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REAL-TIME FORECAST OF MUF FOR RADIO PATHS FROM CURRENT DATA OBTAINED FROM OBLIQUE SOUNDING WITH CONTINUOUS CHIRP SIGNAL

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Abstract. We present a technique of MUF real-time forecast based on time extrapolation for maximum observed frequencies smoothed over a long-term forecast along a given path. We have validated the technique of fitting current data from the long-term forecast, using the OPEMI model, transmission curve method for short paths, and method of normal waves for long paths (over 2000 km). This technique has been tested using data obtained at the chirp sounding network of ISTP SB RAS during periods of strong and weak solar activity. The quality of the forecast has been found to significantly improve in comparison to the long-term forecast, with advance intervals of real-time forecast from 15 to 30 min. The sessions, in which the real-time forecast error is less than 10 % for 15-min advance interval, comprise from 67 to 96 % of all sessions depending on season and radio path orientation.

Keywords: ionosphere, oblique ionospheric sounding, real-time forecast, radio path, maximum usable frequency.

INTRODUCTION

One of the major characteristics of the decameter radio channel is the maximum usable frequency (MUF) of radio path. On the one hand, MUF is an indicator of space weather in a region of interest; on the other hand, MUF values are important from a practical point of view for the effective operation of decameter radio communication systems. MUF values are determined from ionospheric parameters and mechanisms of radio wave propagation from a transmitter to a receiver. In practice there are three types of MUF forecasts: long-term (LTF), short-term (STF), and real-time (RTF) [Ivanov, Ryabova, 2007]. MUF LTF is used to predict long-term, regular processes for several months in advance based on radio wave propagation and ionospheric models as a function of spatial coordinates, local time, season, and level of solar activity [Vertogradov et al., 2007; Barabashov, Anishin, 2013; Ponomarchuk et al., 2016]. STF is given for a period from several hours to several days. The forecast of ionospheric conditions uses indices characterizing the solar flux (F10.7 index or Wolf number) and geomagnetic activity (K_p or *Dst* indices). There are several ways of solving the problem. One of them is to use effective corrections to the ionospheric model, which account for MUF variations with solar and magnetic activity [Blagoveshchensky, Borisova, 1989; Krasheninnikov et al., 2008]. Another is based on the correlation between MUF and key geoeffective parameters of the interplanetary medium: solar wind and interplanetary magnetic field [Barkhatov et al., 2006]. However, with such a formulation of the problem, despite years of research, practically important techniques have not been developed yet. This is primarily due to the complexity of the ionospheric response to disturbing factors and mismatch between models and real processes occurring in near-Earth space by the impact of solar radiation. By RTF is usually meant the time extrapolation of measured ionospheric parameters or MUF values for a period from several minutes to several hours in advance. This forecast is largely based on the presence of inertia in time series or on the identified physical laws. RTF relies mainly on ground-based ionospheric sounding (VS, OS) data or GNSS data [Barabashov et al., 2016; Ponomarchuk et al., 2013; Barabashov et al., 2006; Smirnov et al., 2013]. RTF differs from LTF largely because it accounts for current measurements. In the problems related to the analysis of time series, by the forecast is meant the extrapolation of a function specified by readings.

Nowadays, an integral part of the modern high-frequency (HF) communication system is the ionosphere-wave and frequency-control service [Ionospherno-..., 1989]. One of the problems solved using equipment of this service is the real-time forecast of radio conditions, which involves producing recommendations for holding a communication session in the nearest future applied to a selected frequency resource and available data transmission facilities. Initial data for the forecast are the results of previous sounding sessions, for example, with chirp signals. For practical radio communication, an admissible relative error in determining MUF is no more than 10 %.

In fact, there are two types of radio path MUF RTF [Ryabov, Ivanov, 2002]: from MUF time series for a given (or close) path [Kurkin et al., 1997; Kiselev, 2017] and from the ionospheric model corrected at one or more points from current ionospheric sounding data [Kuzmin, Chalkin, 2013; Arefyev et al., 2016]. Strictly speaking, RTF of the second type is not so much a forecast as a way to determine radio physical parameters of a path in near real time.

In this paper, for MUF RTF we propose a method of time extrapolation smoothed over MOF LTF along a given path. LTF of MUF has been made using the transmission curve method [Kiyanovsky, 1971] with the OPEMI model [Polyakov et al., 1986; Dvinskikh, 1988] for short paths and the method of normal waves [Kurkin et al., 1981, Ponomarchuk et al., 2016] with IRI [Bilitza et al., 2017] for long paths (over 2000 km). We have validated the technique of fitting the current data from the long-term forecast. This technique has been tested using experimental data acquired at the chirp sounding network of ISTP SB RAS during periods of strong and weak solar activity.

