Space Weather

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Key Points:

- Continuous magnetogram traces are available in London, United Kingdom for August and September 1959
- Serendipitously, two observatories recorded the Carrington flare and the subsequent storm
- We digitize the archive paper records to produce a correctly timed and scaled digital set of digital values for further analysis

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Digitized Continuous Magnetic Recordings for the August/September 1859 Storms From London, UK

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Abstract Dedicated scientific measurements of the strength and direction of the Earth's magnetic field began at Greenwich and Kew observatories in London, United Kingdom, in the middle of the nineteenth century. Using advanced techniques for the time, collimated light was focussed onto mirrors mounted on free-swinging magnetized needles which reflected onto photographic paper, allowing continuous analog magnetograms to be recorded. By good fortune, both observatories were in full operation during the so-called Carrington storm in early September 1859 and its precursor storm in late August 1859. Based on digital images of the magnetograms and information from the observatory yearbooks and scientific papers, it is possible to scale the measurements to International System of Units (SI units) and extract quasi-minute cadence spot values. However, due to the magnitude of the storms, the periods of the greatest magnetic field variation were lost as the traces moved off-page. We present the most complete digitized magnetic records to date of the 10-day period from 25 August to 5 September 1859 encompassing the Carrington storm and its lesser recognized precursor on 28 August. We demonstrate the good correlation between observatories and estimate the instantaneous rate of change of the magnetic field.

Plain Language Summary The Carrington storm of September 1859 is one of the largest known geomagnetic storms in the historic record. Two observatories in London were operating at the time and by good fortune both recorded the extreme geomagnetic storm on paper records. These are held at the British Geological Survey and have been made available online as digital images. The next step is to digitally trace over the magnetograms to produce useful digital values. However, scaling the values of digital pixels to International System of Units (SI units) of degrees of angle and nanoTesla is not easy as the original scaling factors are not available. We use a mixture of written reports at the time and notes from the observatory yearbooks to track down plausible scaling factors and to explain the process of digitization of very old records. The data for 10 days covering 25 August to 5 September 1859 are now available for other researchers to use.

1. Introduction

Analysis of historic space weather events is important for improving our knowledge of the potential hazard to technology posed by the Sun, particularly from large geomagnetic storms. While modern technological society has become increasingly vulnerable to extreme space weather (Oughton et al., 2018), we have experienced relatively few large events in the digital era (post-1980) of ground magnetic records. This makes extreme events difficult to analyze and understand in a modern context (Boteler, 2019; Xiong et al., 2016). There are even fewer large events in the continuous magnetic satellite era (post-1999) leaving a large uncertainty as to how even moderate space weather can affect the operation of spaceborne platforms (Hapgood et al., 2022; Oliveira et al., 2020; Oughton et al., 2017).

Geomagnetism has a long history of high-quality observations from the era of exploration and sail between the sixteenth and nineteenth centuries to modern day (Jackson et al., 2000). Curiosity about the Earth's field and how it changes in time prompted measurements of declination in London from the sixteenth century onward (Barraclough et al., 2000; Malin et al., 1981). In the late seventeenth century, Edmund Halley led several voyages to produce maps of declination across wider areas of the Atlantic Ocean primarily for the purpose of longitude determination; though he later realized that secular variation (SV) significantly reduced the accuracy of his maps after a few years (Murray & Bellhouse, 2017). In 1832, Gauss developed a method for measuring total field

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intensity (Garland, 1979; Glassmeier & Tsurutani, 2014) which launched an international "magnetic crusade" to make high-quality measurements around the world (Collier, 2014). Dozens of magnetic observatories were established from the 1840s onward—from whose data we still benefit today. Long time series contribute to our understanding of diverse geophysical phenomena from the study of flow in the outer core (Huder et al., 2020) to long term solar climatology (Lockwood et al., 2022).

The analog records of ground-based geomagnetic observatories collected prior to the 1980s offer the chance to investigate the magnitude and evolution of large historic storms. Several extreme geomagnetic storms have been examined for their magnitudes and impacts on technology at the time and to assess how similar events might affect modern critical infrastructure today, as exemplified with the October 1870 (Vaquero et al., 2008), February 1872 storm (Hayakawa et al., 2018), the May 1921 storm (Hapgood, 2019), the 1940 storms (Hayakawa et al., 2020; Hayakawa, Oliveira, et al., 2022; Love et al., 2023), and the August 1972 storm (Knipp et al., 2018).

Among existing recorded space weather events, the Carrington storm of September 1859 has been regarded, arguably, as a worst-case scenario in terms of the impact that such an extreme event could have on society (Cliver & Dietrich, 2013; Hayakawa, Nevanlinna et al., 2022; Tsurutani et al., 2003). While Richard Carrington hinted at some link between the observed flare and solar flare effect (SFE) in his 1859 paper (Carrington, 1859), Julien Bartels was the first person to directly associate the Carrington flare with the subsequent geomagnetic storm (Bartels, 1937). This was actually quite a brave assertion at the time, going against the general scientific consensus since Lord Kelvin had famously dismissed any link based on the contemporary understanding of available energy in the solar wind (Cliver, 1994).

Though the Carrington storm is often posited as the greatest geomagnetic storm ever recorded, whether it was merely a very large storm or of an entirely different nature to those experienced since remains unknown at present and is subject to a long-running debate (Chapman et al., 2020; Cliver et al., 2022; Cliver & Svalgaard, 2004; Hayakawa et al., 2019). Its exact magnitude and chronology has been recently reanalyzed using data from the Colaba observatory in Mumbai (India) which offers not only the typical hourly measurements but disturbance time values at high cadence with readings for every 5–15 min (Fergusson, 1860; Hayakawa, Nevanlinna, et al., 2022). At higher latitudes, some observatories in Finland and Russia made hourly measurements during the storm (Nevanlinna, 2008) and at lower latitudes records from Guatemala have been described (Ribeiro et al., 2011). However, it was in London (United Kingdom [UK]) that two sets of continuous and near complete high time-resolution records were collected (Table 1).

