Long-term variation of geomagnetic activity, I; the *IHV*-index

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Abstract…

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1. Introduction

Graham [1724] discovered that the compass needle is in constant motion. *Celsius* [1740] and *Hjorter* [1747] noted that large movements of the needle were accompanied by auroras thus establishing that the activity of the magnetic field was an indicator of phenomena in the Earth's environment. Hjorter made more than 20,000 observations (about 20 per day). He recognized that there were both *regular* daily variations and larger *irregular* disturbances that occurred from time to time, and that "it would be very difficult, if not impossible, to bring these […] magnetic motions under rule and order". During the late eighteenth and early nineteenth centuries, specially constructed iron-free huts were put in place for geomagnetic observations, an activity that continues to the present day. It has always been a problem to condense the mass of observations into useful measures that capture the essence of the observations. Over time, a large number of such measures, geomagnetic *indices*, have been proposed and implemented. Indices, expressly constructed and calibrated to show how geomagnetic activity varies over long periods of time, were built and published starting with *Wolf* [1884] and culminating with Mayaud's monumental work, the *aa*-index [1972, 1973, 1980]. In the present paper, we propose and evaluate yet another geomagnetic activity index, the Inter-Hour Variability (IHV) index. The *IHV*-index is constructed to be completely objective, reproducible, and straightforward, with the potential of reaching back into the eighteenth century.

2. Design Criteria

It was realized long ago [*Bartels*, 1940] that solar electromagnetic radiation (primarily EUV) and solar "corpuscular" radiation (what we today call the "solar wind") give rise to different classes of fluctuations of the geomagnetic field. EUV radiation creates and maintains the ionospheric layers. Solar (and lunar) tidal motions of the ionosphere and thermally driven ionospheric winds produce the regular daily S_R variation by dynamo action. On the other hand, the solar wind induced activity is the quantity sought measured by the geomagnetic index *aa*. Many indices are a mix of both effects. It is desirable that an index is derived characterizing a well-defined class of causes. That is, the index should measure cleanly, either the effect of the solar EUV or of the solar wind. If this is possible, the index becomes a *proxy* for the corresponding solar property and can be used to study the sun. Derivation of an index like *aa* involves both the ability of the observer to correctly identify the fluctuations caused by the solar wind and the availability of appropriate conversion tables. As stations or instruments change over time, new conversion tables have to be drawn up and intercalibrated with the previous tables. The entire process cannot easily be duplicated and the quality of the index values is difficult to gauge. The long time-series of hourly values of the magnetic components from several stations form a rationale for investigating if an index measuring solar wind related activity can be constructed from them with the following properties:

- Easy to understand (existing indices are often derived via a process that is convoluted, intricate, and in its details largely unknown to most researchers)
- Objective (no need for determination of baselines, quiet background, or the like)
- Easy to duplicate by other researchers for verification purposes
- Physically quantitative (expressed directly in or proportional to magnetic variations measured in nT)
- Suitable for studies of long-term variations (on time scales of weeks and longer)
- Clearly stated and understood limitations
- Constant calibration over time for any given station (not requiring conversion tables or daily or seasonal adjustment tables)

Because we are constructing an index for long-term trends, we can largely bypass the problem caused by the solar EUV influence by only using data from the night-hours at midlatitude stations. During the six hours around local midnight, the influence of the S_R variation is minimal. This could be a contentious point, but we shall show that our assertion is validated *a posteriori* by the close correlation between our new index and the best approximation available to an index that measures almost exclusively the influence of the solar wind alone, Mayaud's *am*-index. [*Mayaud*, 1967, 1980]. The close relationship between solar wind parameters and the *am*-index has been demonstrated by many workers, maybe most extensively by *Svalgaard* [1977], thus validating *its* efficiency as a proxy for these solar wind parameters. By only using six hours of each day (thus throwing away 75% of the data and 99% of the problems) we get an index that is a statistical *sample* of the true activity. The sample is biased by any UT-variations of activity, but for investigations of long-term variations of the activity itself, that is a price that is easily paid.

3. Definition

3.1. The Inter-Hour Variability

The *IHV* index is defined as the sum of the differences, without regard to the sign, of hourly means (or values) for a geomagnetic component from one hour to the next over the six-hour interval around local midnight where the S_R variation is absent or minimal:

$$IHV^{\mathrm{H}}\ (\mathrm{nT}) = \sum_{h=h1}^{h=h1+5} \mathrm{abs}\ (H_h - H_{h+1}) \qquad (1)$$

where $h1$ is the starting hour (0 to 23) of the six-hour interval. The upper limit $h1+5$ should be counted modulo 24 to wrap around to the following day, if needed. H_h is the hourly mean value for the hth hour. If any of the hours in the interval does not have data, the IHV value is not calculated for that day. The *IHV*-index can be defined for any geomagnetic component (H, D, Z, X, Y, I, F) which may be denoted by an appropriate superscript, *e.g.* IHV^{H} for the H-component. Components that are expressed as angles must be converted to force units (*e.g.* D (nT) = D (tenth of arc minutes)·H/34377). The *IHV*-index is computed as one value per day, but is not a *daily* index, as we only sample part of the day. An average over an interval of many day values (*e.g.* over a month) is expected to approximate the average activity over the interval. Very rarely, *IHV* may exceed 750 nT. For these cases, the *IHV*-values are artificially capped at 750 nT, similar to the way *am* is capped at 667 nT.

3.2. Historical Note

The *IHV*-index springs from the same well as the classical *u*-index [*Bartels*, 1932], building on a concept by *Moos* [1910] who defined the interdiurnal variability *U* of the horizontal component at a given station as the difference between the mean values for that day and for the preceding day taken without regard to sign. The δ-index defined by *Chernosky* [1960] is a generalization of the inter-hour variability index where δ could be taken as any value, not just one hour. Both the *u*-index and the δ-index suffer from contamination from S_R. *Chernosky* [1983] attempted to eliminate S_R by computing the unsigned difference between corresponding three-hourly means on *successive* days, but was only partly successful, because S_R itself varies from day to day. Our solution is more radical as our aim is somewhat lower. We do not attempt to construct an index value for every hour or three hours or even a day, but are content with a statistical sample based on the ¼ of the data when S_R is not present. Such a sample, based on an unbiased selection (always the same UT interval), can be expected to provide a reliable estimate of the average level of activity for intervals of weeks or longer, and will be almost free from contamination by S_R.

Mayaud himself [1980, p. 13] describes how he tried to evaluate the contamination by S_R in the interdiurnal variability *U* by comparing with the quantity *U´* computed using only the first and last six local hours of each day instead of all 24 hours. He notes that “thus the daytime hours are eliminated, and most of the contribution of S_R should disappear”. We narrow the interval further to only the first and last three hours of the local day, further reducing the contamination. Mayaud continues: “It appears that attempts could be made to compute *U´* values for some tropical observatories and to compare them with interdiurnal D_{st} values. If the comparison is significant, the series could be extended backward to early years and would be of value”. The present paper seeks to carry out this program for midlatitude stations and the *am*-index.

4. *IHV* at Stations along the 290th Meridian

4.1. *IHV* at Fredericksburg

The geomagnetic observatory at Fredericksburg, Virginia (FRD, Geogr. lat. 38.20˚N, long. 282.63˚E; Geomagn. lat. 49˚N, long. 353˚E) has been in operation since 1956 (with a brief gap 1981-83). Hourly values can be downloaded from the World Data Centers for Geomagnetism. This observatory is located close to the ideal geomagnetic latitude of 50˚ for discerning the class of activity used in derivation of the *am*-index (and is, in fact, one of the stations contributing to the *am*-index - and to the *ap*-index, as well). Figure 1 shows the variation of the three components for several days in May 1999. The S_R variation is clearly seen, including its day-to-day variability. An “effective” noon can be defined as the time where the H-component has its maximum excursion. This is also the time when the excursion in the D-component changes sign. It is evident that for this station, the interval 00-06 UT is the optimal interval for calculation of the *IHV*-value. It is fortuitous that this interval just contains the first two 3-hour intervals of the UT-day. We can thus easily compare our *IHV*-values with the corresponding *am*-values. This is done in the bottom panel of Figure 1. We can compute the average *am*-value over the six-hour interval for the day for direct comparison with the IHV-value for the day. We denote this average value by *Am2* to distinguish it from the daily average (customarily denoted by *Am*). Because of intrinsic UT-variations of geomagnetic activity and possible residual systematic errors due to uneven station distribution, *Am2* is expected to be systematically different from *Am*. In fact, *Am2* = 0.986*Am*, on average (R^2 = 0.8642).

