Polar Cap (PC) index calculation methods

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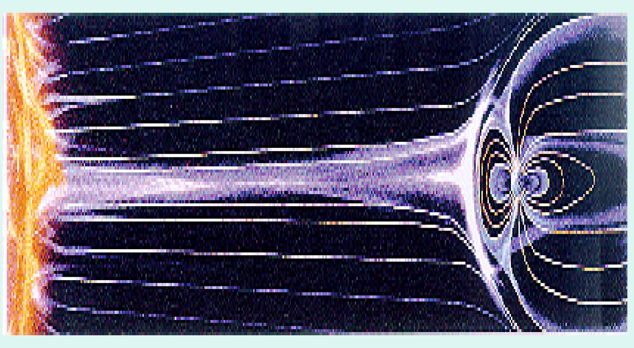

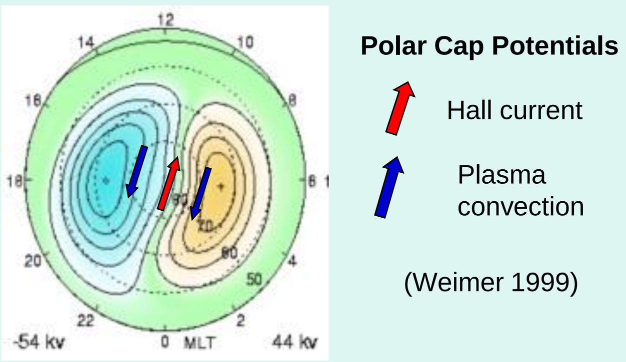

Basics. Polar cap horizontal magnetic field variations ***ΔF*** are strongly correlated with the "Geo-effective" (or "merging") Electric Field, E_M, that controls the global energy input from the Solar wind to the Earth's Magnetosphere (*Kan and Lee*, 1979):

$$E_M = V_{SW} \bullet B_T \bullet \sin^2(\theta/2) \qquad (1)$$

$B_T = (B_Y^2 + B_Z^2)^{1/2}$:IMF transverse magnetic field component
$\theta =$ arctan(B_Y/B_Z) : IMF polar angle with respect to the GSM Z-axis.

The correlation is substantiated by projecting ***ΔF*** through an angle, φ, to an "optimum" direction in a polar cap coordinate system fixed with respect to the Sun-Earth direction (the X-axis in the GSM system). Hence we are looking for a linear relation between the projected polar cap horizontal magnetic field variations ΔF_{PROJ} and the Solar Wind "Geo-effective Electric Field" E_m of the form:

$$\Delta F_{PROJ} = \alpha \bullet E_M + \beta \qquad (2)$$

where β (e.g. in units of nT) is the baseline shift ("intercept"), while the proportionality constant α is the "slope" (e.g., in units of nT/(mV/m)). The parameters are calculated on a statistical basis from cases of measured values through an extended epoch.
From equivalence with E_M the Polar Cap Index PC is now defined by:

$$PC == (\Delta F_{PROJ} - \beta)/\alpha \qquad (\approx E_M) \qquad (3)$$

The PC index is a measure of the polar geomagnetic activity but could also be considered a measure of the transpolar convection of plasma and embedded magnetic fields and a proxy for the geo-effective electric field E_M in the solar wind.

Definition of magnetic variation vectors.

In the calculation of magnetic variations, three variants have developed to derive the magnetic variation vector, ***ΔF,*** from the observed magnetic data, $\mathbf{F_{OBS}}$, which could be described by the following defining equations:

$$\Delta \mathbf{F} = \mathbf{F_{OBS}} - \mathbf{F_{BL}} \qquad \text{.... DTU-S (formerly DMI\#2)} \qquad (4a)$$

$$\Delta \mathbf{F} = (\mathbf{F_{OBS}} - \mathbf{F_{BL}}) - \mathbf{F_{QDC}} \qquad \text{.....DMI} \qquad (4b)$$

$$\Delta \mathbf{F} = (\mathbf{F_{OBS}} - \mathbf{F_{BL}}) - (\mathbf{F_{QDC}} + \mathbf{F_{SS}}) \qquad \text{.... AARI, IAGA} \qquad (4c)$$

In these expressions $\mathbf{F_{BL}}$ is the slowly (secularly) varying baseline vector for the day in question; $\mathbf{F_{QDC}}$ is the quiet day (QDC) variation vector for the time in question; $\mathbf{F_{SS}}$ is an IMF By-related, solar wind sector (SS) dependent correction vector for the day in question. For the present DMI method the IMF By-related (solar wind sector related) contribution is included in the calculation of the QDC vector.