A dedicated manual observation program was set up in 1838 at Greenwich (GRW) as part of the Royal Observatory's work to support navigation at sea. Given the onerous requirement on labor to work through nights and on days of worship (e.g., Sundays), continuous recording instrumentation on photo-sensitive paper was developed less than a decade later (Brooke & Airy, 1847). The equipment consisted of a collimated light beam shining onto a mirror at the end of a suspended magnetized needle. The light reflected from the mirror fell on photosensitive paper which burned a trace. The paper was set on a rolling drum which rotated once per day, giving a continuous record of the magnetic field variation. Weekly calibrations were needed to establish the absolute baseline and scaling factors from which the variations of the traces could be converted to true magnetic field strength and direction (Newitt, 2007).

Discontentment with the scientific establishment at Greenwich, and London's exclusive Royal Society in particular, led a different group of researchers to form their own society known as the British Association for the Advancement of Science in 1831. They set up a rival observatory at Kew (KEW), south of the Botanic Gardens (around 20 km west of Greenwich), which was established in 1842. Continuous recording of magnetic field variations to photographic paper began in 1857. The two observatories operated in parallel for almost 70 years until the early twentieth century when the electrification of the railway lines around London precluded low noise observations of natural magnetic fields. Greenwich moved magnetic operations to Abington, south of London by 1924 and later to Hartland in the southwest of England in 1957. Kew moved the majority of its operations to a new site at Eskdalemuir in southern Scotland in 1908, well away from any future interference from rail line electrification, though magnetic observations continued in London until 1924, ending with the retirement of the final superintendent.

The magnetogram records from both observatories are held by the British Geological Survey (BGS). In total, digital images of about 350,000 magnetograms from all eight UK observatories have been captured and are available online. The scanned magnetograms are accompanied by the yearbooks from each observatory. These provide

Table 1
Available Analog Magnetogram Records by Observatory Including Annual Mean Values for 1859.5

				Annual means		
Observatory	Years available	Lat (°N)	Long (°E)	Dec (°E)	Horz (nT)	Vert (nT)
Greenwich, London	1836–1926	51.483	0.0	−21° 23.5′	17,460	44,208
Kew, London	1857–1924	51.463	−0.31	−21° 47.4′	17,517	44,153

vital metadata and information on the observatory operations, observing equipment and observation methods required to interpret the magnetograms and other geophysical data (Beggan, Eaton, et al., 2023). In this study we describe the extraction of magnetic field values from the Greenwich and Kew magnetograms covering 25 August to 5 September 1859 extreme geomagnetic storms and the work required to convert them to digital values of time and International System of Units (SI units) of magnetic field strength.

2. Digitizing the Carrington Storms

2.1. Historic Magnetograms

Instrumentation at pre-digital geomagnetic observatories was relatively simple in terms of the concept of operation. Depending on the component of the magnetic field, the measurements of variation generally consisted of the observation of the behavior of long magnetized needles. The needles were either suspended by quartz fibers or clamped to the vertical and had mirrors placed at their tips. To record continuous variations of the field, light-sensitive paper was mounted on a rotating drum which turned once per day capturing the trace of a collimated beam of light reflected from the mirrors on the needles. The paper was typically changed over in the morning and the traces were photographically "fixed" before derived or indicative measurements such as the three-hourly K index for the observatory were manually estimated the following day. These were later published in the official observatory yearbooks often alongside meteorological and other geophysical observations. For further detail, Nevanlinna (1997) offers an explanation of the types of historic instrumentation used.

The UK magnetic records consist of the magnetic variation of three components of the field; usually the horizontal and vertical force and the declination angle (the deviation of the compass needle away from true North). For space weather research, the horizontal components of the magnetic field are of most interest, as these create the induced ground electric field which poses a hazard to grounded technology such as high voltage power grids, pipelines and the operation of rail networks (Hapgood et al., 2021). Longer term trends such as SV were also captured by observatories, particularly in the monthly and annual means (Barraclough et al., 2000).

The original paper magnetograms are in relatively good condition considering their age and the manner of preservation over the past century. For Kew and Greenwich, the magnetogram pages were carefully extracted from the nineteenth century bindings before being photographed against a mm-scaled background. Figure 1 shows four example magnetograms. Panels (a) and (b) display the declination angle variation from 2 to 5 September 1859 at Kew observatory. Kew magnetograms often record multiple days onto one sheet; perhaps to save on cost at the time, as the observatory's operation was often threatened by a lack of funding. The curves (occasionally overlapping) are the variation of the field and the horizontal lines along the bottom of the magnetograms are the baseline to which the variation is referenced.