4.2. Comparison with the *Am*-index

Figure 2 shows how well our new index compares to the *Am2*-index on a time scale of a month. We selected the interval 1970-76, because of the frequent occurrence of high-speed solar wind streams, especially during 1973-74 at a time away from solar maximum when the solar EUV emission was relatively low. The *IHV*-index seems nearly as good as the *am*-index in picking up activity caused by the solar wind. This is shown quantitatively in Figure 3 that displays the correlation between monthly means of *IHV* and *Am2* for the entire interval (1959-2001) where data is available. The linear correlation coefficient is 0.9274. The right-hand panel of Figure 3 shows that the correlation coefficient between *Aa2* and *Am2* is 0.9569. The *IHV*-index does nearly as well.

Figure 4 compares monthly means of *IHV* and *Am2* for the 40-year interval 1960-1999, both for single months and for the one-year running mean. The two measures track each other well over the entire interval. Table 1 summarizes regression analyses for each of the 10-year subintervals. There is no statistically significant differences between the decades, so we conclude that the relationship between *IHV* and *Am* is stable and constant, at least since 1960. To the extent that *Am* represents true activity, this conclusion is not surprising.

4.3. *IHV*-index for Other Elements

Figure 5 shows the *IHV*-index for all three geomagnetic elements. It is evident that the *IHV*-indices for all three elements display essentially the same variations and that either element can be used. This is particularly important for the D component, because only the D-component was recorded for the earliest stations. The Z-component is normally not used in derivation of activity indices as it is especially susceptible to induction effects (often if near a coast), but does not look too bad as far as *IHV* is concerned. The linear correlation coefficients for monthly means with *Am2* for the entire interval 1959-2001 are: for IHV^H 0.927, for IHV^D 0.885, and for IHV^Z 0.875.

4.4. *IHV* at San Juan

The geomagnetic observatory at San Juan, Puerto Rico (SJG, Geogr. lat. 18.38˚N, long. 293.88˚E; Geomagn. lat. 29°N, long. 5˚E) has been in operation since 1926. This observatory is normally considered to be at too low latitude to be useful for contributing to a midlatitude index such as *am*. However, as Figure 6 shows, the IHV^{H} values computed from San Juan compare very favorably with the *Am2*-index (linear correlation coefficient 0.934 for interval 1959-2001). By coincidence, the values are so alike that we had to mark the *Am2* curve with little circles to make it distinguishable from the SJG *IHV* curve as the two curves fall on top of each other. The correlation with IHV^{H} values for Fredericksburg is equally strong. The best-fit relation is

$$IHV^{\mathrm{H}}_{\mathrm{FRD}} = (1.287\pm0.022)\, IHV^{\mathrm{H}}_{\mathrm{SJG}} \qquad (2)$$

with no statistically significant offset (constant term).

San Juan is close to the same meridian as Fredericksburg (only 0.75 hours difference) so the same 00-06$^{\mathrm{h}}$ UT interval was used in the calculation of *IHV*. Since the *IHV*-index is bound to the six-hour interval over which it is computed, we could include the interval in the designation, *e.g.* ${}^{0}IHV^{\mathrm{H}}$ for the interval 00-06$^{\mathrm{h}}$ UT, but this quickly becomes cumbersome, so we have decided not to.

4.5. *IHV* at Cheltenham

We know that this is tedious, but bear with us, The geomagnetic observatory at Cheltenham, Maryland (CLH, Geogr. lat. 38.70°N, long. 283.20˚E; Geomagn. lat. 50°N, long. 353˚E) started operations in 1901 and was the standard USGS station until being superceded in 1956 by Fredericksburg. The two stations operated simultaneously for 273 days during 1956 and *IHV* values for the two stations are very strongly correlated (e.g. $IHV^{\mathrm{H}}_{\mathrm{FRD}} = 0.9588\, IHV^{\mathrm{H}}_{\mathrm{CLH}}$; $R^2 = 0.9878$). One could contemplate combining the Cheltenham and Fredericksburg *IHV* series to get a unified series going back to 1901 using the data in 1956 to calculate the calibration factor between the stations. It is, however, preferable not to base the intercalibration between the two stations only on such a short overlap (which doesn't even cover a full year, so the chance of a seasonal bias exists).

We can get an independent crosscheck on the calibration by comparing Cheltenham with San Juan before and comparing Fredericksburg with San Juan after the changeover in 1956. Computing the linear regression constants for the monthly means, we find:

1926-1955: $IHV^{\mathrm{H}}_{\mathrm{CLH}} = 1.3652\, IHV^{\mathrm{H}}_{\mathrm{SJG}}$; $R^2 = 0.8361$
1956-2001: $IHV^{\mathrm{H}}_{\mathrm{FRD}} = 1.2873\, IHV^{\mathrm{H}}_{\mathrm{SJG}}$; $R^2 = 0.8753$

The ratio 1.2873/1.3652 = 0.9429 is comparable to the 0.9588 found above for 1956 alone using daily values, justifying combining the two stations, now based on an overlap of 30 years, providing a firm anchor for the earlier series.

4.6. *IHV* at Vieques

The geomagnetic observatory at Vieques, Puerto Rico (VQS, Geogr. lat. 18.15˚N, long. 294.55˚E; Geomagn. lat. 29°N, long. 6˚E) was in operation 1903-1924. Operations were moved to San Juan around 1925 and no overlapping data exists. The data downloaded from the World Data Center purports to be organized in UT, but was actually in local time, off by four hours. After correcting the time, *IHV* values were calculated using eq. (1) in the now usual manner. Just as San Juan could be used to calibrate Cheltenham, now Cheltenham can be used to calibrate Vieques. The result is:

$$IHV^{\mathrm{H}}_{\mathrm{CLH}} = 1.4884\, IHV^{\mathrm{H}}_{\mathrm{VQS}}; \quad R^2 = 0.7078$$

yielding:

$$IHV^{\mathrm{H}}_{\mathrm{SJG}} = 1.4884/1.3652\, IHV^{\mathrm{H}}_{\mathrm{VQS}} = 1.0902\, IHV^{\mathrm{H}}_{\mathrm{VQS}}$$

where 1.0902 then becomes the multiplier to use to reduce VQS values to SJG values. Table 2 summarizes the various cross-calibration constants for IHV^{H}. We can now compare the intercalibration of the three stations, CLH, FRD, and SJG, and for good measure *Am2* for the entire interval 1901-2001. From Table 2 we get the values we should multiply the *IHV* values from Vieques, Cheltenham, and Fredericksburg by to reduce them to the same overall mean (more accurately, a best-fit slope of 1) as *IHV* values for San Juan, which is the station with the longest record. Thus we reduce the VQS and SJG series to a series SJG′ based on these two stations, and the CLH and FRD series to a series SJG″ based on these two stations, and finally *Am2* to a series *Am2′* that matches SJG as closely as possible. We can summarize the calibration using the following formalism (SJG stands for $\mathrm{IHV}^{\mathrm{H}}_{\mathrm{SJG}}$, *etc*):

$\mathrm{SJG}' = (1.0902\ \mathrm{VQS})_{1903\text{-}1924}, (1.0000\ \mathrm{SJG})_{1926\text{-}2001}$
$\mathrm{SJG}'' = (0.7325\ \mathrm{CLH})_{1901\text{-}1955}, (0.7768\ \mathrm{FRD})_{1956\text{-}2001}$
$Am2' = (0.8\, Am2 + 4)_{1959\text{-}2001}$

As we want the *IHV*-index to stand on its own (rather than being a substitute *am*-index), we modify *am* to compare with, rather than the other way around. Figure 7 shows the result. It seems that a reasonable intercalibration of the three stations can be carried out and that the resulting series compares very well with *Am2′*; in Mayaud's words, "the comparison is significant".

Because the two *IHV* series agree so well, it would make sense to further combine them into a Northern Hemisphere index for the longitude sector (say) 270-310˚E. The two groups of stations are on opposite sides of the S_q current vortex and cover the zone away from the auroral and equatorial electrojets, the "Northern midlatitudes". Because SJG′ and SJG″ are so similar and yet are derived from stations covering such a large range in geomagnetic latitude (from 50˚ to 29˚), the *IHV*-index seems to be relatively insensitive to small changes in geomagnetic latitude. This is especially important for a long-term index where such changes are bound to occur.

5. Spectral Analysis

5.1. FFT Frequency Spectra

Figure 8 shows the FFT frequency spectrum of *IHV* ^{H}, *Am2*, and *Aa2* since 1959. (In what follows we shall use the combined *IHV*-index as defined above unless specified otherwise). The *IHV* ^{H} and *Am2* (and the *Aa2* - with one exception as noted below) spectra are substantially identical, showing that the series reflect the same phenomenon to a high degree. Although Fredericksburg is used both for the derivation of *IHV* and for *am*, San Juan makes up half of the signal for *IHV*, and Ottawa, Argentine Island, South Georgia, and Trelew go into the *am*-index for this longitude sector.

