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Observatory Data as a Proxy of Space Weather Parameters: The Importance of Historical Archives

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ABSTRACT
Old geomagnetic observations are traditionally understood to be an important source of information about the structure and temporal behaviour (secular variation) of the internal geomagnetic field. A compilation of geomagnetic data from various parts of the world, recorded over several years allowed Gauss (*1839*) to separate the magnetic field into its parts of internal and external origin, and to prove that most of the geomagnetic field was of internal origin.

Each day satellites produce a huge amount of data on processes on the Sun, in the solar wind and in the Earth's environment, however, their span of operation is too short to allow for understanding of these processes and changes therein in the long term. On the other hand, geomagnetic observatories have been in operation for about 180 years; back ward reconstruction of solar processes may be possible based on the time series of various indices derived from observatory data that reflect responses to different combinations of solar wind parameters. Thus, digitization of these analogue observatory records and their printed records has become nowadays an exigent task. This paper contains a historical review of magnetic studies and measurements since the 16th century, followed by a case study in digitizing old magnetograms from the Prague-Clementinum Observatory. The problems connected with digitization, scaling and further processing of the data are discussed and preliminary results presented.

Key words: Geomagnetic observatory, Geomagnetic indices, Sunspot numbers, Space weather.

INTRODUCTION: REVIEW OF MAGNETIC OBSERVATIONS

Jonkers et al. (*2003*) collected over 150,000 declination measurements and nearly 20000 inclination measurements made between 1510 and 1930. The first sustained series of measurements at a single site in Greenwich showed that the geomagnetic field was subject to time-dependent change. Regular measurements of declination were started in Greenwich in 1816 to assist in the calibration of ships' compasses. The first measurements of declination in Paris were performed in 1541, and the Royal Astronomical Observatory was founded in Paris in 1667. Also regular measurements of inclination were carried out since 1671. A method for absolute measurements of magnetic intensity was proposed by Gauss (*1833*). The method combines vibration and deflection experiments in order to separate the intensity of the magnetic field and magnetic moment of the magnet used in the experiment. The method has now been re-interpreted by Van Baak (*2013*). In 1833, Gauss and Weber finished the construction of the magnetic observatory in Göttingen and developed or improved instruments to measure the magnetic field, such as the unifilar and bifilar magnetometer. The Göttingen Observatory became the prototype for many other observatories worldwide. The method of absolute determination of magnetic intensity made it possible to calibrate instruments locally.

Construction of instruments and improvements in observatory practice was not the purpose of Gauss' work, but just a tool for understanding of the nature and basic properties of the Earth's magnetic field. Gauss and Weber, therefore, joined the activity of Alexander von Humboldt in establishing a worldwide chain of observatories, known as the Göttingen Magnetic Union, which made simultaneous measurements at specific intervals (term days). The results were published in six volumes of the Results of Observations of the Magnetic Union (*Gauss and Weber, 1837-1843*). The simultaneous measurements started with 9 European observatories (6 of them in Germany) in 1836 and the number increased to 31 observatories in 1841: 18 in Europe (Berlin, Breda, Breslau (Wroclaw), Brussels, Christiania (Oslo), Copenhagen, Cracow, Geneva, Göttingen, Heidelberg, Kremsmünster, Leipzig, Makerstoun, Marburg, Milano, Prague, Stockholm, Uppsala), 4 in Russia (St. Petersburg, Ekaterinburg (Sverdlovsk), Nertschinsk, Barnaul), 3 in India (Shimla, Madras, Trivandrum), Auckland Island, Cambridge (US), Cape of Good Hope, St. Helena, Toronto, Van Diemens-Land (Tasmania). Most of them measured declination and horizontal intensity, others only declination. Publication of the Results ceased in1843. Prague Observatory discontinued these measurements in 1849.

