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A study on the great geomagnetic storm of 1859: Comparisons with other storms in the 19th century

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Abstract

Magnetic data (hourly observations) from the Helsinki magnetic observatory were applied to the reconstruction of the extreme geomagnetic Storm on August 28–September 3, 1859. The storm occurred in two stages: on August 28 and September 1–3. Magnetic field variations were recorded visually from oscillating magnets. During the most intensive phases of the storm the oscillations were so rapid that only few observations could be made. Comparisons between St. Petersburg-Pavlovsk and Helsinki observatory data are given as well as descriptions of auroral displays during the storm. The great storm of 1859 was probably the most intensive space weather phenomena during the last 150 years. As measured by the *aa*-index, the next greatest storm occurred in 1960.

Keywords: Carrington event; Magnetic data; Magnetic and auroral signatures; Geomagnetic storm of 1859

1. Introduction

Much interest has recently been focused on the extreme magnetic storm of 1–2 September 1859 (e.g., Tsurutani et al., 2003). The storm was probably the greatest recorded by magnetometers since the 1840s. From the historical point of view the storm is of great scientific importance because the occurrence of a bright solar flare and the consequent magnetic storm some 18 h later were causally connected for the first time, i.e., a specific solar disturbance caused a geomagnetic storm. Since about 1850 it was known that the annual occurrence of magnetic disturbances and auroras correlates with the sunspot number within the course of the 11-year sunspot cycle (e.g., Cliver, 1994). However, it took about 70 years before the scientific community accepted that magnetic storms are physically linked with solar flares (e.g., Chapman and Bartels, 1940).

In the mid-19th century geomagnetic disturbances and visual auroral occurrences were the only signatures of solar perturbations in the Earth's magnetosphere that could be observed. Geomagnetically induced (GI) currents accompanying magnetic storms caused disturbances in telegraph wires giving some information about the occurrence time of severe magnetic storms (e.g., Boteler et al., 1998). Magnetic field variations were mostly observed visually by observing changes in the direction of a magnet in a fixed time-schedule, e.g., hourly as in the Helsinki magnetic observatory since 1844 (e.g., Nevanlinna, 1997, 2004a). A variometer recording photographically was in use at the Greenwich observatory since 1846 (Chapman and Bartels, 1940). Usable magnetic data for storm analyses exist from other magnetic observatories (e.g., Oslo and St. Petersburg-Pavlovsk) from 1840s. The time resolution is typically 1–2 h. A magnet for observations of the horizontal magnetic field component (H) during these early times of geomagnetism is shown in Fig. 1. The magnet was in operation in the Helsinki magnetic observatory 1844–1912.

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Fig. 1. The magnet for the *H*-variometer used in the Helsinki Magnetic Observatory 1844–1912. The length of the magnet was 60 cm and weight about 1.5 kg. For more technical details, see Nevanlinna (1997).

Written descriptions, although rather scanty, of the time and place, forms, colours and movements of auroral displays in the 19th century and before can be found in several auroral catalogues compiled, e.g., by Fritz (1873) for Europe and North America (based on the compilation by Lovering, 1868), Rubenson (1882) for Sweden, and Tromholt (1902) for Norway. The study on auroral occurrence during the storm of 1859 by Kimball (1960) and Chapman (1957) contains useful information about the auroral observations during the geomagnetic storm of 1859. That kind of documents are important sources for studies of long-term variations of space climate conditions (e.g., Silverman, 1992). The data in such catalogues do not give much quantitative information for reconstructing the phases of a single storm event. However, clues to important parameters as the approximate maximal size of the auroral oval can be determined for single magnetic storms from archived auroral descriptions.

In this paper, we present hourly data (the horizontal (*H*) and declination (*D*) components) from the Helsinki magnetic observatory (Lat. 60.1°N; Lon. 24.9°E; Geomagn. Lat. 56.5°N) (1844–1912) that can be utilized for studies of the morphology of the exceptional magnetic storm of 1859. (The digital data for the period 1844–1897 can be obtained from the author on request). Some magnetic data from the Russian observatory in St. Petersburg-Pavlovsk are included in the analysis. Descriptions of auroral display in Scandinavia in connection with the September 1859 magnetic storm will be given.

