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Key Points:
- We study geomagnetic indices at auroral latitudes
- We define a new hourly index, Delta H
- We find that no Sq subtraction is necessary

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Revisiting geomagnetic activity at auroral latitudes: No need for regular quiet curve removal for geomagnetic activity indices based on hourly data

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Abstract The main objective of our study is to determine if the regular quiet daily curve (QDC) subtraction is a necessary procedure in quantifying the irregular geomagnetic variations at auroral latitudes. We define the hourly ΔH index, the absolute hour-to-hour deviation in nanotesla of the hourly geomagnetic horizontal component, which assigns each sample to sample deviation as geomagnetic activity without separating the "regular" and "irregular" parts of the daily magnetic field evolution. We demonstrate that the hourly gradient of the regular *Sq* variation is very small with respect to the irregular part, and a bulk of the nominal daily variation is actually part of the variation driven by solar wind and interplanetary magnetic field and traditionally classified as irregular. Therefore, attempts to subtract QDC can lead to a larger error, often caused by residual deviations between the used different mathematical and methodological tools and corresponding presumptions themselves. We show that ΔH provides the best and most consistent results at most timescales with the highest effective resolution among the studied indices. We also demonstrate that the ΔH index may equally be useful as a quick-look near-real-time index of space weather and as a long-term index derived from hourly magnetometer data for space climate studies.

1. Introduction

An ever growing number of geomagnetic ground stations have been monitoring the Earth's magnetic field, with the first observations starting as early as the middle nineteenth century. From the point of view of space sciences, the deviations from the main field generated in the core are of interest. These deviations are often referred to as the external magnetic field, because they are generated by currents flowing in the coupled ionosphere-magnetosphere system due to solar wind forcing. A further classification may identify irregular changes of the field at various timescales that are superposed on ever present regular variations.

Regular geomagnetic variations are believed to be caused by thermospheric tidal winds in the dynamo layer of the ionosphere, dominantly driven by the solar EUV and soft X-ray radiation [*Mayaud*, 1980; *Xu*, 1989]. Since the position of the induced electric vortices is fixed relative to the Sun, one therefore detects the regular occurrence of their magnetic effect on the ground every day. Because these currents are also present during quiet ionospheric-magnetospheric and near-Earth space conditions, they are, together with their induced magnetic variations, often referred to as solar quiet (*Sq*) variations. In the present work, we refer to the smooth regular daily variation as the quiet daily curve (QDC) for reasons to be explained below.

Irregular variations are present when nominal conditions in the solar wind are disturbed, e.g., due to elevated solar wind speed, southward interplanetary magnetic field (IMF), resulting in an active ionosphere-magnetosphere system with enhanced energy inflow from the solar wind. Per definition, these variations are classified as geomagnetic activity.

While most information on the solar wind forcing may be deduced directly from the actual magnetograms, the correct interpretation of these data require certain expertise. Therefore, quasi-quantitative indices have been developed, which give summarized and simplified information of the time-varying complex phenomenon of geomagnetic activity [*Rostoker*, 1972]. If the index series is homogeneous in time and the index is significantly representative of the phenomenon, it also becomes a tool for long-term statistical studies [*Mayaud*, 1980].

The fundamental aim of geomagnetic activity indices is to quantify the irregular ground magnetic effects of the coupled ionospheric-magnetospheric currents driven by solar wind-magnetosphere energy transfer in a

Table 1. Information on Stations Used[a]

Station	IAGA Code	GG Lat	GG Long	GM Lat	MN
Tromsø	TRO	69.66	18.94	66.81	23
Sodankylä	SOD	67.47	26.60	63.96	22
Fredericksburg	FRD	38.20	282.63	48.59	05

[a]Geographic latitude (GG Lat), geographic longitude (GG Long), and geomagnetic latitude (GM Lat); all in degrees. Magnetic coordinates are calculated using the International Geomagnetic Reference Field 2000 model. MN hours indicate the local midnight hour in UT.

set of discrete values and separate them from the QDC. It is important to note that the QDC is fundamentally unknown; therefore, its exact quantification is problematic. Over time, a relatively large number of geomagnetic activity indices have been implemented for monitoring the global disturbance level or specific current systems flowing in the ionosphere-magnetosphere system.

The local *K*/*Ak* indices [*Bartels et al.*, 1939] were originally hand derived from the analogue records of one or more magnetic components at a given geomagnetic observatory. The range of deviation in nanotesla of the observed irregular variation from the regular quiet daily curve is translated to the *K* (quasi-logarithmic scale) and *ak* values, in each 3 h interval. Note that after averaging the 3-hourly values each day the nomenclature changes the linearly scaled index name, "*ak*," to "*Ak*." Based on the *ak* series of two antipodal stations data, Canberra, Australia, and Hartland, England, the 3 h *aa* index [*Mayaud*, 1973, 1980] was formed, which is the longest continuous time series of geomagnetic activity. Note that the 3-hourly *aa* index gives only a very crude estimate of the global activity level and does not allow diurnal studies. The *aa* index therefore should be properly used rather as daily or longer averages [*Menvielle and Berthelier*, 1991; *Menvielle and Berthelier*, 1992]. Therefore, the index cannot be used for a study of individual and/or localized events [see *Rostoker*, 1972].

For many years the *aa* index was the only available proxy of geomagnetic activity that could be used to make deductions about the long-term evolution of the solar wind [*Feynman and Crooker*, 1978; *Lockwood et al.*, 1999] or that of global climate change [*Cliver and Boriakoff*, 1998]. Subsequently, the long-term consistency of the *aa* index was repeatedly seriously questioned by a number of independent studies [e.g., *Svalgaard et al.*, 2003, 2004; *Le Sager and Svalgaard*, 2004; *Jarvis*, 2005; *Mursula and Martini*, 2006; *Lockwood*, 2013]. Because the early analogue observations are not available in digital format in sufficiently high sampling, the *aa* index, despite the crucial role the index played in sustaining the above listed long-term claims, could not be reliably tested and verified. Furthermore, due to the above mentioned limitation of the index, it neither could be used for more regional statistical studies. This created the need for making the best independent estimate of the *K* variation that one can make based on digitized hourly mean geomagnetic data, which are readily available for most stations since the beginning of their operation. The need subsequently led to the implementation of a number of more recent indices of geomagnetic activity. When implementing these indices, the explicit aim was to produce a digital proxy of *Ak* that, by using the available digitized hourly values and a documented technique, is homogenous, more straightforward and verifiable than the hand-scaled indices, and thus better suited for long-term studies. With the implementation of indices based on hourly geomagnetic data, such as the interhour variability (IHV), Ah, median (*m*) [*Lockwood et al.*, 2013], or AhK indices, means were developed to independently verify the former claims on the long-term development of the interplanetary conditions.

Out of these indices the IHV indices, the Ah indices, and the AhK indices have been extensively tested and compared against *Ak* at the auroral Sodankylä station (SOD; for the station details the reader is referred to Table 1) for the time period of 1914–2000 [see, e.g., *Mursula and Martini*, 2006, 2007a, 2007b; *Martini et al.*, 2011, 2012a, 2012b]. We therefore give a more detailed introduction here to these indices and use them in our study. Restricting the time period of this study to 1914–2000 makes our results directly comparable with works referred above for the inclined reader.

The daily interhour variability (IHV) index is defined [*Svalgaard et al.*, 2004; *Svalgaard and Cliver*, 2007] as the average of the six absolute differences of the successive hourly values of the *H* component centered about 00 local time (LT). This definition was based on the assumption that the regular *Sq* variation, being centered about LT noon, is largely absent in the midnight sector. Therefore, no specific *Sq* treatment is applied, which makes the IHV index simple and straightforward to derive. There is a trade-off, however, in that the IHV index is restricted to daily (as opposed to 3-hourly) resolution and quantifies daily geomagnetic activity based only on the information from local nighttime (and thus dominantly linked to current wedge activity).

To define the regular variation for the 3-hourly Ah index [*Mursula and Martini*, 2006], we first used monthly averaged QDCs, defined from the hourly horizontal (*H*) component of the geomagnetic field on the five quietest days of each month. The method is often referred to as the "iron curve" method, due to its rigidity in taking into account day-to-day variation of QDC that occasionally can be significant. This averaged QDC was then used to calculate the 3 h Ah ranges in each day of the month (similarly to the *K* method, fitting the QDC as upper and lower envelope to the actual data separately in each 3 h sector).

We have recently further improved the Ah index by the implementation of the AhK index [*Martini et al*., 2011], where the QDC variation is defined by a robust recursive Kalman filter [*Kapio and Somersalo*, 2005]. Using the Kalman filter algorithm, one is able to assign a variable QDC for each day separately and the method is independent from any other geomagnetic index, which may have been used to define the five quietest days of the month, prior to the Ah index derivation.

