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An updating of the SIRM model

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Abstract

The SIRM model proposed by Zolesi et al. (1993, 1996) is an ionospheric regional model for predicting the vertical-sounding characteristics that has been frequently used in developing ionospheric web prediction services (Zolesi and Cander, 2014). Recently the model and its outputs were implemented in the framework of two European projects: DIAS (*DIgital upper Atmosphere Server*; http://www.iono.noa.gr/DIAS/) (Belehaki et al., 2005, 2015) and ESPAS (*Near-Earth Space Data Infrastructure for e-Science*; http://www.espas-fp7.eu/) (Belehaki et al., 2016). In this paper an updated version of the SIRM model, called SIRMPol, is described and corresponding outputs in terms of the F2-layer critical frequency (*fo*F2) are compared with values recorded at the mid-latitude station of Rome (41.8°N, 12.5°E), for extremely high (year 1958) and low (years 2008 and 2009) solar activity. The main novelties introduced in the SIRMPol model are: (1) an extension of the Rome ionosonde input dataset that, besides data from 1957 to 1987, includes also data from 1988 to 2007; (2) the use of second order polynomial regressions, instead of linear ones, to fit the relation *fo*F2 vs. solar activity index R_{12}; (3) the use of polynomial relations, instead of linear ones, to fit the relations A_0 vs. R_{12}, A_n vs. R_{12} and Y_n vs. R_{12}, where A_0, A_n and Y_n are the coefficients of the Fourier analysis performed by the SIRM model to reproduce the values calculated by using relations in (2). The obtained results show that SIRMPol outputs are better than those of the SIRM model. As the SIRMPol model represents only a partial updating of the SIRM model based on inputs from only Rome ionosonde data, it can be considered a particular case of a single-station model. Nevertheless, the development of the SIRMPol model allowed getting some useful guidelines for a future complete and more accurate updating of the SIRM model, of which both DIAS and ESPAS could benefit.
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1. Introduction

The study of the ionosphere, together with other geophysical disciplines like meteorology, oceanography and geomagnetism, plays an important role in basic and applied sciences. The cold plasma environment, forming the ionosphere and enveloping the Earth, represents the main driver of the terrestrial and Earth-space radio systems, affecting radio communications in the HF range, interrupting trans-ionospheric commands, controls and communication systems, compromising global positioning networks, and inducing damaging currents in land-based power grids and transcontinental pipelines (Zolesi and Cander, 1998). Therefore, variations in the ionosphere have a prominent impact on numerous daily activities on Earth and for this reason ionospheric modeling, long-term prediction and short-term forecasting are of primary importance.

The development of ionospheric models represents a very interesting challenge because the parameters that

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characterize the ionospheric structure and dynamics are subject to spatial and temporal variations that can be periodic and/or irregular. In addition, ionospheric characteristics used for the electron-density height profile reconstruction for a given location experience systematic daily, seasonal and solar cycle variations (Kutiev et al., 2013). Finally, ionospheric behaviour shows a clear dependence on latitude, with a climatological mid-latitude ionosphere being easier to characterize compared to the equatorial, low-latitude and polar ionosphere.

Since its discovery, many models of the Earth's ionosphere, based on different physical approaches, on various mathematical techniques and describing different parameters, have been developed. In general, ionospheric models can be divided in three main groups (Zolesi and Cander, 2014):

- Theoretical, parameterised, and empirical models that define the ionospheric electron density profile and also the profile parameters in terms of the ionospheric characteristics at every point on the globe;
- Assimilation models for a full three-dimensional (3-D) electron density profile;
- Empirical and physical models or methods for two-dimensional (2-D) global, regional, and local mapping of the ionospheric characteristics and parameters for both long-term prediction and nowcasting in the field of radio propagation and navigation.

Currently, the most widely used models are the International Reference Ionosphere (IRI) (Bilitza, 2001; Bilitza and Reinisch, 2008; Bilitza et al., 1990, 2014) and the NeQuick2 model (Nava et al., 2008). The IRI model is an international project sponsored by the Committee on Space Research (COSPAR) and the International Union of Radio Science (URSI), based on an extensive database and able to capture most of the systematic characteristics of the ionosphere as a function of height, location, and time for quiet and storm-time periods (Araujo-Pradere et al., 2011, 2013; Zakharenkova et al., 2013; Bilitza et al., 2017). IRI is an empirical model representing the reference model for the ionospheric community.

The NeQuick2 model represents the second version of NeQuick (Hochegger et al., 2000; Radicella and Leitinger, 2001), an empirical ionospheric model widely used for the estimation of vertical electron density profiles and related parameters. Moreover, it is a quick-run model particularly tailored for trans-ionospheric applications that allows calculation of the electron concentration at any given location in the ionosphere, and thus of the Total Electron Content (TEC) along any ground-to-satellite ray path by means of numerical integration (Zolesi and Cander, 2014).

During last decades, there has been a trend to focus on regional models, rather than global, because of their capability to produce a more accurate ionospheric representation over particular areas, which gives better results for both telecommunications and geophysical modeling (Brown et al., 1991; Rawer, 1991). At the same time, *Single Station Models* (*SSMs*) have been introduced for both long-term prediction and short-term forecasting. These models, based on an accurate study of the most important ionospheric characteristics, for which a long history of observations is available, can be considered the extreme limit of regional models (Zolesi and Cander, 2014).

Regarding regional models, numerous techniques based on different spatial and temporal fitting algorithms have been proposed for the European sector (Dvinskikh, 1988; Singer and Dvinskikh, 1991; Zolesi et al., 1993; Reinisch et al., 1993; Mikhailov et al., 1996; De Franceschi and De Santis, 1994; Bradley et al., 1994; Pietrella and Perrone, 2005; Pietrella, 2012; Pezzopane et al., 2011, 2013; Mikhailov and Perrone, 2014). The development of regional techniques for the description of median and real-time specifications arose (1) from the request to improve performances for specific areas, (2) in response to the availability of denser network of stations and, (3) to simplify the complex ionospheric morphology over a restricted area.

The Simplified Ionospheric Regional Model (SIRM) by Zolesi et al. (1993) was developed under the Co-operation in the field of Scientific and Technical Research (COST) Action 238 'Prediction and Retrospective Ionospheric Modeling over Europe' (PRIME, Bradley, 1995), and improved and tested under the COST Action 251 'Improved quality of service in Ionospheric Telecommunication Systems planning and operation' (IITS, Hanbaba, 1999).

The introduction of SIRM allowed to examine important questions about how to model the ionosphere in areas with a sparse network of vertical incidence ionosondes and how to use data from inhomogeneous periods. In this modeling, the monthly median behaviour of *fo*F2, *M*(3000)F2, *h'*F, *fo*F1, and *fo*E over Europe is expressed as function of geographic coordinates, of the local (or universal) time, and of the 12-month running mean of the monthly mean sunspot number R_{12} (Zolesi et al., 1996). The procedure is based on the assumption that at constant local time there are no longitude changes of the ionospheric characteristics and that their diurnal and seasonal variations can be well represented by a Fourier expansion with a relatively small number of numerical coefficients (Zolesi et al., 1996). The main aim of the model is to treat the problem of modeling the key ionospheric characteristics of vertical incidence in a restricted area, and to demonstrate how well the model fits the measured data. For this purpose, a limited region in Europe is considered where the spatial resolution of the measured F region maximum electron density may be sufficiently high in comparison to the typical horizontal scale sizes of dynamical phenomena involved in its generation (Zolesi and Cander, 2014). Moreover, such a mid-latitude area is not subject to complex physical processes like those occurring at high and low latitudes. Therefore, the monthly median behaviour of the ionospheric characteristics should not be a function of geographic longitude for the selected area (Khachikyan et al., 1989), and only the model dependence on the geographic latitude can be taken into account (Zolesi et al., 2004).

The aforementioned Fourier coefficients are calculated from the analysis of the hourly monthly median values of the ionospheric characteristics measured at mid-latitude stations over the European region and collected under the COST Actions. For every different month, as a first approximation, the Fourier coefficients are considered linearly dependent on both the solar activity and the geographic latitude. The COST251 testing procedure, that consisted of comparing measurements of all hourly median data available from a given set of ionospheric stations and values predicted by different models, showed that the overall root mean square (RMS) error from SIRM was smaller than the RMS error for the ITU recommended model (ITU-R, 1994; Levy et al., 1998). This validation proved that SIRM performances are satisfactory for the description of median ionospheric conditions at mid latitudes. Furthermore, SIRM also provides an efficient and user-friendly software program with a very simple mathematical formulation of the ionospheric medium.

