"foF2 VARIATIONS MEASURED BY THE ROME OBSERVATORY DURING SOLAR MINIMUM IN THE LAST THREE SOLAR CYCLES"

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Article history
Receveid May 18, 2018; accepted September 9, 2018.
Subject classification:
foF2; Ionospheric storm; Ionosonde data; Ionosphere.

ABSTRACT

The last three solar cycles have been considered for a study on the variation of the ionospheric parameter foF2 during solar minimum. Hourly observations recorded by the ionospheric station of Rome have been considered for the years 1985, 1986, 1987, 1995, 1996, 1997, 2007, 2008 and 2009. Background values of foF2 have been computed considering a 27-day running median. A variation of foF2 of more than ± 15% over the background level and with a minimum duration of 3 hours, is here considered as an anomaly. For each anomaly, a study of the geomagnetic condition has been carried out, considering the value of the a_p index at the time when the anomaly is detected and for the previous 24 hours. The auroral electrojet index AE has also been investigated in relation with each observed foF2 anomaly, considering 6 hours before the occurrence of the anomaly since TADs, related to upsurges of auroral activity, can reach middle latitudes and consequently perturb the F2 layer. A characterization of the observed foF2 anomalies with respect to the related geomagnetic conditions is presented in this work. Two foF2 storms are studied here in detail, analysing the solar sources.

1. INTRODUCTION

Extending approximately from 50 to 2000 km, the Earth's ionosphere is an ionized plasma region embedded in the geomagnetic field, which affects its properties, and strongly coupled with neutral atmosphere and the overlying magnetosphere through continuous exchange of momentum and energy. Since ionospheric plasma frequency values are typically comparable with HF radio frequencies, it appears useful to use electromagnetic waves in the HF range to study the ionospheric layer of the Earth. The most widely used technique to study the ionosphere is by vertical ionospheric sounding by means of ionosondes, the product of such soundings is a vertical ionogram, in which time delay is measured and plotted against frequency. One of the most important ionospheric parameter that can be deduced from a vertical ionogram, is the critical frequency of the F2 layer, foF2. The Earth's upper atmosphere is, in fact, an open system, with many uncontrolled inputs forcing it both from above (e.g. by solar EUV, magnetospheric and dynamo electric fields, changing thermospheric circulation and neutral composition, TADs etc. [Bremer et al., 2009; Alfonsi et al., 2001; Kutiev et al., 2013; Mikhailov and Perrone et al., 2015] and from below (e.g. planetary and gravity waves, neutral gas vertical motion and eddy diffusion changing thermospheric neutral composition, tropospheric electric fields). Therefore, besides the geomagnetic activity effects, there are many other sources of foF2 variations [Mikhailov et al., 2004; Perrone al., 2018]. Intense Solar activity can produce strong and irregular variations in the geomagnetic field, introducing perturbations in the ionosphere-plasmasphere system characteristics. Solar emissions of extremely energetic particles toward the Earth are the primary sources of strong perturbations in the upper atmosphere. Solar corona and solar wind ions are accelerated in a short time up to energies of 10 MeV–1 GeV, in Coronal Mass Ejection (CME)-driven shock waves or in strong solar flares [Ippolito et al., 2005, Zimbardo et al., 2006]. Ionospheric F2 layer storms are strongly related to geomagnetic activity. A geomagnetic storm, induced by solar flares or Coronal Mass Ejections and characterized by various geomagnetic indices [e.g Perrone and De Franceschi, 1998], often introduces profound changes in the F layer characteristics, determining, in many cases, an ionospheric storm [Cander, 2016; Buonsanto et al., 1999; Fuller-Rowell et al., 1994]. The response of the ionosphere depends on the onset time of geomagnetic storms, season, solar activity and latitude [Prolls, 1995; Buonsanto, 1999]. The ionospheric storm can have a negative and a positive phase, that means a decrease or increase of electron concentration in the F2 layer maximum respect to a 'quiet' value. Physical mechanisms forming both negative and positive F2 layer disturbances, are related to global thermospheric circulation, neutral composition and temperature, electric fields, and plasmaspheric flux changes. The energy input at high latitudes can produce changes in thermospheric wind composition, resulting in significant variations in the ionospheric electron density [Mikhailov and Perrone, 2009]. Day-time positive disturbances in general are associated with small or moderate geomagnetic activity (David and Sojka ,2010; Zevakina and Kiseleva, 1978) that may be related to auroral activity. Nigh-time positive enhancements may be related to plasma influx into night-time F2 region from the plasmasphere. The list of all pertinent processes may be found in Rishbeth [1991] and Prölss [1995]. Therefore, besides the geomagnetic activity effects, there are many other sources of foF2 variations. Morphological studies have shown that the positive storms increase in number during equionox and occur in any LT sector while negative storms are more frequent in the post-midnight - early morning LT sector [e.g. Mikhailov et al., 2012; Tsagouri and Beleaki, 2008; Prolss, 1993; Rishbeth, 1991]. Indeed, the energy input at high latitudes can produce strong equatorwords winds, resulting in significant variations in the ionospheric behaviour [Mikhailov and Perrone, 2009]. In this paper is presented a study on the characterization of the variations of the F2 layer critical frequency, observed at the ionospheric observatory of Rome, Italy, during the minimum of the last 3 solar cycles. It is well-known that the last solar minimum 2008-2009 was very deep and prolonged [Emmert et al., 2010; Gibson et al., 2009; Liu et al., 2011; Qian et al., 2014; Perna and Pezzopane, 2016; Solomon et al., 2013]. The thermosphere and ionosphere manifested unusual variations poorly described by such empirical models as MSISE-00 and IRI. For this reason an additional analyses of that solar minimum period in a comparison with the previous solar minima is of a special interest. In this paper we have analyzes statistics of positive and negative foF2 deviations during three last solar minima. Validated data, coming from the manual scaling of vertical ionograms produced by the Rome observatory, have been taken into account, available on the INGV-eSWua [Romano et al., 2008] web portal (http://www.eswua.ingv.it). At the same web page, it is possible to find real-time values of the ionospheric parameters automatically obtained from vertical ionograms by the Autoscala program [Scotto and Pezzopane, 2002; Pezzopane and Scotto, 2007; Scotto, 2009; Cesaroni et al., 2014]. Although the autoscaling of oblique ionograms is significantly more complex than for the vertical ones, automatic procedures for the interpretation of oblique ionograms are under development at INGV [Ippolito et al., 2015; Ippolito et al., 2016; Ippolito et al., 2018] and will be available in the future as real time products on eSWua web page.