Gauss and his collaborators believed that it would take just a few years of worldwide common observation of geomagnetic phenomena to unravel the mysteries of geomagnetism. It turned out that this view was too optimistic. However, considerable progress in the

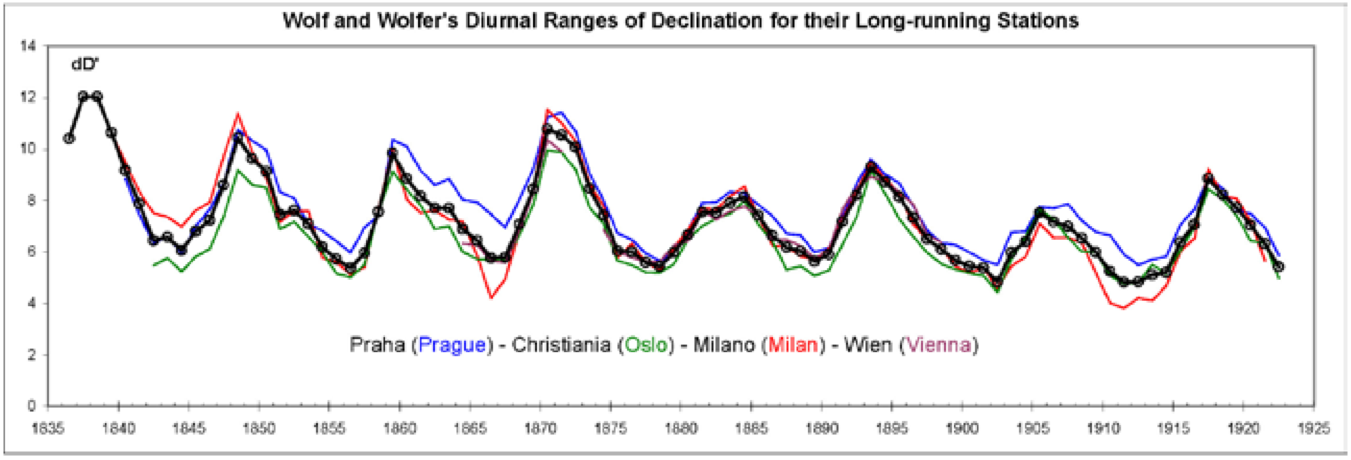

Figure 1. Diurnal ranges of declination obtained by Wolf and Wolfer from observatories in Prague, Oslo, Milano and Vienna and sunspot numbers (black curve), (Svalgaard, 2012)

understanding of geomagnetism was achieved. Already in the third volume of Results, Gauss (*1839*) published the general theory of geomagnetism where he introduced the concept of spherical harmonic analysis and applied it to magnetic field measurements.

Most observatories operating within the Göttingen Magnetic Union were closed already in the 1840's or 1850's. Just a few observatories established before 1850 were in operation up to the year 1900 or later. According to the information about observatories from the regional reports in (*Gubbins and Herrero-Bervera, 2007*) and from the list of observatory yearly means in the WDCs, these were Clausthal, Colaba, Greenwich, Göttingen, Helsinki, Kew (London), Milano, Munich, Oslo (Christiania), Prague, Ekaterinburg (Sverdlovsk), Toronto and Wien.

OBSERVATORY DATA AS A PROXY OF SPACE WEATHER PARAMETERS

In 1806, Alexander von Humboldt organized regular night observations of magnetic declination. On December 21, he observed strong magnetic deflections and noticed the presence of northern lights overhead. Von Humboldt concluded that the magnetic disturbances on the ground and the auroras in the polar sky were two manifestations of the same phenomenon. He called this phenomenon magnetic storm.

The next step from atmosphere – solid Earth relations to true solar – terrestrial relations was taken by Edward Sabine (*1852*) and Rudolf Wolf (*1852*), who found an association between the sunspot cycle and geomagnetic activity. The impact of solar activity on the geomagnetic field was incontrovertibly proven seven years later. In September 1859, Richard Carrington saw by chance a bright outburst of light in a group of large sunspots, which was 17 hours later followed by an extremely strong magnetic storm. Its strength was recently estimated at Dst ~ 1600nT (*Tsurutani et al., 2003*). This event attracted public attention not only due to the extreme northern lights, but also due to the disruption of telegraph transmissions (*Boteler, 2006*).

