Calculation of f_0F2, $hmF2$ at the path center point from experimental slant sensing data. Comparison of calculated values with experimental and IRI values

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The experimental examination of the technique for estimation of f_0F2 and $hmF2$ values in the path midpoint from slant sensing (SS) data is described. The regular data obtained by the chirp-sounder along the Norilsk–Irkutsk path and data of the Podkamennaya Tunguska ionospheric station (located near estimated center point of the path) were used.

Introduction

In monitoring the ionosphere, it is necessary to obtain the environmental information at different points of the region under study, including those, where stations of vertical sensing (VS) are absent. The study of relations between the data of the slant sensing (SS) and VS is important for solving this problem.

There are many papers[1–3] devoted to the problems of diagnostics and prediction of SW radiochannel parameters from SS data. However, experimental examination of techniques for obtaining the ionospheric parameters from SS data is difficult because of the absence of experimental VS data along the SS path. In the best case, actual data on ionosphere can be obtained during the SS session at the transmitting and receiving points.

A simple method for determination of the critical frequency f_0F2 at the SS path center point from the distance–frequency characteristics (DFC) measured along single-reflection path, based on the Smith method, was proposed.[4–6]

In this paper we propose a simple method for calculating not only f_0F2 but also the height of the electron concentration maximum $hmF2$ under the same conditions. As well, we present the results of experimental testing of the calculated f_0F2 and $hmF2$ values using the data of regular measurements in 2003–2004.

Calculation of height–frequency characteristics at the center point of SS path

Since at SS the signal is reflected from the ionosphere near the path center point, it is possible to determine some parameters of ionosphere at this point from the obtained SS data. The technique of obtaining VS parameters from SS data assumes a high accuracy of the measured radiophysical parameters. The absolute propagation time of the decameter signal along a selected path was measured in SS experiments at ISTP SB RAS in Irkutsk (53°N, 104°E) using the FMCW signal[7] (the receiving point of the FMCW sonde was situated near the village Tory, about 95 km to the south-west from Irkutsk). The reference to the GPS satellite system made it possible to obtain reliable data on the absolute propagation time.

With the known dependence of the absolute propagation time on the SS frequency (i.e., DFC), one can obtain the altitude–frequency characteristics (AFC) at the path center point, hence, f_0F2 at this point as well. The technique for determining the ionosphere parameters using the DFC is described in detail in Ref. 6. It is based on the Smith method,[8] which for the spherical-layer ionosphere is an approximate analogue of the method of “transmission curves” for a plain-layer medium. The necessary input data are the SS path length, SS frequency, and the absolute propagation time corresponding to this frequency.

When processing the SS experimental data, the operator selects the DFC track relating to the $1F2$ mode of an ordinary component. The track is stored as an array of frequencies and delays. Then these SS frequencies and delays are recalculated to frequencies and actual heights of VS (as the result, the DFC is obtained). Figure 1 shows the result of the recalculation of the experimental DFC (with the Khabarovsk–Tory path as an example) to the effective AFC, which can be approximately related to the center point of the path.