2. METHODOLOGY

The aim of this work is to provide a characterization of the anomalies in the critical frequency of the F2 layer, at mid latitudes. For this purpose, ionospheric data from the AIS-INGV ionosonde have been investigated, in particular foF2 validated data have been considered for the years 1985, 1986, 1987, 1995, 1996, 1997, 2007, 2008 and 2009. Rome Ionospheric observatory (Latitude 41.8 N Longitude 012.5 E) is managed by the Italian Istituto Nazionale di Geofisica e Vulcanologia (INGV) and it is operative since 1935. Hourly observations of foF2 have been analysed for the considered years. In order to define a possible anomaly in the critical frequency of the F2 layer, for each hour, a background value of foF2 has been computed, considering a 27-days running median [Kutiev and Mutharov, 2001; Marin et al., 2000]. At this point, has been calculated the deviations δf of hourly values of the foF2 from the background, as follows:

$$\delta f = \frac{f_{(hourly)} - f_{(background)}}{f_{(background)}} \tag{1}$$

Variations in the foF2 parameter of more than ± 15% ($\delta f = (f_{(hourly)} - f_{(background)}) / f_{(background)} \geq 15\%$) [Mikhailov et al., 2012] with respect to the background level, and with a duration greater than 3 hours, have been assumed as anomalies. Once identified all the ionospheric anomalies in the F2 region, observed during the minimum of the last 3 solar cycles, at the Rome station, a deep study on the geomagnetic conditions related to each detected anomaly, has been conducted through the analysis of the geomagnetic index a_p and the auroral electrojet index AE. Indeed, quiet and disturbed periods defined by these geomagnetic indices, have been distinguished in relation to the observed ionospheric anomalies. For each anomaly, the values of the a_p index, at the time when the anomaly is detected and for the previous 24 hours, have been taken into account. This to consider possible relations between any geomagnetic disturbance recorded at global level, and the observed anomalies. Every observed foF2 anomaly has been classified according to the classification of the a_p index level provided by the National Oceanic and Atmospheric Administration (NOAA) (http://www.swpc.noaa.gov/noaa-scales-explanation) and showed in Table 1.

a_p (nT)	LEVEL	GEOMAGNETIC ACTIVITY
0- 32	G0	Quiet
39-56	G1	Minor Storm
67-94	G2	Moderate Storm
111-154	G3	Strong Storm
179-300	G4	Severe Storm
179-300	G5	Extreme Storm

TABLE 1. Classification of the ap index level as provided by the National Oceanic and Atmospheric Administration (NOAA) (http://www.swpc.noaa.gov/noaa–scales–explanation).

The auroral electrojet index AE has also been investigated in relation with each detected ionospheric anomaly. An interval of 6 hours before the occurrence of the anomaly has been studied, to consider the neutral winds effect on the ionospheric layer [Buonsanto and Witasse, 1999; Prolss, 1993]. As it is well known, global manifestation of neutral winds effects, starts at auroral latitude where the Joule heating produced by the convection electric field and the energetic particles precipitation due to the perturbations in the interplanetary medium, contribute to increase the temperature of the thermosphere at high latitudes. This results in an enhancement of the equatorward winds and travelling ionospheric disturbances, which from the polar regions, can easily reach mid latitudes and consequently perturb the F2 layer. In this work AE values less than 100 nT are considered as representative of quiet auroral electrojet activity. Each anomaly in the critical frequency of the F2 layer has been classified according to the geomagnetic condition as defined by the classes of ap index. For quite ap level, identified as G0 class, the associated values of AE has been introduced. This allows to define a strictly quiet geomagnetic condition class for which the ap index is at G0 level, and AE is less than 100 nT.

3. RESULTS

A total number of 1020 anomalies of the critical frequency of the F2 layer, have been observed over the ionospheric observatory of Rome, during the minimum of the last 3 solar cycles.

