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MAGNETIC STORMS AND THEIR INFLUENCE ON NAVIGATION

This article presents the nature of the Sun's and Earth's magnetic fields, their mutual connection and anomalies. The number of sunspots, that increase and decrease in unequal cycles, correspond to the number of registered magnetic storms on the Earth. 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 a causal connection was the most extreme magnetic storm that has occurred during the last two Sun Cycles. It lasted from October 28th to November 2nd 2003. Successful navigation depends on taking into consideration all the changes on the Earth that arises from changes on the Sun.

Key words: *Sunspots, solar cycles, geomagnetic field, geomagnetic storms, navigational instruments*

1. INFLUENCE OF MAGNETIC STORMS ON NAVIGATIONAL INSTRUMENTS

Modern navigation operates on the basis of electronic navigational instruments: digital compasses and inertial systems, radio-navigational systems and radar. It is able to determine a position even in conditions of poor visibility. An Integral Navigation System consists of at least two different navigational systems which are integrated to achieve their mutual control [1, 2]. Among all modern navigational systems the satellite radio-navigational system GPS (Global Positioning System) is one to which new units can be added most quickly and it is also the most widely-used among civilian users.

Of all electronic navigational systems which are used today for determining the position, inertial systems are the only autonomous systems. For the determination of direction they use only those parameters which are related to the vehicle itself: ship, automobile, train, airplane, satellite or spaceship. Magnetic and digital compasses determine direction only by measuring the Earth's magnetic field. All forms of radio-navigation use the distribution of radio-waves through space. The Earth's magnetic field and the method of radio-wave distribution through space are under the constant influence of disturbances originating from the Sun. These disturbances are seen as magnetic storms and changes in the way microwaves are conducted through the ionosphere.

At the end of October and the beginning of November 2003 new units were added to the national network of permanent GPS stations in the Republic of Slovenia. During this period, after the re-establishment of the whole network, significant problems and even black-outs of the whole geodesic system were observed.

2. 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 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 [3]. 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.

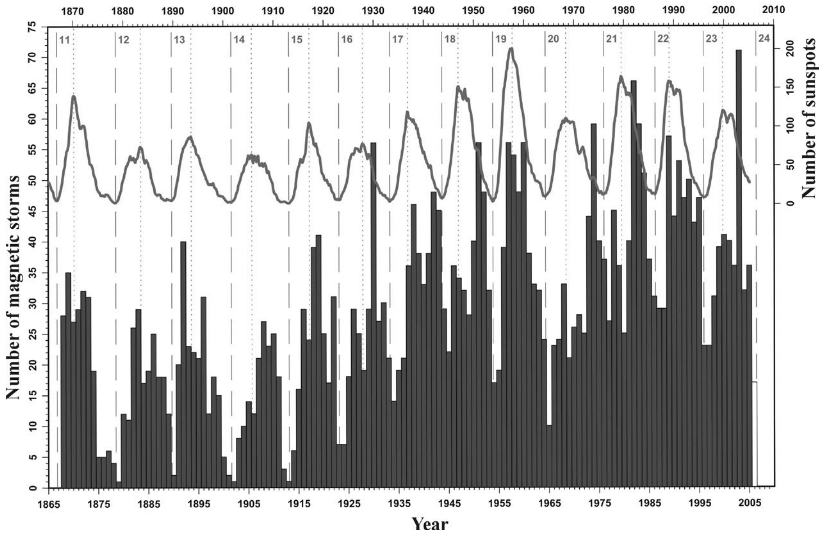

Fig. 1: Solar cycles (unbroken line) and yearly number of geomagnetic storms (columns) [5]

The Sun's outer layers, the reddish chromosphere and the radiant corona located above it, which are otherwise hardly visible, may be observed during a total solar eclipse. In the areas with sunspots and at the poles these beams of elementary particles are noticeably influenced by strong magnetic fields [4].

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.

On the basis of the 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 changes in the number of geomagnetic storms during each year are completely in keeping with the changes in the number of sunspots. 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. VARIATIONS OF 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 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 [6].

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 a periodic change in the recorded geomagnetic field components, whose period lasts one solar day, is called the regular daily variation S_R. 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 [7, 8].

