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# Time scheduling of magnetic surveys in mid-latitudes with respect to forecasting geomagnetic activity

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The quality of magnetic surveys is essentially influenced by the geomagnetic activity. As the in situ measurements are usually limited to very short time period, they must be compared with observatory continuous registrations. When reducing measurements one makes an assumption that diurnal variations of the magnetic field are identical at both the station and the reference observatory. During magnetically quite periods, this assumption is satisfied to an acceptable extent. However, under high geomagnetic activity, the error may easily exceed the acceptable limit. Our analysis indicates that, in mid-latitudes, magnetic surveys should not be made, if some of the Kp values are over 5. Long-term and medium-term forecasts of geomagnetic activity are based on known periodicities (11-year, half-year and 27-day). Short-term forecasts are based on the knowledge of the actual conditions on the Sun, in the solar wind and in the interplanetary magnetic field. Regional Warning Centres, associated in the International Space Environment Service (ISES) deal with forecasts of geomagnetic activity. Links to all 12 centres can be obtained through http://www.ises-spaceweather.org/about_ises/index.html.

**Key words:** Magnetic surveys, repeat stations, geomagnetic activity.

## 1. Introduction

Geomagnetic activity has a significant effect on the quality of magnetic surveys. Data themselves measured within a short time interval are but of little significance. They only become significant when compared with permanent magnetic observatory data. It is assumed thereby that the variation of the magnetic field at the observatory and the measured survey point is the same, affected at the most by the time shift of the daily variation curve with regard to the difference in the geographic longitudes of the measuring points (Schulz and Beblo, 1984). During magnetically quite periods, this assumption is satisfied to an acceptable extent. However, under high geomagnetic activity, the error may easily exceed the acceptable limit, and the invested funds and time spent come to waste.

The authors of this paper were contacted by a prospecting company, which was using airborne magnetometry as one of the methods of comprehensive exploring selected localities, during the period of Halloween geomagnetic storms. By permanently monitoring solar wind parameters, the interplanetary magnetic field and the current geomagnetic field at the observatory, we were able to produce short-term (in terms of hours) forecasts of geomagnetic activity, and thus enable the company to carry out its measurements without wasting flying time.

Nevertheless, this paper is focused on the problems of magnetic repeat station surveys. It is difficult to determine the errors of repeat station observations, because only a few discrete values are available, or in the case of a local variometer a short interval of continuous data. In view of the dense observatory network coverage in Central Europe, however, we are able to replace the observatory repeat station pair by a pair of observatories in studying the dependence of the difference between two sites on the degree of disturbance of the geomagnetic field.

As is well known, geomagnetic activity depends strongly on geomagnetic latitude. This is reflected not only in the size of the amplitude, but also in the different behaviour of the seasonal variation (Newitt *et al.*, 1996). Variations of the geomagnetic field are expressed in terms of indices. At low latitudes by hourly Dst indices, which reflect the intensity of the ring current, at mid-latitudes by three-hour K-indices, reflecting the degree of disturbance of the geomagnetic field at a given location, and finally at high latitudes by 2.5-minute AE indices, reflecting the current density in the systems of magnetospheric currents, which close in the polar ionosphere. This paper is devoted to the mid-latitudes, where the authors have practical experience with magnetic surveys, as well as with forecasting geomagnetic activity.

## 2. Analysis of the Difference of the Geomagnetic Field Variation

The typical distance of a repeat station from a reference observatory ranges from hundreds to thousand of kilometres. The dense coverage of geomagnetic observatories in Central Europe enables the difference in the variation of the geomagnetic field to be analysed for different distances and degrees of disturbance of the geomagnetic field. The minute data, published on the INTERMAGNET 2002 CD ROM (www.intermagnet.org) were used, and the monitored quantity was the absolute value of the daily maximum deviation from the average. The data were then grouped by

