A method for f_0F_2 monitoring over Spain using the El Arenosillo digisonde current observations

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Abstract

Ionosphere monitoring implies: observations, prediction and mapping of ionospheric parameters. A case with one available (El Arenosillo) ionosonde is considered. Some statistical methods for f_0F_2 short-term (1-24 h in advance) prediction are compared. The analysis of multi-dimensional regression for Δf_0F_2 (relative deviation from running median) with A_p, $F_{10.7}$ and previous Δf_0F_2 observations has shown that inclusion of additional terms with A_p and $F_{10.7}$ improves the prediction accuracy for lead time more than 15 h. For lead time 1-6 h a linear regression with earlier observed Δf_0F_2 provides the f_0F_2 forecast with Relative Mean Deviation (RMD) 6-11%. This is acceptable from a practical point of view. A 24-h forecast can be done with RMD 10-11%. Multi-regressional methods provide better prediction accuracy than the usual 10-day running median or quasi-inertial method based on such median. Hourly f_0F_2 values may be used to calculate the effective index $R_{12\mathrm{eff}}$ used as input to the ITU-R monthly median model. This allows the ITU-R model to «breathe» following hour-to-hour f_0F_2 variations. Then standard surfering methods may be applied for f_0F_2 mapping over the whole area. The f_0F_2 mapping accuracy based on the hourly $R_{12\mathrm{eff}}$ index is shown to be 9-11% depending on solar activity level.

Key words *ionospheric F_2 layer – short-term prediction methods – ionospheric mapping*

1. Introduction

Monitoring of the ionospheric F_2-region should be considered as a part of the upper atmosphere monitoring in the framework of the Space Weather Program. There is also a practical aspect of such activity related to the provision of HF radio-wave communication – both current performance and short-term prediction. The term «ionospheric monitoring» implies current ionosphere observations with ground-based and topside sounders, ionospheric prediction and mapping of ionospheric parameters over the area using observed and predicted values. The ideology of such ionospheric monitoring is given in a book *Ionospheric Service* (1987). Although topside sounders can provide useful observations their practical usage is limited due to technical problems with obtaining information in real-time. Therefore ground-based ionosonde network observations are still considered as the main source of ionospheric information which really can be used for nowcasting and prediction of ionospheric conditions.

While the ionospheric E and F_1 region parameters normally do not demonstrate strong variations and their predictions can be provided with an acceptable accuracy using the empirical

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models, the main ionospheric F_2-region is very variable. Strong day-to-day and hour-to-hour f_0F_2 variations are due to the thermosphere (neutral composition, temperature, winds) as well as to electric fields and plasmaspheric flux variations. The existing empirical (monthly median) f_0F_2 models like ITU-R (1997) can be applied only for quiet time periods close to monthly median conditions. An attempt to apply modern 1-3D theoretical models of the F_2-region to predict even the simplest quiet time NmF_2 and hmF_2 daily variations gives overall unsatisfactory results (Anderson *et al.*, 1998). Negative F_2-layer storm effects which are the most crucial for HF radio-wave communication cannot be satisfactorily modelled without special fitting of aeronomic parameters for each particular ionospheric storm (*e.g.*, Richards *et al.*, 1989, 1994). This is due to the F_2-region electron concentration dependence on many input and poorly controlled parameters. Therefore, an empirical approach to the f_0F_2 short-term prediction based on statistical methods is still recommended for practical use (*e.g.*, Mikhailov, 1990; Muhtarov *et al.*, 1998).

The final step is to used the observed (for nowcasting) and predicted f_0F_2 values for f_0F_2 mapping over the area of interest. If the number of ionosondes is sufficient in the area such mapping can be done using any method of surfering (*e.g.*, Teryokhin and Mikhailov, 1992). In the case considered in this paper in which only one ionosonde is available the other approach may be used. Observed (or predicted) hourly f_0F_2 value is used to specify an effective sunspot number $R_{12_{\text{eff}}}$ using any monthly median f_0F_2 model, say ITU-R. This $R_{12_{\text{eff}}}$ is used as the input parameter to the model to give a map over the area in question. Such approach allows the ITU-R model to «breathe» following hour-to-hour f_0F_2 variations. A possibility to apply such approach to f_0F_2 monitoring over Spain with one available El Arenosillo digisonde is considered in the paper.

