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SOME COMMONLY USED MAGNETIC ACTIVITY INDICES: THEIR DERIVATION, MEANING AND USE

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ABSTRACT

Magnetic activity indices may be grouped into three categories according to the region from which the records come that are used in their derivation, namely:

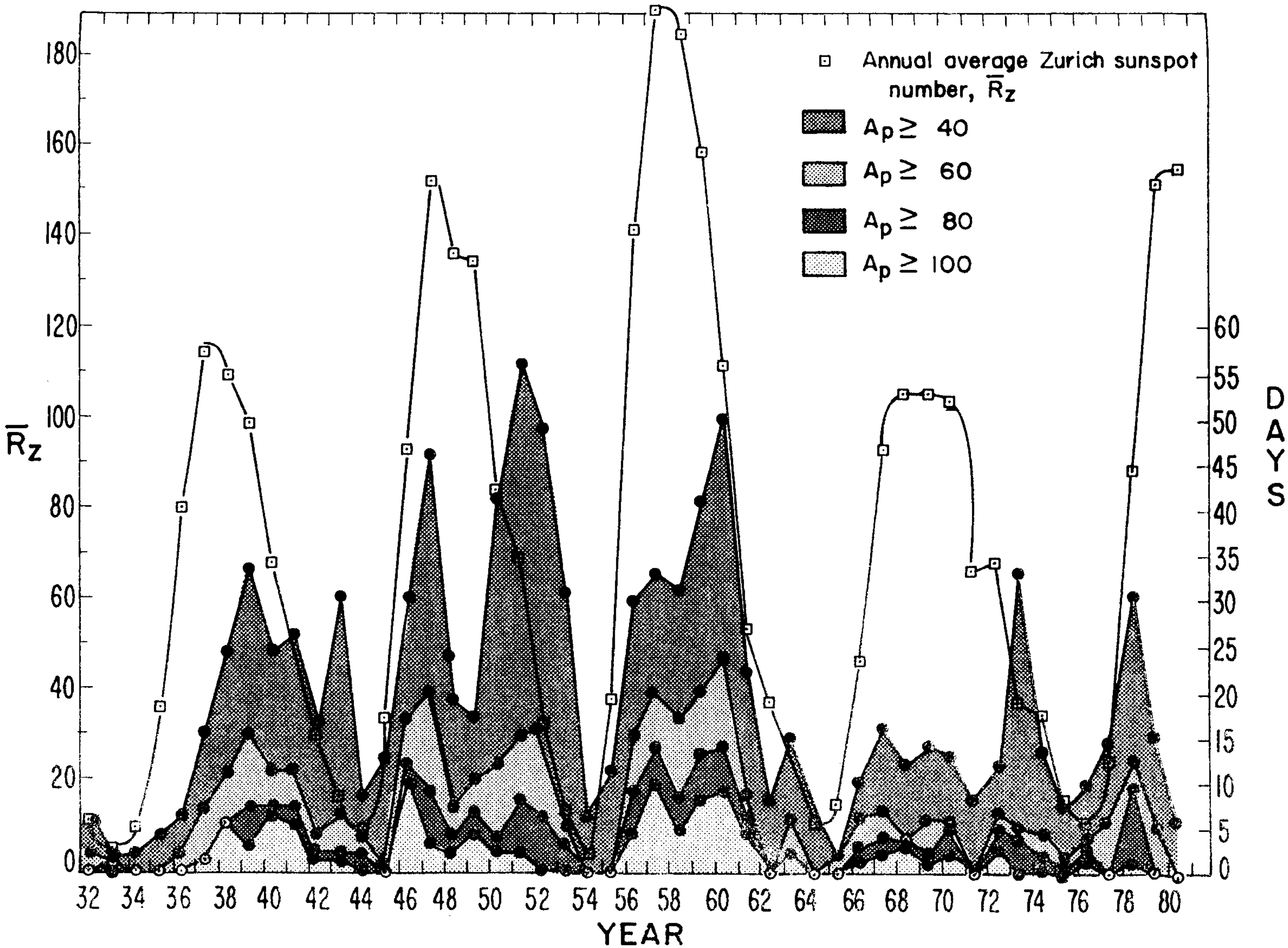
(1) Auroral zone; (2) Mid-latitude; and (3) Low-latitude.

In these categories, the indices most often used are: AE (incuding the related indices AU and AL); Kp (including Kn, Ks, Km and their corresponding a-type indices) and aa; and Equatorial Dst. Examples are given of indices in relation to solar cycle activity, of seasonal index variations, and of association with auroral substorms. Examples are shown of selected applications relating indices to interplanetary conditions. Station networks for each are shown and the index derivations discussed. Results of index comparisons are shown with the conclusions that all K-type indices are highly positively correlated and that AE and Dst indices have unique information about magnetic variations in their regions.

Magnetic activity indices are used and often misused by many persons who wish to characterize the state of local, regional or global magnetic conditions at a particular moment or during some interval of time. The indices are usually much more accessible than the mass of data processed in their derivation; some are available quickly at relatively low cost; some exist for hundred-year or greater spans of time; and the most useful have often been found to have applications beyond those envisaged by their creators. However, as Fr. Mayaud cautioned, "<u>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</u>" (Mayaud, 1980). The objective of this presentation is to enhance this desirable understanding by drawing on materials prepared for the International Solar-Terrestrial Predictions Workshop Proceedings (Allen & Feynman, Vol. 2, 1979) and used in papers presented at the 23rd IUGG's "Mayaud Symposium" (Allen & Kroehl and Allen & Kamei, Dec. 1979).

The most commonly used "global" magnetic activity indices, distinguished by different latitude zones of origin, are: <u>AE</u> (Auroral Electrojet) and its components <u>AU</u> and <u>AL</u> (auroral zone); <u>Kp</u> or <u>Km</u>, related K-type indices or the a-type "equivalent amplitude" counterparts and the antipodal <u>aa</u> indices (mid-latitude); and <u>Dst</u> (equatorial). Each is described in Mayaud's monograph "Derivation, Meaning, and Use of Geomagnetic Indices" (Mayaud, 1980) and the many references listed there.

<u>Figure 1</u> shows the smoothed annual Zurich sunspot numbers Rz for solar cycles from 1932 (the beginning date for Kp indices) through 1980, about 4½ - cycles. Plotted beneath the Rz curve are envelopes showing the number of days each year for which the Ap daily index of magnetic activity exceeded various threshhold values. A day for which Ap≥40 is at least moderately disturbed. Ap values between 40 and 60 often persist for three- or four-day intervals. These extended disturbed intervals are usually associated with the 27-day recurrent passage of



1. Smoothed Sunspot Numbers vs. Time - compared with number of days per year having different levels of Ap. Shows general relation between level of solar activity and magnetic disturbances as characterized by the Ap index. Also, shows different patterns of magnetic activity for each solar cycle.