Sunspot number is the oldest observed space weather (SW) parameter. These observations date back to the 17th century. As the time series of sunspot numbers were rather heterogeneous due to non-uniform methodology used in deriving them, Rudolf Wolf started a thorough revision around 1850 and defined a standard procedure for their derivation. In 1852, he discovered a connection between sunspots and the diurnal variation of the geomagnetic field and subsequently used the diurnal variation of declination to re-calibrate the sunspot numbers. Telescopic observations of sunspots were made by several observers as early as 1609 (*Stern, 2002*). The rapid increase in the number of observations and their quality was interrupted by the long period between 1645 and 1715 (the Maunder Minimum) when sunspots nearly disappeared. After sunspots became frequent again, they were not investigated systematically. Around 1850 Wolf began a search of historical sunspot observations, and during the next 40 years he produced a record of the sunspot number from 1700 onwards. His index is known as the Wolf Sunspot Number. It is defined as ten times the number of sunspot groups plus the number of individual sunspots, all multiplied by a correction factor for each observer. As the sunspots were observed by hundreds of observers, the homogeneity of the time series is the main concern.

Wolf realized that the connection between sunspots and diurnal variation of the geomagnetic field could be used as an independent check of the calibration of sunspot numbers. As the diurnal variation displays a strong seasonal dependency, the comparison was done on the basis of annual means. Wolf and his successor Wolfer carried out this comparison continuously using declination data from the observatories of Oslo, Prague, Milano and Wien (Vienna)

(Figure 1). The results, published annually under the title Astronomische Mitteilungen, represent the first systematic study of the approximation of terrestrial phenomena with extraterrestrial, and vice versa. It was recently shown (see e.g. *Mursula et al, 2009*) that because the relation between the daily declination range and sunspots varies with season, the relation between the corresponding yearly averages is rather arbitrary and unreliable. It, however, does not detract from the importance of the Wolf's pioneering work.

In spite of Wolf's discovery, the mechanisms by which processes on the Sun can influence the Earth's environment remained unclear until the satellite observations in the 1960's. Since then, substantial progress has been achieved in our knowledge of Space Weather including the ability of short-term predictions. The complexity of geomagnetic variations has been characterized by various indices of geomagnetic activity. Their comparison with satellite observations revealed that some of them are closely related to solar wind parameters.

Julius Bartels defined the u-measure as the monthly or yearly mean of the unsigned differences between the mean values of the H-component on two successive days (expressed in units of 10nT). Svalgaard and Cliver (*2005*) found that essentially the same results are obtained using the mean over the whole day, over a few hours or only one hour. In the extreme, the same result is obtained even from a single night value. They also changed the scaling to units of 1 nT and called the index IDV (InterDiurnal Variability). The advantage of the IDV-index consists in the ability to compute a homogeneous series also for observatories with just a few recorded observations per day. However, such an advantage can be realised only when there exists at least one point value within a fixed night time. Comparison with satellite data has shown that on a timescale of a year the IDV-index is correlated with the Interplanetary Magnetic Field magnitude B, and, on the other hand, is insensitive to solar wind speed, V. It thus provides basic information about the yearly average of IMF 100 years before the satellite era (*Svalgaard and Cliver, 2005*, Figure 6).

Svalgaard and Cliver *(2007*) also introduced the IHV-index (InterHourly Variability) defined as the sum of the absolute values of the six differences between hourly values of any of the geomagnetic components for the seven hours spanning local midnight. The IHV-index averaged over Bartels rotation is a good proxy of BV^2. The index can be modified to hourly means instead of hourly point values. However, attention must be paid to proper recalibration (*Mursula and Martini, 2006*). As most observatories published printed yearbooks with hourly means derived from photo registration in the "pre-digital" era, there exists a vast quantity of valuable data that can be used for computation of improved quality of the IHV-index.. However, the oldest observatories in the 19th century (including Prague) often carried out manual measurements with just a few point values per day; the IHV-index thus cannot be calculated.

More detailed information about the utilization of geomagnetic observatory data for space weather studies has been detailed by Svalgaard (*2009*), He wrote: "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."

GEOMAGNETIC MEASUREMENTS AT PRAGUE OBSERVATORY

The observatory had its seat in the Clementinum College situated in the Old Town, close to the Charles Bridge. At the beginning of 18th century, an astronomical tower was built there, and in 1752 the Astronomical Observatory was established. An uninterrupted series of high quality temperature measurements dates back to January 1, 1775 and is well known to climatologists all over the world (*Sima, 2001*).

