, resolution 5) for stations at geomagnetic latitudes higher than about 65°. It was then defined by the hourly range in tens of gammas for each horizontal component. Consequently, the regular variations are included in it, but one may consider that at high latitudes their own range within an hourly interval is small in comparison with that of the irregular variations. Possibly the index does not become zero when there are no irregular variations at all in the daytime but especially in the polar caps (the most interesting for such an index) a complete absence of irregular variations is quite rare.

The quarter hourly index Q was proposed by *Fukushima and Bartels* [1956] at the time of the International Geophysical Year. Again the request came to geomagneticians from other disciplines; thus ionospheric and auroral measurements made in a discrete way at a cadency of four per hour necessitated an index with a time resolution finer than 3 hours or even 1 hour. The definition proposed by these authors and adopted by IAGA (*IAGA Bulletin, 16,* 1960, p. 402, resolution 4) for auroral stations was similar to that of the K index except for two points. (1) The regular variation varies little during so short a time interval, and any effect from it would be negligible. But in order to avoid that the Q index becomes small or almost null when a disturbance of a few hours maximizes (say, for instance, the effect of one or the other of the auroral electrojets) a zero level is considered, which is the regular variation itself and its zero level at night. If the field crosses it during the quarter hour interval, the index is defined by the range of the irregular and regular variations during the interval; if the field remained on the same side of the regular variation, the index is defined by the absolute deviation from it. (2) Twelve classes of ranges are defined instead of ten with the K index, and they do not vary with latitude. To some extent, one can consider that the Q index was a forerunner of the AE index, as was the storminess. It takes a great deal of effort to scale, and nowadays only one station, Sodankylä, is continuing its scaling. We would say that the Q index is probably overdone at the time of the digital recorders and computers, which give other means for analyzing the records and extracting the desired information from them with a high time resolution. In any case, we will no longer consider the Q index in this review.

Because the K index is extensively used in deriving various planetary indices (e.g., Kp, am, and *aa*), it is necessary to have a clear understanding of its meaning and of the way by which one must deal with it in such derivations. This is why the next sections concern the 3-h K index much more than the 1-h R index.

'The larger range of the irregular variations (that is, after eliminating the variation S_R) observed over a 3-h interval in the two components H or D is ranked into one of the range classes (such as they are defined for each observatory) to which a number $K = 0$ to 9 corresponds.' Such a sentence summarizes all the problems involved in the meaning and the use of the K index. (1) What is the physical meaning of the range (difference between the highest and lowest values recorded in a given component)? At least, it should be compared with other quantitative parameters by which one could characterize the irregular variations within the interval chosen. (2) But does the result obtained with a given quantitative parameter depend on the length of the constant time interval chosen and on a variation of the morphology of the irregular variations with latitude or with the activity level? (3) If the range, by definition, makes abstraction of the zero level, what is the consequence for the physical meaning of the index? (4) What does the use of the larger range observed in the components H and D mean? (5) What is the meaning of numbers varying from 0 to 9? Are they nothing other than a pure code? Does the definition of the range classes at each observatory permit one to average such numbers? (6) To what extent is the elimination of the regular variation S_R reliable?

Each of these questions needs an answer which will introduce a true understanding of the K index and of its use. The difficulty is that some of the questions overlap. For instance, the meaning of the range depends on the length of the constant time interval chosen, and the elimination of the S_R is made possible and reliable by the use of classes of ranges. Hence the survey of each question will not be always completely independent of the others.

4.2. *The Range or Other Alternatives*

An immediate choice for monitoring a given phenomenon is to take its average intensity over the interval chosen. It is the advantage of the *Dst* index to aim at monitoring a simple phenomenon (the equatorial ring current) which varies on a time scale of a few hours with only few erratic fluctuations of short duration; hence the average hourly value at each station after subtraction of an adequate zero level (secular variation and regular variation) is a suitable quantitative parameter which gives reliable information after averaging with longitude. But an average intensity does not provide any information concerning the variability of the phenomenon within the interval. At first sight the only advantage of the range with respect to average values over a given constant time interval is that it gives information on this variability. *Mayaud* [1967*a*] tried with more or less success to develop a meaning of the range indices that states that they are a rough measure of the amplitude of the geomagnetic noise observed in the records. Recently, *Menvielle* [1979] pointed out how the mathematical concept of 'norm' may open the way to relate the range to the average temporal volumic density of energy of the irregular variations. Before setting forth this new point of view on a physical meaning of the range itself, we shall consider two other quantitative parameters which have been recently proposed in order to be substituted for the range in characterizing the geomagnetic activity: the standard deviation and the total power spectrum.

4.2.1. The standard deviation. The starting point of *Joselyn* [1970], in introducing the standard deviation as an alternative for the range index K, can be described with the following quotation. 'K figures are not applicable to computerized use because they are subjective and depend on not easily definable quiet-day curves. Also, one must wait until at least the end of a particular 3-h period in order to estimate its K index. Another disadvantage is that K figures reflect only maximum activity: a 3-h period with a single disturbance near the end might have the same K index as a period that was continuously disturbed.' The problem of the apparent subjective character of the K index is set forth below in section 4.7; we do not think that Joselyn, by using 1-hour running averages (or any other), correctly solves the problem of the discrimination between regular and irregular variations. On the contrary, it is plainly correct to assert that a single disturbance or fluctuation within the interval gives the same index K as do continuous disturbances. But one has to be aware that the standard deviation suffers from other limitations.

Let us assume that the disturbance during a given time interval of length T is a sinusoidal wave of period T with an amplitude a. The standard deviation takes a certain value, say σ_a. It will keep the same value if one has a train of sinusoidal waves within the interval whose period and amplitude are $T/2$ (or $T/3$, ... T/n) and a. Range and standard deviation give the same result. The difference between the standard deviation and the range appears in the case of an isolated fluctuation: for instance, a fluctuation whose period and amplitude are T/n and $(n)^{1/2}a$, respectively, still gives a value σ_a of the standard deviation, while the range takes the value $2(n)^{1/2}a$. Hence neither the standard deviation nor the range is able to describe by only one quantity the complexity of the morphology of irregular variations within an interval. (An analogous problem exists with correlation analyses: one cannot describe the configuration of a cloud of points by a single quantity.) The defect of the range in being very sensitive to isolated fluctuations was already noticed by early workers (see section 3.1) and must be evaluated with respect to the morphology of the geomagnetic irregular variations to be monitored. And this mainly depends on the length of the constant time interval chosen: it is not as serious with 3 hours as with 24 hours (see section 4.3).

The standard deviation could appear to be a statistical concept more appropriate than the range. One has to take care, however, that it is conceived for estimating the scattering of discrete and randomly disturbed quantities. When used for estimating the behavior of continuous fluctuations the well-known positive conservation extensively described by Bartels [see *Chapman and Bartels,* 1940, chap. 16] interferes with and radically changes the properties of the concept. This is why, for instance, a single wave and a train of waves with the same amplitude have the same σ_a.

As far as the K indices are concerned, the meaning of the range has to be evaluated from the viewpoint of the planetary indices derived from them. In that case, if the network of stations is suitably chosen and since the K indices are mainly sensitive, as we shall see, to auroral variations, the final result for a given interval depends on the superposition of each of the set of disturbances (or noise) observed at various longitudes. This corresponds in general to an average noise made up of fluctuations spread evenly over the whole interval, and one is very close to a situation where range and standard deviation give the same result. One has no information concerning the density of the fluctuations, but it does not vary much with the activity level (see section 4.3). Hence information derived from the ranges scaled in a planetary network of stations (when they are combined in a proper way, that is, by a direct average of the ranges) may be considered to avoid the defect of this quantitative parameter, that is, sensitivity to isolated fluctuations of short duration.

4.2.2. The average spectral power. *Lanzerotti and Surkan* [1974] pointed out how there is no good one-to-one relationship between the energy content in the fluctuation band they investigated (45 min to 16 s) and the K index from Fredericksburg, a station near the longitude where the total power spectrum data were obtained. They proposed that the introduction of geophysical indices based upon geomagnetic power levels should eventually provide more physical insight into geomagnetic disturbance phenomena.

Figure 6 is a record of Fredericksburg for the most disturbed day of the 12-day sample investigated; the daily *am* is equal to 46. Let us note that 7 out of the 12 days can be considered to be truly quiet according to the criteria given in section 6.1.1. In some respects this is a limitation when evaluating the quality of a magnetic activity index. Figure 7 displays the data compared. Durham is a station located 5°N of Fredericksburg, while Lac Rebours and Girardville are again about 5°N and 6°N from Durham; Siple is a southern station whose conjugate point is close to the two more northerly stations. Since the spectra are computed over 2-h nonoverlapping intervals, the K_{FR} plotted is either the index of the 3-h period containing the 2-h period of the spectral point or the average of two K_{FR} indices when a 2-h interval straddles two K_{FR} intervals. Furthermore, the K_{FR} used are those which result from the two components H and D while the power spectrum data are computed from H only. These two facts make the comparison more difficult and probably contribute to a lessening of any one-to-one relationship. According to the *am* index the two periods really disturbed are, on the one hand, the second half of January 10 and all of January 11 and, on the other, the last 3 days of the sample. One may say that the same is observed in the K_{FR} indices and in the power spectrum data: the level of the power clearly increases during these periods, with the exception of curious anomalies which occur at only one station at a given time: at Durham for the last two values of January 10, at Lac Rebours

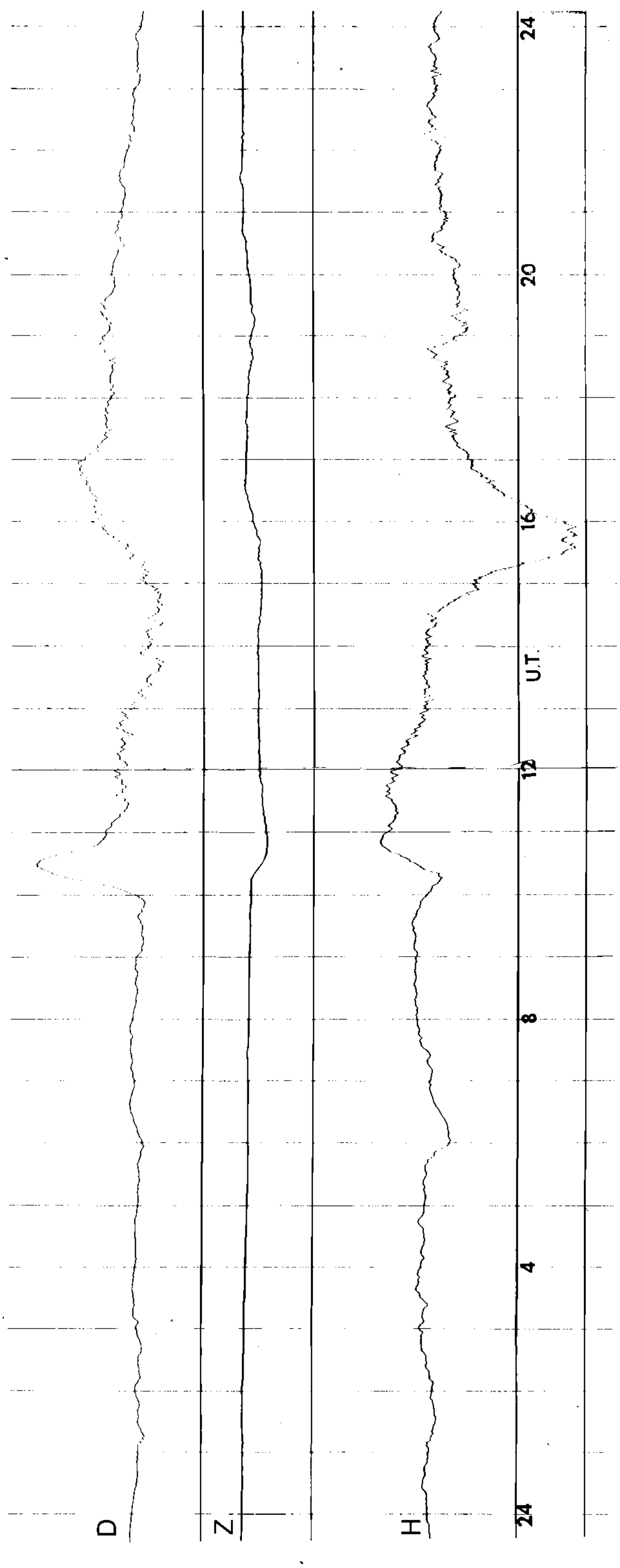


Fig. 6. Record of Fredericksburg on January 16, 1972. The scale values in H and D are 48 and 58 γ for an ordinate equal to 1 hour in abscissa.

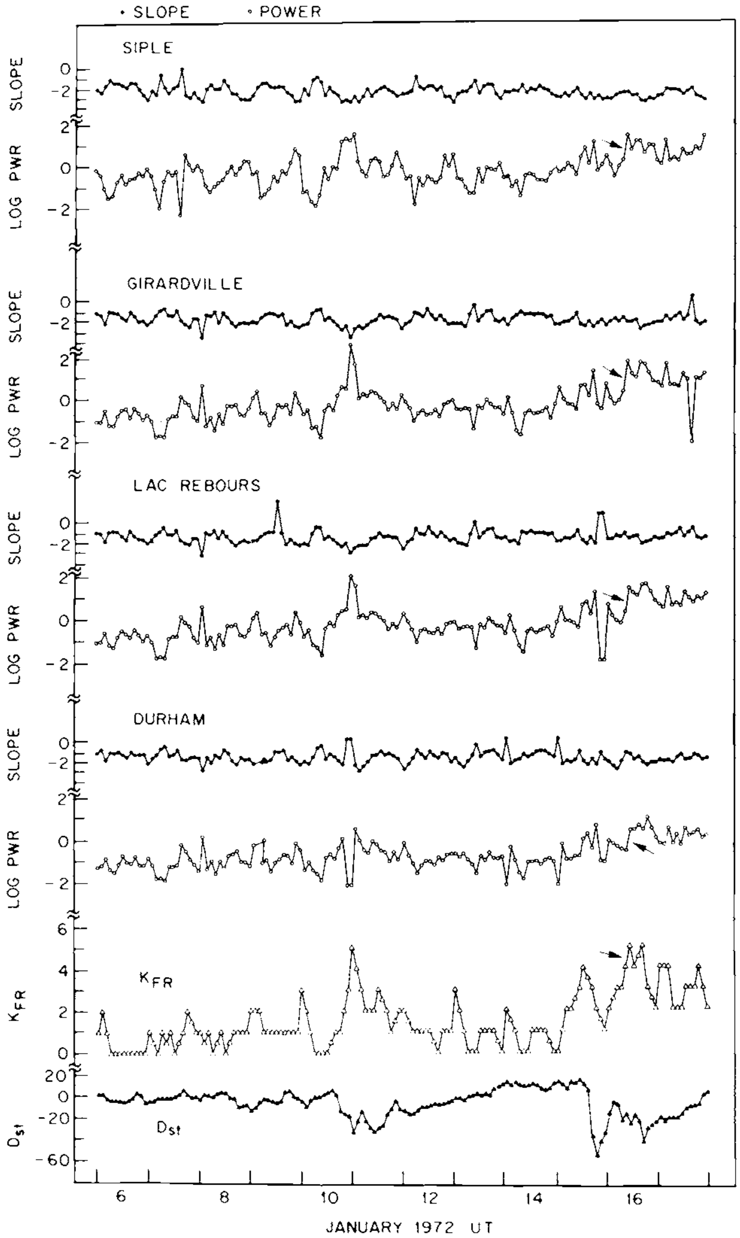


Fig. 7. Two-hour total power spectrum values and spectral slopes for the period January 6–17, 1972. The K_{FR} and *Dst* indices are plotted at the bottom. The arrows drawn close to some curves indicate the border between the fifth and sixth 2-h interval of January 16 [after *Surkan and Lanzerotti,* 1974].

for those of January 15, and at Girardville for the ninth value of January 17. Hence a first point is that a certain correlation appears between both sets of data. Second, if one looks at the variations occurring during January 16, there exists a clear change in the power spectrum level between the fifth and the sixth 2-h values of the day: it is the time, when in the Fredericksburg record, irregular variations of very short period begin to occur (see Figure 6): a power spectrum computed in the band 45 min to 16 s must be very sensitive to them. On the other hand, the fifth and the sixth values plotted for K_{FR} are strongly sensitive to the large disturbance observed in the component *D* around 1000–1100 UT, which is not taken into account in the power spectrum analysis. Finally, the two sets of data are probably not so disconnected as it is claimed by Lanzerotti and Surkan, but they are certainly not sensitive to the same band of frequencies. The power spectra data under consideration concern fluctuations of short periods (a few minutes), and the *K* indices are mainly sensitive to fluctuations whose period is longer than the low border of the frequency domain scanned, that is, a frequency corresponding to 45 min. Using the spectral analysis technique, to be properly sensitive to fluctuations which last easily 1 or 2 h necessitates the analysis of time intervals of 6 or maybe 10 h. In these conditions, the sampling rate of the index would be too low to describe the daily variation of the activity, at least from nonoverlapping intervals. Furthermore, the problem of the S_R elimination would be extremely difficult to solve.

4.2.3. A possible physical meaning of the range. *Menvielle* [1979] starts from the mathematical concept of 'norm.' Let us consider a vector **V** defined, for instance, by the positive functions $a(t)$, $b(t)$, and $c(t)$: the quantity

$$N_n(\mathbf{V}, \tau, \Delta t) = \left\{ \frac{1}{\Delta t} \int_{\tau}^{\tau+\Delta t} [a^n(t) + b^n(t) + c^n(t)]\, dt \right\}^{1/n}$$

where n is a positive integer, is a norm $\|\mathbf{V}\|_n$ of the vector **V** within the interval Δt. When $n \to \infty$, one has

$$N_\infty(\mathbf{V}, \tau, \Delta t) = \operatorname*{Sup}_{t \in \Delta t} [a(t), b(t), c(t)]$$

which is a norm of the vector **V** within Δt. These definitions remain valid for any function by using a formalism such as

$$a(t) = a_+(t) - a_-(t)$$

with

$$a_+(t) = a(t) \qquad a_-(t) = 0 \qquad \text{if} \quad a(t) > 0$$

$$a_+(t) = 0 \qquad a_-(t) = -a(t) \qquad \text{if} \quad a(t) \leq 0$$

The first point of Menvielle's argumentation consists in noting the following fact. If the functions a, b, and c take the value 0 at least once during the interval Δt, the variation range r which is largest among the ranges of these functions is equal to the norm N_∞. Now, considering that the range of a given function (say, the range r_a of the function a) is an upper bound of the quantity

$$\left\{ \frac{1}{\Delta t} \int_{\tau}^{\tau+\Delta t} a^2(t)\, dt \right\}^{1/2}$$

the norm

$$N_2(\mathbf{V}, \tau, \Delta t) = \left\{ \frac{1}{\Delta t} \int_{\tau}^{\tau+\Delta t} [a^2(t) + b^2(t) + c^2(t)]\, dt \right\}^{1/2}$$

can be bounded by substituting for each function a, b, and c the largest range r, that is,

$$N_2 \leq 3^{1/2} r$$

This upper bound will be reached only (1) if the three functions have the same range and (2) if the variation of each function is of the type $a(t) = r_a$; but this is excluded by the condition that each function takes the values 0 at least once during the interval.

Because it is not possible to define a lower bound of the norm N_2 with respect to the norm N_∞ for all possible functions (that is, supplementary conditions must be satisfied by the functions a, b, and c), the second point of the argument then consists in assuming that a, b, and c are the components of the vector $\boldsymbol{\beta}(t)$ of the irregular variations of the geomagnetic field, as reckoned from the regular variation S_R or from its night level (we will have to consider that point when dealing in section 4.4 with the zero level). Under certain conditions related to the morphology (with respect to the interval $\Delta t = 3$ h) and the occurrence (during at least one fourth or one third of the interval Δt) of the irregular variations, the norm N_2 would have a lower bound of approximately $0.20r$ in the majority of cases. It is obvious, in particular, that intervals during which only one short and isolated fluctuation occurs do not satisfy such a bound. However, let us note that the estimation of this lower bound is made by assuming that two out of the three functions are zero over the whole interval.

Finally, one would have

$$0.20r \leq \left(\frac{1}{\Delta t} \int_{\tau}^{\tau+\Delta t} (\boldsymbol{\beta})^2\, dt \right)^{1/2} \leq 3^{1/2} r$$

where r is a quantitative parameter which corresponds to the largest range observed in the three components and from which the K index is determined.

Such bounds for the square root of the average temporal variation of $(\boldsymbol{\beta})^2$ within Δt would seem to cover quite a large domain. In fact, this domain can be considered to be much narrower. Thus concerning the upper bound, it is inconceivable that a well-shaped baylike variation would be observed which lasts exactly 3 h and has the same amplitude in the three components: in such a case, however, the upper bound would be still of about $1.0r$. Similarly, and concerning the lower bound, a complete absence of any irregular variation in two out of the three components is rather rare; most of the time, irregular variations occur in the three components (particularly at subauroral latitudes, which we consider to be best adapted to the K index, they have often the same range in the components H and D), and the lower bound can be evaluated at about $0.3r$. Finally, one can reasonably estimate that, in the majority of the intervals, lower and upper bounds are located at about 0.3 and 0.7 times r (let us note that the root mean square (rms) of a sinusoidal function is $0.35r$ and that the rms of the sum of the squares of two such functions is $0.50r$). The bounds become all the more reliable when one works with spatial averages (in deriving a planetary index) or temporal averages (when dealing with a set of time intervals Δt); it is obvious, for instance, that a compensation from one station to another takes place when averaging the ranges.

Consequently, the square root of the temporal average of $(\beta)^2$ (we symbolize it by $\|\beta\|_2$ in the following) would be proportionate to about $0.5r$. Now, such a parameter is analogous to the rms of an alternating current and might be identified as the rms of the field β within Δt or the square root of the temporal average energy density (per unit volume) variation of the main field B if one has $\mathbf{B} \cdot \beta = 0$. Such a condition is not far from being satisfied for the ring current variations and worldwide fluctuations (for reasons of symmetry) and for the auroral variations at subauroral latitudes (if they are mainly due to field-aligned currents); it is no longer true for the DP 2 variations which correspond to electric currents flowing within the ionosphere.

Let us note that the standard deviation proposed by *Joselyn* [1970] would not need the considerations made above concerning the range, since its mathematical formula is identical to the one of the rms. Thus it could seem an excellent quantitative parameter in the line of this interpretation but, if used, it should be called 'root mean square of deviations,' and not 'standard deviation,' which corresponds to a statistical concept not suitable for analyzing continuous curves. Anyway, the difficulty of its use is not so much the cost of the operation (or the necessity of having digital records); it is, in our opinion, the impossibility of defining a significant zero level because of the variation S_R (see sections 4.6 and 4.7).

4.3. *The Length of the Constant Time Interval*

The choice of the length on which the range is measured has to be judged from the morphology of the irregular variations that one wishes to monitor. And because this morphology changes with certain zones of latitudes, it would be vain to think that a given length is well adapted to the whole earth.

As was mentioned above, in choosing a 3-h time interval for the K index, Bartels had the bays especially in view, and the choice was certainly suitable. And because the bays occur everywhere, it could follow that the K index is well adapted for every latitude. That is not our feeling, however, because other phenomena interfere.

Thus within the polar caps, other species of irregular variations dominate, especially during daytime, and their duration is much shorter. Then the choice of the hourly range indices R by Nikolsky and other workers was perfectly right and is much better for these latitudes so that they follow the variability of the phenomenon with time.

At the other extreme, that is, at low latitudes, it is not evident that the 3-h index K itself or any range index is completely suitable. The elimination of the daily variation S_R is obviously indispensable, but because the auroral variations become small in relation to it and because sharp changes in the auroral variations are very much attenuated, their discrimination from the S_R is difficult. The contamination of the indices by the S_R can become significant (see, in particular, *Mayaud* [1967*a*, pp. 61–65] for the low-latitude afternoon/evening disturbances). During storms the effect of the ring current variations becomes predominant, and the range badly measures a variation whose duration is much longer than the time interval on which it is scaled. Furthermore, the influence of the short worldwide fluctuations becomes significant with respect to that of the auroral variations, and a 3-h interval is of little significance for them. Equatorial electrojet latitudes, with the very large enhancement of the fluctuations during daytime, correspond to a particular situation. They would merit special treatment; the constant time interval chosen could probably be reduced to 1 h. A proper elimination of the daily variation, however, would be difficult, especially because of the large day-to-day variability due to the counterelectrojet [*Mayaud*, 1977*b*]. Furthermore, such indices would probably be of limited interest if they could not be compared with similar indices obtained at low latitudes where the equatorial enhancement disappears.

Between these extremes (polar caps and low latitudes) we have the auroral, subauroral, and mid-latitudes. We think that the band of latitudes which is best adapted to the 3-h range index is the subauroral one; and we understand it to be included within rather narrow limits, that is, between about 55° and 40° corrected geomagnetic latitudes. At auroral latitudes, secondary details in the auroral variations are often strongly accentuated, and a 3-h time interval is probably too long; this is still true down to about 60° (see in section 4.6.3 the problem of the assimilation of frequency distributions of the *K*). At mid-latitudes the great day-to-day variability of the S_R in the *H* component makes its elimination much more difficult with respect to the auroral variations whose intensity has already greatly decreased, and the scaling of the ranges is less reliable. The subauroral latitudes are more suitable for a valuable and reliable 3-h index; remember that *K* indices were first introduced for the Niemegk Observatory, whose corrected geomagnetic latitude is 49°.

We tried previously [*Mayaud,* 1967*a*, pp. 21–30) to estimate the variation in the amplitude of the ranges for various time intervals (between 1 and 24 h) at a subauroral station. We are not fully convinced of the significance of these comparisons. Our conclusion, however, was that the right time interval is between 1 and 3 h. Four reasons in our opinion make the scales go in the direction of a 3-h choice, the first two being given by Bartels himself. (1) A 3-h length is well adapted to one of the main irregular variations, the baylike disturbances, and not too many will be cut into two parts at the border between two successive intervals. (2) Eight values per day are much more economical than 24 per day and still give information concerning any variation within the day. In these conditions, *K* scalings, although they are difficult, are one of the less taxing methods of extracting valuable information from the records. (3) At latitudes lower than the auroral latitudes the elimination of the S_R variation would be more difficult with a 1-h interval. Indeed, in a certain number of cases, the uncertainty in identifying the S_R can be raised because the range or, more precisely, the class of ranges (see section 4.6) is determined by an irregular variation which clearly dominates all of the other variations within the 3-h interval. It would not be the case with a 1-h interval. (4) When dealing with the zero level a further point will come out in favor of a 3-h interval.

Once the length is chosen, one has to ask whether the morphology of the irregular variation significantly changes with the level of the activity. A positive answer would mean that a certain inconsistency would result when comparing or averaging data for various activity levels. Figure 8 shows normal sensitivity records for 2 different days at a subauroral station, but the low-sensitivity record is also given for the day which is much more disturbed. It appears, by comparing the top record and the bottom record, that the morphology of the variations looks very similar in spite of the change in the activity level (it is in a ratio of 4.5/1.0 in these 2 days according to the *am* index). We believe that this observation is of general value, although we do not statistically check it (it obviously corresponds to the configuration of the magnetosphere). However, when a very violent storm occurs, the morphology becomes completely different. Irregular variations in the form of pulsations, whose period is about 5–10 min, take place and last for hours. In that case the range falls under the same defect as the standard deviation (see section 4.2.1) because it does not detect the change in the morphology. But from the viewpoint of the quantity $\|\boldsymbol{\beta}\|_2$, this does not matter much: an rms quantity is not very sensitive to the period.

4.4. *The Zero Level*

Range indices by definition make abstraction of any zero level, and it seems superfluous to comment on that. However, this implies some consequences.

An illustration of what happens at a low-latitude station on some occasions is given in Figure 9. It displays an *H* record at the time of the main phase of a storm, and the range within each 3-h interval is indicated. Obviously, the range does not measure the intensity of the disturbance, which in that case, would be approximately the deviation from the dashed line drawn on the left-hand part of the record (it represents a possible identification of the regular variation S_R on that day). Even so, one does not know whether this level is a true zero level for the ring current. Furthermore, any range scaled over a time interval of a few hours is a meaningless measurement of the ring current variations, since their variation rate makes their duration much longer; the same is true of any irregular variation whose duration is longer than the constant time interval on which the range is scaled.

At subauroral latitudes the range of the auroral variations usually dominates during the main phase of the storms, and one may say that *K* indices are not sensitive to the latter. Furthermore, at such subauroral latitudes it is rare that the amplitude and the duration of an auroral variation cause a significant deviation from the apparent zero level (nighttime level, or S_R) for a time interval longer than 3 h. But this is no longer completely true at auroral or low latitudes (in particular, for the eastward auroral electrojet and the low-latitude negative afternoon/evening disturbances); in the *Z* component it would be the same at the subauroral latitudes themselves (see section 4.5). In that sense, irregular variations in the horizontal components at subauroral latitudes have certainly the morphology which is the most suitable in order to be monitored by a quantitative parameter such as a 3-h range. The same could be

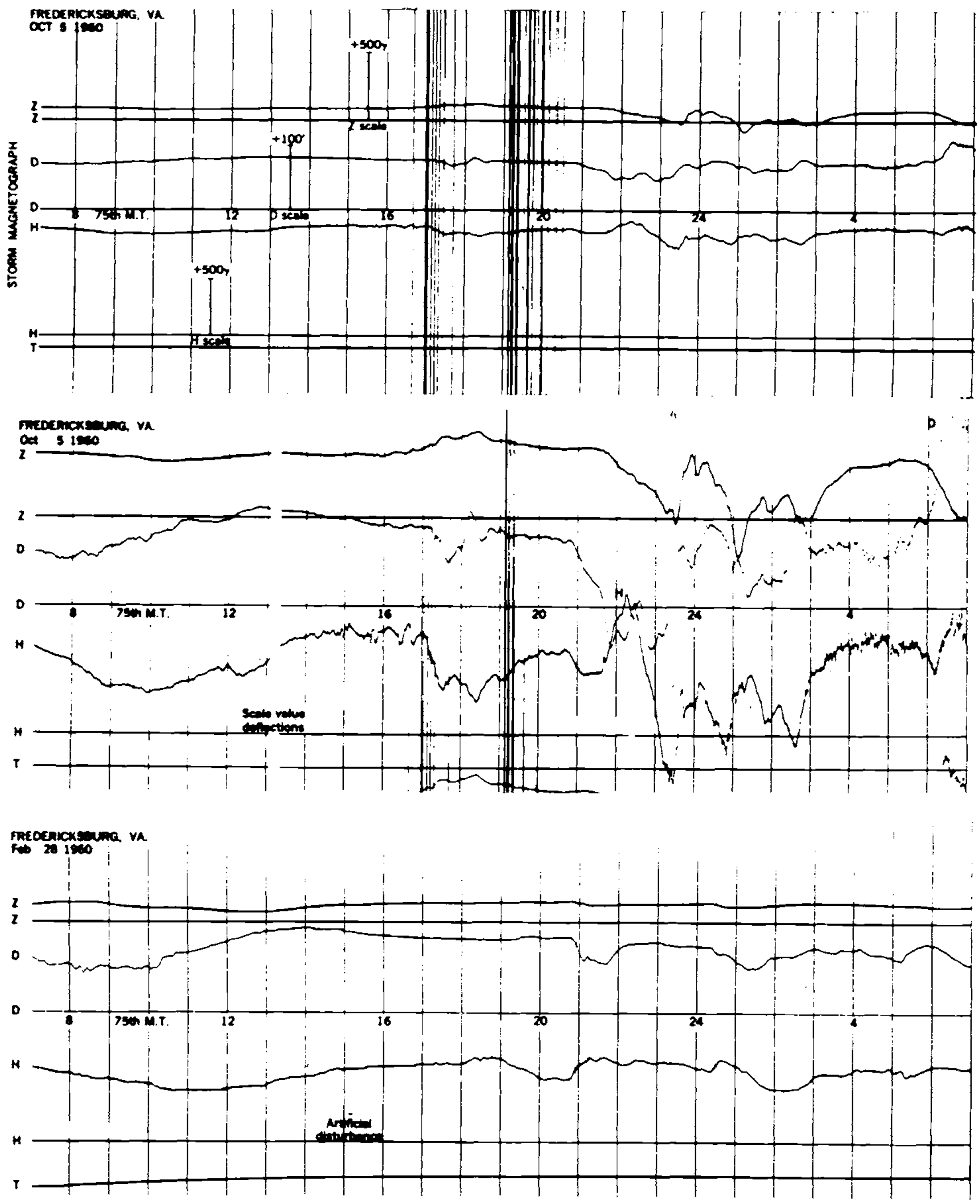


Fig. 8. Comparison of various Fredericksburg (a subauroral station) records showing that the morphology of the main irregular variations to which *K* indices are mainly sensitive does not vary much with the level of the activity [after *Mayaud,* 1967*a*].

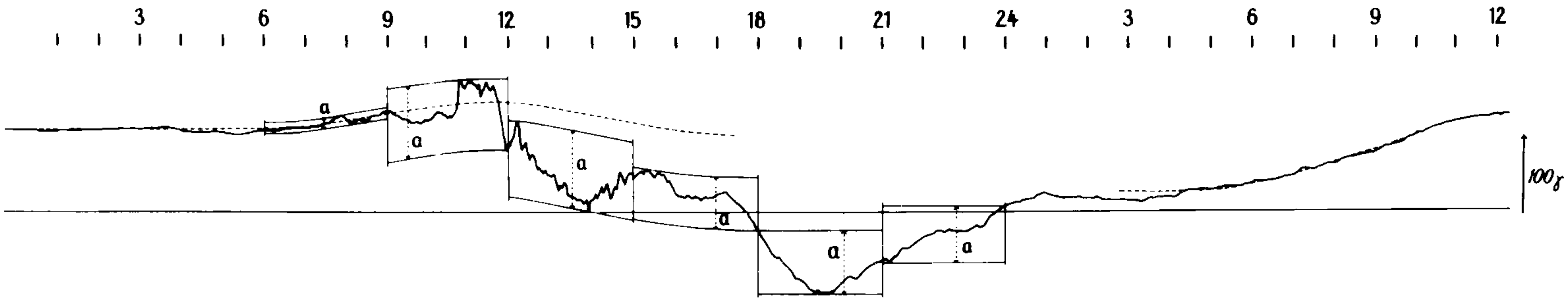


Fig. 9. A record of the H component at Guam, a low-latitude station. For some of the 3-h intervals the range a corresponding to the definition of the K index (i.e., difference between the extreme of the variation within the interval after eliminating the S_R) is indicated [after *Mayaud*, 1967*a*]. Let us note that this figure also illustrates the process of the elimination of the regular variation S_R when scaling the K indices. Assuming that the variation S_R from 6 to 18 hours may be estimated to be the dashed line (this estimation is, however, probably very doubtful because it would mean that the intensity of the S_R would be much smaller on that day than on the following day [see *Mayaud,* 1967*a*, pp. 58–59]) one draws within each 3-h interval two lines parallel to this assumed S_R. The upper one passes through the observed maximum, and the lower one through the observed minimum. The distance between these lines corresponds to the range of the irregular variations after subtraction of the assumed variation S_R. Although similar curvilinear rectangles are not drawn during the following day when the assumed S_R is almost identical with the observed curve, it well appears that no elimination of the S_R would give values of K almost identical with those obtained during the storm. This clearly illustrates the necessity of the elimination of this regular variation. See the atlas of K indices [*Mayaud*, 1967*a*] for the practical way for an observer to scale the K indices (in particular, it does not necessitate the drawing of each upper and lower lines within each interval).

said concerning the 1-h R index in the polar caps; the morphology of the irregular variations there is such that a shorter constant time interval becomes significant.

These various remarks are of importance for the validity of the interpretation of the range by $\|\beta\|_2$. This interpretation implies that the variations from which the range is scaled go through the zero level during the interval Δt. If one considers that the ring current effects whose pseudo-period is longer than 3 h are excluded from β (that is, the indices defined so do not monitor the ring current effects), one may assert that at subauroral latitudes the other irregular variations included in β cross, most of the time, a zero level identified as the regular S_R or its level at night. When they do not, the deviation from it is small and does not greatly increase the upper bound. This is no longer true at auroral latitudes or at low latitudes and certainly less strictly true at mid-latitudes than at subauroral latitudes.

Let us note finally that the absence of any reference to a zero level, so difficult to determine, greatly facilitates the scalings. We shall see how difficult it is to solve this problem in the case of the *AE* or *Dst* indices. However, with the K indices the difficulty arises at another step: the elimination of the variation S_R (see sections 4.6 and 4.7).

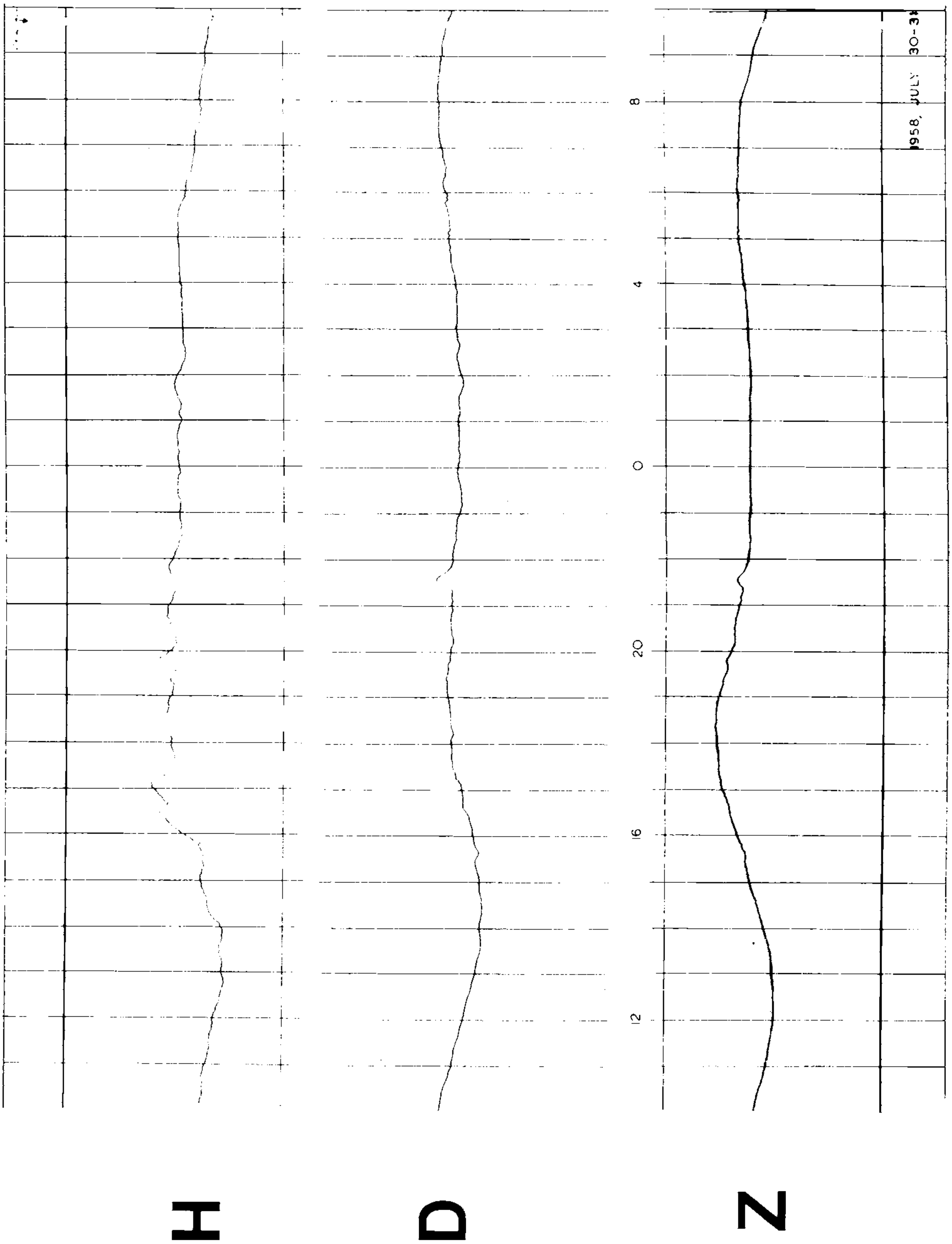
4.5. *Use of the Largest Range in the Horizontal Components*

Obviously, the choice of the largest range concerns only the K index, since the R index is given for each of the horizontal components. But it would similarly concern an index based on the standard deviation or the power spectrum if one wishes to keep a single number for each time interval. We shall see, anyway, how important the use of both horizontal components is.

At the beginning, the Z component was taken into account in deriving K indices. IAGA decided in 1963 that it must be no longer used (*IAGA Bulletin, 19,* 1963, p. 359, resolution 4). Two reasons motivated such a decision. (1) Abnormal underground-induced effects are more frequent and large in this component. (2) No index derived from a single station can be a 'planetary' index, but must represent, as far as possible, the effects of the disturbances at the latitude of the station. Now, the Z component is more sensitive, especially in the case of the auroral variations, to field sources which are farther from the station. Let us suppose, for instance, that one wishes to study the latitude variation of the activity: the maximum obtained will be less acute with the Z component. A third reason may be added: the elimination of the S_R variation is much more difficult in the Z component because sometimes irregular variations become very smooth, particularly at subauroral latitudes, and are practically impossible to discriminate from the regular variations (see Figure 10).

The image of the 'box' given by *Bartels et al.* [1939] (see section 4.1) describes the process used (choice of the largest range), but this is not a physical justification. With the nonuse of the Z component, the box becomes a rectangle and *Mayaud* [1967*a*, pp. 16–21] tried to discuss quantitatively to what extent the largest range approximates a derivation based on the length of the diagonal. In fact, the K indices (that is, the classes of ranges) in each component taken separately, and not the ranges themselves, are used in this discussion. This weakens the reliability of the conclusion according to which the diagonal of the rectangle is correctly estimated most of the time. Indeed, the derivation suffers from the same defect as the Crichton Mitchell index (see section 3.5): the irregular variations do not maximize at the same instant in both components. The only difference with the Crichton Mitchell index is that Bartels does not call for a physical formula to justify this choice.

Before evaluating the meaning of the largest range in the horizontal components with respect to $\|\beta\|_2$, an observational result must be mentioned here. Figures 11 and 12 represent the daily variations, at the three seasons, of the ratio of the activity in components D and H as derived from K indices scaled in each of them and converted into ranges (see section 4.6.1). In Figure 11 a 3-year sample is used at each of the stations of a meridional chain extending from the auroral zone (TR) down to latitudes lower than that of the S_R vortex focus (KS). In Figure 12 an 11-year sample is analyzed at a subauroral station (Chambon-La-Forêt): the bottom row of curves corresponds to all days, while the successive rows correspond to various levels of activity, which increase upward. In the winter (*d*) the daily variation of the ratio D/H is very small, which indicates that at every latitude or activity level the local and universal time modulations are approximately the same in both components. According to Fig-


1958, JULY 30-31
8
4
0
20
16
12
H
D
Z

ure 11 the activity is larger in H at auroral and low latitudes (ratio less than one unit) and larger in D at subauroral latitudes. This is an expected result for the effects of the auroral electrojets (it does not matter whether one considers return currents from them in the ionosphere or through field-aligned currents). In that sense, K indices derived from each component reflect a clear physical feature of the auroral variations. The significant daily variation of the ratio which exists in the summer (j) corresponds to a 12-month wave in the magnetic activity, extensively studied by *Mayaud* [1977*a*] and interpreted by *Mayaud* [1978*a*] as being caused by the DP 2 fluctuations.

Consequently, if we now focus the discussion at subauroral latitudes, we may state the following remarks. (1) Because the D component intervenes often in the final derivation of the K indices and according to the physical configuration of the complete circuits of the auroral electrojets, information is obtained at a given subauroral station on the auroral variations whose primary source is not always at its longitude but is located within a longitude sector more or less spread along the auroral zone. Then any planetary monitoring of the auroral variations can be obtained with a network of stations whose longitudinal distribution is not very dense (it is not the case with the AE index). (2) The contribution of the DP 2 fluctuations to the magnetic activity has not to be judged only from the daily variation of the ratio, which appears quite large, especially at low activity levels. According to the study made either on a 103-year sample in two antipodal subauroral stations or on a 16-year sample in eight sectors of longitude [*Mayaud,* 1977*a*], the 12-month wave induced by the DP 2 fluctuations remains a secondary phenomenon with respect to the auroral variations. The former can be predominant at a low activity level, but they tend to be merged into the latter when the activity level increases. Note that DP 2 fluctuations are well monitored by the D component in the local morning at a given subauroral station and by the H component in the local afternoon. (3) At any time of the local day and at low levels of activity, worldwide fluctuations contribute to K indices, mainly through the H component; as soon as the activity level increases, they merge into the auroral variations. (4) Remember (see section 4.4) that at subauroral latitudes, K indices are not very sensitive to the ring current variations. (5) Finally, but not least importantly, the auroral oval is sufficiently remote from the subauroral latitudes that its dynamic motions have little effect there; the intensity recorded at these latitudes corresponds

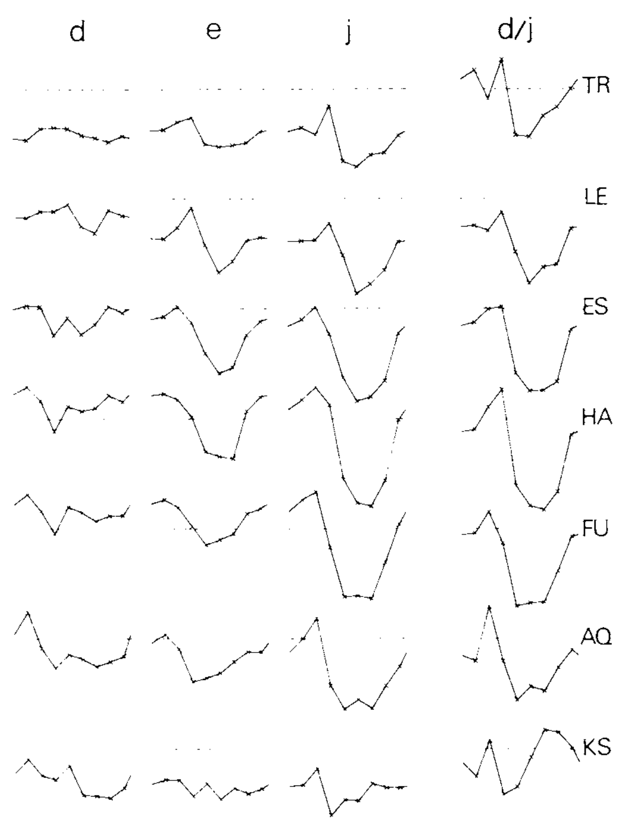


Fig. 11. Daily variation of the ratio D/H of the geomagnetic activity (derived from K indices scaled separately in each component D and H and transformed into midclass ranges) for the three Lloyd seasons (d, December solstice; e, equinoxes; and j, June solstice) of a 3-yr sample in a chain of seven observatories whose longitude is about the same around 10°E and whose latitude varies from the auroral zone (TR) down to about 30° corrected geomagnetic latitude (KS). The ordinate of each dashed line is 1.0, and the distance between two such dashed lines is equal to 0.8 [after *Mayaud,* 1977*a*].

Fig. 10. (opposite) Hartland record for July 30-31, 1958, At this subauroral station the Z variation appears around 1600-2100 LT as regular (in the geometrical sense) as it was around 1000-1500 LT. However, in the former case, it is an irregular (in the temporal sense) variation, since it does not regularly appear and can effectively be related to the occurrence of an eastward auroral electrojet at Tromsö (auroral station). In such a record it is impossible to discriminate between the S_R variation and the irregular variation superimposed on it. In the component D the S_R at these hours is very close to the average curve. In H component, irregular variations (in the geometrical sense) dominate the regular variation S_R whose increase can, however, be easily discerned after 1300-1400 LT [after *Mayaud*, 1978*a*].

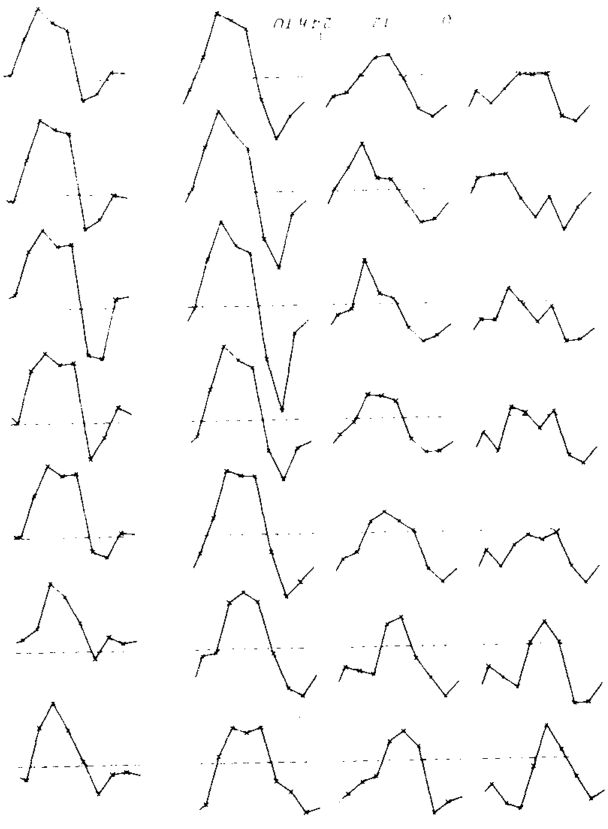


Fig. 12. Daily variation of the ratio D/H of the magnetic activity for the three Lloyd seasons of an 11-yr sample at Chambon-la-Forêt (located between Hartland (HA) and Fürstenfeldbruck (FU); see Figure 11). Bottom row of curves is for all days. In other rows the activity level increases upward from a very low level (daily values of the index *aa* between 2 and 8) up to a high level (between 60 and 120). Same ordinates as those in Figure 11 [after *Mayaud,* 1977*a*].

mainly to the intensity of the primary source and not to its variable location.

These various statements indicate only to which irregular variations the K indices are sensitive and to what latitudes they are most favorable for a significant derivation. They are not a physical justification. If we consider the interpretation of the range by $\|\beta\|_2$, the main point concerns the nonuse of the Z component. Now, the deviations in this component can become quite large at auroral latitudes, when the auroral electrojet current is not far from the station; in such cases, the range obtained from horizontal components only does not satisfy the interpretation. On the other hand, at subauroral latitudes the range in the Z component is practically always smaller than the largest in the horizontal components. Hence the final value of the range is not changed by such a definition, and the bounds given in section 4.2.3 are still valid; furthermore, the contribution of the Z component to the rms of $(\beta)^2$, although it is apparently ignored in the scalings, plays a role and tends to increase the value of $\|\beta\|_2$ with respect to the lower bound.

4.6. Classes of Ranges and K Indices

We deal now with one of the most controversial aspects of the K indices, which can also be the source of many misuses. It is possible that we consider the class of ranges in a different way from its conceiver, Bartels: it is certain that we are stricter now than when we were preparing the atlas of K indices [*Mayaud,* 1967*a*]. Anyway, we try to set forth how we now understand the various problems raised.

4.6.1. A pure code. Apparently, *Bartels et al.* [1939] do not give any explicit indication concerning the substitution of the K numbers, varying from 0 to 9 by units, to the range itself. It is only said that 'the Potsdamer erdmagnetische Kennziffer has served as a model for K, because it had proved satisfactory' [*Bartels et al.,* 1939, p. 417]. One must add to that the wish 'to strike a balance between the required precision and the necessary economy' [*Bartels et al.,* 1939, p. 412]. We think that this aim is fully reached if one uses the K indices in the right way, that is, if one considers the 10 possible values that they can take as a pure 'code' which represents successive classes of ranges. We shall discuss later the limits chosen for each class at a given observatory and from one observatory to another. But this corresponds to other problems which must not conceal the main point: the K index is a code. Letters could as well be substituted for the numbers (this could prevent some misuses).

Let us assume that the choice of the class limits is suitably made: what is the justification of such a coding? This coding is necessary because of the elimination of the S_R which has to be made. Uncertainties in identifying the regular variations are often such that any scaling of the actual range would be extremely difficult and not reliable; but, in most cases, the scaling of a range class reduces these uncertainties to a negligible level. We do believe that this fact constitutes the main justification of the choice made by the conceiver, and it satisfies the required precision and the necessary economy. In the line of an interpretation by $\|\beta\|_2$, this is extremely important. Indeed, the uncertainty in the S_R identification often results in an

TABLE 1. Successive Upper Limits of the Classes of Ranges Defined for the Niemegk Observatory

K	0	1	2	3	4	5	6	7	8	9
r	5	10	20	40	70	120	200	330	500	....∞

uncertainty in the knowledge of the range itself, which corresponds to the width of a class (see section 4.7 on that point). Hence the uncertainty in the range covers a certain domain, as it is with the uncertainty in the knowledge of $\|\beta\|_2$, which is itself measured by the domain included between certain bounds. The conditions to be satisfied are (1) that the relative width of these domains (that is, the ratio between the range values at the borders or limits of a given class and the ratio between the upper and lower bounds of $\|\beta\|_2$) be approximately the same and (2) that the whole of the range classes discriminate properly between the possible observed ranges. We shall see below that these conditions are relatively well fulfilled. Let us note that both types of uncertainties are lessened when spatial or temporal averages are used.

But because the K index is only a code, any direct use of it is dangerous. The only reliable use is to convert each K index into an equivalent range by using the midclass range. We give the justification of this assertion when describing the basic 'quasi-logarithmic scale' introduced for Niemegk and the limitations of the principle of the assimilation of frequency distributions. We shall deal next with the quantization problem raised by *Bubenik and Fraser-Smith* [1977] and with the proper weights to be used for the midclass ranges.

4.6.2. The quasi-logarithmic scale. One commonly uses the expression quasi-logarithmic scale when one speaks of the successive limits defining the range classes. This expression is misleading if one infers from it that K indices may be used as quasi-logarithms and that computations may be made with them. In particular, no arithmetic average made with logarithms is justified; it is much less so when the numbers are not true logarithms.

What is this scale? The model of all scales is the one introduced for Niemegk, a typical subauroral station. The description and the justification given by *Bartels et al.* [1939, p. 417] for the limits of the successive steps is as follows (see Table 1): 'the scale proceeds by multiples of 2 up to the range $r = 40\ \gamma$ but then more slowly because otherwise the index would have become too coarse (for instance, $320 \le r < 640\ \gamma$ for $K = 7$), and the higher indices 8 and 9 would never be reached. Other possibilities (for instance, K as a function of log r) were studied but rejected in favor of the scale given. The upper limit $r = 5\ \gamma$ for $K = 0$ was practically given by the scale values of the records (about 3 γ/mm) which make it difficult to estimate smaller ranges with certainty.'

In our opinion this choice is common sense and stands on its own. It constitutes a succession of steps which makes easy the scalings in the records for the lower indices; and the progression has to be distorted for the higher indices in order to avoid that the classes become too wide. It has, however, to be evaluated according to the following: (1) Is the resulting frequency distribution satisfactory? (2) What is the reliability of the conversion into the ranges?

In answer to the first question, *Bartels et al.* [1939] said 'that the choice of the scale has been adequate may be seen from the following distribution of K at Niemegk for the sunspot maximum year 1938; the number of 3-h intervals was

K =	0	1	2	3	4	5	6	7	8	9	Total
Number	348	730	743	599	295	149	38	11	5	2	2920
%	11.9	25.0	25.5	20.5	10.1	5.1	1.3	0.4	0.2	0.1	

This distribution shows that the graduation of K distinguishes as well between the lowest grades ($K = 0$ and 1) as between the higher degrees of disturbance which are well discriminated by $K = 5$, 6, 7, 8, and 9. The intermediate figures $K = 2$, 3, and 4 were assigned to about 56 per cent of all intervals.'

The distributions (Table 2) derived from a 103-year series at two antipodal observatories whose corrected geomagnetic latitude is identical to that of Niemegk show that the sample given above is significant for a high activity level only. In fact, low indices are much more numerous, but the very low percentage of high indices indicates that no information is lost, which is a very impor-

TABLE 2. Frequency Distributions at Two Subauroral Observatories for a 103-yr Sample

	K									
	0	1	2	3	4	5	6	7	8	9
N,%	24.33	24.95	22.13	17.44	7.78	2.61	0.59	0.12	0.04	0.02
S,%	25.65	29.57	20.97	14.84	6.39	1.97	0.46	0.12	0.03	0.01

N, northern observatory; S, southern observatory.

tant point. Furthermore, the progression of the scale by multiples of 2 meets the other condition stated above: ratios between the ranges of two successive limits are equivalent to the ratio between the bounds of $\|\beta\|_2$.

On the other hand, it appears that the distribution is extremely asymmetric when the abscissae used are the K numbers. *Bartels* [1963], evaluating the distribution of 30 years of *Kp*, said, 'The distribution is quite skew. But no apology is needed: nobody will blame the Beaufort scale of wind strength for leading to a similarly skew distribution, because the rare occurrence of intense storms is a feature which should not be suppressed in scaling by forcing an unnatural symmetry on the frequencies of the weakest and strongest winds.' Our own comments on that problem [*Mayaud,* 1967*a*, pp. 31–33] took a similar viewpoint; we believe now that they are insufficient. In fact, this skewness is due to the arbitrary value (K . 0, 1, ...) given to each quasi-logarithm. When one studies the distribution by using the true logarithm of the range of the upper border of each class and if one takes into account the reasons for which the distribution cannot be logarithmonormal (positive conservation, modulation by the solar cycles, etc.), one can point out [*Mayaud,* 1976*c*] from a long series (100 years) that the distributions of the ranges are logarithmonormal, as those of many geophysical phenomena are. Consequently, the fact that one can check such an expected property shows that the apparently arbitrary choice of the various steps of the quasi-logarithmic scale does not distort the data, and it is an a priori justification of the possibility to convert each K into its midclass range, since the ranges, as a whole, have a coherent distribution. But the skewness of the direct K distribution prevents one from making a direct use of them in any average.

Concerning the reliability of the conversion into ranges (the second question posed), let us consider a sample of K indices. Its distribution maximizes for a given value of K, say K_M. A priori, the actual ranges are symmetrically distributed into the class K_M; they should have a tendency to be more numerous in the upper part of the classes for the indices lower than K_M; and it would be the contrary for indices higher than K_M.

In order to check that obvious assertion, one cannot use data from a subauroral station, since actual ranges are impossible to scale with certainty. It becomes more possible at a polar station where regular variations are negligible with respect to the irregular variations. Table 3 gives a result obtained from Fort Rae data during the Second International Polar Year. K_M is somewhere between $K = 2$ and 3. For $K > 2$ the average $\bar{r}$ is lower than the midclass range r_K of the class; for $K < 2$ it is the contrary. Obviously, the sample is too short to provide a perfect experimental confirmation, but the tendency is as is expected, and the logarithmonormal distribution observed for very long series ensures that the conversion is statistically reliable; furthermore, when deriving statistical averages, the error committed in the conversion of the low indices is compensated by that made in the conversion of the high indices. Let us note that any empirical estimation sample of the weights to be used for K [see *Lebeau,* 1965] is dangerous when it's made from a little sample.

We must now draw consequences for the use of the K indices. Three main uses exist: (1) a K index taken separately, (2) the building of a planetary index derived from K indices, and (3) any statistical investigation made either from K indices at a given station or from planetary indices.

It is obvious that the uncertainty on the actual range corresponding to a K index taken separately is measured at least by the width of the class. It is in fact greater because of the more or less large frequency of borderline cases. In this respect, an individual K index is indeed very 'rough' information.

When building a planetary index, one has to average in a single number the K indices from dif-

TABLE 3. Averages $\bar{r}$ of the Actual 3-h Ranges Within Each *K* Class and Values r_K of the Midclass Range at a Polar Observatory

	K									
	0	1	2	3	4	5	6	7	8	9
n	103	236	558	678	484	445	297	96	8	0
$\bar{r}$	7.5	20.6	42.6	82.0	149	274	460	732	1120	
r_K	5.0	20.0	42.5	87.5	163	283	478	793	1243	

The number of ranges within each class is given by n. Values are given in gammas.

ferent latitudes and longitudes. Let us suppose that the *K* scale is well adapted to every latitude (see section 4.6.3). Given the local time daily variation of the activity, *K* values for a given 3-h interval may differ by several units from one longitude to another. Clearly, a direct use of the quasi-logarithmic *K* is not possible; one must convert them into their midclass ranges. If the network is suitably chosen, the average value obtained may be rightly considered to be representative of the average range of the irregular variations within this interval because the above uncertainties (point 1) are reduced in the average.

When dealing with time variations, *K* indices from different time intervals have to be mixed, and in that case they take any value from 0 to 9 (or finer grades with planetary indices). The distortion in using directly quasi-logarithmic *K* indices becomes much more severe; the conversion into the midclass ranges is absolutely necessary.

In all these respects, *K* indices have to be strictly considered as pure codes, which in itself is a necessary intermediate step to make possible the scalings. But finally, the empirical progression of the scale chosen has no effect at all on the results if one is always careful to convert the indices into the midclass ranges. And when one works with average (spatial or temporal) ranges, one probably closely approximates the quantity $\|\beta\|_2$.

4.6.3. Variation with latitude of the quasi-logarithmic scale. The activity intensity greatly varies with latitude, and the scale chosen for Niemegk has to be modified for other latitudes. *Bartels et al.* [1939] proposed a proportionate variation of all the limits between successive classes; the right choice at each latitude has to be such that the frequency distributions be the same (principle of the assimilation of frequency distributions). In that way, a given value of *K* has the same significance at all the observatories, and direct computation with the *K* would apparently be possible. Such computations are already made by these authors at the end of their study.

