Temporal Variations of the Three Geomagnetic Field Components at Colaba Observatory around the Carrington Storm in 1859

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Abstract

The Carrington storm in 1859 September has been arguably identified as the greatest geomagnetic storm ever recorded. However, its exact magnitude and chronology remain controversial, while their source data have been derived from the Colaba $H$ magnetometer in India. Here, we have located the Colaba 1859 yearbook, containing hourly measurements and spot measurements. We have reconstructed the Colaba geomagnetic disturbances in the horizontal component ($\Delta H$), the eastward component ($\Delta Y$), and the vertical component ($\Delta Z$) around the time of the Carrington storm. On their basis, we have chronologically revised the interplanetary coronal mass ejection transit time as $\leq 17.1$ hr and located the $\Delta H$ peak at 06:20—06:25 UT, revealing a magnitude discrepancy between the hourly and spot measurements ($\sim 1691$ nT versus $\sim 1263$ nT). Furthermore, we have newly derived the time series of $\Delta Y$ and $\Delta Z$, which peaked at $\Delta Y \approx 378$ nT (05:50 UT) and $\Delta Z \approx 173$ nT (06:40 UT). We have also computed their hourly averages and removed their solar quiet field variations in each geomagnetic component to derive their hourly disturbance variations (Dist) with latitudinal weighting. Our calculations have resulted in disturbance variations with latitudinal weighting of Dist $Y \approx 328$ nT and Dist $Z \approx 36$ nT, and three scenarios of Dist $H \approx -918$, $-979$, and $-949$ nT, which also approximate the minimum Dst. These data may suggest preconditioning of the geomagnetic field after the August storm ($\Delta H \leq -570$ nT), which made the September storm even more geoeffective.

Unified Astronomy Thesaurus concepts: Solar coronal mass ejections (310); Geomagnetic fields (646); Space weather (2037); Solar-terrestrial interactions (1473)

1. Introduction

Solar eruptions occasionally launch geoeffective interplanetary coronal mass ejections (ICMEs), which cause geomagnetic storms and extend the auroral oval equatorward (Gonzalez et al. 1994; Daglis et al. 1999; Hudson 2021). Analyses of such space weather events are important not only for improving our knowledge of the solar–terrestrial environment, but also for assessing the social impact of space weather, as modern civilization has become increasingly vulnerable to extreme space weather events through its increasing dependence on technological infrastructure (Baker et al. 2008; Lanzerotti 2017; Riley et al. 2018; Hapgood et al. 2021). Among recorded space weather events, the Carrington storm on 1859 September 2 has been frequently described as a worst-case scenario, in terms of the impact that such an extreme geomagnetic disturbance (Tsurutani et al. 2003; Siscoe et al. 2006; Cliver & Dietrich 2013) would have on modern technological infrastructure (Baker et al. 2008; Riley et al. 2018; Oughton et al. 2019; Hapgood et al. 2021).

The Carrington storm has formed one of the benchmarks in space weather studies. It has been associated with the earliest reported white-light flare on 1859 September 1 (Carrington 1859; Hodgson 1859; Stewart 1861) and one of the most intense solar flares, fastest ICMEs, the greatest geomagnetic disturbances, and the most significant auroral extensions in the observational history (Tsurutani et al. 2003; Cliver & Svalgaard 2004; Boteler 2006; Green & Boardsen 2006; Silverman 2006; Siscoe et al. 2006; Cliver & Dietrich 2013; Freed & Russell 2014; Curto et al. 2016; Hayakawa et al. 2019, 2020; Miyake et al. 2019). Its geomagnetic disturbance has been variously estimated for a minimum Dst index of $\sim -1760$ nT in spot values and $\sim -850$ to $\sim -1050$ nT in hourly averages, on the basic of the Colaba $H$ magnetometer (Tsurutani et al. 2003; Siscoe et al. 2006; Gonzalez et al. 2011; Cliver & Dietrich 2013), which also captured an exceptionally intense negative $\Delta H$ excursion of $\sim 1600$ nT (Figure 3 of Tsurutani et al. 2003; Figure 1(a) of Kumar et al. 2015). In the mid-nineteenth century, British colonial observatories conducted magnetic measurements in mainland England, Ireland, Canada, Australia, India, and South Africa (Cawood 1979; Gawai et al. 2015). Among them, the Colaba Observatory managed to obtain a unique record of this storm reportedly in 15 minute cadence in the stormy interval and hourly cadence otherwise, allegedly without data gaps, in the...
low to mid-magnetic latitudes (MLATs; Tsurutani et al. 2003). The Colaba records are contrasted with other magnetograms from mid- to high MLATs, which were most likely affected by auroral electrojets and field-aligned currents (Nevanlinna 2006, 2008; Blake et al. 2020).

