Two Centuries Space Weather.
What we have learned from the past and what we think the future might hold

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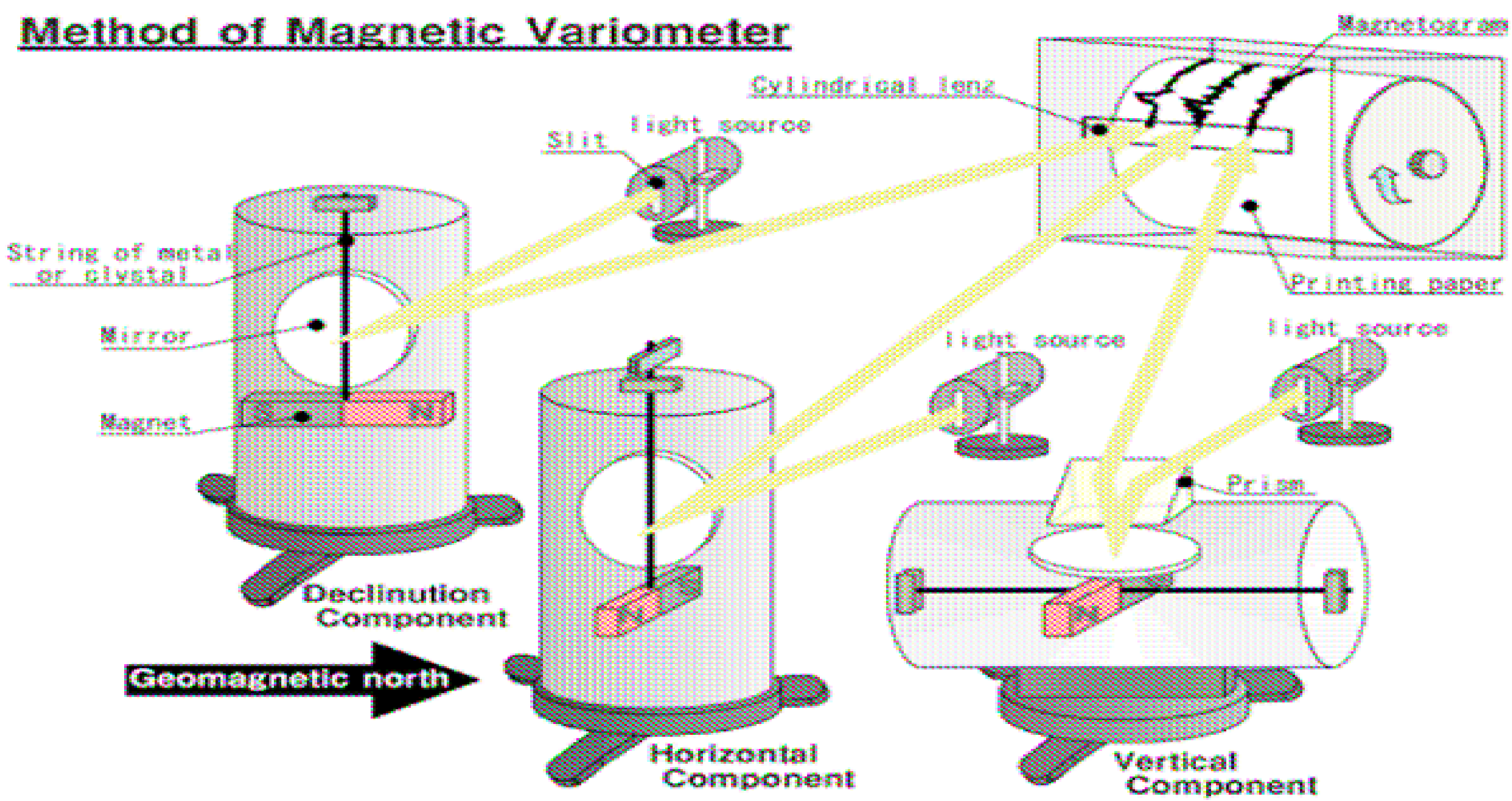
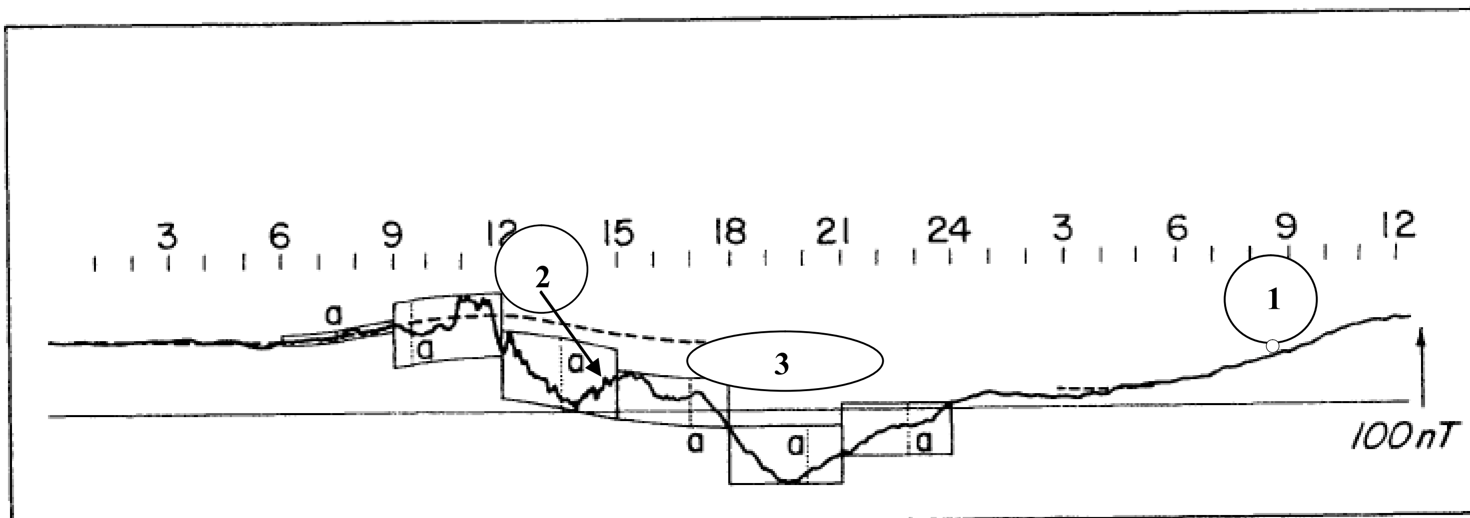
Using the Earth as a Measuring Device for Space Weather: Geomagnetic Variations



The Central Problem of Geomagnetic Variations

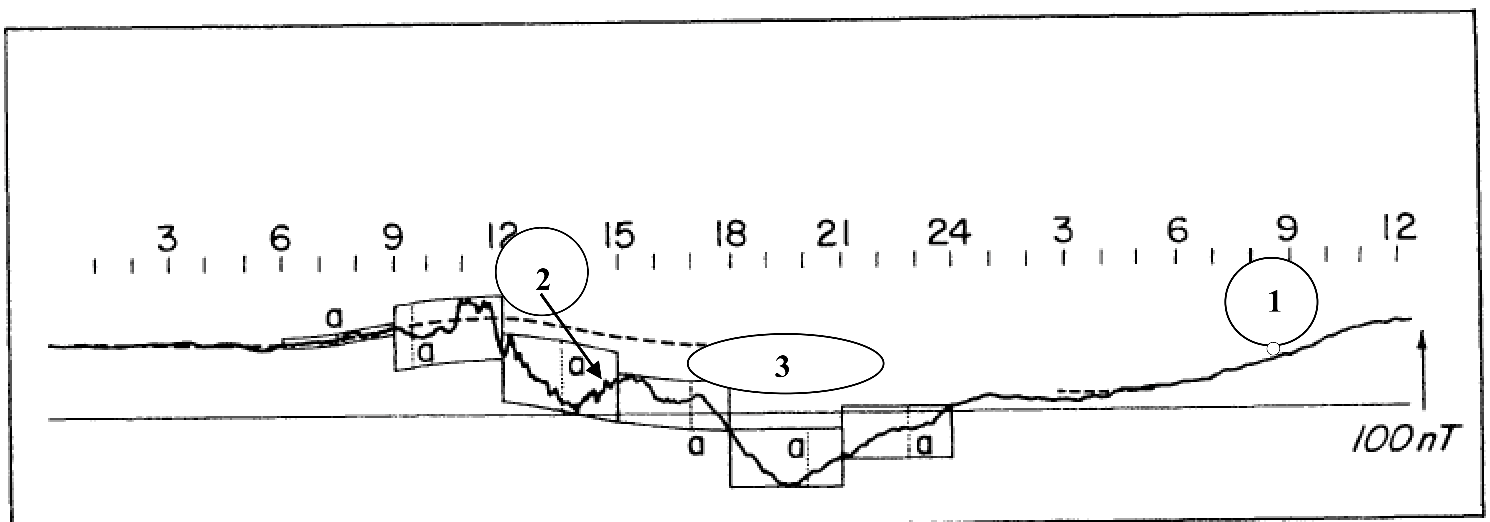
The geomagnetic record shows a ***mixture*** of signatures from different physical processes:

- the regular daily variation (1),
- irregular short duration [1-3 hours] variations (2),
- and ‘storms’ typically lasting a day or more (3).



The Central Problem of Geomagnetic Variations

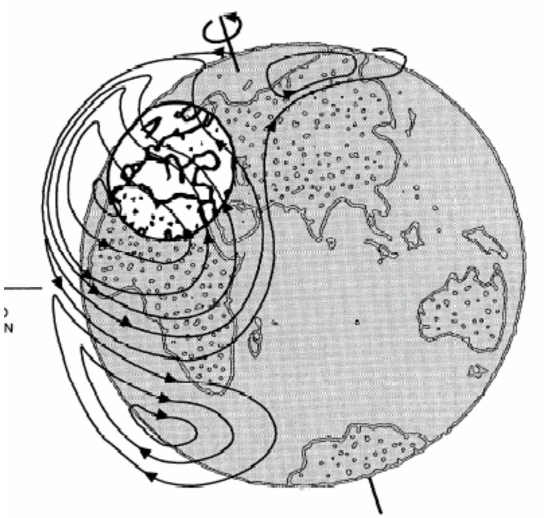
Geomagnetic ***indices*** have been devised to characterize and quantify these three types [ignoring special effects like pulsations, eclipse effects, etc]. An experienced observer can usually distinguish the various types from the general character of the curves and from hers/his knowledge of the ***typical*** variations at the observatory. Various computer algorithms more or less successfully attempt to supplant the need for a human, experienced observer, but in any case the ***high-frequency*** part of the record is the necessary ingredient in the process:

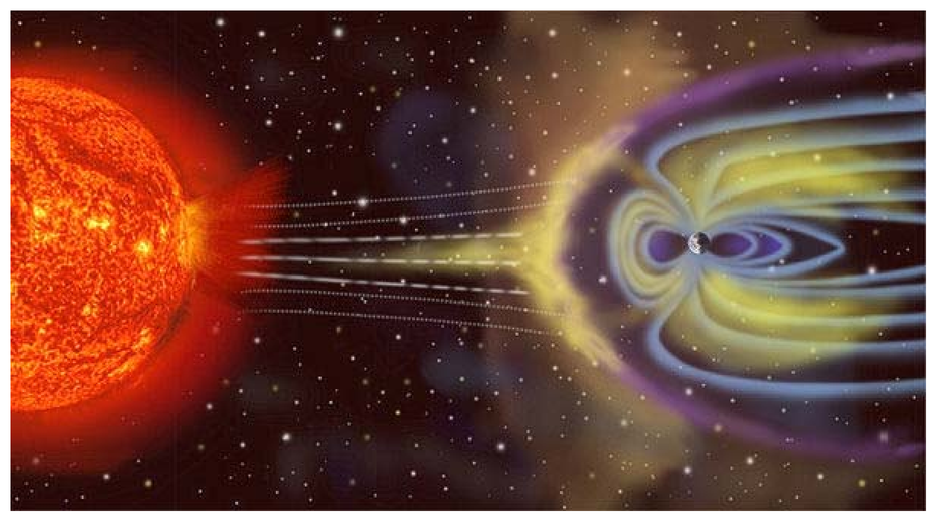


Geomagnetic Indices

Regular Irregularity and Irregular Regularity

We would like to devise indices that describe distinct physical processes. Some variations are due to variation of ***solar UV*** and rotation of the Earth, and some variations have their cause in the interaction of the ***solar wind*** with the Earth's magnetic field.





Regular Variations

George Graham discovered [1722] that the geomagnetic field varied during the day in a regular manner. He also noted that the variations were larger on some days than on other days. So even the ‘regular’ was irregular…

Disturbances and Aurorae

Pehr Wargentin [1750] also noted the regular diurnal variation, but found that the variation was ‘disturbed’ at times by occurrence of Aurorae. Graham, Anders Celsius, and Olaf Hjorter had earlier also observed this remarkable relationship.

The First Index (Regular–Irregular)

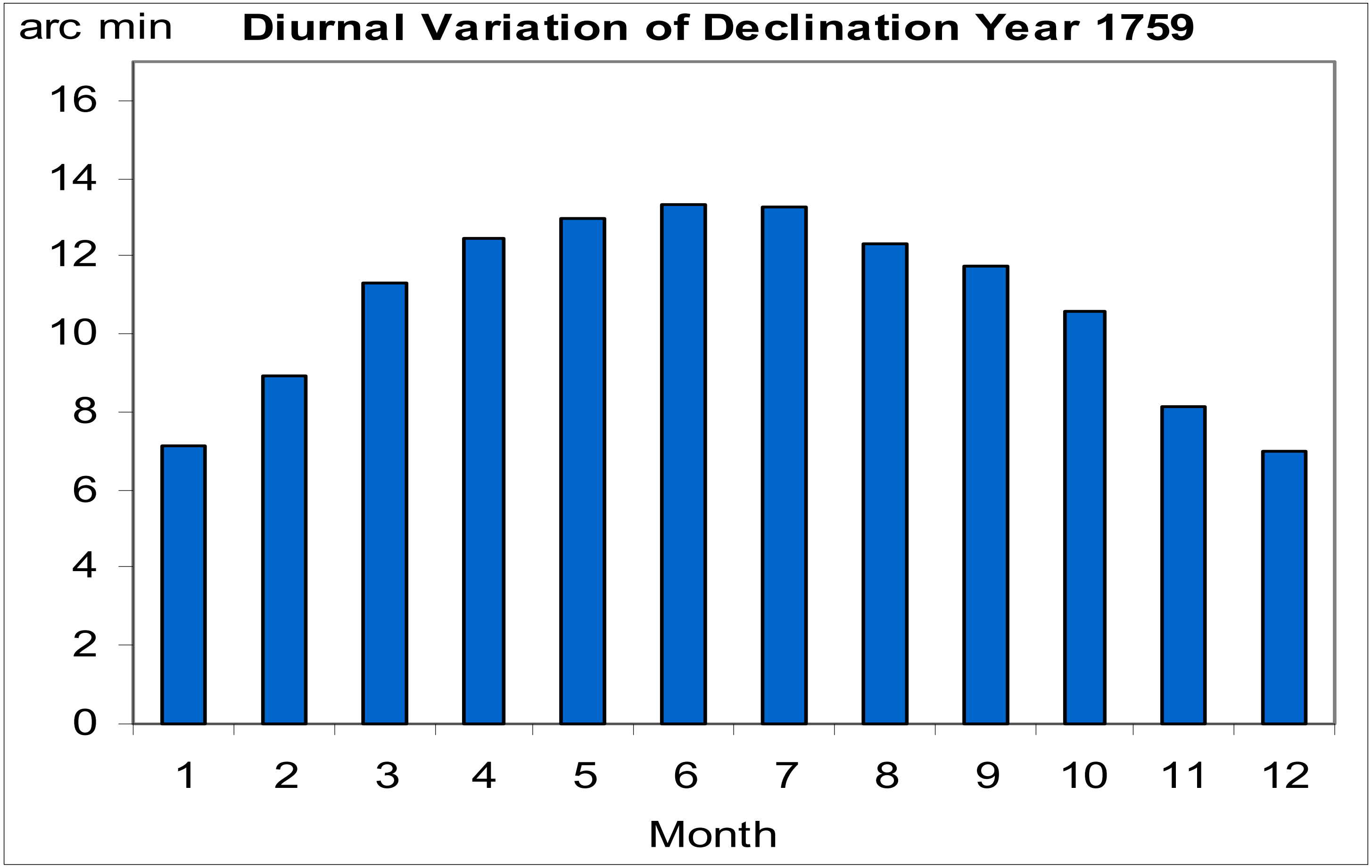
John Canton [1759] made ~4000 observations of the Declination on 603 days and noted that 574 of these days showed a ‘regular’ variation, while the remainder (on which aurorae were ‘always’ seen) had an ‘irregular’ diurnal variation.

Classification - Character

The First Index was thus a *classification* based on the ‘character’ of the variation, with less regard for its amplitude, and the ancestor of the C-index (0=quiet, 1=ordinary, 2=disturbed) that is still being derived today at many stations.

The availability of the Character Index enabled Canton to discover another Regularity on Quiet days.

The Regular Seasonal Variation



Nice Application of the Scientific Method, but wrong nevertheless…

More than One Cause

And to conclude that “*The irregular diurnal variation must arise from some other cause than that of heat communicated by the sun*”

This was also evident from the association of days of irregular variation with the presence of aurorae

Another Regular Variation

George Gilpin sailed on the *Resolution* during Cook's second voyage as assistant to William Wales, the astronomer. He joined on 29 May 1772 as astronomer's servant. John Elliott described Gilpin as "a quiet yg. Man".

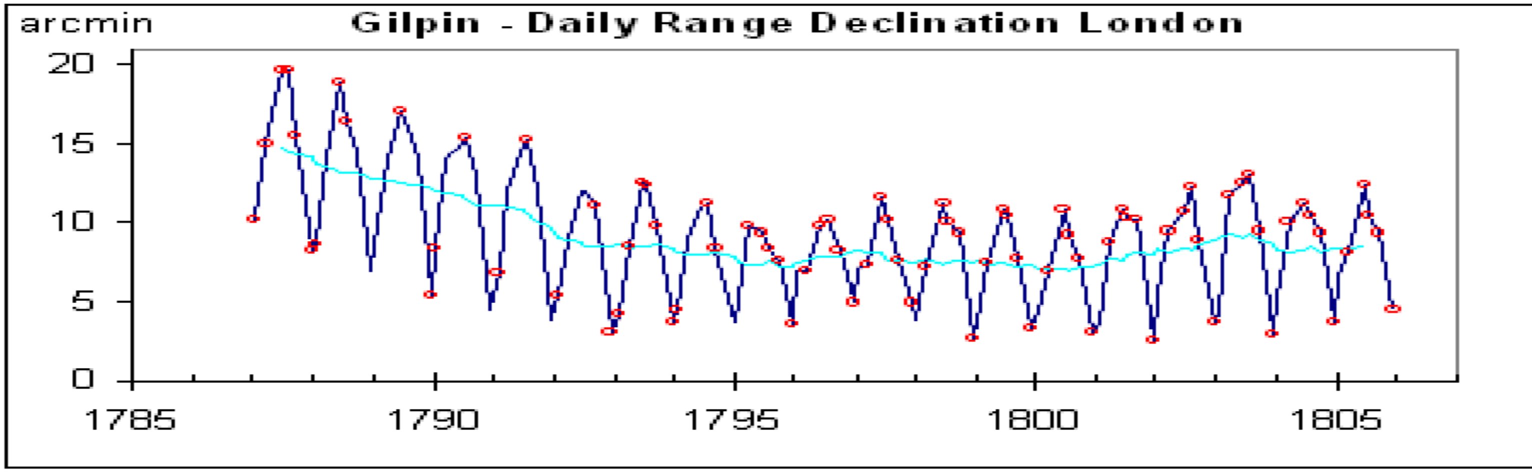
Gilpin was elected Clerk and Housekeeper for the Royal Society of London on 03 March 1785 and remained in these positions until his death in 1810.

