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Influence of the interplanetary magnetic field on the variability of the mid-latitude F_2-layer

Jürgen Bremer (¹), **Jan Laštovička** (²) **and Yurdanur Tulunay** (³)
(¹) *Institute of Atmospheric Physics, Kühlungsborn, Germany*
(²) *Institute of Atmospheric Physics, Prague, Czech Republic*
(³) *Middle East Technical University, Department of Aeronautical Engineering, Ankara, Turkey*

Abstract
The structure of the Interplanetary Magnetic Field (IMF) is responsible for an essential part of the variability of the ionospheric plasma as demonstrated by investigations of the influence of IMF sector boundary crossings as well as of ΔB_z-changes (defined from satellite observations) to the maximal electron density of the F_2-layer at different stations in mid-latitudes. It could be shown that negative B_z-values cause distinct negative ionospheric effects. Maximal effects were detected at high geomagnetic latitudes (ionospheric response decreases with decreasing latitude), high solar/geomagnetic activity, equinoxes and night-time conditions.

Key words *IMF – variability – ionosphere*

1. Introduction

As known from satellite observations and ground-based geomagnetic measurements in high latitudes the Interplanetary Magnetic Field (IMF) in the Earth's orbital plane is subdivided into more or less regular sectors with a magnetic field directed away from (*A*-polarity) or towards the sun (*T*-polarity). Each IMF sector can also be characterized by its vertical magnetic component B_z in the solar-magnetospheric coordinate system. After Dungey (1961) and Russell and McPherron (1973) this B_z-component plays a dominant role in the energy transfer from solar wind into the Earth's magnetosphere. A negative B_z-component should favour this energy transfer whereas positive B_z-values should reduce such an energy input. Therefore, sectors with negative B_z-values are called pro sectors and sectors with positive B_z-values anti sectors. As shown in detail in Bremer (1988) an IMF with *A*-polarity induces positive B_z-values during the spring half-year and negative B_z-values in the autumn half-year, whereas an IMF with *T*-polarity causes inverse signs of B_z, respectively.

The most marked ionospheric effect should be expected during changeover of IMF polarity, the so-called IMF sector boundary crossings. The ionospheric response to such sector boundary crossings is summarized in section 2.1.

Beside the B_z-changes during these more or less regular sector transitions, in satellite data also more irregularly occurring B_z-changes of shorter duration are detected. During such events which often last only some hours marked B_z-changes can be observed. The ionospheric response to such events with $\Delta B_z = B_z(t_1) - B_z(t_2) > 2$nT ($t_1$: time before, t_2: time after B_z changeover) is presented in section 2.2.

Mailing address: Dr. Jürgen Bremer, Institut für Atmosphärenphysik an der Universität Rostock, Schloßstraße 4-6, 18225 Ostseebad Kühlungsborn, Germany; e-mail: bremer@iap-kborn.d400.dc

2. Experimental results

2.1. *Ionospheric response to IMF sector boundary crossings*

In this section it is intended to describe the influence of the IMF sector boundary transitions on the critical frequency of the F_2-layer, f_0F_2. The influence on other ionospheric parameters is described in Bremer (1992).

To derive the mean ionospheric response during sector boundary crossings for each sector transition the following expression was calculated

$$df_0F_2 = \frac{\overline{f_0F_2}(\text{pro}) - \overline{f_0F_2}(\text{anti})}{\overline{f_0F_2}} \cdot 100\%. \quad (2.1)$$

Here $\overline{f_0F_2}$ (pro) and $\overline{f_0F_2}$ (anti) are mean values of f_0F_2 during 4 days before or after the sector boundary crossings at pro or anti sector condition, whereas $\overline{f_0F_2}$ is the mean value of f_0F_2 during 8 days around the sector crossing. Using f_0F_2 noon values of Juliusruh df_0F_2 values after eq. (2.1) were calculated for 643 sector boundary crossings (1957-1982) after dates published by Svalgaard (1976) and Wilcox (1982, private communication). The results are summarized in the histogram shown in fig. 1. The mean deviation of f_0F_2 during pro sector compared with anti sector condition is $df_0F_2 = -2.6\%$.