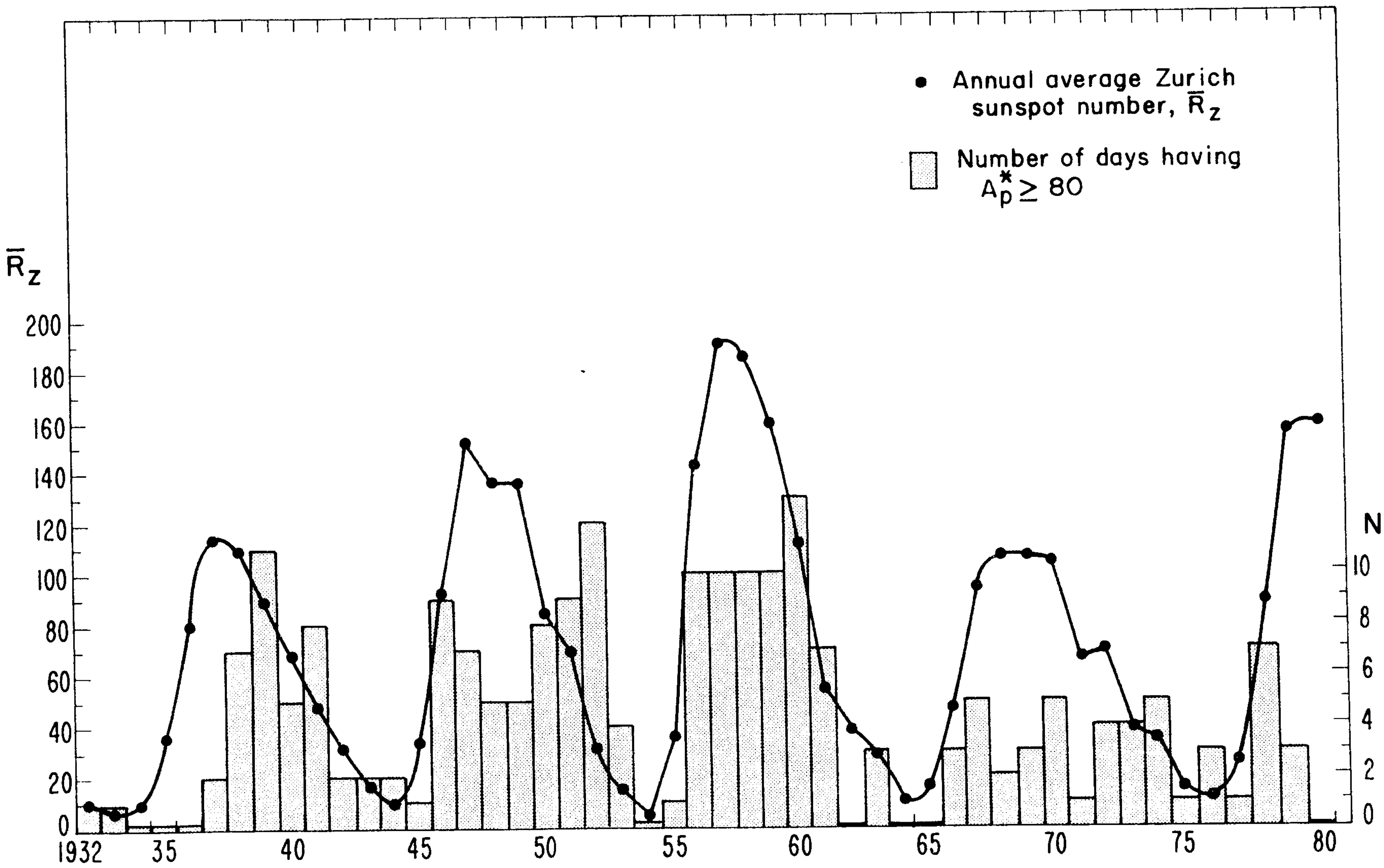
coronal holes transiting the solar disk. This is the recurrent type of magnetic disturbance that is so successfully predicted during the years of the declining phase of the sunspot cycle.

As the amplitudes of daily Ap rise above 60, the probability increases that they are associated with flare events (sometimes superposed on recurrent disturbances). Perhaps the most interesting features evident in this figure are that the pattern of disturbance distribution stays much the same for both recurrent and flare related events and that each of the last four completed solar cycles had significantly different patterns of disturbances: the bimodal distribution of storms during the first cycle has both peaks on the descending phase; the next cycle also has a bimodal storm distribution but the first peak is on the ascending phase; the third cycle has essentially a unimodal distribution with no significant decrease in activity during any part of the solar cycle; and the last cycle shown had relatively little activity during the entire cycle until the closing upsurge in recurrent disturbances. The current cycle is similar during its first half to that beginning in 1944 with a peak in magnetic activity during the rising half of the sunspot cycle and an even deeper decline in disturbances around the time of maximum.

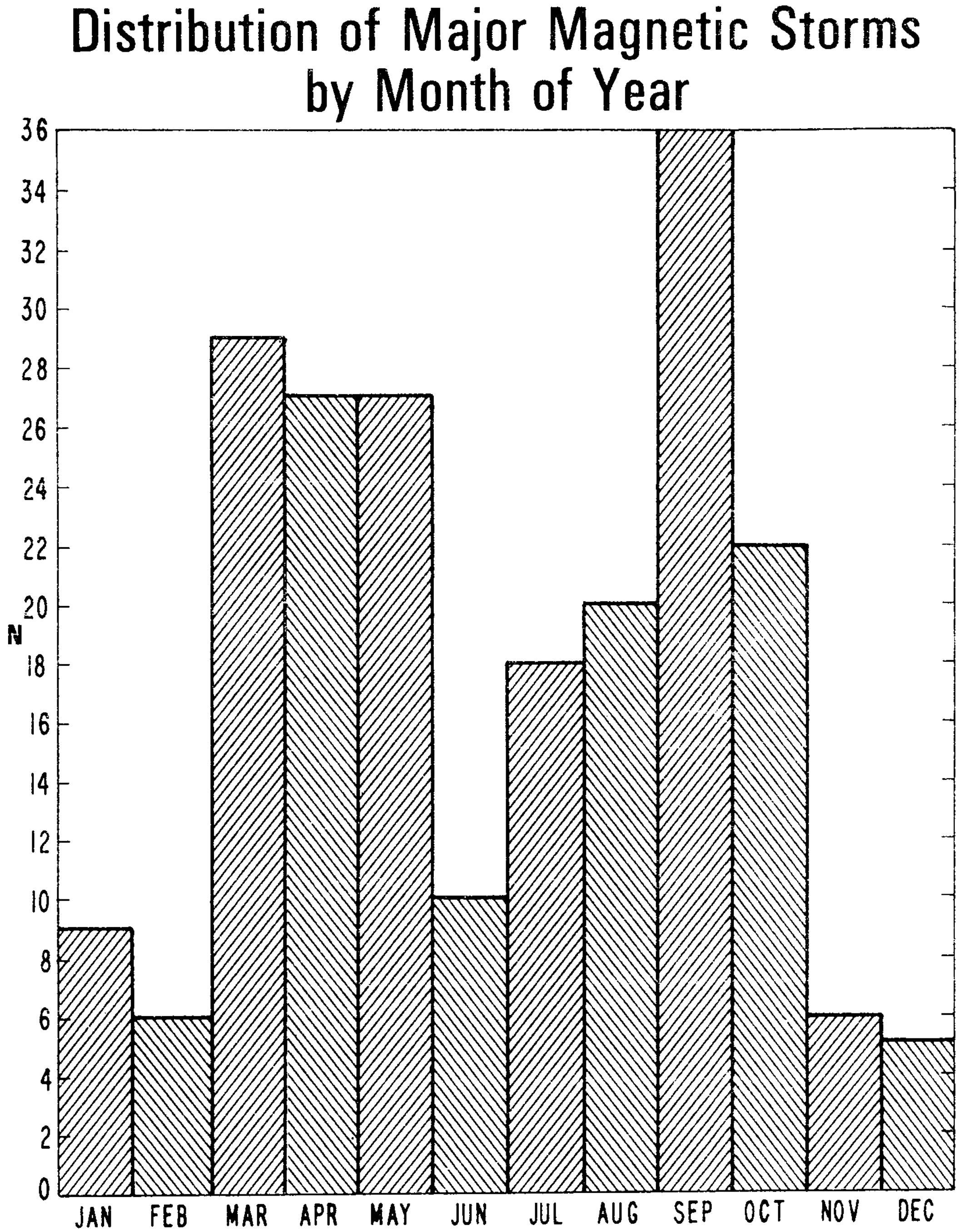
The Ap index is the UT-day average of the eight 3-hourly a_p indices. In an effort to develop a simple storm maximum-intensity index to allow for relative classification of event amplitudes, a running 8-point mean of 3-hourly a_p values was computed from 1932 through the present. Beginning and ending times of each event were identified as the 3-hour intervals when values of the mean first exceeded and declined below a threshhold value. For each distinct event, the largest mean value was designated Ap^*. When this most-disturbed 24-hour period coincided with a UT day, $Ap^* = Ap$ (about 1/8th of the time). The distribution of truly large storms ($Ap^* \geq 80$) was similar to that for the smaller recurrent storms of each solar cycle as shown in Figure 2(A). These large storms also occur with a seasonal pattern which peaks during the equinoctial months when the magnetospheric cross-section presented to the solar wind is oriented for most efficient coupling with the interplanetary magnetic field, Figure 2(B). These figures illustrate the complex linkage between magnetic activity, as characterized by an index, and solar activity affecting the earth over times ranging from years to months.

Figure 3 shows an auroral substorm as recorded by a DMSP satellite in dawn-dusk orbit on 26 January 1973. The dots mark locations of northern hemisphere magnetic observatories in position to record variations arising from currents that caused this event. A coordinate grid and boundaries of the Feldstein oval for Q = 5 (an IGY quarter-hourly range index of magnetic activity) are superposed on the aurora. The widest extent of the aurora is located over Siberia and the lights of Moscow may be seen at the lower left of the image.