Originally, the application of the assimilation principle was carried out as follows: 'For the highly disturbed months of January and April 1938, and also for June and October 1938, the actual ranges r in γ were determined for each interval in which they exceeded 40 γ; by counting the intervals with $r \geq 40$, $r \geq 50$, ..., the lower limit for $K = 5$ at the station considered was then fixed so that there were about as many indices $K = 5$ to 9 at that station as at Niemegk' [*Bartels et al.,* 1939, p. 418]. Two other factors were taken into account, but the way in which they have intervened is not clear. The operation was realized for seven observatories and resulted in lower limits of 300, 350, 500, 600, and 1000 γ for $K = 9$, but the proportionate variation of the successive limits with respect to those of the Niemegk scale was biased by rounding processes in some cases. (Thus the scale with a lower limit for $K = 9$ of 350 γ starts with 4 instead of 3.5 and then proceeds by multiples of 2, on the basis of 4, up to $K = 3$; other values seem to be rounded to 5 γ.) The deviations from the truly proportionate scale can go beyond 10%, and this fact troubled us when, recently, we became aware that some *am* observatories used such scales, while in the computation of the *am* index we assumed that all the scales are strictly proportionate. Such scales were rapidly adopted by other observatories without any further checks (see, however, *Bartels et al.* [1940, pp. 334–335] for a rather complex process which was never used). With time, it appeared (1) that incorrect choices were made at some stations and (2) that the principle of the frequency assimilation by the single proportionate variations of the limits does not work for all latitudes. We shall indicate next a way for the right choice to be made.

Examples of incorrect choices can be taken from stations used in planetary indices derived from K indices. Thus Agincourt (now closed) had a lower limit of 600 instead of 700, while Eskdalemuir should use 650 instead of 750. A difference of 3 to 1 in the number of high indices in a 12-year sample results for these *Kp* stations. Similarly, Victoria and Gnangara, both *am* stations, have lower limits of 500 and 350, respectively, instead of 650 and 450 (we indicate later on how this is taken into account when deriving *am* indices). Sources of such errors are difficult to localize. Probably, there was a hesitation to use other lower limits than those proposed by *Bartels et al.* [1939], in particular in filling the gap between 350 and 500. Certainly, the use of the centered dipole latitude was the cause of too loose choices. A given observatory took (or was attributed to have taken) a certain limit because of its latitude in this coordinate system; one now knows that such a system does not work in organizing the data as far as auroral variations are concerned. A resolution was adopted by IAGA in 1963 (*IAGA Bulletin, 19,* 1963, p. 359, resolution 4) for avoiding in the future incorrect choices at a new observatory: the Working Group on Geophysical Indices must be consulted.

The latitude variation of the irregular variations to which K indices are mainly sensitive is such that proportionate scales will never give an assimilation of the distributions within a wide range of latitudes. *Bartels et al.* [1940] and *Bartels* [1957*b*] already noticed this point. Two main facts interfere according to our own feeling; we never checked their influence by statistical investigations in the records, but they are probably the correct interpretation of the observed discrepancies. Figure 13 gives an example. It represents for a 3-year sample the frequency distribution of K indices at the three *Kp* stations whose latitudes are the highest (that is, Lerwick, Sitka, and Meanook) and at the other eight *Kp* stations. Clearly, there are more high indices at the former and possibly more very low indices ($K = 0$). With the high indices, the difference is the greatest around $K = 6$ and 7. This indicates that the source of the difference is not the great disturbances but intermediate disturbances. At the three high-latitude *Kp* stations, dynamic motions of the auroral oval have still important effects and increase the intensity of a certain number of auroral variations. At the other extreme of the frequency distribution the cause of the difference is much less clear; this is partly due to the fact that the sample used corresponds to early K indices (the

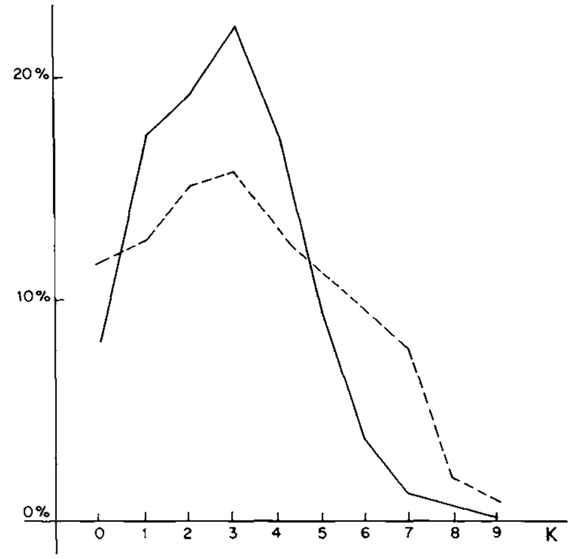


Fig. 13. Frequency distributions of K indices for the 3-yr sample used in the derivation of the conversion tables used for computing the *Kp* indices. The dashed line is the distribution at the three highest latitude observatories of the network (see Table 5). The solid line is the distribution at the eight other observatories of the network [after *Mayaud,* 1965*e*].

sample is made of a 3-year sample during the 1940's) whose quality is sometimes very poor. But we have already said that the influence of worldwide fluctuations becomes important with low indices. Now, their amplitude tends to decrease poleward, while the size of the K scales increases. Then fluctuations, if no auroral variation occurs, can give a $K = 1$ at lower latitudes but $K = 0$ at higher latitudes. These various facts imply that the frequency distribution can be made similar only in successive bands of latitude. How may one choose the optimum K scale?

One can proceed as follows. Suppose one knows the variation law $A(\delta)$ of the average 3-h range of the irregular variations as a function of a latitude parameter δ suitably chosen. Since the scale introduced for Niemegk appears to be reasonable in distributing the ranges within the different classes, the other scales are derived by the formula

$$L(\delta) = L(\delta_0) \times [A(\delta)/A(\delta_0)]$$

where $A(\delta_0)$ is the value taken by $A(\delta)$ at the latitude δ_0 taken as a reference and $L(\delta_0)$ is the lower limit used there. Then the size of the scale is proportionate to the average 3-h range of all the irregular variations. Although the distributions vary with latitude, differences within a limited latitude band around δ_0 are not so great that they prevent one from obtaining a reasonable assimilation of the distributions. Which latitude parameter and which law $A(\delta)$ are to be chosen?

The corrected geomagnetic coordinate system [*Hakura,* 1965] has proved its superiority in organizing auroral phenomena. However, if this is true at the latitudes of the primary sources of the auroral variations (the auroral zone), there is no reason to think that at lower latitudes the intensity of the auroral variations are still well organized in this system. The distance to the auroral zone will be the best parameter because this distance is not constant along a given corrected latitude line. Thus at subauroral latitudes the angular distance to the auroral zone must be retained as the latitude parameter δ. The auroral zone itself is defined by the latitude 69° in the corrected geomagnetic coordinate system. (See in Table 12 how the parameter δ is not equal to the difference of the corrected geomagnetic magnitudes $69° - \lambda$.)

A 9-year sample of K indices, scaled at a chain of European stations, is used to determine the law $A(\delta)$. The indices of each station are converted into midclass ranges, and this operation is not biased by more or less erroneous choices of the scales at each observatory (suppose, however, that the error made does not go above 20%). Crosses in Figure 14 indicate the average range A observed at the observatories (the circle corresponds to a partial extrapolation and is not used), and the law $A(\delta)$ is fitted by least squares through these values. Any heterogeneity caused by abnormally induced effects has some chance of being eliminated. The reference value $A(\delta_0)$ is computed from the equation of this curve for $\delta_0 = 19°$, and $L(\delta_0)$ is taken to be equal to 500.

This is the method used for estimating what would be the correct scale at an *am* observatory (see section 5.2.1). Let us note that Niemegk gets a value $L = 502$ with it. It was also the method used in recent years when a new observatory consulted the Working Group on Geophysical Indices; in that case the $L(\delta)$ value is rounded to the nearest 50 γ.

What are the limitations of the method? It was conceived [*Mayaud,* 1968] for the subauroral and mid-latitude band (included approximately between the two lines drawn on the curve of Figure 14). We would say that at lower latitudes a constant $L = 300$ can be chosen. At higher latitudes the law $A(\delta)$ is not well determined and the formula cannot be used, but the corrected geomagnetic latitude becomes again a suitable parameter. Thus around 60°, 65°, and 70°, L values of 1000, 1500, and 2000 are probably appropriate; they should decrease again inside the polar caps. Finally, at no latitude is there a limitation in the use of the K if one agrees that they always have to be converted into their midclass

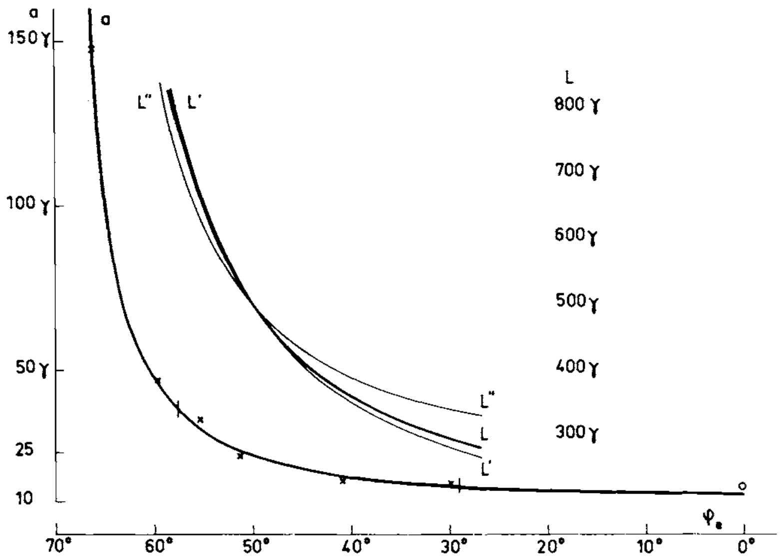


Fig. 14. Curve *a* is the latitude variation of the average 3-h range of the geomagnetic activity (crosses indicate the experimental points to which the curve is fitted). Curve L displays the latitude variations of the lower limit for $K = 9$, as derived from the preceding curve (see section 5.2.1 for a discussion of the curves L' and L''). The latitude parameter φ_e used in the abscissae is equal to $50° + \delta$. The two bars drawn across curve *a* indicate the approximate upper border of the subauroral latitude band and the approximate lower border of the mid-latitude band [after *Mayaud,* 1968].

ranges. However, we will have to evaluate the partial incidences of the method in the computation of the *am* indices.

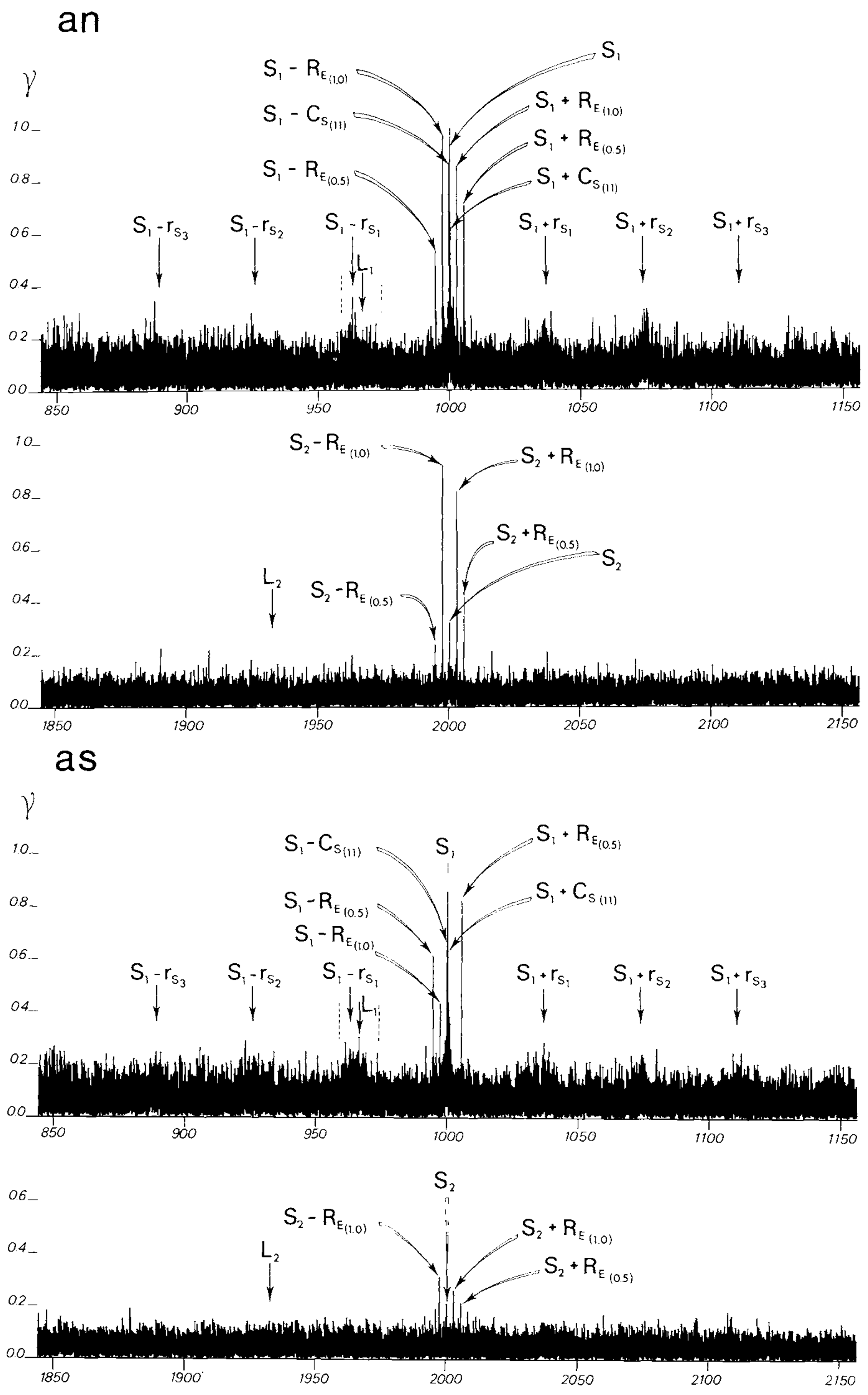
4.6.4. The quantization problem. This last point has been recently raised by *Bubenik and Fraser-Smith* [1977]. Studying the frequency distributions of *Kp* and *aa* indices (such planetary indices are derived from *K* indices), they observe irregularities in the distributions that they attribute to the 'quantization' of the *K* indices; that is, because *K* indices consist in scaling classes of ranges and not the ranges themselves, the midclass ranges resulting from the conversion of the *K* constitute a set of discrete values instead of a continuous series of ranges. The authors assert that such a process induces strong artificial components in the indices which, for instance, could 'affect the most common studies undertaken with them.' They note, however, that irregularities in the distributions tend to disappear when one uses, for instance, daily averages instead of the 3-h indices themselves. *Mayaud and Svalgaard* [1978] already commented on that problem in order to prevent possible misinterpretations of this study. Other remarks can be added.

Let us assume that it would be possible to scale the actual ranges. In any study of their distributions, one would have to rank them into classes; if not, their distribution would be irregular as long as one has not at his disposal a series of thousands of years. *K* indices already make the necessary operation of a distribution into a series of classes. Would one obtain a different result in doing this operation from the actual ranges?

Any sample extracted from an infinite population shows deviations from the ideal distribution which governs or which is suspected to govern the phenomenon. It is the aim of statistical studies to evaluate by some tests if those deviations are above or below a certain threshold from which one can assert whether or not the distribution observed follows the ideal distribution. Now, the geophysical phenomena are never completely distributed at random, but they are submitted to a positive conservation and to a certain number of modulations. What is the length of the sample which is necessary for approaching the ideal distribution of an infinite population?

Bubenik and Fraser-Smith claim the existence of strong artificial components induced by the quantization process in some studies but do not give any examples. Now, when investigating a 103-year series by spectral analyses, *Delouis and Mayaud* [1975] could observe that in the domain of the low frequencies (say, those corresponding to periods equal to or longer than the 27-day period), the spectra are strictly identical when using the 3-h values themselves and when using averages of them for 1 or 8 days, in spite of the fact that such averages diminish the quantization according to Bubenik and Fraser-Smith. Figure 15 reproduces some parts of a spectrum obtained at high frequencies from the 3-h *K* indices themselves (converted into midclass ranges) of two observatories for 103 years. One does not notice any strong artificial components in these spectra but one observes only the following, as is expected: first, a strong 1-day line corresponding to the local time daily variation of the activity in each observatory, and second, a series of nice doublets as are commented on in the legend. The same is observed for and around the one-half day line (see Figure 15) and also for and around the one-third day line (not displayed in the figure). Even in this extreme region of the spectrum, close to the Nyquist frequency (one fourth of a day) where the quantization process should be the most effective, no artificial component appears.

Fig. 15. (opposite) Amplitude spectra of the 3-h midclass ranges in a northern observatory (labeled *an*) and in antipodal southern observatory (labeled *as*) around the 1-day line S_1 (frequency of 1000 cycles per 1000 days) and the half-day line S_2 (frequency of 2000 cycles per 1000 days) for a 103-yr sample. The 1-day lines have been truncated at an ordinate of 1 γ; their true amplitudes are 6.2 and 4.7 γ, respectively. The arrows identify these lines or the various doublets due to the modulation of the daily variation (lines S_1 and S_2) by the 11-yr cycle (labeled $C_{S(11)}$), the 1-yr variation (labeled $R_{E(1.0)}$), the 6-month variation (labeled $R_{E(0.5)}$), and the 27-day recurrences (labeled r_{s_1}) and their harmonics (r_{s_2} and r_{s_3}). The lines of the doublet $C_{S(11)}$ and the line S_1 are not resolved in this drawing: they can be clearly resolved in an enlarged drawing and allow the determination of the average period of the 11-yr line for the 103-yr series much more accurately than the spectrum does at the frequencies of this line (it would be 11.53 yrs instead of 11.13 yrs). Distances between the lines of the doublets $R_{E(1.0)}$ and $R_{E(0.5)}$ give exactly the expected frequencies. Arrows labeled L_1 and L_2 indicate the position of the frequencies corresponding to an ionospheric lunar effect (24 h 50 m 50 s for L_1); the width of the band within which this effect could be felt (±12 min for the variation of the lunar day) is indicated by the dashed lines around the arrow L_1. If any ionospheric lunar effect exists, it is below the level of the noise, since the increase of this noise around L_1 must be interpreted to be due to the 27-day recurrence r_{s_1} which also appears at the symmetrical frequency $S_1 + r_{s_1}$ [after *Mayaud,* 1975].


an
γ
S1 - RE(1.0)
S1 - CS(11)
S1 - RE(0.5)
S1
S1 + RE(1.0)
S1 + RE(0.5)
S1 + CS(11)
S1 - rS3
S1 - rS2
S1 - rS1
L1
S1 + rS1
S1 + rS2
S1 + rS3
S2 - RE(1.0)
S2 + RE(1.0)
S2 + RE(0.5)
S2
L2
S2 - RE(0.5)
as
S1 - CS(11)
S1
S1 + RE(0.5)
S1 - RE(0.5)
S1 - RE(1.0)
S1 + CS(11)
S2 - RE(1.0)
S2 + RE(1.0)
S2 + RE(0.5)

Certainly, any access to the actual ranges would be of interest. We think that we have clearly shown that such an access is not possible at the subauroral latitudes, where the K indices are the most interesting because of the necessary elimination of the S_R. But it truly seems that the quantization process does not invalidate the reliability of the K indices.

4.6.5. Midclass ranges (or weights) for the conversion of the K indices. What values should be used for the transformation of the K? Table 4 gives the first weights given by *Bartels and Veldkamp* [1954, p. 4] and given again by *Bartels* [1957*b*, p. 229] and in the present *IAGA Bulletins 32* and compares them with the true midclass ranges r_m for a K scale with a lower limit of 250 γ for $K = 9$. We shall discuss the differences which appear in section 5.1.3 when reviewing the equivalent range *ap*. In our opinion the best weights are the values r_m which themselves are not strictly proportionate to the weights given in the atlas of K indices [*Mayaud,* 1967*a*, p. 34]. We misinterpreted at that time the weight for $K = 9$ (hence see the other possible choice for $K = 9$ in section 5.1.3).

4.7. Subjective Character of the K Scalings?

In the recent literature, it has been asserted several times that the K scalings are subjective; that is, they greatly depend on the personal judgment of the observer [see *Alldredge,* 1960; *Joselyn,* 1970; *Van Wijk and Nagtegaal,* 1977]. In the course of discussions with colleagues, we often heard similar statements. It is obvious that the K scalings can become highly subjective if the observer has not the professional requirements for doing them. We believe, in fact, that such scalings are objective if two conditions are fulfilled. (1) The observer has a true knowledge of the S_R day-to-day variability during daytime and of the possible extension of the S_R during parts (or the whole) of the nighttime in the records scaled. (2) He follows a very ancient rule of human wisdom: 'When in doubt, don't.'

Bartels et al. [1939, p. 413] were very clear on the first point. Unfortunately, the reference made to a paper by *Bartels and Johnston* [1939] in the same issue had a dramatic incidence: many observers understood that the average so-called *Sq* is the non-*K* variation to be eliminated. The method was so extensively used that *Bartels* [1957*a*] gave it a name, the 'iron curve' method. When the author himself computed the *Kp* index for some early years (1932–1936, less the Second Polar Year itself), he could observe the obvious incidence of this method by comparing K indices of the *Kp* observatories. The result was a communication to the IAGA Assembly at Helsinki [*Mayaud,* 1961] and then the publication of an 'atlas of K indices' [*Mayaud,* 1967*a*] in which the S_R variability is extensively described. But this work is not a final point: as was stated in the atlas [*Mayaud,* 1967*a*, p. 91], each observer has to set up (or should find when he begins) an atlas of the records of his own observatory with typical examples of this variability. This is the only way either to acquire true and realistic knowledge of it or to remember it when one is hesitating during the scalings.

By the old proverb quoted above, what we mean is the following. The difficulty in scaling the K indices does not arise in the extreme cases, very quiet days or very disturbed periods. In the first case, the S_R appears in its pure shape; in the second case, it becomes negligible with respect to the irregular variations. But it is obvious that the precision with which the identification of the S_R has to be made varies inversely with the intensity of the activity. In intermediate cases, quiet parts of the records permit the observer, in general, to identify the S_R; but, as soon as reasonable uncertainties arise, the only way to be objective is to refuse to speculate. When one does not see the S_R, one has not to inject any assumed S_R. It would be a return to a method like that of the iron curve

TABLE 4. Comparison Between the Weights a_K given by Bartels for a K Scale With a Lower Limit of 250 γ and the True Midclass Ranges r_m of Such a Scale

	K									
	0	1	2	3	4	5	6	7	8	9
a_K	0	3	7	15	27	48	80	140	240	400
r_m	1.25	3.75	7.5	15.0	27.5	47.5	80.0	132.5	207.5	400

because at one time one would inject a given S_R and at another time, another one. In order to maintain a consistency (or an objectivity) either between the scalings of a given observer or between two observers scaling the same records or from one observatory to another, any observer has to be more and more prudent when the S_R becomes undiscernible, i.e., apply the above proverb.

Recently, we had the opportunity to visit 24 observatories to discuss the way of scaling with the observers [*Mayaud and Menvielle,* 1980]. We can assert that when they practice both of the above points, the number of differences in scalings falls below a proportion of a few percent. The remaining differences could be solved only by a careful comparison with records of observatories located at other longitudes; this is beyond the accuracy needed in such measurements.

Are computer scalings able to solve that problem in an objective way? Two attempts have been made up to now. Before reviewing them, we have to rule out a proposal sometimes heard: change the definition of the K indices in order to be able to scale them with computers. We would answer as follows: Is science made for computers or computers for science?

Alldredge [1960] proposes 3-h running averages (or longer averaging periods) for simulating the variation S_R. The choice is certainly suitable because it is rare that the S_R undergoes sharp changes or secondary deformations which would not be almost exactly followed by such running averages. That is not the main difficulty. Indeed, the duration of some of the irregular variations is such that very clearly at auroral and low latitudes a part of them would often be eliminated. Even at subauroral latitudes the same is not rare. The records of Figure 8 (from a subauroral station) were chosen for illustrating another feature. But it is clear, when looking at the second record, that the irregular variations in H from 2300 LT to 0400 LT would be partly eliminated, as the regular S_R variation between 0700 LT and 1600 LT would itself be rightly eliminated. Morphological features permit the experienced observer to discern the superimposition of irregular variations upon the regular one, but qualitative features are very difficult to quantify and consequently to insert into a computer program. Their introduction would mean a very complicated program as well as a very high sampling rate. Let us note here to what extent a good optical adjustment of the traces facilitates the observation of the morphological features in the classical records, and the scalings; one already loses a part of these facilities with pen records. Finally, we do not think that this proposal is a suitable solution for the K scalings.

Recently, *Van Wijk and Nagtegaal* [1977] proposed another approach. Harmonic analyses are made for the quiet days of the month which can be considered to be control days. Their number could be varied, and if there is no quiet day, the control days could be chosen in other suitable periods. Then each day is successively scanned with each control day retained, and the K indices are scaled from each one. The lowest range obtained is retained for the final determination of the index because this lowest range would mean that the actual S_R of the day considered is the best approximated one in that case. This is not a use of the iron curve method, since several S_R variations are tested. We think, however, that this other computer method raises several difficulties. First, small but long irregular variations during the nighttime of the control days will always interfere. Second, the variability of the S_R is so large that the probability of properly fitting each day with some control days is very small. Third, and this is the most important point, an identification of the S_R must be consistent during the whole day. What happens if different control days are selected and used for some of the 3-h intervals in a given day because they provide the lowest range? Finally, we had the opportunity of comparing our own scalings with the computer scalings of Van Wijk and Nagtegaal for a 4-month sample of the Hermanus records. Differences observed reached 43% instead of the 32% obtained by these authors, and they are more asymmetrical: 33% of the computer scalings are too high, and 10% are too low. This point shows clearly that the control days are insufficient for taking the variability of the S_R into account. Differences are more numerous in the D component than in the H component for the 2 summer months tested; this corresponds to the very great variability of the S_R in the D component at Hermanus. Differences are more numerous in the wintertime (46%) than in the summertime (39%); this corresponds to a lower activity in the first period (the elimination of the S_R with the computer method becomes more difficult in that case). However, the variability of the S_R at Hermanus is one of the most spectacular that we have observed when investigating this phenomenon;

consequently, it should be said that the conditions for testing a computer method are particularly severe at such a station.

One cannot assert that a proper and satisfactory computer method will not be adjusted in the future. Anyway, we think that K scalings do not need computers to be objective. Furthermore, as long as a correct computer method is not available for identifying the S_R, no choice for a quantitative measurement other than the class of ranges is possible.

4.8. *Conclusion*

Concerning the various uses of the K indices, three points are important: (1) a 3-h index K, taken separately, provides only very loose information, (2) K indices are the most significant at subauroral latitudes, and (3) K indices must always be converted into the midclass range. Concerning their meaning, and especially when used for deriving a planetary index,the K indices provide at least a reasonable monitoring of the range of geomagnetic noise made up mainly by the auroral variations. They probably give a good approximation of the quantity $\|\beta\|_2$, with a factor of about $0.5r$.

The 1-h R index was not mentioned in the last three sections because the problems set forth there do not intervene. We would say that within the polar caps (in a strict sense) it has a similar meaning to that of the K index (converted into a midclass range) at subauroral latitudes.

5. Planetary Indices Derived From *K* Indices (*Kp*, *am*, and *aa*)

Three planetary indices have been successively proposed and adopted by the IATME and the IAGA: the *Kp* index [*Bartels,* 1949], the *am* index [*Mayaud,* 1968], and the *aa* index [*Mayaud,* 1973]. To what extent do they succeed in monitoring the planetary activity on a worldwide scale? The following sections try to answer this question.

5.1. *The Kp Index*

We first describe the preliminary tentative planetary indices which preceded the well-known *Kp* index approved by IATME in 1951 (*IATME Bulletin, 14,* 1954, p. 368, resolution 6). Its derivatives (that is, *Cp, Ap,* and *ap*) are reviewed after its description. Most of the severe criticisms that we are setting forth about the *Kp* index appeared to us when we were computing by hand the first years of *Kp* (1932–1936), and the best way of understanding and evaluating an index is probably to go through all of the details of the computation and thus see how the method works. We hope that our attitude will not appear unfair to the memory of the late Professor Bartels, to whom we are greatly indebted; we merely believe that, with time, progress in knowledge necessarily increases and causes an evolution of viewpoints. Chapter 4 has shown, and the next sections, 5.2 and 5.3, will show to what extent the K indices of which Bartels was the conceiver are an irreplaceable tool for monitoring the magnetic activity on a worldwide scale. Besides, the *Kp* itself, with the extraordinarily wide use made of it during the last 30 years, has largely proved its temporary value.

5.1.1. Preliminary attempts (Km and Kw). 'The eight observatories give eight K indices for each 3-h interval. The average of these eight indices is *Km*; in future, it is hoped that the number of collaborating observatories will be higher' [*Bartels et al.,* 1939, p. 443]. The network used is made up of all the observatories for which K scalings were available at that time, that is, the U.S. Coast and Geodetic Survey observatories (Sitka, Cheltenham, Tucson, San Juan, and Honolulu), the Carnegie Institution observatories (Watheroo and Huancayo), and finally the Niemegk Observatory at which the 'Potsdamer Kennziffer' index K was conceived by Bartels himself. The letter *m* in the symbol *Km* recalls that the index is obtained by the simple mean of the K. Values 2 *Km* (that is, averages are rounded to 0.5) are given for the first 6 months of 1938 in this paper. One has the impression that at this early stage the idea was to follow the scheme used with the *Ci* index (see also the end of this section).

Daily averages are also proposed where the range itself is used in the following way. The 3-h indices are converted into their midclass ranges, and because the principle of the assimilation of frequency distributions is supposed to work correctly, the operation is made directly on the *Km*. Then the average of these midclass ranges is converted back by the K scale; hence a daily amplitude B is expressed in 2 K units. Furthermore, monthly averages are also proposed; they are expressed either by the average of the *Km* indices or by the average of their midclass ranges, itself expressed in gammas on the basis of the scale of Niemegk (a choice has to be made, since scales are not the same at all observatories). Differences resulting from these two processes (averages of quasi-logarithms and averages of ranges) are emphasized, and Bartels later indicated his preference for the latter; thus the index *ap*, which he preferred to the index *Kp*, is derived from *Kp* itself. A third set of data is given, the frequency distributions themselves. This is information which Bartels has always considered to be of importance (see, for instance, the *IAGA Bulletins 12* and *18*, where they are always given, or *Bartels'* [1963] paper, where they are studied at length). They are, however, difficult to handle (see section 6.2).

The understanding of the *K* indices, as developed in section 4.6, invalidates such a derivation of *Km* by a simple average in particular because of the local time daily variations of the activity: in a given 3-h interval, ranges of different longitudes are systematically too different to be averaged by their logarithms. The daily variation of the *Km* for the 6-month sample worked was, however, judged sufficiently small to be negligible. But, in a paper published soon after, the same authors [*Bartels et al.,* 1940] proposed to substitute the *Kw* index (*w* for 'worldwide') for the *Km* index. The reason was probably that with a longer sample the daily variation of *Km* became too large. Three reasons, in any case, are put forward for this new planetary index. (1) The frequency distribution assimilation between observatories appears to be insufficient. (2) Daily variations of the magnetic activity at each observatory are too different, a fact already noticed in the preceding paper: Huancayo has a daytime maximum, the amplitude of the daily variation is very different at Niemegk and Cheltenham, although these stations are approximately at the same latitude, Honolulu presents a double maximum, and the phase at Sitka differs from that of the other nonequatorial stations. (One is impressed that thanks to these first samples of *K* indices the authors are discovering all the complexity of the daily variation with latitude and longitude, but sometimes the true features are masked by the too short a length of the sample.) (3) A summer-winter difference does exist. Now all these factors cannot be properly averaged out in a planetary index with an insufficient network of observatories. Consequently, a standardization has to be made, although 'it obliterates the possible universal daily variation in the worldwide index' [*Bartels et al.,* 1940, p. 335] that *Bartels* [1925] predicted. Such a standardization can be only an empirical one. It consists of again applying the principle of the frequency distribution assimilation in order to average out the influence of these three factors. A frequency distribution of reference (fdr) is made up from a given sample of *K* indices, and tables of conversion are established in assimilating a particular frequency distribution, that is, for a given 3-h Greenwich interval (factor 2) of a given season (factor 3) at a given observatory (factors 1, 2, and 3), to the fdr. Then each *K* index is converted into a *Kr* index by these tables, and the average of the *Kr* gives the *Kw* index (still expressed in 2 *K* units). The fdr chosen is made up of the total frequency distributions at each season for the 2 years, 1938 and 1939, for Niemegk, Cheltenham, and Watheroo used in the combination ((Niemegk + Cheltenham + 2 × Watheroo)/4), which gives equal weight to the two hemispheres in order to balance the summer-winter difference (factor 3). We shall comment below on this method when describing the *Kp* index, which uses a similar one, and on the differences between the fdr chosen in each case. Let us note here only that the network used (the only one available at that time for *K* indices) cannot give a reliable result as it consists of one high-latitude station (Sitka) but only three subauroral stations (Niemegk, Cheltenham, and Watheroo) and three mid- or low-latitude stations (Tucson, San Juan, and Honolulu) and one dip-equatorial station (Huancayo). The last four stations, however, are used with a half weight only when averaging the *Kr* indices.

The *Kw* index was computed for the years 1938-1946; values are tabulated for the first 2 years in *Bartels et al.* [1940], but only their diagrams are published in the first *IATME Bulletins 12.* Note that the *Kw* indices tabulated in this bulletin and in the bulletins 12*a*, 12*b*, 12*c*, 12*e*, and 12*f* for the years 1940–1951 are in fact simple averages of *K* indices (as the *Km* indices described above); the only difference is that because of the much higher number of cooperating observatories they are given in tenths of *K* units. To some extent, this temporary publication of averages of *K* from all observatories confirms the impression that some members of the Committee on Characterization considered that the *K* are similar to the *C*. But the *Kp* index ought to supersede the *Kw* index soon, and it seems that the first announcement concerning it in the literature is from *Bartels and Veldkamp* [1949].

5.1.2. The scheme of the Kp index and its computation. The definition of *Kp* [*Bartels,* 1949] is basically similar to that of *Kw*: the *K* indices of each 3-h interval for a certain network of observatories are standardized through the means of an fdr into *Ks* (analogous to the *Kr*), and after being averaged, they give the *Kp*. Several differences appear: (1) the *Kp* which is expressed in 3 *Kp* (instead of the 2 *Kw*), (2) the network of observatories, (3) the definition of the fdr, (4) the existence of transition tables, and (5) the sample of reference.

1. '*Ks* — and the final *Kp* — is conceived as a continuous variable between 0.0 and 9.0; the interval, say, 1.5 to 2.5, equivalent to the class $K = 2$ is divided equally into thirds, designated by 2_-, 2_0, and 2_+' [*Bartels,* 1949, p. 97]. This symbolization, so popular now, was taken from *Stagg* [1937] who used it for auroral intensity figures. However, symbols 0_0 and 9_0 comprise only 1/6 of the full interval because, for instance, the first class $K = 0$ is considered to correspond to the interval 0.0-0.5. A finer division of the quasi-logarithmic scale is thus introduced, which is used not only for the final step but also in the conversion tables for the standardization of *K* into *Ks*.

2. The first observatory network used includes 11 observatories: Table 5 gives the list with their geographic coordinates (and other data to be discussed later). With time, some of them were closed and replaced by new stations (they are given in brackets, under the previous station, and the year indicates the date at which the new station began to operate). In 1954, Lovö was associated with Rude Skov, and the indices of each of them are used with a half weight; similarly, in 1970, Toolangi was associated with Amberley and is now with Eyrewell. A decision will have to be taken when Meanook closes without any station to replace it; this decision will be an important one because the frequency distribution of *K* indices at Meanook, a high-latitude station (see Table 5), is very different from the other stations because of its latitude but has contributed to the fdr (see section 5.1.4). We have not found in any of Bartels' publications the reasons for the substitution of this network to the *Kw* network. Probably, the idea expressed by *Bartels et al.* [1940, p. 377] was plainly taken into

TABLE 5. The Eleven Observatories of the *Kp* Network

	Geographical Location						
	Latitude	Longitude	Λ	λ	δ	*L*	*l*
(1) Meanook	54°37′	246°40′	61.8°	62.5°	6.2°	1360	1500
(2) Sitka	57°03′	224°40′	60.0°	59.8°	8.4°	1020	1000
(3) Lerwick	60°08′	358°49′	62.5°	58.9°	9.5°	920	1000
(4) Agincourt	43°47′	280°44′	55.1°	57.2°	12.8°	700	600
(Ottawa, 1968)	45°24′	284°27′	56.8°	58.7°	11.3°	790	750
(5) Eskdalemuir	55°19′	356°48′	58.5°	54.3°	13.7°	660	750
(6) Rude-Skov	55°51′	12°27′	55.8°	52.8°	15.2°	600	600
Lovö, 1954	59°21′	17°50′	58.1°	55.9°	12.4°	720	600
(7) Cheltenham	38°44′	283°10′	50.1°	52.1°	17.8°	530	500
(Fredericksburg, 1956)	38°12′	282°38′	49.6°	51.8°	18.4°	520	500
(8) Wingst	53°45′	9°04′	54.5°	50.9°	16.9°	550	500
(9) Witteveen	52°49′	6°40′	54.1°	50.2°	17.5°	540	500
(10) Abinger	51°11′	359°57′	54.0°	49.7°	18.2°	520	500
(Hartland, 1957)	51°00′	355°31′	54.6°	50.0°	17.7°	530	500
(11) Amberley	−43°09′	172°43′	−47.7°	−50.0°	17.7°	530	500
(Eyrewell, 1978)	−43°25′	172°21′	−47.8°	−50.2°	17.3°	540	500
Toolangi, 1970	−37°32′	145°28′	−46.7°	−48.0°	18.5°	510	500
(Canberra, 1979?)	−32°39′	149°30′	−43.8°	−45.2°	24.0°	420	450

A change of site is indicated by listing the new observatory in parentheses. For Rude-Skov and Amberley another observatory was associated from the date given with the original station. It is indicated below the latter. Λ and λ are the dipole and corrected geomagnetic latitudes. *L* is the lower limit for $K = 9$ computed from the angular distance δ to the auroral zone and *l* is the lower limit used for the *K* scalings. All observatories are listed with respect to the λ values.

account: 'magnetic effects of the corpuscular radiation, especially the lower degrees $K = 0$ to 3, are naturally more easily distinguished in the magnetograms of polar stations'. Then two polar stations were added (Lerwick and Meanook), and all the equatorial, low- or mid-latitudes stations were replaced by subauroral stations (including the southern station of Amberley, which substituted Watheroo). One of the main criticisms made of the *Kp* for a number of years (see already the foreword of J. Coulomb, President of IATME in the *IATME Bulletin 12f*, published in 1952) concerns the geographical distribution of this network. We shall come back to that point later. However, one must not forget that at the end of the 1940's, Bartels, as President of the Committee on Characterization of Magnetic Disturbances, was being asked continually by IATME and URSI urgently to provide a new worldwide index. When we were discussing that point with him, he always answered that he deeply regretted that restrictions in the international relations during the postwar years prevented him from using a better network. We believe that this was the main reason for this apparently poor choice, one, however, which is a clear improvement with respect to the *Kw* network.

3. The fdr is made up (*a*) for each of the Lloyd seasons, (*b*) by the sum of the frequency distributions of the two 3-h Greenwich intervals nearest to the local midnight, (*c*) at the 11 observatories taken with the same weight. Furthermore, in order to take the summer-winter difference mentioned above (see description of the *Kw* index) into account, (*d*) the fdr at the June solstice (which is the summer at 10 out of the 11 observatories) is made similar to that of the December solstice in increasing the number of $K = 0$ by 15% and subtracting that amount in equal parts from the numbers of $K = 1$ and 2. Again, we did not find any comment by Bartels on the differences between the choices made for the fdr of the *Kw* index and those of the *Kp* index. With feature *b* the reference is no longer the average frequency distribution for the eight 3-h Greenwich intervals. This means that each of the six frequency distributions not used in the fdr are more greatly modified and therefore distorted by the standardization process. One has probably to see in this choice the belief that night intervals represent better the effect of the corpuscular radiation. With feature *c*, the same weight is given to all the observatories, which are, however, concentrated mostly in Europe, which has such a small area, and feature *d* accentuates the preference given to the northern hemisphere in partly suppressing the 12-month variation. The use of only one southern observatory probably made this last choice necessary. Another point has to be mentioned concerning the establishment (and use) of the conversion tables obtained from the fdr. Attention is given to the relative uncertainty of the conversion in some cases (see below the detailed description of a table) by allowing some limits in the choice of the *Ks* for a given interval.

4. Transition tables are also established; they aim at smoothing the transition from one season to the other when using the conversion tables.

5. The sample used for the fdr and consequently for the conversion tables (let us recall that each of the tables is obtained by the assimilation of the frequency distribution of a given 3-h Greenwich interval of a given season at a given observatory to the fdr) is taken from the years 1943–1948 but does not include the full 6 years. All the days of 1946 and 1947 and the second halves of 1945 and 1948 are used. Furthermore, in order to get more data for the rarer higher degrees of *K*, all remaining days with $Ci \geq 1.2$ of the years 1943–1948, supplemented by 1 day before and 1 day after (in order to avoid a systematic influence of the curvature effect; see *Bartels and Johnston* [1939]) are added. This corresponds to the addition of about 60–80 days per season. The activity level of the sample can be appreciated from Figure 4: it is intermediate between the highest levels and the middle levels. Is the apparent shortness of the sample caused only by the nonavailability of indices at some of the observatories at the time of the preparation of the conversion tables? Or is it caused by the wish to take sunspot maximum years as a reference? It is difficult to judge, since the *IAGA Bulletin 12b* (the one which contains the *Kp* conversion tables) indicates that data were available since 1940 at all *Kp* stations except at Wingst.

Figure 16 illustrates the standardization process for the December solstice at three observatories. The top line gives the even scale of successive frequency sums for the 3-h frequency distributions displayed below for three observatories; there are 424 intervals corresponding to the 424 days of the sample for that season. Then the fdr is displayed under the label 'standard.' Limits indicated for *Ks* correspond to the frequency sums of all the *K*

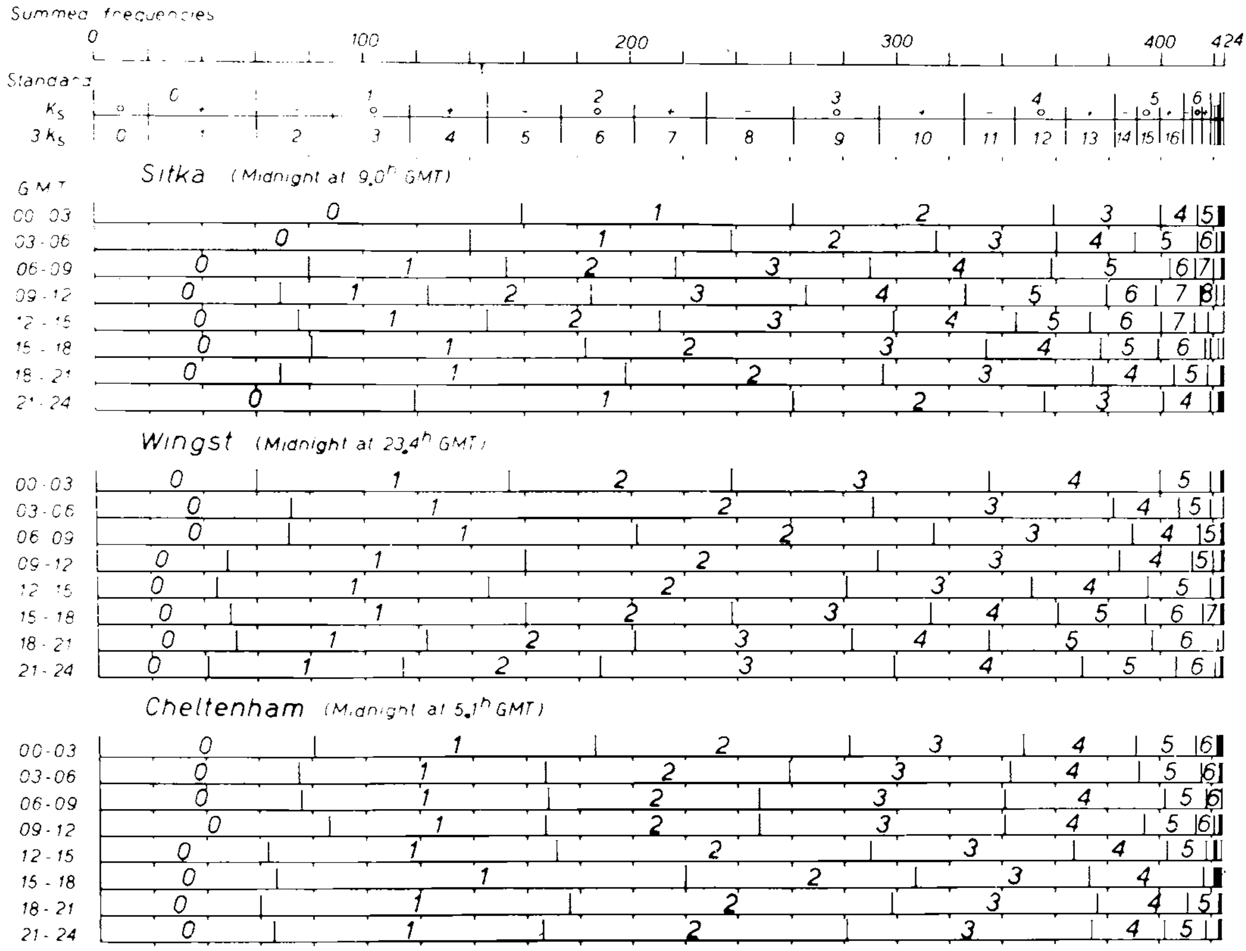


Fig. 16. Standardization for group JFND, i.e., for the months of the December solstice [after *Bartels,* 1949].

contributing to the fdr; remember that the total number of these indices is equal to 2 (the two night 3-h Greenwich closest to local midnight) × 11 (the 11 observatories) × 424 (the number of days in the sample), that is, 9328 indices. The limits indicated for the 3 *Ks* correspond to a division of each *Ks* domain into three parts (except for $Ks = 0$ divided into one third and two thirds). The other three parts of the figure show at three of the *Kp* observatories the frequency distributions of the sample for the eight 3-h intervals of the Greenwich day, each of which has to be standardized by the fdr (the local midnight is indicated). Each *K* number is placed at the center of its respective domain within each distribution, so that its corresponding 3 *Ks* in the conversion table can be read by going straight upward to the scale of the fdr. Thus at Sitka, for 0000–0300 GMT, $K = 1$ gives 3 $Ks = 7$, and the limits of the domain of this $K = 1$ are 3 $Ks = 5$ and 3 $Ks = 8$. When the distance between limits exceeds a range of 4 in 3 *Ks* units, it is integrated in the table (see Figure 17). The way by which the standardization works becomes obvious. Let us take Sitka, where the daily variation is particularly large in amplitude (its maximum is on the fourth interval where low indices are the least numerous: $K = 2$ is more to the left than the other 3-h Greenwich intervals, and $K = 8$ appears on the right-hand side). Now, the resulting conversion table (see Figure 17) indicates that the 3 *Ks* are equal to or are a little smaller than 3 times *K* for the third, fourth, and fifth intervals but larger or much larger for the others. It means that, as expected from characteristic *b* of the fdr, the standardization systematically raises the observed data to a night level of activity. Let us note, however, that in this table all the standardized 3 *Ks* for $K = 0$ or $K = 9$ are taken equal to 0 or 27 (the same is true for all the tables) in spite of the fact that this does not correspond to the standardization rules. Thus in Figure 16, all the $K = 0$ should have a corresponding 3 *Ks* equal to 1 or higher, and two of the $K = 9$ (see Figure 17) should have a corresponding 3 *Ks* equal, respectively, to 24 and 23 instead of 27. Such a distortion is, however, the

	Sitka JFND							
K = 0	$\textcircled{0}^{0}_{5}$	$\textcircled{0}^{0}_{4}$	0	0	0	0	0	$\textcircled{0}^{0}_{4}$
K = 1	7	6	3	3	3	$\textcircled{4}^{2}_{6}$	$\textcircled{4}^{2}_{6}$	$\textcircled{6}^{4}_{8}$
K = 2	10	9	6	5	6	7	8	10
K = 3	13	11	8	7	8	10	11	13
K = 4	16	13	11	10	10	12	14	17
K = 5	19	16	14	12	12	14	18	21
K = 6	22	19	17	14	14	16	21	23
K = 7	24	22	19	16	16	19	24	25
K = 8	26	25	22	19	19	22	26	26
K = 9	27	27	27	$\textcircled{27}^{21}_{27}$	$\textcircled{27}^{19}_{27}$	27	27	27

Fig. 17. Table of conversion of Sitka for the December solstice. The columns of the table correspond to the eight 3-h intervals of the Greenwich day. For instance, if a $K = 6$ is observed at Sitka during the second (or the fifth) 3-h interval, the corresponding 3 *Ks* is equal to 19 (or to 14). Figures associated wtih the 3 *Ks* in circles indicate the extreme limits of the corresponding 3 *Ks* in some cases [after *Bartels,* 1949].

necessary condition for sometimes obtaining a *Kp* $= 0_o$ or 9_o. It seems that it corresponds to a systematic application of the use of the limits kept in the tables for some of the *Ks*: 'If the *Ks* for one observatory deviates considerably from the *Ks* for the other stations, the limits given in the conversion tables are used occasionally to change that *Ks* by one or two thirds in the direction of the value for the other stations. This provides a welcome lee-way in rounding off, particularly for $Kp = 0_o$ and 0_+, and for 9_-, 9_o' [*Bartels,* 1949, p. 108].

5.1.3. Tabulation of the Kp index and of its derivatives (Cp, Ap, and ap). *Kp* values are distributed very regularly bimonthly or monthly on request by the Geophysikalisches Institut of Göttingen. They are also given in Solar Geophysical Data, prompt reports, and in the Journal of Geophysical Research. From 1949 onward, they were published in the yearly *IATME* or *IAGA Bulletins 12,* and since 1970 they are published in the yearly *IAGA Bulletins 32.* Values for 1945–1948 were inserted in *Bartels* [1949]. The years 1940–1944 soon appeared in *IATME Bulletin 12c* (1950), and the 13 months of the Second International Polar Year (August 1932 to August 1933) in the special *IATME Bulletin 12d* (1950); the years 1937–1939 appeared in the *IATME Bulletin 12g* (1954) after the scalings of *K* indices at Meanook and Agincourt were carried out by Bartels himself. Finally, the gap between 1932 and 1937 was filled (*Bulletin 12l,* 1961) after the author made the scalings of the indices at six of the *Kp* observatories (note that the *K* indices of Amberley were not available for that period). Let us note furthermore that values of the *Kp* index and its derivatives are tabulated for the years 1932–1961 by *Bartels* [1962]. From the beginning and according to a scheme already used by *Bartels et al.* [1939], any tables of the *Kp* were accompanied by the graphical representation which was to become famous under the name of 'musical diagrams' given by Bartels himself (see an example in Figure 18). They well illustrate the solar recurrence by using the 27-day solar Bartels rotations.

The origin of the various derivatives of *Kp* is complex. This is due to an erroneous (in our opinion) request of IATME at the Oslo meeting (1948), according to which 'proposals for a method of the determination of *Ci* from *K* indices which would give a homogeneous series of the former' be developed (*IATME Bulletin, 13,* 1950, pp. 22–23). Without that request, Bartels would have developed directly the *ap* indices from the *Kp,* according to the way already proposed in previous papers [*Bartels et al.,* 1939, 1940]. We are convinced that Bartels did not agree with the request (all his criticisms of the *Ci* index are again set forth in the work introducing the *Cp* index). But he immediately undertook the task. The result [*Bartels,* 1951*a*] was (1) the new daily *Cp* index presented jointly with (2) a monthly *Ap* index. The 3-h equivalent range *ap* indices, which would have been plainly sufficient in themselves for defining a substitute for the subjective *Ci,* were proposed some years afterward [*Bartels and Veldkamp,* 1954]; when describing them, we shall try to clarify the problems raised by what one calls the *ap* scale.

In order to satisfy the IATME request, Bartels avoided working directly with the *Kp* but used a method similar to that of *Bartels et al.* [1939]: to transform the *Kp* into their equivalent ranges. A direct use of the former would minimize too much, because of their quasi-logarithmic character, the influence of 3-h intervals which are more disturbed and would provide a poor characterization of the day. Consequently, a weight *g*, which is an equivalent range expressed in 2 γ units, is attributed to each *Kp*; and limits of their daily sums *G* define classes of *G*, each of which corresponds to a given value of *Cp*. The graduation of the latter is identical to that of *Ci,* that is, 0.0–2.0. The other five classes, 2.1–2.5, allow only for discrimination between the most disturbed days. (Such days are relatively rare, since, for instance, there are only 10 days with $Cp > 2.0$ in the sample 1940–1949.) *Cp* and *Ci* are

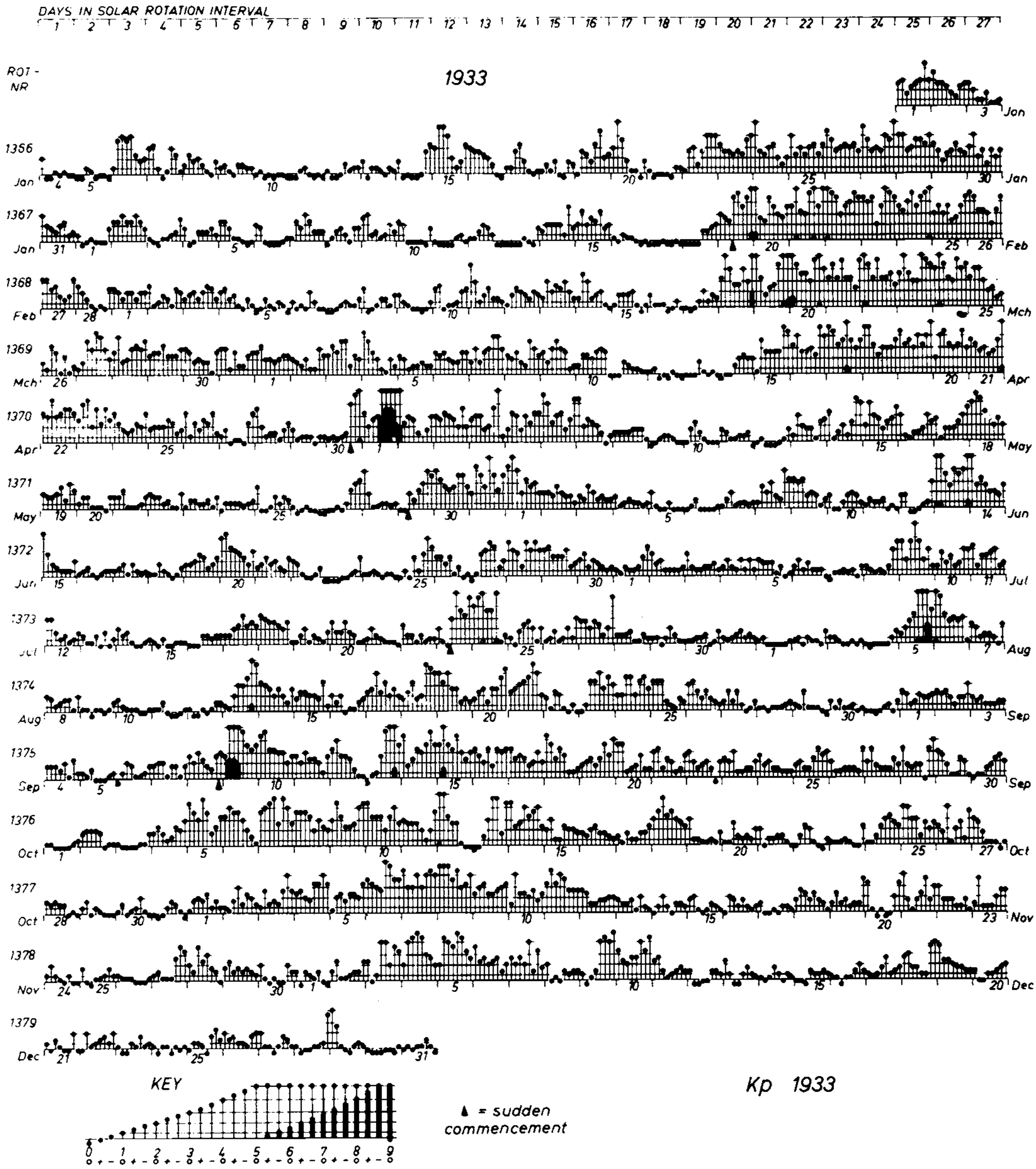


Fig. 18. A 'musical' *Kp* diagram. See Figure 1, where the year 1933 is also displayed from *C9* indices (any 27-day row can be easily identified by the number of the Bartels' rotation) [after *Bartels,* 1962].

made as similar as possible by a choice of the limits of the classes *G* in such a way that an assimilation of the frequency distributions of both indices be carried out for the years 1940–1949.

Bartels [1951*a*] discusses at length residual differences between *Ci* and *Cp*, and we would think that the main interest of this work for him was to display the defects of the *Ci* index (see section 3.2, which refers to this work). Afterward, the *Cp* index was never substituted for the *Ci* as it was foreseen in the IATME request. To some extent, the *Cp* index permitted Bartels to continue the series of the beautiful *C9* diagrams published in the same year [*Bartels,* 1951*b*] from the *Ci* indices (see the example given in Figure 1) with a much less subjective index.

Any empirical influence by the use of a limited sample in the building of an index is dangerous. Given that the *Kp* index from which it is derived suffers from the same defect and from others, we do not think that the *Cp* index is of great value. However, if it is discontinued, one would certainly have to preserve the continuation of the *C9* diagrams with another index.

In the same work, *Bartels* [1951*a*] introduces a monthly *Ap* index. The reason was that he could easily show that some information is lost in the monthly averages of the daily *Ci* and, consequently, of the daily *Cp*. Indeed, the limits chosen for the daily sums *G* when assimilating the *Cp* to the *Ci* correspond to a quasi-logarithmic scale (which indicates that the scale of the *Ci* is also of this type, and that is an interesting point to note). Now, the average of quasi-logarithms is avoided when one directly uses the intermediate weights *g* in order to obtain the monthly average. Bartels calls it *Ap* (*A* for amplitude). A first table of monthly *Ap* is given in *Bartels* [1951*a*, p. 137], and curiously, they are expresed in gamma units while all the subsequent and similar tables have been expressed in 2 γ units as the 3-h *ap* are.

Indeed, the holding onto this 2 γ units for the equivalent 3-h range *ap*, an index introduced by *Bartels and Veldkamp* [1954] in order to satisfy another request of IATME (*IATME Bulletin, 14,* 1954, p. 36), seems to correspond to the wish 'not to give the illusion of an accuracy not justified' [*Bartels,* 1957*b*, p. 229]. On the contrary, if the origin of the *ap* scale was obscure to us as it was for *Rostoker* [1972*b*], we think that we have probably found the complete solution in preparing this work. And this means that we misinterpreted it in the Atlas of *K* indices [*Mayaud,* 1967*a*] and in the description of the computation of the *am* indices [*Mayaud,* 1968]. The *ap* scale, identical to the *g* scale of *Bartels* [1951*a*], strictly corresponds to the midclass (or midsubclass) ranges of the fundamental scale of Niemegk.

Table 6 gives the comparison of the table of equivalence between 3 *Kp* and *ap*, with the midclass ranges r_m of the Niemegk scale expressed in 2 γ units (or of a *K* scale with a lower limit of 250 γ, as was clearly said by *Bartels and Veldkamp* [1954, p. 4]). Indeed, each class of the *K* scale is divided into three equal subclasses, as it is for the transformation of the *Ks* into 3 *Ks* (or *Kp* into 3 *Kp*; see section 5.1.2), and each midsubclass range gives the value *ap*. It is obvious, furthermore, that the first and last classes (*Kp* = 0 and 9) are dealt with according to their special definition: two subclasses only, with respective widths of ⅓ and ⅔ (*Kp* = 0) or ⅔ and ⅓ (*Kp* = 9). And the last two *ap* are fully understood in that way if one assumes that Bartels chose an upper limit of 1100 γ for the class *K* = 9 with the Niemegk scale, a value to compare with the outstanding 3-h interval to which *Bartels et al.* [1939] refer when describing the Niemegk scale and introducing the *K* scales for other observatories (see also section 4.6.3). Between 0600 and 0900 UT on April 16, 1938, a 3-h range of 1900 γ was observed in *H* at Niemegk (see *Chapman and Bartels* [1940, p. 329] for a display of the record). Now, in spite of this exceptional range, Bartels had the wisdom not to raise too much the two highest *ap* values, completely in accordance with the scarcity of such events. The frequency distributions given in Table 2 indicate that with a 100-year series the number of *K* = 9 observed is so low that the probability of going beyond 1100 γ is itself extremely low. On the other hand, there

TABLE 6. Equivalence Between 3*Kp* and *ap* and Values r_m of the Midclass Ranges of the Niemegk Scale Expressed in 2-γ Units

3*Kp*	*g* = *ap*	r_m
0	0	0.42
1	2	1.67
2	3	2.9
3	4	3.8
4	5	4.6
5	6	5.8
6	7	7.5
7	9	9.2
8	12	11.7
9	15	15.0
10	18	18.3
11	22	22.5
12	27	27.5
13	32	32.5
14	39	39.2
15	48	47.5
16	56	55.8
17	67	66.7
18	80	80.0
19	94	93.3
20	111	110.8
21	132	132.5
22	154	154.2
23	179	179.2
24	207	207.3
25	236	235.8
26	300	300.0
27	400	400.0

exists a certain ambiguity for the first two *ap* in spite of the correct rounding (in 2 γ units). If the rounding was made in gamma units and the value kept in these units, one would have $ap = 1$ for $Kp = 0_0$, then $ap = 3$ for $Kp = 0_+$, instead of 0 and 4, where one transforms the 2 γ units *ap* values into 1 γ units. One recognizes here a wish to have a null value at the beginning of the scale. This accentuates the distortion existing in the first grades $Kp = 0_0$ and 0_+ (they cover a full class by two grades of unequal length). Furthermore, any $K = 0$ does not necessarily mean a complete absence of activity, and the following quotation is very clear on that point: 'even $K = 0$ means only that the intensity of disturbance does not exceed a certain threshold; in fact, a complete absence of the slightest disturbance for a full three-hour interval is very rare' [*Bartels*, 1940*a*, pp. 341–342].

