Abstract: The discovery of the sunspot cycle and the first results of the ‘Magnetic Crusade’ together made it clear that solar and geomagnetic activity are intimately related and that observing one is learning about the other [both ways]. Understanding of this magnificent relationship had to await more than a century of progress in both physics and observations, and only in the last few decades have we achieved the elucidation that in the middle of the 19th Century was so fervently hoped for: The lack of rapid progress so frustrated the observers [and their funding agencies] that many observatories were shut down or had operations severely curtailed, because as von Humboldt remarked in vol. 4 of his Cosmos: “they have yielded so little return in proportion to the labor that had gone into collecting the material”. The confirmation by spacecraft measurements of what workers in solar-terrestrial relations had so long suspected namely that a solar wind connects the magnetic regimes of the Sun and the Earth has finally brought about an understanding of one half of the relationship [activity] while the discovery of the ionosphere and measurements of solar ultraviolet and X-ray emissions have brought understanding of the other half [regular diurnal variation]. We now have a quantitative understanding of these phenomena [although the microphysics is still debated] allowing us to model quantitatively the geomagnetic response to solar and interplanetary conditions. The immense complexity of geomagnetic variations becomes tractable by the introduction of suitable geomagnetic indices on a variety of time scales. Because different indices respond to different combinations of solar wind parameters we can invert the response and determine solar wind speed and density and interplanetary magnetic field strength from simple hourly mean values as far back as these are available, as we will show in this talk. In addition, the understanding of the ionospheric response to solar Far UltraViolet, allows us to infer FUV in the past as well, with the possibility of checking [and correcting] the sunspot number and calculating the Total Solar Irradiance. As geomagnetic variations have been monitored for ~170 years with [for this purpose] constant calibration, we have a data set of immense value for understanding long-term changes in the Sun. We argue that all efforts must be expended to preserve and digitize these national and scientific treasure troves.
In Memoriam: Emil Kring Lauridsen
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). 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:
The Difficulty with the Regular Daily Variation

Recognizing and quantifying the regular daily variation, what Mayaud called $S_R$, is the main problem. The amplitude of this variation varies from day to day; near the focus of the current system, even the type of the variation changes from day to day. In deriving both the $Dst$ index and the $K$ range index, $S_R$ must be recognized and removed. We all know the problems associated with that, with the insufficiency of using the ‘5 Quiet Days’ as the basis for determining $S_R$, with the error of using an average ‘iron curve’, etc. The pattern-recognition capabilities of the experienced observer can not be transferred to successors.

Long-Term Geomagnetic Indices

Mayaud’s heroic construction of the $aa$-index (back to 1868) is unlikely to be duplicated. The international cooperation and effort that are providing us with the $ap$ (1932-), $am$ (1959-), and $Dst$ (1957-) indices cannot be replicated or extended into the past. It is difficult to gauge the long-term stability of the calibration of the range indices. The vast collection of 19th century yearbook data seems useless to many people to the point where the data is not being preserved or digitized for modern processing methods.

In this talk, I’ll show how these problems can be overcome and provide a rationale for the preservation and digitization of the yearbook data.
IHV-index: Use of Night Hours Only

IHV-index (InterHourly Variability): sum of the six absolute differences between hourly values of any of the geomagnetic components [initially for H] for the seven hours spanning local midnight [falling within the 4th hour].

In practice, we determine the number of hours to skip from 0 UT, before beginning to sum the following six hourly absolute differences. Local midnight is also the time where the correlation with interplanetary parameters $BV^2$ maximizes.
IHV is Strongly Correlated with the Am-index

There is a strong correlation between IHV [blue] and the am-index [red]. For monthly means for FRD we can calculate am from IHV:

\[ am_{calculated} = 0.7475 \, IHV. \]

The calculated am-index [pink] is a good proxy for am using the same six-hour interval [00-06 UT] as was used in the calculation of IHV.