The total number of positive and negative foF2 anomalies observed per year at Rome is given in Figure 1.

The relationship between the number of the observed ionospheric anomalies (positive and negative) and the solar and geomagnetic activity is clearly visible and also described by Table 2, in which the total number of ionospheric anomalies are reported in relation with the values of F10.7 an Ap, averaged over the three years considered for each solar cycle minimum studied.

SOLAR CYCLE MINIMUM	N. OF foF2 ANOMALIES	AVERAGE SOLAR INDEX F10.7	AVERAGE Ap INDEX
21°	444	78.3	12.4
22°	328	76.8	10.1
23°	268	70.8	6.1

TABLE 2. Total number of ionospheric anomalies in relation with the indices F10.7 and Ap, averaged over the three years considered for each solar cycle minimum studied.

The first analysed solar minimum, 1985-1987, is characterised by a greater solar and geomagnetic activity, with respect to the others. This can be seen in the larger number of the observed ionospheric anomalies with respect to the 2007-2009 minimum, characterised by solar low geomagnetic activity. The number of positive anomalies is greater than the number of negative ones, but they are with the same order of magnitude. The following panels of Figure 2 describe the number of the foF2 positive and negative anomalies, in relationship to the geomagnetic condition, for each analysed year.

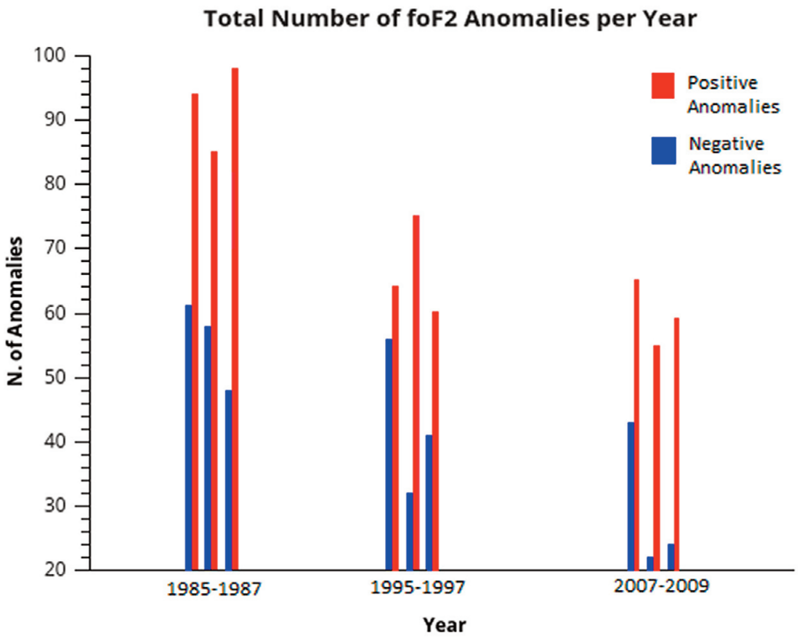

FIGURE 1. Total number of positive and negative foF2 anomalies observed per year at the Rome observatory.

