Monthly median f_0F_2 and $M(3000)F_2$ ionospheric model over Europe

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Abstract
Monthly median f_0F_2 and $M(3000)F_2$ ionospheric model, $MQMF_2$, based on the multiquadric (MQ) method of spatial interpolation and a new ionospheric index MF_2 describes the monthly median f_0F_2 and $M(3000)F_2$ over Europe for any UT moment, month and level of solar activity. The multiquadric method allows a surface to be drawn strictly over a given set of points unlike many other currently used ionosphere mapping methods. A non-linear dependence of f_0F_2 and $M(3000)F_2$ on solar activity level (expressed by MF_2 index) is used to establish local models for each ionosonde station. Observations on 28 ionosondes for f_0F_2 and 19 for $M(3000)F_2$ over 10-30 years were used for model derivation. The $MQMF_2$ provides better accuracy than the CCIR model in retrospective mode over Europe. Long-term f_0F_2 prediction with the help of MF_2 index for the rising part of solar cycle 22 is shown to provide better prediction accuracy than the CCIR model based on sunspot number R_{12}. $MQMF_2$ is implemented as a code for PC AT-386/387 or compatible, providing tables, plots and maps.

Key words *ionospheric index – regional ionospheric model – multiquadric F_2-region parameters mapping – long-term prediction*

1. Introduction

One of the PRIME (Prediction and Retrospective Ionospheric Modelling over Europe) project objectives is to derive a reference monthly median f_0F_2 and $M(3000)F_2$ model to be used in long-term planning. As Europe is a data-rich area, a new regional model should demonstrate advantages over the world-wide CCIR model (CCIR, 1967). This paper describes one approach to achieving that improvement. The improvement may be reached by using more accurate dependence of F_2-layer parameters on solar activity level and an advanced spatial approximation method. The new effective ionospheric index MF_2 (Mikhailov and Mikhailov, 1995) and the multiquadric method of spatial interpolation (Teryokhin and Mikhailov, 1993) were used in the $MQMF_2$ model. Ionospheric indices such as IF_2 (Minnis and Bazzard, 1960), IG_{12} (Liu *et al.*, 1983), T (Caruana, 1990), $RESSN_{12}$ (Mikhailov *et al.*, 1990a) and MF_2 (Mikhailov and Mikhailov, 1995) have already been shown to have some advantages over direct solar indices (Liu *et al.*, 1983; Mikhailov *et al.*, 1990a; Mikhailov *et al.*, 1990b) for the ionospheric F_2-layer parameter modelling and long-term prediction. This results from that direct solar indices mostly reflect the upper atmosphere ionization effects, while the ionospheric F_2-region is formed under the influence of many processes which are not directly related to sunspot numbers R_{12} or EUV fluxes. On the other hand, ionospheric indices reflect the entire effect of all processes on the F_2-region and the efficiency of some of them is not yet well known. Thus, the use of ionospheric indices

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for F_2-region modelling and prediction seems very promising compared to the traditional solar index R_{12}.

There are some approaches to global as well as regional mapping of ionosphere parameters. In the Jones and Gallet (1965) method accepted by CCIR and the Rush *et al.* (1989) method accepted by URSI, monthly median f_0F_2 diurnal variations at each individual observatory are Fourier-analyzed up to the seventh order and then world-wide mapping by Legendre development is carried out for each Fourier coefficient. Fox and McNamara (1986), Chernishov and Vasiljeva (1973) applied spherical harmonic analysis to observed monthly median f_0F_2 values right away. An optimum interpolation method using empirical orthogonal eigenfunctions was applied by Dvinskih and Naidenova (1971) to represent world-wide as well as regional F_2-layer parameter spatial variations. These approaches are based on the least squares method which provides minimum mean world-wide standard deviation but may result in sufficient errors at particular stations, especially in data-sparse regions. As Rawer (1987) underlined, this kind of «democratic vote» operation giving «equal rights» to all stations leaves few chances for a station with abnormal diurnal variation to survive in this procedure.

Some approaches to regional mapping were proposed in the framework of the European PRIME project. The SIRM model (Zolesi *et al.*, 1993) is based upon the Fourier analysis of monthly median ionospheric characteristics and the SCHA (De Franceschi *et al.*, 1994) approach applies the spherical cup harmonic analysis where the coefficients are determined by a least squares fit of the observational data as in the approaches mentioned above. The UNDIV model (Bradley *et al.*, 1994) adopted for PRIME uses linear latitudinal dependence for ionospheric parameters without taking into account longitudinal variations and applied interpolation between reference monthly median f_0F_2 and $M(3000)F_2$ maps for three reference levels of solar activity.

An interesting method for regional mapping was proposed by Paul (1991). The method's efficiency was demonstrated on f_0F_2 mapping over the European region. This method was analyzed and compared with the multiquadric one (Teryokhin and Mikhailov, 1993). The latter mapping method was shown to be more precise and faster than Paul's one.

The $MQMF_2$ is a monthly median f_0F_2 and $M(3000)F_2$ model over the European region. The distribution of European ionosonde stations and CCIR buffer points used in its generation is shown in fig. 1. The $MQMF_2$ model comprises the *MAIN AREA* and the *BUFFER ZONE*. The *MAIN AREA* covers the European region (30°N < lat. < 70°N; 10°W < long. < 60°E) and includes 28 ionosonde stations. Local models are derived and stored in the $MQMF_2$ model code for each ionosonde station. All these 28 stations (19 for $M(3000)F_2$) are available for the analysis. The *BUFFER ZONE* around the *MAIN AREA* is confined by 10°N < lat. < 90°N; 40°W < long. < 90°E) and includes 30 buffer points where f_0F_2 and $M(3000)F_2$ values are calculated according to the CCIR model.

The $MQMF_2$ model smoothly interfaces with the world-wide CCIR model outside the European area (see fig. 1). The interfacing problem was discussed in (Harrison, 1992). The difference between points inside the area and buffer points around should be emphasised. Internal points are real ionosonde stations where measured f_0F_2 and $M(3000)F_2$ were used to derive local models. Buffer points are just locations where the CCIR model values are calculated for given R_{12}, month and UT times. To provide smooth interfacing with the CCIR model around the European area, the buffer points along with real internal ones are included in the mapping procedure (multiquadric method). So there is a buffer zone along the European area boundary where both internal and CCIR buffer points define the f_0F_2 and $M(3000)F_2$ distributions (*). The model is derived in a geographic coordinate system (northern latitude and eastern longitude). Diur-

(*) Attention is drawn to the fact that the mapped area size and buffer zone treatment differ from those adopted in *PRIME* project.