REAL-TIME FORECASTING TECHNIQUE

Time series and function extrapolation are typically analyzed using expansions in orthogonal functions (e.g., Fourier expansion) with a small number of terms, or certain interpolation polynomials. For example, as a basis in the forward time extrapolation we can choose the Newton formula of interpolating polynomial for equidistant values of an independent variable [Gelfond, 1967]. Then, RTF through extrapolation of experimental values for preceding moments can be made by restricting our consideration to various degrees of the representations [Kurkin et al., 1997]. The Newton formula allows RTF to be made based only on experimental data. Kurkin et al. [1993] have shown that MUF along different paths are related by adiabatic relations to ionospheric parameters. We can therefore assume that this is also true for one path at different times, and hence we can use additional information on the time dependence of MUF, gained, for instance, from LTF model calculations. Assuming that this forecast qualitatively correctly describes the time dependence of MUF, the increment of the function in the previous time interval can be replaced by the increment of the function in the interval of interest, but calculated from the LTF model. The reference value is taken from experimental data, and successive differences in the interval considered can be computed both from model calculations and from experimental data.

This extrapolation method is widespread in the literature in two variants: increments are calculated only by a model or in addition they are scaled if model values differ considerably from measured ones. In fact, both the methods include a model curve drawn through a measured point in the former case by adding a constant, in the latter by multiplying by a constant. The projected points are searched for on the extension of the curve. In this case, we can simply use the points on the curve rather than calculate them from the interpolation formula, which itself introduces an additional error. Both the forecast methods employ one measured point, and hence the forecast has its errors, although it accounts for the local trends of measured value described by the model. It, however, ignores local trends of measured values if they differ from model ones.

Unlike the forecasting techniques in which only the initial point is taken from the experiment, whereas differences are taken from LTF, for a small number of points, starting from the first one, we can use regression. As a regression function we take a normalized or scaled-up LTF, i.e. LTF is multiplied by a coefficient a such that the sum of LTF squared deviations from several current experimental points is minimum. The coefficient a is found from n points of experimental and LTF data, using a least square technique:

$$\min \sum_{k=1}^{n} \left[f_{\exp}(k) - a f_{\mathrm{LTF}}(k) \right]^2; \; a = \frac{\sum f_{\exp}(k)\, f_{\mathrm{LTF}}(k)}{\sum f_{\mathrm{LTF}}^2(k)}.$$

Then, for the forecast we employ the formula

$$f_{\mathrm{pr}}(k+1) = f_{\mathrm{LTF}}(k+1)\, a.$$

When using this forecast model, a question arises as to how many points should be selected for fitting data by an LTF model, and, consequently, about the choice of the LTF model.

To calculate MUF in automated complexes for selecting working radio frequencies, it is more preferable to use simple engineering algorithms for calculating propagation characteristics and models of the main ionospheric parameters without computing the electron density profile. In practice, MUF LTF for ionospheric layers can be made according to recommendations of the International Telecommunication Union [Metody, 2016]. Along the radio paths of up to ~2000 km equipped with ionosphere diagnostic tools, as a DFC and MUF forecast method it is worth using an algorithm based on a modified transmission curve method [Davies, 1973]. To account for the curvature of the ionosphere and natural magnetic field, we add correction terms [Kiyanovsky, 1971; Kopka, Meller, 1971]. The input characteristic for computing DFC is the height-frequency characteristic of vertical sounding (HFC) at the path midpoint. This characteristic can be measured directly with an ionosonde in the vertical sounding mode or calculated from corrected predictive ionospheric models. Using the semi-empirical ionospheric model (SEIM) [Polyakov et al., 1986], ISTP SB RAS has developed an operational model of HFC parameters (OPEMI) based on natural orthogonal functions of HFC nodal parameters: f_oE, f_oF1, f_oF2, hF, hF2, h_pF, hF1 [Dvinskikh, 1988].

To longer radio paths algorithms are usually applied of calculating signal path characteristics [Lukin, Spiridonov, 1971; Vertogradov et al., 2007], which require specifying a propagation medium – electron density profiles along a propagation path. To predict propagation conditions of decameter waves and to study ionospheric properties at any point of space, the International Union of Radio Science (URSI) recommends using the IRI model [Bilitza et al., 2017] as a standard ionospheric model. We employ the method of normal waves [Kurkin et al., 1981] to calculate propagation characteristics along paths longer than 2000 km. Within a complex algorithm involving the calculation modules of the global ionosphere model and radio wave propagation characteristics in the framework of a waveguide approach, operational algorithms for calculating MUF and DFC along oblique propagation paths have been implemented [Ponomarchuk et al., 2016]. In this paper, to calculate a long-term forecast of MUF from the method of normal waves, we use the IRI model.

In the proposed RTF method, measured data are smoothed and the number of points to be smoothed can be determined based on measured value variability. The day-to-day MUF variability for this path during a month according to the literature (e.g. [Ivanov, Ryabova, 2007]) averages around 20 %, but can reach 50 %. In this case, the monthly average median of LTF can comprise a systematic deviation due to the difference between the predictive level of solar activity in use and the real one. This causes additional error in LTF. However, for the proposed technique, when a real data segment is fitted by an LTF segment, such deviations are insignificant. The main factor is that the model correctly accounts for geographic and temporal (time of day) path features. Decade medians of measured values also take this into account; however, because of the day-to-day displacement of the terminator, drastic changes of MUF in the median are extended in time, although not very much, but thereby causing an additional nonrandom error. Figure 1 illustrates the MUF variability at each time point from day to day. Its monthly average standard deviation (SD) is given for two paths Khabarovsk–Irkutsk and Magadan–Irkutsk for January 2014.