The relative simplicity of the SIRM model led to the introduction of a real-time updating method of SIRM, with the assimilation of autoscaled ionospheric characteristics observed by four European digisondes (Bibl and Reinisch, 1978), in order to enable SIRM to capture the instantaneous distribution of ionospheric characteristics for disturbed periods. The *SIRM UPdating* (*SIRMUP*; Zolesi et al., 2004; Tsagouri et al., 2005) method is based on the idea that real-time *fo*F2 and *M*(3000)F2 at one location can be determined with SIRM by using an effective sunspot number R_{eff} (Houminer et al., 1993), instead of the 12-month smoothed sunspot number R_{12}.

In light of the results reported by Perna and Pezzopane (2016) concerning the relationships *fo*F2 vs. *Solar Index*, it is interesting to discuss how and whether the SIRM model can be improved accordingly. This is especially important considering that the SIRM model and the corresponding outputs are integrated into two European projects: DIAS (*DIgital upper Atmosphere Server*; http://www.iono.noa.gr/DIAS/) (Belehaki et al., 2005, 2015) and ESPAS (*Near-Earth Space Data Infrastructure for e-Science*; http://www.espas-fp7.eu/) (Belehaki et al., 2016). Specifically, the DIAS project uses the SIRM model to generate long-term and nowcasting maps of *fo*F2 and *M*(3000)F2, while the ESPAS portal provides access to several data archives, and among these the one produced in the framework of DIAS. In the present paper the preliminary results obtained through a partial updating of the SIRM model are displayed and discussed. In Section 2, the mathematical description of the SIRM model, in its original form, and its performances for low and high solar activity levels, are reported. In Section 3, according to the results obtained by Perna and Pezzopane (2016), a modified version of the SIRM model, named *SIRMPol* (*Simplified Ionospheric Regional Model Polynomial*), is presented, and corresponding preliminary results are discussed in Section 4. Conclusions and guidelines for a future complete implementation of the SIRM model are the subject of Section 5.

2. The SIRM model: A short recall and a comparison with *fo*F2 measured data at Rome in 1958, 2008, and 2009

The SIRM model is a regional long-term prediction model developed by Zolesi et al. (1993, 1996) to predict the key standard vertical incidence ionospheric characteristics (*fo*F2, *M*(3000)F2, *h*′F, *fo*F1 and *fo*E) over a restricted area of Europe. The first version of the SIRM model provided a description of the aforementioned ionospheric characteristics in terms of their monthly median values.

The database used to develop the model was collected by the Centre National d'Etudes des Telecommunications (CNET) in Lannion (France) and by the Word Data Center-A (Boulder, Colorado), and it consisted of monthly median values of the ionospheric characteristics available for several years, recorded by the European vertical incident ionospheric stations listed in Table 1 and mapped in Fig. 1.

Considering the seven stations of Table 1, the SIRM model spans an area of about 25° in longitude and about 20° in latitude. Given the limited longitudinal range, it is expected that, at mid latitudes considered by SIRM, the variability of the ionospheric characteristics should not be longitudinal-dependent. Therefore, only the dependence on geographical latitude is taken into account by the model.

Dominici and Zolesi (1987) found that monthly median values of the ionospheric characteristics at Rome station vary linearly with the sunspot number (monthly mean or median values) or its 12-month running mean R_{12}. Therefore, the first step of the procedure is a linear regression of monthly median values for a given ionospheric characteristic $\Theta_{\mathrm{h,m}}$, taken at local (or universal) time, against the solar index R_{12}:

$$\Theta_{\mathrm{h,m}} = \alpha_{\mathrm{h,m}}(R_{12}) + \beta_{\mathrm{h,m}}. \quad (1)$$

In Eq. (1) $\alpha_{\mathrm{h,m}}$ and $\beta_{\mathrm{h,m}}$ are two matrices of 288 coefficients (24 h × 12 months), one for each hour (h) of the day, and for each month (m) of the year. Using Eq. (1),

Table 1
Geographic latitude, longitude and available dataset of European ionospheric stations used to develop the SIRM model.

Station name	Geog. Lat.	Geog. Lon.	Dataset
Uppsala	59.8°N	17.6°E	1967–1976
De Bilt	52.1°N	5.1°E	1968–1976
Lannion	48.6°N	3.5°W	1971–1984
Poitiers	46.5°N	0.3°E	1964–1984
Grocka	44.8°N	20.5°E	1964–1985
Rome	41.8°N	12.5°E	1957–1987
Gibilmanna	38.0°N	14.0°E	1976–1979 and 1984–1987

Fig. 1. Map of European ionospheric stations used to develop the SIRM model.

it is considered that the solar cycle variation of monthly median values can be fully described at any ionospheric station, for each month and hour, by only two levels of solar activity and the straight line joining them (McNamara, 1991). The linear regression analysis is then considered as the best prediction of measured data at every single station. Two values of solar activity, $R_{12} = 0$ and $R_{12} = 100$, are chosen and used to describe low and high solar activity levels, respectively, and two sets of synthetic monthly median values of the ionospheric characteristic are then correspondingly obtained by using Eq. (1), for every station in question.

The second step of the procedure consists of doing a Fourier analysis of synthetic datasets obtained at the end of the first step:

$$\Theta_{\mathrm{h,m}} = A_0 + \sum_{n}^{l} A_n \sin\left(\frac{2\pi nt}{T} + Y_n\right), \tag{2}$$

where n is the harmonic number, $T = 288$ h corresponds to a fundamental period of a "virtual year" with a fixed level of R_{12}, t is the time in hours for which $t = 1$ corresponds to 00:00 LT of January and $t = 288$ to 23:00 LT of December. It is clear that with coefficients A_0, A_n and Y_n, where $n = 1, 2, \ldots, l = 144$, the Fourier synthesis repeats the $\Theta_{\mathrm{h,m}}$ values that are obtained from Eq. (1) through the two matrices $\alpha_{\mathrm{h,m}}$ and $\beta_{\mathrm{h,m}}$. Zolesi et al. (1993, 1996) have shown that A_0 and 12 pairs (A_n, Y_n) of dominant Fourier coefficients are sufficient to reproduce the main features of the diurnal, seasonal and solar cycle behaviour of the mid-latitude ionosphere under quiet conditions. Using this technique for every considered station of Table 1, Zolesi et al. (1993) found a good agreement between the results of the Fourier synthesis and the results of a simple linear regression. In this way, it is possible to reproduce the temporal variations of the key ionospheric characteristics at each ionospheric station and, according to this evidence, Fourier coefficients A_0, A_n and Y_n in Eq. (2) can be considered, as a first approximation, linearly dependent on R_{12}:

$$\begin{aligned} A_0 &= a_0(R_{12}) + b_0, \\ A_n &= a_n(R_{12}) + b_n, \\ Y_n &= c_n(R_{12}) + d_n. \end{aligned} \tag{3}$$

Eqs. (3) are applied to the database of the seven ionospheric stations shown in Fig. 1, using a local time (LT) format and taking into account the differences between LT and the local standard time through the phase Y_n in Eq. (2). Zolesi et al. (1993) found that results for coefficients A_0, A_n and Y_n used in the evaluation of *fo*F2, *M*(3000)F2 and *h*'F, corresponding to $R_{12} = 0$ and $R_{12} = 100$, show a linear variation with the geographic latitude thus confirming the validity of the concept that the coefficients a_0, b_0, a_n, b_n, c_n and d_n, can be regarded as a linear function of the geographic latitude ϕ in a restricted area. Therefore, the spatial distribution of A_0, A_n and Y_n can be expressed as:

$$\begin{aligned} A_0 &= (a_0^1\phi + a_0^2)R_{12} + b_0^1\phi + b_0^2, \\ A_n &= (a_n^1\phi + a_n^2)R_{12} + b_n^1\phi + b_n^2, \\ Y_n &= (c_n^1\phi + c_n^2)R_{12} + d_n^1\phi + d_n^2. \end{aligned} \tag{4}$$

The numerical coefficients a_0^j, b_0^j, a_n^j, b_n^j, c_n^j, d_n^j with $j = 1$, 2 can be easily calculated by a linear regression of Fourier coefficients of every ionospheric station versus their latitudes (Zolesi et al., 1990, 1991).

The SIRM model is completely described by Eqs. (1)–(4). To fix the key points, the main characteristics of the model are here summarized:

- Linear regressions between monthly median values $\Theta_{h,m}$ and R_{12};
- Consideration of two solar activity levels: $R_{12} = 0$ (low solar activity) and $R_{12} = 100$ (high solar activity). Other levels of solar activity are considered by a linear interpolation between these two boundaries;
- Linear regressions between Fourier coefficients A_0, A_n and Y_n and the R_{12} index;
- Linear regressions between Fourier coefficients A_0, A_n and Y_n and the latitude ϕ;
- No variations in longitude.

