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On the derivation of an hourly local index to define the normal ionosphere

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Abstract
In this paper an hourly local ionospheric index f_nF_2 is proposed to define the normal level of the undisturbed ionosphere. For the determination of this index a model is developed where the normal values of the f_0F_2 parameter were reproduced using multiple regression analysis. For each month of the year, for a given station, a set of 48 or 72 coefficients are calculated, depending on the monthly sunspot activity. Then, the normal values of the f_0F_2 parameter are computed as a function of the daily sunspot number. The analysis of the model results revealed the following characteristics for the f_nF_2 index: first, the temporal variations that characterize the normal ionosphere, imposing some artificial effects on the monthly median values, are eliminated from the newly derived f_nF_2 index. Second, the f_nF_2 index does not follow the false steplike variations observed in the monthly median f_0F_2 time series, in transition periods from one month to another. Third, during intervals of low magnetospheric activity, the f_nF_2 index presents a very good degree of fit with the observed f_0F_2 parameter, compared to the monthly median f_0F_2 behaviour. During disturbed conditions, the f_nF_2 index remains at the normal level, whereas median values are affected by ionospheric disturbances. In general, the data analysis showed that the f_nF_2 index varies only with the daily sunspot number Rz and is independent of the magnetospheric activity, approaching the level of the normal ionosphere with a high degree of confidence.

Key words *reference ionosphere – ionospheric disturbances – ionospheric indices*

1. Introduction

The magnetosphere - ionosphere system is strongly governed by the activity of the Sun. The solar energy is transferred to the Earth's upper atmosphere in two very different ways. First, solar radiation in UV range is directly absorbed in the sunlit upper atmosphere. There it is responsible for the formation of the undisturbed ionosphere. Secondly, solar wind energy is captured by the magnetosphere, transformed and dissipated in the polar upper atmosphere. It is the latter source which is responsible for the ionospheric disturbance effects known as ionospheric storms (Prolss, 1995).

The real ionosphere is characterized by a number of pecularities. They arise both from the irregularities of the ionizing solar radiation and large scale ionospheric dynamics. Disturbances in the solar wind and the geomagnetic field lead to a complex morphology of temperature, winds, electric fields and composition changes (Prolss, 1995; Dominici, 1998; Rishbeth, 1998). *F*-region storms are the most important disturbances, concerning perturbation of the ionization density at *F*-region heights. Severe changes that are caused at subauroral latitudes are essentially of a transient nature (Prolss, 1995). The forecasting of ionospheric disturbances such as *F*-region storms are also of practical interest since they may severely affect transionospheric radio communications.

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A major problem is the quantitative definition of the dramatic effects in the ionospheric F region produced by storms. A basic problem is the forecast of daily variations in order to characterize ionospheric disturbances in a quantitative way. The diurnal control curve from which excursions are reckoned may be defined as: 1) the monthly mean pattern; 2) the monthly median pattern; 3) the mean of the 5 or 10 geomagnetically quiet days of the month, or 4) a single quiet day prior to the storm (Cander, 1993). There are various arguments for and against each of these candidates. The first two methods lead to a definition of the normal ionosphere whose level is strongly influenced by the geomagnetic activity. The two last methods have also some limitations. The geomagnetically quietest days of the month do not necessarily ensure that these are ionospheric quiet days, in the absolute measure of quietness. It is obvious that in the case of a very disturbed month, it is impossible to apply the two last methods to define the normal ionosphere. Besides all the above arguments, the normal behaviour of the ionosphere is usually approached by the monthly median value of the f_0F_2 parameter (Cander and Mihajlovic, 1998). Reference to median values for a relatively long period of time (a month) is very useful to cancel most of the great ionospheric variability with small and medium periods (from some hours to a few days), which constitutes a great drawback in studying ionospheric morphology on a large space-time scale (Dominici, 1998).

Nevertheless monthly median values carry many artificial effects (Kozin *et al.*, 1995; Belehaki *et al.*, 1999), so that in many cases they are not representative of the normal state of the ionosphere:

1) From their definition, during geomagnetically active months, the median values are strongly influenced by the ionospheric variations, resulting in artificial deviations of the observed values from the monthly median ones.

2) False variations are observed in transition periods from one month to another, especially when the level of geomagnetic activity varies from month to month.

3) The index Δf_m (which is the absolute deviation of the measured critical frequency from the monthly median, $\Delta f_m = f_0F_2\text{-}MED$) does not eliminate temporal variations of the quiet ionosphere, that are caused by ionization effectiveness and variations of the sunlit part of the day. According to Kozin *et al.* (1995) from the lower solstice (December 21st) until the upper solstice (June 21st) Δf_m values in the first part of each month would be negative and in the second part would be positive. For the period from the upper solstice until the lower solstice the picture of artificial undisturbed variations of Δf_m would be opposite. Ionospheric disturbances thus are superposed on the above mentioned not eliminated temporal variations of the quiet day.

In the past, some efforts have been made to define a more appropriate index to express the normal level of the F_2 layer. In the frame of the PRIME project (Zolesi and Cander, 1998), provisional criteria of ionospheric quietness have been formulated (Cooper *et al.*, 1993). Since then a regional PRIME catalogue of ionospheric disturbed and quiet days from 1964 to 1992 (Gulyaeva and Stanislawska, 1994) and the local Athens Catalogue (Moraitis, 1994) have appeared, based on the analysis of ground-based vertical incidence sounding data (f_0F_2 and $M(3000)F_2$, an equivalent of h_mF_2). Gulyaeva *et al.* (1995) proposed the use of a metamedian to identify quietness, negative and positive disturbances in topside sounding data over Europe. Also, according to Bremer and Lastovicka (1993) the use of either monthly medians or 27-days running means was proposed as a quiet reference. On the contrary, Kozin *et al.* (1995) suggested that for periods of study lasting more than one day, as a correct index the initial information with filtered out high-frequency components may be used.

Obviously the index used to define the normal level of the undisturbed F_2 layer should follow the F_2-layer anomalies and the seasonal variation as well. The term «anomaly» originally meant any departure from solar-controlled behaviour, in which critical frequency f_0F_2 varies regularly with the solar zenith angle χ, as it does in the well known Chapman layer (Rishbeth, 1998). The midlatitude F_2-layer anomalies may be considered as follows: the maximum electron density of the F_2 layer occurs in the daytime of winter months instead of summer months. Also in this layer the daily maxima of ionization often occur just before and after the local noon in wintertime and near the local sunset in summertime. Finally, in summertime large ionization exists at nighttime, which is not much lower than that in the daytime. These anomalies constitute a component of the normal behaviour of the F_2 layer. The seasonal variation should be another important component of the normal level of the F_2-layer.

