Long-term Variations of Open Flux in the Heliosphere

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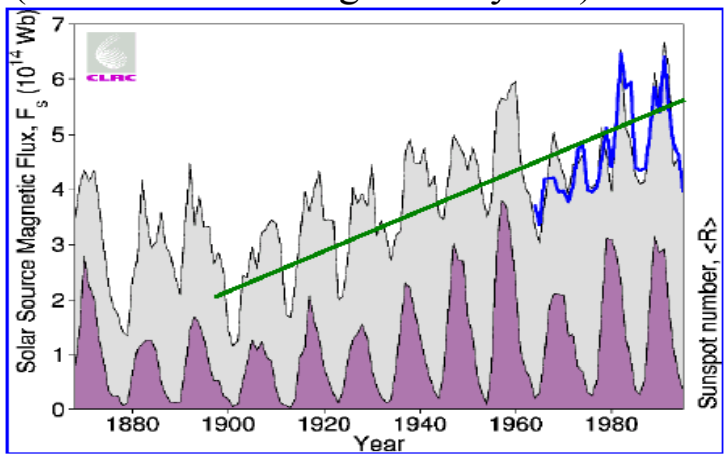
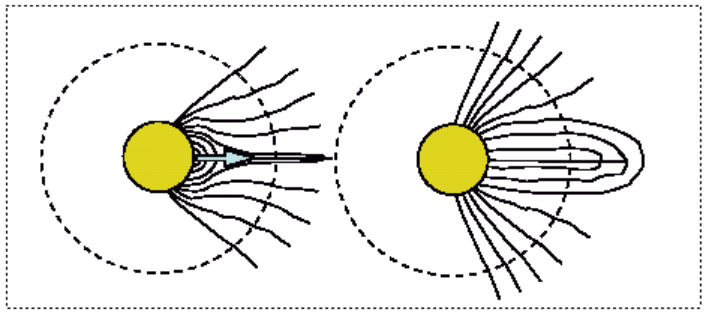
Abstract: The geomagnetic record allows us to infer the strength of the Interplanetary Magnetic Field, $|\boldsymbol{B}|$, at Earth for the past ~175 years. We find B to be $4.0 + 0.29\ (\mathrm{SSN})^{1/2}$ nT, where SSN is the sunspot number. We interpret the SSN-dependent part to be closed flux related to CMEs and flare ejecta, effectively riding on top of a constant minimum of open B of 4.0 nT. At each solar minimum as SSN goes to near zero, the field strength B approaches the same constant value of 4.0 [±0.5] nT (plus a small SSN-related residual if the SSN didn't go all the way to zero), corresponding to a nearly constant open flux of $\sim 4 \times 10^{14}$ Wb. We review the evidence (and the growing consensus) for this startling conclusion. As the sun's polar fields vary considerably from cycle minimum to cycle minimum, it seems that the Heliospheric field is not fully determined by the polar fields, contrary to what is commonly held. As the open flux apparently has stayed close to constant over the past ~175 years, it means that it, in particular, did not double during the past century. In fact, the IMF during the current cycle 23 is very much the same as it was during cycle 13 a century ago. The above conclusions are consistent with GCR-based determinations of B under the assumption that transients play a major role in GCR modulation.

What is "Open Flux"?

All open flux (*e.g.* M. Lockwood):
(more than doubling in 100 years)



Some open, some closed (*e.g.* P. Riley):



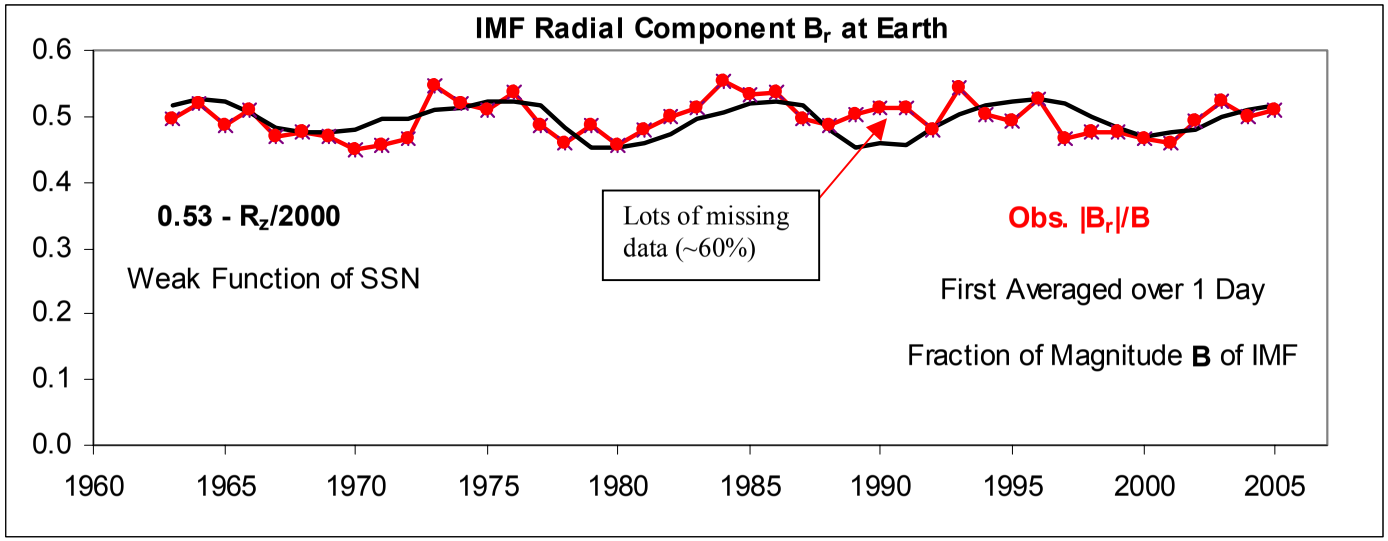
No open flux (Maxwell):

$$\nabla \cdot \mathbf{B} = 0$$

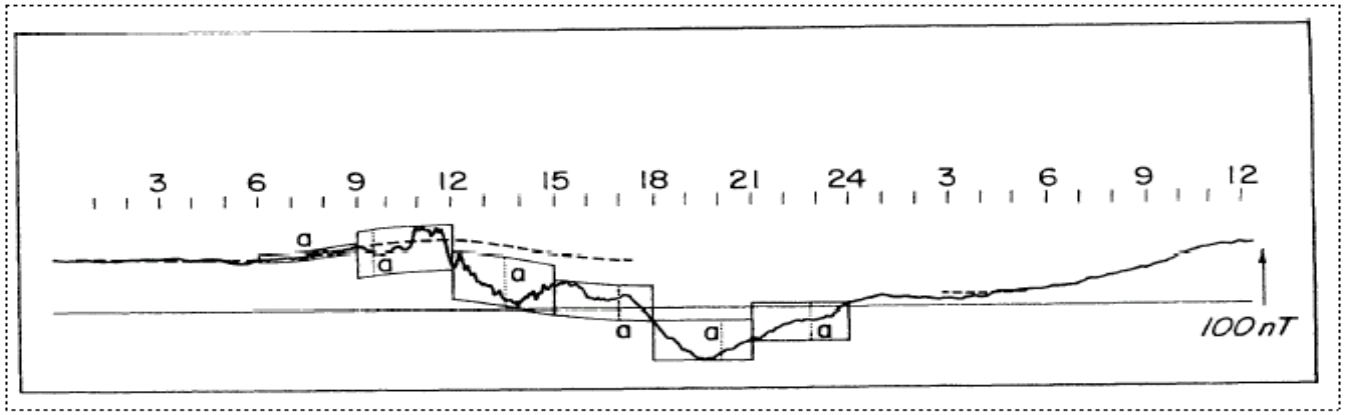
The (unsigned, to circumvent Maxwell) magnetic flux, F, in the Heliosphere is calculated by integrating the unsigned radial component, $|B_r,|$ of the IMF over a surface ("effective" radius R_F) enclosing the Sun. There are some disagreements over whether to count the flux twice (once for each polarity), so we write

$$F = |B_r|\ 4\pi\ R_F^{\,2} / p \qquad \text{where } p = 1 \text{ or } 2.$$

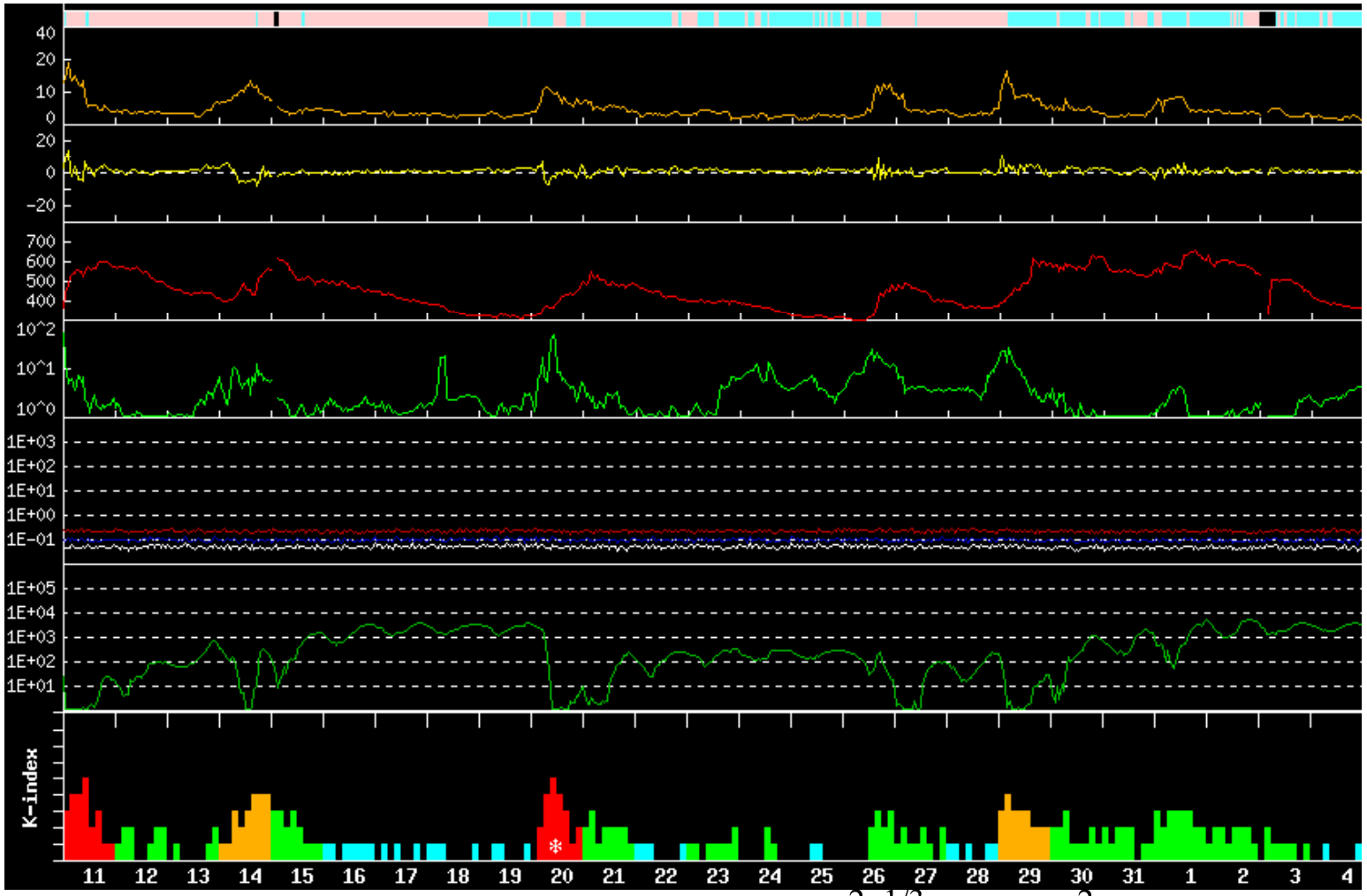
Calculating the radial component is tricky as the IMF varies considerably in direction on many time scales and B_r thus depends on the averaging interval. Often, as we are interested in the large-scale structure) one day is used. One finds that the ratio $|B_r|/B$ is about 0.5 with a small (weak) variation with the SSN: more solar activity makes the direction vary more and thus lowers $|B_r|/B$ slightly. To first order we can thus determine B_r from B. From geomagnetic activity we can determine B and thus estimate the long-term behavior of the flux.



The Earth's magnetic field is confined by the solar wind to a "magnetosphere", which is sensitive to the interplanetary magnetic field and the kinetic energy of the solar wind impinging upon it. The resulting continual adjustment to the ever-changing solar wind conditions is called "geomagnetic activity". Here is a typical example (as measured at the surface of the Earth):

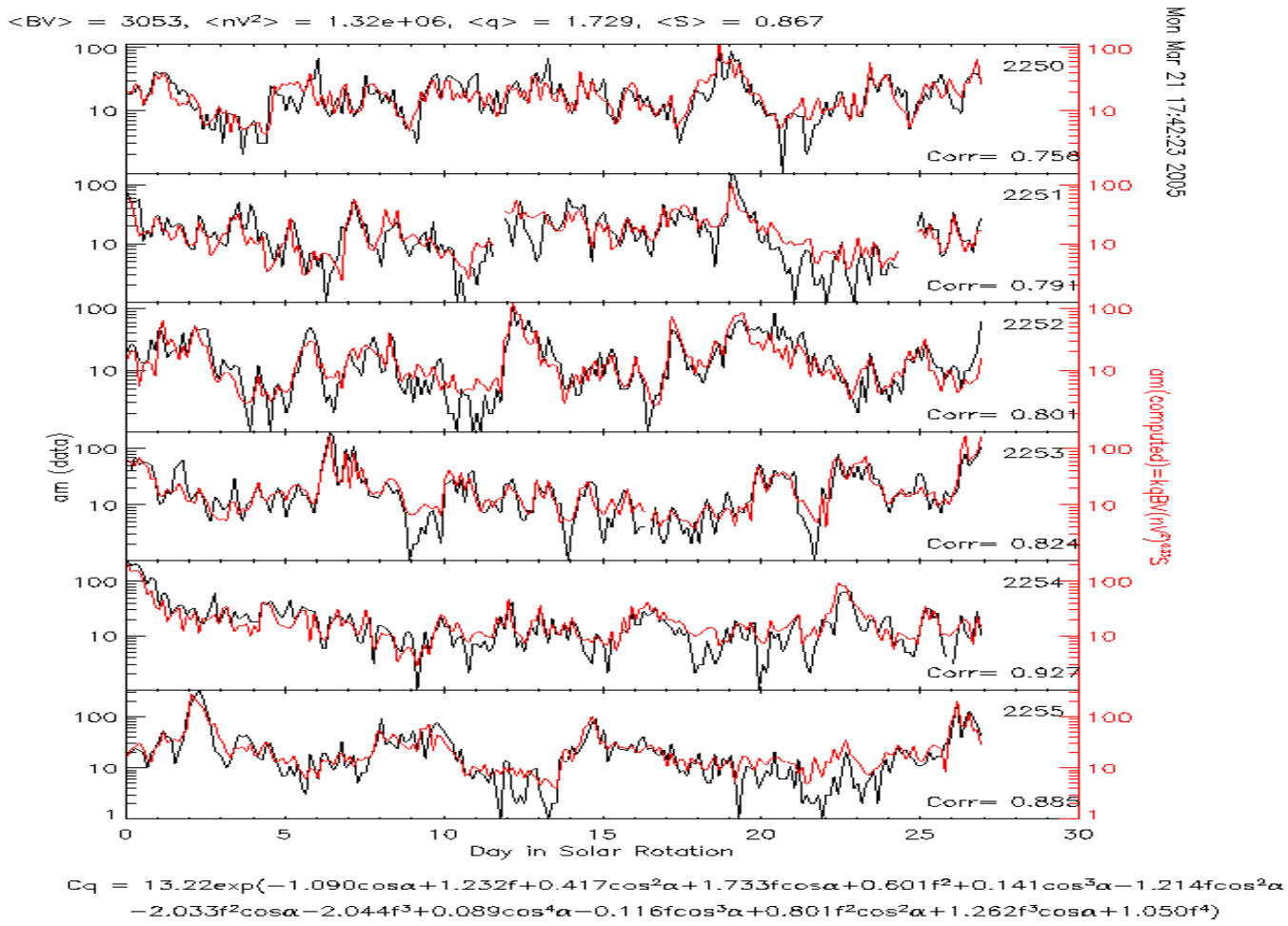


From the amplitude of the variation of the field ***within*** a certain interval (three hours in the above example) one constructs a geomagnetic "index" that codifies that variation and can be used as a proxy for solar wind conditions during the interval. Note the difference between this 'range' index and the D_{st} index (total deviation from quiet level).