Using several stations at different longitudes a global composite IHV can now be constructed. The correlation with am is very high, which means that we can construct the am-index as far back as we can get IHV.
For all (~120) stations that had [essentially complete] data during 1996-2003, we calculated the average IHV over that interval and plotted it against corrected geomagnetic latitude. The auroral zones are clearly visible and we limit ourselves now to stations below 55° corrected geomagnetic latitude, for which the variation with latitude is slight.
We use 12 independent longitude [and North/South] “boxes” plus an Equatorial band [blue station symbols]. For each box, a reference station is shown in pink. All other stations in the box are normalized to the reference station and the average is computed for the box. Finally, each box is normalized to the European box [Ref: Niemegk].
Composite Box IHV-indices

IHV15N

IHV130N

IHV290N

NGK-WNG-WIT-CLF-ABN-RSV-HAD

KAK-SSH-MMB-KNY

CLH-SJG-FRD
IHV exhibits the ‘usual’ equinoctial semiannual variation. We plot here the seasonal variation of IHV for all stations [during 1996-2003] below 55° corr. geomagnetic latitude as a function of the Universal Time of local midnight for each station. This variation is well described by the ‘$S$’-function of the Earth’s dipole tilt, $\Psi$, against the solar wind direction. We remove this purely terrestrial effect simply by dividing the raw $IHV$ for each station by the $S$-function for that station.

\[
S(\Psi) = \frac{1}{1 + 3 \cos^2(\Psi)}^{2/3}
\]

$\Psi$ is ‘dipole tilt’ against the solar wind direction.
By averaging [with equal weight] all the normalized ‘box’ composites we arrive at a *global* composite IHV-index that covers all UT hours. The graphs show Bartels 27-day rotation averages [with a 13-rotation running mean]. Note that there is no clear seasonal difference between North and South. Arrows show years with strong high-speed streams.
Comparison with Amplitude Indices

![Graph](image)

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 for comparison with $IHV$: 
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. [using a preliminarily corrected $aa$-index]
Physical Meaning of IHV (and am, aa, ap)

Geomagnetic activity as given by the three-hour $am$-index has been found [Svalgaard 1978] to depend on solar wind parameters and the geometry of their interaction with the Earth as this:

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

- $B$ = Interplanetary Magnetic Field strength
- $V$ = Solar Wind Speed
- $q$ = function of angle $\alpha$ between IMF and Earth’s magnetic field
- $f$ = variability $= \sqrt{(\sigma_{Bx}^2 + \sigma_{By}^2 + \sigma_{Bz}^2)/\sigma_B}$

Here we show how very good the fit is for individual three-hour intervals [red curves = calculated; note the log-scale]. Only for very small values of $am$ [<5 nT] where $am$ is almost impossible to measure correctly do we have a persistent discrepancy: $am$, or rather $Km$, is too low. $K = 0$ is always a problem.
For intervals longer than three hours the variables are weakly correlated and the relation becomes slightly modified to $am \sim BV^2$. We would therefore expect a similar relationship for $IHV$. This is indeed what is observed:

![Graph showing relationship between $BV_o^2$ and $IHV$]

$BV_o^2 = 4.34 (IHV - 6.5)$

$R^2 = 0.76$

And here is a sample of how well the calculated values match the observed. $IHV$ is thus a good proxy for $BV^2$. It is somewhat remarkable that $am$ [conceived long ago] also is.

$Vo = V/100 \text{ km/s}$

$B$ and $IHV$ in nT

All data 1963-2005

27-day Bartels rotation means
Power Input to the Ionosphere

During geomagnetic activity, magnetospheric particles are accelerated and precipitate into the upper atmosphere over the polar regions where the energy thus deposited can be directly measured by polar-orbiting satellites (POES). From the satellite data, the total energy input (in Gigawatt) to each hemisphere can be estimated. Such estimates exist back to 1978:

Different colors denote the different satellites used. The abscissa is Bartels rotation numbers from the year 1978 to the present. There is some ongoing discussion about the correct calibration of Hp. The above is my own.
$IHV$ is directly proportional to the power input ($Hp$) to the upper atmosphere:

$$Hp = 0.6029 \times IHV$$

$$R^2 = 0.8859$$

*Image of statistical auroral oval with color gradient representing $Hp$ and $IHV$.*