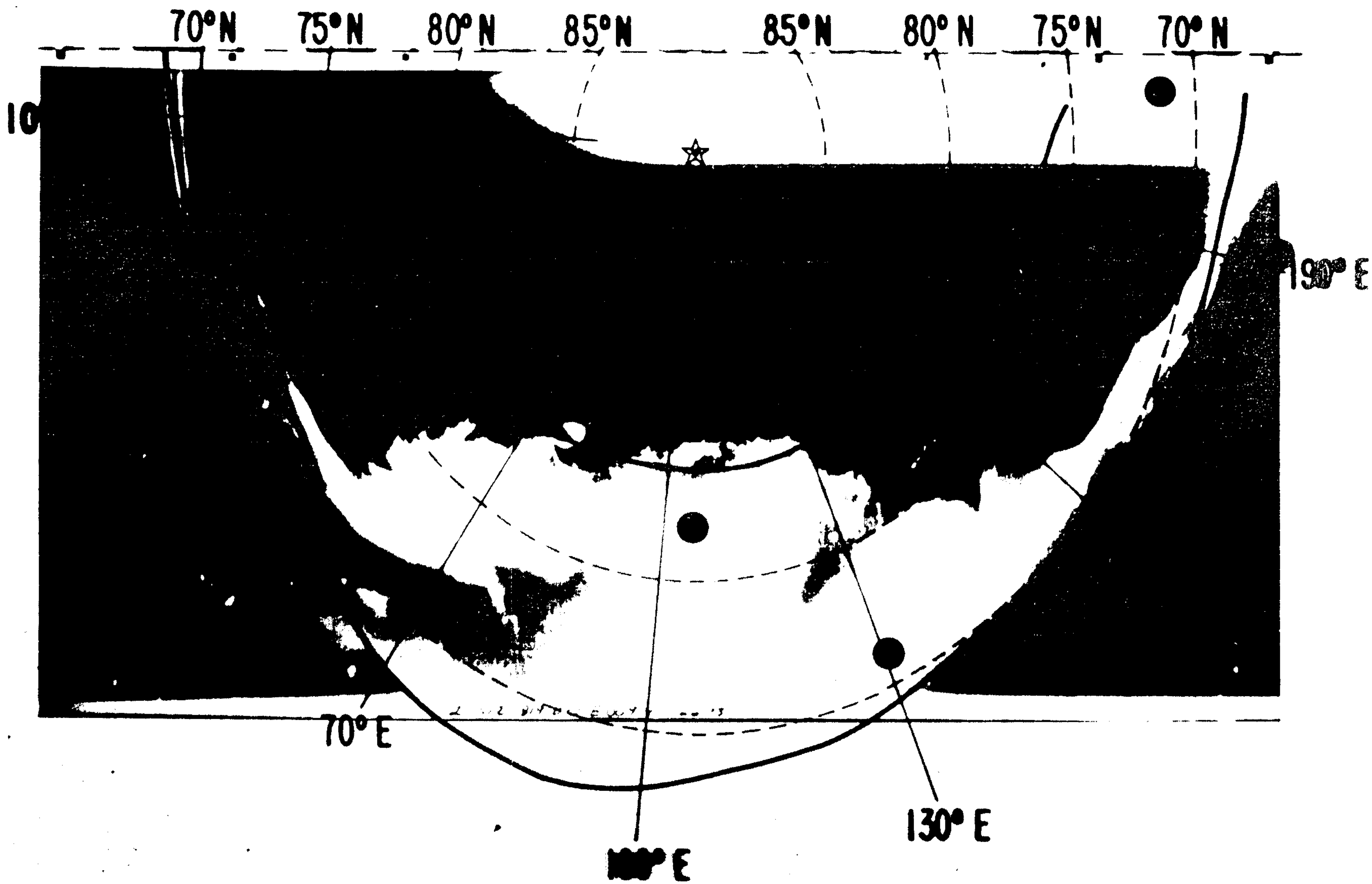
Common-scale H-component magnetograms are shown in Figure 4 for the eight observatories that best recorded variations during this event. A vertical bar marks the time of satellite passage over the auroral display. If the variations traces were superposed to a common zero-level, their upper and lower envelopes of extreme values would define the AU and AL indices, respectively. The range between AU and AL is, by definition, the AE index. These indices may be scaled instantaneously from the deviation at that moment of the two most disturbed (+ and -) auroral zone stations or averages may be calculated for any interval.



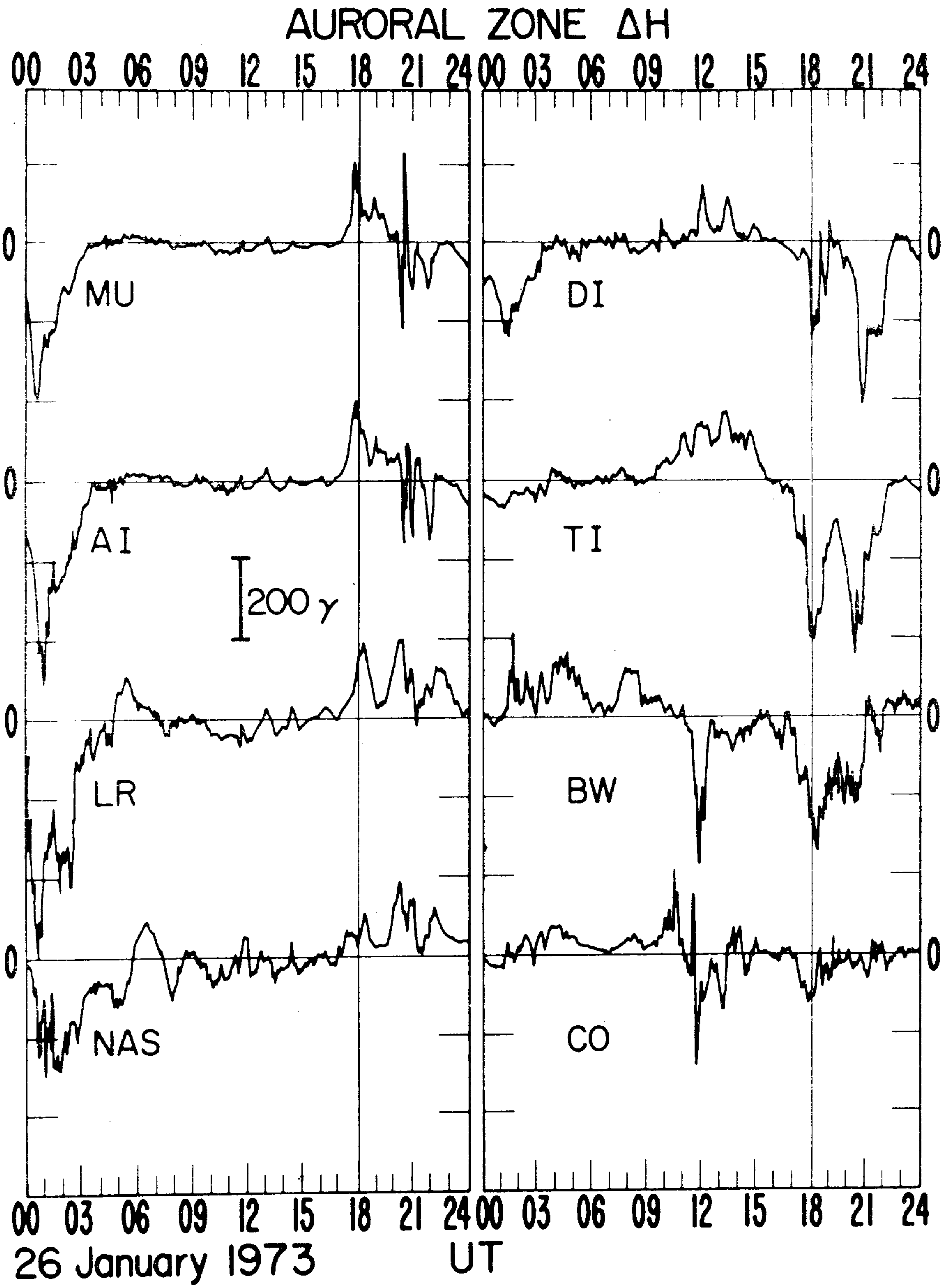
2A. Annual Number of Large Magnetic Storms - count of truly large magnetic storms in each year compared with smoothed annual sunspot number from 1932-1980. Classification by modified Ap index, $Ap^* \geq 80$.