It is important to underline how the total representation involves only 100 numerical coefficients for each ionospheric characteristic and therefore yields considerable economy in data storage and computation.

Preliminary results showed that the SIRM model *fo*F2 outputs match the input data used in their generation with a standard deviation of about 0.5 MHz (Zolesi et al., 1990). The reliability of SIRM *fo*F2 outputs have also been tested making comparisons with station measurements not used when generating SIRM coefficients. For high solar activity, typical differences of around 0.7 MHz or less have been observed (Zolesi et al., 1991, 1993).

Zolesi et al. (1996) have tested SIRM performances with several inhomogeneous datasets from a sparse network of ionospheric stations in mid-latitude areas such as northeastern North America, southeastern South America, northeast Asia, and southeast Australia. The results show that the agreement between the model and observed data for *fo*F2 and *M*(3000)F2 is quite remarkable when taking into account simple assumptions, that is, no longitudinal-dependent variations, linear variation of model coefficients with the geographic latitude, and their reduced number.

However, it is expected that for mid-latitude areas with a dense ionosondes network and continuous, long and reliable datasets, such as the European region, SIRM outputs would provide very good agreements with observed data. In fact, due to its high-quality results in the European area, economy in computation and quick response, the SIRM model and its real-time version SIRMUP, have been used in the European project DIAS to produce long-term and nowcasting maps of *fo*F2 and *M*(3000)F2, which are also accessed by the ESPAS portal.

As reported by Liu et al. (2011), the last solar minimum has shown an unprecedented prolonged and low solar activity, providing a perfect natural window to study the ionospheric plasma response and the reliability of ionospheric models for such particular conditions. Therefore, thanks to a very long, continuous and reliable dataset available for the Rome station, it is very interesting to compare SIRM outputs with Rome ionosonde monthly median values, limiting the study to the most important ionospheric characteristic *fo*F2.

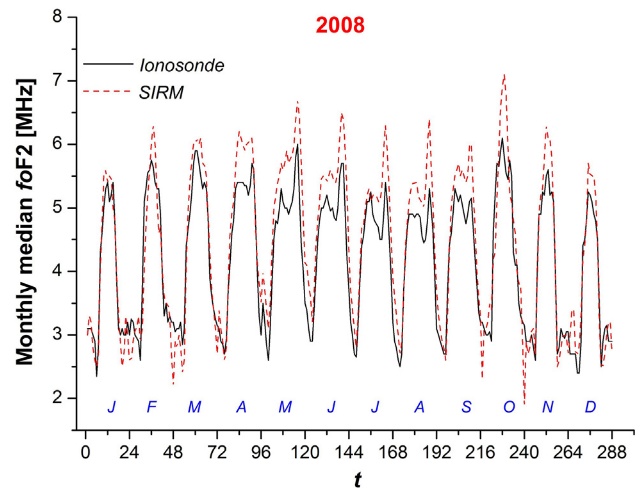

Fig. 2. Hourly monthly median *fo*F2 values at the Rome station as measured by the ionosonde (black) and calculated by the SIRM model (dashed red) for the whole year 2008. The x axis spans from $t = 0$ (00:00 LT of January 2008) to $t = 288$ (23:00 LT of December 2008). Capital letters in blue identify months from January (J) to December (D). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Figs. 2 and 3 report the comparison between hourly monthly median values calculated by SIRM and those measured by the ionosonde at Rome, for 2008 and 2009, which represent the deepest phase of the last solar minimum. SIRM outputs provide a good agreement with ionosonde data for both 2008 and 2009, using as input observed values of the solar index R_{12}. To quantify SIRM performances, the mean deviation $(\sum_{i=1}^{n}|foF2_{SIRM} - foF2_{obs}|_i/n)$ has been calculated, where $foF2_{SIRM}$ and $foF2_{obs}$ are monthly median *fo*F2 values coming from SIRM and ionosonde, respectively. The mean deviation values are 0.47 MHz and 0.43 MHz for the whole 2008 and 2009 respectively, confirming the good results provided by SIRM.

These results are not surprising because, as mentioned, it is expected that SIRM provides good correspondences with ionosonde data in mid-latitude areas with a dense ionosondes network. Furthermore, (1) Rome ionosonde data were used to develop the SIRM model (see Table 1) and (2), as shown in Table 2, R_{12} values for 2008 and 2009 are very low and close to the value $R_{12} = 0$ that is one of the two levels of solar activity set in the model.

However, Figs. 2 and 3 also show the following features: (1) the SIRM model tends to overestimate the daily peak of *fo*F2, in particular for 2008; (2) night-time values are well described by the SIRM model during summer and spring

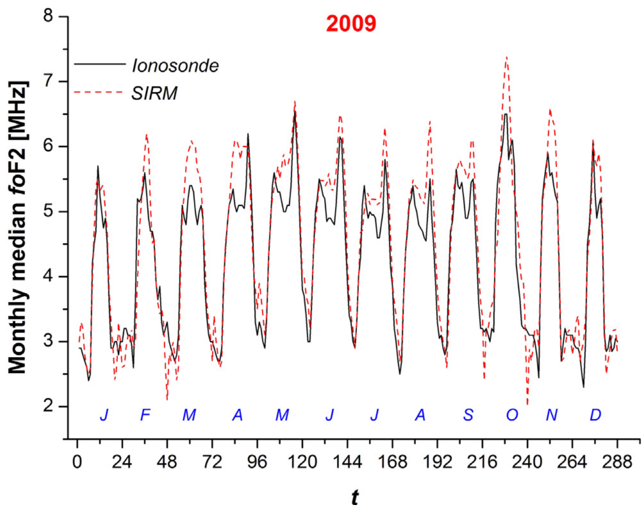

Fig. 3. Same as Fig. 2 for 2009.

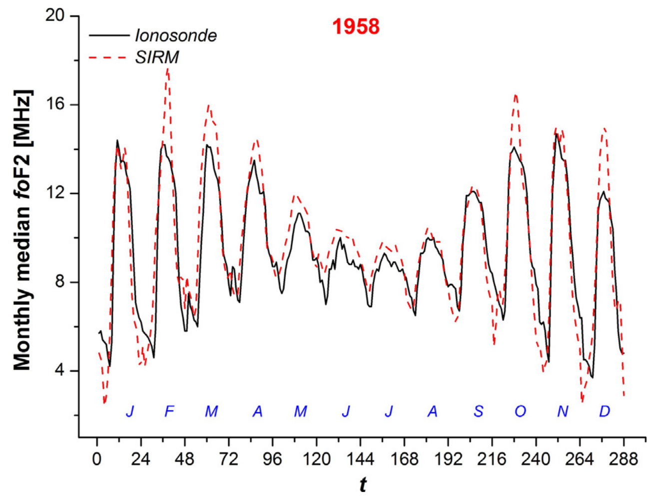

Fig. 4. Same as Fig. 2 for 1958.

months, while more pronounced differences characterize winter and autumn months (in particular January, February, September and October).

Moreover, we have to take into account that, for mid and very high solar activity, hysteresis and saturation effects (Kane, 1992; Mikhailov and Mikhailov, 1995; Liu et al., 2006; Rao and Rao, 1969; Triskova and Chum, 1996) become important, in particular when *fo*F2 vs. *Solar Index* relationships are considered using mean or median values, such as in the SIRM model. In particular, it was shown how the saturation can be viewed as a second order effect that, using linear regressions for *fo*F2 vs. R_{12} relationships, can lead to pronounced model overestimations (Perna and Pezzopane, 2016, and references therein). Fig. 4 shows a comparison between *fo*F2 values calculated by SIRM and those recorded at Rome, for 1958, a year of very high solar activity (maximum of solar cycle 19, see Table 2).

Contrary to 2008 and 2009, the year 1958 is included in the dataset used to develop the SIRM model (see Table 1), therefore good results should be expected. This high solar activity year has been chosen to test SIRM outputs, because for all months the R_{12} value is markedly higher than that of the saturation level, therefore it is expected that using the linear regression (1) pronounced overestimations can occur. This is confirmed by the mean deviation between SIRM and ionosonde values for the whole year 1958 which is 1.04 MHz, more than 50% higher than the results obtained for 2008 and 2009. Furthermore, Fig. 4 shows that during daytime hours for February, March, October, and December, SIRM overestimations as high as 3–4 MHz are obtained.

Table 2
R_{12} values for 2008, 2009 and 1958.