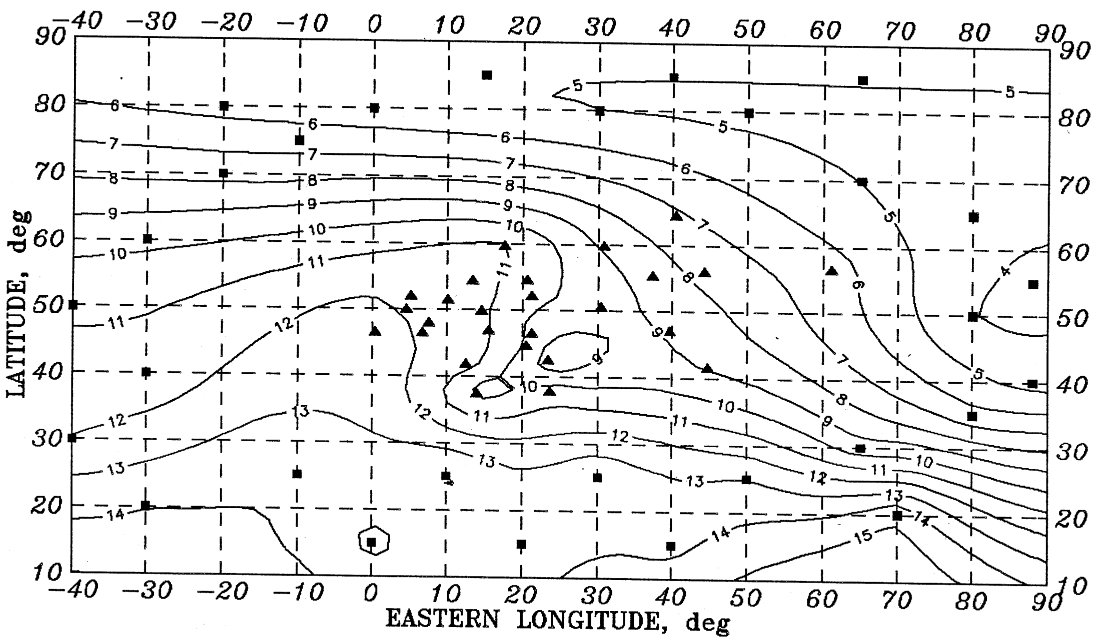


Fig. 1. European ionosonde locations (triangles) where f_0F_2 and $M(3000)F_2$ local models are derived and buffer points (squares) where CCIR model values are calculated. The use of buffer points provides smooth interfacing (as shown in the figure) of the main area ($MQMF_2$ model) with the global CCIR model.

nal variations of ionospheric parameters are given in UT and maps may be presented in any rectangular area not surpassing that shown in fig. 1 for any UT moment.

2. Model input parameters and options

2.1. *Solar activity indices*

Northern hemisphere monthly ionospheric indices MF_2 and 12-month running mean sunspot numbers R_{12} (used as an input to the CCIR code) are stored in the $MQMF_2$ model for the period 1949-1992 and will be chosen by the $MQMF_2$ code automatically if «year» and «month» are in range. These MF_2 indices are listed in table I.

For the current period after December 1992 monthly MF_2 indices may be calculated provided that noon monthly median f_0F_2 are available from the northern hemisphere ionosondes. The reliability of calculated MF_2 index depends on the number of stations involved (the more the better) but a minimum number is supposed to be 10. A special code (MF_2 INDEX) attached to the main $MQMF_2$ software is to be used for MF_2 index calculation after 1992. The method is based on the use of f_0F_2 versus MF_2 regressions over the European ionosonde network (local models). Local MF_2 indices averaged over 10-20 European ionosondes can give the MF_2 index with an acceptable accuracy (mean relative deviation is about 3%). Values of MF_2 derived from f_0F_2 observations are also used for the $M(3000)F_2$ model evaluations.

Local f_0F_2 and $M(3000)F_2$ models were derived for 24 moments of UT, 12 months for each of the European ionosonde stations with long enough (not less than a solar cycle) periods of observation. Data on 28 stations were available for f_0F_2 modelling and only on 19 of them – for $M(3000)F_2$. The list of European ionosonde stations used for model generation is given in table II.

Table I. Monthly MF_2 indices for the period of 1949-1992 derived for the northern hemisphere.