Let us note that the a_k and r_m values given in section 4.6.5 (see Table 4) strictly correspond to the midclass ranges of a Niemegk scale, expressed in 2 γ units from $K = 1$ to $K = 6$. The a_k values are higher than the midclass range for $K = 7$ and 8 (we ignore the cause of this choice), and this accentuates the distortion already existing (for high indices the average true range is smaller than the midclass range). It is also possible that the weight for $K = 9$ is too high, and the choice made by error for the *am* index (that is 333.5 in a *K* scale of 250 γ for $K = 9$) is perhaps closer to a regular progression in the scale steps: the half widths of the classes $K = 6$, 7, and 8 are 20, 32.5, and 42.5, respectively, while the half width of the class $K = 9$ is 150 with the weights given in Tables 4 and 6. Now, this half width with a weight 333.5 for $K = 9$ would be 83 γ, which is already a rapid progression when compared to the widths of the preceding classes.

The first IATME bulletin in which 3-h *ap* values were tabulated with *Kp* values is issue 12*g* for the year 1952. This index, derived from *Kp* in a unequivocal way, became rapidly popular among the workers but, maybe, was not sufficiently used with respect to the older *Kp* which is easier to handle. In particular, daily sums of the *Kp*, as given in the first monthly sheets from the beginning, were never completely 'dethroned' by the daily values *Ap* in spite of the numerous comments of Bartels on the more reliable significance of the latter. (Note that *IAGA Bulletin 18* contains only the daily values *Ap* for years prior to 1952, with the exception of the years 1932–1936 newly computed; but this is without importance, since *ap* is unequivocally related to *Kp*.)

The reliability of the indices *ap* and *Ap* is evidently dependent on that of the *Kp* index. We shall now try to make an evaluation of it.

5.1.4. Remarks on the Kp derivation. Most of the quantitative results given below are taken from a previous study [*Mayaud*, 1965*e*]; the comments made on them are sometimes different because of a better understanding. The problem is to evaluate how the fdr of the *Kp* index works.

1. It has often been noticed that there exists a universal time variation in the *Kp* indices [see *Michel*, 1964] which is not a true geophysical effect. We take three samples, each of which is made up of 3 years (say, s_1, 1934–1936; s_2, 1940–1942; and s_3, 1950–1952, the sample used by Bartels being the sample s_0), and we establish new conversion tables from each sample by the Bartels method. Let us call t_j a set of conversion tables based on a given sample s_j. In order to estimate the amplitude of the daily variation of the resulting *Kp*, we convert them into their corresponding range *ap* and compute the quantity $r = \Sigma\ |\bar{ap}_{i=1,8} - \bar{ap}_m|$, where the $\bar{ap}_i$ is the average of each 3-h ap_i of the Greenwich day and $\bar{ap}_m$ is their full average. Since different tables are established for each season, we cannot average the seasons. Then only results for the intermediate season, the equinox, will be given.

Table 7 shows how the quantity *r* varies for a given sample s_i whose *Kp* are computed by a set t_j. Clearly, and as is expected, *r* is smallest on the diagonal but is greater and sometimes much greater in the other cases. It means that the standardization process works well only for the sample used in deriving the set of tables.

2. With a 3-year sample the total number of indices contributing to the fdr of each season is about 10,000. Such a number must not conceal the fact that each frequency distribution standardized by the fdr is made up of about only 450 intervals, distributed within 10 different classes ($K = 0$ to 9). Are such small samples significant? One can try to make the sample longer. The first

TABLE 7. Values of *r* When One Computes the *Kp* Values of a Sample s_i With a Set t_j of Tables

	s_0	s_1	s_2	s_3
t_0	1.9	6.3	14.0	13.3
t_1	13.6	1.1	10.0	8.1
t_2	15.4	3.5	2.6	11.4
t_3	13.2	3.3	8.3	2.1

TABLE 8. Values of r When One Computes the *Kp* Values of a Sample s_i With the Set t_0 or With the Set $t_{0,1,2,3}$

	s_0	s_1	s_2	s_3	s_4
t_0		6.3	14.0	13.3	12.0
$t_{0,1,2,3}$	10.2	2.7	7.0	3.2	7.4

row of Table 8 gives again the quantities of the first row of Table 7 (except the first one since it corresponds to s_0 reduced by t_0) and for comparison the values r obtained by establishing conversion tables with a sample made up of the sum of the four samples s_0, s_1, s_2, and s_3. Let us call $t_{0,1,2,3}$ the set of tables thus obtained. However, since each of the above samples contributes to the derivation of the set $t_{0,1,2,3}$ for one fourth, *Kp* are computed for a fifth control sample s_4 (years 1958–1960).

The most significant point is that sample s_4, which is independent of the reference sample, is better reduced by the set $t_{0,1,2,3}$. Paradoxically, with the latter set the s_0 sample is the one whose reduction is the poorest, and other differences which appear indicate that the frequency distributions greatly vary from one sample to another. Such a fact is due to the changes in the morphology of the magnetic activity in the course of a solar cycle. During the increasing part, violent and short storms occur and are separated by relatively quiet periods (this is the case of the sample s_0); during the decreasing part, recurrent stormy periods often cause an almost constant moderate activity, hence a variation in the frequency distributions. And any empirical choice for a given fdr cannot be adapted to a long series. On the other hand, if one takes an fdr based on such a long series, it will not work suitably for each part of the series. Let us note that the fact of adding disturbed days in the sample s_0 (see section 5.1.2) has probably accentuated the particularity of the fdr used for the present *Kp*. It was, however, probably necessary for avoiding a complete absence of indices $K = 7$, 8, or 9 in some of the frequency distributions which are to be standardized (see Figure 16).

3. The fdr includes only the two 3-h Greenwich intervals closest to local midnight at each observatory. That choice can be questioned for two reasons. (*a*) The time of the daily variation maximum varies with latitude (it occurs later when one approaches the auroral zone); and this must interfere, since the latitude distribution of the *Kp* network is not homogeneous. (*b*) The distortion imposed on the standardized frequency distributions with such an fdr is greater than with an fdr including all the 3-h Greenwich intervals. Now, Table 9 gives the quantities r obtained with the fdr based on the latter choice and on the sample s_0 (tables t_0') and compares them with those obtained with the Bartels tables t_0. Quantities r decrease less than in the preceding experiment (Table 8), but the improvement appears to be quite systematic. Let us note here a further point. By the standardization process, the universal time variation of the magnetic activity is averaged out as already stated by *Bartels et al.* [1939, p. 448; 1940, p. 335], but the phase variation of this phenomenon in the course of a given season (for instance, the phase rapidly changes in the course of the equinoctial season) necessarily induces spurious effects in the individual *Kp*.

4. The aim of the fdr is also to reduce residual differences which exist in the frequency distributions of observatories with latitude or because of an incorrect choice of the lower limit for $K = 9$ (see in section 5.1.1 the enumeration of the factors which led to the use of the standardization process). Now let us suppose that one uses for the fdr only the eight observatories of lower latitude whose frequency distributions of the K clearly differ from those of the three higher latitude observatories (see Figure 13). Let us call t_0'' the set of conversion tables thus derived with the sample s_0. In this new experiment we compute the r quantities for the *Kp* still derived from the 11 observatories (in the *Kw* scheme a similar process was used: all the observatories do not contribute to the fdr). Table 10 gives the results thus obtained.

The decrease of r is again systematic but much smaller with the sample s_1 which corresponds to a lower activity level. In that case, the influence of the expected effect must obviously be smaller because the difference between frequency distributions of different observatories is itself smaller in the part of the distributions corresponding to the lower indices.

TABLE 9. Values of r When One Computes the *Kp* Values of a Sample s_i With the Set t_0 or With the Set t_0'

	s_1	s_2	s_3	s_4
t_0	6.3	14.0	13.3	12.0
t_0'	4.0	10.9	9.8	9.1

TABLE 10. Values of r When One Computes the Kp Values of a Sample s_i With the Set t_0 or With the Set t_0''

	s_1	s_2	s_3	s_4
t_0	6.3	14.0	13.3	12.0
t_0''	5.8	10.0	9.0	8.3

Thus, no fdr can, in the standardization process, completely reduce too large differences between the frequency distributions (see Figure 13). In individual Kp indices the resulting effect is accentuated because two out of the three high-latitude observatories are in North America; and Agincourt, in the same reigon, has too small a lower limit l (see Table 5). Other remarks can be made from this table. Meanook is too high in latitude to consider the L value computed to be significant. Anyway, with a 12-year sample made up of the samples s_0, s_1, s_2, and s_3, this station has almost twice as much $K = 7$ as Lerwick (whose l value used for the K scalings is close to the L value computed) does but has half as much $K = 8$ and 9. This shows that Meanook is much too high in latitude for its frequency distribution to be correctly standardized by an fdr. Fortunately, except at Agincourt and Eskdalemuir (and at Lovö, used with a half weight), the K scales used for the Kp observatories are almost correct (compare l and L values in Table 5).

5. A further point is very critical. In the first description of the Kp index, *Bartels* [1949, p. 97] adds another reason for using a standardization process to those set forth when describing the Kw scheme: 'The practical difficulty in eliminating the non-K variations provides a possibility for another (personal) cause of daily variation in K frequencies.' This indicates that he was fully aware of the poor quality (insufficient elimination of the S_R) of some of the K scalings. But some lines higher up, a statement is made which seems impracticable: 'A change in the scaling practice, even if it were an improvement in the direction of the original conception of K, should never be made without an urgent reason. For the 11 Kp observatories, in particular, a change would mean that their K indices could no longer be used for Kp' (see also *Bartels and Veldkamp* [1949] for a similar statement). From the viewpoint of the use of the conversion tables in deriving Kp, the statement is plainly correct (and demonstrates the fragility of any empirical standardization when deriving indices). But we think that it is impossible to ask an observer to follow indefinitely a subjective way of scaling the K indices chosen by another person (even the iron curve method is subjective because the choice of the average Sq taken as a reference can vary from one observer to another). And experience has shown that methods of scalings varied a lot. Bartels himself during the IAGA meeting at Helsinki (1960), as the Chairman of the Committee on Characterization of Magnetic Disturbances, made the decision to initiate the preparation of an atlas of K indices in order to obtain an objective way of scaling at all observatories according to the original conception of K. No restriction was made for Kp observatories. Now when one looks at the conversion tables given in *Bartels* [1949], it is quite clear that contamination by the S_R exists in them. The effect of the fdr, since it includes only two local night 3-h intervals of the day, should be to raise the 3 Ks during daytime at any activity level, that is, for all the K values. Now for the low values of K in the tables, it often appears that the 3 Ks are lower during daytime than at nighttime, and the effect is greater in the summertime. The contamination by the S_R variation is obvious. One could find in the work of *Mayaud* [1965*e*] an analysis of the low indices K for the five samples s_i, which demonstrates that the sample s_0 was strongly contaminated by subjective K scalings and that the way of scaling has varied in the course of time. Under these conditions there exists in the present Kp indices (and has existed for a long time) a feedback of the S_R contamination in the conversion tables: it is important for low values.

6. A last experiment can be made. What happens if, in spite of the clear insufficient distribution in the observatory network, one computes the Kp by a simple average of the K of each 3-h interval without any standardization? Table 11 gives the quantities r thus obtained for the five samples

TABLE 11. Values of r When One Computes the Kp Values of a Sample s_i With Bartels Tables t_0 or Without Any Standardization

	s_0	s_1	s_2	s_3	s_4
t_0		6.3	14.0	13.3	12.0
No standardization	7.7	2.6	6.0	8.2	4.8

s_i and compares them with the result obtained by the Bartels tables t_0.

It appears that a simple average of the *K* gives a better result. This does not mean that such a process is sufficiently reliable for a planetary index but it shows that the standardization process can induce in any sample from which conversion tables are not derived spurious daily variations; they vary from one sample to another in amplitude (and in phase) and are mainly caused by the effect described in point 2.

Among the five experiments made for evaluating the reliability of the standardizing process used in the *Kp* derivation, the most critical is probably the second one. Each frequency distribution to standardize by the fdr should be made of a sufficient number of *K* indices in order to be significant, but variations in the shape of the distribution with solar cycle prevent the use of too long a sample. With time it appears that the method cannot work because of the geophysical properties of the phenomenon itself. Furthermore, what is the incidence of a change of site for a given observatory (see Table 5) when one uses, as it is made, the conversion tables established for the old site, although the principle of the assimilation of the frequency distributions forbids that?

5.1.5. Meaning and use of the Kp index. All the problems involved in the derivation of the *Kp* index prevent one from saying that the 3-h *ap* provides the correct planetary range for a given 3-h interval. One cannot infer it from Europe and North America only, in spite of the fact that the magnetic activity is most of the time a worldwide phenomenon. And the information used is submitted to so many empirical treatments that one cannot consider the result other than being an approximation. Levels in the magnetic activity are, however, so variable that such an approximation with its quantitative background provided in the past, and has provided up to now, the possibility of classifying periods of time in a much better way than the *Ci* index (which is only a daily and qualitative index) could do. Consequently, the *Kp* index has been a useful tool for classifying 3-h intervals, but one cannot ever be sure that this classification is always correct. Thus *Mayaud* [1970*a*, pp. 122–123] gives some examples where *Kp* differs by more than one unit from the *Km* index. Such uncertainties are caused by the effects

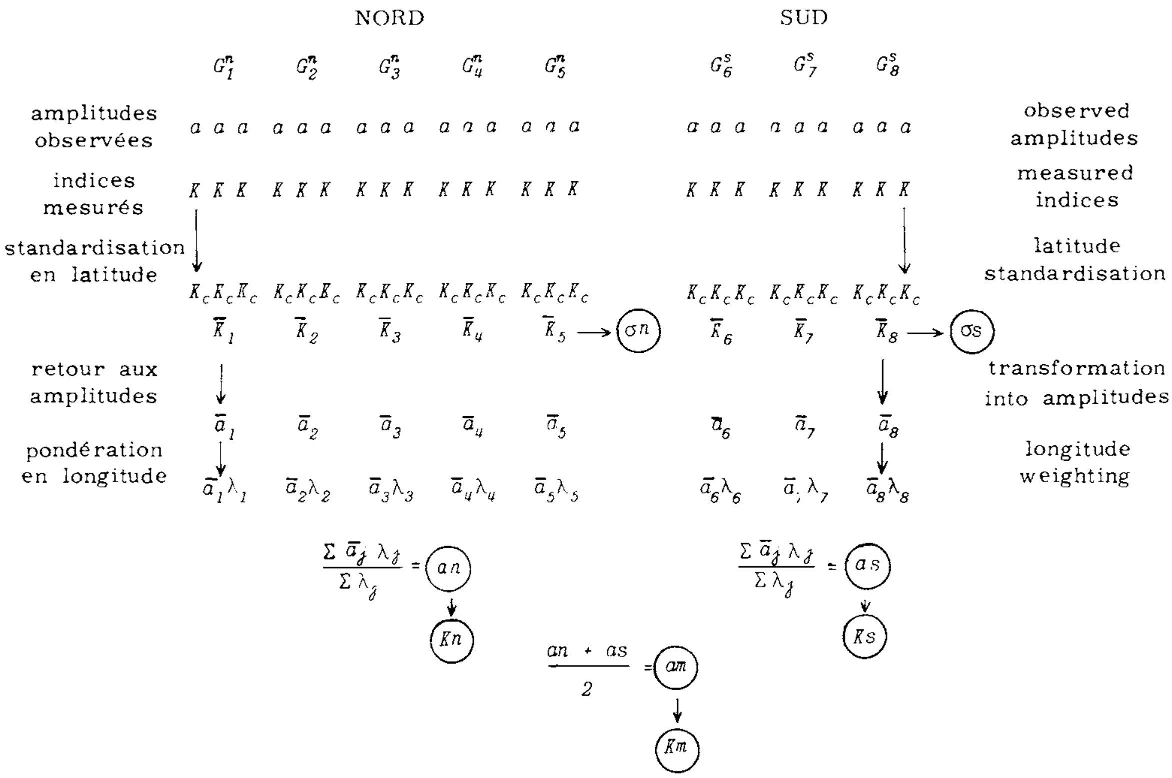


Fig. 19. Scheme of the *am* range index computation. The symbols surrounded by a circle are those which are tabulated in the IAGA yearly bulletins [after *Mayaud,* 1968]. Let us note that, after consultation of the Working Group on Geophysical Indices, the group $G_6{}^s$ was split up into two groups as of January 1, 1979; see the text p. 65.

described in the experiments of the last section, by the lack of information for the largest part of the globe and finally for low indices by the S_R contamination in the conversion tables. *Mayaud* [1976*b*] pointed out another example of the failure of the *Kp* index in properly classifying the periods. The 20 quietest days with $Ap = 0$ in the years 1932–1969 have a very uneven distribution in the course of a year (10 at the December solstice, 7 at the equinoxes, and 3 at the June solstice), which indicates that the *Kp* index is sharply influenced by the northern network of observatories. By using the *aa* index, an apparently much poorer index, since it is derived from only two antipodal observatories (see section 5.3), one gets for the years 1932–1969 a much larger number of exceptionally quiet days (about 100), although eight of the quietest days obtained with the *Ap* index are excluded from them (they are not exceptionally quiet according to the *aa* index). Furthermore, the distribution is as expected: the same amount of days at both solstices, a lower number at the equinoxes. For all these reasons, the *Kp* index does not monitor the magnetic activity with sufficient accuracy to be considered a good reference for a classification of periods.

Concerning any statistical studies, the *Kp* index suffers from much more severe limitations. (*a*) It does not give any information on the universal time daily variation of the magnetic activity. Now, recently, a component other than the one predicted by *Bartels* [1925] and detected by *McIntosh* [1959] has been discovered: an effect of the azimuthal component of the interplanetary magnetic field predicted by *Russel and McPherron* [1973] and detected by *Berthelier* [1975, 1976] in the *am* index. Let us note that *Svalgaard* [1976a] reintroduces in the long *Kp* series a universal time variation thanks to an empirical standardization made by comparing the *ap* and *am* indices for a limited sample. This was made for testing the validity of the inferred interplanetary field polarity prior to spacecraft data, that is, for a limited scope. But such a practice has to be cautiously used because one does not improve data already empirically distorted by adding a new empirical treatment. (*b*) The standardization included in the *Kp* derivation canceled more or less completely the summer-winter difference, which is a true feature of the magnetic activity. (*c*) This standardization raises more or less arbitrarily the planetary index to a certain night level and does not make that in a homogeneous way (see section 5.4).

5.2. *The am Range Index*

Bartels was forced to use an empirical standardization process because of the nonavailability of a suitable network of observatories at the time of the request made by IATME in 1948. It is, however, interesting to note that the association asked a very short time later (that is, at Brussels in 1951, see *IATME Bulletin, 14,* 1954, p. 36) for a revision of the network used. With time, various factors intervened. One of them permitted one to overcome the difficulty stated by *Rostoker* [1972*b*] in his conclusion ('the nonuniform observatory distribution militates against any efforts to define new indices that will improve the level of information that can be obtained from the indices described in this paper'), and the others required one to retake the ideal scheme described by *Bartels et al.* [1940, pp. 334–335] in improving it. (*a*) Access to other observatories became possible, especially including southern stations such as Kerguelen or Argentine Islands set up at the time of the IGY (see below the importance of them for monitoring the activity in the southern hemisphere). (*b*) The various universal time daily variations mentioned at the end of the last section have been discovered, and it would be a pity that a geomagnetic index used as a reference in many other geophysical disciplines does not display all the properties of the magnetic activity. (*c*) The knowledge of the time and latitude variations of the magnetic activity made progress, and a planetary index can be built in better conditions. All these factors should permit IAGA to provide a better index to the scientific community: this was the aim of the *am* index adopted at its Madrid meeting in 1969 (*IAGA Bulletin, 27,* 1969, p. 123, resolution 2).

Let us note that we entitle this section 'the *am* range index' and not 'the *Km* index.' This is of significance in so much as terminology and symbols are important. The first two publications concerning the *am* index [*Mayaud,* 1967*b*, 1968] were given the title of symbols *Km,* and the reason was an attraction to the very popular symbol *Kp.* In fact, we believe that it is time to return to Bartels' original intuition according to which the *K* index is a 3-h range index (see the title of the paper of *Bartels et al.* [1939]). We think that the description of the *am* index that we are making will plainly justify this point; indeed, this index may be defined as being 'the average 3-h range observed, in each hemisphere, within a band close to a 50° corrected geomagnetic latitude.'

Concerning the first attempt made by *Mayaud* [1967*b*], whose index values were never published, we would be rather critical. Indeed, we used in this attempt simple averages of the K from a worldwide network of subauroral observatories because we were impressed by the result obtained with the last experiment of section 5.1.4. It was an error because the K index is a pure code; but at that time we were not sufficiently aware of that which is developed in section 4.6.

A full description of the *am* index is given by *Mayaud* [1968]. The one that we are now making results from a better understanding of the problems involved.

5.2.1. The ideal scheme of the am range index. Figure 19 illustrates the scheme of the derivation. It tries to stress that most of it is based on the ranges themselves and that K indices are only an intermediate.

The starting point is the 3-h range, measured, however, under the form of a class of ranges (the K index) as observed at stations making up several groups in various longitude sectors of the northern and southern hemispheres (G_j^n and G_j^s). The final indices are the average ranges in each hemisphere (*an* and *as*) and their average *am* (*m* for mondial). To what extent may one assert that the average ranges *an, as,* and *am* are truly representative of the average range of the geomagnetic activity at the earth's surface? Two steps ensure that, with an ideal distribution of the observatories used, this result is reached.

1. First step. Each group of observatories represents a longitude sector in a given hemisphere within a latitude band close to a 50° corrected geomagnetic latitude. To some extent, a single observatory would be sufficient in each sector. There are three reasons for using several observatories: (*a*) one has some chance in that way to compensate differences in underground induced effects from one observatory to another, (*b*) any change of site of a given observatory will have a smaller incidence on the final result when it occurs, and (*c*) small differences in K scalings (take, for instance, the borderline cases) are reduced within each sector. In this step the goal is to obtain a $\bar{K}_j$ index which would be the one scaled if the ideal single observatory used was located exactly at a 50° corrected geomagnetic latitude. This is obtained by a latitude standardization of the K indices of each group. The transformation of each $\bar{K}_j$ into a range $\bar{a}_j$ gives the quantities used in the second step. Each of them represents the range of the geomagnetic activity in a given sector at the above latitude.

2. Second step. Assuming always that the distribution of the observatory network is an ideal one, i.e., a uniform longitude distribution of the longitude sectors, the simple average of the $\bar{a}_j$ ranges within each hemisphere gives the average range of the geomagnetic activity in them. The local time daily variation of the geomagnetic activity should be averaged out in the proper way, and the universal time variation is kept with all its known components (McIntosh effects, Russel and McPherron effects). However, residual daily variations may arise from various sources. (*a*) The amplitude of the local time daily variation can vary with longitude. We know, for instance, that the component of the activity due to the DP 2 fluctuations probably varies with longitude; it would be greater on the east of the meridian of the magnetic pole in each hemisphere [*Mayaud,* 1977*a*, 1978*a*]. (*b*) Any abnormal underground induced effects, insufficiently compensated for in a given sector, can give rise to a daily variation in an hemispheric index. (*c*) Any asymmetry in the main geomagnetic field, at auroral zone latitudes, may cause differences in the average intensity of the auroral variations. Other items should perhaps be listed. The main point is that the simple average of the ranges $\bar{a}_j$ includes all these possibilities and eliminates any assumption (observations are taken as they are), and the average is possible because the linear ranges are directly comparable with one another. Indeed, all of them are those observed at the same latitude, more precisely at the same angular distance from the auroral zone (that is, an angular distance δ of 19° from an auroral zone located at 69° in the corrected geomagnetic coordinate system). Furthermore, such subauroral latitudes permit the final index to be sensitive to most of the auroral variations even if the longitude distribution of stations is not very dense (see section 4.5 on that point and on the various advantages of such latitudes for a planetary index derived from K indices).

In fact, an ideal distribution of the observatories is not available for various reasons: the main ones are the existence of the oceans (a rather severe limitation in the southern hemisphere) and the nonavailability of observatories in some of the right places. Because of that, the longitude sectors used have not a uniform distribution, and this fact necessitates a 'longitude ponderation' (see Figure 19) when making the average of the $\bar{a}_j$. It will be described in the next section. Before that, something has to be said with regard to the latitude standardization of the K within each sector. It is important, indeed, to point out to what extent the method used is free or not of any empirical assumption.

All the observatories are not at the ideal latitude (a 19° angular distance from the auroral zone), and one has to be sure that the K scale used at each observatory properly takes the latitude variation of the intensity of the magnetic activity into account. We described in section 4.6.3 a method for evaluating the correct lower limits L for $K = 9$ to be used within the subauroral band of latitude; it originates in the definition itself of the K index (a class of ranges whose midclass ranges are representative of the actual range) and means that the K indices scaled with such limits L are standardized in latitude. We shall evaluate below the rate of empirical approximation involved in this method. But how does one proceed if the lower limit l used at a given observatory differs from L? Figure 20 illustrates the way by which K indices are corrected in order to carry out a complete latitude standardization. Let us assume that the K scale used at a given observatory is $l = 500$ when it should be $L = 600$. If one scales $K = 6$ with the former, one would scale sometimes $K = 5$ and sometimes $K = 6$ with the latter, and one would scale $K = 6$ more often. Now, the middle of the class $K = 6$ of the scale l corresponds to a certain position within the class $K = 6$ of the scale L. The borders of the latter class may be reckoned as corresponding to 5.5 and 6.5, respectively; and linearizing the K scale within this class (and, also, within each class) gives a values $K_c = 5.67$ in the scale L for the middle of the class $K = 6$ in the scale l. That value is closer to 6 than to 5, as is expected: according to Figure 20, one would obtain with the scale L about twice as many K equal to 6 as K equal to 5 when one has $K = 6$ with the scale l.

The K_c of each observatory in Figure 19 are obtained by such a process. Since the computed value L of each observatory is rounded to the nearest 10 γ and the K indices scaled with a scale l

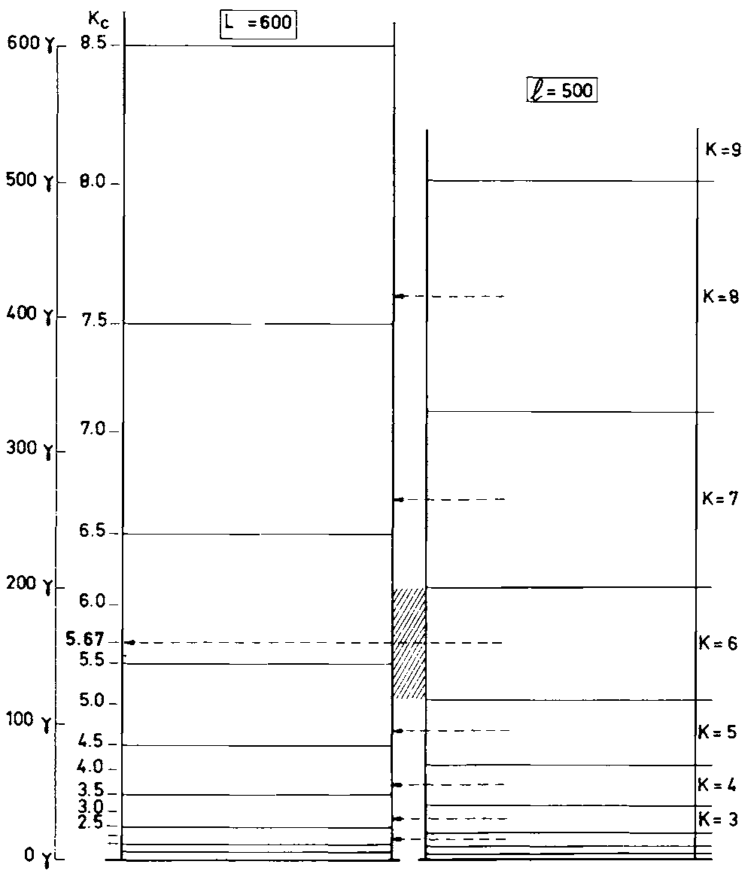


Fig. 20. Diagram illustrating the process used when the lower limit l for $K = 9$ used at a given observatory for the K scalings differs from the lower limit L which would be the correct one for the latitude of the observatory [after *Mayaud,* 1968].

are corrected when $l \neq L$, it means that the K_c are made comparable within a margin of about 1% (5 γ with respect to 500 γ, the most common lower limit L). What are the limitations of such a latitude standardization? Does it contain an empirical bias? We shall examine these points and add some related remarks concerning the transformation of the $\bar{K}_j$ into the $\bar{a}_j$.

The correction process from the K to the K_c implies that the actual ranges are uniformly distributed within each class: even so, a distortion is introduced because a hundredth part (the K_c is taken with two decimals) of a given K class has not the same width as that of the subsequent upper (or lower) class. The second fact does not interfere too much as long as the ratios L/l do not differ too much from the unit (see next section on that point). But the first fact has no influence at all, since it exists as well with the K indices scaled with a correct lower limit L. If it plays somewhere, it is as the level of the transformation of the $\bar{K}_j$ into the $\bar{a}_j$.

The computation of the correct lower limit L implies the use of a limited sample of observations, when determining the law $A(\delta)$ for the latitude variation of the average 3-h range (see section 4.6.3). Furthermore, these observations are obtained from stations located at a particular longitude. The first point is the more critical, but a preliminary remark is necessary. When the activity level increases, the auroral zone tends to go equatorward. Let us suppose that all the stations used are at an angular distance of exactly 19° from the average auroral zone: the intensity observed there would be more increased than at the auroral oval latitude, since the observatories become closer to the auroral oval. One cannot overcome that difficulty: such an effect is, however, less great at subauroral latitudes than at auroral latitudes (*AE* index). Let us consider now a chain of stations in a given sector; it is obvious that the curve $A(\delta)$ of Figure 14 is displaced in latitude with each particular event, and its slope varies within the subauroral band. Again, one cannot overcome that difficulty. Curves L' and L'' of this figure give an estimation of such an effect; they have been computed with two 3-year samples (instead of the 9-year sample used for curve L), corresponding to the years 1958–1960 and 1964–1966, respectively. Their activity levels can be appreciated from the long series displayed in Figure 4: L' and L'' correspond, respectively, to average values of the *aa* index equal to 30 and 16 while L corresponds to 23. The activity level of the sample from which the law $A(\delta)$ is obtained and consequently from which the latitude standardization is carried out through the correct L values, is a little too high (the average value of the *aa* index for the whole series displayed is equal to 18.4). One encounters here a difficulty similar to that described for the *Kp* index in the second experiment of section 5.1.4. However, the resulting empirical limitation in the derivation of the *am* index plays a role only within the groups where some observatories are too far from the latitude at which K indices are standardized, i.e., the angular distance of 19° (see the next section). On the other hand, from one longitude sector to another, any limitation would come from an important variation with longitude in the shape of the $A(\delta)$ law. This is very likely improbable as far as the auroral variations are concerned. Indeed, at subauroral latitudes, field-aligned currents are the cause of the auroral variations observed, and the latitude parameter used (distance to the auroral zone) guarantees the homogeneity with longitude. If within a given longitude sector the average intensity of the ranges is greater because of external (or internal?) sources, the index $\bar{K}_j$ (and the $\bar{a}_j$) will also be greater. This is an observational fact that one has no reason not to integrate in the final result.

Because of the necessary use of several stations within a given longitude sector, one has to make an arithmetical operation on the K (or K_c) by taking their average. This is justified because within a given longitude sector and for a given 3-h interval, K values are almost identical and do not differ by more than one unit. One can go further and consider an ideal case where all the observatories of a given sector would be at the same latitude and the K indices scaled with the same and correct value L. All K indices of the sector should be equal, except because of either borderline cases, slight uncertainties in interpretation of the S_R variation, or small differences in the underground effects. Let us suppose that there are two stations measuring $K = 5$ and $K = 6$ because of a borderline case. Using the average K gives a value of 5.5, which results after transformation into the corresponding range in a value very close to the true range (that is, 120 γ, the border range between both indices). Using the average of the corresponding midclass ranges of the $K = 5$ and 6 would result in a higher value (that is, 128 γ). The difference is not much, but the former process reduces the uncertainty coming from the necessity of using classes of ranges as an intermediate step.

However, if one evaluates the latitude standardization made with the K_c with respect to a K index understood to be a pure code, one must say that the process keeps the trace of a time when the author was not completely aware of the fact that any arithmetic operation made on the $K = 0, 1, 2, \ldots, 9$ is incorrect and has to be avoided. In the present case the division of each step of the quasi-logarithmic scale into 100 equal parts is clearly not satisfactory because it mingles linear and quasi-logarithmic progressions. A much simpler and more logical process would be the following. Within a given latitude band and a given longitude sector the K indices of a given 3-h interval are strictly comparable with each other if the l value used for the scalings at each station is equal to the L value corresponding to the angular distance δ to the auroral zone. Then, when converting the K index into its midclass range, one must not use the midclass ranges of the scale $L(\delta)$ but those of the scale $L(\delta_0)$ corresponding to the angular distance δ_0 chosen as a reference (that is, 500 γ for the $K = 9$ lower limit). Thus the midclass range obtained for each station would be the one which would be obtained if the station were located at an angular distance δ_0. But because in general, l is different from $L(\delta)$, one has furthermore to multiple the range obtained by the correction factor $L(\delta)/l$. With such a method, all quasi-logarithmic distortions are avoided. In fact, differences between the two processes (correction applied at the level of the K or at the level of the midclass ranges) are small, and all the more small as l does not differ much from $L(\delta)$.

The ranges used for the transformation of the $\bar{K}_j$ into the $\bar{a}_j$ [see *Mayaud,* 1968] are those corresponding to the correct K scale for an angular distance of 19° from the auroral zone (L = 500 γ) that is, the original scale of Niemegk. Since the $\bar{K}_j$ are rounded to a tenth, each class is divided into ten equal parts, the tenth subclass being on either side of each limit between subsequent classes. We noticed in section 5.1.3 that the choice made for $K = 9.0$ differs, because of a misinterpretation, from the corresponding value of the *ap* scale; we also said that this *ap* value is possibly too high. On the other hand, special treatment is applied to the two first classes 0 and 1, i.e., for $\bar{K}_j$ = 0.0 to 1.5. Both classes have the same width (successive limits are 0, 5, and 10 γ), although there are only 5 $\bar{K}_j$ grades in the first one (0.0–0.4) instead of 10 as in the second. Now when scaling K indices, the discrimination between $K = 0$ and $K = 1$ is sometimes uncertain. Then both classes $K = 0$ and 1 are considered to be a single class, which is divided into 15 equal parts. Thus a certain distortion is introduced, since, for instance, $\bar{K}_j$ = 0.5 or 1.0 corresponds to $\bar{a}_j$ = 3.33 or 6.67 γ instead of 2.50 and 7.50, respectively. This has to be judged at the level of the final result (average of the $\bar{a}_j$). Indeed, if $K = 0$ is scaled in all observatories of a given group, it means that one is not close to a borderline case, and the activity is rather low in this sector; it is all the more true for a given hemisphere if $K = 0$ is scaled in all observatories of each group. When $K = 1$ is scaled in some places, there is some chance that the activity level be higher. Consequently, the final result (that is, values of *an, as,* or *am* comprised between 0 and 10 γ) should correspond to a significant progression in the low-activity levels. We keep a value $\bar{a}_j = 0$ for $\bar{K}_j = 0.0$ in spite of Bartels remark on the *ap* scale quoted in section 5.1.3. It falls under the same criticism as does *ap* = 0 for *Kp* = 0_o. However, with the *am* index, information is taken in each hemisphere from approximately evenly distributed longitude sectors; hence a value *am* = 0 probably signifies a very low level of activity, which is not necessarily the case with the *ap* index (see the example concerning exceptionally quiet days given in section 5.1.5).

Let us finally note that the quantization of the *ap* index is approximately a third of that of the K index itself. With the *an, as,* and *am* indices, the quantization existing in the contributing K is strongly attenuated in the course of the derivation through the average of the $\bar{a}_j$.

5.2.2. The actual derivation: To what extent, in fact, does the observatory network used deviate from an ideal distribution? Table 12 gives the list of all the stations used with their geophysical coordinates and other items; Table 13 indicates which stations were effectively used in the course of time.

The setting up of Kerguelen and Argentine Island during the IGY provided the supplementary observatories necessary to a reliable index in the southern hemisphere. But data from Kerguelen are too poor before 1959 for deriving the southern index during the IGY. Changes in the network which we shall comment on below either have been imposed by circumstances or correspond to a deliberate wish to improve the network. In our opinion it is better to give priority to

TABLE 12. The Eight Observatory Groups of the *am* Network With Their Geographical Coordinates, the Corrected Geomagnetic Latitude λ, the Angular Distance δ of the Observatory to the Closest Point *P* of the Auroral Zone, and the Corrected Geomagnetic Longitude φ of That Point *P*, the Computed Lower Limit *L* for *K* = 9, and the Lower Limit *l* Used

		Geographical Location						
		Latitude	Longitude	λ	*l*	δ	φ	*L*
			G_1^n					
MG (MGD)	Magadan	60°07′	151°01′	53.8°	14.9°	212°	610	*500*
PK (PET)	Petropavlosk	53°06′	158°38′	46.4°	21.6°	219°	450	*350*
MT (MMB)	Memambetsu	43°54′	144°12′	37.4°	31.3°	207°	340	350
			G_2^n					
PT (POD)	Podkammenaya Tugunska	61°36′	90°00′	57.2°	13.4°	161°	670	650
SV (SVD)	Sverdlosk	56°44′	60°38′	52.2°	17.6°	137°	530	550
TM (TMK)	(Tomsk)	56°28′	84°56′	52.4°	18.4°	154°	510	350
NS (NVS)	Novossibirsk	55°02′	82°54′	50.8°	19.8°	155°	480	500
			G_3^n					
WI (WIT)	Witteveen	52°49′	06°40′	50.2°	17.5°	88°	540	500
HA (HAD)	Hartland	50°59′	355°31′	50.0°	17.7°	77°	530	500
NI (NGK)	Niemegk	52°04′	12°40′	48.8°	19.0°	94°	500	500
			G_4^n					
OT (OTT)	Ottawa	45°24′	284°27′	58.9°	*11.2°*	357°	790	750
FR (FRD)	Fredericksburg	38°12′	282°38′	51.8°	18.4°	354°	510	500
			G_5^n					
NE (NEW)	Newport	48°16′	242°53′	54.8°	12.8°	303°	700	*600*
VI (VIC)	Victoria	48°31′	236°35′	53.9°	13.8°	296°	660	*500*
TU (TUC)	Tucson	32°15′	249°10′	39.7°	27.1°	316°	380	350
			G_6^s					
AM (AML)	(Amberley)	−43°09′	172°43′	−50.0°	17.7°	256°	530	500
(EYR)	Eyrewell	−43°25′	172°21′	−50.2°	17.3°	256°	540	500
TO (TOO)	Toolangi	−37°32′	145°28′	−48.0°	18.7°	221°	510	500
(CAN)	Canberra	−32°39′	149°30′	−45.2°	24.0°	224°	420	450
GN (GNA)	Gnangara	−31°47′	115°57′	−44.1°	22.4°	181°	440	*350*
			G_7^s					
KG (PAF)	Kerguelen	−49°21′	70°12′	−58.0°	*11.7°*	119°	760	750
CZ (CZT)	Crozet	−46°26′	51°52′	−52.4°	19.2°	102°	500	500
HR (HER)	Hermanus	−34°25′	19°14′	−41.1°	*39.1°*	79°	300	300
			G_8^s					
AR (AIA)	Argentine Island	−65°12′	295°42′	−49.7°	19.5°	10°	490	500
SG (SGE)	South Georgia	−54°17′	323°31′	−41.0°	30.0°	30°	350	350
TW (TRW)	Trelew	−43°15′	294°41′	−27.8°	*41.5°*	8°	290	*350*

The three-letter symbols in parentheses are taken from the new list of observatories contained in *IAGA Bulletin 32h*. Toolangi will soon be superseded by Canberra, while Eyrewell supersedes Amberley from 1978 onward. Let us note that, after consultation of the Working Group on Geophysical Indices, the lower limits *l* used at MG, PK, NE, VI, GN, and TW were modified on January 1, 1979 by choosing the value *L* rounded to the nearest 50 γ (see text p. 65). See also the legend of Figure 19 concerning a modification of the group G_6^s.

TABLE 13. Network of the Observatories Used Each Year

Year	G_1^n	G_2^n	G_3^n	G_4^n	G_5^n	G_6^s	G_7^s	G_8^s
1959	MT	TM SV	NI WI HA	FR	VI TU	AM TO GN	KG HR	AR
1960	MT	TM SV	NI WI HA	FR	VI TU	AM TO GN	KG HR	AR
1961	MT	TM SV	NI WI HA	FR	VI TU	AM TO GN	KG HR	AR
1962	MT	TM SV	NI WI HA	FR	VI TU	AM TO GN	KG HR	AR
1963	MT	TM SV	NI WI HA	FR	VI TU	AM TO GN	KG HR	AR
1964	MT	TM SV	NI WI HA	FR	VI TU	AM TO GN	KG HR	AR
1965	MT	TM SV	NI WI HA	FR	VI TU	AM TO GN	KG HR	AR
1966	MT	TM SV	NI WI HA	FR	VI TU	AM TO GN	KG HR	AR
1967	MG MT	TM SV	NI WI HA	FR	VI TU	AM TO GN	KG HR	AR
1968	MG MT	TM SV	NI WI HA	FR	VI TU	AM TO GN	KG HR	AR
1969	MG PK MT	TM SV	NI WI HA	FR	VI TU	AM TO GN	KG HR	AR
1970	MG PK MT	TM SV	NI WI HA	FR	VI TU	AM TO GN	KG HR	AR
1971	MG PK MT	SV	NI WI HA	FR	VI TU	AM TO GN	KG HR	AR
1972	MG PK MT	SV	NI WI HA	FR	VI TU	AM TO GN	KG HR	AR
1973	MG PK MT	PT SV	NI WI HA	FR	VI TU	AM TO GN	KG CZ HR	AR TW
1974	MG PK MT	PT SV	NI WI HA	FR	VI TU	AM TO GN	KG CZ HR	AR TW
1975	MG PK MT	PT SV	NI WI HA	OT FR	VI NE TU	AM TO GN	KG CZ HR	AR SG TW
1976	MG PK MT	PT SV	NI WI HA	OT FR	VI NE TU	AM TO GN	KG CZ HR	AR SG TW
1977	MG PK MT	PT SV	NI WI HA	OT FR	VI NE TU	AM TO GN	KG CZ HR	AR SG TW
1978	MG PK MT	PT SV	NI WI HA	OT FR	VI NE TU	EY TO GN	KG CZ HR	AR SG TW

any improvement as soon as possible, even if one has to sacrifice an apparent continuity in the series. Such improvements correspond either to the establishment of new observatories or to the wish to have more than one observatory in a given sector, a fact not sufficiently taken into account for the first years. In group G_1^n, the addition of Magadan and Petropevlosk was foreseen from the beginning [see *Mayaud,* 1968, p. 41], and it intervened as soon as data became available. In G_2^n, the closing of Tomsk made it necessary to find other observatories. Nevossibirsk is planned to be used when a new site free of disturbances will be available. In G_4^n, the wish to have more than one observatory prevailed on the too high latitude of Ottawa. In G_5^n, the new observatory of Newport was integrated to compensate for the latitude of Tucson which is a little too low. In G_7^s, the establishment of Crozet was made by a French organization in order to improve the quality of the definition of the magnetic activity in this sector. Finally, in G_8^s, data from Orcadas [see *Mayaud,* 1968] were never available. Then Trelew, in spite of its too low latitude, was introduced and was soon complemented by South Georgia, set up by a British organization for the same reason as was Crozet. Furthermore, Amberley was superseded by Eyrewell in 1978, and Toolangi will be superseded by Canberra in the near future. Let us insist again on the fact that any changes in the network do not interfere much as long as they do not modify the longitudinal distribution of the groups themselves. We now have to judge the deviations from an ideal distribution at the levels of the two steps of the derivation.

1. First step. The main condition to fulfil is that observatories be located within the subauroral zone defined by limits of 55°–40° in the corrected geomagnetic latitudes or 14°–29° for the angular distance δ to the auroral zone. In Table 12, angular distances which do not clearly meet this condition are in italics. Groups G_1^n, G_3^n, and G_6^s are certainly the best: observatories close to 19° (the ideal distance at which K indices are standardized) or evenly distributed on either side. Groups G_2^n, G_5^n and G_7^s are reasonably good. In G_7^s, the low latitude of Hermanus is compensated for by the high latitude of Kerguelen, and in G_2^n and G_5^n, the compensation between observatories is less suitable but deviations from the ideal band (Tugunska and Newport) are small. G_8^s and G_4^n are less satisfactory. In G_8^s, it seems to be necessary to retain Trelew because of the uncertainty in the maintenance of the antarctic observatories of this group. (Note that the same is true for Kerguelen and Crozet in the group G_7^s, and this indicates that the continuation of the *as* index is fragile.) In G_4^n, the addition of Ottawa has been commented on above.

The lower limits l used are clearly incorrect at six stations (such values are in italics in Table 12). This does not greatly interfere in the derivation, since the differences between L and l values are taken into account in the latitude standardization. But it would probably be worthwhile to modify them because (*a*) the standardization process certainly works better when l is not very different from L (see section 5.2.1), and (*b*) comparisons between frequency distributions are easier to make and are useful in order to check the quality of the K scalings. With the approval of the Working Group on Geophysical Indices, the values have been modified at the beginning of 1979 by using the L value rounded to the nearest 50 γ.

Anyway, as far as the first step of the derivation is concerned, any empirical incidence comes almost solely from the groups G_4^n and G_8^s. Then the final results are probably not very sensitive to any spurious effects brought about by the latitude standardization (except those coming from motions of the auroral oval).

2. Second step. In the northern hemisphere the greater availability of observatories allows for the definition of five longitude sectors. Only three sectors could be made up in the southern hemisphere (the largest gap being in the Pacific Ocean), and their longitudinal distribution is far from satisfactory. Then a longitude weighting appears to be suitable: it is carried out by giving to each sector j, when averaging the $\bar{a}_j$ (see Figure 19), a weight proportionate to the longitude distance between the gravity centers of the observatories of the two groups surrounding the group j. However, the longitude used for each observatory (see the quantities φ in Table 12) is that of the point P of the auroral zone which is the closest to the observatory, and this longitude is computed in the corrected geomagnetic coordinate system. One knows, indeed, that auroral variations are better organized as a function of the geomagnetic local time, and it is logical to use it at the auroral zone latitudes. Such a choice is also consistent with that made for the latitude observatories (angular distance δ to this point P of the auroral zone). Table 14 gives the resulting weights.

TABLE 15. Effects of the Longitude Weighting in the Northern (N) or Southern (S) Hemispheres

	i							
	1	2	3	4	5	6	7	8
				Without Weighting				
N	−0.1	1.1	1.7	1.3	0.1	−1.1	−1.7	−1.3
S	5.6	17.2	18.7	9.2	−5.6	−17.2	−18.7	−9.2
				With Weighting				
N	−0.8	0.4	1.4	0.9	0.8	−0.4	−1.4	−0.9
S	1.7	10.0	12.5	7.6	−1.7	−10.0	−12.5	−7.6

Values are the averages for the eight 3-h intervals i of the sinusoids of amplitude equal to 100.

The first impression is that differences between these weights do not appear to be much greater in the southern hemisphere than in the northern hemisphere, and one might think that results would be satisfactory in both hemispheres. However, one can estimate how this weighting works by averaging in universal time sinusoids whose phase is the same in local time at each group and whose amplitude is taken to equal 100. Table 15 gives the results for the eight 3-h intervals of a day without or with weighting.

The values obtained are partly arbitrary, since they depend on the phase chosen for the sinusoids with respect to the centers of the 3-h intervals, but the differences are small. It is significant to compare the values obtained in the two hemispheres. The nonuniform distribution in the northern hemisphere is almost compensated for by the availability of five groups; with only three groups, it is no longer true in the southern hemisphere. In the latter case, the longitude weighting improves the compensation but only by a factor of about ⅔. Thus one can expect a significant residual daily variation in the index *as* and, consequently, in the index *am*. We shall discuss this point later (section 5.2.4).

Unequal longitudinal distances between observatories within each group can increase this residual variation. Now, such distances are rather

TABLE 14. Values Used for the Longitude Weighting

G_1^n	G_2^n	G_3^n	G_4^n	G_5^n	G_6^s	G_7^s	G_8^s
1.111	0.868	1.076	0.973	0.873	1.125	0.854	1.021

small in the northern hemisphere (see φ values in Table 12) and can be considered to have no influence. But this is not true in the southern hemisphere. The larger distance is about 80° for the group G_6^s, 40° for the group G_7^s, but only 20° for the group G_8^s. Consequently, the daily variation of the $\bar{a}_j$ is much more reduced in the first group (by 10%). This fact accentuates the incorrect compensation between the local time daily variations of the various groups and was not sufficiently noted by us when distributing into the groups the available observatories of the southern hemisphere (we shall come back to that point in section 5.2.4).

Finally, one can conclude that deviations of the actual *am* network from an ideal distribution interfere mainly at the level of the second step of the derivation, when averaging the $\bar{a}_j$ of the southern hemisphere.

5.2.3. Tabulation of the am index and of its various by-products ($\bar{K}_j$, σn and σs, Kn, Ks, and Km). Provisional *an*, *as*, and *am* 3-h indices with some of their by-products (σn, σs, *Km, Kn,* and *Ks*) described below are distributed monthly by the Institut de Physique du Globe de Paris on request. Provisional *Km, Kn,* and *Ks* are published in Solar Geophysical Data (prompt reports) and in the *Journal of Geophysical Research.* These indices are provisional at the time of the first distribution for two reasons. (1) The scalings of the indices at the austral or antarctic stations, where observers change almost every year, have to be checked at the central agency in charge of these stations after the magnetograms have been sent back there. (2) In order to satisfy the prompt publication in the Solar Geophysical Data, the provisional computation is made even if all stations contributing to a given group have not yet sent their data by the deadline.

The definite *an, as,* and *am* indices are computed after the end of the year when all data are available. They have been regularly published (with σn, σs, *Kn, Ks,* and *Km*) in the yearly *IAGA Bulletins 32* since 1970. Previous years can be found in the *IAGA Bulletin 39* (1959–1963), in the work of *Mayaud* [1968] (1964–1967), and in *IAGA Bulletins 32b* and *32a* (1968 and 1969, respectively).

Figure 21 gives an example of the yearly diagrams, which are associated with the definite tabulation of the *am* and associated indices in the *IAGA Bulletins 32* from 1976 onward. A series of similar diagrams is given in the supplementary *IAGA Bulletin 39* for the years 1957–1975. They aim at being a summary of the magnetic activity for a given year by illustrating the variation of $am = (an + as)/2$ and $(an - as)/2$, to which are associated a similar diagram for the *Dst* index and a graphical list of the storm sudden commencements.

In the work of *Mayaud* [1968, pp. 52–53] an example of a synoptic table containing intermediate elements of the computation was given, and it was planned to send microfilms of such tables to the WDC. This was done only for the first years but not continued, although tables are still being prepared.

Three sets of by-products are obtained when deriving the range indices *an*, *as*, and *am* (Figure 19): one of them, $\bar{K}_j$, is only deposited in the WDC on magnetic tape (they are given in integers on the form 10 $\bar{K}_j$); the others are printed with the range indices in the yearly *IAGA Bulletins 32.*

1. The meaning and the interest of the $\bar{K}_j$ are obvious. It is of value to keep at the disposal of the scientific community such intermediate information which is related to various sectors of longitude. Indeed, for particular studies the activity level in a given sector is more significant than the planetary level. Such data must be used after conversion into ranges (see Table 2 of *Mayaud* [1968]).

2. Indices σn and σs aim at discriminating between two extreme cases: either disturbances of the same intensity in all sectors or disturbances localized in a single longitude sector. They are derived from the standard deviations of the $\bar{K}_j$ in each hemisphere. These quantities are multiplied by 6 and rounded to the unit in order to obtain numbers betwen 0 and 9 (when the result is higher than 9, the value 9 is kept). Hence low or high values mean that the activity is worldwide or nonworldwide, respectively, within a given 3-h interval, whatever that activity level may be. The use of a statistical concept such as the standard deviation with only three or five values could obviously be subject to criticism; the only reason for choosing this quantity instead of the average deviation is that the former quantity accentuates the effect of any difference greater than one unit.

We do not think that σn and σs indices are adapted to statistical use. They are of interest for estimating to what extent the activity is worldwide within a given 3-h interval. Unfortunately, because such quantities are very sensitive to any contamination of the original *K* indices by the S_R

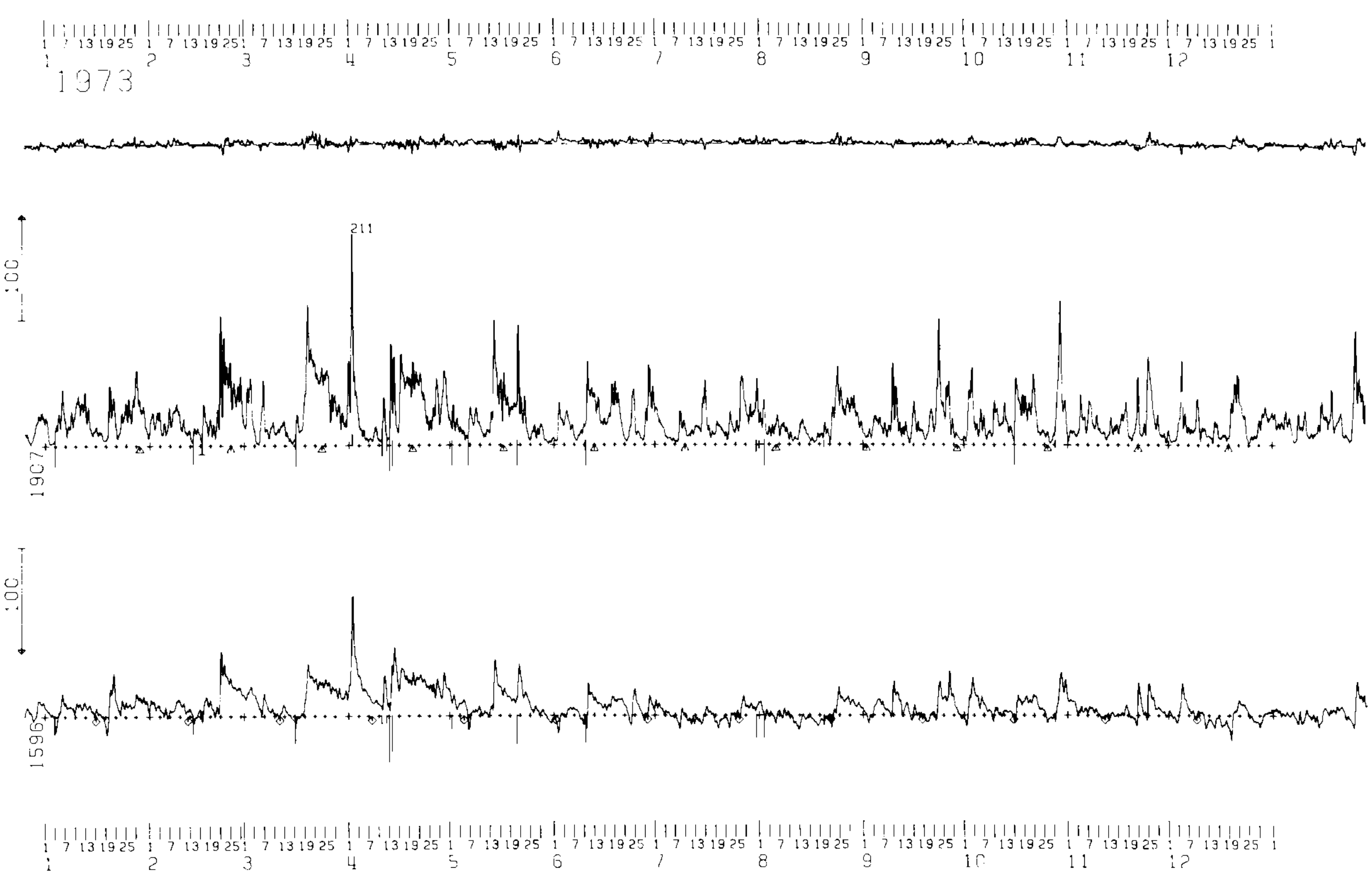


Fig. 21. A diagram summarizing the geomagnetic activity during a whole year. The top curve and the middle curve correspond to $(an - as)/2$ and $am = (an + as)/2$, respectively. By mentally adding or subtracting these curves, one gets an idea of the amplitude of *an* or of *as*. The bottom curve corresponds to the *Dst* index (reversed). In all of them, there is a point per 3-h interval, but the ordinate drawn is a running average over 12 hours. The beginnings of Bartels solar rotations are indicated by triangles and those of Carrington by rhombi. The number of each set of rotations is obtained from the number on the left-hand side which corresponds to the rotation within which the first 3-h interval of the year is included. These symbols are drawn in order to facilitate the detection of the 27-day recurrent stormy periods; it is also the reason for which curves are drawn for the last days of the preceding year and the first days of the first year. Bars below the *am* curve indicate the occurrence of sudden storm commencements (ssc); their length is proportionate to the morphological quality of the ssc. Below the *Dst* curve, bars are proportionate to the amplitude of the ssc (see *IAGA Bulletin 39*, 1977, p. 128, for other details) [after *Mayaud and Romana*, 1977].

variation, it is difficult to give at present the true average level of them for different activity levels. One could find in the work of *Mayaud* [1967*b*, p. 616] a preliminary estimation based on only 3 years; the effect of the S_R contamination is quite clear in the northern hemisphere (see again section 5.2.4 on that point).

3. Indices *Kn, Ks,* and *Km,* contrary to the preceding by-products, do not provide any supplementary information. The *ap* index, as it is derived from the *Kp* index, is of interest because ranges are much more significant than the quasi-logarithms. With the *an, as,* and *am* indices, a return to such quasi-logarithms is made for two reasons. (*a*) In estimating the degree of disturbance within a given 3-h interval the scale of *K* indices is so familiar to many workers that it is useful to provide such numbers. (*b*) When dealing with frequency distributions, such indices provide a ranking of the range indices into classes.

The scale chosen for their derivation from the range indices *an, as,* and *am* is still based on the Niemegk scale. Slight modifications have been introduced [see *Mayaud,* 1968, pp. 47–50] in order to smooth the resulting quantization.

5.2.4. Artificial and true features in the an, as, and am indices. Various features of the *an, as,* and *am* indices are reviewed in this section. Some have to be considered as artificial: they are caused either (1) by the deviation of the *am* network from an ideal distribution or (2) by the imperfect quality of the *K* scalings at some observatories. Others are true features of the geomagnetic activity. Thus (3) the activity level is higher in the northern hemisphere (*an* index) than in the southern hemisphere (*as* index) because the intensity of the main field is lower in the northern hemisphere than it is in the southern hemisphere, and a similar feature is observed in the sectorial $\bar{a}_j$ in each hemisphere. (4) There exist two universal time pseudo-components in the daily variation of the *an* and *as* indices: an 'auroral' zone pseudo-component and a 'permanent field' pseudo-component. The latter is related to the preceding feature, and because it is in phase in both hemispheres, it also appears in the *am* index. On the other hand, because the former, whose origin is ionospheric, is out of phase from one hemisphere to the other, it is approximately averaged out in the *am* index. (5) There also exist a universal time component and a 6-month wave due to the variation of the angle ψ_M between the solar wind and the dipole axis: they are in phase from one hemisphere to the other, and then the *am* index is fully sensitive to them. (6) The DP 2 variations induce another universal time pseudo-component and a 12-month wave in the *an* and *as* indices; the latter is approximately averaged out in the *am* index. (7) Because the ψ_M angle which depends on the universal time modulates the local time daily variation at any longitude, a 12-month wave is brought about in the sectorial $\bar{a}_j$; it would be averaged out with a perfectly uniform distribution, with longitude, of the observatories. (8) With respect to the random occurrence of the activity, the conjugacy between hemispheres appears to be rather great. (9) There exists a difference between the activity level in each hemisphere according to the orientation of the interplanetary magnetic field. (10) Universal time components and 12-month waves are also brought about by the interplanetary magnetic field; their phases depend on the sign of the azimuthal component of this field. (11) While all the preceding true features are permanent features, one may observe for some years various components of the annual variation due to either the irregularities in the solar sources or to long-lived *M* regions [*Bartels,* 1932]. They tend to disappear when averaging very long periods. We describe now the various topics.

1. Figure 22 illustrates the daily and annual variations of *an* and *as* indices from a 16-year sample. Data are ranked by sectors of solar longitude whose width is 6° (about 6 days), and the average daily variation is drawn within each of them. By continuity from one sector to another the annual variation appears clearly.

We now consider only the daily variations close to the equinoxes (solar longitudes 0° and 180°), a time at which the universal time daily variation due to the modulation by $\sin^2 \psi_M$ (ψ_M is the angle between the solar wind and the dipole axis and is the geometrical factor the existence of which was predicted by *Bartels* [1925]) becomes very small and maximizes twice a day (1030 UT and 2230 UT). The total amplitude of the daily variation of the *an* index is small, as is expected, but that of the *as* index is still great (about 4–6 γ). This is partly due to the insufficient number of the observatory groups in the southern hemisphere and to their unequal distribution.

