INFLUENCE OF MAGNETIC STORMS ON COMPASS

Katarina Sadovski
Higher Education Centre Sezana, Laboratory for Geomagnetism and Aeronomy
Kraska 2, 6210 Sezana, Slovenia
katarina.sadovski@viviss.si

Spomenko J. Mihajlovic
Geomagnetic Institute Grocka
Put za Umcare 3, 11306 Grocka, Serbia

Rudi Cop
Higher Education Centre Sezana, Laboratory for Geomagnetism and Aeronomy
Kraska 2, 6210 Sezana, Slovenia
rudi.cop@viviss.si

ABSTRACT

This article presents the nature of the Sun’s and Earth’s magnetic fields, their mutual connection and anomalies. The number of magnetic storms increases and decreases in unequal cycles which correspond to the increases and decreases in sunspots cycles. The Sun’s plasma streams that shoot out from the sunspots cause an increase in the solar winds and in doing so they affect the geomagnetic field and the Earth’s atmosphere. One example of such occasional causal connections was the very extreme magnetic storm that occurred during the last two Sun Cycles, and lasted from October 28th to November 2nd 2003. In that time extensive changes in the geomagnetic field were recorded. This resulted in additional coincidental errors in navigation magnetic instruments (compass). The magnetic compass is today an instrument of secondary importance, but it is included as compulsory in navigation devices with enhanced accuracy, reliability and robustness: integral navigation systems, autopilots, ARPA radars and systems for drilling platform adjustment. Today it is possible to forecast the appearance of a geomagnetic storm. This means that errors at navigation devices caused by such storms may also be predicted and that they may be managed systematically.

Keywords: Sunspots, solar cycles, geomagnetic field, geomagnetic storms, compass

1 SUN’S CYCLES

In 1843 the German astronomer Heinrich Schwabe (1789-1875) published the results of his daily tracking of sunspots over several decades. He observed that the number of sunspots increases and decreases in unequal cycles that last approximately 10 years. The range within which these sunspots emerge also changes cyclically; it expands and contracts. In the vicinity of the sunspot cycle peak, sunspots release into their surroundings a vast amount of energy in the form of X-rays, radio waves and very high-speed plasma streams. These plasma streams are responsible for the magnetic storms on Earth. The Sun’s plasma outbursts are accompanied by abrupt solar flares. The English astronomer Richard C. Carrington (1826-1875) made the first observation of the sun’s flares by telescope. By observing the sunspots’ movement he also discovered that the speed of the Sun’s rotation depends on the solar latitude. The Sun makes one full revolution in relation to Earth approximately every 27 days. While it spins, its equatorial regions rotate faster than its polar regions. This unequal rotation, together with the migration of plasma from the Sun’s interior towards its surface, is the basic explanation of the emergence of the Sun’s magnetic field [1]. According to this explanation the sun is a huge magnetic dynamo which spreads its magnetic field into interplanetary space because of the asymmetry in its rotation.
The areas on the Sun’s surface which are observed in the visible light spectrum as sunspots are areas with increased density of the magnetic field. The strong magnetic field in an individual sunspot may slow down the temperature transfer and therefore a sunspot is cooler than its surroundings. The reason for this phenomenon has not yet been explained. A stronger and less homogenous solar magnetic field is produced during periods with a greater number of sunspots. The 11-year cycle of sunspots, which has only positive amplitudes, coincides approximately with the cycle of the Sun’s magnetic field or Hale cycle (named after George Ellery Hale). George Ellery Hale (1868 – 1938), the builder of the astronomical observatory on Mount Palomar in California, discovered this cycle together with his co-workers. The Sun’s magnetic cycle has both positive and negative amplitudes, which means that the magnetic field’s polarity is reversed every 11 years. After a 22-year cycle the polarity of the Sun’s magnetic field reverses back to its original state.