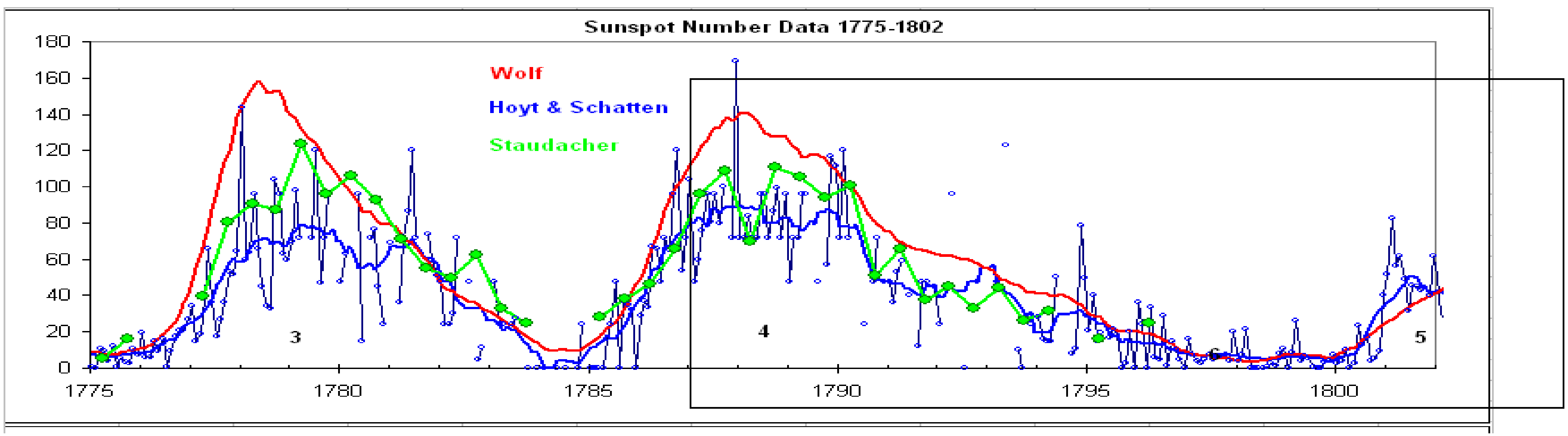
George Gilpin [1806] urged that regular measurements should be taken at fixed times during the day.

And demonstrated that the seasonal variation itself varied in a regular manner

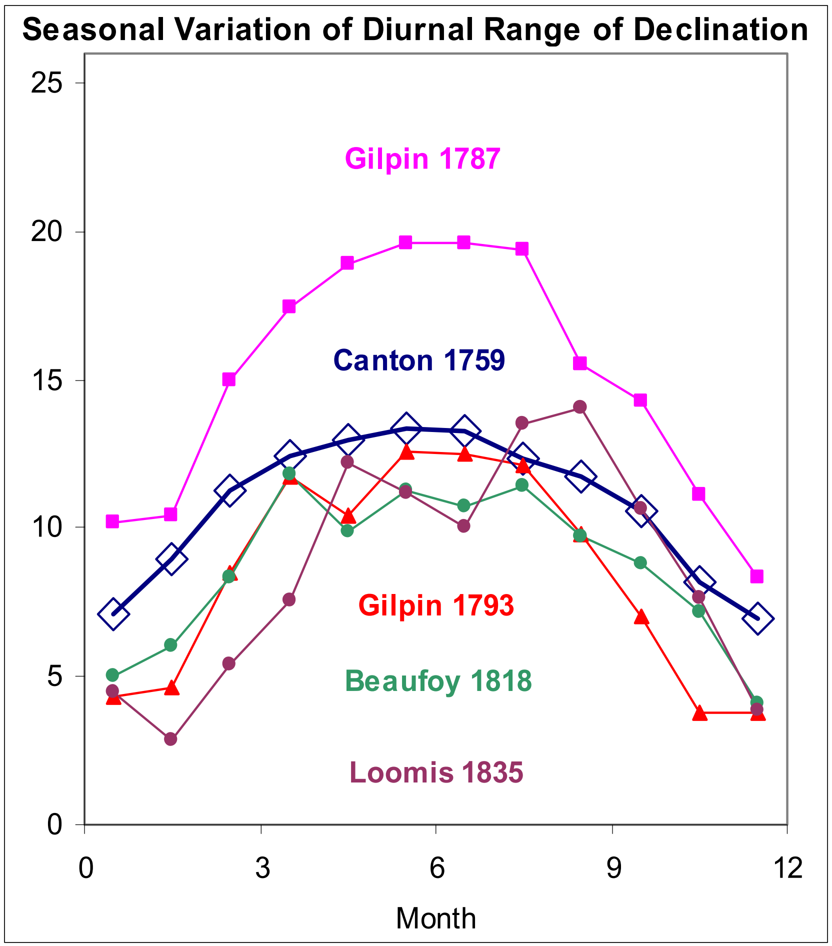
Hint of Sunspot Cycle Variation

though unknown to Gilpin, who thought he saw a temperature effect





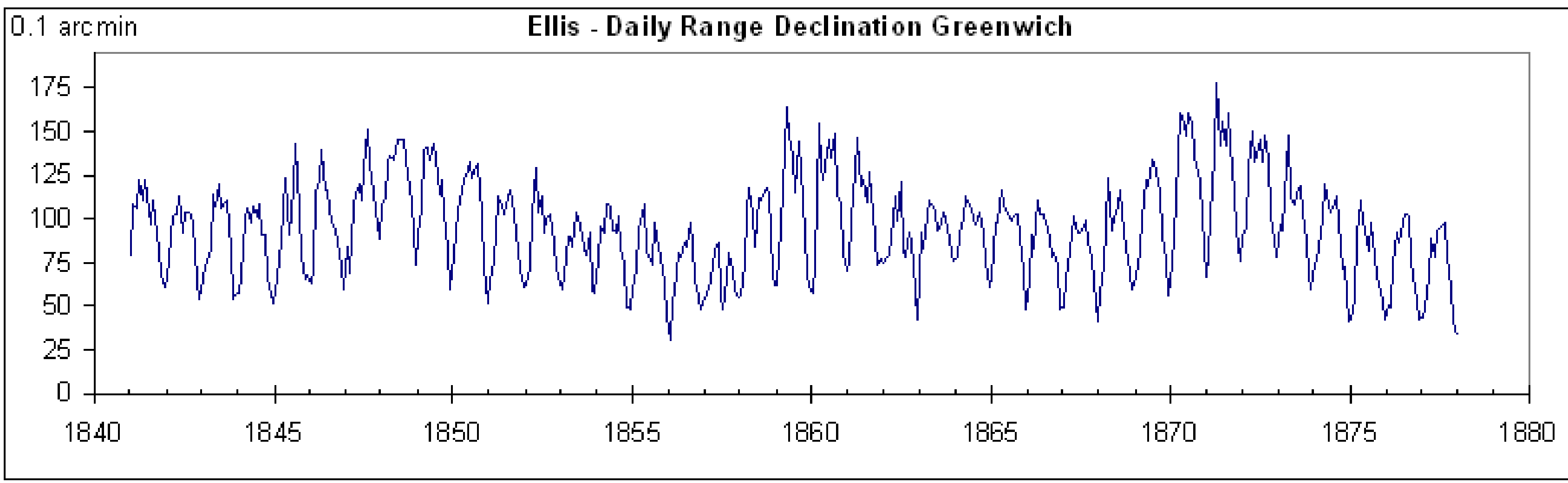
Alas, Paradise Lost



Canton's great insight [that there were different causes of the variations during quiet and disturbed times] was lost with Gilpin and some later workers, and a new and simpler 'index' won acceptance, namely that of the *Daily Range.* The 'raw' Daily Range is, however, a *mixture* of effects.

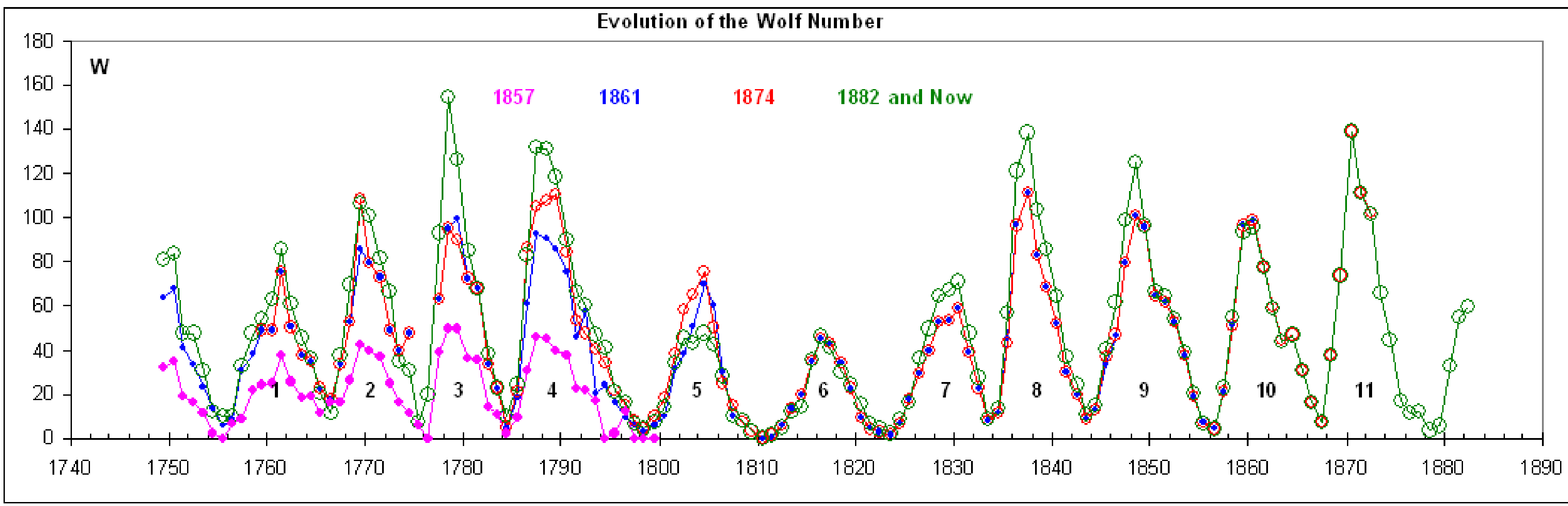
The Daily Range Index

The Daily Range is simple to calculate and is an ‘objective’ measure. It was eventually noted [Wolf, 1854] that the range in the Declination is a proxy for the Sunspot Number defined by him.

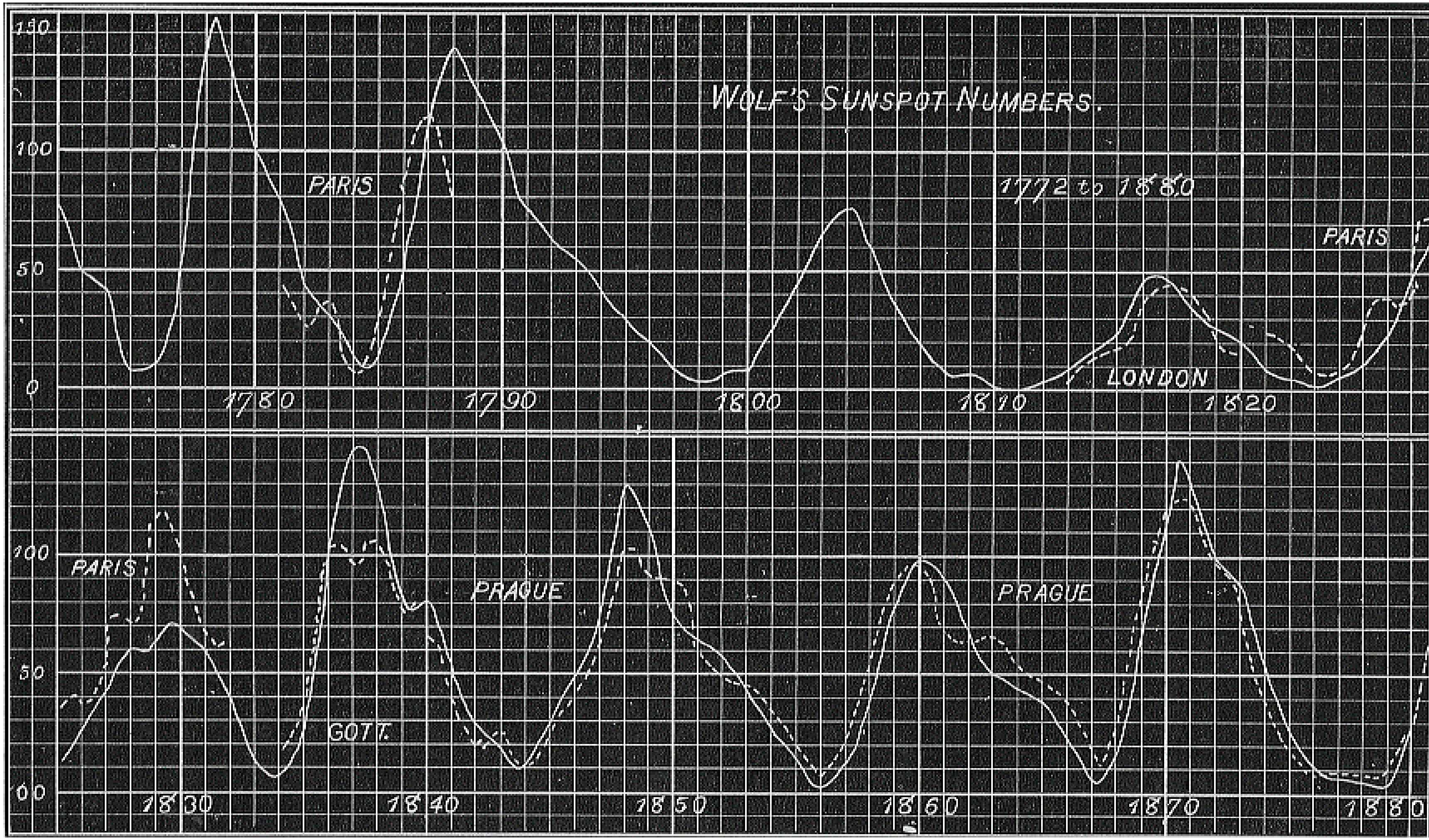


Rudolf Wolf’s Sunspot Number

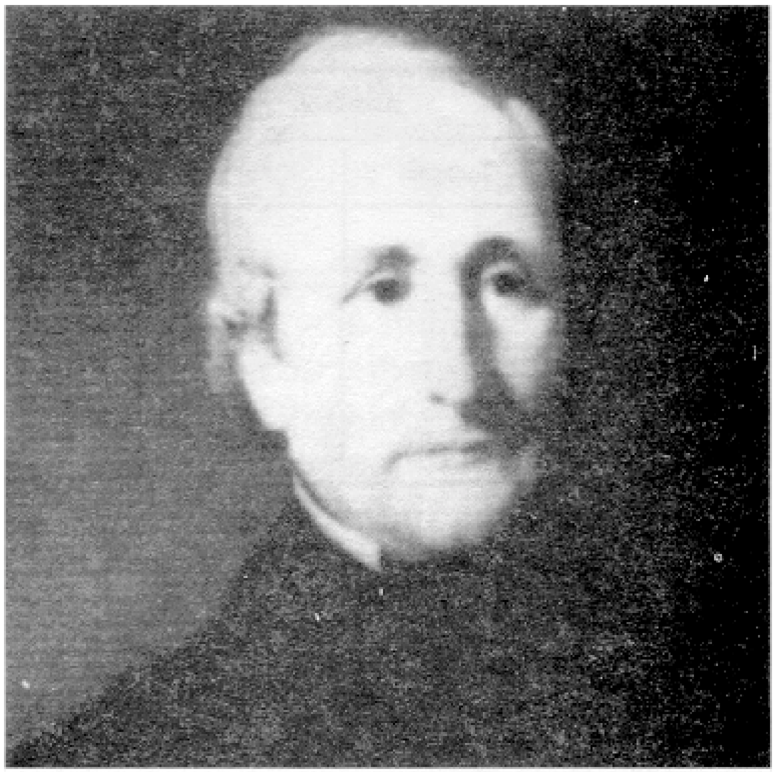
Wolf used this correlation to calibrate the sunspot counts by other observers that did not overlap in time with himself



Young’s Version of the Correlation



How to Measure Disturbance



Edward Sabine [1843], mindful of Canton’s insight, computed the hourly mean values for each month, omitting ‘the most disturbed days’ and defined Disturbance as the RMS of the differences between the actual and mean values.

The Ever-present Tension

- Quiet time variations – their regular and irregular aspects

- Disturbance variations – their irregular and regular aspects

One cannot conclude that every regularity is a sign of ‘quiet’ and that every irregularity is a sign of ‘activity’. This is an important lesson.