Not only longer-term space climate studies rely on hourly or 3-hourly indices based on hourly or higher sampling data. Even near-real-time space weather applications use hourly measure of geomagnetic disturbance. These indices aim at not the detailed monitoring of storm/substorm processes but to provide a quick look on the current space weather conditions. The NOAA scale of global disturbance level is based on the *Kp* (planetary *K*) index often used to characterize global activity level, ranging from quiet ($Kp < 5$) to extreme disturbance ($Kp = 9$) [http://www.swpc.noaa.gov/noaa-scales-explanation]. This is routinely used by power grid operators to define critical events when widespread voltage control problems may occur; by aviation to define if polar flights have to be rerouted due to consequences of high geomagnetic activity, such as the increased radiation dosage or severely impaired quality of radio communication; by users of global positioning systems or of transionospheric radio links for the same latter reason; or by tourism, especially at high latitudes, in order to catch the beautiful polar spectacle, the aurora. While space weather most severely affects the auroral region, it is precisely here in the auroral region where global measures of geomagnetic activity, such as *Kp*, regularly fail to describe properly the actual regional space weather conditions. It is because, as we will further demonstrate shortly, the auroral ionosphere is practically continuously disturbed, and large (although not extreme) activity regularly occurs during even globally quiet or moderately disturbed hours. Therefore, as users gain more in-depth knowledge on how space weather affects their system, the space weather segment increasingly relies on regional or even local measures of geomagnetic activity, especially so at auroral latitudes.

One of such measures is the hourly AZ index [http://flux.phys.uit.no/ActIx]. AZ, as the local measure of geomagnetic activity in the auroral zone, is calculated for a number of high-latitude Norwegian stations. The index is also one of the federated products provisions for geomagnetic conditions within Space Situational Awareness Programme of the European Space Agency (http://swe.ssa.esa.int/web/guest/geomagnetic-conditions). It provides near-real-time monitoring capability of geomagnetic activity in the auroral zone primarily intended for nonspace system operators affected by space weather, such as airlines and aerospace sector, power system and pipeline operators, resource exploitation, and tourism. The AZ index derivation avoids exact *Sq* (or QDC) quantification: the hourly AZ index is defined as the averaged absolute deviation of the minute sampled *H* component in nanotesla from its daily running mean value (http://flux.phys.uit.no/ActIx/). When implementing the AZ index, it was probably considered that current activity should be defined with respect to the average level of the *H* component in preceding daylong (24 h) period characteristic to the station. This may be understood in terms of force of habit, arising from the *Sq* treatment applied at lower latitudes.

As noted above, these geomagnetic indices aim to give a summarized, semiquantitative information on the state of the complex ionospheric-magnetospheric system. Let us quote here *Mayaud* [1980]: "… 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"; and *Mayaud* [1976]: "[the QDC] interpretation … should always be the simplest and least speculative." It is crucial to understand that the main limitation in defining a geomagnetic activity index is, therefore, the impossibility of proper identification of QDCs at all times, especially during disturbed periods [*Hopgood*, 1986]. Therefore, simplicity is not an aesthetic requirement here, but it is something to strive for in order to ensure that observed features are not merely caused by the residual errors of the derivation method used, especially so when indices with different derivation methods are compared. The above

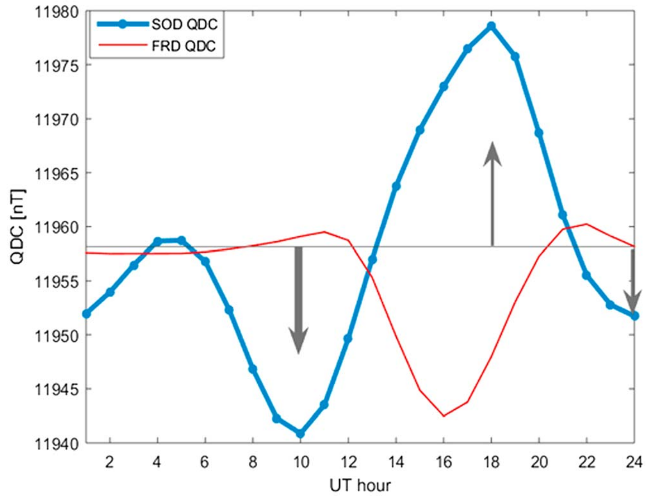

Figure 1. The overall average QDC defined by the Kalman filter from the hourly *H* component at SOD in 1914–2000. SOD LT = UT + 2 h. Note the strong depression at 10 UT caused by the *Sq* current system (thick arrow), the enhanced values at 18 UT caused by the EEJ (upward arrow), and the nighttime valley caused by the WEJ (downward arrow). For comparison the average QDC at FRD, scaled to SOD range, is also shown (thin line). FRD where LT = UT − 5 h.

listed digital indices require a fair amount of a priori knowledge of QDC characteristics (Ah and IHV) or the use of a priori assumptions and empirical parameters (AhK indices); ergo, they are not in the least very simple.

The paper is organized as follows. Section 2 discusses the diurnal QDC characteristics at auroral latitudes in detail. Section 3 introduces a new index of geomagnetic activity, dedicated to quantifying geomagnetic activity at auroral latitudes. Section 4 compares the properties of the new index at two auroral stations with the previously introduced indices. Section 5 summarizes the main results and their implications.

2. Diurnal Regular Variation at Auroral Latitudes

The traditional definition of geomagnetic activity discussed above originates from the well-known diurnal evolution at middle and low latitudes. Yet the separation of regular versus irregular variation carries on to date as the fundamental guideline for defining geomagnetic indices at all latitudes, including auroral latitudes.

Figure 1 depicts the overall average QDC (i.e., regular variation) in 1914–2007 at SOD station, as defined by Kalman filtering used to produce the AhK index introduced above. The clear signature of the ionospheric *Sq* current can be identified near local noon (10 UT; note SOD LT = UT + 2 h) in the form of the apparent strong depression in the *H* component. For comparison, the QDC similarly defined for the midlatitude Fredericksburg station (FRD) is also depicted in Figure 1. At local noon (16 UT; note FRD LT = UT − 5 h) a similar depression is observed in FRD *H* component. Similarities, however, end here; the daily curve formation at auroral latitude is quite different from that at midlatitude. While the FRD QDC gradually returns to the undisturbed level outside the local daytime, the SOD QDC shows significant enhancement in the local afternoon sector and a second valley at local night.

Even during globally quiet conditions, the geomagnetic field at auroral latitudes remains continuously disturbed. The continuously varying solar wind flow creates ever present disturbances in the magnetospheric boundary layers and the cross-polar potential that, in turn, drive currents closing through the ionosphere in the auroral oval in channels of enhanced conductivity known as auroral electrojets (westward electrojet, WEJ, on the dawn and eastward electrojet, EEJ, on the dusk side) [*Nagata*, 1963; *Xu*, 1989; *Campbell*, 1982]. As a consequence of the orientation of the two electrojets and SOD position relative to them, WEJ (EEJ) causes a negative nighttime depression (positive evening enhancement) in the daily records of *H*. Studies on the statistical occurrence of auroral electrojet peak values showed that the WEJ (EEJ) peaks in the local early dawn (late afternoon) [*Allen and Kroehl*, 1975; *Finch et al.*, 2008], roughly coinciding with the effects of WEJ and EEJ at SOD seen in Figure 1. Note that the amplitude of the electrojet effects is comparable or even larger than that of *Sq*.

We emphasize that the nominal QDC, i.e., the regular component in geomagnetic variations on all but the quietest days at auroral latitudes is not equal to the geomagnetic *Sq* curve induced by the corresponding midlatitude ionospheric *Sq* current system, but it is also strongly affected by currents that are driven by solar wind and IMF. We note that the EEJ and WEJ signatures often dominate the diurnal evolution of QDC, especially during the winter months when, due to the lack of solar illumination in the arctic, the *Sq* pattern at noon becomes subordinate in comparison (not shown). As a result, traditionally defined regular and irregular variations coinciding with the quiet and disturbed (active) conditions often intermingle, which strongly

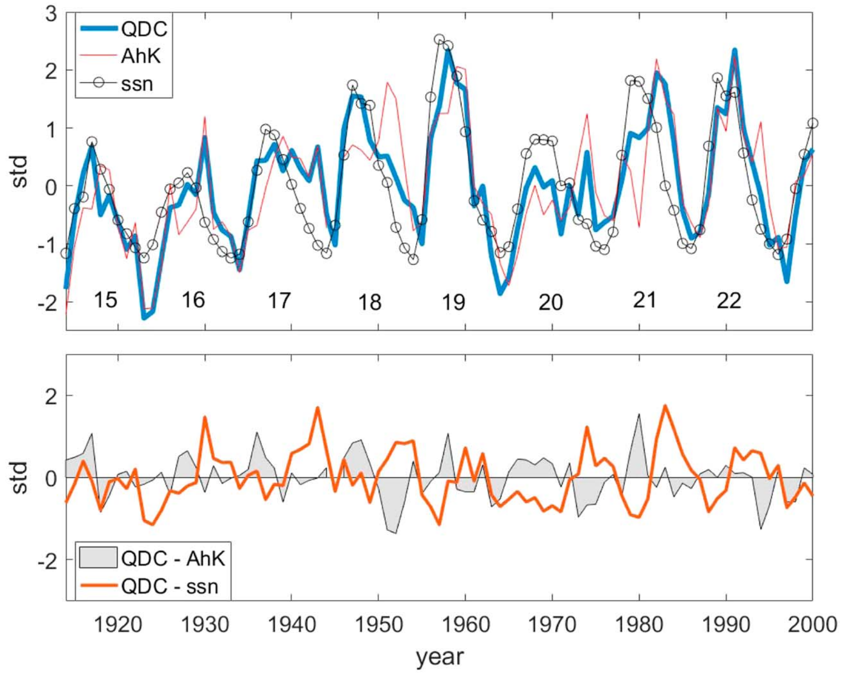

Figure 2. (top) Standardized annually averaged daily QDC ranges (thick line) and AhK index (thin line) at SOD, and the annual sunspot numbers (*ssn*; thin line with dots) with corresponding cycle numbers. (bottom) Residual differences of the standardized series.