Examining the spectra, we find the dubious Bruckner period (*Clough* [1905], *Ahluwalia* [1998]) at 34 years (frequency f = 0.0297), the usual solar cycle peak at 10 years (f = 0.1), the expected peak caused by the semiannual variation at six months (f = 2), and a prominent peak at one year (f = 1). Regarding the latter, *Mayaud* [1977] pointed out, "dans le secteur N_4 (cote Atlantique de l'Amérique du Nord), l'onde semiannuelle est presque masquée par une onde annuelle prédominate". Power at one year is usually a sign that the data is contaminated by S_R (which has an annual variation) and the spectra of the *Am*-index (not shown) and of the *Aa2*-index show no such peak. In this case, however, instead of raising a severe criticism of the index, the one-year peak is actually a very strong argument that the *IHV*-index captures geomagnetic activity very closely, apart from the obvious fact that it agrees strongly with *Am2*. The reason for the annual peak in *IHV* and *Am2* is the dominant equinoctial component of the semiannual variation. The lack of *any* hint of a peak right at one year for the *Aa2* index is a bit of a puzzle and the reason for it is unknown.

5.2. Semiannual Variation

Svalgaard [1977] and *Svalgaard et al.* [2002] show that the equinoctial mechanism component of the semiannual variation of geomagnetic activity (as expressed by the *am*-index) can be described by

$$am \sim (1 + 3\cos^2\Psi)^{-2/3} = S(\Psi) \qquad (3)$$

where Ψ is the angle between the solar wind flow direction and the Earth's magnetic dipole axis. *Mayaud* [1977] proposed the function $\sin^2\Psi$ that is not much different from $S(\Psi)$ over the actual range of Ψ. The function $S(\Psi)$ varies both with the month of the year and with universal time (UT). Figure 9a shows the variation of S with month of year calculated for the eight possible cases of six-hour UT-intervals (the base interval for the *IHV*-index) that start on a three-hour boundary. FFT analysis of one hundred years of synthetic $S(\Psi)$ data for the UT-interval 00-06^{h} shows clearly both the annual peak and a semiannual peak of 60% of the annual peak. Since the annual and semiannual peaks shown in figure 8 for *IHV* and *Am2* have about the same amplitude (the semiannual peak slightly lower), either an additional 35% of the semiannual variation must be accounted for in other ways or part of the annual peak is indeed caused by S_R contamination. *Svalgaard et al.* [2002], *Cliver et al.* [2000], and *Crooker and Siscoe* [1986] suggest that 25-35% of the semiannual variation is caused by other mechanisms than the equinoctial effect. This leaves very little room (maybe at most 10% of the annual wave) for possible S_R contamination.

Figure 9b shows that the observed variation of *IHV* during the year matches the variation of *Am2′* as observed or of $25 \cdot S(\Psi)$ computed from eq. (3) for the interval 00-06^{h} UT (the 25 being average the *Am2′* for the equinoxes where S = 1), thus explaining the presence of the annual line in the frequency spectrum. The excellent quantitative agreement is perhaps slightly fortuitous, as there should still be minor contributions from the other sources.

6. *IHV* at Stations along the 10th Meridian

Proceeding as in section 4 (and we shall spare the reader the tedious details) we can construct *IHV* series for several sets of stations in Europe. Table 3 gives an overview of the possibilities. For the present paper, we were limited to data available through the World Data Centers. We were able to construct two long series: De Bilt-Witteveen-Wingst (1903-present) and Potsdam-Seddin-Niemegk (1890-present). There is data for several other series, going even further back in time, but, as yet, the data is not readily available, but certainly exists in form of yearbooks from the observatories. The optimum UT-interval for these European stations is from 21^{h} through 03^{h}, so when comparing with the *Am*-index we should compare with values from these two three-hour intervals.

We emphasize at this point that the *IHV*-index for a given station stands on its own and is *primary* data. The piecing-together of a long series from a station and its replacement stations depends on the cross-calibration forded by either simultaneous observations or by a third station 'bridging' the time of the station change. Once you have established a single *IHV*-series for a station and its replacement stations, you calibrate it to match the *Am*-index since 1959 (using, of course, the appropriate UT-intervals). At this point you can compare the resulting series for different stations. Figure 10 shows such a comparison between the four series we have derived up to now. To facilitate the comparison we have selected the year within each solar cycle since 1890 where the yearly average sunspot number was closest to R_z = 40 during the ascending phase of the cycle, and plotted the *IHV*-index for each month of that year for all the series for which we have data. This allows us to compare the indices during times with similar disturbance characteristics. There does not seem to be any significant difference between the four series with time from the earliest cycle (13) through the latest cycle (23). This justifies computing a composite index using all four series by simple averaging.

7. Comparison with the *Aa*-index

Having constructed a composite index for 1901-2001, the next step is obviously to compare it with the *Aa*-index computed over the same three-hour of the UT day as were used for the *IHV*-index. The result is shown in Figure 11. It is evident that the two indices compare well back to about 1957, but it has not escaped our attention that the *Aa*-index is systematically and progressively lower as we go further back in time. This behavior was already noted by *Svalgaard et al.* [2003] and will be the subject of a later paper in this series. Several workers, from *Mayaud* [1972], *Svalgaard* [1977], *Feynman and Crooker* [1978] to *Lockwood et al.* [1999], have noted a secular increase since 1900 of the average level of *Aa* by about a factor of two and have interpreted this as likely due to a corresponding increase of the interplanetary magnetic field and, by inference, of the open magnetic flux in the solar corona [*Lockwood et al.*, 1999]. The composite IHV-index (see figure 10) does not show a similar increase. Figure 10 also shows the open flux calculated using the formulae given by *Lockwood et al.* [1999] and it is clear that there is a problem. Although there does not seem to be a secular increase in the *IHV*-index over the last one hundred years, there are short intervals of extreme quietness, such as the year 1901, as well of extreme disturbance, such as 1991.

8. Comparison with the *Ap*-index

The *Ap*-index does not relate linearly to the *Aa* and *Am*-indices [*e.g. Mayaud*, 1980] meaning that the *Ap*-index does not monitor all activity levels in the same way as the *Aa* and *Am*-indices, making statistical comparisons hard to interpret. For monthly means during the interval 1957-2001, we find the following close relation $Ap = 0.33\,Aa^{1.235}$ ($R^2 = 0.94$). This suggests calculating the ratio *Ap/IHV* for each month to compare the variation over time of *IHV* and *Ap* (and *Aa* too, for good measure). We are, of course, using the combined *IHV*-index and comparing with *Ap* and *Aa* over the same UT intervals as were used in the derivation of the *IHV*-index. Figure 12 shows that there is no significant secular change in the ratio *Ap/IHV* = 0.64 over the interval 1932-2001 for which *Ap* exists. The ratio *Aa/IHV* shows a clear discontinuity between 1956 and 1957, being 0.84 before 1957.0 and 0.95 thereafter, a discontinuity not found for *Ap/IHV*. It seems that *Ap* and *IHV* agree on the level of activity back to 1932.

The frequency spectra (Figure 12) of the ratios both show a similar, but weak, solar cycle peak. Incidentally, *Aa* and *IHV* have comparable semiannual lines (Figure 8), so it is to be expected that the lines cancel out in their ratio as observed. The annual line for the ratio *Aa/IHV* is observed as expected (because *IHV* has an annual line and *Aa* does not). A possible explanation for the solar cycle line that comes to mind is that there is a slight S_R contamination of *IHV* in the sense that at sunspot maximum the enhanced S_R-variation "spills over" into the early and late night hours, interfering with our assumption that there be no S_R-variation during the local night, adding to the variability of the field components and hence increasing the *IHV*-index. A problem with this "explanation" is that the solar cycle variation of the *Ap/IHV* and *Aa/IHV* ratios goes in the wrong direction (corresponding to a smaller *IHV*-index at sunspot maximum). The direction is good for the suggestion that *Aa* and *Ap* are too high at sunspot maximum and that it is them that are contaminated. In any event, the solar cycle line is weak, so the effect is slight. One could be tempted to "correct" for this effect, but that would be a mistake at this point. The strength of the *IHV*-index is that no corrections or adjustments are made, apart from a single factor to calibrate between stations.