Table 16, similar to Table 15, indicates to what extent a different distribution of the available observatories in the southern hemisphere could partly remedy this significant limitation of the *as*

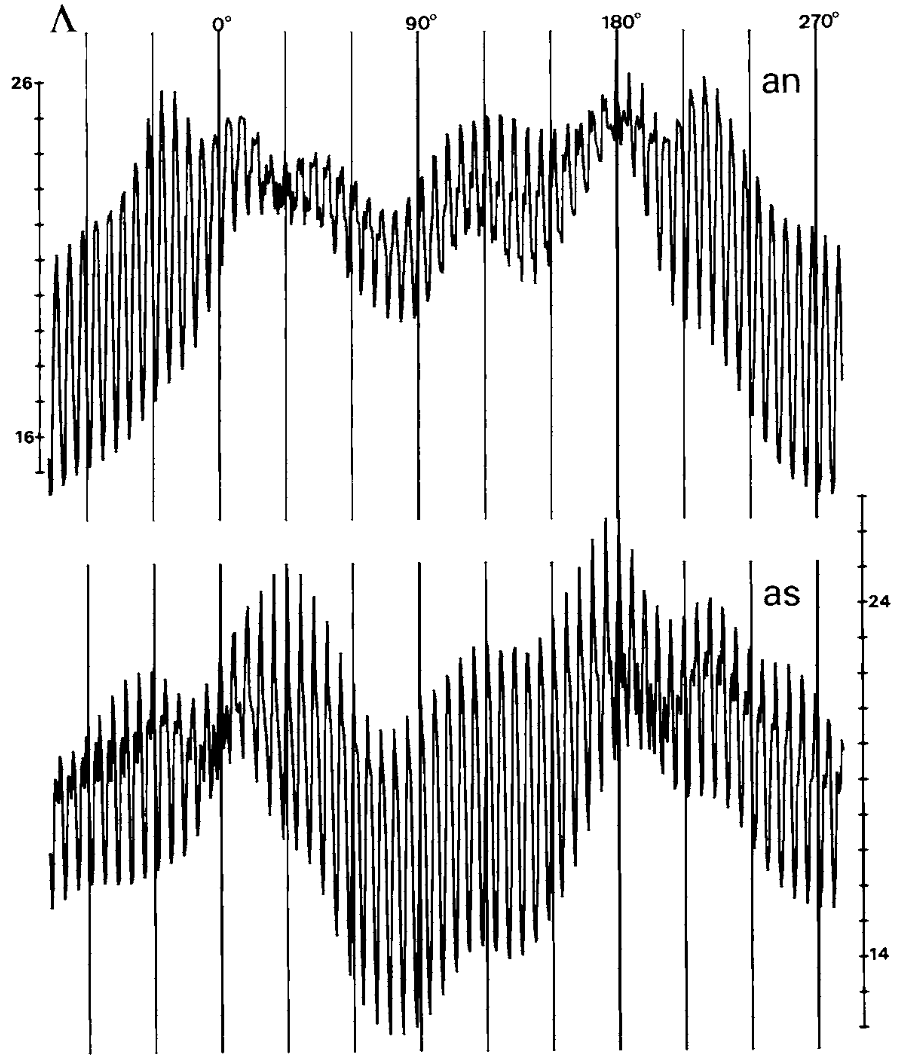


Fig. 22. Annual and daily variations of the *an* and *as* indices for a 16-yr sample (1959–1974). The solar longitude (or geocentric longitude of the sun) is chosen to be the time parameter in the course of a year, and indices are averaged for each 3-h universal time interval within a 6°-wide longitude sector; each solar longitude sector is centered at $\Lambda = -3° + m$ times 6°, m varying from -13 to 47. The average daily variation in a given sector m is drawn from the abscissa $\Lambda = (m - 1)$ times 6° to the abscissa $\Lambda = m$ times 6°. It means that the vertical lines drawn at $\Lambda = 0°, 30°, 60°, \ldots$ are the left borders of the sectors $m = 1, 6, 11, \ldots$ (or 0–6°, 30–36°, and 60–66°) and correspond for each of these sectors to 0000 UT. By continuity from one sector to another the annual variation is displayed as well. In order to reduce the solar noise which still appears in a much longer series (see legend of Figure 29), the average daily variations displayed are in fact 'running' averages obtained as follows. For a given sector Λ_m, one takes, for instance, 3 times the value of the interval 0000–0300 UT of the sector Λ_m, 2 times that of the sectors Λ_{m-1} and Λ_{m+1}, and 1 times that of the sectors Λ_{m-2} and Λ_{m+2}; this process is applied twice. Ordinates are in gammas.

index. Let us suppose that one makes up two groups with the observatories of the group G_6^s (see Table 12): Eyrewell would constitute one group, while Toolangi and Gnangara would make up the second group. With these two new groups and the other two (G_7^s and G_8^s) in the southern hemisphere, an average of the sinusoids results in the values given in the rows labeled S of Table 16. When comparing row S (with weighting) with the corresponding one of Table 15, it appears that the residual variation could be reduced by a factor of about 3. A further advantage would be the suppression of the limitation due to great distances between the observatories of the present group G_6^s (see the φ values in Table 12).

Figure 23 illustrates the result of several tests made from the data themselves. The top curves are statistical results obtained from the *am* network as it is listed by groups, in Table 12, that is, only three groups in the southern hemisphere. The

TABLE 16. Effects of the Longitude Weighting in the Southern Hemisphere (S) With Two Different Distributions S and S′ of the Observatories in Four Groups

	i							
	1	2	3	4	5	6	7	8
				Without Weighting				
S	−12.2	−6.6	2.8	10.6	12.1	6.6	−2.8	−10.6
S′	5.7	2.9	−2.2	−6.0	−5.7	−2.9	2.2	6.0
				With Weighting				
S	−4.6	−0.2	3.4	4.6	4.6	0.2	−3.4	−4.6
S′	0.6	0.5	0.0	−0.6	−0.6	−0.5	0.0	0.6

The process used is the same as that in Table 15 (see the text for the description of the distributions).

sample worked out contains the 16 years 1959–1974, but only 20 days are used at each equinox (10 days on either side of the solar longitude $\Lambda = 0°$ or 180°). In these conditions the average daily variation computed should contain a priori only the $\sin^2 \psi_M$ modulation culminating at 1030 and 2230 UT. Such maximums appear in the *as* curve but do not culminate at the same level (besides, a phase shift of the second one exists). Let us note that, paradoxically, these two maximums are not clear in the *an* curve, which still contains a significant daily variation in spite of the five groups used (see in Table 15 the expected reduction by the longitude distribution of the northern groups of the local time daily variation). However, the maximums appear again relatively well in the *am* curve. Now the middle row of curves of Figure 23 corresponds to a computation

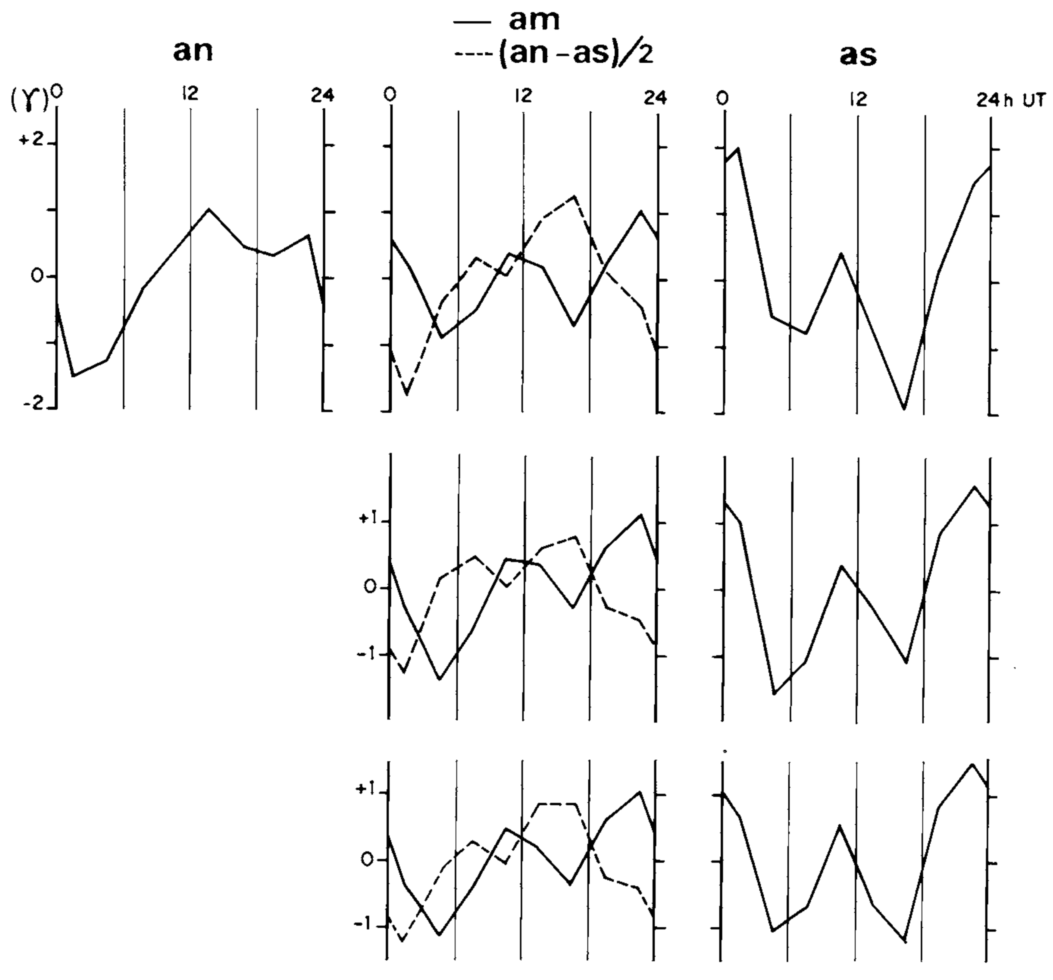


Fig. 23. Daily variations of *an*, *am* = (*an* + *as*)/2, (*an* − *as*)/2, and *as* for a 16-yr sample (1959–1974) obtained by using only 20 days at each equinox. The top row of curves was obtained with the distribution of observatories described in section 5.2.2 (five northern groups and three southern groups). The middle row of curves is obtained in computing *as* indices from a distribution of the southern observatories into four groups ($G_{6'}$ is split into two groups, (1) Amberley and (2) Toolangi and Gnangara). The bottom row of curves is obtained in computing *as* indices after arbitrarily shifting by 45°E the southern group made up by Amberly only.

in which four groups are used in the southern hemisphere according to the way indicated above. The range of the variation of the new *as* curve obtained in that way is already reduced, and the expected maximum at 2230 UT is observed at that time; the other maximum at 1030 UT still culminates at a lower level. The third test corresponds to an arbitrary one. We assume that the group made up by Amberley for the period 1959–1974 is located 45°E from its true longitude, in view of filling the present (and inevitable) gap due to the Pacific Ocean; rows S′ of Table 16 when compared with rows S show that, in such a case, the direct average of the sinusoids has an amplitude twice as small and that the average made with the ponderation gives an almost perfect result by the suppression of any daily variation. A computation of the individual 3-h indices *as* is not possible by assuming that the K index recorded at Amberley has been recorded at 45° on the east; but when using statistical values, one can shift by 3 hours the average daily variation observed at Amberley before averaging it with the average daily variations in the other groups in view of obtaining the average daily variation of *as*. The result thus obtained (bottom row of Figure 23) shows a further improvement with respect to the preceding one, but there still exists a daily variation superimposed upon the $\sin^2 \psi_M$ effect: it has a similar range to the one observed in the northern hemisphere. We shall describe to what true features in the indices these residual daily variations in both hemispheres are due; in other words, it would be illusive to believe that the daily variation should be only due to the $\sin^2 \psi_M$ modulation.

Consequently, we suggested (see legend of Figure 19) that a modification should be introduced in the derivation of the *as* index by making up two groups from the present group G_6^s. The expected improvement can be appreciated by the difference between the curves *as, am,* and $(an - as)/2$ of the top and middle rows in Figure 23, and the artificial residual daily variation still existing in the *as* index would be of the order of magnitude of the difference between the curves *as* of the middle and bottom rows. However, the improvement thus carried out at the level of the second step of the derivation should not be lost at the level of the first step by using a single station in one of the groups. The new station of Lauder, although only 1.5° south of Eyrewell, could be used in association with it. Furthermore, it would be fine to associate a station in Tasmania with Toolangi (or Canberra) and Gnangara, in order to prevent stations in this group from being too low in latitude (see Table 12). In our opinion, it is better to make any valuable improvement as soon as possible; a too conservative attitude, in order to maintain a certain continuity, would not be realistic, all the more so because the first years of the series suffer from another defect which we shall now describe and which one may expect will soon disappear.

2. *Mayaud* [1970*a*] tries to evaluate the influence of incorrect K scalings in the final results of the first 9 years (1959–1967) of the series. Figure 24 illustrates that point by a comparison between *an* and *as* indices. Ratios An/Am and As/Am of the average ranges are computed for various levels of the activity defined by sorting the 3-h intervals of the 9 years into various classes. For instance, the class $Km \geq 0_0$ contains all the 3-h intervals of the sample, the class $Km < 1_0$ retains only the quietest ones, and the class $Km \geq 4_0$ only the most disturbed. The process was also applied to the corresponding *ap* indices by using ratios $2Ap/Am$ (the factor of 2 takes into account the fact that *ap* is expressed in 2 γ units).

The symmetry, with respect to a ratio equal to one unit, of the curves An/Am and As/Am results from the definition of the indices. But if one could understand that the activity level is systematically greater in the northern hemisphere, the very important variation of the ratio when the activity level decreases is troubling. *Mayaud* [1970*a*] pointed out how, when applying the same method to the K indices of various observatories in a given hemisphere, one obtains opposite variations of the ratios as it is for *an* and *as* (even between observatories belonging to the same group). This cannot be due to a natural phenomenon but is caused by incorrect K scalings at some of the observatories. The behavior of the $2\,Ap/Am$ ratio at low-activity levels has the same source. At high-activity levels it corresponds to the various effects described in section 5.1.4: the *ap* index is not linearly related to the *am* index.

Figure 25 gives the An/Am and As/Am curves for the 9 subsequent years 1968–1976. At the highest level, values are almost identical (1.045 for An/Am instead of 1.035) in spite of the changes in the *am* network (see Table 13). On the other hand, at a low level of activity the difference between An and As is much smaller; thus, for $Km < 1_0$, An/Am becomes 1.19 instead of 1.47. Such a change indicates an improvement in the K scalings since 1967, the date of the publication of the atlas of K indices. Differences still existing in the fre-

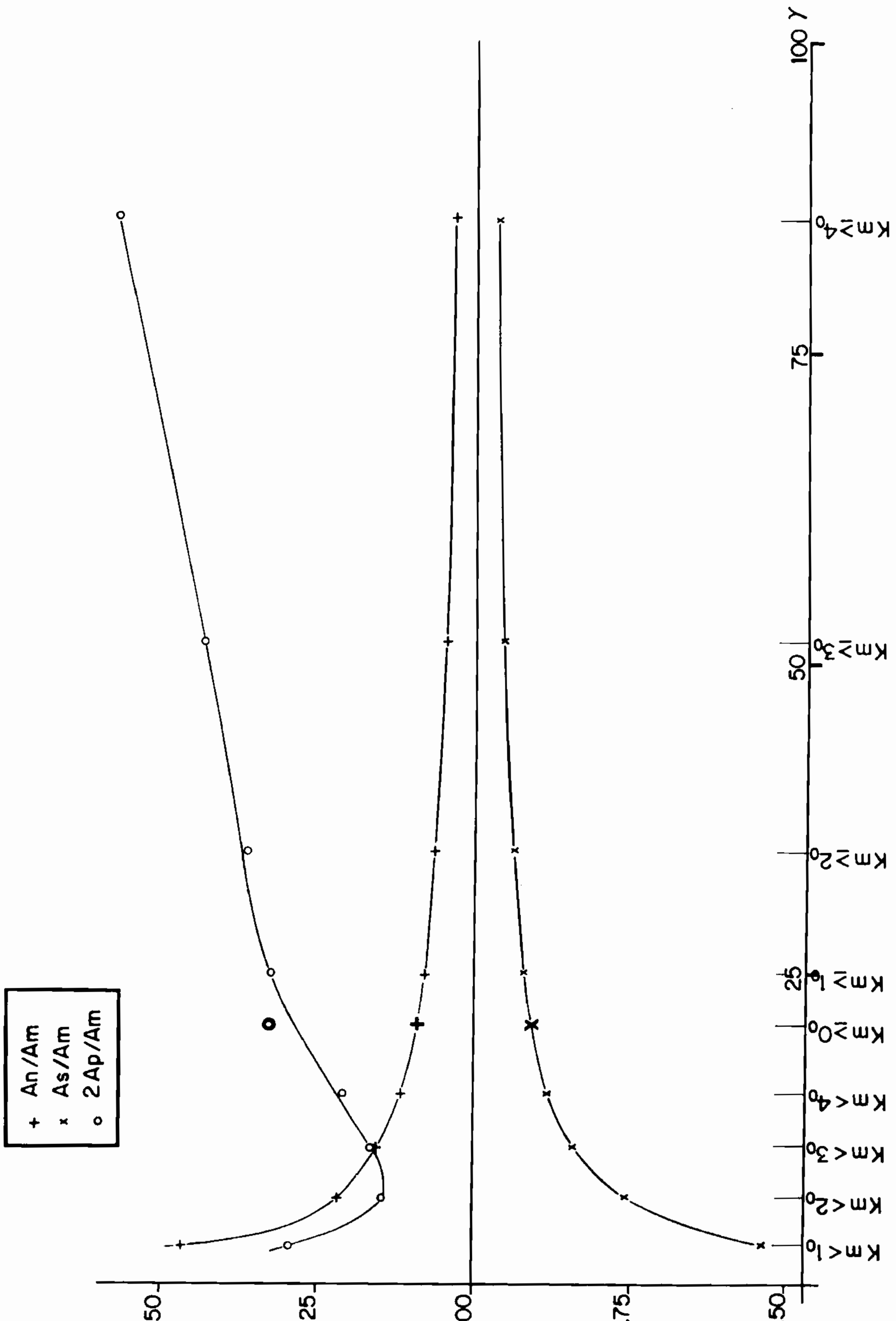


Fig. 24. Variation of the ratios *An/Am*, *As/Am*, and $2Ap/Am$ as a function of the activity level for the 9 years 1959–1967 [after *Mayaud*, 1970*a*].

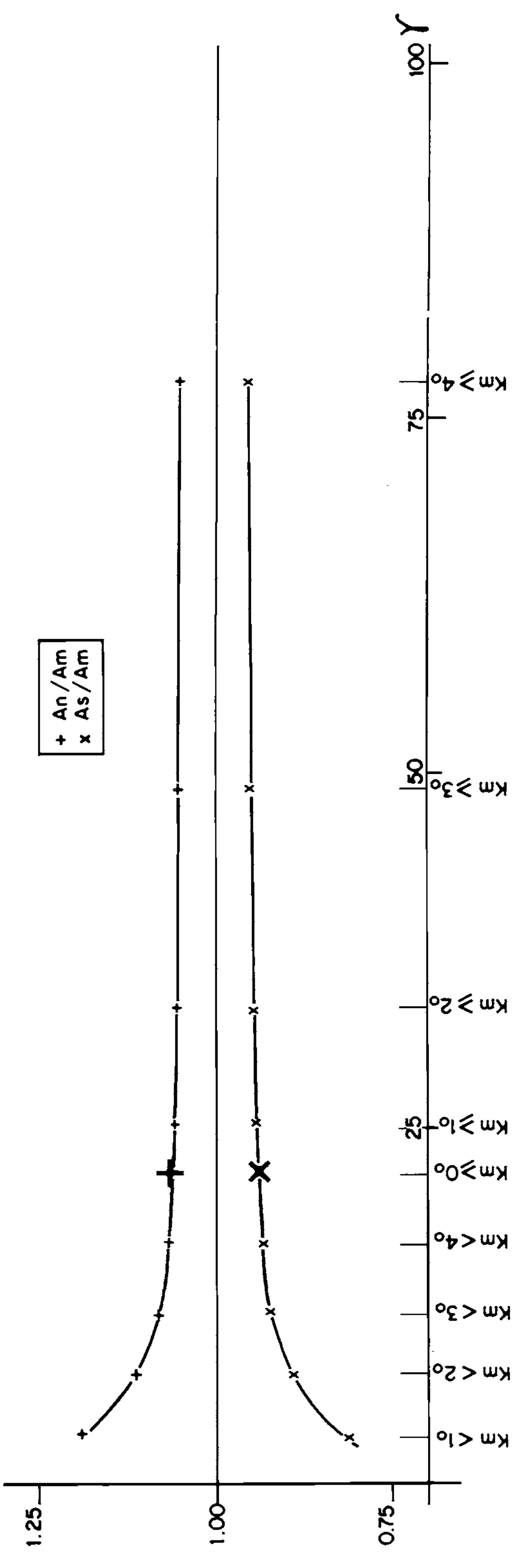


Fig. 25. Variation of the ratios *An/Am* and *As/Am* for the 9 years 1968–1976.

quency distributions of the K indices at neighboring stations of the *am* network are still significant. At the Seattle meeting in 1977, IAGA asked the author to visit all the *am* observatories for discussions with the observers, and one can hope that an objective way of scaling will soon be reached at all of the observatories of the *am* network (see section 4.7 and *Mayaud and Menvielle* [1980]).

3. Is the difference at high activity level between *an* and *as* significant? Should the ratio become almost constant at every activity level? At this point we encounter true features of the indices. Concerning the first question, a definitive statement is probably difficult because of possible underground effects. Thus *Mayaud* [1970*a*] pointed out how, at the three observatories of group G_3'', ratios of the intensity of activity to the average intensity of the group for the intervals $Km \geq 3_0$ of the years 1959–1967 (in order to avoid the effects of incorrect K scalings at low activity levels) are 1.03, 1.12, and 0.85, respectively. Such differences have to be entirely imputed to underground effects and reveal the possible importance of them. Given the difference in the activity levels within this group (about 25%), one cannot a priori assert that the difference observed for 18 years (1959–1976) between *as* and *an* (that is, about 7%, which should be reduced to 4 or 5% when taking the incorrect K scalings into account) is not due to the residual underground effects. However, it is improbable that according to the apparent compensation existing in the group G_3'', a similar compensation within each hemisphere does not take place. *Berthelier* [1979] relates the level difference between *an* and *as* to a greater size of the auroral zone in the northern hemisphere than in the southern one. The latter fact is difficult to evaluate because of the very limited number of southern observatories at maximum auroral latitudes. But her interpretation is likely correct, since the feature that we are describing must cause such a difference. Indeed, the permanent geomagnetic field along each of the auroral zones is larger on the average in the southern hemisphere than in the northern by 5%. Furthermore, the intensity of the permanent field varies along each auroral zone (see Figure 26), and one should find a variation in the activity levels for one group to another in each hemisphere. Table 17 gives the values of the $\bar{a}_j$ quantities (for each group of observatories) for the years 1959–1974, and the longitude φ of each group. The maximum and minimum of the $\bar{a}_j$ in each hemisphere are

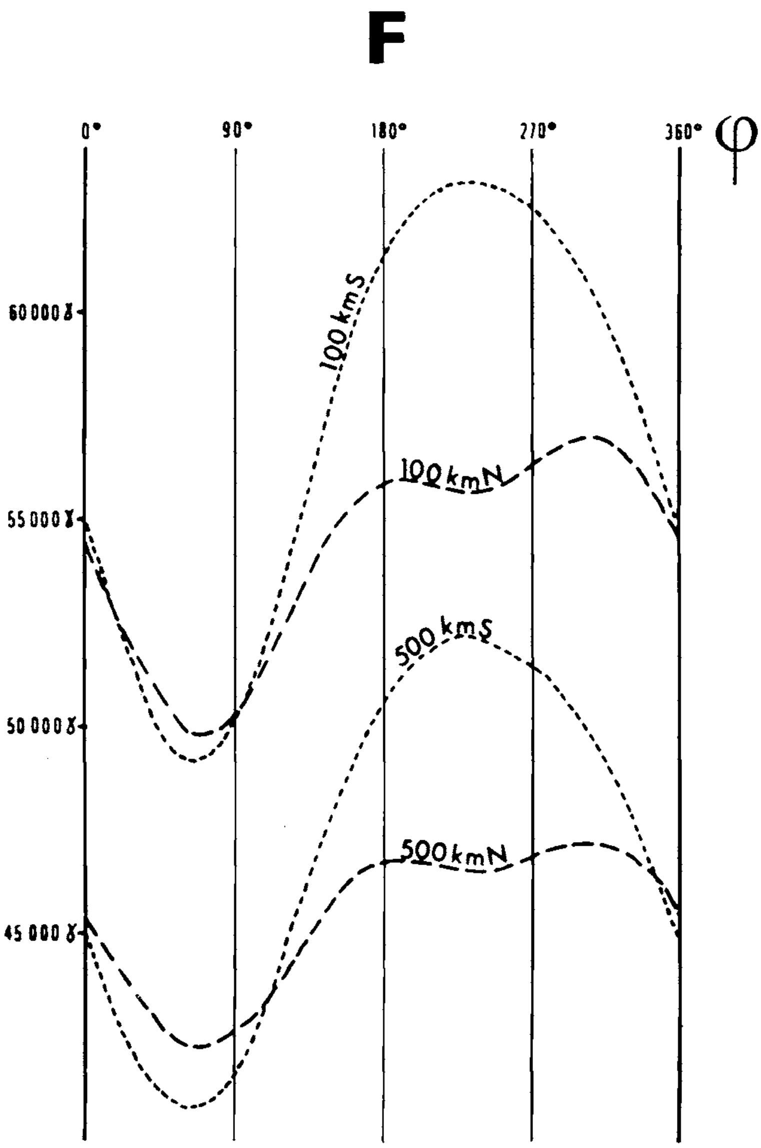


Fig. 26. Variation as a function of the geomagnetic corrected longitude φ, of the total intensity F of the main field along each auroral zone at altitudes of 100 km and 500 km. Values of the field have been computed on a network of points located at $\varphi = 0°, 20°, 40°, \ldots$ and at the corrected geomagnetic latitudes $\pm 71°$, $\pm 68°$, and $\pm 65°$. This network makes up a band about 650 km wide approximately centered on either side of the auroral zone. Average values have been computed for sectors of 80° longitude width over the width of the latitude band itself [after *Mayaud,* 1967*b*].

located approximately at the same longitudes as the minimum and maximum of the field, and the differences observed between the $\bar{a}_j$ are of the same order of magnitude as the difference between *an* and *as*, given the amplitude of the variation of the field along each auroral zone (by 16% in the northern hemisphere and by 26% in the southern hemisphere). Hence one may consider that differences in the intensity of the permanent field of the earth are able to induce differences in the intensity of the activity from one hemisphere to the other and with longitude. Such an effect would be identical with the one detected by *Siebert* [1977] from the long series of *aa* indices (see section 5.3.4). But if so, one should observe a further effect: since the activity is greater at some longitudes, the range of the local time daily variation should be also greater, and a universal time pseudo-component would be induced in the *an* and *as* indices (we call it pseudo-component because it would be due in the elaborated indices *an* and *as* to a longitude effect and is not a global universal time effect as the modulation caused by $\sin^2 \psi_M$ is).

4. Such a pseudo-component probably exists; the difficulty for demonstrating its existence is

TABLE 17. Average Values $\bar{a}_j$ of the Activity in Each Observatory Group and Corrected Geomagnetic Longitude φ of the Group

	G_1^n	G_2^n	G_3^n	G_4^n	G_5^n	G_6^s	G_7^s	G_8^s
$\bar{a}_j$	21.4	24.5	24.3	22.6	21.5	17.0	20.4	21.8
φ	205°	145°	85°	355°	305°	220°	105°	15°

Note that these a_j values correspond to all the intervals. Hence the ratio north/south is higher than the one given above for the intervals with $Km \geq 4_0$.

that another one exists also. Let us look in Figure 23 at the curves $am = (an + as)/2$ and $(an - as)/2$. In the latter curve, since the $\sin^2 \psi_M$ modulation is in phase in both hemispheres, it should be eliminated for the most part if one assumes that its intensity is the same in each of them. The daily variation of $(an - as)/2$, as it appears, is quite large in amplitude, and in the top curve is exactly similar in shape to that obtained by *Mayaud* [1970*b*] for the years 1959–1967 (see in his Figure 7 the curve E12,00, which corresponds to the use of about 24 days at each equinox instead of the 20 days in the Figure 23 of this book). This variation, according to the study referenced above, has the same phase and the same range at every time of the year; it had already been detected by *Mayaud* [1967*b*] in the preliminary attempt at deriving *an* and *as* indices. It was called 'auroral zone' effect and interpreted as a universal time pseudo-component of the daily variation of these indices. Indeed, the center of the auroral zone is strongly displaced with respect to the geographical pole; because of that the ionospheric conductivity as far as it depends on the height of the sun above or below the horizon is not the same at a given epoch all along the auroral zone. Table 18 gives, for each hemisphere, the average height (positive values) or depression (negative values) of the sun at longitudes of the auroral zone which are farthest from or closest to the geographical pole.

It is obvious that at any season the ionospheric conductivity is greater during the night at $\varphi = 170°$ than at $\varphi = 350°$ in the northern hemisphere. In the *an* index a daily variation can be induced which would correspond to a maximum at 15.3h UT; it is the universal time at which the maximum of the local time variation occurs at $\varphi = 170°$ in the corrected geomagnetic coordinate system, assuming that this maximum is at 22h LT (see *Mayaud* [1977*a*, p. 494] for such a choice). In the southern hemisphere the daily variation would culminate at 1.3h UT (the time for 22h LT at $\varphi = 20°$). Now, in the top curves of Figure 23 the daily variation of $(an - as)/2$ has its extremums close to these times, and when looking at the curves *an* and *as* themselves, one can better understand each of them: in the *an* curve a wave maximizing around 1500 UT would be present and in the *as* curve a wave minimizing around 1300 UT. In this case, with a better distribution of the observatories within four groups (see the middle curves), the wave still appears in *as*, but its amplitude is better evaluated: the smaller range of the $(an - as)/2$ middle curve demonstrates that a part of the *as* daily variation was artificial with only three groups of observatories. But because the northern and the southern auroral zone effects

TABLE 18. Average Values α Between 2100 and 0300 LT of the Height of the Sun Above the Horizon at the Corrected Geomagnetic Longitudes φ Which Are at the Greatest or Smallest Distances ω From the Geographical Pole in Each Hemisphere

	Northern Hemisphere		Southern Hemisphere	
	$\varphi = 350°$, $\omega = 35°$	$\varphi = 170°$, $\omega = 15°$	$\varphi = 200°$, $\omega = 35°$	$\varphi = 20°$, $\omega = 6°$
d	−45.9°	−31.7°	−8.9°	+24.7°
e	−27.6°	−12.7°	−27.6°	+4.8°
j	−8.9°	+8.5°	−45.9°	−15.1°

Values are computed at equinoxes (*e*) for a declination of the sun equal to zero and at the June (*j*) or December (*d*) solstices for a declination equal to ±20° [after *Mayaud,* 1967*b*].

have approximately opposite phases (10 hours between $\varphi = 170°$ and $20°$), they are almost averaged out in $am = (an + as)/2$.

In these conditions, is there an explanation for the fact that the maximums of *am* due to the $\sin^2 \psi_M$ modulation are not at the same level? According to Figure 26 the permanent field of the earth is smaller in both hemispheres at a longitude $\varphi \sim 60°$; as was noted above, this would induce a daily variation. Again taking 22h LT as a reference, such a daily variation would culminate at 22.4h UT, which can readily explain the asymmetry observed between the levels of the two maximums due to the $\sin^2 \psi_M$ modulation and would be consistent with the other two effects described above (activity greater in the northern than in the southern hemisphere and activity greater in each hemisphere at the longitude where the field is smaller).

Consequently, one would have in the daily variations of the *an* and *as* indices two universal time pseudo-components (the auroral zone effects which have approximately opposite phases in each hemisphere and the permanent field effects which have approximately the same phase). Such components are true features of the geomagnetic activity. Their amplitude is much smaller than the amplitude of the $\sin^2 \psi_M$ modulation at the solstices. Their amplitude and phase do not vary with season [*Mayaud,* 1970*b*] as do those of the $\sin^2 \psi_M$ modulation. But this means that it would be futile to expect that the daily variations of the *an* and *as* indices at the equinoxes would be made up by the $\sin^2 \psi_M$ modulation only. An ideal distribution of observatory groups in the southern hemisphere would mean having at one's disposal a group located 45°E of New Zealand and would give daily variations close to those illustrated in the bottom curves of Figure 23. The new distribution in four groups, as suggested earlier and illustrated by the daily variations in the middle curves of this figure, would certainly be a step forward because it would greatly eliminate an artificial feature existing in the *as* index and approximately equal to the difference between the top and middle curves $(an - as)/2$.

Let us note finally that the amplitude of the auroral zone and permanent field effects must not be overestimated. The range of the former is of about 2 γ in each hemisphere (curve $(an - as)/2$), the one of the latter is probably of the same order of magnitude. This is very small in comparison with the $\sin^2 \psi_M$ modulation which appears at the solstices in Figure 22.

5. However, according to this same Figure 22 the shape of the daily variation of the *an* or *as* indices varies much more than a pure $\sin^2 \psi_M$ modulation, and the pseudo-components just described permit one to expect. In particular, a great asymmetry appears from winter to summer: in the first season, the shape appears to be rather regular, and in the other, it is rather complex and a supplementary phenomenon seems to be superimposed.

In Figure 27, curve *a*, illustrating the annual and daily variations of the index *am*, greatly smoothes these asymmetries. The 12-month wave existing in the *an* and *as* indices disappears almost completely, and at each solstice the daily variation is mainly a 24-h wave. When looking at curve *b* drawn below and corresponding to a least squares fit of curve *a* by the modulating factor $\sin^2 \psi_M$ and at the residues of curve *c*, it appears that the greatest part of the daily variation in the *am* index is due to this modulating factor. Note that its phase reversal from one solstice to the other, which is very clear in the *b* curve, is equally clear in the *am* curve. This feature, with the 6-month variation, is the most spectacular and important in the *am* index. It has the same importance in the *an* and *as* taken separately but is distorted by the supplementary effect that we noticed above, and we will be describing it (the DP 2 effect) next.

At the equinoxes the *am* index (curve *a* of Figure 27) still undergoes a daily variation much larger and more complex than the one of $\sin^2 \psi_M$ (curve *b*). This is due to the residual and artificial variation in the *as* index but as well to the permanent field pseudo-component described above and partly to the presence of the DP 2 effect which is still present at the equinoxes.

6. *Mayaud* [1977*a*] investigated extensively the 12-month wave existing in the *an* and *as* indices (Figure 22) and pointed out how it is due to a particular phenomenon, which takes place in local afternoon at subauroral latitudes; and soon afterward [*Mayaud,* 1978*a*] he could identify the source of this phenomenon as being due to the DP 2 fluctuations (see Figures 11 and 12 and the comments made on them in section 4.5). Then, *Mayaud* [1979*b*] set forth the reasons for which the interpretation of *Damaske* [1977] concerning the 12-month wave (a significant curvature of the dipole axis by tail currents) does not seem to be correct.

Furthermore, such local time effects, which are important (see Figures 11 and 12), are not averaged out in the planetary indices *an* or *as* because

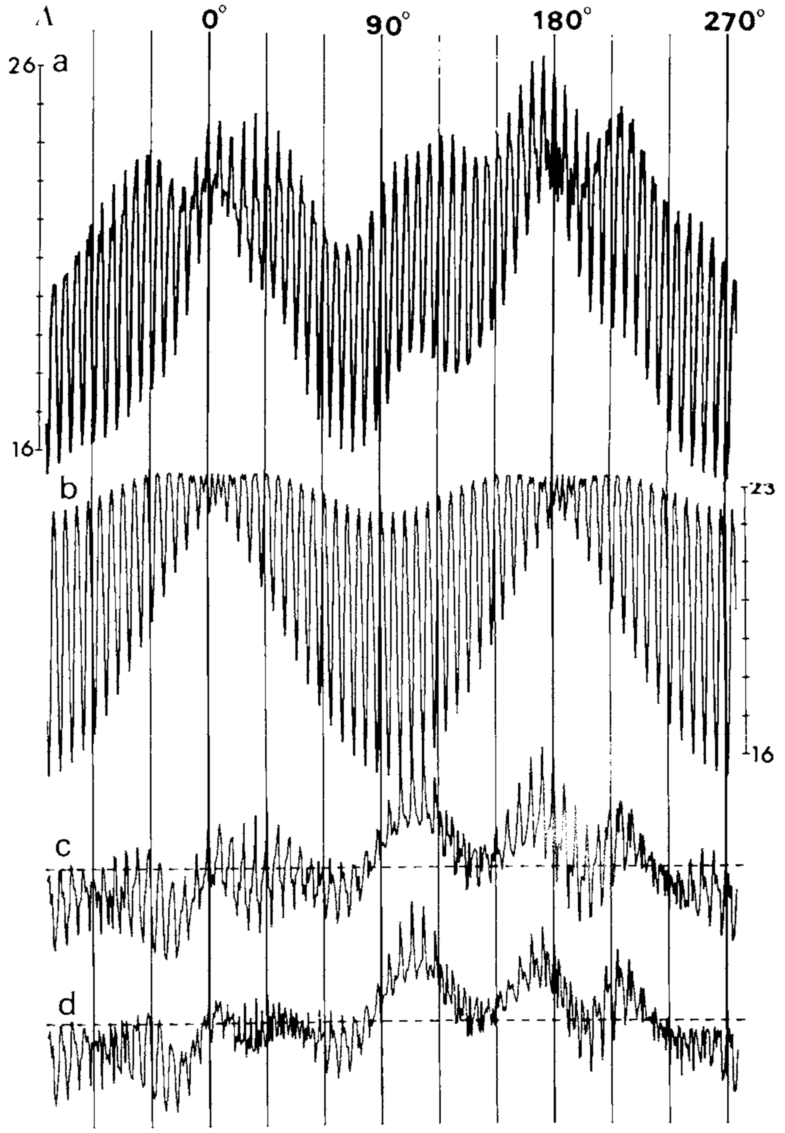


Fig. 27. Annual and daily variation of the *am* index for a 16-yr sample (1959–1974). Curve *a* corresponds to the data themselves and has been built in the same way as the curves for *an* and *as* of Figure 22 (see its legend). Curve *b* is obtained by a least squares fit of curve *a* with the formula $A_0 + A_1 \sin^2 \psi_M$ where ψ_M is a function of the solar longitude Λ and of the universal time. Given this formula, such a curve also gives a correct idea of the $\sin^2 \psi_M$ variation in the course of a year, with its phase reversal from one solstice to the other. The daily variation is mainly a 24-h wave during the whole year, and the phase reversal intervenes very rapidly in the form of a 12-h wave within a few sectors. The whole curve shows also how the 6-month wave is related to the change in the daily variation with the solar longitude Λ. Curve *c* represents the residues (differences between curve *a* and curve *b*). Curve *d* corresponds to other residues resulting from an attempt to interpret the residues of curve *c*, which is criticized in the text [after *Mayaud,* 1977*c*]. Let us note here that all vertical lines in this figure are misplaced: for instance, the line labeled Λ = 0° corresponds in fact to Λ = 6°.

one observes a significant variation with longitude of their amplitude [*Mayaud,* 1977*a*]. Hence they bring about a universal time pseudo-component in the indices, which is very important in summertime and is the main cause of the distortions of the daily variation, as they appear to be in summertime (see Figure 22). In wintertime they disappear almost entirely, and the $\sin^2 \psi_M$ modulation becomes the predominant feature. Its amplitude is greater in the southern hemisphere. This is partly due to the artificial daily variation of the *as* index (compare the curves *as* in Figure 23, the differences between them are approximately in phase with the phase of $\sin^2 \psi_M$ at the June solstice), but one cannot neglect an effect of the permanent field and auroral zone pseudo-components, since their phases are constant through year while the $\sin^2 \psi_M$ phase changes.

It could seem to some workers that this DP 2 effect strongly complicates investigations concerning relationships of geomagnetic activity with its interplanetary sources. It is certainly a drawback of the subauroral K indices and then of any planetary index derived from them to be sensitive both to the auroral variations and to the DP 2 fluctuations and as well to worldwide fluctuations. Given that, the advantage of the *AE* index is probably that it is only sensitive to the auroral variations because they mainly contribute to the extreme deviation from which the index is derived (see Chapter 7, where some limitations of this statement are, however, set forth), and the DP 2 effects are probably one of the reasons for the differences between the *AL* index and the *am* index described by *Maezawa* [1978]; one would have to be sure that it is the main one (see section 7.4). Anyway, the diagrams of Figure 22 accentuate the importance of the 12-month wave if one does not notice that its range is of only about 3 γ. When looking at Figure 21, the annual variation in the top curve is hardly noticeable with respect to the random variations of the activity. However, the curve is systematically above the zero level (dashed line) around the June solstice and close to this level in the December solstice: this gives a correct indication of the relative amplitude of the DP 2 phenomenon.

7. The summer-winter difference already detected by *Bartels et al.* [1939] (see section 5.1.1), which is due to the DP 2 fluctuations, tends to disappear when one passes from the *an* or *as* indices to the *am* index. A similar process, concerning another 12-month wave, takes place when one averages the $\bar{a}_j$ of the different observatory groups within each hemisphere. Indeed, Figure 28 shows what the annual variation of the magnetic activity in each group for the years 1959–1974 is; drastic changes of the 12-month wave appear in the an-

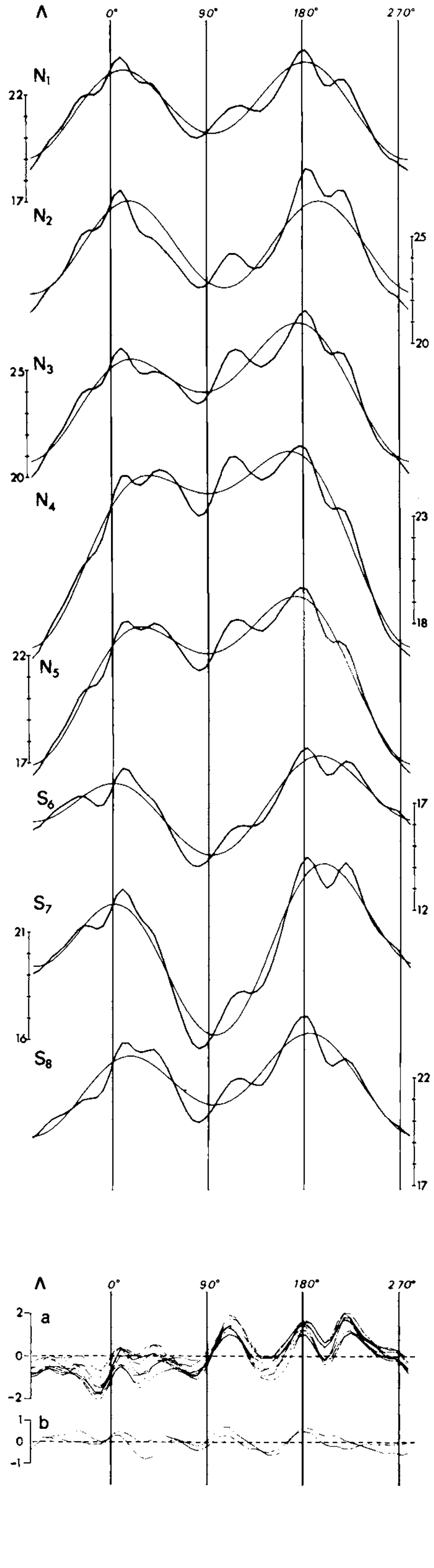


Fig. 28. (opposite) Annual variation (bold curves) as a function of the solar longitude Λ of the $\bar{a}_j$ in each observatory group for a 16-yr sample (1959–1974). Curves are built as those of Figure 22 are, except that only the average value is drawn within each 6°-wide solar longitude sector. N_1–N_5 and S_6–S_8 correspond to $G_1{}^n$–$G_5{}^n$ and $G_6{}^s$–$G_8{}^s$, respectively. The thin curves are obtained by an harmonic analysis of the curves with two terms (Λ and 2Λ). In the bottom graph, the eight curves *a* drawn from the same zero level correspond to the residues of the analysis described in the text. Curves *b* correspond to a similar analysis made for the two antipodal observatories of the *aa* index with a 103-yr sample [after *Mayaud,* 1977*a*].

nual variations of the $\bar{a}_j$ from one group to another. Thus there exists a spectacular phase reversal between S_6 (or S_7) and S_8, that is, in the same hemisphere; there is no 12-month wave in the N_2 curve, and it is extremely large in the N_4 curve. The model used by *Mayaud* [1977*a*] permits one to completely allow for these apparent anomalies. Sets of 3-h average values (similar to those displayed in Figures 22 or 27) were analyzed in each sector by the sum of two functions: one simulates the DP 2 effect, and the other simulates the modulation of a local time daily variation (itself simulated by the sum of 24-h and 12-h waves) by $\sin^2 \psi_M$. Now it is easy to understand that the effect of $\sin^2 \psi_M$ (which depends on the universal time) varies with the phase of the local time variation.

Table 19 gives the values of $\sin^2 \psi_M$ at the time of its maximum or minimum around the day close to $\Lambda = 90°$ (June solstice) or 270° (December solstice). Let us assume that the longitude of the observatory is such that the maximum of the local time variation occurs at 1030 UT (or 2230 UT): the action of the modulation factor would be symmetrical from one solstice to the other, and no 12-month wave is brought about. It is no longer true if this maximum occurs at 0430 UT (or 1630 UT). In this case, the intensity of the maximum will be more reduced at the December solstice (or the June solstice) than at the other solstice. Thus a 12-month wave is brought about whose amplitude varies according to a sinusoidal law with longitude in each hemisphere and has the same sign at a given longitude from one hemisphere to the other. The residues as drawn at the bottom of Figure 28 show that the apparent anomalies in the annual variation of the $\bar{a}_j$ in each sector are completely reduced by the association of the 12-month wave due to the DP 2 fluctuations (it maximizes in the summertime in each hemisphere, and its amplitude varies with longitude) and the 6-month and 12-month waves due to the effect of $\sin^2 \psi_M$ on the auroral local time daily variation (the amplitude of the 12-month wave varies with longitude and changes in sign, but effects are in phase in both hemispheres). This is again a true feature of the geomagnetic activity. It is approximately averaged out in the planetary *an* and *as* (or *am* indices). But it shows that for particular studies the use of the $\bar{a}_j$ of a given observatory group can be extremely useful.

8. Let us note that the curve (*an* − *as*)/2 of Figure 21 (remember that it corresponds to a 12-h average) shows how great is the degree of conjugacy between hemispheres over periods of that length. Differences are very small with respect to the random noise existing in the *am* curve. They sometimes become larger in absolute value during storms but are not such if one considers the ratios. Conversely, an example of a rather strict conjugacy would be the small substorm mentioned by *Rostoker* [1972*b*], to which the *Kp* index is not sensitive. The phenomenon takes place on October 7, 1970, between 0600 and 0900 UT. Now during this 3-h interval, one observes a slight increase in both hemispheres, since the *an* and *as* indices take values equal to 11 and 10, while the preceding or subsequent values are equal to 5 and 6 or 7 and 4, respectively.

TABLE 19. Values of $\sin^2 \psi_M$ for Two Epochs at the Solstices

	0430 UT	1630 UT
June solstice	0.96	0.67
December solstice	0.67	0.96

9. *Siebert* [1968] first pointed out the existence of differences in the average activity levels in each hemisphere according to the sign of the azimuthal component B_Y of the interplanetary magnetic field. The study was made by using individual *K* indices of various stations. *Berthelier and Guérin* [1973] showed the existence of this difference by using the *an* and *as* indices, and *Berthelier* [1979] gives a quantitative estimation for the value of the hemispheric asymmetry (5.4%) from a sample of 6 years (1964–1969). Furthermore, in the same work, she points out another nice effect: the intensity of the asymmetry depends on the value of B_Z.

10. From these indices, *Berthelier* [1976] has also detected the existence of a universal time daily variation related to the azimuthal component B_Y. Its phase reverses with the sign of this azimuthal component as well as the phase of the 12-month wave induced by it (this 12-month wave maximizes at one or the other of the equinoxes according to the sign of the component). *Svalgaard* [1978] gets a similar result in investigating the analytical and observed variations of the ratio $2\,(\overline{am}_{away} - \overline{am}_{toward})/(\overline{am}_{away} + \overline{am}_{toward})$, with respect to the universal time and the day of the year; he concludes that the variation of this ratio, such as is caused by the variation of the in-

terplanetary field orientation (away or toward), amounts to 60% (see his Figure 20). All these phenomena are true features of the indices which appear when one classifies time intervals according to the sign of the azimuthal component. The daily variations should not completely average out when using all the days (including those where the azimuthal component is small or very small), since their amplitude maximizes at one or the other equinox. Now, there exists in Figure 22 a paradoxical asymmetry in the range of the daily variations observed at each equinox. (This range is greater in the spring than in the fall with *an*, and the contrary is true with *as*.) One could think that this corresponds to the combination of such daily variations whose phase changes from one equinox to the other but not from one hemisphere to the other and of the universal time pseudo-components whose phase is constant through the year but changes for one of them (the auroral zone component) from one hemisphere to the other. Further analyses will have to be made with a longer and better series (absence of contamination by the variation S_R and better distribution of the observatory groups for the *as* index). But, as far as one may judge from Figure 22, it is not possible to attribute with certitude the observed asymmetry to the effect of the azimuthal component.

11. In Figure 27, in spite of the 16-year average, the annual variation of *am* (curve *a*) undergoes secondary fluctuations which also appear clearly in curve *c* corresponding to the residues of the analysis of curve *a* by the theoretical function displayed in curve *b*. Their period is about 70° in solar longitude (that is, about 70 days). Such a feature appears as well in *an* and *as* (see Figure 22) and in the $\bar{a}_j$ of each observatory group (see in Figure 28 the $\bar{a}_j$ but also the residues of the analysis performed for each group, where such fluctuations are extremely consistent from one $\bar{a}_j$ to another). Consequently, this feature is not artificial but corresponds to the irregularities in the solar phenomena which are the source of the geomagnetic activity. A very long series would be necessary for completely averaging them out. For instance, they are greatly reduced with a 103-year series (see Figure 29, which compares the annual variation of the *aa* indices for the years 1868–1970 with that of the *am* indices for the same sample as the one used in Figure 27), but they still appear. The same can be said of the apparent 12-month wave existing in all the residues of Figure 28: it maximizes in the fall. This is a true feature, studied for instance by *Meyer* [1972], and is probably due to the recurrent stormy periods. In the course of several subsequent years, long-lived *M* regions of the sun [*Bartels*, 1932] sometimes occur in succession and give rise to apparent 12-month waves centered on one or the other of the equinoxes (their effect is less reduced by the $\sin^2 \psi_M$ factor around the equinoxes). But this 12-month wave is not a permanent feature of the magnetic activity nor are the secondary fluctuations mentioned above.

Finally, among the various true features of the geomagnetic activity displayed by the *am* range index or its associated indices (topics 3–11), the most important ones are those which depend on the $\sin^2 \psi_M$ factor (angle between the solar wind and the dipole axis) or on the sign of the azimuthal component of the interplanetary magnetic field. The former correspond to a very stringent modulation, which seems to act only on the auroral variations. Since the indices are mainly sensitive to these variations, it is always possible for a worker to eliminate such a modulation when studying relationships with solar phenomena. This can be done easily by dividing the indices by the value of $\sin^2 \psi_M$ in a given 3-h interval. A similar process cannot be used to allow for the sign of the azimuthal component, since, in that case, one deals with an excitation mechanism rather than with a modulation one. Among the permanent features, on the one hand, the universal time pseudo-components (the permanent field effect and the auroral zone effect) are also directly related to the auroral phenomena: they necessarily appear when deriving planetary indices and correspond to the nondipole character of the main geomagnetic field or the noncoincidence between the geomagnetic invariant poles and the geographical poles. On the other hand, the summer-winter difference in the activity level in each hemisphere shows that the indices *an* and *as* (and consequently *am*, where the summer-winter difference is averaged out but where the activity level is increased by this effect) are not sensitive to a single phenomenon, the auroral variations, but also to the DP 2 fluctuations. This fact must not be forgotten when using such indices, although such fluctuations contribute relatively little to them (see the comments above on Figure 21). We do review all the true features existing in the indices as we presently know them. Those concerning the daily variation appear very complex: they

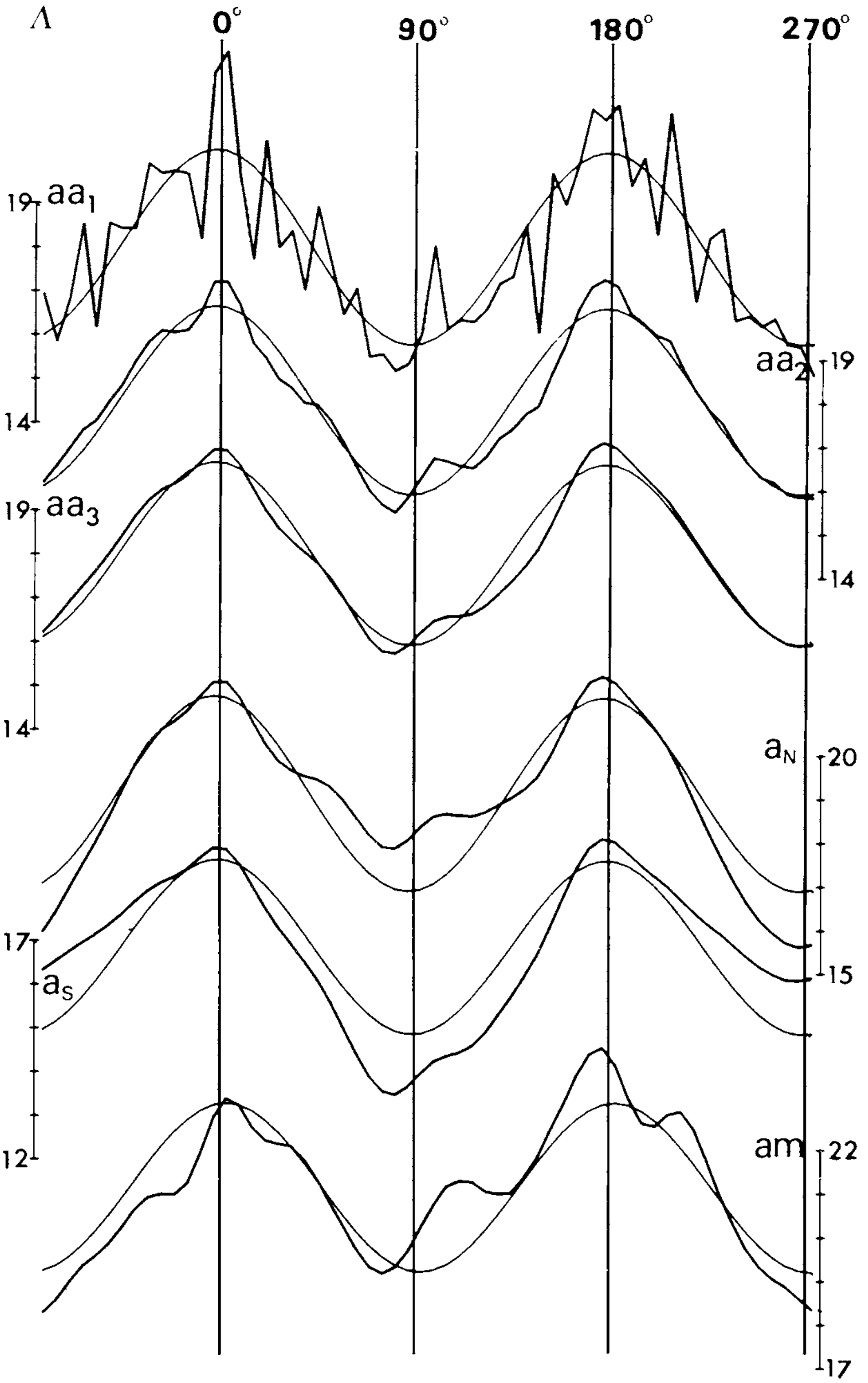


Fig. 29. Curves aa_1, aa_2, and aa_3 display the annual variation of the index *aa* for a 103-yr sample. In aa_1, no running average has been made, but each point corresponds to the direct average of the indices within each 6°-wide sector of solar longitude (each value corresponds to the average of about 618 days). In aa_2 and aa_3, the running average process described for Figure 22 is applied once and twice, respectively. The first curve shows the importance of the residual solar noise in spite of the length of the series and justifies the running average process. Curves a_N and a_S display the annual variation (for the same 103-yr sample) of the *K* indices (after transformation into the midclass ranges) at the northern and southern antipodal observatories from which the *aa* index is derived (the running average process is applied twice). Curve *am* displays the annual variation of *am* for a 16-yr sample (the running average process is also applied twice) [after *Mayaud,* 1977*c*].

must not worry the user when he is dealing with the indices independently of the daily variation.

One may conclude that the *am* range index and its associated indices monitor the magnetic activity as it occurs at subauroral latitudes with all its complexity. If they are not sensitive to the equatorial ring current variations, very few auroral variations escape them. One may assert that the original intuition of Bartels, in defining the 3-h range indices K, proved correct: the various true features that planetary indices derived from them are able to display are an a posteriori proof of the physical significance of the indices.

5.3. *The aa Index*

A request of the Royal Society of London, presented at the IAGA meeting in Madrid in 1969 by S. Chapman, is at the origin of the *aa* index. Workers at that time wished to extend the *Ci* index backward, that is, before 1884. In fact, *C* indices scaled in the very small number of observatories in these early years (only three are available) would have been of very poor significance. But the availability of records at two old observatories, Greenwich and Melbourne, which are almost antipodal, gave the possibility of obtaining a quantitative reliable long series if K scalings were made on their records. The necessary work was undertaken and resulted in this new index adopted by IAGA at Grenoble in 1975 (*IAGA Bulletin, 37,* 1975, p. 128, resolution 3). In reviewing it, we shall insist on the fact that the 3-h values, in spite of their availability, are not significant when taken one by one; only individual daily values (or half daily values?) are. A full description of the index is given by *Mayaud* [1973].

5.3.1. The ideal scheme of the aa index. The scheme of the *aa* index is identical with that of the *am* index, and the two steps described for the latter are still valid. Let us note that the network chosen (only two subauroral observatories) is evidently imposed by the condition to go back as far as possible in the past.

A latitude standardization (first step) is applied to each 3-h index K in order to obtain a value identical with the one which would be obtained at a distance of 19° from the auroral zone. It means that a correction is applied for taking into account the difference between the computed lower limit L for $K = 9$ and the lower limit l used for the scalings. However, if we take again the terminology used in section 5.2.1, there is only one observatory in each of the two groups used. Consequently, the correction of the K into K_c before averaging the K of a given group is no longer necessary; it can be made directly on the midclass range corresponding to each K by multiplying it by the ratio l/L; hence a value a_j. Let us call a_n and a_s the 3-h values thus obtained at each of the antipodal observatories.

The second step evidently consists of the simple average of a_n and a_s. An empirical correction for taking the imperfect antipodal character of Greenwich and Melbourne concerning the longitude into account is avoided.

The *aa* index shares with the *am* index the advantage of being based on subauroral observatories. This condition is more strictly fulfilled with the *aa* index, since the two observatories of the network (or those which replaced Greenwich and Melbourne in the course of time) are very close to the distance $\delta = 19°$ (see in Table 12, the values for Hartland and Toolangi). The almost antipodal character of the observatories cannot guarantee that any auroral disturbance and DP 2 fluctuation are monitored by the *aa* index, as they probably are with the *am* index. But it guarantees that in the course of each day the general trend of the irregular variations is followed, as it is in the course of each year for these phenomena which undergo a 12-month modulation opposite in phase from one hemisphere to another. We shall discuss later on quantitative differences between the *aa* and the *am* indices (see section 5.4).

As is true with the *am* index, the midclass ranges in gammas used correspond to the fundamental scale of Niemegk ($L = 500$) for the auroral zone distance 19° at which K indices are standardized. However, two remarks have to be made. (*a*) With only two observatories, it becomes meaningless to use the process described for the classes $K = 0$ and 1 in the case of the *am* index (see section 5.2.1). Then the true midclass ranges are used for $K = 0$ and 1 (that is, 2.5 and 7.5). A further and arbitrary choice is made for $K = 0$. A value 2.3 is in fact retained for $K = 0$ in order to systematically obtain a value equal to 2 for the *aa* index itself at the time of the rounding process when $K = 0$ is scaled at both observatories (see in the next section the further corrections which are applied for taking the changes of site into account and which could result in a value of 3 if such a precaution was not taken). Then the lowest value taken by the *aa* index is equal to 2 instead of 0 with the *am* index. (*b*) With the 3-h indices *aa*, the quantization inherent to the *K* indices is considerably increased for two reasons. First, because of the antipodal location of the observatories the *K* indices observed in a given 3-h interval often differ by several units (the largest difference goes up to 5), but they can be also equal. The various possible combinations of the corresponding midclass ranges and the very different occurrence frequencies of each of them result in an extremely irregular distribution (see Figure 30). Second, this irregularity is increased by the slight changes of the midclass ranges used, which intervened because of the necessary corrections for the changes of site (see the next section). We think that it does not interfere if one uses the *aa* indices properly.

Indeed, the first aim of the *aa* series is to provide a daily characterization of the geomagnetic activity. We pointed out in Chapter 3 how such a characterization cannot be made by a single measurement per day; such a constant time interval is not adapted to the morphology of the transient irregular variations. Furthermore, there is no reason to give preference to the Greenwich day as there was with the *Ci* index. Consequently, if the *aa* index is computed for each 3-h interval (and thus deposited in the WDC), the reason is to provide users with the possibility of computing a daily average for any local day (more precisely, any local day beginning at 0000, 0300, ..., 2100 UT) or to make statistical analyses including the study of the daily variation. As soon as such conditions are satisfied, the quantization tends to disappear. For instance, in the case of daily averages, 16 midclass ranges are used, and this is sufficient to obtain a significant distribution as it was with the 3-h *am* indices.

*5.3.2. **The actual derivation.*** We said already that at the level of the second step no correction is introduced for taking into account the fact that there are only 10 h in longitude between the antipodal observatories: this is a deviation from an ideal scheme. Again, stress has to be put on the fact that the shortest constant time interval for which the index begins to be significant is a 24-h interval. At that level the above deviation interferes little.