In this paper we propose a local index for the determination of the normal level of the ionosphere, which varies with the solar activity, while it is independent of the magnetospheric activity. Moreover we will show that the proposed index is clear of the artificial effects that make the use of monthly median values not the most adequate especially for the analysis of the long-period ionospheric disturbances.

2. Model description

Soon after the introduction of regular ionospheric measurements, it was found that the critical frequency of the F_2 layer is closely correlated with the relative sunspot number Rz. Several ionospheric indices have been derived using a linear relationship to fit the curve produced from the plot of maximum frequency *versus* sunspot number, although there is sometimes evidence of saturation at higher sunspot numbers. A number of studies have been published on the derivation of ionospheric propagation indices (Minnis and Bazzard, 1960; Joachim, 1966; Turner, 1968; Liu *et al.*, 1983; Smith, 1986; Klobuchar, 1987; Feess and Stephens, 1987; Brandley, 1993; Mikhailov and Mikhailov, 1995; Wilkinson, 1995; Secan and Wilkinson, 1997) aiming at the prediction of the critical frequency for the ionospheric propagation based on the predicted sunspot number.

The dependence of the critical frequency f_0F_2 observed at Rome ionospheric station at 1800LT, on the daily sunspot number Rz during the 21st solar cycle (1976-1986) is presented in fig. 1. It is obvious that for $Rz < 80$ the response of the f_0F_2 values to the solar variability can be considered linear, while for a higher level of solar activity ($Rz > 80$) a parabolic curve gives obviously the best fit. A similar result was obtained by examining the relation between the f_0F_2 parameter and the sunspot number Rz, at other local times as well. The fitted curve represents the normal ionosphere while any deviation from it is due to the ionospheric disturbances.

Taking into account the given relationship between the f_0F_2 parameter and the sunspot number, the normal f_0F_2 values were reproduced, based on the assumption that when magnetospheric activity ceased, the fitted curve, which is a polynomial calculated using the least squares method, represents very closely the normal state of the F_2-layer. Following this general trend, the hourly values of the «normal» f_0F_2 parameter, hereafter the f_0F_2 index, were reproduced on a monthly basis, to predict also the three noticeable anomalies of this layer, presented in the Introduction, that constitute components of the «normal» behaviour of the F_2 layer. The degree of the fitted polynomial was determined as a function of the monthly mean sunspot number Rz_m. More precisely, when $Rz_m \leq 80$, the fitted polynomial is of first degree, so that the hourly index f_nF_2 is given by the equation

$$f_nF_{2_{i,j}} = \alpha_j + \beta_j \cdot Rz_i \tag{2.1}$$

where i denotes the number of the day and j denotes the number of the hour. For months of higher solar activity, when the monthly mean sunspot number is higher than 80 ($Rz_m > 80$), the fitted polynomial is of second degree and the hourly index f_nF_2 is given by the equation

$$f_nF_{2_{i,j}} = \alpha_j + \beta_j \cdot Rz_i + \gamma_j \cdot Rz_i^2. \tag{2.2}$$

Applying the multiple regression method, a set of 48 (α_j, β_j) or 72 (α_j, β_j, γ_j) coefficients – depending on the level of solar activity – is derived to reproduce the normal level of the F_2 layer, which is finally given by the hourly f_nF_2 index, for each month of the year for a given station. A summary presentation of the model is given in table I.

For the construction of the new index f_nF_2, only the hourly f_0F_2 values of the month that correspond to geomagnetically quiet intervals were used. Quiet intervals were classified ac-

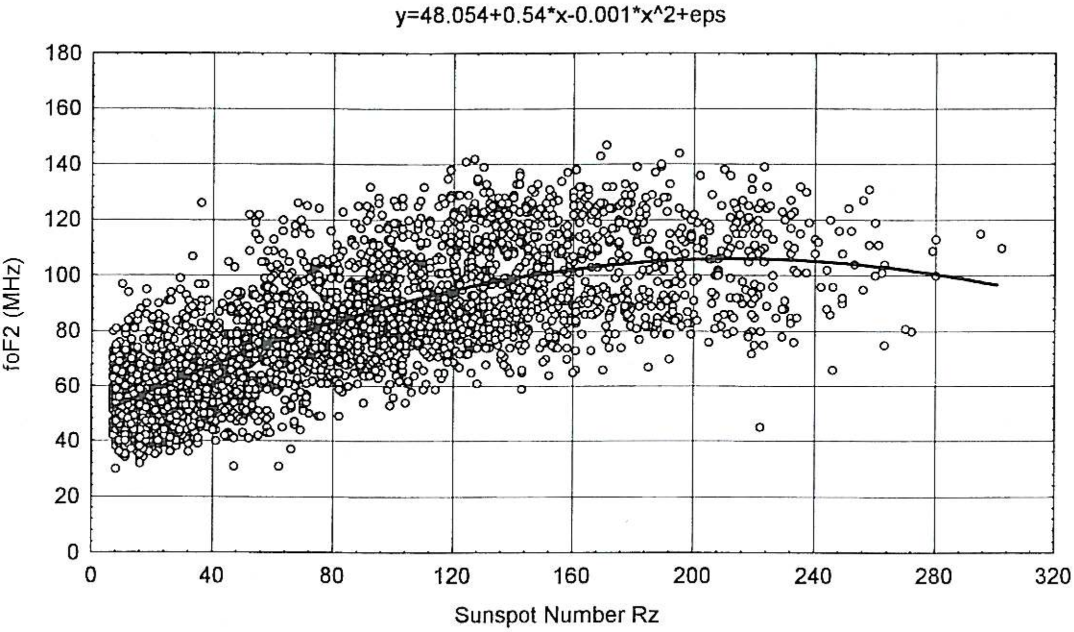

Fig. 1. The critical frequency f_0F_2 at 1800LT from Rome ionosonde station is plotted *versus* the daily sunspot number *Rz* during the 21st solar cycle (1976-1986). The overplotted curve corresponds to a second degree polynomial fit. It is obvious that for $Rz < 80$ the response of the f_0F_2 values to the solar variability can be considered linear, while for higher levels of solar activity ($Rz > 80$) a parabolic curve gives the best fit.

Table I. A summary presentation of the model for the calculation of the f_nF_2 index.

Months with $Rz_m < 80$	Months with $Rz_m \geq 80$
Method: linear least squares fit	Method: second degree least squares fit
Calculation of two hourly coefficients a_j and β_j for each day of the month	Calculation of three hourly coefficients a_j, β_j and γ_j, for each day of the month
Calculation of the quiet f_0F_2 parameter: $f_nF_{2i,j} = a_j+\beta_j\cdot Rz_i$, *j*: hour of the day, *i*: day of the month	Calculation of the quiet f_0F_2 parameter: $f_nF_{2i,j} = a_j+\beta_j\cdot Rz_i+\gamma_j\cdot Rz_i^2$, *j*: hour of the day, *i*: day of the month

cording to the 3-hourly *aa*-index. According to Mayaud (1980) this planetary index is probably the best for investigating the modulations of the geomagnetic activity, which have their source in the solar activity itself. Throughout the following analysis, a 3-h interval is considered to be geomagnetically quiet when the *aa*-index is less than 20 ($aa < 20$).