9. Conclusion

9.1. Summary

We have shown (1) that by using only a six-hour interval around local midnight a measure of geomagnetic activity (the *IHV*-index) can be constructed that on a statistical basis (e.g. monthly means) can be used as an accurate proxy for the *am*-index. (2) The *IHV*-index is objective in the sense that it is derived from simple hourly averages (or values) without any problematic attempt to eliminate the variations not caused by the solar wind. (3) *IHV*-indices derived from several stations substantially agree. (4) The *IHV*-index does not exhibit a secular increase over the last one hundred years. (5) The *IHV*-index disagrees with the *aa*-index before 1957. (6) The *IHV*-index agrees with the *ap*-index since 1932.

9.2. A Plea for Assistance

Because almost none of the pre-1900 data is available from the World Data Centers, the authors ask the geomagnetic community for help in collecting the early data. Hourly readings of the magnetic declination (albeit not at all hours) exist for various European observatories going back to the 1780's [*Wolf*, 1884]. It should be possible to derive *IHV*-indices from these, maybe 6-month values. These could be compared to modern values by 'degrading' the modern observations to the same hours for which early readings exist.

9.3. Concluding Remarks

It is a truism that work challenging the current paradigm seldom proceeds as planned. Such was the case with this study that began when one of us (LS), impressed by the possibility of a doubling of the solar open magnetic flux since 1900, attempted to verify it by using magnetic data from early Arctic and Antarctic expeditions and obtained a contra-result. That initial unsuccessful attempt, and others that followed, led to the suspicion that *aa*, the unquestioned standard of long-term geomagnetic indices and the basis of the *Lockwood et al.* [1999] result (and numerous others), was in error. Hence the development of the *IHV*-index (following the suggestion by *Mayaud* [1980] of excluding daytime hours to eliminate the influence of S_R) which substantiated that suspicion. Much remains to be done. The cause of the non-constant calibration of the *aa*-index needs to be determined. In addition, the *IHV*-index should be extended to years before ~1900 and its implications for solar and solar-terrestrial physics explored.

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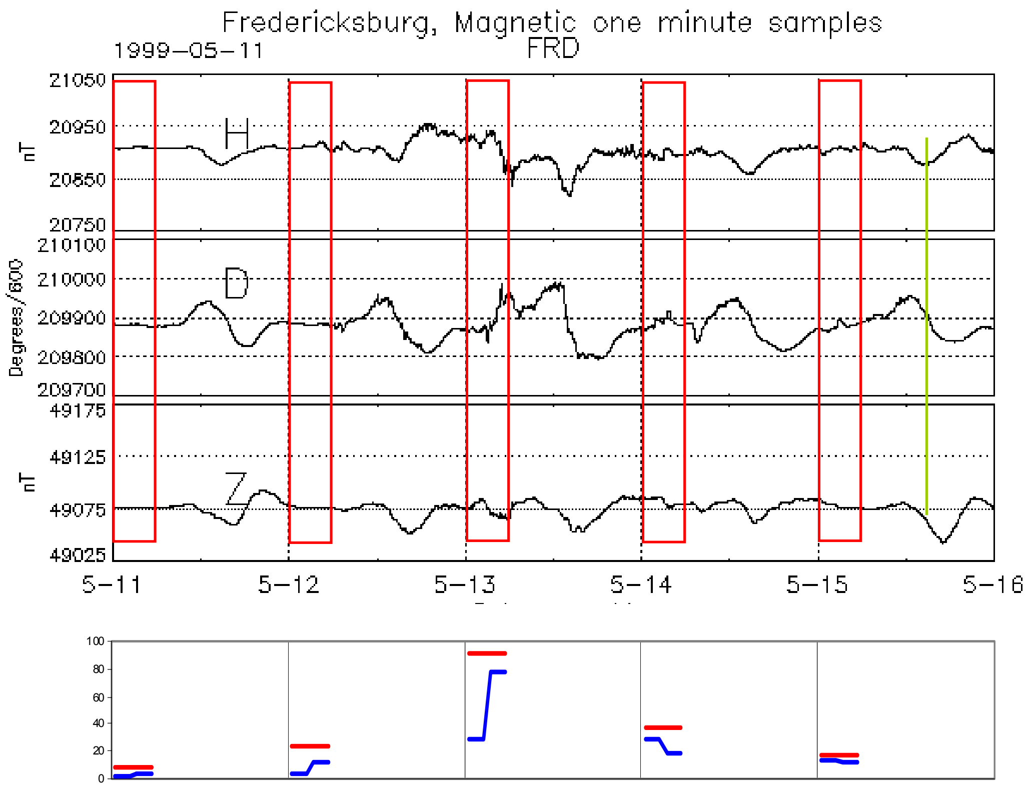


Figure 1. (Top) Variation of the geomagnetic elements at Fredericksburg May 11-15, 1999 (UT). The "effective" noon is marked with a green line on May 15. The red boxes indicate the six hours around midnight where the regular variation is absent or minimal. These intervals are used to define the *IHV*-index. May 11 is a good example of a day with very little activity. It is, in fact the, famous day where "the solar wind disappeared". The solar wind momentum flux was only 1% of its usual value and the magnetosphere diameter was five times larger,. The interplanetary magnetic field was not affected and had its usual properties. The variability of S_R is clearly seen by comparing May 11 and May 15. (Bottom) The *am*-index (blue) for these six-hour intervals and the IHV^H-index (red) calculated for each interval.

Table 1. Linear regression coefficients for $IHV^H = a + b \cdot Am2$ for each decade since 1960 for Fredericksburg. The right-hand column fixes the offset at $a = 5$.

Epoch	Best Fit to IHV^H FRD (Monthly means)	Constant Offset = 5
1960-69	5.0±0.7 + (1.050±0.031)Am2	5 + 1.05Am2, R^2=0.907
1970-79	3.7±0.9 + (1.153±0.041)Am2	5 + 1.10Am2, R^2=0.866
1980-89	5.9±1.3 + (1.019±0.054)Am2	5 + 1.06Am2, R^2=0.833
1990-99	7.8±0.9 + (0.925±0.037)Am2	5 + 1.03Am2, R^2=0.828
Average	**5.6±1.0 + (1.04 ±0.06)Am2**	**5 + 1.06Am2, R^2=0.859**

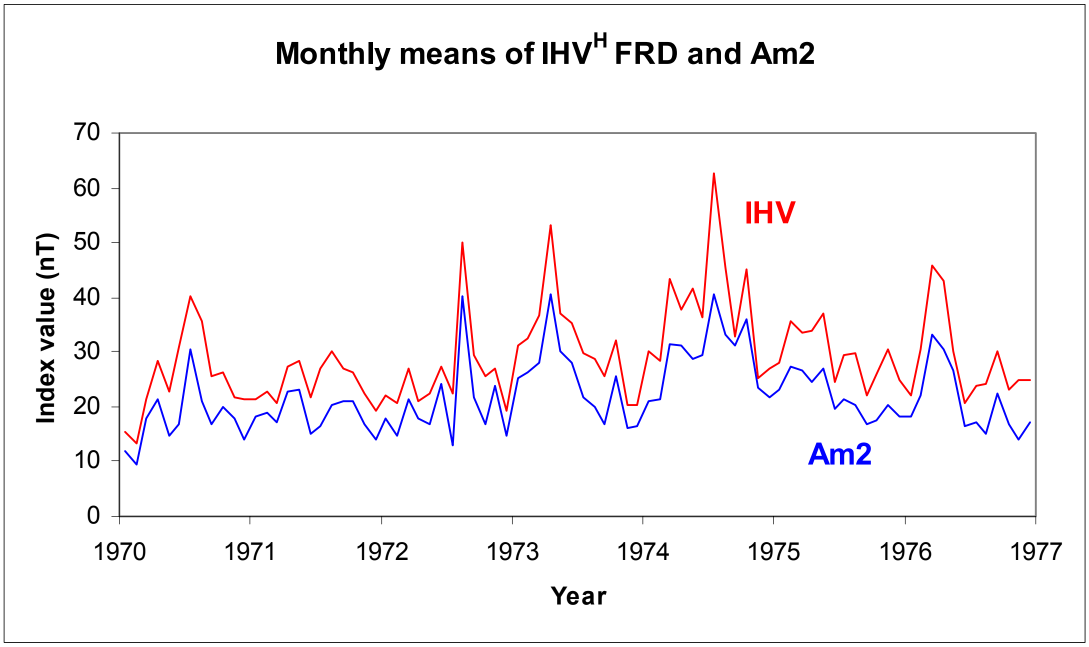


Figure 2. Comparison of monthly means of the *IHV*-index (red) calculated for the H-component at Fredericksburg and the *Am2*-index (blue) for the interval 1970-76. The year-labels on the abscissa mark the beginning of each year.