At the level of the first step, deviations from the ideal scheme (a distance of 19° from the auroral zone) are almost nonexistent. But another fact interferes: the changes of site. Up to now, Greenwich had been superseded by Abinger (in 1925) then by Hartland (in 1957) and Melbourne by Toolangi (in 1920). Further changes will intervene (thus Canberra will soon replace Toolangi). We mentioned, when reviewing the *am* index, that one of the reasons for using several observatories in each longitude sector is to minimize abnormal underground effects; in section 5.2.4 we also mentioned how much the average activity level at

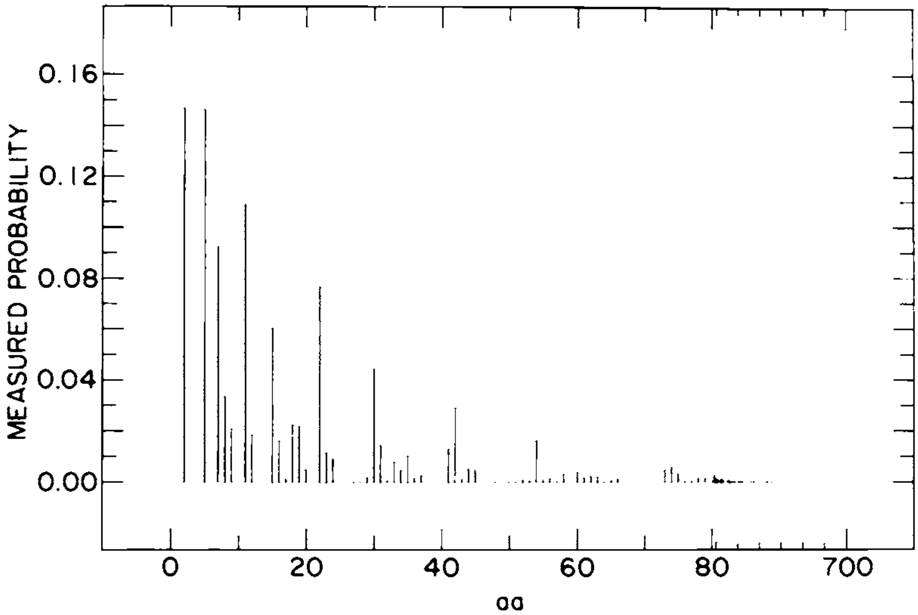


Fig. 30. The frequency distribution of the 312,648 *aa* indices in the interval January 1, 1868, through December 31, 1974. Note the compression of the abscissa scale for values greater than 80 [after *Bubenik and Fraser-Smith,* 1977].

Hartland differs from those of neighboring observatories. If one wishes to maintain the quantitative homogeneity of the series which allows studies of long-term variations, it is necessary to introduce some corrections.

The difficulty here is that there exists no definite criterion for deciding if a given observatory is normal or abnormal, or more precisely to what extent this observatory is abnormal. (For instance, the activity level at Hartland is certainly too low, but to what extent?) For the northern antipodal observatory, which corresponds to three successive observatories, the following procedure was used. Two years of K scalings have been carried out at a neighboring observatory for a time before each change of site and after it. By using them a normalization was made by giving the same weight to each of the three sites. For the southern observatory (two successive sites) no neighboring observatory was available; then the normalization has been carried out with respect to the normalized northern series of 100 years (1868–1967). The resulting correction factors (including the normal latitude standardization) are given by *Mayaud* [1973]. Any further change of site should be made with respect to this first normalization; it means that the series will depend on the first three sites of the northern antipodal observatory. One can hope that the average of more or less abnormal induced effects at these three sites is not too far from the norm.

Finally, interpolations for missing records at the northern antipodal observatory have always been made from other existing records in England or in France. For the southern observatory, existing records could always be found after 1902 in New Zealand or Australia. Before that time, interpolations were made from the northern antipodal observatory by taking into account the local time daily variation of the activity; they correspond to about 1400 3-h intervals. To some extent, the only empirical limitation in the actual scheme of the derivation arises from the problem of the changes of site (differences in latitude which can interfere in the *am* network are negligible in the *aa* index). We think that the way by which these changes have been taken into account guarantees its homogeneity (we deal with the problem of the quality of the K scalings in section 5.3.4).

5.3.3. Tabulation of the aa index. During the International Magnetospheric Study (IMS), *aa* indices are distributed weekly by telex in the middle of the following week by the Ursigram Service of Meudon, France, to any agency asking for them. Figure 31 gives an example of the telex message. In that case, the 3-h indices *aa* themselves are given with the Greenwich daily average because they permit the user to detect any rapid change in the activity level. Values have to be considered as provisional because of the check of the K scalings made afterward at the observatories. One will have to decide if the effort thus asked of the contributing antipodal observatories for a prompt communication of their data is to be continued at the end of the IMS.

From the beginning the other tabulations of the *aa* index do not give the 3-h indices themselves in order to prevent any misuse of the individual values. Such values are deposited on magnetic tape in the World Data Centers. Figure 2 gave, for another purpose, an example of the data tabulated. In columns N and S, daily averages for the Greenwich days at both antipodal observatories are given. They provide information about differences between activity levels in each hemisphere, but such differences should not be emphasized too much. It is obvious, for instance, that if a storm begins abruptly, the difference can arise only from the local time daily variation which is out of phase from one antipodal observatory to the other. In columns M, half daily averages of the Greenwich day are given. The ideal tabulation would have been to choose the way used by *Bartels et al.* [1939], which gave eight values per day for their index B; each of them corresponded to the local day of a given date beginning at a given 3-h universal time interval. This

```
INDAA 51124
1/011 00700 90220 42054 04102 2/020
2/033 01502 20300 30030 01501 5/024
3/011 01506 30750 30007 00701 5/028
4/018 00701 10110 11011 00501 1/011
5/022 01102 20220 30015 01100 7/018
6/015 02204 20750 42073 09004 1/050
7/054 04203 00300 75054 06006 0/051
```

Fig. 31. Example of a telex message giving the *aa* values 3 or 4 days after the end of a given week. The code is as follows. The first group of five digits gives the last digit of year, the month and the date of the first day of the week. The next seven rows correspond to the days of the week, from Monday to Sunday (numbered 1–7). The eight 3-h values have to be read by sequences of three digits without taking the blanks into account. The three last digits correspond to the daily average.

would take too much space, and within the era of computers, any worker can obtain such data from the 3-h indices deposited in the WDC. The choice of the half daily values for the Greenwich day does not mean that they are significant in themselves. Figure 5 of *Bubenik and Fraser-Smith* [1977] clearly shows that the activity level is on the average higher in the first part of the Greenwich day; it is due to the eastward 10-h difference in longitude from the northern antipodal observatory to the southern one. The main reason for which half daily values are given is that the number of characters available on one row with the ordinary computer printing machines gives the possibility to write two columns under the item *M*: the supplementary information given permits one to see if there is an abrupt change in the activity level in the course of the Greenwich day. The full meaning of the letters *C* and *K* will be given in section 6.2.1.

Monthly and yearly average values are given for *N*, *S*, and *M*. In both cases, differences between *N* and *S* values are certainly significant. Most of the time, one can see on them the effect of the 12-month wave in the activity, which is out of phase (see the next section for the average difference in the activity level of the antipodal observatories).

Monthly tables are distributed each month by the International Service of Geomagnetic Indices at De Bilt, jointly with the international classification of days of the month and a preliminary report on rapid variations (storm sudden commencement and solar flare effect). These monthly tables are also published in the Solar Geophysical Data prompt reports and in the *Journal of Geophysical Research.*

Yearly tables, made up of the same 12-month tables, are published from 1976 onward in the yearly *IAGA Bulletins 32.* The beginning of the series (1868–1967) was given in the supplementary *IAGA Bulletin 33;* yearly diagrams, which resemble the one of Figure 21, are given. They are a fascinating illustration of the variations in the magnetic activity over a century. The years 1968–1975 are contained in the supplementary *IAGA Bulletin 39.* Let us note that new editions of the years 1969–1975 have been prepared; they are distributed by the editor of the *IAGA Bulletins 32* under the form of loose leaves in order to be directly inserted in the corresponding bulletins. Furthermore, each yearly *IAGA Bulletin,* from 1976 onward, contained a summary table of the monthly values from 1868 onward, which supersedes the similar table edited for the *Ci* index.

5.3.4. Artificial and true features of the aa index. 1. The main artificial feature in the *aa* index can come from incorrect *K* scalings. And this index is much more sensitive to such an effect than the *am* index, since it is based on only two observatories. For the first 100 years of the series (1868–1967), *K* indices were available for Abinger from 1929 and for Toolangi from 1942. Preceding years have been scaled by the author for building the series, and among the years already scaled, those which were judged insufficient have been rescaled. The quality of the scalings of these first 100 years is then guaranteed. Recently, a deterioration of the quality of the scalings became very clear; for instance, a difference of two to one appears between the average monthly levels of the antipodal observatories [see *Lincoln,* 1977*b*]. After an investigation the necessary years have been rescaled, and a new edition of the *aa* indices has been prepared and will be distributed as was mentioned in the section above. Various tests will be carried out in the future which would ensure that the quality of the scalings remains at a normal level.

2. In any use of the 3-h indices *aa* for statistical studies the existence of a residual local time variation, due to the difference of 10 h only in longitude between the antipodal observatories, has to be taken into account. Concerning the 12-month wave, with its two components (see section 5.2.4), Figure 29 shows that it is approximately averaged out in the *aa* index. Compare curve aa_3 on the one hand, and curves a_n and a_s on the other hand: the thin curve in each case corresponds to a fit of the actual data (bold curve) by the expression $A_0 + A_1 \sin^2 \psi_M$ which does not allow for any 12-month wave when A_1 is not a function of the local time. In some aspects, this is a fortunate chance, given the complex interaction between the two components of the 12-month wave. Let us suppose that antipodal observatories would have to be chosen in the groups $G_1{}^n$ and $G_8{}^s$ (they are 11 h apart in longitude); Figure 28 shows that one would have a strong 12-month wave in the *aa* indices, maximizing at the June solstice. When we undertook the work for this series in 1970, we knew only the existence of a 12-month wave maximizing in summertime [*Bartels et al.,* 1939; *Mayaud,* 1956, 1965*a*; *McIntosh,* 1959], but we entirely ignored its true complexity, as it is

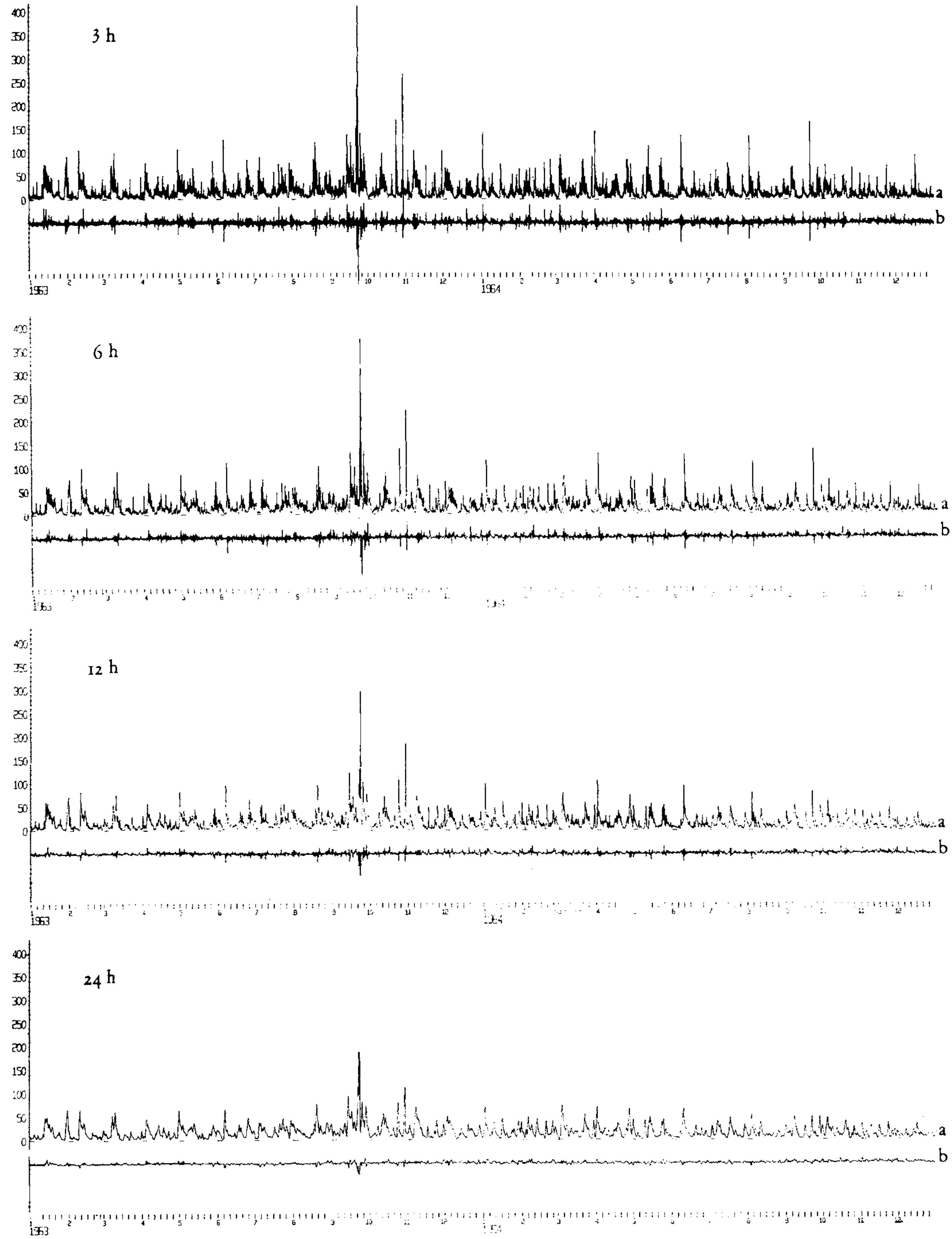


Fig. 32. A comparison of the indices *am* and *aa* for the 3-h values themselves and various running averages. Curves *a* correspond to *am* values, and curves *b* to *am* − *aa* differences. Two full years are displayed [after *Mayaud,* 1971].

displayed in Figure 28. According to *Mayaud* [1977*a*] and for the first 103 years of the series, the total amplitude of the component due to the DP 2 fluctuations (or similar phenomena) is 5.3 and 3.4 γ, respectively, in the northern and southern antipodal observatories; the one due to the $\sin^2 \psi_M$ modulation is of -1.8 and -1.0. (In that case, the negative sign means that it culminates in wintertime.) Let us note that a much longer series of the *am* indices (and a series with correct K scalings) would be necessary for knowing if the actual *am* network keeps the balance between the hemispheres for the 12-month wave.

3. All the geophysical features contained in the *am* index also belong a priori to the *aa* index (at the exception, however, of the universal time pseudo-components of the daily variation, which are caused by longitude differences in the activity level from one observatory group to another). But any study of the various universal time components of the daily variation is made more difficult by the existence of the residual local time daily variation due to the nonperfect antipodal character of the observatories.

4. Figure 32 shows how the *aa* index tends very rapidly toward the *am* index when one averages for longer and longer periods. At the top, 3-h values of the *am* index (curve a) and the 3-h differences *am* − *aa* (curve b) are plotted. Then similar curves for running averages over 6, 12, and 24 h are given. In the first case, differences are significant and mainly due to the residual daily variation in the *aa* indices; its amplitude varies with the level of the activity. One can still see a small daily variation with the half daily values. The daily values are very close to those of the *am* indices. Such a result indicates to what extent the geomagnetic activity is a worldwide phenomenon, since for 24-h periods, two antipodal observatories are sufficient for providing values close to those of a truly worldwide network. The latter is, however, necessary for characterizing the geomagnetic activity at a higher sampling rate, and we saw that the available network itself is not absolutely satisfactory for this.

We shall discuss later (section 5.4) differences between averages made on monthly or yearly averages. One may assert at this point that when averaging the *aa* index over periods equal to at least 1 day, the result obtained is almost as good as with the *am* index (remember that it can be made, in particular, for any local day beginning at a given 3-h universal time interval).

5. Figure 4 displays the long-term variation of the geomagnetic activity, as measured by the *aa* index. It is probably one of the points where the index is superior to any other one, given the homogeneity of the series. Recently, *Siebert* [1977] analyzed this long-term variation and pointed out how it contains a linear component: the activity level increases because of the decrease of the main geomagnetic field over the period considered. We saw (section 5.2.4), when we described the true features of the *am* index, that differences in the main field from one hemisphere to the other and along each auroral zone have a similar effect. Another part of the long-term variation is due, as proposed by the same author or by *Mayaud* [1972], to the 90-year cycle of the solar activity. The effects of the 11-year cycles are not less obvious and appear with all their complexity: no cycle resembles another one.

Finally, in spite of the apparent small quantity of information contained in it, the *aa* index appears to be quite reliable in monitoring and characterizing the geomagnetic activity level at a worldwide scale. Its main interest stands in two extreme directions. On the one hand, its possible very rapid distribution (every week) provides workers an almost immediate knowledge of the level of disturbances or quietness at the earth's surface. On the other hand, its homogeneity allows for comparisons of remote time intervals or studies of long-term variations.

5.4. *A Quantitative Comparison of the Average am, aa, and ap Indices*

Any comparison of the 3-h indices is meaningless, since the daily variations are not the same because of true or artificial causes (see the preceding sections). Then we shall study average values only and only for the sample 1959–1976. We take as a reference the *am* index whose derivation is obviously the most reliable; however, a contamination by the regular variation S_R, clearly existing in it, does not permit one to consider it as a completely reliable reference.

Table 20 and Figure 33 make up the basis of the discussion. The linear correlation coefficient r of (*aa* and *am*) and (*ap* and *am*), computed for values averaged over various time intervals, differ little, but they are systematically higher with *aa*; and the angle α between the two regression lines (for instance, *aa* with respect to *am* and *am* with respect to *aa*) are very small. But as soon as one

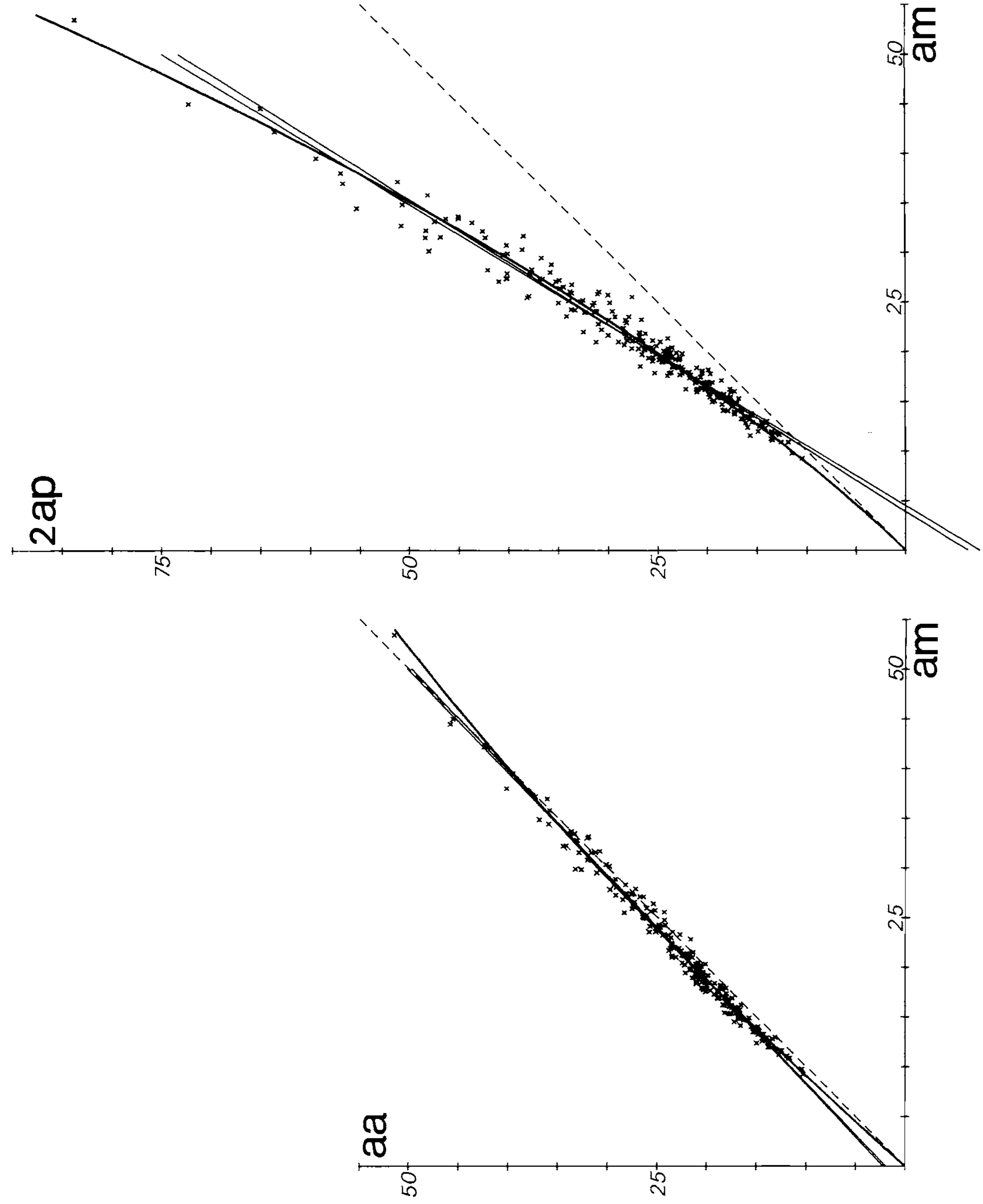

2ap
75
50
25
25
50
am
aa
50
25
25
50
am

Fig. 33. A comparison of the monthly values of *aa* and 2 *ap* indices with respect to the monthly values of *am* indices for a 18-yr sample (1959–1976). Crosses are the 216 monthly data points. The dashed line represents the diagonal. The two regression lines are drawn in each diagram, and the parabolae through the origin are fitted by least squares.

takes into account the phase of the residual daily variation of the *aa* index due to the nonabsolute antipodal character of the *aa* observatories with respect to the longitude (that is, if one uses half days beginning at 0600 and 1800 UT instead of 0000 and 1200 UT), the angle α decreases (see parenthetical values in the table). In Figure 33 the clouds of data points for the monthly averages indicate that the linearity between the indices is not evident. In view of checking if it is the reason for which the regressions lines do not go through the origin (every index should tend toward zero when the activity is very small), one can try to fit the data with a parabola passing through the origin. Coefficients of the regression lines or of the parabolae are given in Table 20. As is expected, a negative (or positive) value of the quadratic term corresponds to a positive (or negative) ordinate at the origin of the regression line and to a slope of it lower (or higher) than 1 unit. The standard deviations σ of the data are a little higher or hardly smaller with the parabolae than with the regression lines, which indicates that something prevents the data from being fitted properly by a function passing through the origin. Several causes contribute to this fact. On the one hand, the contamination by the S_R in the *am* index tends to increase the abscissae of the data points for the low-activity level. On the other hand, while the index *aa* is probably free of any S_R contamination, the weights used for the transformation of K indices into ranges are higher than those used with the *am* index for low values, and this compensates (but to what extent?) the spurious effect existing in *am*. Concerning the index *ap*, there exists a contamination by the S_R (in the K indices used for the derivation but also because of the feedback existing in the conversion tables), which introduces also a compensation of the effect existing on *am* (again, to what extent?). We do not believe that a quantitative estimation of these various effects can be carried out.

However, when looking at Figure 33, the curvature of the parabola is extremely small in the case of the *aa* index, and all data points are almost around the diagonal, that is $aa \simeq am$ for any level. The same would be true for the yearly averages; thus for the range of abscissae within which data points exist (any extrapolation would be dangerous) the *aa* observed differs by no more than 1 unit from the *aa* computed at the abscissa *am*. On the other hand, the curvature of the parabola and its deviation from the diagonal

TABLE 20. Quantitative Comparison of the Indices *aa* and *ap* With Respect to *am*

				$y = a + b \cdot am$			$y = a \cdot am + b \cdot am^2$		
y	N	r	α	a	b	σ	a	b	σ
				Half Days					
aa	13,150	0.977 (0.980)	1.32° (1.15°)	1.80	0.970	4.54	1.039	−0.00028	4.65
2*ap*		0.971	1.47°	−6.53	1.610	8.49	1.321	0.00140	8.77
				Days					
aa	6,575	0.988	0.70°	1.62	0.979	2.99	1.043	−0.00029	3.12
2*ap*		0.978	1.12°	−6.59	1.607	6.58	1.302	0.00178	6.92
				Months					
aa	216	0.993	0.42°	2.28	0.950	0.82	1.133	−0.00332	0.86
2*ap*		0.983	0.90°	−6.13	1.588	2.15	1.048	0.01026	1.98
				Years					
aa	18	0.997	0.16°	3.12	0.908	0.36	1.192	−0.00606	0.33
2*ap*		0.989	0.57°	−4.52	1.512	1.17	1.081	0.00961	1.03

N is the number of data points for each time interval analyzed; r_e, the linear correlation coefficient; α, the angle between the regression lines; a, b, and σ, coefficients and average quadratic deviation resulting from the fit of the data points by the equations written at the top. (Let us note that the a values as obtained for the regression lines (*aa* and *am*) are close to 2, which could refer to the constraints existing in the *aa* index whose lowest value is 2 instead of 0 for *am*.)

become important with *ap*. Then one may assert that *aa* and *am* are almost strictly linearly related to each other, and this relation is approximately a straight line of slope 1 passing through the origin (the diagonal), while the relation between *ap* and *am* is approximately a parabola passing through the origin, whatever be the time interval. The scattering is furthermore much larger. The main causes of these differences between *am* and *ap* are the lack of homogeneity, with latitude, of the *Kp* network and the choice of a night level for the frequency distribution reference.

When describing the international classification of days (section 6.1), we shall see that the *aa* index will perhaps have to be used for that purpose. It is important to know what the differences with *am* for individual values are. The daily averages *aa* observed again differ little from the *aa* computed at the abscissae *am* (less than +1.0 for $am < 25$, about 1.5 around $am = 70$, 0.0 for $am = 150$, −3.0 for $am = 200$, then about −15.0 for $am = 300$). But the individual daily averages can differ much more according to the standard deviation. (In Table 20, one has $\sigma = 3.12$ with the parabola.) Table 21 gives the distributions of the average *aa* indices, with respect to classes of the corresponding values of *am*, either for the days or for 48-h periods (see section 6.1.2 for the interest of a classification based on that length). The sample worked out corresponds to the years 1959–1976 (with the revised *aa* values for the years 1969–1976), and only low values of *am* are considered. The maximum of the distributions is observed for $aa - am = +1$. This is the result expected for the 24-h period according to the parabola; on the other hand, the scattering is smaller with this low-activity sample (more than 67% of the values are within the classes $aa - am = 0$, +1 and +2) than for all values, which is also expected; a great part of the differences contributing to the value $\sigma = 3.12$ comes from the most disturbed days. However, the scattering still existing for a low-activity level could seem rather great if one wishes to use the *aa* index for an international classification. We shall evaluate this point in section 6.1.2. Can one give the reason why such differences appear in quiet days between *am* and *aa*? The fact is that most of the largest differences (for instance, those corresponding to $aa - am \geq +5$) occur during solstice days. Then the most obvious interpretation would be to attribute this effect to the DP 2 fluctuations. Figure 12 shows that their effect is quite large during quiet days, and *Mayaud* [1977*a*] pointed out that the

TABLE 21. Numbers of 24-h or 48-h Periods Which Have a Given Difference *aa* − *am* for a Given Class of *am*

am	Values of *aa* − *am* −4	−3	−2	−1	0	+1	+2	+3	+4	+5	+6	+7	+8	Percentage
						24-h Periods								
0–2	0	0	0	0	11	23	27	2	0	0	0	0	0	2.6
3–4	0	0	0	7	76	132	62	12	0	0	0	0	0	11.9
5–6	0	0	6	38	123	185	105	27	11	0	0	0	0	20.3
7–8	0	0	6	44	136	154	116	56	**9**	**1**	0	0	0	21.4
9–10	0	1	15	57	124	159	119	**52**	**24**	**1**	**4**	0	0	22.8
11–12	1	0	18	48	103	127	**108**	**70**	**27**	**6**	0	1	1	20.9
Percentage	0.0	0.0	1.9	8.0	23.5	32.0	22.0	9.0	2.9	0.3	0.2	0.0	0.0	
						48-h Periods								
0–2	0	0	0	0	0	0	0	0	0	0	0	0	0	0.0
3–4	0	0	0	3	22	82	37	4	0	0	0	0	0	7.2
5–6	0	0	0	13	89	159	76	16	1	0	0	0	0	17.1
7–8	0	0	3	23	130	185	143	38	**4**	0	0	0	0	25.4
9–10	0	0	3	38	121	170	137	**51**	**8**	**3**	**1**	0	0	25.7
11–12	0	0	5	34	103	178	**114**	**56**	**12**	**7**	0	0	0	24.6
Percentage	0.0	0.0	0.5	5.4	22.5	37.4	24.5	8.0	1.2	0.5	0.0	0.0	0.0	

The total numbers are 2435 and 2069, respectively; this means that some of the 48-h periods overlap (see section 6.1 for the definition of the 48-h periods). The sample used corresponds to the years 1959–1976. Numbers printed in bold type will be commented on in section 6.1.2.

DP 2 fluctuations are more intense to the east of the meridian of the magnetic pole in each hemisphere. The two antipodal *aa* observatories are located in these regions; hence the effect would be larger in the *aa* index than in the *am* index with which it is lessened by the use of data from other longitudes.

One could argue that the comparisons *aa* − *am* and *ap* − *am* made above are not significant because the derivation of *aa* is similar to that of *am* (and furthermore the two antipodal observatories belong to the *am* network), while the derivation of *ap* is basically different. But this argument is not valid if one recalls that the *am* network is much more representative than the *ap* network and that the derivation is almost entirely free of any empirical processes, which is not at all the case for the *ap* index. The parabolic relation obtained between *ap* and *am* indicates that the *ap* index does not monitor all activity levels in the same way and that its use can induce erroneous conclusions in any statistical comparison with other phenomena; the much larger scattering questions any classification of periods with the *ap* index and also the use of the individual *Kp*.

Concerning the *aa* index, one must note that to some respects the result $aa \simeq am$ at any level is a pure chance; any other abnormal induced effects at one of the antipodal observatories or a localization at other longitudes for these observatories (see all the longitude effects described from the *am* index) must have given a relation such as $aa \simeq c \times am$, where c is a constant. But this paradoxical result might seem to question the usefulness of the effort made by using so many observatories for the *am* index. The answer has already been given: a single 3-h index *aa* cannot be considered to characterize properly a single 3-h interval. But the fact that as soon as one considers daily, monthly, ... values, the average *aa* is so close to the average *am* demonstrates the planetary character of the irregular variations monitored by such indices.

Finally, a further interest of this result is that one may be fully confident in the reliability of the long series of *aa* indices.

6. Classification of Days or of Any Interval of Time

In order to derive the *AE* and *Dst* indices, as we will see in Chapters 7 and 8, it is necessary to have at one's disposal a selection of the quiet days. This is why we must now deal with the topic of the classification of days before looking at these indices, which anyway cannot be used for such an aim: the *Dst* indices do not monitor the whole geomagnetic activity, and the *AE* indices, derived from the northern observatories only, cannot be considered as being truly planetary.

The problem of the classification can be considered in two ways. Any worker may choose special days or time intervals for a particular study, such as those which correspond to a certain activity level, and he is entirely free in choosing his own criteria. For many studies it is the best road to follow. But as we said in section 3.3, the reason for an international classification of days is to allow for the comparison of studies made with identical samples, and this fact must not be underestimated. We shall set forth (1) the problems raised by any classification in describing and evaluating the international classification and (2) some remarks concerning the estimation of the activity level in view of selecting or comparing various time intervals.

6.1. The International Classification

6.1.1. The present method of selection. The method presently used for classifying the international selected days was proposed by *Johnston* [1943]. The geomagnetic indices used were first (from 1942) the forerunners of the *Kp* index (see section 5.1.1), then the *Kp* index itself from 1950 onward.

An 'order number' is assigned to each day of a month according to each of the three following criteria: (1) the sum of the eight values of *Kp*, (2) the sum of the squares of these values, and (3) the greatest of the eight values of *Kp*. Days with the lowest or highest average order number are selected as the 5 quietest days or the 5 most disturbed days of the month. Further modifications were successively introduced from 1969 onward. They partly take into account the suggestions made by *Mayaud* [1969] concerning the classification of days. The terminology became the one which should always have been used: the days selected are not the 5 quiet (or disturbed) days but the 5 quietest (or most disturbed) days of the month. The selected days are not listed according to their chronological order but according to their degree of quietness (or disturbance). In order to draw the attention of the workers to the fact that the 5 days selected are not truly quiet (or truly disturbed), certain absolute criteria are used. Thus for the quietest days a day is considered as not being quiet if its *Ap* daily value is higher than 6, and *A* is printed beside the date of the day in the list (*A* criterion); a day is considered as not being truly quiet if one $Kp \geq 3_0$ or two $Kp \geq 3_-$ intervals occur on that day, and *K* is printed (*K* criterion). For the most disturbed days an asterisk is printed if the *Ap* of a selected day is smaller than 20. We shall consider now the meaning of these various criteria.

1. With the daily *Ci* index, the only way to select the days was the order number of the *Ci* values of the month. The availability of indices defined within time intervals shorter than 1 day gave the possibility of taking into account the distribution of these indices within the day. For the quietest days the effect of Johnston's method seems to be evident: it favors, for an average daily level of activity, the days whose scattering of the 3-h index values is the smallest and leads to the elimination from the selected days of some intervals more or less slightly disturbed. One can evaluate [see *Mayaud,* 1969] in various ways the improvements thus obtained, but one must not forget that they concern only the degree of quietness and not the existence of true quietness, which can be defined only by absolute criteria.

First, Table 22 illustrates the way in which the various criteria work. In these statistics, Johnson's method is applied to the *ap* values instead of the *Kp* values and to 48-h periods instead of 24-h periods. The first two examples in the table are the most frequent. The 48-h period which comes in the sixth rank with the single criterion *a* (that is, the Σ *ap* for the 16 intervals labeled *Ap* in the table) takes the place of the 48-h period which had the fifth rank. This is already obtained by the addition of the criterion *b* in the first example but happens only with the further addition of the criterion *c* in the second example. In both cases, the 48-h period which contains a much higher 3-h *ap* value (which corresponds to $Kp = 3_0$) is rejected from the final selection. The third example concerns much rarer cases: the period which comes in the eighth rank with the criterion *a* is finally selected with the fifth rank. This seems quite reasonable when one compares its *ap* values with those of the intermediate rejected periods. However, the period which finally comes in the fourth rank still contains an $ap = 15$, which is not satisfactory and indicates the interest of absolute criteria.

Second, when investigating a sample of 432 months (the years 1932–1967), it appears that

TABLE 22. Examples Showing How Johnston's Method Works in the Selection of the Quietest Days

			Sixteen 3-h *ap* Values																		
a	*b*	*c*	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	*Ap*	*ab*	*abc*
1	1	1	3	3	3	4	5	3	3	2	4	3	4	4	0	2	3	3	3.0	1	1
2	3	2	3	3	0	2	0	0	2	4	7	6	5	4	4	3	3	4	3.1	2	2
3	4	2	5	4	7	4	6	6	4	2	2	2	3	0	0	2	2	2	3.2	4	4
4	2	2	4	2	2	5	6	3	3	4	4	2	7	3	3	0	2	2	3.3	3	3
5	7	4	**15**	4	3	7	5	3	4	5	3	3	0	2	0	0	2	4	3.8	6	6→
6	5	2	7	6	5	4	4	3	3	4	5	7	4	2	0	4	2	3	4.0	5	5←
1	1	2	2	0	2	7	2	2	2	0	0	2	0	2	0	0	2	2	1.6	1	1
2	2	2	3	2	2	0	0	0	4	2	2	0	2	7	2	2	2	0	1.9	2	2
2	3	1	2	0	2	0	0	0	2	5	3	3	0	2	0	2	6	3	1.9	3	3
3	4	1	6	5	3	3	0	2	2	2	2	0	2	0	0	0	2	5	2.1	1	4
4	6	4	0	2	0	2	0	0	2	2	4	2	0	2	**15**	4	4	4	2.7	5	6→
5	5	2	3	3	0	2	0	2	6	3	5	4	4	0	0	5	7	3	2.9	5	5←
1	1	1	3	2	0	4	5	2	3	0	0	0	0	4	0	2	2	4	1.9	1	1
2	2	1	3	3	4	3	3	0	0	5	3	2	0	4	5	2	3	0	2.5	2	2
3	6	5	3	4	5	5	7	*15*	4	3	3	3	4	3	3	0	0	5	4.2	4	4
4	7	6	6	3	0	2	0	4	3	2	3	4	5	**18**	7	4	4	3	4.3	5	6→
5	3	4	0	3	6	4	4	3	2	3	3	4	4	*12*	7	7	5	4	4.4	3	3
6	8	6	3	4	5	**18**	7	4	4	3	0	3	6	4	4	3	2	3	4.6	7	7
7	5	3	3	5	5	9	9	7	2	3	7	6	2	4	4	5	3	5	4.8	6	5
8	4	2	7	6	2	4	4	5	3	5	6	3	5	4	6	7	5	7	4.9	6	4←

Each set of rows concerns 1 month. The 16 *ap* of the 48-h period are listed for each period. The greatest *ap* value of each set of periods is printed in bold characters. Values higher than 9 (i.e., $Kp > 2_+$) are printed in italic characters. On the left-hand side, order numbers of the three criteria *a*, *b*, and *c* are given, and on the right-hand side, the average *Ap* of the period is given, then the order numbers for the criteria $a + b$ and $a + b + c$. Arrows indicate the period rejected and the period which takes its place [after *Mayaud*, 1969].

Johnston's method, which uses the *Kp* indices, improves a selection made with the single criterion *a* (ΣKp) in 35% of the months. This indicates that the scattering of the indices during long periods of low-activity levels is often sufficiently small but that the addition of the other two criteria is useful in a number of cases. It might seem more logical to use Johnston's method with the linear *ap* values instead of the quasi-logarithmic *Kp* values (at the time when Johnston introduced his method the *ap* index was not defined). Indeed, with the same sample of 432 months, a selection made with the single criterion Σap differs from the selection made with the three criteria ΣKp, ΣKp^2, and max *Kp* by 24% only. This shows that the linear range indices should be preferred to the quasi-logarithmic indices for the classification of the quietest days.

2. Was Johnston right to use the same three criteria in order to select the most disturbed days? The answer depends on the concept that one has of a disturbed day. But Table 23 illustrates how criteria *b* and *c* work when they are associated with criterion *a* in selecting the most disturbed days. The fact that *ap* values and 48-h periods are used instead of *Kp* values and 24-h periods accentuates the effects of criteria *b* and *c* (linear values and long period) but does not invalidate the demonstration according to which periods with greater scatterings between the 3-h indices are finally selected. Indeed, the periods labeled *b* or *bc* in the table are partly highly disturbed and partly almost quiet when one compares them with the rejected periods *a*. And we would say that, in our opinion, the periods *a* better satisfy the concept of most disturbed day because they do not include intervals which are too quiet. At least, this shows to what extent the concept of the most disturbed days is ambiguous (see section 3.3) and that if Johnston's method is perfectly correct when selecting the quietest days, it tends to select disturbed periods during which the activity level greatly varies from calm 3-h intervals to highly disturbed 3-h intervals.

3. Any absolute criterion or threshold is more or less arbitrary. The choice of $Ap > 6$ (*A* criterion) in order to indicate that one of the quietest days selected is not truly quiet is a com-

TABLE 23. Examples Showing How Johnston's Method Works in the Selection of the Most Disturbed Periods

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
							$\Sigma ap \rightarrow \Sigma ap, \Sigma ap^2$									
a	9	18	9	15	9	6	7	15	9	12	9	12	15	18	9	12
b	**67**	9	12	18	15	15	6	6	7	3	2	5	3	5	5	3
a	22	39	22	12	27	39	18	15	22	27	18	15	12	15	18	22
b	15	9	7	15	32	39	56	**111**	15	15	7	5	5	4	3	2
a	67	32	22	94	56	56	15	12	15	18	6	15	12	22	22	12
b	32	39	39	**111**	94	6	3	4	9	4	4	12	15	18	18	56
a	56	27	32	32	27	56	48	27	39	48	56	80	48	67	22	22
b	12	6	7	3	4	4	32	132	**179**	80	48	48	48	12	12	18
							$\Sigma ap, \Sigma ap^2 \rightarrow \Sigma ap, \Sigma ap^2$, *Max ap*									
a	22	18	7	9	22	12	22	9	15	9	15	12	9	9	12	6
bc	9	4	6	7	7	4	5	9	7	9	7	18	15	18	12	48
a	15	18	18	15	15	18	22	18	39	32	48	39	39	27	39	32
bc	39	**111**	80	12	15	5	6	7	7	9	7	6	4	7	6	5
a	39	15	9	27	39	27	22	15	32	22	32	39	32	80	56	56
bc	4	3	2	4	3	7	7	7	18	15	32	67	48	56	**111**	15
a	56	67	48	111	67	48	32	39	39	67	80	56	80	27	39	48
bc	12	5	7	15	18	22	7	7	32	80	80	111	**179**	80	111	56

The 16 *ap* values for a 48-h period are listed for the period selected with the single criterion *a* and for the period which takes its place with the addition of the criterion *b* or with the addition of the criteria *b* and *c*.

promise [*Mayaud,* 1969]. Indeed, a given threshold has not the same meaning at any latitude. At auroral stations (for instance, Tromsö or College) the regular daily variation S_R can be readily discerned only when the Ap values go down to 3. At tropical latitudes, one can discern it up to $Ap \leq 8$ or 10. The threshold chosen ($Ap > 6$) corresponds to a limit below which the S_R variation may be easily identified at corrected geomagnetic latitudes of about 50°–40°. Any worker, however, must remember that (1) such a threshold does not mean a complete absence of irregular variations and that (2) the amplitude of these residual irregular variations rapidly increases poleward. One could find in the work of *Mayaud* [1976*b*] examples of exceptionally quiet days, equivalent for their activity level to days with $Ap = 0$, during which residual disturbances still cause a small negative variation occurring in the late evening and contaminating the average regular variation obtained from such days. It is obvious therefore that residual disturbances are contained in the 5 quietest days selected in each month, and Table 24, obtained from a sample of 432 months, provides significant information on the relative quietness of the days selected by Johnston's method. The number of days (out of the 5 selected days) which do not satisfy a given threshold of quietness rapidly increases when this value decreases. It appears that the number of days with $Ap > 6$ is still important; it would become very great with a limit $Ap > 4$. Figure 2 is a good example of a period (which is a part of the International Geophysical Year, the subject of many studies) for which the selection of the five quietest periods clearly does not correspond to truly quiet days. It would now seem clear from the above remarks that when analyzing secondary details in statistical results obtained from the international quietest days, one can never exclude

TABLE 24. Number of Months Out of a 432-Month Sample Which Have Only *n* Greenwich Selected Days That Satisfy the Threshold Value Indicated

Threshold Value	Values of *n*: 4	3	2	1	0	Percentage
$Ap \leq 10$	4	1	0	0	0	1.2
$Ap \leq 8$	8	11	4	1	0	5.8
$Ap \leq 6$	24	14	13	12	4	15.5

The percentage of months with less than 5 days for a given threshold is given in the last column.

the existence and the effects of significant residual disturbances. Furthermore, because of the rapid variation with latitude of the disturbances (while the regular variations do not undergo such a rapid and monotonic variation), one cannot compare without severe limitations results obtained with data from a wide range of latitudes. For instance, *Sq* harmonical analyses (we use this symbol in its widely used meaning: the average of the hourly values for the 5 international quietest days) made from data of Sodankylä and Sitka are not comparable with similar studies made from tropical latitudes.

4. The usefulness of the second absolute criterion for the quietest days (*K* criterion) appears to be evident from Table 22. The occurrence of more or less isolated disturbances within quiet intervals is not rare and sometimes is not sufficient to raise the Ap value above the threshold value $Ap = 6$. Therefore it is worthwhile to draw the attention of workers to such an occurrence of residual and significant disturbances within the period selected. However, one has at present no evaluation of the effect of this *K* criterion in comparison with the effect of the *A* criterion for 24-h periods, since it was proposed and justified by *Mayaud* [1969] for 48-h periods and later applied to the 24-h periods. In the former case, both criteria seem to be consistent with each other. Thus with the 432-month sample, 342 *A* periods and 313 *K* periods are included within one or the other set of the five quietest periods of each month; and only six *A* periods are not themselves *K* periods, while only 12 *K* periods have a final order number (with Johnston's method applied to *ap* values) greater than that of an *A* period of the same month. This indicates that the *K* criterion is effectively systematically less severe.

5. The absolute criterion ($Ap < 20$) chosen to indicate that one of the 5 most disturbed days of a month is not really disturbed is extremely arbitrary (again, what does the 24-h disturbed period signify?). Tables 25 and 26 provide statistics which give a rough idea of the meaning of the threshold chosen.

The number of months which do not satisfy the concept of truly disturbed days vary extremely rapidly with the threshold value. Since we knew that the average value of *ap* is about 15 for the sample studied, it seemed reasonable to choose a threshold $Ap < 20$, which is not too severe with regard to the percentage of months with less than 5 days above it. Let us note, however, that a

TABLE 25. Number of Months Out of a 432-Month Sample Which Have Only n Greenwich Selected Days That Satisfy the Threshold Value Indicated

Threshold Value	Values of n 4	3	2	1	0	Percentage
$Ap \leq 15$	31	27	14	9	4	17.3
$Ap \leq 25$	40	64	46	55	47	58.3
$Ap \leq 35$	27	47	78	84	117	81.7

The percentage of months with less than 5 days for a given threshold is given in the last column.

longer series of activity indices, such as the *aa* range index series, indicates that the average level of the activity is much lower (about 9 in *ap* units); then the number of selected most disturbed days which cannot be considered to be truly disturbed with such a threshold (see Table 26) could be considerably greater. In this respect, see also the first part of Figure 2, which shows the complete absence of such days in some months.

6.1.2. An evaluation of the international classification. Any classification at an international level, which consists of the selection of a limited and fixed number of days within each month, is submitted to severe limitations because it necessarily leads to the inclusion of periods which do not satisfy the qualification of quiet or disturbed. The correct terminology (quietest or most disturbed) and the absolute criteria recently adopted are only a partial solution to this problem because they will never completely prevent some workers from considering the periods selected as representative of the qualification given to them. Concerning the quietest days, the danger is certainly greater for geomagneticians, since residual disturbances contaminate the analyses; in other disciplines, the limitations are perhaps less severe.

Anyway, the international classification has a twofold interest: to permit the workers to make studies with identical samples (let us remember, however, that comparisons made for too wide a range of latitudes can be strongly biased by the unequal effects of the residual disturbances) and to provide choices of periods which may be considered to be objective because they are outside of the worker's control. We now evaluate various aspects of the classification and suggest possible improvements.

1. We previously suggested [*Mayaud*, 1969] the discontinuation of the selection of the most disturbed days because the concept is very poor and vague. A remark made by S. R. C. Malin (private communication, 1969) has almost convinced us that such a decision could be a mistake. Indeed, according to him, to eliminate the 5 most disturbed days of each month from a full sample of days is a good means of partly evaluating the effects of the disturbances (for instance, when analyzing long series of data in view of studying the lunisolar variation). On the contrary, any use of the selected disturbed days by themselves is dangerous. Such a selection, made arbitrarily for the Greenwich day, induces that which has been called the curvature effect by *Bartels* [1923]. Thus as described by *Bartels and Johnston* [1939], 'magnetic activity consists of a train of irregular waves; the disturbed days are selected on the crests, the quiet days on the troughs. Now the curve will be predominantly convex on the crests, concave on the troughs, and this curvature will appear in the average daily variation' of the disturbances averaged for such days. This is a spurious effect which should be, at the very least, always taken into account when using such data. In many respects, it would be better to make full use of the possibilities provided by the 3-h range indices; one can scan all the 3-h intervals and select, with some suitable criteria, periods of unequal length beginning or ending at any 3-h interval of the Greenwich day.

2. Concerning the selection of the most disturbed days, we pointed out how Johnston's method is probably not the correct one. It would be more suitable to use the single sum Σap. It has an effect which is intermediate between the single criterion *a* (ΣKp) and the association of the three criteria *a, b,* and *c*. *Mayaud* [1969] compared a classification made with Johnston's method (used with the *Kp* values) and a classification made either with Σap or with ΣKp; the percentages of the months which do not get the same selection of days are 18% and 29%, respectively. Furthermore, given the defects to which the *Kp* is submitted (see section 5.1.4), it would probably be suitable to substitute the *am* or *aa* range indices to it.

TABLE 26. Number n of Days With a Given Value of the Ap Daily Value Which Are Selected as One of the Five Most Disturbed Days of a Month for the Years 1932-1967

Ap	14	13	12	11	10	9	8	7	6
n	27	40	33	22	20	12	13	5	3

3. With regard to the selection of the quiet periods, the main problem is what length of period to choose. To retain the Greenwich day is completely arbitrary because it only corresponds to the European local day and not to the one or other longitudes. When looking, for instance, at the yearbooks of the U.S. Coast and Geodetic Survey observatories, we are always impressed by the tabulation chosen for the average hourly values of the international quietest days. Hourly values of each day are presented in local time, and the sequence of the quiet values is split into two rows in view of reminding the user that the Greenwich days selected correspond to sequences of values which do belong to two successive local days. In such cases, the elimination of the noncyclic 24-h variations is extremely arbitrary because the extreme values to be compared (the assumption of a linear noncyclic variation has to be made, given the ignorance about its true behavior) also contain an effect due to the day-to-day variability of the variation S_R. Any statistical and global study of this variation, from the present selected days, is submitted to limitations because either the phenomenon under study is arbitrarily split into two parts separated by the nighttime at many longitudes or the elimination of the noncyclic variation is made from one local midnight to the subsequent local midnight without knowing if one of them, outside of the quiet time interval selected, is quiet or not (see, for instance, *Price and Stone* [1964, pp. 67–71] for a discussion of that problem). Consequently, it seems much less arbitrary to define the time intervals selected over a 48-h interval centered on the Greenwich noon. Any local day, having the same date as the Greenwich noon occurring at the center of the interval, could be considered to be as quiet as the Greenwich day contained in this interval. To recommend that the observatories compute, in their yearbooks, the average *Sq* for the local days corresponding to the periods selected would permit workers, in the future, to make direct and reliable comparisons between such data. *Mayaud* [1969] made an evaluation of the advantages that such a choice would bring.

Table 27 clearly illustrates how, on some occasions, a very quiet Greenwich day precedes or follows disturbances and shows to what extent the elimination of the noncyclic variation can be difficult. Table 28 gives, for a 432-month sample, the distribution of the values *r* (see the caption of Table 27) for the 608 quiet periods (i.e., 28% of the periods selected in this sample) which are modified when one passes from a selection based on the Greenwich day to the selection based on the 48-h period.

Table 29 (to be compared with Table 24) indicates how the number of *A* periods varies with the threshold value chosen for the *A* criterion. One can refer to section 6.1.1 for the respective numbers of *A* and *K* periods with such 48-h periods when the threshold chosen is $Ap \leq 6$. Furthermore, one could find in the work of *Mayaud* [1969] a complete list of the 48-h periods thus selected for the years 1932–1967.

4. Concerning the method of selection of the quietest days, Johnston's method is certainly correct but should be used with the linear range indices rather than with the quasi-logarithmic indices. Furthermore, is the *ap* index satisfactory for a good selection? Among the defects of the *Kp* (or *ap*) index described in section 5.1.4, those which most bias a selection are the nonplanetary character of this index (an insufficient network especially because of the too great weight of the European stations and of the almost complete absence of southern stations) and the feedback effect through the conversion tables of the iron curve method systematically used in the early

TABLE 27. The *ap* Values for Greenwich Days Selected With a 24-h Period and Eliminated From the Selection When a 48-h Period is Used

Preceding 12 Hours				Greenwich Day								Subsequent 12 Hours				*r*
7	5	5	2	0	0	4	3	3	0	3	4	39	27	67	80	4.4
4	5	5	4	4	4	3	2	2	3	2	5	7	32	48	22	2.4
56	56	12	4	4	2	2	3	2	5	7	9	9	7	3	3	2.0
0	0	2	2	0	2	0	5	3	7	2	3	5	15	12	18	1.6
9	18	6	7	3	2	4	3	3	2	0	2	0	0	0	2	1.2

Values *r* are the ratio between Σap for the 48-h period, centered on the Greenwich day, which is eliminated and Σap for the 48-h period having the fifth rank in the selection and taking the place of the former.

TABLE 28. Number n of Days in a 432-Month Sample for Which the Ratio r is Included Within Certain Limits

r	1.0–1.25	1.25–1.5	1.5–2.0	2.0–2.5	2.5–3.0	>3.0
n	347	120	99	25	8	9

years. The second defect becomes very important in quiet periods. We previously pointed out (section 5.1.5) how the seasonal distribution of the days with a daily average $Ap = 0$ is completely inadequate, a fact which proves the inadequacy of the *Kp* index to select the quiet days on a worldwide scale.

The *am* range index should seem much more suitable for a good selection, but a practical drawback interferes. Its final computation may be made only with a delay of about 1 year because *K* scalings of the austral or antarctic stations of the network (AR, SG, KG, and CZ) have to be checked by the end of each wintering at the central agencies of these stations. Such a delay for the selection would be unacceptable because many observatories need an immediate selection for the preparation of their yearbooks. *Mayaud* [1973] attempted a selection of quiet (24 h and 48 h) periods from the *aa* range index, whose derivation can be made very rapidly. Figure 2 gives an example of the results. Johnston's method was not used, since periods are not classified according to their degree of quietness, but absolute criteria were defined and were the only ones used for selecting the periods which can be considered as truly quiet or calm (*C* periods) or almost quiet (*K* periods). A comparison made with the available years of the *am* index at that time showed that results obtained with both indices were approximately the same [see *Mayaud,* 1973, pp. 24–27]. The other comparison set forth in Table 21 for a 18-year sample shows, however, that sometimes the differences can be great. But if one keeps a threshold $Aa \leq 13$ for the *A* criterion, a classification made with *am* or *aa* will differ only for a number of periods approximately equal to the values in bold type in Table 21; a factor of ½ has, however, to be applied at the first of these values in each row, since the periods are arranged by classes of 2 units for *am*. And the selection with *aa* will be more severe. Furthermore, most of such periods would have been classified as *K* periods with the *am* index. Therefore we believe that the *aa* index, in spite of its derivation from two observatories only, is fully reliable when estimating the activity level over a period of 24 hours and a fortiori of 48 h. The main condition to be ensured, however, would be the quality of the *K* scalings at both the antipodal observatories of the *aa* network. Johnston's method associated with the *A* and *K* criteria would give the selection of the 5 quietest periods according to the degree of quietness. But we do not see any reason for limiting the list to 5 (or 10) periods per month and not completing the selection with all the truly quiet periods of a given month as they exist. When looking at the list of *Mayaud* [1969] mentioned above or to the selection of quiet 24-h and 48-h periods given in *IAGA Bulletin 33,* one sees that the months with much more than five truly quiet periods are not rare, especially at the time of sunspot minimums. These sunspot minimums are extremely interesting because abnormal features of the regular S_R variation are more often observed at these times, and to give complete information concerning quiet periods is certainly of interest for the study of these phenomena. Possibly, the selection could be made for both 24-h and 48-h periods, but we think that stress should be put on the use of the latter which is much less arbitrary than the use of the Greenwich days.

5. In *IAGA Bulletin 33* the threshold chosen for the *A* criterion is 13 γ. It is equivalent to $Ap \leq 6$ (2 γ units) discussed above but has been slightly increased because the smallest value taken by the *aa* index is 2 γ instead of 0 γ with the *ap* (or *am*) index. Various attempts were made [see *Mayaud,* 1973, pp. 24–27] to improve the absolute *K* criterion used by *Mayaud* [1969].Table 30 gives the weights p attributed to the *aa* indices when scanning them in each period and the limits of their sums Σp which define the *K* criterion. The aim searched for in this other choice is to smooth out any abruptness of the *K* criterion by widening

TABLE 29. Number of Months Out of a 432-Month Sample Which Have Only n 48-h Periods Satisfying the Threshold Value Indicated

Threshold Value	Values of n: 4	3	2	1	0	Percentage
$Ap \leq 6$	35	27	23	17	20	28.2
$Ap \leq 8$	17	11	13	4	4	11.3
$Ap \leq 10$	13	5	2	1	0	4.9

Percentage of months with less than 5 days for a given threshold is given in the last column.

TABLE 30. Values p of the Weights Attributed to the *aa* Indices When They Are Higher Than a Given Value

aa	17	21	28	32
Km	2_+	3_-	3_0	3_+
p	1	2	4	6

When $\Sigma p \geq 4$ (24-h periods) or $\Sigma p \geq 6$ (48-h periods) with $Aa \leq 13$, the period is classified as a *K* period instead of as a *C* period. *Km* values corresponding to *aa* values are also given.

the range of the slightly disturbed 3-h intervals which are contributing to it (*Km* values corresponding to *aa* values are also given). One could find in the work of *Mayaud* [1973, p. 26] the distribution of the *C* and *K* periods for a 100-year sample, selected by using such criteria.

Besides, a comparison between the international classification of the 5 international quietest days and the one that we just described is easy to evaluate from 1884 onward in *IAGA Bulletin 33* by looking at the yearly tables (see Figure 2 for an example). The 5 *Q* days are always one of the 24-h *C* periods when the number of the latter is clearly higher than 5 or when the contrast between quiet and disturbed day is sharp during the month. It is not so when *C* periods are less numerous, and it is not rare that a *Q* day is found not to be a *C* period nor even a *K* period.

6. Let us note that recently *Campbell* [1979] proposed a new method of selection from *Dst* and *AE* indices. Anyone can compare his Tables 1 and 2 with the classification of the truly quiet days given by *Mayaud* [1973] or *Mayaud and Romana* [1977], as derived from the *aa* index. It will appear that often very quiet days are not selected by him, while disturbed days are. Thus in 1958, out of 39 quiet days selected by Campbell, 23 are classified 'disturbed' by Mayaud, and only 4 are classified 'quiet' for the 48-h period, although there are 35 such days during the year; in November, none of the 7 such days are selected. In 1964, none of the 18 truly quiet 48-h periods of December are selected by Campbell, and out of the 100 such days in this year, only 20 are selected; besides, he retained fewer quiet days in this year than he did in 1958 because the criteria chosen vary from one year to another. This is consistent with a selection of a certain number of quietest days per year but may be misleading if one wishes to provide users with reference days to be chosen to correspond to a quiet level. Furthermore, one can wonder whether the method used is reliable. First, there is, to some extent, a vicious circle, since the *Dst* and *AE* indices used for the selection need a selection of the 5 quietest days of each month in their derivation. Second, we shall see (section 7.4) that the low values of the *AE* index are contaminated by the variation S_R, and they are contaminated not in the same way in summer as in winter. The northern network of these indices accentuates this defect when one wishes to select worldwide quiet days. Third, the *AE* index because it is derived from extreme values at two longitudes (see section 7.1) can be sensitive to local disturbances; the advantage of the *am* index is to be an average range for all longitudes in both hemispheres. Fourth, a double weight in the selection is given to the *Dst* index by using separately Dst_+ and Dst_- values. Now, the *Dst* variations are far from being most frequent and great in amplitude among the irregular variations. Fifth, dealing separately with Dst_+ and Dst_- values is very critical because the zero level of the *Dst* index is entirely arbitrary (see section 8.3), since it depends on the selection of the quiet days. Such a zero level does not mean that Dst_+ values always correspond to a compression of the sunside boundary of the magnetospheric cavity; in many cases, they are due to fluctuations in the ring current intensity, especially during quiet periods. Finally, the fact that Dst_+ and Dst_- values are mutually exclusive raises a difficulty when associating them with the *AE* values, whatever be the choice made for solving it.

6.2. *Classification of Time Intervals From an Estimation of the Activity Level*

It is obvious that any worker can always classify time intervals of any length for particular investigations. For instance, one may use the 3-h indices and select local quiet days for a given longitude. The method described above is still valid. However, the problem of the classification concerns any level of activity and not only the two extremes (quietest or most disturbed periods). It is, indeed, one of the main purposes for which geomagnetic indices are established.

It is in this area that the two pieces of advice so often stated by Bartels (since the beginning of his work: see, for instance, his paper of 1932 on the *u* index) become extremely important. (1) Any average of linear quantities is a better indicator than the average of nonlinear quantities (see, for instance, ***Bartels*** [1951*a*], concerning the comparison between the monthly *Ap* and *Ci*). (2)

Because of the positive conservation existing in the geomagnetic activity it is never sufficient to consider only the averages of the linear quantities in order to classify periods of a certain length; approximately equal averages can correspond to very different frequency distributions (see *Bartels* [1963] for his last statement on that point).

The average of the linear range indices is the main parameter to use, and it already gives a significant indication of the activity level. But handling the frequency distributions is not easy. *Mayaud* [1976*a*] tried to associate the geometric average with the arithmetic average of the linear ranges for evaluating the width of the distribution. Indeed, the quotient Q of these averages is equal to 1 if all the values contributing to the averages are identical, and it decreases when the width of the frequency distribution increases. It has been verified that behavior of the quotient Q greatly differs when one uses the natural series of the indices *aa* (a sample of 103 years) and when one uses a series made up of the same values arranged at random (see Figure 6 of *Mayaud* [1976*a*]). Let us note that when computing the geometric average, one has to use not the quasi-logarithmic indices (they necessarily induce distortions whose effects are difficult to evaluate) but the true logarithms of the ranges.

Figure 34, derived from the *aa* series, displays the variation of Q for various time intervals and that of the arithmetic average. One must note that in the case of the curves relative to 4-month and 1-year intervals the successive points do not correspond to independent values, since running averages are used in view of drawing a value at the abscissa of each month. This accentuates the impression that one gets with regard to the decrease in the random aspect of the variations when the length of the time interval increases. Such a decrease is, however, quite real and shows to what extent any average over a certain time interval tends to mask the basically random characteristics of the geomagnetic activity. One of the most spectacular exceptions to that property is a time interval of a certain length in the course of the year 1930. In the 1-year curve, the narrow maximum occurring during 1930 is the one which emerges the most clearly from the surrounding curve; one can follow its evolution in the other curves, and it can still be seen in the 10-day curve. Table 31 gives the average value of the quotient Q and their standard deviations for the various time intervals displayed in Figure 34. Note that the frequency distributions of the quotients Q (see Table 3 of *Mayaud* [1976*a*]) are close to a normal distribution (68% are included within the limits $\pm\sigma$) but that they are clearly asymmetrical. The distributions are spread more toward lower values, and this corresponds to time intervals where a few high indices make the quotient Q much smaller.