2. Short-term f_0F_2 prediction

It is known that NmF_2 ($NmF_2 = 1.24\ 10^4 f_0F_2^2$) values demonstrate a good inter-hour correlation for normal (not disturbed) conditions within a day (*e.g.*, Muhtarov *et al.,* 1999). During daytime hours the characteristic time of NmF_2 changes with respect to recombination is about 1.5 h. But the daytime F_2-region is strongly controlled by the thermosphere (neutral composition, temperature) and the characteristic time of changing for these parameters is much longer than 1.5 h. So the interval of an acceptable level of temporal correlation may be up to 3-6 h depending on geophysical conditions. During night-time the characteristic time with respect to the loss process is more than 10 h due to low linear loss coefficient at the hmF_2 height and the NmF_2 inter-hour correlation is very good for night-time hours. Therefore the f_0F_2 prediction method should include linear regression with previous f_0F_2 observations. But this inter-hour correlation breaks down during geomagnetic storm periods and one may try to include the dependence on magnetic activity indexes such as A_p or K_p (Wrenn, 1987; Wrenn *et al.,* 1987; Muhtarov and Kutiev, 1998). Unfortunately, such planetary geomagnetic indexes do not reflect the F_2-region behaviour properly during disturbed periods. Depending on season and local time of geomagnetic storm onset and the geomagnetic latitude the F_2-region storm effect may have different signs (positive or negative storm phase). Such indexes poorly describe the magnitude of the ionospheric storm. Further, the disturbance may start immediately after the geomagnetic storm onset, but may be delayed up to half of a day. So there is not much chance to predict properly any individual disturbance with the help of such indices, but their inclusion in the regression may improve the prediction accuracy in a statistical sense. Although the approach proposed by Wrenn (1987) looks promising, it requires the 3-h *ap* indexes to be available. But at present only a 3-day forecast of daily A_p index is available and the prediction accuracy is not very high. The f_0F_2 prediction for magnetically quiet periods can be made with an acceptable accuracy without taking into account the magnetic activity (Mikhailov, 1990). From a practical point of view the most important thing is to predict the F_2-layer negative storm effect as it results in a narrowing of the HF performance band. Usually there is a delay between geomagnetic and ionospheric disturbances and this is usually used in ionospheric predictions. As we have one predicted A_p value for the whole day it can be nominally prescribed to the 12 UT moment. Then such daily A_p indices may be spline-interpolated to give hourly values which are used for training the method.

The F_2-region depends on solar EUV radiation, the latter is usually described with the help of $F_{10.7}$ indices. There are two channels of this influence – via neutral composition and temperature and via ionizing radiation with $\lambda \leq 100$ nm. The ionizing EUV solar flux is mostly controlled by slow-varying background $F_{10.7}$ radiation and to a lesser extent by current (measured) $F_{10.7}$ radio emission (Nusinov, 1992). A similar situation is the dependence of neutral composition and temperature on solar activity level. According to the thermospheric MSIS model a 3-month average $F_{10.7}$ provides the main contribution to the thermospheric parameter variations. So one should not expect any strong day-to-day changes in solar EUV. Nevertheless, by analogy with the A_p index we included the linear regression with $F_{10.7}$ index taken for the previous day just to estimate the effect of such inclusion.

The regression used in our analysis may be written as follows:

$$\Delta f_0F_2(\mathrm{UT}+n) = \\ = C_0 + C_1\Delta f_0F_2(\mathrm{UT}) + C_2A_p + C_3F_{10.7} \quad (2.1)$$

where $\Delta f_0F_2 = (f_0F_2 - f_0F_{2\mathrm{med}}) / f_0F_{2\mathrm{med}}$, and $f_0F_{2\mathrm{med}}$ being the running median over the training period, n = the lead time. The unknown coefficients C_i are found using the standard multi-regressional methods.

A two-month period of April-May 1993 was chosen for our analysis. It comprises geomagnetic storms with A_p up to 90. Daily index $F_{10.7}$ was 68-130 during the period in question. At the first step we analyzed the f_0F_2 prediction accuracy in dependence on the number of terms in (2.1) and on the length of the training period. The prediction accuracy averaged for all lead times (1-24 h) is given in table I for different length of the training period (given in days, top line). The results obtained with the usual quasi-inertial method as well as with running median calculated over the training period are given for comparison. The quasi-inertial method uses the following prediction expression:

$$f_0F_2(\mathrm{UT}+n) = \\ = f_0F_2(\mathrm{UT}) / f_0F_{2\mathrm{med}}(\mathrm{UT}) \times f_0F_{2\mathrm{med}}(\mathrm{UT}+n) \quad (2.2)$$

where $f_0F_{2\mathrm{med}}$ = running median over the training period.