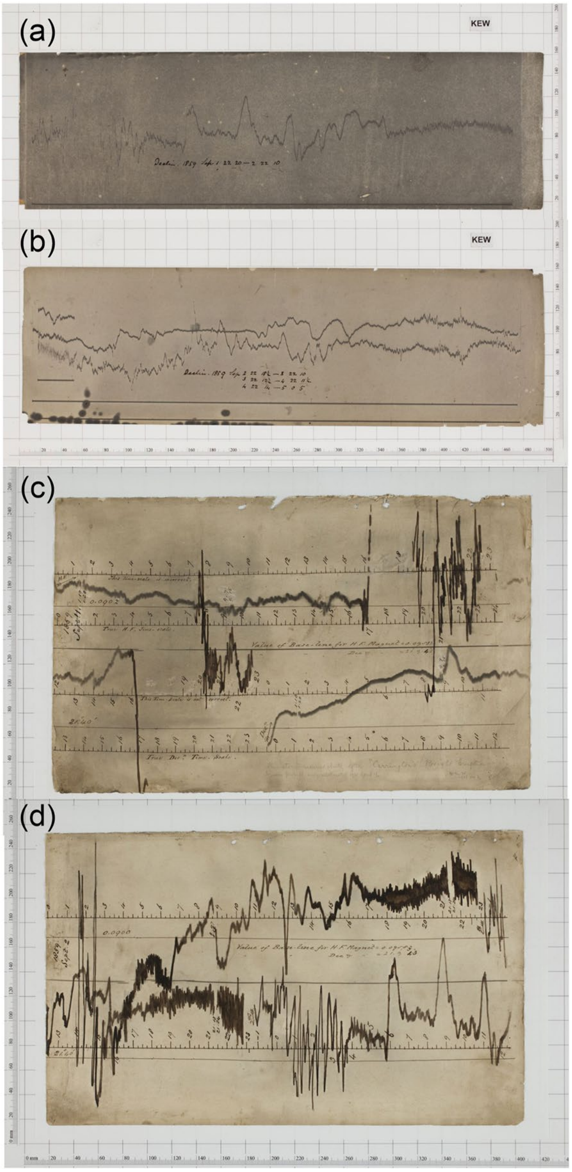

Figure 1. Magnetograms from Kew and Greenwich observatories: (a, b) Declination angle at Kew from 10:20 UT 2 September 1859 to 12:05 UT 5 September 1859; (c, d) Horizontal Force (denoted H.F.) [top line] and Declination (denoted Dec) [bottom line] at Greenwich from 12:00 UT (noon) 1 September 1859 to 12:00 UT 3 September 1859. Note the traces go off page around 05:00 Universal Time on 2 September (marked 17 hr).

The Greenwich observatory magnetograms in Figures 1c and 1d record the horizontal force and the declination angle for a single 24 hr period on the same sheet. The traces are offset by half a page in the horizontal axis to reduce overlap, though it still occurs during the most active periods. The traces also wrap around the paper with a small gap at the rightmost edge where the paper was folded beneath itself on the drum. Panel (c) shows the traces from noon on 1 September 1859, just after the first-ever observed solar flare at 11:15 Universal Time (UT) (Carrington, 1859) and synchronized SFE in the geomagnetic field (Stewart, 1861). The storm commences later on the following night (Bartels, 1937; Hayakawa, Nevanlinna, et al., 2022; Siscoe et al., 2006).

At Kew, the beginning and end times of observation were written manually onto the paper, usually with short gaps during which the photographic paper was changed over. For Greenwich the timescale has been explicitly added with hourly markers. In the case of the magnetograms of the Carrington storm, there have been revisions made to the original time-scale, the words "This Time-Scale is not correct" noted on some pages for example, with a new scale offset by about 1 hr drawn in. Additional care must be taken in correctly interpreting time on older magnetograms as Astronomical rather than Civil Time was commonly used until the early twentieth century (Boteler, 2006). At Greenwich, which was primarily an astronomical observatory, the day began at local noon (in Greenwich Mean Time or UT in modern terms) when the sun reached its local (mean) zenith. Kew also followed the Astronomical Time convention. As an example the Carrington flare (11:15–11:25 UT on 1 September 1859) has occurred just prior to the start of the declination curve on Figure 1c as the paper was changed around noon (12:00 UT) on 1 September. The time on the magnetogram thus denotes "0" hr indicating the start of the new day in Astronomical Time. Thus the recovery phase from the SFE is captured as is the onset of the storm later the following day (2 September in UT). The time scale was later revised slightly and further notes hand-written on the original paper in pencil were added, dated 1938.

2.2. Digitization of the Traces

We extracted the traces of the Declination and Horizontal force for the entirety of the two large storms between 25 August to 5 September capturing several days either side to include quiescent periods (Beggan, Clarke, et al., 2023). From images of the magnetograms, the initial step is to convert the line traces and metadata to digital values before scaling to SI units. Following the method outlined in Beggan, Eaton, et al. (2023) we used Engauge Digitizer to convert the lines on the magnetogram images to digital values. Engauge Digitizer is a free open-source program that allows a user to import image files containing graphs, manually trace over a graph by clicking points with a mouse and output a text file containing the digitized coordinates of the graph referenced to units such as millimeters or a fixed scale on the graph.

The first common problem is that very often during geomagnetic storms, rapid changes in amplitude cause the trace to become illegible. If there is a gap where the data are missing or become illegible, a new curve is started when digitizing the remainder of the trace. This ensures that there are no values within the missing time period and the gap is not interpolated across. In later years, a mirror and prism system allowed the magnetogram traces to "wrap-around" and they appear at the top or bottom of the paper. However, this technology was not in operation at either London observatory during 1859.

The horizontal time axis is defined using the hour marks for each component or taken from the handwritten times. Where more than one component or day is included on the magnetogram, each is handled separately with an independent x-axis. This is straightforward for Greenwich which has hour marks on the x-axis. For Kew, care must be taken to ensure the length of the baseline is scaled to the total number of hours and minutes noted manually. These changes can be made later using a spreadsheet or programming language (Python3.7 in our case) to correctly annotate the time and to shift 12 hr from Astronomical to UT.

The vertical axis is defined using the length of the scale bar in millimeters on the magnetogram image. On most magnetograms, a baseline indicating the absolute value of the field is given (either written on the paper or in a year book). The baseline values are usually constant or with a small amount of linear change over a day. The time-varying part of the field can usually then be scaled relative to the baseline value where a scale value for each component is found to allow conversion between millimeters and the SI unit (e.g., arc-minutes or nanoTesla [nT]). To correctly scale each component, the amplitude of the time series is calculated using the relative distance between it and the baseline. Typically, both the time series and baseline must be traced to give the absolute value of the component.