It can be seen that these variations account for 15–20 % and depend on the time of day. In fact, they give the LTF error plus the error caused by the difference between current solar and geomagnetic activity, which can also vary both during the day and from day to day.

Against the background of the MUF diurnal variation there are short-period variations induced both by small-scale irregularities and by different wave processes. Their sign can change from one session to another even within 15 min, so it is worth identifying the most significant MUF variations and smoothing variations associated with both the small-scale inhomogeneous structure of the ionosphere and errors in determining MUF, but preserving the most significant variations with a period of 1 hr and more.

To estimate the dependence of MUF forecast error using the proposed technique on the duration of the smoothing intervals determined by the step of data acquisition and by the number of points when calculating the coefficient *a*, we have made test calculations of SD of LTF from RTF. We have used experimental data on maximum observable frequencies (MOF) from the oblique sounding network of ISTP SB RAS [Ivanov et al., 2003]. The coefficient *a* was calculated from 2, 3, 4, 8, 12, and 16 points, which for the 15-min sounding interval corresponded to smoothing intervals of 15, 30, 45 min, 1, 2, 3, and 4 hrs respectively. It can be seen (Figure 2) that for the advance intervals of less than one

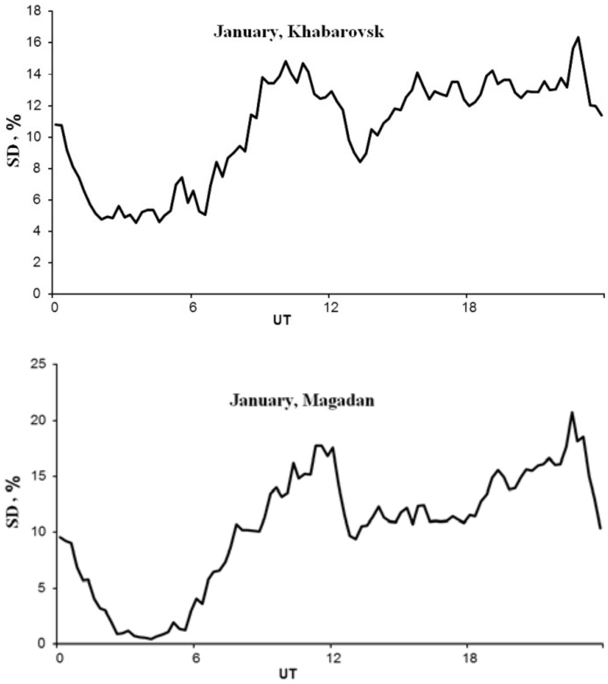

Figure 1. Standard deviation of MUF during a month for two paths in January 2014

hour, short data histories have an advantage. For large smoothing intervals, errors increase and weakly depend on the history of data for the forecast.

As a model for the forecast, we can take moving medians of experimental data for several previous days. In the literature, some authors recommend using an averaging interval from 5 to 10 days. Our analysis of the relatively small sample shows that results of the forecast with the 3 hr advance interval differ slightly (Figure3); therefore in the technique in hand we deal with the median LTF model.

The difference between SD values in Figures 2 and 3 is that Figure 3 presents a smaller sample. Thus, the expected error in RTF from four current points with a model in the form of a median LTF is less than 12 % for the 3 hr advance interval and about 5 % for the 1 hr advance interval.

In principle, similar results can be obtained if the similarity factor is calculated not from the least square deviation of the model from measured values but from a weighted average of several similarity factors; there are, however, no arguments for selecting the type of the average. Our selection of the similarity factor corresponds to weights

$$a = \sum_{k=1}^{n} \frac{f_{\exp}(k)}{f_{\mathrm{LTF}}(k)} \left(\frac{f_{\mathrm{LTF}}^{2}(k)}{\sum_{i=1}^{n} f_{\exp}^{2}(i)} \right),$$

i.e. the weight of the point increases with the model MUF value, and weights change with time.

RTF error in any of these techniques differ little, since the coefficients are close, and slightly differ from the interpolation-formula extrapolation for 1 hr smoothing of experimental points.

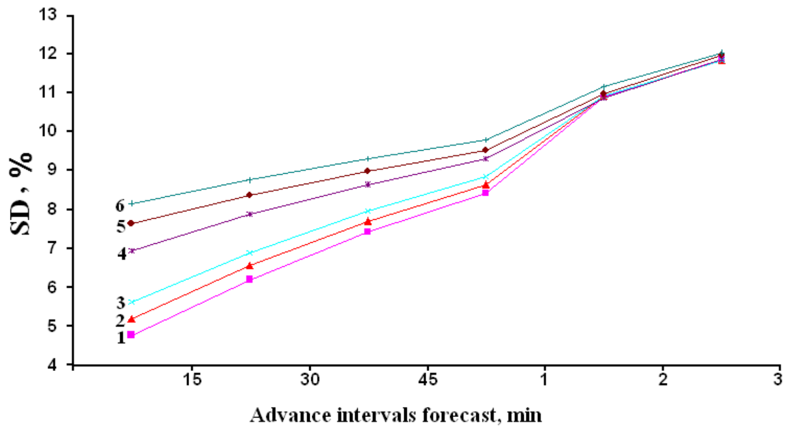

Figure 2. RTF SD for various histories for the forecast with the 15 min sounding interval: 1 – 2 points, 2 – 3 points, 3 – 4 points, 4 – 8 points, 5 – 12 points, 6 –16 points