$$A = k\, q(a, f(V))\, (B\, V)\, (n\, V^2)^{1/3} \sim B\, V^2$$

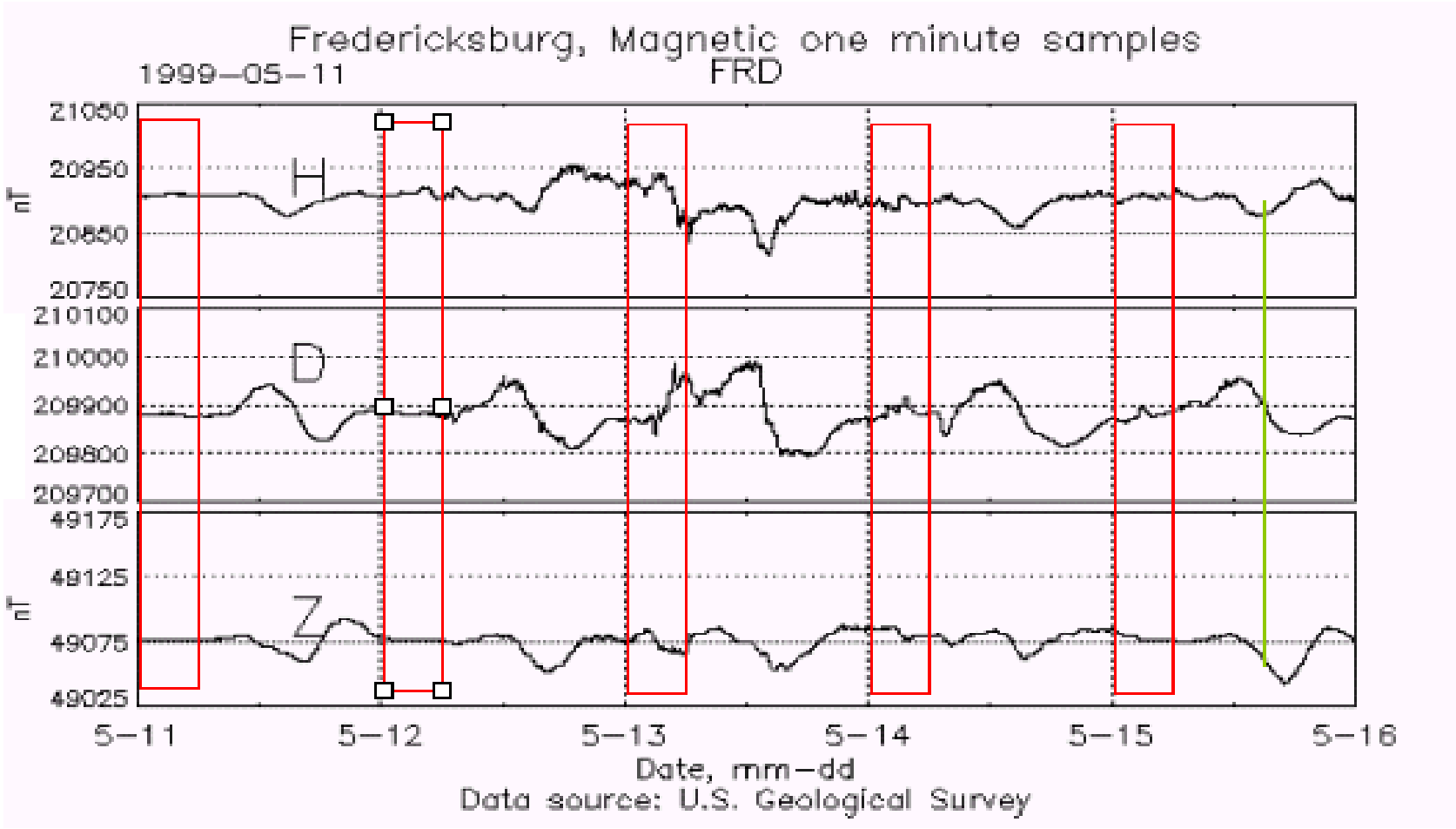
Typical Bartels solar rotation showing high-speed streams and their geomagnetic effect.



Am-index calculated from solar wind parameters. Very good fit, except for the lowest values of *am* which are very difficult to measure.

We can calculate *am* from *B* and *V*, or by inversion of the formula, the quantity BV^{2} from *am*. But we need to **separate** *B* and *V*, and *am* only goes back to 1959. The long-term index *aa* (back to 1868) cannot be recreated and its calibration cannot be checked, so we cannot be sure that trends are quantitatively correct.
The fundamental problem is to remove the quiet –time diurnal variation, *Sq*, as *am*, *aa*, and *ap* are defined as the amplitude of the variation with *Sq* removed. Identification of *Sq* is very difficult and requires a very skilled observer or [for computer automated methods] a record with high time resolution.

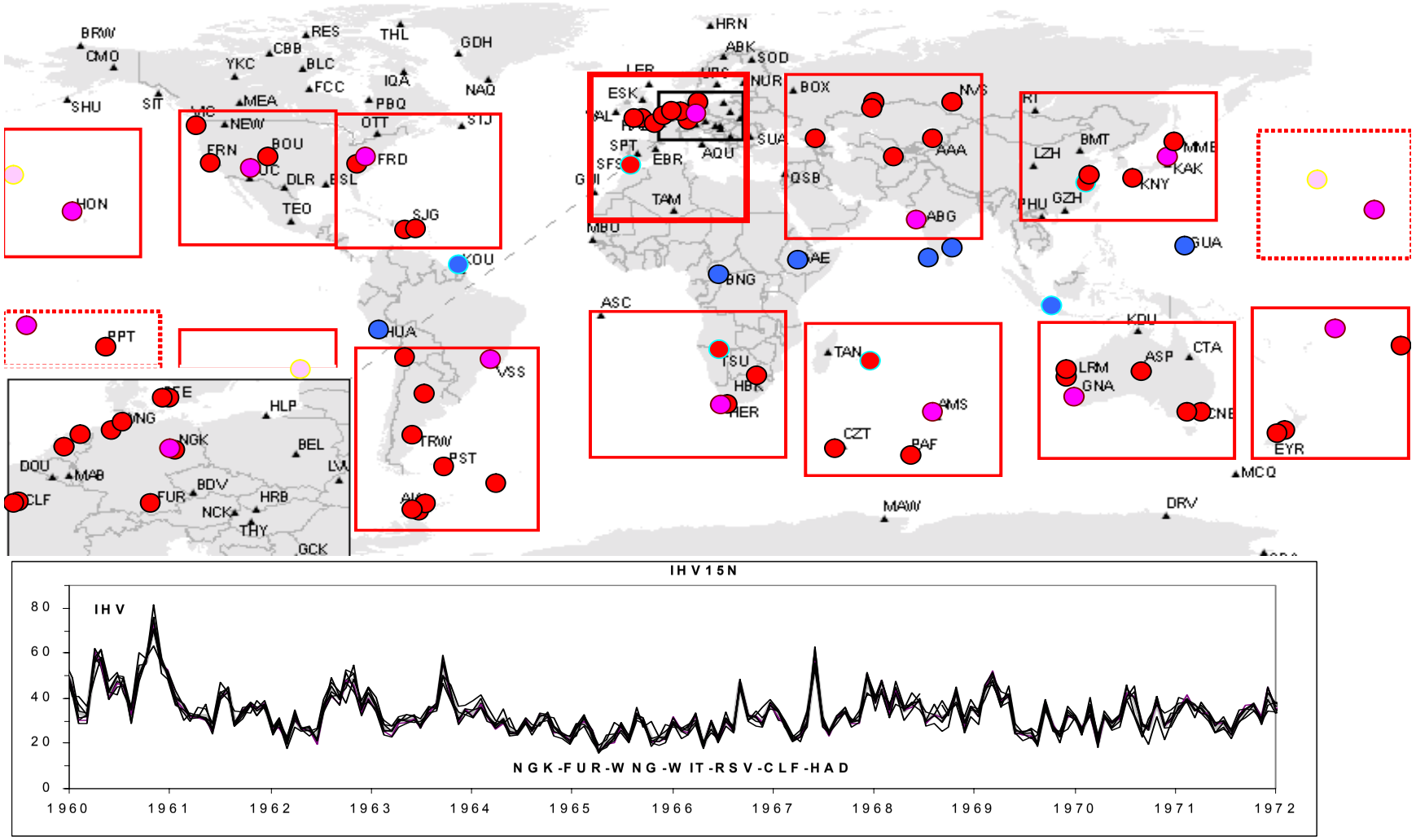
Some years ago Ed Cliver and myself found a way around these problems leading to the realization that we can reliably [to within 10%] infer both *B* and *V* from the oldest continuous geomagnetic records [back to the 1830s and in some cases beyond] with only one reading per hour. This talk will show how we do it and what conclusions can be drawn from this work as well as comment on other attempted reconstructions. **The basic idea is that if the Sq during the day gives you grief; use only data from the deep night side. This throws away 75% of the data, but also 99% of the problems.**

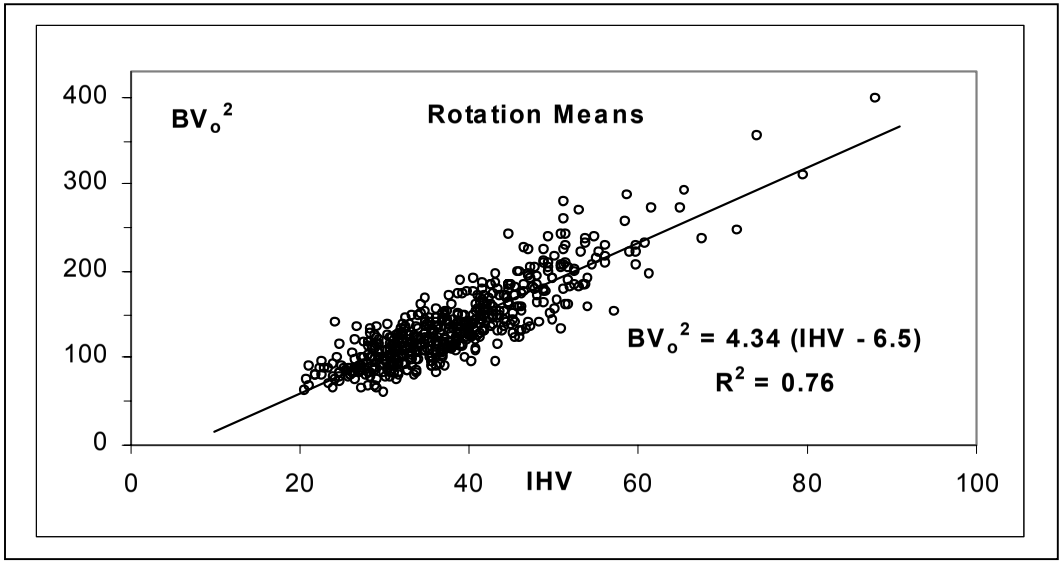


New index: InterHourly Variability index, IHV

IHV = sum of unsigned differences between 7 hourly means centered at midnight

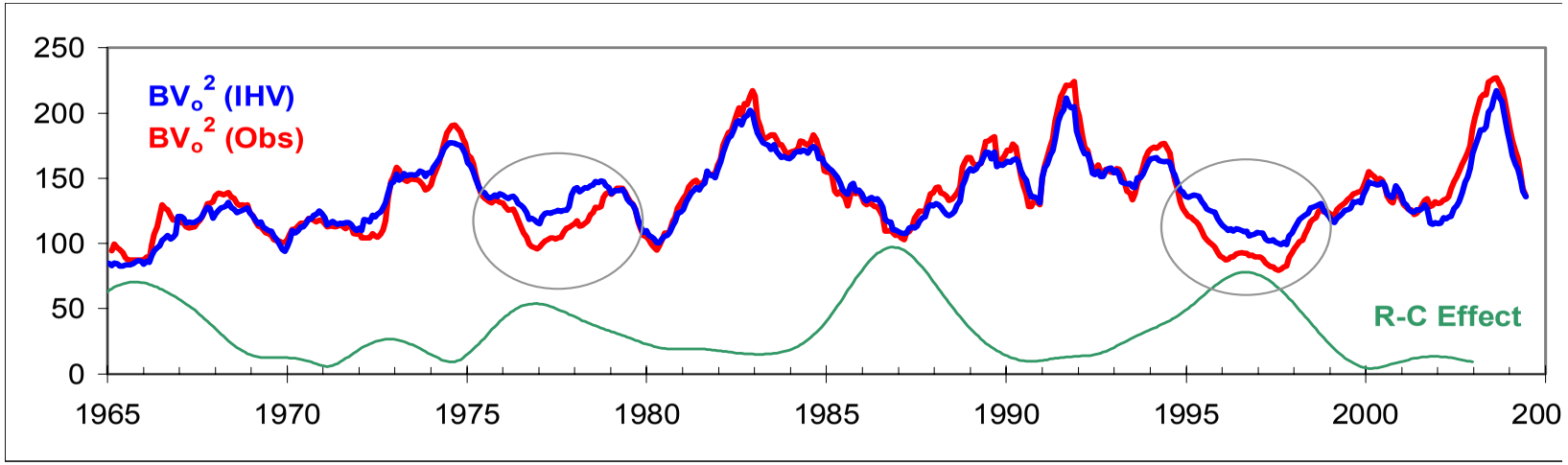
Stations Used for Construction of IHV-index

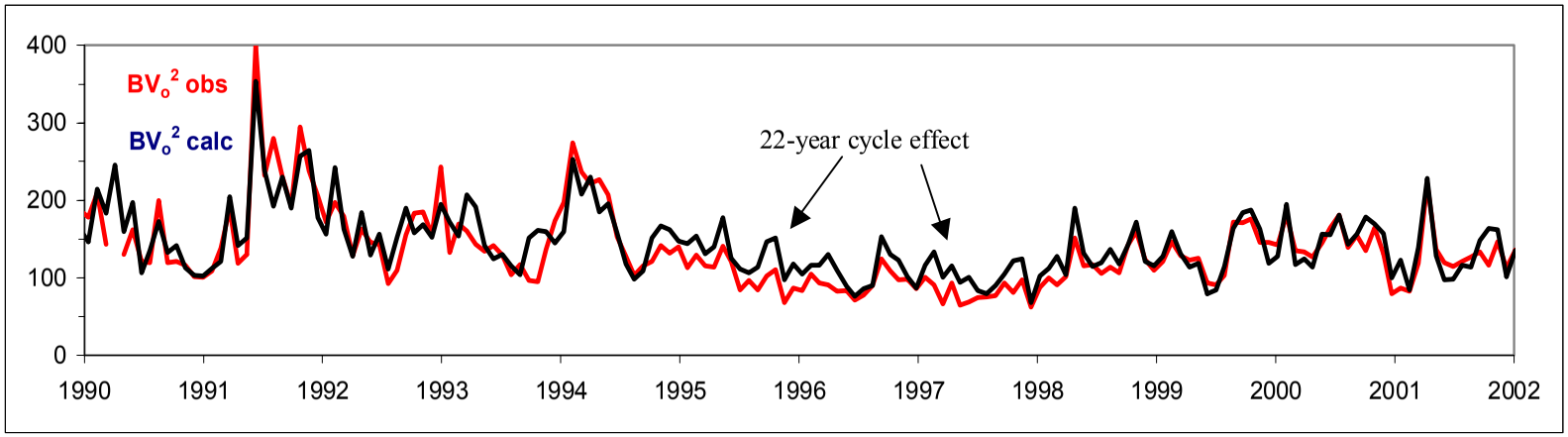




The IHV-index is strongly correlated with BV^2 on a 27-day rotation basis.