questions the rationale of QDC subtraction at these latitudes [*Mayaud*, 1980]. In order to highlight this composite nature of the regular daily curve at auroral latitudes in contrast to the regular diurnal evolution found at lower latitudes, we use the word QDC when referring to the regular daily curve. In Figure 2 (Figure 3) we calculate the annually averaged daily QDC ranges at SOD (at FRD, respectively) and compare them with the

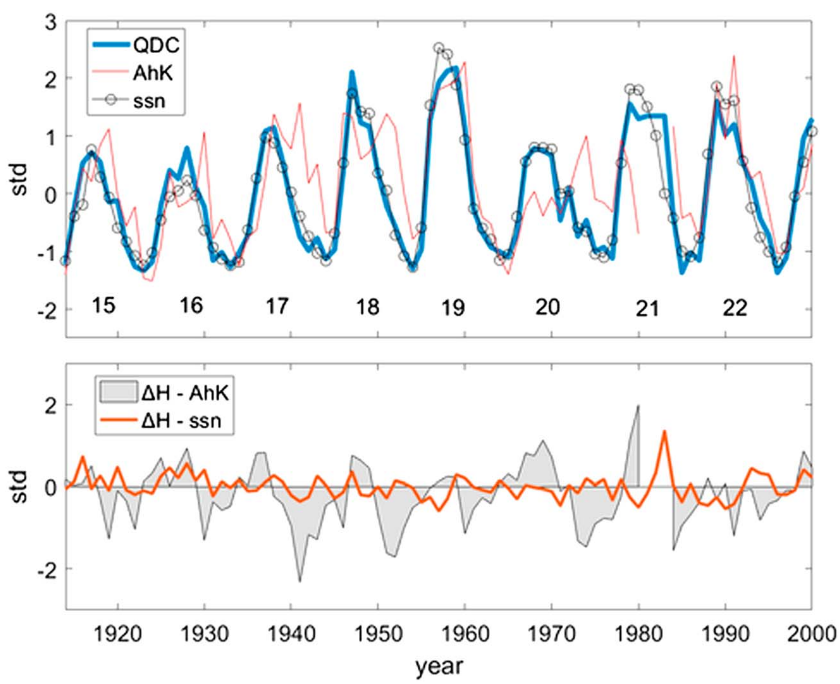

Figure 3. (top) Standardized annually averaged daily QDC ranges (thick line), AhK at FRD (thin line), and the annual sunspot numbers (*ssn*; thin line with dots) with corresponding cycle numbers. (bottom) Residual differences of the standardized series are shown.

local annual AhK indices and the annual sunspot numbers (*ssn*). We standardized the time series by removing their mean over the studied interval of 1914–2000 and dividing by the standard deviation which is used as the unit measure about the mean (this is also known as the *Z* score method; for further details, see *Martini et al*. [2012a, 2012b, 2015]). The long-term evolution of QDC range at SOD follows mostly that of geomagnetic activity (see also Figure 5), with an upward centennial trend in minimum values and maxima often following sunspot maxima with a few years lag in the declining solar activity phase, when high-speed solar wind streams (HSS) dominate geomagnetic activity. This feature is apparent in most declining solar activity phases (solar cycles 16, 17, 20, and 21), while in cycles 18 and, to a lesser extent, in cycle 22 QDC range fails to detect the strong HSS effects. QDC correlates better with geomagnetic activity ($r = 0.86$) than with the *ssn* ($r = 0.79$). The QDC − *ssn* differences at SOD (see Figure 2) are typically larger and typically occur in the declining solar activity phase. This pattern is in good agreement with the known strong solar wind modulation in the formation of high-latitude QDC [*Feldstein and Zaitzev*, 1968; *Xu*, 1989; *Kroehl*, 1989] as opposed to that of middle to low latitudes, where QDC = *Sq* and is dominantly driven by the dynamo effect of thermospheric winds. The long-term evolution of the annual QDC range at FRD (see Figure 3) follows very closely the *ssn*, so much so that the two curves are often difficult to distinguish. FRD QDC correlates extremely well with the *ssn* ($r = 0.95$), while the correlation with AhK is only moderate ($r = 0.65$). FRD AhK deviates from the other two curves typically in the declining phase, with the most clearly visible patterns in cycles 17, 18, and 20. While the QDC − *ssn* differences remain very small and random, the QDC − AhK differences have rather large amplitudes in comparison. Note that the FRD QDC pattern indeed reproduces the expected pattern in the case when *Sq*, which is driven by solar illumination, dominates the QDC.

3. New Index of Auroral Geomagnetic Activity

We note, concluding the above results, that the QDC at auroral latitudes is not only fundamentally unknown, but variations defined elsewhere as irregular (i.e., geomagnetic activity), driven by the solar wind and IMF, are a significant part of its regular or nominal pattern. Therefore, the definition of geomagnetic activity at auroral latitudes, let alone its quantification, is not trivial. It is also known that the typical relative amplitude of irregular variations at auroral latitudes is considerably larger than of *Sq* (Note that precisely because of this feature, there is no attempt made to remove auroral zone *Sq* effects of midlatitude currents, when deriving the auroral electrojet (*AE*, *AU*, and *AL*) indices [*Mayaud*, 1980; *Allen and Kroehl*, 1975]). These inevitably lead to our key question: Is it at all practical and even reasonable to try to define and separate the QDC “and” activity at auroral latitudes? (The quotation mark signals that QDC cannot be separated from activity in reality, for QDC ≠ *Sq*). This question is especially valid in case of the above discussed digital *Ak* proxies that have often been used in specifically long-term studies as annually averaged series [*Lockwood et al*., 2013].

We locally define the hourly ΔH index as the approximation to the first time derivative of the hourly mean geomagnetic *H* component:

$$\Delta H = |H_{t+1} - H_t|, \tag{1}$$

where *t* is time in hours. ΔH offers the highest, hourly time resolution among the studied indices. The index is very simple to calculate, especially in comparison with some of the indices introduced above. Its derivation requires no mathematical sophistication; neither does it require any a priori knowledge or assumption about the QDC. In addition, interhour variability indices are the most immune to drifts in the calibration of the instrument or in noise level, for they are defined on short intervals when the drifts are typically small [*Lockwood et al*., 2013]. All these facts ensure homogeneity in derivation and straightforward reproducibility, which are imperative for any meaningful interstation and long-term comparison. ΔH provides a continuous amplitude measure of activity (unlike *K/Ak*) and is better suited for near-real-time applications, for its derivation is not dependent on the actual or estimated QDC of the day.

4. Index Comparisons

Here we study whether the subtraction of QDC is a necessary step in defining a digital geomagnetic activity index based on hourly data at auroral latitudes. We compare the ΔH index to the other above discussed digital indices that acknowledge the QDC variation in their derivation. For this study we use data from two auroral geomagnetic observatories, SOD and Tromsø (TRO). For the station details the reader is referred to Table 1.

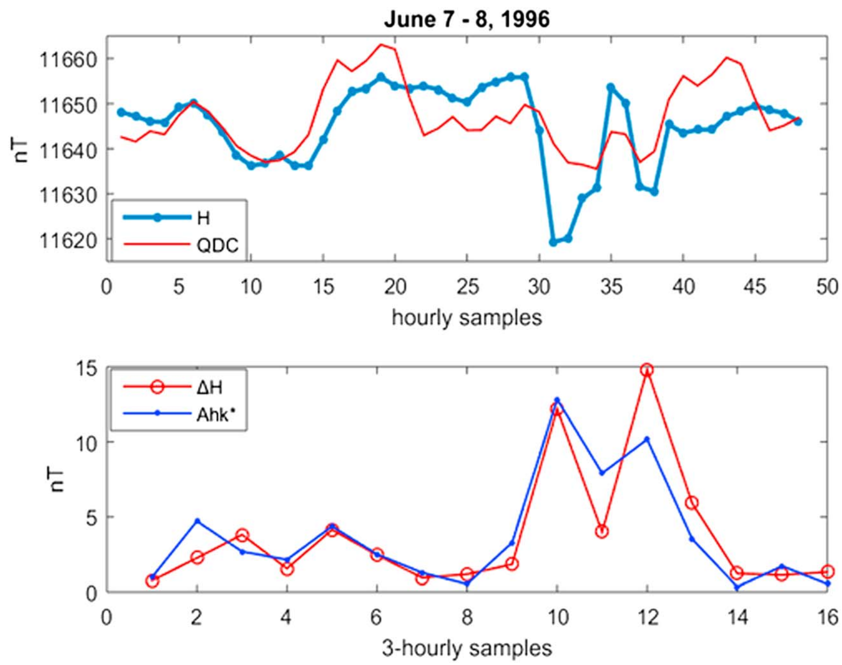

Figure 4. (top) Hourly *H* component at SOD on 7–8 June 1996 (thick curve with dots) together with the corresponding QDCs defined by the Kalman filter (thin curve). (bottom) Three-hourly AhK* (curve with dots) and Δ*H* (circle marks). AhK* was scaled to Δ*H* by linear regression using the OLS method.