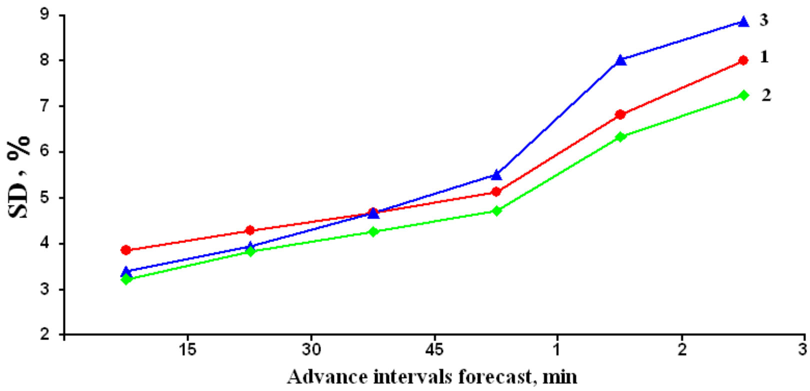

Figure 3. SD of LTF and RTF for different median calculation intervals at the 15 min sounding interval: 1 – 5 days, 2 – 7 days, 3 – LTF

ANALYSIS OF EXPERIMENTAL DATA

To evaluate the efficiency of the developed method, we have selected data for two years with different solar and geomagnetic activity indices: 2009 and 2014. During 2009, the solar activity index *F*10.7 changed slightly – its annual average *F*10.7≈70.5 and standard deviation σ (*F*10.7)≈2.8. In 2014, *F*10.7 ranged widely – from 89 to 253. The annual average *F*10.7≈146 and σ (*F*10.7)≈27. The annual average of the magnetic activity index A_p in 2009 was ≈4 nT, corresponding to low magnetic activity. In 2014, magnetic activity was higher – annual average A_p≈7.7 nT, corresponding in general to disturbed conditions.

The quality of RTF and LTF is compared with experimental data as follows: for a continuous dataset, take 1 hr observations. From these observations and LTF for the same period, calculate a coefficient by which LTF should be multiplied to minimize its deviation from measured data. Then, the multiplied LTF is used to make a forecast for the desired time: 15, 30 min, etc. The time is shifted by 15 min and the procedure is repeated. The relative error is calculated between the predicted and measured values. Over a period of time (usually one month), we calculate SD of this error, i.e. SD of the forecast from measurements (root mean square deviation).

To compare the quality of RTF and LTF, we take experimental data from Khabarovsk–Irkutsk, Magadan–Irkutsk, and Norilsk–Irkutsk paths for different seasons at high and low solar activity.

Figures 4–6 plot diurnal variations in MUF for Khabarovsk–Irkutsk in January 2014, Magadan–Irkutsk in April 2009 and January 2014, Norilsk–Irkutsk in September 2009 and January 2014 respectively. These Figures also present the results of LTF and RTF for 15 and 30 min in the selected observation periods.

Tables 1–5 list SD of LTF and RTF with 15, 30 min, and 1 hr advance intervals, and the number of forecast points deviating from measured ones by less than 10 %.

These data show that the accuracy of RTF for 15 min is the highest and is much higher than the accuracy of LTF. The accuracy of RTF decreases with time, but for 1 hr and even 2 hr RTF its error is less than that of LTF. Quantitative characteristics depend greatly on the path and season, but in any situation SD of RTF from measured values does not exceed 9 %; in most cases, it is less than 5 %. The number of points that deviate by less than 10 % in a 15 min forecast generally exceeds 70 % and in some cases 90 %. Exceptions are winter months when LTF and RTF errors are higher, especially over the meridional path Norilsk–Irkutsk.

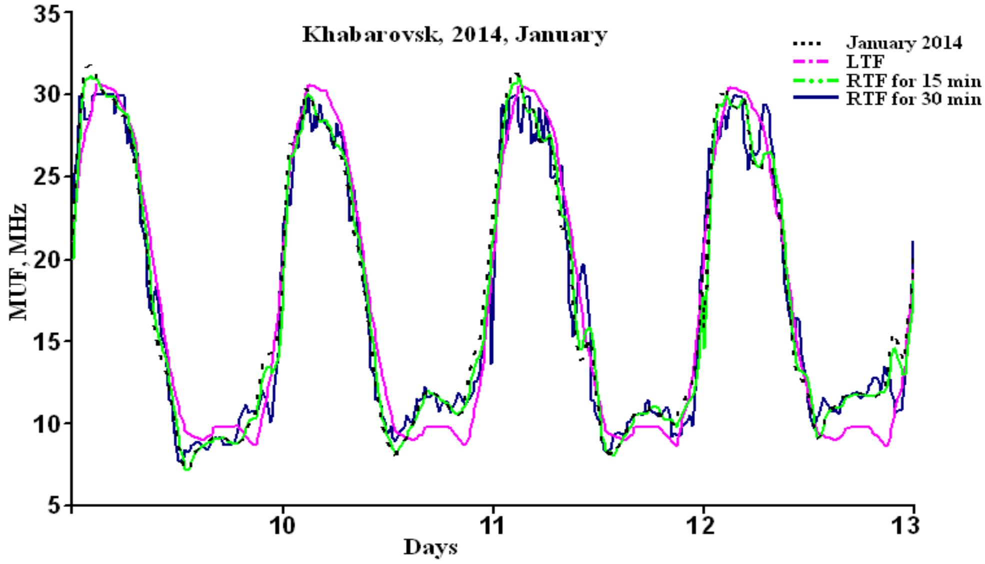

Figure 4. Diurnal variation in real data along the Khabarovsk–Irkutsk path in January 2014