2B. Seasonal variation in cumulative number of truly large storms, 1932-1980.



3. DMSP auroral imagery for substorm interval - shows locations of critically placed magnetic observatories with superposed Feldstein auroral oval (Q=5) for January 26, 1973, auroral event over Siberia.



4. Magnetograms from auroral zone observatories recording effects of electrojets during January 26 substorm and showing time of DMSP passage relative to the disturbed H-traces. These station records would be used in deriving AE and related indices by superposition of common-scale H-traces to their common zero level giving AU as the amplitude of the upper envelope and AL as amplitude of the lower envelope of the disturbances. AE = AU - AL.

While AE was defined primarily as a simple quantitative measure of substorm intensity and for timing use, it has been related successfully to a variety of parameters. For example, Figure 5, Holzer & Slavin have correlated the AL index with the transfer of magnetic flux into the magnetotail due to enhanced solar wind and southward IMF. Hernandez, Roble, and Allen have shown a function of AE to be highly correlated with thermospheric temperatures measured at Fritz Peak (near Boulder, Colorado), a site some 25° equatorward from the region where the auroral electrojet effects were measured, Figure 6. Murayama and Maezawa have shown AL indices to be highly correlated with the solar wind and IMF ($B*V^2$) and Perrault and Akasofu have used AE to approximate the energy coupled into the magnetosphere from the solar wind. Figure 7 is the "Kitchen Sink" correlation result of Smart, Garrett, and Shea in which they compared many combinations of interplanetary parameters with selected magnetic activity indices.

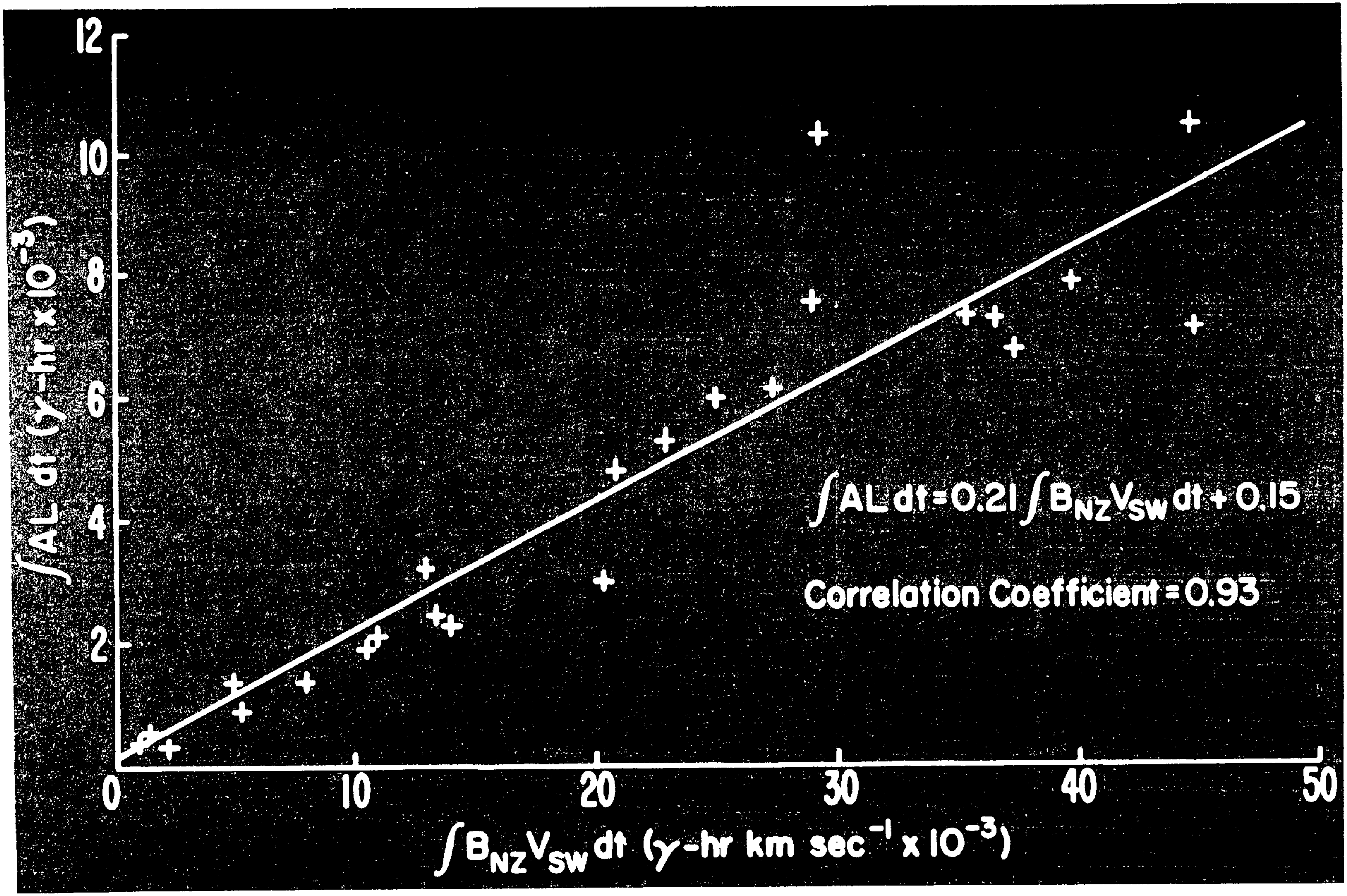
Figure 8 shows a comparison of a year of daily Ap values with daily average AE. Obviously, the two indices both reliably detect the major magnetic disturbance events; however, many relatively large events are recorded at other times in the auroral zone index but missed by the lower-latitude index. This raises the points: (1) What regional effects may be embodied in the different indices? and (2) How are different indices alike or different? Answers may be sought in an examination of the station networks for different indices, their method of derivation, and through statistical correlations.

The map of Figure 9 shows the regional distribution of observatories whose records are used for derivation of the major global magnetic activity indices. Circles show the 12 northern hemisphere standard auroral zone observatories used for AE. Triangles mark the northern and southern hemisphere sites from which Kn and Ks, respectively, are derived. The global index Km is obtained by averaging Kn and Ks. Squares mark the mostly northern hemisphere sites used for Kp. Stars show the stations used for equatorial Dst. Two of the Kp stations, Hartland and Toolangi, are also used for derivation of antipodal a-indices, aa.

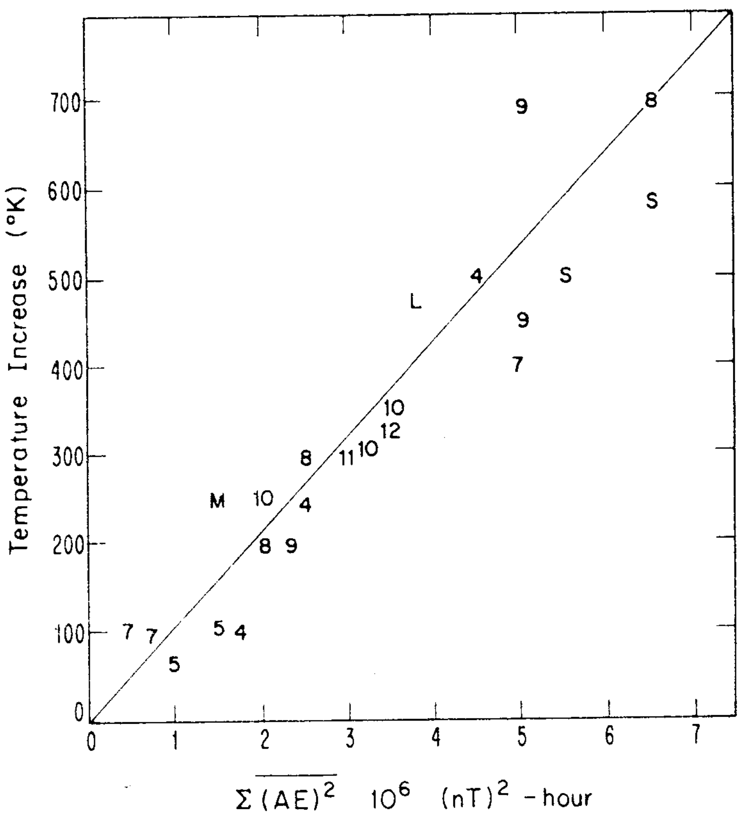
Irregularities in station distribution for a given index may introduce a local time dependency and mixing records from stations in northern and southern hemispheres can add a seasonal component. Gaps in the longitude distribution of AE stations are evident and differences in station geomagnetic latitudes within different longitude sectors may cause interesting variations in the indices; however, a recent study by Akasofu compared AE(55) with AE(12) and showed that the indices derived from the much smaller network were almost identical with those from the extensive network (personal communication).