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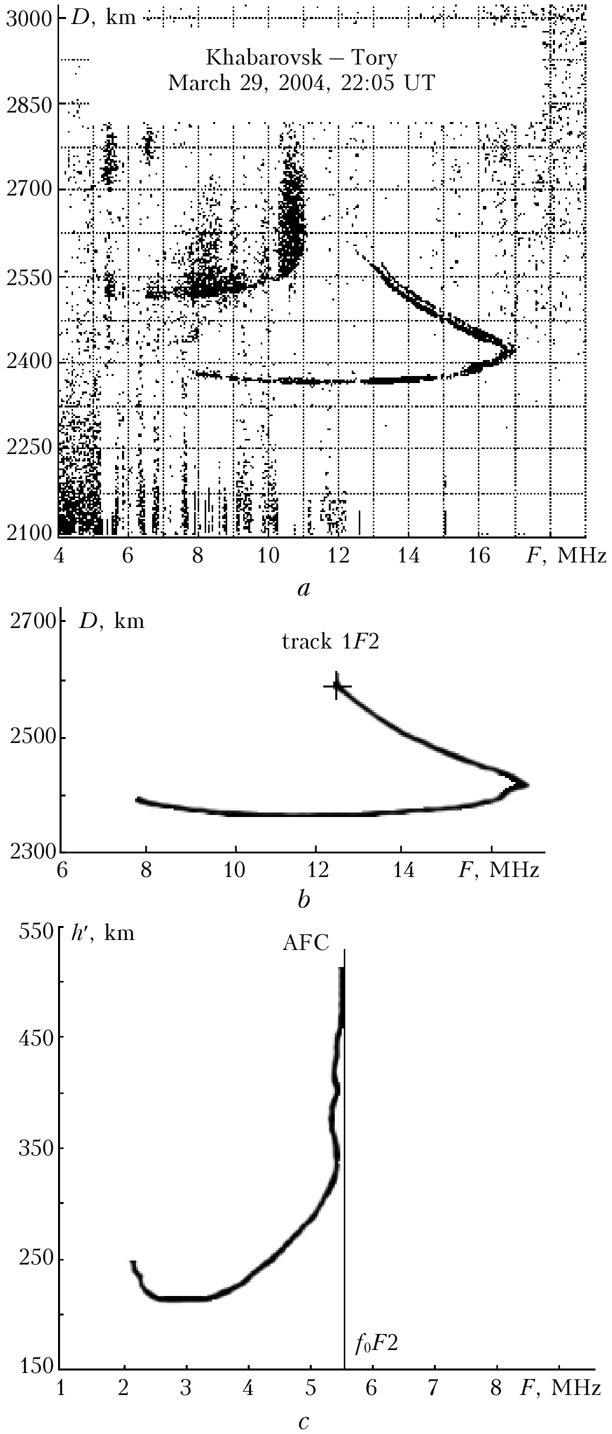

Fig. 1. Example of recalculation of DFC (*a*, *b*) to AFC (*c*).

Calculation of f_0F2 at the center point of the SS path

To determine the parameter f_0F2, it is necessary (and sufficient) to fix on the SS ionogram the frequency and delay of the top beam (the "last" point marked by cross in Fig. 1*b*), the trajectory of which before reflection is close to the Pederson beam passing the height of the ionization maximum in the vicinity of the path center point. These frequency and delay of the "last" point are recalculated to the critical frequency and the actual height of reflection from the layer $F2$ maximum by the operation inverse to the Smith method.

In the modified "transmission curves" method, the linear relation between VS and SS frequencies is determined by the factor ($k \sec\varphi$), where k is the coefficient of the Earth sphericity.

For the path Norilsk–Tory, $k = 1.06983$ (the path length D is 2088 km). The k values for other path lengths are presented in Ref. 9. The angle φ of the beam incidence on the layer, according to the equivalence theorem, is related to the actual height h' by the following formula[8]:

$$\varphi = \arctan\left(\frac{\sin(D/2R)}{x - \cos(D/2R)}\right), \qquad (1)$$

where $x = (R + h')/R$, R is the Earth radius.

The absolute time of the decameter signal t_{SS} propagation along the slant path is determined as follows[8]:

$$t_{SS} = \frac{2R}{c}\,\frac{\sin(\Omega - \varphi)}{\sin\varphi}, \qquad (2)$$

where $\Omega = \arcsin(x \sin\varphi)$; c is the light speed.

To determine the sought value of h' corresponding to the delay of the top beam of the single-reflection propagation, the looking over actual heights is carried out with a step of 200 m, starting from 200 km (to decrease the time of the search), and such value of the group path is selected by formulae (1) and (2), which corresponds to the experimental value.

According to the secant law, f_{SS} and f_0 are connected by the formula $f_H = f_0 k \sec\varphi$. Then $f_0F2 = f_{SS}/(k \sec\varphi)$, where f_{SS} corresponds to the "last" point of DFC marked by cross in Fig. 1*b*. This simple way of the recalculation makes it possible to determine promptly the f_0F2 value for the center point of the SS path.