Month	2008	2009	1958
January	4.2	1.8	199.0
February	3.6	1.9	200.9
March	3.3	2.0	201.3
April	3.4	2.2	196.8
May	3.5	2.3	191.4
June	3.3	2.7	186.8
July	2.8	3.6	185.2
August	2.7	4.8	184.9
September	2.3	6.2	183.8
October	1.8	7.1	182.2
November	1.7	7.6	180.7
December	1.7	8.3	180.5

As it was already mentioned, the simple formulation of the SIRM model makes it easy to interface it with other regional or global models. Moreover, the model can be also used as a suitable tool to study the basic physical processes controlling the behaviour of the F region and to provide a quick prediction of ionospheric conditions (Belehaki et al., 2005, 2015). For these reasons and in light of the results shown in Figs. 2–4, it is interesting to test the results of a partial updating of the SIRM model, named SIRMPol, implemented according to the conclusions reported by Perna and Pezzopane (2016) about the *fo*F2 vs. *Solar Index* relationship.

3. The *SIRMPol* model: Main features

Recent results about the *fo*F2 vs. *Solar Index* relationships (e.g., Liu et al., 2011; Chen et al., 2011; Perna and Pezzopane, 2016) provide useful information to improve the reliability of ionospheric models. In particular, the work of Perna and Pezzopane (2016), concerning the very long, continuous and reliable *fo*F2 dataset of Rome ionosonde, showed that: (1) the relationships *fo*F2 vs. *Solar Index* can be well described with a quadratic polynomial regression; (2) the use of linear fitting relationships *fo*F2 vs. *Solar Index* gives rise to significant overestimations of observed data, because of both the saturation effect at high solar activity and the extremely low and prolonged solar activity like that characterizing the minimum between solar cycles 23 and 24.

Accordingly, a first improvement that can be introduced in the SIRM model is to consider a second order polynomial regression for the relationship *fo*F2 vs. R_{12}:

$$foF2_{h,m} = \hat{\alpha}_{h,m}(R_{12})^2 + \hat{\beta}_{h,m}(R_{12}) + \hat{\gamma}_{h,m}, \tag{5}$$

where coefficients $\hat{\alpha}_{h,m}$, $\hat{\beta}_{h,m}$ and $\hat{\gamma}_{h,m}$ are calculated through a polynomial regression.

The proposed update of the SIRM model, named *SIRMPol* (*Simplified Ionospheric Regional Model Polynomial*), is based on very simple changes that can be summarized as follows:

1. The input dataset for Rome station has been updated, spanning from January 1957 to December 2007 (the SIRM model is based on the dataset for Rome from January 1957 to December 1987). With regard to this, it is important to highlight that the dataset is composed by hourly validated values recorded from the 1st January 1957 to the 31st December 2007, hence covering solar cycles 19, 20, 21, 22, 23. The values were validated according to the International Union of Radio Science (URSI) standard (Wakai et al., 1987). The validation was performed from traces recorded by classical ionosondes, which cannot tag the different polarization characterizing the two different modes of propagation of the electromagnetic wave. A VOS-1 chirp ionosonde produced by the Barry Research Corporation, Palo Alto, CA, USA (Barry Research Corporation, 1975) sounded from January 1957 to November 2004, and then it was replaced by an AIS-INGV ionosonde (Zuccheretti et al., 2003), for which the ionograms were validated by using the Interpre software (Pezzopane, 2004). This means that the *fo*F2 validated time series recorded at Rome represents a reliable and homogeneous dataset. Data were downloaded from the electronic Space Weather upper atmosphere database (eSWua; http://www.eswua.ingv.it/) (Romano et al., 2008).
2. Nine synthetic *fo*F2 datasets are constructed by considering nine different values of solar activity: $R_{12} = 0$, 25, 50, 75, 100, 125, 150, 175 and 200 (the SIRM model considers only two different values of R_{12}: 0 and 100).
3. A polynomial fit between Fourier coefficients A_0, A_n and Y_n and the solar index R_{12} is applied (a linear fit is instead applied by the SIRM model):

$$\begin{aligned} A_0 &= \hat{a}_0(R_{12})^m + \hat{b}_0(R_{12})^{m-1} + \ldots + \hat{\delta}, \\ A_n &= \hat{a}_n(R_{12})^m + \hat{b}_n(R_{12})^{m-1} + \ldots + \hat{\gamma}, \\ Y_n &= \hat{c}_n(R_{12})^m + \hat{d}_n(R_{12})^{m-1} + \ldots + \hat{\nu}. \end{aligned} \tag{6}$$

Before showing the results of the SIRMPol model, it is interesting to discuss, clarify and justify briefly the proposed changes.

As a first consideration, it is worth noting that, owing to a lack of data, it was not possible to consider the aforementioned changes for the other six ionosondes used to develop the SIRM model (see Table 1). Consequently, the SIRMPol model takes as input only data recorded at Rome and then provides a description, in terms of *fo*F2 monthly median values, only for this station. Therefore, the updating proposed here has to be considered only a partial/local updating of the SIRM model and can be considered a particular case of a single-station model. However, it is important to underline that the main aim behind the development of the SIRMPol model is to obtain useful information to draft a list of guidelines for a future accurate and complete updating of the SIRM model by additional ionospheric stations for which reliable datasets are now available.

The choice of the second order polynomial regression (Eq. (5)) should improve the reliability of outputs for high solar activity levels, and for the very low solar activity levels of the last solar minimum, according to what it was shown by Perna and Pezzopane (2016). In support of this, Fig. 5 shows scatterplots of *fo*F2 vs. R_{12} for the Rome dataset (1957–2007), for March, June, September and December, at 01:00 LT and 13:00 LT. Red lines and blue curves identify respectively a linear and a second order regression of the dataset. Red dots represent values of the last solar minimum (years 2008 and 2009) that are not included in the fits. The figure shows how the saturation effect presents a seasonal dependence, being more pronounced during the ionospheric spring-summer. However, this feature is well represented by a second order regression which, at the same time, represents quite well the low values of the last solar minimum.

To implement the SIRMPol model, nine levels of solar activity have been considered from $R_{12} = 0$ to $R_{12} = 200$, with a step of $R_{12} = 25$. This change should provide a better representation of the ionospheric plasma for both levels of solar activity between the two anchor points of the SIRM model ($R_{12} = 0$ and $R_{12} = 100$) and high solar activity levels. Furthermore, considering nine values of R_{12}, it has been observed how relations A_0 vs. R_{12}, A_n vs. R_{12}, and Y_n vs. R_{12} are no more linear, as they are in the SIRM model.

This is clearly shown in Fig. 6, where relationships A_{13} vs. R_{12} (black squares) and Y_{13} vs. R_{12} (blue squares) are displayed. It is noticeable how linear regressions calculated on the basis of the only two values $R_{12} = 0$ and $R_{12} = 100$ (red lines), as it is done in the SIRM model, are inadequate. In general, it has been concluded that, for all Fourier coefficients, polynomial (either second or third order) regressions provide the best choice to represent the relationships between Fourier coefficients and R_{12}, as indicated by the third-order polynomial regressions shown in Fig. 6. It is worth noting that a test extending the series to 16 pairs (A_n, Y_n) of dominant Fourier coefficients has not improved significantly the performances of SIRMPol. Therefore, as reported by Zolesi et al. (1993), it is confirmed that 12 pairs (A_n, Y_n) of dominant Fourier coefficients are sufficient to