The geographical distribution of stations used for derivation of Km indices is obviously more even than that used for Kp. However, evaluation of the desirability of using hemispheric indices (Kn or Ks) or the global index Km in place of the better-known and widely used Kp index is continuing among those most concerned. Until a definitive result is obtained and publicized, most users of indices probably will continue present practice and request Kp.

At most mid-latitude observatories, 3-hourly ranges of variation from the estimated quiet-day curve are scaled for the H and D-traces. The most disturbed element gives the K value for that interval. Based on a standard scale adjusted for the observatory latitude (to normalize the frequency of occurrence of different amplitudes of disturbances) a local K value is assigned from the range 0 (quietest) to 9 (most disturbed). After further standardization, the Kp index



5. Correlation between integrated AL index and energy coupled into the magnetosphere via the magnetotail - Holzer & Slavin.



6. Correlation between thermospheric temperatures and integrated function of AE index - magnetic variations from auroral zones and temperatures from the Boulder area (Fritz Peak) about 40 degrees north - Hernandez, Roble & Allen.

CROSS CORRELATIONS BETWEEN VARIOUS SOLAR WIND PARAMETERS AND BETWEEN THE SOLAR WIND PARAMETERS AND MAGNETIC ACTIVITY INDICES AE, a_p, and Dst

	$B_z(SM)$	$B_z(SE)$	$\langle B_z(SM)\rangle$	$\langle B_z(SE)\rangle$	v	$v\langle B_z(SM)\rangle$	σ_B	$v\sigma_B$	T	ρ	ρv^2	$v^2\langle B_z(SM)\rangle$	B^2	$vB^2\sin^4\frac{\theta}{2}$	B	AE_1	a_{p1}	Dst_2
1. $B_z(SM)$	1.0																	
2. $B_z(SE)$	.90	1.0																
3. $\langle B_z(SM)\rangle$	.82	.74	1.0															
4. $\langle B_z(SE)\rangle$	.73	.82	.88	1.0														
5. v	.01	.00	.04	.04	1.0													
6. $v\langle B_z(SM)\rangle$	.80	.72	.97	.85	-.09	1.0												
7. σ_B	.00	.01	-.12	-.11	.29	-.17	1.0											
8. $v\sigma_B$	.00	.01	-.09	-.08	.57	-.18	.93	1.0										
9. T	.00	.01	-.02	-.01	.71	-.12	.45	.65	1.0									
10. ρ	-.01	.00	-.14	-.14	-.34	-.10	.26	.10	-.14	1.0								
11. ρv^2	-.01	.00	-.15	-.14	.25	-.20	.52	.54	.35	.75	1.0							
12. $v^2\langle B_z(SM)\rangle$	.73	.65	.88	.77	-.21	.97	-.20	-.25	-.22	-.05	-.23	1.0						
13. B^2	.01	.01	-.33	-.32	.06	-.34	.51	.46	.25	.30	.46	-.33	1.0					
14. $vB^2\sin^4\frac{\theta}{2}$	-.55	-.43	-.65	-.52	.14	-.70	.38	.39	.27	.16	.35	-.71	.62	1.0				
15. B	.00	.01	-.34	-.33	.09	-.35	.56	.50	.29	.31	.47	-.33	.93	.57	1.0			
16. AE_1	-.57	-.51	-.62	-.55	.42	-.67	.33	.42	.38	.04	.33	-.68	.28	.52	.34	1.0		
17. a_{p1}	-.37	-.32	-.51	-.45	.43	-.59	.47	.57	.44	.14	.49	-.64	.49	.62	.49	.68	1.0	
18. Dst_2	.38	.30	.46	.39	-.39	.51	-.24	-.34	-.32	.17	-.13	.53	-.32	-.47	.34	-.50	-.60	1.0

$B_z(SM)$: Z-component of Interplanetary Magnetic Field in Solar Magnetospheric coordinate system.

$B_z(SE)$: Z-component of Interplanetary Magnetic Field in Solar Ecliptic coordinate system.

$\langle B_z(SM)\rangle$: Only southward Z-component in SM.

$\langle B_z(SE)\rangle$: Only southward Z-component in SE.

v: Solar Wind velocity.

σ_B: rms standard deviation of interplanetary magnetic field.

T: Solar Wind temperature.

ρ: Solar Wind density.

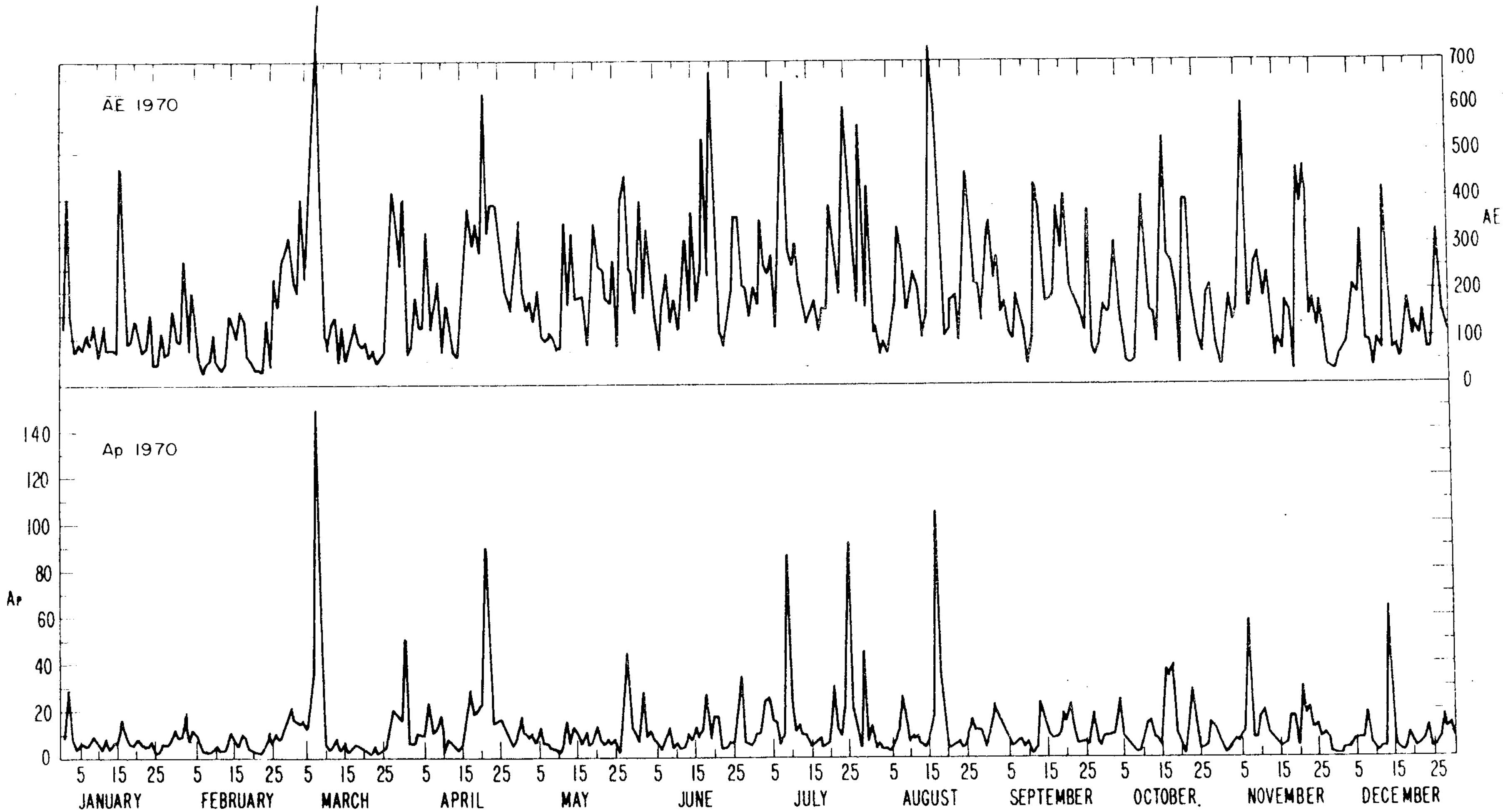
ρv^2: Proportional to Solar Wind kinetic pressure.

