A Method for *fo*F2 Short-Term Prediction

D. Marin[1], G. Miro[1] and A. Mikhailov[2]

[1]Atmospheric Sounding Station “El Arenosillo”, I. N. T. A., Ctra San Juan del Puerto-Matalascanas Km. 33, 21130 Huelva, Spain
[2]Institute of Terrestrial Magnetism, Ionosphere and Radio Wave Propagation, Academy of Sciences, Troitsk, Moscow Region 142092, Russia

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Abstract. A method for *fo*F2 short-term prediction with 1-24 hour lead times is proposed. It is based on Δ*fo*F2 (deviation of hourly *fo*F2 from running median) regression with the previous Δ*fo*F2 observations and hourly spline-interpolated daily Ap index. An optimum training time interval of 25-30 days, which is close to one solar rotation, has been revealed. The effect of Ap index inclusion is seen only for large (more than 3 hours) lead time prediction. The prediction accuracy was shown to depend on Ap/*fo*F2 time shift interval, the latter being dependent on local time of the storm onset and this may be taken into account in the prediction method. For quiet and moderate disturbed conditions the basic method provides *fo*F2 forecast with relative mean deviation of 8-13% which is acceptable from practical point of view. A version of the basic method is proposed to predict *fo*F2 during severe storm periods. This modified method in comparison with the basic one and the Wrenn′s *et al.*, (1987) approach was shown to provide the best prediction accuracy and may be recommended for practical use.

1 Introduction

Short-term ionosphere prediction of the F2-layer parameters is still a very challenging problem. While the ionospheric E and F1 region parameters usually do not demonstrate strong variations even during disturbed periods and can be described with an acceptable accuracy using the empirical models, the F2-region is very variable. Strong day-to-day and hour-to-hour *fo*F2 variations during disturbed periods are due to the thermosphere (neutral composition, temperature, winds) as well as to electric fields and plasmaspheric fluxes variations. The existing empirical (monthly median) *fo*F2 models like ITU-R (1997) can be applied only for quiet time periods close to monthly median conditions. Attempts to apply modern 1-3D theoretical models of the F2-region to predict even quiet time *fo*F2 and *hm*F2 daily variations give different results depending on geophysical conditions and model used (Anderson *et al.*, 1998), but the overall result of this models inter-comparison may be estimated as an unsatisfactory one. Negative F2-layer storm effects which are the most crucial for HF radio-wave communication cannot be satisfactory modelled without special fitting of aeronomic parameters for each particular ionospheric storm (e.g. Richards, *et al.*, 1989, 1994). This is due to the F2-region electron concentration dependence on many input and poorly controlled parameters. Therefor there are not many chances to use theoretical models in practice for the F2-layer prediction and an empirical approach based on statistical methods still should be recommended for practical use (e.g. Mikhailov, 1990; Muhtarov *et al.*, 1998). A statistical approach to the [illegible]

and the efficiency of its application to strong mid-latitude F2-layer storms is discussed.

2 Method Description

It is known that *Nm*F2 demonstrates a good inter-hour correlation for usual (not disturbed) conditions within a day. During daytime hours the characteristic time of *Nm*F2 changes with respect to recombination is about 1.5 hours. But daytime F2-region is strongly controlled by thermosphere (neutral composition, temperature) and the characteristic time of changing for these parameters is longer than 1.5 hours. So the time interval of an acceptable level of temporal correlation may be up to 3-6 hours depending on geophysical conditions. During night-time the characteristic time with respect to the loss process is more

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Correspondence to: D. Marin

than 10 hours due to low linear loss coefficient at the *hm*F2 height and the *Nm*F2 inter-hour correlation is very good for night-time hours. Therefor the *fo*F2 prediction method should include the linear regression with previous *fo*F2 observations. But this inter-hour correlation breaks down during geomagnetic storm periods decreasing to 1-3 hours, and one may try to include the dependence on magnetic activity indexes such as *Ap* or *Kp* (Wrenn, 1987; Wrenn *et al.*, 1987; Muhtarov and Kutiev, 1998). Unfortunately, such planetary geomagnetic indexes do not reflect properly the F2-region behaviour during disturbed periods. Depending on season and local time of the geomagnetic storm onset as well as the geomagnetic latitude the F2-region storm effect may have different sign (positive or negative storm phases). 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 24 hours. So there are not many chances to predict properly any individual disturbance with the help of such indices, but their inclusion into the regression may improve the prediction accuracy in a statistical sense as this is shown below.