Quiet Time Variations

Diurnal	25 nT	
Focus	Change of sign	(irregular)
Lunar Phase	X 0.1	
Annual	X 2	
Solar Cycle	X 3	(irregular)
Secular	10%/century	(irregular)

Mixture of regular and irregular changes

Disturbance Variations

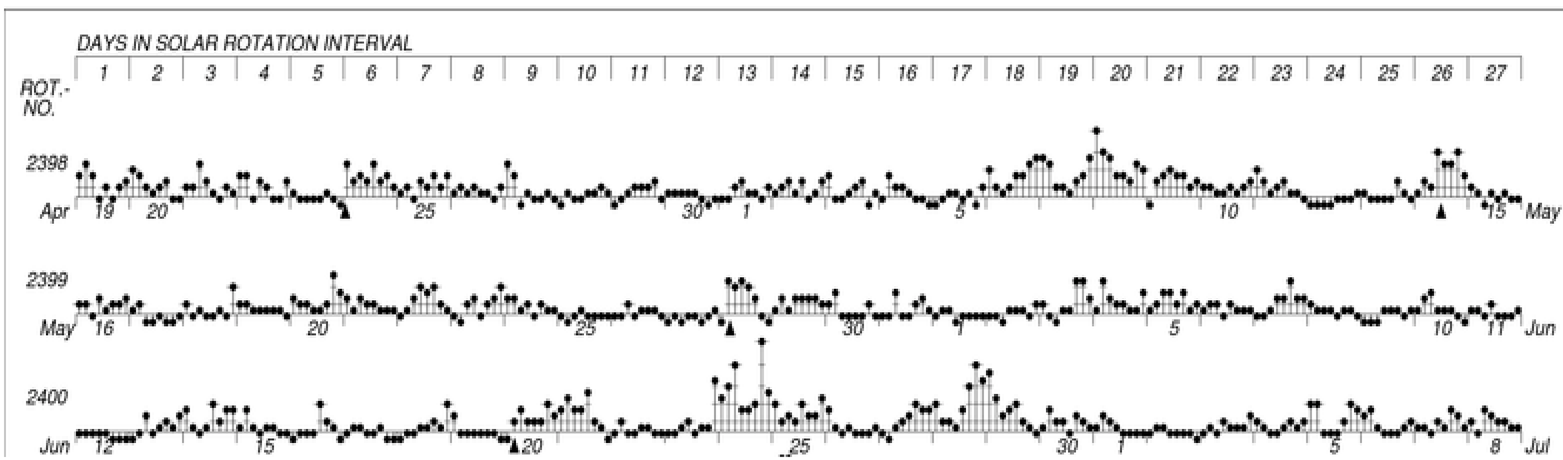
❑ Sporadic Storms	300 nT	
❑ Recurrent Storms	100 nT	(recurrent)
❑ Semiannual/UT var.	25%	(modulation)
❑ Annual	5%	(modulation)
❑ Bays	20-50 nT	
❑ Secular	?	

Mixture of irregular and regular changes

Note: As seen at mid-latitudes

Qualitative Indices

An *index* can be a short-hand *code* that captures an essential *quality* of a complex phenomenon, e.g. the C-index or the K-index:



Quantitative Indices

We also use the word index as meaning a *quantitative* measure as a function of time of a *physical* aspect of the phenomenon, e.g. the Dst-index or the lesser known Tromsø Storminess-index:

Model of Geomagnetic Variations

It is customary to decompose the observed variations of the field B, e.g. for a given station to first order at time t:

$$B(t) = B_o(t) + Q(l,d,t) + D(t) \cdot M(u,d)$$

where u is UT, d is day of year, l is local time, and M is a modulation factor. To second order it becomes a lot more complex which we shall ignore here.

Separation of Causes

To define an index expressing the effect of a physical cause is now a question of subtraction, e.g.:

$$D(t)\cdot M(u,d) = B\,(t) - [B_o(t) + Q(l,d,t)]$$

or even

$$D(t) = \{B\,(t) - [B_o(t) + Q(l,d,t)]\} \,/\, M(u,d)$$

where M can be set equal to 1, to include the modulation, or else extracted from a conversion table to remove the modulation

Fundamental Contributions

Julius Bartels [1939,1949]

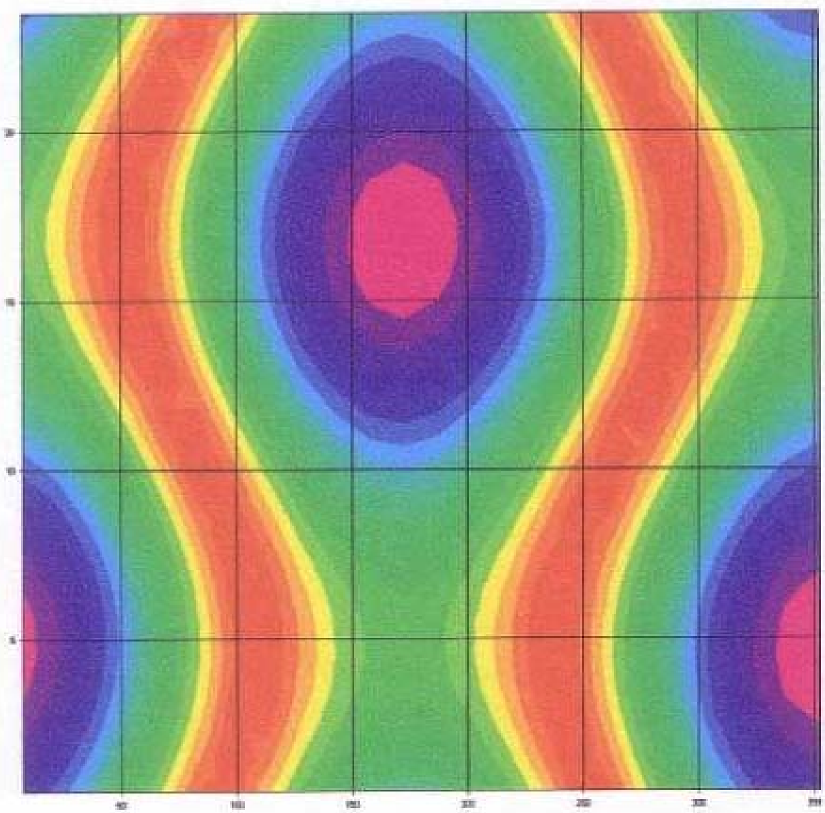
- Remove B_o and Q judiciously, no ‘iron curve’
- Timescale 3 hours, match typical duration
- Scale to match station, defined by limit for K = 9
- Quasi-logarithmic scale, define a typical class to match precision with activity level

The Expert Observer

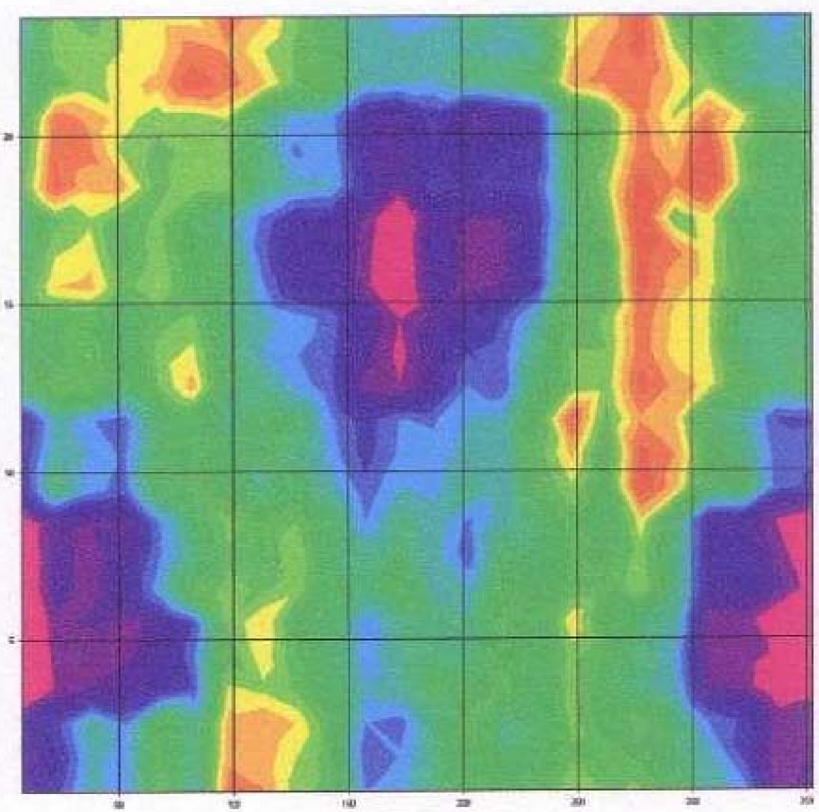
Pierre-Noël Mayaud, SJ [1967;1972] put Bartels' ideas to full use with the *am* and *aa*-indices.

A subtle, very important difference with Bartels' Ap is that the modulation, M, is *not* removed and thus can be studied in its own right.

The Semiannual/UT Modulation

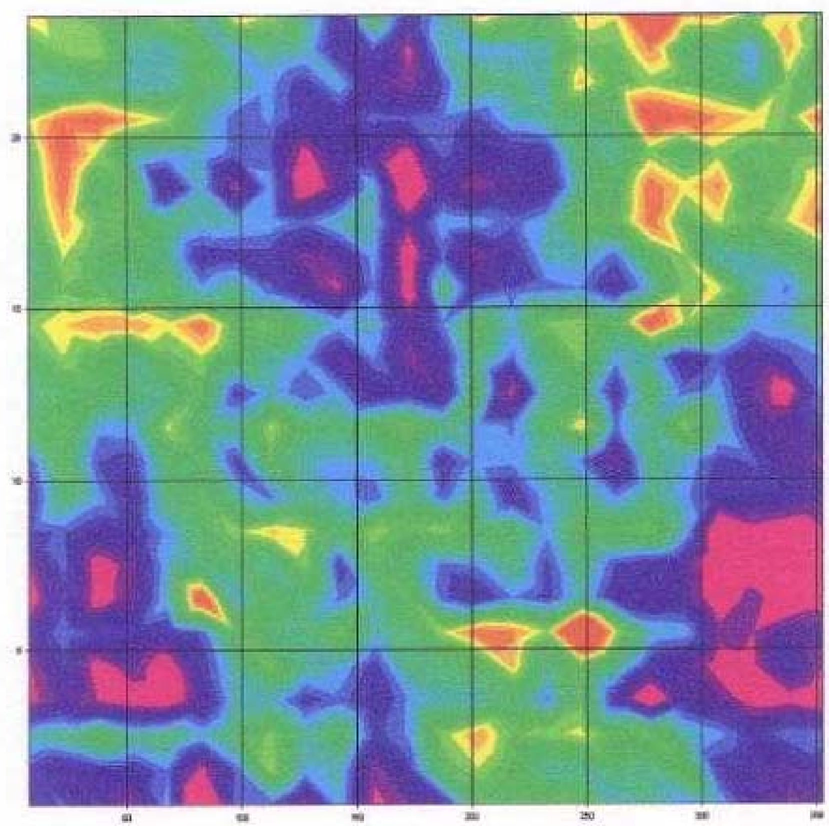


Dipole tilt, Ψ

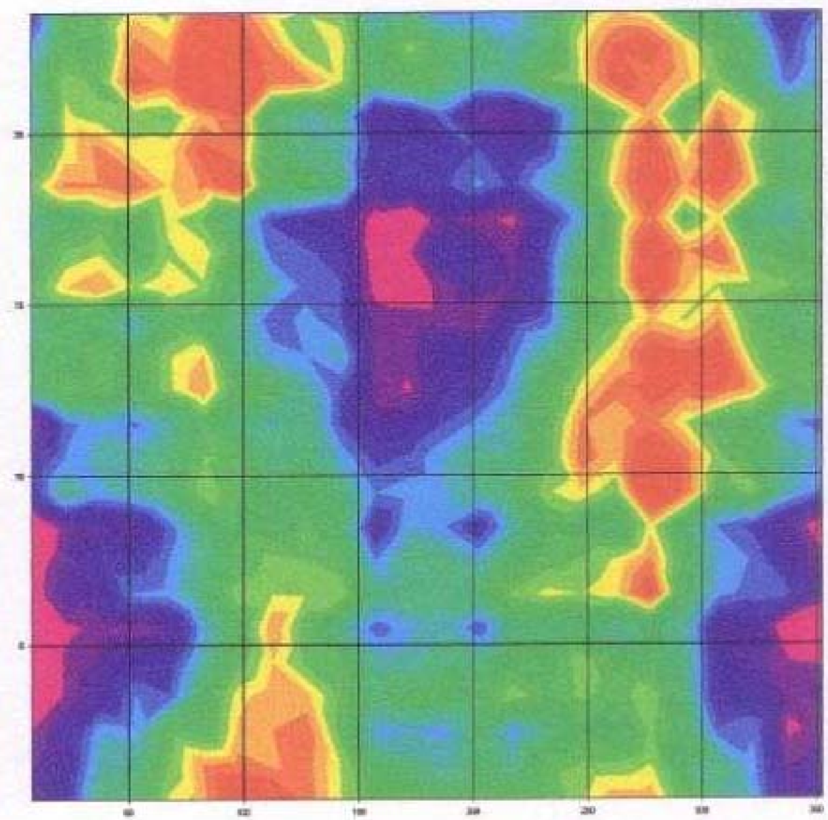


All orientations of α

Exists both for Southwards and for Northward fields (permanent feature)

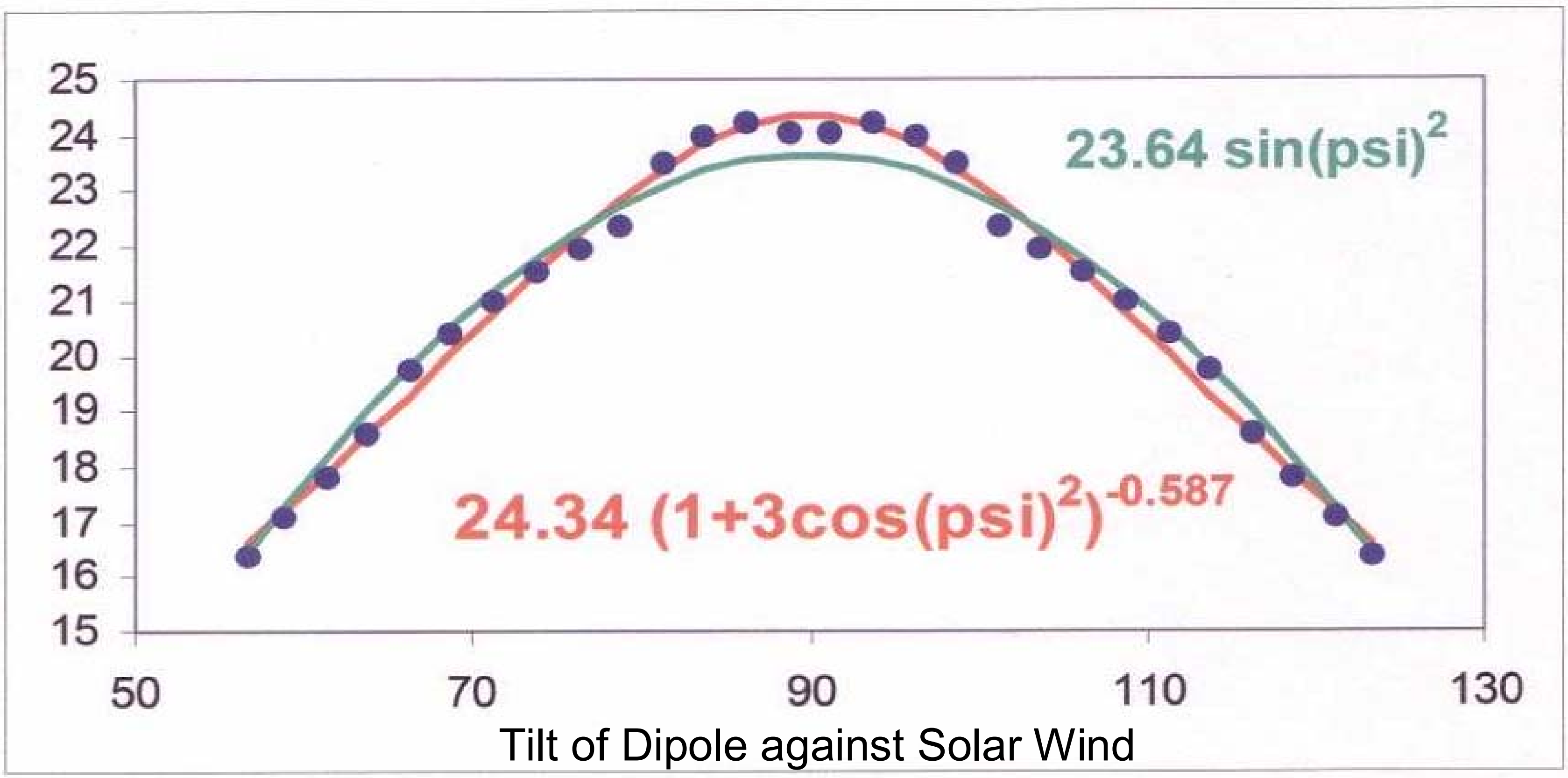


Bz (GSM) > 0 (North)



Bz (GSM) < 0 (South)

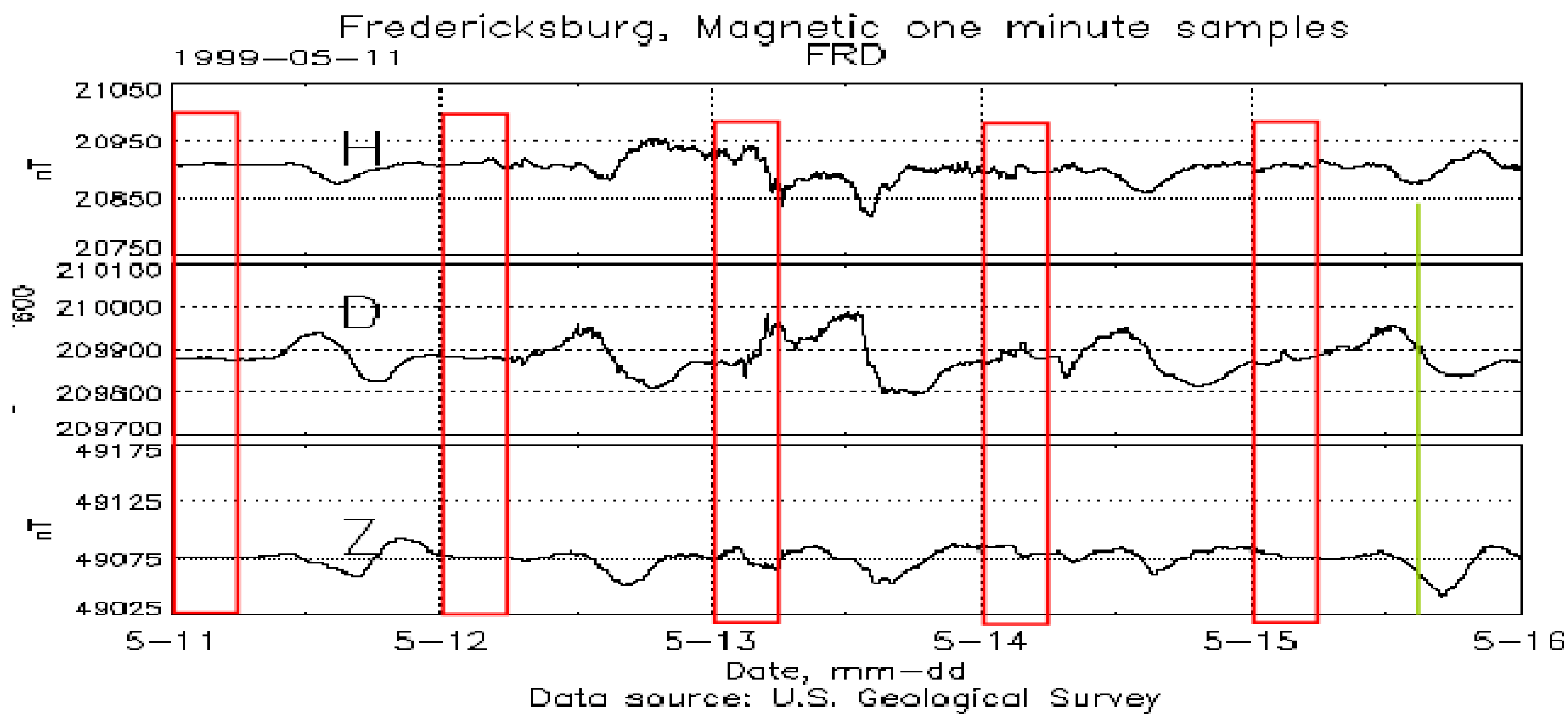
The Modulation involves a factor with $(1 + 3\cos^2(\Psi))$ which basically describes the Field Strength of a Dipole