IAGA-endorsed calculation of final and real-time PC index reference levels.

In the AARI version endorsed by IAGA in 2013, the QDC is found by averaging quiet data over an interval longer than the short period sector structure variations. An IMF By-related sector structure (SWS) contribution is calculated separately and added to QDC.

The construction of the solar wind sector term (SS) is explained and illustrated in Janzhura and Troshichev, 2011, (hereafter J&T2011). The near-real time version is explained in p. 1496, while a post-event example for the H-component (H_{SS}) for June 2001 is illustrated in their Fig. 6.
The solar sector terms are constructed from median values of the respective component. For the post-event values the median values are smoothed over 7 days with the day of interest at the middle. For the near-real time values, where only pre-event data are available, the solar sector term is derived by forward extrapolation of 3-days average median values from every other of the preceding 9 days.
Fig. 3 illustrates for June 2001 the 1-day (black line) median values and the 3-days (green line) average median values on the scale to the left. The post-event Hss term derived at DTU-Space is displayed in magenta line on the lower right scale. The post event Hss term calculated at DMI is displayed in black line with dots and agrees with the values supplied from DTU-Space. The real-time Hss term calculated at DMI is displayed in blue line. Smoothed values of IMF By are shown in red line on the upper right scale.

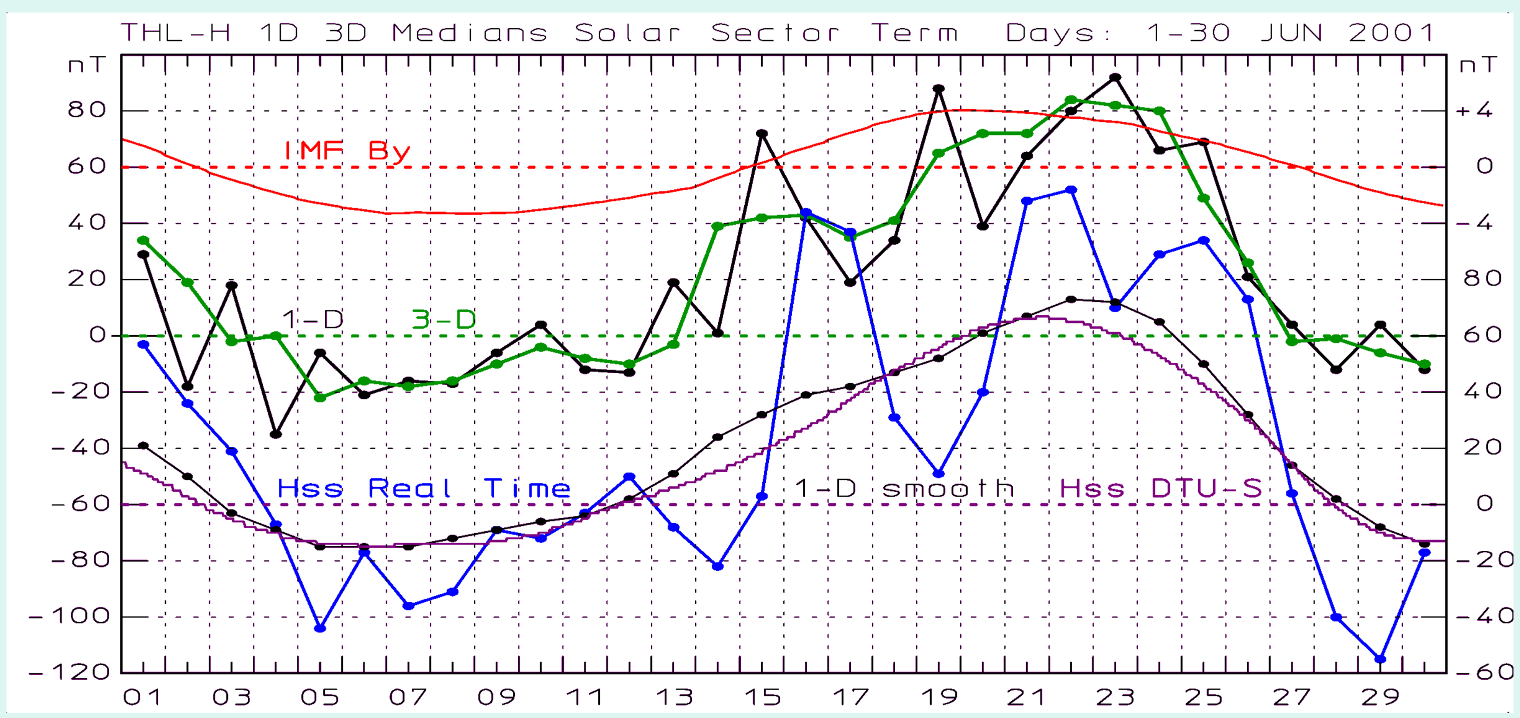

Fig. 3 Construction of solar sector (H_{SS}) terms in post-event (final) and real-time versions.

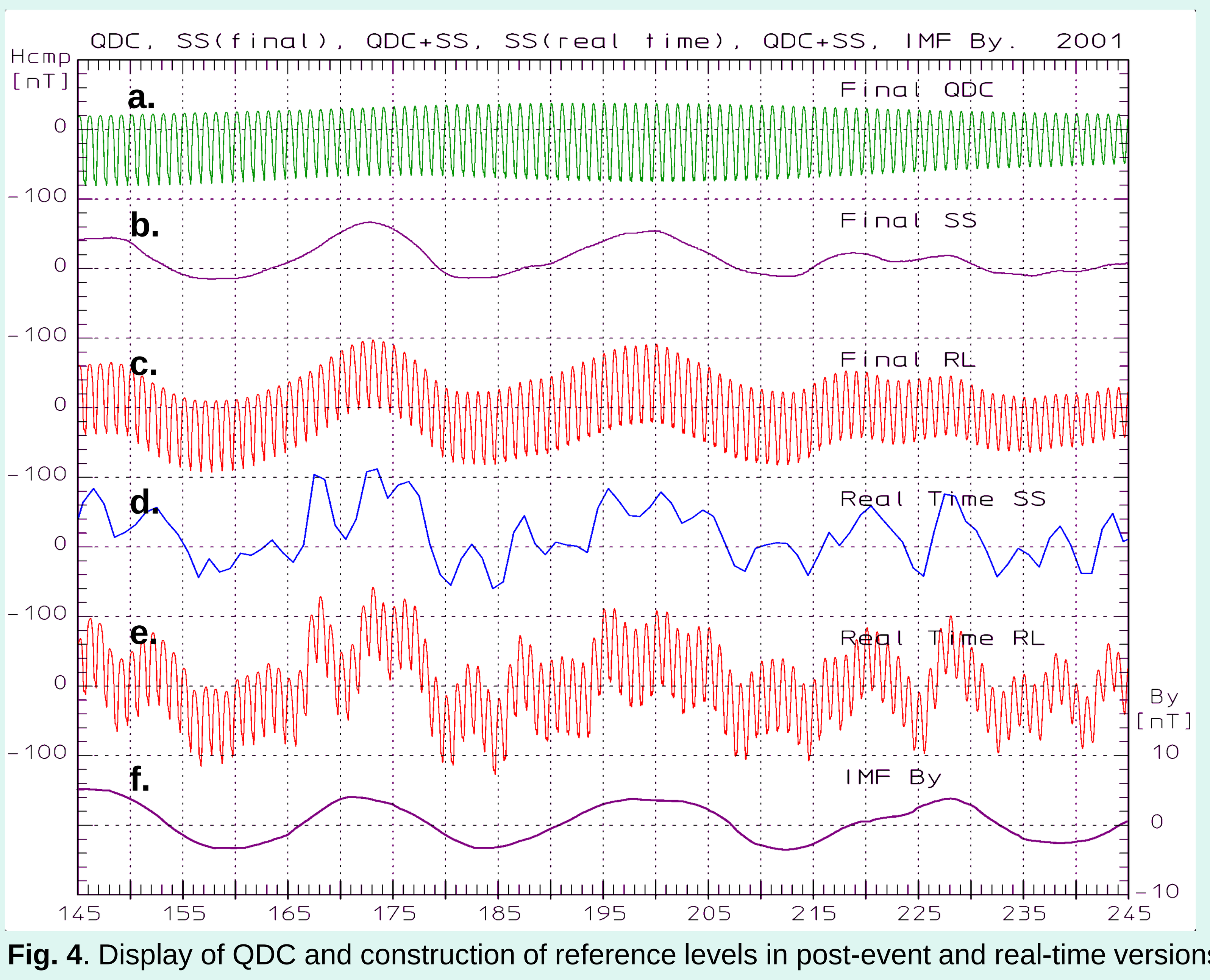

Fig. 4. Display of QDC and construction of reference levels in post-event and real-time versions.