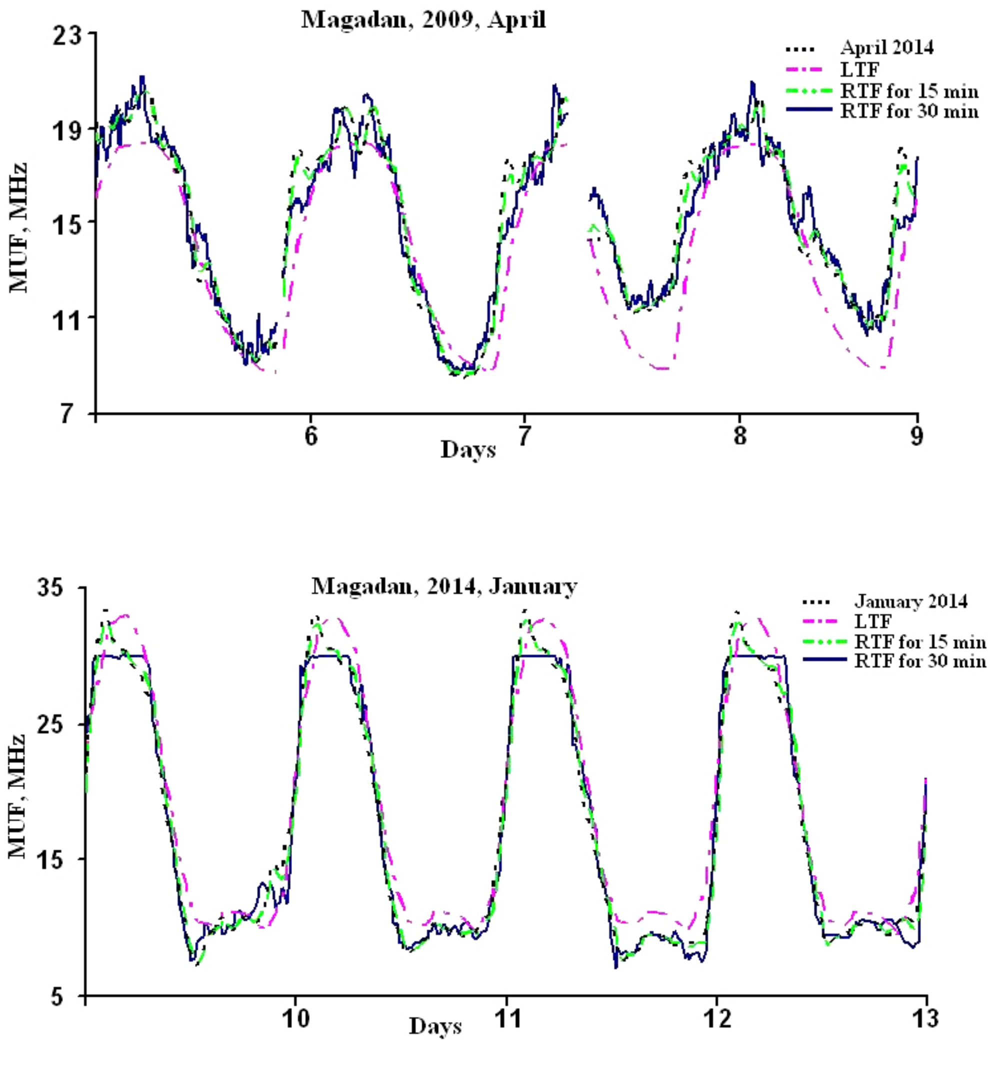

Figure 5. Diurnal variation in real data along the Magadan –Irkutsk path: April 2009 and January 2014