During a solar cycle the observatories may register several events of unexpected geomagnetic disturbance, which are the component parts of the geomagnetic field compound structure. These magnetic storms may be of the SSC-type (with sudden commencement) or of the g-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.

Tab. 1: Geomagnetic mid-latitude European Observatories

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

4. GEOMAGNETIC STORMS DURING SOLAR CYCLES 22 AND 23

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

Geomagnetic storm	Start	End	Level [nT]	Indices g.m.a. K
1982, July 11	13.07.1982: 16 17 UT	15.07.1982: 22 00 UT	420 nT	9
1986, February 6	06.02.1986: 13 15 UT	10.02.1986: 23 45 UT	445 nT	9
1989, March 13	13.03.1989: 01 28 UT	15.03.1989: 21 50 UT	574 nT	9
1990, April 9	09.04.1990: 08 44 UT	15.04.1990: 06 00 UT	584 nT	9
1991, October 17	17.10.1991: 13 33 UT	21.10.1991: 19 20 UT	392 nT	9
2000, July 14	14.07.2000: 06 46 UT	17.07.2000: 13 54 UT	478 nT	9
2003, October 29	29.10.2003: 06 12 UT	01.11.2003: 21 00 UT	700 nT	9
2004, November 7	07.11.2004: 02 57 UT	11.11. 2004: 14 00 UT	500 nT	9

Analyses of the geomagnetic field daily variations, of the geomagnetic field disturbances and of 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 the Solar Cycles 22 and 23. A total of 37 of the SSC-type magnetic storms with sudden commencement were analyzed. The highest amplitude and the magnetic storms' duration were taken into consideration. During the Solar Cycles 22 and 23 each magnetic storm lasted about seventy-two 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 the purposes of verification, the Extreme Geomagnetic Storms (Table 2) were compared 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) [9].

5. EXTREMELY SOLAR AND GEOMAGNETIC CHANGES DURING OCTOBER 2003

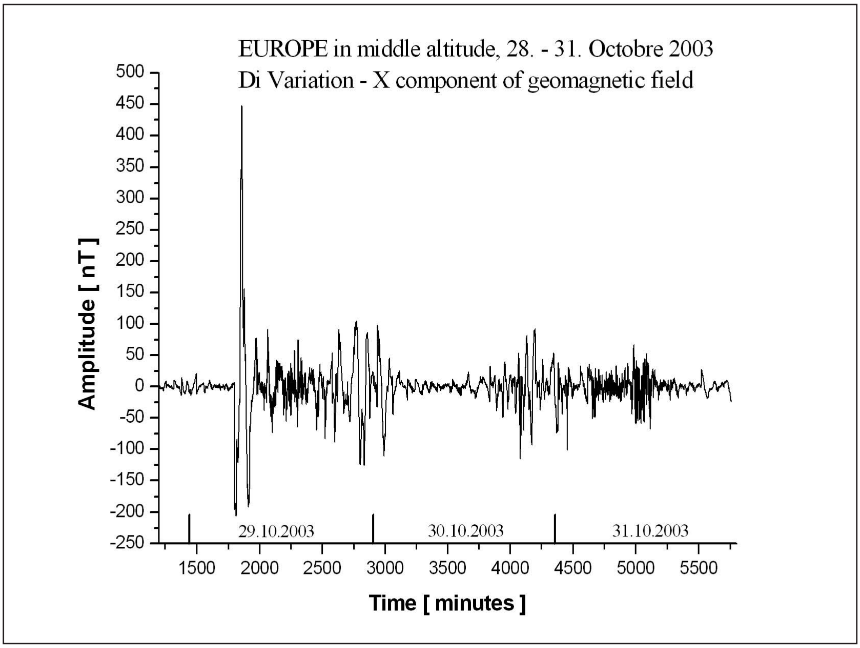

Fig. 2: Extreme relative changes of the geomagnetic field measured in the geomagnetic observatories Tihany (Hungary)

In October 2003, the solar activity moved 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. The big Catania 70 sunspot group appeared on the eastern section of the solar disc in October 23, 2003. It occupied 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 the Earth [10]. The solar wind speed was extremely high. On October 28, 2003 the speed reached about 2,125 km/s, and over the next two days it was about 1,950 km/s. The interplanetary magnetic field (IMF) reached about -50 nT.