However, interpretation of this geomagnetic superstorm has been challenging. This exceptionally large negative excursion has been controversially explained by an enhancement of the ring current (Tsurutani et al. 2003; Keika et al. 2015), auroral electrojet (Akasofu & Kamide 2004; Green & Boardsen 2006; Cliver & Dietrich 2013), and field-aligned currents (Cid et al. 2015). The Colaba H data set has been subjected to numerous geospace simulations by considering balance between solar wind energy input and loss of ring-current ions (Keika et al. 2015; Blake et al. 2021). The storm chronology has also been controversial, as the peak magnitude has been located at either 10:26 (Figure 3 of Tsurutani et al. 2003) or 11:12 (Figure 1a of Kumar et al. 2015) in Bombay local time (LT). Furthermore, the contemporary solar quiet (Sq) field variations have not been evaluated, whereas—by definition—these variations must be subtracted from the ΔH time series to reconstruct the Dst index (Sugiura 1964; Yamazaki & Maute 2017). In this context, we have recently located a published version of the Colaba yearbook for 1859 (Fergusson 1860), containing source tables not only for geomagnetic measurements of the horizontal force (H) component, but also those of the eastern declination (D) and vertical force (Z) components (Figure 1). On this basis, we modified the controversial magnitude and time series for the Colaba H component, newly derived the Colaba D and Z components around the Carrington storm, and assessed the impact of contemporary Sq variations to form a quantitative basis for further scientific discussions of the Carrington storm.

2. Materials and Methods

The Colaba Observatory was situated in Bombay (N18°54', E072°48') and had conducted magnetic measurements since 1845 (Gawali et al. 2015). In 1859, the Colaba Observatory measured geomagnetic variations with a declinometer, two horizontal force magnetometers (large and small), and one vertical force magnetometer with instrumental thermometers, dip circles, and apparatus for deflection (Fergusson 1860, pp. vi—xiii). From 1846–1847, the observatory continued using Grubb’s large magnetometers (Royal Society 1840) and supplemented these measurements with small magnetometers (unifilar and bifilar portable magnetometers; see Riddell 1844; Tsurutani et al. 2003). The deflection apparatus was used to determine absolute H, approximately every week.

Regular magnetic and meteorological observations at Colaba Observatory were recorded in their archives and published in yearbooks. Copies of the Colaba 1859 yearbook (Fergusson 1860) can be found in several archives such as the India Office Records and Private Papers of the British Library (IOR/ V/18/215). This yearbook contained tabulated geomagnetic measurements of the eastern D, H, and Z components, with
astronomical timestamps (running from noon to noon) in Göttingen Mean Time (GöMT = UT + 40 minutes–12 hr). These measurements have been summarized in two series of tables (Figure 1). The hourly tables do not provide hourly averages, but rather hourly spot measurements conducted on a regular basis, except on Sundays and certain holidays (Fergusson 1860, pp. vii and 2–153). Additionally, spot values of “disturbance observations” were recorded generally every 15 minutes—and occasionally every 5–10 minutes—during significant geomagnetic disturbances (Fergusson 1860, p. vii). The latter data offer slightly more detailed data for the stormy interval than in Tsurutani et al. (2003), which visualized the data in 15 minute cadence during the peak of the Carrington storm. The large magnetometer measured the spot values of the D component at full time, the H component 2 minutes after full time, and the Z component 2 minutes before full time (Fergusson 1860, pp. 154–179).

The hourly measurement tables from Grubb’s large magnetometers record the eastern D measurements in angular minutes (°), while the H and Z measurements are recorded in absolute values with English units (EU) and scale readings with temperature corrections (Figure 1(a)), where 1 EU equals 4610.8 nT (Barraclough 1978, p. 3). The spot-measurement tables for the large and small magnetometers commonly present the eastern D measurements in angular minutes but the H and Z measurements only as scale readings, without temperature measurements, while the instrumental temperature (T(t)) is presented separately in °F (Figure 1(b)).