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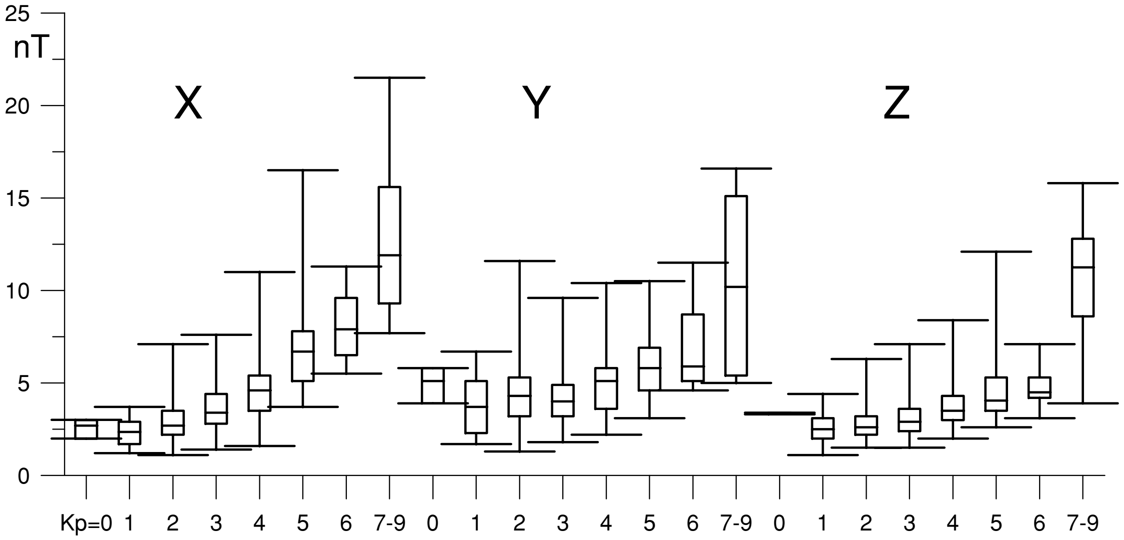

Fig. 1. Daily maximum of the difference of the variation of the geomagnetic field between the observatories of Tihany and Nagycenk (distance 110 km). The data for 2002 have been grouped by maximum Kp index for the given day. The plots show the min, max, median, lower and upper quartiles (one half of the values lies within the box).

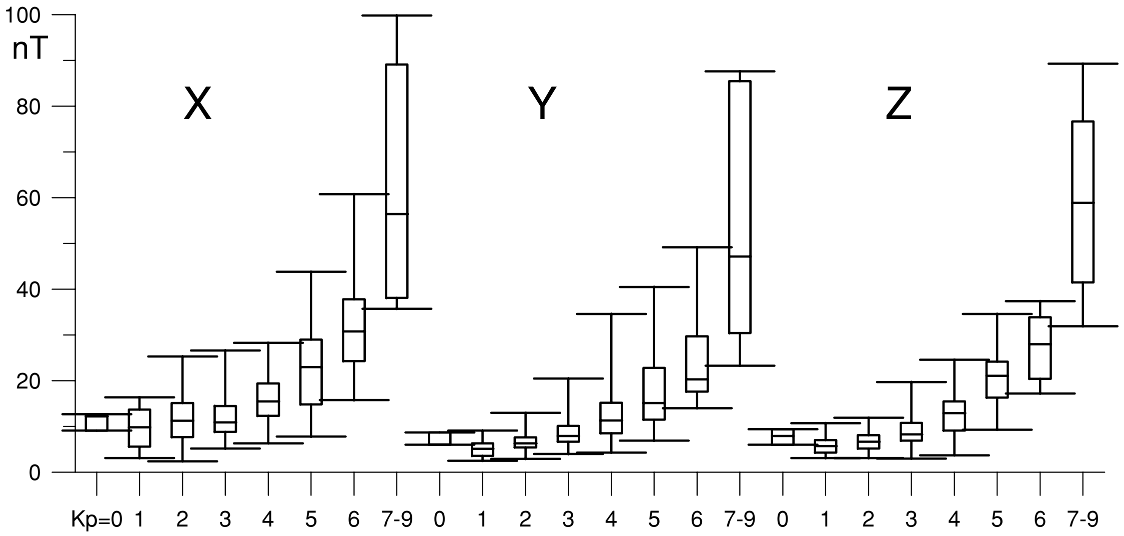

Fig. 2. Daily maximum of the difference of the variation of the geomagnetic field between the observatories of Niemegk and Fürstenfeldbruck (distance 450 km). For text refer to Fig. 1.

maximum Kp-index value for the given day. This procedure produced more convincing results than grouping by individual three-hour Kp-indices. This is due to oscillations of the magnetic field appearing in the recovery phase of a geomagnetic storm, although the Kp-index may vary between 2 and 3.