There are some second-order effects [22-year cycle] that we can either ignore (they are small) or correct for:




400
300
200
100
0
BV_o^2 obs
BV_o^2 calc
22-year cycle effect
1990
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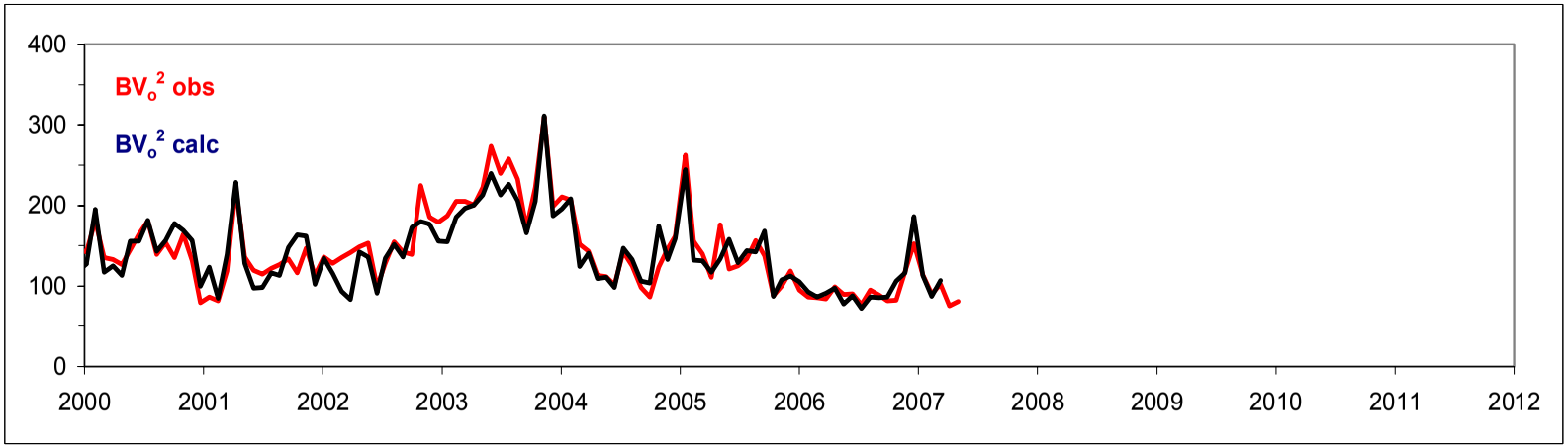
400
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BV_o^2 obs
BV_o^2 calc
2000
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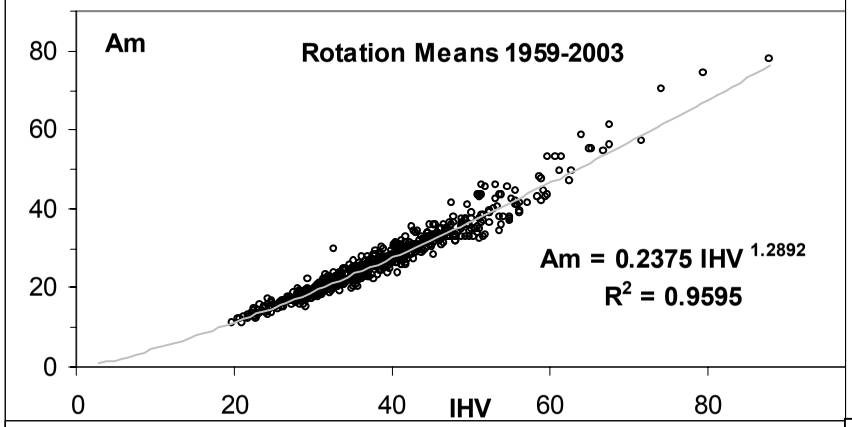
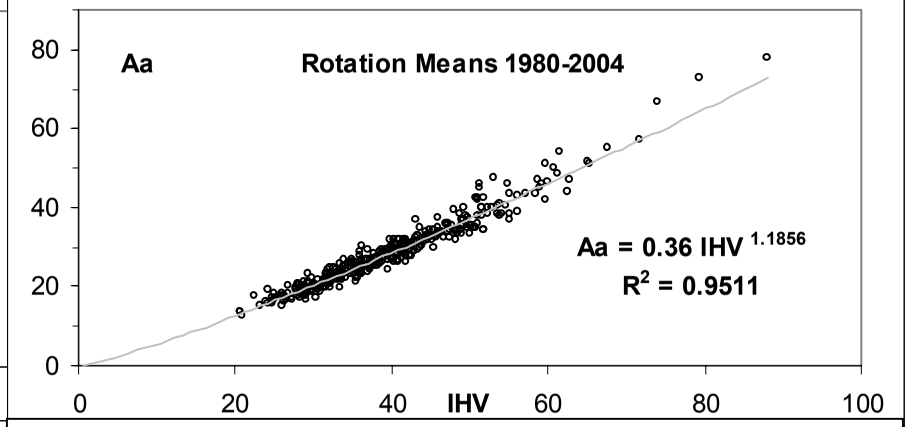
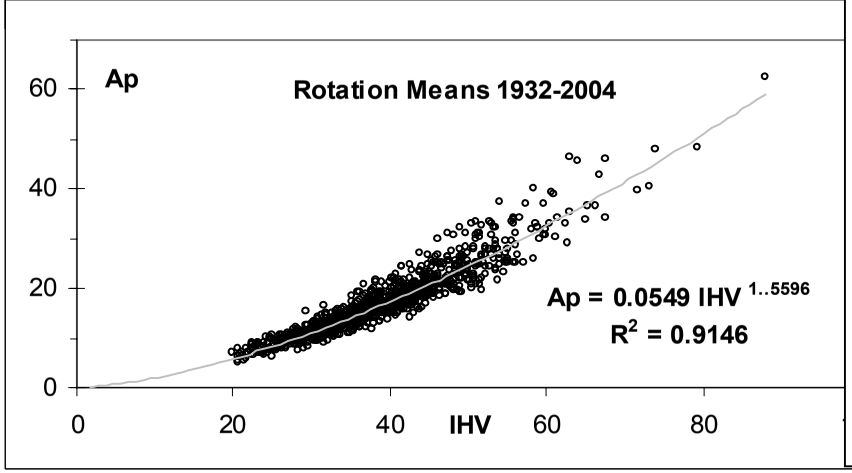
2012

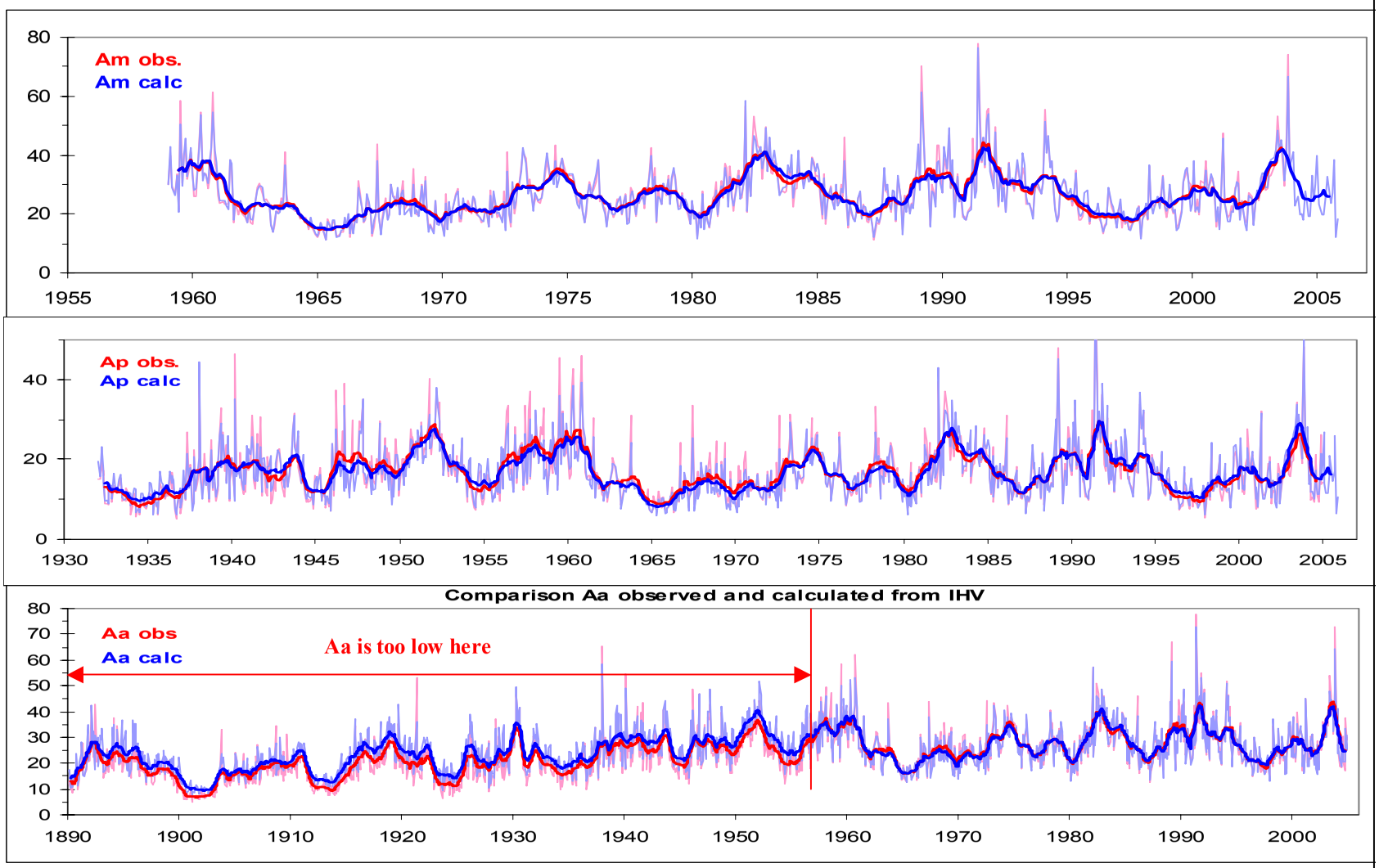
Comparison with Amplitude Indices



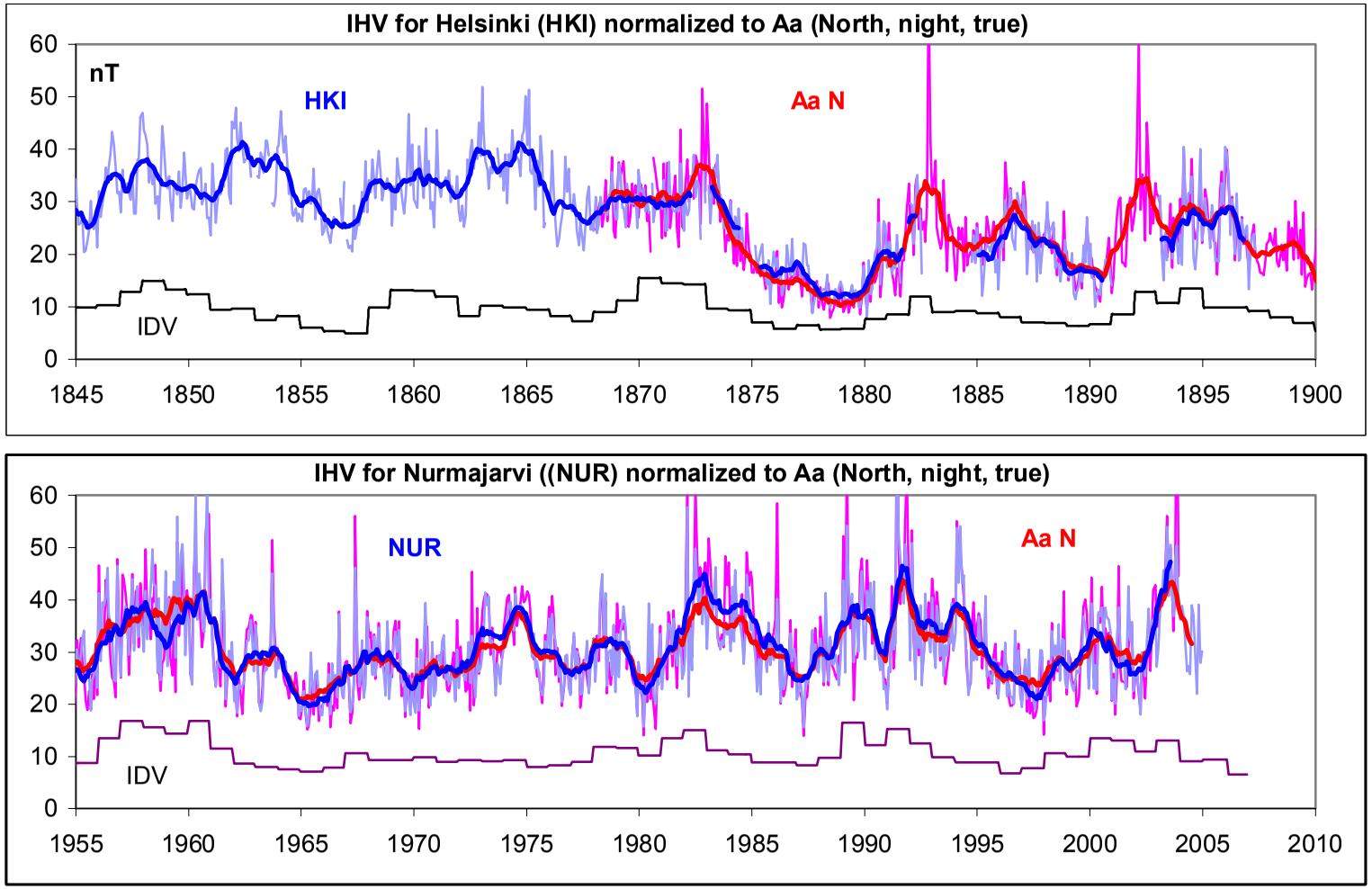




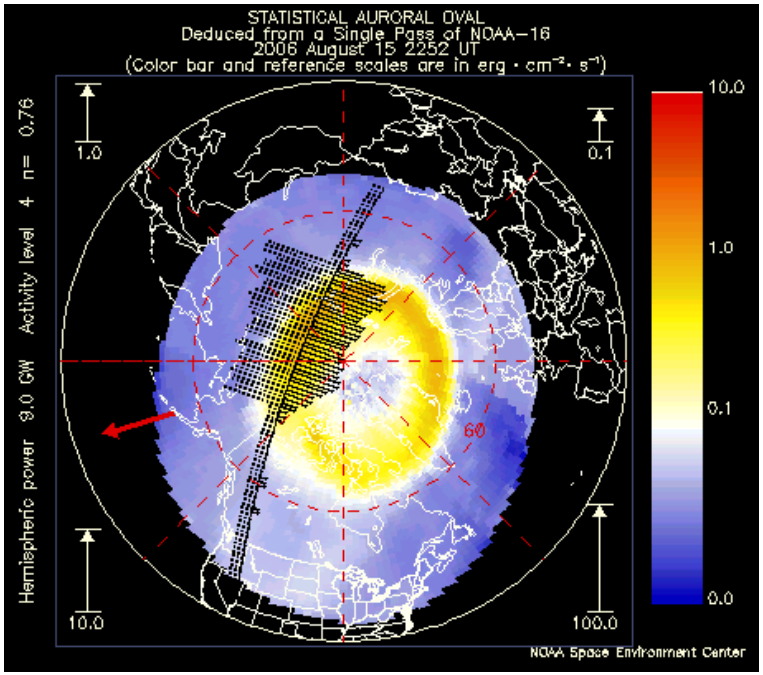
The relationships are slightly non-linear [most so for the *Ap*-index]. For the *Aa*-index we have chosen the time since 1980 where there has been no change in stations [and, hopefully, in procedures and calibration]. We can now use these empirical relations to *calculate* the classical amplitude indices:



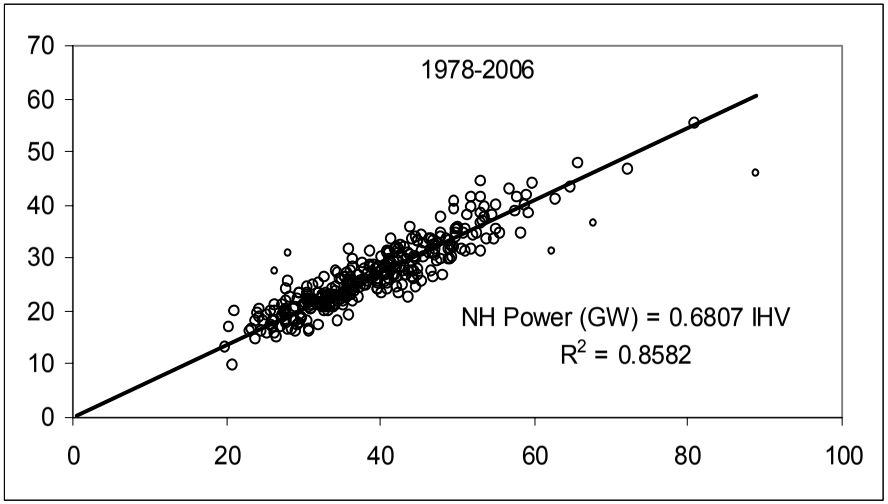
It would seem that the *aa*-index is in need of a recalibration before 1957.

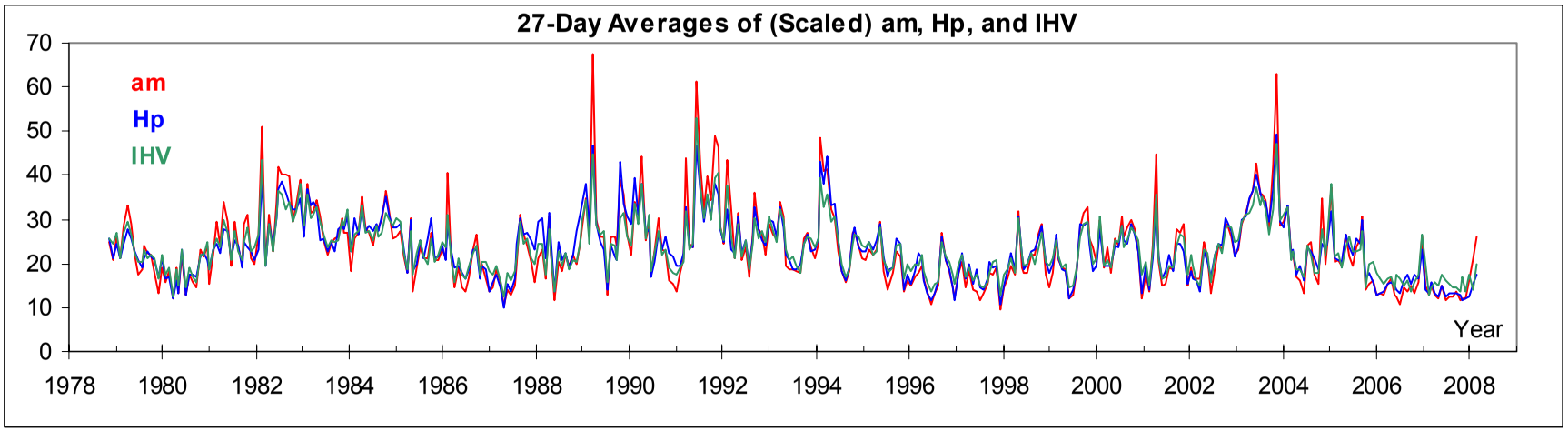


Here is an example of what can be done using Helsinki back to 1844.



Physical meaning of the IHV-index = Energy input to upper atmosphere

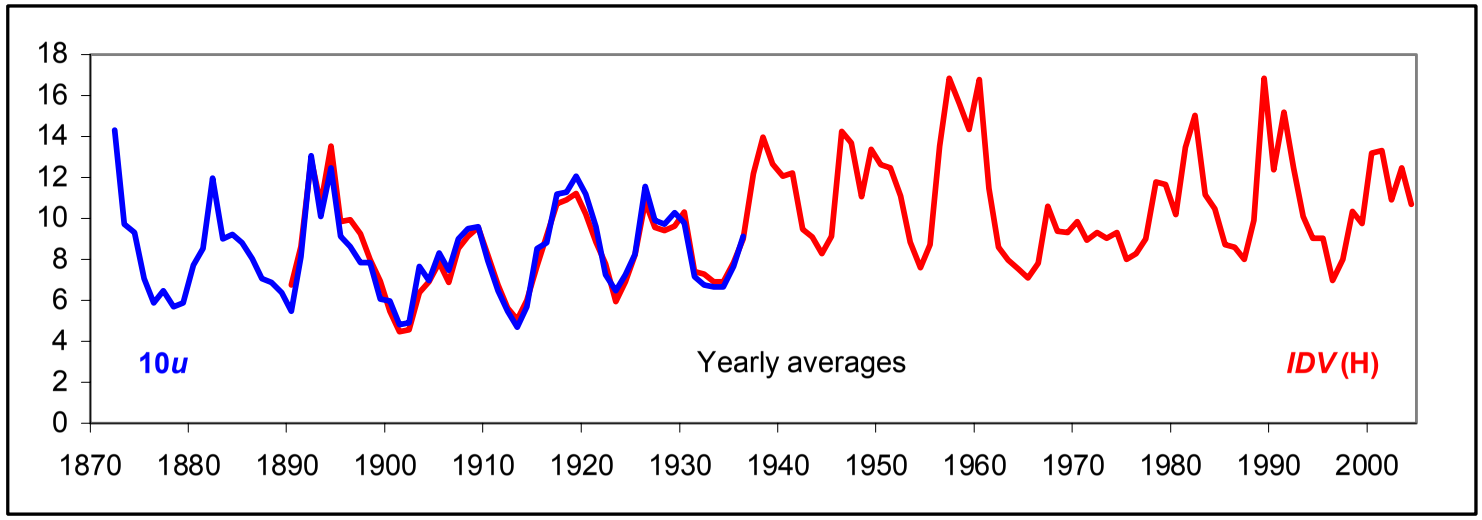




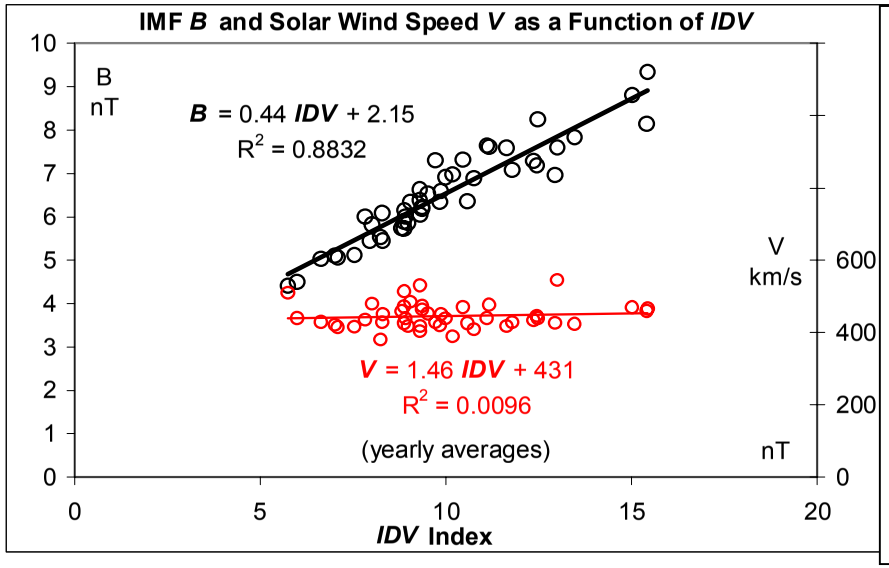
The IDV-Index, a Modern Version of Bartels' *u*-measure

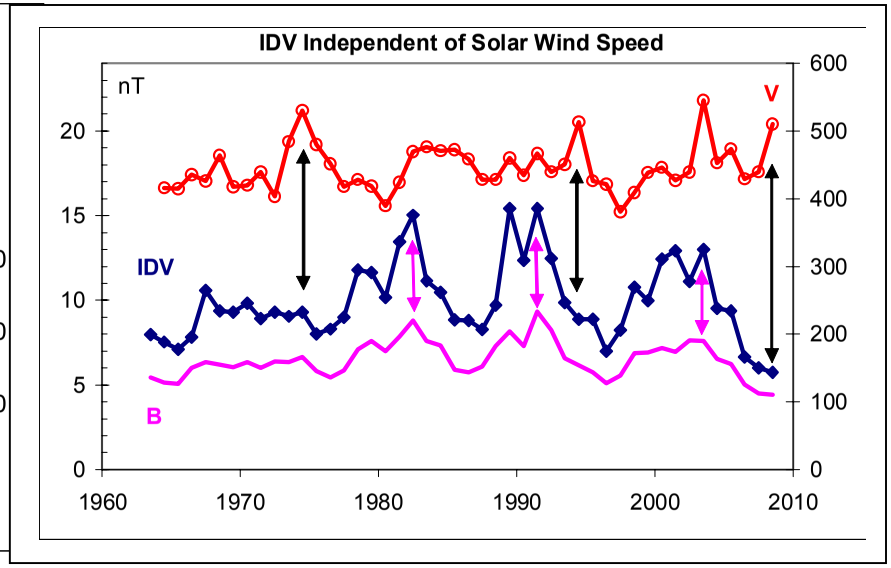
The *IHV*-index captures activity on a time scale of hours. How about on a time scale of days? Julius Bartels defined his *u*-measure as the monthly (or yearly) mean of the unsigned differences between the mean values of the H-component on two successive days. We found that you get essentially the same result using the mean over the whole day, a few hours, or only one hour. Our InterDiurnal Variability index *(IDV*) is then simply the average *u*-measure (in nT, not the original 10 nT units) using only one hour (preferably the midnight hour if available) for as many stations as possible below 51° corr. geomagnetic latitude:

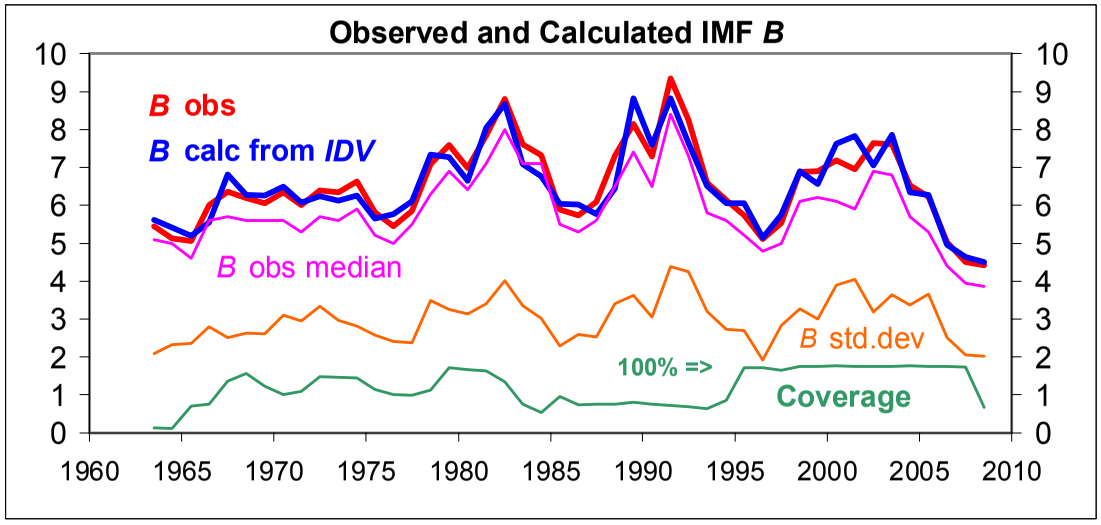
Note that *u* and *IDV* did not register the strong high-speed streams in 1910, 1930, 1952, 1974, 1994, and 2003. This (especially 1930) was a deadly blow to the *u*-measure.



What is the *IDV*-index Measuring? IMF Strength !



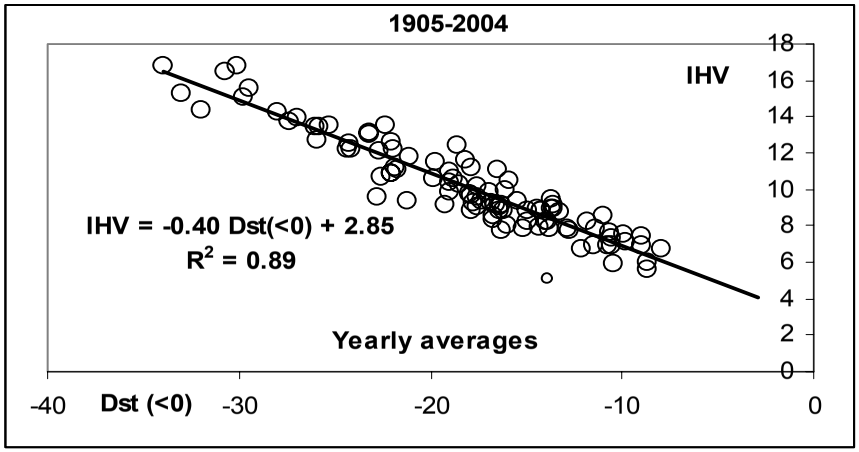




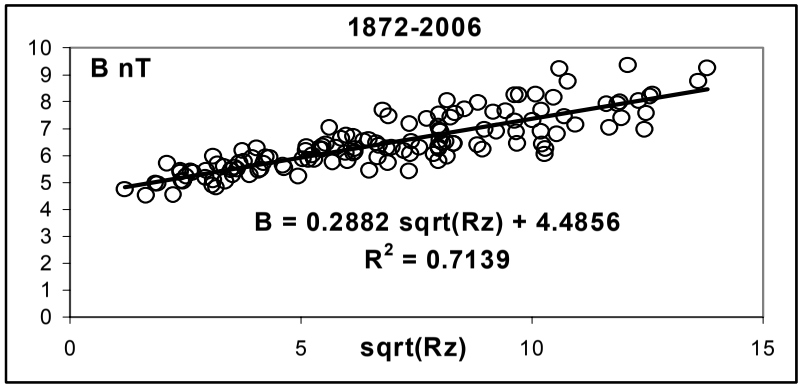
IDV does not 'see' the high-speed solar wind. But there is a robust correlation with the IMF magnitude, *B*.
So instead of the *u*-measure being a failure, its modern equivalent [*IDV*] has a very useful property: response to *B* only.