2. Magnetic storms of August and September 1859

As can be seen in Fig. 2 and Tables 1 and 2 showing magnetic field values for the storm, there are long gaps in the observations at the Helsinki observatory during both storms so that only the onset and recovery phases of the storms have been recorded. The reason for the gaps is in difficulties of visual observations of the *H*- and *D*-magnets of Gaussian type (see, e.g., Nevanlinna, 1997). During the most intensive phase of the storm, the magnets have been in a rapid oscillation and it was thus impossible to get exact readings of the position of the magnet. A picture of the *H*-magnet that was in operation in the Helsinki observatory 1844–1912 is given in Fig. 1.

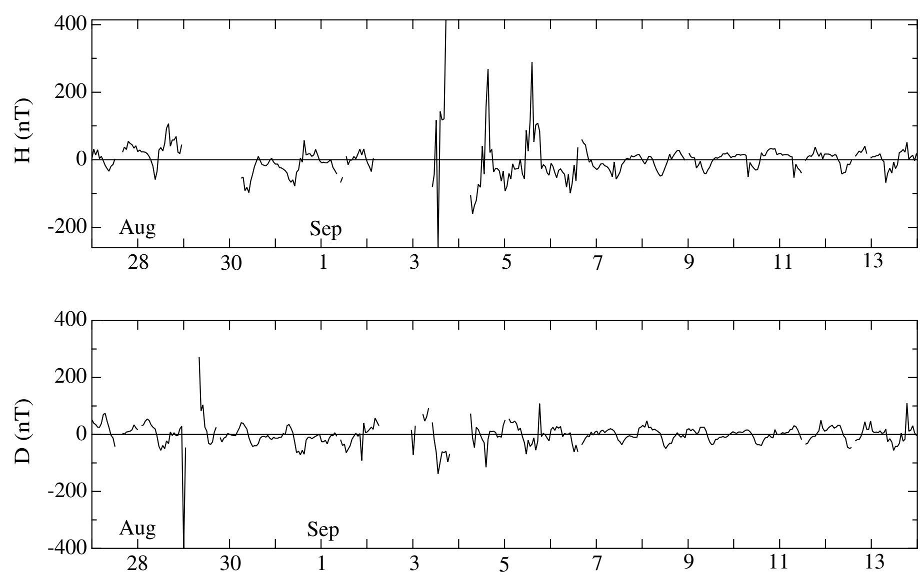

Fig. 2. Hourly deviations of the horizontal (*H*) magnetic field (upper panel) and declination (*D*) (lower panel) during the extreme magnetic storm from August 27 to September 7, 1859. The time is in UT. Note that the deviation of ±200 nT corresponds to the value 9 in the 3-h geomagnetic activity index scale *K*. The corresponding digital content of the figures are given in Tables 1 and 2.

Table 1
Hourly values (ΔH) of the H-component during the storm of 1859 (August 27–September 7)