Data from the observatories of Belsk, Budkov, Fürstenfeldbruck, Nagycenk, Niemegk and Tihany were included in the analysis. Figure 1 shows the results for the two closest observatories, Tihany and Nagycenk. For Kp $\leq$ 3 at least 3/4 of all maximum daily deviations are under 5 nT. A significant increase occurs for Kp $\leq$ 4. It is common knowledge that the Z-component is less sensitive to magnetic disturbances, but for Kp $\geq$ 7 this difference nearly vanishes. Figures 2 to 4 depict the data for observatories, the distance of which is approximately 500 km, however, whereas Niemegk and Fürstenfeldbruck are nearly at the same geographic longitude, Niemegk and Belsk are on the same parallel, and Budkov and Belsk lie on the diagonal. It was again found that a principal change in the trend occurs at around Kp $=$ 4. This result was also supported by other computations. Repeat station measurements should thus not be made, if some of the Kp values are 5 or higher. The day will be denoted as magnetically disturbed if there is at least one value Kp $=$ 5 and another two values Kp $=$ 4.

The graphs may create a pessimistic impression, because the deviations exceed 20 nT even under low geomagnetic activity. The reader should be reminded that the graphs show the maximum daily deviation, and that the resultant error will be substantial smaller after several series of measurements have been made. It is, however, indisputable that the error increases with the degree of disturbance of the geomagnetic field.

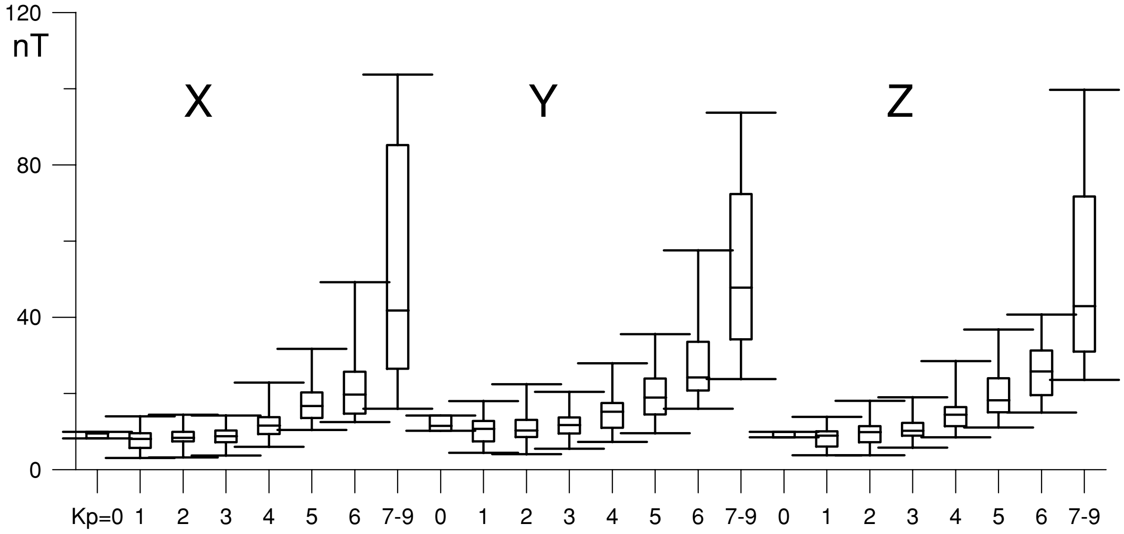

Fig. 3. Daily maximum of the difference of the variation of the geomagnetic field between the observatories of Niemegk and Belsk (distance 555 km). For text refer to Fig. 1.