Calculation of *hmF2* at the center point of the SS path

To find *hmF*2, a more complicated way is required.

In this case, the profile $N(h)$ is reconstructed at the center point of the path. To do this, the AFC, obtained by the DFC recalculation, is transformed to the profile $N(h)$ using the ITERAN program by T.L. Gulyaeva (Ref. 10).

The lack of DFC information about all ionospheric layers hampers the calculation of the AFC total profile. To calculate f_0F2, it is sufficient to have data only on the top beam of the mode $1F2$, but to calculate the total profile, characterizing the path center point, the complete DFC is necessary (including the E layer). The E layer manifests itself in DFC of the path Norilsk–Tory as the mode $2E$.

Figure 2 presents the AFC determined with the use of DFC for March 30, 2004 (circles), as well as $N(h)$ (dotted line) reconstructed from the AFC using the program ITERAN.

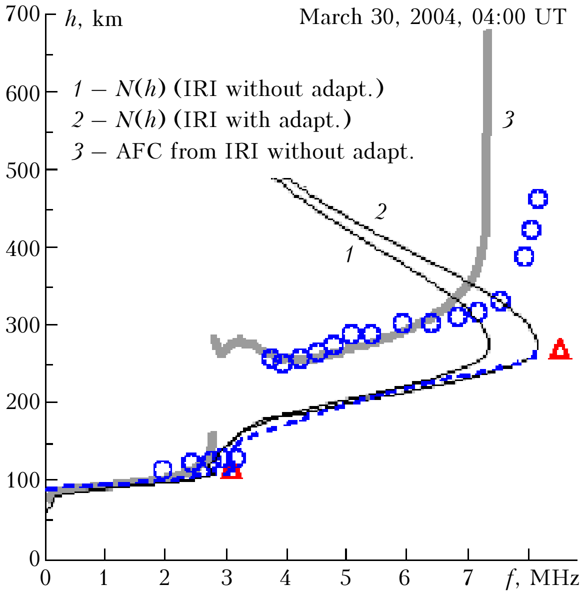

Fig. 2. Profile $N(h)$ and AFC at the center point of the path Norilsk–Tory.

Solid lines show the profiles obtained using the model IRI (with f_0F2-adaptation and without adaptation), as well as AFC obtained from one of these profiles. Triangles mark the values of the critical heights f_0F2, f_0E, and the height of the maximum ionization $hmF2$ determined using the simplified Dadney formula[11,12]:

$$hmF2 = \frac{1490}{M(3000) + 0.253/(f_0F2/f_0E - 1.215)} - 176 \quad (3)$$

from the experimental values of f_0F2, f_0E, and $M(3000)F2$ for the station Podkamennaya Tunguska (the height of the E layer maximum is taken from the IRI model).

Comparison of calculated f_0F2 with experiment and the model IRI

The attempts to experimentally test calculations of ionosphere parameters from SS data were undertaken earlier[4] in 1989 on the path Magadan–Tory (the path length is about 3034 km). The ionosphere VS station was specially located at the center point of the path. Unfortunately, the restriction of the range of working SS frequencies to 30 MHz in that period of the solar activity maximum ($F_{10.7} \approx 217$) did not allow obtaining DFC up to the maximally applicable frequency (MAF).

The maximum observed frequency (MOF) restricted by 30 MHz was essentially lower than the calculated MAF. Nevertheless, the restricted set of DFC at that time (night and transitional period), when MAF could be determined (as the frequency of closing the highest and lowest beams), made it possible to draw conclusions about the determining effect of VS parameters at the center point of the path when finding MAF by calculations. The error in comparison of both MAF and f_0F2 calculated from DFC was, on average, 5%.