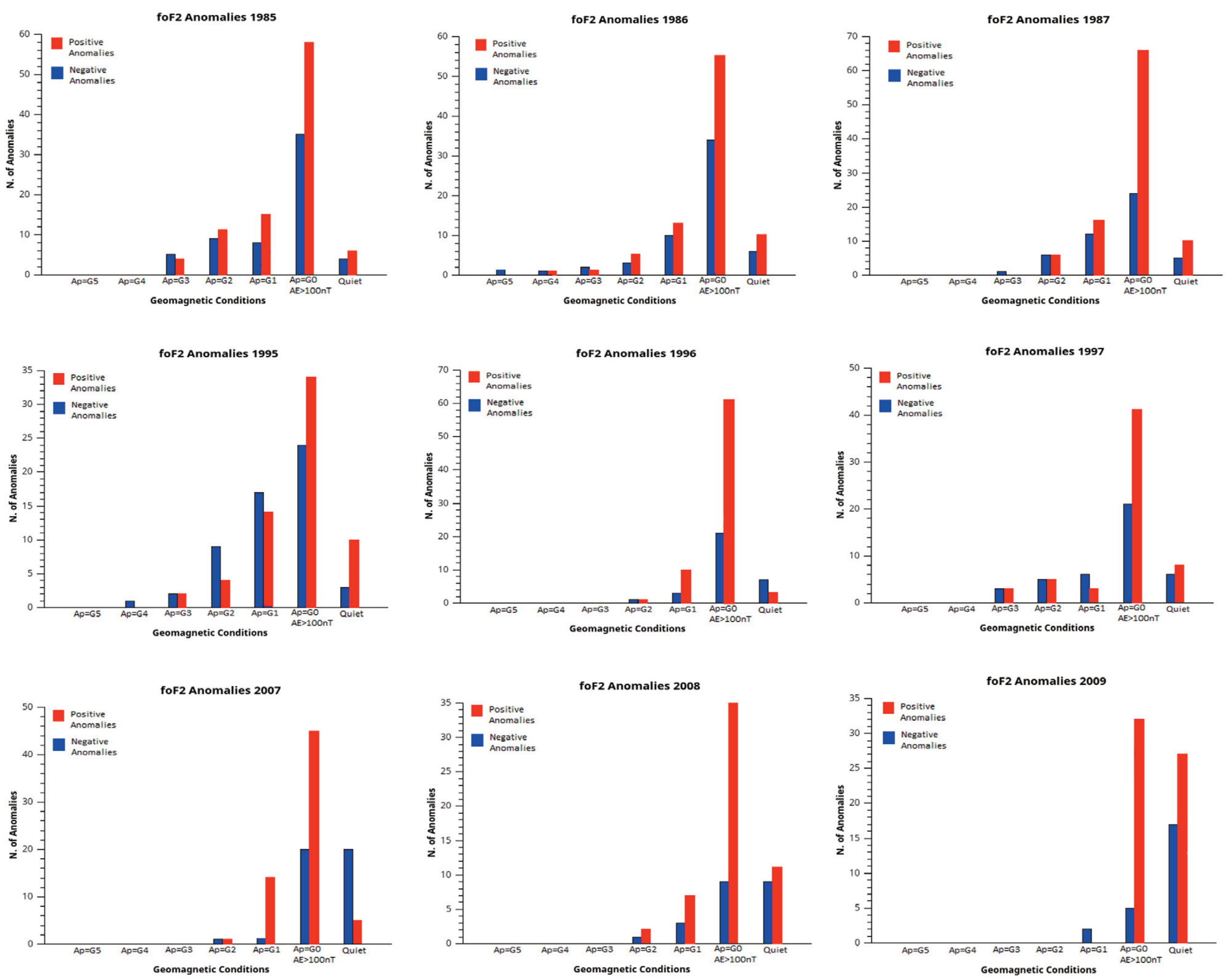

FIGURE 2. Number of positive and negative anomalies foF2 per year, in relationship to the geomagnetic condition.

The number of anomalies observed in Quiet condition, during the minimum of 21th and the 22th solar cycle, is comparable. The percentages of anomalies in relation with the geomagnetic conditions have also been computed, considering, for each geomagnetic level, the number of days per year. Due to the low number of data with AE < 100nT, higher values of the anomalies percentages are observed for the years 1987, 1995 and 1996. The number of anomalies observed in quiet conditions during the minimum of 23th solar cycle is remarkable, this is probably due to the higher number of days with AE <100 nT. The number of anomalies found in the minimum of 23th solar cycle is less than in other solar cycles, this is due to the number of data in G0 level. The anomalies found in the years 1985-1986-1987-1995-1997 in the levels, G1-G2, are comparable in number and percentage, due to the higher number of data in these intervals. There is no data, for the deep solar minimum, in the levels G3 – G5. The solar minimum of the 21th solar cycle presents the greatest number of anomalies due to the higher number of geomagnetic disturbed days.

4. CASE STUDIES OF IONOSPHERIC STORMS

An ionospheric storm can be seen as a set of disturbances recorded in the ionospheric medium, directly related to a geomagnetic storm [Hargreaves, 1992]. Individual case studies of foF2 storms are to be considered as powerful instruments for a better understanding of the physical process underlying the electron density variations in the ionosphere. For strong perturbation of the geomagnetic field, it is well known how, at mid latitude, the critical frequency foF2 is usually reduced, after an initial increase [Martyn 1953b,c; Matsushita 1959, Prolss, 1993; Rishbeth, 1991]. Several papers show how, as a consequence of strong geomagnetic storms, a positive variation in the foF2 for some hours is followed by a negative variation of foF2. The related depression in the NmF2 may be down by 3-5 times depending on the intensity of a storm. This kind of ionospheric storm is catalogued as *negative*, but individual ionospheric storm can be either negative or positive. A correlation between the major changes in NmF2 at dipole latitudes (20°-45°), and the time (LT) of the beginning of the main phase of a geomagnetic storm, is suggested by Thomas and Venables [1966]. Two case studies, a negative ionospheric storm and a positive ionospheric storm respectively, are here presented. Data coming from the Rome observatory have been analysed from 06 to 13 February 1986 and from 20 to 26 November 1997.

4.1 07 FEBRUARY 1986 IONOSPHERIC STORM

A strong negative foF2 storm has been observed for some days starting from February the 7th 1986. In Figure 3 is reported the percentage variation of the hourly values of the critical frequency foF2, from the background, starting from 07/02/1986 at 08:00 UT. As can be seen, in the initial phase of the storm, a strong enhancement of the foF2 up to 54%, is recorded on February the 7th, then a negative phase of the storm begins on February the 8th.