Year	Month											
	I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII
1949	8.44	11.33	12.81	12.01	11.32	9.27	8.79	8.42	9.14	10.98	10.61	8.78
1950	8.09	8.75	10.25	9.99	9.67	8.74	7.94	6.95	6.24	7.64	6.71	5.34
1951	5.98	6.29	7.50	7.53	7.80	7.75	7.23	6.84	6.34	7.36	6.95	5.35
1952	5.56	5.83	5.81	6.19	6.53	6.69	6.62	6.01	5.90	6.21	5.85	4.67
1953	5.28	4.84	5.04	6.03	5.98	6.18	5.63	5.52	5.33	5.46	4.88	4.25
1954	4.49	4.53	4.16	5.43	5.89	5.91	5.67	5.29	4.87	5.67	5.08	4.17
1955	4.93	5.11	5.63	5.70	6.53	6.48	6.85	6.25	6.33	7.85	7.59	6.18
1956	6.85	8.00	10.84	9.87	10.00	9.45	8.55	9.06	10.77	12.45	11.88	10.92
1957	11.79	12.12	12.75	12.72	9.87	9.86	9.59	9.32	10.85	12.74	12.41	10.87
1958	11.20	11.68	12.90	12.68	10.50	9.52	9.26	9.76	11.49	12.85	11.82	9.80
1959	10.75	11.37	12.19	11.55	10.58	9.66	8.91	9.07	9.89	10.79	10.28	8.28
1960	9.65	10.38	10.54	9.56	9.36	8.72	8.54	8.36	9.68	9.87	9.65	7.32
1961	6.85	7.10	8.03	7.63	7.59	7.70	7.23	7.44	7.01	7.36	6.45	5.01
1962	5.07	5.67	6.59	6.53	7.43	6.96	6.45	5.78	5.94	6.19	6.07	4.49
1963	4.86	5.14	5.74	6.18	6.59	6.67	6.20	5.78	5.56	6.20	5.82	4.23
1964	4.59	5.17	6.04	5.96	5.96	6.08	5.71	5.41	5.45	5.61	5.12	4.19
1965	4.48	5.16	5.93	6.15	6.27	6.40	6.15	5.75	5.49	6.31	5.83	4.21
1966	4.77	5.25	6.02	6.83	7.35	7.33	7.25	6.90	6.64	7.80	7.25	5.68
1967	6.80	8.09	10.14	10.09	8.51	7.88	8.13	8.09	8.67	9.84	8.62	7.49
1968	8.51	9.22	9.92	9.73	9.24	8.46	8.24	8.11	8.49	9.93	8.59	7.59
1969	7.28	8.84	10.92	10.41	9.33	8.73	8.30	8.25	8.76	9.72	8.93	6.66
1970	7.79	9.57	10.66	10.69	9.84	8.92	8.66	8.11	9.09	10.01	9.85	7.14
1971	7.11	8.04	8.94	8.30	7.79	7.60	7.37	6.67	7.21	7.49	7.29	5.80
1972	6.20	7.48	9.86	9.14	8.61	8.44	8.23	7.66	8.33	8.63	7.14	5.24
1973	5.56	6.30	6.57	6.57	7.24	6.96	6.49	6.18	6.55	6.71	5.87	4.52
1974	4.64	4.94	5.75	6.22	6.71	6.61	6.43	5.87	5.72	6.83	5.98	4.60
1975	4.94	4.52	5.42	5.43	5.91	6.07	5.93	5.81	6.07	6.35	5.47	4.19
1976	4.43	4.59	5.34	6.01	6.29	6.28	5.87	5.68	5.55	6.16	5.06	4.30
1977	4.56	5.38	6.01	6.08	6.66	6.94	6.51	6.14	6.15	7.21	6.48	5.19
1978	5.78	7.67	9.36	8.98	8.86	8.54	8.56	7.74	8.87	10.66	9.38	7.78
1979	8.93	11.38	12.32	10.45	10.43	9.45	8.74	9.00	10.23	12.52	11.54	9.52
1980	9.21	10.53	12.03	11.67	11.03	10.03	9.40	9.15	10.00	11.80	11.29	9.62
1981	8.64	10.82	12.55	11.76	10.91	9.75	8.87	9.06	11.16	12.15	11.66	9.15
1982	9.05	10.40	11.88	10.77	9.88	8.67	7.94	7.88	8.69	10.80	10.02	8.37
1983	7.43	7.80	8.16	7.60	8.81	8.34	7.83	7.49	7.18	8.25	7.30	5.57
1984	5.80	6.81	8.31	7.35	7.77	7.36	6.65	6.03	5.77	5.85	5.45	4.60
1985	4.90	5.17	5.40	5.69	6.15	6.21	5.95	5.53	5.45	5.90	5.37	4.33
1986	4.70	4.88	5.66	6.07	6.15	5.89	5.82	5.29	5.24	6.15	5.48	4.44
1987	4.43	4.93	5.40	6.35	6.93	6.46	6.04	6.13	5.82	6.70	7.00	5.25
1988	5.61	5.78	7.33	8.54	8.05	8.22	7.50	7.83	8.98	10.95	9.81	8.59
1989	8.82	10.89	11.73	11.52	10.28	9.49	9.81	8.69	10.50	11.91	11.86	9.44
1990	9.60	9.67	11.21	11.03	10.24	9.84	8.96	8.84	10.46	11.22	10.22	8.46
1991	9.45	11.52	12.79	12.62	10.10	8.70	8.65	8.33	10.07	10.92	9.89	8.78
1992	9.78	11.89	11.44	12.05	8.87	8.08	7.80	7.15	7.62	8.23	8.88	7.02

Table II. The list of European ionosonde stations used for f_0F_2 local models derivation. Stations with asterisks are those used for $M(3000)F_2$ models.

Station	Lat. N	Long. E	Station	Lat. N	Long. E
* Arkhangelsk	64.60	40.50	* Lindau	51.60	10.10
Athens	36.00	23.60	* Miedzeszyn	52.20	21.20
* Bekescsaba	46.67	21.17	* Moscow	55.50	37.30
Beograd	44.80	20.50	* Peterburg	59.95	30.70
De Bilt	21.10	5.20	* Poitiers	46.60	0.30
* Dourbes	50.10	4.60	Pruhonice	50.00	14.60
Freiburg	48.10	7.60	* Rome	41.90	12.52
Gibilmanna	37.59	14.01	* Rostov	47.20	39.68
* Gorky	56.15	44.28	Schwarzenburg	46.60	6.70
Graz	47.10	15.50	* Slough	51.50	359.43
* Juliusruh	54.60	13.40	Sofia	42.60	23.40
* Kaliningrad	54.70	20.62	* Sverdlovsk	56.70	61.10
* Kiev	50.72	30.30	* Tbilisi	41.70	44.80
* Lannion	48.45	356.73	* Uppsala	59.80	17.60

A cubic parabola was used to approximate the dependence on solar activity level (MF_2 index) both for f_0F_2 and $M(3000)F_2$ since linear dependence on solar activity recommended by CCIR is not appropriate to observe f_0F_2 and $M(3000)F_2$ variations (Kouris and Agathonikos, 1992; Mikhailov, 1993; Bradley, 1994).

2.2. *Model options*

There are four options for $MQMF_2$ Model output:

1) Diurnal f_0F_2 and $M(3000)F_2$ variations in UT for any ionosonde from the station list. Standard deviation ε (in MHz) and mean relative deviation δ (in %) are given for 24 moments of UT and each ionospheric characteristic. The estimates of ε and δ are made in accordance with the expressions

$$\varepsilon = ((\Sigma\Delta^2 - (\Sigma\Delta)^2/n)\ /\ (n-1))^{0.5};$$

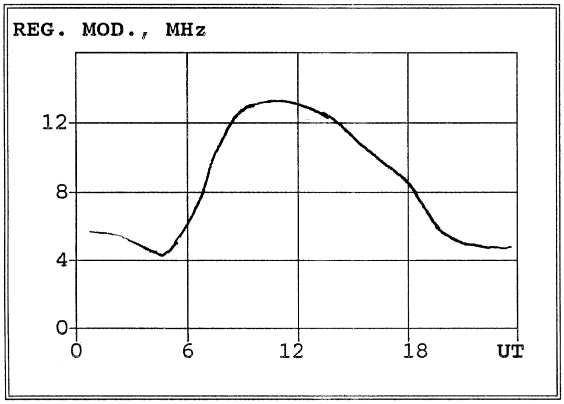
$$\delta = (\Sigma\,|\,\Delta/f_0F_{2_{\mathrm{obs}}}\,|)/n$$

where $= \Delta = f_0F_{2_{\mathrm{mod}}} - f_0F_{2_{\mathrm{obs}}}$ and n – number of points used for any local model derivation. The results may be screened and presented in a table form or as a plot. An example of output is shown in fig. 2. The $M(3000)F_2$ model parameter may be absent for some ionosonde stations resulting from the absence of observations or an insufficient amount of data for local model derivation.