From the records in this yearbook, we have derived the variations in ΔY, ΔH, and ΔZ at Colaba Observatory in 1859. We first derived the baselines of the three reported components (DH, HB, and ZH), selecting the five quiet days in 1859 August based on the Ak index (Nevanlinna 2004) and averaging their absolute measurements on the closest quiet day to the storm onset (in this case, August 25 in civil GöMT). Following contemporary textbooks (Gauss 1838; Lamont 1867), we derived the ΔY variations using Equation (1), abbreviating the reported D variables as D(t). Our approximation is valid for D(t) – DH = ΔD(t) ≪ 1°, which was actually the case at Colaba at that time (Figure 1). Here, we need to emphasize that the H and Y components are not orthogonal. Still, northward component (ΔX) approximates with ΔH here, as the eastern declination remained ≪ 1° (Figure 1; Fergusson 1860):

ΔY(t) = HB [sin(D(t)) – sin(DH)] ≈ HB(D(t) – DH).  

(1)

The hourly H values are provided as both absolute values (HAB), in EU, and as scale readings values (HSR), as shown in Figure 1(a). Their values are based on the large H magnetometer, as the small magnetometer was only used as a crosscheck “under various disadvantages” (Fergusson 1860, p. xi). The yearbook (Fergusson 1860, p. x) uses Equation (2) to describe the relationship between HAB and HSR, where T represents the temperature of the thermometer (in °F) attached to the large horizontal magnetometer. The hourly tables verify this equation with a steady offset of HAB = HSR + 28 ± 1. In our study, we converted these parameters to the modern unit (nT) and corrected this steady drift, as summarized in Equation (3). Here, the temperature coefficient of 13.6 nT for each degree of Fahrenheit. For Z, the respective coefficients are 50.72 nT/scale division and 1.5 nT per Fahrenheit. The temperature coefficients seem slightly large in H and slightly small in Z. Their causes may be better understood if we can in future locate and analyze the original magnetometers used in Colaba at that time. The H baseline (HAB) was subtracted when deriving ΔH variations (Equation (4)):

\[
H_{AB}(t)[\text{EU}] = 8.0340 + 0.0164[H_{SR}(t)
+ 0.18(T - 80) - 20.00],
\]

(2)

\[
H_{AB}(t)[\text{nT}] = 4610.8[8.0340 + 0.0164[H_{SR}(t)
+ 0.18(T - 80) - 20.00]] + 28 \pm 1,
\]

(3)

\[
\Delta H(t) = H_{AB}(t) - H_B.
\]

(4)

In the hourly Z table, Fergusson (1860) provided two columns for the Z measurements, as scale readings (ZSR(t)) and absolute values (ZAB(t)), where ZAB was calculated from the absolute H and I, ZAB = HAB tan (IAB). While the conversion equation is not clarified in the 1859 yearbook, the 1860 yearbook (Fergusson 1861, p. xiii) allows us to summarize it as Equation (5). In 1860, the contemporaneous baseline (Q) varied over time, with values of 2.78821 from January 1 to October 9, 2.8652 from October 9 to December 29, and 3.0491 after December 29. If we apply the initial value (Q = 2.78821), this shows a steady offset of HAB = HSR – 504 ± 2, which was corrected using Equation (6). We derived ΔZ taking the Z baseline (ZB) into account (Equation (7)):

\[
Z_{AB}[\text{EU}] = Q + 0.011
\times (Z_{SR} + 0.03(T - 80) - 40.0),
\]

(5)

\[
Z_{AB}[\text{nT}] = 4610.8[Q + 0.011
\times (Z_{SR} + 0.03(T - 80) - 40.0)] - 504 \pm 2,
\]

(6)

\[
\Delta Z(t) = Z_{AB}(t) - Z_B.
\]

(7)

3. Results

Figure 2 illustrates our reconstruction of the geomagnetic measurements of ΔH, ΔY, and ΔZ at the Colaba Observatory from 1859 August 26 to September 5, with the timestamps corrected from astronomical GöMT to UT. This figure shows two extreme geomagnetic storms on August 28/29 and September 2. This figure captures the August storm only in the recovery phase as observations were not conducted on August 28 because it was on Sunday (Fergusson 1860, p. vii). The intensity of these measurements for August 28 can be conservatively interpreted as ΔH ≲ –570 nT, ΔY ≳ 55 nT, and ΔZ ≳ 128 nT, respectively. Following the August storm, the geomagnetic field intensities recovered to only ΔH ≈ –85 nT, ΔY ≈ 9 nT, and ΔZ ≈ 77 nT at local midnight on September 1/2, respectively.