Values of Table 31 are probably also valid for the *am* indices and should permit one to evaluate how much the quotient Q of a given sample deviates from the more normal value. Thus Table 32 gives some examples concerning the time interval equal to 1 month. January 1938, September 1957, and July 1959 (these months and the other months quoted are labeled in Figure 34) appear to be very disturbed months which are more normal than March 1940, often quoted by Bartels as a particularly abnormal month (May 1921 is also extremely abnormal). September 1957, with its sequence of four violent storms and very few quiet days, is typical in that respect, while during March 1940 there occurred two very violent storms preceded by a certain number of days relatively quiet. (Most of the months labeled in Figure 34 and not listed in Table 32 resemble September 1957; that is, they have a Q equal to about 0.5.) But April 1930 and August and September 1943 (the last two often quoted by Bartels for their contrast with March 1940) are typical of a completely different behavior of the geomagnetic activity: it is made up of recurrent stormy periods which last almost without interruption but correspond to a moderate activity level only. These various examples are extreme cases which are not very frequent, but any classification of periods in view of their comparison has to take such differences into account, even if they are smaller.

One must, however, take care because a comparison of the Q values for too different values of *aa* (or *am*) could be misleading. Thus it is obvious that for very low values of *aa* the frequency distribution is necessarily narrow and Q takes a high value. This well appears in Figure 34. In the 1-year curves the Q values are systematically greater than the average at the time of the minimums of the *aa* in the first part of the series during which the activity is extremely low; this is no longer true afterward. Furthermore, and this seems to be inconsistent with the above observation, the average value of Q is systematically lower during the first 33 years of the series (0.618 $\pm$ 0.027) than during the last 33 years (0.647 $\pm$ 0.029). This is due to the higher level of the activi-

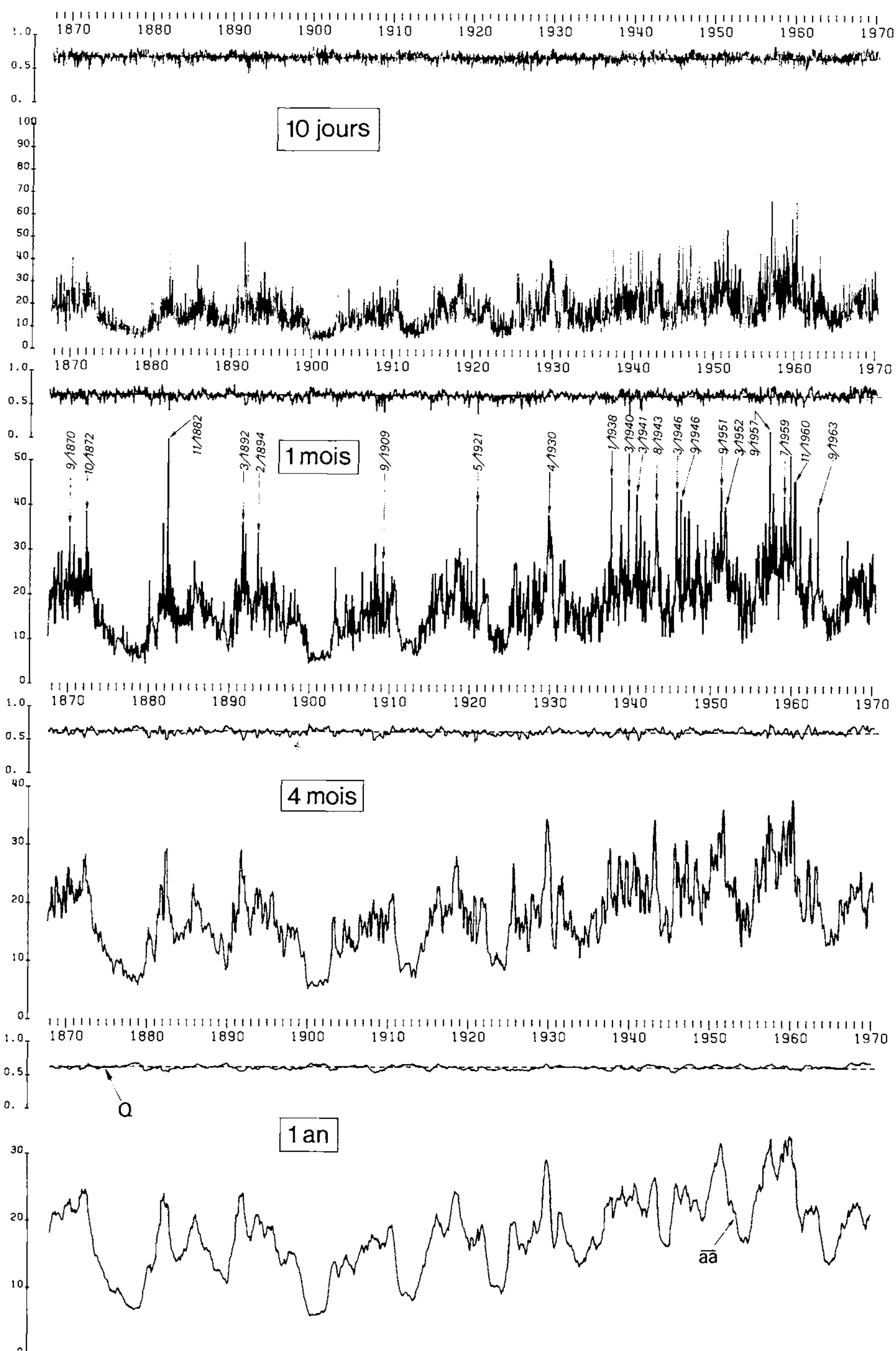


Fig. 34. Average values of the indices *aa* or of the quotients *Q* (geometric average/arithmetic average) for the years 1868–1970. Four time intervals are used: 10 days, 1 month, 4 months, 1 year. In the last two cases, 4-month or 1-yr running averages are used so that there is one point plotted per month. Year marks are plotted at the abscissa of the 1-yr average corresponding to a full year, at the abscissa of the 4-month running average corresponding to May–August, at the middle of the 12 months (or of the 36 10-day periods) in the other two cases. Note that the ordinate scales (in gammas) vary from one plot to another for the *aa* curves; they do not vary for the *Q* values. The dashed line drawn through the *Q* curves corresponds to the average value of *Q* for the whole period [after *Mayaud,* 1976*a*].

TABLE 31. Average Values of the Quotient Q and Values of the Standard Deviation σ of These Quotients for Various Time Intervals

Time Interval	10 Days	1 Month	4 Months	1 Year
Q	0.682	0.649	0.635	0.629
σ	0.086	0.063	0.043	0.031

The values are derived from a 103-yr sample of *aa* indices. One could find in Figure 6 of *Mayaud* [1976*a*] similar values for shorter or longer time intervals.

ty during the latter part, where stormy periods occur at such a rhythm that they tend to dominate the quiet periods; during the former part, stormy periods alternate much more with the quiet periods, hence a less narrow frequency distribution. Therefore the quantity Q is a complex parameter of which one cannot ask too much: a single number cannot give all the information contained in a frequency distribution just as a correlation coefficient cannot describe a cloud of points. However, the quantity Q is easier to handle than the frequency distribution.

7. The *AU, AL,* and *AE* Indices

The *AE* index and the joint *AU* and *AL* indices were introduced by *Davis and Sugiura* [1966] as a measure of the global auroral electrojet activity. We describe them before the *Dst* indices because, from the point of view of the phenomenon which they monitor, they are closer to the planetary range indices which are themselves mainly sensitive to the auroral variations. They share with the *Dst* indices two advantages on the range indices: (1) to monitor a well-defined species among the irregular transient variation and (2) to be a summarized information only from the point of view of the coverage of these species on a worldwide scale. Indeed, concerning this second point, a planetary record of the phenomenon can be potentially obtained for any sampling rate. On the contrary, the range indices are discrete values defined over a constant time interval whose length depends on the morphology of the variations and any time interval cannot be chosen.

The *AE* indices were adopted by IAGA at its Madrid meeting in 1969 (*IAGA Bulletin 27,* 1969, p. 123, resolution 2); unfortunately, they cannot yet be included in the yearly *IAGA Bulletins 32* because of the necessary delay in their derivation which necessitates a semiautomatic 2.5-min digitalization of the standard records at most of the stations. One may expect that such a delay will be greatly shortened when all the *AE* stations provide digital records and that their inclusion in these bulletins will become possible.

7.1. *The Ideal Scheme of the AU, AL, and AE Indices*

From 1966 onward, knowledge of the spatial and temporal behavior of the auroral variations has made considerable progress. The last review on that topic is from *Rostoker* [1972*a*], who stresses the polar magnetic substorms. But data acquired along meridional and dense chains of stations on either side of the auroral zone continuously reveal the great complexity of the phenomenon. The main difficulty is to estimate, from a network made up of a limited number of stations, what part of the variations observed in a given point is due to the intensity variation of the field source and what part is due to its spatial mo-

TABLE 32. Values of *aa* and Q for Various Months

	4/1930	1/1938	3/1940	3/1941	8/1943	9/1943
$\bar{aa}$	38.1	46.6	43.9	42.8	40.9	35.3
Q	<u>0.701</u>	<u>0.539</u>	<u>0.383</u>	0.610	<u>0.733</u>	<u>0.788</u>
	9/1951	3/1952	4/1952	9/1957	7/1959	9/1963
$\bar{aa}$	44.4	40.1	37.9	56.9	42.5	40.2
Q	0.644	0.650	0.657	<u>0.536</u>	<u>0.565</u>	0.637

The Q value is underlined when its deviation from the average Q is greater than the standard deviation.

tion. In that respect, the *AE* index, derived from the single *H* component in a limited network of stations, is only summarized information.

Broadly speaking, an agreement among workers exists on the following fact. The predominant feature of the auroral variations is the transient and irregular occurrence of an eastward current (parallel to the auroral zone) over a limited longitude sector during the local afternoon/evening and of a westward current during the local late evening/early morning. These currents or electrojets flow within the low ionosphere and are very probably linked to remote current sources in the magnetosphere through field-aligned currents. As was first shown by *Harang* [1946], the average latitude of the eastward electrojet is lower by a few degrees than that of the westward electrojet. And as was expressed by *Rostoker* [1972*a*], the substorms would be 'a marked intensification of only a limited part of the westward electrojet near midnight.'

Given the direction of these electrojets, the *H* component is obviously the most suitable for monitoring their temporal variations. Let us suppose that one chooses the average quiet time level in this component as a reference level (which implies that the regular variation S_R is not eliminated). At auroral stations 'the deviations ΔH from this reference level are directly related to the magnitude of the eastward ($\Delta H > 0$) or westward ($\Delta H < 0$) electrojets. If the distribution of stations were infinitely dense and if the superpositions were made of all the *H* traces arranged by universal time, these traces would define upper and lower envelopes between which all the curves would lie' [*Davis and Sugiura,* 1966]. Such upper and lower envelopes define the *AU* (*U* for 'upper') and *AL* (*L* for 'lower') indices, monitoring, respectively, the eastward and westward electrojets (see Figure 35 for such envelopes). The ΔH deviations caused by the electrojets are often several tens of times greater than the deviation due to the S_R variation; consequently, each time that a certain auroral activity exists the envelopes are defined uniquely by the deviations observed at the stations located within the favorable local time sector for one or the other electrojets. *Davis and Sugiura* [1966] state, from various practical considerations, that an 'ideal station network would be one with a spacing of roughly 30° of longitude around the entire auroral zone and with a further condition, though unlikely to be readily met in practice, that every other station be roughly 5° to the south of the auroral zone.'

Figure 36 illustrates the first attempt at deriving such indices, which was, however, obtained from only five northern and two southern auroral stations; the sampling rate is of 2.5 min. The morphology of the variations of the auroral electrojets, as they appear in such a record, can be compared (see Figure 37) to that resulting from a network made up of 11 northern auroral stations. However, one must note that losses of traces at some of the stations during the second day displayed in Figure 36 accentuate the differences.

The first example raises a fundamental point concerning the zero level of the indices, which leads *Davis and Sugiura* [1966] to define complementary indices. The great storm beginning on February 11, 1958, at 1.4h UT is included in the series of days displayed; obviously, the *AU* and *AL* records appear to be depressed from about 0400 UT on that day, and the phenomenon is sufficiently strong so that the *AU* index takes negative values, which is contrary to its definition (*AU* should always be positive). A record of the *Dst* index, plotted in the same figure, indicates that the ring current which becomes extremely intense ($-400\ \gamma$ around 1100 UT) is the cause of this apparent anomaly. Given the auroral latitude of the stations, the ring current effect is about twice as small there but largely sufficient for contaminating the *AU* and *AL* indices. The same fact is observed on the first set of records of Figure 37, although the effect is smaller. This was why *Davis and Sugiura* [1966] introduced the *AE* index, equal to $AU - AL$; it corresponds to 'the separation between the *AU* and *AL* envelopes, depends solely upon the maximum eastward and westward electrojet currents and is independent of zonal currents, if any, existing in the ionosphere, or of the axially symmetric component of magnetic fields from any distant sources.' Similarly, they define $A_0 = (AU + AL)/2$, which is 'an approximate measure of the equivalent zonal current.' However, given the frequent asymmetry in the strength of the eastward and westward electrojets, this last quantity is rather a measure of the added effects of such an asymmetry and of the ring current itself. On the contrary, the *AE* index correctly eliminates the ring current variations at any time (other contaminations by the S_R variation, however, are still included). But the physical meaning of the *AE* index is much less obvious

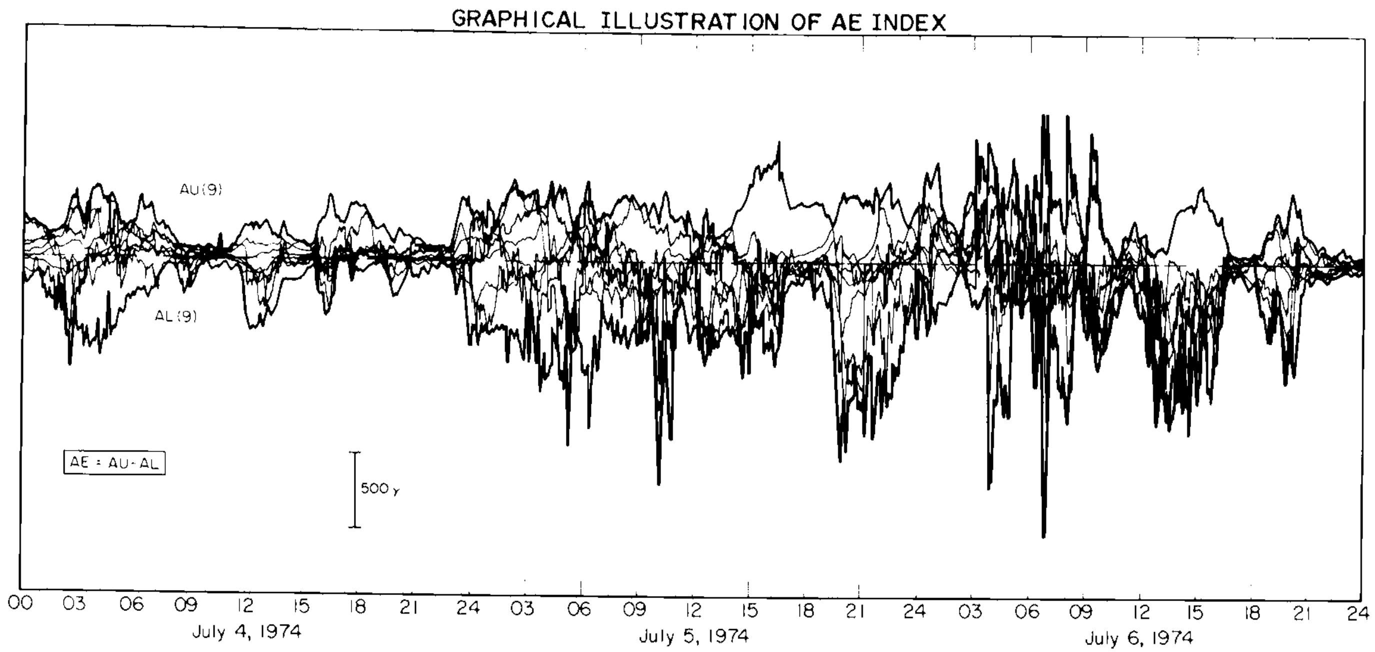


Fig. 35. Traces of the *H* records at nine auroral stations are superimposed for a series of 3 days. The resulting upper and lower envelopes are drawn in bold curves [after *Allen et al.*, 1976].

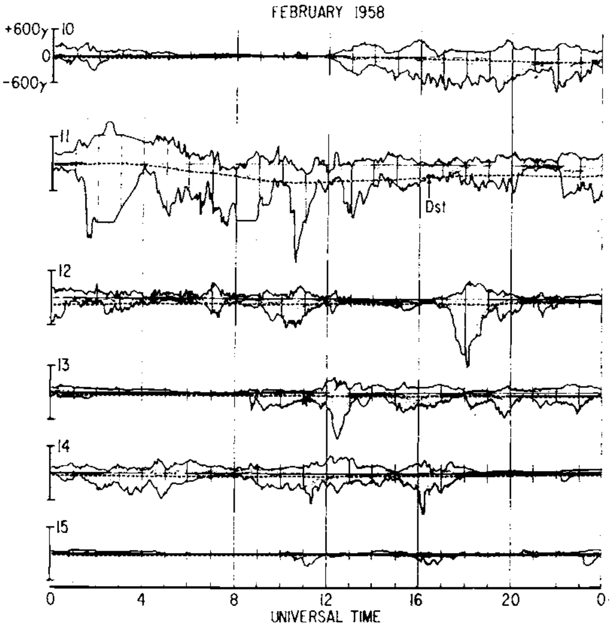


Fig. 36. Graphical representation of the *AU* index (upper curve in each day) and of the *AL* index (lower curve) for a series of 6 days. The dashed curve represents the *Dst* index [after *Davis and Sugiura,* 1966].

than the one of the *AU* and *AL* indices taken separately. Indeed the eastward and westward electrojets may fluctuate independently of one another [*Rostoker,* 1972*a*], and certainly 'it may often be useful to treat *AU* and *AL* indices as independent indices' [*Rostoker,* 1972*b*]. It is all the more true as we shall see (subsection 7.4) that the annual variation of both indices is not the same.

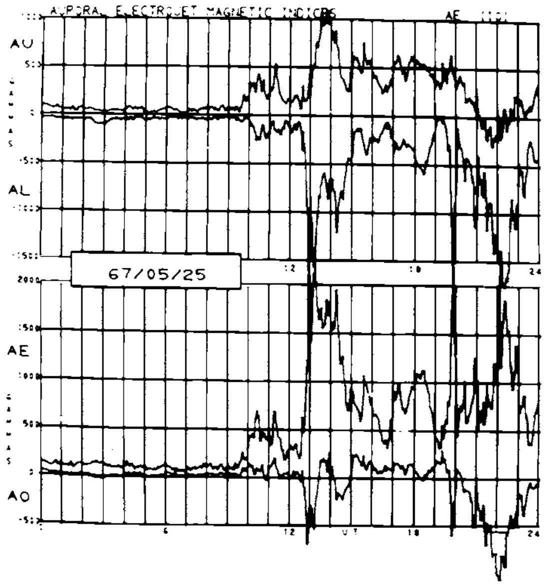
In comparison with the contamination by the ring current variations, the one caused by the S_R variation is quite small, since the amplitude of the latter is a few tens of gammas at auroral latitudes, while the electrojet variations are often hundreds of gammas. Such a contamination has two sources. (1) The quiet time average taken as a reference level at each station means that the zero level chosen is below the night zero level (the S_R variation is mainly negative in H at auroral latitudes). Then the *AU* index (or the *AL* index) is systematically slightly too large (or too small) at the times when the upper (or the lower) envelope is defined by an auroral variation; in such cases, the contamination is caused only by the reference level. (2) When no auroral variation occurs, the envelope is defined by the S_R variation itself, and this is true for both the *AU* and *AL* indices, since the zero level is not the nighttime level. We shall discuss these points later (see section 4.4.4). However, if one considers that probably *AU* and *AL* indices are more interesting for the study of individual events than for statistical studies, only the first source interferes, and in this case, the contamination is negligible. A look at the records displayed in Figures 36 and 37 shows that it is easy to discriminate the times when no auroral variation occurs (absence of irregular variations) from those where the auroral electrojets are present.

Finally, Figure 38 indicates to what extent information is lost when the sampling rate becomes lower. Its further interest is to illustrate how much the K index (3-h sampling rate) and its planetary derivatives mask the complexity of the phenomena. We stated in Chapter 4 the reasons for this apparently very low sampling rate.

7.2. *The Actual Derivation*

The fundamental problem for the derivation of the *AE* indices is the choice of the network or, more exactly, the availability of stations at the right locations. Table 33 gives the various stations used from 1957 to 1965, and Figure 39 schematically illustrates the position of the stations before 1966 (part A) and from 1966 onwards (part B) in the corrected geomagnetic coordinate system; Figure 40 permits one to evaluate for the present network how difficult it is to find a narrow band close to the auroral zone (that is, close to $\lambda = 70°$) such that there would exist no wide longitude sector without land or island. Another constraint exists: 'The magnetograms should come from established observatories whose records would continue to be available on a timely basis through the World Data Center System, and such a choice involved some compromise between the wish to use as much data as possible and the high cost of digitizing analog magnetograms' [*Allen et al.,* 1976]. Note that in order to inform users of the true number of stations used in the derivation (it may vary either because a given station did not produce magnetograms for 1 or several months or because a new station becomes available) this number is indicated within parentheses after the symbol *AE*, e.g., *AE*(10) or *AE*(11).

The derivation itself is as follows. A constant quiet time reference level is determined for each month at each station from the average of the H component during the 5 international quietest days of the month. For each 2.5-min H value of each station this reference level is subtracted. The deviations thus obtained at the network station are compared, and extreme positive and negative


AURORAL ELECTROJET MAGNETIC INDICES
AU
AL
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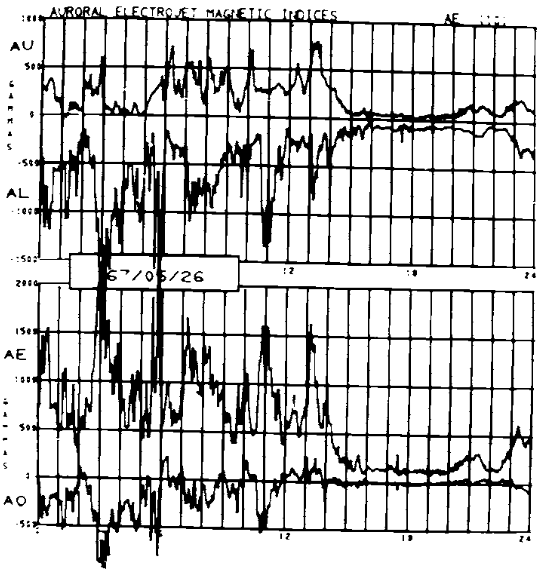
AE
AO
UT


AURORAL ELECTROJET MAGNETIC INDICES
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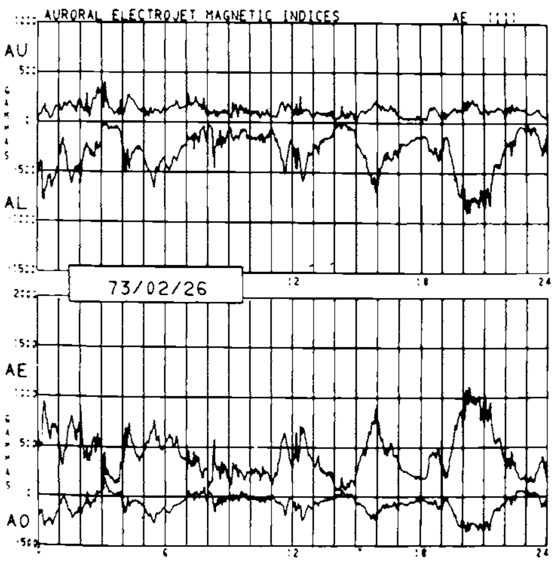
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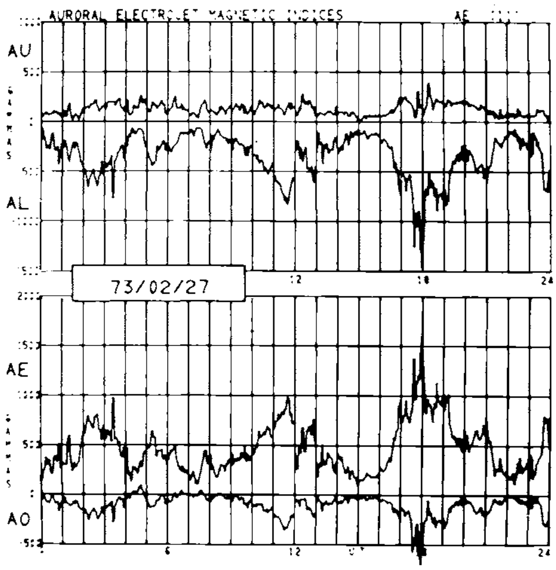
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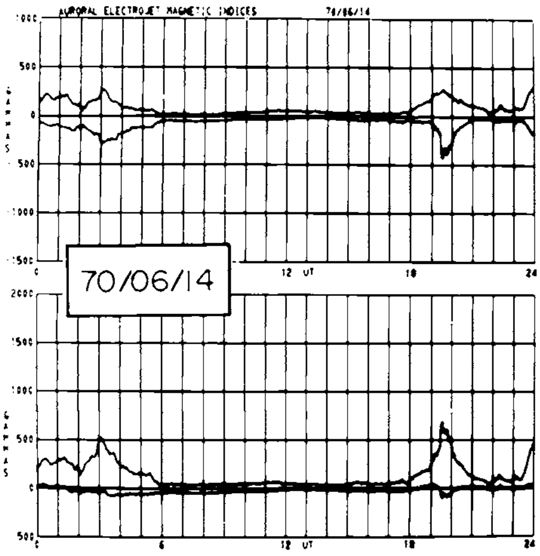
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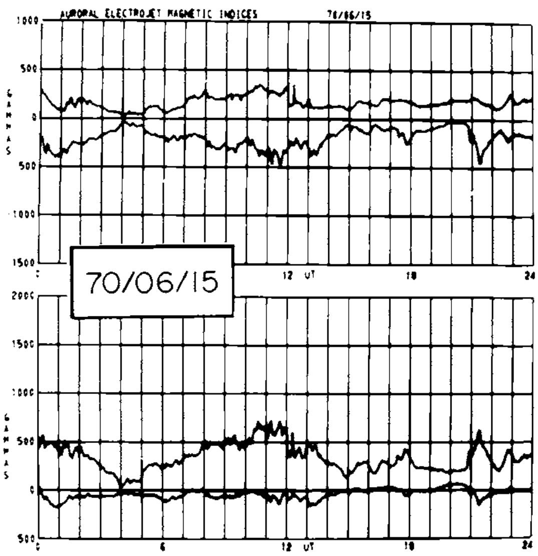
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deviations define the *AU* and *AL* indices, respectively. As stated by *Allen et al.* [1976], this technique when used for the quiet time reference level may introduce month end discontinuities in *AU* or *AL*. When looking, however, at the tables of these reference levels (see section 7.3) which vary only by a few gammas most of the time, discontinuities thus introduced on the 2.5-min *AU* and *AL* values are negligible. One may note that uncertainties concerning the base lines do not interfere, since the quantities used are the deviations. Finally, 'when the *H* traces is suddenly lost at a critically located station that was supplying either *AU* or *AL*, then some other station having the most extreme *H* deviation at that instant

Fig. 37. (opposite) An example of the daily graphs of the *AU, AL, AE,* and A_0 as they are presently given in the UAG reports (see section 7.3). In each graph the two upper curves correspond to *AU* and *AL*, and the two lower to *AE* and A_0. Three sets of 2 days have been chosen to illustrate various morphological features. In the top set a storm begins with a sudden commencement (at 12.6 h UT) on May 25, 1967. Note that the auroral activity begins earlier. This is a common feature [*Chapman,* 1956], which appears also in Figure 35 (the sudden commencement is at 01.4 h UT on February 11, but it is not certain that the subauroral activity existing for 12 h before the sudden commencement has to be entirely considered as a precursor of the storm). During the storm itself, sharp variations occur; they are larger in the *AL* index than in the *AU* index, although they are also relatively large and sharp in the *AU* index. The average value of the *am* index for the 24 h during which the storm is most active is 290. On February 26 and 27, 1973 (second set of daily graphs), the activity is much smaller (one has *am* = 50 for the 48-h period displayed), and these days belong to a series of 10 days where the activity remains at that level. The contrast between *AU* and *AL* is much greater: *AU* is continuously waxing and waning around at about 150–200 γ, while *AL* undergoes large variations. But the latter are much longer in duration in this storm than during the above storm. When looking at series of daily graphs in the UAG reports, such features appear to be the most common. However, this morphological notation may be biased by the fact that the solar cycle period presently covered by these reports mainly concerns a time when the recurrent *M* regions were predominant. And the two days of February 1973 illustrated here certainly belong to disturbances related to the *M* regions (see in Figure 21 the set of recurrent stormy periods from February to June). The last two days (June 14 and 15, 1970) correspond to a lower activity level, and the first of them is almost quiet (*am* = 12 but with a significant difference between both hemispheres, since *an* = 15 and *as* = 9). In that case, a relatively well-isolated substorm appears in the *AL* index (around 19.5 h in the first day), and the disturbance lasts longer in the *AU* index. This, however, is not a necessary feature: one can observe a substorm in the *AL* index without a significant associated disturbance in the *AU* index [after *Allen et al.,* 1974, 1975; *Allen,* 1972].

TABLE 33. Network of Stations Used in the Derivation of *AE* Indices From 1957 to 1965

1957	HB			LE	DO			SO		DI		TI	UE	CO	SI	ME			BY
1958	HB			LE	DO	TR				DI		TI	UE	CO	SI	ME	BL		BY
1959	HB			LE	DO			SO		DI		TI	UE	CO	SI	ME			BY
1960	HB			LE	DO			SO		DI		TI	UE	CO	SI	ME			BY
1961	HB	NWS		LE				SO		DI		TI	UE	CO	SI	ME			BY
1962	HB			LE	DO			SO		DI		TI	UE	CO	SI	ME			BY
1963	HB			LE	DO			SO		DI		TI	UE	CO	SI	ME			BY
1964	HB				DO			SO		DI		TI	UE	CO	SI	ME			BY
1965			LR				KI		MM	DI	CC	TI	UE	CO	SI	ME		FC	

Symbols for the stations are listed with respect to corrected geomagnetic longitude. From 1966 onward, the stations used are those appearing in Figure 39, part B, with the exception of NAS used only from 1968 onward and of SO substituted for Abisko in 1966 and 1967. In alphabetical order, symbols in this table and in Figure 39 correspond to the following stations: AI, Abisko; BL, Baker Lake; BY, Byrd; BW, Point Barrow; CC, Cape Chelyuskin; CO, College; DI, Dickson; DO, Dombas; FC, Fort Churchill; GWR, Great Whale River; HB, Halley Bay; KI, Kiruna; LE, Leirvoguir; LR, Lerwick; LE, Leirvoguir; ME, Meanook; MM, Murmansk; NAS, Narssarssuaq; NWS, Norway Station; SI, Sitka; SO, Sodankyla; TI, Tixie Bay; and UE, Cape Wellen.

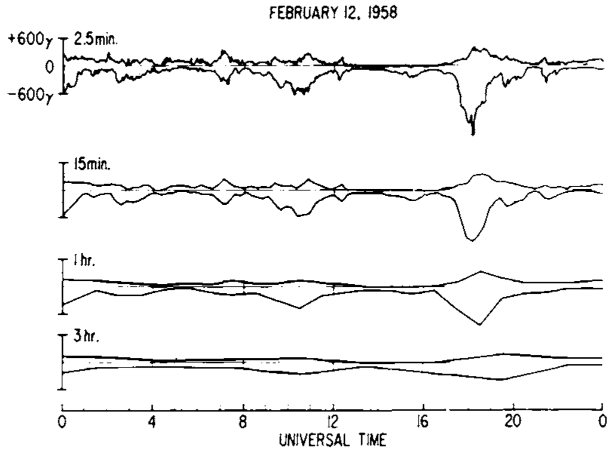

Fig. 38. Plot of the upper (AU) and lower (AL) envelopes obtained on February 12, 1958, using 2.5-min scalings and 15-min, 1-h and 3-h averages of the 2.5-min scalings. The contrast between the results obtained with the last two sampling rates is enhanced by the use of the averages instead of the extreme deviations observed within a given interval; the latter process would not reduce the amplitudes, but all details would still be lost [after *Davis and Sugiura,* 1966].

begins to take the place of the lost data source and becomes the key to the affected index, ...and such intervals have the effect of producing a large bay-like feature in the affected AU or AL trace' [*Allen et al.,* 1976]. They are called missing data effects (mde) and are labeled in the tabulation of the data.

In section 7.4 we shall discuss the problem of the reference level chosen and of the contamination by the ring current variations and the variation S_R. Three other points have to be examined at this step because they interfere more or less on the resulting indices. The first two can change the apparent latitude of the stations, and the third one concerns the distribution of the network stations.

1. Abnormal underground induced effects may affect the indices. This is all the more probable in that since the primary source (the auroral electrojets) is at a low altitude and fluctuates rapidly, the induced effects are at low depth. It would be of interest to get information concerning the conditions of the induction at each AE station. Besides, one has to be aware that even at a station which

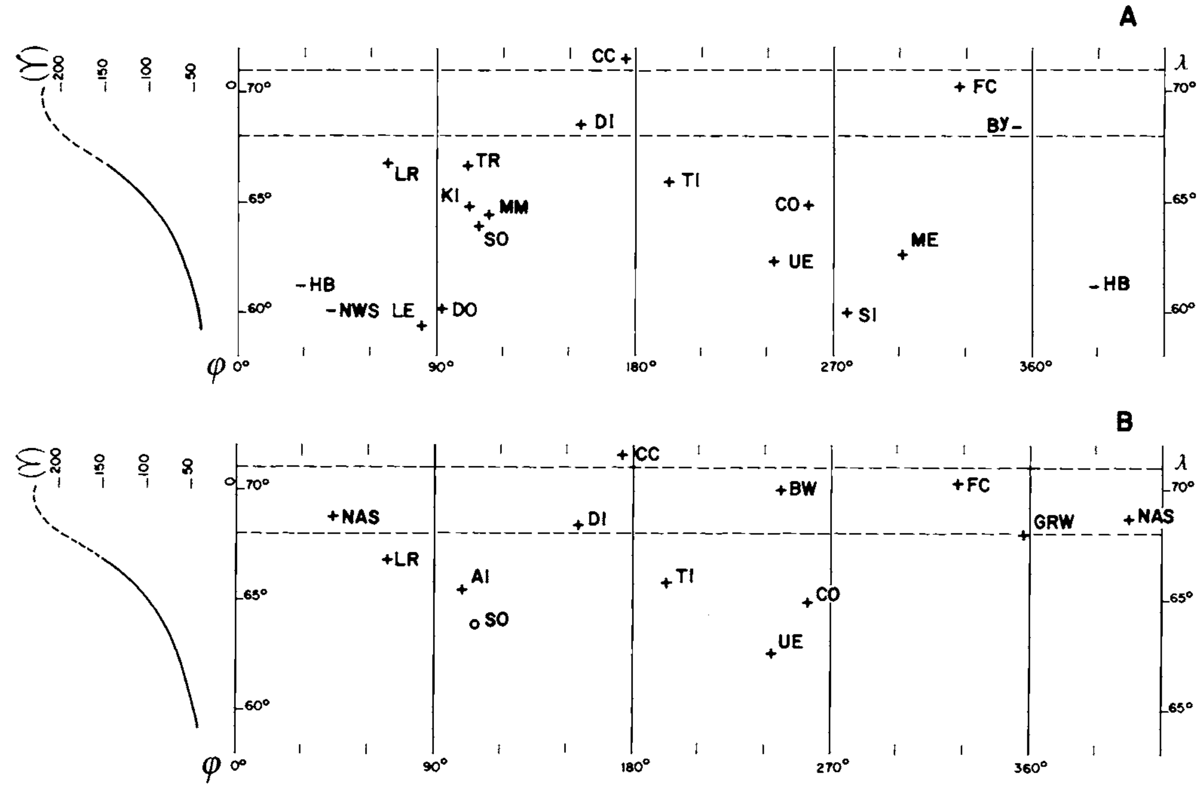

Fig. 39. Schematic diagram illustrating the position of the AE stations in the corrected geomagnetic latitude (λ) and longitude (φ) coordinate system before 1966 (part A) and after (part B). Position of northern (or southern) stations is indicated by a plus sign (or a minussign). The latitude zone which is most favorable for AE stations is included between the two straight dashed lines. In part A the position of Baker Lake (BL), with $\lambda = +75.2°$ and $\varphi = 320.0°$, is not drawn. On the left-hand side, the curves illustrate the latitude variation of the activity level, as measured with K indices: the dashed part of the curve is an extrapolation. See Table 33 for the names of the station corresponding to a given symbol.

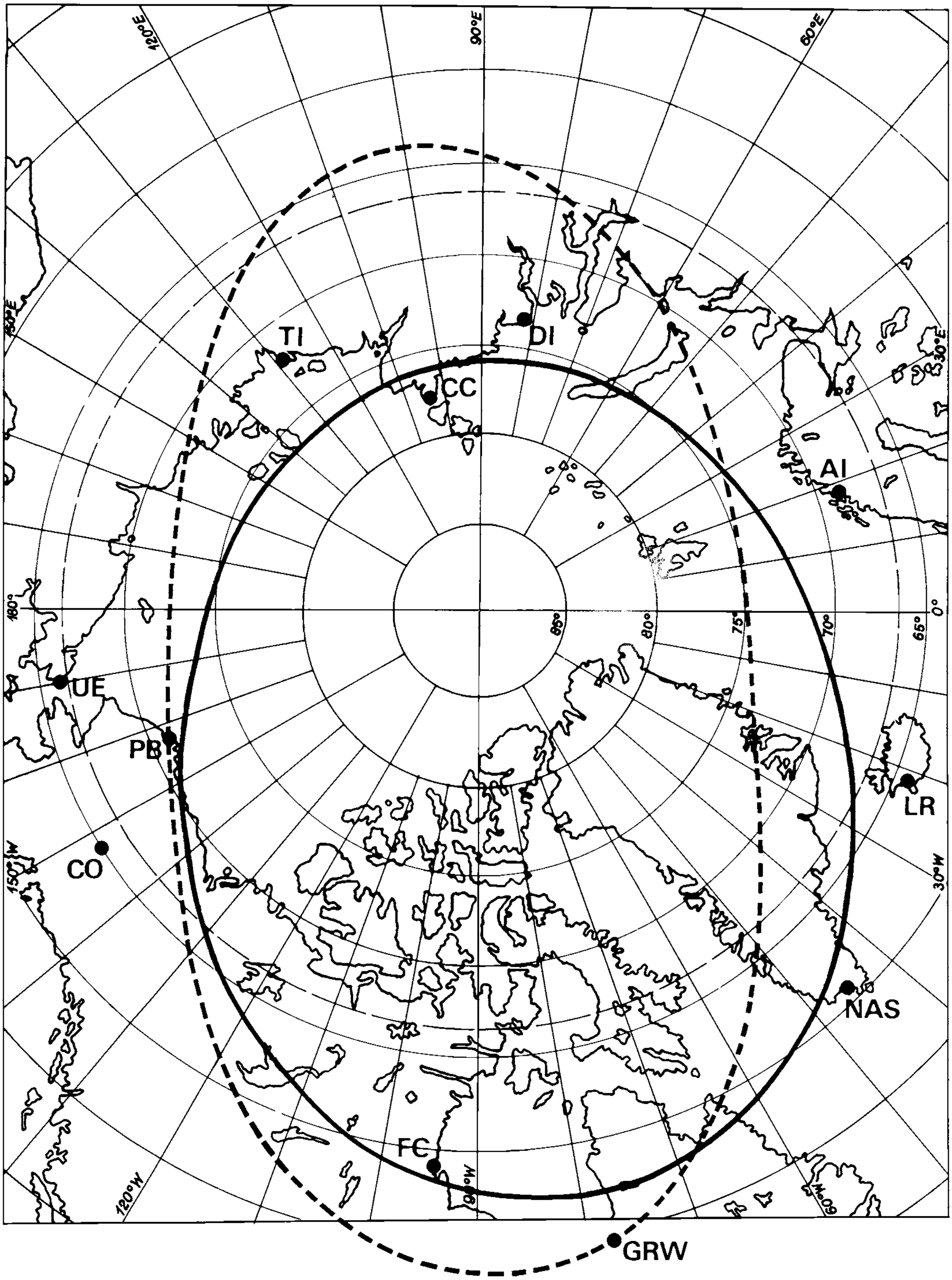

Fig. 40. A map illustrating the path of the line corresponding to a corrected geomagnetic latitude λ = 70° over land and sea. The dashed curve corresponds to the isocline 80° at ground (approximately equivalent to a 70° latitude).

could be considered to be normal the intensity of the induced effects depends on the variation speed of the intensity of the primary source. In other words, the deviation observed is not strictly proportionate to the intensity of the primary source. And probably because they are derived from auroral stations, the *AU* and *AL* indices are the most sensitive, of all the IAGA indices, to possible abnormal induced effects.

2. The magnetic meridian at ground, that is, the direction along which the *H* component is recorded, is not necessarily normal to the direction of the auroral electrojets. Let us consider that, on the average, these electrojets are parallel to the lines of equal corrected geomagnetic latitude (the introduction of this coordinate system partly finds its justification in this fact). Isoclines at ground deviate considerably (especially in the northern hemisphere because of the large Siberian anomaly) from the former. Since magnetic meridians at ground are normal to the isoclines, it means that the reference coordinate recording system causes systematic differences between stations. (In Figure 40 an isocline is drawn in order to illustrate this fact.) Such an effect changes systematically the apparent latitude of the station (as would any abnormal underground induced effect). However, this could be taken into account in the future either by changing the recording axis or, more simply, when digital records are available, by computing the value of the component normal to the corrected geomagnetic latitudes.

3. Figure 39 permits one to evaluate to what extent the actual distribution of the *AE* stations deviates from the ideal distribution described by *Davis and Sugiura* [1966]. The curve on the left-hand side is derived from *K* indices data. (It is identical with that of Figure 14 for its solid line part and is inferred from the works of *Mayaud* [1956], *Loomer and Whitham* [1963], and *Berthelier* [1979] for the dashed line part.) At corrected geomagnetic latitudes higher than $\lambda = 60°$, range *K* indices certainly provide reliable information on the latitude variation of the auroral variations intensity; the only restriction is that with such a statistical result the width of the latitude band within which these variations are the greatest is increased, since the gravity center of the events varies from one to another. Given the extremely rapid variation of the activity level in these latitudes (a ratio from 1 to 6 from $\lambda = 59°$ up to $\lambda = 69°$–$70°$), it is obvious that the most favorable band would be the region of the maximum (about 68°–71°). When looking at Figure 40, one can see that this is the only band that crosses or passes close to lands or islands over the Atlantic Ocean (south of Greenland, Iceland, and northern Europe). Now, Figure 39 shows that the present network used (part B) is less scattered with latitude than is the previous one; it has also the advantage not to include any southern station (neither Great Whale River nor Narssarsuaq existed at the time of the former, which obliged Davis and Sugiura to fill the gap with southern stations). Anyway, it is obvious that a priori the level of the *AE* index is certainly lower before 1966 than afterward.

From Figure 40 it is clear that the ideal distribution (a spacing of roughly 30° of longitude at $\lambda =$ 69°–70°, with every other station roughly 5° to the south) cannot be met over the Atlantic Ocean. College with respect to Point Barrow and Tixie with respect to Cape Chelyuskin represent a step in this direction. However, Figures 41 and 42, which show the frequency contribution of each station to the *AU* and *AL* indices for the year 1970, do not permit the conclusion that the non-negligible contribution of College and Tixie at the times of the main peaks is only due to their lower latitude. It would be necessary to be sure that the wide longitude gaps between Point Barrow and Fort Churchill (i.e., 80°) on the one hand and between Cape Chelyuskin and Point Barrow (i.e., 70°) do not favor such secondary contributions. The inclusion of Yellowknife (at a favorable latitude in the middle of the former gap) and the one of a new station in the middle of the second gap would certainly be a great improvement of the network. Secondary improvements would be a supplementary station in Novaya Zemlya (at the right latitude) between Abisko and Dixon and, possibly, the use of a station of higher latitude than Abisko in northern Europe.

Could one consider the introduction of a latitude standardization in the derivation of the *AU* and *AL* indices, as it is made for the *am* indices? Laborious investigations would be needed to know what is exactly the latitude variation law, which is probably not the same for both auroral electrojets. Furthermore, because the stations are, and have to be, within the region of the electrojets, it would be very difficult to take spatial motions of the electrojets into account. And in this respect, one never knows if the extreme deviations recorded at the station network (that is, the *AU* and *AL* indices) are the true intensities of one or

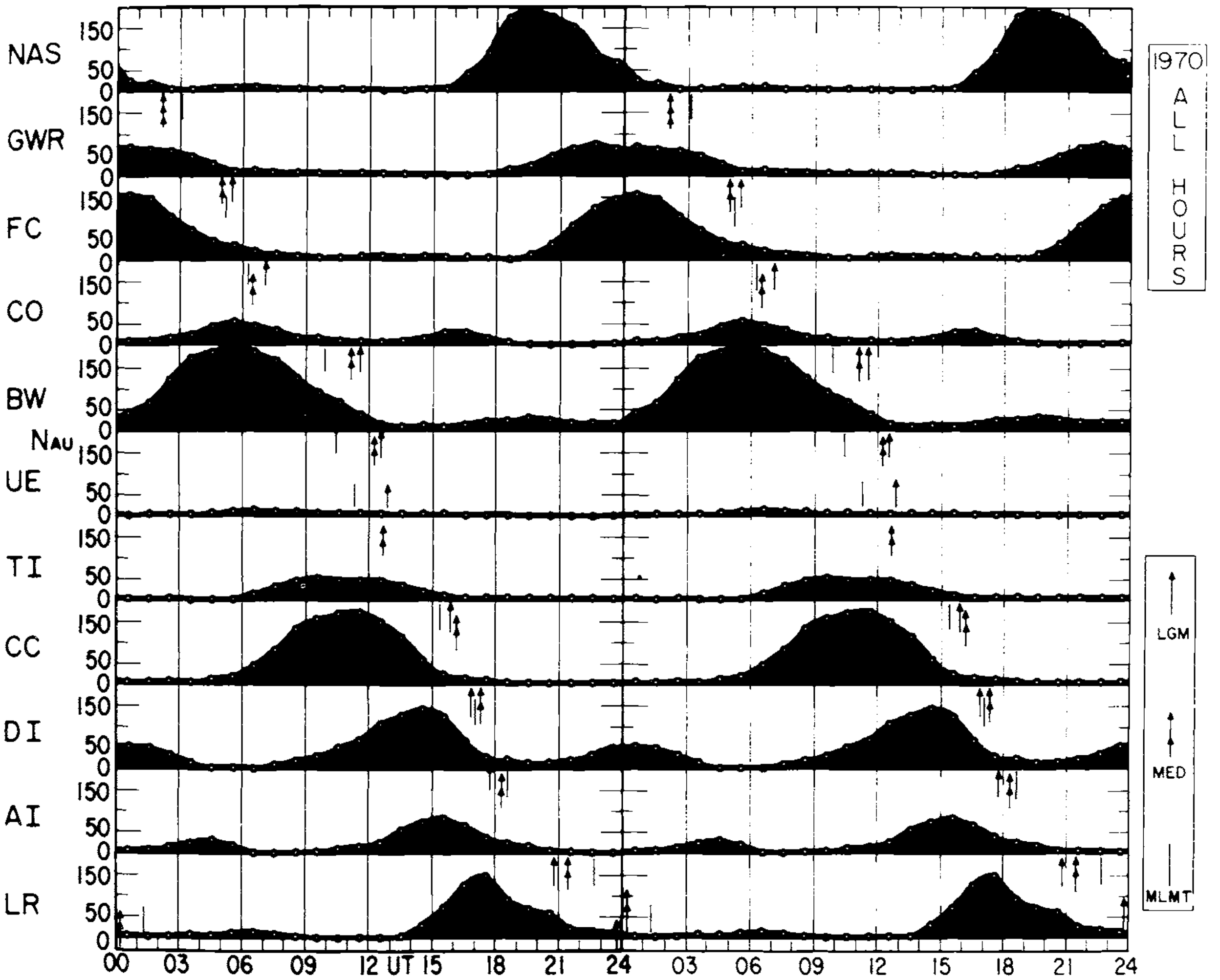

Fig. 41. Frequency of hourly *AU* contributions by each *AE* station for 1970. UT times of midnight local mean time (MLMT), local geomagnetic midnight (LGM) and midnight eccentric dipole (MED) are marked for each station. The last two quantities correspond to the dipole geomagnetic coordinate system and to the eccentric dipole coordinate system, respectively. See *Chapman and Bartels* [1940, chapter 18] for the definition of the latter. *Vestine* [1938] pointed out that MED is more suitable for auroral phenomena than is the LGM. However, it is not as good as the local midnight in the corrected geomagnetic system introduced later on [after *Allen and Kroëhl,* 1975].

the other electrojets at a given moment. Thus if one considers the example given by *Rostoker* [1972*b*] of a substorm sequence on October 7, 1970, during which the current system peaks near $\lambda = 72.5°$ (see its Figure 3) with an amplitude of 400 γ, it is clear that the *AL* index does not record it properly. It is, however, noteworthy that the *AL* index undergoes two small variations of about 100 γ at the time of this sequence. This confirms the statement of *Allen et al.* [1976] that 'past experience does not suggest that small events could be frequently missed entirely.' But at the time of low auroral activity the intensity of the auroral electrojet is almost always underestimated because the center of the phenomenon is more poleward than usual. On the other hand, this is still true at the time of high auroral activity because the phenomenon is then more equatorward.

7.3. *Tabulation of the Indices*

The data for 1957–1964 are available in the form of hourly values in the University Alaska Reports prepared by T. N. Davis, Y. S. Wong, and C. Echols and published in 1967 and 1968; these values are also available on magnetic tape from the WDC. The data for 1965 were prepared by NASA, and 2.5-min or hourly values are available on magnetic tape. We describe below the tabulation prepared from 1966 onward by the WDC-A, which presently has the responsibility of the project.

Provisional indices, derived from about two

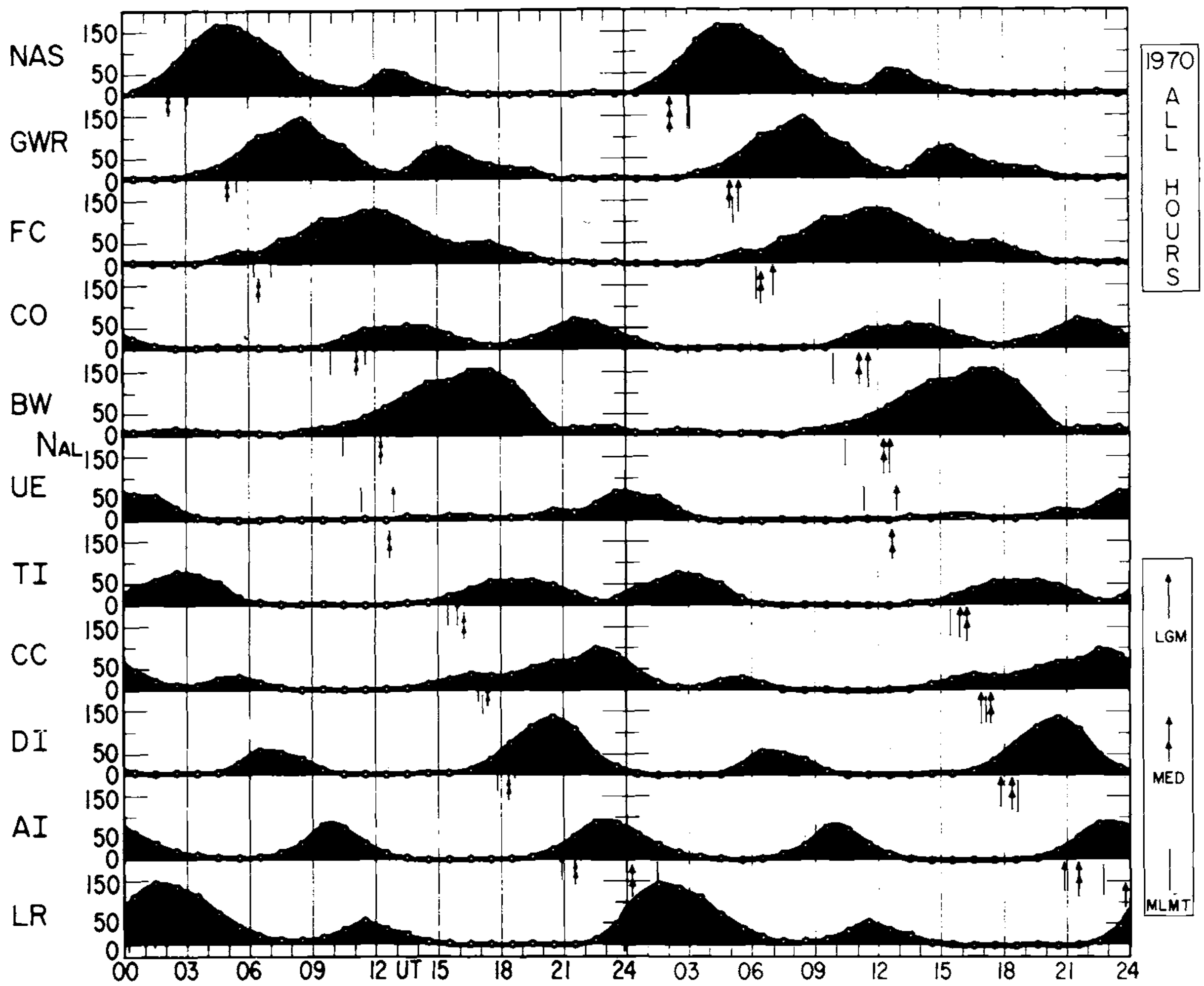

Fig. 42. Frequency of hourly *AL* contribution by each *AE* station. See legend of Figure 41 [after *Allen and Kroëhl,* 1975].

thirds of the stations of the network, are published monthly with a delay of about 18 months in support of the International Magnetospheric Study (beginning January 1976 and ending December 1979). The monthly booklets contain all the data described below and some others (such as copies of all the records used in the derivation).

The sampling rate of the *AU* and *AL* indices is 2.5 min, and it is on this form that they are most interesting for the users. Because it is practically impossible to handle numerical values at this sampling rate (they are available on magnetic tape), the producers of the indices provide daily graphs for all days, which have been published in the UAG reports of World Data Center A from 1966 onward and can be obtained on microfilm (see Figure 37 for examples of these daily graphs). They constitute the basic data to consult, and we believe that although the indices cannot be considered an absolute quantitative measure of the electrojets, such graphs give the scientific community the most significant summarized information concerning the auroral variations. They have to be used jointly with the monthly tables contained in the same reports and indicating at which station of the network the extreme deviations supplying *AU* and *AL* have been recorded during a given universal time hourly interval.

The reports also contained monthly tables of hourly averages, daily averages, and hourly averages for special groups of days (quietest and most disturbed international days) corresponding to each index (*AU*, *AL*, *AE*, and A_0). Furthermore, a special table gives the monthly quiet time values used, as a reference level, at each station.

7.4. *Artificial and True Features in AU and AL Indices*

Artificial features in the *AU* and *AL* indices are caused either by a contamination by (1) the ring current variations or by (2) the regular variation S_R or by (3) the insufficient distribution with latitude and longitude of the observatory network. Suggestions are made to reduce the first two effects; any improvement of the network would be desirable, but dynamic motions of the auroral oval and the true intensity of the auroral variations will never be monitored by a limited network of stations. (4) The difficult problem of the statistical daily and annual variations of the *AU* and *AL* indices is investigated; it appears that the *AL* index would be relatively close to the *an* index (except for the saturation effect) if the defects described in the first two points above could be eliminated; but the *AU* index definitely has a different behavior. (5) Effects of the azimuthal component B_Y of the interplanetary magnetic field and (6) some differences between the response of the *AE* and *am* indices to various solar parameters are reviewed. (7) The limitation imposed by a derivation of the indices from northern observatories only is considered.

1. The ring current effects are eliminated from the *AE* indices but not from the *AU* and *AL* indices, which are certainly more significant. Practically, the contamination becomes important with respect to the auroral variations only at the times when the *Dst* index becomes large (see for instance Figure 36, the second day, Figure 37, the first set of days, and also Figure 21 as an example of a year during which such a contamination would be extremely small). However, one may wonder if it would not be of interest to eliminate the ring current variations in the derivation. One could subtract an interpolated *Dst* index from the 2.5-min values recorded at each station in allowing for the dipole latitude of the station and the angle between ground magnetic and dipole meridians. This would have the further advantage that the quiet time value chosen as a reference level would become more significant because the average level of the *Dst* index during the 5 quietest days is not necessarily the same during other quiet parts of the month. Then 'quiet time departures of station values from their monthly average' [*Allen et al.,* 1976] would be partly eliminated, and the reference level would be certainly improved with such a process.

2. An artificial feature in the *AU* and *AL* indices is caused by the regular S_R variation and appears clearly in Figures 41 and 42, when compared to Figures 43 and 44, which represent the frequency contributions for *AU* or $|AL| \geq 50\ \gamma$. Very clearly, only the low values of the indices contribute to the secondary peaks (a local noon peak with *AL*, appearing at all the stations, and a local morning peak with *AU*, appearing at some of the stations), but one must also note that they contribute much more to the main peaks of *AU* than to those of *AL*. Most of these features can be explained by the S_R variation. If one considers the schematic drawing of Figure 45, one sees first that with the average quiet time reference level chosen (average for the 24 h), the positive S_R contamination lasts a longer time than the negative one. Second, most of the latter one occurs at times when auroral electrojet effects are absent, and deviations due to this contamination are larger: hence, we have a systematic secondary peak with the *AL* indices around the local noon. Furthermore, it is quite significant (see Figure 42) that these secondary peaks are larger at College (CO) and Wellen (UE) than at Point Barrow (BW), while the main peak is larger at the latter: the S_R is smaller at Point Barrow which is higher in latitude, while the westward electrojet effect is larger (see Figure 39 for the respective latitude and longitude of these three stations). Third, during a part of the main peak of *AU* the S_R contamination has the same direction as the eastward electrojet effect; hence both the S_R and the eastward electrojet contribute to the main peak for low values of *AU*. This is not true for the main peak of *AL*, since they are of opposite directions. Finally, particular features of the S_R variation can explain the fact that the secondary morning peaks of *AU* appear only at some stations (see Figure 41): (1) at Leirvoguir (LR), Narssarsuaq (NAS), and Great Whale River (GWR) the declination is strongly to the west ($>20°$W), and this accentuates negative values of the S_R in the morning (hence there is no significant secondary morning peak); (2) at Dixon (DI) and Cape Chelyuskin (CC) the declination is strongly to the east ($>20°$E), while at Tixie (TI) it is to the west (hence the secondary peak appears at Dixon, which is lower in latitude than Cape Chelyuskin, and does not appear at Tixie); (3) at College, Point Barrow, and Wellen, two facts can interfere, a declination to the east ($>20°$) and in summertime the superimposition of the abnormal positive effect of the S_R variation of *H* occurring around 1800 UT and increasing with latitude [*Mayaud,* 1965*c*]; and (4) at Abisko (AI), where the declination angle is very small, a wintertime phenomenon, the largest at European longitudes, could explain the secondary peak. Since about

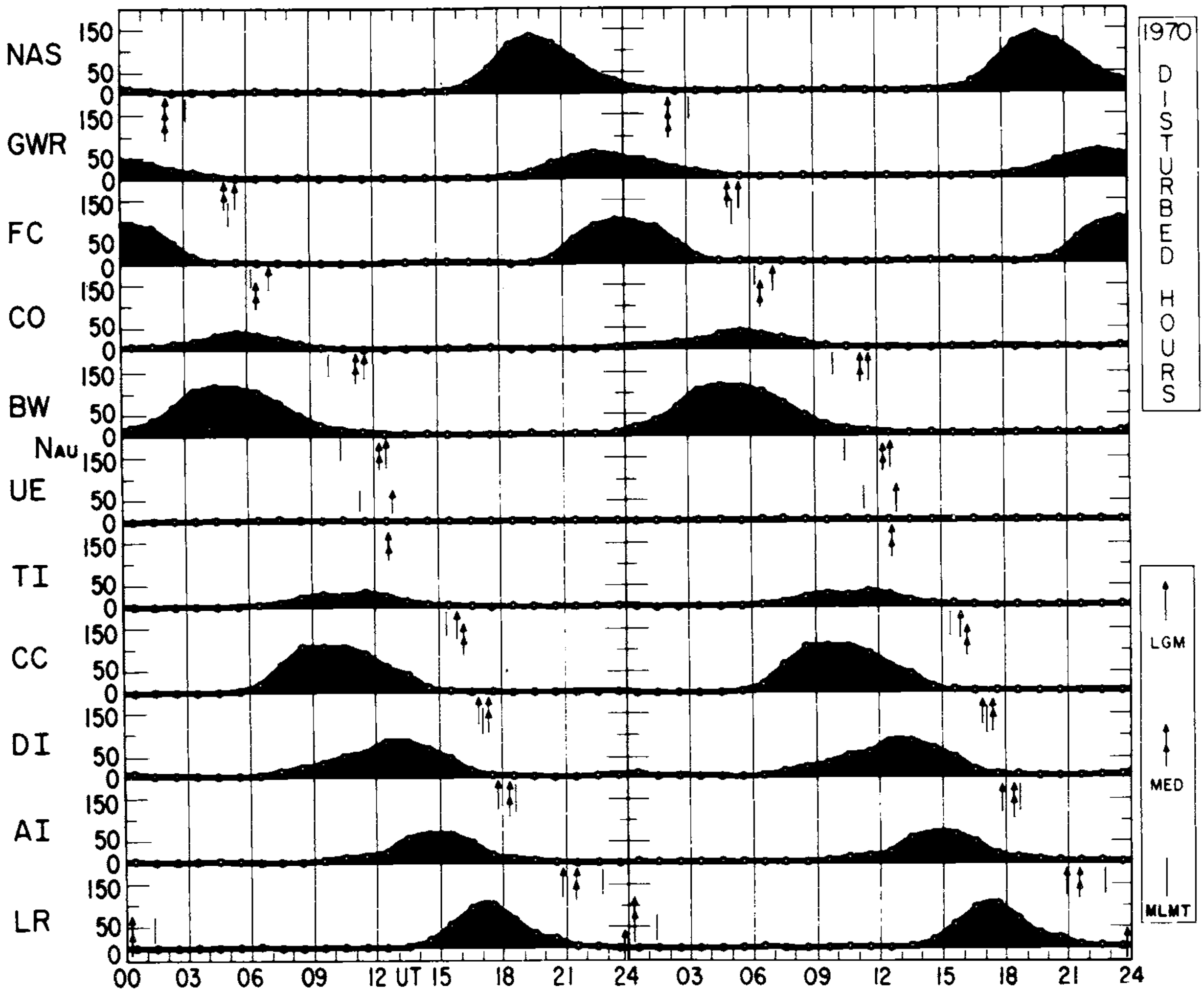

Fig. 43. Same as Figure 41 when only disturbed hours with $AU \geq 50$ are considered [after *Allen and Kroëhl,* 1975].