AE_1: Auroral Electrojet hourly average index with 1-hour time lag behind solar wind parameters.

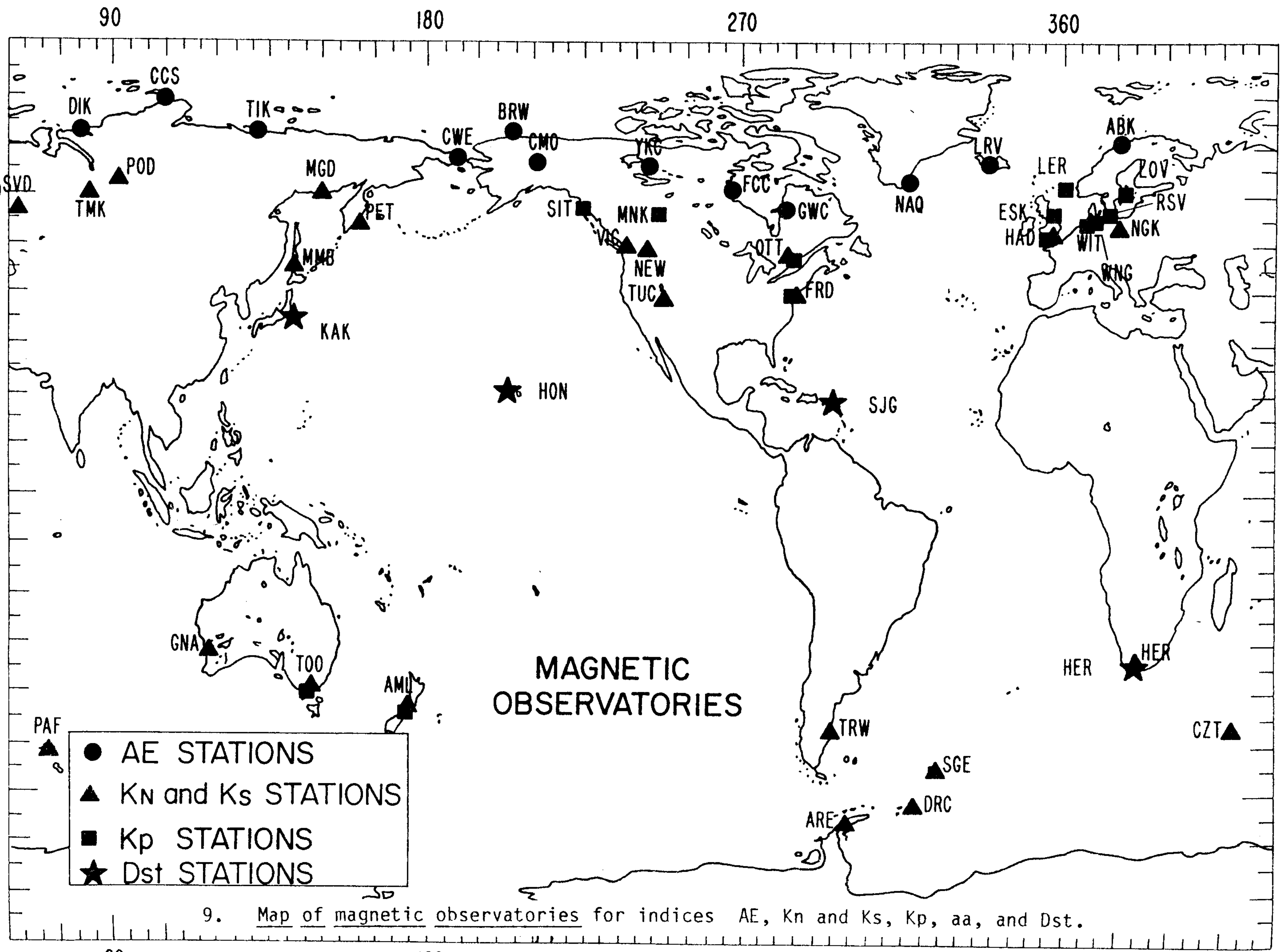
a_{p1}: Hourly a_p interpolated from 3-hourly indices and used with 1-hour time lag.

Dst_2: Hourly Dst used with 2-hour time lag behind solar wind.

7. "Kitchen Sink" correlation between different interplanetary parameters and indices - Smart, Garrett, and Shea.



8. Comparison between Ap and daily average AE for a year - raises question as to the extent that different indices show the same or different information. Major events seen in both indices but AE showing relatively more disturbed days.



9. Map of magnetic observatories for indices AE, Kn and Ks, Kp, aa, and Dst.

is obtained as the mean of the local K indices. It is expressed in 1/3-units, i.e. Kp = 0o, 0+, 1-, 1o, 1+, 2-, ..., 9-, 9o. One of the most familiar diagrams of magnetic activity over 27-day and yearly periods is the "musical note" diagram depicting the 28 levels of Kp for each 3-hours of the UT day with varying density of shading on a line pattern similar to a musical staff.

Corresponding to each K or Kp 3-hourly index there is an "equivalent amplitude" index, a or ap. These are linearizations of the psuedo-logarithmic K indices and are more suitable for averaging (e.g., to obtain the daily index Ap) and for correlation with other parameters. The a-type indices are in magnetic field units (2 gamma units for a standard station) and can be thought of as the mid-range or average amplitude variation corresponding to a given level of K or Kp. To convert between ap and Kp, the following table may be used:

Kp =	0o	0+	1-	1o	1+	2-	2o	2+	3-	3o	3+	4-	4o	4+	5-
ap =	0	2	3	4	5	6	7	9	12	15	18	22	27	32	39

Kp =	5o	5+	6-	6o	6+	7-	7o	7+	8-	8o	8+	9-	9o
ap =	48	56	67	80	94	111	132	154	179	207	236	300	400.

These tables are from the IAGA Bulletin 32 series which contains additional details in each annual publication for: indices, rapid variations, and special interval data and explanations.

The antipodal a-indices, aa, are obtained by averaging the local a-indices from Hartland (UK) and Toolangi (Australia), roughly antipodal observatories. This simple index can be derived quickly and made available to meet nearly real time needs for a global mid-latitude magnetic activity index.

Equatorial Dst indices are derived from low-latitude (but not equatorial) observatory records. After removal of secular variations from station records, the H-values are translated to equatorial values, averaged and harmonically analyzed to give the first harmonic which is Dst. These indices measure the globally symmetrical contribution of the ring-current as it produces the large main-phase depression associated with major magnetic storms. Because Dst is derived from stations not actually near the equator, the problem of large variations due to the equatorial electrojet is avoided.

At WDC-A for STP an effort was made to compare many of the magnetic activity indices with Kp for those years when all existed (1966-1974). The nine sets of indices used and their counterparts derived for each 3-hours are shown in Figure 10. The original K-type indices (Kp, Km, Kn, and Ks) were used as received from the institutions that derive them. The a-type indices (aa and the components a-Hartland and a-Toolongi) were converted to K values using the table relating Kp and a_p. For AE and Dst, average functions were derived which would give the best possible correlation with 3-hourly Kp. In computing the several correlations, each index was shifted by lead and lag hours to examine whether this would improve the level of correlation. It did not and the values shown here are from the same 3-hour intervals of the UT day. Results from this study were presented (Allen & Kamei) in the Mayaud Symposium of the 23rd IUGG and have not appeared in a published paper although they are available in draft.

GEOMAGNETIC INDICES COMPARED (1966-1974)

Kp	→	KP
Km	→	KM
Kn	→	KN
Ks	→	KS
aa	→	KAA
a (Hartland)	→	KAN
a (Toolangi)	→	KAS
AE	→	KAE
Dst	→	KD1

10. Converted indices: original K-type indices used unchanged; aa, a_H, and a_T changed to corresponding K indices; AE and Dst converted to 3-hour functions to correlate with Kp.