The results of table I shows that the more terms in (2.1) are taken into account the longer the training time interval required to obtain the best (bold) prediction accuracy, but in each case the optimum length of training period exists. It is less than a period of one solar rotation, so in practice one month of previous observations is sufficient to train the prediction method. The

Table I. Averaged over all lead times (1-24 h) relative mean deviations (in %) of f_0F_2 prediction for different lengths of the training period (in days, top line). The results of using expression (2.1) with different number of terms are compared with the quasi-inertial method (2.2) and running median.

Terms in (2.1) and methods	10	12	15	17	20	22	25	27
2 terms	11.07	**10.89**	10.99	11.05	11.14	11.29	11.51	11.72
3 terms	13.29	12.56	12.29	10.75	**10.59**	10.84	11.28	11.53
4 terms	17.01	14.04	13.36	11.71	11.24	11.15	**10.98**	11.19
Quasi-inertial	**13.40**	13.71	14.16	14.24	14.54	14.86	15.42	15.70
Median	**11.79**	11.86	12.16	12.26	12.25	12.40	12.50	12.61

best lengths of training period for the quasi-inertial method and for prediction with running median are ≤ 10 days. Indeed, a 10-day running median is widely used in practice for ionospheric prediction.

Figure 1 gives the prediction accuracy of the above mentioned methods as a function of lead time. The cases corresponding to the best length of the training period (table I) are used for this comparison. Regression with three terms in expression (2.1) provides the best prediction accuracy, it is better than 12% for all lead times. Expression (2.1) with two terms provides practically the same accuracy for the lead times less than 12-15 h, but then a 10-day median turns out to be more efficient. A four-term expression (2.1) with $F_{10.7}$ provides less accurate prediction for lead times less than 17 h, but then the prediction accuracy becomes close to the two-term case. This result confirms a small expected effect of day-to-day solar EUV variability. Therefore there is no need to include the dependence on $F_{10.7}$ index in the expression (2.1). The quasi-inertial method provides much worse prediction accuracy compared to the other methods. Figure 1 shows that the worst prediction accuracy corresponds to the lead time of 12-15 h. This result is understandable as in this case we predict daytime conditions using night-time observations

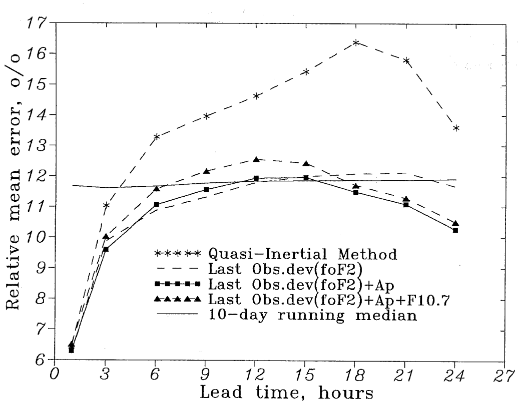

Fig. 1. A comparison of 5 methods for short-term f_0F_2 prediction. The results are obtained for the April-May, 1993 period.

and *vice versa*. Mechanisms of the F_2-region formation are different for daytime and night-time hours and the relation between daytime and night-time f_0F_2 is not that good as during one and the same period of a day.

An interesting result is the increase in the prediction accuracy by the end of the 24-h period. This peculiarity was pointed out earlier (Rodionov, 1963; Mikhailov, 1990). It tells us about some «ionosphere memory» on the situation of the previous day. This effect needs special consideration, but the most plausible explanation seems to be related to daily neutral composition variations when the ionosonde station turns out to be alternatively in the daytime and night-time sectors where the thermospheric circulation pattern is similar for the successive days (Skoblin and Förster, 1993; Prölss, 1995).

A combination of different methods taking into account two, three terms in (2.1) for different lead times along with running median may be proposed as a method for practical use. Figure 2a,b gives the results of such combined method application to the f_0F_2 prediction during the disturbed period of May 06-12, 1993. The A_p index was up to 48 (shown in the bottom) and pronounced negative storm effects were observed. Figure 2a,b shows that the observed f_0F_2 storm time variations may be fairly well predicted with lead time up to 4 h with two terms in the expression (2.1). We used the same two-term expression (2.1) for daytime hours and a combination with the running median during the night-time period for lead times $4 < n < 7$ h. For lead times $n > 7$ h we used a three-term expression (2.1) during daytime and a combination with the running median for the night-time period. The results show that quiet time f_0F_2 variations (May 06, $A_p = 9$ and May 11, $A_p = 4$) may be fairly well predicted with any lead time, the running median being a pretty good prediction method in this case. On the other hand the running median cannot be applied during disturbed periods – for instance on May 10 with $A_p = 48$ when a pronounced negative storm effect took place. The results clearly show that inclusion of the dependence on A_p index generally improves the f_0F_2 prediction although large errors may occur especially for large lead times (fig. 2b).

