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A new verifiable measure of centennial geomagnetic activity: Modifying the K index method for hourly data

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[1] The K indices have long been a very important way to estimate geomagnetic activity. However, they have some basic and practical problems which restrict their reliability and applicability for long-term (centennial) studies. Here we discuss these problems, modify the K method and construct a new, straightforward, easily verifiable and homogeneous index, the so called A_h index, which is based on digital, hourly data and is dedicated for centennial studies. The local A_h indices correlate with the local K and ak indices very well and extend them typically by several decennia. A_h indices at all studied stations verify that geomagnetic activity has increased during the last century. However, the amount of centennial increase varies greatly with latitude, being largest at high latitudes, smaller at low latitudes and, unexpectedly, smallest at mid-latitudes. The centennial increase in the aa index is roughly twice larger than in the A_h index at similar mid-latitudes. This is due to the erroneous scaling of the aa index in the late 1950s, requiring aa to be revised. The global A_h index correlates uniquely well with the Ap index, better than aa or the not-K based IHV (Inter-Hourly Variability) index. Thus A_h yields the most accurate extension of the Ap index by roughly 30 years.

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1. Introduction

[2] Geomagnetic activity is a crucial parameter to study the long-term change in the Sun and near-Earth space. E.g., the aa index was used to suggest that the open solar magnetic field was more than doubled since 1900 [*Lockwood et al.*, 1999]. The increasing trend is supported by cosmogenic isotopes [*Usoskin et al.*, 2003] and solar activity [*Solanki et al.*, 2000]. However, despite this seeming consistency, serious concern has been raised on the centennial increase [*Svalgaard et al.*, 2003, 2004] and the consistency of the aa index [*Mursula et al.*, 2004; *Jarvis*, 2005; *Lockwood et al.*, 2007; *Mursula and Martini*, 2006].

[3] Geomagnetic indices aim to estimate irregular variations, excluding regular variations like the solar quiet (S_q) daily variation. K index method defines irregular variations as the range (difference) between the upper and lower fitting quiet daily curves during each three-hour interval, associating this with an integer (0 to 9) [*Bartels et al.*, 1939; *Mayaud*, 1980; *Menvielle and Berthelier*, 1991]. Since K scale is quasi-logarithmic, K indices are often linearized to equivalent amplitudes, the ak indices. Kp and Ap indices, based on 13 stations, are perhaps the most reliable long-term measure of global geomagnetic activity but only exist since 1932. The aa index runs since 1868 and was long the only centennial measure of geomagnetic activity.

[4] Despite their merit, K indices have some problems for long-term studies. K index is based on the observer's personal evaluation and, with changing observers, the long-term consistency is hard to guarantee. (Since 1990s K indices are mostly determined by computer methods; see *Menvielle et al.* [1995].) The K method to "digitize" ranges to 10 values is problematic, forcing the observer to select, often arbitrarily, between two K values. This is particularly difficult for low K levels where the exact form of the S_q curve is important. Because of the great number of low K values, the selection has a large effect. Different selection principles may cause, e.g., the different distributions of low K values at different stations. This problem can be avoided by using continuous range values ("amplitudes") instead of digitized K values. Also, the fixed K = 9 limit is problematic for long-term studies. During increasing activity such a limit may underweight the highest disturbance levels, leading to an erroneously small trend. (Changing the K = 9 limit would compromise homogeneity.) This problem can also be avoided using continuous range values with no artificial limits.

[5] A practical problem is that the early measurements are not in digital format at high sampling. Thus, examining the correctness and homogeneity of K and ak values is difficult. Recent analyses of aa suggest that the calibration was changed by roughly 2 nT in the 1950s [*Jarvis*, 2005; *Lockwood et al.*, 2007]. Accordingly, the long-term consistency of aa is questionable and the index must be revised. Clearly other, more straightforward and easily verifiable measures of geomagnetic activity are needed for centennial studies. Data availability problem is corrected in the IHV index [*Svalgaard et al.*, 2003, 2004], a recent alternative measure of geomagnetic activity. (IHV is calculated from absolute differences between successive hourly values of the H component during seven night hours in the aim to minimize the effect of the daily curve.) Using hourly digital values available at the World Data Centers (WDC), IHV can be examined in detail [*Mursula et al.*, 2004; *Mursula and Martini*, 2006]. However, IHV is a measure of hourly variability while the K index is a three-hourly range measure. IHV is a daily index including only night-time activity, while the eight three-hourly K indices cover both day and night, which matters since geomagnetic activity has a strong diurnal variation. Thus, IHV and K indices measure somewhat different processes of the near-Earth space.