2) Diurnal f_0F_2 and $M(3000)F_2$ variations in UT at a given point (geographic northern latitude and eastern longitude) inside the area (90°N ≥ lat. ≥ 10°N; −40°W ≤ long. ≤ 90°E). Model f_0F_2 and $M(3000)F_2$ values are read from the surface drawn over the area with the help of a multiquadric method. Coordinates of the point may coincide with those of any ionosonde station and calculated f_0F_2 and $M(3000)F_2$ values will be the same as in Option N1 in this case. But unlike Option N1 statistical characteristics are absent for this Option. The results may be screened and presented in table form or plotted as in Option N1.

3) A comparison of diurnal f_0F_2 or $M(3000)F_2$ variations for different years, months or locations on one plot (up to 10

Station	lat	long	year	month	UT	R12	MF2
Graz	47.10	15.5	1958	February		200.9	11.68



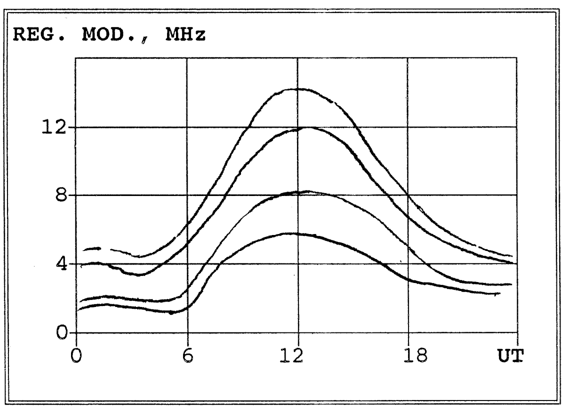
UT	foF2	SD(MHz)	MRD(%)
0	5.53	.354	6.400
1	5.38	.261	4.976
2	5.26	.270	5.449
3	4.96	.237	5.179
4	4.60	.298	6.325
5	4.35	.383	6.838
6	5.81	.307	4.346
7	9.17	.268	3.213
8	11.32	.504	4.124
9	12.39	.668	5.169
10	12.67	.755	5.793

Arrows to continue list,
ESC to exit

Mode 1: Model for one station *** FoF2 computation ***

Fig. 2. Screened f_0F_2 (MHz) model diurnal variations for Graz ionosonde, February 1958. Standard deviation SD (in MHz) and mean relative deviation MRD (in %) are given for each UT moment.

Comparison of results for several years and/or months



LEGEND

Sta	Lat	Lon	Mon	R12	MF2
Jul	54.60	13.4	2	200.9	11.6
Jul	54.60	13.4	2	125.0	10.3
Jul	54.60	13.4	2	74.8	7.1
Jul	54.60	13.4	2	12.0	5.1

ESC to exit

Report *** FoF2 computation ***

Fig. 3. Screened of model f_0F_2 (MHz) diurnal variations for Juliusruh for the months of February 1958, 1960, 1961 and 1965.

curves). An example of such a comparison is shown in fig. 3.

4) Spatial f_0F_2 and $M(3000)F_2$ variations in the form of maps may be drawn over a specified area within the European region (Δ latitude, Δ longitude) with any chosen set of isolines for a given UT moment. A map may be screened and plotted. Examples of such maps for February 1979 and 16 UT are shown in figs. 4 and 5. All model options handling are described in ($MQMF_2$ MANUAL) attached to the main $MQMF_2$ code.

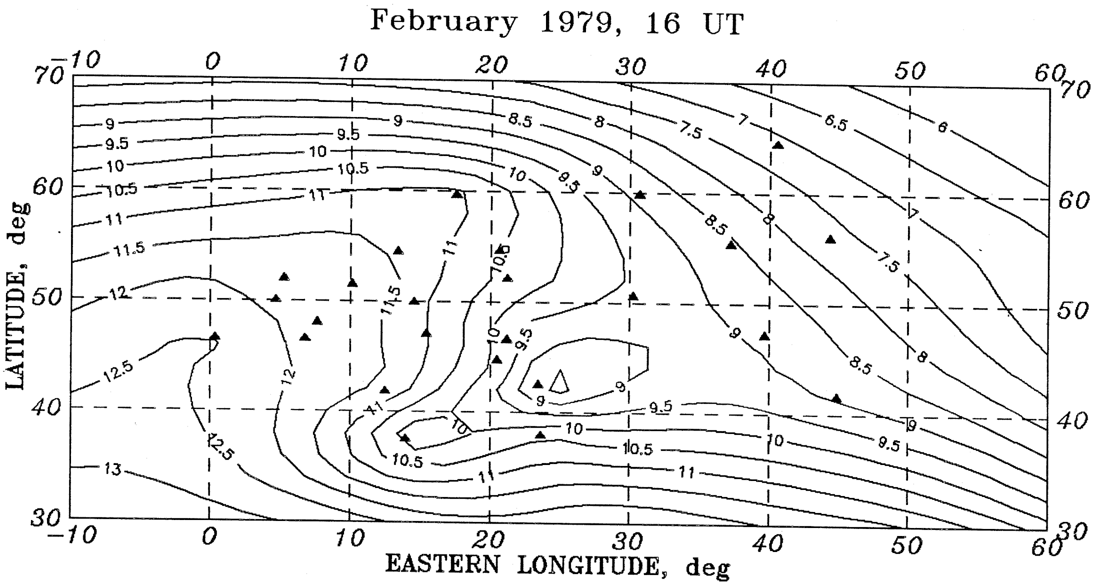


Fig. 4. $MQMF_2$ model distribution of f_0F_2 (MHz) over Europe for February 1979, 16 UT as a program optional output.