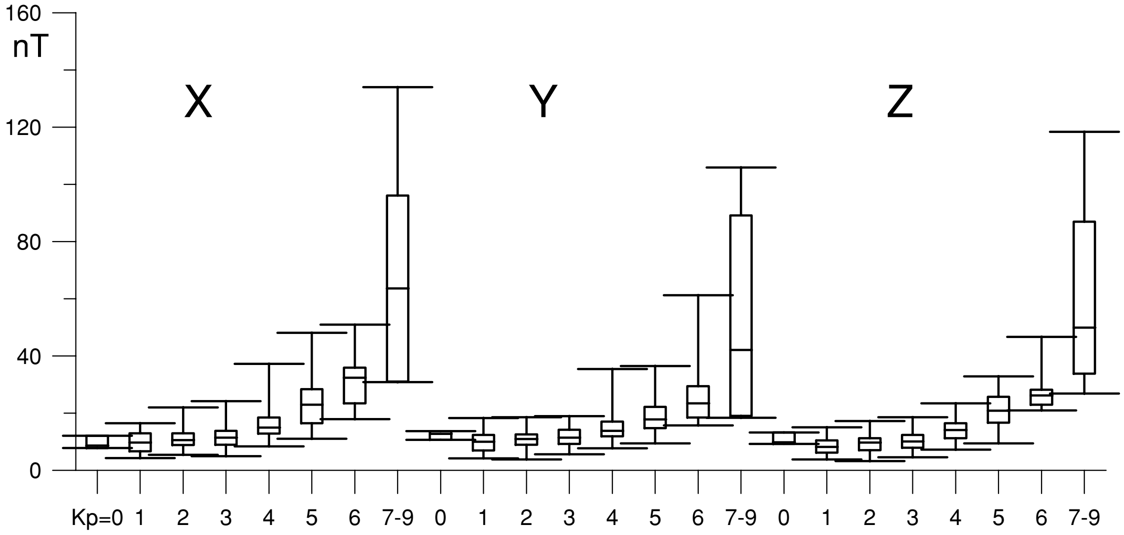

Fig. 4. Daily maximum of the difference of the variation of the geomagnetic field between the observatories of Budkov and Belsk (distance 560 km). For text refer to Fig. 1.

## 3. Forecasting Geomagnetic Activity at Mid-Latitudes

Long-term and medium-term forecasts of geomagnetic activity are based on known periodicities (11-year, half-year and 27-day). The eleven-year cycle is related to solar activity, the geomagnetic cycle lagging in phase behind the solar cycle by approximately two years (see Fig. 5). This information is, however, used relatively little in planning repeat station measurements, because the measurements are usually carried out in an interval of two to five years, and measurements in the neighbourhood of the maximum of geomagnetic activity cannot be avoided. The more significant are short-term forecasts, which we shall be dealing with below.

The half-year period of geomagnetic activity displays a distinct dependence on geomagnetic latitude. With the exception of polar regions its maximum occurs at the time of equinoxes (Fig. 6). This provides a good opportunity to carry out measurements in the summer months.

In planning magnetic measurements it is expedient to take into consideration the 27-day period of solar rotation. Active formations on the solar surface do develop dynamically; nevertheless they mostly last for a period of several solar rotations. One can thus expect that certain manifestations will reoccur after 27 days. For the purpose of studying this phenomenon, the magnetically disturbed days were divided into three groups, defined as follows:

- Low – at least one value $\mathrm{Kp} = 5$ and another two values $\mathrm{Kp} = 4$
- Medium – at least three values $\mathrm{Kp} = 5$
- Strong – at least three values $\mathrm{Kp} = 6$

Figure 7 shows the disturbed days in the period of minimum solar activity, arranged according to Bartels rotations. The disturbed days pass continuously from one Bartels ro-

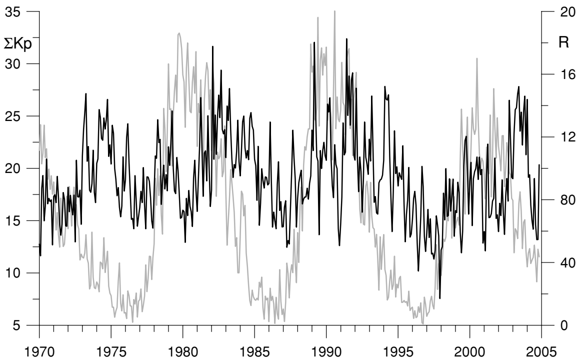

Fig. 5. Monthly averages of the index of geomagnetic activity ΣKp (black) and the number of sunspots (grey).

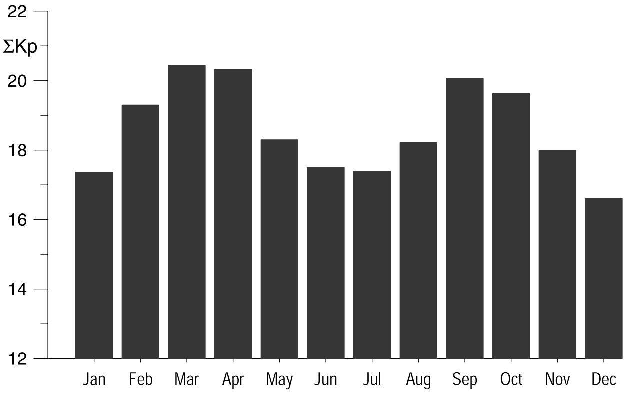

Fig. 6. Monthly averages of the index of geomagnetic activity ΣKp for the last 50 years.