The Lesson From Mayaud

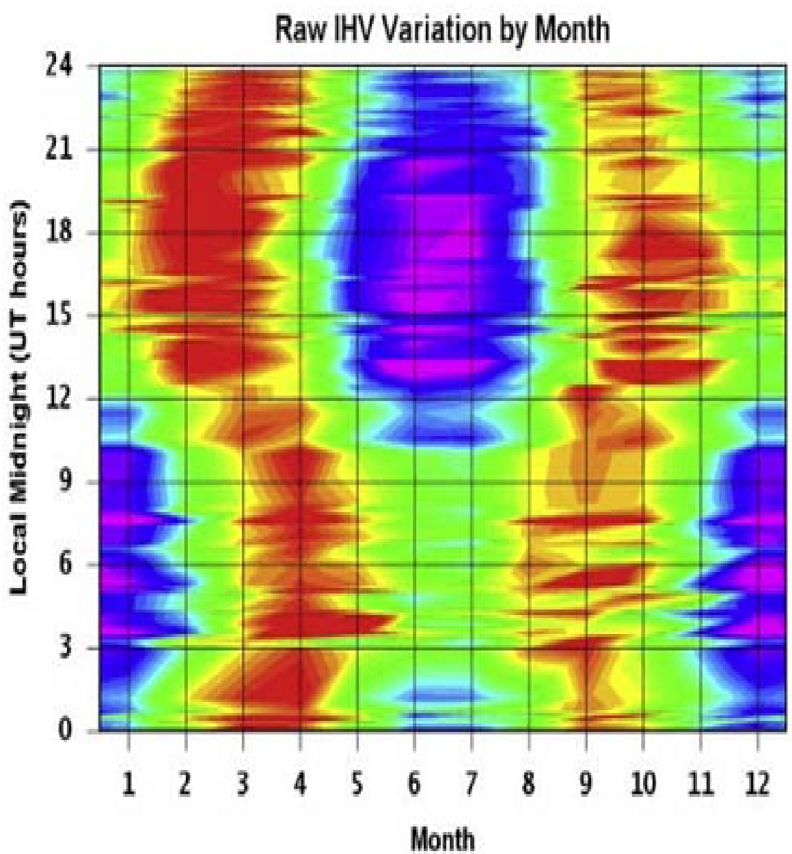
- Mayaud stressed again and again not to use the ‘iron curve’, and pointed out that the observer should have a repertoire of ‘possible’ magnetogram curves for his station, and ‘*if in doubt, proceed quickly*’.
- He taught many observers how to do this. Unfortunately that knowledge is now lost with the passing of time [and of people].

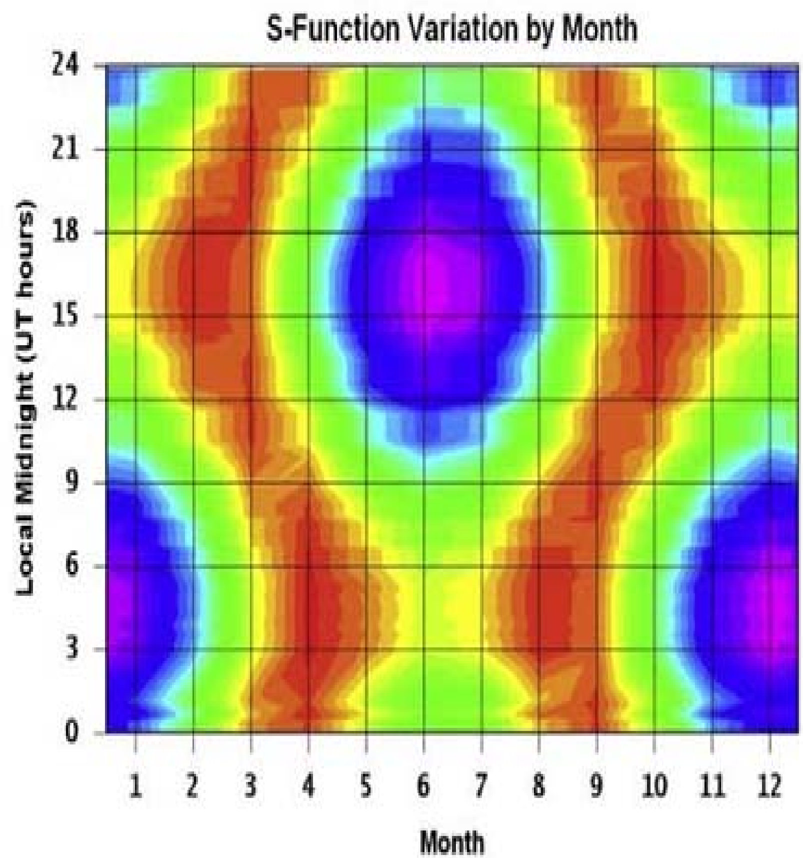
Since Determination of the Quiet Field During Day Hours is so Difficult, We Decided to Only Use Data Within ±3 Hours of Midnight (The *IHV* Index)



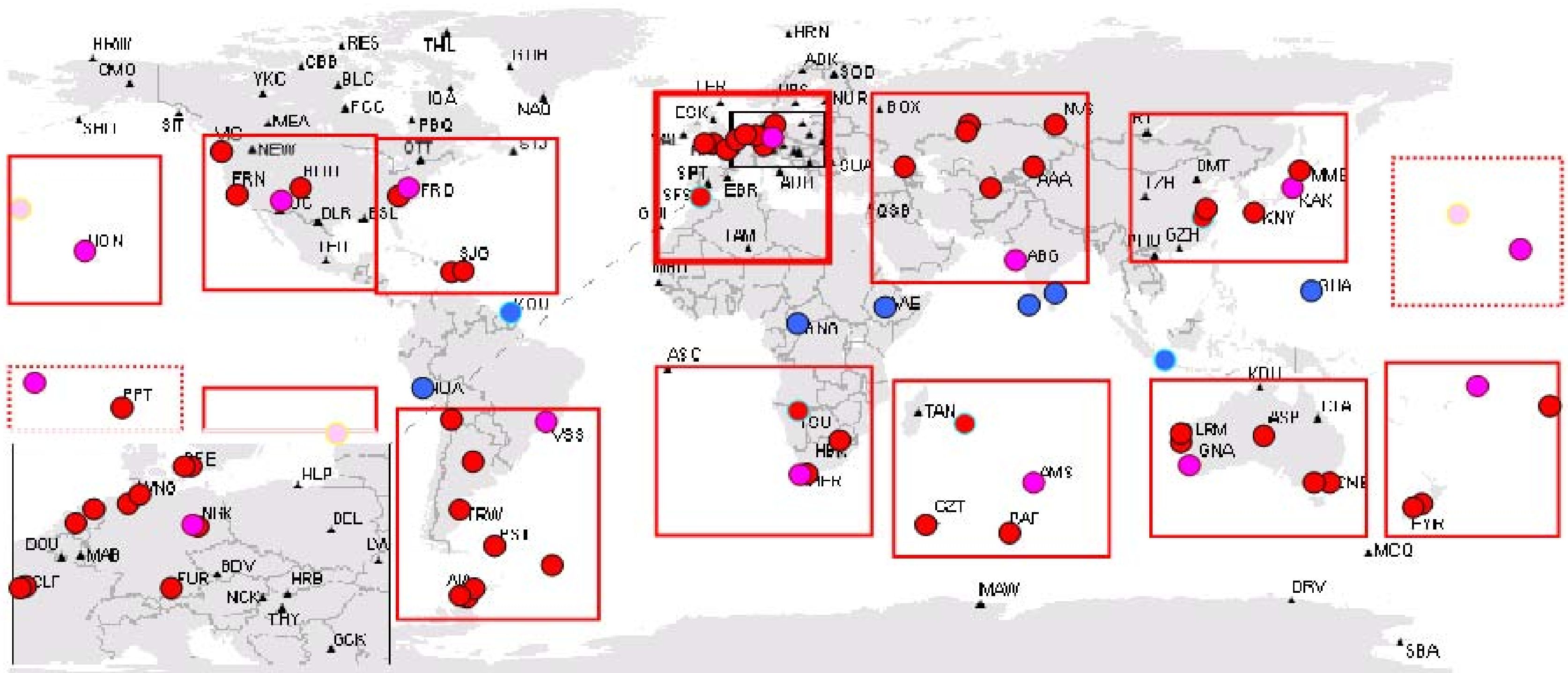
IHV is defined as the sum of the unsigned differences between hourly means or values for this 6-hour period around midnight.

The Midnight Data Shows the Very Same Semiannual/UT Modulation as all Other Geomagnetic Indices (The ‘Hourglass’)



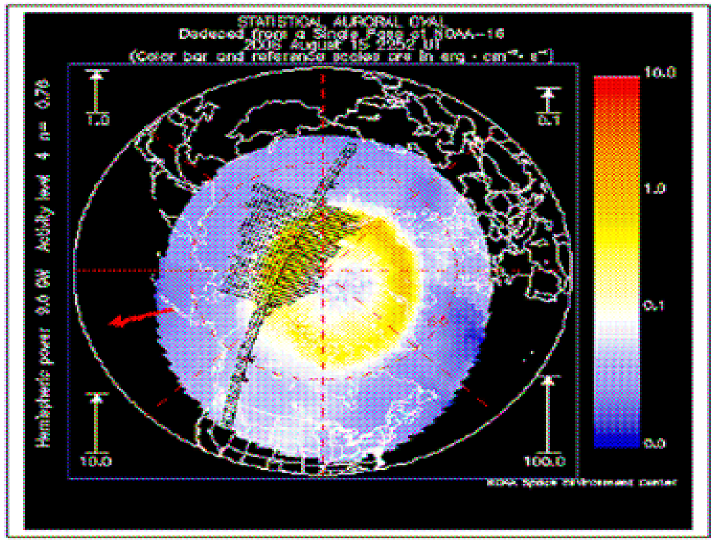


The Many Stations Used for *IHV* in 14 ‘Boxes’ well Distributed in Longitude, Plus Equatorial Belt

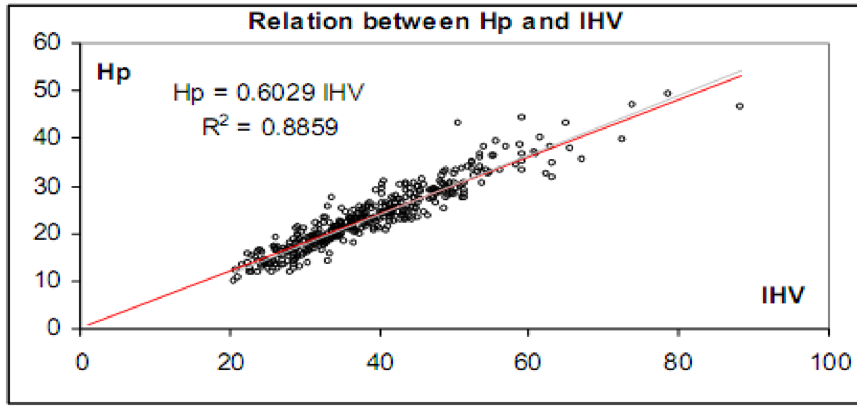


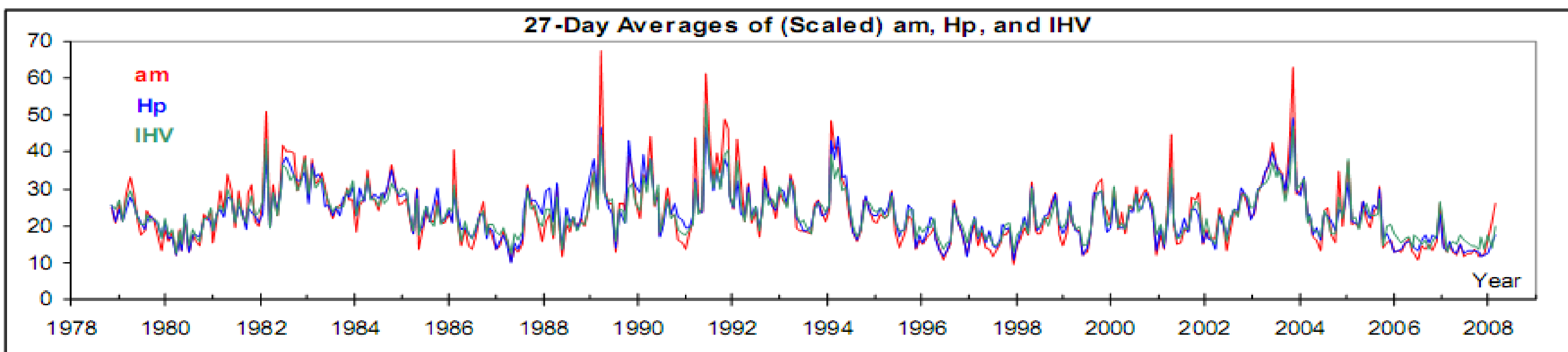
The importance of the *IHV* index is that we do not need the high-frequency part of the variation to characterize geomagnetic activity, but can use simple hourly values from ***yearbooks*** published by the observatories.

IHV is a Measure of Power Input (GW) to the Ionosphere (Measured by POES)

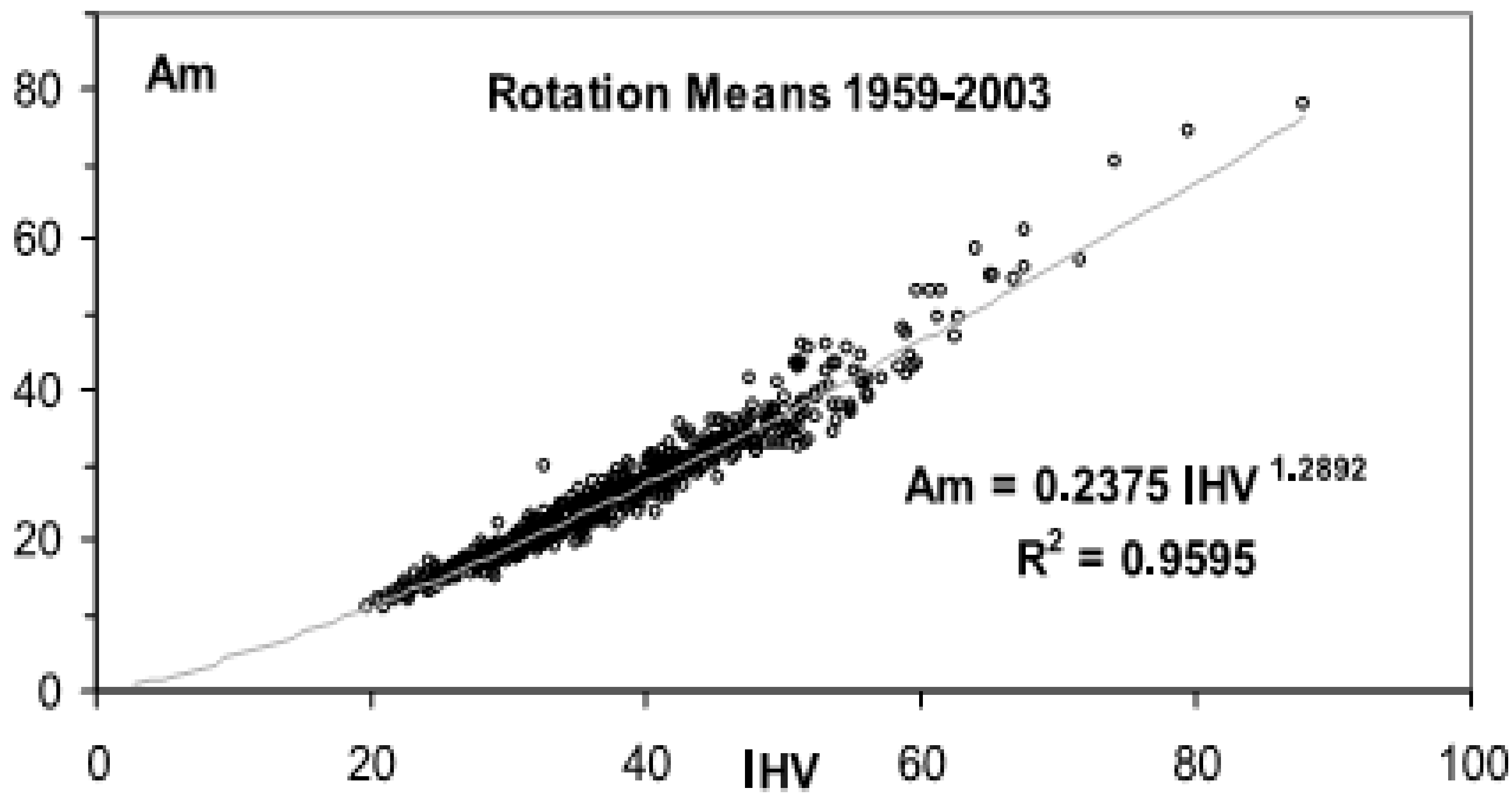


IHV is directly proportional to the power input (*Hp*) to the upper atmosphere:

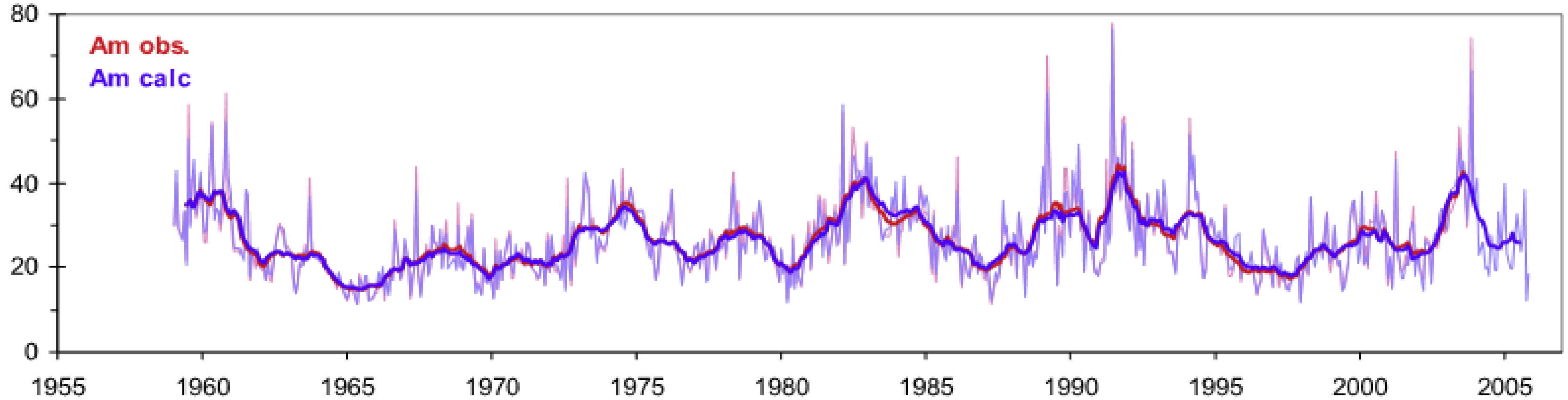


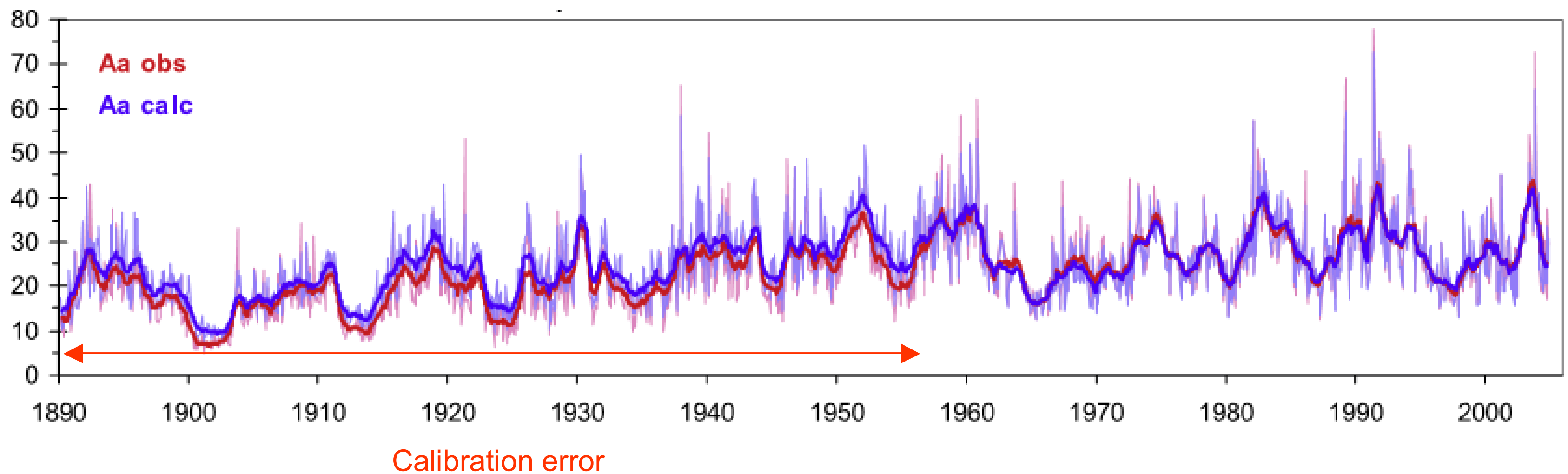


IHV has Very Strong (Slightly Non-Linear) Relation with *Am*-index

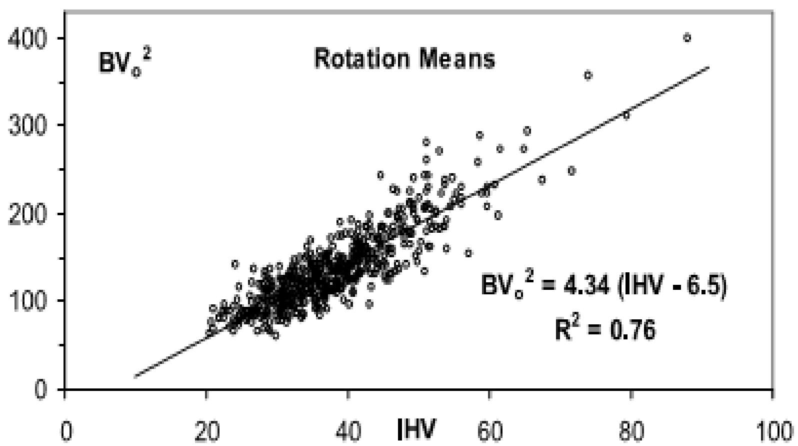


So We can calculate *Am* [and *Aa*] from *IHV*





We can also Determine BV^2



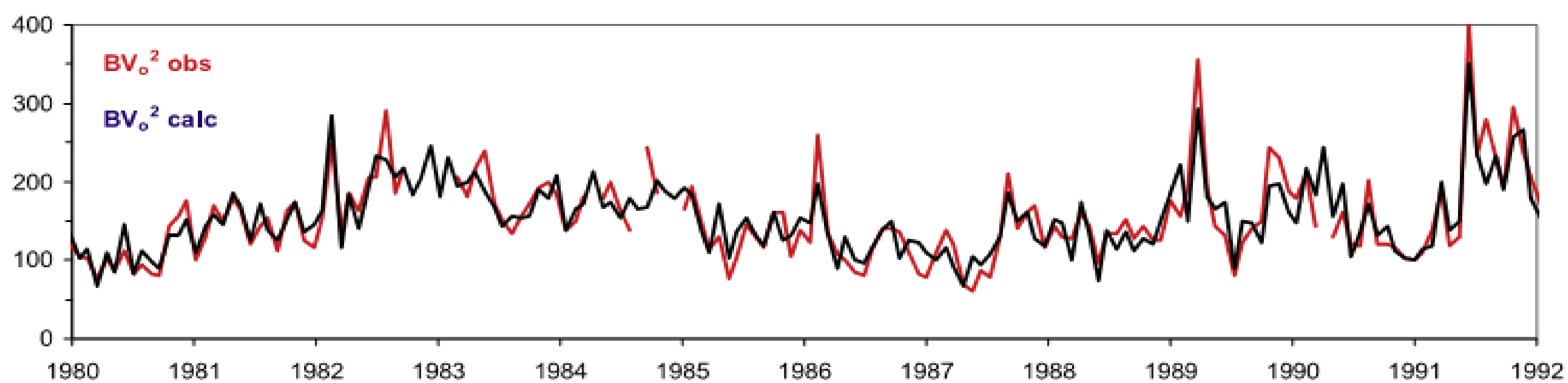
Solar Wind Coupling Function

[Momentum, Reconnection, Modulations]

$$am = k\,(nV^2)^{1/3}\,(BV)\,q(\alpha,f)\,S(\Psi)$$

For averages over a day or more this simplifies to

$$Am \sim BV^2$$



Solar Wind Coupling Function

Today we would characterize geomagnetic activity as those variations that result from the interaction between the solar wind and the magnetosphere:

1. Compression and confinement of the Earth's magnetic field
2. Transferring flux to the magnetotail by magnetic reconnection.

When (and afterwards) the stressed magnetosphere gives way and relaxes to a lower energy state, electric currents flow. Their magnetic effects we call geomagnetic activity and we try to characterize the phenomenon by indices.

Solar Wind Coupling Function

These are thus the physical "inputs" to the system:

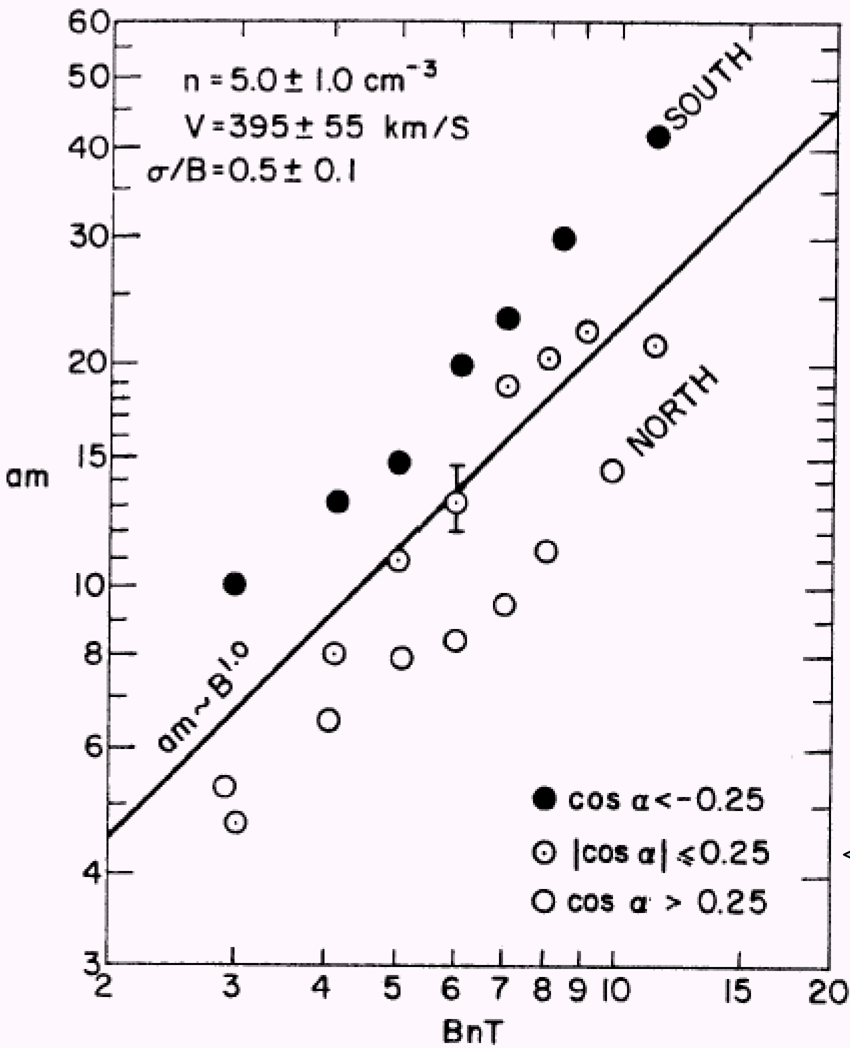
1. The interplanetary magnetic (B) flux per unit time and area, $F = B V$

2. The solar wind momentum ($n V$) flux per unit time and area, $P = (n V) V$

3. The angles between the Earth's magnetic field and the HMF direction (α) and flow direction (ψ)

4. The time scale of interest (hours to days) and the variability within that (hiding the microphysics under the rug)

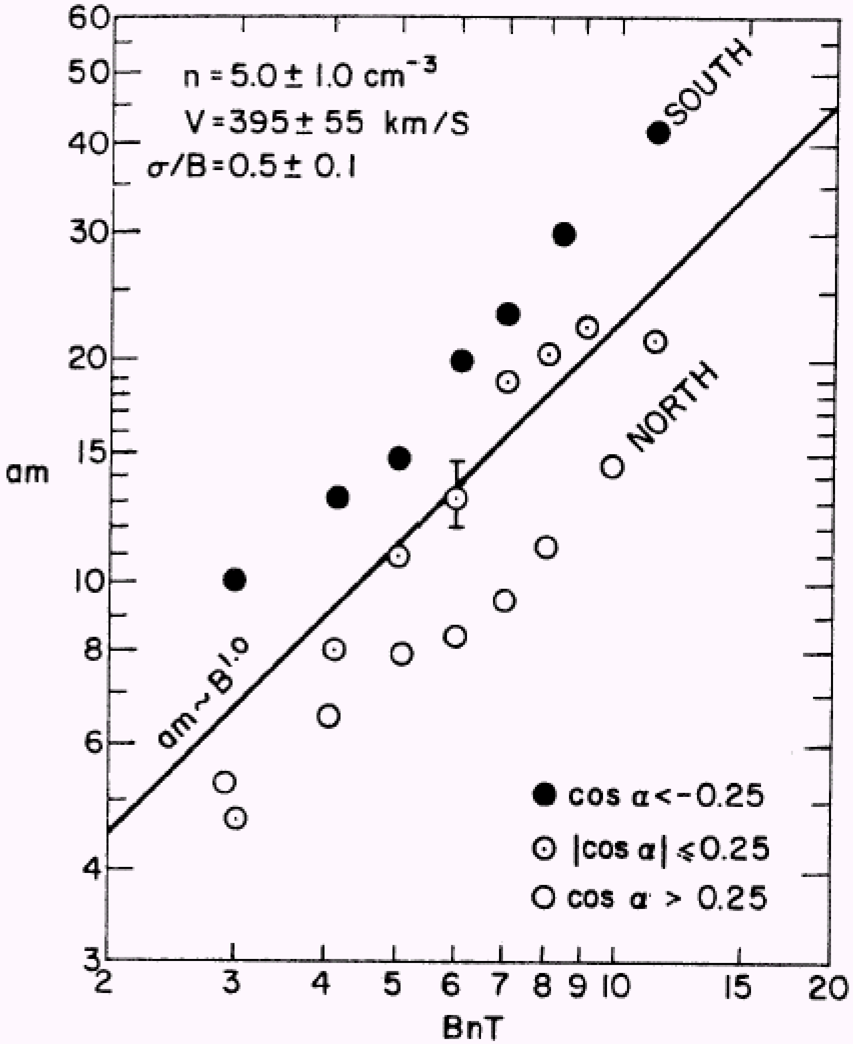
Solar Wind Coupling Function



A common technique in laboratory physics is to keep all variables nearly constant except one and investigate the effect of varying only that one. We can simulate this approach by selecting subsets of the vast dataset available (~250,000 hourly values).

We first vary only the HMF field strength

Solar Wind Coupling Function



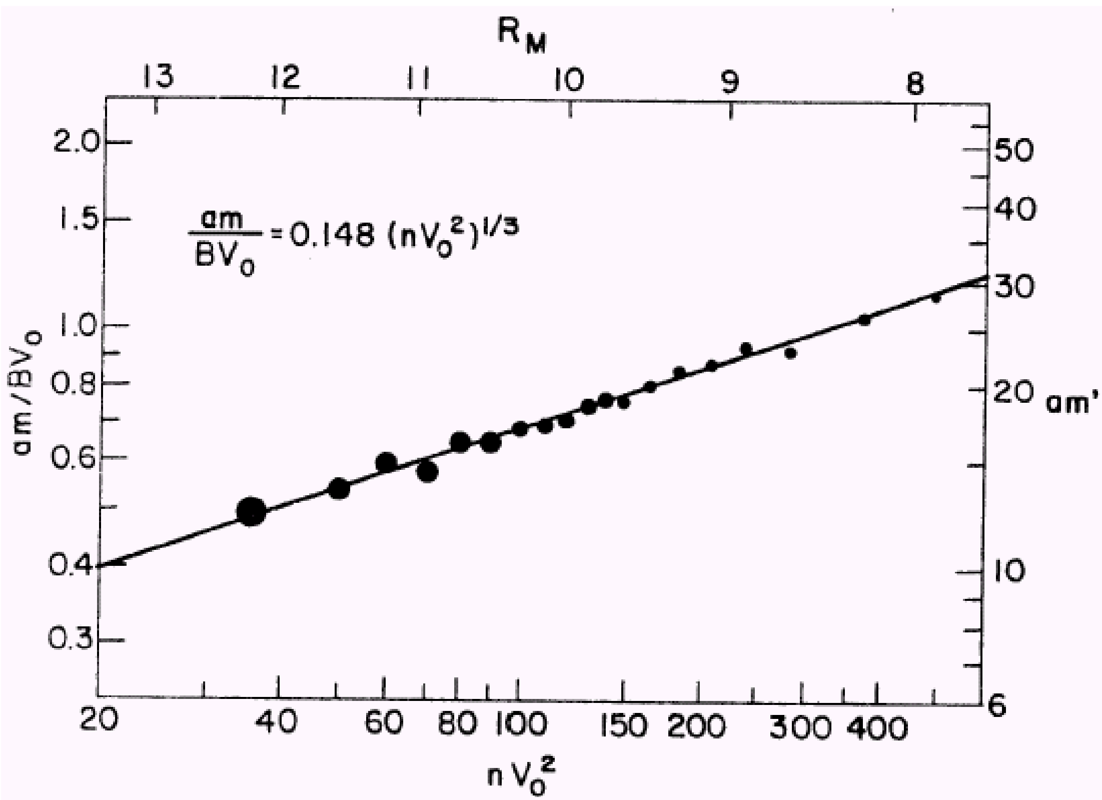
The *am*-index seems to vary with the first power of *B* both for Northward (cos α > 0) and for Southward (cos α < 0) merging angles.

This suggests that we can *eliminate* the influence of *BV* by dividing *am* by *BV*.

Solar Wind Coupling Function

Here we investigate how activity (reduced by BV_0) depends on the momentum flux, nV_0^2

V_0 is used as abbreviation for V/100 km/s

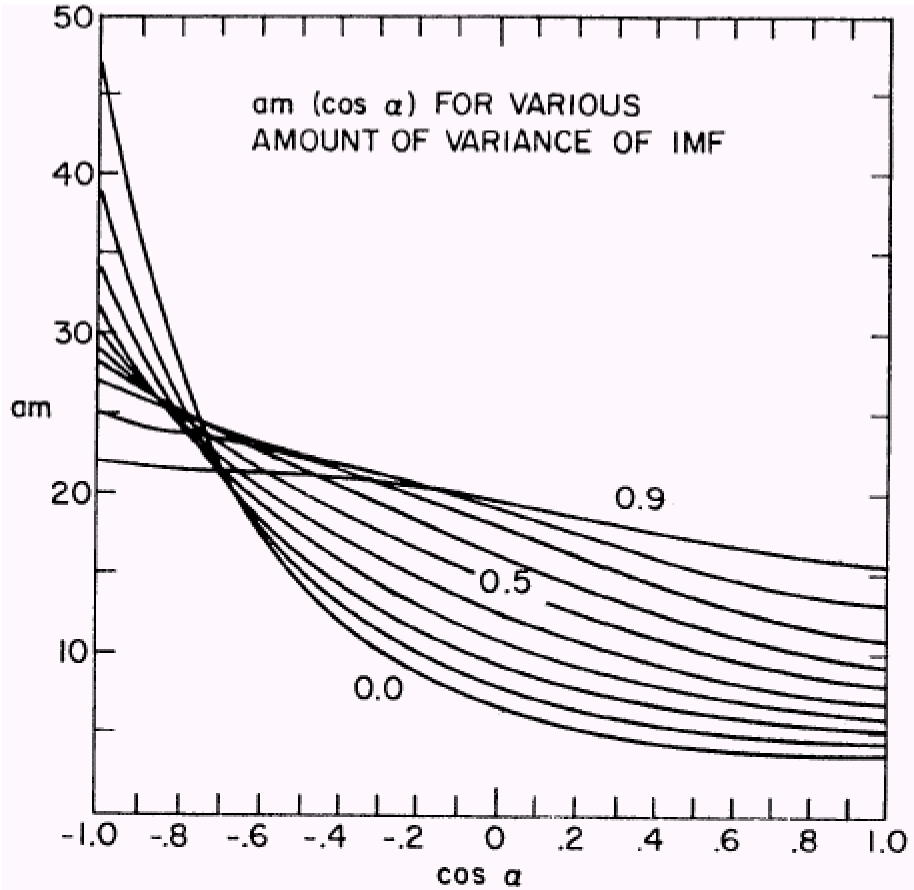


It appears we can eliminate the influence of the solar wind momentum flux by dividing by the cube-root of nV^2, calculating a *reduced* value of *am*:

$$am' = am\,(\langle BV\rangle / \boldsymbol{BV}) \cdot (\langle nV^2\rangle / \boldsymbol{nV^2})^{1/3}$$

where <…> denotes the average value.