The use of more popular magnetospheric indices, such as *AE* and D_{st}, with one hour resolution was avoided for the following reasons: the *AE* index represents the auroral electrojets and consequently the amount of energy input causing the composition changes, while D_{st} index follows a long normal shape in a fashion that is typical of phenomena that result from a number of contributing sources acting either serially or concurrently (Cambell, 1996). As a consequence, the ionospheric disturbances during the expansion phase are better correlated to the *AE* index, while during the recovery phase they are better correlated to the D_{st} index. As a general behaviour, statistical results showed that *AE* variations precede ionospheric disturbances, which are followed by the D_{st} variations (Tsagouri *et al.*, 1999).

3. Comparison between the f_nF_2 index and the monthly median f_0F_2 values

An example of the model application to reproduce the f_nF_2 index over a monthly data set are presented in fig. 2. The monthly median values of the cut-off f_0F_2 frequency as well as the local hourly index f_nF_2 computed for Rome station are presented during May 1981 in the first and second panel respectively. The observed f_0F_2 hourly values are overplotted for comparison. In the last two panels, the 3-hourly planetary index *aa* and the hourly D_{st} index are presented to give an overall view of the magneto-

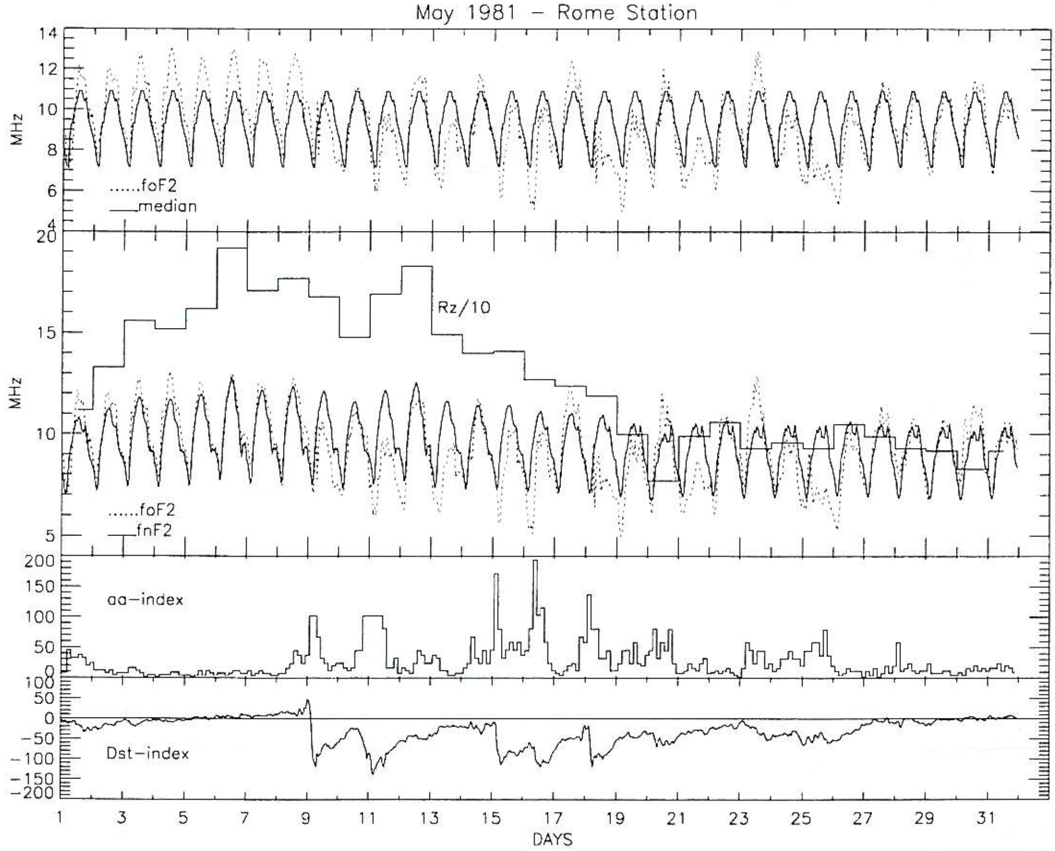

Fig. 2. The hourly values of the cut-off frequency f_0F_2 (dotted line) from Rome station are presented during May 1981. The monthly median values and the hourly f_nF_2 index (solid line) are overplotted for comparison with the observed f_0F_2 values in the first and second panels respectively. In the last two panels, the 3-hourly planetary index *aa* and the hourly D_{st} index are presented to give an overall view of the ionospheric-magnetospheric activity.

spheric activity. This specific month was chosen to present as a case study for two reasons: first, a sudden intensification of magnetospheric activity was observed on the 9th of May, following a prolonged interval of very quiet conditions, as can be seen from *aa* and D_{st} variations. Secondly, the sunspot number *Rz* exhibited a significant variation throughout this month, allowing for the testing of the f_nF_2 dependence on the solar activity and its relation to the magnetospheric activity as well.

As can be seen in fig. 2, the monthly median values are strongly affected by the ionospheric disturbances that are the dominant feature of this month. Indeed, from 9th until 26th May, at least 8 negative storms were observed in Rome station, resulting to the depression of the monthly median f_0F_2 values in comparison to the corresponding values of the «normal ionosphere». This depression of the median f_0F_2 values results in a noticeable difference from the observed f_0F_2 values, seen during the first 8 days of the month. It is obvious that the use of the median values to define the normal level of the undisturbed ionosphere during this period will lead to artificial results given that no disturbances are observed in the overall ionospheric-magnetospheric system. On the other hand, the f_nF_2 index presented in the second panel of fig. 2, represents quite successfully the normal level of f_0F_2 variations the first 8 days of the month since its deviation from the observed values is negligible, especially during days 5th through 8th May, when the magnetosphere was in ground state.

A noticeable observation is that during the 12th day of this month the ionospheric response with respect to the monthly median and the f_nF_2 index had opposite characteristics. A detailed presentation of the ionospheric disturbances recorded in Rome station from May 10th to May 13th is given in fig. 3. The two hourly magnetospheric indices *AE* and D_{st} are presented in the bottom of this figure. Considering the monthly median pattern as the reference level of the normal ionosphere a positive storm effect was recorded, while if one considers the f_nF_2 index representative of the normal ionosphere, a negative storm effect is observed until 1700UT. Soon after that, the onset of a positive storm effect can be detected. According to *AE* and D_{st} indices the first half of 12th May is characterized by the recovery of a storm event which occurred in the previous days while at 1400UT a substorm onset was recorded in *AE*-index. Rome station at the recovery of the storm event was passing through the early morning (0000-0600LT) and prenoon (0600-1200LT) sectors while during the substorm event it was passing through the post-noon (1200-1800 LT) sector.