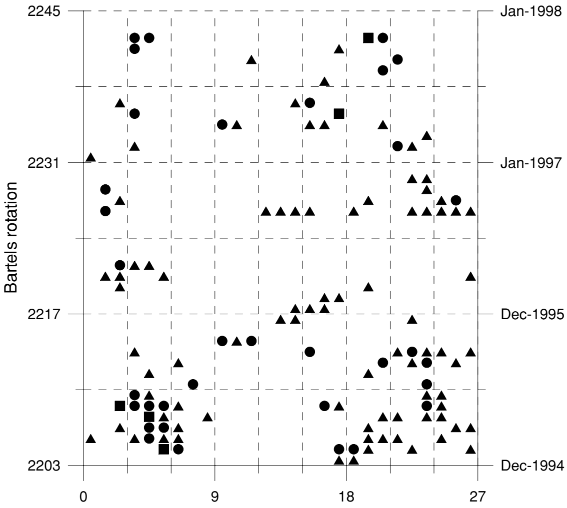

Fig. 7. Magnetically disturbed days in the period around solar minimum in 1995–1997 (triangels–low, circles–medium, squares–strong). The data have been arranged according to Bartels rotations and indicate recurrent behaviour of geomagnetic activity.

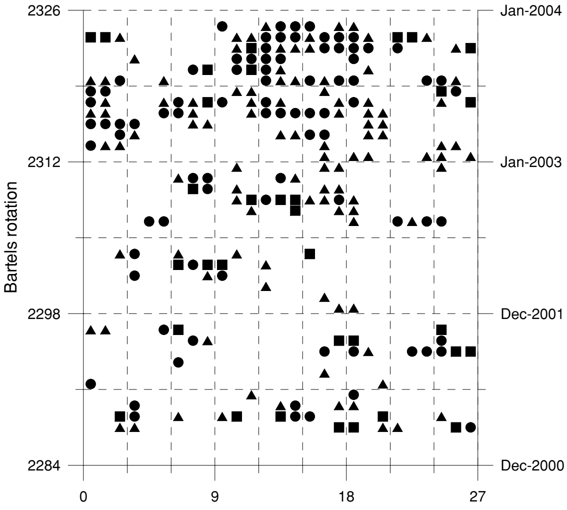

Fig. 8. Magnetically disturbed days in the period around solar maximum in 2001–2003 (triangels–low, circles–medium, squares–strong), arranged according to Bartels rotations.

tation to the next, the gradual shift in time being the consequence of differential solar rotation (the Sun does not rotate as a solid body). Quiet periods are seldom disturbed by increased geomagnetic activity. At the time of solar maximum (see Fig. 8) the diagram displays a more chaotic nature and one must rely on short time forecasts.

The causes of geomagnetic disturbances are either high-velocity streams of solar wind, originating in coronal holes or coronal mass ejections. The coronal holes on the pictures from the Yohkoh satellite, taken in the soft X-ray spectrum, appear as locations of very low intensity (Bochníček and Hejda, 2002). Synoptic maps of coronal holes (see Fig. 9) constructed from the individual pictures of the Yohkoh satellite and supplemented with the curves of the relevant solar wind parameters and K-indices, indicate that the velocity of the solar wind streams interacting with the Earth's magnetosphere and, hence also the intensities of geomagnetic disturbances, depend on the location of the coronal holes on the solar disk, on their shape and area. The region of minimum intensity of soft X-rays, associated with high-velocity streams of solar wind, are usually wedge-shaped, the wedge being open towards the pole and located nearly exclusively on the solar hemisphere facing the Earth (the northern hemisphere in autumn, the southern hemisphere in spring). The central meridian passage of the coronal holes precedes the occurrence of high-velocity streams in the vicinity of the Earth's magnetosphere by about 3.5 days, i.e. the period required for the solar wind with a velocity of about 600 km/s to reach the Earth. The ion concentration as well as the amplitude of the Bz-component of the interplanetary magnetic field (IMF) increase at the head of the high-velocity stream. The proton temperature Tp of the high-velocity streams exceeds $10^5$K. Coronal holes are the main cause of magnetic disturbances in the descending phase of the solar cycle and in the period around the solar minimum. In view of the relatively high stability of these formations, the repetition of the situation from the preceding solar rotation may be expected. This assumption can be further specified from the moment the coronal hole appears at the solar disk limb. It will then take another 8 days for the geomagnetic storm, if any, to occur (5 days to central