IDV measures the same as the Negative part of Dst Index

Coronal Mass Ejections (CMEs) add (closed) magnetic flux to the IMF. CMEs hitting the Earth create magnetic storms feeding energy into the inner magnetosphere ("ring current"). The *Dst*-index is aimed at describing this same phenomenon, but only the negative contribution to *Dst* on the nightside is effectively involved. We therefore expect (negative) *Dst* and *IDV* to be strongly related, and they are:

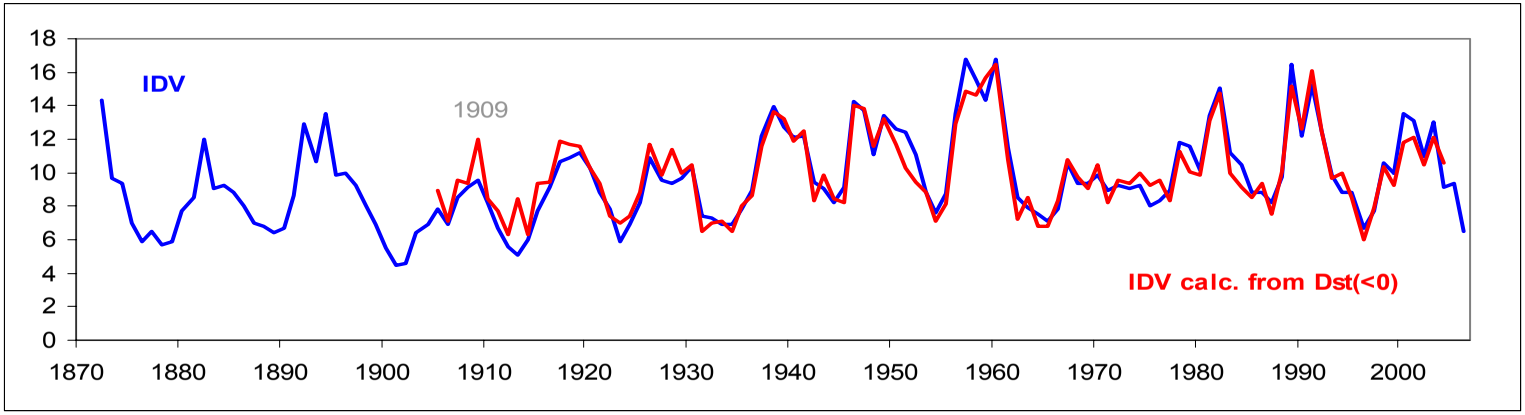


We used a derivation of *Dst* by J. Love back to 1905. Similar results are obtained with the *Dst* series by Mursula *et al.* (to 1932) or with the "official" *Dst* series (to 1957).
The very simple-to-derive *IDV* series compares favorably with the much more elaborate *Dst*(< 0).

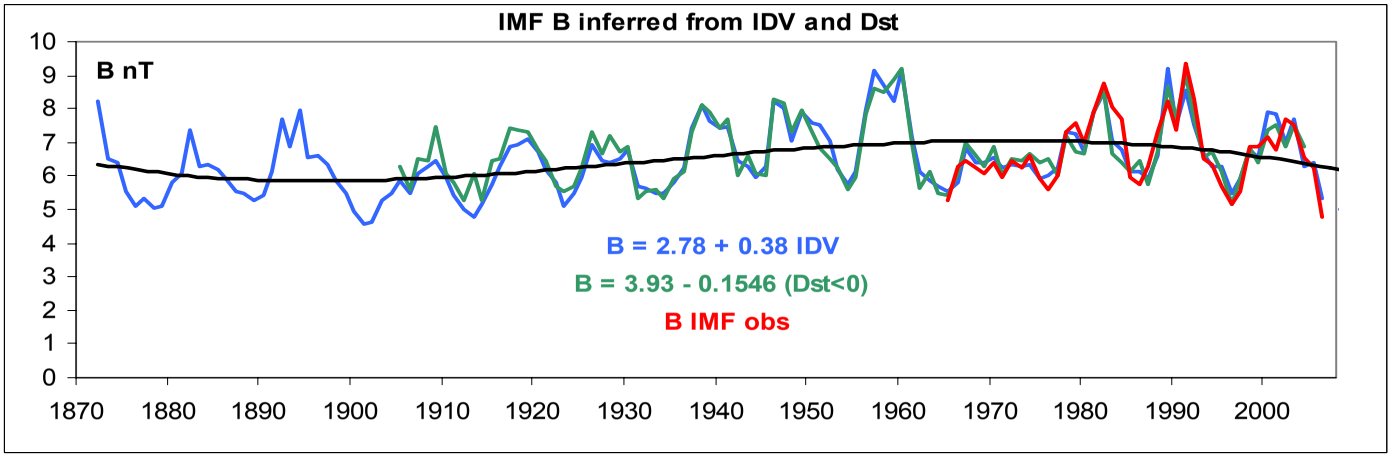


Since there is also a good correlation between *B* and the square root of the sunspot number (left), we can infer *B* from *Rz* as well.

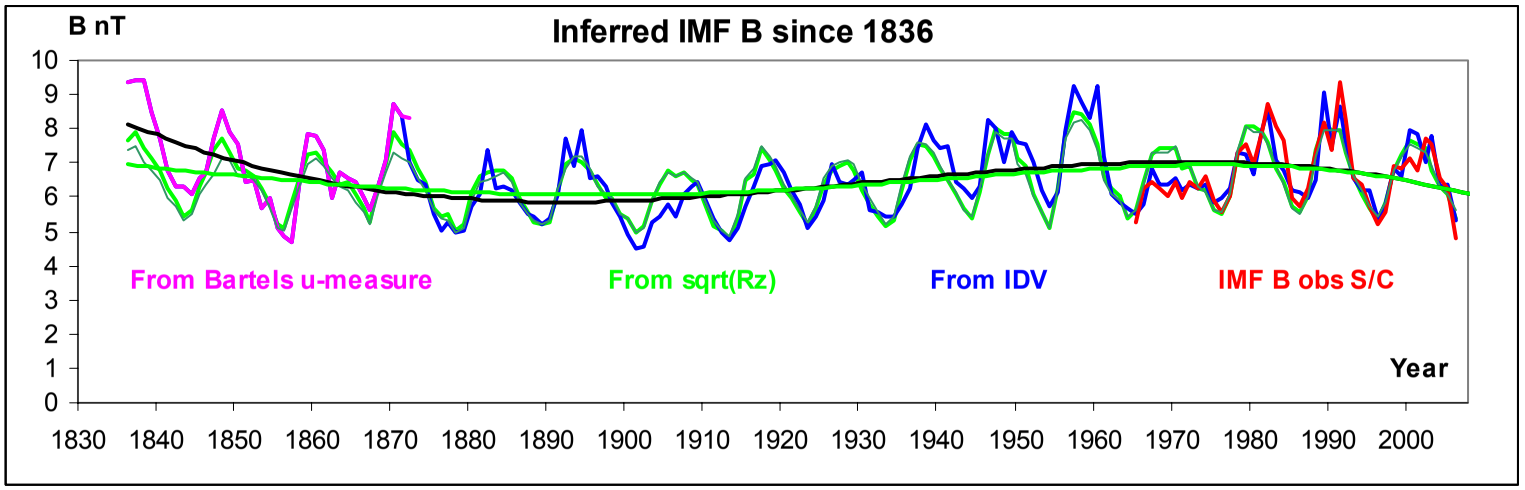
Here are both time series (*IDV* and *IDV* calculated from *Dst* (< 0)):

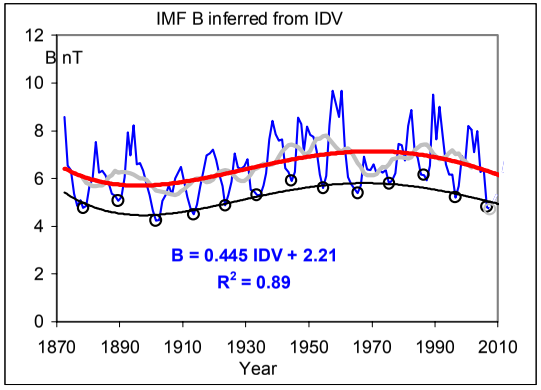


Using regressions of *IDV* and *Dst* (< 0) on IMF *B* we can directly estimate *B* back to 1872:

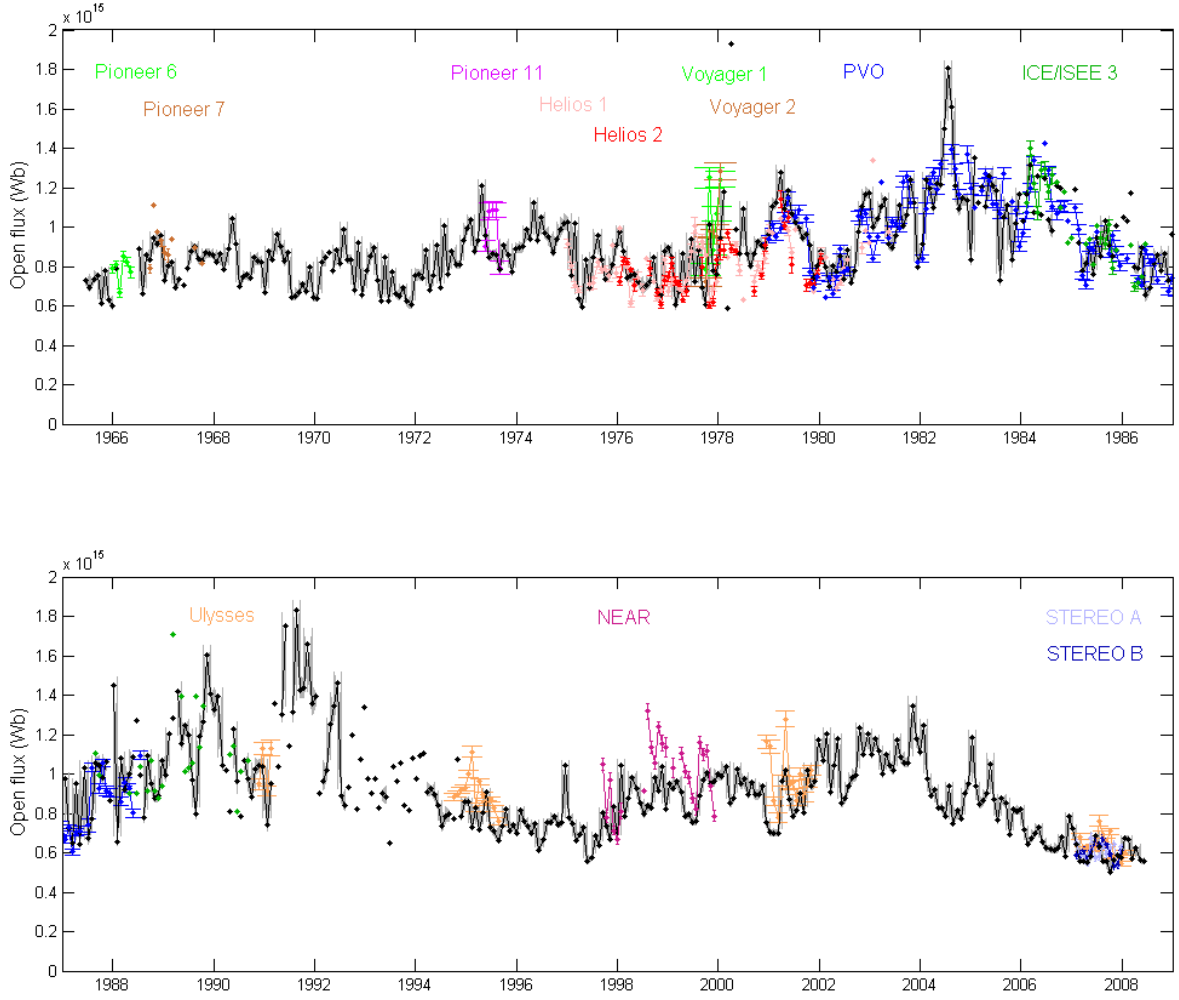


Can we go further back in time? Bartels had determined the *u*-measure from 1836 on, but with less confidence before 1872. Here is what we get if we infer *IDV* (and then *B*) from *u* back to 1836:





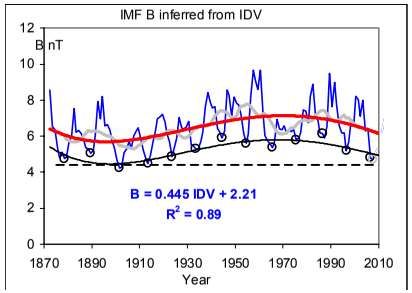
The smooth curve is a 4th-order polynomial fit. One can also just fit the values at solar minima (to eliminate most solar activity) with essentially the same result. We may be approaching another minimum in the Gleissberg cycle. The IMF *B* for 2008 (so far) is the lowest in the last 107 years.



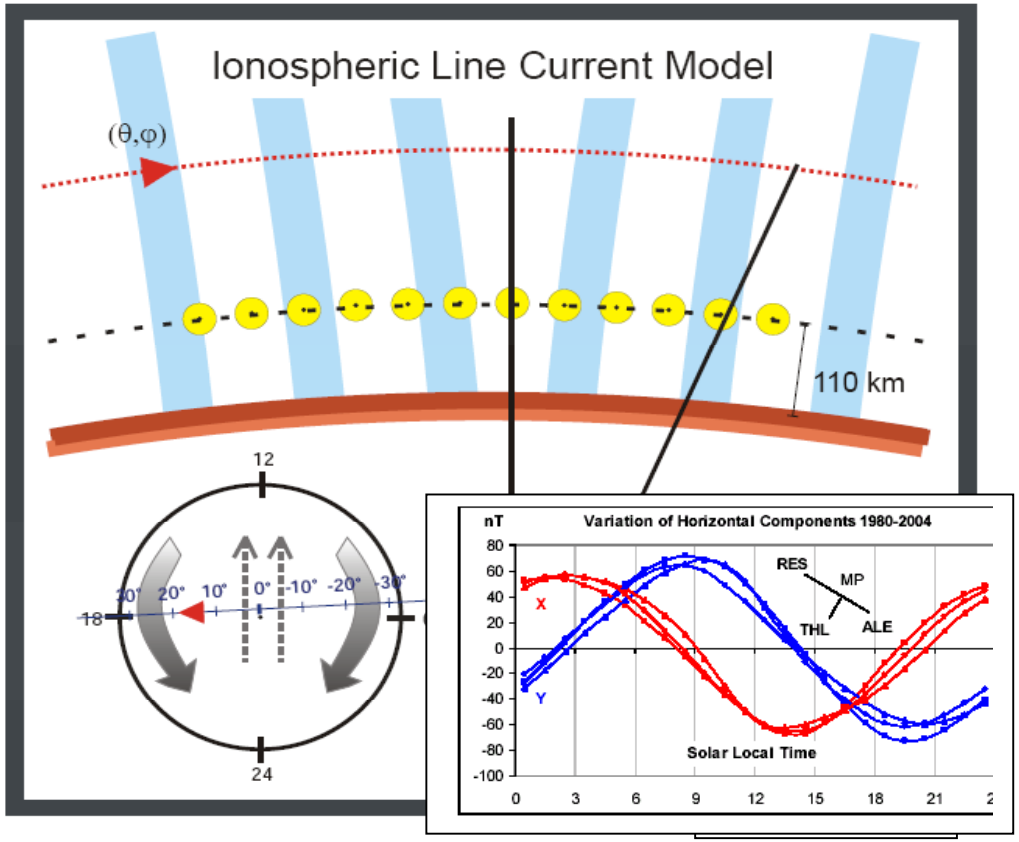
Owens et al. (under review): Open flux independent of latitude. Very similar to our *B* derived from IDV

The latest IMF data show *B* [and hence |*Br*|] that are the smallest yet during the spacecraft era (although not much smaller), in fact B is at its 'floor' as it was 107 years ago.