Note that SOD is in fact situated at the southern boundary of the traditionally defined auroral zone and may therefore be referred to as a subauroral station. However, we refrain from making this distinction in the text for simplicity and refer to SOD (together with TRO) as "auroral."

4.1. Sodankylä Station

Because the SOD station has a fairly long (since 1914) and homogeneous series of geomagnetic observations in the region, the station data, as noted above, was frequently used in long-term studies. The *Ak* index was determined at the station, while the IHV, Ah, AhK, and Δ*H* indices were calculated by methods described above from the hourly mean *H* component data readily available from the World Data Center for Geomagnetism (for further details on data sources, the reader is referred to the Acknowledgements). In order to demonstrate the index derivation principles, Figure 4 shows the SOD *H* component on two arbitrarily selected days, 7 and 8 June 1996. The corresponding QDCs were defined by the Kalman filter, after which in each 3 h the deviation of *H* from the QDC (i.e., amplitude) provides the AhK value in nanotesla. In contrast, the Δ*H* index is calculated with no specific QDC derivation. Note that for the sake of comparison the hourly Δ*H* values were averaged each 3 h. It is clear that despite the different derivation methods, the two indices depict essentially the same pattern (with $r = 0.89$) by capturing well the main deviation from the smooth regular daily curve on June 8. We therefore conclude that for the chosen hourly sampling of *H*, both the Δ*H* and AhK indices are, in essence, sensitive to the same type of irregular variation of presumably external origin. Note in addition that the biggest difference between the two indices occurs in the eleventh and twelfth 3-hourly values (Figure 4, bottom), precisely where the Kalman algorithm erroneously assigns part of the positive irregular jerk as regular QDC at hours 35 and 36 (Figure 4, top), resulting in a smoother AhK feature.

Figure 5 shows the annual averages of all the five indices derived for SOD in 1914–2000. The overall evolution of the long-term geomagnetic activity is apparently captured similarly by all indices. It is not trivial which index should be chosen as a reference index. *Ak* may be selected as a reference on the basis that it is the only analogue index, meaning that it was either derived from analogue magnetograms or high-sampling digital data, as opposed to the other indices that are derived from hourly means. Averaging introduces smoothing, implying that none of the indices based on hourly data give information on variations within the hour. On the other hand, *Ak* reflects only maximum activity; a 3 h period with a single disturbance may have the same *Ak* value as a continuously disturbed period. That is, none of these indices are able to describe the complex

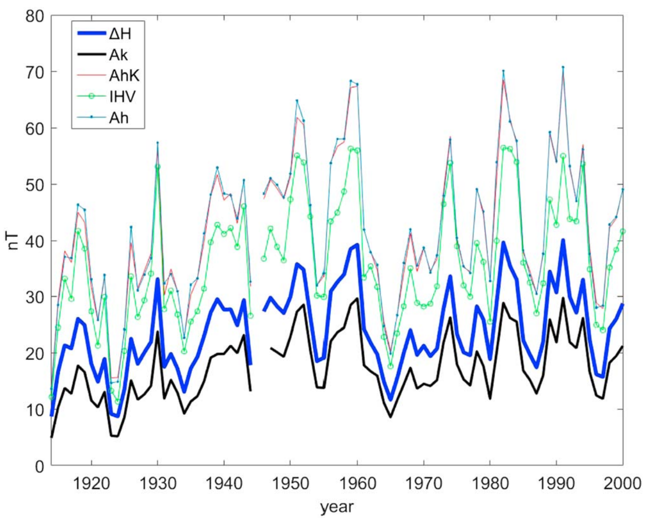

Figure 5. Annual averages of the five geomagnetic activity indices at SOD in 1914–2000 used in the study. Note the different amplitudes obtained by the different derivation methods. Note also that amplitudes of ΔH are the most similar to *Ak*.

morphology of irregular variations by only one quantity [*Mayaud*, 1980] (see also Figure 17 and related discussion below). This, however, is not the aim of the indices, for they were designed, as discussed above, to provide simplified and summarized information about the state of the geomagnetic field. It has been shown [*Mursula et al.*, 2004; *Mursula and Martini*, 2007b; *Svalgaard and Cliver*, 2007; *Martini et al.*, 2012a, 2012b; *Lockwood*, 2013] that these different methodological approaches result in a number of inherent differences between the indices that cannot be eliminated. In some cases these differences are quite moderate (e.g., for Ah or AhK), while in some cases these are more severe, making the interchangeable use of the indices in question less straightforward (we will shortly further discuss this subject in relation to the IHV index). With these facts in mind, we chose *Ak* as the reference index, to which others are compared. Note in addition that the IHV is daily, while *Ak*, Ah, and AhK are 3-hourly, and ΔH is an hourly index. In addition, IHV is derived using only local night measurements.

The linear Pearson correlation coefficients (r) between *Ak* and all other indices at annual resolution are virtually identical; $r = 0.99$ for ΔH, and 0.98 for AhK, IHV, and Ah (the confidence level is better than 99.99% for all the indices). In Figure 6 the correlation determinations (r^2), expressed in percentages, are depicted as a function of averaging timescale, where the timescale runs from 1 day to annual with 1 day steps. Correlation determination is indicative of the explained variance in *Ak*. The 95% confidence interval for the correlation between *Ak* and ΔH is also depicted as dotted line but is hardly visible being roughly within the width of the correlation curve. As seen in Figure 6, the differences between AhK and ΔH are quite small yet significant. Considerably larger differences are found between the other curves. Surprisingly, the simple ΔH index with no dedicated QDC treatment performs not only as well as the other digital indices but shows the strongest correlation with *Ak* at most timescales. The only exception, when AhK correlates better with *Ak*, is the averaging timescale from solar rotation (~27 days) to half a year, indicating a difference in the response to HSSs.

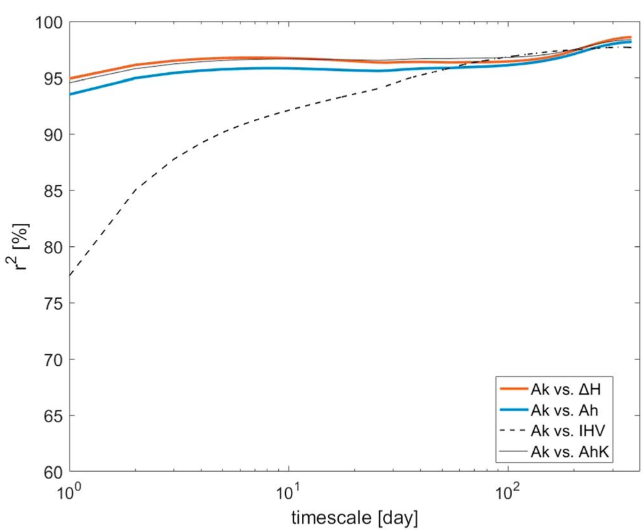

Figure 6. Correlation determination, r^2, expressed in percent at SOD between the *Ak* and ΔH, Ah, IHV, and AhK indices as a function of averaging timescale in 1914–2000. The timescale runs from 1 day to 1 year with daily steps. Significances of the coefficients are better than 99.9% for all indices over the whole timescale. The 95% confidence interval for *Ak*-ΔH correlations is indicated with dotted lines, and it roughly equals the width of thicker lines. Note that the x axis, due to the rapid increases of the values at higher frequencies, is in logarithmic scale.