Solar Wind Coupling Function



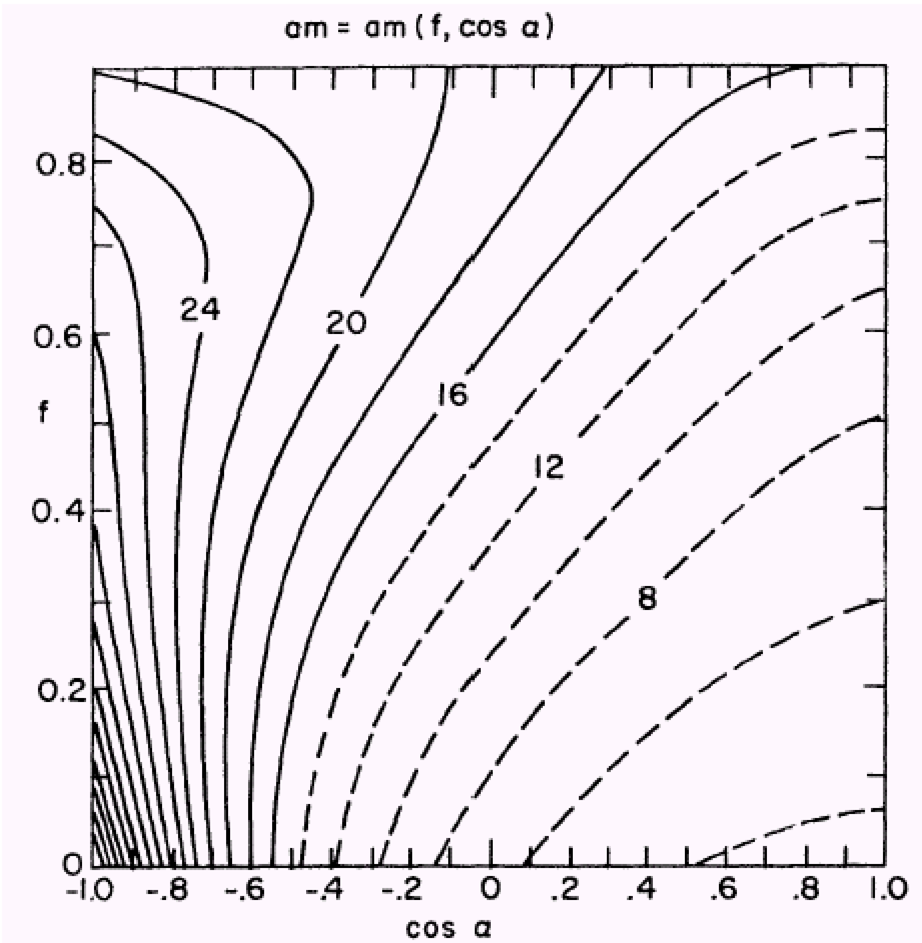
We express the variability of the HMF by the ratio

$$f = (\sigma_{BX}^2 + \sigma_{BY}^2 + \sigma_{BZ}^2)^{1/2}/B$$

The efficiency of the coupling between the solar wind and the magnetosphere depends on the merging angle α, but also critically on the variability, *f*.

When $f = 1$, there is no real dependence on α as the field varies randomly within the time interval, but for $f = 0$, there is a strong effect of the steady southward fields ($\cos \alpha < 0$).

Solar Wind Coupling Function



The coupling function of f and $\cos\alpha$ looks like this (left) and can be modeled by an exponential

$$q(f,\cos\alpha) \sim \exp[-p_4(f,\cos\alpha)]$$

where p_4 is a fourth-order polynomial fit to f and $\cos\alpha$.

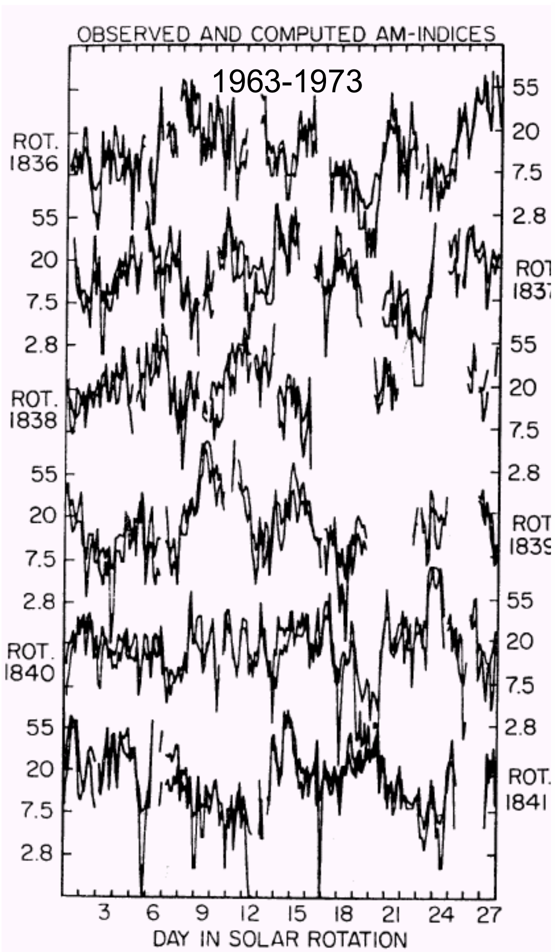
This relationship is, of course, purely empirical and aims only at a (as it turns out, fairly accurate) *description* of the dependence.

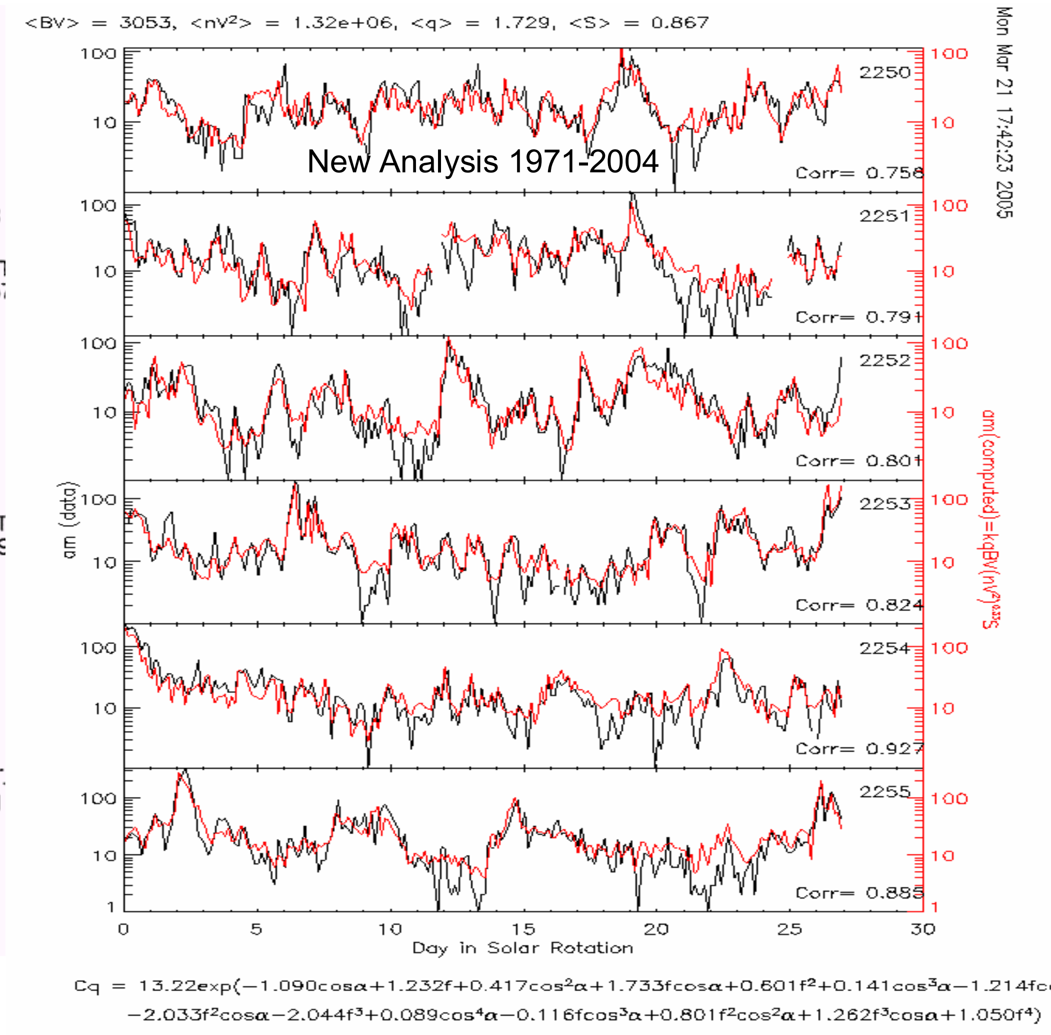
We can then write

$$am \sim BV\,(nV^2)^{1/3}\,q\,(f, \cos\alpha)$$

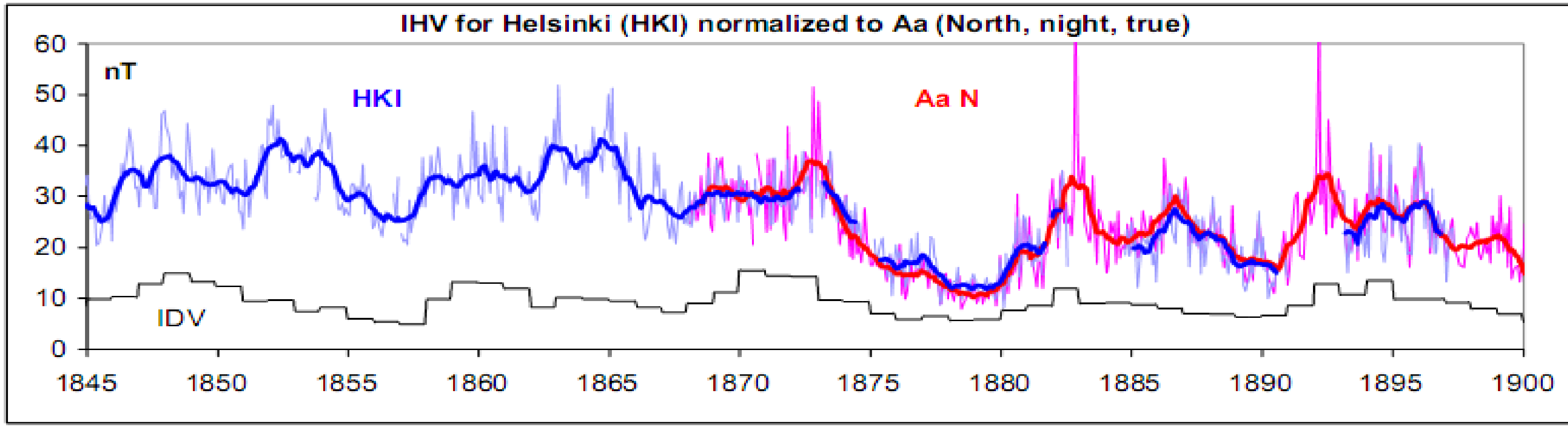
We can then calculate *am* directly from solar wind observations

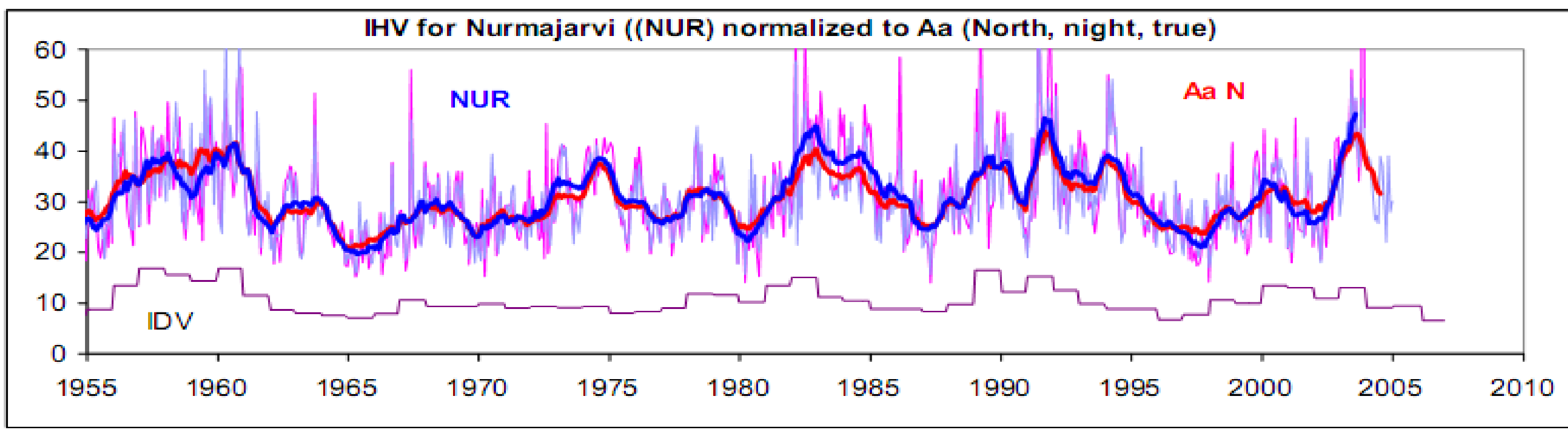
The Coupling Function is a Very Good Description of *Am*