In some situations a magnetic storm on Earth and a strong increase in the scattering of the Sun’s basic particles can result even if it was not accompanied by the preliminary emergence of a solar flare. In this case, above certain sunspot areas a disturbance in the form of balloon will be created which broadens as it leaves its source. This solar matter eruption which occurs in the solar corona is called a Coronal Mass Ejection (CME). This phenomenon was revealed for the first time by cameras on space probes at the end of the 1970s.

2

CHANGES IN THE GEOMAGNETIC FIELD

The geomagnetic field vector changes with time and place. During certain periods of time the changes in the geomagnetic field occur uniformly and regularly and therefore it is possible to determine a rule for the nature of such changes. There are however periods of time during which their amplitudes and intervals are constantly changing. Firstly then, on the basis of the observatory’s geomagnetic measurements, the normal values of the geomagnetic field are determined. These are yearly mean values determined over a longer measurement period, which is, for example, as long as a solar cycle. For example the normal density of the Earth’s magnetic field in Slovenia slightly exceeds 47,000 nT.

Table 1: Geomagnetic mid-latitude European Observatories

<table>
<thead>
<tr>
<th>Observatory</th>
<th>Code</th>
<th>Geographical Latitude</th>
</tr>
</thead>
<tbody>
<tr>
<td>Panagjurishte</td>
<td>PAG</td>
<td>40.6°N</td>
</tr>
<tr>
<td>Ebro</td>
<td>EBR</td>
<td>40.8°N</td>
</tr>
<tr>
<td>L'Aquila</td>
<td>AQU</td>
<td>42.4°N</td>
</tr>
<tr>
<td>Grocka</td>
<td>GCK</td>
<td>44.6°N</td>
</tr>
<tr>
<td>Tihany</td>
<td>TIH</td>
<td>46.3°N</td>
</tr>
<tr>
<td>Chambon-la-Foret</td>
<td>CLF</td>
<td>50.1°N</td>
</tr>
<tr>
<td>Belsk</td>
<td>BEL</td>
<td>50.2°N</td>
</tr>
<tr>
<td>Niemegk</td>
<td>NGK</td>
<td>54.1°N</td>
</tr>
<tr>
<td>Wingst</td>
<td>WNG</td>
<td>54.5°N</td>
</tr>
<tr>
<td>Brorfelde</td>
<td>BFE</td>
<td>55.6°N</td>
</tr>
</tbody>
</table>

The next step is to determine the changes in the geomagnetic field, which arise from sources under the Earth’s surface or on it, by the statistical analysis of the measurement data from each geomagnetic observatory. The changes in the Earth’s magnetic field caused by the external sources originated from the solar activity, the sun’s magnetic field and solar winds. With regard to their form and size they may be divided into several different classes.
The daily changes in the geomagnetic field during magnetically calm days define the constant changes in the geomagnetic field. This type of periodic change in the recorded geomagnetic field’s components, whose period lasts one solar day, is called the regular daily variation $S_R$. While processing the geomagnetic field’s changes, this component will be extracted as the basic component which defines the geomagnetic activity. The amplitudes of the regular daily variation $S_R$ will reach their highest value during the summer solstice and the minimum value during the winter solstice. At the geomagnetic mid-latitude observatories (Table 1) the measured regular daily variation amplitudes during the summer were about 60 nT and, during the winter, 20 nT. The direct influence of the Sun over the geomagnetic field is proven by this finding [2, 3].

During a solar cycle the observatories may register several events of unexpected geomagnetic disturbance, which are the component parts of the geomagnetic field’s compound structure. These magnetic storms may be of the SSC-type (with sudden commencement) or of the GSC type (with gradual commencement). Geomagnetic storms are the most typical external disturbance of the Earth’s magnetic field. Their absolute and relative amplitude of geomagnetic field density exceeds 100 nT and this is their common characteristic.

On the basis of analysis of the data which were collected through the daily tracking of the Sun’s activity over several decades it was observed that the number of sunspots increases and decreases in cycles that last 11 years (Figure 1). This solar activity cycle was determined as a time interval between two successive minimum numbers of sunspots. The Sun’s activity curve is composed of three parts; Part 1 – 11 years long, basic component; Part 2 – approximately 1 year long, the component with almost periodic changes; Part 3 – 1 month long, the component with sudden changes.