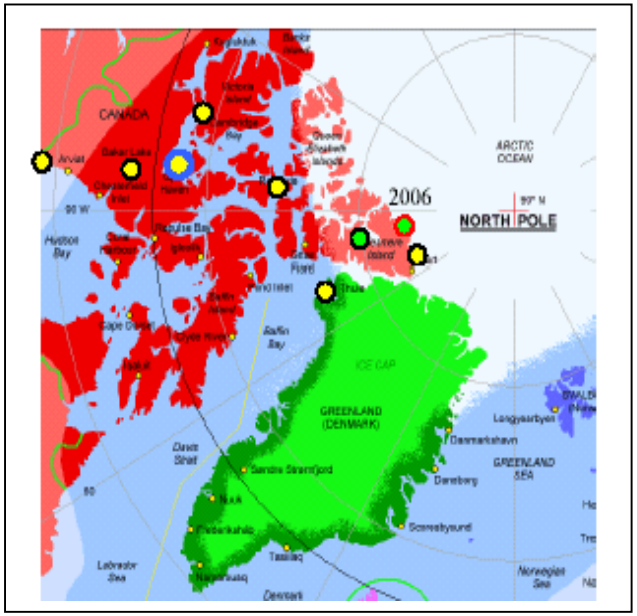
Note that the Ulysses polar passes in 1994-1995 were not yet at solar minimum, as is duly reflected in the somewhat higher flux.



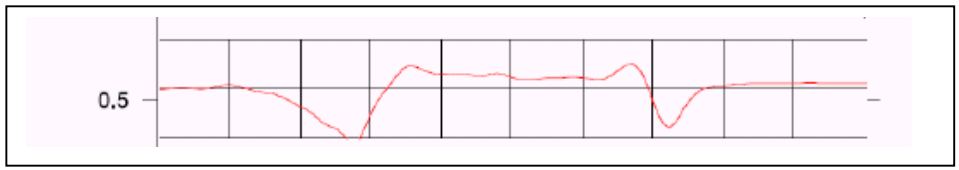
Polar Cap Current and Polar Cap Potential

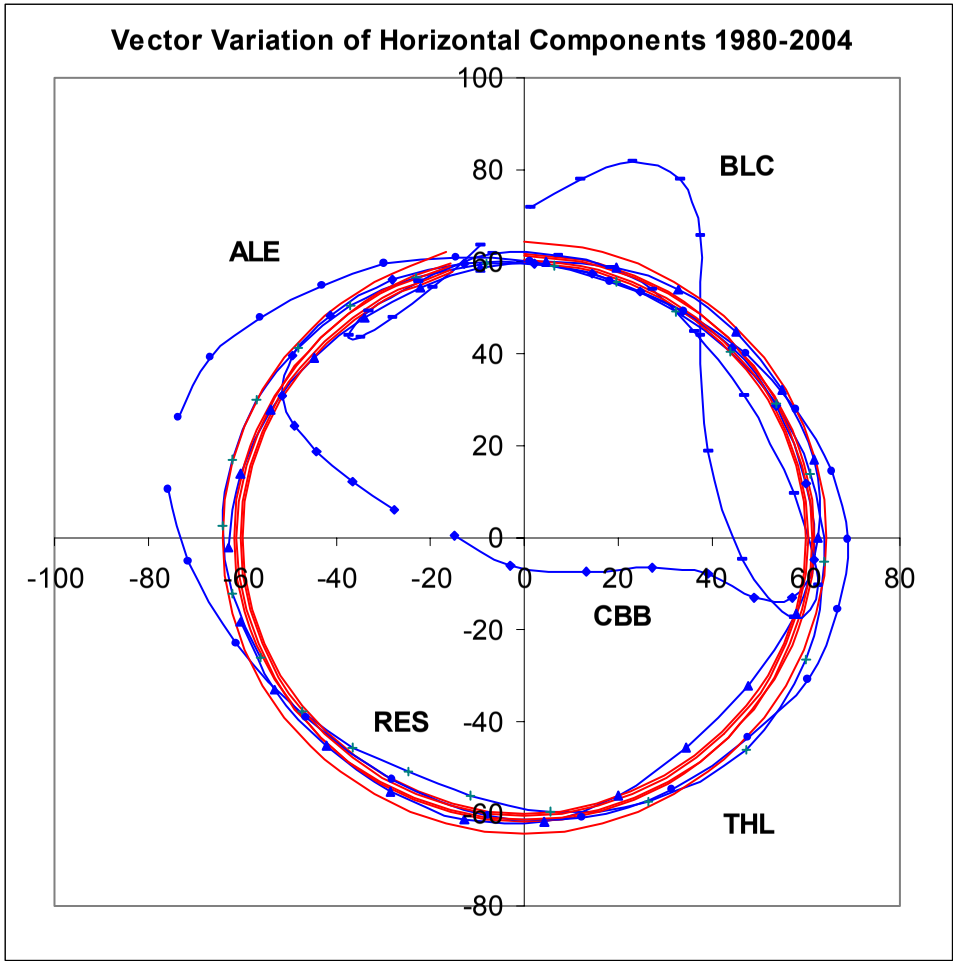


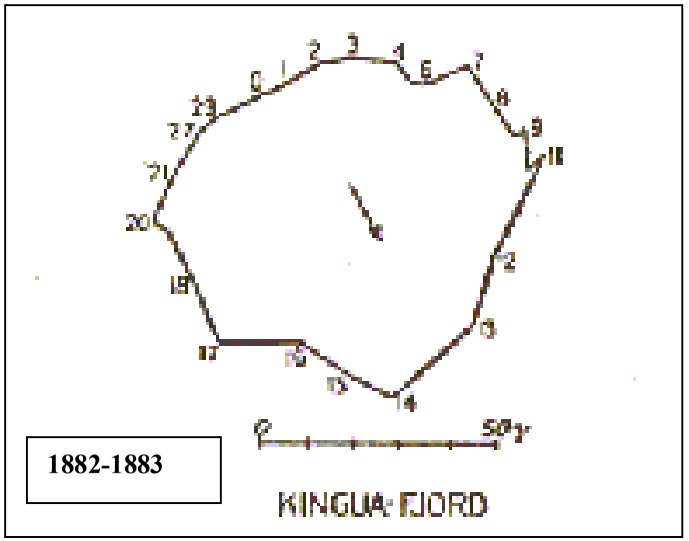
Across the Earth's polar caps flows a current in the ionosphere. The current is fixed in relation to the direction to the Sun. Its magnetic effect is readily (and has been since 1883)



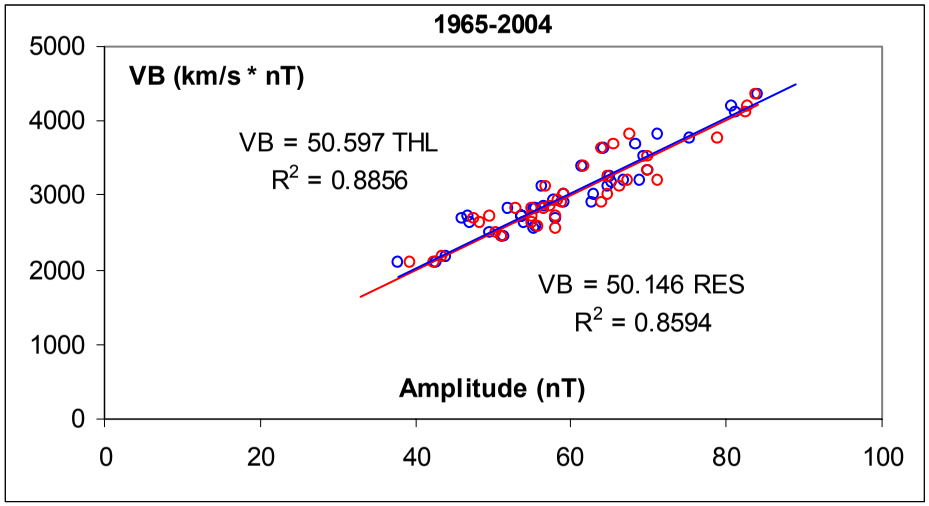
The current derives from the Polar Cap Electric Potential





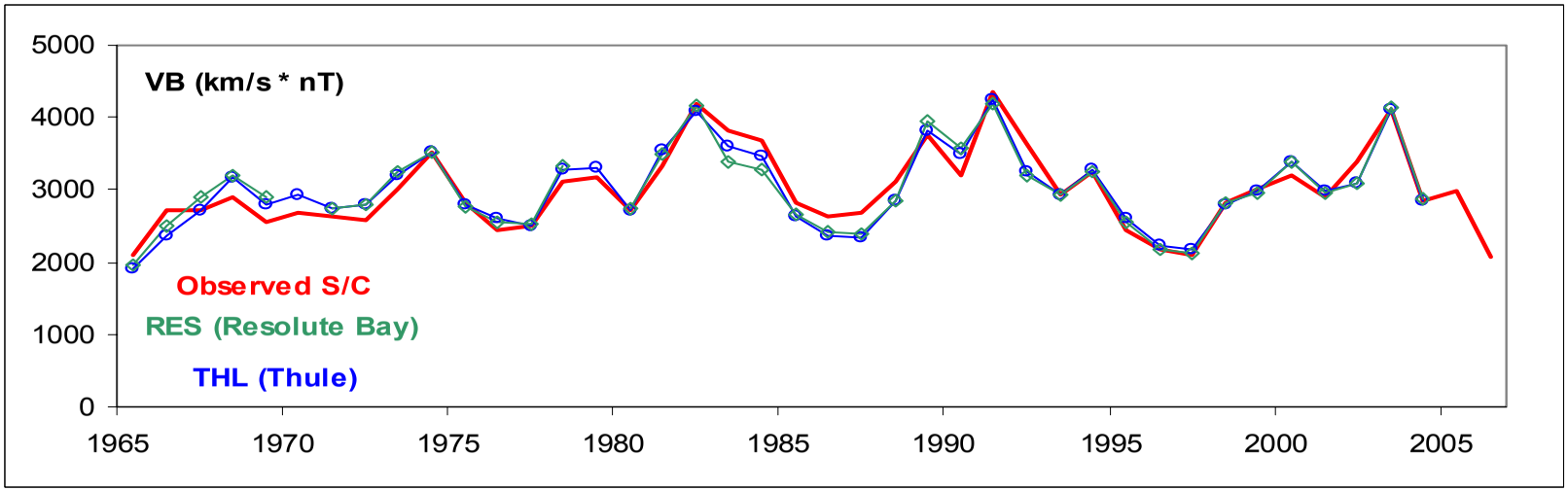


The radius of the circle traced out by variation of horizontal components is a measure of the polar cap potential. For stations near the polar cap boundary the circle is only partial.



Here we show for each year of 1965-2004 how the average radius depends on the product of B and V for Thule (THL) and Resolute Bay (RES). The radius of the circular variation is the same for all stations in the cap.

We can then estimate BV:

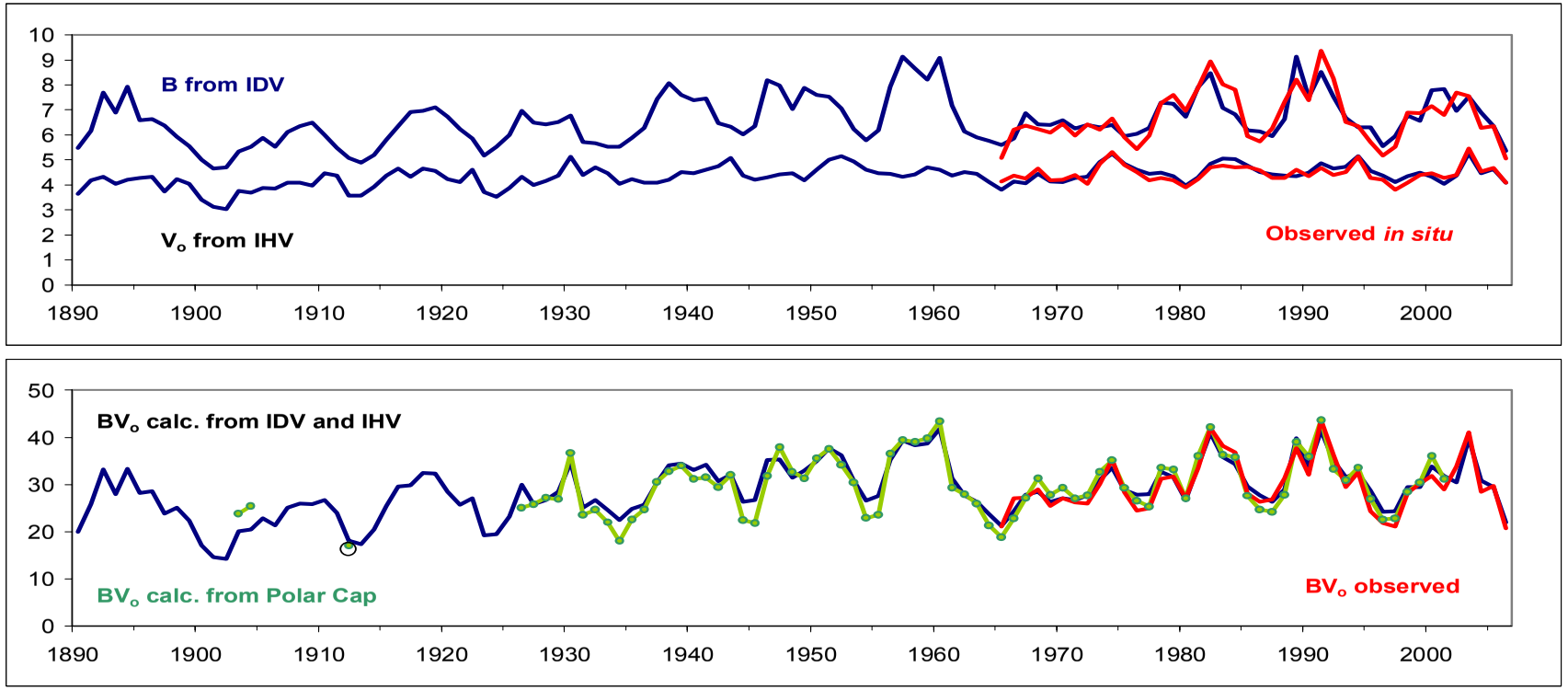


We now have three independent ways of estimating solar wind and IMF parameters:

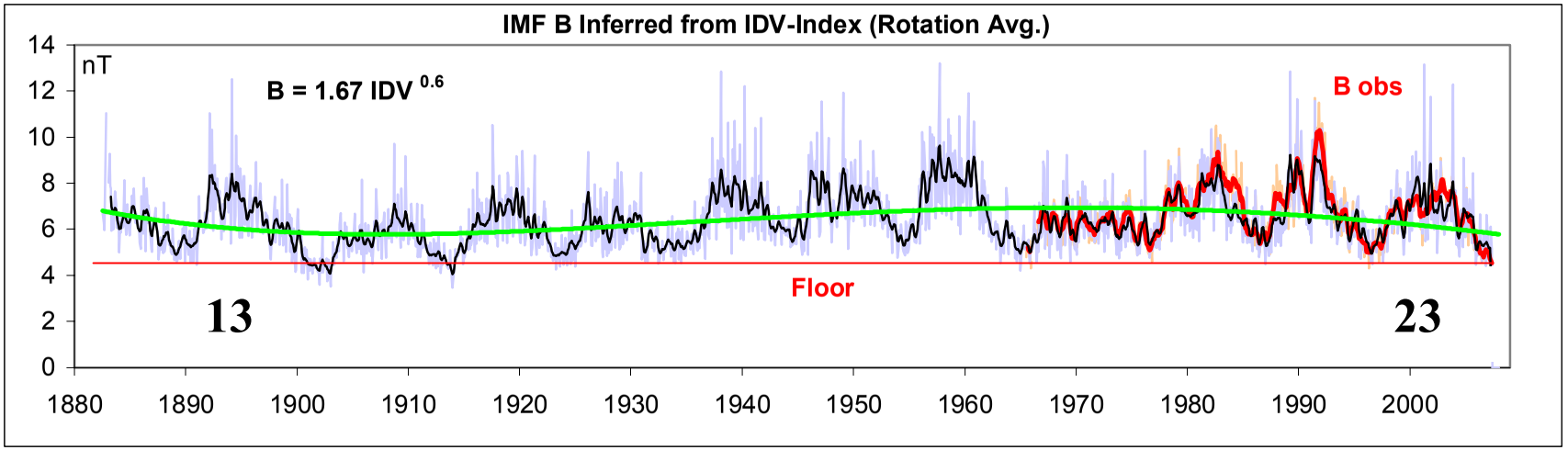
An Over-determined System:

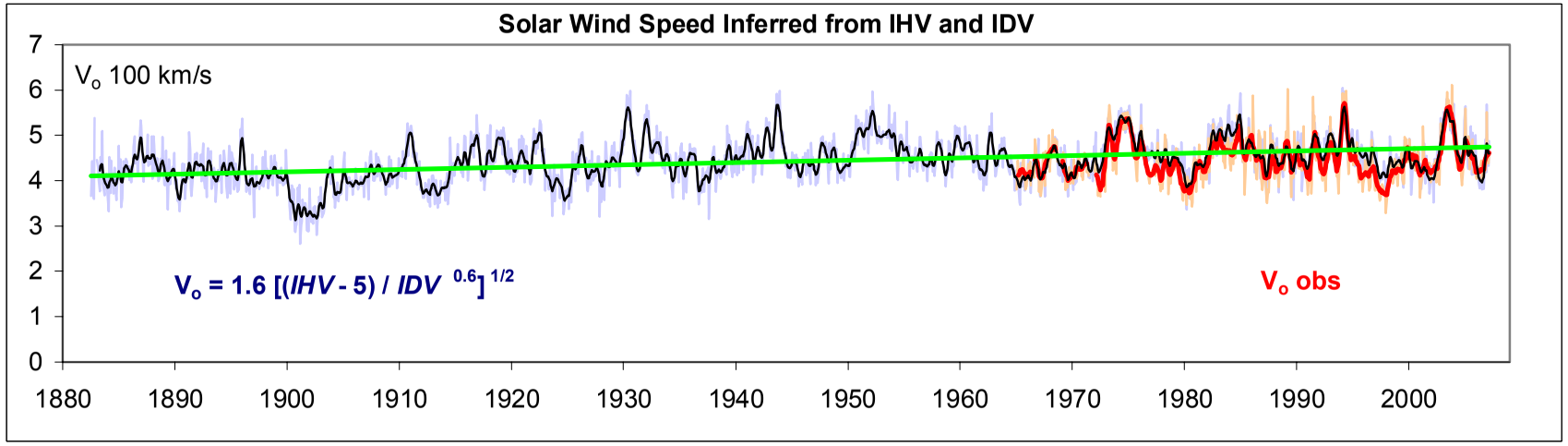
1. The *IHV*-index, estimating BV^2
2. The *IDV*-index, estimating B
3. Polar Cap Potential index, estimating BV

These indices are readily computed from simple hourly means (or values) for which we have measurements stretching back well into the 19th century. We can thus estimate $V = \sqrt{[(BV^2) / B]}$ and use that value to calculate BV for comparison with the estimated BV.



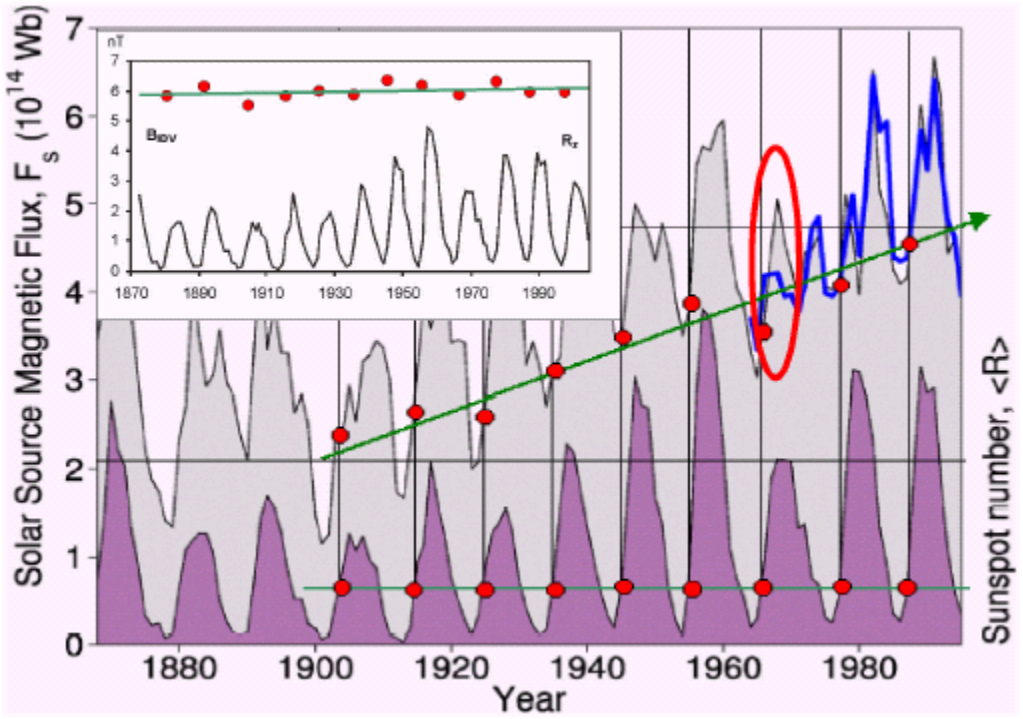
We can even determine *B* and *V* on a time scale of solar rotations:





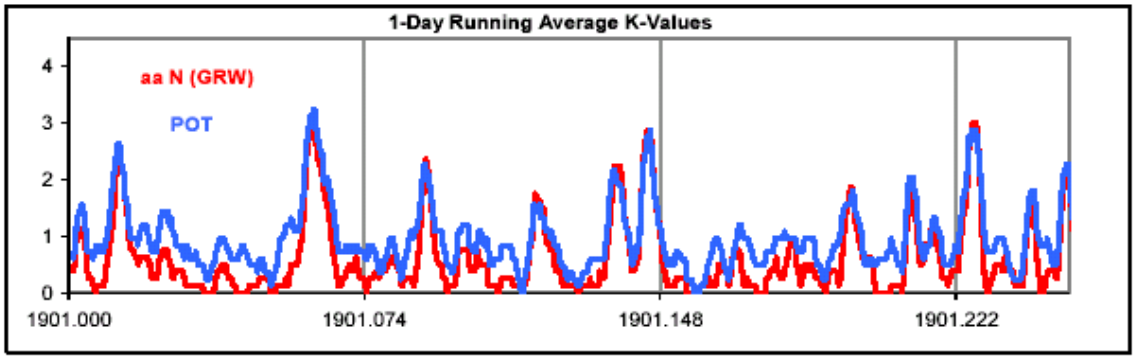
Note the 'floor' under which IMF *B* does not seem to fall.

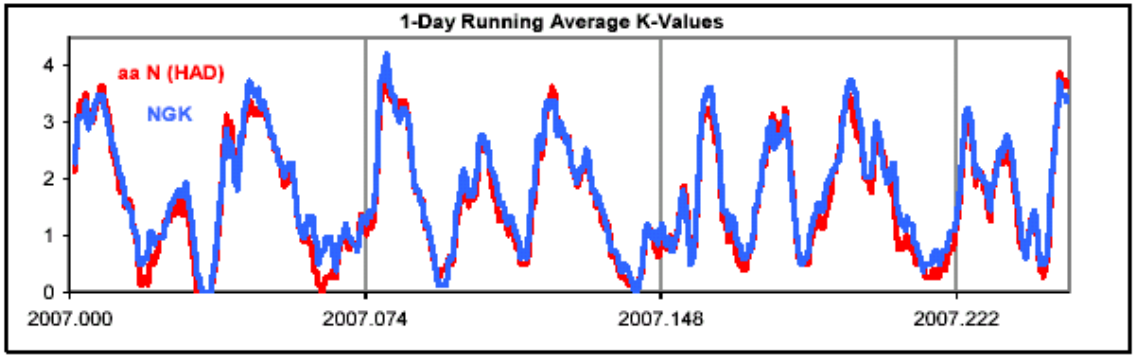
Back in 1978 I proposed that the Sun's "open" flux had doubled since the 1900s. Lockwood *et al.* in a famous 1999 paper extended the analysis to 1995 and inferred an increase by a factor of 2.3 independent of the sunspot number:



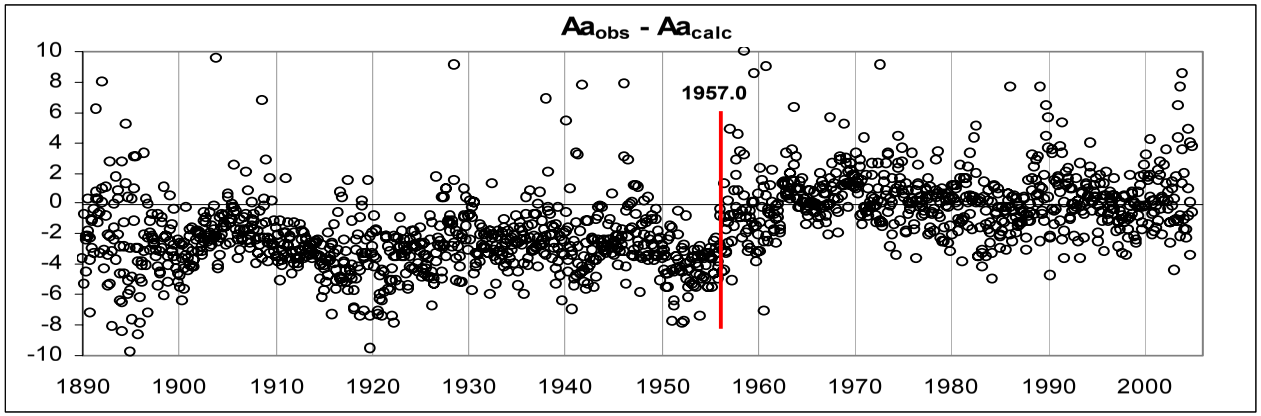
Both analyses was based on the *aa*-index. Subsequent work by several groups has shown that the calibration of *aa* is too low before 1957. In addition, there is an inhomogeneity in about 1937. Before that time Mayaud [who constructed the *aa*-index] had himself scaled all the geomagnetic records, after that he used existing scalings by others.

The most difficult K-value to scale is K = 0 [no activity at all] because it requires the correct removal of the [ever changing] daily variation due to solar FUV generated currents. Mayaud was the great expert at this and dared classify many intervals as K = 0 where other people conservatively opted for K = 1:





The net result was that *aa* was on the average 3-5 nT too low during the early years, which for the solar minima years 1901 and 1912 would amount to about 40%, so no wonder we all miscalculated IMF *B* and the open flux.



Difference between *aa* observed and *aa* calculated from IHV (for 1980-2004):

$$Aa = 0.36\ IHV^{1.1856}$$

$$R^2 = 0.9511$$

The keys to the recent breakthrough in inferring solar wind properties in the past are

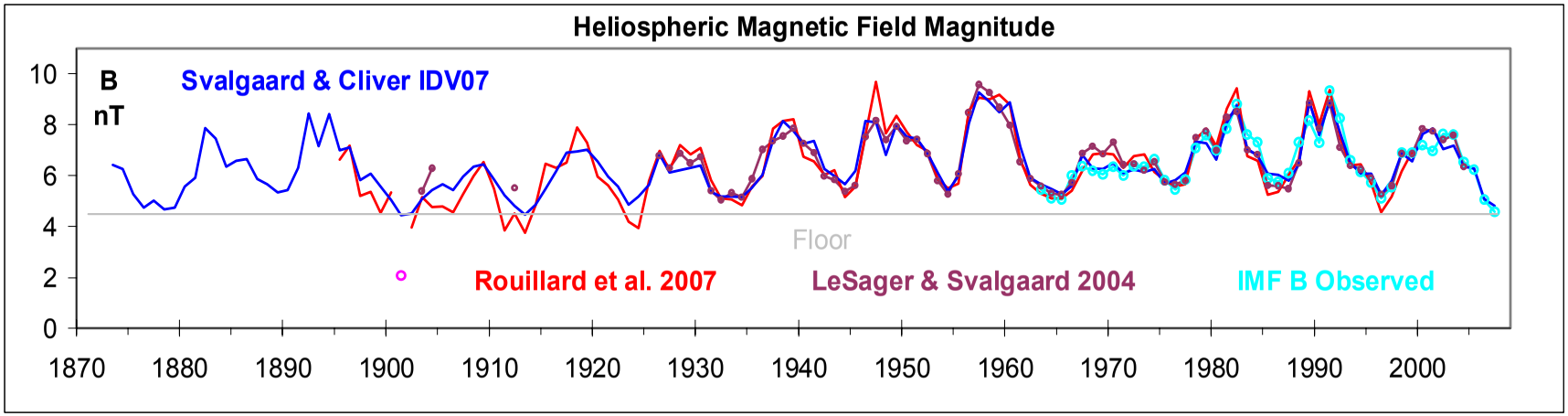
1. Realization that Hourly Values of the geomagnetic field can be used, opening up the total historical record for processing by modern means
2. Definition of new indices that depend on different combinations of B and V
3. Using nightside data only, to eliminate contamination by Sq

Initially, our work was met with great resistance, but people have stopped bickering by now and instead started to explore what we opened up with indices and analysis of their own. So, several new indices of geomagnetic activity have recently been introduced:

Geomagnetic index	**Function of**	$B\,V^{\alpha}$	**Proponents**
IDV, [D_{st}<0]; u	B	$\alpha = 0$	Svalgaard & Cliver; Bartels
m	$B\,V^{0.5}$	$\alpha = 0.5$	Lockwood et al.
PCP	$B\,V$	$\alpha = 1$	Le Sager & Svalgaard
IHV	$B\,V^2$	$\alpha = 2$	Svalgaard & Cliver
aa, am; ap	$B\,V^2$	$\alpha = 2$	Mayaud; Bartels

The indices depend on different functions of B and V, so we can infer both B and V in the past, having , in fact, an over-determined system that inspires confidence.