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 2). 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. The normal maximum values for the geomagnetic index were also recorded during the intervals of several hours: Kp = 7, Kp = 8 and Kp = 9. The geomagnetic storm lasted till November 1, 2003. Its intensity reached 800 nT, and it was the biggest deviation from the geomagnetic field mid-value recorded at the mid-latitude Observatories (Table 2).

6. CHANGES OF ELECTRO-MAGNETIC WAVES PROPAGATION THROUGH THE IONOSPHERE

The ionospheric characteristics are also highly variable on timescales ranging from eleven years of a solar cycle to a few seconds. Even during its quietest periods, the Sun produces the electromagnetic radiation and the solar wind, which simultaneously affect a variety of geomagnetic and ionospheric phenomena [11]. For the solar-terrestrial conditions surrounding the 29 - 30 October 2003 storm the vertical TEC (total electron content) data obtained from IGS - GPS (International GNSS Service - GPS) site of Graz (15.5 E, 47.1 N) are shown in Figure 3. This displays the evaluation of the 10 minutes TEC values from 28 to 30 October 2003. It can easily be seen that the total ionospheric content was highly disturbed both in time and space over the Mid - European area. As expected, the negative phase of the ionospheric storm for the total electron content is detected from the early hours of October 30. Figure 4 shows TEC depletions relative to the TEC values on the quiet ionospheric day of October 11. The ionospheric storm consists of both significant initial positive (dTEC increases > +100%) associated with travelling ionospheric disturbances and negative (dTEC decreases < -40%) phases.

This example suggests that vertical TEC data obtained from a worldwide network of ground-based GPS measurements can be an important tool for retrieving ionospheric features that appear during storm conditions. Although the large variations in TEC are interpreted as significant enhancements or depletions characteristics of the storm behaviour, the exact explanation of the physical mechanisms that lead to such a complex behaviour is even beyond the scope of this paper.

During decades of ionospheric measurements, studies and modeling, knowledge about the morphology of the ionospheric response to the geomagnetic storms have accumulated, and the physical mechanisms that drive storms have been understood in significant detail. At mid-latitudes, thermospheric winds and electromagnetic fields are believed to play a dominant role in the ionospheric plasma changes seen here in TEC temporal and special variations.

Negative storm phases have been attributed to changes in the atomic to molecular neutral density ratio. The positive phases are generally believed to be caused by uplifting of the F region by equatorward winds in the early hours of a storm development. As studies continue to search for the actual physical mechanisms that explain the spatial and temporal morphologies over various space weather events and to test forecasting algorithms for practical ionospheric applications, it would be useful to have a well defined pattern of mid-latitude ionosphere/plasmasphere storm and a technique to forecast it.

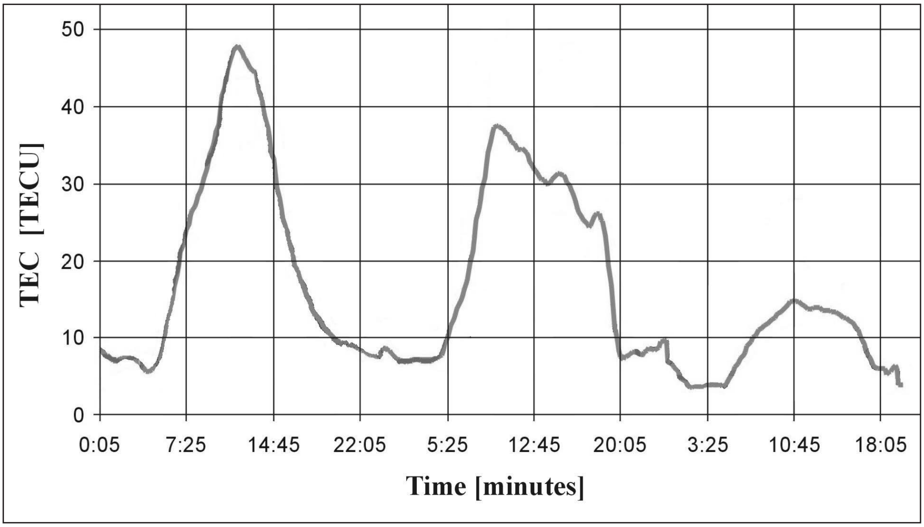

Fig. 3: Diurnal vertical TEC values at Graz (Austria) during 28-30 October 2003 in TECU (1 TEC unit = 10^{16} electrons/m)