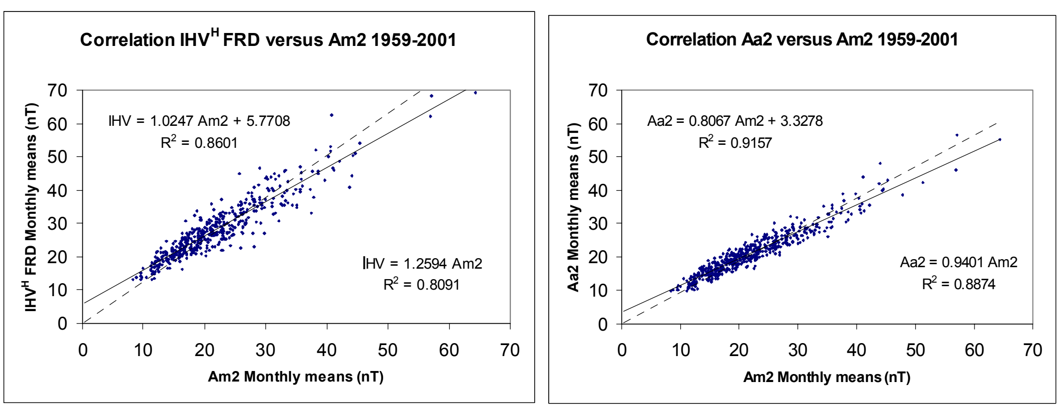
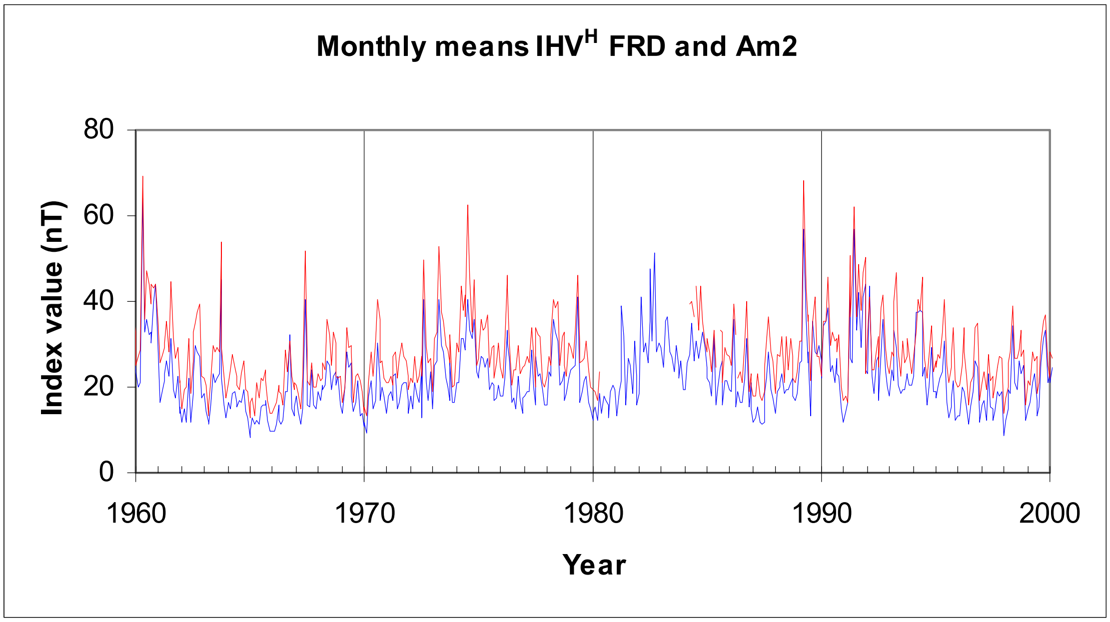


Figure 3. (Left) Linear correlation between the 467 monthly means of data of *IHV* ^{H} at Fredericksburg where more than twenty days of data were available in each month versus corresponding monthly means of the *am*-index calculated using only the 00-03 and 03-06 three-hour UT-intervals. (Right) Linear correlation between monthly means of the *aa*-index versus monthly means of the *am*-index for these same three-hour intervals and months. The dashed lines show the correlations when forced through the origin.



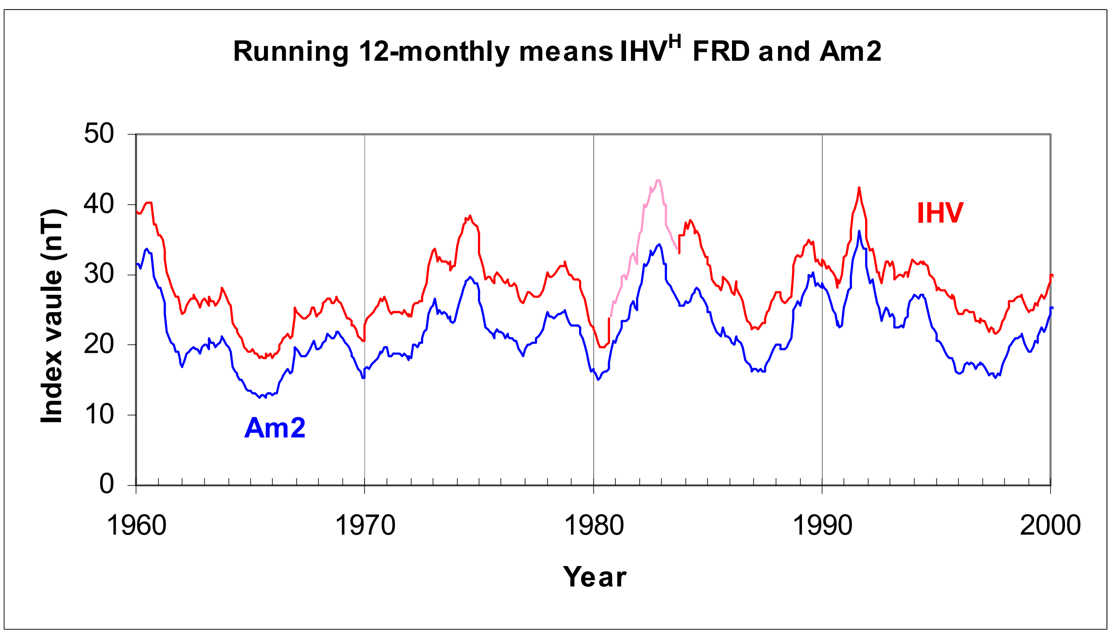


Figure 4. (Top) Monthly means of the *IHV*-index (red) for the H-component at Fredericksburg and the *Am2*-index (blue) for the interval 1960-1999. The year-labels mark the beginning of the year. (Bottom) 12-month running mean of the same data. The missing data (1980.5-1984.0) is filled-in using the relationship *IHV* (filled-in) = 1.26 · *Am2* (from Figure 3) and shown in lighter color. The filling-in was done to preserve to "flow" of the curve.

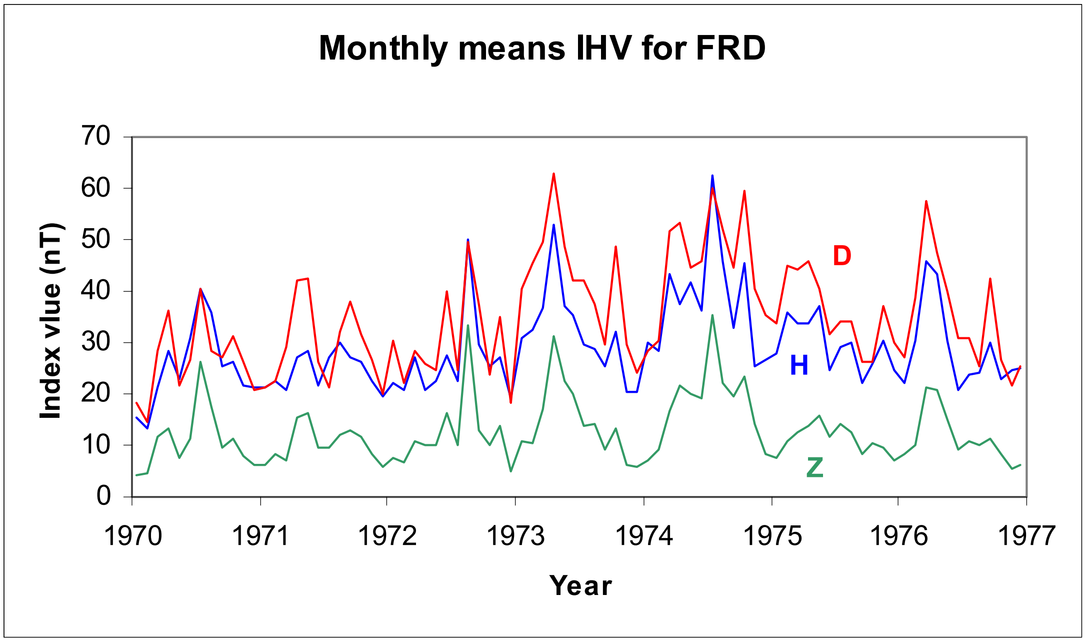


Figure 5. Comparison of monthly means of the *IHV*-index calculated for all three magnetic elements (H blue, D red, Z green) at Fredericksburg for the interval 1970-76 in the same format as Figure 2.

