A Critical Evaluation of the *AE* Indices

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The computation of the total eastward and westward auroral electrojets from numerical modeling techniques for three different intervals during disturbed conditions provides a unique opportunity to evaluate the accuracy of the standard Auroral Electrojet indices *AU*(12) and *AL*(12). The effect on the indices of replacing the local magnetic coordinate system with a global system, of increasing the latitudinal coverage by increasing the number of stations from 12 to 57, and of integrating the current density to obtain the total current is considered as new indices are correlated with the standard ones. We conclude that *AL*(12) is a reasonable measure of the westward electrojet current in a statistical sense, that *AU*(12) is not as good a measure of the eastward current, and that values of *AU*(12) and *AL*(12) during quiet conditions, i.e., less than 50 nT, must be treated separately from disturbed conditions. It should also be noted that a rotation of the perturbation vectors into a global coordinate system improves the indices more than an increase in the number of stations.

1. Introduction

The Auroral Electrojet indices, *AL*, *AU* and *AE*, have become important indirect measures of ionospheric electrodynamic variability, of the state of the magnetosphere, and of the degree of ionosphere-magnetosphere-solar wind coupling. Although the indices only attempt to describe the maximum current density of the eastward and westward auroral electrojets, their variability is considered by many to be the ionospheric manifestation of many magnetospheric energy processes, e.g., magnetospheric convection and magnetospheric substorms, and have become important to the inference of magnetosphere-ionosphere coupling with field-aligned currents.

These indices, as defined in DAVIS and SUGIURA (1966), measure the maximum current density of the westward auroral electrojet (*AL*) and eastward auroral electrojet (*AU*). For the standard *AE*(12) indices, the *H*-component variations from 12 standard magnetic observatories are placed on top of each other. The indices are then defined from the envelope of these traces, with *AU* being the maximum positive (or least negative) value for a given time resulting from an eastward equivalent current, and *AL* the minimum value (or least positive value) for that time resulting from a westward equivalent current. *AE* is the difference between the two, i.e., *AU*–*AL*, and is unaffected by zonal equivalent currents in the ionosphere or

magnetosphere. As such, AE is designed to be a measure of total auroral currents.

Results from several statistical analyses of the interindex, the seasonal, the Universal Time and the local time variability of the AE , AU and AL indices have been reported. KAMIDE and FUKUSHIMA (1972) reported that AU is approximately $1/3$ of AL . ALLEN and KROEHL (1975) reported that the AU index is dominated by an annual variation due to enhanced conductivities in the local summer ionosphere. On the diurnal variation of the indices, three papers reported different results. AFONINA and FELDSTEIN (1971) found a maximum at 2100 UT, but this was probably due to the use of South Pole data. ALLEN and KROEHL (1975) reported no significant diurnal variation for the 1970 indices. However, when the data are organized by the interplanetary magnetic field (IMF), BERTHELIER *et al.* (1974) reported a preference for magnetic noon during local winter and midnight during local summer. This variation was associated with the perpendicularity of the Earth's magnetic axis with the solar ecliptic plane. ALLEN and KROEHL (1975) found that the station nearest to 0300 magnetic local time (MLT) most often contributed the AL index and that the station nearest to 18 MLT most often gave the AU value.

Numerous statistical analyses related variations in the solar wind to the intensity of the auroral electrojets, although different authors reported different results; e.g., ARNOLDY (1971), AKASOFU *et al.* (1973), CLAUSER *et al.* (1981), HOLZER and SLAVIN (1982), to name a few. Sometimes these differences are dismissed as resulting from inherent inaccuracies in the derivation of the indices used in the correlation studies (ROSTOKER, 1972; KAMIDE and AKASOFU, 1983). Most common among the concerns are: (1) a current enhancement at latitudes higher than that of the AE station would not be observed, i.e., the standard network should be augmented with stations at higher latitudes, (2) the indices may saturate as the maximum current densities move equatorward of the network, (3) the total current, i.e., the latitudinal integral of the current density, may have different spatial and temporal characteristics than the indices have, and (4) local magnetic north at some stations may be significantly different from geomagnetic north at that location from a magnetic field model, so that the component does not accurately describe the ionospheric effects of a true east-west equivalent current. The purpose of this note is to use the results of a recent magnetogram-inversion technique to compute the total eastward and westward electrojet currents and to compare those parameters with the present AE indices; in other words, to conduct one of the critical tests of the accuracy of the standard AE indices and to address the above comments.