Hour (UT)	ΔH	K	ΔH	K	ΔH	K	ΔH	K	ΔH	K	ΔH	K
	August 27		August 29		August 31		September 2		September 4		September 6	
	23		–		25		27		149		54	
0	3		–		−13		8		–		−11	
1	31	5	–	–	−13	1	−9	–	–	–	−20	4
2	14		–		−23		−20		–		−38	
3	30		–		−25		−34		–		−54	
4	4	4	–	–	−28	0	3	–	–	–	−32	5
5	11		–		−33		−1		–		−27	
6	−3		–		−39		–		−105		−37	
7	−17	1	–	–	−59	2	–	–	−160	6	−43	5
8	−26		–		−67		–		−135		−82	
9	−34		–		−60		–		−121		−44	
10	−20	3	–	–	−78	5	–	–	−72	5	−99	6
11	−14		–		−37		–		−82		−71	
12	3		–		−30		–		40		−16	
13	–	–	–	–	5	5	–	–	−43	8	−63	7
14	29		–		−7		–		156		36	
15	–		–		57		–		269		–	
16	23	–	–	–	14	5	–	–	21	9	60	–
17	38		–		16		–		31		49	
18	30		–		18		–		−36		44	
19	55	4	–	–	10	3	–	–	−25	6	14	4
20	48		–		14		–		−27		−8	
21	44		–		30		–		−33		−1	
22	35	3	–	–	13	4	–	–	−64	5	−19	2
23	42		–		−2		−115		−33		−25	
	August 28		August 30		September 1		September 3		September 5		September 7	
	34		25		14		400		116		23	
0	24		–		−9		–		−93		−29	
1	29	3	–	–	−8	2	–	–	−79	6	−24	3
2	23		–		−9		–		−40		−14	
3	23		–		−9		–		−57		−12	
4	22	3	−103	–	−4	2	–	–	−13	5	−18	2
5	17		–		−2		–		−29		−20	
6	9		−55		−23		–		−27		−26	
7	−2	3	−52	6	−31	1	–	–	−26	5	−35	4
8	−19		−92		−42		–		2		−51	
9	−59		−82		–		–		−42		−6	
10	−34	6	−98	4	−68	–	–	–	−57	8	−57	6
11	28		−63		−52		−44		87		−48	
12	36		−43		–		117		25		−37	
13	26	4	−20	0	10	–	−261	9	118	9	−15	4
14	47		−4		−15		143		290		−8	
15	93		9		−1		118		53		2	
16	106	6	−3	4	−1	3	121	9	103	4	5	3
17	40		−15		10		414		108		0	
18	59		−16		3		–		85		12	
19	59	3	−18	0	17	4	–	–	−27	6	9	2
20	69		−13		31		–		−15		11	
21	23		−2		14		–		−20		15	
22	19	4	5	3	32	4	–	–	−39	1	16	2
23	45		−7		8		−69		−46		7	

ΔH is the deviation (in nT) from the mean H-value during the period. Three-hour K-index derived from the field variations is included as well as the daily activity character (the number under the date). A short line marks missing observations. Note that the K-indices have not been determined as deviations of the mean value but relative to the daily regular variation curve of the magnetic field within each 3-h bin. For more details from determining the K-index using a numerical algorithm, see Nevanlinna et al. (1992) or Menvielle et al. (1995).

There were two successive magnetic storms in August and September 1859. According to the magnetograms in Kew (see, e.g., Fig. 35 in Chapman and Bartels (1940), vol. I, p. 333) the first one started about 2300 UT on August 28, and the second one in the morning on September 2 about 0500 UT. The magnetic field was very

Table 2
Hourly values (ΔD) of the D-component during the storm of 1859 (August 27–September 7)