The common characteristic for each solar activity cycle is a rapid increase in sunspots from the minimum to the maximum and a considerably slower decrease in sunspots to the
minimum. Measurements during several solar cycles proved that there is a mutual connection between the changes in solar activity and changes in the geomagnetic field. The changes in the number of geomagnetic storms during each year are completely in keeping with the changes in the number of sunspots (Figure 1). The number of sudden changes in the geomagnetic field is also cyclical and the cycle length is also 11 years, but in comparison with the solar cycles they have a delay of 15 – 18 months.

3 GEOMAGNETIC DISTURBANCE

Geomagnetic activity may be analysed during a month on the basis of mid-time values and in this way regular and periodic variations may be selected as components of the geomagnetic structure. During certain days of the month recorded data for geomagnetic activity may show disordered, irregular and non-periodic variations in the geomagnetic field. They emerge at irregular time intervals and have different periods; the amplitudes/intensity of these variations may have several dozens to several hundreds of nT.

Table 2: List of Extreme Magnetic Storms during Solar Cycles 22 and 23

<table>
<thead>
<tr>
<th>Geomagnetic storm</th>
<th>Start</th>
<th>End</th>
<th>Level [nT]</th>
<th>Indices g.m.a. K</th>
</tr>
</thead>
<tbody>
<tr>
<td>1989, March 13</td>
<td>13.03.1989: 01 28 UT</td>
<td>15.03.1989: 21 50 UT</td>
<td>574 nT</td>
<td>9</td>
</tr>
<tr>
<td>1990, April 9</td>
<td>09.04.1990: 08 44 UT</td>
<td>15.04.1990: 06 00 UT</td>
<td>584 nT</td>
<td>9</td>
</tr>
<tr>
<td>2003, October 29</td>
<td>29.10.2003: 06 12 UT</td>
<td>01.11.2003: 21 00 UT</td>
<td>700 nT</td>
<td>9</td>
</tr>
<tr>
<td>2004, November 7</td>
<td>07.11.2004: 02 57 UT</td>
<td>11.11.2004: 14 00 UT</td>
<td>500 nT</td>
<td>9</td>
</tr>
</tbody>
</table>

In the disturbed category of geomagnetic activity come disturbed daily variations and non-periodic disturbed variations, as well as short-term periodic changes in the geomagnetic field, which are observed as pulsations. All the aforementioned geomagnetic field variations which have all the aforementioned characteristics, or some of them, constitute a geomagnetic disturbance. Researchers selected some morphological characteristics common to all geomagnetic disturbances by analyzing and investigating a great number of magnetic storms and other magnetic disturbances [5, 6, 7]. Each geomagnetic disturbance is composed of: the regular part of the geomagnetic field's disturbance (DS); non-periodic variations (Dₙₕ); and the irregular part of the geomagnetic field's disturbance (Dᵢ). Selecting the days when geomagnetic disturbances were recorded as the days for analysis and applying the method of geomagnetic field variation processing, it is possible to regard the morphology of the variations, which are integral parts of the geomagnetic disturbances, in a different light. The geomagnetic field variations which may be expressed as the mid-time variation values for the days during the disturbance are defined as the regular part of geomagnetic disturbance or the DS-variation of the geomagnetic field. The subtraction of the geomagnetic field variations, which were recorded during the geomagnetic storm, from
the defined DS-variation will present the non-periodic and irregular part of the geomagnetic disturbance.