Starting from the 17:00 UT (18:00 LT) of February the 8th, a second strong positive phase is observed in the vari-

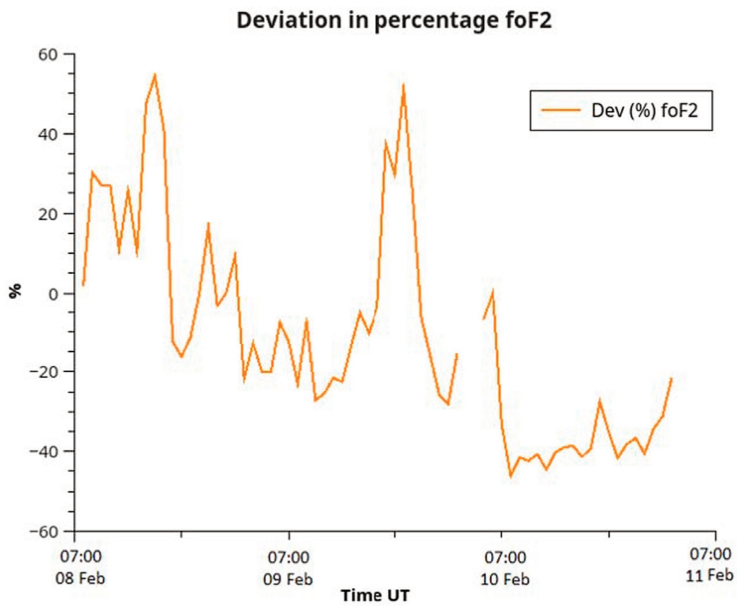

FIGURE 3. Daily variations of δf (in %) for the storm started at 08:00 UT on 07/02/1986.

ation of the critical frequency of the F2 layer, then, a longer negative phase of the considered foF2 storm, can be seen starting on 08/02/1986 at 22:00 UT (23:00 LT). It is clear from the plot, how the percentage of variation of foF2 reaches a deep minimum of -46% on February the 9th. At the end of this strong negative phase, a recovery phase of the F2 layer starts from the first hours of February the 10th, and it takes until February the 13th, to return back to quiet conditions, in terms of deviation from the background value, for the critical frequency foF2. The behaviour of the foF2 storm observed from February the 7th 1986, and described above, can be easily seen in Figure 4. In panel a) of Figure 4 is plotted the deviation from the background of the hourly values of foF2. Red horizontal lines represent the thresholds assumed to identify strong positive and negative disturbances, while the yellow horizontal lines give the threshold for a moderate positive or negative disturbance in the F2 layer. In panel b) is reported in red the hourly values of foF2 recorded by the ionospheric observatory of Rome, from 06/02/1986 to 13/02/1986. The green line represents the hourly running median for the same ionospheric parameter, for the considered days.

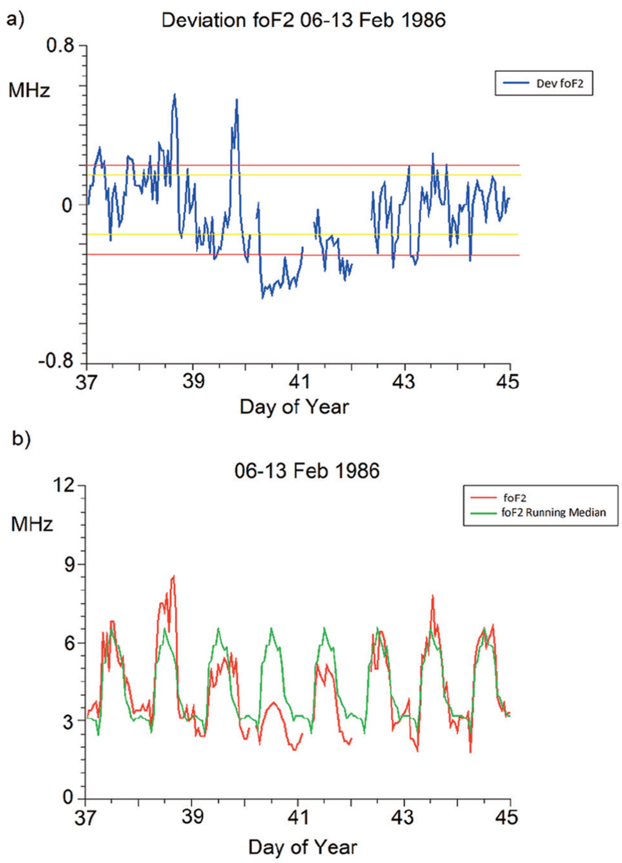

FIGURE 4. The behaviour of foF2 during the ionospheric storm observed from February the 7th 1986, over the Rome observatory.

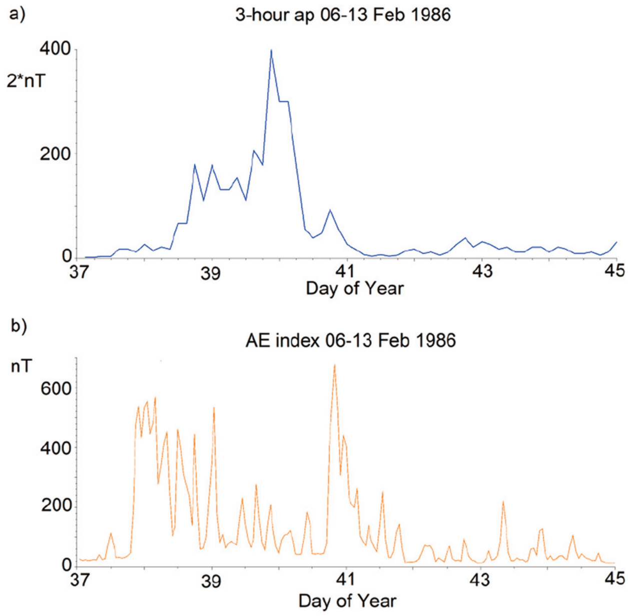

FIGURE 5. Variations of the geomagnetic indeces a_p and AE during the ionospheric storm observed from February the 7th 1986 over the Rome observatory.