Hour (UT)	ΔD	K	ΔD	K	ΔD	K	ΔD	K	ΔD	K	ΔD	K
	August 27		August 29		August 31		September 2		September 4		September 6	
	23		55		22		32		75		22	
0	53		−402		−14		10		–		17	
1	39	4	−46	–	−14	1	17	3	–	–	24	4
2	35		–		−11		26		–		14	
3	26		–		−9		19		–		27	
4	25	3	–	–	3	3	57	5	–	–	22	3
5	38		–		0		45		–		27	
6	70		–		30		30		73		−8	
7	73	5	–	–	35	3	–	–	−12	7	2	4
8	47		272		22		–		−46		1	
9	25		82		7		–		24		1	
10	−2	3	104	7	−27	5	–	–	17	5	5	4
11	−14		26		−64		–		−2		−31	
12	−43		11		−59		–		−18		−62	
13	–	–	−31	3	−71	4	–	–	−30	7	−37	4
14	−21		−36		−56		–		−115		−61	
15	–		−27		−70		–		−17		–	
16	4	–	8	5	−20	5	–	–	11	4	−36	–
17	1		25		−11		–		10		−26	
18	8				−9		–		11		−14	
19	10	2	−11	–	−15	3	–	–	7	5	−5	3
20	11		−27		−11		–		−9		−8	
21	16		−14		−6		–		−6		8	
22	33	4	−9	3	−2	2	–	–	−9	5	−2	3
23	23		3		0		16		32		8	
	August 28		August 30		September 1		September 3		September 5		September 7	
	34		13		35		58		51		11	
0	16		1		−26		−71		51		11	
1	–	–	−2	1	−26	2	30	–	–	–	−2	3
2	30		−3		−21		–		55		11	
3	33		−5		−33		–		42		14	
4	47	4	10	3	−14	4	–	–	41	2	7	2
5	54		22		−3		72		47		13	
6	48		41		−5		47		38		17	
7	33	3	39	4	5	3	61	6	14	4	20	2
8	26		29		−6		92		22		17	
9	19		19		–		–		−8		11	
10	−6	5	−11	3	−18	–	42	–	−30	5	−2	2
11	−42		−30		−39		−18		−70		−20	
12	−56		−42		−34		−62		−21		−26	
13	−39	4	−40	3	−64	4	−139	6	−42	4	−36	3
14	−50		−40		−52		−96		−34		−23	
15	−22		−33		−40		−61		−12		−14	
16	−33	5	−14	3	−17	3	−64	3	−55	6	−8	1
17	8		−8		−6		−59		−24		−5	
18	−3		−6		4		−98		108		−6	
19	5	4	−9	2	−6	3	−68	–	−8	7	−9	2
20	−5		−3		2		–		4		−11	
21	−3		−14		−92		–		−2		−9	
22	19	5	−18	2	39	7	–	–	−14	4	22	4
23	29		−11		5		–		−23		26	

ΔD (nT) is the deviation from the mean D-value during the period. For further explanations, see Table 1.

stormy until September 5 in Helsinki (see, Fig. 2 and Tables 1 and 2) and St. Petersburg-Pavlovsk (see, Fig. 3). The August storm has clearly been very intensive but short in duration because the magnetic field condition was nearly normal on September 1 prior to the solar flare signal in the magnetic field at 1115 UT that can be seen in the magnetogram of the Kew observatory (see, Chapman and Bartels, 1940).

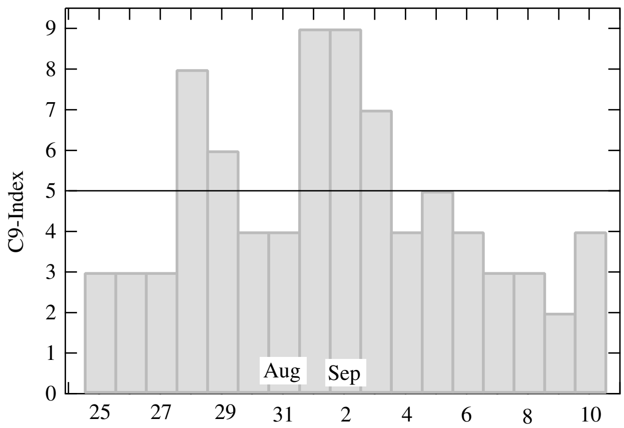

Fig. 3. Daily values of the geomagnetic amplitude index *C*9 from August 28 to September 10. The data are from the St. Petersburg observatory (Russia) where magnetic variometers similar to those in Helsinki were in operation. The *C*9-indices have been compiled by Zosemovich (1981). The horizontal line shows the limit of major magnetic storms.