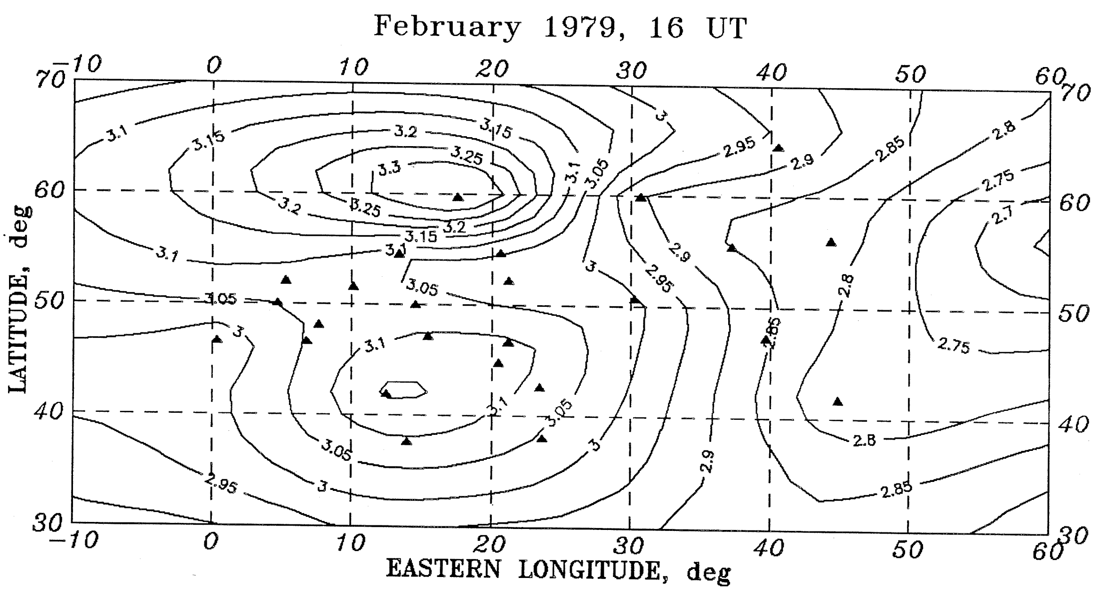


Fig. 5. $MQMF_2$ model distribution of $M(3000)F_2$ over Europe for February 1979, 16 UT as a program optional output.

3. Model accuracy estimates

The multiquadric method of mapping used in the $MQMF_2$ model draws a surface over the points strictly. That is why it is important to discuss the accuracy of:

1) local models developed for the network of ionosonde stations;

2) interpolation and extrapolation by the multiquadric method.

Both of these questions were considered in (Teryokhin and Mikhailov, 1993; Mikhailov and Mikhailov, 1995). Here we present some further testing results. We also show for f_0F_2 the most consistent dependence on MF_2 and other commonly used indices.

To get an idea of the local models accuracy, non-linear f_0F_2 regressions versus the new index MF_2, sunspot number R_{12}, ionospheric index IG_{12} (Caruana, 1990) and $RESSN_{12}$ (Mikhailov *et al.*, 1990a) are analyzed. Data for the four widely separated European ionosonde stations Uppsala (59.8°N, 17.6°E), Athens (38.0°N, 23.6°E), Moscow (55.5°N, 37.3°E) and Slough (51.5°N, 359.4°E) were analyzed. The f_0F_2 and $M(3000)F_2$ dependence on various indices for Moscow, 14LT and 02LT is shown in figs. 6 and 7, as an example.

Similar calculations for four stations (for f_0F_2 parameter only), all months of the year and all hours of the day were made and the results of f_0F_2 regression versus four indices (standard deviation ε (in MHz) and relative mean deviation δ (in %); both expressions are given above) are presented in tables III, IV and V. The results are given for different seasons, time of day and levels of solar activity.

The statistics presented in tables III to V show that use of the new ionospheric index MF_2 significantly improves the f_0F_2 regression accuracy. The average standard deviation decrease is 20-30% in comparison with R_{12} for «mid-latitude» stations of Moscow and Slough. Maximum improvement (ε decrease) takes place for day-time hours (about 35%), low and moderate solar activity (more than 30%). The least improvement, about 13%, takes place for night-time hours. Similar results are obtained for the «high-latitude» Uppsala station. A somewhat lower improvement takes place for the «low-latitude» station Athens but the tendency is the same: maximum improvement is for day-time hours (27%), during winter and equinox (33%), low and moderate solar activity (19%). Minimum improvement takes place for night-time hours (10%), summer time (6%) and high solar activity (12%). A comparison with two 12-month running mean ionospheric indices IG_{12} and $RESSN_{12}$ gives similar results. The standard and relative deviations listed in tables III to V give an idea of the accuracy of local models used in the $MQMF_2$ model.

A comparison of our local (for ionosonde stations) models with world-wide ones such as CCIR or MUF Forecast (Chernishov and Vasiljeva, 1973) demonstrates a much higher accuracy of the local models. This is not surprising as a local model should be more accurate than a global one for any ionosonde station. To get an idea of the overall accuracy improvement we compared $MQMF_2$ and CCIR predictions of f_0F_2 for three levels of solar activity and three seasons using all available observations (table VI).

This retrospective comparison shows the obvious advantage of $MQMF_2$ over the CCIR model. The overall standard deviation decrease is 30-50%. Maximum gain takes place in winter (46-51% decrease of the standard deviation) at all levels of solar activity. Minimum improvement – in summer (32-39%). The statistics are quite enough (16000-18000 comparisons) to consider the results meaningful.

To estimate the spatial approximation possibility of the multiquadric method hourly f_0F_2 values were used for the European network of observatories. Various seasons, levels of solar and geomagnetic activity were considered. Observations are often absent for the periods of interest (dashes in table VII).

Excluding observatories one by one from the list the comparison of observed and calculated (interpolated or extrapolated) f_0F_2 values for those stations gives the estimation of the method's accuracy. The best approximation results are achieved for summer and equinox periods regardless of the level of solar and geomagnetic activity. During winter time when the F_2-region is under strong control of dynamical processes and is very variable, the approximation is poorer especially at high solar activity (January and November 1958, see table VII).