In panels a) and b) of Figure 5 respectively, the 3-hourly values of ap index for the considered period, and the hourly auroral electrojet index AE, are plotted for the same period. It can be clearly seen from these panels, how the geomagnetic condition was perturbed during the considered time interval. Indeed it is worth to notice the correspondence between the enhancement of the deviation of the foF2 values from the background, and the increase of the ap and AE values. In particular it can be seen from panel a) of Figure 5 how the geomagnetic index ap reach values catalogued as Extreme Storm conditions (G5 range).

A further analysis of the solar activity in the days leading up the storm, shows an increase in the solar F10.7 index, as reported in Figure 7. An X class flare has been observed by GOES satellite (https://www.ngdc.noaa.gov/stp/space-weather/solar-data/solar-features/solar-flares/x-rays/goes/xrs/), on February the 6th 1986 at 06:18, at coordinate S04 W06 on the solar disk. A CME, presumably associated to the observed X flare, has been detected by the NASA Solar Maximum Mission (SMM) (https://www2.hao.ucar.edu/mlso/solar-maximum-mission/smm-cme-catalog), probably responsible of the enhancement of the solar flux F10.7 index described Figure 5. Due to its position on the solar disk, the observed CME is probably responsible of a SEP event at 1 AU, [Ippolito et al., 2005]. The enhancement in the auroral activity highlighted by the high values of AE index, suggests that the perturbation in the critical frequency of the F2 layer, observed by the Rome ionospheric station, is probably due to a Travelling Atmospheric Disturbance (TAD). This is also suggested by the analysis conducted on the variation of foF2 values recorded in the same days by Juliusruh ionosonde and reported in Figure 6. The red line represents the hourly values of foF2 from 06/02/1986 to 13/02/1986. Looking at the comparison between the hourly foF2 and the hourly monthly median, the green line in the plot, the same behaviour observed in Rome can be seen from Juliusruh data. Indeed, the energy input at high latitudes can produce changes in thermospheric wind, inducing equatorward winds, which result in significant variations of the ionospheric electron density also at mid latitude [Mikhailov and Perrone, 2009].

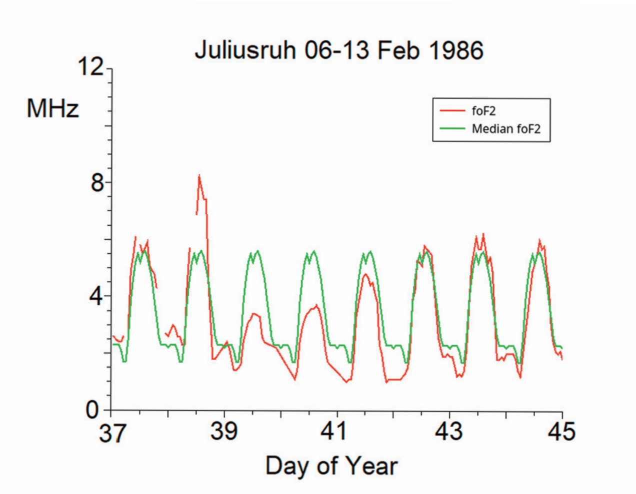

FIGURE 6. The behaviour of foF2 from 06/02/1986 to 13/02/1986, observed by the Juliusruh observatory.

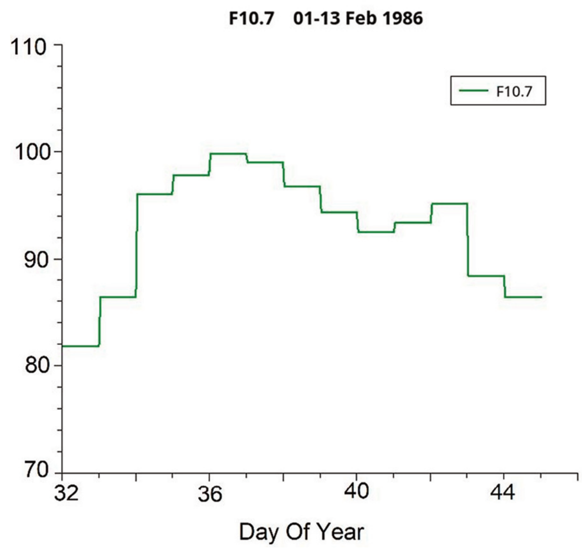

FIGURE 7. Variation of the solar index F10.7 from 01/02/1986 to 13/02/1986. An enhancement in the solar index F10.7 possibly related to the observed ionospheric storm can be seen from the figure.

4.2 22 NOVEMBER 1997 IONOSPHERIC STORM

A positive ionospheric storm has been detected by the Rome ionosonde, starting from November the 22nd 1997.