2.1. Activity indices of the 1859 magnetic storm

Fig. 3 depicts the daily values of the (local) *C*9-index from August 25 to September 10, 1859 derived from the St. Petersburg-Pavlovsk (Russia) magnetic observatory (Lat. 59.9°N; Lon. 30.3°E) data. The observation methods were similar to those used in Helsinki observatory. The observatory locates some 300 km east of from Helsinki and the magnetic space weather conditions were thus rather similar in the two observatories. The index determination has been carried out by Zosemovich (1981) from the hourly observations of *H* and *D*. Note, however, that originally the *C*9-index was a global activity character (0,1,...,9) derived from many observatories based on a subjective evaluation on the magnetic storminess on daily basis (for the definition, see, e.g., Lincoln, 1967). *C*9-index, which was still in use during the IGY (International Geophysical Year, 1957–1958), has been later superseded by the planetary *Kp*-index (see, e.g., Rangarajan, 1989). In the case of St. Petersburg-Pavlovsk, the name *C*9-index is used although the index is a local one. It is a measure of the deviation of the magnetic field from the normal diurnal variation similar to the *K*-index. The maximum deviation of *H* or *D* (in the unit of magnetic field strength) from the regular daily curve has been converted into the 10-bin scale. The $C9 = 9$ value was fixed to be 600 nT. $C9 = 5$ is the lower limit of a major magnetic storm.

During the storm of 1859, the highest index ($C9 = 9$) values in St. Petersburg-Pavlovsk were reached on September 1 and 2. On August 28, *C*9 was one unit lower than the maximum value 9.

The uniqueness of the September storm is emphasized by the rare occurrence of the highest *C*9 values in the St. Petersburg-Pavlovsk data series. For 20 years (1841–1864), the $C9 = 9$ level has been reached only during seven other storms (see Table 3).

The hourly observations of *H* and *D* at the Helsinki observatory have been converted to 3-h *K*-indices using the *K*-algorithm for automatic index calculations from observatory data (Menvielle and Berthelier, 1991; Nevanlinna et al., 1992; Menvielle et al., 1995). The calibration of the 10-bin (0,1,...,9) *K*-index scale was made by comparing Helsinki *K*-values with the nearby (40 km) Nurmijärvi magnetic observatory data and assuming that magnetic variations are, on the average, similar at both observatories. By adjusting the percentage of *K*-values in each bin to be the same in Helsinki and Nurmijärvi data, it was found that an amplitude of 200 nT for $K = 9$ in the hourly Helsinki data yields the closest distribution as compared with the Nurmijärvi data in which the $K = 9$ limit is 750 nT.

A summary of the space climate conditions in 1844–1912 based on the Helsinki activity index series has been given by Nevanlinna (2004a).

In order to compare the September 1859 magnetic storm with other storms, the magnetic activity index series *aa* (1868 – present) (Mayaud, 1972 for the description of data. Updated data can be found in the www-site of, e.g., British Geological Survey) together with the Helsinki extension (1844–1897) (Nevanlinna, 2004a) gives the longest available magnetic data sequence covering 160 years. The September 1859 storm is the strongest but the daily activity index *aa* (Helsinki) = 400

Table 3
Greatest magnetic storms in 1844–1864 according to Helsinki daily activity index *aa*

aa	Day	Year	Maximum *C*9
400	September 3	1859	9
186	September 7	1860	6
183	October 23	1847	9
171	September 7	1851	9
169	December 17	1857	7
166	March 29	1860	5
161	February 18	1852	9
159	December 20	1847	5
150	October 4	1862	9
149	September 4	1859	9
138	February 21	1848	9
136	December 17	1847	5
136	March 20	1848	7
133	October 24	1847	9
128	August 14	1864	3
127	September 27	1847	9
119	November 17	1848	8
116	September 5	1859	9
114	August 7	1860	7
113	September 4	1851	9
112	June 23	1858	6
105	April 29	1859	7
101	November 18	1848	8

*C*9 refers to the maximum index value of each storm as determined in the St. Petersburg-Pavlovsk observatory.

on September 3 must be regarded as a crude approximation because so much data are missing in the Helsinki observations. As measured by the *aa*-index, the next greatest storm occurred in November 1960 (see, Table 4).