**Figure 2:** The morphology of a geomagnetic storm shown in three phases: the initial phase (I.Ph), the main phase (M.Ph) and the recovery phase (R.Ph)

One of the most important attributes of magnetic storms is that these geomagnetic disturbances have three phases: the initial phase, the main phase and the recovery phase (Figure 2). The appearance of an SSC impulse in the recorded data signifies the beginning of a magnetic storm (SSC impulse - Sudden Storm Commencement). It is followed by a sudden change ("jump") in the intensity of the geomagnetic field’s horizontal component (ΔH) which is recorded over a short interval, which can last 3-5 minutes. These are very important parameters which describe the morphology of the SSC impulse and announce the sudden commencement of SSC-type magnetic storm.
Changes in the Earth’s Magnetic Field, without a predetermined period and different amplitudes, are determined as geomagnetic disturbances. The most typical geomagnetic disturbances are magnetic storms. They are represented by intensive variations in the geomagnetic field. These variations have a complex morphology. The line of increase in the geomagnetic field’s horizontal component values determines the initial phase of a magnetic storm.

The initial phase can last for 30 minutes to a few hours (Figure 2). The main phase of a magnetic storm starts with the moment of decrease in the intensity of the geomagnetic field’s horizontal component. The decrease in the field’s intensity can last for a few hours to a few days. During the main phase of a magnetic storm, geomagnetic field variations with different amplitudes and periods can be recorded. It can be assumed that the recovery phase of a magnetic storm starts when the horizontal component values start their return to the level before registration of the storm. The described geomagnetic field changes which occur during magnetic storm are a macro-structural model of the magnetic storm. This model highlights the cumulative, principal characteristics associated with the magnetic storm phenomenon.

4 GEOMAGNETIC STORMS DURING SOLAR CYCLES 22 AND 23

Analyses of the geomagnetic field's daily variations, the geomagnetic field's disturbances and the magnetic storms classified as Extreme Geomagnetic Storms were made on the basis of the data recorded at the geomagnetic mid-latitude observatories (Table 1) during Solar Cycles 22 and 23. A total of 37 of the SSC-type magnetic storms (with sudden commencement) were analysed. The highest amplitude and the magnetic storms’ duration were taken into consideration. During Solar Cycles 22 and 23 each magnetic storm lasted about seventy-two (72) hours. Table 2 contains a group of eight Extreme Geomagnetic Storms which were taken from the total number of the magnetic storms which were recorded during this period. For purposes of verification, the Extreme Geomagnetic Storms (Table 2) were compared with the magnetic storm categories designated during observations at the Japanese observatories of Kakioka (KAK), Memambetsu (MEM) and Kanoya (KNY) (Tsunomura et al, 1999). A comparison was also made with the monthly reports on the rapid variations.
which were recorded at the worldwide network of magnetic observatories and published by ISGI (International Service of Geomagnetic Indices) [8].

5 SUDDEN SOLAR AND GEOMAGNETIC CHANGES DURING OCTOBER 2003

In October 2003 solar activity move from a low level in the first half of the month to an extremely high level of activity during the last ten days. A few large groups of sunspots were observed on the solar disc, and they were designated as the Catania sunspot group.

![Graph showing extreme relative changes in the geomagnetic field Di(x) recorded at Geomagnetic observatory Grocka (GCK)](image)

Figure 4: Extreme relative changes in the geomagnetic field Di(x) which were recorded at Geomagnetic observatory Grocka (GCK)

The big Catania 70 sunspot group appeared on the eastern section of the solar disc in October 23, 2003 (Figure 3). It occupies 0.23% of the solar disc surface. This was one of the biggest sunspot groups recorded during Solar Cycle 23. Its magnetic activity was demonstrated by several types of extremely strong solar flares. Many flares emerged in the area of the central solar meridian and they sent very fast radiation, Coronal Mass Ejections (CME), streaming towards Earth [9, 10]. The solar wind speed was extremely high. On October 28, 2003 the speed reached about 2,125 km/s, and the over next two days it was about 1,950 km/s. The interplanetary magnetic field (IMF) reached about -50 nT. The normal values are around ten-time lover.
All these extremely strong Coronal Mass Ejections influenced conditions in the geomagnetic field. At 06:12 UT, on October 29, 2003 the SSC impulse (SSC - Sudden Storm Commencement) marked the commencement of one of the strongest magnetic storms recorded during the last ten solar cycles (Figure 4). During this geomagnetic storm the geomagnetic activity planetary index was extremely high; on October 29 the geomagnetic index was Kp = 58; on October 30 the geomagnetic index was Kp = 56. Normal maximum values for the geomagnetic index were also recorded during intervals of several hours – Kp = 7, Kp = 8 and Kp = 9. The geomagnetic storm lasted till November 1, 2003. Its intensity reached 700 nT, and it was the biggest deviation from the geomagnetic field's mid-value recorded at the mid-latitude Observatories (Table 2).