A possible scenario for the time sequence of thermospheric-ionospheric storm effects was proposed by Prolss (1995) and can be summarized as follows: heating by Joule dissipation and particle precipitation maximizes along an annular region at polar latitudes inducing composition changes, which are restricted to the higher latitude except for the midnight/early morning sector. Here winds designated as midnight surge transport composition changes toward subauroral latitudes. A burst of substorm activity launches a Traveling Atmospheric Disturbance (TAD) moving in the form of global and circumpolar front toward lower latitudes reaching middle latitudes about 1-2 h later and at the same time expansion of the polar heating zone toward middle latitudes at the midnight/early morning sector (see fig. 8.3.12 from Prolss, 1995), especially if the geomagnetic activity remains at high levels (geomagnetic storm). At the recovery phase of the storm the composition disturbance zone generated in the early morning sector has simply rotated into the prenoon sector and is now located there.

According to the above scenario a middle latitude ionosonde station located in the early morning/prenoon sector during the expansion/recovery phase of a storm it will be affected by the composition changes and therefore it will record negative storm effects. On the other hand, a station located somewhere between 0800-1800 LT or 2200-0400 LT about 2 h after the sudden energy release could be affected by TAD recording a positive storm effect. This picture obtained from the Prolss (1995) model, agrees with the disturbances recorded in Rome station, considering f_nF_2 index an indicator of the normal level of the undisturbed ionosphere. The negative storm recorded until 1700UT is due to the recovery phase of the storm which occurred the previous day, while the positive peak distur-

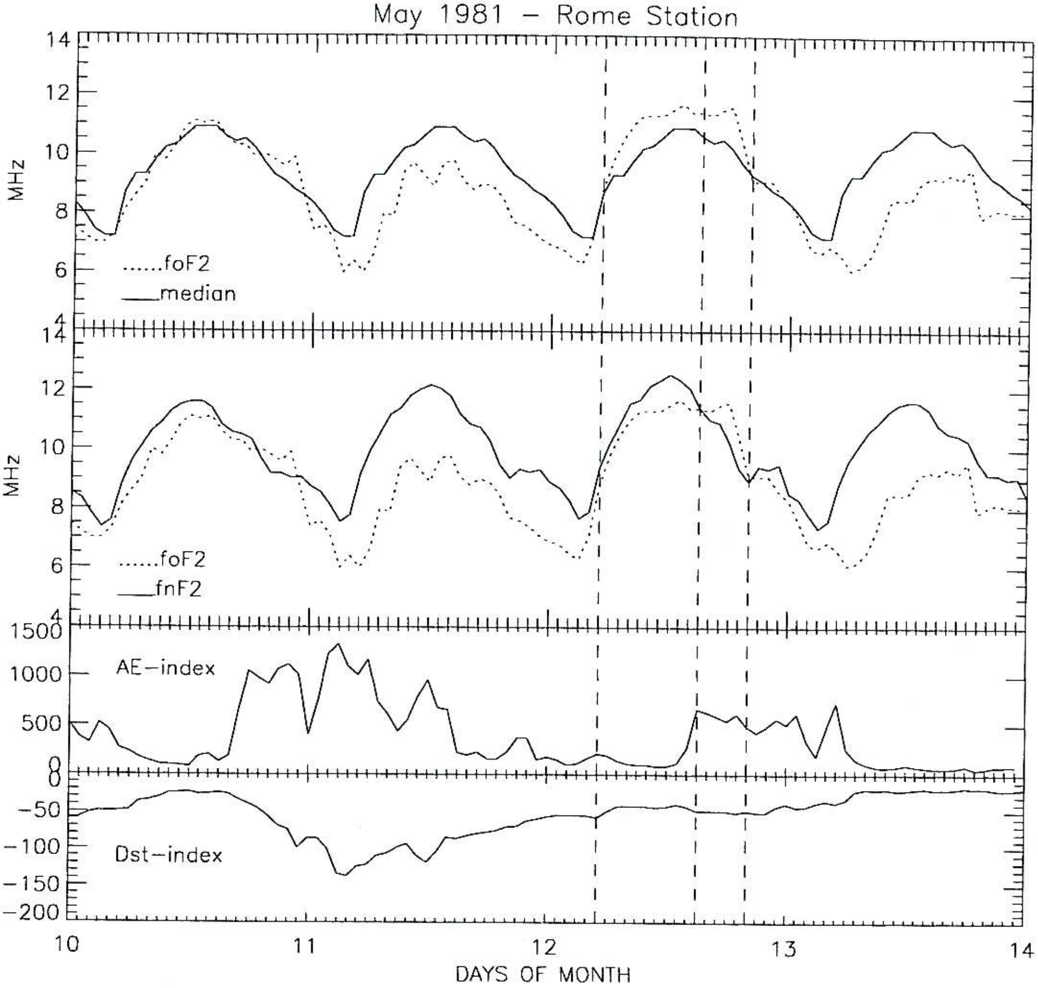

Fig. 3. A detailed representation of the f_0F_2 variations (dotted line) with respect to the monthly median values (first panel) and to the f_nF_2 index (second panel) from 10th to 13th May 1981. The hourly AE and D_{st} indices are presented at the bottom of this figure.

bance of the f_0F_2 with respect to the f_nF_2 index is due to TAD.

Moreover, one could note that positive storms are unlikely to be observed during the month of May. According to Prolss (1995), positive ionospheric storms are mainly observed in winter. This may largely be explained by the limited extent of the composition disturbance zone in this season.

Finally an interesting observation arising from fig. 2 concerns the dependence of the f_nF_2 index on the solar activity and its relation to the magnetospheric activity. The daily variation of the f_nF_2 index during days of extremely different levels of magnetospheric activity and almost equal sunspot number was compared. The days under comparison were 7th and 9th May, with $Rz \cong 165$ and 6th and 12th May with $Rz \cong 185$.