Here We Compare [Corrected *Aa*] with *Aa* computed from *IHV*

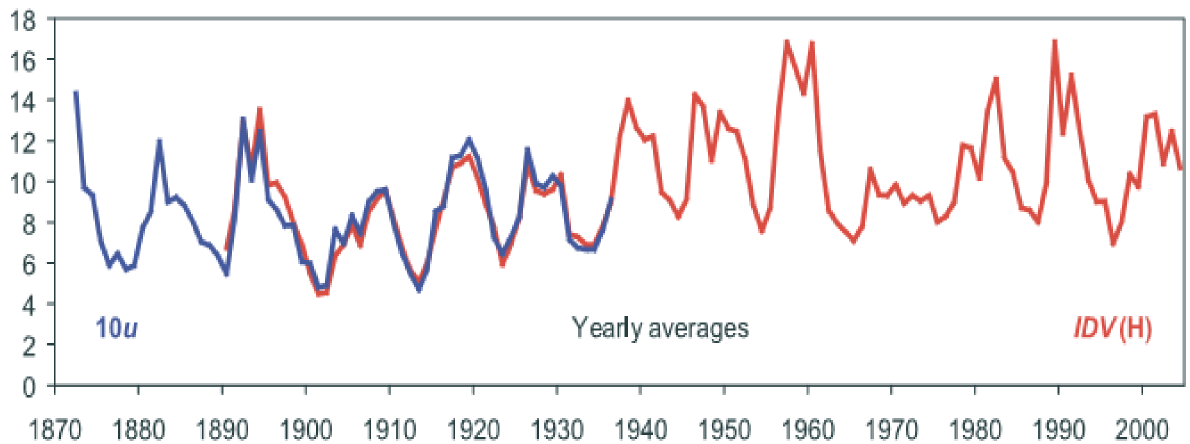


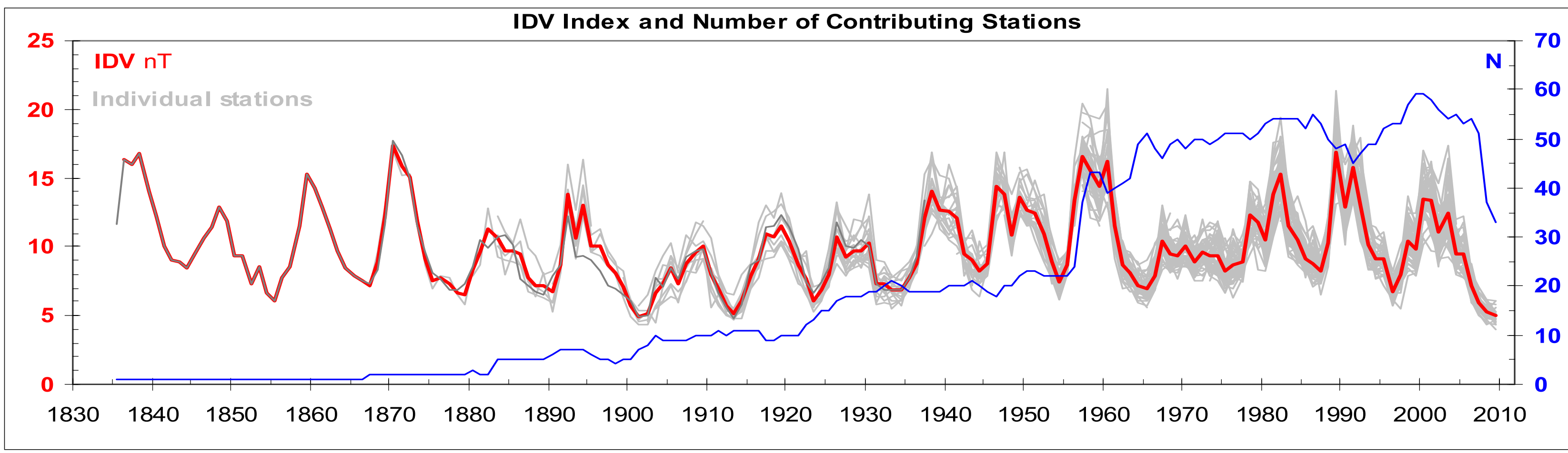


Bartels' *u*-measure and our *IDV*- index

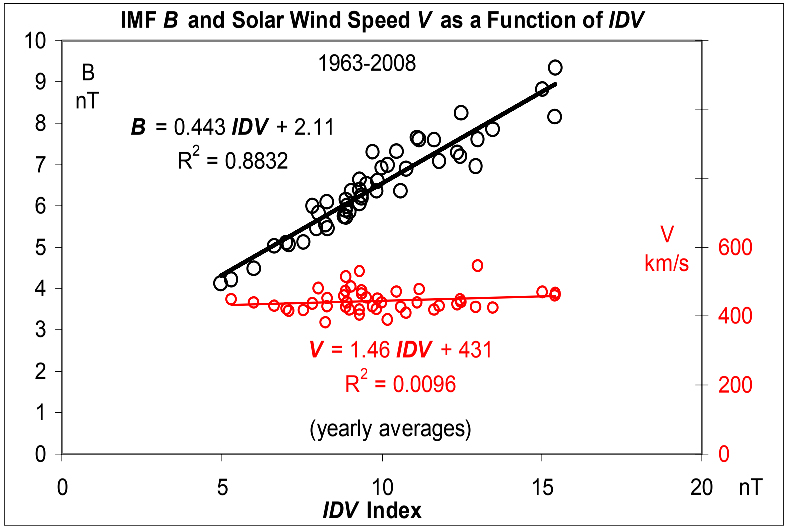
u: all day |diff|,
1 day apart

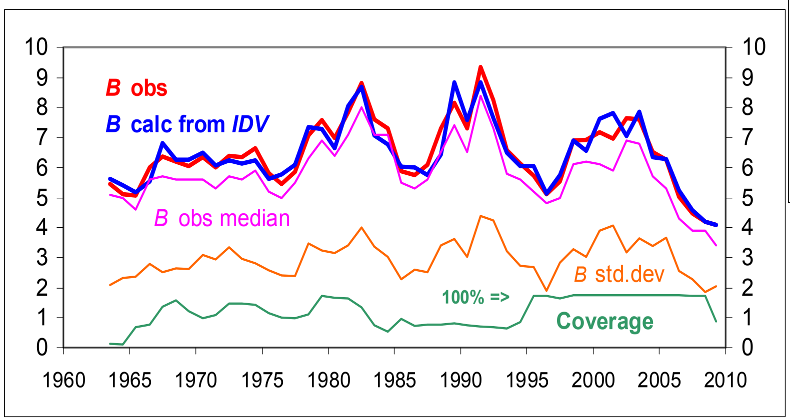
IDV: midnight
hour |diff|,
1 day apart

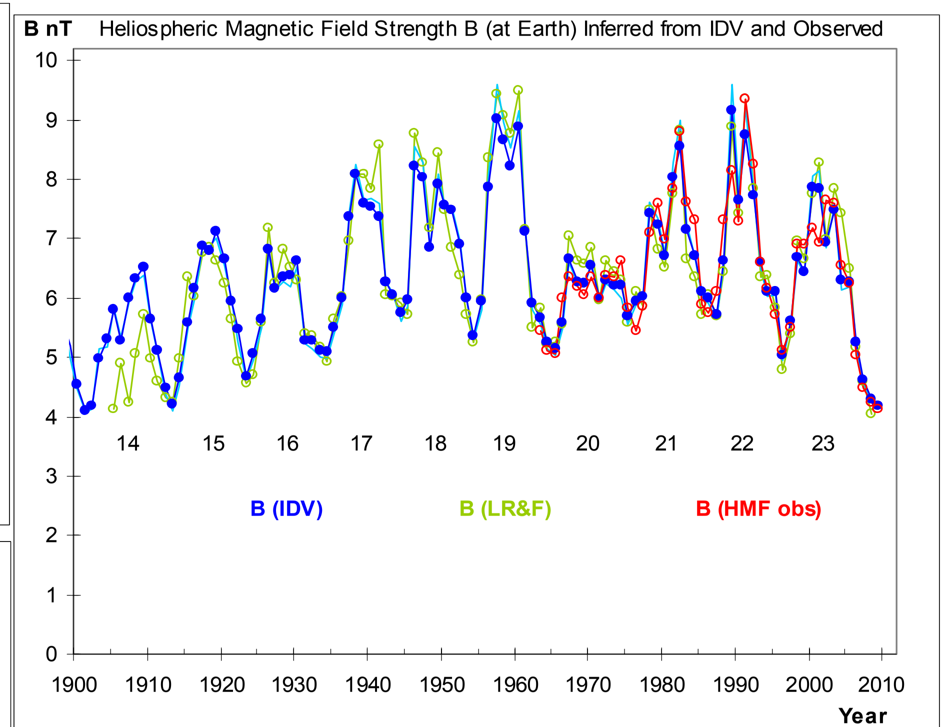




IDV is 'Blind' to *V*, but has a Significant Relationship with HMF *B*

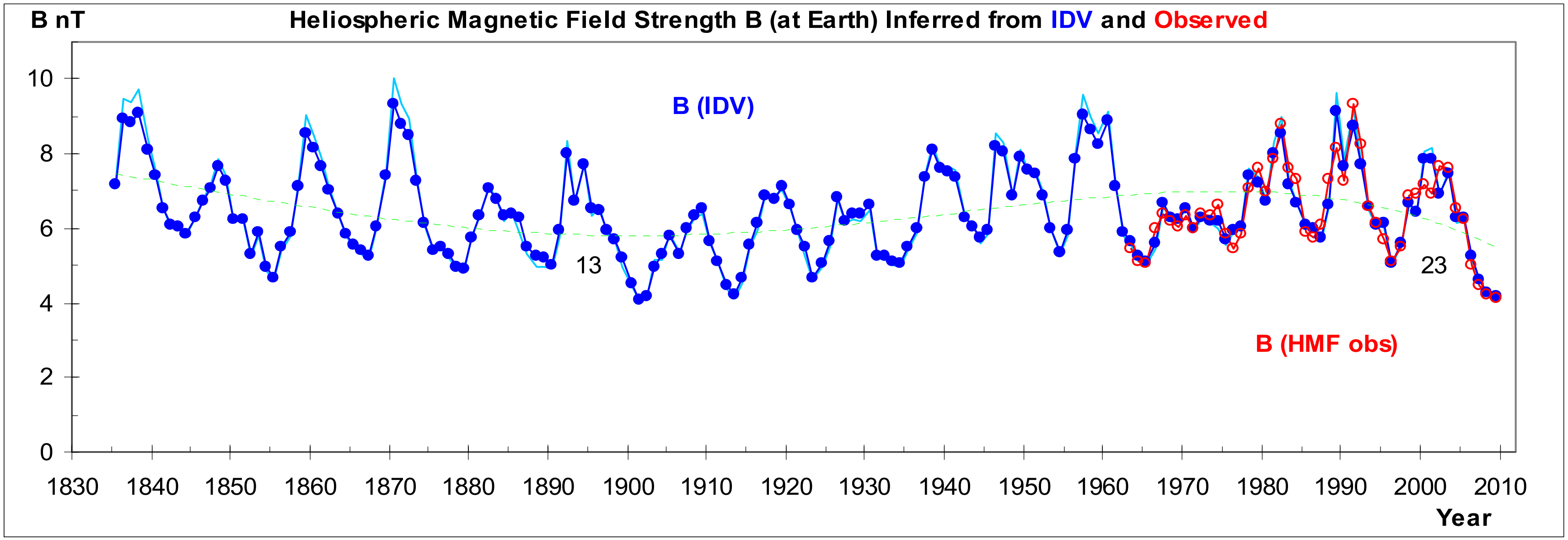






The HMF back to 1900 is strongly constrained

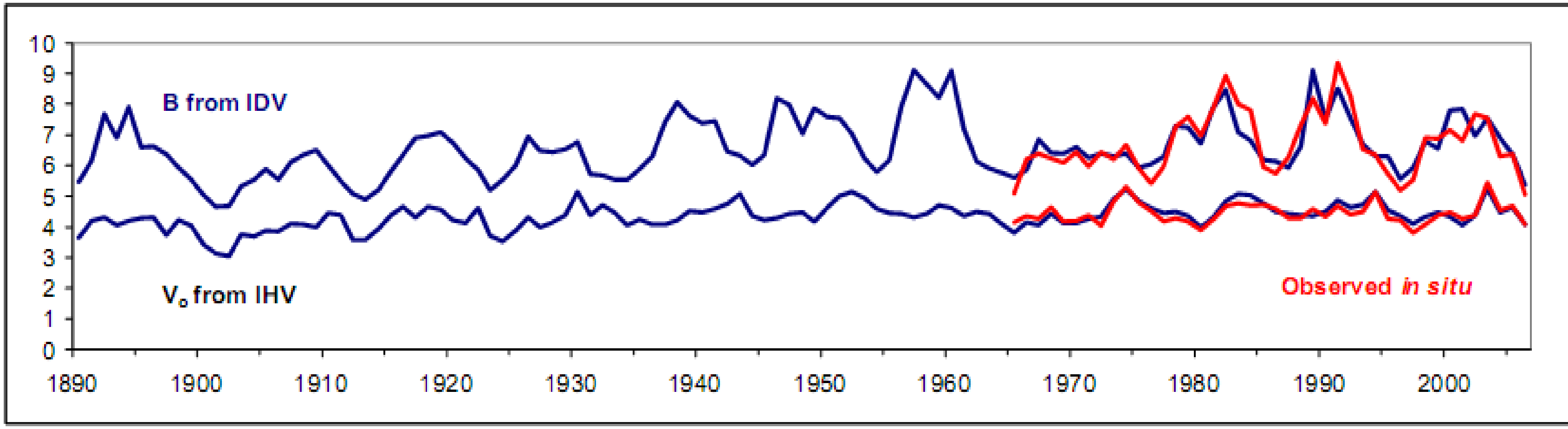
We Can Even [With Less Confidence] Go Back to the 1830s

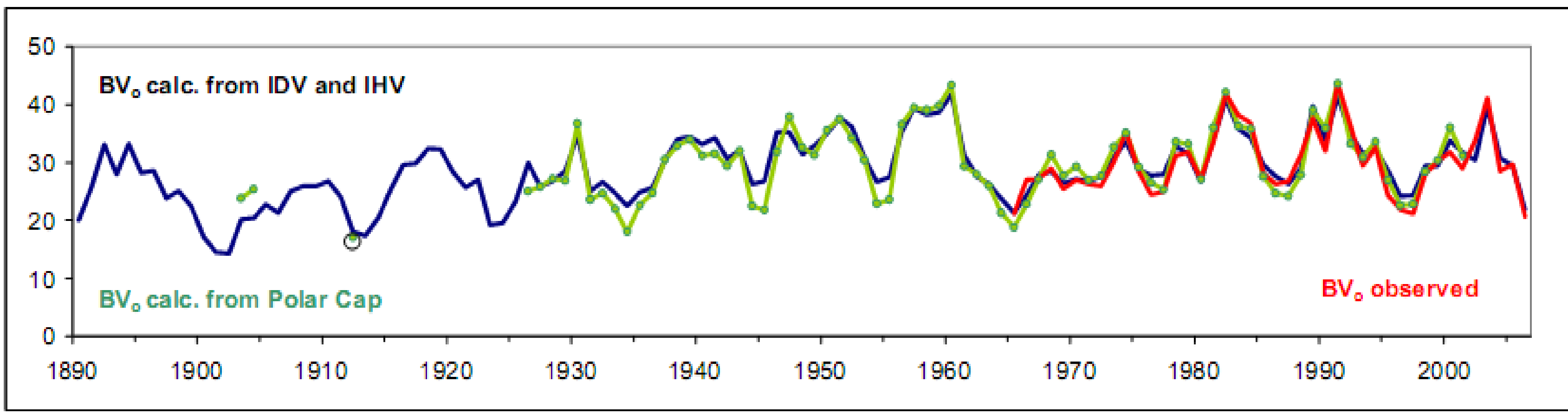


From *IHV*-index we have	BV^2	=	f(*IHV*)
From *IDV*-index we have	B	=	g(*IDV*)
From *PC*-index we have	BV	=	h(*PCI*)

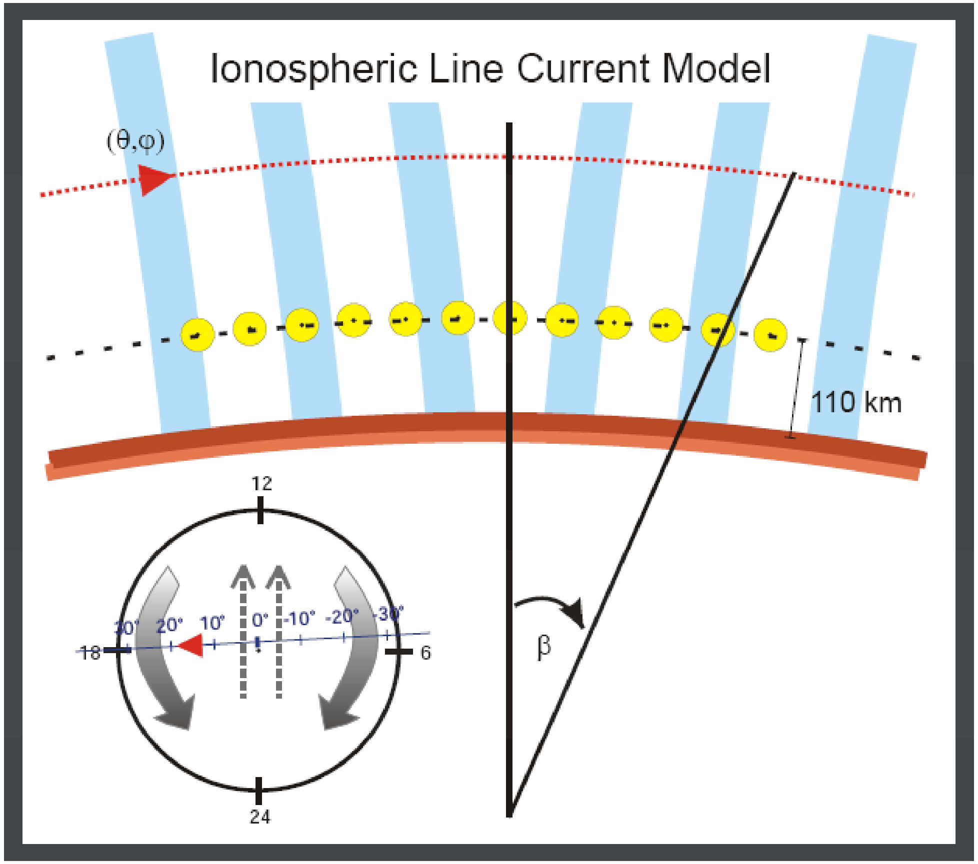
Which is an over-determined system allowing *B* and *V* to be found and cross-checked ➔

With Good Agreement





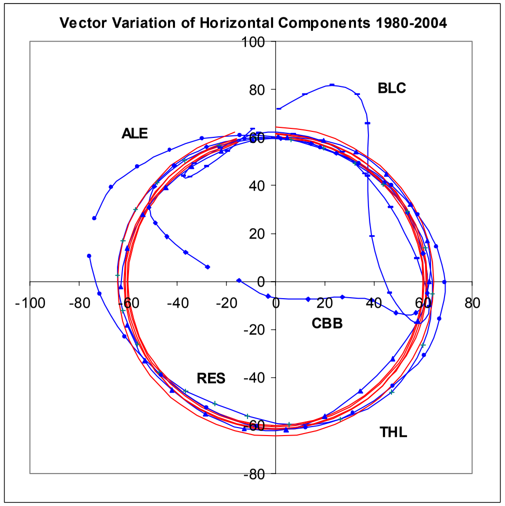
Polar Cap Current

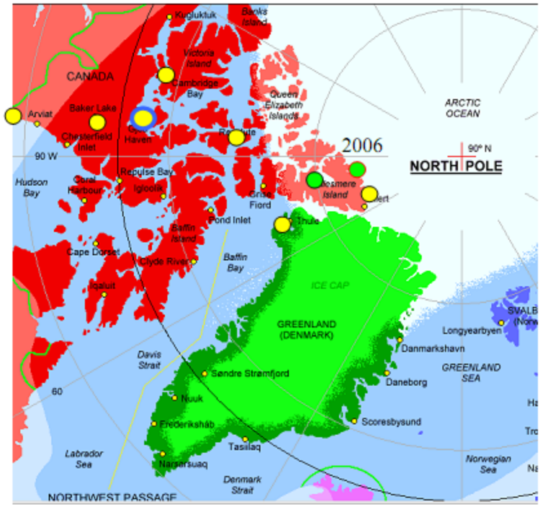


Across the Earth's polar caps flows a current in the ionosphere. This is a Hall current basically flowing towards the sun. The Earth rotates under this current causing the magnetic effect of the current to rotate once in 24 hours. This rotating daily effect is readily (and has been since 1883) observed at polar cap magnetic observatories.

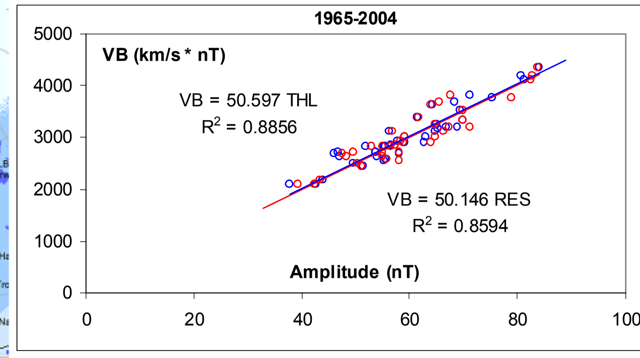
The current derives from the Polar Cap Electric Potential which is basically the electric field ($\boldsymbol{E} = \boldsymbol{V} \times \boldsymbol{B}$) in the solar wind mapped down to the ionosphere.