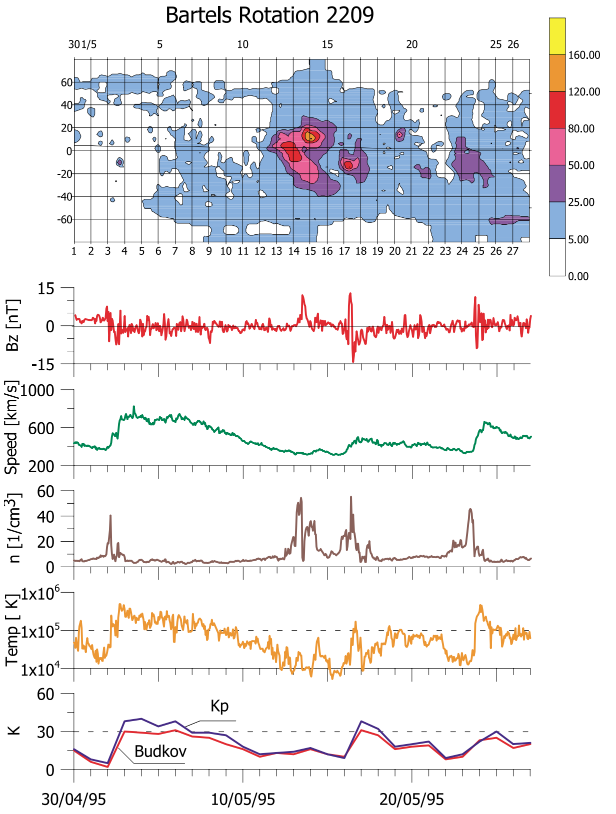

Fig. 9. Events on the Sun in the solar minimum period and geomagnetic activity. The upper part shows a synoptic map of solar soft X-rays intensity (in relative units) of Bartels rotation no. 2209, constructed from the individual pictures of the Yohkoh satellite as a time series of the central meridian profiles. There was approximately one snapshot per day. Coronal holes correspond to the regions with the intensity below 5 relative units and active regions to the spots above 80 relative units. The graphs (from top to bottom) show the N-S component of the interplanetary magnetic field, velocity, particle density and temperature of the solar wind, derived from the data of satellite located in front of the forward boundary of the magnetosphere. The bottom graph shows the geomagnetic activity expressed in terms of the daily sum of K indices. Planetary indices, ΣKp (blue line), are usually slightly higher than the indices of the Central European observatory Budkov (red line). The figure indicates that the cause of the increase of geomagnetic activity are coronal holes (light locations of low soft X-ray intensity), as well as active regions (May 12 to 14). The interval between the central meridian passage of the coronal hole or the active region and the response in the magnetosphere is 3 to 4 days, depending on the solar wind velocity. The edge of the coronal hole on the left side passed central meridian on 29 April.