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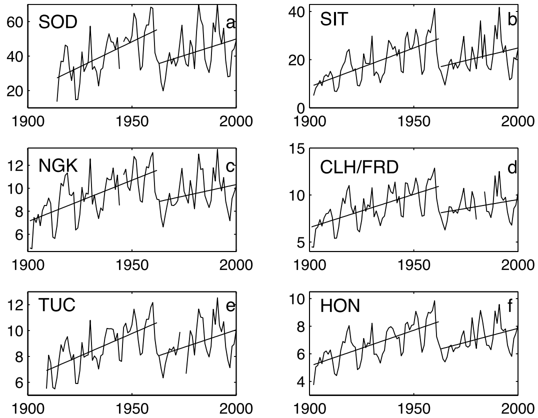

Figure 1. Yearly averages of the sampling corrected A_h index (in nT) for the six stations included in the study. For each station two best fitting lines are included, one for the early period from data start until 1962 and another for 1963–2000.

[6] Here we aim to combine the simplicity and easy verifiability of IHV with the basic principles of the K method by introducing a new index of geomagnetic activity, the A_h index (A for amplitude, analogue of the equivalent amplitude ak; h for hourly data), which is tailored for long-term studies.

2. Calculating the A_h Index

[7] We use six long-operating stations (Sodankylä SOD, Sitka SIT, Niemegk NGK, Cheltenham/Fredericksburg CLH/FRD, Honolulu HON, Tucson TUC) that have the longest and most uniform records of magnetic observations from early 1900s onwards (for more information, see *Mursula and Martini* [2006, Table 1]). They include two high-latitude (SOD, SIT), two mid-latitude (NGK, CLH/FRD) and two low-latitude (HON, TUC) observatories, allowing to study latitudinal differences in centennial evolution.

[8] We use hourly data available at WDC. Note that the very early hourly values (at most stations until 1915) were hourly spot values, not hourly means [*Mursula and Martini*, 2006]. Since spot values include more variability than means, the early A_h indices would, without due correction, remain too large and their centennial increases too small. We have corrected the A_h indices for this effect in a similar way as the IHV indices [*Mursula and Martini*, 2006] using high-sampling data for the more recent years. While the sampling correction of the A_h indices is presented in detail elsewhere (see D. Martini and K. Mursula, Centennial geomagnetic activity studied by a new, reliable long-term index, submitted to *Journal of Atmospheric and Solar-Terrestrial Physics*, 2007), note that the reduction needed for A_h, roughly 20%, is smaller than the 30% reduction typically required for IHV [*Mursula and Martini*, 2006].

[9] To derive the A_h index we first calculate the quiet daily variation. We use local IHV indices [*Mursula et al.*, 2004; *Mursula and Martini*, 2006] to find the five quietest days in each month at each observatory. Using local rather than global quiet days gives a better account of local conditions. Also, the official global quiet days exist only since 1932. The S_q curve is the average daily curve of the H component in the five quietest days of each month. This takes into account the seasonal variation of the quiet daily curve even more accurately than the seasonal model curves typically used by observers. Also, the quiet daily variation is no longer subjective and can be easily reproduced and examined.

[10] As for the K index, the quiet daily curve is fit to the data in each three-hour interval as an upper and lower limiting envelope curve. The difference (range) between the two envelope curves is the A_h index of the respective three-hourly interval. No digitization of the range value is made, contrary to the K method. Accordingly, the continuous range (or amplitude; analogue to ak) is the fundamental, linear parameter. Thus, the A_h index solves the above mentioned problems of the K method in long-term studies.

3. Centennial Increase and Its Latitudinal Variation

[11] We have depicted the yearly A_h indices for the six stations in Figure 1. Despite large differences in absolute level, all six A_h series depict the same qualitative long-term pattern [*Mursula et al.*, 2004; *Mursula and Martini*, 2006]: on top of solar cycle variation, there is an increase from the beginning of the century until about 1960, then a dramatic dropout in early 1960s, and a weaker increase thereafter. (A two-line fit emphasizes this behavior.) A qualitatively similar behavior is also found, e.g., for Ap, aa, and IHV indices [*Mursula et al.*, 2004; *Mursula and Martini*, 2006]. However, the various indices differ significantly in quantitative details, e.g., the centennial trend.