More precise analysis of the Dst-variation hourly values during October 2003 indicated that the geomagnetic activities in this period were divided into three parts. The hourly changes in the geomagnetic field’s H-component intensity H [nT] are indicated with the index D_{ST}. This index showed that in 2003 the period from October 1 to October 13 was very quiet and the period from October 14 to October 27 was only moderately disturbed with index D_{ST} < - 100 nT. From October 28 to November 2, geomagnetic activity was extremely high. Three successive magnetic storms were recorded. The highest index D_{ST} = - 401 nT was recorded on October 30 at 23:00 UT (Hourly Equatorial D_{ST} Values, 2003).

The Fourier transformation of the non-periodic variation (D_{at}) signal, which was recorded during October Geomagnetic Storm, showed that the changes in the geomagnetic field’s H-component intensity came about in cycles with a frequency from \( \Delta \omega = 0.05 \) to \( \Delta \omega = 0.38 \) cycles per hour, that is their periods were \( \Delta T = 150-180 \), \( \Delta T = 200-240 \), \( \Delta T = 500 \), \( \Delta T = 600 \) and \( \Delta T = 1000-1200 \) minutes (Figure 5). In the amplitude spectrum of the non-periodic variation (D_{at}) signal the dominant changes were the changes in the geomagnetic field’s H-component intensity, which were from \( \Delta H = 2 \) nT/minute to \( \Delta H = 6 \) nT/minute, and they were recorded at the Geomagnetic Observatories of GCK (Figure 4.).

6 CONCLUSION

Navigation is a process which makes it possible to travel safely and in accordance with the current transport conditions. In its basic meaning it is a planning science, aimed at control and guidance of ships from their port of departure to their port of destination. Today the science of navigation means guidance of ships, road and railway vehicles, aircraft and
spacecraft over a predetermined time via the shortest and most convenient route. The modern theory of navigation is based on knowledge from several natural and social sciences, mathematics, optimal guidance theory and from several areas of technical science [12, 13]. During his everyday work a navigator must necessarily take into consideration the weather and climate conditions. Such conditions are under the direct influence of geomagnetic storms. Today it is possible to forecast the appearance of a geomagnetic storm. This means that errors in navigation devices caused by such storms may also be predicted and that they may be managed systematically.

The records of geomagnetic activity during Solar Cycle 23 (which occurred from 1996 to 2006) indicate several extremely intensive A-class geomagnetic storms. These were storms classified in the category of Extreme Magnetic Storms. During a phase designated as a post-maximum phase in solar activity (PPM - Phase Post maximum), near the autumn equinox, on October 29th 2003, an extremely strong and intensive magnetic storm was recorded. The level of geomagnetic field variations which were recorded for the selected Extreme Magnetic Storm, was $\Delta D_{st} > 350$ nT. For Extreme Magnetic Storm the indicated K-index was 10+. This index is directly related to the maximum amount of fluctuation (relative to a quiet day) in the geomagnetic field over a three-hour interval. This index indicates also the error of compass in indication of direction.

A geomagnetic storm causes changes in the atmosphere and in doing so it also causes changes in the way radio waves are dispersed. This in turn means that the conditions for application of radio-navigation systems also change: satellite and hyperbolic navigation systems and radio lighthouses (beacons) [14]. This is why knowledge about extreme changes in the geomagnetic field is so important for the use of primary navigation systems of both passive and active types.

REFERENCES