In spite of the large scatter of the individual events this mean deviation is statistically significantly different from zero at the confidence limit of 99.9% (Taubenheim, 1969). The relatively broad distribution points to the high ionospheric variability which is caused by factors other than IMF polarity changes (*e.g.*, variability of solar radiation, internal atmospheric processes). Therefore, the ionospheric response to IMF sector transitions can only be detected by mean values, in individual cases, however, the IMF effect may be masked by other ionospheric processes.

Using the same data as in fig. 1 the mean ionospheric response to IMF sector boundary crossings was investigated in dependence on season (winter: November-February; summer: May-August; equinox: March, April, September, October), for different levels of solar activity (R_{min}: months with $R_{12} \leq 40$, R_{max}: months with $R_{12} \geq 110$) as well as for high geomagnetic activity (months with $A_p \geq 18$). The results are summarized in table I. In general during equinoctial months the IMF effect is most pronounced for all levels of solar and geomagnetic activity whereas the effect is smallest during winter. With increasing solar activity the effect becomes stronger, and the most marked ionospheric response is observed during months with high geomagnetic activity. The maximal effect was derived for high geomagnetic activity during equinoxes with $\overline{df_0F_2} = -7.2\%$.

The results presented in fig. 1 and table I were derived from f_0F_2 noon data (11-13 LT) only. To get an impression of the diurnal variation of the IMF effect, in fig. 2 mean df_0F_2-values are presented at four different local mean times during the day (*i.e.*, sunrise: at 6 LMT; noon: 12 LMT; sunset: 18 LMT; midnight: 24 LMT). Here again f_0F_2 data of Juliusruh were used for the whole year, but for the period

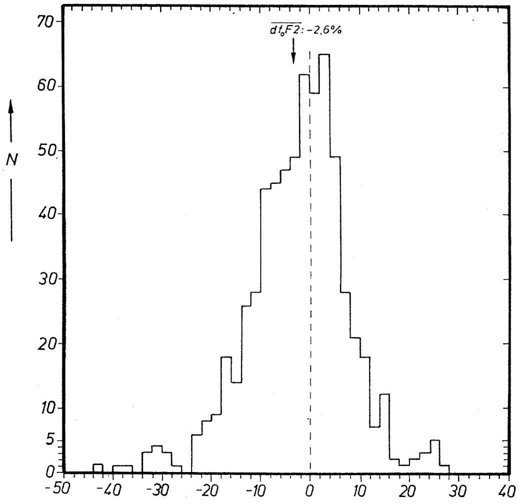

Fig. 1. Histogram of df_0F_2-values derived after eq. (2.1) during IMF sector boundary crossings using f_0F_2 noon values of Juliusruh during 1957-1982.

Table I. Mean f_0F_2 deviation df_0F_2 (%) calculated after eq. (2.1) with f_0F_2 noon data of Juliusruh during IMF sector boundary crossings in dependence on season.

	Year	Winter	Summer	Equinox
1957-1982	−2.6	−1.3	−2.1	−4.5
$R_{12} \leq 40$	−1.7	−1.0	−1.3	−2.8
$R_{12} \geq 110$	−4.8	−3.2	−4.3	−6.8
$A_p \geq 18$	−6.6	−5.6	−5.9	−7.2

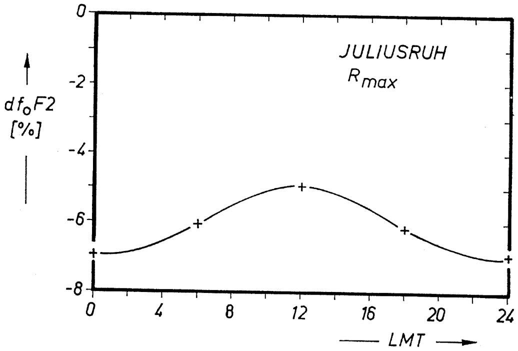

Fig. 2. Diurnal variation of df_0F_2-values derived after eq. (2.1) during IMF sector boundary crossings using f_0F_2 values of Juliusruh at high solar activity (1978-1982).

of high solar activity only (1978-1982). During all times we observed a negative effect, most marked near midnight (−6.9%) and smallest near noon (−4.9%).

All results presented so far are restricted to Juliusruh (54.63°N, 13.38°E). In fig. 3 mean df_0F_2-values are presented in dependence on geomagnetic latitude using f_0F_2-data (noon, whole year) of nine stations of the northern hemisphere for high solar activity (1978-1982, some low latitude stations 1967-1974). In the PRIME region (geogr. lat.: 35°-55°N; geomag. lat.: 30...38°-49°...57°N) the negative effect in df_0F_2 becomes markedly smaller with decreasing latitudes (−5% near 55°, −0.7% near 35°).