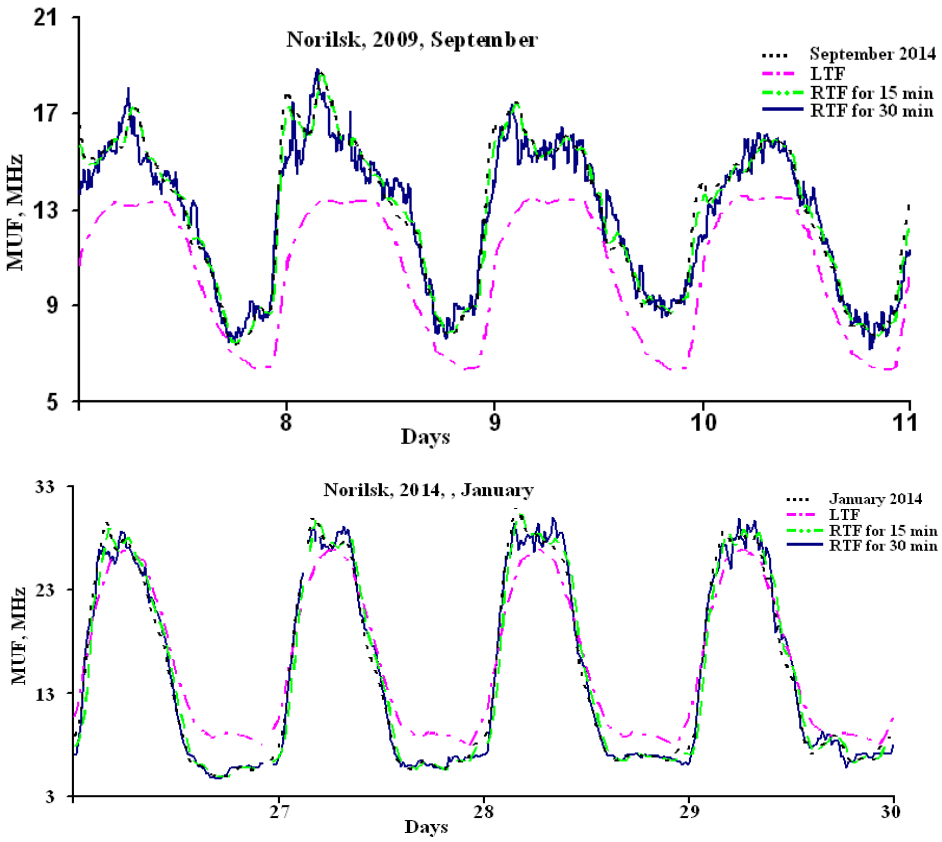

Figure 6. Diurnal variation in real data along the Norilsk–Irkutsk path: September 2009 and January 2014

Table 1

LTF and RTF SD with 15, 30 min, and 1 hr advance intervals
for the Khabarovsk–Irkutsk path (2014)

	LTF, %	RTF for 15 min, %	RTF for 30 min, %	RTF for 1 hr, %
January	13.1	9.6	10.7	16.3
March	19.7	4.68	5.74	7.3
June	19.2	5.6	6.96	9.3

Number of points differing by less than 10 %

	RTF for 15 min, %	RTF for 30 min, %	RTF for 45 min, %	RTF for 1 hr, %
January	78.6	75.8	67.4	61.5
March	96.2	92.3	87.9	83.8
June	92.2	82.1	74.8	70.5

Table 2

LTF and RTF SD with 15, 30 min, and 1 hr advance intervals for the Norilsk–Irkutsk path (2009)

	LTF, %	RTF for 15 min, %	RTF for 30 min, %	RTF for 1 hr, %
January	35.8	11.34	14.3	19.9
February	29.3	12.99	16.5	22.5
September	23.4	6.13	7.22	8.9

Number of points differing by less than 10 %

	RTF for 15 min, %	RTF for 30 min, %	RTF for 45 min, %	RTF for 1 hr, %
January	66.9	59.25	53.3	47.9
February	68	60.9	55.45	49.9
September	90.56	85.79	80.84	77.04

Table 3

LTF and RTF SD with 15, 30 min, and 1 hr advance intervals for the Norilsk–Irkutsk path (2014)

	LTF, %	RTF for 15 min, %	RTF for 30 min, %	RTF for 1 hr, %
January	23.02	9.3	11.66	15.46
April	15.49	6.36	8.03	10.97
June	22.44	5.2	6.3	7.6

Number of points differing by less than 10 %

	RTF for 15 min, %	RTF for 30 min, %	RTF for 45 min, %	RTF for 1 hr, %
January	75.9	66.8	59.4	53.2
April	89.5	84.7	80.2	74.9
June	94.8	91.4	87.87	85.1

Table 4.

LTF and RTF SD with 15, 30 min, and 1 hr advance intervals for the Magadan– Irkutsk path (2009)

	LTF, %	RTF for 15 min, %	RTF for 30 min, %	RTF for 1 hr, %
January	26.18	10.9	13.64	18.41
February	19.25	10.5	13.2	17.5
April	13.46	5.75	6.95	8.9

Number of points deviating by less than 10 %

	RTF for 15 min, %	RTF for 30 min, %	RTF for 45 min, %	RTF for 1 hr, %
January	73.2	64.5	58.6	54.15
February	78.44	71.03	64.6	60.2
April	90.27	84.6	81.1	77.7

Table 5.

LTF and RTF SD with 15, 30 min, and 1 hr advance intervals for the Magadan–Irkutsk path (2014)

	LTF, %	RTF for 15 min, %	RTF for 30 min, %	RTF for 1 hr, %
January	12.7	9.4	14.5	15.3
March	29.7	4.3	5.4	7.2
June	15.1	6.7	8.2	11

Number of points RTF of which deviates by less than 10 %

	RTF for 15 min, %	RTF for 30 min, %	RTF for 45 min, %	RTF for 1 hr, %
January	76.9	68.2	62.2	57.9
March	97.2	93.4	88.45	82.6
June	88	80	73.2	67.6

Table 6.