To test experimentally the technique once again, we took the data, which were obtained during the moderate solar activity (for MAF fell inside the range of the sensing frequencies). Since the experimental VS data for the center point of the selected path should be known, we used the path Norilsk–Tory (69.2°N, 88°E and 51.8°N, 103°E, respectively), observation on which were conducted since 2003 in individual series. The path is disposed meridionally (Fig. 3), and its half lies in Arctic and sub-Arctic zones (a path length is about 2088 km).

Fig. 3. Map of the experiment. The Norilsk–Tory path and st. Podkamennaya Tunguska as the nearest VS station to the calculated center point of the path.

Coordinates of the path center point are $\varphi = 60.7°N$, $\lambda = 97.5°E$. The nearest VS station is situated in Podkamennaya Tunguska ($\varphi = 61.6°N$, $\lambda = 90°E$). Unfortunately, there is no complete coincidence between this site and the path center point (they are spaced by 416 km).

Hourly values of the critical frequencies of $F2$- and E-layers, as well as the coefficient $M(3000)F2$ of st. Podkamennaya Tunguska were kindly presented by specialists of the station in the form of tables. More than 250 hourly values of the obtained f_0F2 values were compared with those calculated from SS data by the aforementioned technique and characterizing the ionosphere at the center point of the path.[13] The f_0F2 diurnal behavior for one day taken from the observational series of each season 2003–2004 is shown in Fig. 4.

The compared series of calculated and experimental f_0F2 values were reduced to UT taking into account the longitudinal effect. When reducing,