The prediction for quiet or moderate disturbed periods can be done with an acceptable accuracy without taking into account the magnetic activity (Mikhailov, 1990). But from practical point of view the most important is to predict the F2-layer negative storm effect as it results in narrowing of the HF performance band. Usually there is a delay between geomagnetic and ionospheric disturbances and this is used in practice. As we have one predicted *Ap* daily value for the whole day it can be formally prescribed to 12 *UT*. Then such daily *Ap* indices may be spline-interpolated to give hourly values to be used for training the method. In practice a simultaneous survey of Ap and *fo*F2 current variations helps the operator to make a conclusion about the storm onset and to choose a proper method for *fo*F2 prediction (see below).

The F2-region parameters depend on solar *EUV* radiation as well, the latter usually is described with the help of $F_{10.7}$ indices. There are two channels of this influence - via neutral composition and temperature and via ionising radiation with $\lambda \leq 100$ nm. The *EUV* solar flux mostly is determined by slow-varying background $F_{10.7}$ and to less extent by observed $F_{10.7}$ (Nusinov, 1992). Similar situation is with the dependence of neutral composition and temperature on $F_{10.7}$. 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 the solar *EUV*. Indeed, $F_{10.7}$ index inclusion to the linear regression was shown not to improve the prediction accuracy (Mikhailov et al., 1999).

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

$$\Delta foF2(UT+n) = C_0+C_1\,\Delta foF2(UT)+C_2\,Ap(UT+n-m) \qquad (1)$$

where $\Delta foF2=(foF2-foF2med)/foF2med$, *fo*F2med being the running median over the training period, *n* – the lead time, and *m* – the Ap/*fo*F2 time shift. The unknown coefficients C_i are found using the least-squares multi-regressional method over the whole training period. The coefficients C_i are calculated using the previous $\Delta foF2$ and Ap hourly values to predict $\Delta foF2$ with any 1-24 hour lead time *n*. Parameter *m* in (1) is a time shift between *fo*F2 and Ap variations (see below). Hourly *fo*F2 observations on Rome (41.8*N*, 12.5*E*), Tortosa (40.8*N*, 0.5*E*), and El Arenosillo (37.1*N*, 353.3*E*) were used in our analysis.

3 Ap index inclusion effect

To demonstrate the effect of Ap index inclusion into the regression (1) a period of Feb 27 – Mar 5, 1982 (high solar activity with monthly $F_{10.7}$=210) was analysed using the El Arenosillo observations. This period includes a severe geomagnetic storm on Mar 1-2 with Ap up to 107 resulted in a strong negative *fo*F2 storm effect on Mar 02. Predictions of *fo*F2 were made with 1-24 hour lead times using running median and the expression (1) with 2 and 3 terms. Daily averaged relative mean deviation (RMD in %) between observed and predicted *fo*F2 values were calculated (Figure 1). For small (3-4 hours) lead times both approaches are seen to give practically the same results, but for larger lead times the effect of Ap inclusion is obvious. The prediction accuracy is much better in this case compared to the two-term expression (1). The accuracy of the latter method is seen to decrease steadily for large lead times approaching to the prediction accuracy provided by the running median (solid line). So, the prediction method should include a dependence on Ap index. The problem with time shift of Ap variation with respect to the prediction period is discussed below.

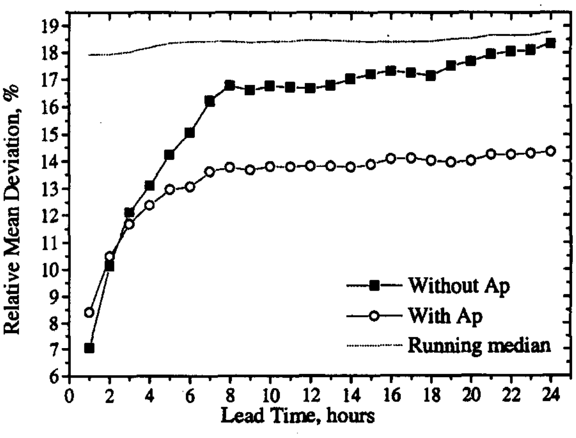

Fig. 1. The effect of Ap index taking into account to the expression (1). The Feb 27 – Mar 5, 1982 was used for the analysis.