All the converted indices did the job of indicating when magnetic activity was in progress. This is seen in Figure 11 which shows the similar musical note diagrams produced for the same 27-day interval as computed from each of the converted indices. However, there are differences which become apparent when the indices are correlated for each 3-hour interval of the nine years.

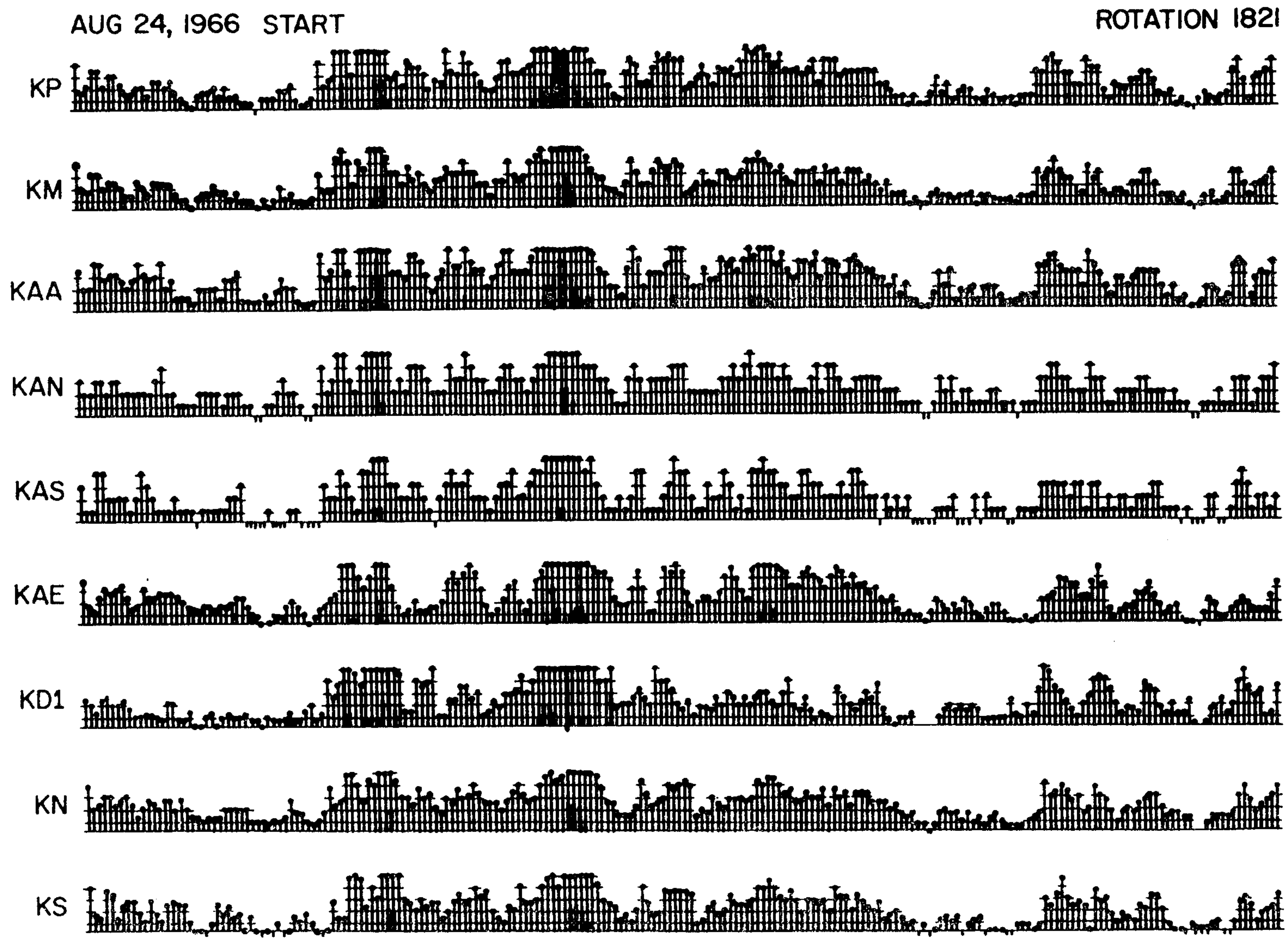
Figure 12 shows the result of correlating KAA (the converted aa index) with each of the other indices for each 3-hour interval of the UT day. Three points are especially evident: (1) All original K-type indices have high correlation coefficients (for most $r \geq 0.90$); (2) There appears to be a significant, but lower, correlation between the sub-auroral zone KAA and auroral zone KAE; and (3) There is much less correlation with the converted Dst function (3-hourly average differential Dst).

The striking clustering about high correlation values, whether for a global K-type index or the K indices from a single station (KAN and KAS), suggests that user needs often may be met by substituting one for another. In particular, either Kp or Km could often be estimated using an index from two well- placed observatories (e.g., by using aa). Perhaps Toolangi and Hartland or another two antipodal sites could provide near-real-time KAA indices by relaying variations from one via geostationary satellite to a collection and processing site at or connected to the other observatory.

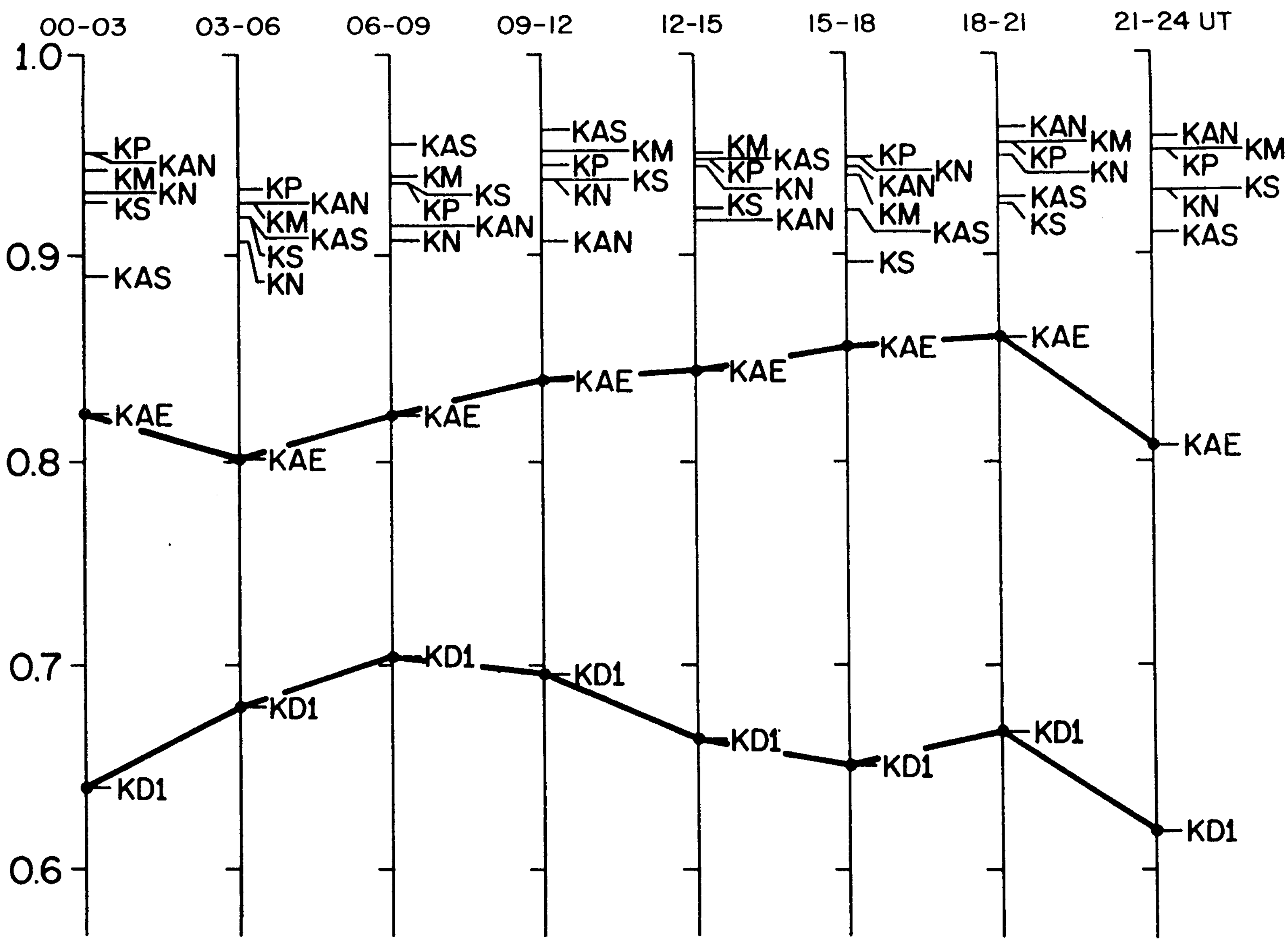
Figure 13 shows the correlation between the converted auroral zone index KAE and each of the K-type or converted indices for each 3-hour interval during the years when they coexist. The largest contributor to AE is the negative-H bay (substorm), associated with westward auroral electrojet, that gives the AL component. These AL indices arise most often from the observatory critically located in the auroral zone at the longitude near 0330 Local Geomagnetic Time. However, for any individual substorm, the station supplying AL may be located anywhere within a wide range of longitudes spanning times from 2200 to 0600 LGT, on the dark hemisphere. Thus, it is reasonable to refer to AE as essentially a "nighttime" index and it is derived exclusively from northern hemisphere sites.