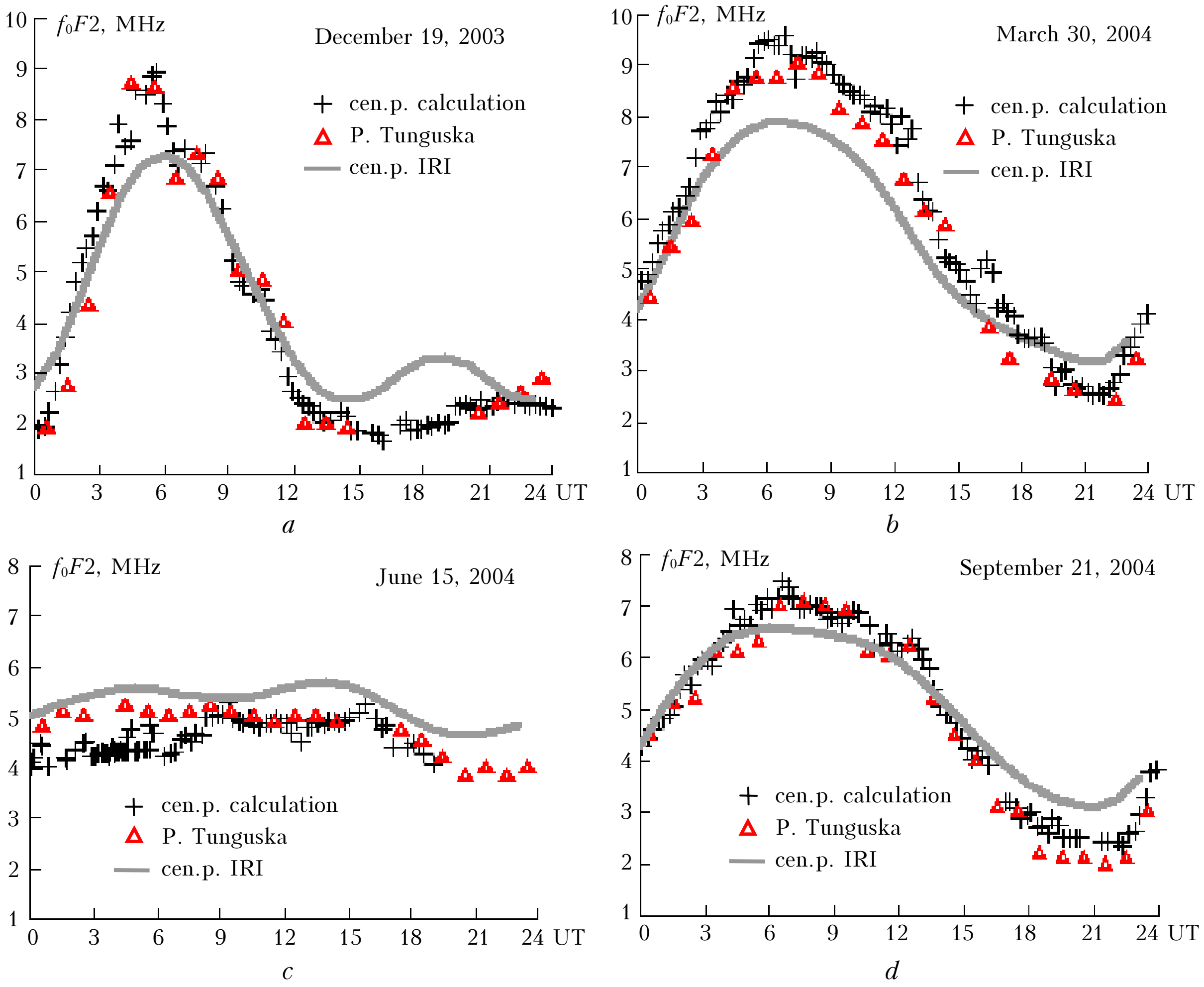

Fig. 4. Diurnal behavior of f_0F2 at the center point of the Norilsk–Tory path and at Podkamennaya Tunguska: monthly mean $F_{10.7}$ values are 111.4 (*a*); 111 (*b*); 100.5 (*c*); 104.1 (*d*).

data for Podkamennaya Tunguska were shifted by a half an hour because of the difference between longitudes of the path center point and Podkamennaya Tunguska. It is seen that the recalculated values are in quite good agreement with the experimental ones. Quantitative comparison shows that the error is, on the average, about 8% (with a 25% maximum for some hours). The absolute mean deviation of f_0F2 values in Podkamennaya Tunguska from the calculated at the center point of the path, according to the SS data, is 0.34 MHz; and the correlation coefficient between the f_0F2 values is 0.96. The greatest error is observed in the daytime in summer, that can be explained by the Smith method peculiarity, ignoring effects related with the wave delay in the lower layers.

The results of comparison presented in Fig. 4 show the qualitative and quantitative correspondence of the critical frequencies obtained by different techniques. The quite simple technique for calculating f_0F2 at the center point of the SS path makes it possible to obtain additional information about the medium. The difference in f_0F2 values can be explained by the existing longitudinal and cross gradients due to the difference in coordinates.

The experiments require much more expenses and resources than numerical experiments using different models of the ionosphere, most widely used of which is the IRI model. The diurnal behavior of the critical frequencies at the path center point, calculated by IRI and adapted to the monthly mean index of solar activity $F_{10.7}$ is shown in Fig. 4 as well. The coefficients for calculating f_0F2 correspond to URSI as the recommended standard for users of the models. The comparison with IRI shows that the median model values differ from the daily ones. In spite of the satisfactory agreement between the model and experiment, in the absence of experimental data the recalculated SS data are more preferable as compared to the model ones (even after adaptation of the model by the index $F_{10.7}$).

Comparison of calculated *hmF*2 with the experiment and IRI

Figure 5 shows diurnal behavior of the hourly *hm*F2 values obtained for the same days as in Fig. 4 by different techniques: using the data of IRI, of the station Podkamennaya Tunguska, as well as the $N(h)$ profiles reconstructed from AFC (by Gulyaeva's technique) and calculated from experimental DFC.

For June 15, 2004, the AFC can be calculated only at nighttime (by LT) using the data of SS, because of the absence of the complete daytime DFC. Only top beams and the screening sporadic layer *Es* are present in almost all DFC of this period, which makes it possible to calculate only critical frequencies at the path center point, but it was impossible to obtain maxima of *hmF*2 heights using this technique. It is seen that the *hmF*2 values are in quite good agreement with each other. Since the procedure of obtaining the heights of the *hmF*2 maximum by this algorithm is quite cumbersome, although realizable, then the *hmF*2 value from IRI can be used to save time and when it is impossible to calculate *hmF*2 from the SS data.