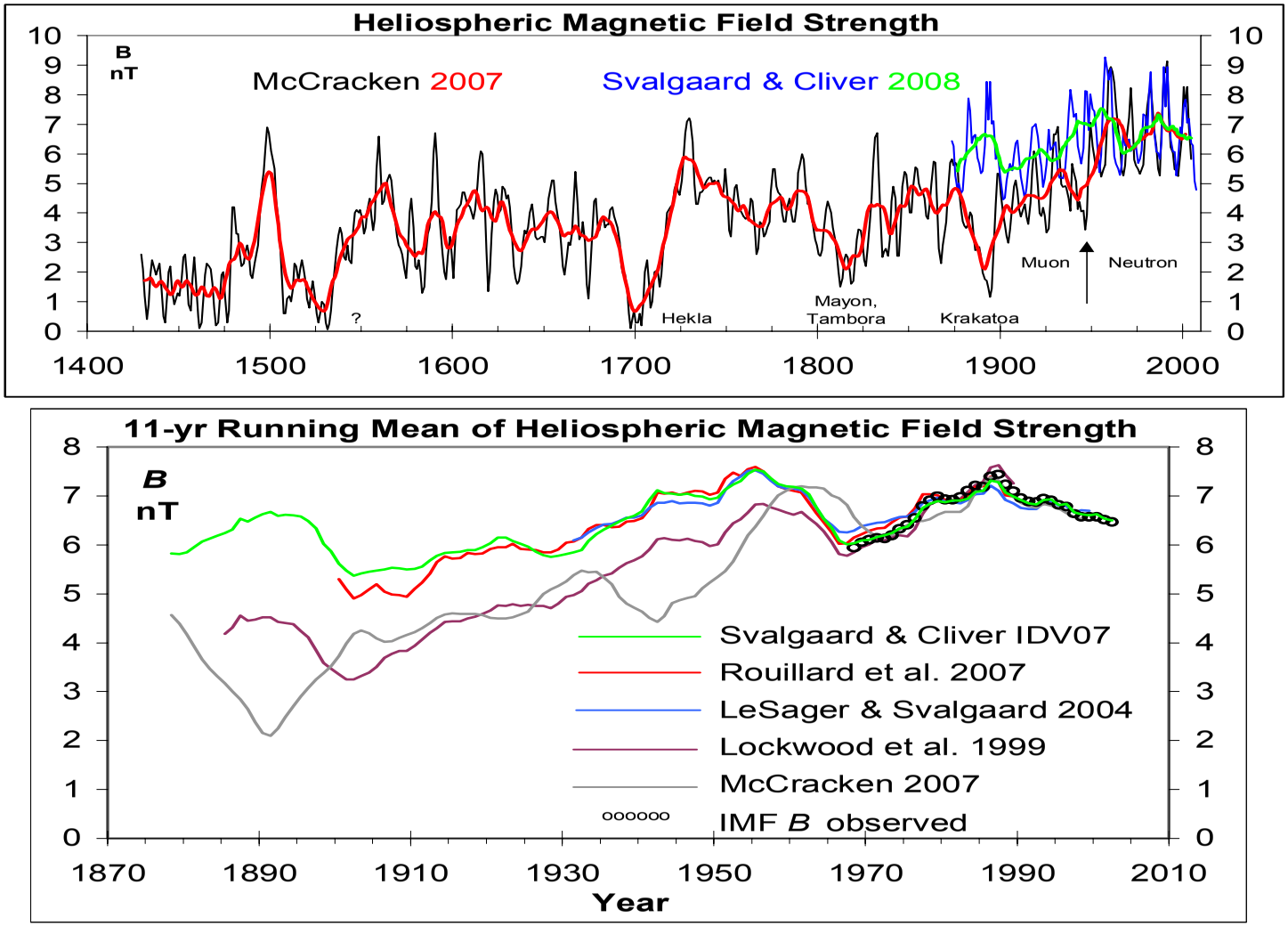
Using their new '*m*-index' and the corrected *aa*-index, the Lockwood group (Rouillard et al., 2007) has recently recalculated IMF *B* and obtained results that are very close to ours, although Lockwood still maintains that the 1999 result is valid [c.f. Solanki at SORCE]…

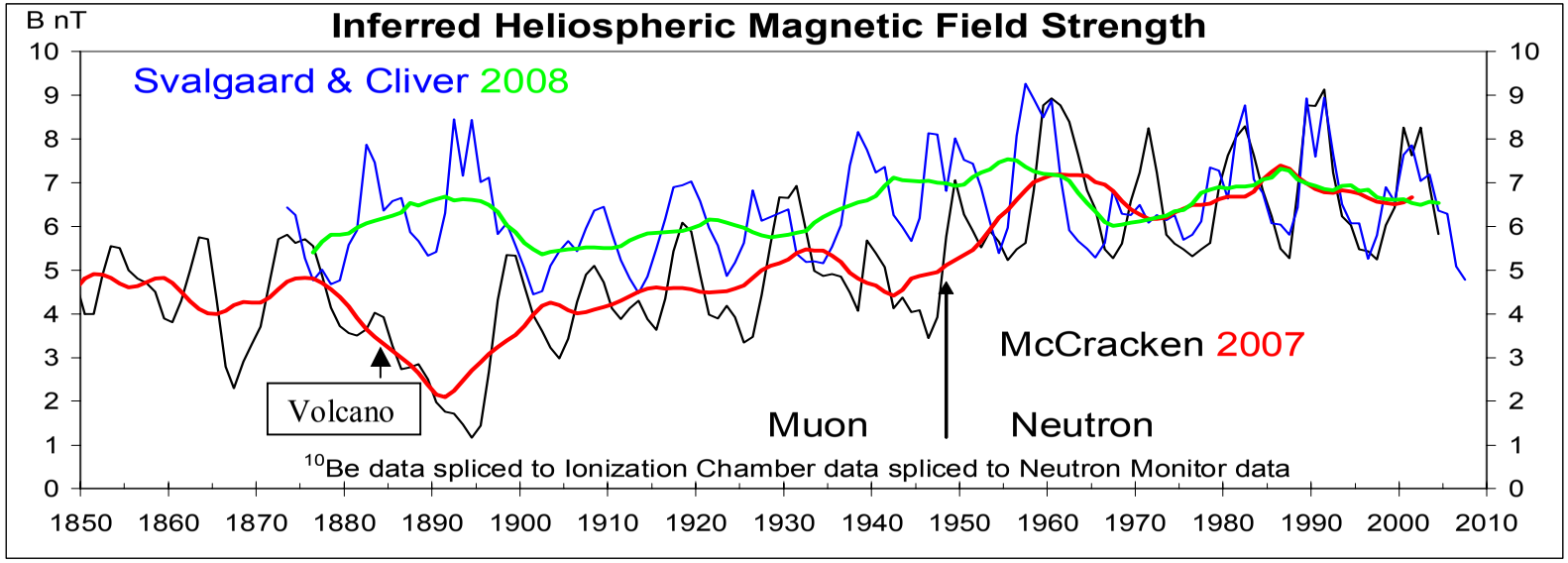


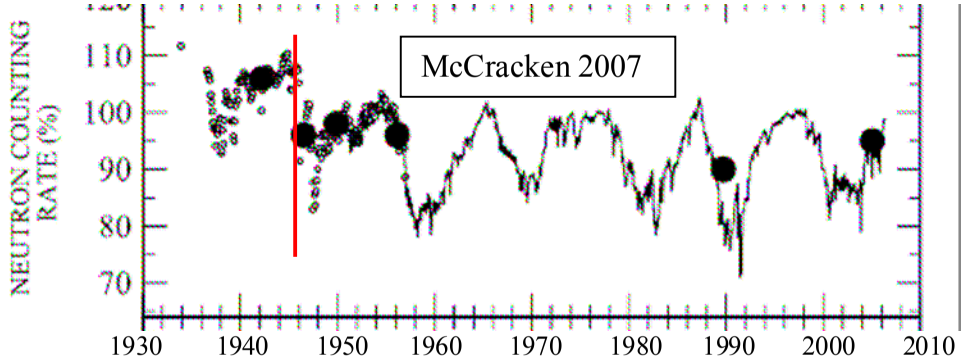
The point for 1901 is in error (Rouillard, Pers. Comm., 2007) and their result before 1910 is based on very few stations with resulting large error bar. Apart from such details, the various groups trying to reconstruct *B* and *V* are converging on a common position that should be taken into account now by other researchers, rather than relying on the superceded earlier results.

This re-assessment of the "open" flux calculated from *B* has implications for reconstructions of various solar proxies that postulate a secular increase of the "open" flux.

One example is McCracken [2007] who inverted the cosmic ray flux (inferred from ^{10}Be fitted to the secular change) to calculate the IMF *B* (or the HMF as he calls it):



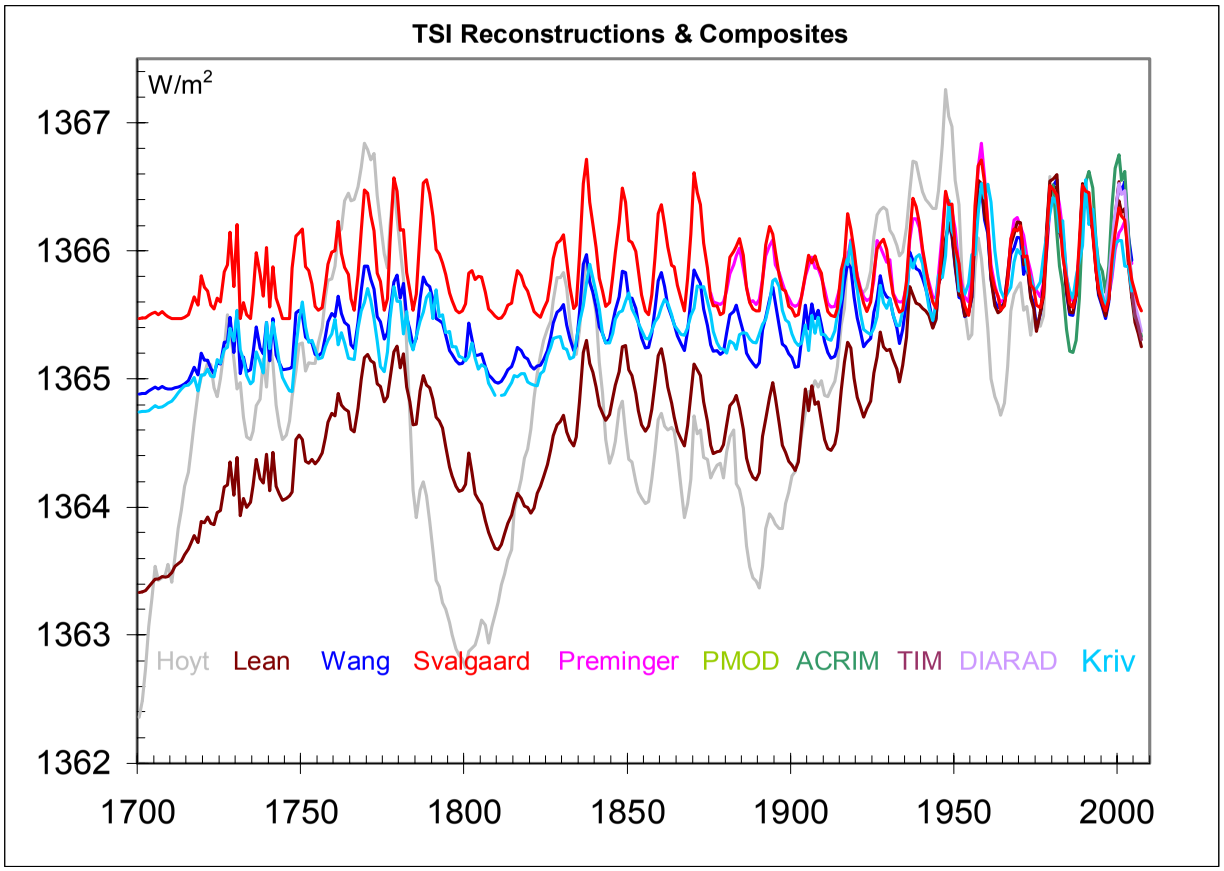




Neher's balloon data was used to carefully calibrate the old ionization chamber data into 'equivalent' neutron monitor counts. The 'jump' around 1945 is what caused the inferred HMF *B* to drop by 1.7 nT.

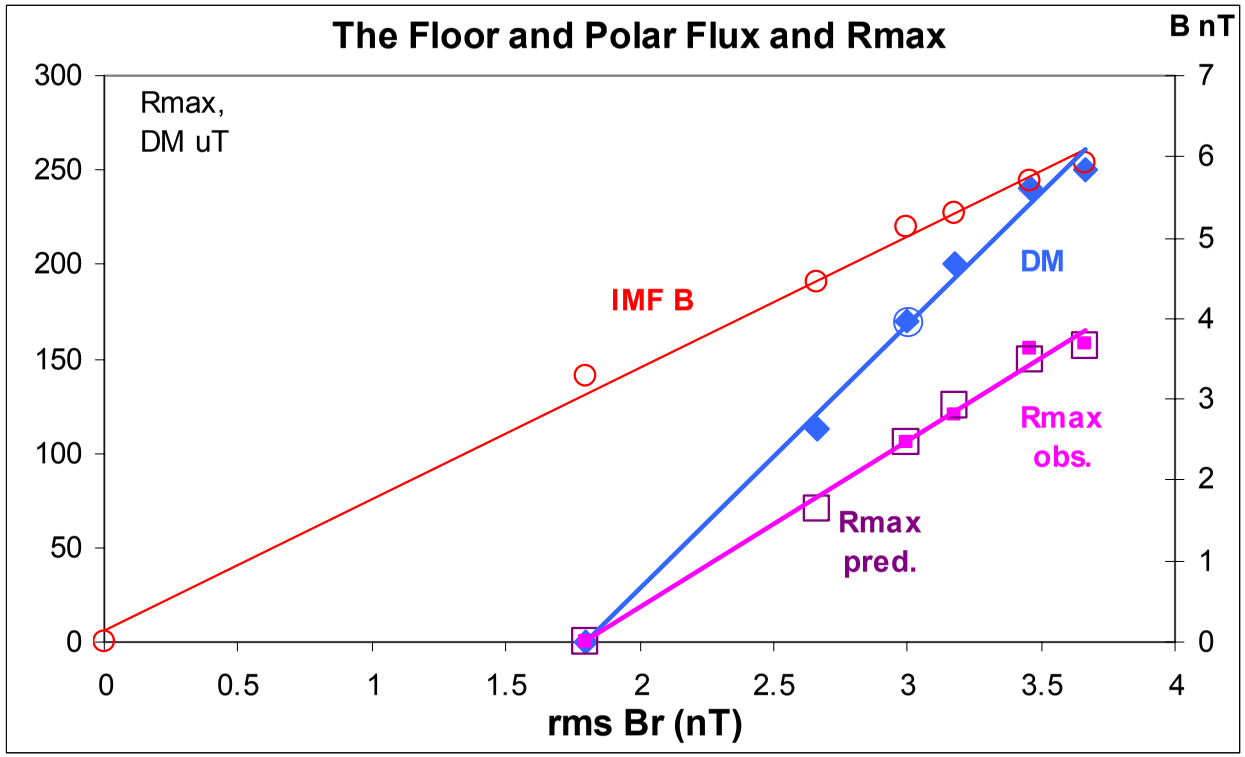
It is evident that the inferred HMF *B* is at variance with the 'consensus' *B*. We urge a critical re-examination of the reconstructed cosmic ray flux and associated HMF *B*. before any conclusions are drawn from that data. [e.g. as in next seminar on 23rd Sept by Steve Kahler].

Another example is reconstructions of TSI (Total Solar Irradiance) which often rely on an "open flux background":



Without the background "rise" 1900-1960, the TSI seems to have varied less than commonly assumed.

Speculation about the Floor, the Polar Fields and the Predicted Sunspot Maximum:



The WSO polar fields [DM uT] do not scale proportionally with the 'open flux' at solar minimum [represented by the root-mean-square value of Br – this to overcome the problem of averaging interval], but seems to require the same 'floor' as we found for IMF).

Conclusion

Geomagnetic activity can bee used to infer the HMF [or the “open” solar magnetic flux] before the Space Age. Earlier, these inferences were discordant and controversial. In the last couple of years, the sources of these disagreements have been uncovered and corrected and a remarkable consensus is now emerging, with the result that the heliospheric magnetic field and the solar wind speed can now be considered to be well constrained to a level of ~10% or better.

The end