Note that IHV correlation strongly degrades toward shorter averaging timescales. It is because, being a nighttime measure only, the activity of the storage-release system of the magnetosphere is more prominent in its values than in all other indices [*Martini et al.*,

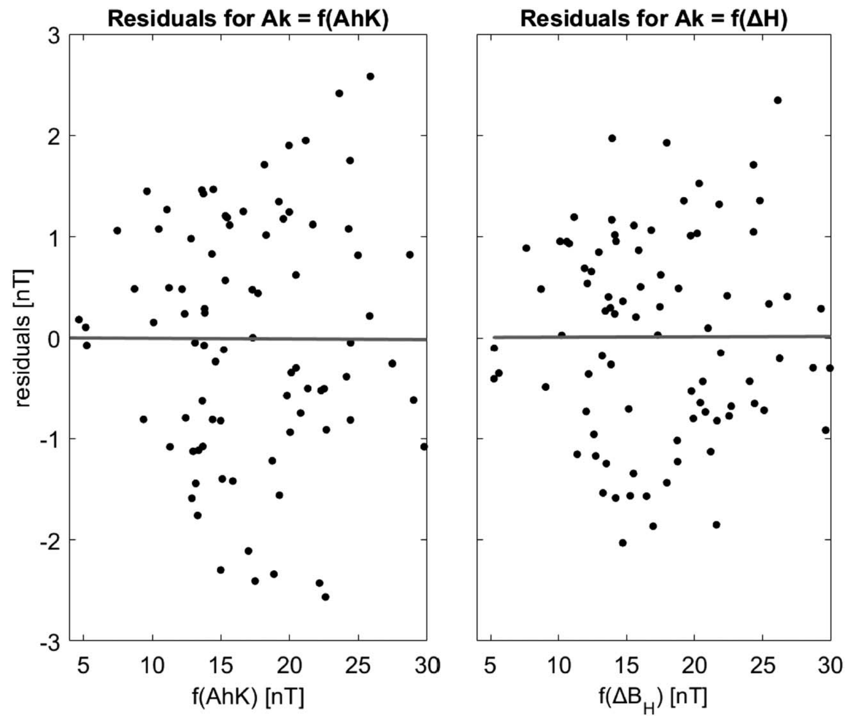

Figure 7. Annual (left) AhK and (right) ΔH fit residuals as a function of the fitted value. Note that AhK spread increases more with increasing fitted values as the sign of a more heteroscedastic fit.

2012a, 2012b; see also *Finch et al.*, 2008]. This makes IHV incomparable with the other indices in a straightforward manner. Note that this incomparability is merely caused by striving to avoid *Sq* that is a simply unnecessary effort as ΔH clearly demonstrates. Therefore, the seemingly subtle difference between the derivation of IHV and ΔH has a crucial consequence in the interchangeable use of the two indices. Because of this, we omit IHV in following studies that are concerned with shorter timescales.

Figure 6 shows that there are systematic differences on shorter timescales and that AhK and ΔH correlate systematically better with *Ak* than the other two indices. Therefore, we further study the quality of the annual regression between AhK and ΔH with *Ak* in Figure 7, where the fit residuals are plotted as a function of fitted value. As expected the differences are moderate but in favor of the ΔH index. ΔH residuals show a more moderate trend in their spread, thus indicating higher homoscedasticity. Note that the explicit objective of AhK implementation was to present a reliable proxy for the *Ak*-type geomagnetic variations for long-term studies [*Martini et al.*, 2011] (similarly for Ah [*Mursula and Martini*, 2006]); thus, homoscedasticity is a legitimate, even though relative, measure when defining the "goodness" of the index series.

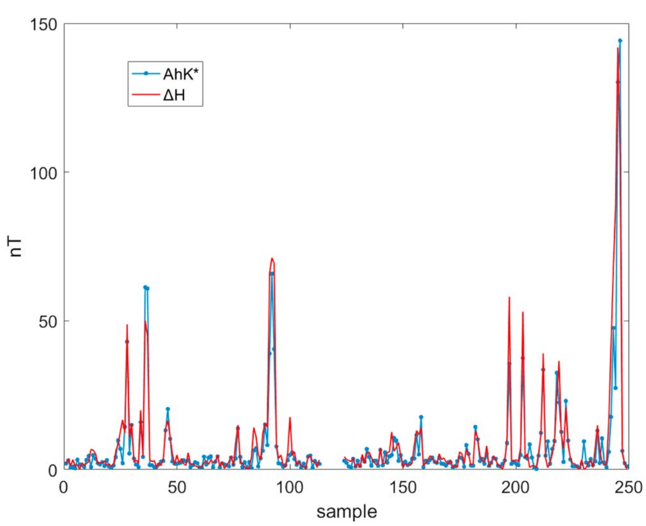

Figure 8. The 3-hourly AhK* (curve with dots) and ΔH (thin curve) on 5 January to 5 February 1921. AhK* was scaled to ΔH by linear regression using the OLS method.

Considering higher sampling rates, *Ak*, Ah, AhK, and ΔH are all available down to 3 h resolution.

Figure 8 compares the 3-hourly AhK* and ΔH indices in the arbitrarily selected 1 month interval of 5 January to 5

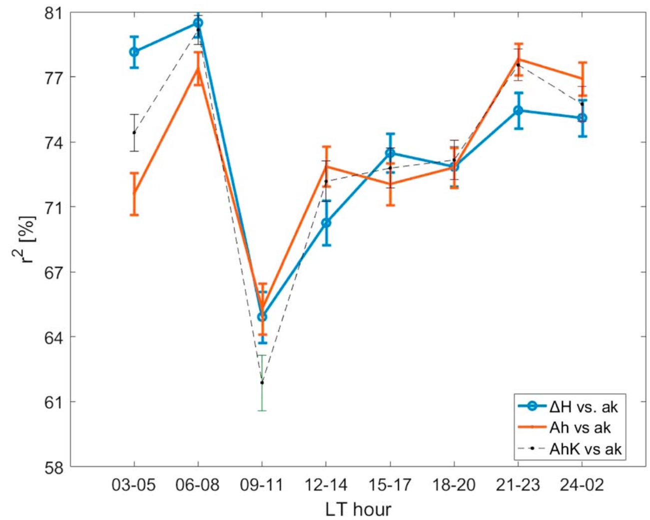

Figure 9. The correlation determinations, r^2, between the eight 3-hourly UT sectors of *ak* and Δ*H* (thick line with circle), *ak* and Ah (thick line), and *ak* and AhK (thin dashed line with dots) at SOD in 1914–2000. The 95% confidence interval is indicated for each coefficient.

February 1921. (AhK* was scaled to Δ*H* by linear regression using the ordinary least squares (OLS) method). This interval consists of both relatively quiet and disturbed days, which helps in evaluating the consistency of index derivations. The two 3-hourly indices during the total period of 1914–2000 (254,216 data points) correlate as well as $r = 0.91$. It is thus apparent that down to the highest resolution, the QDC removal is superfluous, for Δ*H* without such procedure consistently delivers a highly similar quantitative estimate of geomagnetic activity.

We define eight new geomagnetic indices for each of the previously studied indices by treating each 3 h bin separately and forming the corresponding eight new annually averaged series. The advantage of this formulation is that the eight UT (or LT, correspondingly) bins allow studying the diurnal variation of the prediction efficiency, r^2 (Figure 9). Most interestingly, Δ*H* shows virtually the same coefficient of determination as Ah (and significantly stronger than AhK) in the third UT sector around local noon, where *Sq* dominates. That is, the elaborate QDC treatments of AhK and Ah are apparently unnecessary. Δ*H* has considerably the strongest correlation with *Ak* in the first UT sector that eventually leads to the observed strongest overall correlation of the daily/yearly averaged index (see Figure 6) and somewhat weaker correlation than the others in the evening sector. In the afternoon sector all three indices correlate roughly equally well with *Ak*, the differences being insignificant in this LT sector.

We have also calculated in Figure 10 the average values of the *ak* and Δ*H* indices in 1914–2000 in the eight 3-hourly UT sectors separately. Accordingly, geomagnetic activity has a strong diurnal variation with maximum values in the night sector and the minimum in the third (prenoon) sector. This probably explains why the correlations are the weakest in this same sector in Figure 9: because the activity is the smallest, relative differences between methods are enhanced, leading to a somewhat weaker (but still strong) correlation. The diurnal variation is very similar in the two indices: the correlation coefficient between the curves is $r = 0.99$, implying a confidence level better than 99.99%.

Last but not least, note that the Δ*H* amplitudes were averaged to coincide with the 3 h *Ak* sectors. Δ*H* method in fact allows studying geomagnetic activity up to finer temporal detail than any of the other indices, *ak*, IHV, Ah, or AhK (see, e.g., Figure 10, bottom), due to its hourly sampling.

4.2. Tromsø Station

The 10 min TRO geomagnetic data since 1987 are available at http://flux.phys.uit.no/ArcMag/. We derived AhK and Δ*H* for TRO from 10 min *H* component data, first forming hourly mean averages of *H*, then calculating the hourly time derivative, Δ*H*, and the 3-hourly AhK. If more than half of the 10 min *H* values were missing within the hour, the hour was discarded. Because this policy resulted in a fairly patchy data series in 1987, the study starts in 1988 instead and ends in 2000 as above.

In order not to repeat all the same calculations carried out for SOD, we use slightly different approaches to demonstrate our fundamental claim, by putting the shorter-term space weather applicability of the index more in focus. (We note, however that repeating the same study at TRO leads essentially to the same conclusions).