The H-component of the Quiet Day Curves (QDCs) calculated at DTU Space (Anna Willer, private comm.) are displayed for the days 145-245 of 2001 in green line in the upper field (a.) of Fig. 4 while the Hss term from DTU Space is displayed in the second field (b.) in magenta line. Note that the SS-term has little effect on the QDC's since they are derived for 30 days at a time such that the 27.4 days solar rotation effects related to the IMF-By component shown at the bottom (f.) are largely evened out.

The reference level (RL) from which the disturbances are measured comprises the QDC terms plus the solar sector terms and is displayed for the H-component in field (c.) in red line and is quite similar to that of Fig. 1 in J&T2011 claiming to be the QDCs.
The near-real time values of the Hss component derived by cubic spline extrapolation of 3-days median values following the description in J&T2011 to the letter are displayed in the next lower field (d.) in blue line, while the resulting H-component reference level (RL) is displayed in field (e.) by the jagged red line assuming same real-time and final QDCs.

In spite of the apparently quite simple derivation process, a number of different PC index versions have emerged (Stauning, 2013).

1. **AARI#1:** PCS index based on Vostok magnetometer data..
   Published description: Troshichev et al., (1988). Programmer: V. G. Andrezen.
2. **AARI#2:** PCS index based on Vostok data.
   Published description: Not available. Programmer: R. Yu. Lukianova.
3. **AARI#3:** PCS and PCN indices based on Vostok and Thule data, respectively.
   Published description: Troshichev et al., (2006). Programmer: A. Janzhura.
4. **AARI#4:** PCS and PCN indices based on Vostok and Thule data.
   Published description: Troshichev, 2011. Programmer: A. Janzhura.
5. **DMI#1:** PCN indices based on Thule data
   Published description: Vennerstrøm, (1991). Programmer: S. Vennerstrøm.
6. **DMI#2** = **DTUS#1:** PCN indices based on Thule data.
   Published description: Vennerstrøm, (1991). Programmer: S. Vennerstrøm.
   Program modifications: V. O. Papitashvili and O. Rasmussen.
   Published description: Papitashvili et al., (2001). Programmer: V. O. Papitashvili.
7. **DMI# 4:** PCN and PCS indices based on Thule and Vostok data.
   Published description: Stauning et al., (2006) (SR06-04). Programmer: P. Stauning.
8. **IAGA-endorsed**: PCS and PCN indices in prompt and archival versions.
   Published description: J. Matzka (2014). Programmer: A. Janzhura.
9. **DMI:** PCS and PCN indices based on Thule, Vostok, Resolute and Dome-C data.
   Published description: Stauning, 2016. Programmer: P. Stauning.