Our analysis has shown that the prediction for quiet and slightly disturbed periods using expression (1) with two or three terms gives close results, so the three-term expression (1) can be used in all cases as it provides more accuracy predictions during disturbed geomagnetic periods. It may be recommended for practical use to predict during quiet and moderately disturbed conditions. The problem of prediction during disturbed periods is discussed below.

4 Length of the training period

An analysis of the *fo*F2 prediction accuracy in dependence on the training period length was made for 5 different disturbed periods. An optimum training period proving the best prediction accuracy was found always to exist. Usually it is 25-30 days, which is close to one solar rotation. An example of such analysis is given in Table 1 for the period of Apr 10-16, 1981 which comprises a geomagnetic storm with Ap = 121 on April 13.

Table 1. Relative mean deviations (in %) of *fo*F2 prediction for the period of Apr 10-16, 1981. The results for different number of training days and lead times are given. Shadow cells show the best prediction accuracy cases.

Lead Time (hours)	Number of training days								
	20	22	24	26	27	28	29	30	31
1	6.24	6.18	6.03	6.00	5.91	5.96	5.95	5.98	5.9
2	11.07	10.94	10.24	10.03	9.93	10.02	10.13	10.08	9.76
3	14.95	14.81	13.72	13.28	13.24	13.39	13.60	13.47	13.02
4	17.84	17.6	16.40	15.84	15.89	16.1	16.33	16.14	15.68
5	21.23	20.89	19.62	18.67	18.55	18.55	19	19.21	19.32
6	22.22	21.9	20.66	19.58	19.44	19.35	19.88	20.34	20.64
12	23.06	23.40	23.38	22.8	22.85	22.87	23.44	24.21	23.77
24	23.84	24.51	22.74	22.31	22.49	22.12	23.79	23.33	22.83
Average (1-6)	15.59	15.39	14.45	13.90	13.83	13.90	14.15	14.20	14.05
Average (1-24)	17.56	17.53	16.60	16.06	16.04	16.05	16.52	16.60	16.37

5 Ap/*fo*F2 time shift

According to the observations and present-day understanding of the F2-layer storm mechanisms there is a pronounced dependence of negative ionospheric storm onset on local time (Prölss, 1995 and references therein). Negative ionospheric storms commence most frequently in the early morning and very rarely in the noon and afternoon LT sectors. This is due to global wind circulation pattern helping the disturbed neutral composition (responsible for the ionospheric negative storm effect) to penetrate to lower latitudes in the night-time sector and restricting the perturbation to higher latitudes in the daytime sector. So storms with their onset during daytime hours will be "delayed" until the next morning for mid-latitude stations. An example of this type is given in Figure 2,a for the storm period of July 24-27, 1980 for El Arenosillo. The storm started during day-time hours (in the European sector) on July 25, but the observed *fo*F2 remained close to the running median until the next morning despite the fact that it was a very strong storm. Figure 2,b gives an example of a strong winter time storm during the period of Feb 28-Mar 3, 1982. The first splash of geomagnetic activity took place during day-time hours on Mar 01, resulted in a pronounced positive storm effect typical of winter season (Mikhailov et al., 1995). But the main storm started around midnight and this resulted in *fo*F2 decrease with a small (3-6 hours) time delay. Therefore, if a geomagnetic storm onset is registered using ground-based or satellite observations, then the Ap/*fo*F2 time shift is known and it can be inserted into the prediction program as an input parameter. The prediction method is retrained for this Ap/*fo*F2 time shift and *fo*F2 disturbed variations are predicted for this particular storm.