Mean deviation and standard deviation of predicted values from real ones
for the Khabarovsk–Irkutsk path, March 2014

Advance interval	Mean value, %				SD, %				%, from –10 % to +10 %			
	1 t	2 t	3 t	4 t	1 t	2 t	3 t	4 t	1 t	2 t	3 t	4 t
15 min	0.10	0.13	0.17	0.21	4.58	4.76	5.19	5.63	96	98	96	96
30 min	0.18	0.22	0.26	0.29	5.96	6.19	6.55	6.89	92	95	94	91
45 min	0.28	0.31	0.34	0.37	7.64	7.41	7.69	7.96	87	92	90	90
1 hr	0.36	0.39	0.42	0.45	8.30	8.42	8.64	8.84	82	88	87	88
2 hrs		0.63	0.64	0.65		10.90	10.91	10.91		79	81	81
3 hrs		0.73	0.74	0.75		11.86	11.83	11.83		73	73	74

Table 6 lists average and standard deviations of predicted values from real ones for the Khabarovsk–Irkutsk path for March 2014 and for a period when real MUF are lower than the cutoff frequency of 30 MHz (8–23:45 UT).

Thus, the LTF error is much larger than the RTF error, but the median LTF works satisfactorily as a model used in the proposed technique of real-time forecast.

CONCLUSION

We have described a technique of MUF real-time forecast based on time extrapolation for maximum observed frequencies smoothed over a long-term forecast along a given path. We have analyzed this technique using MOF data from the chirp sounding network of ISTP SB RAS for different seasons and solar activity levels. The quality of the forecast has been found to significantly improve in comparison to the long-term forecast, with advance intervals of real-time forecast from 15 to 30 min. The sessions in which the real-time forecast error is less than 10 % for the 15 min advance interval comprise from 67 to 96 % of all sessions depending on season and radio path orientation.

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REFERENCES

Arefyev V.I., Kocherova M.K., Talalayev A.B., Tikhonov V.V. Methods of diagnostics of ionosphere characteristics for a given region, and correction of ionospheric models to improve the accuracy of predicting the propagation of decameter radio waves. *Vestnik Tverskogo gosudarstvennogo universiteta* [Herald of Tver State University. Ser. Applied Math. 2016, no. 1, pp. 33–51. (In Russian).

Barabashov B.G., Maltseva O., Pelevina O. Near real time IRI correction by TEC-GPS data. *Adv. Space Res.* 2006, vol. 37, pp. 978–982.

Barabashov B.G., Anishin M.M. Software package “Trassa” for predicting trajectory and power characteristics of 2–30 MHz radio channels. Part 1. *Tehnika radiosvyazi* [Radio Communication Engineering]. 2013, N 1 (19). P. 25–34. (In Russian).

Barabashov B.G., Anishin M.M., Rychagova M.S. On the real-time forecast of MUF for HF radio paths. *Tekhnika radiosvyazi* [Radio Communication Engineering]. 2016, no. 2 (29), pp. 16–26. (In Russian).

Barkhatov N.A., Revunov S.E., Uryadov V.P., Vertogradov G.G., Vertogradov V.G., Valov V.A. Prediction of the maximum observed frequency of the ionospheric HF radio channel using the method of artificial neural networks. *Geomagnetizm i aeronomiya* [Geomagnetism and Aeronomy]. 2006, vol. 46, no. 1, pp. 84–93. (In Russian).

Bilitza D., Altadill D., Truhlik V., Shubin V., Galkin I., Reinisch B., Huang X. International Reference Ionosphere 2016: From ionospheric climate to real-time weather predictions. *Space Weather*. 2017, vol.15, is. 2, pp. 418–429.

Blagoveshchensky D.V., Borisova T.D. On the correction of HF radio channel model with consideration for variations of solar and magnetic activities. *Geomagnetizm i aeronomiya* [Geomagnetism and Aeronomy]. 1989, vol. 29, no. 4, pp. 696–698. (In Russian).

Davies K. *Radiovolny v ionosphere* [Ionospheric Radio Waves]. Moscow, Mir, 1973, 502 p. (In Russian).

Gelfond A.O. *Ischislenie konechnykf raznostei* [Difference Calculus]. Moscow, Nauka,1967, 395 p. (In Russian).

Dvinskikh N.I. Expansion of ionospheric characteristics fields in empirical orthogonal functions. Adv. Space Res. 1988, vol. 8, no. 4, pp. 179–187.

Ionosferno-volnovaya sluzhba svyazi [Ionospheric-Wave Communication Service]. Ed. M.M. Krylov. Moscow, Voenizdat, 1989, 152 p. (In Russian).

Ivanov V.A., Kurkin V.I., Nosov V.E., Uryadov V.P., Shumaev V.V. Chirp ionosonde and its application in ionospheric research. *Izvestiya vuzov. Radiofizika* [Radiophysics and Quantum Electronics]. 2003, vol. 46, no. 11, pp. 821–851. (In Russian).

Ivanov V.A., Ryabova N.V. Modern approaches to short-term forecasting of noiseproof ionospheric radio channels for decameter telecommunication systems. *Vestnik Povolzhskogo gosudarstvennogo tekhnologicheskogo universiteta* [Herald of Volga State University of Technology]. Ser. Radio Engineering and Infocommunication Systems. 2007, no. 1, pp. 23–34. (In Russian).