First we revisit whether QDC removal is necessary for properly quantifying irregular activity, as measured by Δ*H*. Figure 11 depicts the *H* ground geomagnetic variation on an arbitrarily selected day, together with the

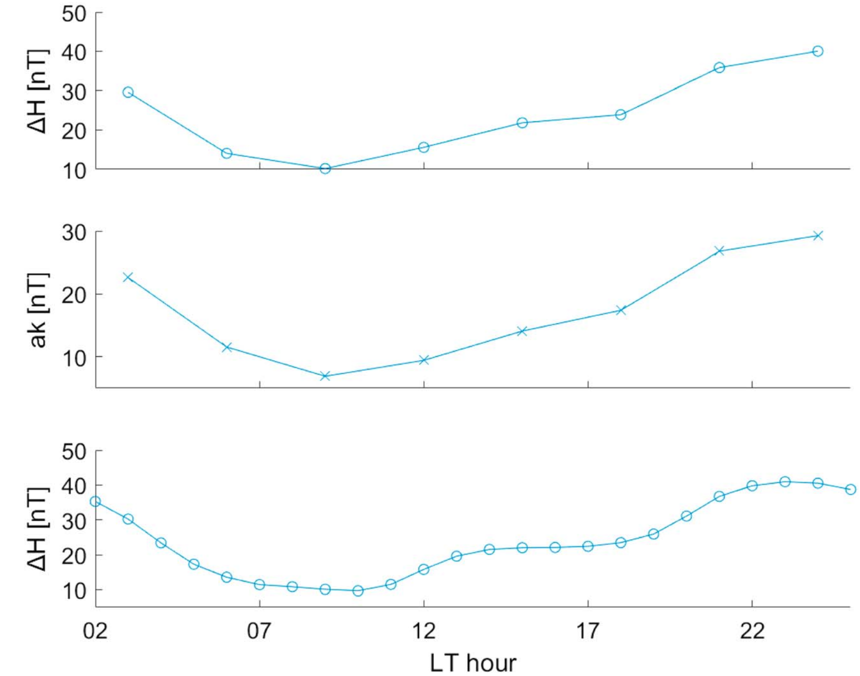

Figure 10. Average values in 1914–2000 of (top) SOD ΔH indices and (middle) *ak* indices in the eight 3-hourly UT sectors. (bottom) Hourly ΔH indices. The 3-hourly sectors are centered to the middle hour.

corresponding QDC as defined by the Kalman algorithm. We derive two ΔH series for 1988–2000; one is calculated from the untreated H component (as previously), and one after the QDC has been removed from H. Note that the latter way would be the traditional approach. The results are shown in Figure 12. It is clear that the two ΔH curves are very nearly identical, with correlation determination as high as $r^2 = 99.8\%$ for 37,992 data point pairs. (For comparison, the same calculation leads to $r^2 = 98.1\%$ for SOD ΔH series in 1914–2000,

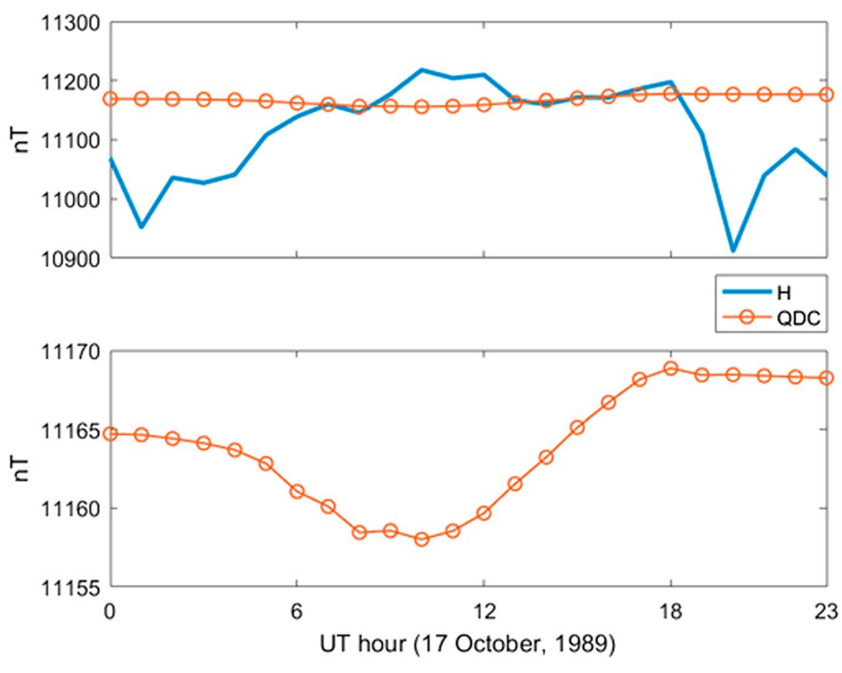

Figure 11. (top) Hourly H component at TRO on 17 October 1989 (thick curve) together with the corresponding QDC defined by the Kalman filter (thin curve with circle). (bottom) The 24 QDC values for the same day separately.

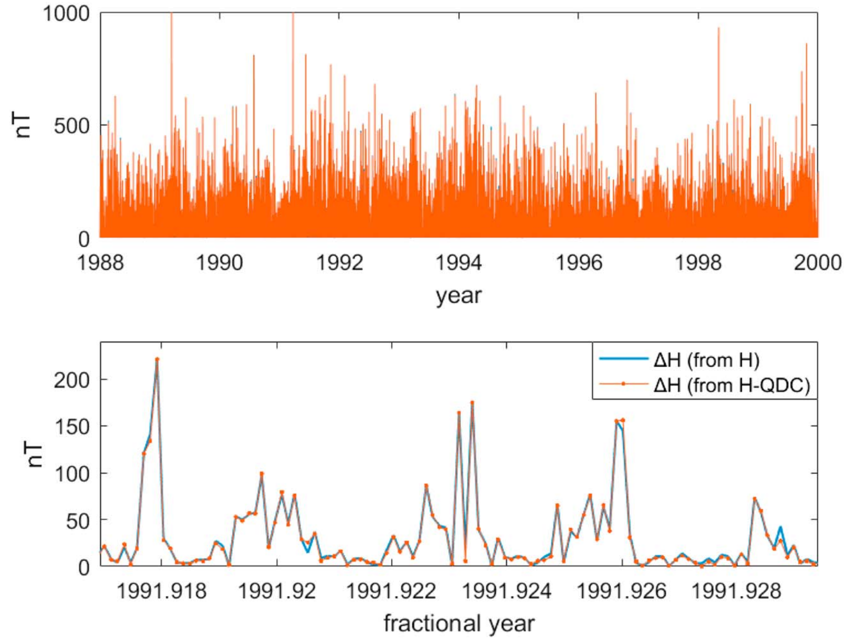

Figure 12. (top) The hourly ΔH index at TRO calculated from the untreated H component (thin curve) and from H after the QDCs were subtracted (thin curve with dots) in 1988–2000. Note that the two curves are indistinguishable in this resolution. (bottom) Same as Figure 12 (top), with an arbitrarily selected period enlarged.

with 762,648 data point pairs). Summarizing, there is a 0.2% variation in the data after QDC is traditionally subtracted that is not explained by the simple hour-to-hour absolute difference, ΔH, possibly the rounding error. Thus, the ΔH index satisfies the fundamental condition required from a geomagnetic activity index [*Mayaud*, 1980]: in the auroral zone it is, to the greatest extent, sensitive to irregular variations only. At auroral latitudes the slope of hourly QDC is simply too small relative to that of the virtually ever present irregular variations to play any significant role when calculating the hour-to-hour absolute differences (see Figure 11, top). In addition we note that *Sq* all but disappears during the winter months at TRO, due to the total lack of solar illumination in the arctic. This further undermines the rationale of the use of QDC removal algorithm based on pattern recognition.

The seasonal diurnal variation of the ΔH (top) and AhK indices (bottom) is shown in Figure 13. Both indices show the clear signal of equinoctial effect [*Bartels*, 1925; *Cliver et al*., 2000], and the diurnal evolutions of AhK and ΔH are highly similar. The ΔH index, however, allows studying the characteristics of irregular variations up to finer details with its hourly (as opposed to 3-hourly) resolution. Note that the average diurnal variations of mean values deducible from the figure would be highly similar to those found at SOD (Figure 10).

4.2.1. Comparison With the AZ Index

As discussed above in paragraph 1, a less widely used geomagnetic activity index, the hourly AZ index, is calculated since 1987 at TRO observatory. The AZ index has been provided as the measure of auroral activity within the Space Situational Awareness Programme of the European Space Agency. Figure 14 (top) depicts the hourly ΔH in arbitrarily selected June 1996, together with the daily running average values of ΔH, where each data point is defined as the simple arithmetic mean of the preceding 24-hourly values. When comparing them to the corresponding AZ* (Figure 14, bottom; AZ* was scaled to ΔH by linear regression using the OLS method), it becomes clear that the AZ* derivation method produces an index highly similar to the ΔH daily running averages. While the prediction efficiency is very low between the hourly ΔH and AZ indices ($r^2 = 13\%$), it increases dramatically to 87% between the hourly AZ and corresponding daily running average series of ΔH in 1988–2000 (113,976 data points).