In figs. 1 to 3 and table I all IMF sector boundary crossings were used independent of their direction. In table II the results are, however, divided into IMF transitions from anti → pro sectors and from pro → anti sectors. In all cases independent of solar and geomagnetic activity the anti → pro sector transitions cause stronger ionosphere effects.

2.2. *Ionospheric response to negative B_z events*

As described in detail in Tulunay (1994) from satellite measurements of the solar wind and the IMF during the period from 1963 until 1986 special events were selected with southward turning of the IMF. Here clearly defined events were chosen with B_z-changes $\Delta B_z > 2$ nT and the same B_z polarity both 4 h before and 4 h after the turning. For the investigations of the ionospheric response during such negative B_z events differences δf_0F_2 of the observed critical frequencies of the F_2-layer from undisturbed «quiet-time» values are estimated. The «quiet-time» values are derived for each hour from 15 days around the B_z-event using only data of those days with A_p less than 6.

The general ionospheric response is presented for some stations in Tulunay (1994): starting from a relatively constant δf_0F_2 level before the effect (near zero or slightly negative) δf_0F_2 decreases often some hours before the B_z-effect, reaches a marked minimum at the first day after the IMF southward turning and recovers during the following days. The maximum ionospheric effect (difference between minimum value and nearly constant level before the effect) is presented in dependence on

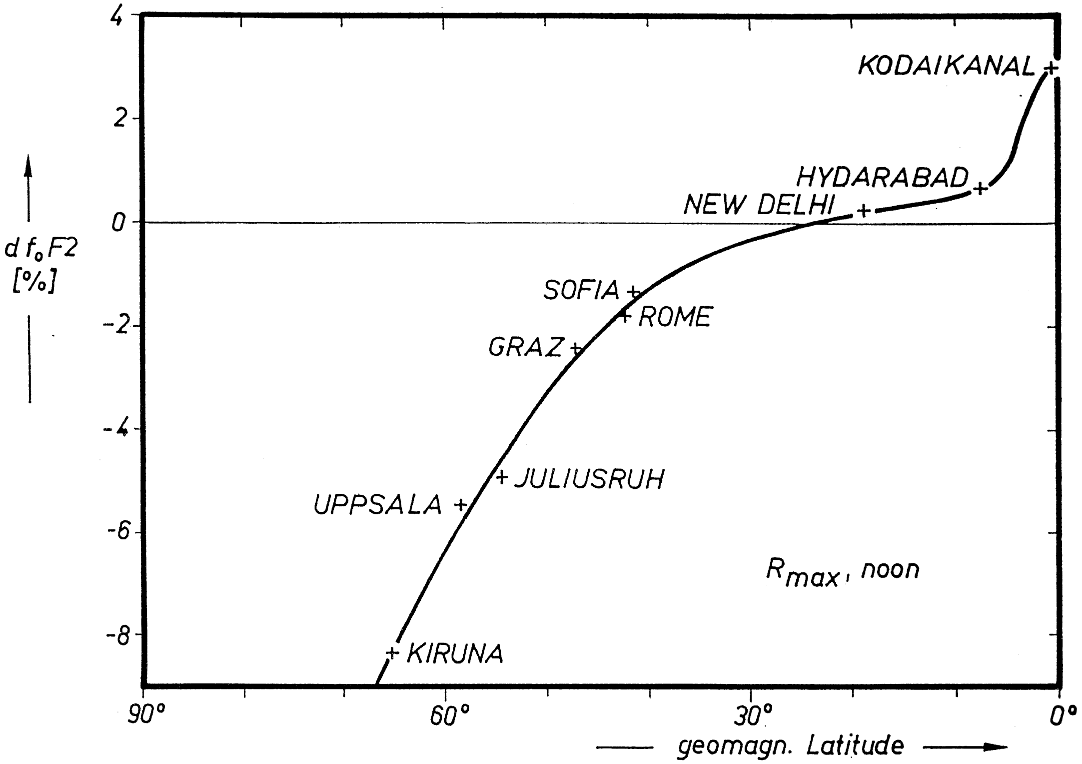

Fig. 3. Mean variation of df_0F_2-values derived after eq. (2.1) during IMF sector boundary crossings in dependence on geomagnetic latitude at high solar activity (1978-1982 or 1967-1974).