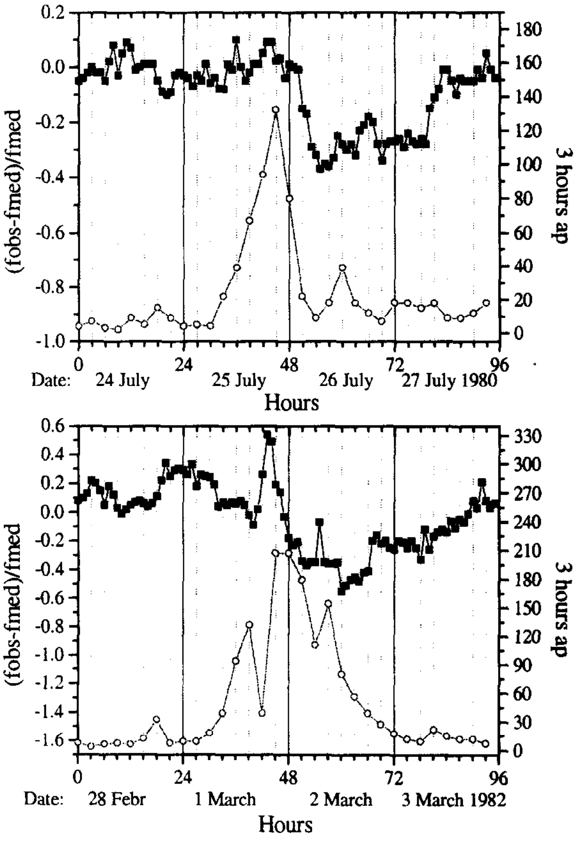

Fig. 2. An example of "delayed" negative storm effect for a daytime storm onset – (a), and the effect of night-time storm onset – (b). Squares – observed hourly Δ*fo*F2 variations. Circles – 3 hours ap values.

It should be pointed out that a short-term (1-3 hours in advance) *fo*F2 prediction can be done with an acceptable accuracy without taking into account geomagnetic activity at all (Mikhailov, 1990; Mikhailov et al., 1999). This is due to a pretty good inter-hour *fo*F2 correlation within a characteristic time mentioned above. An example of such *fo*F2 prediction is shown in Figure 3 for the period of Feb

27- Mar 5, 1982, comprising a geomagnetic storm with Ap=107. A two-term version of the expression (1) was used for this prediction. The observed *fo*F2 variations are predicted with a reasonable accuracy with lead time 1-3 hours both for quiet and disturbed days. But other approaches are required for prediction during strong disturbed periods with larger lead times (see below).

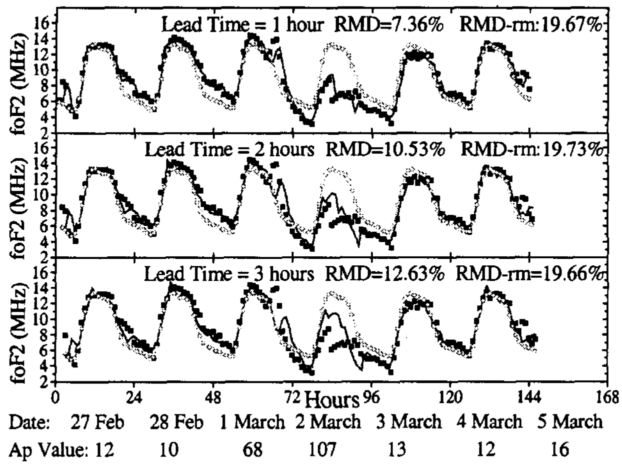

Fig. 3. An example of *fo*F2 prediction without taking into account the geomagnetic activity. Solid line – prediction with a two-term expression (1); Circles – a 28-day running median; Squares – observed *fo*F2. Relative mean deviations of predicted *fo*F2 with respect to observations are given.

6 Prediction accuracy for moderate disturbed periods

The method testing for quiet and moderately disturbed periods, has shown that the prediction accuracy practically does not depend neither on lead time (more than 3 hours) nor Ap/*fo*F2 time shift used for the method training, and RMD is around 10-13%. Such RMD is quite acceptable from practical point of view. Examples of such testing are given in Table 2 and 3 for two moderately disturbed periods Apr 24-30, 1974 (mean Ap=20) and Mar 7-13, 1975 (mean Ap=30).