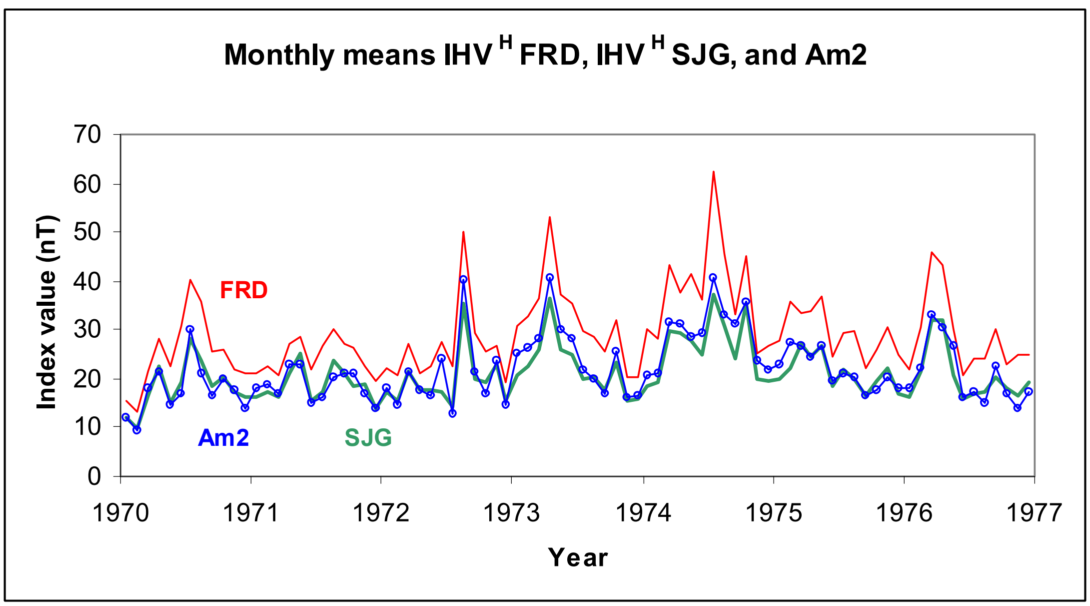


Figure 6. Monthly means of IHV^{H} for Fredericksburg (red), San Juan (green), and *Am2* (blue with circles) for the interval 1970-76.

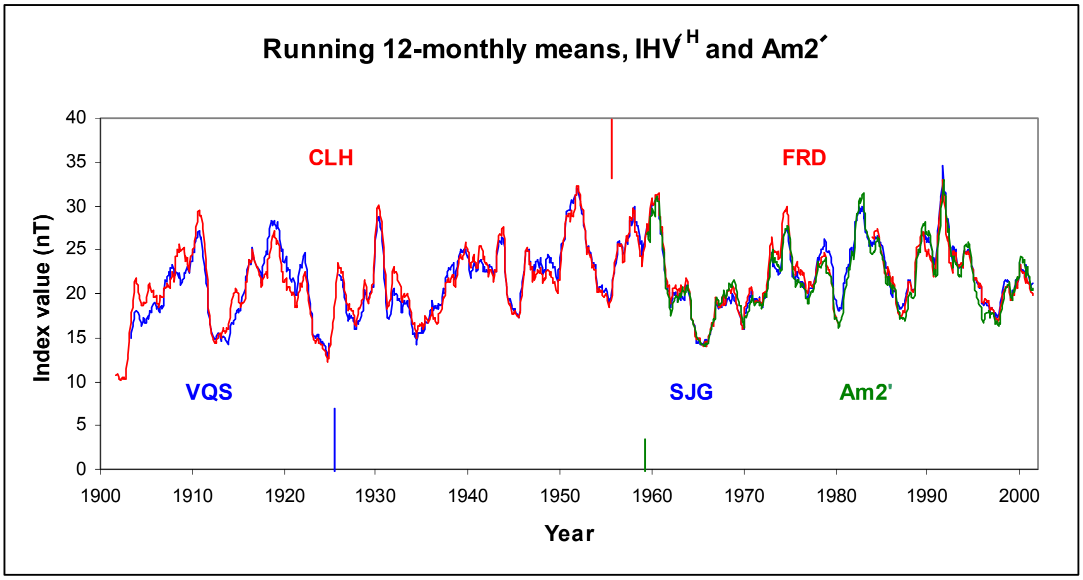


Figure 7. Running 12-monthly means of calibrated IHV^{H} for Cheltenham (CLH, red; before 1956.0), Fredericksburg (FRD, red; after 1956.0) and Vieques (VQS, blue; before 1925.0) and San Juan (SJG, blue; after 1926.0). For comparison $Am2' = 0.8\, Am2 + 4$ is shown in green since 1959.0. Often the curves fall on top of each other and it can be hard to distinguish between them. This is good.

Table 2. Calibration factors to go from IHV^{H} at one station to IHV^{H} at another station, e.g. $IHV_{CLH} = 1.3652\ IHV_{SJG}$. Factors that are derived directly are shown in bold text.

FRD	1.4034	**1.2873**	0.9429	1.0000
CLH	**1.4884**	**1.3652**	1.0000	1.0605
SJG	1.0902	1.0000	**0.7325**	**0.7768**
VQS	1.0000	0.9172	**0.6719**	0.7125
To / From	VQS	SJG	CLH	FRD