2. Index Definitions and Intervals

In this paper we use five-minute values of eight different indices of magnetic activity at auroral latitudes. The five-minute values were computed from a mixture of single point measurements and one-minute averages recorded near the beginning of the five-minute interval. $AU(12)$ and $AL(12)$ are the standard AE indices generated by T. Kamei and T. Araki of WDC-C2 for Geomagnetism, Kyoto University, Kyoto, Japan. $AU^*(12)$ and $AL^*(12)$ were computed from the north-

ward variations in the global, corrected geomagnetic (cg), coordinate system of GUSTAFSSON (1984) from the same stations. For $AU^*(57)$ and $AL^*(57)$, we increased the number of stations from 12 to 57 and the latitude range to include all data between 55° and 75° cg latitude. The total eastward and westward current indices, I_e and I_w , were computed by integrating the horizontal, ionospheric current density between 55° and 75° which were determined from the KRM method (KAMIDE *et al.*, 1981).

$AU(12)$ is the maximum variation at a given time recorded at twelve auroral zone observatories in the local magnetic northward component (H) from a mean quiet time value defined as the mean of the five international quiet days for each month. $AL(12)$ is the minimum variation in the local magnetic northward component. The temporal resolution is one minute.

$AU^*(12)$ is the maximum variation in the cg northward component (X_m) from the daily mean value of the nearest quiet day for that time. $AL^*(12)$ is the minimum value of such variations. The observatories used are the same as above, although we needed both the H and D (or X and Y) component data to compute the variations in the X_m and Y_m components which are in a global coordinate system. The largest rotation occurred at Tixie Bay, where local north is nearly 45° from corrected geomagnetic north; see KAMIDE and AKASOFU (1983) for the rotation angles at other observatories.

Figure 1 shows the cg coordinates of the 57 stations from which data were used to compute $AU^*(57)$ and $AL^*(57)$. The figure is an orthogonic polar projection. The 12 stations used in the $AE(12)$ and $AE^*(12)$ indices are noted as heavy solid circles. $AU^*(57)$ and $AL^*(57)$ were then computed from the same procedure as $AU^*(12)$ and $AL^*(12)$ indices.

The latitudinal integral between 55° and 75° of the eastward and westward current densities was calculated for each hour of MLT from the KRM scheme (KAMIDE *et al.*, 1983). The I_e index was the maximum integral value for all MLTs. I_w resulted from the same procedure for the maximum westward current density. These indices represent the first direct measure of total current and, as such, provide us with the first opportunity to objectively evaluate the previously stated concerns about the standard *AE* indices. To do this, we used a simple regression analysis technique.

Because this analysis required execution of the extensive KRM program, we were limited to three special intervals shown in Fig. 2: (1) March 17–19, 1978, a special International Magnetospheric Study, meridian magnetometer interval, which was selected for an international data modeling workshop and was highlighted by an extensive paper (KAMIDE *et al.*, 1982a); (2) 0600–1800 March 22, 1979, as a Coordinated Data Analysis Workshop-6 (CDAW-6) interval; and (3) 1200 March 31–0600 April 1, the other CDAW-6 interval. An updated version of the Rice Conductance Model of SPIRO *et al.* (1982) was used for all three interval computations, although the conductance does not drastically affect the ionospheric current computation according to KAMIDE and RICHMOND (1982).

The first interval is characterized by approximately ten electrojet current

Fig. 1. Location of ground magnetometer stations in corrected geomagnetic coordinates. Geomagnetic variations data were used from 57 stations between 55° and 75° in latitudes to compute the $AU^*(57)$ and $AL^*(57)$ indices. The standard *AE* stations are noted with an additional $\bullet$.

enhancements, some of which were dominated by the convection-type current system and others by the substorm expansion current system (CLAUER and KAMIDE, 1985). The second interval contained two large, isolated substorms preceded by four hours of relatively quiet magnetic conditions. The third interval consisted of almost continuous activity. (See MCPHERRON and MANKA (1985), KAMIDE and BAUMJOHANN (1985), and KROEHL and KAMIDE (1985) for a complete discussion of the CDAW-6 intervals.) We would like to emphasize that these conditions limit this paper to discussing magnetically active times only.

Fig. 2. The standard $AU(12)$ and $AL(12)$ indices are plotted to show the character of the three intervals examined in this paper.

3. Results

We conducted a number of numerical tests in the evaluation of the standard $AE(12)$ indices. The most pertinent results are shown in Figs. 3–5 and Table 1. Other relevant conclusions are stated but the data are not plotted. The solid line in Figs. 3 and 4 denote equal values of AU and AU^* and AL and AL^* . The dashed lines are the linear regression lines noted on each plot. The linear correlation coefficients are also noted. (The scatter plots were generated on a line printer and suffer from a lack of spatial resolution.) We also correlated the data sets using polynomial regression techniques and found the change in the correlation coefficient to be quite small; thus the remainder of the paper reports only the linear regression results.