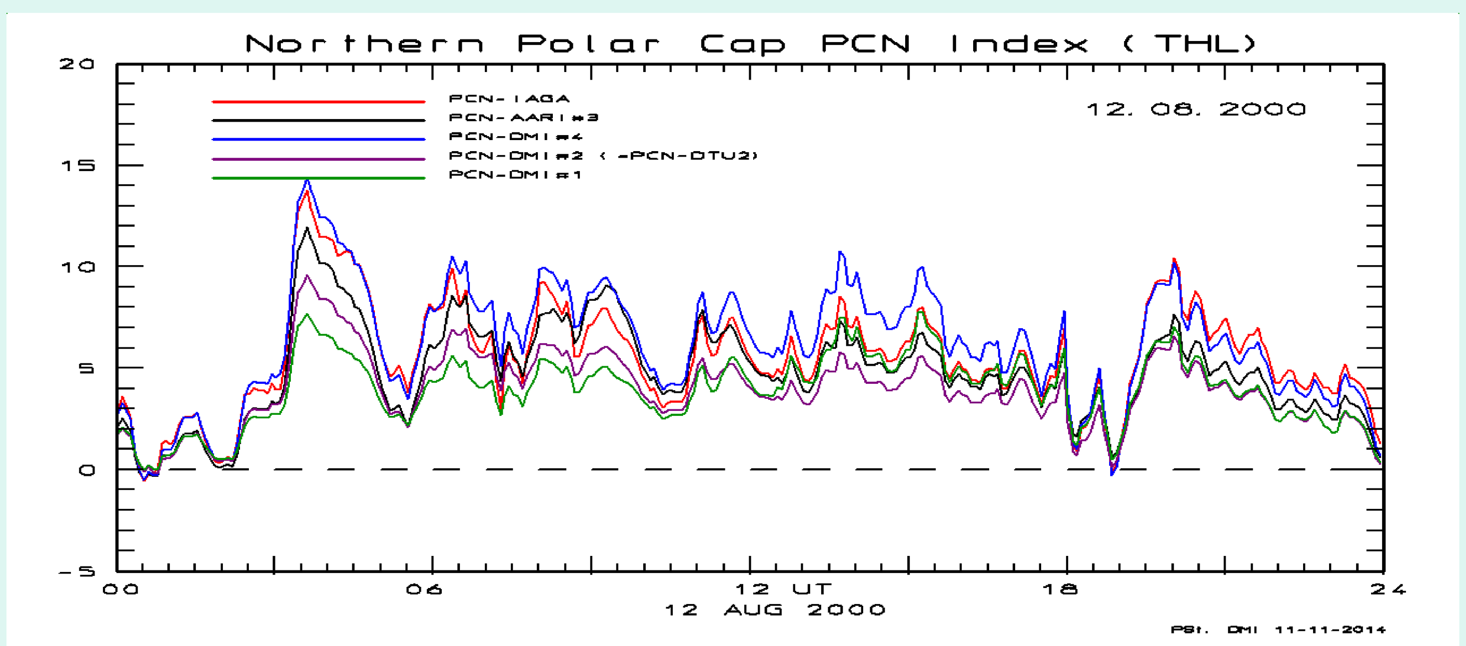

Fig. 1 The example here shows IAGA, DMI#1, DMI#2 (=DTU-S), DMI#4, and AARI#3 PCN index values all derived from Thule data for 12 August 2000.