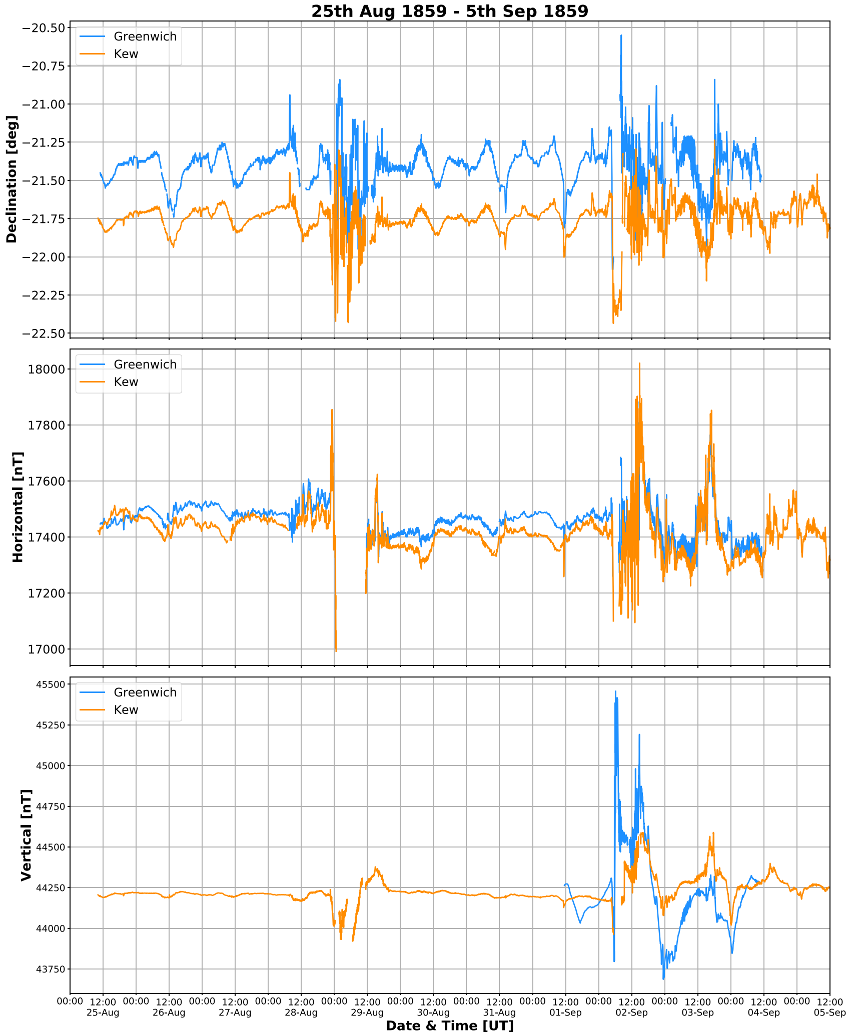

Figure 2. Declination, Horizontal and Vertical field at Greenwich and Kew from 25 August to 5 September 1859.

However, a second problem is that for the 1859 magnetograms there are no scaling factors available for Kew and the ones for Greenwich are uncertain. Greenwich provides baseline values for the Declination and Horizontal components but no direct scaling factors. Thus a significant effort was made to understand, cross compare and check that the magnetogram variations were correctly captured. A relatively complete Vertical trace for Kew was also extracted but the Greenwich Vertical trace is largely missing or obviously incorrect, suggesting the instrument was not operating properly for much of this period. The points for each of the traces were extracted as closely spaced as possible to capture the changes. This led to a variable temporal spacing, depending on the line thickness and its clarity on the page. Where the field varies rapidly, special care was taken to capture the change in as much detail as possible. The final trace values were interpolated to on-the-minute "spot" values.

As observed in Beggan, Eaton, et al. (2023), digitizing separate days can lead to mistakes in assembling the time-series with portions out of sequence and baseline step errors creeping in. These were corrected by comparison between the observatory magnetogram images and checking the digital traces and the magnetograms match. An important point to emphasize is that the traces for H and Z, as presented on the magnetograms, are inverted meaning an upward movement of the trace is actually a decrease of the total strength in that component. This was not obvious at the beginning of the processing, being the opposite of modern convention, and was only discovered upon careful checking against previously published work in the literature (Bartels, 1937; Stewart, 1861).

Figure 2 shows the traces of each of the three components, Declination angle (D), Horizontal (H) and Vertical (Z) field for the Greenwich and Kew observatories from 25 August to 5 September 1859, which have been scaled and corrected to the best of our efforts. The traces are visibly similar but do not have a perfect direct correlation due to slight timing offsets and the different response of respective instruments to the storm. Given the distance between the stations (~20 km), the difference in the external field magnetic field variation should be negligible, although the induced field may well be different as this depends on the local subsurface electrical conductivity. In addition, crustal magnetic fields can cause small differences in the absolute field value and Declination angle. We next describe the process and evidence used to arrive at our current scaling and offset factors.

2.2.1. Scaling the Greenwich Traces

A scanned digital copy of the Greenwich yearbook for 1859 is available in the BGS archive. The yearbook lists tables of "spot" values of the magnetic field variation in "parts of the whole," that is, the fraction of the full field value, for the Horizontal and Vertical components and the angle of Declination in degrees and minutes. For the full field values of H and Z at Greenwich, which are not directly given in the yearbook, we looked at the annual mean values, also preserved in the BGS archive.

At Greenwich the annual mean value at 1859.5 for the H component was 17,460 nT, with a SV of about +5 nT/month. Given 2 months elapsed between July and September, we add 10 nT to the annual mean to provide a "whole" or full field value of 17,470 nT. Similarly for the Z component, the annual mean was 44,208 nT with a monthly SV of +3.5 nT/month, giving a full field value of 44,215 nT. The declination annual mean value was 21° 23.5′ West of North (i.e., negative in the standard observatory convention), which accords well with the baseline values written on the magnetogram. The SV of declination was around 9′/year or 0.025° change in 2 months so is ignored as negligible for our purposes.

In the 1859 yearbook, spot values as fractions of the whole for each component were tabulated for each day of the year. However, these are not true spot values in the modern sense (i.e., taken independently and separately from the main instrumentation) but are described as "indications are taken from the sheets of the Photographic Record" according to the notes in the tables. This suggests they are derived from the magnetogram records rather than being measured separately for calibration purposes. However, they are extremely useful for scaling millimeters to angle or nT. Declination is given in degrees and minutes of arc so is easy to scale. Using least squares fitting of spot values to the digital trace values gives a scaling factor of 0.00586°/mm in Declination. The H and Z values are given as fractions of the full field value which allows us to compute scaling factors. For H, a value of 2.943 nT/mm was computed. The baseline for H at 02:00 UT on 31 August 1859 was assumed to represent an "average" quiet-time period and so was set to be the full field value calculated from the annual mean (17,4670 nT).

From inspection of the magnetograms, it was obvious that the Vertical component at Greenwich had not been operating correctly for several weeks prior to the large storms, though it was still responding to large magnetic field variations. The spot values given in the yearbook suggest a variation of over 1,500 nT in Z which is not corroborated by the statements in Stewart (1861) who estimated a maximum of around 400 nT at Kew. If we believe the Greenwich yearbook tables, however, the scaling factor for Z is 7.14 nT/mm. We will return to this point later.