The effective low-pass filtering of the AZ derivation method makes the direct comparison of AZ with the other indices of geomagnetic activity less straightforward and renders AZ useless for near-real-time monitoring. We first demonstrate this in Figure 15, where the geomagnetic H component is shown on a particularly

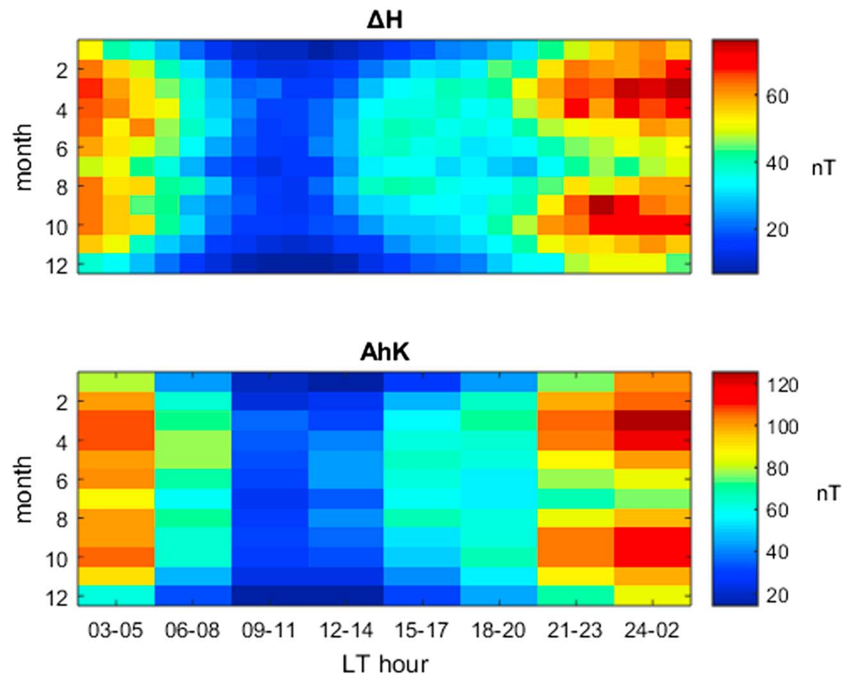

Figure 13. Monthly average (top) ΔH and (bottom) AhK amplitudes at TRO in 1988–2000. The scales give the corresponding nonstandardized index values.

quiet day, 7 June 1996, together with the corresponding AZ and ΔH indices. The *Sq* depression at local noon is clearly present even at TRO latitude on this summer day. (The average *Sq* amplitude at TRO varies during the course of the year from about only a few nanotesla in the winter to its summer maximum of about 15–20 nT). The WEJ effect in the midnight LT hours is only moderate, but the EEJ effect is clearly present in the afternoon sector (see also Figure 1). Note that assuming this daily variation to be close to the ideal

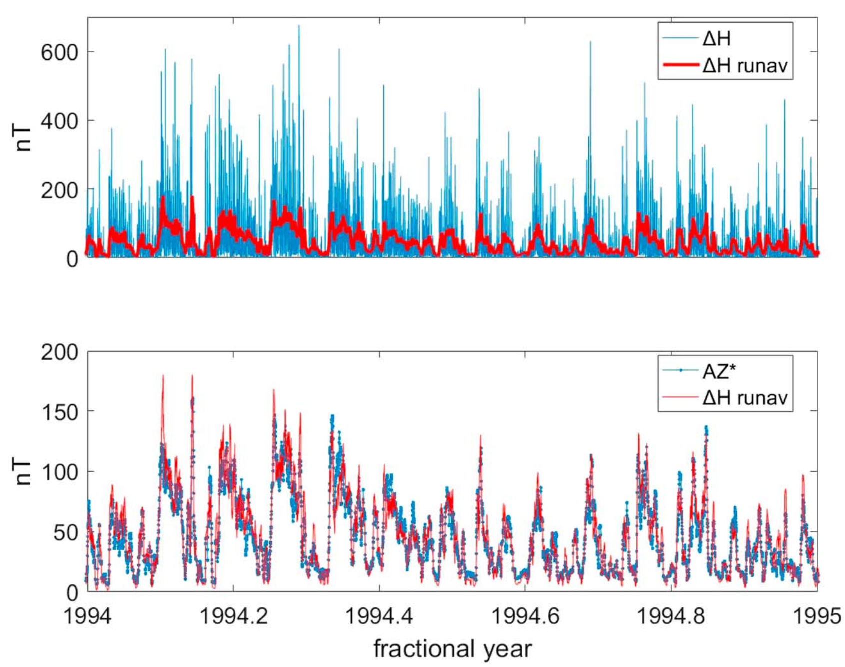

Figure 14. (top) Hourly ΔH index (thin line) and its daily running average (thick line) at TRO in 1994. (bottom) AZ* (thin line with dots) and the daily running average of ΔH (thick line) for the same period.

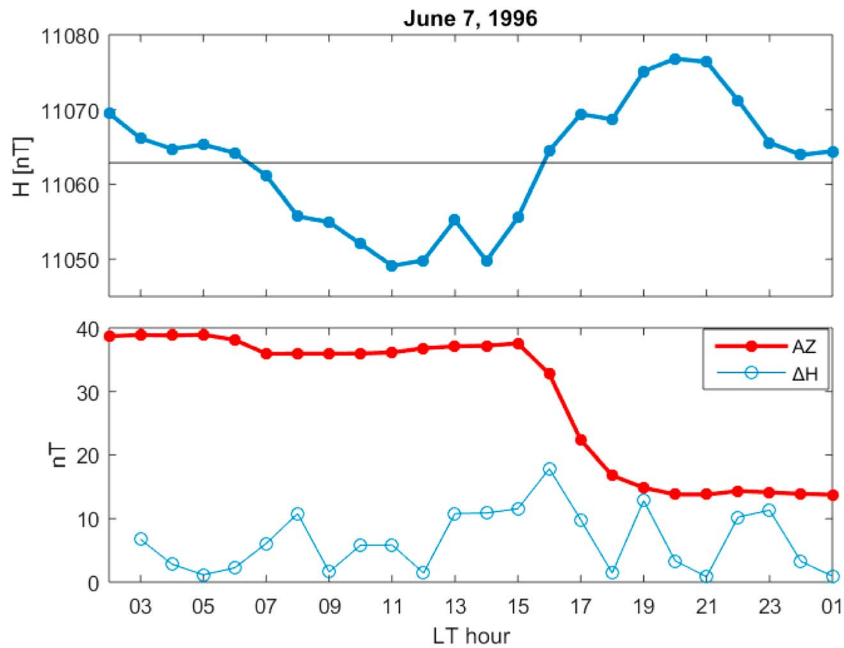

Figure 15. (top) The hourly TRO *H* component on a particularly quiet day with corresponding daily mean. (bottom) The corresponding derived geomagnetic activity indices, AZ (thick line with dots) and Δ*H* (thin line with circles).

QDC at TRO, an ideal activity index should assign 24 values very close to zero for this day, thus producing a flat line (with the exception of the few hours affected by the electrojets, where the "ideal" values would depend on the QDC definition, whether it is defined as regular variation or merely *Sq*). In contrast, AZ derivation assigns values with maximum range as large as about 39 nT and standard deviation (std) of 11 nT. The daily evolution of AZ has little to do with the magnetogram of the actual day and only the last few points, where the running daily mean is increasingly affected by the mean of the actual day, return quantitatively similar values as Δ*H*. On the other hand, Δ*H* results in a maximum value of 18 nT and std = 5 nT, i.e., less than half of those of AZ, and the curve is clearly more isotrope. These maximum index values should be compared to the typical amplitude of hourly "irregular" deviations in the auroral zone, which is on the order of hundreds of nanotesla even in a solar activity minimum year as 1996 (see Figure 14, top).

Figure 16 (top) depicts the geomagnetic *H* component in a selected 24 h period. Several small to moderate irregular field disturbances can be identified around 13 and 15, and 20:30 and 23:30 UT. Δ*H* (Figure 16, middle) is clearly far more capable in identifying the successive irregularities as separate individual activity patterns than AZ (Figure 16, bottom). In fact, the hourly AZ index is noninformative about the hour-to-hour geomagnetic variation to a degree that it is effectively useless as near-real-time measure of hourly geomagnetic activity. For quantitative comparison, the standard deviation of the Δ*H* index during the day is 114 nT, i.e., considerable, while that of AZ is only 4 nT.

It is somewhat surprising that the European Space Agency provides an index for space weather applications that is only suited for longer-term statistical studies and not for monitoring the near-real-time space weather conditions in the auroral zone. Whether the day is quiet (see Figure 15) or disturbed (see Figure 16) the AZ index values, despite being derived from high frequency minute data (as opposed to hourly means used by Δ*H*), carry equally very little useful information on the real space weather conditions of the hour. It is because for a considerable part of the actual day the effective running averaging is much affected by previous day's activity. We therefore argue that Δ*H* is a more versatile, economic, and practical index for space physics use, for it allows studying actual hourly activity in near-real time. Further averaging may easily be tailored to user requirements, which, by selecting the right subset size, can even produce a highly similar index to current AZ if needed. In contrast, AZ remains in effect a daily index despite its hourly sampling. We therefore propose replacing AZ with the provision of the hourly Δ*H* index for near-real-time monitoring of the geomagnetic conditions in the auroral zone.