Figure 3 shows two scatter diagrams, one for $AU(12)$ vs $AU^*(12)$ and the other for $AL(12)$ vs $AL^*(12)$. The AU plot shows that $AU^*(12)$ is larger than $AU(12)$ until they reach 302 nT, then $AU^*(12)$ is less than $AU(12)$. Thus the rotation of the ΔH and ΔD vectors into ΔX_m variations generally increases the value of the eastward, maximum current density, especially for the values less than 300 nT. The AL plot shows that the regression line intercepts the vertical axes at $AL^*(12) = -45$ nT and $-1,389$ nT (compared with $-1,400$ nT) and that $AL = AL^* = 1,125$ nT. Thus, the rotation of the ΔH and ΔD vectors into ΔX_m vectors causes an increase in $|AL|$, noting that an 11 nT change in $|AL|$ at $-1,400$ nT is insignificant. The correlation coefficient increases to 0.94 for $AL(12)$ vs $AL^*(12)$.

In Fig. 4, we test the value of increasing the number of stations from 12 to ~ 57 , depending upon the interval selected. We note that the slope of the regression line is now greater than one, indicating that $AU^*(57)$ increases with an increase in the standard index, that $AL = AU = 0$ intercepts are roughly the same in Figs. 3 and 4, and that the correlation coefficients are essentially unchanged. These imply that the higher latitude stations contributed little new information, that the standard indices tend to saturate at the higher values and that there is no obvious need to increase the number of stations for correlation studies.

In Fig. 5, we show the effect of intergrating the computed current density for the eastward and westward electrojets between 55° and 75° for each hour of MLT and compare the maximum value so obtained with the corresponding indices of current density. I_w is the total current of the westward electrojet and I_e is the total current of the eastward electrojet. In general, we note that the data points show more scatter about the regression line, that the correlation coefficients are smaller, and that $AL(12)$ is a better measure of the westward total current than $AU(12)$ is of the eastward current. Specifically, we note that $AU(12)$ describes about 56% of the variance in I_e while $AL(12)$ describes about 78% of the variance in I_w .

4. Discussion

We have presented the results of a statistical analysis to compare the standard $AU(12)$ and $AL(12)$ indices of auroral electrojet current density with the $AU^*(12)$,

Fig. 3. A scatter diagram of the standard and rotated $AU(12)$ indices, (a), and the $AL(12)$ and $AL^*(12)$ indices, (b). The solid line and "α's" denote equal values of the two. The dashed line is a linear regression line fit to the data. (The data were plotted on a line printer with limited horizontal and vertical spatial resolution.)

Fig. 4. Same as Fig. 3 for AU(12) vs AU*(57), and AL(12) vs AL*(57).

Fig. 5. Same as Fig. 3 for $AU(12)$ vs I_e , and $AL(12)$ vs I_w . It should be noted that the AU and AL indices are a measure of current density, while I_e and I_w are modeled values of current in Amperes.

Table 1. An error analysis of $AU(12)$ and I_e .

$AU(12)$ (nT)	Number of samples	Mean I_e ($\times 10^5$ A)	Standard deviation	Standard error	Correlation coefficient
0–49	155	1.39	0.55	0.04	0.33
50–99	314	2.11	0.69	0.04	0.33
100–149	297	2.89	1.17	0.07	0.26
150–199	208	3.52	1.49	0.10	0.09
200–249	113	4.10	1.39	0.13	0.18
250–299	64	4.74	1.22	0.15	0.29
300–349	27	5.89	2.16	0.42	0.14
350–399	20	7.62	2.37	0.53	0.24
400–449	9	8.07	2.67	0.89	0.09
450–500	7	7.11	1.52	0.57	0.33

$AU^*(57)$, $AL^*(12)$ and $AL^*(57)$ indices of electrojet current density and the I_e and I_w indices of total electrojet current determined from the KRM magnetogram inversion program. The intervals were all relatively active, so that the conclusions apply primarily to magnetically disturbed conditions.

Considering the concern that the H component at some stations is not aligned along a global magnetic meridian (KAMIDE and AKASOFU, 1983), the perturbation vectors of the same stations were rotated into the corrected geomagnetic coordinate system. Then the new northward variation was used to define the new index. In general, this rotation yielded large values of the AU^* and $|AL^*|$ indices, although the larger index values were somewhat decreased. Because the auroral electrojets are large-scale systems, we would expect that a global magnetic field model would better organize the data than the local magnetic field would. However, this would not explain why the effect of the rotation on AU was much larger than the effect on AL , or why there exists a relatively large amount of scatter about the linear regression line even though the linear regression coefficients are fairly large. Because the ordinate intercept values are 46 nT for AU^* and -45 nT for AL^* , serious questions are raised about the accuracy of small values, i.e., less than 50 nT, of the indices. Thus, from Fig. 3 we recommend that the X_m component be computed and used in the computation of the AE indices.