[12] We have quantified the centennial increase in A_h in two ways. First, we calculated the average values of A_h during the last (1979–2000) and first (1901–1922) 22 years of the last century. (Note that the stations cover slightly different fractions of the first 22 years.) Thereby one can quantify the centennial increase between the beginning and end of the last century, neglecting everything (e.g., the local peak around 1960) in between these time intervals. This method is independent of the normalization of indices. We have depicted the average levels and the percentage changes (relative centennial increases) in Table 1. All six A_h series

Table 1. Mean Values of A_h Indices for Six Stations at the Beginning and End of the Last Century, Their Relative Increase, and the Slope of the Best-Fit Line for the Mean Normalized Values in 1914–2000[a]

Station or Index	A_h Start	A_h End	Relative Increase	1000 * Slope
SOD	33.35	46.85	40.5%	3.87
SIT	13.46	23.14	71.9%	3.22
NGK	8.17	10.01	22.5%	0.65
CLH/FRD	7.61	9.13	20.0%	0.65
TUC	7.61	9.66	26.9%	1.89
HON	5.94	7.49	26.1%	1.58
A_{h6}	0.9186	1.0436	13.6%	1.64
aa-1914	17.90	24.63	37.6%	4.48
A_{h3}	0.8055	1.1023	36.8%	3.57
aa-1902	15.20	24.63	62.0%	5.88

[a]Beginning is until 1922 and end is 1979–2000. Similarly for the mean normalized 6-station (1914–2000) and 3-station (1902–2000) global A_h and for the mean normalized aa-1914 and aa-1902 indices.

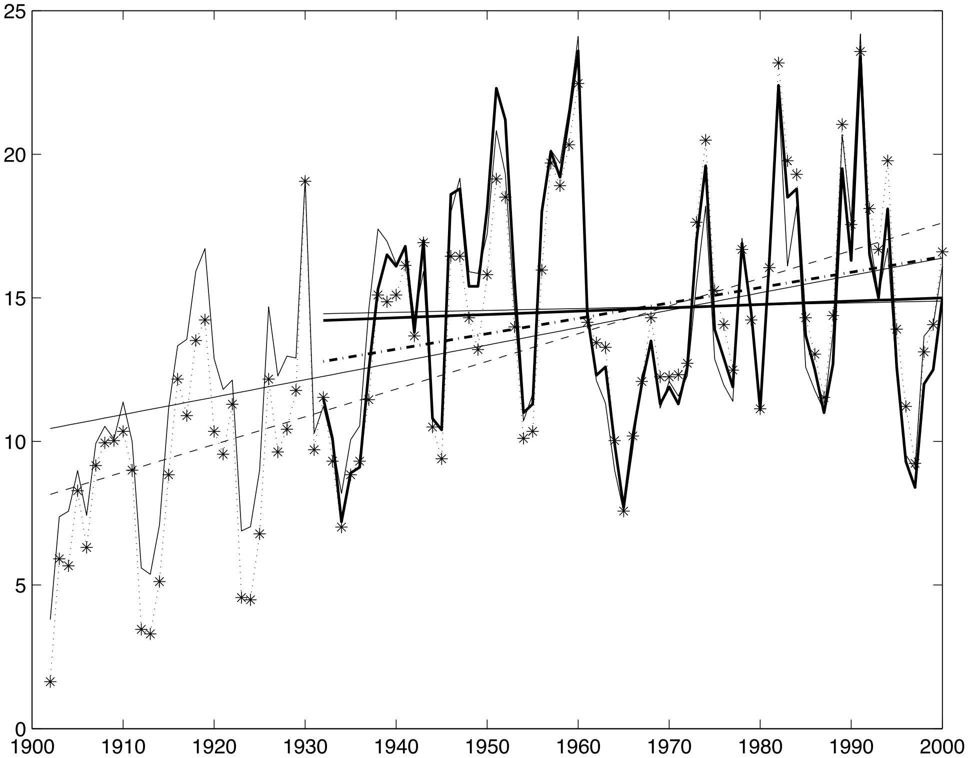

Figure 2. Yearly averages of the Ap index (thick line), the Ap correlated A_{h3} index (thin line) and the Ap correlated aa index (dotted line with stars), together with the respective best fitting lines in 1932–2000 (Ap, thick; A_{h3}, thin; aa, dash-dotted) and in 1902–2000 (A_{h3}, thin; aa, dashed). While the Ap and A_{h3} lines in 1932–2000 can hardly be distinguished from each other, the aa line depicts a clearly higher increase. The difference between A_{h3} and aa is even more dramatic in 1902–2000.