Kreil commenced work at the observatory of the Vienna University and in 1831 became assistant at the observatory de La Breda of Milano. He introduced magnetic observations there and participated from the very beginning in simultaneous measurements within the Göttingen Magnetic Union. In 1838 he was transferred to the Prague Observatory, of which he became Director in 1845. His main interest was in magnetic observations. He installed similar magnetic instruments at Prague, as he had used in Milano in order to continue his research. In view of the interest in science, reigning in Prague, he found willing collaborators there, and commenced regular hourly observations. Regular magnetic observations were started in July 1839 (*Kreil, 1842*). The equipment of the observatory were similar to the prototypes used in Göttingen. Simultaneous measurements at specific intervals (term days) within the Göttingen Magnetic Union were performed until 1849. In the first decade, measurements with a frequency of 2 minutes were also carried out during periods of magnetic storms. Due to increasing urban noise from the beginning of the 20th century, the observations were limited to the declination only, and the observatory was closed in 1926.

From the very beginning all measurements were published in the yearbooks called Magnetische und Meteorologische Beobachtungen zu Prag. The yearbooks contain tables of variation observations (magnetic and meteorological), reports on absolute magnetic measurements and discussions concerning their conversion to physical units. Variation observations were published in scale units (scale-divisions) until 1871. In the period

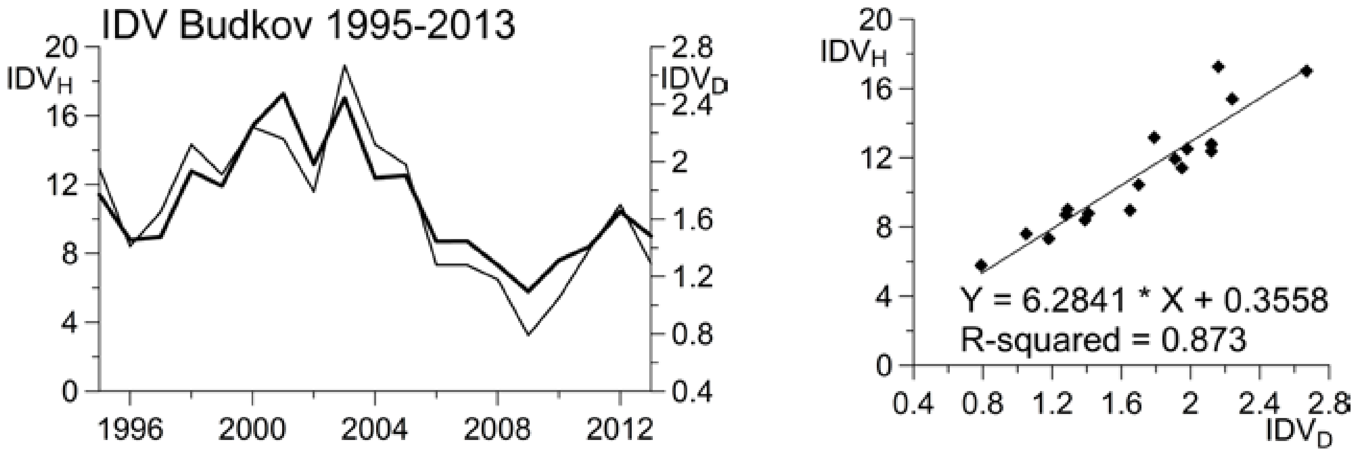

Figure 2. Left: Yearly means of the IDV-index computed from the horizontal intensity (IDVH thick line) and declination (IDVD – thin line) of Budkov Observatory. Right: IDVH vs. IDVD and the linear fit by rms. The index was calculated from momentary values at 21:20 UT, which corresponds to the calculation of IDV from Prague Observatory data in the period 1855-1904.

Table 1. Summary of daily measurements published in the yearbooks Magnetische und meteorologische Beobachtungen zu Prag.