39% of the AU and AL values are lower than 50 γ (these statistics are taken from a 7-year sample, 1968-1974), the contamination by the S_R is relatively important from the point of view of the number of hourly values which are affected. When looking at Figure 45, one may wonder whether it would not be a step toward the aim sought by the conceivers of these indices to determine the envelopes by using for each index only the traces corresponding to a certain local time interval at each station (for instance, 15 ± 5 h for the AU index and 3 ± 5 h for the AL index). Given the widest longitude gap between AE stations (that is, 80°), the auroral electrojets would be practically always scanned by two stations. A large part of the S_R contamination would be avoided, and the indices would definitely be sensitive to only one species of irregular variations, the auroral disturbances.

Table 34 reveals another feature which can also be easily interpreted by an S_R contamination. As is expected, the histogram of the hourly AL indices is much richer in high values than that of the AU indices, but paradoxically, it is also richer in low values. Most of the lowest AL values are found in the wintertime (that is, 56% of the $|AL| < 20$ during January, February, November, and December); this is easy to understand, since the S_R minimum around noon becomes very small at that time. But Figure 45 shows the asymmetry existing during the little disturbed days when the eastward (or westward) electrojet tends to appear later (or sooner), as shown by *Allen and Kroëhl* [1975]. At these times the S_R contribution to the indices, since this variation is reckoned from the daily average, increases the AU values but decreases the AL values. Then one can wonder if a further modification in the derivation of the indices would not improve the results by suppressing such an asymmetry. To choose as a reference level the

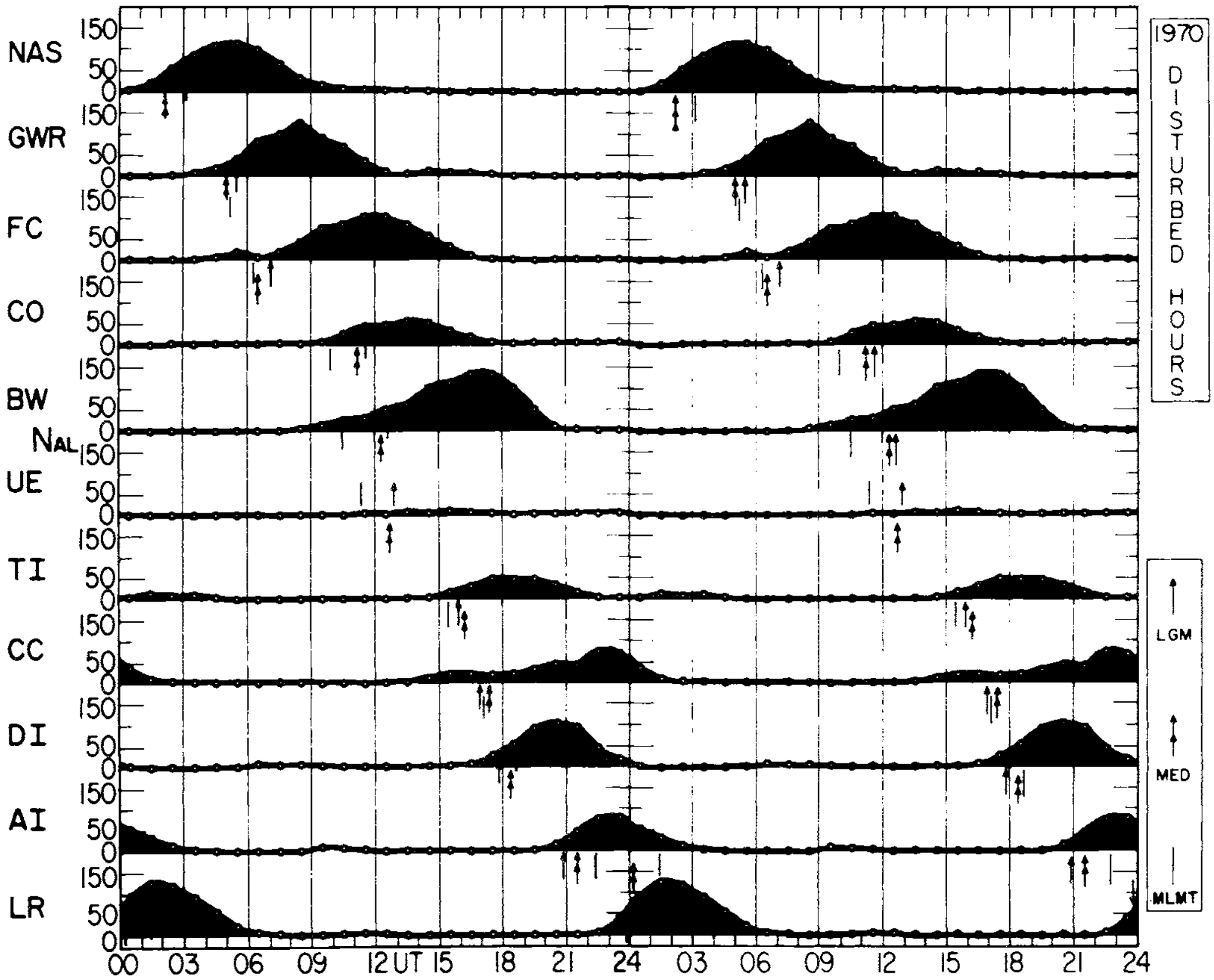

Fig. 44. Same as Figure 42 when only disturbed hours, with $|AL| \geq 50$ are considered [after *Allen and Kroëhl,* 1975].

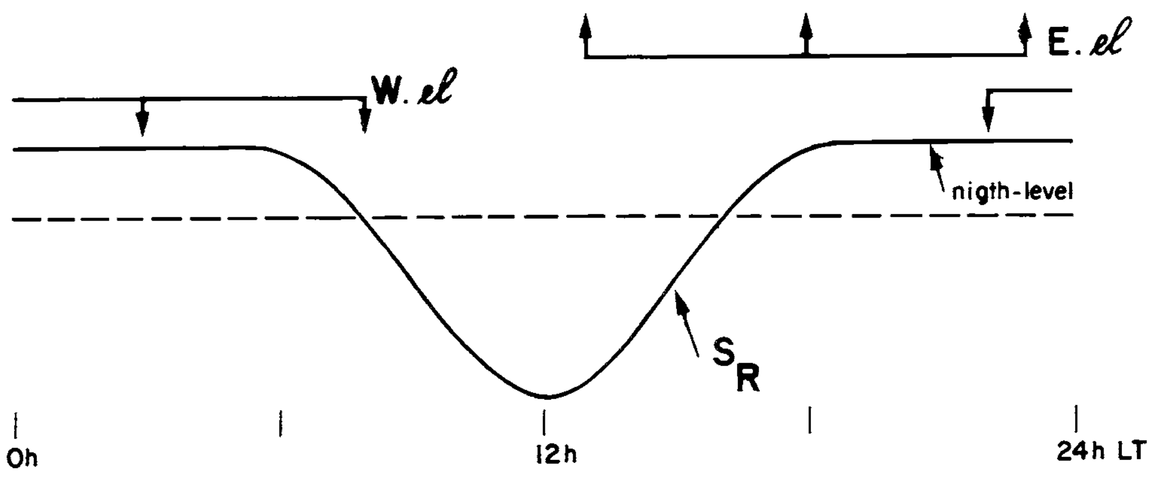

Fig. 45. A schematic diagram comparing an idealized variation S_R in H at an auroral station and the times of occurrence of the eastward electrojet (E.el) or of the westward electrojet (W.el); associated arrows indicate the direction of variation in H for each of them. The dashed line represents the average of the 24 hourly values of the S_R in a quiet day in the absence of any disturbance.

TABLE 34. Percentages of Hourly AU and AL Values Lower Than a Given Threshold a

	a										
	10	20	30	40	50	75	100	150	200	300	500
AU	1.45	9.72	19.93	30.03	38.96	56.26	68.76	84.56	92.96	98.56	99.96
AL	6.20	15.86	26.05	34.03	39.65	49.65	57.25	68.45	76.55	87.55	97.25

Statistics were made with a 7-yr sample (1968–1974).

local night values, at each station, of the 5 international quietest days instead of the full daily averages would be as reliable in spite of the smaller number of hourly values used. Most of the residual disturbances (which can be as well positive or negative) occur at night, and their weight would apparently become greater, but the suppression of the local daytime values would consist in eliminating the systematic error made by the systematic negative contribution of the variation S_R. *Allen and Kroëhl* [1975] mentioned the possibility of a similar modification but noted that it would increase the secondary noon peak of the frequency contribution for AL; this objection is no longer valid if the other modification (to scan traces of each station only at the times of the occurrence of each electrojet) is also carried out.

This new definition for the reference level would cause much smaller effects at the time of great disturbances than the elimination of the Dst variations. It would not permit one to assert that the true zero level of the disturbances is always obtained. Such a requirement would suppose a laborious visual identification in the records of constant levels during quiet nights, and it is not always possible at auroral stations to find a few of them during each month. But there is some probability that residual positive and negative disturbances cancel out each other; when looking at them on daily graphs of AU and AL for the quiet days, one gets the impression that this is approximately true with the days which are really quiet. (Any statistics from the present AU and AL values would be vitiated by the present reference level.) Anyway, one may note here how difficult is, when deriving indices, to make a correct discrimination between regular and irregular variations.

3. Figure 46 gives magnetograms for a meridional chain of stations located between Fort Churchill and Point Barrow. The substorm which begins at 0702 UT on June 15, 1970, at the station labeled FTMU has been extensively studied by *Kisabeth and Rostoker* [1971], who also point out how another current system begins to develop at 0732 UT. These records can be compared with the daily graph of the AL index for the same day in Figure 37. The result is extremely deceiving; furthermore, from 0500 UT to 0900 UT, the extreme deviation defining the index is observed at Narssarsuaq, whose longitude is about 100°E from the chain of stations. The other substorm of July 2, 1970, studied by *Kisabeth and Rostoker* [1971], corresponds to an event which is much better shaped in the corresponding daily graph of the AL index (it looks like the one of the end of June 14, 1970, in Figure 37), but the comparison is still extremely deceiving because again Narssarsuaq (or Great Whale River) yields the extreme deviation.

This extreme deviation in Figure 46 reaches $-900\ \gamma$ at FTMU (corrected geomagnetic latitude $\lambda = 65°$), and the perturbation still reaches $-600\ \gamma$ at FTCH ($\lambda = 68.5°$), whose latitude is the same as that of Narssarsuaq which defines an index $AL = -200$ only at those times. It is highly probable that if a station of the AE network existed at the longitude of the chain (remember that the gap of 80° between Fort Churchill and Point Barrow is the widest in the network), the AL index would be defined by the deviation at this station. Consequently, the significance of the comparison made above between Figures 46 and 37 may be greatly questioned. But three remarks can be inferred from it or from Figure 46 itself. First, to complement the AE network (as was stated in section 7.2) between Fort Churchill and Point Barrow, Point Barrow and Tixie–Cape Chelyuskin, and Dixon and Abisko would certainly be important in reducing great discrepancies between the AL (and AU) index and records in particular stations as they can still be observed. Second, even if an improvement is made for the distribution in longitude, discrepancies between events recorded at a given station and the indices will still occur. This appears from the fact that the event of Figure 46

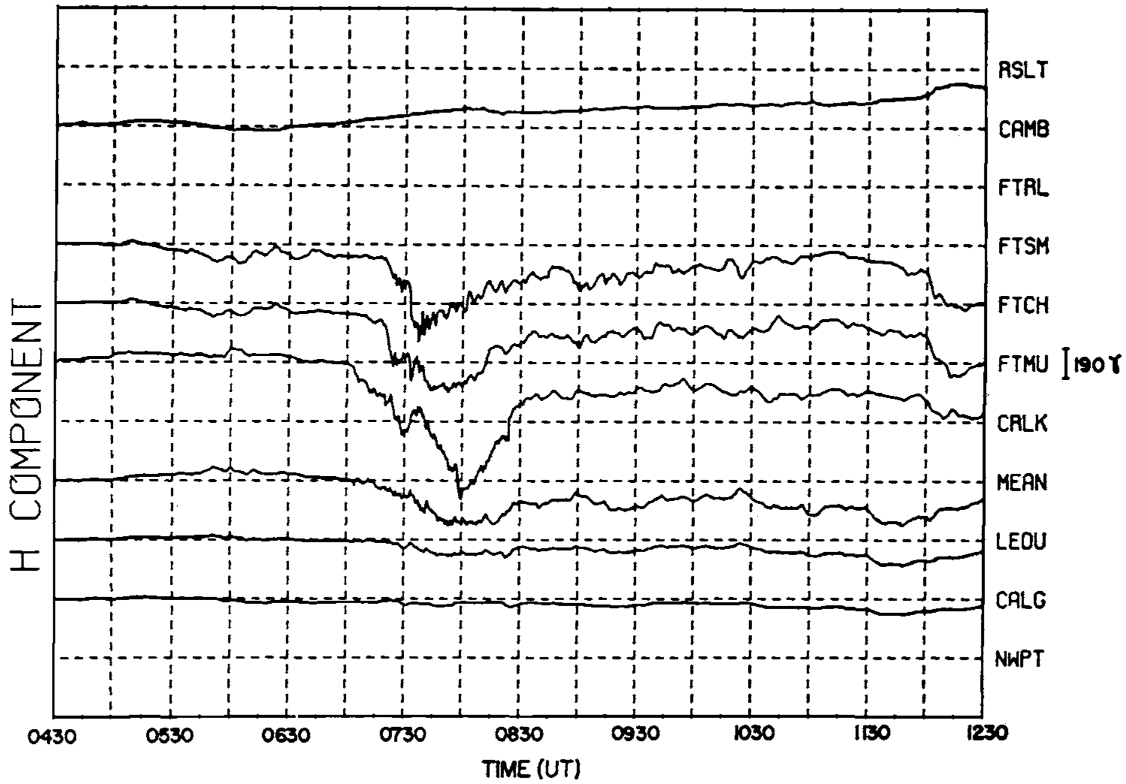

Fig. 46. *H* component of normal magnetograms on June 15, 1970, at a chain of stations along corrected geomagnetic meridian ~302°E through western Canada. The stations labeled FTRL (where unfortunately the record is missing) and FTSM are at λ = 71.4° and 68.5°, respectively. CAMB is at λ = 77.0° and LEDU at λ = 61.2° [after *Kisabeth and Rostoker,* 1971].

corresponds to an *AL* extreme deviation recorded at Narssarsuaq (100°E from the chain) and not at Fort Churchill (only 26°E from it); this is due to the latitude of Fort Churchill (λ = 70.3°), too high for recording this event which is equatorward. Figure 44 indicates, however, that (1) the time of this event (it culminates at 0800 UT) is only at the beginning of the main peak of the frequency contribution at Fort Churchill and that (2) the frequency contribution is greater at Fort Churchill than at Abisko, whose latitude λ = 65° is similar to that of station FTMU of Figure 46, where the largest disturbance is observed. Then the latitude of Fort Churchill is probably more significant than the latitude of Abisko, but the ideal scheme described above (that is, to detect any auroral electrojet effect with its approximate amplitude, it would be necessary to have a pair of stations every 30° in longitude, with one in the latitude band λ = 68°-71° and the other 5° south) is probably still insufficient. Even so, auroral electrojet effects during quiet periods would be insufficiently scanned because their center is polewards of the band λ = 68°-71°. Figure 40 shows the impossibility of such a network. Third, the *AU* or *AL* indices cannot give details similar to those appearing in Figure 46, especially this nice shift with latitude of a sharp beginning of the negative disturbance from station FTMU to station FTSM. Such details are necessarily lost in the indices, which inextricably mingle effects of the temporal intensity variations and spatial motions of the primary source. In other words, the indices cannot be used to identify the onset of a given substorm any more than the individual records of Figure 46 can. As was pointed out by *Saito* [1961] and stressed by *Rostoker* [1972*a*], the only reliable indicator is the *PI* 2 pulsations, hence the interest of a special index based on them.

Does this comparison between Figure 46 and the *AL* index mean that the auroral electrojet indices are not reliable? An ideal network will never be available, and improvements to the present network can be made in the future. But as they stand, the indices provide summarized information which is irreplaceable because on the one hand they should prevent workers from giving too great a weight to a particular longitude (at least when the extreme deviations defining the indices are not recorded at the longitude worked out), and on the other hand they monitor the auroral variations in the best possible way given by the present worldwide network of stations. But indices *AU* and *AL* cannot be considered a true quantitative estimation of the auroral electrojet intensity at a given instant: given the definition of these indices (the largest deviation observed in the stations of the network), one is never sure that a larger deviation did not occur at another location (in latitude and in longitude) of the auroral zone. To some extent, because the *am* index is an average of ranges observed at subauroral latitudes and at various longitudes, it is much less sensitive to the motions of the auroral oval and to the gaps between the network stations and probably gives a more reliable quantitative estimation of the intensity variations of the auroral activity (see, for instance, the saturation effect described below). Conversely, this index gives this quantitative estimation with a much less satisfactory sampling rate, does not discriminate between the eastward and westward electrojets, and is sensitive to other species of irregular variations.

4. Annual and daily variations of the *AU* and *AL* indices have been studied by *Allen and Kroëhl* [1975], but the use of a sample of only 1 year makes any detailed analysis difficult; however, a 12-month wave in both electrojets with a maximum in summertime appears clearly. *Berthelier* [1976] used the *AE* index itself, a method which presents the drawback, as we shall see, of mingling indices whose behavior seems to be greatly different. There exists in any such study a basic difficulty: the lack of homogeneity in the station network induces spurious effects in the daily variation. Figures 47 and 48 give various statistics which we now discuss.

Data concerning the *AU* and *AL* indices are derived from a 7-year sample (1968–1974) for which the 11 stations of the network did not change; those concerning the storminess (see section 3.6) correspond to a 30-year sample, which is interesting because of its length, and is probably free of contamination by the S_R variation. However, since only one station is used with the storminess, its daily variation would be of little significance for a comparison with those of the *AU* and *AL* indices; furthermore, the comparison of the annual variations has to be made by taking a quantity similar to the extreme deviations from which the *AU* and *AL* indices are derived. Then we average the hourly values of the positive storminess (*PS*) at the time of their extremum (i.e., between 1400 and 1800 UT) and those of the negative storminess (*NS*) at the time of their extremum (i.e., between 2200 and 0200 UT). Finally, the average annual variations of the *aa* index for the years corresponding to each sample are used as a reference.

The main feature in Figure 47, when one looks at the curves *AU* (or *AL*) for all the intervals and at the curves *PS* (or *NS*), is the predominance of a 12-month wave which does not appear in the *aa* index. Note that the asymmetry from one equinox to the other appears in all the indices; it is more or less visible in *AU* and *PS*. The annual curves corresponding to the ratio between a given auroral index and the *aa* index show, however, that there probably exists a 6-month component in the *AU* and *PS* indices, since the annual variation of the ratio becomes closer to a pure 12-month wave. Anyway, this fact is clear: the 6-month wave is more important in the indices monitoring the westward electrojet (*AL* and *NS*). Second, the annual variations drawn for *AU* and *AL* by using only hourly values above a certain threshold are very surprising: from the threshold $|AL| > 25$ the 12-month wave disappears almost entirely in the annual variation of *AL*, while it remains the main feature with *AU*. In our opinion the method which consists of the use of such thresholds for suppressing a part of the data is dangerous because it arbitrarily breaks the set of values of the temporal series. But the effect is too clear not to be true. Besides, it corresponds to the fact mentioned above: most of the very low values of *AL* occur in the wintertime and are obviously the cause of the 12-month wave in the *AL* index. One can wonder if there would be any such 12-month wave with a reference quiet time level chosen at night. Consequently, the 12-month wave in the *AL* index is maybe only an artificial effect, and anyway the behavior of the *AU* and *AL* indices appears greatly different with regard to the 12-month wave. Third, Figure 48 yields a strong confirmation of this difference. We use the classical method of *McIntosh* [1959] for the detection of the universal time daily variation which must exist if the 6-month wave is due to the annual and daily variations of the angle ψ_M (between the solar wind and the dipole axis). With *AL*, the difference between the daily variations at both solstices results in a beautiful sinusoid, exactly in phase with the theoretical prediction (maximum at 0430 UT and minimum at 1630 UT), and this difference exists at all levels of activity. (The only deceiving point, however, is that its amplitude does not increase with the activity level.) With *AU*, nothing appears

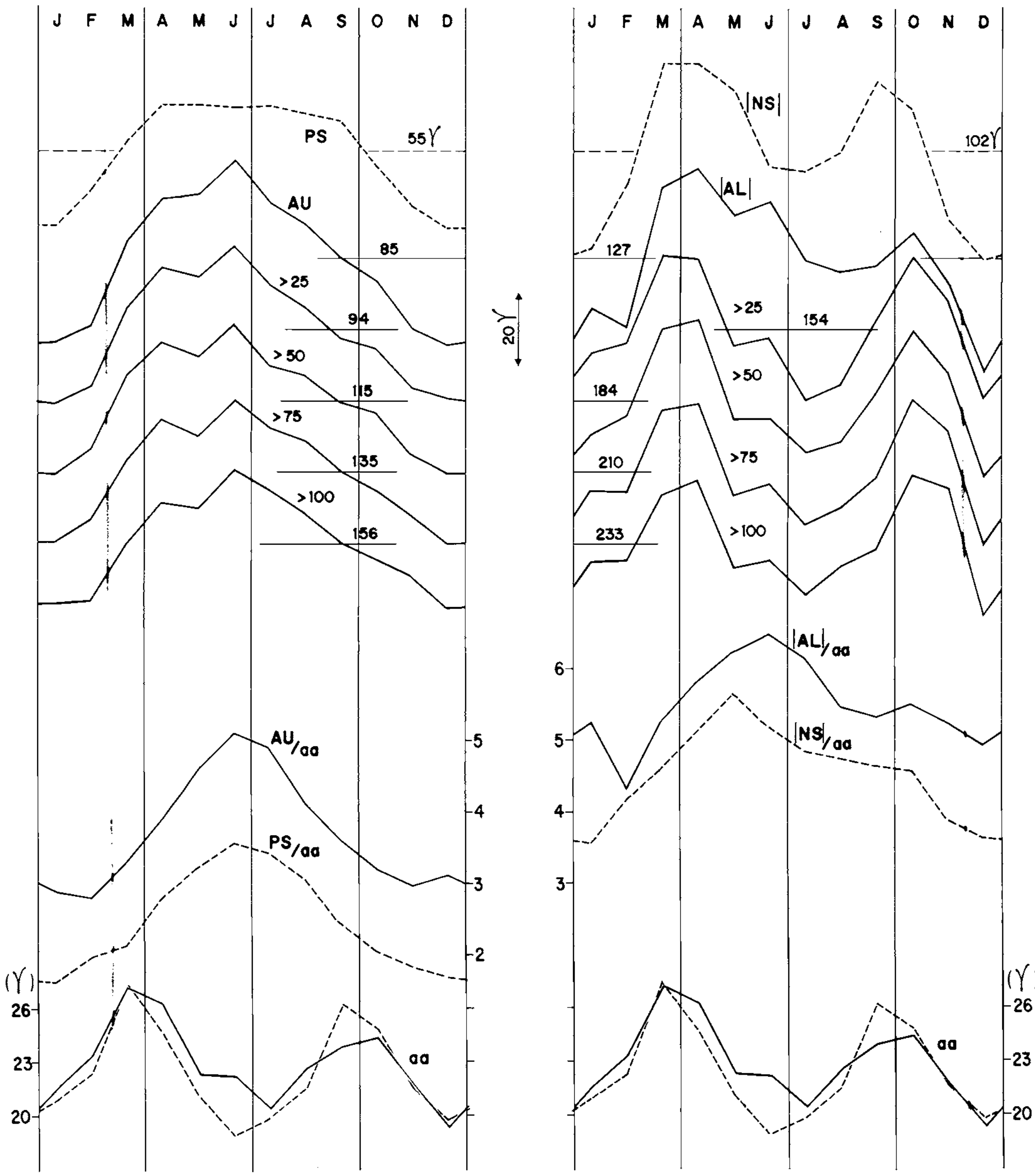

Fig. 47. Annual variations of various indices or of their ratio. Note that the successive thresholds used for making up other samples with the *AU* and |*AL*| indices have been applied to 3-h values of the indices and not to 1-h values in order to smooth their effect. For *AU*, |*AL*|, *PS*, and |*NS*| the average value of the index for the sample concerned is given above the horizontal line indicating its ordinate. The *aa* curves are computed for the same years as the electrojet auroral indices (1968–1974) or the storminess (1930–1959).

in the curve derived from all the hourly values; a very small effect is possibly visible in the levels $AU > 50$ and $AU > 75$, which only prevent a strict conclusion that there is no modulation at all by the ψ_M angle. Such a difference between the daily variations of *AL* and *AU* is very consistent with the difference in the annual variations. And one can assert that the *AL* index (and the westward electrojet) is fully sensitive to the variations of $\sin^2\psi_M$, while the *AU* index (or the eastward electrojet) is hardly sensitive to them. Fourth, a supplementary effect of this

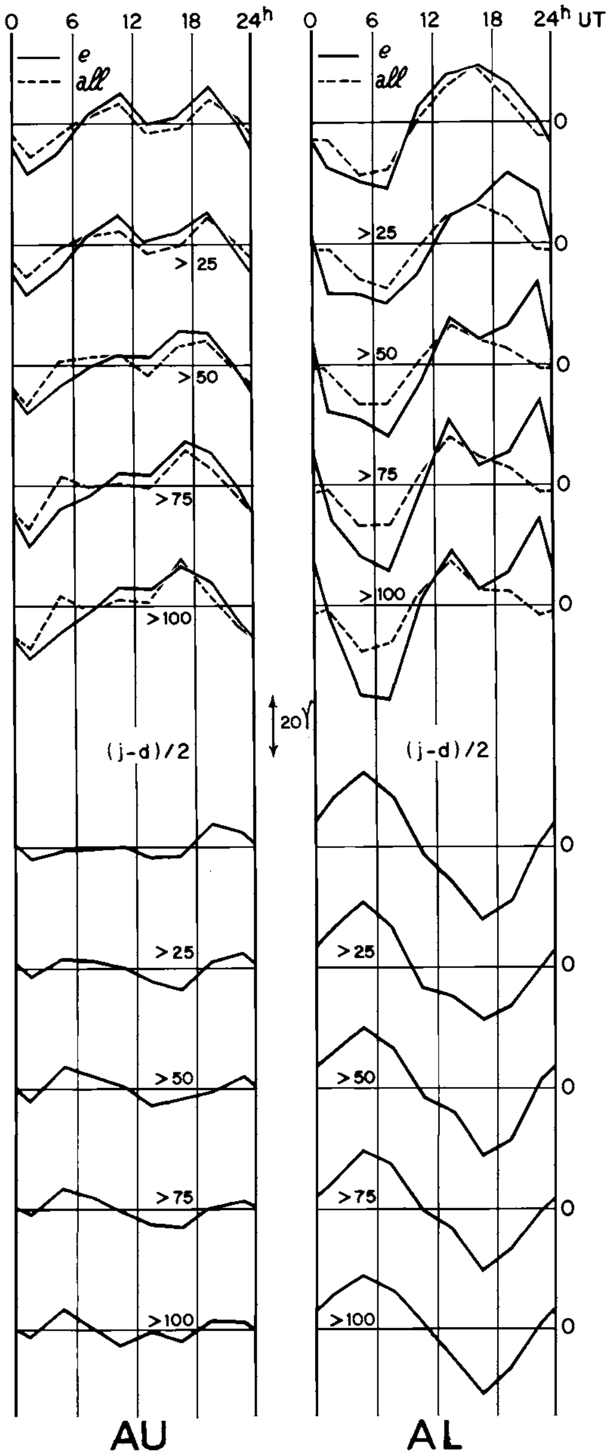

Fig. 48. Daily variations of the AU and $|AL|$ indices for 1968–1974. The meaning of the successive thresholds is the same as those in Figure 47. The equinoctial curves (e) correspond to a sample of 10 days on either side of March 21 and September 21 (i.e., 40 days per year); see curve b of Figure 27, which displays the variation of $\sin^2 \psi_M$ around these dates. The curves labeled 'all' correspond to an average of all months in the year. For the sample j (or d), only June and July (or January and December) are used to represent the daily variation $(j - d)/2$ at the solstices. The zero level of each curve corresponds to the average value of the daily variation.

angle can be observed in the equinox curves of AL. Maxima should be observed at 1030 and 2230 UT; such a maximum is observed very clearly at 2230 UT, when the activity level increases, and another one tends to appear at 1330 UT. Such features do not appear at all with AU. Fifth, the main component of the daily variation at the equinoxes or for the average of all months (when the effect of $\sin^2 \psi_M$ is averaged out) greatly differs from AL to AU. With the former, the time of the single maximum corresponds to that of the main peak for the AL frequency contribution of Point Barrow; those of the two maxima of the latter correspond to the main peaks for the AU frequency contribution of Cape Chelyuskin (1030 UT) and Narssarsuaq (1930 UT). Another explanation is difficult to put forward before ruling out heterogeneities in the network. Let us note, however, that one could wonder why the time of the minimum of AU corresponds to the main peak for the AU frequency contribution of Point Barrow. We do not believe, anyway, that such data allows for a discussion similar to the one made for the residual daily variation of the indices *an*. On the contrary, the 12-month wave, much more important in the AU indices, obviously comes from the seasonal variation of the ionosphere conductivity, more important in the local afternoon or early evening (eastward electrojet) than in the local late evening or early morning. Sixth, the comparison of the daily variation of the index *an* (see Figure 23) with the one of AL for $|AL| > 50$ at the same season (that is, curves e of Figure 48) raises a question: a certain resemblance cannot be denied. This resemblance becomes greater if one remembers that the auroral zone universal time pseudo-component should become largest not at 15.3 h UT (see section 5.2.4) but at about 19 h UT (by taking 2.5h LT for the local time of the maximum of the westward electrojet effects). Such a shift can be seen, especially for the time of the minimum. These remarks have not to be emphasized too much, but there is a point which will have to be understood in the future, that is, the reason why the *an* index (and consequently the *am* index) seems to be much closer to the AL index than to the AU index.

5. *Berthelier* [1976] has pointed out how the modulation due to the azimuthal component B_Y of the interplanetary magnetic field is present in the AE index, as it is in the *am* index. It would be of interest to investigate whether it exists in both AU and AL indices or mainly in the AL index.

6. Figure 49 is taken from a much more complete series of examples in the work of *Berthelier* [1979]. It shows that the *am* and *AE* indices do not always react in the same way to various parameters recorded within the interplanetary medium. In the examples displayed in this figure, only two parameters are considered: the plasma velocity *v* and the vertical component B_Z of the interplanetary magnetic field. Within a sample of 2 years, significant events are chosen when one of these parameters varies without significant changes of the other. The periods thus chosen are analyzed by the superimposed epoch method. When comparing the two panels of Figure 49, it is clear that the response of the *am* index is greater than that of the *AE* index in the case of the *v* events; the contrary is true for the B_Z events. By analyzing *K* indices in a network of stations at different latitudes for the same events, Berthelier shows that the main cause of the difference is due to an equatorward motion of the auroral oval with the *v* events. Such an effect could also be the cause of the saturation effect when the interplanetary magnetic field is large, as described by *Maezawa* [1978] for the *AL* index; the *am* index is not saturated so much because it is less sensitive to the motions of the auroral oval. Other differences between the indices are displayed in the works of Berthelier and Maezawa.

7. *AU* and *AL* indices are, and can be, derived from northern observatories only. The conjugacy between both hemispheres is rather strict. Given the fact that the 12-month wave is rather small in the *AL* indices, one may consider that such indices give reliable information for the southern hemisphere itself. The same cannot be said for the *AU* indices.

Finally, it appears that, most of the time, it is more suitable to use the *AU* and *AL* indices separately. The artificial features contained in them could be partly supressed by eliminating the *Dst* variations and most of the effects of the S_R variation. Latitude and longitude inhomogeneities in the station network probably prevent one from considering the indices a true and perfectly correct measure of the intensity of each auroral electrojet. For the study of particular events they constitute, thanks to their sampling rate, an excellent reference. With regard to statistical studies, an *AL* index less sensitive to an S_R contamination would be a better planetary indicator than the *AU* index. The strong 12-month wave contained in the latter raises a question concerning the *an* and *as* indices themselves. Indeed, we attributed in section 5.2.4 the local afternoon activity maximum to the DP 2 variations only. Further investigations would have to be made in order to check this point. However, the morphology of the auroral variations is such that the duration of the substorms is much shorter than that of the disturbances due to the auroral electrojets themselves; *K* indices at subauroral latitudes are probably more sensitive to the former, which have effects on a very wide band of longitudes through the field-aligned currents. This can be the source of the deficiency of the *an* and *as* indices in monitoring the very important annual variation of the eastward electrojet.

8. The *Dst* Index

J. Bartels, as Chairman of the Committee on Characterization of Magnetic Disturbances of IATME and IAGA, was constantly concerned with stimulating studies for deriving an index monitoring the equatorial ring current variations. Such a topic is mentioned by him under the symbol *ERC* in each of his reports to the association at Brussels (1951), Rome (1954), Toronto (1957), Helsinki (1960), and Berkeley (1963) (see the relevant *IATME* or *IAGA Bulletins 14*, p. 227; *15*, p. 319; *16*, p. 318; and *19*, pp. 69–70 and 222). With the *u* index, he was himself an initiator in this field (see section 3.7).

Among all geomagnetic indices, the *Dst* index is probably the one that monitors and records with the greatest accuracy the phenomenon for which it was designed. This is due to the great simplicity of the magnetic variations caused by the ring current: they are nearly axially symmetric and do not depend on longitude or local time. Assuming that other transient regular or irregular variations are averaged out in the derivation, one would obtain an index which is no longer summarized information but a pure record of the phenomenon, and any sampling rate could be chosen.

Many difficulties, however, are encountered in eliminating properly the other transient variations; furthermore, the secular variations which vary from one observatory to another interfere as soon as one wishes to maintain the homogeneity of the series over years. Preliminary attempts [*Kertz*, 1964; *Sugiura*, 1964] deal with the tran-

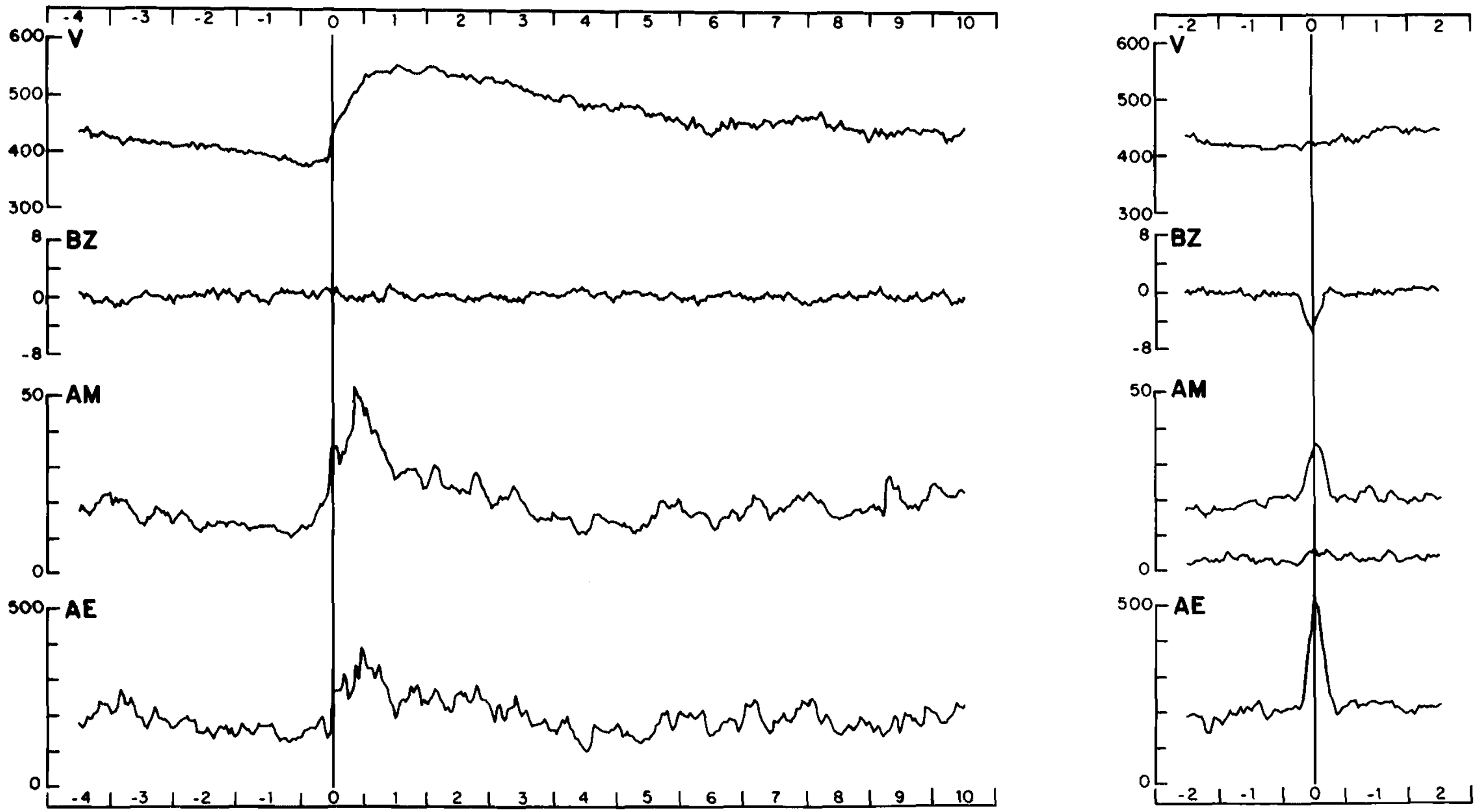

Fig. 49. Variations of the *Am* and *AE* indices at the time of a set of either 34 events (left-hand panel) or 54 events (right-hand panel) with a significant change either of the plasma velocity v or of the component B_Z of the interplanetary magnetic field. The superimposed epoch method is used in averaging the various parameters or indices plotted. On abscissa, negative (or positive) numbers correspond to the days before (or after) the beginning of the event [after *Berthelier*, 1979].

sient variations in two different ways. *Sugiura and Hendricks* [1967] tried to take the secular variations into account in a definite way for long series. At its Madrid meeting (1969), IAGA adopted the *Dst* index, as developed by Sugiura and his coworkers (*IAGA Bulletin 27,* 1969, p. 123, resolution 2). The terminology retained (*Dst* instead of *ERC*) comes from the one used in the first attempt of *Sugiura* [1964] and is justified as follows. 'It is convenient to analyze the storm variation *D* in two parts, *Dst* and *DS*. Given an instant of time, *Dst* is the average of *D* over all longitudes. *DS* is defined by *D* − *Dst*. For a well-defined storm *Dst* and *DS* can be determined as functions of storm time that is measured from the onset of the storm (a method first introduced by *Moos* [1910]). However, the determination of *Dst* need not be limited to times of magnetic storm but can be extended to periods of less magnetic activity or even to magnetically quiet times. In fact, *Dst* may be determined continuously as a function of universal time regardless of occurrence of magnetic storms.'

8.1. The Previous Attempts

Since the field of the equatorial ring current is roughly parallel to the dipole axis, its effect at ground mainly appears in the *H* component and is greater at low latitudes than at other latitudes. A further advantage of these latitudes is the smaller amplitude of the irregular variations which originate at auroral latitudes. But in these conditions, one of the main problems in deriving an index is the elimination of the regular variation S_R which is rather large in this component at low latitudes. *Kertz* [1958, 1964] and *Sugiura* [1964] choose radically different approaches for solving that problem. Kertz uses only night values recorded at various groups of stations (see Figure 50), while Sugiura computes from the 5 quietest international days of each month the average regular variation resulting from the addition of those observed at each network station (see also Figure 50 for his network), makes a double Fourier analysis with respect to the months and the universal time, and subtracts the thus computed average obtained from the actual values. The constant time interval chosen is 1 hour, and each station contributes to the hourly index. Because, with Kertz's method, each group of stations contributes to the index only by its local night values, a complex choice has to be made for the overlapping from one group to the next, and it results in the derivation of 3-h indices; furthermore, a smoothing running process is applied twice. In both methods, a geometric correction, with respect to the dipole latitude of the stations, is applied (this is made at each station by Kertz, in also taking the declination into account, and at the final step by Sugiura in using the average latitude of the stations), and the secular variation is considered; however, given the length of the series (the 18 months of the IGY), this last problem interferes only a little.

Figure 51 [after *Sugiura,* 1964] shows a comparison of the indices obtained by these two methods. The shorter time interval used by Sugiura allows for many more details, which are strongly smoothed in Kertz's process which involves only 3-h values (resulting furthermore from running averages). But the most important difference is a diurnal variation, sometimes quite large, which appears in Kertz's index (see, for instance, the days before and after the sharp minimum due to a storm on September 13, 1957). *Sugiura* [1964] states that 'it is probably due to *DS* not being averaged out.' Indeed, the classical work of *Akasofu and Chapman* [1964] introduced the concept of partial ring current, which means that there exists a local time component in the ring current effect (see also *Fukushima and Kamide* [1973] for a review on that topic). It is obvious that an index, derived from only one longitude sector at each universal time interval, is much more sensitive to such a local time effect than an index derived from all longitude sectors at any time. Let us note furthermore that such a diurnal variation is not constant in phase (compare, for instance, the days around September 13 and the days around September 27) and is very irregular in its intensity, which can be also interpreted to be due to a partial ring current effect.

In any case, the existence of the partial ring current probably prevents one from ever using Kertz's method in order to eliminate the regular variation S_R when deriving a ring current index. The only way to minimize the irregular and local time effects of the partial ring current is to use data from all longitudes. With a uniform distribution of the stations with longitude, one can expect that any residual average diurnal *SD* variation will be averaged out. However, because such effects are always negative in the *H* component (they correspond to the low-latitude afternoon/evening negative disturbances), they do still contribute to the index.

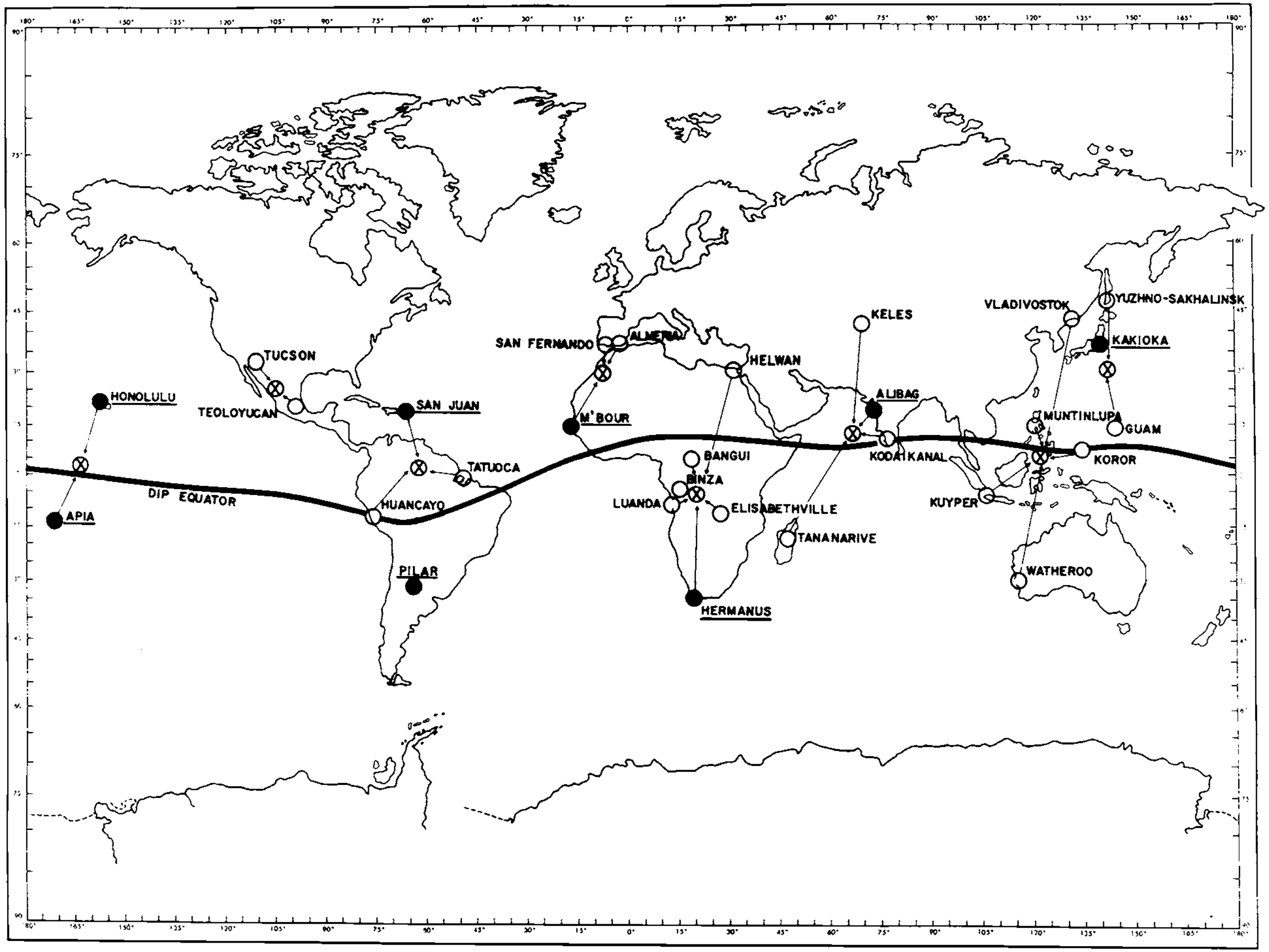

Fig. 50. Map illustrating the position of the observatories used by Sugiura (solid circles) and by Kertz (open circles or solid circles associated with an arrow). The mean position for each of the eight groups used by Kertz is indicated by a cross in an open circle [after *Sugiura*, 1964].

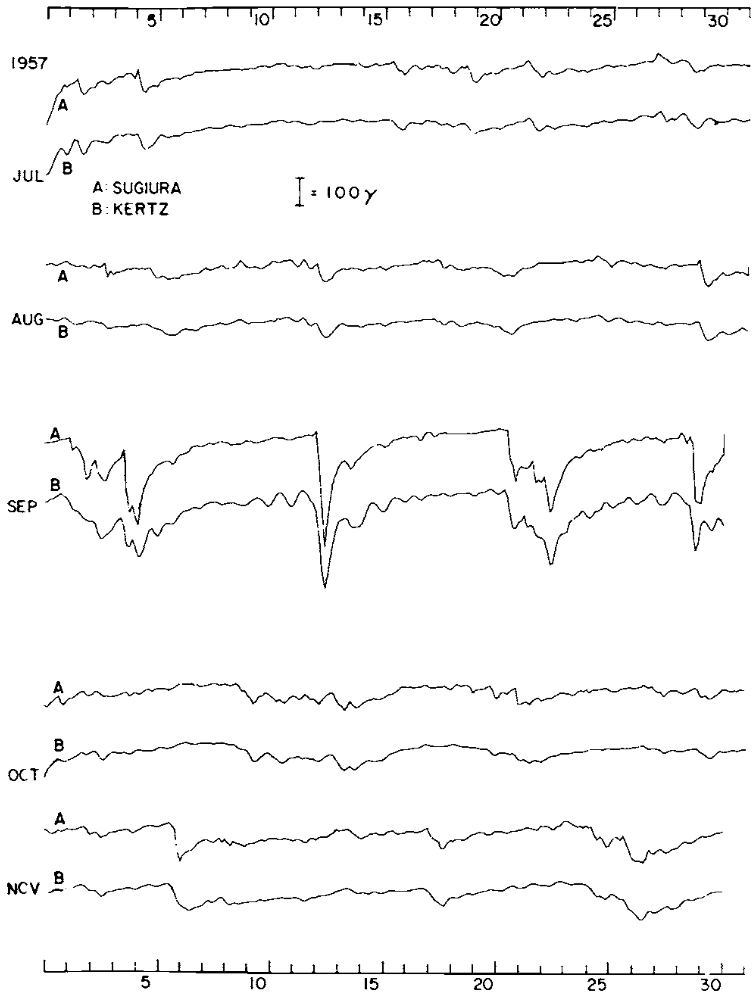

Fig. 51. Comparison of *Dst* (A) determined by Sugiura (1964) with Dst (B) based on Kertz's indices [after *Sugiura,* 1964].

8.2. The Ideal Scheme of the Dst Index

The two main problems to solve in order to derive a reliable *Dst* index are (1) the elimination of the transient variations which are not caused by the ring current and (2) the choice of a reference level, in which the secular variation and consequently the quality of the base line control interfere. A third one, the choice of the stations, will be described later.

1. Among the transient variations, the irregular variations which have a zonal component will fully contribute to the index, that is, not only the ring current variations themselves (main phase of a storm which can be considered to be a temporary enhancement of the ring current, 'slow oscillation' as described by *Mayaud* [1965*a*], any more or less irregular variation of the ring current in course of time) but also variations due to the interaction of the earth's permanent field with the solar wind (storm sudden commencement or sudden impulse, first phase of a storm, and worldwide fluctuations). Some of the latter whose duration is much shorter than the present sampling rate of the index, that is, 1 h, are obviously averaged out; but the first phase can significantly contribute to the index. In that sense, the symbol *Dst* is more suitable than the symbol *ERC*, which apparently would mean that only ring current variations are monitored. Other irregular variations can interfere at low or relatively low latitudes: the DP 2 fluctuations and the auroral disturbances. The former could significantly contribute only at dip equatorial stations; such stations must not be used because of their particular behavior for the regular variation S_R. The latter necessarily interfere, and those related to the westward electrojet do it much less than those related to the eastward electrojet [see *Mayaud,* 1967*a*, pp. 50–53]. As far as such eastward auroral electrojet related effects are now recognized [see *Fukushima and Kamide,* 1973] as being due to the

partial ring current, they can be considered as an integral part of the phenomenon monitored. On the other hand, the elimination of the regular daily variation S_R is absolutely necessary and raises a difficult problem.

When describing the K indices, we saw that the problem of the identification of the S_R gets a satisfactory solution because the scaling of the index consists of the determination of a class of ranges and not of the range itself. Given the day-to-day variability of the S_R, it would be an extremely laborious and practically impossible task to determine the S_R every hour at each station within a few gammas. At first sight, Kertz's method, by using only the night values, seems to be elegant; but one has to solve an overlapping problem (all stations do not contribute to each value). The result is not satisfactory. Then, as was done by Sugiura, one is forced to use a statistical approach (derived from an average S_R, that is, the Sq for the 5 international quietest days). This could be qualified as being an iron curve method, since the S_R in a given day of the month often differs significantly from the Sq of this month. However, the contamination by the regular variations thus introduced has to be judged along two lines. With regard to individual values, the deviation of the true S_R from Sq in a given station may be partly compensated by the deviation in an opposite direction, at another station, and is certainly minimized by the absence of such deviations at the stations which are within local night. With regard to statistical averages, it is difficult to conceive that the statistical Sq is significantly different from the average of the S_R for all days. On the other hand, various statistical approaches can be retained; the one presently used is described and evaluated in section 8.3.

2. The reference level problem did not interfere with the range indices. In the case of AE indices, we saw that improvements could be carried out, but the problem has a correct solution because the physical phenomenon monitored (the auroral electrojets) can be rightly considered as nonexisting during quiet periods, and the reference level can be chosen during these periods (for instance within each month). With the Dst index, the difficulty is that the phenomenon monitored is, as far as the ring current is concerned, a permanently existing phenomenon, and one consequently ignores its true intensity. In that sense, the Dst index is only a measure of the variations of its intensity, not of its absolute intensity. Now the field variation recorded at each station includes also the secular variation, which becomes quite significant at some stations when one considers long periods of time, and it is important to eliminate it properly in order 'to derivate, for instance, solar cycle changes' [*Sugiura and Poros*, 1971] in the Dst index values.

The determination of the secular variation implies, at first, a good calibration of the base lines, a requirement not always met at every observatory. It is furthermore a difficult problem because it is not easy to discriminate in the average values recorded (yearly values, for instance) what is the average contribution of all the transient variations and what is the contribution of the internal main field. Among others, *Courtillot and Le Mouël* [1976] pointed out that once a parabolic trend is eliminated, most of the residual energy contained in the spectra of the annual values between 2 and 20 years can be related to the 11-year variation in the activity of the sun and consequently is not of internal origin; furthermore, the latitudinal variation in X and Z is close to the one due to a zonal effect, indicating that it is mainly due to the ring current. The consequence is that a fit of the annual averages of H by a parabola, as made by Sugiura (see next section), is the best way to eliminate the secular variation whose origin cannot be attributed to the ring current. Let us note that if one can use a series of annual values much longer than the average duration of the solar cycle, the result will be all the more reliable. However, this does not imply that one succeeds in detecting the true zero level, but one only succeeds in reaching the goal assigned by *Sugiura and Poros* [1971]: the solar cycle changes in the intensity of the ring current will be monitored as well as the rapid variations.

3. Since the effects of the ring current are mainly zonal, a single station should be sufficient. However, in that case, the partial ring current effects, which present a very strong local time component, would have a great influence; they need several stations well distributed in longitude in order to be minimized at a given moment and averaged out in statistical means (daily variations, for instance). On the other hand, the density of the network does not need to be very high, since the main phenomenon monitored is zonal. And in order to preserve the homogeneity of the index over long-term periods, it is better to use a few stations which have high quality base line control. Let us note that among all the present indices we

are reviewing in this work the *Dst* index is the only one submitted to the last constraint: for all the others, good scale values are sufficient.

It is not easy to specify a priori the best latitude for the stations of the network (assuming, as was noticed in section 8.1, that a correction is introduced according to the dipole latitude of the station). However, the latitude has to be rather low in order to minimize a contamination by the auroral disturbances. But are either the stations close to the focus of the S_R current systems (the amplitude of the $S_R(H)$ becomes very small) or those which can be considered tropical (the amplitude of the $S_R(H)$ is practically always positive) the more suitable (see, for instance, in Figure 50, either Hermanus and Kakioka or Apia and M'Bour)? The smaller amplitude of the S_R could incline one to prefer the former, but once the statistical method is used in view of eliminating the S_R (and it has to be used in any case), the day-to-day variability of S_R will interfere in the same way whatever be the latitude. The final ideal choice has probably to be made from only empirical considerations: to choose, among the existing stations (remember the inevitable restriction due to the oceans), a few stations which are close to each other in latitude in order to better average out any other transient irregular variations than the *Dst* variations and which offer the guarantee of a long-term and good base line control.

Finally, a priori the stations do not need to be equally distributed in both hemispheres. We shall see, however (see section 8.5), that the recent finding of *Malin and Isikara* [1976] concerning an annual latitude variation of the ring current would impose, for an ideal scheme, that stations are equally distributed in both hemispheres.

Given the method of derivation of the index, any sampling rate can be chosen (it depends only on the sampling rate of the original data themselves). Variation rate of the main phenomenon monitored, the ring current, is rather low; then a 2.5-min sampling rate, as with the *AE* indices, is certainly unnecessary. To choose average values over 1 hour is sufficient for following the variations of the ring current itself. Probably, one loses information about the beginning of the first phase, but the advantage of a simple tabulation (24 values per day) cannot be neglected.

8.3. *The Actual Derivation*

We describe the actual derivation for the last values computed by Sugiura as they are already available in the WDC and expected to be published in the special *IAGA Bulletin 40.*

The network is made up of Honolulu, San Juan, Hermanus, and Kakioka (see Figure 50). Table 35 gives various elements concerning these stations.

There are three northern stations and one southern station. Let us note that a station such as Alibag (143.7° longitude) would exactly fill the longitude gap between Hermanus and Kakioka (see the values Δ in Table 35) but would break the relative homogeneity of the network with respect to the dipole (0.99 for the cosinus at such a station). With respect to the variation S_R, Figure 50 with the dip equator drawn on it permits one to appreciate that Alibag is much closer to this line; it is clearly a tropical station. One knows that the foci tend to follow lines roughly parallel to this equator. Now, Hermanus and Kakioka are close to the focus (note that the path of the focus is fur-

TABLE 35. Dipole Coordinates, Cosine of the Latitude Λ, Distance Δ Between Two Consecutive Stations, and UT Hour *h* Corresponding to 1800 in Local Dipole Time

	Dipole Coordinates				
	ϕ	Λ	cos Λ	Δ (long), h	*h*
HO	266.4°	21.0°N	0.93		4.9
				6.5	
SJ	3.2°	29.9°N	0.87		22.4
				5.1	
HR	80.3°	33.3°S	0.84		17.3
				8.4	
KA	206.0°	26.0°N	0.90		8.9
				4.0	
HO	266.4°	21.0°N	0.93		4.9

ther from the dip equator in the southern hemisphere than in the northern; see *Malin* [1973] for instance). San Juan can be considered a near-focus station. On the other hand, Honolulu is intermediate between a focus station and a tropical station, but it is the only station available in the Pacific Ocean (Apia is much more tropical). Then one has to consider that the *Dst* network is made up of stations which are mainly focus stations and not tropical stations. We said in the above section that finally the necessary use of a statistical method makes focus stations as reliable as tropical stations in spite of the apparent greater S_R variability from day to day. Furthermore, the advantage of such latitudes would be that the effects of the partial ring current are smaller at such latitudes [*Fukushima and Kamide,* 1973].

For the elimination of the S_R, a statistical *Sq* is first computed at each station for each month by using the 5 local days that have a maximum overlap with the 5 international quietest days. And the noncyclic change is removed from *Sq* by assuming that it is linear from midnight to midnight on the local quiet days selected. This method is certainly better than the one first used by *Sugiura* [1964], where the 5 international days were strictly used and the noncyclic change evaluated from Greenwich midnight to Greenwich midnight. We discussed this problem in section 6.1.2 and suggested the need for an international classification based on 48-h periods centered on the Greenwich noon. Such a classification appears clearly to be necessary in such a case, since the local midnight occurs 10.7 h (or 9.3 h) out of the Greenwich international day at Honolulu (or at Kakioka) and one has consequently no guarantee concerning the qu̇ietness of them.

From the series of the monthly *Sq* for a given year, a double Fourier series is expanded as follows:

$$\sum_{n=1}^{6} \sum_{m=1}^{6} A_n^m \cos (mT + \alpha_m) \cos (nM + \beta_n)$$

where T is the local time and M the month. This corresponds to the computation of 48 unknown coefficients while one has 12 × 24 experimental data. The hourly values of a synthetic *Sq* variation are computed from the Fourier series (a month number with one decimal is assigned to each day) and are subtracted from the original hourly values.

What is the advantage of such an apparently sophisticated statistical method with respect, for instance, to a direct use of the monthly observed *Sq*? We said above (section 8.2) that any statistical method for removing the variation S_R resembles an iron curve method and is not able to remove perfectly the S_R because of its day-to-day variability. Now, each of the observed monthly *Sq* can be distorted either by an especially abnormal S_R on a given selected quiet day or, as well, by residual disturbances. To compute such a double Fourier series consists of assuming that there exists a systematic coherency in the intensity and phase variations of the S_R all through the year; then the effects of the possible distortions mentioned above should be reduced. Deviations of the true S_R in a given day from the synthetic *Sq* will be still there and will be included in the derivation, but the statistical method used is probably the most suitable, since the true S_R cannot be identified with the necessary accuracy every day.

Let us note that one could consider that it would be better to compute a synthetic *Sq* for the average of the four stations in universal time (it was the first choice made by *Sugiura* [1964] for the derivation of the IGY values with eight stations). But it is evident that, in such a process, the observed *Sq* would be made up of fluctuations much shorter than 24 h because of the longitude distribution of the stations, and the coefficients A_n^m would become unsignificant for the low values of m.

For the definition of the reference level at each observatory a parabola is fitted with respect to the annual means of H for the 5 international quietest days of the months and not for the full annual means. The use of the former is certainly extremely suitable because it already eliminates from the secular variation of the annual means a large part of the external effect due to the ring current. Let us call H_0 that value which is a function of time t. One could refine the process a little more by using only local night hourly values during the international quiet days: this would eliminate this other part of the external effect due to the S_R variation and would be fully consistent with the use of a synthetic *Sq* reckoned from the night level.

Finally, at each observatory j, if $H_{obs,j}$ is the hourly average of the horizontal field recorded, one obtains a Dst_j such that

$$Dst_j = H_{obs,j} - Sq_j(t) - H_{o,j}(t)$$

However, such a value can already be contaminated either by some transient irregular variations which are not due to the ring current (or at least have no zonal component that is strongly dependent on the local time: see section 8.2) or by a residue of the S_R. Then the Dst_j values are averaged before applying the correction 1/cos Λ_j, necessary for obtaining the value of the ring current effect at the dipole equator. In that way, all local time residual effects are minimized, and the correction is applied to the resulting $\overline{Dst}$ value with the factor $1/\overline{\cos z\Lambda_j}$. This last operation of the derivation shows to what extent it is important that the latitude of the stations does not differ too much.

8.4. *Tabulation of the Dst Index*

The tabulation is extremely simple; it consists of a monthly table containing 24 values (in gammas) for each day of the month. Values can be positive as well as negative; they become strongly negative at the time of a geomagnetic storm.