depict clearly larger values at the end of the century. The centennial increases at the six stations depict the same latitudinal ordering as the IHV indices [*Mursula and Martini*, 2006]. Although the increases can not be simply compared because of different start years, it is clear that the largest increases are found at high latitudes (SOD, SIT), smaller increases at low latitudes (TUC, HON) and, surprisingly, the smallest increases at mid-latitudes (NGK, CLH/FRD). This latitudinal ordering of the centennial increases is systematic and even more clear than in IHV.

[13] Second, we calculated the slopes of the best fit lines in 1914–2000 (see Table 1). For that, we normalized A_h indices by their means in 1914–2000. One can see that the latitudinal ordering is clearly valid also for slopes. Mid-latitude stations depict quite a small slope while slopes at low (resp., high) latitudes are more than twice (five times) larger.

4. Global A_h Indices

[14] We have taken the latitude variation of trends into account by including stations from different latitudes in our estimates of global Ah indices. We have constructed two versions of global A_h indices. First, each local A_h index was normalized by its mean in 1914–2000 and then averaged, yielding a six-station global index A_{h6}. In order to extend to earlier years, we constructed similarly the A_{h3} index for 1902–2000 using one station from high (SIT), mid (NGK) and low (HON) latitudes.

[15] Table 1 shows the relative increases and slopes for A_{h6} and A_{h3}. A_{h6} depicts an increase of 13.6% and a slope of $1.64 \cdot 10^{-3}$ in 1914–2000, to be compared with 37.6% increase and $4.48 \cdot 10^{-3}$ slope for aa (aa-1914 in Table 1). Similarly, A_{h3} shows a 36.8% increase and a slope of $3.57 \cdot 10^{-3}$ in 1902–2000 to be compared with 62.0% and $5.88 \cdot 10^{-3}$ for aa (aa-1902 in Table 1). Thus, the centennial increase in global A_h indices is clearly lower than in aa. Also, the centennial increase in A_h at mid-latitudes is about 21%, i.e., much smaller than the 62% increase in aa, also based on mid-latitude stations. Clearly, aa greatly exaggerates the centennial increase. However, because the qualitative similarity of centennial change, A_{h3} and aa are fairly well correlated (cc = 0.946).

5. Comparison With Ap

[16] Annual Ap correlates well with aa (cc = 0.95), but even better with A_{h3} (0.97) and A_{h6} (0.98). We have depicted in Figure 2 the yearly Ap and the (correlated) A_{h3} and aa together with the best fit lines in 1932–2000 and in 1902–2000. The lines for Ap and A_{h3} in 1932–2000 are so close that they can hardly be distinguished (slopes 0.0116 and 0.0065) but the aa line shows a larger increase (slope 0.0536). The difference between A_{h3} and aa becomes even more clear in the early years (A_{h3} slope is 0.0606, aa slope is 0.0965).

[17] We have depicted Ap-A_{h3} and Ap-aa differences in 1932–2000 in Figure 3. Despite fluctuations, Ap-aa is