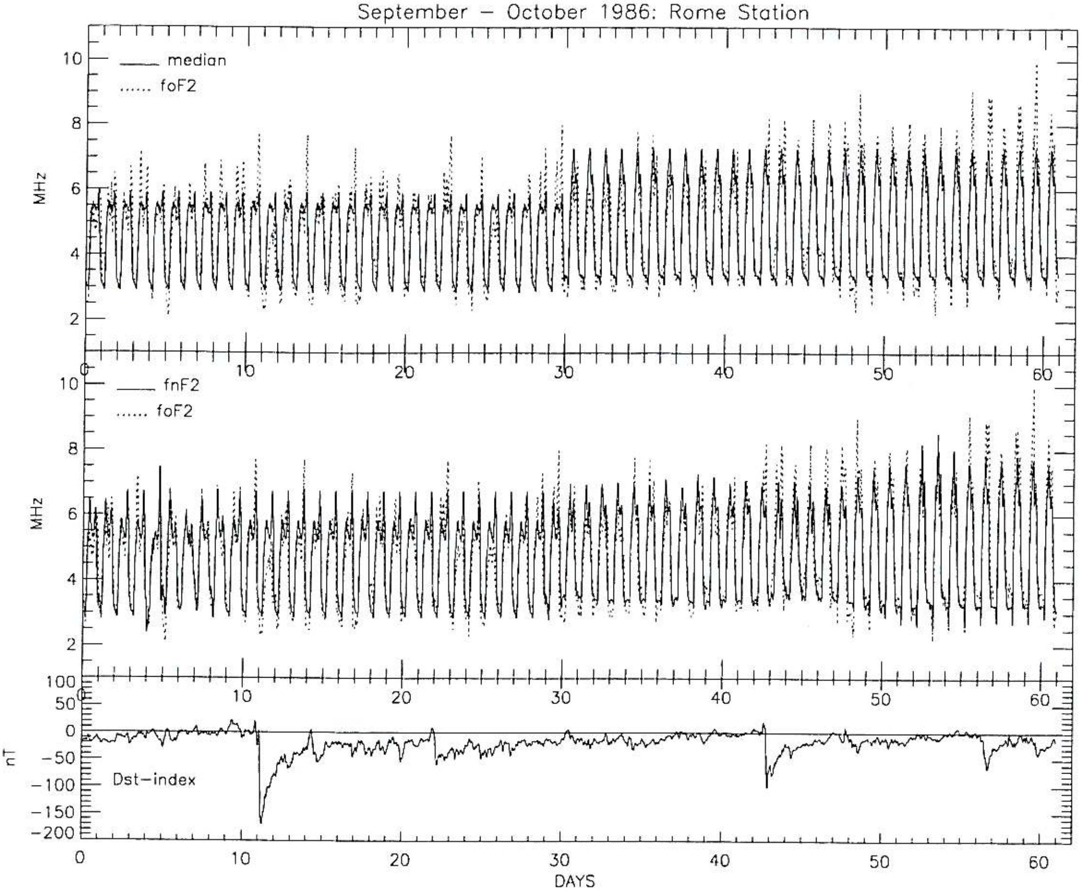

Fig. 4. The monthly median values of the f_0F_2 parameter and the computed hourly f_nF_2 index from Rome station are presented during two successive months, September and October 1986. Together with dotted lines, the hourly values of the f_0F_2 parameter are presented for comparison. Finally, in the last panel, the hourly values of the D_{st} index are given as an indication of the level of magnetospheric activity.

From a careful examination of fig. 2 it results that the f_nF_2 index is independent of the magnetospheric activity and varies only with the sunspot number, according to eqs. (2.1) and (2.2) of the model presented in Section 2.

To study the behaviour of the f_nF_2 index in transition periods, from one month to another, the hourly f_0F_2 variations are presented in fig. 4 together with the f_nF_2 index and the monthly median f_0F_2 for comparison, during two successive months. In the last panel of fig. 4, the hourly values of the D_{st} index are presented, to have an overview of the ionospheric-magnetospheric activity. As can be seen, the first month – September 1986 – is much more disturbed in comparison to the geomagnetic activity recorded during October 1986. The strong magnetic storm having its onset on September 11th, has as a consequence major ionospheric disturbances at middle latitudes, with main manifestations the three negative storms recorded in Rome station on 12th, 24th and 26th September, with the final result of a depression of the monthly median values. An artificial step-like change in monthly median values is observed in the transition period from September to October 1986. It is suggested that this difference of ~ 1.2 MHz is due to the different level of geomagnetic activity and a minor contribution due to the seasonal effect of the peak f_0F_2 value might also exist. On the contrary, a smooth variation is observed in the f_nF_2 time series, attributed to the seasonal effect. This can be explain by recalling the definition of the f_nF_2 index, as the value that represents with a high degree of confidence the normal level of the undisturbed ionospheric F_2 layer, which varies only with the daily sunspot number and it is independent of the magnetospheric activity.