Table 2. Relative mean deviations (in %) of *fo*F2 prediction for the period of Apr 24-30, 1974. The geomagnetic activity was taken into account only for lead time more than 7 hours. The results for different Ap/*fo*F2 shift and lead times are given.

Lead Time (hours)	**Ap/*fo*F2 Shift (hours)**						
	0	**4**	**8**	**12**	**16**	**20**	**23**
1	7.30	7.30	7.30	7.30	7.30	7.30	7.30
3	10.08	10.08	10.08	10.08	10.08	10.08	10.08
6	11.39	11.39	11.39	11.39	11.39	11.39	11.39
12	11.75	11.77	11.77	11.77	11.74	11.74	11.75
18	11.81	11.83	11.84	11.85	11.85	11.84	11.84
24	12.39	12.38	12.38	12.35	12.33	12.29	12.27

Such insensitivity of the method accuracy to Ap/foF2 time shift and lead time is due to the fact that El Arenosillo is a relatively low latitude station where small geomagnetic disturbances are not seen in *fo*F2 variations which remain very close to a running median.

Table 3. Relative mean deviations (in %) of *fo*F2 prediction for the period of Mar 7-13, 1975. The geomagnetic activity was taken into account only for lead time more than 7 hours. The results for different Ap/*fo*F2 shift and lead times are given.

Lead Time (hours)	**Ap/*fo*F2 Shift (hours)**						
	0	**4**	**8**	**12**	**16**	**20**	**23**
1	8.32	8.32	8.32	8.32	8.32	8.32	8.32
3	11.32	11.32	11.32	11.32	11.32	11.32	11.32
6	12.59	12.59	12.59	12.59	12.59	12.59	12.59
12	13.74	13.75	13.73	13.61	13.51	13.39	13.35
18	13.92	13.93	13.89	13.76	13.56	13.37	13.37
24	12.37	12.42	12.43	12.38	12.30	12.22	12.23

7 Strong disturbances and large lead times

There are some possibilities to predict *fo*F2 variations during severe storms with large (more than 3 hours) lead times:

1. To train the proposed method not with hourly *fo*F2 values observed for the previous period as before, but with specially chosen really disturbed days. About 30 geomagnetic storms with a pronounced negative effect in *fo*F2 were selected using El Arenosillo, Tortosa, and Rome observations. The three European stations have close geomagnetic latitudes and are in one and the same longitudinal sector, so such observations can be combined for our analysis. By analogy with the above general description daily Ap indexes corresponding to the selected disturbed days were used for training and the expression (1) was used for the *fo*F2 prediction. So, the proposed approach comprises a general method based on the expression (1) to predict quiet and moderately disturbed conditions with switching to a special version to predict highly disturbed periods.
2. The other possibility is based on the idea proposed by Wrenn *et al.*, (1987). The idea is to derive typical daily variations of $\ln(N/N_0) = 2\ln(foF2/fo)$ (where N is *Nm*F2 while No and *fo* - are quiet time reference values) using *fo*F2 observations for disturbed conditions at different levels of solar activity and seasons, and use them for *fo*F2 prediction under such conditions. The Wrenn's method implies the use of the time accumulation ap(τ) index. This ap(τ) index which reflects the recent history of the geomagnetic activity was calculated for every 3-hour interval for the period 1960 – 1995 using the expression

$$a_p(\tau) = (1-\tau).(a_p + \tau.a_{p-1} + \tau^2.a_{p-2} + \ldots),$$

with the recommended value of $\tau = 0.75$ and a_{p-1}, a_{p-2} being the 3 hours ap values for –3 hours, -6 hours, etc. Two levels of disturbance are accepted: "Disturbed" when $18 < ap(0.75) < 30$; and "Very Disturbed", $30 \le ap(0.75)$.