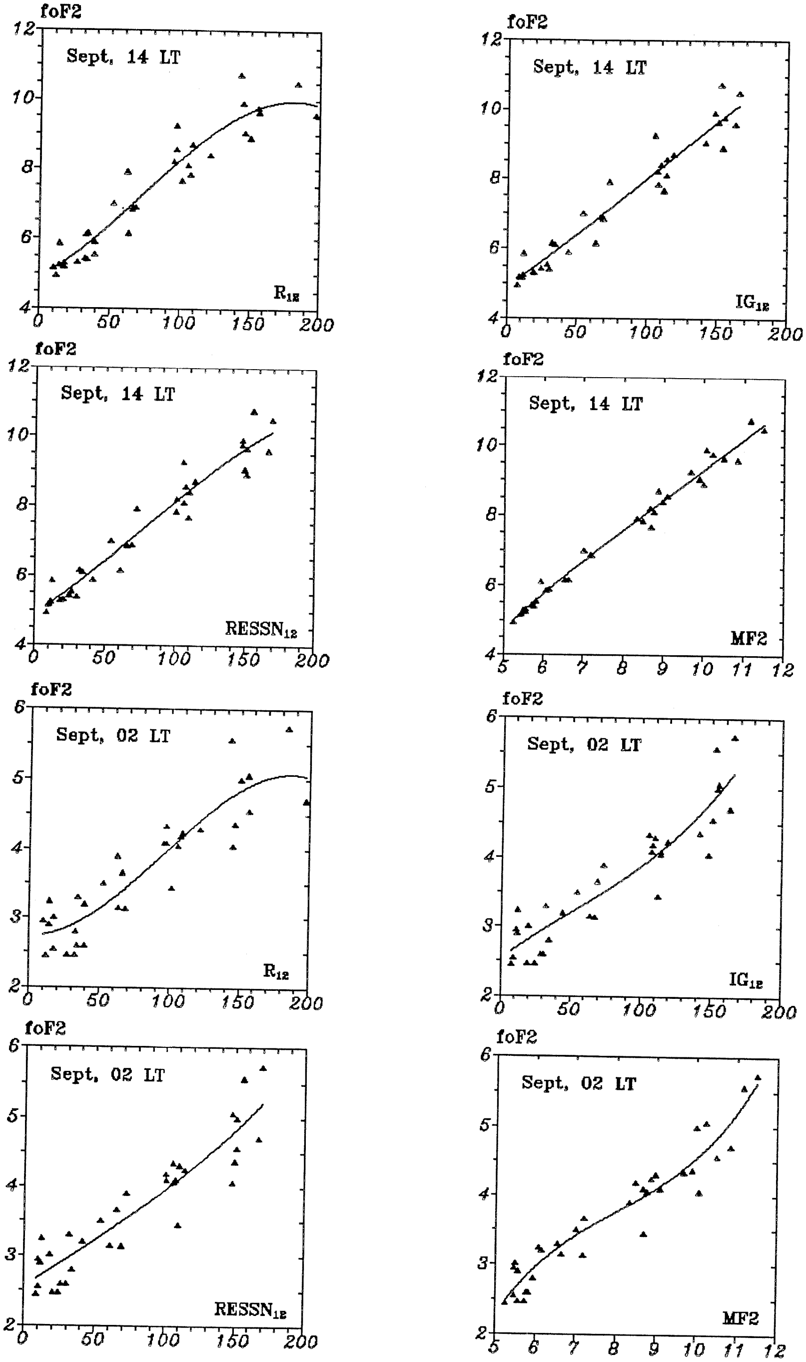


Fig. 6. Dependence of f_0F_2 (MHz) on different activity indices for the years of 1957-1991 (Moscow, September, 14 and 02UT).

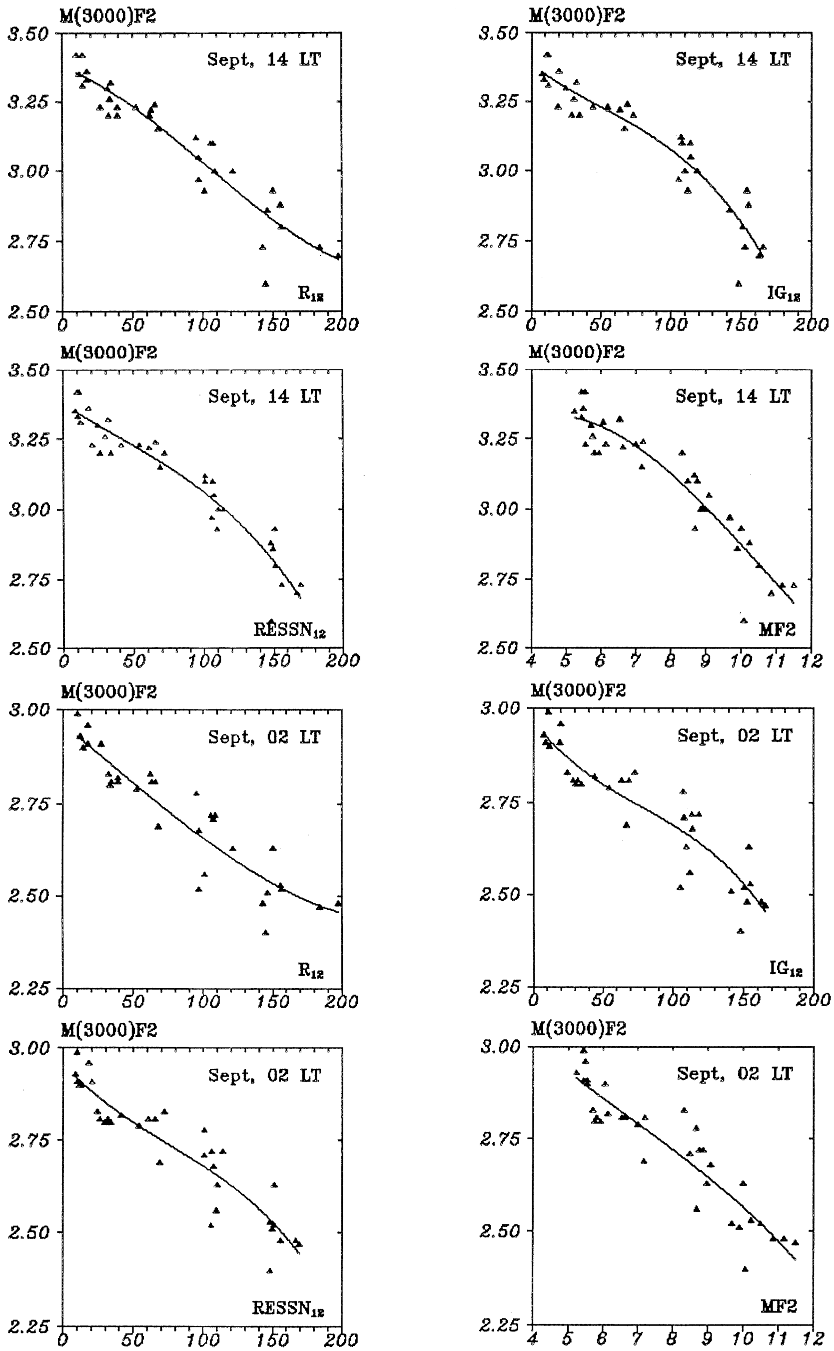


Fig. 7. Dependence of $M(3000)F_2$ on different activity indices for the years of 1957-1991 (Moscow, September, 14 and 02UT).

Table III. Daily mean ε in MHz and (δ in %) of f_0F_2 regression versus R_{12}, IG_{12}, $RESSN_{12}$ and MF_2 indices. Number of comparisons – the third column.