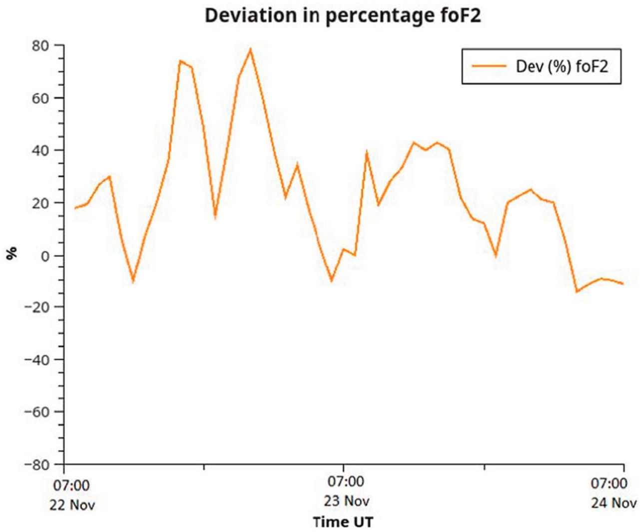

FIGURE 8. Variation in percentage, starting from 22/11/1997 at 07:00 UT (08:00 LT), of the hourly values of the critical frequency foF2 observed by the Rome ionospheric station, from the background values.

In Figure 8 the enhancement of measured foF2 is reported, expressed by its deviation in percentage from the background level, starting from 22/11/1997 at 07:00 UT (08:00 LT). As can be seen, an increase up to 30% is observed during the first phase of the storm. A second and stronger enhancement in the critical frequency of the F2 layer is recorded in the second half of the day, as described by the values of δf observed from 14 UT (15:00 LT), which reaches a maximum percentage of variation of 74%. The last phase of the positive storm is represented by an increase of foF2 at the end of November the 23rd, starting from 20:00 UT (21:00 LT).

The recovery characterised by small variation of foF2 with respect to the background level, is observed until November 26th, when the ionosphere reaches a quiet status.

Also in this case, the behaviour described above is represented by the plots in the panels of Figure 9. As the previous ionospheric storm, from red line in panel b), it is possible to observe the variation of the hourly values of foF2, recorded by the Rome observatory from November 20 to November 26, compared with the background value, which is represented by the green line in the plot. As can be seen from panel a) of Figure 9, a strong increase in the deviation of the critical frequency of the F2 layer, is reflected in the variation of foF2 showed in panel b). This corresponds to a sudden enhancement of the geomagnetic index ap, as reported in the plot of pan-

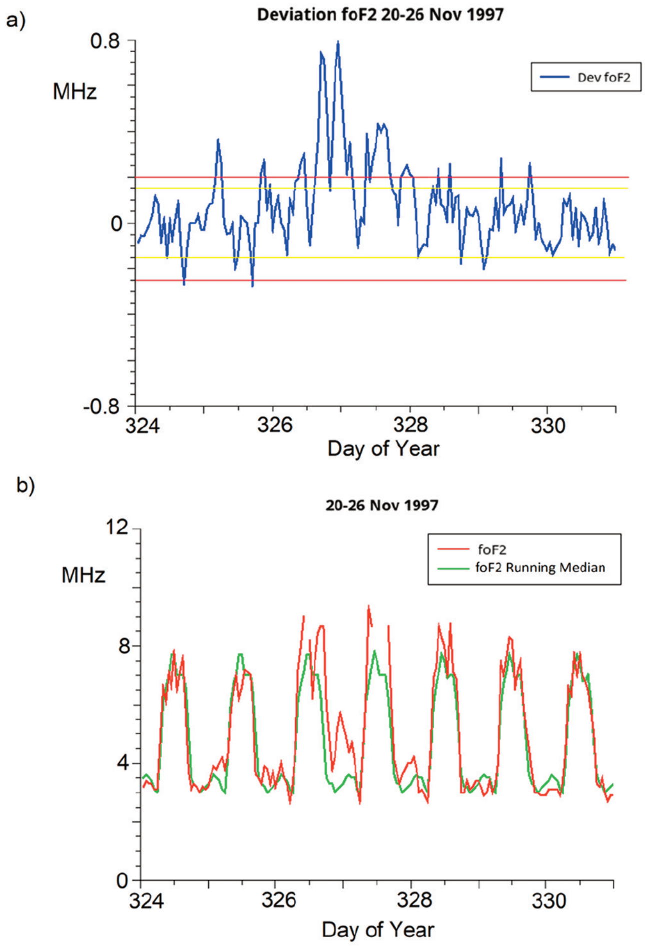

FIGURE 9. The behaviour of the foF2 parameter during the ionospheric storm observed from February the 20th 1997, over the Rome observatory.