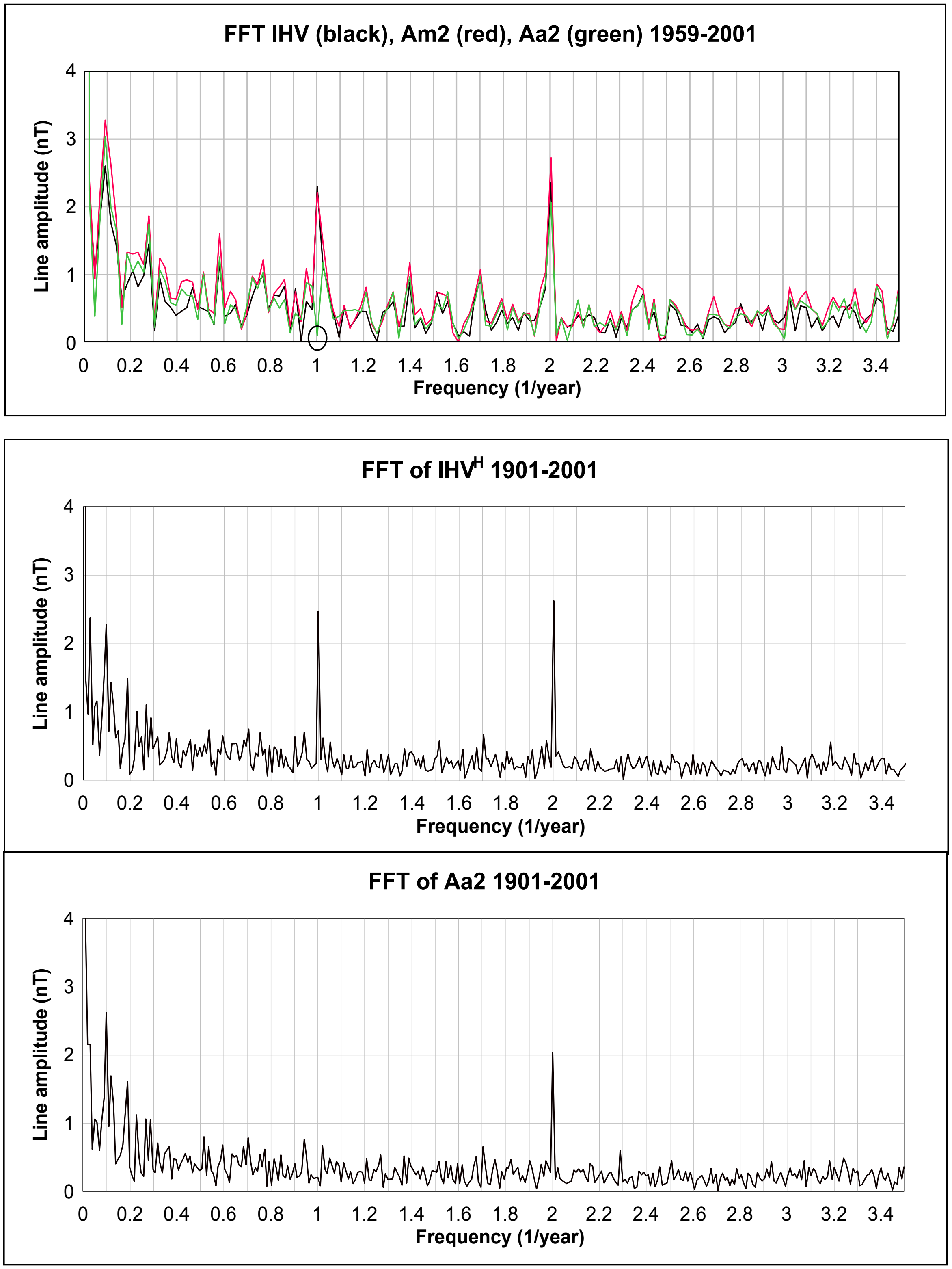


Figure 8. FFT frequency spectra of (top) IHV^{H} (black), *Am2* (red), and *Aa2* (green) for 1959-2001. (Bottom) IHV^{H} and *Aa2* for 1901-2001.

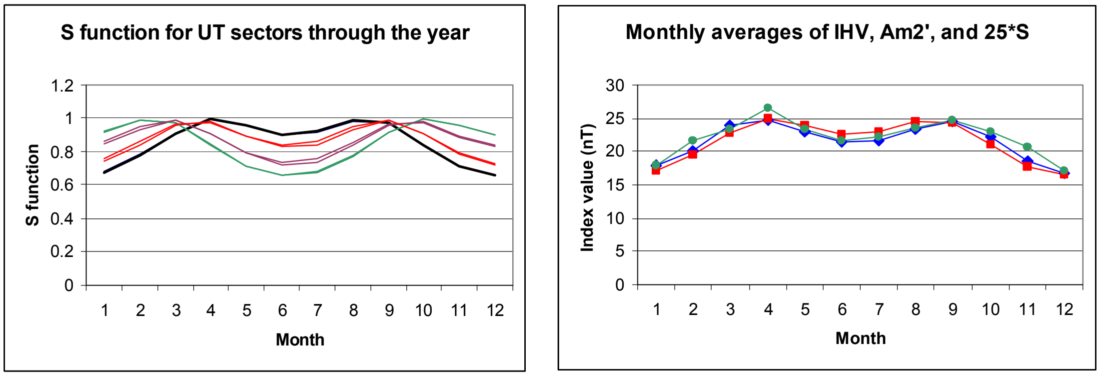


Figure 9. (a, Left) Monthly average values of the function $S(\Psi)$ (eq. (3)) for eight six-hour UT intervals: 00-06^h, 03-09^h, 06-12^h, …, 21-03^h. Due to symmetries there are only half as many different curves. The curves for 00-06^h (for which *IHV* is calculated for the 290˚E longitude sector) and for 03-09^h are shown as heavy black lines. The curves for 06-12^h and 21-03^h are shown in red, for 09-15^h and 18-24^h in purple, and for 12-18^h and 15-21^h in green. (b, Right) Monthly average variation through the year of IHV^H for 1901-2001 (blue), of *Am2′*, for 1959-2001 (green), and of 25 nT times $\langle S(\Psi)\rangle$ (red, corresponding to the black curves in the left panel).

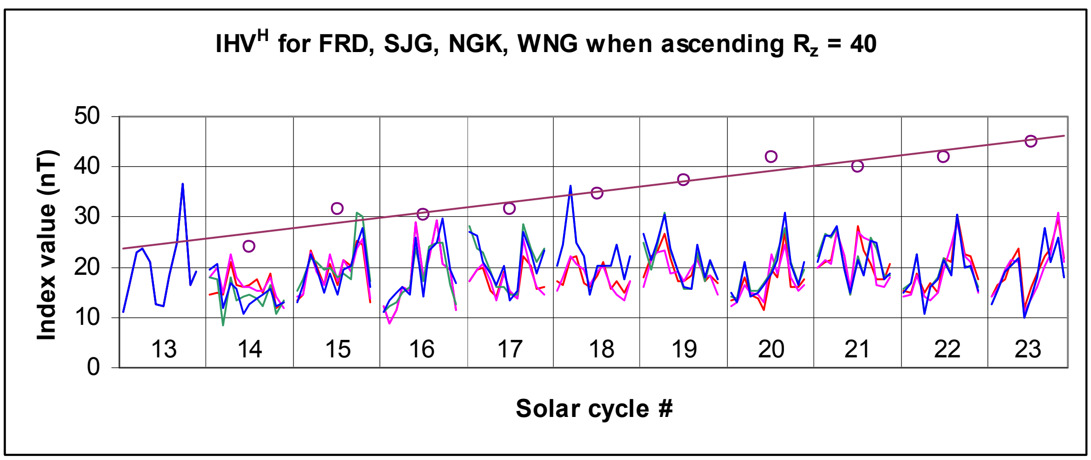


Figure 10. Comparison of four *IHV* series for the years (monthly values centered on 1891.5, 1904.5, 1915.5, 1925.5, 1935.5, 1945.5, 1955.5, 1966.5, 1977.5, 1987.5, 1998.0) in the ascending phase of each solar cycle since 1890 where the yearly average sunspot number was $R_z \approx 40$. In most years, a semiannual variation is discernible. The differences between the curves are mostly real, reflecting the longitude difference between the American (FRD and SJG) series and the European series (NGK and WNG). The FRD series (CLH, FRD) is shown in red, the SJG series (VQS, SJG) in orange, the NGK series (POT, SED, NGK) in blue and the WNG series (DBN, WIT, WNG) in green. Often the curves cover each other. Open circles (with trendline) show the open flux (in units of 10^{13} Wb) calculated by *Lockwood et al.* [1999] for these years.

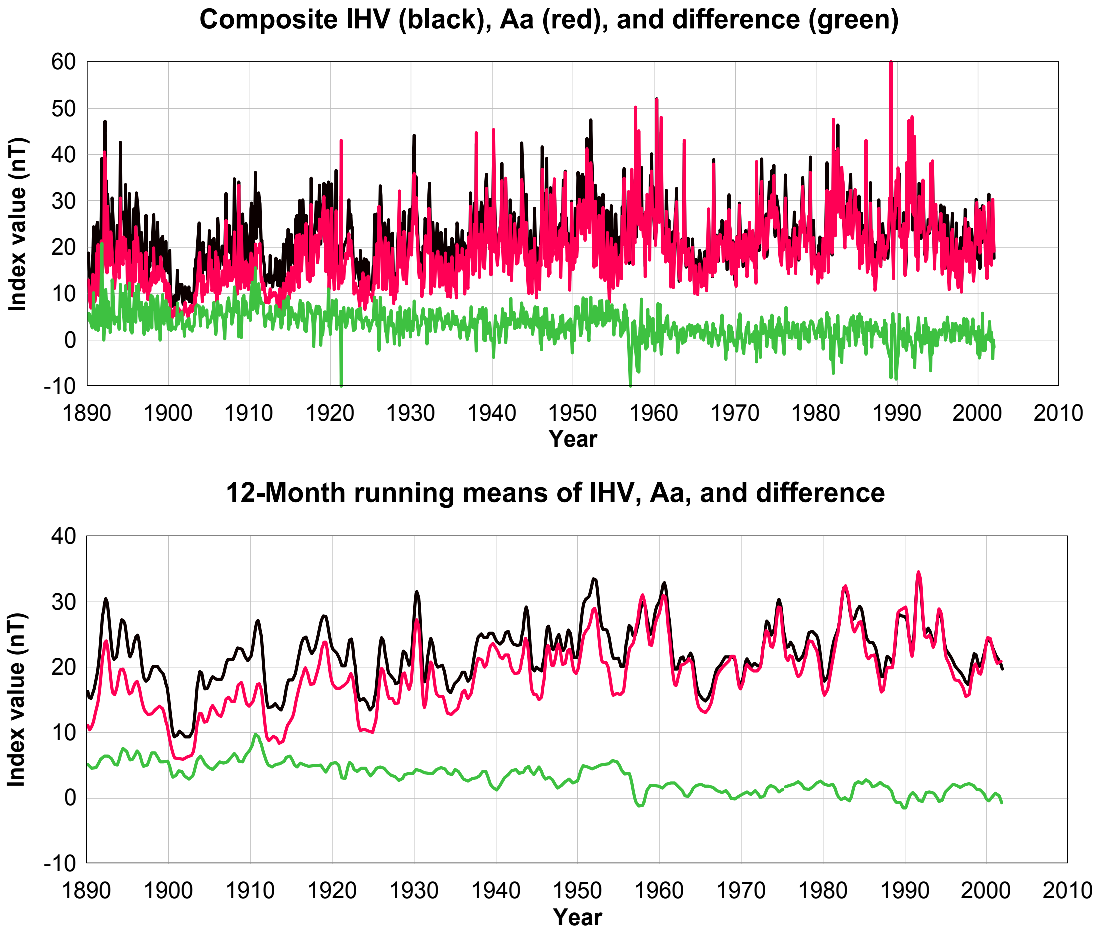


Figure 11. Comparison between the combined IHV^{H} series (FRD, SJG, NGK, and WNG) with *Aa*. (Top) Monthly means for 1901-2001 (Combined IHV^{H}: black; *Aa* red, difference (green), (Bottom) 12-monthly running means of same data. In computing the values for *Aa*, the same three-hour intervals were used as for *IHV*.