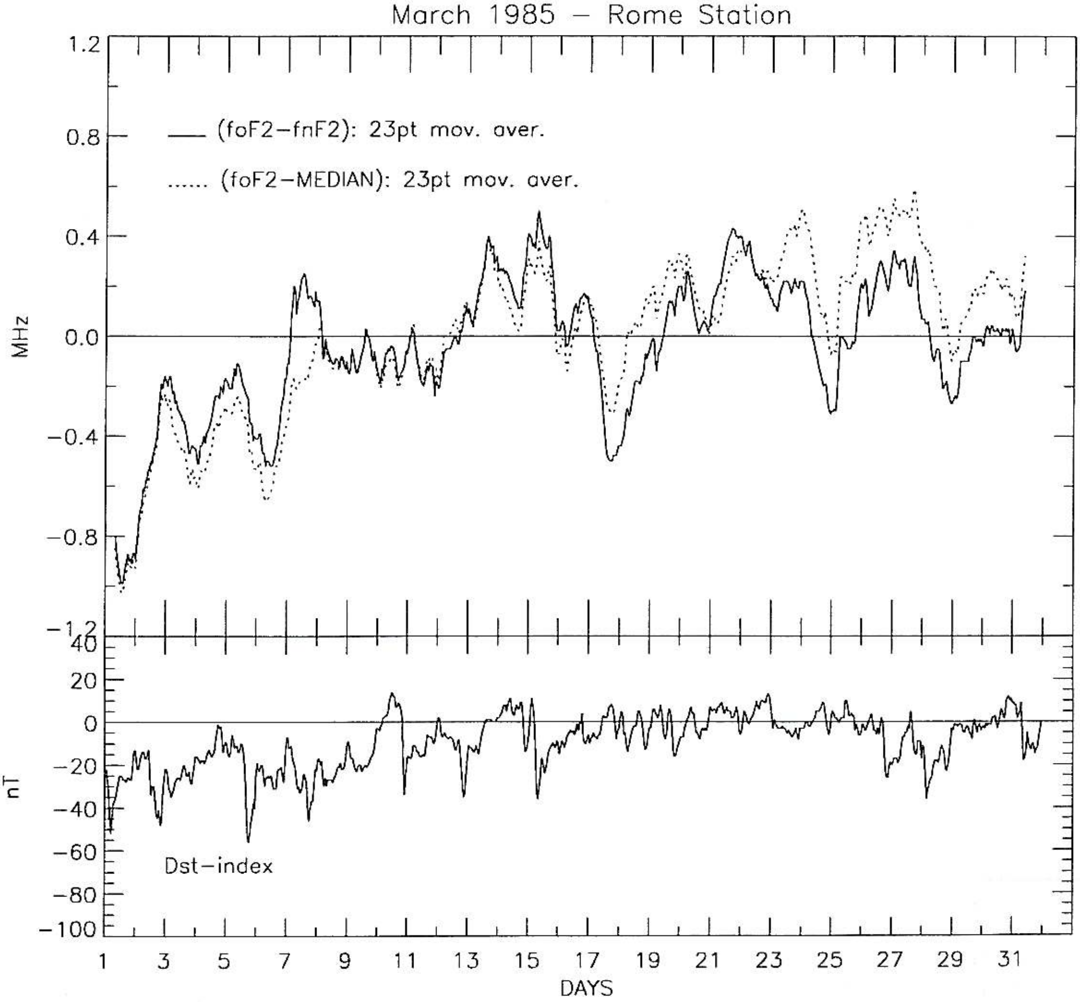

Fig. 5. The deviation of the observed f_0F_2 values from the f_nF_2 index (solid line) and from the monthly median values (dotted line) is presented in the upper panel for March 1985. The hourly values of the D_{st} index are presented in the lower panel.

As noted in the Introduction, temporal variations of the quiet ionosphere affect the monthly median f_0F_2 values. Examining the behaviour of the $\Delta f_n (= f_0F_2 - f_nF_2)$ index during relatively undisturbed months ($D_{st} > -80\gamma$), it resulted that the f_nF_2 index is free from the artificial effects imposed on the monthly median f_0F_2 values, due to temporal variations of the quiet ionosphere (Kozin *et al.*, 1995). The time plots of the smoothed (23 points moving average) Δf_m and Δf_n indices are presented in fig. 5, for March 1985. Ionospheric data are also obtained from Rome ionosonde. During March 1985, the ionosphere was relatively undisturbed by magnetospheric activity as resulted from the D_{st} data presented in the second panel. It can be seen that the Δf_m index (dotted line) is more negative than the Δf_n index (solid line) at the beginning of the month and more positive than the Δf_n index during the second part of the month. In general, during this month with relatively undisturbed ionospheric conditions, the Δf_n index

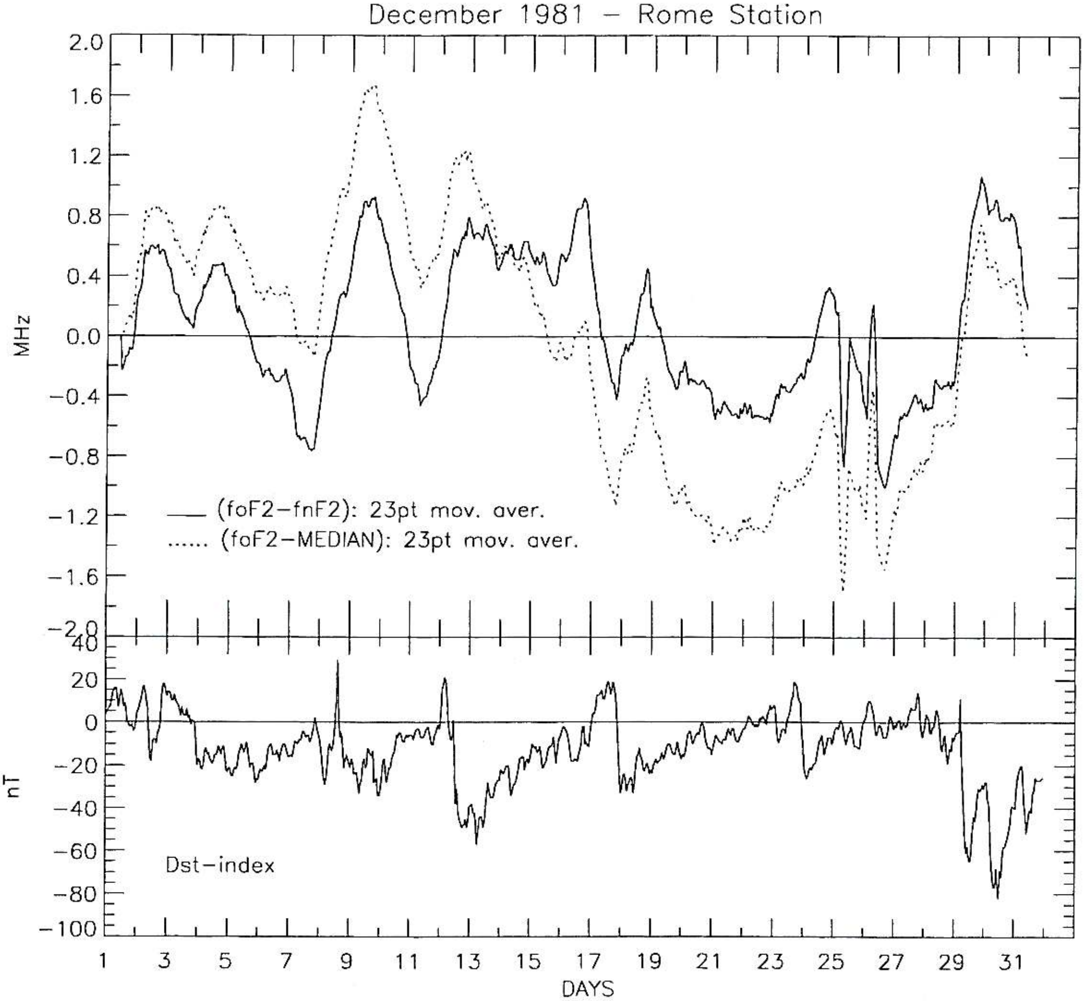

Fig. 6. Same as fig. 5 for December 1981.

varies around zero, while Δf_m exhibits large variations with large negative and positive values at the beginning and end of the month respectively.

The same effect can be seen in fig. 6 where the time plots of the smoothed (23 points moving average) Δf_m and Δf_n indices are presented during December 1981 together with the hourly values of the D_{st}-index. In this case, the opposite behaviour of the Δf_m index is observed. Indeed, at the beginning of the month Δf_m is positive, while at the second half of the month it is negative. The Δf_n index follows closely the variations of Δf_m, but is more negative in the first half of the month and more positive in the second half. It is obvious that the shift of the Δf_n index with respect to the Δf_m index is due to the absence of the temporal variations from the f_nF_2 index.