Hourly ln(N/No) values were calculated for Tortosa station for the same time period as ap(0.75) and quiet reference *fo* values were determined in accordance with Wrenn *et al.*, (1987). Mean ln(N/No) values were obtained for all 3 hour intervals corresponding to "Disturbed" and "Very Disturbed" conditions and binned in station time (0-23 hours), seasons (winter, equinox and summer) and levels of solar activity ($F_{10.7} < 100$, $100 \leq F_{10.7} < 150$, $150 \leq F_{10.7} < 200$ and $200 \leq F_{10.7}$). The three-hour intervals containing a storm sudden commencement and the succeeding two intervals were eliminated from the summations.

Figure 4 gives an example of such daily variations for $150 \leq F_{10.7} < 200$ and three seasons. The mean ln(N/No) values corresponding to 0-12 h are repeated to give a better picture of daily variation. An analysis of these mean ln(N/No) variations shows the agreement with general F2-layer storm concept. The largest deviations take place in the early morning LT sector and the least ones during daytime. The deviations are systematically higher for larger disturbances. Positive storm effects are clearly seen during daytime hours in winter, but only negative storm effects take place in equinox and summer. Similar results were obtained by Wrenn *et al.*, (1987) for higher latitude stations. So the derived typical storm-time ln(N/No) variations in principle can be used for *fo*F2 short-term prediction. However, it should be stressed that the scatter in ln(N/No) values used to create these typical curves is pretty large, so the *fo*F2 prediction accuracy may turn out to be not very high. Indeed, daily average standard deviations corresponding to very disturbed conditions and $150 \leq F_{10.7} < 200$ are: 0.45 for winter, 0.43 for equinox and 0.38 for summer.

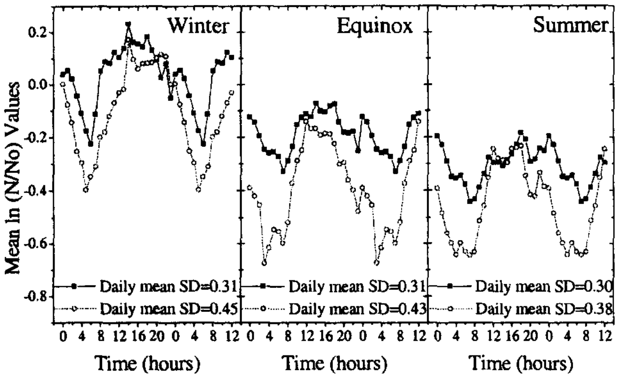

Fig. 4. "Disturbed" (squares) and "Very disturbed" (circles) daily variations of mean ln(N/No) for $150 \leq F_{10.7} < 200$ and three seasons. Daily mean standard deviations are given as well.

8 Comparison of methods

The three methods described above: (1) the basic one using the previous days for training; (2) the same basic method but trained on disturbed days only, and (3) the method based on the Wrenn *et al.*, (1987) approach were run to predict 5 different storm days observed in El Arenosillo with strong negative effects in *fo*F2 to compare the methods. The applied method of testing simulated a real *fo*F2 prediction for future 24 hours, that is using the last available observations on 23UT a prediction was made with 1-24 lead times and compared with *fo*F2 observations. Table 4 gives the list of storms analysed and the results of methods comparison.

Table 4. The list of periods analysed and relative mean deviations of predicted *fo*F2 with respect to observations. Three methods and a prediction with a 28-day running median are compared. Daily Ap for previous and given days as well as monthly average $F_{10.7}$ are given.

Storm Date	Ap	$\overline{F_{10.7}}$	Relative Mean Deviation in %			
			Method 1	Method 2	Method 3	Running Median
26/7/80	$^{46}/_{26}$	184.8	17.27	14.05	13.86	35.35
12/4/81	$^{39}/_{96}$	223.2	82.37	24.64	42.47	79.97
13/4/81	$^{96}/_{121}$	223.2	43.45	22.58	28.05	63.41
02/3/82	$^{68}/_{107}$	210.5	53.97	16.36	36.14	52.64
10/5/93	$^{48}/_{48}$	112.4	32.01	15.56	16.12	26.43