2.2.2. Scaling the Kew Traces

For Kew, we follow the descriptions of the data given by the Kew superintendent, Balfour Stewart, in Stewart (1861). He states that the recorded components for the magnetographs at the observatory have "… increasing ordinates [which] denote decreasing westerly declination, decreasing horizontal, and decreasing vertical force." This shows that the solar flare effects caused a decrease in the magnitude of the H and Z components in London and that the y-axes of the magnetograms are inverted compared to modern plotting convention. Though Bartels (1937) does show a scale bar with H and Z increasing downwards, this was not readily apparent on initial inspection.

Stewart also describes the properties of the Carrington SFE at KEW noting that "the westerly declination was increased …by 13.2′ [i.e., arc-minutes]" or ~0.22°. He also states that the "horizontal force was diminished by …0.0075 of the whole force." Assuming the full horizontal component was 17,520 nT (as derived from the annual mean), the diminished (smaller) value is: $17{,}520 \times -0.0075 = -131$ nT. The Vertical change is described as being "diminished by 0.0013 parts of the whole force" which equates to: $44{,}153 \times -0.0013 = -57$ nT.

We also checked the information on the scaled diagrams in the original printing of Balfour Stewart's paper. The three accompanying plates contain 12 days of traces within a box measuring 9.1 inches (or 231 mm). On page

424, Stewart writes that a change of one inch in the ordinate (*y* axis) represents a change of 55′ in declination, while for the horizontal force it denotes a change equal to 0.0237 of the whole (=415 nT), and for the vertical force a change equal to 0.006 of the whole (=265 nT). Courtesy of the Royal Astronomical Society library collection, measurement of the physical size of the page from an original paper copy (using a ruler) indicates the height of the SFE was around 8 mm (or 0.315 inches) which gives a horizontal field value of 130 nT. Given the potential distortions of the original lines from the printing process, the reduction of the line thickness and hand scaling at the time, this can easily produce an uncertainty of ±10 nT, though an SFE value of 130 nT is consistent with Stewart's numerical estimate on page 428 of his paper. We also cross-checked these measurements against another original paper copy of Stewart (1861) in the BGS archive to confirm the scaling. For the Kew images, we applied the Stewart scaling factors based on 1 September SFE to produce scaling factors of 0.011°/mm in Declination, 7.222 nT/mm in Horizontal and 4.384 nT/mm in Vertical. Note these are approximate and subject to uncertainty depending on the thickness of the trace, the resolution of the image and any distortions introduced during the photographing of the magnetogram or the original recording.

As a final cross-check, the low temporal resolution representation of 1 and 2 September traces from Stewart (1861) as reproduced in Bartels (1937) were digitized using the scaling bars given in his paper. These do not have a baseline associated with them so the adjusted values from the annual means were added to them to allow a direct comparison to the traces from the original magnetograms.

2.2.3. Cross Comparison of Data Sources

The Greenwich spot values and the traces extracted from Bartels (1937) are shown in Figure 3. We have focussed in on the period from 31 August to 4 September around the Carrington storm to illustrate the detail. The Greenwich spot values are close to the extracted trace up until midday 2 September. After this the spot values do not align correctly to the trace for Declination. For the Horizontal field there is no correlation after 2 September. The spot values for the vertical field follow the trace until midday of the second. Beyond this time, there are only six more spot values provided in the yearbook. It is not clear why the spot values are incorrect post-2 September. We noted that there are other mistakes in the tables of the yearbook, perhaps creeping in at the typesetting stage for example, as some days are incorrectly labeled and out of order. There may be other days out of sequence too.

The traces extracted from the Bartels paper were provided without a baseline so they have been aligned to the Kew Declination, Horizontal and Vertical by adding constants of −21.66°, 17400, and 44,215 nT respectively. These independently extracted traces from Bartels' paper mostly agree with the original magnetogram traces, adding confidence that the digital values reflect the variation measured by the instruments at Kew.

Although the Declination and Horizontal components match well in phase and magnitude, the variation of the Vertical component of Greenwich is much greater than Kew particularly for 2 September peak where a ∼1,500 nT change is suggested. This is way in excess of Stewart's estimate of ~400 nT. It is not clear whether the Greenwich instrument was incorrectly calibrated or was not working as intended. In previous days (not shown), the Z traces are largely sinusoidal with no obvious geophysical signals like the Sq current observed. In some magnetograms, short period oscillations are present at the start of the day which could be impulse tests. In general, it seems that the Vertical trace at Greenwich is not a true record of the magnetic field change and should be treated accordingly.

3. Discussion

Given the length of time that has passed between the recording of the data and the digitization, it is fair to assess the accuracy and fidelity of the original and digital values to the "true" magnetic field variation. The combination of all uncertainties means caution should be exercised in using the exact magnitude in SI units of nT and precise timings of individual events to make solid inferences. Without due appreciation of the inherent errors and recourse to the original magnetograms it is possible to "over-interpret" the data set.

3.1. Correlation and Uncertainty of the Digitized Values

A comparison of all the concurrently recorded values (around 13,500 min values) is shown as a scatter plot in Figure 4. The Pearson correlation between the two sites for the declination angle values (upper axis) is 0.73 while for the horizontal values (lower axis), the correlation is higher at 0.81. The density of linearly correlated measurements is shown by the color coding. While there are widely-scattered points, the vast majority of data lie close