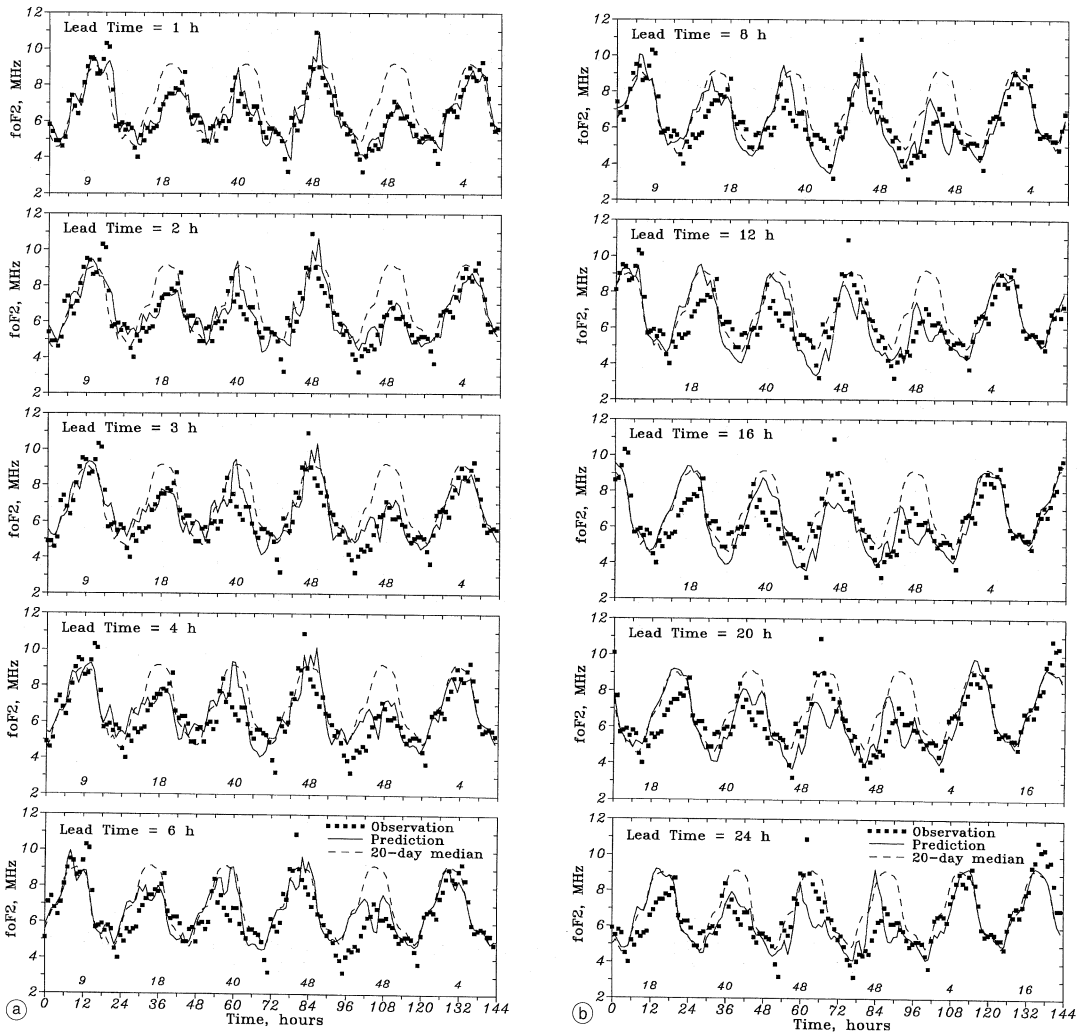

Fig. 2a,b. An application of the proposed method of f_0F_2 forecast to the storm time period of May 06-12, 1993. Daily A_p indexes are given in the bottom. b) Same as in (a), but for 8-24 h lead times.

3. Mapping f_0F_2

Mapping of ionospheric parameters over the area is necessary, for instance, to calculate HF radio-wave communication conditions. If the number of available ionosonde observations is insufficient (the extreme case with one ionosonde), then a possible way to map f_0F_2 (and/or $M(3000)F_2$) is to use any monthly median model (ITU-R, for instance) with an effective hourly R_{12} index as the input. Such an approach is widely used to force a monthly median model to follow hour-to-hour f_0F_2 variations (*e.g.*, Houminer, 1993). Such calculations were performed for the El Arenosillo digisonde for all available hourly observations in 1976, 1977, and 1979.

Table II. A comparison of calculated f_0F_2 with Tortosa observations. Relative mean and standard deviations of the calculated f_0F_2 with respect to the observed ones are given.