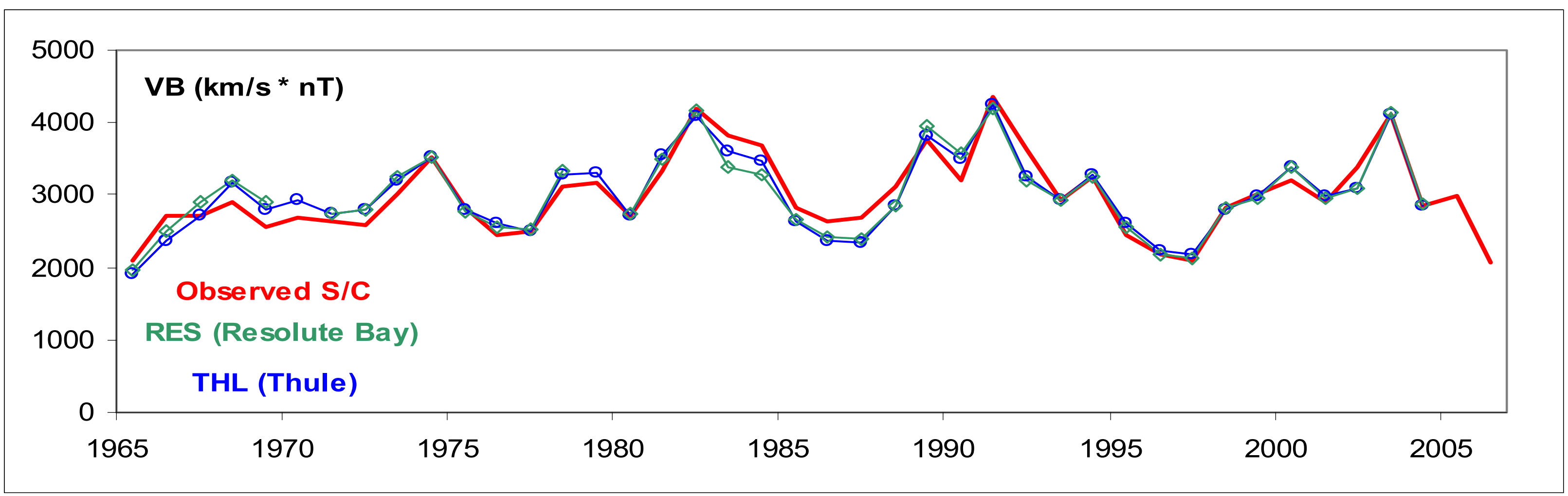
Polar Cap Current





Amplitude of variation ~*VB*

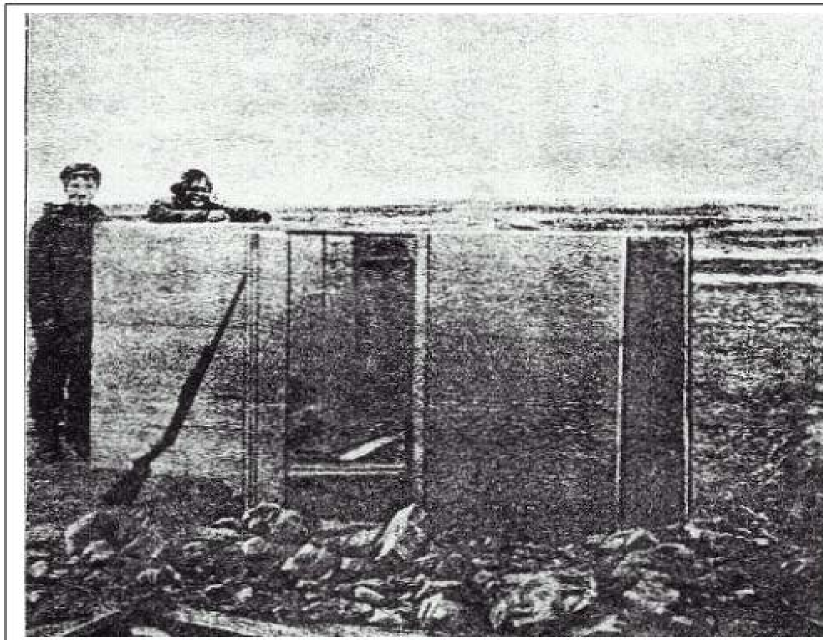




Polar Cap Current

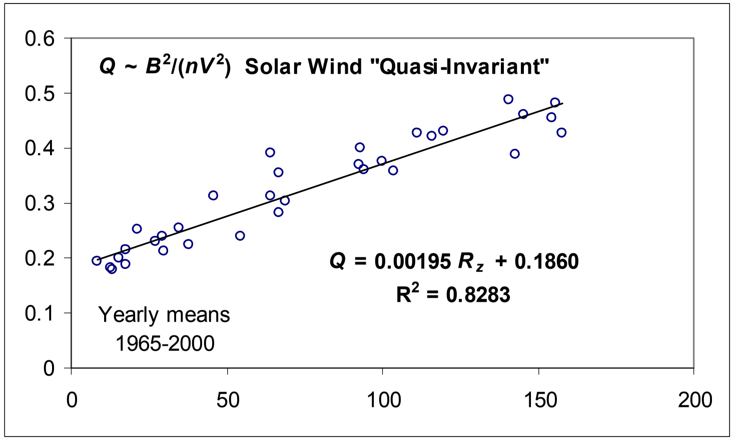
Fig. 4.—Entrance to the Magnetograph House on a fine Spring Day. E. N. Webb climbing c

One of my observers enjoying a fine spring day at Cape Denison close to Dumont d'Urville, 1912.

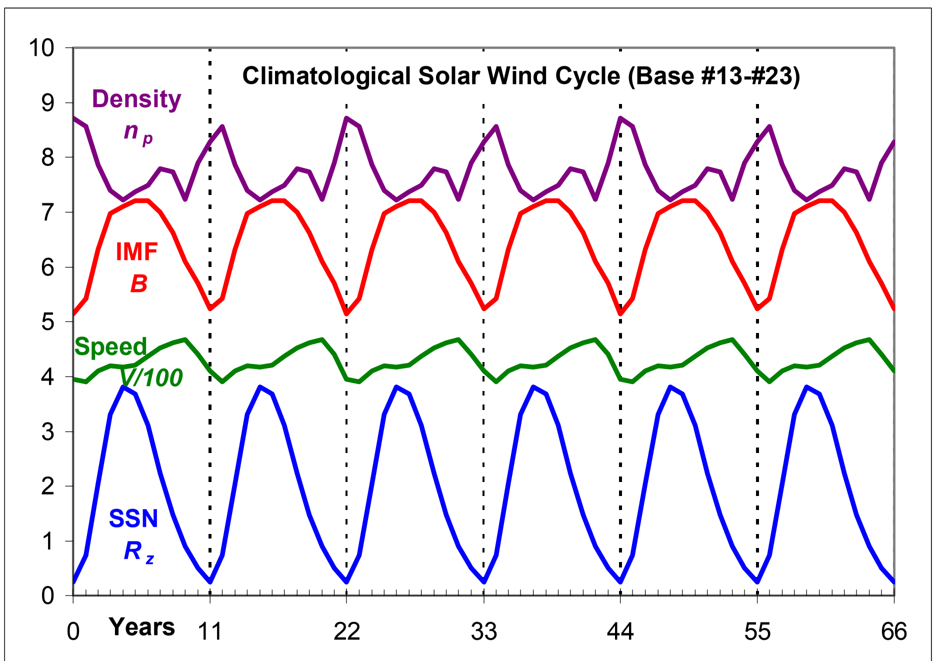


Magnetic variometer hut at Gjoahavn

Determination of Solar Wind Density



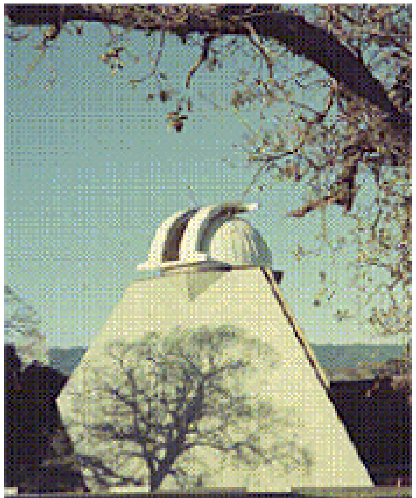
The ratio between Magnetic Energy B^2 and kinetic energy nV^2 is found to depend slightly on the sunspot number R_z

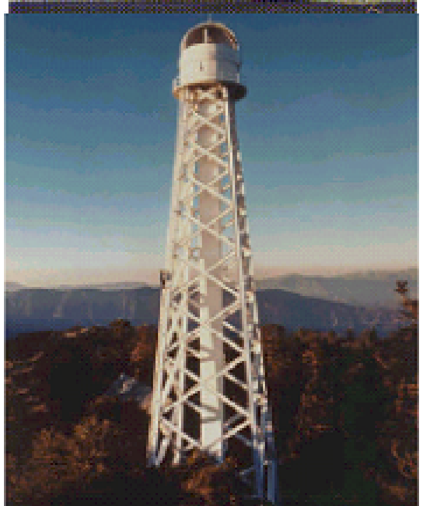


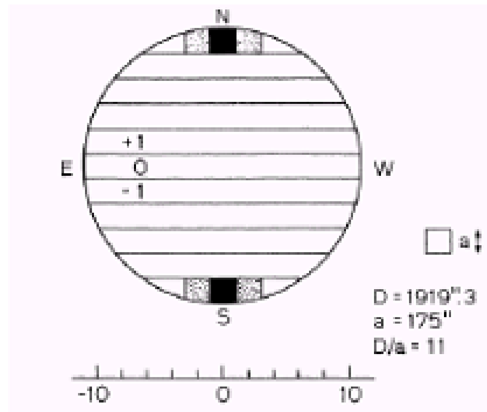
Pulling everything together we can construct the average solar cycle behavior of solar wind parameters from the 11 cycles for which we have good geomagnetic data.

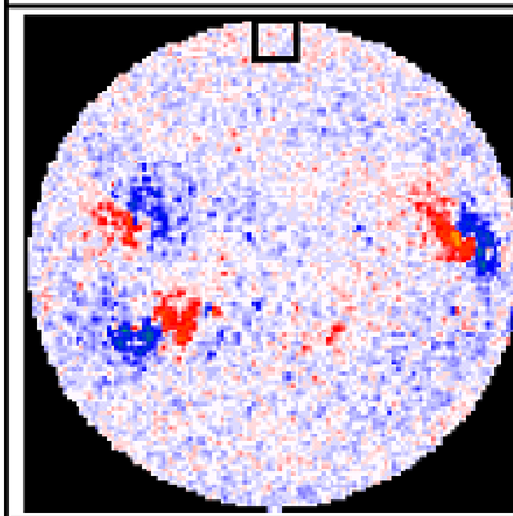
Solar Wind Climate, if you will.

Definition of (Solar) Polar Fields



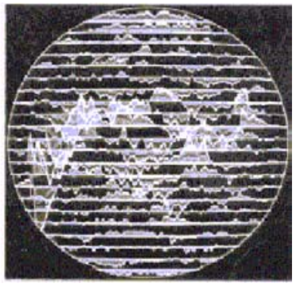




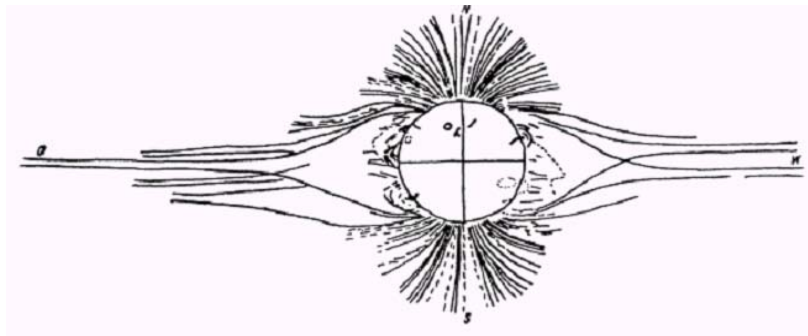


Wilcox Solar Observatory (WSO) **Large aperture: 3'** **Operational Definition of Polar Fields:** *Average field in pole-most apertures (black squares)*	**Mount Wilson Observatory (MWO)** **Small aperture: 0.2'** **Operational Definition of Polar Fields:** *Average field of pixels inside aperture that matches that of WSO*

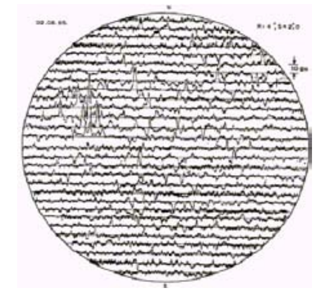
Measurements of Polar Fields

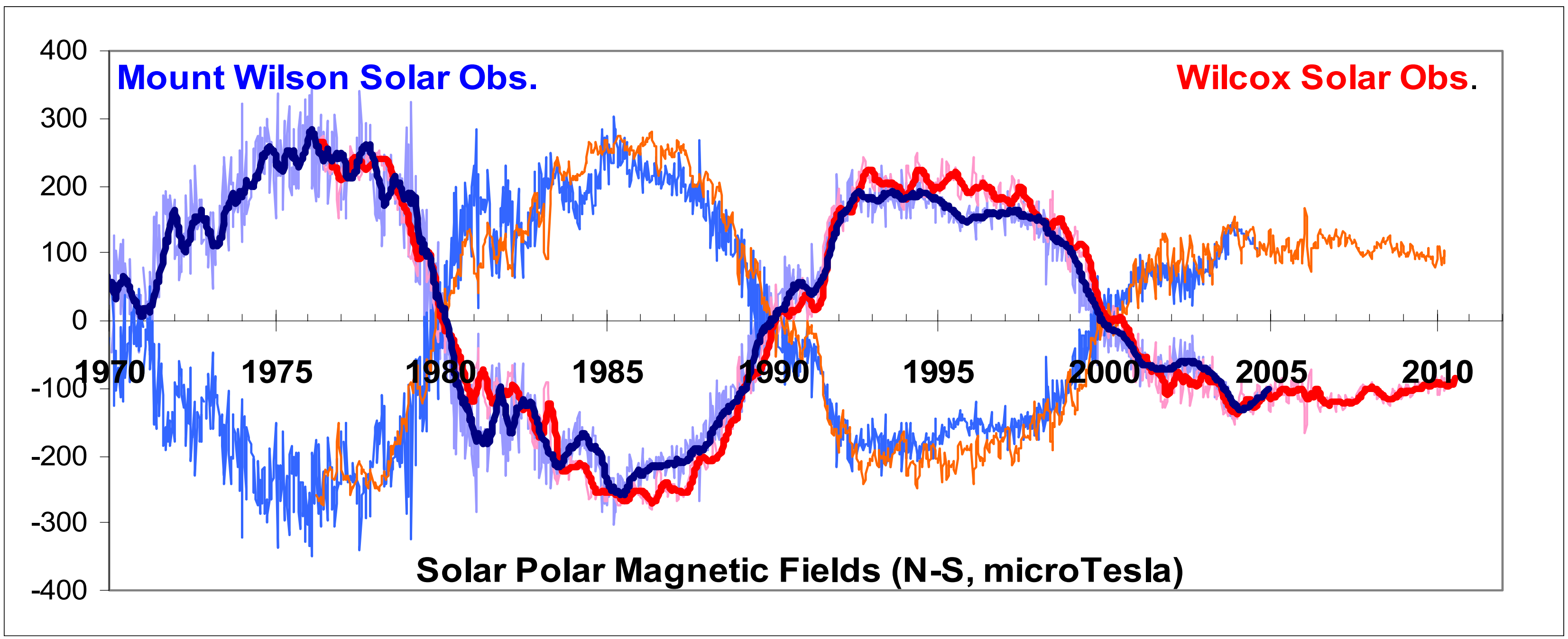


1953

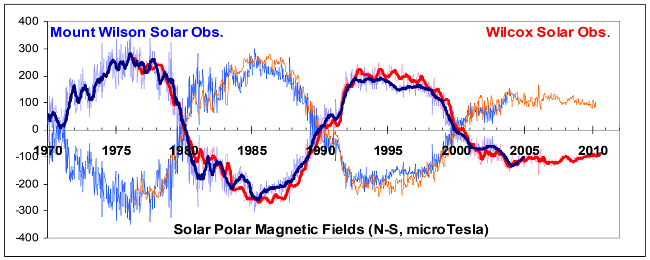


1965



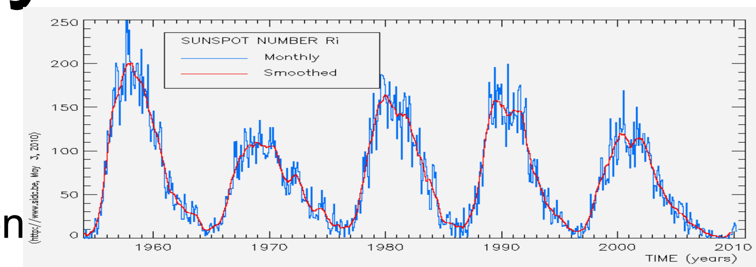


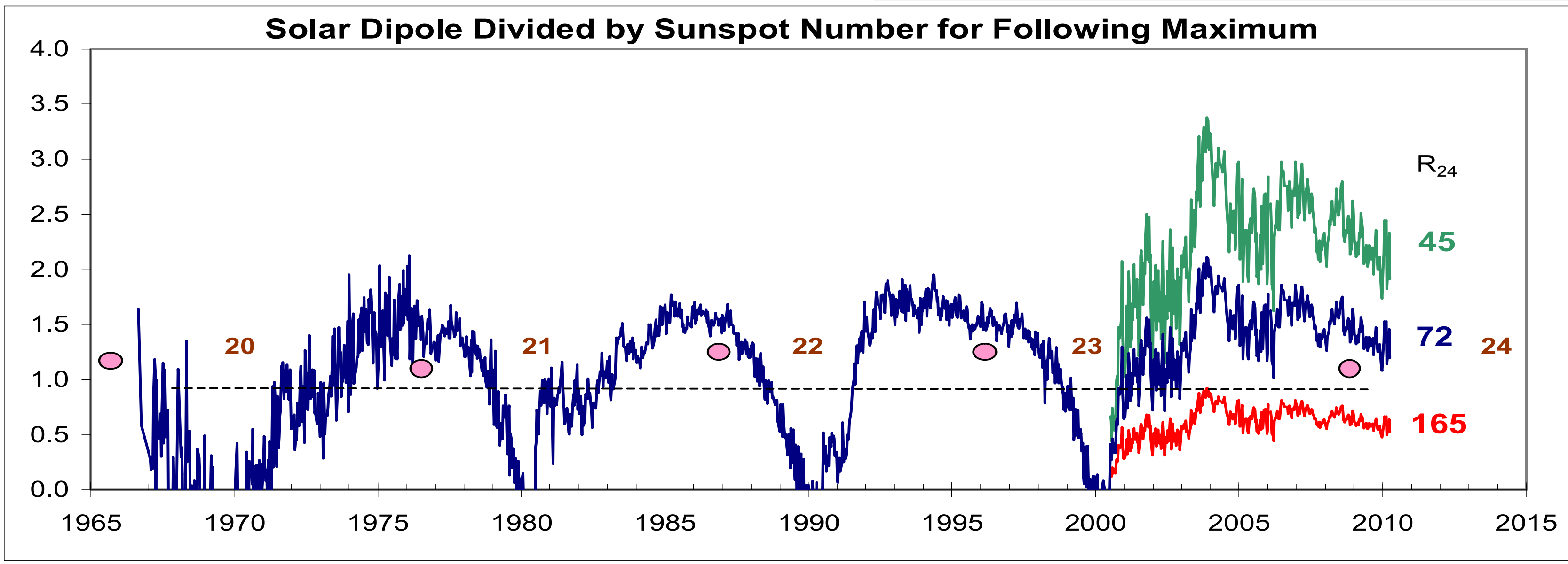
Polar Field Scaled by Size of Next Cycle is Possibly an Invariant



$R_{max24} = 72$

Our Prediction





Solar dynamo models predict that the strength of the polar fields at minimum should determine the size of the next cycle

The Future

- So, we predict cycle 24 to be the smallest sunspot cycle in a hundred years and expect the Heliosphere [magnetic field, cosmic rays, etc] to be correspondingly quiet. The Sun is just back to where it was 108 years ago, so by looking back we should have a good base for looking forward. This means that the Sun’s influence on climate [if any] should be similar to that of a century ago.

Conclusion

From Canton, Sabine, Wolf, Bartels, and Mayaud, the patient recording [by many people] and growing physical insight have brought us to heights that they hardly could have imagined, but certainly would have delighted in.

From their shoulders we see far.

The End

Abstract

In the last decade we have learned how to interpret on a physical basis the ~2 centuries long record of geomagnetic variations. We have learned how to reliably extract values and time variations for the magnetic field in the heliosphere, the solar wind speed, and to some extent the solar wind density back to the time of the beginning of geomagnetic observations. This talk describes our understanding of the physics of the interaction between the various elements of space weather and space climate, and the methods in which this understanding is brought to bear on assessing the long-term variations of the solar input to geospace. The past being a guide to the present, we speculate what the future might bring.