It is especially interesting to note the change in quality of correlation between KAE and the local K indices from Hartland (KAN) and Toolangi (KAS), the two observatories used in deriving the aa-index. KAN correlates best with KAE during the hours 1800-0900 UT, i.e. during the northern hemisphere nighttime hours for a station near the Greenwich meridian. Likewise, KAS correlates best with KAE during 0900-1800 UT when it is nighttime in the southern hemisphere for an observatory in eastern Australia. This regular pattern of higher correlation between KAE and the single station K indices is interpreted as arising from substorm effects seen extending down to latitudes of the stations used for deriving aa (also used in Kp and Km). Apparently, the process for scaling local K indices retains substorm effects. If these locally seen substorm effects are not removed by the standardization and averaging in the derivation of Kp and Km, then this would account for the correlation between those indices and KAE.

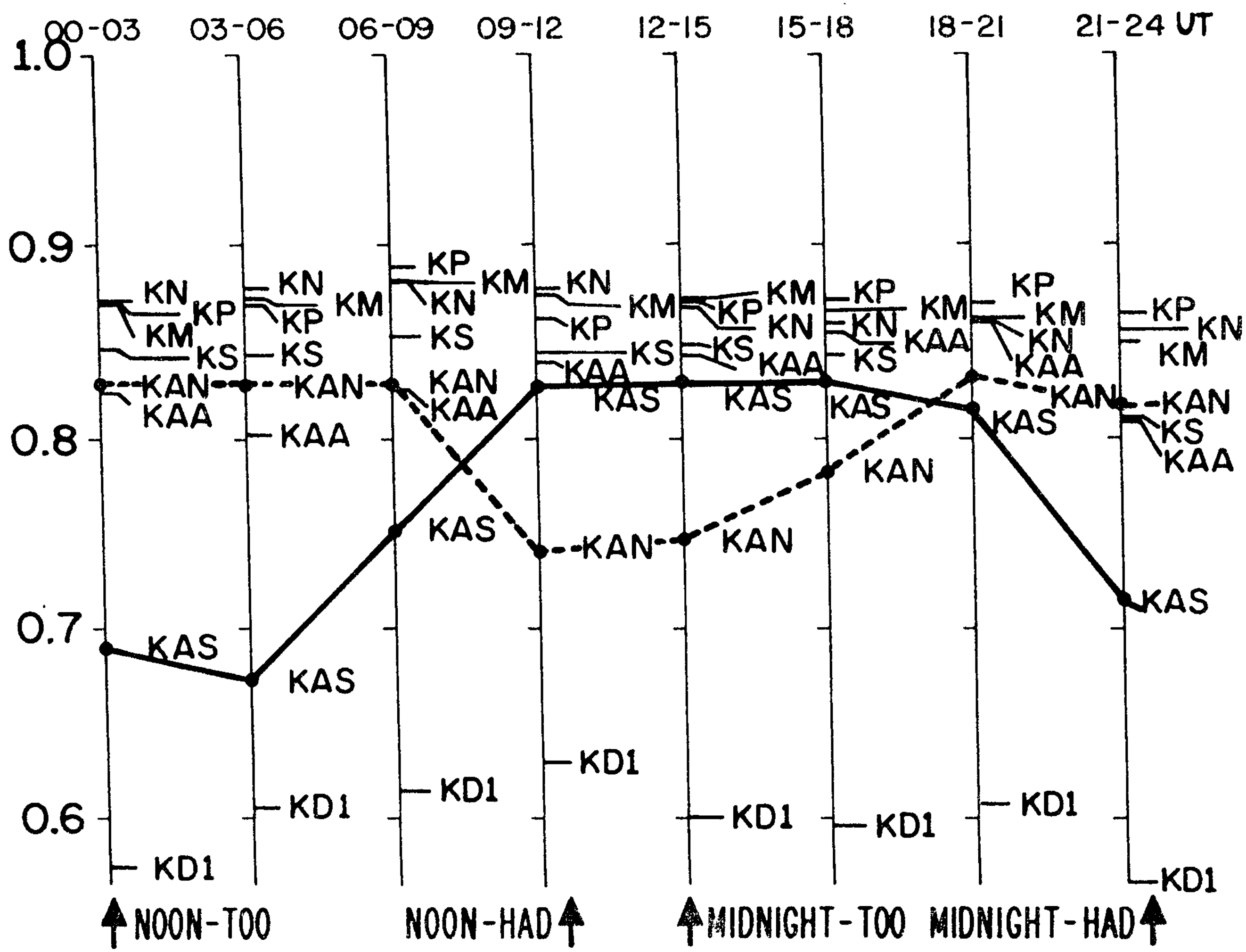
In conclusion I reemphasize that even the global magnetic activity indices most used today have strong regional features based upon the latitude range of stations whose records are used in their derivation. All the K-type indices are highly positively correlated and the aa-index may be a useful, quickly available substitute for Kp (a_p) or Km (a_m). The AE index and its components AU and AL contain unique auroral zone information which may be of particular utility for



11. 27-Day "musical note" display from Kp and converted indices.



12. Correlations for 1966-1974 between KAA and other converted indices - Shows:
(1) All K-type sub-auroral zone indices are highly positively correlated;
(2) Correlation with KAE of some significance, substorm effects on mid-latitude station records are not removed by derivation process for local K indices; and
(3) Correlation with KD1 not significant.



13. Correlations for 1966-1974 between KAE and other converted indices - Shows: Change in quality of positive correlation between KAE and KAS (Toolangi) and KAN (Hartland) such that the best correlations with the northern hemisphere station (1800-0900 UT) and with the southern hemisphere station (0900-1800 UT) are during their respective nighttime hours.

giving a ground-based estimate of interplanetary and magnetospheric conditions to which satellites are subjected. The Dst index is perhaps unique in that it measures relatively cleanly a more simple and globally symmetrical phenomena, the ring current, than any other magnetic activity index. Certainly, it has some features in common with other indices but our best efforts at extracting a converted index to match the others were not successful.

The AE index of magnetic activity offers considerable promise for use in estimating conditions in space. However, the delay in its derivation and its high cost combine to eliminate AE from consideration for either predictive or rapid application in problems related to satellite drag. It will remain perhaps the best of the global indices for historic or statistical studies of the relationship between interplanetary and magnetospheric space disturbances and their consequent effects on the earth. It now appears that efforts to predict the AE index must focus on monitoring solar wind and interplanetary magnetic field parameters combined into an appropriate function monitoring the energy transferred from the interplanetary medium into the magnetosphere. This function could then be used to forecast satellite drag effects.

Of the extensive literature dealing with magnetic activity indices, Mayaud's monograph should certainly be a starting point for anyone interested in further information. Earlier works by Matsushita and Campbell and by Chapman and Bartels contain further information. The annual IAGA Bulletin 32 and its predecessor Bulletin 12 series contain many useful details and index tables. Articles in the Annals of the IGY and Handbuch der Physik are basic and new papers are being published in journals such as JGR which reveal uses of indices incidental to the main purpose of the described research. Unfortunately, many potentially useful articles are buried in workshop proceedings or in abstracts of papers which were presented but never written for publication. Finally, IAGA Working Group V-6, Geophysical Indices, continually monitors the status of those indices now in use and tries to anticipate future needs for new indices. We welcome any contribution from persons interested in satellite drag and related phenomena toward defining needs which might be met by a new index.

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