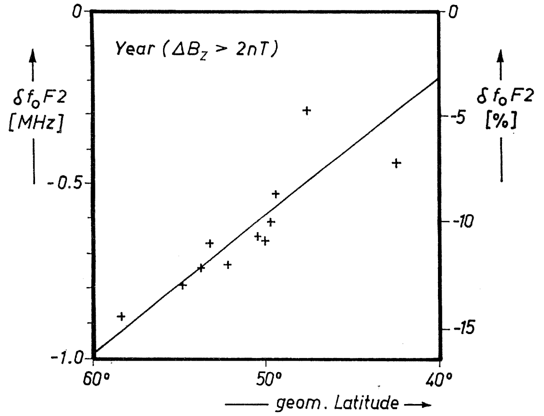

Fig. 4. Mean ionospheric response of δf_0F_2 due to IMF events with $\Delta B_z > 2$ nT in dependence on geomagnetic latitude (data from 1963-1986).

geomagnetic latitude in fig. 4 using data of the whole year for 11 stations in mid-latitudes. The ionospheric effect is presented in MHz (left axis) and in per cent (right axis) using as reference value the mean value $f_0F_2 = 6.1$ MHz of all f_0F_2 data analyzed. As in fig. 3 the ionospheric effect presented in fig. 4 is negative in the whole latitudinal belt and becomes smaller with decreasing latitude (−15% ... −3%). The same analysis was made for the summer as well as winter half-year separately. The results are shown in fig. 5. Also here during both seasons negative effects are observed decreasing in amplitude with decreasing geomagnetic latitude. The effects during the summer half-year (−18 ... −8%) are, however, markedly stronger than during the winter half-year (−11% ... −5%).

3. Discussion

In all figures and tables shown above it was demonstrated that f_0F_2 in mid-latitudes is typically reduced during IMF with negative B_z-values. This effect is, however, often only detectable by statistical methods as the ionospheric variability is not only caused by IMF changes. Nevertheless, an essential part of the ionospheric variability is due to IMF polarity changes.

After figs. 3 to 5 the ionospheric effect caused by the negative vertical component of the IMF decreases with decreasing geomagnetic latitudes, vanishes near 25° geomagnetic latitude and becomes positive near the geomagnetic equator. This latitudinal variation corresponds well with the variation of ionospheric storms (Matsushita, 1959). Therefore, it seems to be quite reasonable to consider the ionospheric effects caused by negative B_z-components like small ionospheric storms (for theory of ionospheric storms see: Rishbeth, 1975; Hargreaves, 1992; Prölss, 1993).

The energy input ε from the solar wind into the magnetosphere can be approximated by an empirical formula derived from Perreault and Akasofu (1978)

$$\varepsilon = vB^2 l_0^2 \sin^4 \vartheta/4 \qquad (3.1)$$

with the velocity of the solar wind v, the magnitude of the IMF B, the constant $l_0 = 7$ Earth's radii and the polar angle ϑ in the y-z-plane of the solar-magnetospheric coordinate system. Due to the term $\sin^4 \vartheta/4$ the energy transfer ε is maximal for $\vartheta = 180°$, *i.e.* during times with negative B_z-values.

The seasonal differences in table I seem to be reasonable. As shown in Bremer (1988), the B_z-values in the IMF pro $(-B_z)$ and anti sectors $(+B_z)$ are maximal near equinoxes. Therefore, during this time the strongest ionospheric events during IMF sector boundary crossings should be expected. The differences in the ionospheric effects between summer and winter (table I, but also fig. 5) can be explained by