The September 1859 magnetic storm occurred 10 months before the sunspot maximum of the cycle 10. Great magnetic storms, as listed in Table 4, often appear just (about 1 year) before or 1–3 years after the sunspot maximum. Fig. 4, showing all magnetic storm days exceeding $aa = 100$, demonstrates the fact that the number of magnetic storms during a solar cycle seems to be proportional to the sunspot maximum number. Most magnetic storms have occurred in the cycle 20 (1954–1964) which had the absolute maximum of the maximum sunspot number of all cycles during the last 250 years. However, the occurrence of exceptionally great magnetic storms is not ruled out during low sunspot maximum cycles like the storms in 1903 and 1909, which are included in the top-ten list of great magnetic storms (Table 4), and which occurred in the sunspot cycle 14 for which the maximum sunspot number was the lowest in the 20th century.

Table 4
Ten greatest magnetic storms in 1844–2004 as classified according to the daily *aa*-index

Rank	Date	Daily *aa*
1	September 3, 1859	400[a]
2	November 13, 1960	352
3	September 18, 1941	350
4	March 13, 1989	348
5	July 15, 1959	347
6	September 25, 1909	329
7	March 28, 1946	322
8	October 31, 1903	308
9	July 8, 1958	305
10	November 20, 1882	305

[a] Estimated from 7 h of Helsinki data.

2.2. Other great magnetic storms

As can be seen from Fig. 4, the space climate conditions before and after the September 1859 magnetic storm during the solar cycle 10 have not been exceptionally high as measured by the number of the occurrence of severe magnetic storms. In fact, the average level of magnetic activity in the solar cycles from 1844 to 1860 was about 25% lower than during the last four solar cycles in the 20th century. As pointed out by, e.g., Feynman and Crooker (1978) and Lockwood et al. (1999), the sunspot and magnetic activity maxima were increasing for about 100 years since the beginning of the 20th century. The absolute maximum of the sunspot maxima occurred in the solar cycle 19 in 1957. However, the corresponding maxima in magnetic activity (as measured by the *aa*-index) occurred several solar cycles later in the cycle 23 (e.g., Nevanlinna, 2004b).

There have been several great magnetic storms from 1840s to 1860s but none of them is comparable to the extreme magnetic storm of September 1859. During 1844–1864 covering most of the solar cycles 9 and 10, there were 15 great magnetic storms as measured by the daily magnetic activity index *aa* (Helsinki *H*-component; $aa > 100$) (see Table 3 and Fig. 4).

The observation interval of the *H*- and *D*-magnets at the Helsinki magnetic observatory was 10 min from 1844 to 1856, later an hour. In 1844–1856, not much data are lost even during the most severe magnetic storms like in October–December 1847, November 1848, September 1851, and in February 1852. The Helsinki data series for 1844–1856 provides, thus, good material for studies of magnetic storms during the 12-year period in the solar cycle 9.

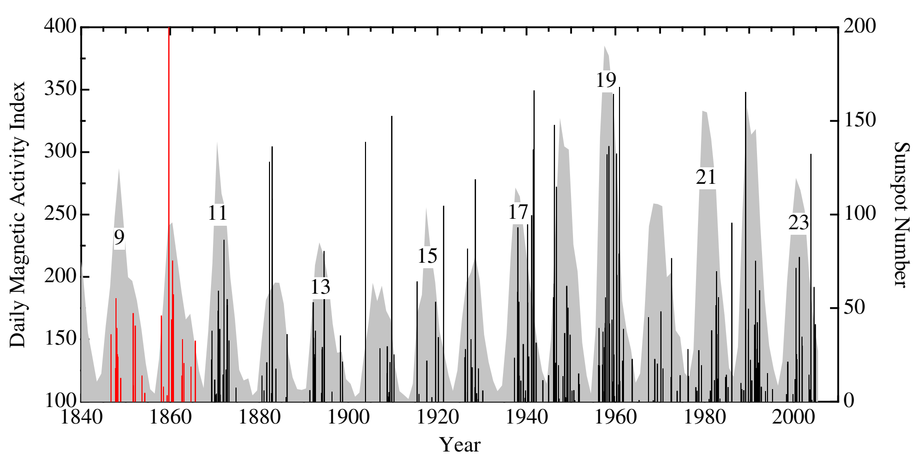

Fig. 4. Vertical lines: daily magnetic activity index of Helsinki extension of the *aa*-index 1844–1867 and Mayaud's *aa* (>100) 1868–2004. The grey area depicts the sunspot number.