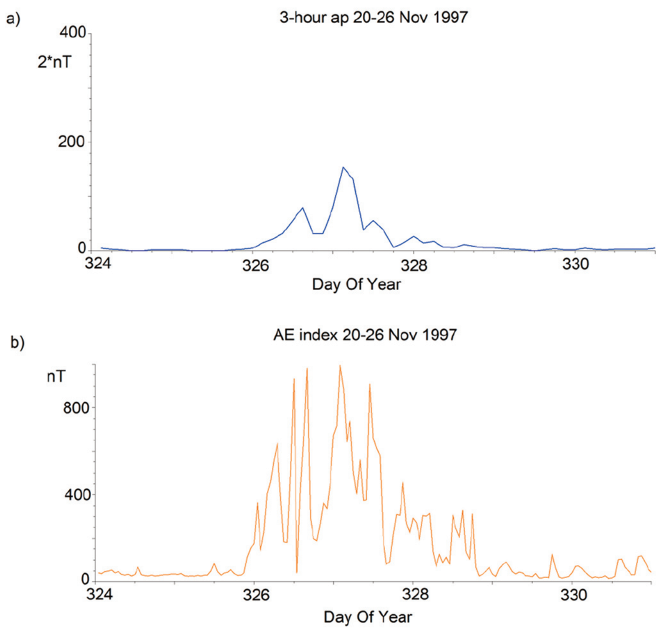

FIGURE 10. Trend of the geomagnetic indices a_p and AE during the ionospheric storm observed from February the 20th 1997, over the Rome observatory.

el a) of Figure 10, where it can be seen how the ap reaches values classified as Strong Storm conditions (G3 range). Such a behaviour is shown also by an increase in the values of the auroral electrojet index AE, starting from the previous day and demonstrated in panel b) of Figure 10.

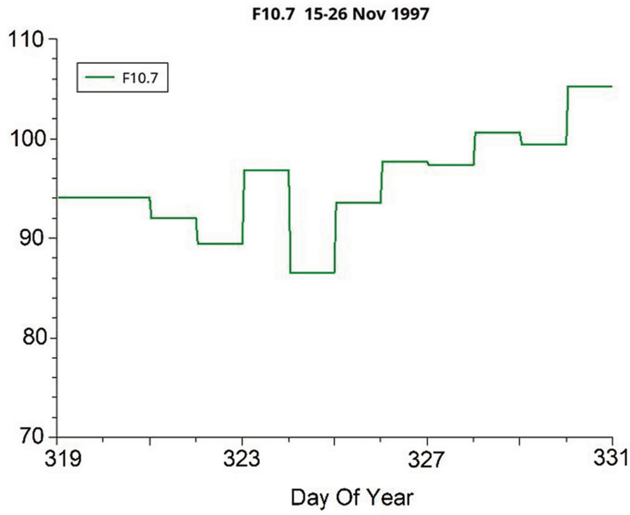

FIGURE 11. Variation of the solar index F10.7 from 15/11/1997 to 26/11/1997. An enhancement in the solar index F10.7 possibly related to the observed ionospheric storm can be seen from the figure.

The ionospheric storm is observed during night-time and, it seems not to be connected with a particular increase of solar activity as shown in the plot of the solar index F10.7 index from 15 to 26 November 1997 (Figure 11), the period preceding the foF2 storm. This suggests that the strong positive variation in the critical frequency of the F2 layer, is probably due to plasmaspheric plasma influx in the ionosphere, which produce a strong enhancement in the electron density at mid latitude.

5. SUMMARY

A study of the foF2 value observed by the ionospheric station of Rome during the solar minimum of the last three solar cycles, has been performed. A characterization of the anomalies in the critical frequency of the F2 layer is presented, in realtion with the geomagnetic activity. A background level of foF2 has been computed through a 27 days running media of the foF2 hourly values observed by the Rome ionosonde. The deviation δf=(*f(hourly) -f(background))/ f(background)*) of the hourly values of the critical frequency of the F2 layer with respect to the defined background has been calculated. A positive ionospheric anomaly has been identified when δf is greater than 15% , while a negative ionospheric anomaly is considered when δf is smaller than -15%. A total number of 1020 anomalies of the critical frequency foF2, have been observed using the described procedure. For each detected anomaly, a study on the geomagnetic conditions has been carried, considering the geomagnetic index ap, which provides a planetary indication of magnetic activity, and the auroral electrojet index AE. The value of the ap index has been considered at the time when the anomaly is detected and for the previous 24 hours, distinguishing 6 levels of magnetic disturbance, from quiet (G0) to extreme storm conditions (G5). The AE values for an interval of 6 hours before the occurrence of the anomaly, have been taken into account, in order to consider the typical travelling time of TADs from high to mid-latitude, and the related perturbation of the F2 layer. AE values less than 100 nT have been here considered as representative of quiet auroral electrojet activity. The conducted analysis shows that negative ionospheric storms particularly occur during strong geomagnetic disturbances and during night-time, especially in summer/equinox season. They are generally preceded by a positive ionospheric storm. Positive ionospheric storms, followed by quiet or positive ionospheric conditions, seem to occur during low or moderate geomagnetic activity at any hour of the day. The studies of the last three solar cycles, put in evidence the peculiarities of the last deep solar minimum, characterized by very few ionospheric anomalies. In particular, for the years 2007, 2008 and 2009, negative storms are observed only during night-time. A deeper analysis of the negative ionospheric storm observed over the Rome observatory on February 7 1986, is here presented, as well as the study on a positive foF2 storm recorded on November 22 1997 by the ionospheric station of Rome.

ACKNOWLEDGEMENTS

This work has been conducted in the framework of LIMADOU-Science project funded by ASI, and e-SAFE project funded by ESA.

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