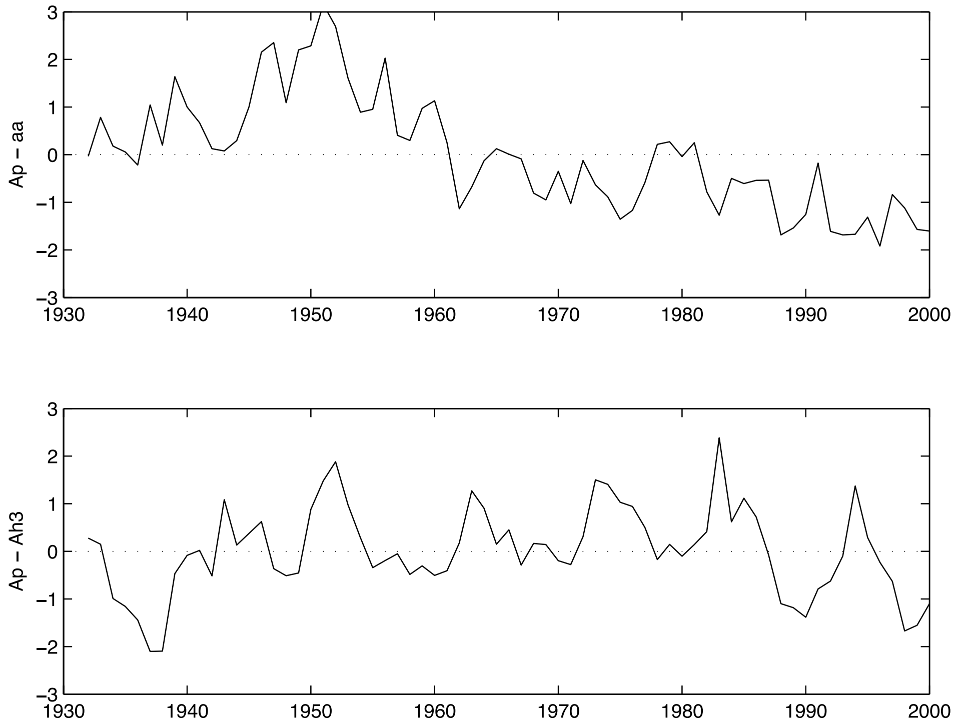

Figure 3. Differences of yearly averages of (top) Ap and the Ap normalized aa index and (bottom) Ap and the Ap normalized A_{h3} index in 1932–2000.

systematically above zero until about 1960 and below zero thereafter. This is in a good agreement with recent studies [*Lockwood et al.*, 2007; *Jarvis*, 2005; *Clilverd et al.*, 1998], concluding that the calibration of aa fails in late 1950s because of the change of the northern aa station from Abinger to Hartland. The average value of Ap-aa difference in 1932–1960 is 1.1 nT and −0.80 nT in 1965–2000, yielding a step of about 2 nT, in a good agreement with earlier estimates. On the other hand, Ap-A_{h3} shows no systematic trend off zero, in agreement with the result that Ap and A_h indices are more consistent and better correlated than Ap and aa.

[18] We have also calculated the correlation between Ap and local $A_h's$ (see Table 2). The highest correlations are found for the two mid-latitude stations. This is understandable since most Kp stations are at mid-latitudes. Note that most correlations between Ap and local A_h indices are better than between Ap and aa. (For low-latitude stations correlations are smallest: for HON it is slightly smaller and for TUC equal to that with aa.) The agreement between Ap and all A_h indices is due to the fairly similar basic definitions and the fact that both indices include geomagnetic activity from all local time sectors. Since Ap correlates with the mid-latitude A_h indices better than with aa, these similarities must be more important than the differences (e.g., different sampling frequency).

[19] We have included in Table 2 the correlation of Ap with local IHV indices. These correlations are also fair but remain clearly below those between Ap and local A_h. (For HON they are equal.) Contrary to correlations between Ap and local A_h, the correlations between Ap and local IHV are, in all cases, below the correlation between Ap and aa. This is because IHV differs from the main principles of the K method. Thus, A_h rather than IHV, should be used to extend the Kp and Ap to earlier times.

[20] We have calculated the average values of SOD ak indices in 1914–2000 in the eight three-hourly UT (or LT; SOD LT = UT + 2.5 h) sectors separately, depicting a strong diurnal variation with activity maximum in the night (Figure 4). The same three-hourly averages calculated for the SOD A_h index depict a very similar diurnal distribution as SOD ak (see Figure 4). The correlation coefficient between the curves is 0.981, implying a probability better than 99.992%. (Note the different absolute scales because of different normalization.) This extremely good correlation yields compelling evidence for the detailed success of the A_h index. Note also that the strong diurnal variation of activity denies a detailed comparison between the K based indices (which include local activity from all LT sectors) and IHV (which includes night sector only). This is a

Table 2. Correlation Coefficients Between Ap and the Local A_h Indices and Ap and the Local IHV Indices at Six Stations

Station Index	Correlation Coefficient
Ap-A_h(SOD)	0.97
Ap-A_h(SIT)	0.96
Ap-A_h(NGK)	0.98
Ap-A_h(CLH/FRD)	0.98
Ap-A_h(TUC)	0.95
Ap-A_h(HON)	0.94
Ap-IHV(SOD)	0.91
Ap-IHV(SIT)	0.92
Ap-IHV(NGK)	0.92
Ap-IHV(CLH/FRD)	0.93
Ap-IHV(TUC)	0.90
Ap-IHV(HON)	0.94