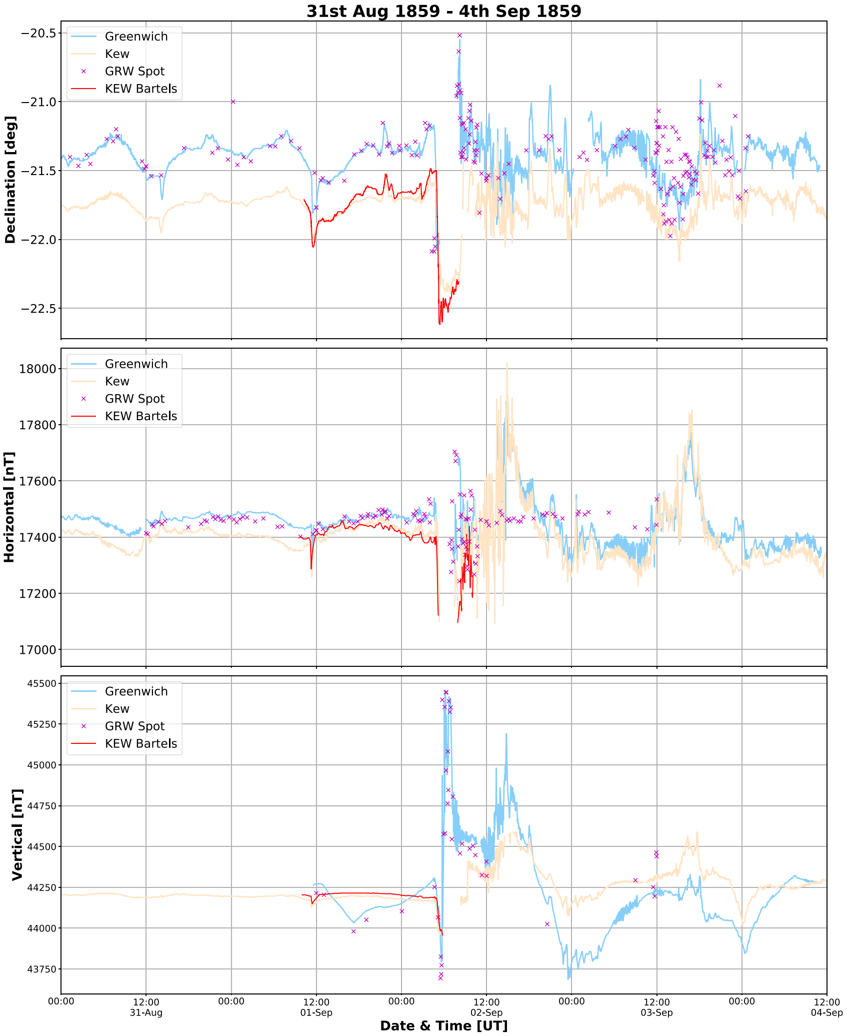

Figure 3. Declination, Horizontal and Vertical field at Kew and Greenwich from 31 August to 4 September 1859 with Greenwich year book spot values and a digitized version of the Kew data from Bartels (1937).

to a line of one-to-one correlation. However, this does not exclude the accidental inclusion of steps between days in the data set, particularly in the Horizontal component.

Estimating the formal uncertainties is difficult as they fall into several overlapping categories: scaling error, timing error, digitization error and instrumental error. The scaling errors are likely on the order of 5% given the estimate of "parts of the whole" is to 4 decimal places. That leads to at least 5–10 nT difference in Z for example. The other uncertainty arises from the thickness of the line traces themselves which can commonly be 1–2 mm. This would add another 5–10 nT difference depending on where the center of the trace was selected.

The error associated with time is on the order of three to five min during periods where there are identifiable features such as the Carrington SFE. Timing accuracy is often not completely reliable either as the drum rotation speed was typically slow, around 1 inch per hour depending on the observatory, meaning rapid changes were either not captured or cannot be deciphered. We are also dependent on the manual declarations of the observer at the time, which as noted on Figure 1c could be revised later. There are also gross errors (usually in Greenwich) where the traces do not align but it is obvious there is around an hour's difference where distinctive peaks of variation occur in both observatories. Where these are found, the traces have been manually re-aligned by eye within the intermediate processing steps. All these issues will also produce the differences in the correlation between the sites and introduce uncertainty in the exact time of events, except around the Carrington SFE which is a clearly documented feature at a known time.