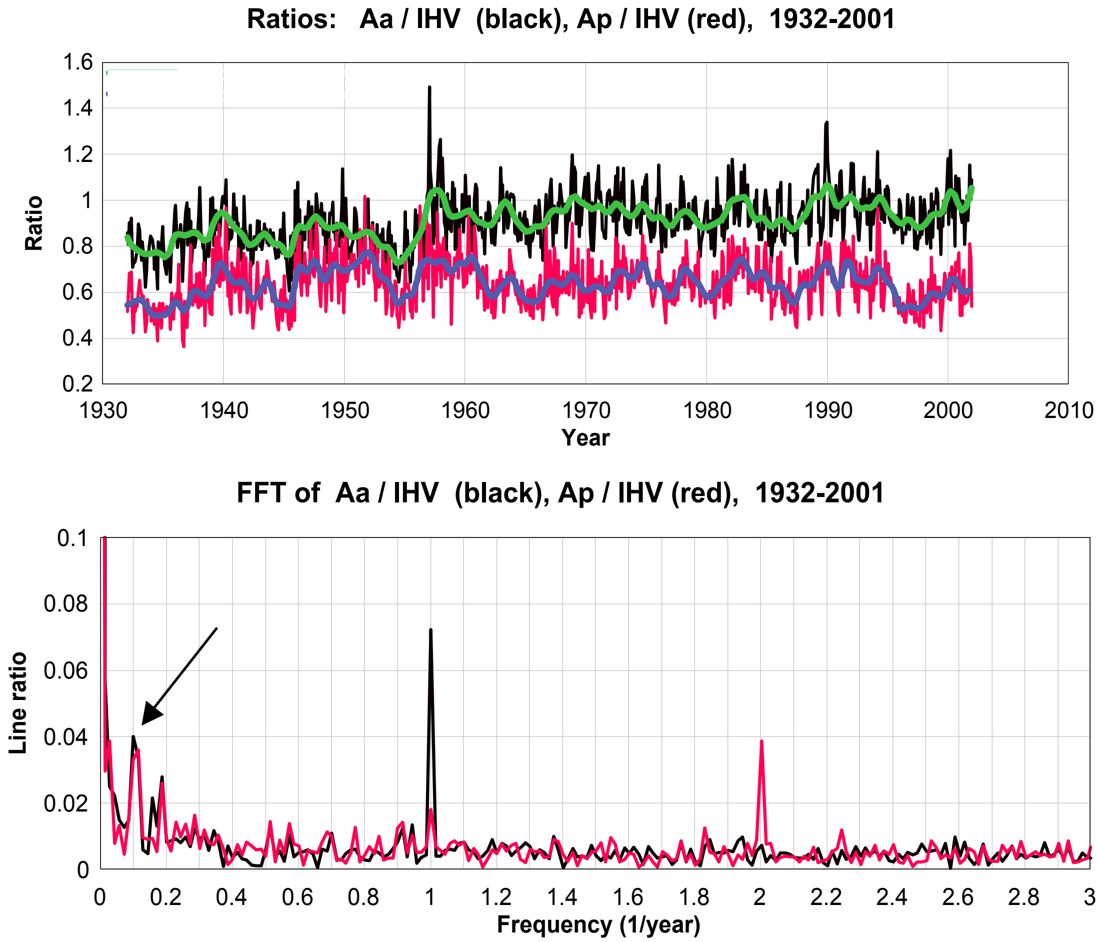


Figure 12. (Top) Ratios of monthly means of *Aa/IHV* (black) and of *Ap/IHV* (red) for the interval 1932-2001. We are using the combined *IHV* series and *Aa* and *Ap* over the same UT intervals. 12-monthly running means are shown as heavy curves. (Bottom) FFT frequency spectra of the above ratios. The arrow points to a solar cycle peak.

Table 3. Geomagnetic observatories with long series of data that may be useful for constructing *IHV*-indices. If a station stopped observing, the next column(s) may give the replacement station(s) (if any). The coordinates given in the first column are geographic longitude and latitude.

Long. Lat	Name	From-To	Name	From-To	Name	From-To	Notes
0E 41N	Ebro	1910-…					
3E 48N	Saint Maur	1883-1900	Val Joyeux	1901-1936	Chambon la Forêt	1936-…	
5E 50N	Uccle	1896-1919	Manhay	1936-1971	Dourbes	1955-…	
6E 52N	Utrecht	1891-1896	De Bilt	1899-1938	Witteveen	1938-1988	
8E 54N	Wilhelmshafen	1884-1911	Wingst	1939-…			
9E 62N	Dombas	1916-…					
11E 60N	Oslo	1843-1930					
13E 52N	Potsdam	1890-1907	Seddin	1908-1931	Niemegk	1932-…	
13E 57N	Copenhagen	1891-1908	Rude Skov	1907-1978	Brorfelde	1978-…	
18E 34S	Cape Town	1932-1940	Hermanus	1941-…			
27E 67N	Sodankyla	1914-…					
31E 30N	Helwan	1903-1959	Missalat	1960-…			
31E 60N	Leningrad	1869-1877	Slutsk	1878-1941	Voeikovo	1947-…	
45E 42N	Tiflis	1879-1905	Karsani	1905-1934	Dusheti	1938-…	
48E 19S	Antananarivo	1890-…					
49E 56N	Kazan	1909-…					
58E 20S	Mauritius	1892-1965					
61E 57N	Sverdlovsk	1887-1978	Vysokaya-Dubrava	1932-…			
69E 41N	Keles	1936-1963	Yangi Bazar	1964-…			
73E 19N	Colaba	1846-1905	Alibag	1904-…			
77E 10N	Kodaikanal	1902-…					
107E 6S	Batavia	1884-1944	Kuyper	1950-1962	Tangerang	1964-…	
114E 22N	Hong Kong	1884-1928	Au Tau	1928-1939	Hong Kong	1972-…	
116E 30S	Watheroo	1919-1958	Gnangara	1959-…			
121E 15N	Manila	1891-1904	Antipolo	1910-1938	Muntinlupa	1951-…	
121E 31N	Zi-Ka-Wei	1875-1907	Lukiapang	1908-1933	Zo-Se	1933-1974	
140E 36N	Tokyo	1897-1912	Kakioka	1913-…			
145E 38S	Melbourne	1865-1921	Toolangui	1922-1980	Canberra	1980-…	
173E 43S	Amberley	1929-1977	Lauder	1977-…			
188E 14S	Apia	1905-…					
202E 21N	Honolulu	1902-…					
225E 57N	Sitka	1902-…					
247E 55N	Meanook	1916-…					
249E 32N	Tucson	1910-…					
261E 20N	Teoloyucan	1923-…					
281E 44N	Agincourt	1881-1969	Ottawa	1968-…			
283E 39N	Cheltenham	1901-1956	Fredericksburg	1956-…			
285E 12S	Huancayo	1922-…					
294E 18N	Vieques	1903-1924	San Juan	1926-…			
294E 22S	La Quiaca	1920-…					
296E 32S	Pilar	1905-…					
316E 22S	Vassouras	1915-…					
334E 38N	Sao Miguel	1911-…					
352E 40N	Coimbra	1866-…					
356E 36N	San Fernando	1891-…					
357E 55N	Eskdalemuir	1908-…					
358E 54N	Stonyhurst	1865-1967					
360E 51N	Greenwich	1846-1925	Abinger	1925-1957	Hartland	1957-…	
360E 51N	Kew	1858-1924					