Testing has shown that Method 2 trained on disturbed days provides overall the best prediction accuracy. The most interesting period of Apr 12-13, 1981 is given in Figure 5 to get an idea of different methods prediction possibility. These two very disturbed neighbouring days demonstrate different *fo*F2 daily variations which cannot be distinguished neither by running median nor by Wrenn's method. The method (1) demonstrates some day-to-day changes, but they are not sufficient to follow the observed *fo*F2 variations as the previous training period did not include such strongly disturbed days. But the Method (2) being trained on specially selected disturbed days more properly reacts to changes in geomagnetic activity level. Therefor, the proposed approach (Method 2) may be considered as promising for practical application, but further steps are required on this way. For instance, the training observations should be divided by season as seasonal differences in F2-layer storm effects are essential. However, strong geomagnetic storms are not very frequent and it may be a problem to collect sufficient number of observations for different seasons. Further; it would be desirable to separate training storms by various local time onsets as this is essential for the method accuracy, but again this may be a problem due to insufficient number of available storms.

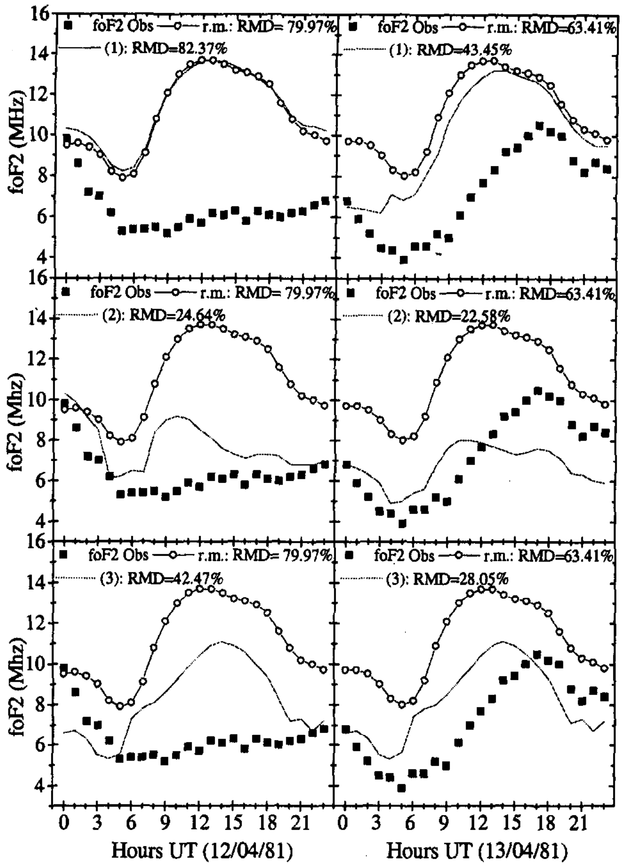

Fig. 5. A comparison of three prediction methods for two very disturbed neighbouring days Apr 2, 1981 (left-hand column) and Apr 3, 1981 (right-hand column). Basic method – top panels; basic method, but trained with disturbed days – middle panels; the Wrenn's approach – bottom panels. Squares – observed *fo*F2, and circles – running median. Relative mean deviations of *fo*F2 prediction with running median (r.m.) and with the three mentioned methods are given.

9 Conclusions

The main results of our analysis may be listed as follows:

1. A method for *fo*F2 short-term (1-24 hours in advance) prediction based on Δ*fo*F2 regression with previous Δ*fo*F2 observations and Ap index has been proposed. The method provides the *fo*F2 forecast accuracy with RMD=8-13% for quiet time and moderately disturbed periods. The optimum length of training time interval was shown to exist being close to one solar rotation.
2. Due to close inter-hour *fo*F2 correlation an acceptable *fo*F2 prediction accuracy with RMD around 10-13% is provided for 1-3 hour lead times at different geophysical conditions including severe storm events. This kind of prediction can be done without taking into account the level of magnetic activity.
3. Special methods are required to predict *fo*F2 during the severe storm periods with lead times larger than 3 hours. Training the proposed method with specially selected storm periods was shown to provide the prediction accuracy higher than can be achieved both with the basic method and Wrenn's *et al.*, (1987) approach based on typical storm daily ln(N/No) variations.
4. The proposed method for practical use comprises the basic version of the method to predict quiet time and moderately disturbed conditions with switching to a special mode to predict strongly disturbed periods. The required input parameters are current *fo*F2 observations and predicted daily Ap index.

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