Vol.	Years	Components	Time of measurements	Comments
1	1839 Jul - Dec	D, H, I	5, 6, 7, 8, 9, 10, 11, 10:30, 11:30, 12:30, 13, 13:30, 14:30, 15:30, 16:30, 18, 19, 20, 21, 22	scale units
1	1840 Jan – Jul	D, H, I	0, 2, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15, 16, 17, 18, 19, 20, 21, 22, 23	scale units
2	1840 Aug – Dec	D, H, I	0, 2 or 4, 6, 8, 10, 12, 13, 14, 16, 18, 20, 22	scale units
2	1841 Jan – Jul	D, H, I	0, 4, 6, 8, 10, 12, 13, 14, 16, 18, 20, 22	scale units
3-4	1841 Aug 1843 Dec	D, ΔD, H, ΔH, I	6, 8, 10, 12, 13, 14, 16, 18, 20, 22	scale units ΔD = difference D(t) –D(t-5min), and similarly for ΔH
5-6	1844-45	D, ΔD, H, ΔH, I	6, 8, 10, 12, 13, 14, 16, 18, 20, 22	scale units not I at 22 h
7-11	1846 – 1850 Apr	D, ΔD, H, ΔH	6, 8, 10, 12, 13, 14, 16, 18, 20, 22	scale units
11-13	1850 May – 1852 Dec	D, H, ΔH, I	6, 8, 10, 12, 13, 14, 16, 18, 20, 22	scale units
14	1853	D, H, I	6, 14, 22	scale units
15-30	1854-69	D, H, I	6, 8, 10, 14, 22	scale units
31-32	1870-71	D, H, I	6, 10, 14, 18, 22	scale units
33-44	1872-83	D, H, I	6, 10, 14, 18, 22	scale units, D and H also in physical units
45-50	1884-89	D, H	6, 10, 14, 18, 22	physical units
51-53	1890-92	D, H	6, 10, 14, 22	physical units
54	1893	D, H	6, 7, 14, 21	physical units
55 - 65	1894-1904	D, H	7, 14, 21	physical units
66 - 78	1905-1917	D	7, 14,21	physical units; increasing urban noise

from 1872 to 1883 data in scale and physical units were published and from 1884 only data in physical units. Time stamps in the yearbooks show Göttingen astronomical time. Compared with Prague astronomical time the difference is 18 minutes. According to astronomical convention, 0 h is midnight and 12 h noon. The summary of magnetic variations is given in Table 1. The time of measurements in the Table corresponds to the Göttingen "civic time", i.e. 12:00 corresponds roughly to 11:20 UT.

DIGITISATION OF YEARBOOKS

Although some summary data were used already by Wolf and his successor Wolfer for calibration of sunspot numbers, the data as a whole stayed available only in the printed form of yearbooks. The recent interest in historical data, documented among others also by the project "Long-term reconstruction of Solar and Solar Wind Parameters" supported by the ISSI grant for 2012-2014, led us to the decision to digitize the data. In the first stage, all volumes of the yearbooks were scanned and transferred into pdf files. They are available via the author's web page *http://ig.cas.cz/en/geomagnetika/hejda*. Although the OCR was part of the scanning process, the adjacent text files contained too many errors to be useable for data digitization. The manual digitization was carried out by means of spreadsheets with pre-programmed templates that allow also for preliminary data check and repair of rough errors: computed monthly means were compared with monthly means published in the yearbooks. All declination and horizontal intensity data of regular observations have already been digitized. The digitization of the data from the disturbed periods will follow.

CONVERSION FROM SCALE UNITS TO PHYSICAL VALUES

The observations were published in scale units until 1871. While considered a drawback at first glance, this in fact had several advantages. The observatory staff understood that data users would have to convert the data to physical units and, therefore, provided not only variometer observations, but also all data obtained during absolute measurements. They are not limited by the parameters for conversion from scale to physical units that were set by editors of the yearbooks. Presently, everything is available for checking the calculations and correcting their errors, if needed. The usual formula for conversion from scale units to physical values is

physical_value = base_value + scaling_factor · (scale_units + instrument_corrections).

The scaling factor for declination or inclination is a geometrical problem of conversion from divisions on the scale to the angle (in degrees and arc minutes). Instrument corrections are not used. The base value must be obtained by comparison with absolute measurements, as the data are transferred (reduced) to the site of the absolute measurements.