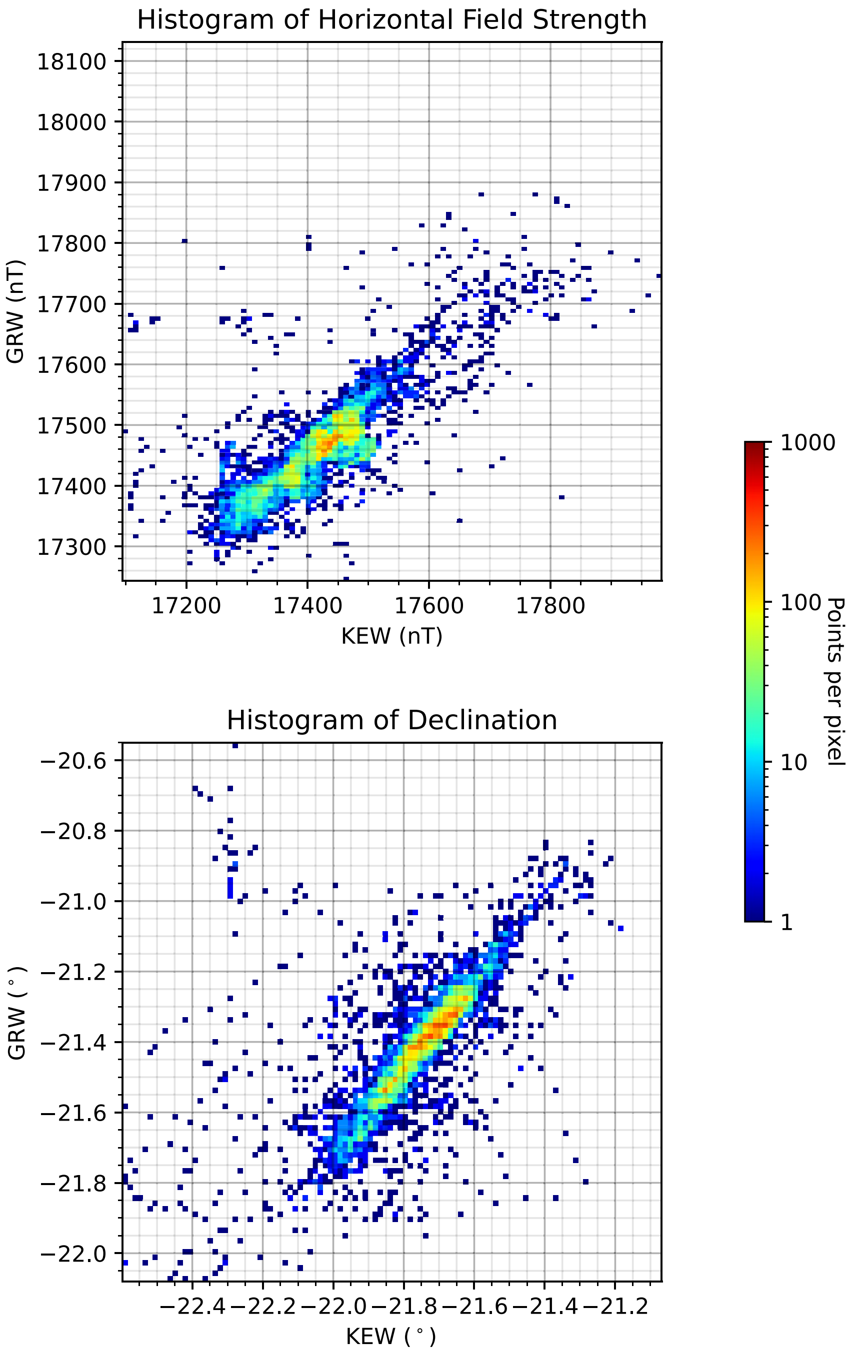

Figure 4. Histogram-scatter plots of the comparison between Greenwich and Kew from 25 August to 5 September 1859. (Upper) Horizontal field and (lower) Declination.

The repeatability of digitizing magnetic traces between different people examining the magnetograms is worth considering. Manually digitizing a storm is subjective, labor-intensive and requires careful pre- and post-processing of the results. Previous experiments suggest that different users will generally trace slightly different points particularly when activity is high (Beggan, Eaton, et al., 2023). Thus, some of the variation between Greenwich and Kew values can be ascribed to the individual hand; this sort of uncertainty is inherent in the digitizing process.

Finally, the magnetic instruments at Greenwich and Kew were bespoke, hand-built and unique with their own mechanical response functions. Historic instrumentation did not accurately record the variations and extremes of the magnetic field, when compared to modern instruments. The Greenwich yearbook gives the period of the horizontal needle to be around 5.5 s while Stewart (1861) suggests the shortest reliable period to be 30 s for Kew. In periods of rapid field change, traces become lighter and more diffuse as the focused light beam did not burn onto the photographic paper. The behavior of the instruments can also become unrealistic. A clear example of an impaired instrumental response is observed in Declination at Greenwich between 02:00 and 02:30 UT on 29 August where the trace in the magnetogram looks unnatural—sharp, sudden variations—and are not comparable to the Kew measurements.

3.2. Great Storm of 28–29 August

Measurements at both observatories show that the field was relatively quiet on 25 to 27 August. Around 22:30 UT on the 28th a large jump occurs simultaneously in both sites prior to the large storm which lasts until late 29 August. Declination variations are large but are continuously measured in both observatories. In contrast, the horizontal field traces at Greenwich and Kew are missing for over 12 hr. The Greenwich Vertical component was not operating correctly during the August storm so only Kew is available, whose measurements are off-scale for part of the storm.

Closer examination of the Kew and Greenwich magnetograms and the digitized traces shows that there are some clear timing mismatches between the observatories. For example, Greenwich has at least an hour of data missing on the 28th. We also suspect the hand-drawn time axis may also be wrong as the Greenwich trace fails to closely match that of Kew. In addition, during the peak of the storm, the Greenwich Declination trace is very angular-looking, with straight non-natural lines, when compared to the Kew measurements, suggesting perhaps that the instrument was not operating correctly during this period of heightened activity or was unable to capture the variation. Indeed, it may be the case that the magnetic field variation was too large or rapid, causing out-of-phase behavior of the needles for variations faster than their natural response period (5.5 s).

The aurora from 28 August great storm was reported widely in the papers at the time (Figure 5 of Hayakawa et al., 2019), but tends to be overlooked in modern literature given the focus on the Carrington event. In his paper, Stewart suggests this first storm was perhaps not quite as large as the September storm but it was impossible to compare the “greatest departures from the mean” between them.

3.3. Carrington Storm of 2 September

A key benefit of digitization is the ability to apply modern computational analysis to data. At around 11:15 UT on 1 September a white-light flare was observed by both Carrington and Hodgson (Carrington, 1859; Hayakawa et al., 2023). Its effect on the ionosphere over London is clearly visible as a dip in declination and the horizontal strength. The main phase of the storm arrived in the early morning on 2 September. Compared to the gaps in the traces on 28 August, only a few short periods of data are missing. However, from simple differencing of the sampled data we can show the rate of change during 2 September storm was much greater with much more rapid variations.

Figure 5 illustrates the rate of change of the horizontal field strength in nT per minute over the 12 day period. While the magnetic trace went off page for both Kew and Greenwich on 29 August for almost 12 hr, the rate of change prior to this did not exceed 250 nT/min. For 2 September storm the magnetic trace only vanished for a few hours but the storm demonstrated enormous rates of change. In both observatories the rate of change peaks around 500 nT/min on 2 September. Stewart suggested at the time that the rate may have exceeded 700 nT/min. If this did occur, it would exceed the 1-in-100 years extreme value estimate of the field change at the given latitude of 350–400 nT/min (Rogers et al., 2020; Thomson et al., 2011) and provide further evidence for the extreme nature of the August–September 1859 storms. However, it must be emphasized that the rate of change derived from digitized values is likely a minimum value, for reasons noted in Section 3.1, and therefore has large uncertainty. Indeed, given the relatively damped response to rapid variation by the instruments of the day, the true rate of change may well have been substantially larger.

4. Conclusions

Continuous magnetic field variation records started at Greenwich in the 1840s, followed by Kew a decade later. Serendipitously, one of the largest-ever known geomagnetic storms, the Carrington storm, on 2–5 September 1859 was measured at both. A precursor and lesser-recognized extreme storm on 28–29 August was also observed.