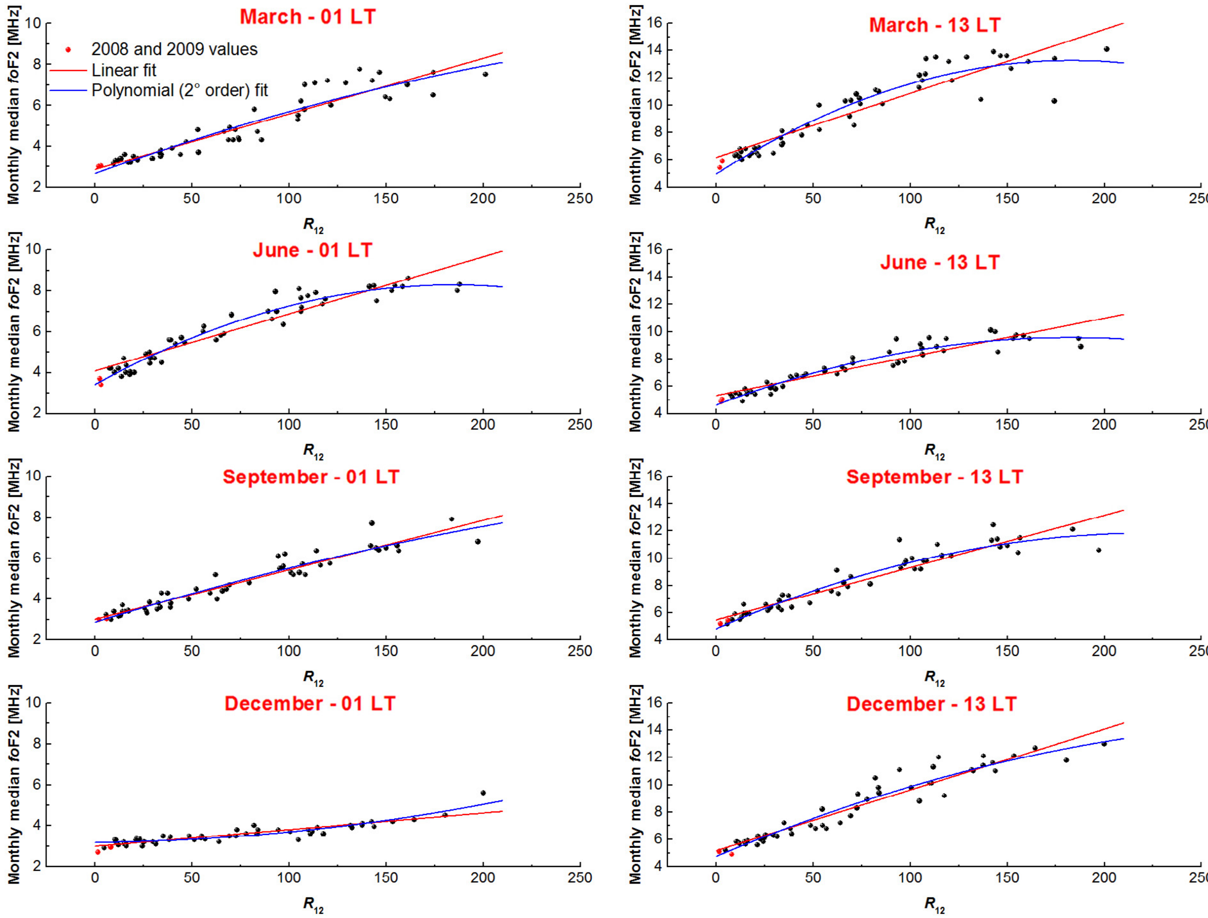

Fig. 5. Monthly mean foF2 vs. R_{12} at 01:00 LT and 13:00 LT for March, June, September, and December for the Rome dataset (1957–2007). The red line and the blue curve represent respectively the linear and the second order polynomial regression. Red dots represent values for 2008 and 2009. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

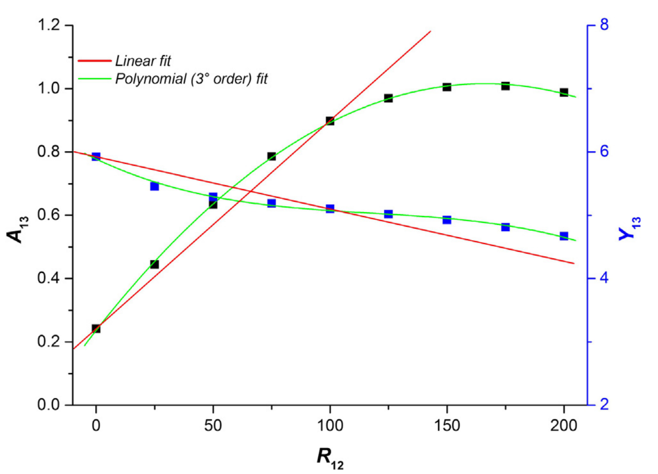

Fig. 6. A_{13} vs. R_{12} (black squares) and Y_{13} vs. R_{12} (blue squares) plots. Red lines represent linear regressions between the two points $R_{12} = 0$ and $R_{12} = 100$, as it is done in the SIRM model, while green curves represent third-order polynomial regressions. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

adequately describe the particular ionospheric characteristic as it was the case in the SIRM model.

4. Results

Figs. 7 and 8 display the comparison of monthly median foF2 values for the Rome station, as measured by the ionosonde, and calculated by SIRM and SIRMPol for 2008 and 2009, respectively. It is evident how, in some cases, the SIRMPol model provides a better agreement with ionosonde data than the SIRM model. In particular, the SIRM tendency to overestimate ionosonde values around midday appears substantially reduced. Similarly, SIRM underestimations observed during night-time hours in January–March and in September–November result to be reduced as well. Mean deviation values for the whole 2008 and 2009 reveal an improvement using SIRMPol, from 0.47 MHz (SIRM) to 0.37 MHz (SIRMPol), for 2008, and from 0.43 MHz (SIRM) to 0.35 MHz (SIRMPol), for 2009. Hence, it is confirmed that a second order regression can be better than a linear one to express the variability of the ionospheric plasma for extremely low solar activity.

Fig. 5 shows how the saturation effect for high solar activity remains an important issue to be studied for a better implementation of this modeling technique. In order to discuss this subject, a comparison between ionosonde data,

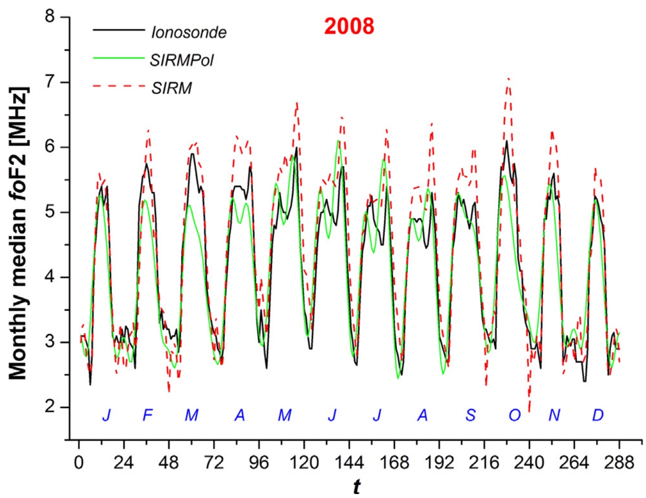

Fig. 7. Comparison of hourly monthly median *fo*F2 values for the Rome station as measured by the ionosonde (black), and calculated by SIRM (dashed red) and SIRMPol (green), for the whole 2008. The *t* parameter on the *x* axis is the same as in Fig. 2. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

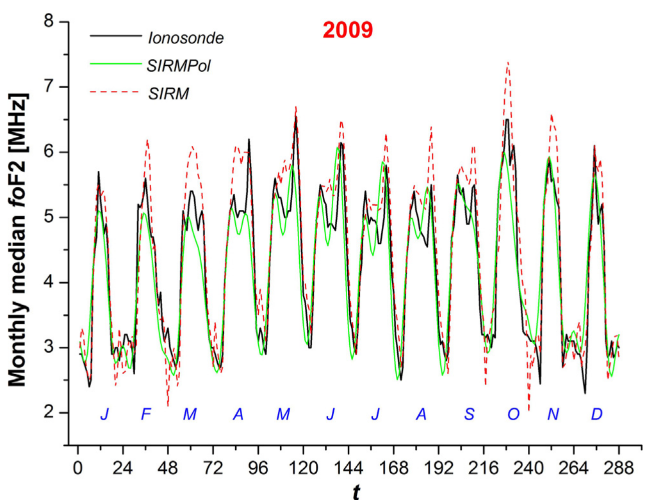

Fig. 8. Same as Fig. 7 for 2009.

and SIRM and SIRMPol outputs has been carried out for 1958, a year of very high solar activity, and corresponding results are displayed in Fig. 9.