Provisional values are distributed extremely rapidly, that is, in the course of each month for the preceding month. The derivation of the definite values needs a longer time, mainly because of the evaluation of the secular variation. They are currently published in the yearly *IAGA Bulletins 32* from 1970 onward: a yearly graph displays the variations of the index for the year by using Bartels' rotations (see Figure 52, which can be compared to the *Dst* curve in Figure 21 where the time scale is much shorter and the ordinate scale much greater). The series 1957-1970 published by *Sugiura and Poros* [1971] which superseded preceding derivations now has to be considered provisional. A special *IAGA Bulletin* (volume *40*) is planned and should contain indices derived from the network of Table 35, with the method described in the above subsection.

8.5. *Artificial and True Features of the Dst Index*

Some features of the *Dst* index have to be considered artificial or true according to the use made of the index, namely, to know the intensity of the ring current variations either at the level of the surface of the earth or at the level of the ring current itself. (1) The *Dst* index is a good tool for cleaning the regular variation S_R in a given day from any smooth irregular variations. Residual variations due to an insufficient elimination of this variation S_R at the observatories of the network used are probably small and smaller than those related to the possible effects of the partial ring current effects. (2) The annual variation contained in the *Dst* index is a true feature if one is interested in the ground effects of the ring current but is probably an artificial effect if one is interested in the intensity of the ring current itself. (3) On the other hand, the residual daily variation is probably an artificial feature due to the partial ring current effects. And (4) one should not expect a strict correlation between the *Dst* index and other indices mainly sensitive to the auroral variations.

1. Various workers have used the *Dst* index as a reference when investigating special features of the regular daily variation S_R. Thus *Hutton and Oyinloye* [1970] subtract the hourly *Dst* values from the hourly averages of the H component at Ibadan (a station located at about 300 km south of the dip equator, which means that strong equatorial electrojet or counterelectrojet effects in the S_R are still effective). Figure 53 displays for some days the H curves, as recorded, and the H_c curves corresponding to $H - Dst$. One must take care, however, that the *Dst* values used are those of *Sugiura and Hendricks* [1967], a series of indices for which the network used is the present network without Kakioka (see Table 35). Among others, various facts can be commented on. (1) On January 7, 1963, a smooth secondary fluctuation of the H curve between 0600 and 1600 disappears in the H_c curve, on January 4 the amplitude of the H variation around noon is greatly reduced when subtracting the *Dst*, and on January 29 the sinusoidal variation between 1600 and 2400 disappears almost entirely. In all these cases, it seems that the use of the *Dst* in the study of the variation S_R improves considerably the data investigated by suppressing some perturbations of the field which are not the S_R but a variation due to the ring current. (In view of all these remarks, we looked at the records of Honolulu and Kakioka in order to check whether the variation subtracted is worldwide, that is, a ring current effect.) In the case of January 29 the perturbation corresponds to a typical slow oscillation [*Mayaud*, 1965*a*]. In the first case, it is a rather short positive fluctuation; in the second one, it is probably a slow oscillation of long duration, about 16 or 20 hours. (2) On January 27 and 28 the large negative effect in the H curve around 1400-1600 is not suppressed by the use of the *Dst* index. This, as was said by Hutton and Oyinloye, confirms that such a negative effect is due to a local phenomenon, that is, the counterelectrojet. Another confirmation comes from the examination of the records of Ad-

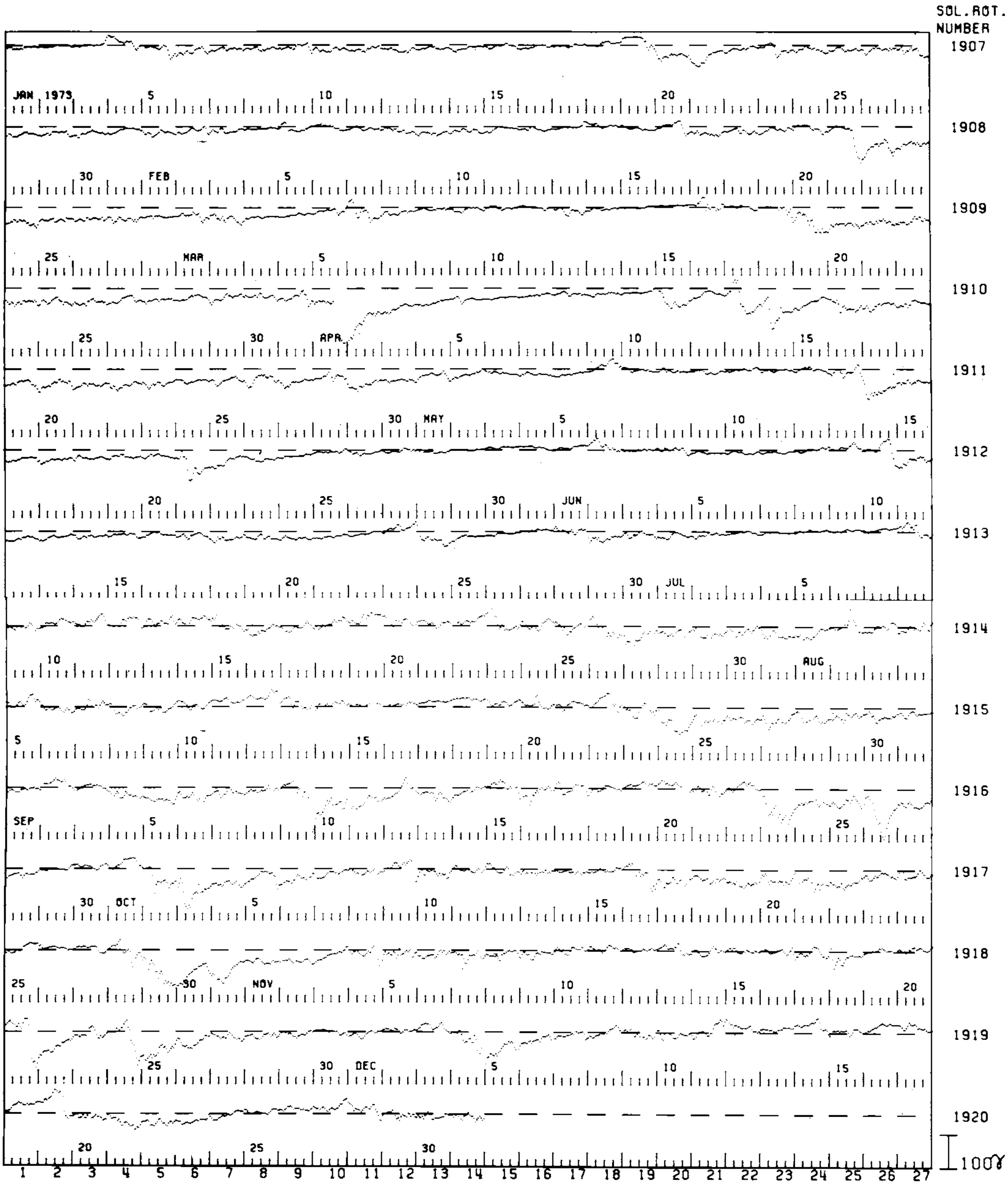

Fig. 52. An example of a yearly *Dst* diagram [after *Sugiura,* 1974].

dis Ababa and Trivandrum in which a similar negative effect appears at the same local time. Then the comparison of these 2 days with January 4 indicates to what extent it can be useful in any S_R investigation to check whether the variation observed is partly due to the ring current. It is especially true when one has no records of stations from other longitudes at one's disposal in order to check whether a given fluctuation is synchronous in local time (it is then the S_R) or in universal time (it is then a disturbance). (3) On January 4 around 0400 the H_c curve appears less smooth than the H curve; the same fact is observed in the mornings of January 28 and 29. When looking at the records of Kakioka or Honolulu at the corresponding times, no clear disturbance appears. Then we would say (remember, however, that the *Dst* values used by Hutton and Oyinloye

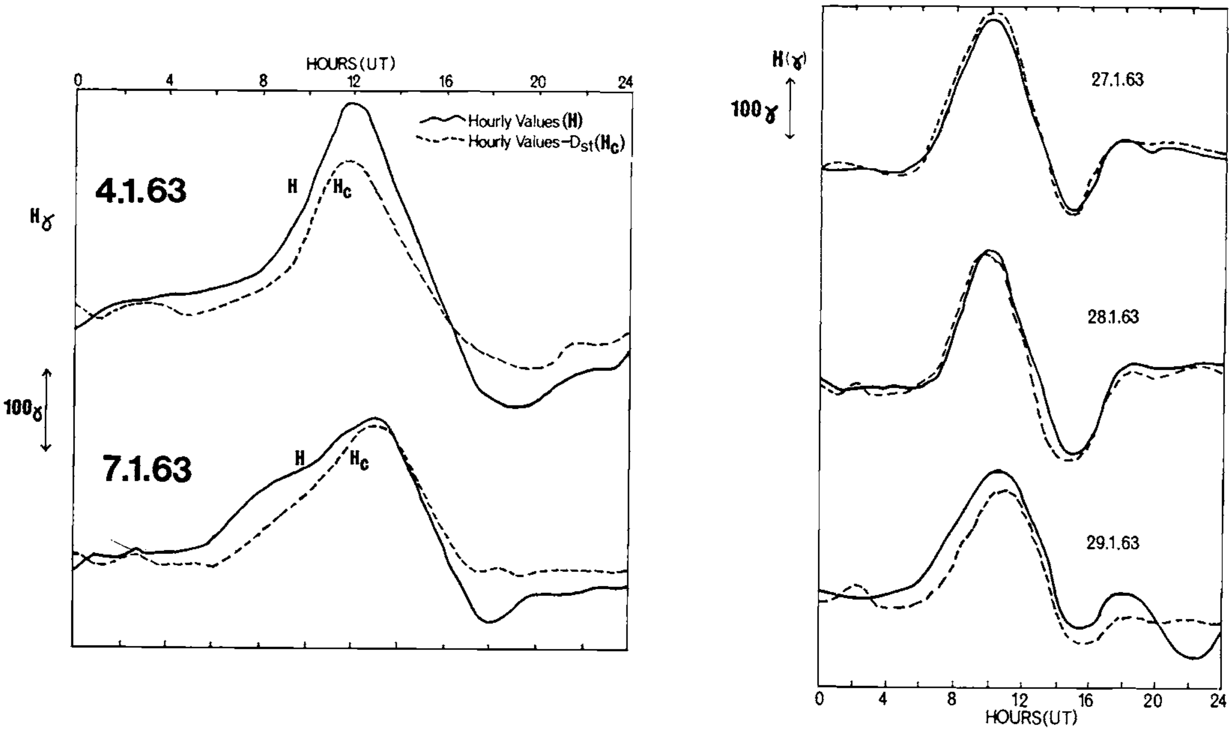

Fig. 53. Comparison of the variation in the H component at Ibadan during some days with the resulting variation when one subtracts hourly *Dst* indices. Daily values of *am* are 14, 14, 3, 3, and 10 in chronological order [after *Hutton and Oyinloye,* 1970].

are derived from only three stations) that these secondary movements in the H_c curves are induced by artificial features in the *Dst* index, which could come from an insufficient elimination of the S_R of the *Dst* stations at such times.

Several times we used the expression 'iron curve' method for qualifying the process chosen for eliminating the variation S_R in the derivation of the *Dst* index, but we insisted on the fact that it is probably the best one can use. The aim of Figure 53 was twofold. On the one hand, the aim is to show to what extent, even in quiet days, the *Dst* index is a good tool for some S_R investigations. (See the daily values of *am* in the legend: January 27 and 28 are very quiet, and January 4 and 7 are just above the limit of a truly quiet day.) On the other hand, the aim is to draw the attention of the users to the possible existence of residual variations superimposed upon the S_R. In the latter case, their source can be the S_R itself in the *Dst* index as well as the local disturbances. But for instance, a worker would be quite right in smoothing the H_c curve at the bottom of the short fluctuation around 0200 on January 29. (The method would be that, at least during a very quiet period, any short fluctuation caused by the subtraction of the *Dst* could be considered an artificial feature of the index because it is not a zonal effect if it does not appear at the station.) One must note, furthermore, that all the problems are not solved: thus in all these days, there still exists a noncyclic change from midnight to midnight in the H_c curves. This indicates that local disturbances are still present (partial ring current effects?) and confirms, as pointed out by *Price and Stone* [1964], how difficult this problem is.

Obviously, any artificial feature in the index due to the S_R tends to become negligible at the time of a storm. In the case of the partial ring current effects they become important, and one could argue at length whether they have to be considered artificial. Starting from the original definition of the *Dst* given by *Sugiura* [1964] (see the introduction of Chapter 8), they are an integral part of the *Dst* index, and one has to be aware that the *Dst* index includes at the time of the storms but as well at any time not only the symmetric ring current effects but also the partial ring current effects and, furthermore, some effects due to the interaction of the main permanent magnetic field with the solar wind (the first phase of a storm is the most typical). Any attempt for going beyond Sugiura's definition, especially a discrimination between the symmetric and partial ring currents, would require extremely elaborated indices like the *DR* indices (see section 8.6), which are probably out of the range of current indices.

2. We have to consider to what statistical modulations the *Dst* index is submitted, and we begin by looking at its annual variation. Figure 54, similar to Figures 22 and 27 as far as the data are organized, represents both the average annual and daily variations of the index for the years 1957–1974; note that in this work [*Mayaud,* 1978*b*] the values of *Sugiura and Poros'* [1971] report are used for the years 1957–1970. This

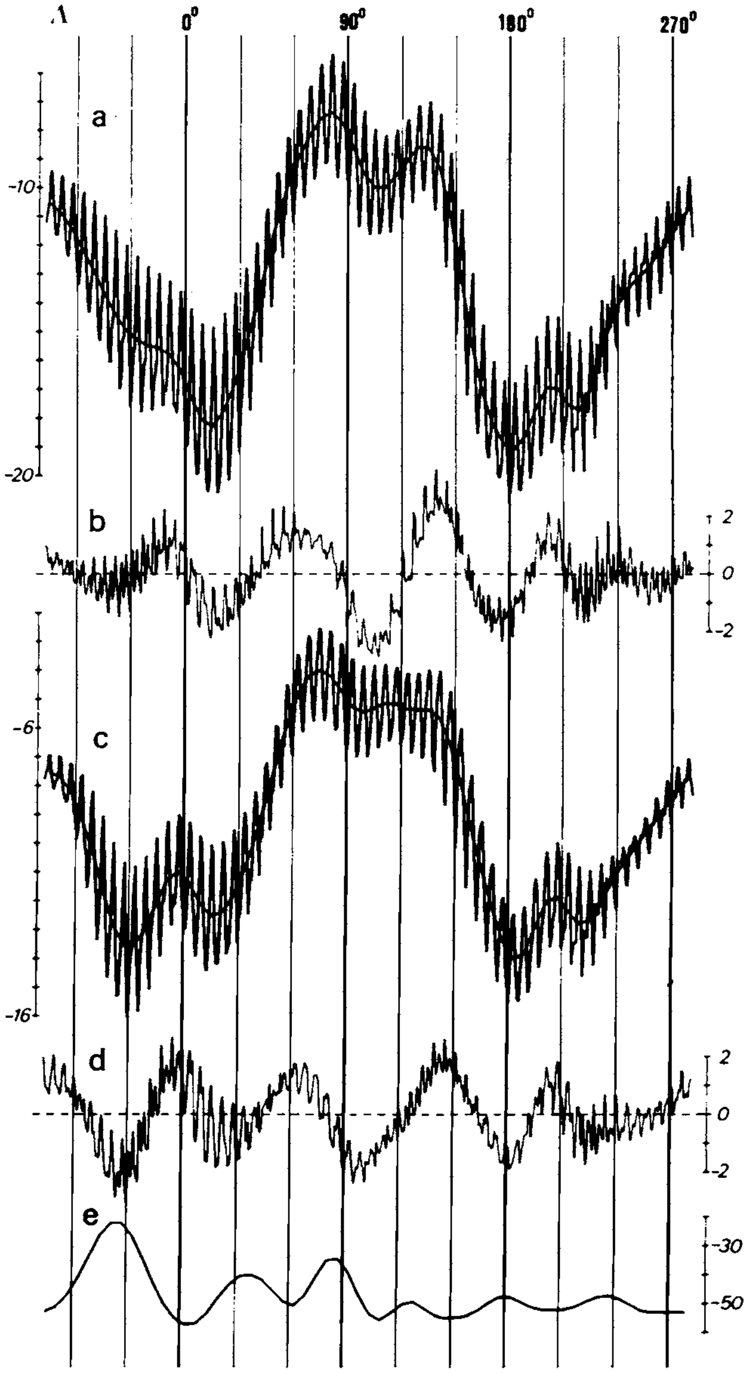

Fig. 54. Annual and daily variation of the *Dst* index for the years 1957–1974. See legend of Figure 22 for the way by which data have been plotted. (*a*) Curve for all days. (*b*) Residues resulting from a harmonic analysis of curve *a*. (*c*) Variation obtained after the exclusion of 257 storms from the full series (the data thus excluded correspond to 10% of the full series). (*d*) Residues resulting from a harmonic analysis of curve *c*. (*e*) Variation obtained for the 257 storms. (In this case, the daily variations are not drawn; note also that the ordinate is not the same as that for the other four curves.) All ordinates are in gammas [after *Mayaud,* 1978*b*].

means the Kakioka observatory is not used in the derivation for the years 1957-1963 and the Hermanus observatory is not used for the years 1964-1970.

If we compare curve *a* of this figure to curve *a* of Figure 27 for the index *am*, a 6-month wave is also the predominant feature. It is opposite in phase (minima at the equinoxes), but one must remember that the field caused by the ring current is a negative one: thus in both cases, the phenomenon appears to be largest at the equinoxes. The coherence between the daily and the 6-month waves of the *am* index (see section 5.2.4) showed that both are due to a modulation by the quantity $\sin^2 \psi_M$ as predicted by *Bartels* [1925] and described by *McIntosh* [1959]. But such a modulation is opposite in phase from one solstice to the other and undergoes at the equinoxes a 12-h wave of small amplitude (see curve *b* in Figure 27). Now it is quite clear in Figure 54 that the daily variation displayed in curve *a* has the same phase over the whole year and is as large at equinoxes as at the solstices. Curve *b* of Figure 54, which represents the residues of a fit of curve *a* by a harmonical analysis as a function of Λ, 2Λ (solar longitude), and *h* (universal time), demonstrates that the phase of the daily variation is constant over the year. Hence the 6-month wave of the daily variation is not due to a modulation of the ring current effects by the angle ψ_M between the solar wind and the dipole axis.

Malin and Isikara [1976] made an extensive analysis of the annual variation of the field elements in a worldwide network of stations by using only local night values to eliminate any influence from the S_R variation and pointed out that both the 6-month wave and 12-month wave displayed by the field elements can be interpreted by an annual variation in the average latitude of the ring current: it would move north at the December solstice when the solar wind (which compresses the earth's magnetic field) comes from the south and would move south at the June solstice. Then in the northern hemisphere the ring current effect is greater at the December solstice than at the June solstice. In the curve of Figure 54 a 12-month wave is clearly present, and the average negative intensity of the *Dst* is greater at the December solstice. This is in agreement with Malin and Isikara's mechanism, since most of the *Dst* observatories are in the northern hemisphere (see Table 35).

Two consequences result from this feature. First, the annual variation (the 12-month as well as the 6-month waves) of the *Dst* index would not be due to an average variation in the intensity of the ring current but only to the latitude variation of it. Thus it is remarkable that curve *c* of Figure 54, which is obtained by suppressing 257 storms from the *Dst* series, displays an annual variation similar to that of the full series and one almost as large; this indicates that the annual variation is not due to the storms only but is a permanent feature of the *Dst* index (see *Mayaud* [1978*b*] for other comments). The 12-month wave contained in it appears to be an artificial feature and could be suppressed by using a similar number of observatories in both hemispheres. The 6-month wave would not be suppressed because it is a true feature of the ring current effects as observed at ground (ideally at the dipole equator and practically from an ideal network equally distributed in both hemispheres). On the other hand, this 6-month wave is an artificial feature for anyone interested in the ring current intensity variations themselves. Second, the annual modulation of the *Dst* index illustrates clearly that the reference level used is not a true zero level for the intensity of the ring current. Without the modulation by the latitude variation of the ring current, the average intensity of the *Dst* index would be of about $-18\ \gamma$ over the year (see curve *a* of Figure 54). Now, the range of the 6-month wave is of about 8 γ: it would mean a very strong modulation for reducing the intensity by almost one half. But any theoretical model of the effects of the latitude variation of the ring current which would give an analytical law for the modulation would permit one to obtain a reasonable evaluation of the zero level and then to obtain the true intensity of the ring current at any moment.

3. What is the cause of the daily variation existing in the *Dst* index (see Figure 54)? Because the *Dst* series used in this figure is not the recent one derived by Sugiura (as mentioned above), one has to check if the daily variation is not partly due to the lack of homogeneity of the observatory distribution for the greater part of this data sample. Figure 55 affords a partial answer. It displays the average daily variation of the *Dst* index either with a sample for 1957-1975 or with a sample for 1957-1970; the solid curves correspond to a computation made from indices always derived from the four observatories listed in Table 35, the dashed curves correspond to the use of Sugiura

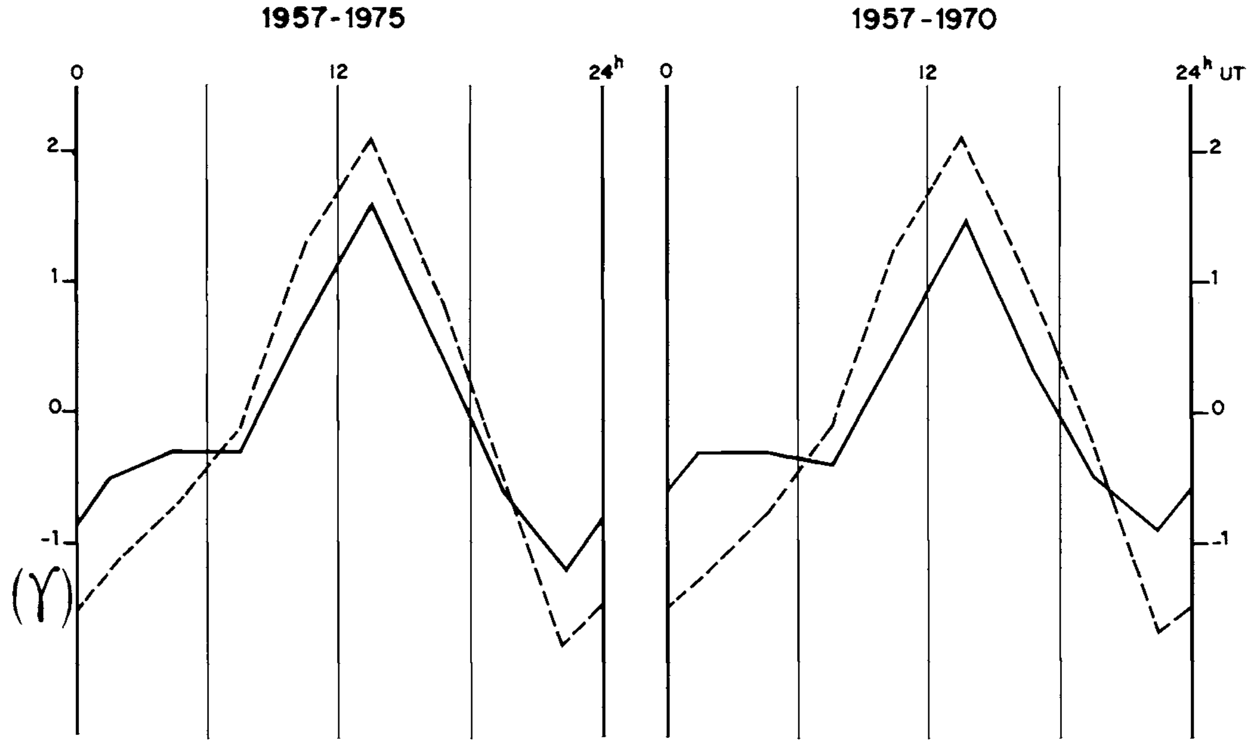

Fig. 55. Average daily variation of the *Dst* index. Two samples are considered. In both cases, solid curves are computed by using the last derivation by Sugiura (from the four observatories listed in Table 35). On the other hand, dashed curves correspond to the use of Sugiura and Poros' derivation for the years 1957–1970.

and Poros' derivation for the time interval 1957–1970. The ratios of the daily variation ranges (definite series with four observatories over provisional series with three observatories only in 1957–1970) are 0.72 and 0.61 for 1957–1975 and 1957–1970, respectively. Since the reduction is greater when using the sample for 1957–1970, when the number of observatories used always differs, it seems that the station distribution plays a role. The daily variation of the dashed curve is more difficult to interpret, since the stations used have not always been the same (Kakioka not used for 1957–1963 and Hermanus not used for 1964–1970). But when one looks at the daily variation of the definite indices for 1957–1975, it appears that the *Dst* index is maximum (that is, the ring current—or the partial ring current?—is smallest) around 1330 UT. Now, the Δ values in Table 35 show that a much larger longitude gap in the network exists between Hermanus and Kakioka, and at the center of this gap, the universal time at which the partial ring current is most effective is 1310 UT. The coincidence with the time of the maximum must not be overestimated. However, one could assume that because of this longitude gap the index is not equally sensitive to the local time effects of the partial ring current, as longitude varies, and hence a daily variation is induced. Consequently, it would be an artificial feature of the *Dst* index. A residue in the S_R elimination could be also considered; it would be of interest to know what the difference between the yearly observed *Sq* and the yearly synthetic *Sq* for the whole series is; we have not at our disposal such information, but it seems much more probable, given the strong local time component existing on the partial ring current effects (no correction is introduced for them in the derivation of the index), that the source of the residual daily variation is in this phenomenon. Such an interpretation would be confirmed by the apparent seasonal variation of the daily variation range: it is smallest in the December solstice. Now a similar feature is observed in the *SD* curves of *Vestine et al.* [1947] for a sample of 12 years at Honolulu. Since the local time variation at low latitudes is mainly caused by the afternoon/evening negative disturbances (or the partial ring current effects), both observations would have this same cause.

Let us note that this artificial feature in the *Dst* index is quite small in amplitude (an average range of 3 γ only) and is in no way a regular daily effect but only a statistical one.

4. Like all the other indices reviewed above,

the *Dst* index undergoes an 11-year solar cycle modulation. Any long series would permit one to check whether the *Dst* index is as sensitive as are the *am* or *aa* indices (mainly auroral) and the *AE* index to the secondary maximum of magnetic activity within each solar cycle (ordinarily 2 or 3 years after the sunspot maximum). The particular behavior of the solar activity during cycle 19 (the one of the IGY) prevents one probably from concluding at present. The fact is, however, that in the years 1960 and 1974 the level of the activity is approximately the same (about 31 $\pm$ 1 γ) for the *am* and *aa* indices but is $-$ 31 and $-$ 14 γ, respectively, for the *Dst* index. The correlation between the *Dst* index and the other indices (*am* or *aa* and *AE*) should not be extremely strong, and it is certainly much lower at the times of the long recurrent stormy periods.

Sugiura and Poros [1977] detected a quasi-biennal modulation in the *Dst* index, which is also found in the sunspot numbers; however, they do not give any interpretation for it, are very cautious in asserting its reality, and published this observation only because it has also been made for other terrestrial phenomena. However, no similar line is found in a spectral analysis of a 103-year sample of the *aa* index [*Delouis and Mayaud,* 1975]; there exists a line at 1.9 years which is probably a harmonic of the 11-year line, but it is no longer found when one breaks the sample into three parts. Any spectral analysis of geomagnetic indices (or other indices related to the solar phenomena) gives a lot of harmonics of the 11-year line, which differ from one sample to another because the solar cycle has not a constant period. (One can say, as proposed by Delouis and Mayaud and further discussed by *Courtillot et al.* [1977], that it corresponds to an astrophysical line and not to an astronomical line as, for instance, does the 6-month line, which is due to the relative movements of celestial bodies).

Finally, among all the geomagnetic indices presently in use, the *Dst* index is probably the simplest because it corresponds to the record of a well-defined phenomenon, the variations of the ring current. It does that in a proper way. When investigating the variation S_R, it may become a good tool for cleaning this phenomenon from spurious variations. For other uses (stormy periods) the residual daily variation which the index contains is negligible; the annual modulation is probably only a ground effect of the phenomenon itself. Any theoretical investigation which could solve (or partially solve) the problem of the zero level would be of great value.

8.6. *The DR Indices*

Kamide and Fukushima [1971] attempted to derive indices which would discriminate between the symmetric and the partial ring current effects. Four parameters are derived: (1) *DRS*, which corresponds to the intensity of the magnetic perturbation due to the symmetric ring current, (2) *DRP*, which corresponds to that due to the effect of the partial ring current, (3) *T*, which is the local time of the center of the partial ring current system, and (4) *W*, which is the longitudinal extent of the latter. A network of at least four stations (at low or relatively low latitude) has to be used. It should be noted that the derivation of the indices requires the use of a complex theoretical model of current configuration, containing various assumptions which do not allow always for the complexity of the phenomenon, and each set of indices is obtained by solving an inverse problem where the ground magnetic observations are iteratively fitted to the model.

Such indices are probably too sophisticated to be of current use on a routine basis. But any information which could permit one to have access to the contribution of the partial ring current in the *Dst* index would be very useful. One can wonder if it would not be possible from the *AU* index, which monitors a phenomenon so strictly related to the partial ring current. The difficulty, however, would be the great seasonal effect existing in this auroral phenomenon (see section 7.4).

9. Conclusion

9.1. *Are Other Geomagnetic Indices Needed?*

The high-frequency domain of the irregular variations, that is, the pulsations, is important. Various attempts have been made to derive indices from them [*Saito,* 1964; *Gul'elmi and Troïstskaya,* 1973; *Verö,* 1975], but they did not reach the level of a planetary derivation. The two main difficulties are as follows. (1) The pulsation records are not always comparable from one station to another because of the differences in the techniques used. (2) Given the variability of the pulsations within any time interval which is longer by several orders of magnitude than their periods, it is not easy to extract summarized information. However, it would seem important to succeed in defining one or several indices, since investigations have shown that one could monitor in that way 'the position and the form of the plasmasphere as well as the variability of the interplanetary characteristics' (*IAGA Bulletin 41*, 1977, p. 57, resolution 5).

The possible interest and the difficulties in deriving an index monitoring the regular variation S_R have been set forth in section 3.8. Concerning the low-frequency domain of the irregular variations, the *Dst* and *AE* indices monitor properly the two most important species, that is, the ring current intensity variations and the auroral disturbances. Planetary derivatives of the *K* indices provide a complement, and we shall set forth in the next section how all these indices may be used.

However, the irregular variations taking place with the polar caps (say, at corrected geomagnetic latitudes $\lambda > 75°$) are not presently covered by the IAGA geomagnetic indices in spite of their particular importance. The interest for them began with the work of *Chree* [1912], and some of the morphological considerations contained in it are still valid. A quotation of *Bauer* [1923, p. 116] related to the numerous discussions of the first decades of this century on the characterization of the activity (see section 3.5) indicates that the geomagneticians were very quickly aware of the special behavior of the magnetic activity at these latitudes: 'In the selection of the desired magnetic measure it would seem that not too much emphasis should be laid upon the question whether the measure will also be wholly suitable for occasional arctic or antarctic stations ... .' But some lines higher up one reads that 'too much must not be expected of any measure of magnetic activity, as it is quite likely that no one measure will suffice for all investigational purposes.' And 'if there exists a considerable controversy centering around the advisability of the adoption of new indices' [*Rostoker,* 1972*b*, p. 948], we strongly believe that indices derived from the polar cap stations are essential to the monitoring of special phenomena which the present indices do not supply.

One could find a recent morphological description of the polar cap variations in the work of *Mayaud* [1978*a*]. Quite clearly, if auroral variations still have effects at these latitudes, a series of other phenomena have their source within the polar caps. Some are worldwide, such as the DP 2 fluctuations or sudden impulses: others, such as the special type of disturbance observed by *Chree* [1912] in the first antarctic polar cap records are confined within these regions. The reason for a special behavior of the polar cap irregular variations was outlined by *Mayaud* [1956] in using the concept of 'horn' contained in the Chapman-Ferraro theory of the magnetic storms [see *Chapman and Bartels,* 1940, chap. 25]. A free entry of the solar wind (recently discovered at that time) through such horns seemed capable of explaining the daily, seasonal, and latitudinal properties of the geomagnetic activity within the polar caps. It maximizes during the daytime and is much greater in summertime; this particular behavior is restricted to an area clearly delimited by the corrected geomagnetic latitudes corresponding to the lines of force of the main field linked to the neutral points in the front of the neutral ionized stream at the basis of the horns. *Dungey* [1963] effectively notes that such horns hit the earth at much higher latitudes than do the auroral zones, and in the magnetospheric configuration they are now called the 'cusps.' The above sketch is presently obsolete for the most part, and modern thoughts go more along the following lines. Penetration of solar wind plasma into the geomagnetic field takes place by means of an electric polarization and the corresponding $\mathbf{E} \times \mathbf{B}$ drift. Electrostatic repulsion tends to spread the polarization charge layers laterally along the magnetic field lines. Because the field lines pass through the conductivity ionosphere, the polarization charge can be neutralized, and the plasma stream will consequently be stopped or retarded. The depolarizing current along the field lines and its closure through the polar cap ionosphere produce magnetic variations which we may identify with the special type of disturbance seen in the polar caps [*Eastman et al.,* 1976; *Svalgaard,* 1977]. Consistent with this picture, another factor neglected by *Mayaud* [1956] but already proposed by *Stagg* [1935] and again put forward by *Lebeau* [1965] is certainly important: the intensity of the effects caused certainly depend greatly on the daily and seasonal variations of the ionospheric conductivity due to the solar wave radiation. In these conditions a great difficulty in the interpretation of the observations and in the derivation of any index arises, since daily, seasonal, and latitudinal variations depend on two modulating factors: (1) the geomagnetic configuration centered on the poles of the corrected geomagnetic coordinate system (that is, 279°E, 80°N and 128°E, 75°S) with its own local time and (2) the ionization centered on the geographical poles with the local time related to them. Between each pair of poles within a given polar cap, the notion of time becomes very complex or ill defined, and the scarcity of the possible observatories in these regions is a further obstacle.

A significant proof of the importance of the polar caps for monitoring special phenomena was the discovery by *Svalgaard* [1968] and *Mansurov* [1969] of a clear relationship between the sector polarity of the interplanetary magnetic field (itself discovered a few years before by *Ness and Wilcox* [1964, 1965]) and some particular irregular variations: basically, a positive (or negative) disturbance occurs during the daytime in the component Z at very high corrected geomagnetic latitudes λ ($\pm$ 85°) when the sector polarity is toward (or away from) the sun. Later, the azimuthal component B_Y of the interplanetary magnetic field was identified [*Friis-Christensen,* 1971; *Friis-Christensen et al.,* 1972; *Berthelier,* 1972] as the source of this phenomenon. Then equivalent current patterns were derived either with respect to the sector polarity [*Mansurov and Mansurova,* 1971; *Svalgaard,* 1973] or with respect to the B_Y component direction [*Berthelier et al.,* 1974; *Friis-Christensen and Wilhjelm,* 1975]. With the refinement of the observations, it appears that the possibility of inferring the sector polarity in the past (see, for instance, the work of *Svalgaard* [1972] for the years 1926–1971 in which he uses the H component at Godhavn, the comment of *Fougère and Russel* [1975], the reply of *Svalgaard* [1975*a*], and the comment of *Berthelier and Guérin* [1975]) is not absolutely reliable: the corrected geomagnetic latitude of Godhavn (λ = 78°) is already too low, and it seems that a reliable inference can be made only from the Z component at latitudes clearly higher than $\lambda = \pm 80°$. The indices provided by S. M. Mansurov et al. (unpublished manuscript, 1975) and *Svalgaard* [1975*b*, 1976*b*] were derived mainly from such data and give daily information on the direction (away or toward) of the sector polarity. As early as 1971, the IAGA showed its interest in the development of such indices (*IAGA Bulletin 31,* 1971, p. 137, resolution 18), and one may expect that a definite index monitoring this phenomenon will soon be officially adopted. We saw in section 5.2.4 that the component B_Y also has some effects at a planetary scale; this reinforces the necessity of obtaining, from ground-based data, information on it. Because of the double modulation described above, any monitoring of the intensity will be probably extremely difficult.

Will the open regions of the magnetosphere, as they exist at polar cap latitudes, permit one in the future to monitor other characteristics of the interplanetary medium? J.Wilhjelm and E. Friis-Christensen (private communication, 1977) think that a part of the daytime agitation is under the control of the B_Z component of the interplanetary magnetic field. Progress in the knowledge of the mechanisms involved in the generation of the daytime activity of the polar caps could open the way to monitor some of these characteristics. The 1-h index R will then perhaps find an application.

9.2. *Meaning and Use of the Present Indices*

First, geomagnetic indices do not have to be considered substitutes for anything and in particular for the original records. The present IAGA geomagnetic indices only provide a reliable evaluation of the intensity of some specific transient irregular variations of the geomagnetic field (*Dst* and *AE* indices) or of the geomagnetic activity level on a worldwide scale (planetary derivatives of the K indices). The use of the former is preferable when one investigates phenomena related to these specific irregular variations. The latter are rather a reference, with respect to the planetary level of disturbance, either for a comparison of periods more or less remote in time from each other or for a systematic classification of time intervals. They are also the basic tool for statistical studies of the time variations of the geomagnetic activity and of its relationship with other terrestrial variations or solar phenomena. *Rostoker* [1972*b*, p. 947] states that 'because of careful weighting procedures used in the computation,' *Kp* and *ap* indices held 'the most promise' for such statistical studies. We believe that this is not correct, and the lengthy description we made of the *Kp* index was aimed at putting users on their guard against the use of such an index; it was very useful for some decades, but in our opinion, it should be discontinued relatively quickly because of its defects. We shall not consider it in the following.

Among the other present indices, the *Dst* index may be considered as the one which best approximates a record of a single and well-defined phenomenon, the ring current. Its contamination by the partial ring current effects can be considered a drawback; this, however, depends on the investigation made. Its daily and annual variations are secondary phenomena, which have to be known but can be neglected in many studies. Any theoretical work opening the way to a knowledge of its true zero level would be extremely precious for the users. The *Dst* index is a good tool in order to clean the records when investigating the regular variation S_R. It is essential for geomagneticians studying the secular variation of the main field because ring current effects are probably the main external source contributing to annual or monthly average values of the field elements. (The effect of the variation S_R can be readily eliminated by using local night values only; at auroral or nearby latitudes the effects of the auroral electrojets can become important but are more difficult to estimate.) In the studies of the magnetic storms the *Dst* index is the first reference, but one must remember that the relationship between the auroral variation intensity and the amplitude (or even the occurrence) of the main phase of a storm is highly complex (see section 8.4). The *Dst* index is sensitive to variable magnetic fields whose source is remote; it is the reason for which this index is important for the studies of the cosmic rays. (These are submitted to a field perturbation over a distance of several earth's radii.) Finally, the *Dst* index monitors a phenomenon whose variation may persist even after the action of solar sources is stopped and conversely which did not react to certain auroral activity, however, due to these solar sources; because of that, it must not be the only indicator used when studying solar-terrestrial relationships.

The *AE* index, and more specifically, the *AU* and *AL* indices are also a record because of their high sampling rate of a single and well-defined phenomenon. But they are already closely associated with summarized information because they cannot follow the dynamic motions of the auroral oval. There will always be significant differences between the record given by either index and the records of the auroral observatories (except for the one from which the extreme deviation defining the index is taken during a given time). We suggested several changes in the computation of the indices which could improve the definition of the zero level and avoid the contamination by the S_R. This would make the use of the indices for statistical studies more reliable. In such statistical studies, one must not forget that the index *AU* (or *AL*) is not derived from values averaged with longitude but from the extreme positive (or negative) deviation recorded in a network of northern auroral stations (itself not absolutely well distributed with longitude and latitude). The indices *AU* and *AL* do not provide an estimation of the average level of disturbances caused by the auroral variations but an estimation of their maximum value as recorded from a given network. Differences between the statistical behavior of the *AU* and *AL* indices would have to be better understood. The northern character of the indices and the resulting annual variation make them less reliable for relationships with some phenomena. The main use of such indices is probably as a starting point of reference in order to infer the presence or the absence of auroral activity: daily graphs, such as those given in Figure 36, are certainly irreplaceable summarized information to be completed by looking at the monthly tables which list for each hour the station contributing to each of the indices *AU* and *AL*. The next step is the use of them for studying individual events and their correlation with other geophysical phenomena recorded at ground or at satellite levels and as well with interplanetary phenomena. The literature is full of diagrams where *AU* and *AL* records (and *Dst* records) are compared with the record of another phenomenon. When averaging records of individual events (for instance, by the superposed epoch method), it would be good on some occasions to take care that an uneven distribution with universal time or season does not introduce biases with respect to the other phenomena studied. The *AE* index itself probably has to be used with a great prudence: its significance (the sum of the extreme deviations recorded at different longitudes) is rather complex. On the other hand, the *AU* index is an excellent indicator for detecting the presence of low-latitude afternoon/evening negative disturbances during quiet or relatively quiet days; it can be a tool not for cleaning the records (as with the *Dst* index) but for brushing aside some of them when investigating the variation S_R. Finally, since the auroral variations are the main phenomena caused by the interaction between the solar wind and the interplanetary magnetic field on the one hand and the magnetosphere on the other hand, the auroral *AU* and *AL* indices constitute the main reference in magnetospheric studies. Their quantitative aspect is limited only by the auroral oval dynamic motions (an effect that is impossible to remove in the indices and that induces the saturation effect mentioned in section 7.4) and by the present insufficient distribution of the *AE* stations.

The *am* (or *an* and *as*) and *aa* range indices are only summarized information with a sampling rate of 3 h. They do not monitor a single species among the transient irregular variations: mainly (or only?) sensitive to the auroral variations when the activity level is high (say, $am > 40$ or 50), they become also sensitive to the DP 2 fluctuations at moderate levels and to the small worldwide fluctuations at very low levels. They are practically insensitive to the ring current variations. They are much less sensitive than the *AU* and *AL* indices to the spatial motions of the auroral oval. They also differ from them in measuring the planetary average level of the activity at a given time and not its extremum with longitude; the $\bar{a}_j$ indices, however, can always be used for evaluating the activity level at a given longitude in a given hemisphere. The *am* (or *an* and *as*) index and, with the necessary restrictions, the *aa* index make this estimation of the planetary activity level at a corrected geomagnetic latitude 50°. The level of the activity at other latitudes (except within the polar caps) can be inferred from a curve such as the one in Figure 14 (or its extrapolation in Figure 39), and indices *σn* and *σs* provide rough information on its variation with longitude for a given interval. The value of the range indices depends on the $\sin^2 \psi_M$ modulation and on the interplanetary field orientation; the former can be easily removed if one wishes. Differences between these geophysical modulations (they mainly reflect those of the auroral variations) and those of the *AU* or *AL* indices would have to be better understood; one has, however, to be aware that these differences partly originate in the derivation (planetary average in one case, extremum at one longitude in the other). In particular, the *am* index is better adapted to studies of the universal time components of the magnetic activity daily variation, and the *an* and *as* indices are the only indices which give the possibility of a comparison between hemispheres (in particular, in view of evaluating the asymmetry due to the interplanetary component B_Y). The *aa* series is highly homogeneous and permits one quantitative comparisons of very remote periods. The homogeneity of the *am* series is limited for the low-activity levels by imperfect scalings of *K* indices; this defect has decreased with time, and one may expect a good standard in the coming years. An individual 3-h range index *aa* cannot be considered completely reliable in characterizing the planetary activity level within a 3-h interval; *am* (or *an* and *as*) have to be used. But for time intervals equal to or longer than 12 h, they become equivalent. The geophysical meaning of the range indices is to be, at least, a rough measure of the amplitude of the geomagnetic noise observed in the records. They are probably related linearly to the root mean square of energy density variation of the geomagnetic field caused by the disturbances, and this in the near environment of the earth (only worldwide fluctuations are due to remote sources). Furthermore, when considering the various properties of the geomagnetic activity displayed by these indices (annual and daily modulations in terms of $\sin^2 \psi_M$ and B_Y, asymmetry between hemispheres with respect to the sign of B_Y, quantitative relationship between *am* and the solar wind parameters such as those that have been established by *Svalgaard* [1977]), each of those properties appears to be an a posteriori proof of their physical significance. Hence these indices constitute a reference in view of a reliable quantitative measure of the planetary geomagnetic activity level whenever ring current or auroral variations are not aimed at themselves; in that sense, they are of a wider use which is only limited by the sampling rate of 3 h. When selecting, comparing, or systematically classifying time intervals with the *am* or *aa* indices, the arithmetic averages have to be used but must sometimes be associated with the geometric averages (see section 6.2) in order to take into account significant variations of the frequency distributions of the ranges within the time intervals considered. Given the worldwide network used, *am* indices are probably the best for investigating the complexity of the modulations of the geomagnetic activity, which are caused by the interaction of the magnetosphere with solar agents in the interplanetary medium. Given the length of the series, *aa* indices are probably the best for investigating the modulations of the geomagnetic activity, which have their source in the solar activity itself. In that case, one has to be aware that the secular variation of the permanent field has to be taken into account in the analysis of very long term variations. Recent results [*Sargent*, 1978; *Simon*, 1979] which tend to indicate that a forecast of the next solar cycle is more reliable from the *aa* index than from the sunspot numbers themselves are very promising.

Finally, one might say that the present IAGA indices properly cover the greater part of the domain of geomagnetic irregular variations and are practically free of any important and significant empirical inference, with the exception of the *Kp* index. Indices derived from the polar cap disturbances and from the pulsations would permit one to cover the whole field of the irregular variations by supplying the scientific community with information not provided by the present indices. Any index monitoring the regular variations, even if it is used only in the form of 12-month running averages (for solving the problem of the annual variation), would give information on the solar wave radiation and nicely complement the long series of *aa* indices which monitor the solar corpuscular radiation.

Appendix A

A Possible Classification of the Irregular Variations

We summarize the main morphological features and statistical laws of the irregular variations. We restrict this description to the variations which can be identified in the standard records; therefore we neglect, apart from the auroral PC 5 pulsations, the vast domain of the pulsations because indices described in this work are not sensitive to them.

The term 'worldwide' means 'extended throughout the entire world'. We first use it to characterize some irregular variations because they may be simultaneously observed everywhere when they occur. In such a case, this means that they have a zonal component. (An obvious example is the main phase of a storm which corresponds at the ground level to a uniform field parallel to the dipole axis within which the earth is embedded.) However, other irregular variations are truly worldwide only when they reach a certain intensity level. We consider them to be potentially worldwide. The other and main feature by which they differ from the former is that they have no zonal component; their magnetic effects can be, in general, described by equivalent vortices of currents flowing within a spherical shell. Basically, this means that, for instance, the sign of the corresponding deviation in *H* component varies with latitude and longitude, while this sign is the same everywhere in the case of the truly worldwide variations.

Worldwide Irregular Variations

Truly Worldwide Irregular Variations (With a Zonal Component)

The 'main phase' of a storm corresponds to a temporary increase of the ring current intensity; it may last for a few hours or as long as a day and a half and may reach hundreds of gammas at the equator. It is followed by a 'recovery phase' which may last several days. The deviation is negative in the *H* component at any latitude. There is no annual or daily modulation.

A 'slow oscillation' corresponds to a slow and temporary fluctuation in the ring current intensity. Its main morphological feature is its smoothness; hence this disturbance is sometimes difficult to discriminate from the regular variation S_R. It ordinarily lasts a few hours, and its intensity is a few tens of gammas. There is no annual or daily modulation.

A 'storm sudden commencement' (ssc) corresponds to a sudden and short variation (a few minutes) at the beginning of a storm. It is made up of two components, magnetospheric (due to a sudden interaction between the solar wind and the magnetosphere) and polar (originating within the polar caps). The former has a zonal component, while the latter is only potentially worldwide. The average amplitude of the magnetospheric component at low latitudes is about 20 γ in *H* but may exceed 100 γ. There is no annual or daily modulation. The polar component undergoes a strong 12-month modulation (culminating at local summer time), and the sign of the deviation depends on the local time at the station. It can be observed from the polar caps down to mid-latitudes and reappears at dip equator latitudes during daytime. The 'sudden impulses' (si) have exactly the same properties. The discrimination between ssc and si is difficult and partly arbitrary; it mainly consists in deciding whether a change of rhythm in the activity level is observed before and after the event (it is then an ssc) or not (it is an si). Let us note that a storm may begin without ssc.

The 'first phase' of a storm is made up of a temporary increase of the *H* component, lasting from about half an hour to a few hours. Its amplitude may reach a few tens of gammas. The phenomenon lasts longer in the local morning. It does not always precede the main phase. There is no annual modulation.

We classify as 'worldwide fluctuations' all the other irregular variations which have a zonal component and which may be identified as such because a deviation of the same sign in H is observed at any longitude. They can be either short deviations which do not have a sudden beginning or ring current oscillations which are not smooth. There is no annual or daily modulation (except in the case of degenerated sudden impulses).

Among these worldwide irregular variations, one may say that any index is hardly sensitive to the ssc and si (these phenomena are too short or too rare). Conversely, the aim of the *Dst* index is to monitor all the others. The *AU* and *AL* indices are contaminated by them, and this can be directly estimated from the *Dst* index value after a suitable latitude correction. Finally, the *am* (or *aa*) index is hardly sensitive to the main *Dst* variations, but when the activity level is low, it is fully sensitive to the worldwide fluctuations even in the case of a short and isolated fluctuation.

Potentially Worldwide Irregular Variations (Without Zonal Component)

The 'auroral' variations correspond either to the eastward electrojet (local afternoon and evening) or to the westward electrojet (late evening and early morning), while the substorms are a marked intensification of only a limited part of the latter near midnight. However, intensifications of the former also occur. The center of a given auroral electrojet event (a current band flowing along a part of the auroral zone and associated with field-aligned currents) is located at about $69° \pm 5°$ corrected geomagnetic latitude but can shift by as much as 5° in the course of the event. The amplitude variation, with latitude, of the effects is difficult to summarize: Figures 14 and 39 give a rough idea of it. Obviously, at electrojet latitudes the effect appears mainly in H (and in Z), but when one leaves these latitudes, it becomes predominant in D at nearby longitudes. At auroral latitudes it is relatively easy to discriminate, from a morphological point of view, between the deviations due to the electrojets themselves and those due to their intensifications. Because of the rapid decrease with latitude of the effects, those of the latter tend to become predominant at subauroral latitudes, where they give rise to the 'bays'. The shape of these bays varies greatly and can be rather complex either because of a move with latitude of the electrojet during a given event or because of the superimposition of several events (remember that the effects of an event are felt over a wider and wider longitude band when one goes equatorward). Furthermore, at low latitudes the most important auroral effects are the local afternoon/evening negative disturbances in H component, related to the partial ring current and to the eastward electrojet. The main modulation for the auroral variations is the local time diurnal variation (due to the configuration of the magnetosphere) with a maximum at night. This diurnal variation is itself modulated by the ψ_M angle between the solar wind and the dipole axis and by the B_Y component of the interplanetary magnetic field.

The 'DP 2 fluctuations' originate within the polar caps where they correspond to a ionospheric dawn-to-dusk flow of currents. These currents give rise to two ionospheric vortices (within each hemisphere) which are rather similar to those corresponding to the polar component of the ssc and si, the main one spreading downward to dip equator latitudes. There the currents are strongly enhanced during daytime. Furthermore, the configuration of these vortices is such that significant effects are observed at subauroral latitudes either in H component in the local afternoon or in D component in the morning. A strong 12-month modulation of these disturbances is related to the conductivity conditions within the polar caps (i.e., with a maximum at local summer time). Such fluctuations last about 1 h, and sequences (or trains) are often observed. At subauroral latitudes, their amplitude is a few tens of gammas.

The aim of the *AE* index is to monitor the auroral variations; it is hardly contaminated by the DP 2 fluctuations because these appear mainly in the D component at auroral latitudes. The *Dst* index is certainly sensitive to the partial ring current effects in spite of their nonzonal character. The *am* (or *aa*) index is fully sensitive to the auroral variations; the DP 2 fluctuations have a significant influence at moderate activity levels.

Nonworldwide Irregular Variations

The 'polar cap' variations compose a first class of the nonworldwide irregular variations. We mean by polar cap variations those which are confined within polar regions. One type is the Svalgaard-Mansurov effect, related to the azimuthal component of the interplanetary magnetic field. The other type includes fluctuations whose duration may vary from 1 hour to a few minutes. Both types have a greater amplitude during local daytime and summertime.

The trains of 'auroral PC 5 pulsations' occur at auroral latitudes during the local morning and afternoon. They are most frequent during the equinoxes and clearly less frequent during summertime. Their amplitude can exceed 100 γ but decreases very rapidly on either side of a 70° corrected geomagnetic latitude.

Finally, the 'solar flare effects' (sfe) are a very particular phenomenon. They appear as a sudden enhancement (for a few minutes, sometimes as long as half an hour) of the regular variation S_R. The fact that their morphology is not always typical makes their identification sometimes rather difficult. These irregular variations probably correspond to the formation of an additional current system within the lower daytime ionosphere. There is no annual modulation in their occurrence.

Given their latitude of occurrence, the polar cap variations have no influence on the present IAGA indices. The auroral PC 5 pulsations are ordinarily masked in the *AE* indices by auroral variations occurring at other longitudes. The *am* (or *aa*) indices are sensitive to the sfe; they are so rare that they give an unsignificant contribution.

Conclusion

We stated above in which manner each index is sensitive to certain irregular variations. The relative influence of the various species interferes little in the case of the *AE* index or of the *Dst* index, since they are conceived to monitor a particular species (auroral variations or ring current variations); it is sufficient to know that the former is presently contaminated by the ring current variations (it could be avoided by improving the derivation), and the latter is contaminated by the partial ring current effects. In the case of the *am* (or *aa*) index, one may say that the main contribution comes from the auroral variations. This can be inferred from the local time daily variation of the activity at subauroral latitudes and from the modulation by $\sin^2 \psi_M$ and B_Y: any estimation is difficult, but we would say that this contribution probably amounts to 80% or more on the average. At high levels of activity, one may consider that practically only auroral variations contribute to the index (i.e., all the other irregular variations are merged into them from the point of view of a scaling based on a range). At moderate or low levels the DP 2 fluctuations have an influence, but their effect is lessened by their local features at subauroral latitudes; the worldwide fluctuations might contribute more because of their worldwide character (i.e., when they occur, they give a contribution at any longitude). At very low levels the latter probably contribute the most. Other events such as ssc, si, and sfe are almost negligible, although they systematically raise the index level when they occur; this is less marked with the sfe because of their nonworldwide character.

For more detailed information on the classification of irregular variations see *Mayaud* [1978*a*].

Appendix B

List of Observatories

According to the role of the observatory in the work, either centered dipole coordinates or corrected geomagnetic coordinates are given. Most of these values are taken from Appendix 9 of *Akasofu and Chapman* [1972]; others have been kindly computed by J. Allen from a similar model. Therefore some of these values may differ slightly from the values given in this work, especially in Tables 5 and 12 because they were taken from the observatory list or tables of *Hakura* [1965].

TABLE B1. List of Observatories

	Geographic Location		Centered Dipole		Corrected Geomagnetic Location	
Station	Latitude	Longitude	Latitude	Longitude	Latitude	Longitude
Abinger	51.2	359.6			49.8	79.5
Abisko	68.4	18.8			65.4	103.6
Addis-Ababa	9.0	38.8	5.4	109.2		
Agincourt	43.8	280.7			56.9	350.5
Alibag	18.6	72.9	9.5	143.6		
Amberley	−43.2	172.7			−50.1	254.1
Apia	−13.8	188.2	−16.1	260.2		
Argentine Island	−65.3	295.7			−49.7	8.6
Baker Lake	64.3	264.0			75.2	320.0
Barrow	71.3	203.2			69.6	246.6
Byrd	−80.0	240.5			−68.3	352.5
Canberra	−32.7	149.5			−42.7	223.9
Cape Chelyuskin	77.7	104.3			71.6	174.2
Cape Wellen	66.2	190.2			62.5	242.6
Chambon-La-Forêt	48.0	2.3			45.9	80.5
Cheltenham	38.7	283.2			52.0	353.6
Colaba	18.9	72.8	9.7	143.6		
College	64.9	212.2			64.8	259.6
Crozet	−46.4	51.9			−52.9	105.5
Dixon Island	73.6	80.6			68.3	154.7
Dombas	62.1	9.1			60.1	91.9
Eskdalemuir	55.3	356.8			54.6	79.0
Eyrewell	−43.4	172.4			−50.4	253.8
Fort Churchill	58.8	265.9			70.3	326.0
Fort Rae	62.8	243.9			69.9	292.0
Fredericksburg	38.2	282.6			51.5	352.8
Fürstenfeldbruck	48.2	11.3			45.0	87.8
Gnangara	−31.8	115.9			−44.2	184.8
Godhavn	69.2	306.5			77.6	41.6
Great Whale River	55.3	282.2			68.0	353.8
Greenwich	51.5	0.0	54.2	83.9	50.1	79.9
Guam	13.6	144.9	4.0	212.9		
Halley Bay	−75.5	333.4			−61.2	27.7
Hartland	51.0	355.5			50.2	76.3
Hermanus	−34.4	19.2	−33.3	80.5	−41.5	79.7
Honolulu	21.3	202.0	21.1	266.5		
Huancayo	−12.1	284.7	−0.6	353.8		
Ibadan	7.4	3.9	10.7	74.7		
Kakioka	36.2	140.2	26.0	206.0		
Kew	51.5	359.7			50.1	79.7
Kiruna	67.8	20.4			64.8	104.3
Ksara	33.8	35.9			27.9	106.3

TABLE B1. (continued)

Station	Geographic Location Latitude	Geographic Location Longitude	Centered Dipole Latitude	Centered Dipole Longitude	Corrected Geomagnetic Location Latitude	Corrected Geomagnetic Location Longitude
L'Aquila	42.4	13.3			38.3	87.9
Lauder	−45.0	169.6			−52.7	251.6
Leirvoguir	64.2	338.3			66.8	69.5
Lerwick	60.1	358.8			59.4	83.0
Lovö	59.4	17.8			56.5	97.1
Magadan	60.1	151.0			53.9	217.4
M'Bour	14.4	343.0	21.3	55.0		
Meanook	54.6	246.7			62.6	300.8
Melbourne	−37.8	145.0			−48.9	219.8
Memambetsu	43.9	144.2			37.5	213.7
Murmansk	68.3	33.1			64.4	113.9
Narssarssuaq	61.1	314.8			68.7	44.2
Newport	48.3	242.9			55.4	299.3
Niemegk	52.1	12.7			49.2	90.1
Norway Station	−70.5	357.5			−60.1	42.7
Novosibirsk	55.0	82.9			51.2	153.4
Orcadas del Sur	−60.7	315.2			−46.2	19.1
Ottawa	45.4	284.5			58.5	356.2
Parc Saint-Maur	48.8	2.5			46.7	81.0
Petropavlosk	53.1	158.6			46.6	224.8
Podkammenaya-Tugunska	61.6	90.0			57.5	161.0
Port aux Francais	−49.4	70.2			58.1	121.2
Potsdam	52.4	13.1	52.5	97.1		
Rude-Skov	55.9	12.5			53.3	91.4
San Juan	18.1	293.9	29.6	3.1		
San Miguel	37.8	334.4	45.6	50.9		
Seddin	52.3	13.0	52.4	97.0		
Sitka	57.1	224.7			59.9	275.9
Sodankylä	67.4	26.6			63.9	108.5
South Georgia	−54.3	323.5			−41.7	24.3
Sverdlovsk	56.7	61.1			52.7	132.4
Tashkent	41.3	69.6	32.3	144.0		
Tikaya Bay	80.3	52.8			74.7	140.8
Tixie Bay	71.6	129.0			65.8	195.5
Toledo	39.9	355.9	43.9	74.7		
Tomsk	56.5	84.9			52.6	155.5
Toolangi	−37.5	145.5			−48.5	220.3
Trelew	−43.3	294.7			−28.4	4.9
Trivandrum	8.5	76.9	−1.1	146.4		
Tromsö	69.7	18.9			66.8	104.8
Tucson	32.3	249.2			39.9	311.4
Victoria	48.5	236.6			54.1	292.4
Watheroo	−30.3	115.9			−42.5	184.9
Wingst	53.8	9.1			51.4	87.8
Witteveen	52.8	6.7			50.6	85.7
Yellowknife	62.4	245.6			69.9	294.4

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List of Geomagnetic Index Symbols

Numbers in parentheses refer to the chapters or sections where the indices are described; the present IAGA indices are listed in bold face.

aa	3-h range index, derived from two antipodal stations (5.3).
AE, AU, AL	2.5 min or hourly auroral electrojet indices (7).
am, an, as	3-h range (mondial, northern, southern) indices (5.2).
ap	3-h range planetary index derived from *Kp* (5.2.3).
C, Ci, ***C9***	daily local (*C*) or international (*Ci*) magnetic character; *C9* was first derived from *Ci,* then from *Cp* (3.2).
Cp	daily magnetic character derived from *Kp* (5.1.3).
Dst	hourly index mainly related to the ring current (8).
K	3-h local quasi-logarithmic index (4).
Km	3-h mean index derived from an average of *K* indices (not to be confused with the *Km* of the next item) (5.1.1).
Km, Kn, Ks	3-h quasi-logarithmic (mondial, northern, southern) indices derived from *am, an, as* (5.2.3).
Kp, Ks	3-h quasi-logarithmic planetary index and the intermediate standardized indices from which *Kp* is derived (not to be confused with the *Ks* of the preceding item) (5.1.2).
Kw, Kr	3-h quasi-logarithmic worldwide index, and the intermediate reduced index from which *Kw* is derived (5.1.1).
Q	quarter hourly index (4.1).
R	1-h range index (4).
R_X, R_Y, R_Z	daily ranges in the field components (3.5).
σn, σs	3-h indices associated with *an* and *as* (5.2.3).
U, u	daily and monthly indices mainly related to the ring current (3.7).
W	monthly wave radiation index (3.8).

Thematic Index

In this thematic index, two items are dealt with in a special manner. For each geomagnetic index, one may find the equivalent of a detailed table of contents, where the main ideas or problems concerning the index are listed. Under certain listings, which are underlined, the pertinence to each geomagnetic index is summarized, affording an immediate comparison between indices.