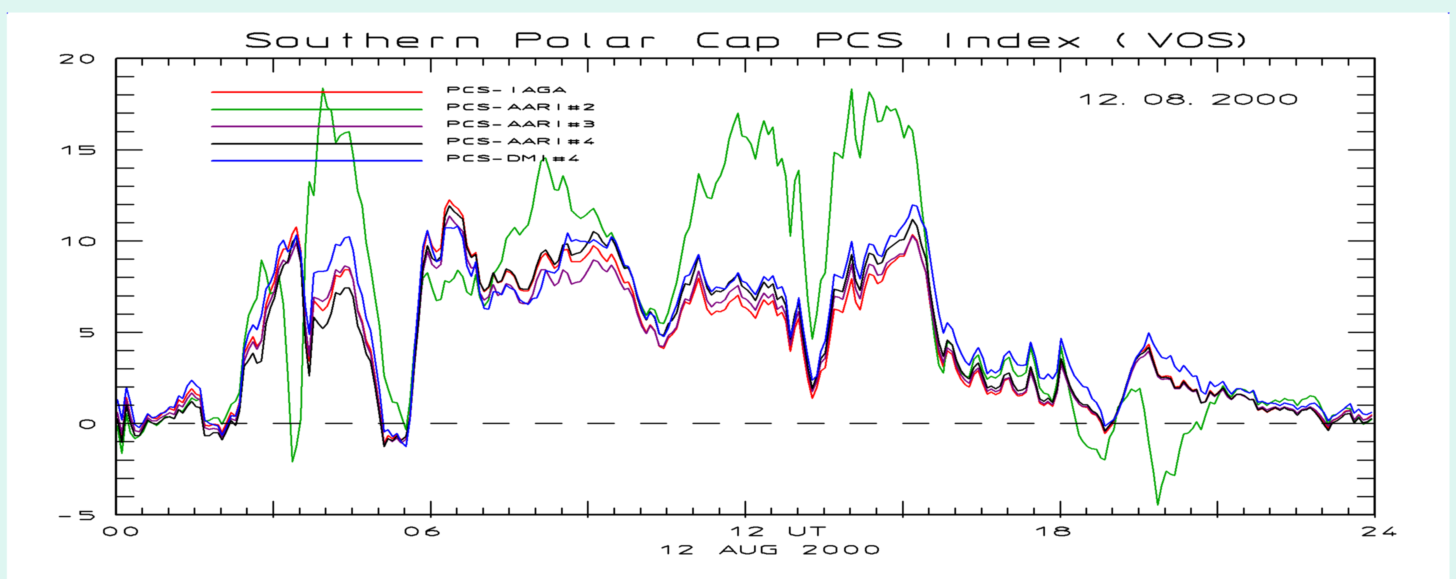

Fig. 2. The example shows PCS data for 12 August 2000 supplied from AARI in versions AARI#2, AARI#3, and AARI#4. In addition, the figure displays IAGA PCS values (in red line) and DMI#4 PCS values calculated for the same day also from Vostok data.

DMI QDC calculations.

The QDC reference level derived at DMI uses the "Solar Rotation Weighted" (SRW) superposition of quiet samples provided from the recorded magnetic data.
The idea is to build the QDC reference level from the quietest samples closest to the day of interest and exposed to the same solar wind conditions.
Data for each hour are examined and a "quietness" weight value is assigned to the average hourly value depending on the variability in the 1-min samples.
In post-event calculations, depending on the separation from the day of interest a further weight value is assigned to the hourly sample according to Fig. 5. The hourly averages are multiplied by the weights, added for an interval of ±40 days, and divided by the sum of weights (Stauning, 2011).

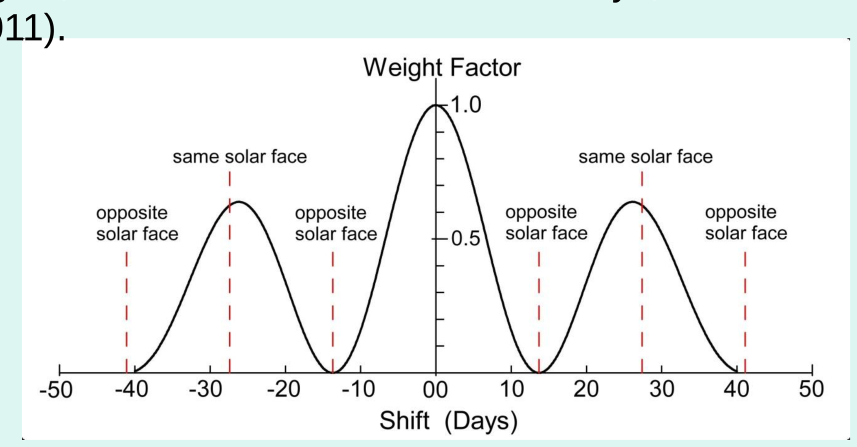

Fig. 5. Solar rotation and separation weights spanning ±40 days (3 solar rotations). Weights in the middle solar rotation period counts 50% while the two other periods count 25% each and balances seasonal effects.

At continuous recording of magnetic data and calculation of PC index values in real time, the stored hourly average values and their assigned quietness weights are combined with the solar rotation and separation weights for the past 40 days up to actual time to provide the best possible QDC value for PC index calculations that now just need the tabulated calibration parameters.
Upon later recalculations the QDC value could gradually be improved as more and more hourly samples with their quietness weights become available. In 40 days after the time of interest, the QDC and PC values are final (if the magnetic data are final).
Contrary to the cubic spline extrapolation based on a succession of 3-days median values for every other of the past 9 days, where missing data from part of a day might generate invalid QDCs, the SRW method is quite tolerant to data gaps.