Considering the whole year, mean deviations from ionosonde data of 1.04 and 0.81 MHz have been obtained for SIRM and SIRMPol, respectively. The difference of 0.23 MHz, for the whole 1958, increases to 0.32 MHz (1.04 and 0.72 MHz for SIRM and SIRMPol respectively) for the time window 10:00–15:00 LT, when the saturation effect is more pronounced during all the year (see Fig. 5). However, the comparison of mean deviations calculated for the whole 1958 gives only a partial view of the improvement done by substituting linear regressions with second order polynomial ones. This is because the saturation effect strongly depends on solar activity, month and hour in question (see Fig. 5). As an example, Fig. 10 reports the scatterplot *fo*F2 vs. R_{12} for March between 10:00 LT and 15:00 LT for the Rome dataset 1957–2007. For this month, the value of R_{12} (201.3) recorded in 1958 is the highest registered during the whole period 1957–2007. The orange triangles in Fig. 10 emphasize right the *fo*F2 value recorded in 1958. The figure suggests that, using SIRM (which is based on linear regressions), important overestimations are obtained, while less pronounced differences are expected using SIRMPol (which is based on second order polynomial regressions). The comparison between ionosonde data, SIRM and SIRMPol outputs for March 1958 is displayed in Fig. 11. The figure shows that SIRM provides relevant overestimations during daytime hours (06:00–17:00 LT), while better agreements are obtained using SIRMPol. If in Fig. 11 we focus our attention on the hours displayed in Fig. 10, the following differences between the model and the ionosonde value are obtained: at 10:00 LT + 1.90 MHz (SIRM) and +0.38 MHz (SIRMPol), at 11:00 LT + 1.30 MHz (SIRM) and −0.59 MHz (SIRMPol), at 12:00 LT + 1.90 MHz (SIRM) and −0.77 MHz (SIRMPol), at 13:00 LT + 1.90 MHz (SIRM) and −1.21 MHz (SIRMPol), at 14:00 LT + 1.50 MHz (SIRM) and −1.23 MHz (SIRMPol), at 15:00 LT + 2.20 MHz (SIRM) and −0.99 MHz (SIRMPol). Therefore, when a pronounced saturation effect occurs, improvement of more than 1 MHz can be obtained using a second order polynomial regression instead of a linear one.

Comparing mean deviations obtained for 1958, 2008, and 2009, it is possible to claim that both SIRM and SIRMPol provide better results for the very anomalous low solar activity of the last solar minimum than for very high solar activity. This feature needs to be further investigated.

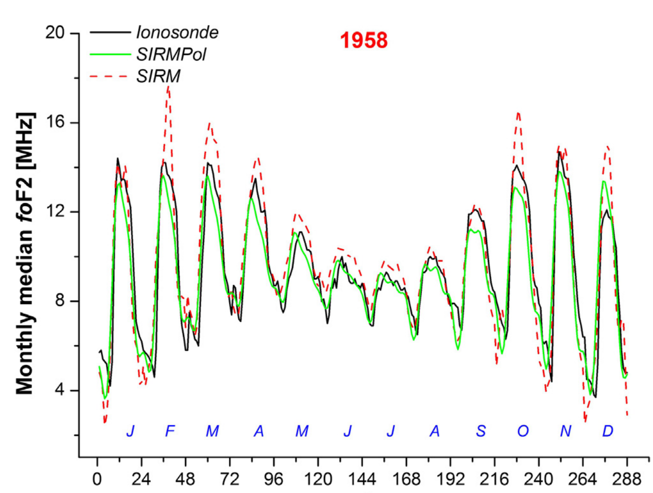

Fig. 9. Same as Fig. 7 for 1958.

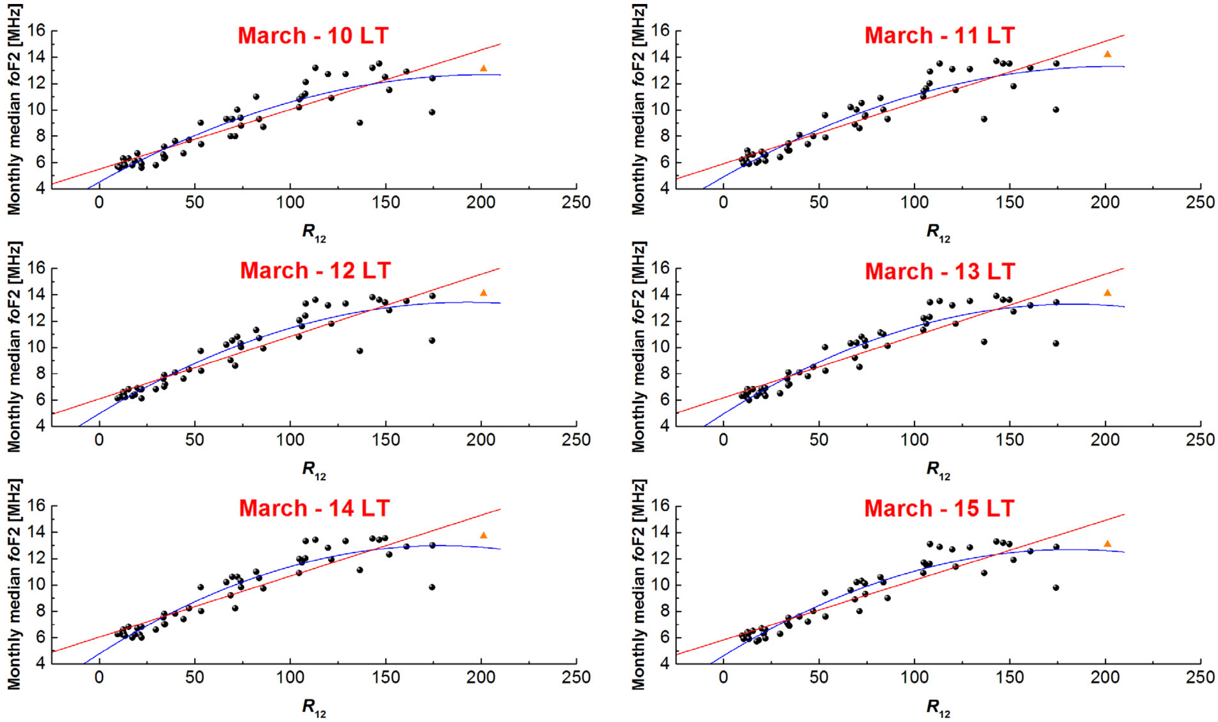

Fig. 10. *fo*F2 vs. R_{12} for the Rome dataset (1957–2007) for March between 10:00 LT and 15:00 LT. Red lines and blue curves represent linear and second order polynomial regressions of the data. Orange triangles identify values for 1958. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

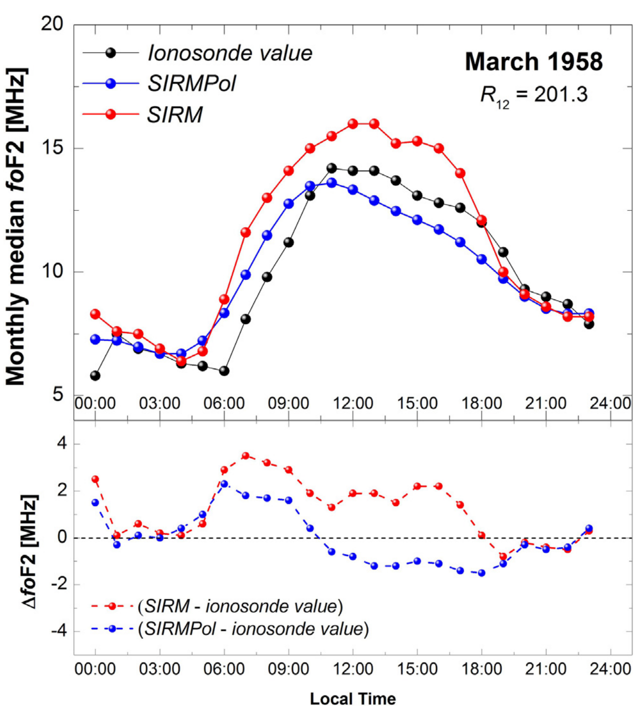

Fig. 11. (Top) Comparison between hourly monthly median foF2 values observed by the ionosonde (black), and calculated by SIRM (red) and SIRMPol (blue) for March 1958. The corresponding value of R_{12} is also displayed. (Bottom) Point-to-point differences SIRM-Ionosonde (red) and SIRMPol-Ionosonde (blue). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

5. Conclusions

In this paper an updated version of the SIRM model, called SIRMPol, was described and corresponding *fo*F2 values have been compared with those recorded at Rome mid-latitude ionospheric station, for years of extremely high (1958) and low (2008 and 2009) solar activity.

The main novelties introduced by the SIRMPol model are: (1) an extension of the Rome ionosonde dataset (from 1957–1987 to 1957–2007); (2) the use of second order polynomial regressions for the relations *fo*F2 vs. R_{12} instead of linear ones; (3) the consideration of nine levels of solar activity instead of only two, and consequently the use of polynomial relations to fit the relations A_0 vs. R_{12}, A_n vs. R_{12} and Y_n vs. R_{12} instead of linear ones. The obtained results show that SIRMPol *fo*F2 outputs are better than those of the SIRM model, specifically when a pronounced saturation effect is observed at high solar activity. Moreover, the outputs of both models are better for low solar activity than for high solar activity.