Station	Season		R_{12}	IG_{12}	$RESSN_{12}$	MF_2
Slough	Winter	(2280)	0.377 (5.2)	0.354 (5.1)	0.371 (5.2)	0.305 (4.6)
	Summer	(2256)	0.269 (4.0)	0.257 (3.6)	0.259 (3.7)	0.221 (3.2)
	Equinox	(2304)	0.453 (5.9)	0.421 (5.5)	0.458 (5.7)	0.323 (4.1)
Moscow	Winter	(3144)	0.444 (6.1)	0.429 (6.0)	0.436 (6.1)	0.324 (5.2)
	Summer	(3168)	0.318 (4.0)	0.294 (3.6)	0.295 (3.6)	0.220 (2.7)
	Equinox	(3168)	0.497 (6.7)	0.447 (5.9)	0.469 (6.1)	0.331 (4.3)
Uppsala	Winter	(1752)	0.360 (6.1)	0.340 (6.1)	0.362 (6.2)	0.282 (5.6)
	Summer	(1752)	0.306 (4.6)	0.293 (4.2)	0.289 (4.2)	0.225 (3.3)
	Equinox	(1728)	0.515 (7.2)	0.446 (6.4)	0.482 (6.7)	0.361 (5.6)
Athens	Winter	(1094)	0.445 (4.5)	0.410 (4.2)	0.414 (4.3)	0.295 (3.1)
	Summer	(1200)	0.663 (6.4)	0.678 (6.3)	0.667 (6.2)	0.619 (5.6)
	Equinox	(1224)	0.439 (5.3)	0.376 (4.3)	0.393 (4.4)	0.294 (3.5)

Table IV. Same as table III for annual average, distinct for three diurnal periods.

Station	Part of day		R_{12}	IG_{12}	$RESSN_{12}$	MF_2
Slough	Daytime	(2327)	0.418 (4.2)	0.391 (3.9)	0.420 (4.0)	0.279 (2.6)
	Nighttime	(2298)	0.307 (5.8)	0.293 (5.7)	0.307 (5.8)	0.270 (5.2)
	Twilight	(2215)	0.389 (4.8)	0.362 (4.5)	0.382 (4.6)	0.311 (3.7)
Moscow	Daytime	(2998)	0.480 (4.7)	0.434 (4.1)	0.450 (4.2)	0.294 (2.6)
	Nighttime	(2897)	0.330 (7.0)	0.314 (6.7)	0.324 (6.9)	0.282 (6.3)
	Twilight	(3585)	0.448 (5.3)	0.422 (4.8)	0.431 (4.9)	0.308 (3.6)
Uppsala	Daytime	(1540)	0.431 (4.8)	0.380 (4.2)	0.404 (4.3)	0.269 (3.0)
	Nighttime	(1504)	0.361 (7.7)	0.342 (7.7)	0.351 (7.7)	0.329 (7.6)
	Twilight	(2188)	0.407 (6.6)	0.369 (5.1)	0.394 (5.3)	0.285 (4.3)
Athens	Daytime	(1354)	0.562 (4.8)	0.525 (4.4)	0.522 (4.4)	0.408 (3.3)
	Nighttime	(1337)	0.498 (5.8)	0.491 (5.3)	0.493 (5.4)	0.445 (4.6)
	Twilight	(827)	0.547 (5.8)	0.531 (5.2)	0.536 (5.3)	0.461 (4.5)

Table V. Same as table III for annual average, distinct for three solar activity groups.

Station	Solar activity		R_{12}	IG_{12}	$RESSN_{12}$	MF_2
	$R_{12} < 35$	(2184)	0.284 (5.4)	0.256 (4.9)	0.254 (4.8)	0.200 (4.0)
Slough	$35 < R_{12} < 105$	(2376)	0.379 (5.0)	0.364 (4.8)	0.379 (4.9)	0.279 (3.9)
	$R_{12} > 105$	(2280)	0.436 (4.5)	0.410 (4.3)	0.452 (4.7)	0.355 (3.6)
	$R_{12} < 35$	(3072)	0.277 (5.5)	0.247 (4.9)	0.245 (4.9)	0.192 (4.1)
Moscow	$35 < R_{12} < 105$	(3240)	0.453 (5.9)	0.432 (5.5)	0.437 (5.7)	0.271 (4.2)
	$R_{12} > 105$	(3168)	0.508 (5.4)	0.468 (5.0)	0.493 (5.2)	0.388 (4.0)
	$R_{12} < 35$	(2016)	0.278 (6.1)	0.233 (5.3)	0.235 (5.4)	0.205 (4.8)
Uppsala	$35 < R_{12} < 105$	(1872)	0.426 (6.2)	0.411 (6.1)	0.420 (6.1)	0.291 (4.9)
	$R_{12} > 105$	(1344)	0.495 (5.5)	0.445 (5.3)	0.496 (5.5)	0.390 (4.9)
	$R_{12} < 35$	(1272)	0.349 (4.9)	0.296 (4.1)	0.294 (4.0)	0.280 (3.7)
Athens	$35 < R_{12} < 105$	(1814)	0.608 (6.0)	0.596 (5.7)	0.601 (5.8)	0.487 (4.4)
	$R_{12} > 105$	(432)	0.638 (4.5)	0.629 (4.2)	0.615 (4.2)	0.557 (4.0)

Table VI. $MQMF_2$/CCIR comparison of f_0F_2 over the PRIME area. Daily mean standard deviation (in MHz) and its decrease (in %) when $MQMF_2$ is used are given. Number of comparisons – in parenthesis.

Solar activity	Winter	Summer	Equinox
$R_{12} < 35$	.221 / .408	.220 / .323	.238 / .415
	45.9% (17304)	32.0% (16144)	42.5% (16824)
$35 < R_{12} < 105$	.338 / .640	.308 / .448	.352 / .645
	47.2% (18158)	31.3% (18763)	45.4% (18035)
$R_{12} > 105$	.518 / 1.05	.345 / .563	.513 / .828
	50.6% (15871)	38.6% (16712)	37.8% (16707)

4. Long-term prediction

Using the regularities in MF_2 index seasonal and solar cycle variation (Mikhailov and Mikhailov, 1995) a method for long-term prediction of MF_2 can be worked out. This method will be described elsewhere in detail, only its main features are given here. The procedure includes two predictions: i) 12-month running mean $MF_{2_{12}}$ (long-term variation), and ii) $MF_2/MF_{2_{12}}$ ratio for a particular month in a given phase of a solar cycle (seasonal variation).