To address the complaint that the AE indices only use data from 12 stations which may or may not be located directly under the major region of the eastward or westward electrojet for any given time, we increased the number of stations from 12 to 57 and found that the regression curves were now offset by a fixed value plus a very small percentage increase, i.e., 1% for AL and 4% for AU . Obviously, as we increase the number of stations used to determine a maximum deviation index, the value of that index will stay the same or increase. Since the linear correlation coefficients are high, as is evident in Figs. 3 and 4, we would conclude that for correlation studies and for descriptive studies of these intervals, very little would be

gained by increasing the number of stations during disturbed conditions. However, it may present a very real problem for statistical studies using event analyses techniques, e.g., one cannot say that event A is twice as large as event B based on the AU or AL index values being twice as large.

A computation of the latitudinal integral of ionospheric current density yields the total eastward and westward current, and provides an opportunity to evaluate the accuracy of the AU and AL indices or their accuracy in predicting the total current. Note that the Figure 5 correlation coefficients have decreased from the Figs. 3 and 4 values, which implies that the electrojets vary in latitude differently than they vary in intensity. We then ordered the I_e values by 50 nT intervals of $AU(12)$ and the I_w values by 50 nT intervals of $AL(12)$. Tables 1 and 2 list the number of sample pairs, the linear correlation coefficient between the two indices and three statistical measures of each interval, i.e. the mean, standard deviation and standard error of the mean. The small (and sometimes negative) correlation coefficients reflect either the large degree of scatter within each interval or the smaller sample size. As expected in this type of comparison, the statistical measures increase together. AKASOFU *et al.* (1983) state, "Although it is not possible to provide a single critical value below which inaccuracy becomes particularly serious, $AE(12) > 250$ nT may be tolerable for practical purposes." Since $AE = AU + |AL|$ and $AU = 1/3|AL|$ during disturbed conditions (KAMIDE and FUKUSHIMA, 1972), this could translate to values of $AU(12)$ below 83 nT and of $AL(12)$ greater than -167 nT. However, Tables 1 and 2 show no statistically significant change in the ratio of the mean to the standard error or the mean to the standard deviation at these points. We do,

Table 2. An error analysis of $AL(12)$ and I_w .

$AL(12)$ (nT)	Number of samples	Mean I_w ($\times 10^5$ A)	Standard deviation	Standard error	Correlation coefficient
0–49	236	–1.34	0.64	0.04	0.36
–50–99	135	–2.04	0.82	0.07	0.22
–100–149	96	–2.81	0.95	0.10	0.17
–150–199	95	–3.65	1.14	0.12	0.11
–200–249	71	–4.78	2.06	0.24	0.29
–250–299	91	–5.27	1.72	0.18	–0.05
–300–349	107	–6.23	2.18	0.21	–0.01
–350–399	88	–6.37	1.97	0.21	–0.02
–400–449	69	–7.61	2.54	0.31	0.12
–450–499	56	–8.46	2.87	0.38	0.17
–500–549	53	–9.40	2.57	0.35	0.12
–550–599	40	–9.95	2.08	0.33	0.26
–600–649	25	–12.5	4.33	0.87	–0.40
–650–699	9	–13.2	3.63	1.21	–0.08
–700–749	11	–13.9	2.34	0.71	–0.35
–750–799	5	–14.0	2.28	1.02	0.08

however, see a change in these ratios when $AL < -600$ nT and $AU > 300$ nT. This may be due to the smaller sample size in the present data set more than the effects of magnetic activity or magnetospheric substorms.

AKASOFU *et al.* (1983) also reported that $AL(12)$ has a tendency to saturate at higher values of I_w (KAMIDE *et al.*, 1982b). In Table 2, this would be shown by an increase in the difference between mean values at the higher intervals, which is certainly the case between the interval (-550 to -599 nT) and the next interval (-600 to -649 nT). However, the difference between the mean values of I_w for larger interval values of $AL(12)$ actually decrease. This may be due to the very small sample size, though it is larger than the data set reported in AKASOFU *et al.* (1983).

Finally, we note a significant difference between the AU and AL statistics, implying different sources of the eastward and westward electrojets, consistent with KROEHL and KAMIDE (1985). The correlation between $AU(12)$ and $AL(12)$ is only 0.63. Thus, users of the $AE(12)$ index must be aware that smaller values may be in error and that the index is summing two indices which vary in latitude and intensity independently. Therefore, the physical meaning of the $AE(12)$ index is not clear.

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