3. Observations of auroras

In Finland there are no auroral observations available during the occurrence of the September 1859 storm. In 1846–1856, the Helsinki magnetic observatory organized a rather comprehensive programme for the observation of auroras in connection with climatological observations in whole Finland (Nevanlinna, 2004b). Systematic observations of auroras started again in 1881. However, in Sweden and Norway, the neighbouring countries of Finland, visual observations of northern lights have been compiled in catalogues containing information of auroral occurrence for several hundreds of years (Rubenson, 1882; Tromholt, 1902). A useful source of descriptions of visual observations of auroras, until 1872, is the catalogue published by Fritz (1873).

According to Fritz's catalogue, exceptional auroral displays were seen in August 28, 1859 in whole Europe and so far south as in Rome (Geomagn. Dip. Lat. 44°N) and Athens (Geomagn. Dip. Lat. 38°N). In North-America auroras were reported, e.g., from Cuba, Jamaica, Florida, and New Orleans (Geomagn. Lat. 34°N as calculated for Havana, Cuba). The most southern observation was reported from a ship in the Atlantic Ocean (Geomagn. Dip. Lat. 34°N).

The auroras accompanying the magnetic storm during 1–3 September were seen at even lower latitudes than in 28 August, e.g., from Hawaii at Geogr. Lat. 20°N; Lon. 157°W (Geomagn. Dip. Lat. 24°N) and from a ship (on September 1) at Geogr. Lat. 14°N; Lon. 24°W (Geomagn. Dip. Lat. 23°N). A map showing the places where visual observations of northern lights from August 28 to September 2 were seen has been published by Chapman (1957) and Kimball (1960).

Note that the geomagnetic coordinates given here are dipole latitudes at the epoch 1860 calculated from the first three spherical harmonic coefficients g_1^0, g_1^1, h_1^1 obtained from the compilation by Barraclough (1978). The calculated geomagnetic dip-pole is at Lat. 78.4°N; Lon. 63.9°W.

3.1. GI effects

Electric wires in telegraphs suffered from induction effects during the extreme magnetic storm. Rubenson (1882) describes a geomagnetically induced damage, which occurred during the extreme magnetic storm of 1859 in Gothenburg (Geomagn. Lat. 56°N), Sweden:

During September 2nd and 3rd atmospheric electricity was so high that the telegraphic connections were broken down for many hours at several occasions. In the City Telegraphic Office it was observed that the galvanometer needle of the telegraph apparatus was sometimes motionless, sometimes it moved restlessly. The telegraphist, who on the morning of September 2nd was disconnecting the earth, got a strong electric shock when touching the cable. On the evenings of September 2nd and 3rd the sky was full of majestic northern lights. On the following evenings they were seen again and the galvanometer behaved similarly but less disturbed. Due to high atmospheric electricity it was impossible to send telegrams for about 24 h.

According to Tromholt (1885) about 150 geomagnetically induced disturbances were reported annually in Norway in 1881–1884 demonstrating that telegraphs were quite vulnerable to the space weather storms. A recent compilation of GI disturbances in various ground-based technological systems in the 19th and 20th centuries has been published by Boteler et al. (1998).

4. Conclusions

The reconstruction of the extreme magnetic storm of 1859 by using the Helsinki magnetic data (hourly readings) reveals large gaps in the data due to the visual observation method of the oscillating magnets. Only the onset and recovery phases of the storm have been recorded. However, for studies of magnetic storms during the solar cycle 9 (1844–1856) the Helsinki data are suitable because the time resolution was better (10 min) and only few data are missing in the observation series.

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