The September storm started at 04:50 UT, according to Bartels (1937), whereas the storm commencement (SC) peaked slightly earlier at 04:20 UT (17:00 GöMT), as shown in Figure 2. This indicates an ICME transit time of ≲17.1 hr (see 17.6 hr in Freed & Russell 2014) and an SC amplitude of ≥119 nT (see ≥120 nT in Tsurutani et al. 2003 and ≈113 nT in Siscoe et al. 2006), taking the chronological offset with the reported solar flare onset at 11:15 UT (Carrington 1859) and the intensity offset with the pre-storm level at local midnight (19:20 UT) into consideration, respectively. These values are no more than conservative estimates, as they are derived from
the hourly spot values, which may have missed the actual SC onset and the actual SC peak.

The storm developed rapidly after the SC peak at 04:20 UT. The geomagnetic field intensities peaked at $\Delta H \approx -1263$ nT (06:25 UT = 19:05 GoMT), $\Delta Y \approx 378$ nT (05:50 UT = 18:30 GoMT) and 377 nT (06:25 UT = 19:05 GoMT), and $\Delta Z \approx -173$ nT (06:40 UT = 19:20 GoMT). Our $\Delta H$ time series chronologically supports the findings of Kumar et al. (2015) over those of Tsurutani et al. (2003), who located the $\Delta H$ peak at 06:20 UT (11:12 in Bombay LT) and $\approx 05:34$ UT (10:26 Bombay LT), respectively. However, several caveats must be noted here. First, the pre-storm level was slightly different from the initial baseline, as shown in this section. Second, we detected a data gap in the $H$ measurement at 06:05 UT (18:45 GoMT), which was previously unknown to the scientific community. Finally, and most importantly, the spot $\Delta H$ amplitude ($\approx -1263$ nT) significantly departs from the hourly $\Delta H$ amplitude of $\approx -1691$ nT at 06:20 UT (19:00 GoMT), whereas the hourly values of $\Delta Y$ (303 nT at 06:20 UT) and $\Delta Z$ ($\approx -22$ nT at 06:20 UT) are more moderate than their spot values.

The $H$ error margin was described as 0.008 EU ($\approx 37$ nT) in Fergusson (1860, p. xi). We have further computed the $\Delta Y$ error margins as 11 nT or 22 nT, following Equation (1) and assuming the D reading accuracy as 1’ or 2’, respectively. The $\Delta Z$ error margins are estimated as 25 nT or 39 nT, if we assume the reading accuracy of the dip circle measurements as 1’ or 2’ and the $I \approx 20^\circ$. On their basis, their error margins are estimated as $\approx 10$–40 nT during the regular measurements. These estimates are valid for the quiet period of the magnetic field before and after the Carrington peak. When the magnetic field is changing rapidly, like during the Carrington storm, the light spot from the mirror attached on the magnet moves on the scale quickly, and this causes problems to the observer to fix the position of the spot on the scheduled time (full time). This is probably a major source of error for the magnetic measurements during the storm. Therefore, it is extremely difficult to quantitatively calculate the error margins during the storm peak, whereas they may have gone beyond $\approx 100$ nT.

### 4. Storm Intensities

Figure 2 shows a much more moderate spot $\Delta H$ amplitude at the Colaba Observatory ($\approx -1263$ nT) than in the previous estimates of $\approx -1600$ nT (Tsurutani et al. 2003; Kumar et al. 2015). In contrast, the reported hourly $\Delta H$ amplitude ($\approx -1691$ nT at 06:20 UT) seems consistent with these previous estimates when we derive the baseline from the local midnight immediately before the September storm ($\approx -1606$ nT). This hourly $\Delta H$ value is the only similar figure in the tables of hourly and spot values (Figure 1; Fergusson 1860), as the spot $\Delta H$ value at 06:20 UT (19:00 GoMT) is $\approx -1208$ nT and even milder than the spot $\Delta H$ value ($\approx -1263$ nT) at 06:25 UT (19:05 GoMT).