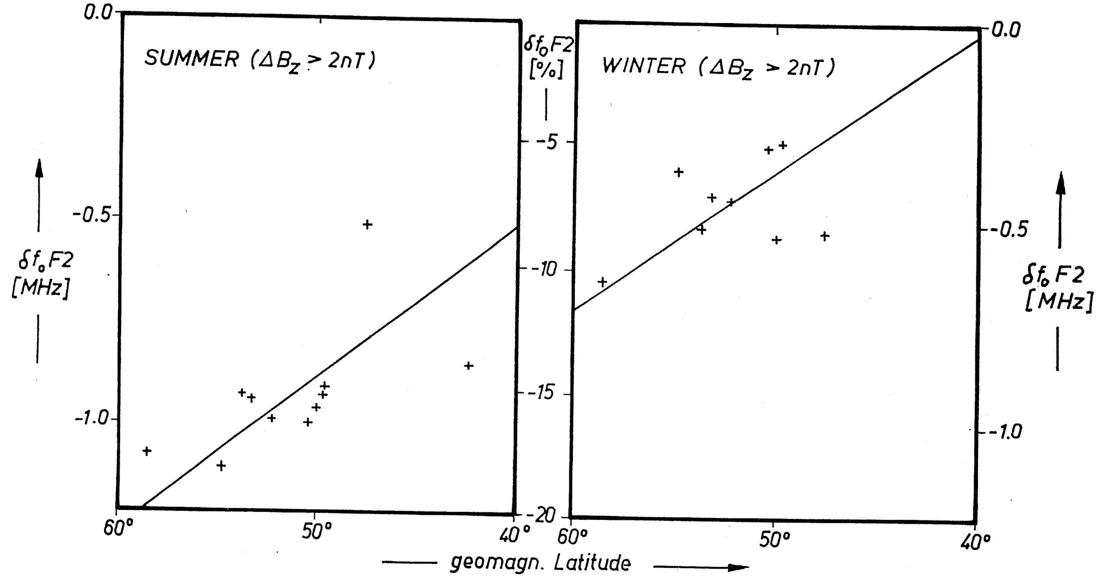

Fig. 5. Mean ionospheric response of δf_0F_2 as in fig. 4, but data are subdivided for summer and winter half-year.

Table II. Mean f_0F_2 deviation df_0F_2 (%) as in table I but subdivided for anti → pro as well as pro → anti sector transitions.

	1957-1982	$R_{12} \geq 110$	$R_{12} \leq 40$	$A_p \geq 18$
anti → pro	−3.2	−5.9	−2.2	−7.7
pro → anti	−2.1	−3.6	−1.2	−5.4

the well-known fact that during winter time ionospheric storms are sometimes positive at mid-latitudes whereas during other seasons negative storms clearly dominate (Hargreaves, 1992).

Whereas the ionospheric response to IMF sector transitions at low solar activity is relatively small, the effect becomes stronger during high solar activity and especially during periods of high geomagnetic activity (table II). This phenomenon may be caused by an increasing energy input ε from the solar wind into the Earth's magnetosphere and ionosphere during these periods due to increasing solar wind speed as well as increasing magnetitude of the IMF. The maximal effects were observed at high geomagnetic activity during equinoctial months (−7.2%).

The influence of the IMF sector structure seems to be more effective during night-time as demonstrated by the diurnal variation in per cent (fig. 2) with maximal ionospheric effects near midnight (−6.9%) and a smaller response during noon (−4.9%).

Significant differences were also observed between ionospheric effects caused by sector boundary transitions from pro → anti sectors (−3.2% in all data from 1957-1982) and anti → pro sector transitions (only −2.1%). This may be connected with the fact that the ionospheric plasma changes for anti → pro sector transitions are steeper than the changes for pro → anti sector transitions (Bremer, 1988, 1992).

In general, the ionospheric effects caused by IMF sector transitions (figs. 1 to 3, table 1 and 2) are not so strong as those caused by the ΔB_z-events (figs. 4 and 5). The reason for this difference is the markedly higher energy input from solar wind into the Earth's ionosphere after eq. (3.1) during the ΔB_z-events due to essentially higher $-B_z$-values.

4. Conclusions

Regular B_z-changes during IMF sector transitions as well as sudden and more irregularly occurring B_z-variations as observed by satellites cause typical changes in the ionospheric F_2-layer plasma. These effects are one important source of the variability of the f_0F_2-region plasma. The effect is more dominant at the upper latitudinal border of the PRIME area and becomes smaller at lower latitudes.

A prediction of such effects is difficult. One simple possibility to predict the IMF sector structure with the dates of sector boundary crossings could be the use of the mean solar magnetic field as observed by the Stanford Observatory (Bremer, 1996). The prediction of short-term ΔB_z-variations which are often the origin of ionospheric storms seems, however, to be impossible at present.

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