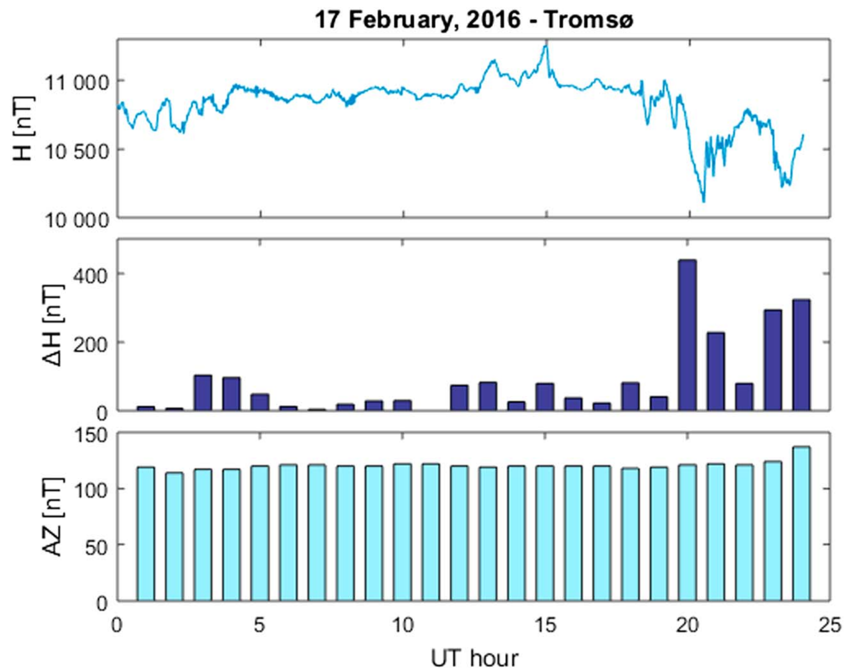

Figure 16. (top) Hourly H component at TRO on 17 February. (middle) The corresponding 24-hourly ΔH index values. (bottom) The corresponding 24-hourly AZ index values.

The standard *K/Ak* index is not calculated for the station; however, the so-called provisional (near-real-time) *K* values based on minute data are available since 1987. Figure 17 depicts the same 24 h period as in the previous figure. As discussed above, ΔH (Figure 17, middle) is capable of identifying a number of the successive irregularities as separate individual activity patterns, especially at 13, 15, 20:30, and 23:30 UT hours. While the *ak* values (Figure 17, bottom) depict well the large-scale morphology of the daily disturbance level, with its

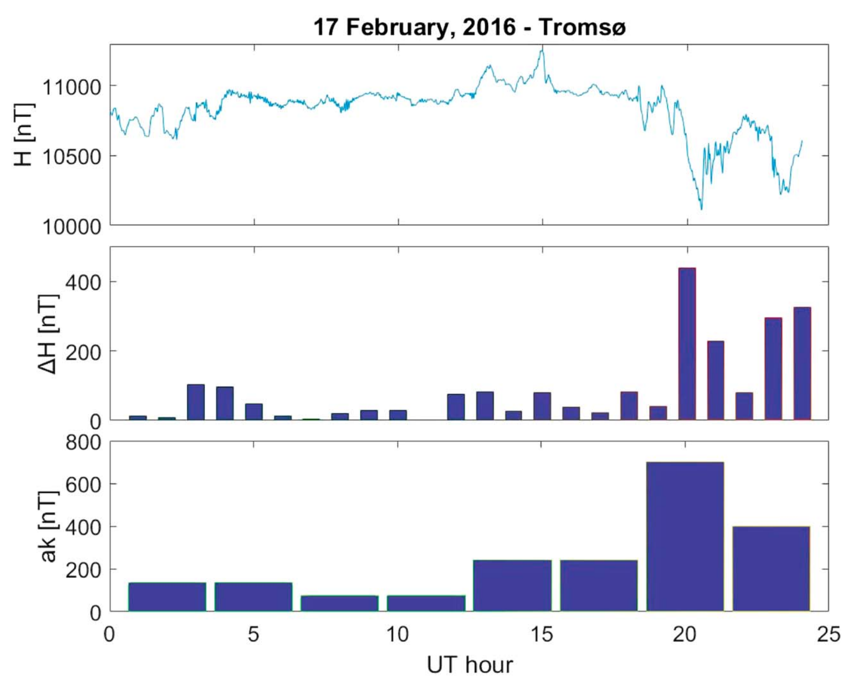

Figure 17. (top) Hourly H component at TRO on 17 February. (middle) The corresponding 24-hourly ΔH index values. (bottom) The corresponding eight 3-hourly *Ak* index values.

3 h resolution it masks all the different disturbances into one relatively smooth activity increase till 20 UT and decrease thereafter. It is therefore somewhat misleading to think that because *ak* is based on high-sampling minute (or analogue) data, it is also better suited for short-term studies. The minute values indeed characteristically register the variation also within the hour. This, however, does not automatically imply the capability of more detailed monitoring of the irregular variations. It is because the minute values are used to define the range difference in 3-hourly time intervals. The choice of length within which the range is defined should be characteristic to the typical morphology of irregular variations. The zone where the morphology of irregular disturbances are best adopted to the 3 h interval is the rather narrow subauroral band of 40° and 50° corrected geomagnetic latitudes. At auroral latitudes short-duration substorms and secondary details in the disturbances are often masked by a 3 h index, and therefore the 3 h time interval was found to be too long [*Mayaud*, 1980]. Precisely this dependency on local morphology is demonstrated clearly in Figure 17. The ΔH index is, in cases, even better suited to shorter-term studies of storm-to-storm (or substorm-to-substorm) details than *ak* (and certainly than all Ah, AhK, AZ, and IHV), which also highlights what we said above in relation to the comparison at SOD: selecting *ak* as reference index was somewhat arbitrary.

The applicability of ΔH is of course limited by its hourly resolution. The hourly mean data do not convey any information on the morphology of irregular variations within the hour. One must keep in mind, however that no geomagnetic index is a substitute for the real data. The geomagnetic activity indices, by providing a summarized information on the level of geomagnetic disturbances on a given timescale, target certain existing user needs. The chosen hourly data input ensures homogeneity over longer time span, thus extending the interval of statistical studies also for periods when only hourly mean data are available. Furthermore, long statistics is also essential for index forecasting models and not only for historical studies. The hourly ΔH index balances between the conflicting needs of high resolution and long-term homogeneity and is therefore suitable for a relatively wide range of both space climate and space weather applications in the auroral zone.

5. Conclusions

The main objective of our study has been to determine if the in certain cases elaborate procedure of the regular quiet daily curve (QDC) quantification and omission is a necessary procedure in quantifying the irregular geomagnetic variations at auroral latitudes or if this traditional step in the index derivation is rather followed from the force of habit inherited from the understanding of midlatitude *Sq* characteristic. We have therefore here defined the hourly ΔH index, the absolute hour-to-hour deviation in nanotesla of the hourly geomagnetic H component (approximating the first time derivative, $|\mathrm{d}H|/\mathrm{d}t$), which assigns each sample to sample deviation as geomagnetic activity without separating the "regular" (QDC) and/or "irregular" parts of the daily magnetic field evolution. We have studied geomagnetic activity at the two auroral stations SOD and TRO by comparing a number of recent and more traditional indices geomagnetic activity, the *Ak*, IHV, Ah, AhK, AZ, and ΔH indices.

We have demonstrated that (i) the hourly gradient of the regular *Sq* variation is very small with respect to the irregular part ("activity") and (ii) a bulk of the nominal daily variation is actually part of the variation driven by solar wind and IMF and traditionally classified as irregular. Therefore, attempts to subtract QDC may in fact lead to a larger error, often caused by residual deviations between the used different mathematical and methodological tools and corresponding presumptions themselves.

The arduous QDC treatment is important at lower latitudes but less so at auroral latitudes (unless, of course, the variation of the QDC in and of itself is of concern). The simple absolute hour-to-hour deviation of the H component (ΔH index) provides a robust and uniform means to quantify geomagnetic activity at auroral and subauroral latitudes. We have found that ΔH provides the best and most consistent results at most timescales with the highest effective resolution among the studied indices. We have also demonstrated that the ΔH index may equally be useful in two different time domains:

1. As a quick look near-real-time index of space weather ΔH better captures the detailed morphology of geomagnetic activity than the hourly AZ index, the latter of which is currently provided by the Space Situational Awareness Programme of the European Space Agency as the measure of geomagnetic activity in the auroral zone. The ΔH index thus should replace AZ for future provisions.
2. As a long-term index derived from hourly magnetometer data for space climate studies ΔH provides the most accurate proxy for the traditional *K/Ak* indices. Using hourly data as input and an easily reproducible derivation method, homogeneous long-term series of geomagnetic activity may be compiled. These

series, in turn, may reliably be used both for long-term studies of geomagnetic activity and as inputs for forecasting models. The hourly resolution of the ΔH index is the highest amongst all the indices studied here, which in cases better allows studying the shorter-term morphology of storm-to-storm details in the auroral zone than even the 3 h range indices based on minute data.

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