4. Statistical results

To demonstrate the behaviour of the f_nF_2 index in comparison to the monthly median f_0F_2 as an indicator of the normal ionosphere, a statistical analysis was carried out over a database of ionospheric parameters derived from Rome ionograms that covers a time period of six years from 1981 to 1986. More precisely, the data set consists of: a) the hourly values of the f_0F_2 critical frequency measured at Rome station from 1981 to 1986; b) the monthly median f_0F_2 parameters from Rome station for the same time interval; c) the hourly f_nF_2 index, for Rome station, computed according to the model presented in Section 2; d) the 3-hourly *aa* planetary index from 1981 through 1986.

The mean deviation over 3-hourly intervals of the f_nF_2 index and of the monthly median from the observed f_0F_2 parameter, was estimated for different levels of magnetospheric activity. The deviation of the observed f_0F_2 values from the normal f_nF_2 values is given by the relation

$$Dn_i = \frac{1}{k}\sum_{j=1}^{k}(f_0F_{2_j} - f_nF_{2_j})^2$$

where $k = 3$, i is the 3-hourly interval of the day, and j denotes the hours. Similarly, the deviation of the observed f_0F_2 values from the monthly median f_0F_2 values (*MED*) is given by the relation

$$Dm_i = \frac{1}{k}\sum_{j=1}^{k}(f_0F_{2_j} - MED_j)^2 .$$

The data set used for this statistical analysis was divided into three groups according to the monthly level of magnetospheric activity: a) months of low magnetospheric activity ($aa < 100$); b) months of moderate magnetospheric activity ($100 \leq aa < 200$); c) months of intense magnetospheric activity ($aa \geq 200$).

For each group, the mean values of *Dn* and *Dm* quantities were computed for the number of 3-hourly intervals with: a) $aa < 30$; b) $30 \leq aa < 70$ and c) $aa \geq 70$. The mean values of *Dn* and *Dm* represent the general fit of the f_nF_2 index and of the monthly median f_0F_2 to the observed values respectively. The smaller the value of *Dn* and *Dm* is, the better the fit with the observed values. The histograms of the mean values of *Dn* and *Dm* for different levels of geomagnetic activity throughout a month are presented in figs. 7, 8 and 9, for the three groups of data.

The results obtained during months of low magnetospheric activity ($aa < 100$) are presented in fig. 7. The percentage difference of the mean *Dn* and *Dm* quantities are given together with the histograms of the above quantities over 3-hour intervals of quiet ($aa < 30$), moderately disturbed ($30 < aa < 70$) and very disturbed ($aa > 70$) conditions. During quiet intervals ($aa < 30$) *Dn* is greater than *Dm* by 27% indicating that the f_nF_2 index fits much better with the observed values than the monthly median values do. For more disturbed conditions, the situation is reversed. Monthly median values fit better with the observed f_0F_2. The same pattern can be extracted by inspecting the statistical results obtained from the analysis of data during months of moderate ($100 \leq aa < 200$) and intense ($aa \geq 200$) magnetospheric activity, presented in figs. 8 and 9 respectively.

Summarizing the statistical results obtained from the above analysis, one could verify the validity of the f_nF_2 index as an indicator of the normal undisturbed level. This index follows

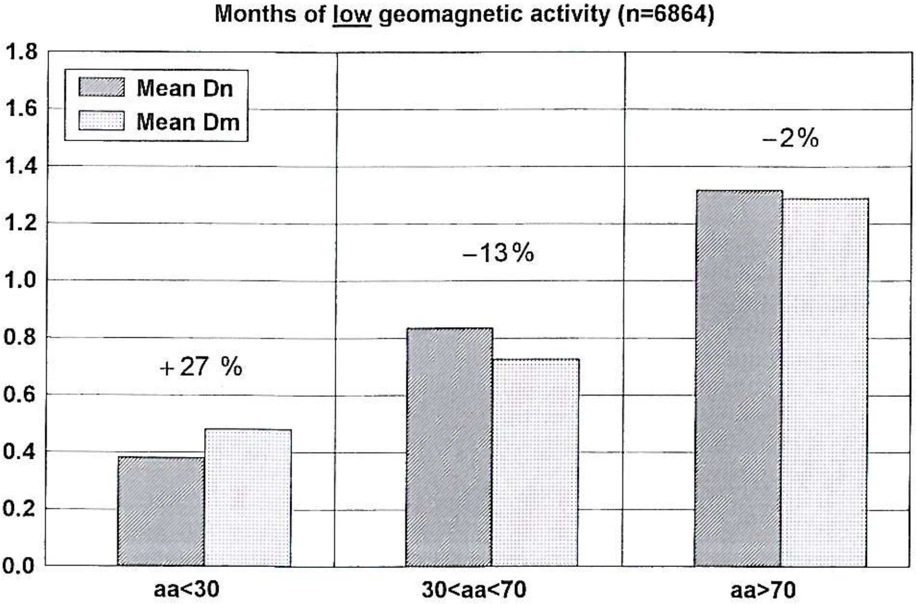

Fig. 7. Histograms of the mean value of *Dn* and *Dm* quantities for the number of 3-hourly intervals with $aa < 30$, $30 \leq aa < 70$, $aa \geq 70$. In this data set, only months of low geomagnetic activity ($aa_{max} < 100$) are included.

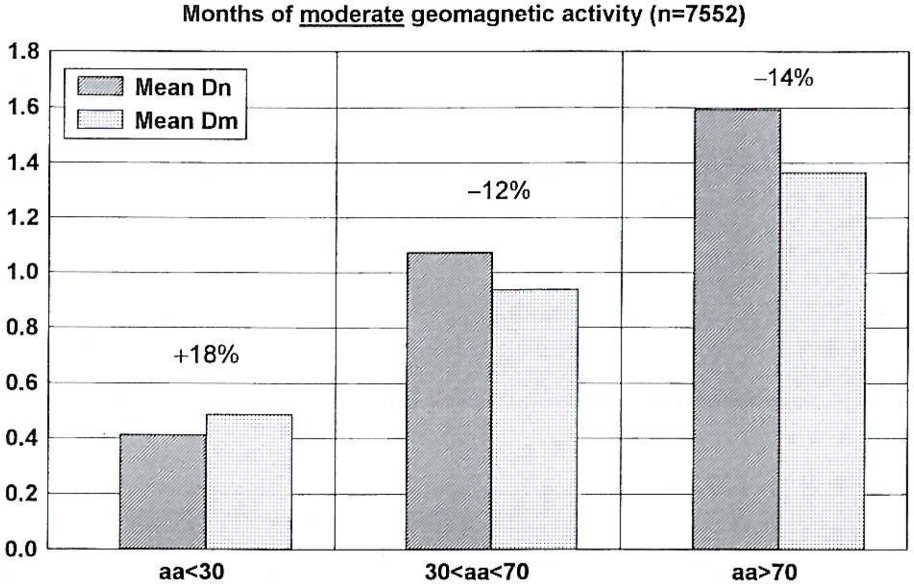

Fig. 8. The same as in fig. 7 for months of moderate geomagnetic activity ($100 \leq aa_{max} < 200$).