Kiselev A.M. Maximum usable frequency statistical model and its application in forecast. *Tehnika radiosvyazi* [Radio Communication Engineering]. 2017, no. 4, pp. 35–48. (In Russian).

Kiyanovsky M.P. Program for computer calculations using a modified method of transmission curves. *Luchevoe priblizhenie I voprosy rasprostraneniya radiovoln* [Radial Approximation and Radio Wave Propagation Problems]. Moscow, Nauka, 1971, pp. 287–298. (In Russian).

Kopka H., Meller H.G. MUF calculations with consideration for effect of Earth's magnetic field. *Luchevoe priblizhenie I voprosy rasprostraneniya radiovoln* [Radial Approximation and Radio Wave Propagation Problems] Moscow, Nauka, 1971, pp. 167–173. (In Russian).

Krasheninnikov I.V., Egorov I.B., Pavlova N.M. Effectiveness of predicting radiowave propagation in the ionosphere based on the IRI-2001 ionospheric model. *Geomagnetizm i aeronomiya* [Geomagnetism and Aeronomy]. 2008, vol. 48, no. 4, pp. 504–510. (In Russian).

Kurkin V.I., Orlov I.I., Popov V.N. *Metod normal’nykf voln v probleme korotkovolnovoi svyazi* [Normal Wave Technique in HF Radio Communication]. Moscow, Nauka, 1981, 124 p. (In Russian).

Kurkin V.I., Nosov V.E., Ponomarchuk S.N., Savkov S.S., Chistyakova L.V. Method for operative diagnostics of the radio channel. *Issledovaniya po geomagnetizmu, aeronomii i fizike Solntsa* [Res. on Geomagnetism, Aeronomy and Solar Phys.]. 1993, vol. 100, pp. 168–188. (In Russian).

Kurkin V.I., Polekh N.M., Chistyakova L.V. Operative prediction of MUF under oblique sounding. *Issledovaniya po geomagnetizmu, aeronomii i fizike Solntsa* [Res. on Geomagnetism, Aeronomy and Solar Phys.]. 1997, vol. 105, pp. 168–174. (In Russian).

Kuzmin A.V., Chalkina N.A. Modeling of algorithm of automatic processing of results of oblique ionosphere sounding with correction of ionosphere model parameters. *Geliogeofizicheskie issledovaniya* [Heliogeophys. Res.]. 2013, no. 6, pp. 74–80. (In Russian).

Lukin D.S., Spiridonov Yu.G. Application of method of characteristics for solving problems of electromagnetic wave propagation through inhomogeneous anisotropic media.

Luchevoe priblizhenie I voprosy rasprostraneniya radiovoln [Radial Approximation and Radio Wave Propagation Problems]. Moscow, Nauka, 1971, pp. 265–279. (In Russian).

Metody prognozirovaniya osnovnoi MPCh, working MPCh I traektorii lucha, razrabotannye MSE-R [Methods of predicting the basic MUF, working MUF, and beam trajectory worked out by MSE-R. Geneva, ITU,2016, 7 p. (In Russian).

Polyakov V. M., Sukhodolʹskaya V. E., Ivelʹskaya M.K., Sutyrina G.E., Dubovskaya G.V., Buzikova M.Yu. *Poluempiricheskaya model ionosfery dlya shirikogo diapazona geofizicheskikh uslovii* [A semiempirical model of the ionosphere for a wide range of geophysical conditions]. Moscow, MCD-B, 1986, 136 p. (In Russian).

Ponomarchuk S.N., Grozov V.P., Kotovich G.V., Mikhailov S.Ya. The processing and interpretation of vertical and oblique sounding ionograms for ionosphere diagnostics on the base of chirp ionosonde. *Vestnik Sibirskogo gosudarstvennogo aerokosmicheskogo universiteta imeni akademika M.F. Reshetneva* [Herald of Acad. M.F. Reshetnev Siberian State Aerospace University]. 2013, no. 5(51), pp. 163–166. (In Russian).

Ponomarchuk S.N., Ilyin N.V., Lyakhov A.N., Penzin M.S., Romanova E.B., Tashchilin A.V. Complex algorithm for calculation of HF radio waves propagation characteristics on the basis of the ionosphere and the plasmasphere model and normal waves technique. *Izvestya vuzov. Physics.* [Russian Physics J.]. Thematic is. 2016, vol. 59, no. 12/2, pp. 71–74. (In Russian).

Ryabova. N.V., Ivanov V.A. Temporal and spatial short-term forecast of MUF. Proc. XXth National Scientific Conference “Propagation of radio waves”. 2002, pp. 115–116. (In Russian).

Smirnov V.M., Smirnova E.V., Tynyankin I.S., Skobelkin V.N., Mal’kovskiy A.P. Hardware-software complex for Earth’s ionosphere real-time monitoring. *Geliogeofizicheskie issledovaniya* [Heliogeophys. Res.]. 2013, no. 4, pp. 32–38. (In Russian).

Vertogradov G.G., Vertogradov V.G., Uryadov V.P. Oblique chirp sounding and modeling of ionospheric HF channel at paths of different length and orientation. Int. J. of Geomagnetism and Aeronomy. 2007, vol. 7, GI2002. DOI: 029/10.12006GI000143.

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