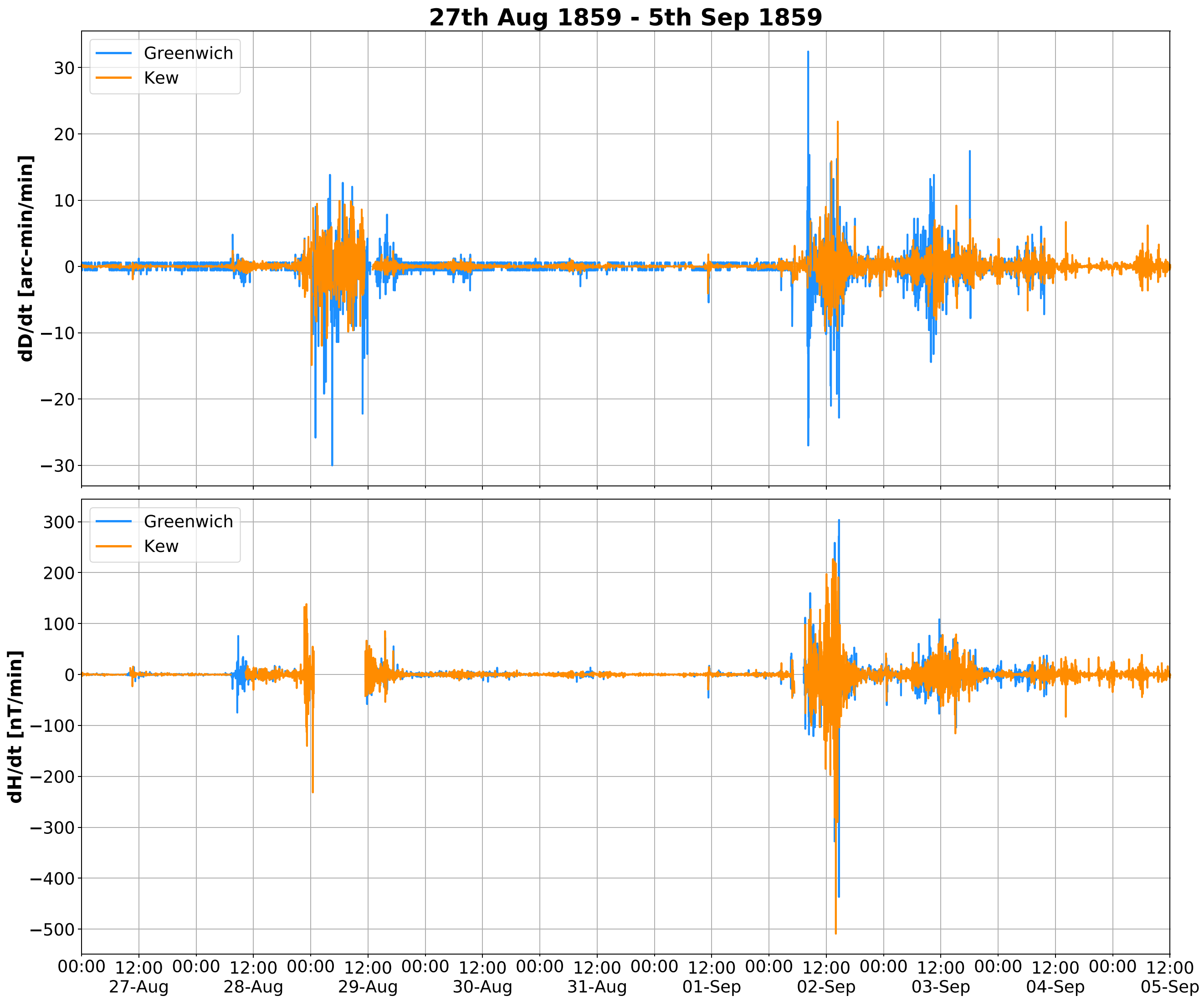

Figure 5. Rate of change of the Declination and Horizontal field at Greenwich and Kew from 27 August to 5 September 1859.

Extracting digital values from these images is difficult and requires time and experience to manually trace over the magnetic field changes and correctly convert traces from millimeters to time and SI units of degrees of angle and nT. In the case of older records careful detective work is required to cross-check the extracted values and ensure the data set was correctly aligned in time and magnitude. With two independent observatories in the same city, this offers a great opportunity to produce a cross-validated set of historic magnetic field variation.

By comparing our extracted traces with semi-independent values from yearbooks and other published information from the period, we provide the first data set of minute cadence values of the August and September 1859 storms extracted from the magnetogram records of Kew and Greenwich magnetic observatories. We find the correlation between the observatory records is relatively high at 0.81 in the Horizontal component and 0.73 in Declination. The Vertical component data are incomplete and questionable at Greenwich though available at almost continuously at Kew. To the best of our ability we have attempted to be consistent in extracting and scaling the magnetograms though cannot completely quantify all errors in general. The digitized magnetograms are made available in IAGA-2002 format.

Initial analysis suggests the rates of change of the field of over 700 nT/min exceeded the 1-in-100 years extreme value of 350–400 nT/min at this latitude based on digital-era records. Further analysis can now be undertaken to understand both of the storms and their evolution in finer detail.

Data Availability Statement

The digitized magnetogram data created in the study are available at the Natural Environment Research Council (NERC) Environmental Data Service (EDS) National Geoscience Data Center at DOI: https://doi.org/10.5285/c03ec758-d74d-4267-97fe-1be409f4c366, in ASCII text and IAGA-2002 formatted files. They are issued under a UK Open Government Licence, subject to the following acknowledgment accompanying any reproduced materials: "Contains data supplied by permission of the Natural Environment Research Council 2023."

The BGS magnetogram collection can be found at: https://www.bgs.ac.uk/information-hub/scanned-records/magnetograms/. The Greenwich Yearbook (1859) can be viewed at: https://geomag.bgs.ac.uk/data_service/data/yearbooks/YBpdf/YB_GRW_1859.pdf. The UK annual means can be extracted from: https://geomag.bgs.ac.uk/data_service/data/annual_means.shtml. All last accessed 10 January 2024.

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