The physical unit of horizontal intensity was Gauss emu ($=10^4$ nT). We converted it to nT in our outputs. As the magnetization of the needle depends to the temperature, the instrument corrections are far from being negligible if the temperature is not kept constant. On the time scale of years one must also account for the aging of the magnets. The calculation of parameters thus requires comparison of series of absolute measurements with variation observations. All declination data from 1840 to 1871 were converted to physical units. The scaling of the horizontal intensity requires a more detailed study of the comments presented in the yearbooks, because there were several interruptions and discontinuities caused, e.g., by fibre rupture and other accidents. Only the period from 1855 to 1871 has been processed so far.

The base value and instrument corrections are not important for space weather applications based on short-term variations (daily or interdiurnal), provided the daily variation of temperature is neglected. As the variation instruments were installed in a building with thick walls, this condition was satisfied. The daily variation was usually a few tenths of degree Reaumur (1ºRe=1.25ºC). Although the IDV index as per definition is calculated from the unsigned difference between the horizontal intensity at consecutive local midnights, the index can also be computed for any hour and for any magnetic element without losing the "IDV signature" (*Svalgaard and Cliver, 2010; Svalgaard, 2014*). This finding is of great importance, because the observations in the early 19th century are noisier than later observations, and the computation of the average of more data series, or their comparison, can improve the quality of the results. We have tested the substitutability of data on the yearly means of the IDV computed from the horizontal intensity, IDV_H, and from the declination, IDV_D, of the Budkov Observatory data for the period 1995-2013, and the results are satisfactory, see Figure 2. This fact can be used not only for improving the performance of the IDV index, but also as a test of the mutual consistency of the scaling factors of the horizontal intensity and declination. As the scaling of the declination is just a matter of geometrical arrangement, the scaling factor is stable. The value of 1 division on the scale changed from 27.226″ in 1839 to 29.064″ in 1872. The comparison of IDV_D with IDV_H can thus be interpreted as a test of the scaling factor of the horizontal intensity. A similar approach has already been applied by Svalgaard (*2014*) in identifying errors in the scale values for the magnetic elements of the Helsinki Observatory.

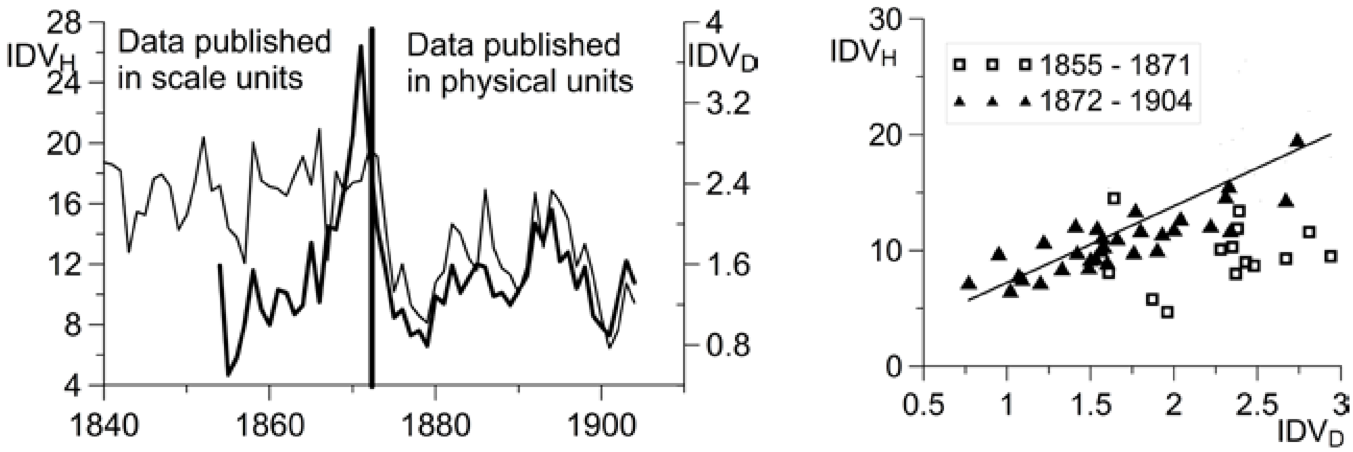

Figure 3. Left: Yearly means of the IDV-index computed from the horizontal intensity (IDVH thick line)and declination (IDVD – thin line) of Prague Observatory in the period 1855-1904. Right: IDVH vs. IDVD and the linear fit by rms. The index was calculated from momentary values at 22:00 Göttingen civic time (about 21:20 UT). Low values of IDVH before 1866 indicate a problem in scaling factors.