There are several possible explanations for this inconsistency. If we assume the original table entirely correct, this large jump can be attributed to the 2 minute time lag between the measurements of hourly values and spot values (Figure 1(a)). This hypothesis requires an extremely sharp positive excursion of $\approx 483$ nT within these 2 minutes ($\approx 241.5$ nT minutes$^{-1}$). Alternatively, if we critically reconsider the original table and
modify the tabulated scale reading value of \(-244\) at 06:20 UT (19:00 GoMT) to 244 (removing the minus sign), this \(\Delta H\) value could be modified to \(-1322\) nT. This value is much closer to the spot values around this peak, whereas this is no more than a speculation. Here, we conservatively place caveats on the reliability of using the hourly \(\Delta H\) value as a spot measurement at 06:20 UT, which probably formed the basis of the greatest \(\Delta H\) spike in existing studies (Tsurutani et al. 2003; Siscoe et al. 2006; Cliver & Dietrich 2013; Kumar et al. 2015).

The Colaba magnetogram has been used to estimate the Dst time series. However, by definition, the Dst index is derived by averaging the hourly disturbance variations (Dist) of the four mid/low-latitude reference stations with latitudinal weighting (Sugiura 1964). In 1859, the Colaba Observatory was located at \(\lambda = 10.2\) MLAT, according to the GUFM1 model (Jackson et al. 2000). Here, we have approximated the Dst time series with the Colaba \(H\) magnetometer using Equation (8):

\[
\text{Dist } H(t) \approx (H_{\text{obs}}(t) - H_S - \text{Sq}(t))/\cos \lambda. \tag{8}
\]

We approximated \(\text{Sq}(t)\) following a classic \(\text{Sq}\) definition to take an average of the five quietest days of a month (Chapman & Bartels 1940, p. 214), whereas we have more modern approaches to compute \(\text{Sq}\) for a given time and location (e.g., Van der Kamp 2013). Here, we have selected the five quietest days in 1859 August, following the Ak index (Nevanlinna 2004). The Colaba magnetometers captured three days of their diurnal variations completely, as two of the five quietest days in August were holidays, and the records were incomplete as a result (Fergusson 1860). Therefore, we have used the diurnal variations for these three days with complete measurements to approximate \(\text{Sq}(t)\) in 1859 August.

To remove the \(\text{Sq}\) variations, we have followed the same procedures for the \(\Delta Y\) and \(\Delta Z\) time series, as shown in Figure 3.

Figure 4 summarizes the hourly Dist \(H\), Dist \(Y\), and Dist \(Z\) with latitudinal weighting. Here, we have interpolated the spot values to 5 minute intervals and taken their hourly averages, as the intervals of the Colaba measurements were uneven around the storm peak (Figure 1). Specifically, we have plotted three scenarios for determining the Dist \(H\) storm peak: (1) accepting the unchanged hourly \(\Delta H\) value at 06:20 UT (19:00 GoMT), (2) accepting only the spot \(\Delta H\) value at 06:20 UT, and (3) taking an average of the hourly and spot \(\Delta H\) values at 06:20 UT.

As shown in Figure 4, the geomagnetic disturbances peaked at Dist \(Y\) = 328 nT at 06:05 UT and Dist \(Z\) = \(-36\) nT at 06:10 UT, and Dist \(H\) = \(-918\) nT (Scenario 1), \(-979\) nT (Scenario 2), and \(-949\) nT (Scenario 3), with latitudinal weighting. The Dist \(H\) intensity is a conservative value, as we have a data gap at 06:05 UT (18:45 GoMT). The minimum Dist \(H\) roughly approximates the minimum Dst estimate for the Carrington storm, whereas we need to be cautious on the LT effects and to ultimately average this with Dist \(H\) in three more reference mid/low-latitude magnetometers (e.g., Sugiura 1964).

Figure 4 also shows that the September pre-storm levels of Dist \(H\), Dist \(Y\), and Dist \(Z\) were different from the baselines, by \(\approx -86\) nT, \(\approx 9\) nT, and \(\approx 78\) nT, respectively. Accordingly, during the September storm, the magnetic field had not completely recovered from the August storm, making the September storm more effective in Dist \(H\) and Dist \(Y\) and less effective in Dist \(Z\). It is slightly challenging to understand their cause, but we can still suggest several possibilities. First, after the August storm, the ring-current decay may have required a longer time. This scenario is unlikely, as the ring-current development down to the geocorona also enhances the decay rate as well. Second, this jump was caused by ions with higher energy. This scenario is possible, as higher ion energy requires longer time for the ring-current decay compared with the typical tens of keV energy range (e.g., Ebihara & Ejiri 2003).
Third, there may have been a continuous supply of source ions for the ring-current enhancement associated with substorm injections. This is also possible, if the coronal hole supplies high-speed solar wind and causes multiple substorms (Tsurutani et al. 2006). Furthermore, it is also known that the continuous magnetic reconnection between the southward component of the Alfvén waves and the Earth’s magnetosphere fields slowly injects solar wind energy into the magnetosphere, which causes slow decay of the ring current and thus the extended recoveries of the geomagnetic storms (Tsurutani et al. 1995; Raghav et al. 2018).