*Graph showing the relation between $Hp$ and $IHV$.*

*Graph showing 27-day averages of (scaled) $am$, $Hp$, and $IHV$.*
Correcting IHV from Hourly Values to the Level of Hourly Means

Starting in 1905 Adolf Schmidt began to use Hourly Means instead of the Hourly point values that had traditionally been reported in yearbooks. And soon most observatories adopted the new practice. [Some waited long, e.g. the French who held out to 1972, before making the switch]. The instantaneous values read once every hour have larger variance which results in larger IHV. This is easily corrected for, e.g. by calculating IHV from hourly means [from the 60 one-minute values] and from hourly point values and comparing the two IHVs. All early observatory data must be so corrected.

The thin red curve is the blue [IHV from one-minute values] multiplied by the slope of the correlation plot. The thick red curve is IHV from the published hourly means.
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 $51^\circ$ corr. geomagnetic latitude:

![Graph showing yearly averages of $10u$ and $IDV (H)$ from 1870 to 2000.]

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!

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**IMF B and Solar Wind Speed V as a Function of IDV**

- **Equation:**
  - $B = 0.44 \times IDV + 2.15$
  - $R^2 = 0.8832$

- **Equation:**
  - $V = 1.46 \times IDV + 431$
  - $R^2 = 0.0096$

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**IDV Independent of Solar Wind Speed**

- **Graph** showing yearly averages of IMF $B$ and solar wind speed $V$.

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**Observed and Calculated IMF B**

- **Graph** showing observed ($B_{\text{obs}}$), calculated from IDV ($B_{\text{calc}}$), and IDV median ($B_{\text{obs median}}$).

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*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:

![Graph showing the relationship between IHV and Dst(<0) from 1905-2004.](image)

$$IHV = -0.40 \, Dst(<0) + 2.85$$

$$R^2 = 0.89$$

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 $Dst(<0)$.

![Graph showing the relationship between B and the square root of the sunspot number from 1872-2006.](image)

$$B = 0.2882 \sqrt{R_z} + 4.4856$$

$$R^2 = 0.7139$$

Since there is also a good correlation between $B$ and the square root of the sunspot number (left), we can infer $B$ from $R_z$ as well.
Here are both time series (*IDV* and *IDV* calculated from *Dst* (< 0)):

![Graph of IDV and IDV calculated from Dst(<0)](image)

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

![Graph of IMF B inferred from IDV and Dst](image)

- **B** = 2.78 + 0.38 *IDV*
- **B** = 3.93 - 0.1546 (*Dst*<0)
- **B** IMF obs
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:

![Graph showing inferred IMF B since 1836](image)

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.
Polar Cap Current and Polar Cap Potential

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 \( E = V \times B \) in the solar wind mapped down to the ionosphere.
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 $BV$. 

![Graph of indices and calculated values over time]

*Observed in situ*

*BV* calc. from IDV and IHV

*BV* calc. from Polar Cap

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

We can even do the analysis for a time scale of solar rotations:
The Declination can be converted to the East component using $Y = H \sin(D)$. 
Using several stations we can construct a composite series of the amplitude, $rY$, of the daily variation of $Y$:

It is well-known that the strength of the $S_R$ current system is a sensitive function of the conductivity of the ionosphere which in turn can be well-described by the 10.7 cm solar radio flux. So, we can translate $rY$ directly into an equivalent $F_{10.7}$ flux:
Because the f10.7 radio flux depends on the sunspot number we can turn the calculated f10.7 flux into an equivalent sunspot number and discover that there are indications that the calibration of even the venerable sunspot number before ~1947 is questionable.

This is ongoing work and the conclusions are still preliminary.
Conclusions

1: The hourly values in yearbooks are an extremely valuable data source that allows us to calibrate our long-term geomagnetic and solar indices as far back as the geomagnetic record reaches.

2: By combinations of newly derived geomagnetic indices we can infer the physical properties of the solar wind in the past.

3: Every effort should be expended to preserve and digitize the treasure trove of 19th century hourly data.