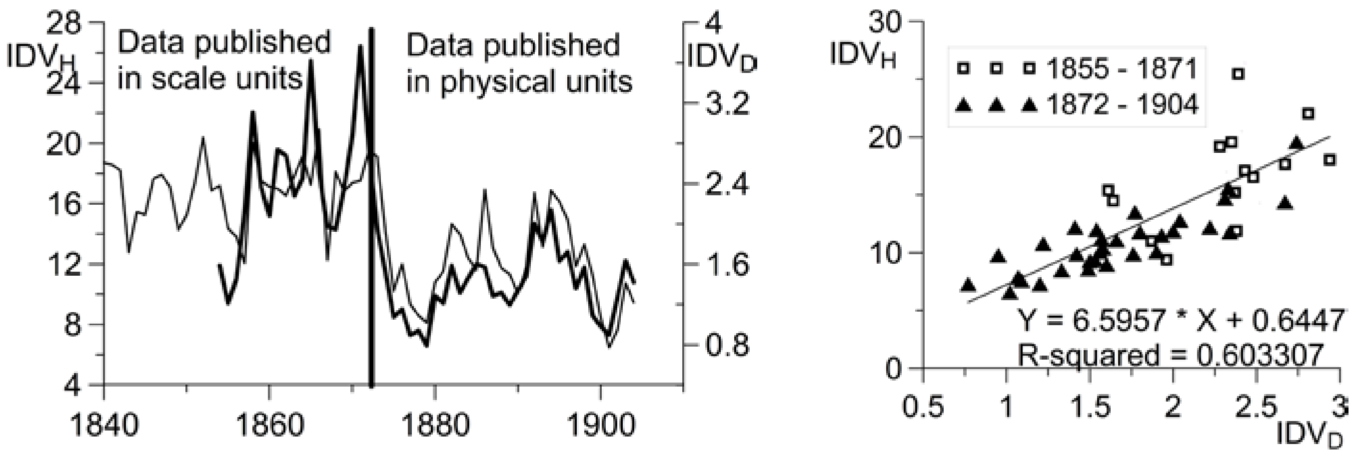

Figure 4. Left: Yearly means of the IDV-index computed from the horizontal intensity (IDVH thick line) and declination (IDVD – thin line) of Prague Observatory in the period 1855-1904. Right: IDVH vs. IDVD and the linear fit by rms. Improved correlation after the error was fixed and the scaling factor corrected.

Figure 3 shows the results of the test of IDV_H and IDV_D in the period from 1855 to 1904. We can see that the relation between IDV_H and IDV_D in the period 1855-1866 is much lower than after 1866. A check of volumes XVII (1856) to XXVII (1866) provided no explanation. However, we found the following footnote in volume XXVIII (1867): "by mistake, the scaling factors presented in Volumes XVII (1856) to XXVII (1866) were not related to physical units (Gauss) but to the horizontal intensity (about 1.9 Gauss)". This means that the scaling factor in this period should be multiplied by 1.9. After this correction, both the IDV_D and IDV_H look much more consistent (see Figure 4). However, these results must still be considered as preliminary and further analyses are required.

CONCLUSIONS

Modern science is based on experimental data and measurements. The data are mostly acquired in laboratories by pre-planned and carefully prepared experiments. By contrast, the laboratory of geophysical research is the entire planet Earth and the experiments are prepared by Mother Nature herself. Geophysical research depends on long-term continuous observations spread all over the globe. These precious data should be fully exploited.

The importance of historical data for space weather studies is manifold. On the one hand, historical data allows backward extension of data series of geomagnetic indices, which bear important information about physical properties of the solar wind in the past. On the other hand, newly derived geomagnetic indices and their alternates represent a suitable tool for detecting and correcting errors in the scaling factors of old magnetic data.

The stable operation and accuracy of absolute measurements at Prague Observatory for over 60 years in the period 1849-1926, provides a valuable resource to extend the series of geomagnetic indices backward in time. This would also be compared with the few long data series available (Greenwich-Kew, Helsinki). The digitization and processing of this data is in progress and first results are presented here.

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