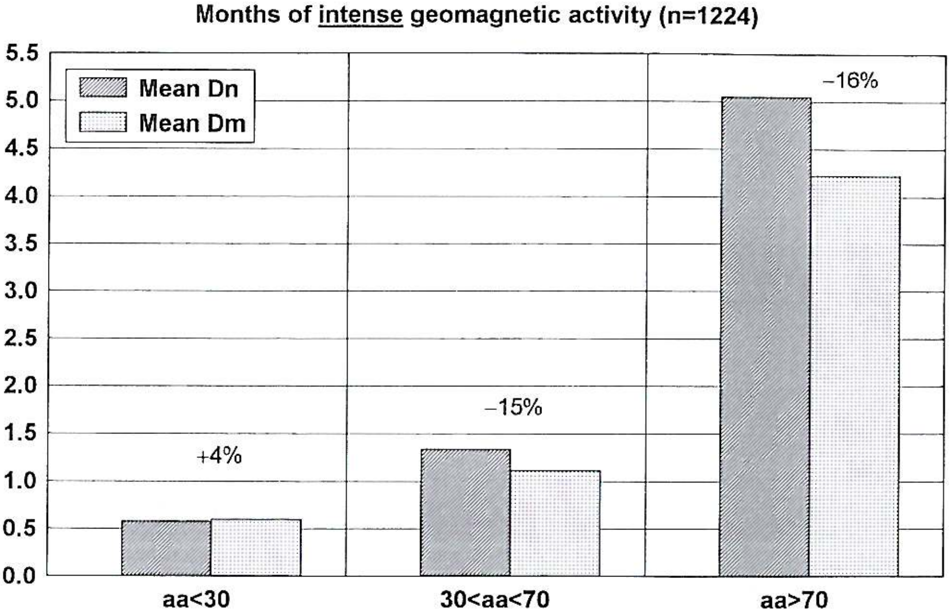

Fig. 9. The same as in fig. 7 for months of intense geomagnetic activity ($aa_{max} \geq 200$).

closely the variations of the f_0F_2 parameter only under quiet conditions. The fit of the f_nF_2 index with the observed values is better than the fit of the monthly median f_0F_2 values by 27%, 18% and 4%, for months of low (fig. 7), moderate (fig. 8) and intense (fig. 9) activity. The degree of f_nF_2 index fit is diminishes as the general monthly level of geomagnetic activity becomes higher. As the geomagnetic activity increases, ionospheric disturbances become dominant and this results in the depression of monthly median values. Interestingly during intervals of disturbed geomagnetic conditions *Dn* quantity is systematically greater than *Dm* quantity. By the definition of *Dn* and *Dm* quantities, one result is that the f_nF_2 index remains in its undisturbed level, as geomagnetic activity increases. This fact provide us with strong evidence that the f_nF_2 index is independent of the ionospheric disturbances triggered by the magnetospheric activity, so that this index corresponds to the normal level of the undisturbed ionosphere at a given station.

5. Discussion and conclusions

In this paper an hourly local ionospheric index f_nF_2 is proposed to define the normal level of the undisturbed ionosphere. The construction of this index was based on the assumption that the least squares polynomial fitted to express the dependence of the f_0F_2 parameter on the sunspot number *Rz*, for a given hour of the day and for a given station, represents the undisturbed level of the ionospheric F_2 layer. Applying the multiple regression method, a set of 48 or 72 coefficients (depending on the level of sunspot activity) is derived to reproduce the normal level of the F_2 layer for each month of the year, for a given station, according to eqs. (2.1) and (2.2) of Section 2.

From a comparison of the f_nF_2 index and of the monthly median f_0F_2 values with respect to the observed f_0F_2 values, during quiet and disturbed intervals, some results were obtained concerning the properties of the f_nF_2 index.

1) The temporal variations of the undisturbed

F_2 layer are eliminated from the f_nF_2 index, as seen by examining the monthly variation of the f_nF_2 index, during relatively undisturbed months. So, when geomagnetic activity is superimposed on the ionospheric reference values, expressed by the f_nF_2 index, meaningful results are obtained concerning the identification of quietness, negative and positive disturbances (figs. 3, 5 and 6).

2) Step-like changes in the transition period from one month to another characteristic of the monthly median f_0F_2 time series, which are due to the different levels of substorm activity from month to month, were eliminated from the newly derived f_nF_2 index (fig. 4).

3) The f_nF_2 index follows closely the variations of the observed f_0F_2 parameter only under quiet conditions. As the geomagnetic activity increases, ionospheric disturbances become dominant and this results in the depression of the monthly median values, whereas the f_nF_2 index remains at its undisturbed level.

4) F_2-layer anomalies appeared in the f_nF_2 index as well. In the case of May 1981 (fig. 2) the daily maximum of the ionization occurs near sunset, after 20th May, while the median values present the daily maxima just before and after local noon, which is a typical anomaly of winter months. Moreover a tendency towards large ionization is seen (fig. 3) at nighttime, which is also an anomaly characteristic of summertime.

5) Seasonal variation constitutes a characteristic feature of the f_nF_2 index. By definition, the derivation of the f_nF_2 index is based on the observed values of the f_0F_2 parameter of the month under question. So it is expected to follow the variation of the observed f_0F_2 parameter. The case presented in fig. 4 gives an example of the seasonal variation of the f_nF_2 index, as the daily peak f_0F_2 increases towards the end of October.

The choice of the appropriate index to determine the undisturbed level of the F_2 layer depends on the time interval under study, its duration and the current magnetospheric conditions. Under quiet magnetospheric conditions, the f_nF_2 index may be considered the most appropriate parameter. The use of monthly median values may lead to meaningful physical results. Under disturbed magnetospheric conditions the use of the f_nF_2 index approaches the undisturbed level quite successfully. Nevertheless, if the general level of activity during a given month is very high, monthly median values do not differ much from the f_nF_2 indices (fig. 9). For long-term studies, including transition periods from month to month, the use of the f_nF_2 index is suggested to secure the elimination of the step-like artificial change at the beginning of each month.

In general, the f_nF_2 index gives a good reference level of the F_2 layer, as it is independent of magnetospheric conditions and varies only with the sunspot activity. On the contrary, monthly median values express an artificial normal level and their use leads to meaningful results when trying to characterize the ionospheric activity, as was justified with the case presented in fig. 3.

Finally, it should be noted that the results presented here were based on ionospheric observations obtained from Rome, which is a typical middle latitude station. Nevertheless, the proposed model has been applied to a number of middle latitude stations, always giving valid results.

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