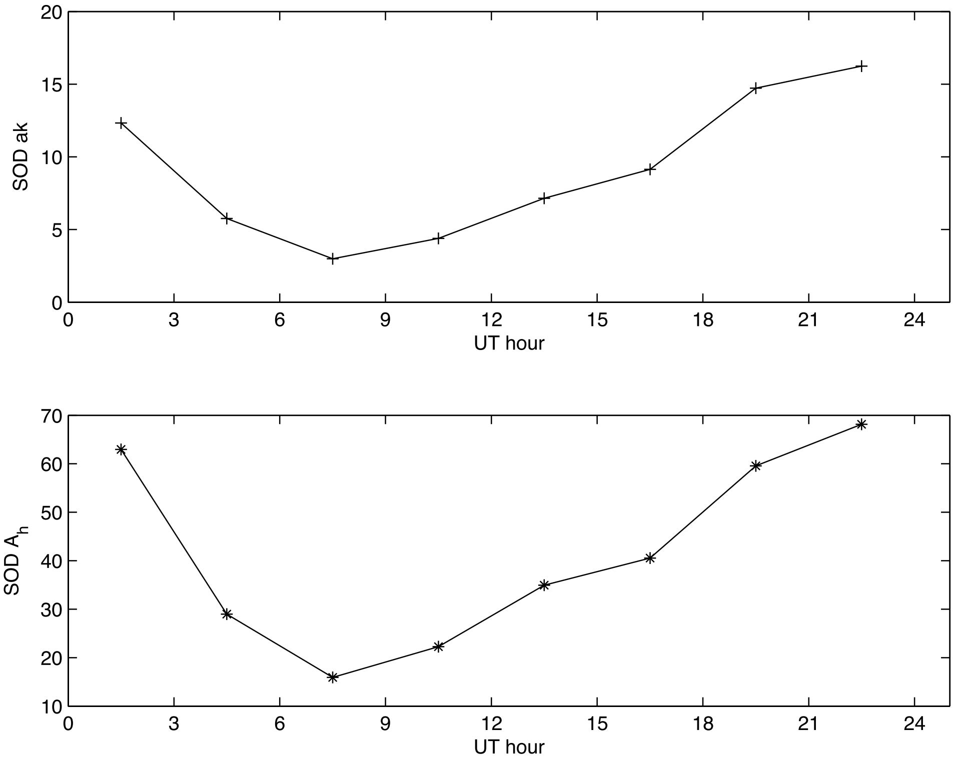

Figure 4. The average values in 1914–2000 of (top) SOD ak indices and (bottom) SOD A_h indices in the eight three-hourly UT sectors separately.

fundamental difference between the K (including A_h) indices, and the IHV index, and suggests A_h rather than IHV to be used as a long-term proxy or extension of local and global K indices.

6. Conclusions

[21] We have discussed here the K index method of geomagnetic activity and its problems for long-term studies. We have modified the K method so that these problems can be avoided and hourly magnetic data can be used to calculate a new, verifiable and homogeneous index, the A_h index, which is dedicated for centennial studies. The A_h indices at six stations studied verify that geomagnetic activity has increased during the last century. However, the amount of centennial increase varies greatly with latitude so that the increase is largest at high latitudes, smaller at low latitudes and, unexpectedly, smallest at mid-latitudes [*Mursula and Martini*, 2006].

[22] While the centennial increase in the aa index is roughly twice larger than in mid-latitude A_h index, comparison with the Ap index verifies that the scaling of the aa index was changed by a few nT in late 1950s, and that the index must be revised [*Lockwood et al.*, 2007; *Jarvis*, 2005]. Local and global A_h indices correlate extremely well with the Ap index, better than aa or the IHV index. A_h indices depict a closely similar trend with Ap since 1932, while aa shows a clearly larger trend. Local A_h indices depict a very similar diurnal variation as local K indices, yielding compelling evidence that the new method preserves the essential properties of the original K indices. Local A_h indices can be used to extend the local K and ak indices by several decennia, and the global A_h index gives the most reliable extension of the Ap index by roughly 30 years.

[23] **Acknowledgments.** We acknowledge the support from the Thule Institute of the University of Oulu and the Hungarian Scientific Research Fund (NI 61013).

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