It has to be noted that the SIRMPol model represents only a partial updating of the SIRM model, because it provides outputs only for Rome ionospheric station and for the characteristic *fo*F2. However, the main aim of the development of the SIRMPol model was to obtain a compendium of guidelines for a future complete and accurate updating of the SIRM model. A summary of the main guidelines is here reported:

o Besides those listed in Table 1, additional ionosondes have to be considered over the European area;
o Concerning the relationship *fo*F2 vs. R_{12}, the model should be based on second order polynomial regressions;
o Concerning the A_0 vs. R_{12}, A_n vs. R_{12} and Y_n vs. R_{12} relationships, the model should be based on polynomial relations.

Furthermore, in the next years, it will be possible to analyze the characteristics of other solar activity indices, such as *MgII* (Viereck et al., 2001) and *EUV* (Judge et al., 1998), when a corresponding longer dataset will be available. The usage of solar indices like *MgII* and *EUV*, instead of R_{12}, should strongly reduce the influence of the hysteresis effect for mid solar activity (Perna and Pezzopane, 2016).

A future development of the SIRM model concerns the addition of new ionosonde stations among which for example El Arenosillo (Spain, 37.1°N, 6.7°W), Kiruna (Sweden, 67.8°N, 20.4°E), and Moscow (Russia, 55.7°N, 37.6°E). This would extend the applicability of SIRM up to 70° in latitude (and 40° in longitude), i.e., to high-latitude regions characterized by a more complex ionospheric dynamics both in time and space. Of course, in this case, when developing the model, also the longitudinal dependence must be taken into account.

References

Araujo-Pradere, E.A., Redmon, R., Fedrizzi, M., Viereck, R., Fuller-Rowell, T.J., 2011. Some characteristics of the ionospheric behavior during the solar cycle 23–24 minimum. Sol. Phys. 274, 439–456. http://dx.doi.org/10.1007/s11207-011 9728-3.

Araujo-Pradere, E.A., Buresova, D., Fuller-Rowell, D.J., Fuller-Rowell, T.J., 2013. Initial results of the evaluation of IRI hmF2 performance for minima 22–23 and 23–24. Adv. Space Res. 51 (4), 630–638. http://dx.doi.org/10.1016/j.asr.2012.02.010.

Barry Research Corporation, 1975. VOS-1A User Manual. Palo Alto, California, USA.

Belehaki, A., Cander, L.R., Zolesi, B., Bremer, J., Juren, C., Stanislawska, I., Dialetis, D., Hatzopoulos, M., 2005. DIAS Project: the establishment of a European digital upper atmosphere server. J. Atmos. Solar Terr. Phys. 67 (12), 1092–1099, 2005. http://dx.doi.org/10.1016/j.jastp.2005.02.021.

Belehaki, A., Tsagouri, I., Kutiev, I., Marinov, P., Zolesi, B., Pietrella, M., Themelis, K., Elias, P., Tziotziou, K., 2015. The European Ionosonde Service: nowcasting and forecasting ionospheric conditions over Europe for the ESA Space Situational Awareness services. J. Space Weather Space Clim. 5, A25. http://dx.doi.org/10.1051/swsc/2015026.

Belehaki, A., James, S., Hapgood, M., Ventouras, S., Galkin, I., Lembesis, A., Tsagouri, I., Charisi, A., Spogli, L., Berdermann, J., Haggstrom, J., The ESPAS Consortium, 2016. The ESPAS e-infrastructure: Access to data from near-Earth space. Adv. Space Res. 58, 1177–1200. http://dx.doi.org/10.1016/j.asr.2016.06.014.

Bibl, K., Reinisch, B.W., 1978. The universal digital ionosonde. Radio Sci. 13, 519–530. http://dx.doi.org/10.1029/RS013i003p00519.

Bilitza, D., Rawer, K., Bossy, L., Kutiev, I., Oyama, K.-I., Leitinger, R., Kazimirovsky, E., 1990. International Reference Ionosphere 1990. NSSDC 90-22, Greenbelt, Maryl., 53, 160. http://dx.doi.org/10.1017/CBO9781107415324.004.

Bilitza, D., 2001. International reference ionosphere 2000. Radio Sci. 36, 261–275. http://dx.doi.org/10.1029/2000RS002432.

Bilitza, D., Reinisch, B.W., 2008. International Reference Ionosphere 2007: improvements and new parameters. Adv. Space Res. 42 (7), 599–609. http://dx.doi.org/10.1016/j.asr.2007.07.048.

Bilitza, D., Altadill, D., Zhang, Y., Mertens, C., Truhlik, V., Richards, P., McKinnell, L.-A., Reinisch, B., 2014. The International Reference Ionosphere 2012 – a model of international collaboration. J. Space Weather Space Climate 4, A07. http://dx.doi.org/10.1051/swsc/2014004.

Bilitza, D., Altadill, D., Truhlik, V., Shubin, V., Galkin, I., Reinisch, B., Huang, X., 2017. International Reference Ionosphere 2016: from ionospheric climate to real-time weather predictions. Space Weather 15 (2), 418–429. http://dx.doi.org/10.1002/2016SW001593.

Bradley, P.A., Cander, L.R., Dick, M., Jodogne, J.C., Kouris, S.S., Leitinger, R., Singer, W., Xenos, T.D., Zolesi, B., 1994. The December 1993 new mapping meeting. In: Numerical Mapping and Modelling and their Applications to PRIME, Proceedings of the PRIME COST 238 Workshop. Eindhoven Univ. of Technol, Eindhoven, Netherlands, pp. 169–179.

Bradley, P.A., 1995. PRIME (prediction regional ionospheric modelling over Europe). COST Action 238 Final Report. Commission of the European Communities, Brussels.

Brown, L.D., Daniell, R.E., Fox, M.W., Klobuchar, J.A., Doherty, P.H., 1991. Evaluation of six ionospheric models as predictors of total electron content. Radio Sci. 26 (4), 1007–1015. http://dx.doi.org/10.1029/91RS00513.

Chen, Y., Liu, L., Wan, W., 2011. Does the F10.7 index correctly describe solar EUV flux during the deep solar minimum of 2007–2009? J. Geophys. Res. 116, A04304. http://dx.doi.org/10.1029/2010JA016301.

De Franceschi, G., De Santis, A., 1994. PASHA: regional long-term predictions of ionospheric parameters by ASHA. Ann. Geophys. – IT 37 (2), 0. http://dx.doi.org/10.4401/ag-4228.

Dominici, P., Zolesi, B., 1987. A model for the normal ionosphere over Rome. II Nuovo Cimento 10C, 191–208.

Dvinskikh, N.I., 1988. Expansion of ionospheric characteristics fields in empirical orthogonal functions. Adv. Space Res. 8 (4), 179–187. http://dx.doi.org/10.1016/0273-1177(88)90238-4.

Hanbaba, R., 1999. Improved quality of service in ionospheric telecommunication systems planning and operation. COSTAction 251 Final Report, Space Research Centre, Warsaw, pp. 102–103.

Hochegger, G., Nava, B., Radicella, S., Leitinger, R., 2000. A family of ionospheric models for different uses. Phys. Chem. Earth, Part C: Sol., Terr. Planet. Sci. 25 (4), 307–310. http://dx.doi.org/10.1016/S1464-1917(00)00022-2.

Houminer, Z., Bennett, J.A., Dyson, P.L., 1993. Real-time ionospheric model updating. J. Electr. Electr. Eng., Australia, IE Australia & IREE Australia 13 (2), 99–104.

ITU-R, 1994. HF Propagation Prediction Method. Recommendation ITU-R P. 533. International Telecommunication Union, Geneva.

Judge, D.L., Mcmullin, D.R., Ogawa, H.S., Wurz, P., 1998. First solar EUV irradiances obtained from SOHO by the CELIAS/SEM. Sol. Phys. 177 (1), 161–173. http://dx.doi.org/10.1023/A:1004929011427.

Kane, R.P., 1992. Sunspots, solar radio noise, solar EUV and ionospheric foF2. J. Atmos. Terr. Phys. 54, 463–466. http://dx.doi.org/10.1016/0021-9169(92)90025-G.

Khachikyan, G.Y.A., Pogoreltsev, A.I., Drobzheva, Y.A.V., 1989. Characteristics of the longitudinal variations of foF2 at middle latitudes in the northern hemisphere: dependence on local time and season. Geomagn. Aeron., Engl. Transl. 29 (4), 437–440.

Kutiev, I., Tsagouri, I., Perrone, L., Pancheva, D., Mukhtarov, P., Mikhailov, A., Lastovicka, J., Jakowski, N., Buresova, D., Blanch, E., Andonov, B., Altadill, D., Magdaleno, S., Parisi, M., Torta, J.M., 2013. Solar activity impact on the Earth's upper atmosphere. J. Space Weather Space Climate 3, A06. http://dx.doi.org/10.1051/swsc/2013028.