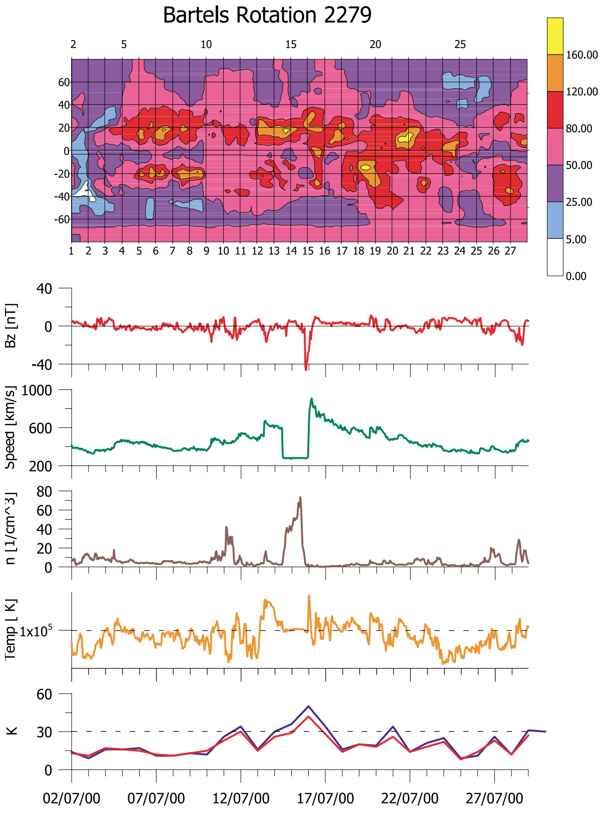

Fig. 10. Events on the Sun in the solar maximum period and geomagnetic activity. For explanation refer to Fig. 9.

meridian passage of the coronal hole and about 3 days for the solar wind to reach the Earth).

In the period around the solar maximum, disturbances are mostly caused by coronal mass ejections, CME. According to the velocity of ejection, CMEs are divided into slow (∼400 km/s) and fast (∼1000 km/s). Slow CMEs are very closely related to eruptive prominences, the visible manifestation of which are disappearing filaments (DSF). The time the slow CME requires to reach the Earth is ∼4 days. Fast CMEs, released as a rule from the edges of active regions, are not associated with any clearly visible phenomenon; nevertheless, hour-long and longer LDEs (Long Duration Events) and radio emission of type II bursts together with type IV bursts were observed to be their precursors. Fast CMEs require ∼2–3 days to reach the vicinity of the Earth. A distinct feature of both types of CMEs is their low proton temperature, which as a rule does not exceed $10^5$K. In comparison with the proton temperature of high-velocity streams it is thus lower (Neugebauer and Goldstein, 1997; Ness, 2001).

The magnetic field frozen in these clouds of ejected solar plasma is closed and accounts higher intensity than the average interplanetary magnetic field (IMF). Since CME field lines are closed, CME's total magnetic vector rotates in the course of its interaction with the Earth's magnetosphere. For half the interaction interval, i.e. over a period of several hours, the CME magnetic field is therefore oriented to the north and half the interaction interval to the south. Several hours of south orientation of the CME magnetic field generates severe magnetic disturbances. An example of such a disturbance, which occurred in the most recent cycle, is the geomagnetic storm of July 15, 2000 (Fig. 10).

The above indicates the difficulties, which are encountered in forecasting geomagnetic disturbances. The active regions on the solar disk are only locations of potential occurrence of CMEs, because it is not evident when, and if solar mass will be ejected at all. The cloud of coronal matter itself, propagating from the centre of the solar disk to the Earth, cannot be observed directly, but its existence may be assumed due to the occurrence of accompanying irregular events. The magnitude of the magnetic disturbance, more-over, depends on the IMF polarity. Forecasts of geomagnetic activity are in this case less successful than in the case of coronal holes, however, even so it is worthwhile to take available information into consideration.

## 4. Conclusions with Regard to Magnetic Surveys in Mid-Latitudes

Removing the effect of magnetic activity from repeat station observations is a complicated problem. Whereas its solution proved to be necessary for high geomagnetic latitudes (Newitt and Walker, 1990) sufficient numbers of quiet days can be found at mid-latitudes. In long-term planning, e.g., in applying for a project, it is necessary to consider the eleven-year solar cycle, as well as the deviations from the cycle of magnetic activity. This applies particularly to once-only or sparsely repeated measurements in a dense network of points. If repeat station surveys are to be carried out in regular one- to three-year intervals, periods with high activity cannot be avoided.

The behaviour of the semi-annual period with a minimum in the summer months is sufficiently well known. In repeat station surveys it is mostly respected also because the measurements are usually reduced to the middle of the year and it is, therefore, convenient to carry them out as close as possible to this date.

The effect of the 27-day period is much clearer in the period of the solar minimum and on the descending branch of the solar cycle. The occurrence of a magnetic disturbance, caused by a coronal hole, may be expected after a month with a probability of about 75%. The evolution of the coronal hole in preceding rotations may also be taken into account.

Short-term forecasts are based on the actual conditions on the Sun, in the solar wind and in the interplanetary magnetic field. Regional Warning Centres, associated in the International Space Environment Service (ISES) deal with forecasts of geomagnetic activity. Contacts to all 12 centres can be obtained through http://www.ises-spaceweather.org/about_ises/index.html.

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