5. Summary and Discussions

In this article, we have reconstructed the geomagnetic disturbances in $\Delta H$, $\Delta Y$, and $\Delta Z$ based on data in the Colaba yearbook (Fergusson 1860). Until this point, the Colaba $H$ magnetometer represented the ground truth for the Carrington storm and any scientific discussions on this event since Tsurutani et al. (2003). However, our analyses have not only revised the $\Delta H$ disturbance but also derived the $\Delta Y$ and $\Delta Z$ disturbances. As shown in Figure 1, the Colaba 1859 yearbook provides two series of geomagnetic measurements, namely, regular hourly measurements and intermittent spot measurements (every 5–15 minutes) during specific geomagnetic disturbances.

We converted the tabulated geomagnetic disturbances from scale readings to SI units (nT) and reconstructed their time series (Figure 2). Accordingly, we have resolved the controversial $\Delta H$ chronology and located the SC peak at 04:20 UT and the storm peak at 06:20–06:25 UT. This indicates that the Carrington ICME had a slightly shorter transit time than previously considered ($\leq 17.1$ hr). This yields a slightly faster average ICME velocity of $\geq 2430$ km s$^{-1}$ than what has been
considered. We have also identified a previously unrecognized data gap at 06:05 UT and an apparent discrepancy between the hourly and spot values in the $\Delta H$ tabulations ($-1263$ nT versus $-1691$ nT). This appears to be slightly abnormal, as the hourly value becomes even larger than the spot values, in contrast with what would be expected for the historical magnetograms. In addition, we have newly derived a $\Delta Y$ and $\Delta Z$ time series, which peaked at $\Delta Y \approx 378$ nT (05:50 UT) and $377$ nT (06:25 UT), and $\Delta Z \approx -173$ nT (06:40 UT).

Our results place caveats on the existing Dst estimate for the Carrington storm, owing to the controversial $\Delta H$ peaks in the spot and hourly values. Furthermore, the definition of the Dst index requires the removal of the Sq variation and baseline, and uses the hourly average of these parameters with latitudinal weighting. Therefore, we derived the Sq variations in each component from the quiet-day measurements (Figure 3) and removed them from the reconstructed geomagnetic disturbances in each component to derive their hourly averages with latitudinal weighting (Figure 4). Accordingly, their intensities are estimated as hourly Dist $Y = 328$ nT, Dist $Z = -36$ nT, and Dist $H = -918$ nT (Scenario 1), $-979$ nT (Scenario 2), and $-949$ nT (Scenario 3). The minimum Dist $H$ roughly approximates the Dst estimate for the Carrington storm, whereas the LT effect still leaves large uncertainty.

The positive $\Delta Y$ value indicates an eastward deflection of the geomagnetic field, which was probably caused by the ionospheric current flowing toward the equator. The equatorward current is thought to be part of the DP 2 ionospheric current system and two-cell magnetospheric convection (Nishida 1968). The large amplitude of $\Delta Y$ suggests an intensification of the magnetospheric convection that is needed to transport hot plasmas and intensify the ring current (Tsurutani et al. 2003).

The August storm was incompletely captured in this data set, due to the weekend break in observations (see also Hayakawa et al. 2018). We have conservatively estimated its intensity as $\Delta H < -570$ nT, $\Delta Y > 55$ nT, and $\Delta Z > 132$ nT. The magnetic field had not completely recovered from the August storm when the September storm broke out. This emphasizes the role of the preceding August storm, which most probably preconditioned the magnetic field and made the Carrington storm being more effective. Overall, the Colaba 1859 yearbook (Fergusson 1860) has significantly benefited our understanding on the space weather variations around the Carrington storm. It is worth investigating Colaba archival manuscripts to further improve our reconstructions for the Carrington storm.

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