Levy, M.F., Dick, M.I., Spalla, P., Scotto, C., Kutiev, I., Muhtarov, P., 1998. Results of COST 251 testing of mappings and models. Rep. COST251TD(98)021, Eur. Coop. in the Field of Sci. and Tech. Res., Brussels, Sept.

Liu, L., Wan, W., Ning, B., Pirog, O.M., Kurkin, V.I., 2006. Solar activity variations of the ionospheric peak electron density. J. Geophys. Res. 111, A08304. http://dx.doi.org/10.1029/2006JA011598.

Liu, L., Chen, Y., Le, H., Kurkin, V.I., Polekh, N.M., Lee, C.-C., 2011. The ionosphere under extremely prolonged low solar activity. J. Geophys. Res. Space Phys. 116, A04320. http://dx.doi.org/10.1029/2010JA016296.

McNamara, L., 1991. The Ionosphere: Communications, Surveillance and Direction Finding. Krieger, Nalabar, Fla., p. 237.

Mikhailov, A.V., Mikhailov, V.V., 1995. Solar cycle variations of annual mean noon foF2. Adv. Space Res. 15, 79–82. http://dx.doi.org/10.1016/S0273-1177(99)80026-X.

Mikhailov, A.V., Mikhailov, V.V., Skoblin, M.G., 1996. Monthly median foF2 and M(3000)F2 ionospheric model over Europe. Ann. Geophys. – IT 39 (4), 791–805, http://hdl.handle.net/2122/1707.

Mikhailov, A.V., Perrone, L., 2014. A method for foF2 short-term (1–24 h) forecast using both historical and realtime foF2 observations over European stations: EUROMAP model. Radio Sci. 49, 253–270. http://dx.doi.org/10.1002/2014RS005373.

Nava, B., Coisson, P., Radicella, S.M., 2008. A new version of the NeQuick ionosphere electron density model. J. Atmos Sol. Terr. Phys. 70 (15), 1856–1862. http://dx.doi.org/10.1016/j.jastp.2008.01.015.

Perna, L., Pezzopane, M., 2016. FoF2 vs solar indices for the Rome station: looking for the best general relation which is able to describe the anomalous minimum between cycles 23 and 24. J. Atmos. Sol. Terr. Phys. 148, 13–21. http://dx.doi.org/10.1016/j.jastp.2016.08.003.

Pezzopane, M., 2004. Interpre: a windows software for semiautomatic scaling of ionospheric parameters from ionograms. Comput. Geosci. 30, 125–130. http://dx.doi.org/10.1016/j.cageo.2003.09.009.

Pezzopane, M., Pietrella, M., Pignatelli, A., Zolesi, B., Cander, L.R., 2011. Assimilation of autoscaled data and regional and local ionospheric models as input sources for real-time 3-D international reference ionosphere modeling. Radio Sci. 46, 5009. http://dx.doi.org/10.1029/2011RS004697.

Pezzopane, M., Pietrella, M., Pignatelli, A., Zolesi, B., Cander, L.R., 2013. Testing the three-dimensional IRI-SIRMUP-P mapping of the ionosphere for disturbed periods. Adv. Space Res. 52 (10), 1726–1736. http://dx.doi.org/10.1016/j.asr.2012.11.028.

Pietrella, M., Perrone, L., 2005. Instantaneous space weighted ionospheric regional model for instantaneous mapping of the critical frequency of the F2 layer in the European region. Radio Sci. 40 (1). http://dx.doi.org/10.1029/2003RS003008.

Pietrella, M., 2012. A short-term ionospheric forecasting empirical regional model (IFERM) to predict the critical frequency of the F2 layer during moderate, disturbed, and very disturbed geomagnetic conditions over the European area. Ann. Geophys. 30, 343–355. http://dx.doi.org/10.5194/angeo-30-343-2012.

Radicella, S.M., Leitinger, R., 2001. The evolution of the DGR approach to model electron density profiles. Adv. Space Res. 27 (1), 35–40. http://dx.doi.org/10.1016/S0273-1177(00)00138-1.

Rao, M.S.J.G., Rao, R.S., 1969. The hysteresis variation in F2–layer parameters. J. Atmos. Terr. Phys. 31, 1119–1125. http://dx.doi.org/10.1016/0021- 9169(69)90110-X.

Rawer, K., 1991. Data needed for an analytical description of the electron density profile. Adv. Space Res. 11 (10), 57–65. http://dx.doi.org/10.1016/0273-1177(91)90322-B.

Reinisch, B.W., Huang, X., Sales, G.S., 1993. Regional ionospheric mapping. Adv. Space Res. 13 (3), 45–48. http://dx.doi.org/10.1016/0273-1177(93)90246-8.

Romano, V., Pau, S., Pezzopane, M., Zuccheretti, E., Zolesi, B., De Franceschi, G., Locatelli, S., 2008. The electronic space weather upper atmosphere (eSWua) project at INGV: advancements and state of the art. Ann. Geophys. 26, 345–351.

Singer, W., Dvinskikh, N.I., 1991. Comparison of empirical models of ionospheric characteristics developed by means of different mapping methods. Adv. Space Res. 11 (10), 3–6. http://dx.doi.org/10.1016/0273-1177(91)90311-7.

Triskova, L., Chum, J., 1996. Hysteresis dependence of foF2 on solar indices. Adv. Space Res. 18, 145–148. http://dx.doi.org/10.1016/0273-1177(95)00915-9.

Tsagouri, I., Zolesi, B., Belehaki, A., Cander, L.R., 2005. Evaluation of the performance of the real-time updated simplified ionospheric regional model for the European area. J. Atm. Sol. Terr. Phys. 67 (12), 1137–1146. http://dx.doi.org/10.1016/j.jastp.2005.01.012.

Viereck, R., Puga, L., McMullin, D., Judge, D., Weber, M., Tobiska, W. K., 2001. The Mg II index: a proxy for solar EUV. Geophys. Res. Lett. 28 (7), 1343–1346. http://dx.doi.org/10.1029/2000GL012551.

Wakai, N., Ohyama, H., Koizumi, T., 1987. Manual of Ionogram Scaling. Ministry of posts and Telecommunications, Japan.

Zakharenkova, I., Krankowski, A., Bilitza, D., Cherniak, Y., Shagimuratov, I., Sieradzki, R., 2013. Comparative study of foF2 measurements with IRI-2007 model predictions during extended solar minimum. Adv. Space Res. 51 (1), 620–629. http://dx.doi.org/10.1016/j.asr.2011.11.015.

Zolesi, B., Cander, L.R., De Franceschi, G., 1990. A simple model for a global distribution of some ionospheric characteristics in a restricted area, in Solar-Terrestrial Predictions: Proceedings of a Workshop at Leura, National Oceanic and Atmospheric Administration, Boulder, Colo., vol. 2, pp. 418–427.

Zolesi, B., Cander, L.R., De Franceschi, G., 1991. Mapping of some ionospheric characteristics over a restricted area using SIRM (Simplified Ionospheric Regional Model). In: Seventh International Conference on Antennas and Propagation, vol. 333, pp. 512–515.

Zolesi, B., Cander, L.R., De Franceschi, G., 1993. Simplified ionospheric regional model for telecommunication applications. Radio Sci. 28 (4), 603–612. http://dx.doi.org/10.1029/93RS00276.

Zolesi, B., Cander, L.R., De Franceschi, G., 1996. On the potential applicability of the simplified ionospheric regional model to different midlatitude areas. Radio Sci. 31 (3), 547–552. http://dx.doi.org/10.1029/95RS03817.

Zolesi, B., Cander, L.R., 1998. Advances in regional ionospheric mapping over Europe. Ann. Geophys. – IT 41 (5–6), 827–842. http://dx.doi.org/10.4401/ag-3823.

Zolesi, B., Belehaki, A., Tsagouri, I., Cander, L.R., 2004. Real-time updating of the simplified ionospheric regional model for operational applications. Radio Sci. 39 (2), RS2011. http://dx.doi.org/10.1029/2003RS002936.

Zolesi, B., Cander, L.R., 2014. Ionospheric Prediction and Forecasting. Springer-Verlag Berlin Heidelberg, p. 240. http://dx.doi.org/10.1007/978-3-642-38430-1.

Zuccheretti, E., Tutone, G., Sciacca, U., Bianchi, C., Arokiasamy, B.J., 2003. The new AIS-INGV digital ionosonde. Ann. Geophys. – IT 46 (4), 647–659. http://dx.doi.org/10.4401/ag-4377.