Year	1976	1977	1979
Annual $F_{10.7}$	73.3	86.9	192.0
RMD (%)	8.61	9.25	11.14
SD (MHz)	0.667	0.472	0.912

Tortosa (40.8N; 0.5E) ionosonde f_0F_2 observations are available for this period and they can be used for testing the mapping procedure. Table II gives the Relative Mean Deviation (RMD) and Standard Deviations (SD) of calculated f_0F_2 with respect to the Tortosa observations.

Table II shows that f_0F_2 mapping accuracy decreases with solar activity level, being around 10% on average. Such an accuracy is acceptable from a practical point of view. An example of f_0F_2 mapping for the most interesting sunrise period (07 UT) when spatial f_0F_2 gradients are the largest is given in fig. 3. Observed f_0F_2 values with El Arenosillo and Tortosa ionosondes are shown for a comparison.

The same approach may be applied to the predicted f_0F_2 values using the method considered. This will provide a continuous f_0F_2 monitoring over the whole area of interest.

4. Summary

The main results of our analysis are the following:

1) A method for f_0F_2 monitoring over Spain with 0-24 lead time is proposed using the El Arenosillo digisonde current observations. The method includes f_0F_2 short-term prediction with 1-24 h lead time and f_0F_2 mapping over the area.

2) An analysis of multi-dimesional regression for Δf_0F_2 with A_p, $F_{10.7}$ and previous Δf_0F_2 observations has shown that the inclusion of additional terms with A_p and $F_{10.7}$ indexes im-

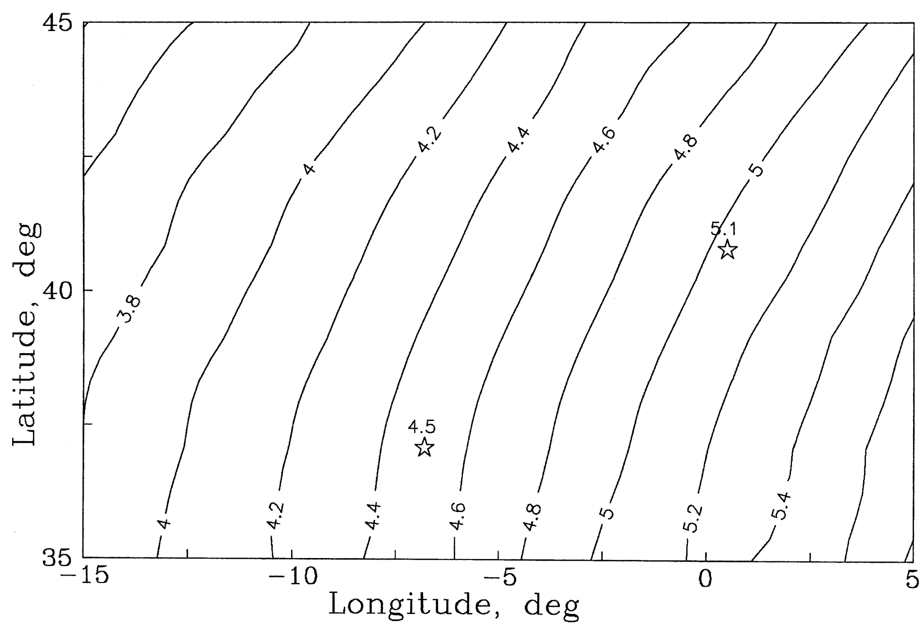

Fig. 3. An example of f_0F_2 mapping over Spain for February 21, 1979 (07 UT). Observed f_0F_2 on El Arenosillo and Tortosa are shown. The El Arenosillo f_0F_2 value was used to derive $R_{12_{eff}}$ as the input to the ITU-R model.

proves the prediction accuracy for lead time by more than 15 h. Linear regression with earlier observed Δf_0F_2 provides the f_0F_2 forecast with a relative mean deviation of 6-11% for lead time 1-6 h. A 24-h f_0F_2 forecast can be done with a relative mean deviation of 10-11%. The optimal length of training period exists for each prediction method and it is less than one solar rotation.

3) Multi-regressional methods provide better prediction accuracy than the usual 10-day running median or quasi-inertial method based on such median.

4) Hourly f_0F_2 may be used to calculate the effective hourly index $R_{12_{\text{eff}}}$ which is used as the input to the ITU-R monthly median model. This allows the ITU-R model to «breathe» following hour-to-hour f_0F_2 variations. Using Tortosa f_0F_2 observations the accuracy of such mapping was estimated to be around 10% for different levels of solar activity and this is acceptable from a practical point of view.

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