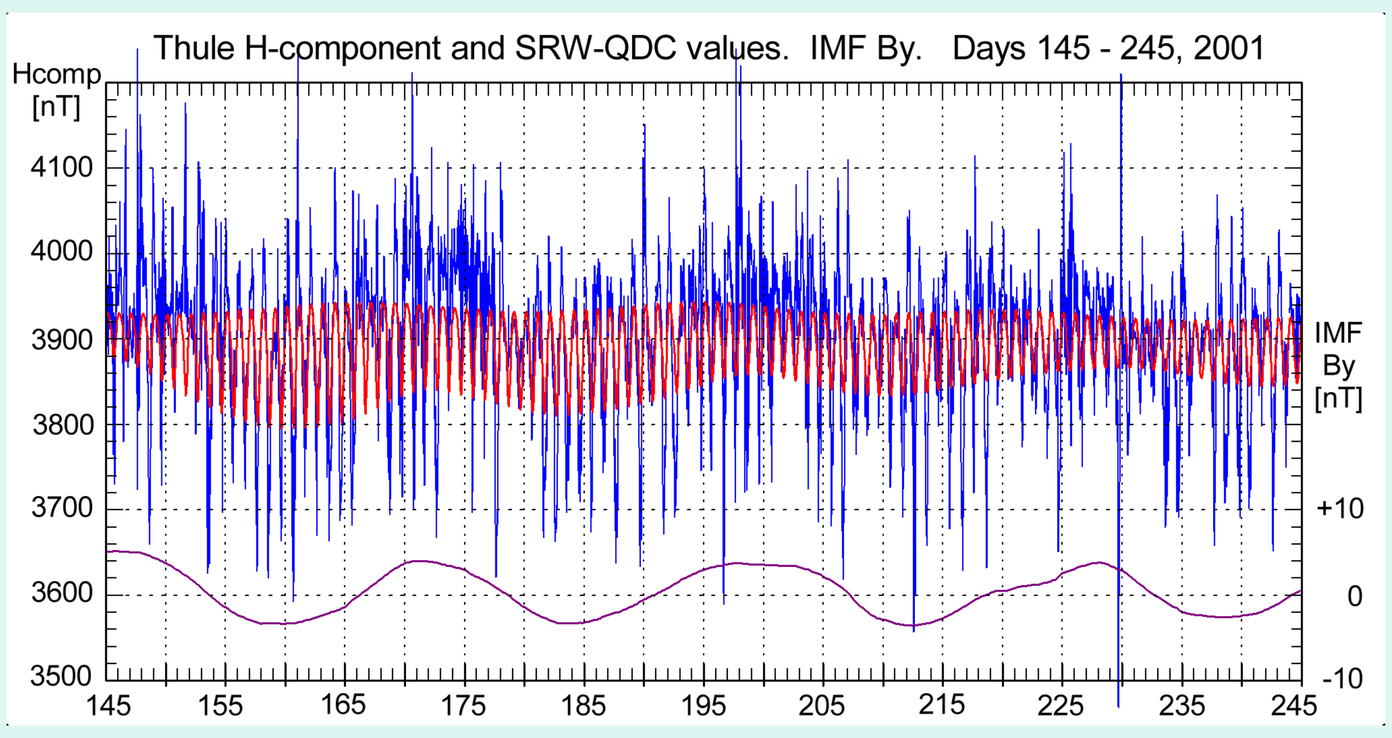

Fig. 6. Example of magnetic recordings and QDC reference level for days 145-245 of 2001. IMF By values are displayed at the bottom on the right scale.

Conclusions.
-The Polar Cap index has the potential to become an important and most useful ground-based magnetic index for Space Weather applications.

- The IAGA adoption of the PC index is an important step. The presentation of archived and near-real time PC index values at the otherwise excellent web site http://pcindex.org could be most useful, among others for forecast (alerts) of geomagnetic storms for power line operators and aurora watchers.

- However, the IAGA PC index derivation procedures should be improved to include proper handling of the IMF By effects on the reference level values. The near-real time PC index values from pcindex.org are often invalid.

- Users should be cautioned against uncritical use of the PCN and PCS final and – in particular – near-real time index values made available at ISGI and PC index web sites.

References:
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Stauning, P. (2013), The Polar Cap index: A critical review of methods and a new approach, *J. Geophys. Res*., Space Physics, 118, 5021–5038, doi:10.1002/jgra.50462. Available (free) at: http://onlinelibrary.wiley.com/doi/10.1002/jgra.50462/pdf
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Troshichev, O. A., Janzhura, A. & Stauning, P. (2006). Unified PCN and PCS indices: method of calculation, physical sense and dependence on the IMF azimuthal and northward components, *J. Geophys. Res.*, *111*, A05208, doi:10.1029/2005JA011402.