The well-known McNish-Lincoln (1949) method is used for $MF_{2_{12}}$ long-term prediction with observed data from the three solar cycles 19-21. Monthly MF_2 for the last 6 months are used to specify three characteristic solar cycle parameters: rising phase steepness, expected $MF_{2_{12}}$ maximum and time of its appearance.

The ratio $MF_2/MF_{2_{12}}$ is determined month by month during a distinct phase of the three cycles (19-21). Then this $MF_2/MF_{2_{12}}$ ratio may

Table VII. The results of f_0F_2 spatial approximation with the method of multiquadric. Number of cases (in %) for $(f_0F_2)_{calc} - (f_0F_2)_{obs}$ deviations less than 20% is presented. Data for all UT hours are involved.

Station list	Coordinates lat. deg. N	long. deg. E	Jan. 1958	July 1958	Mar. 1976	Jan. 1965	July 1965	Nov. 1958
Bekescsaba	46.7	21.2	–	–	100.0	98.9	100.0	–
Budapest	47.4	19.2	92.9	98.3	–	–	–	72.8
De Bilt	52.1	5.2	96.7	100.0	100.0	–	–	76.8
Dourbes	50.1	4.6	98.3	100.0	100.0	97.9	100.0	98.7
Freiburg	48.0	7.6	100.0	100.0	–	93.9	100.0	68.3
Genova	44.6	9.0	97.1	99.2	–	89.0	92.4	–
Gorky	56.1	44.3	–	100.0	100.0	98.9	100.0	88.8
Kaliningrad	54.7	20.6	–	–	100.0	95.8	100.0	–
Kiev	50.5	30.5	–	–	100.0	100.0	100.0	–
Leningrad	60.0	30.7	47.9	–	95.3	82.0	100.0	–
Lycksele	64.7	18.8	60.2	99.2	94.4	81.4	98.7	85.4
Miedzeszyn	52.2	21.2	–	100.0	–	98.9	100.0	89.0
Moscow	55.5	37.3	98.4	100.0	100.0	100.0	100.0	97.6
Murmansk	69.0	33.0	54.2	99.1	95.8	83.5	100.0	61.1
Nurmijarvi	60.5	24.6	61.2	99.2	85.0	64.3	92.6	80.6
Paris	41.9	2.3	–	–	–	100.0	98.7	–
Poitiers	46.6	0.3	98.4	100.0	100.0	100.0	100.0	–
Rome	41.9	12.5	97.6	98.3	96.3	95.8	93.3	97.5
Rostov	47.2	39.7	86.4	100.0	100.0	96.0	100.0	94.4
Slough	51.5	359.4	99.2	100.0	100.0	92.0	98.8	97.5
Sodankyla	67.4	26.6	86.7	99.2	94.4	90.8	100.0	90.2
Sofia	42.3	23.3	–	–	–	94.7	94.9	–
Uppsala	59.8	17.6	85.4	100.0	96.3	–	–	91.5
Heliogeophysical conditions	R_{12}		199.0	185.2	12.2	11.7	15.5	180.7
	$< A_p >$		14.9	24.7	22.0	6.2	7.7	7.8

be used to obtain the MF_2 index, $MF_{2_{12}}$ being known from the above. A special algorithm was worked out to find a proper $MF_2/MF_{2_{12}}$ ratio for a particular month in the past. One thus obtains an MF_2 value that is seasonally corrected; this monthly MF_2 is taken as an input to a regression with f_0F_2. The method may be checked by applying this scheme to the data of a ionosonde station.

The results of such f_0F_2 long-term predictions for the rising phase of solar cycle 22 not used in establishing the prediction are shown in table VIII. With January 1988 as the starting point f_0F_2 forecasts 3, 6 and 12 months in advance were made for St. Petersburg, Moscow and Sverdlovsk.

To obtain an estimate of the accuracy of such a forecast the same f_0F_2 prediction was made with the CCIR model using officially predicted sunspot numbers R_{12} as an input. The results of predictions show an obvious advantage of the proposed method over the traditional one.

Table VIII. f_0F_2 mean deviations (MHz) during rising part of cycle 22. CCIR forecast – in parenthesis.

Station (lat. long.)	Months in advance	00UT	06UT	12UT	18UT
St. Peterburg (60°N, 30.7°E)	3	.268 (.866)	.142 (.437)	.317 (.460)	.181 (.564)
	6	.204 (.856)	.220 (.413)	.341 (.544)	.305 (.571)
	12	.412 (.586)	.271 (.467)	.320 (.776)	.440 (.454)
Moscow (55.5°N, 37.3°E)	3	.234 (.432)	.346 (.298)	.364 (.382)	.218 (.521)
	6	.232 (.472)	.420 (.455)	.487 (.452)	.255 (.501)
	12	.299 (.318)	.358 (.609)	.288 (.606)	.342 (.388)
Sverdlovsk (56.7°N, 61.1°E)	3	.262 (.540)	.236 (.451)	.464 (.353)	.254 (.473)
	6	.238 (.527)	.429 (.644)	.626 (.496)	.215 (.533)
	12	.384 (.554)	.546 (.838)	.432 (.848)	.454 (.718)

5. Conclusions

A new $MQMF_2$ monthly median f_0F_2 and $M(3000)F_2$ model is derived for the European region. Data for 1957-1990 on 28 (for f_0F_2) and 19 (for $M(3000)F_2$) European ionosonde stations with long enough (not less than one solar cycle) periods of observation were used to establish the $MQMF_2$ model. A newly proposed effective ionospheric index MF_2 (Mikhailov and Mikhailov, 1995) of solar activity is used as an input parameter. This monthly MF_2 index provides the best f_0F_2 versus solar activity regression compared to traditional R_{12}, ionospheric IG_{12}, or $RESSN_{12}$ indices. MF_2 indices for the northern hemisphere are produced for the period from 1949 to 1992. For the current period after 1992 MF_2 indices may be calculated provided that monthly median noon f_0F_2 values are available for the northern hemisphere mid-latitude ionosondes (only European network of ionosondes may be used as well). The monthly MF_2 index may be long-term predicted and f_0F_2 prediction accuracy based on MF_2 is much higher than can be achieved with the CCIR model based on R_{12}. A non-linear (cubic parabola) f_0F_2 and $M(3000)F_2$ dependence on MF_2 index is used to derive local models for each ionospheric station. The local models give f_0F_2 and $M(3000)F_2$ diurnal variations for 12 months and any level of solar activity. A very efficient multiquadric method of spatial approximation is used to draw a surface over the European region. Outside the European region the $MQMF_2$ model interfaces the CCIR model. The $MQMF_2$ model is implemented as a code with friendly interface for PC AT-386/387 or compatible, providing a range of optional output formats to meet various operational needs.

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