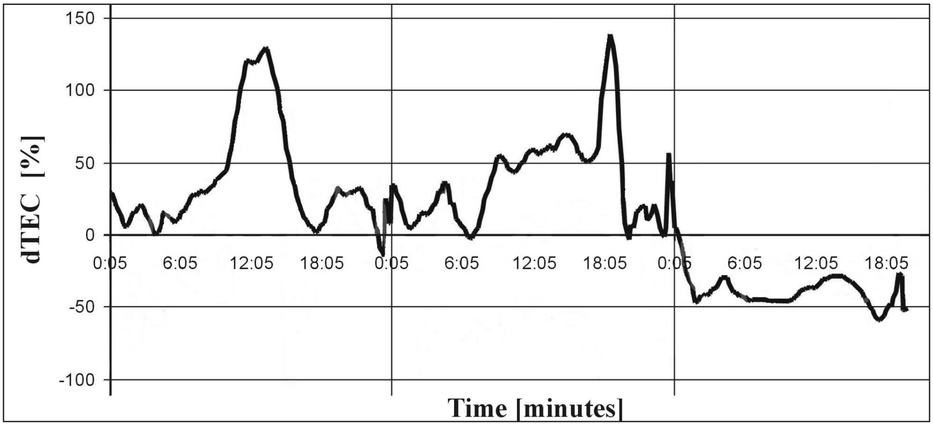

Fig. 4: dTEC in % for Graz (Austria) during 28-30 October 2003

The short-term forecasting of operational parameters for ionospheric and trans-ionospheric radiocommunications is required to improve the quality and reliability of radiocommunication services, including frequency adaptive applications at MF and HF and trans-ionospheric radiodetermination. A significant contribution in that direction is given by updating climatological model predictions of the ionospheric/plasmasphere and propagation parameters.

7. 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 the 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 the knowledge acquired from several natural and social sciences, mathematics, optimal guidance theory and from several areas of the technical sciences [1, 12]. During his everyday work a navigator must take into consideration the weather and climatic conditions. Such conditions are under the direct influence of solar winds as geomagnetic storms.

During the geomagnetic storm in 2003 from October 30th to October 31st, extensive changes in the geomagnetic field were recorded [13]. This resulted in additional coincidental errors in the navigational magnetic instruments (compass). The magnetic compass is today an instrument of secondary importance, but it is included as compulsory with navigational devices of enhanced accuracy, reliability and robustness: integral navigational 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 in navigational devices caused by such storms may also be predicted and that they may be managed systematically.

A geomagnetic storm comes along with changes in the atmosphere and changes in the radio waves propagation. This in turn means that the conditions for the application of radio-navigational systems also change: satellite and hyperbolic navigational systems and radio lighthouses (beacons). This is why the knowledge about extreme changes in the geomagnetic field is so important for the use of primary navigational systems of both the passive and active types.

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Sažetak

MAGNETSKE OLUJE I NJIHOV UTJECAJ NA PLOVIDBU

U radu se prikazuju karakteristike Sunčevih i Zemljinih magnetskih polja, njihova međusobna povezanost, ali i njihove anomalije. Broj Sunčevih pjega, koje se povećavaju i smanjuju u nejednakim ciklusima, odgovara broju registriranih magnetskih oluja na Zemlji. Sunčeve plazma-zrake koje izbijaju iz Sunčevih pjega uzrokuju porast broja solarnih vjetrova i pri tome utječu na geomagnetsko polje i Zemljinu atmosferu. Jedan primjer takve uzročne veze bila je najžešća magnetska oluja koja se pojavila u tijeku posljednja dva Sunčeva ciklusa. Trajala je od 28. listopada do 02. studenoga 2003. godine. Uspješna plovidba ovisi o uzimanju u obzir svih promjena na Zemlji koje nastaju zbog promjena na Suncu.

Ključne riječi: *Sunčeve pjege, Sunčevi ciklusi, geomagnetsko polje, geomagnetska oluja, navigacijski instrumenti.*

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