To simplify *hmF*2 calculations, the fast technique of determining *hmF*2 by Eq. (3) was applied. In this case, parameters of only two DFC points (the point corresponding to MAF and the "last" point) must be known. The f_0F2 value is calculated from the "last" point using the described technique, the f_0E value is taken from IRI, and $M(3000)$ is calculated using the formula $M(3000) = MUF(3000)/f_0F2$, where $MUF(3000)$ is MAF on a 3000 km path.

Since the Norilsk–Tory path length differs from 3000 km, the experimental MAF was first recalculated to AFC point by formulas (1) and (2); then the frequency was determined from the relationship $f_{\rm H} = f_0 k \sec\varphi$, which was assumed to be equal to MAF on the 3000 km path. It was also assumed in calculations, that the medium was spherically symmetrical, and the height of the signal reflection from ionosphere at the MAF frequency was the same for both paths (2088 and 3000 km).

The results of the recalculation are shown in Fig. 6 by crosses. It is seen that values of $M(3000)$ and *hmF*2 are in good agreement with the data for st. Podkamennaya Tunguska and results of calculation by $N(h)$.

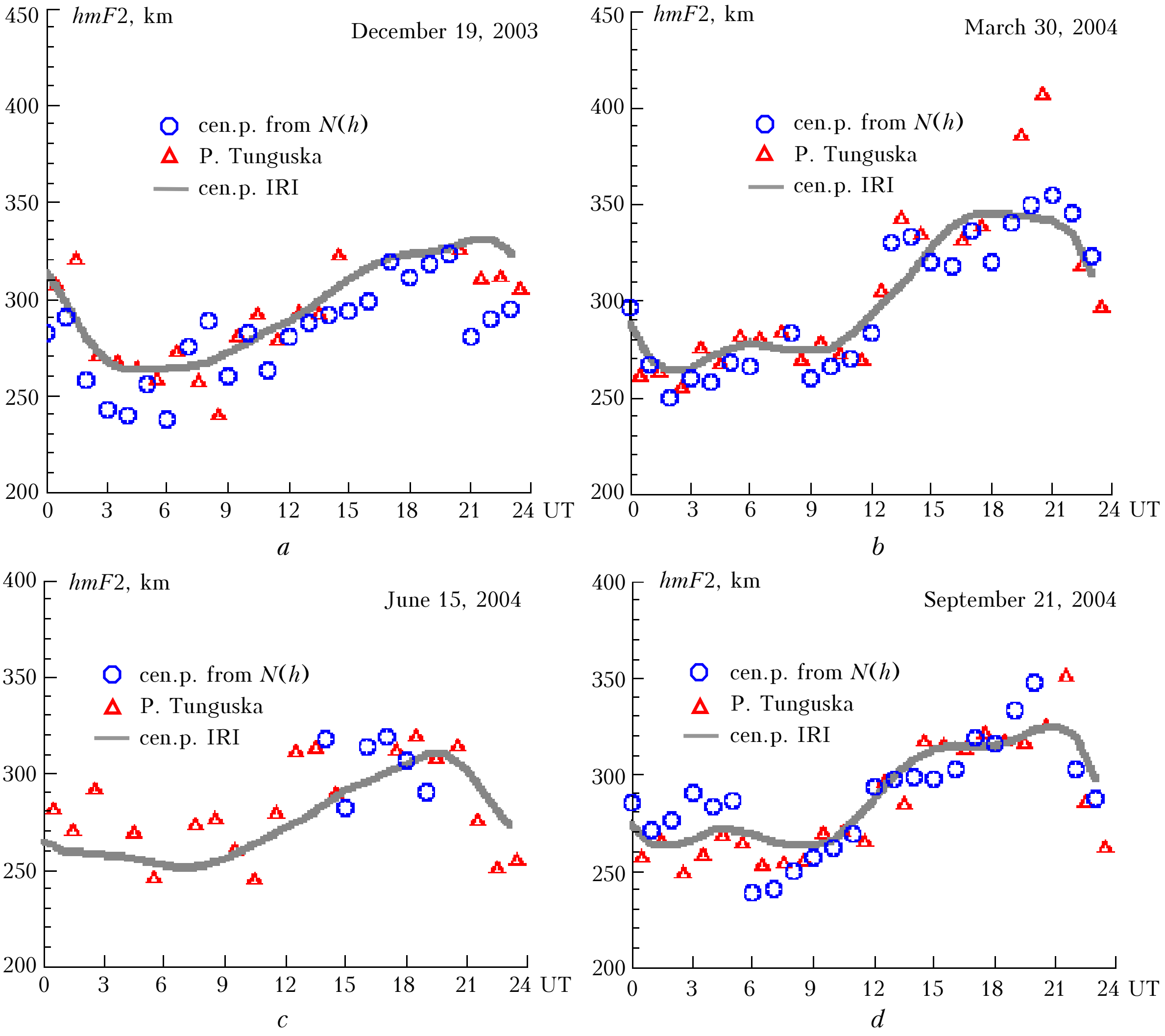

Fig. 5. Diurnal behavior of *hmF*2 at the center point of the Norilsk–Tory path and at Podkamennaya Tunguska.

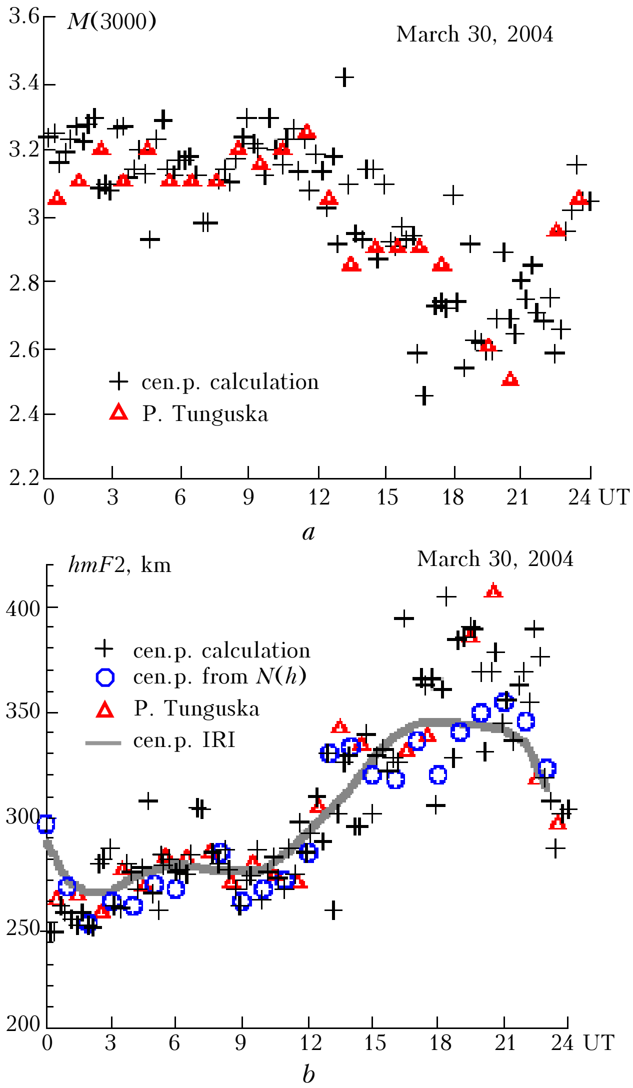

Fig. 6. Diurnal behavior of $M(3000)$ from the data at Podkamennaya Tunguska and DFC calculations (*a*); diurnal behavior of $hmF2$ at the center point of the Norilsk–Tory path and at Podkamennaya Tunguska (*b*).

This technique is more simple and fast as compared to calculations by $N(h)$ because only two points (instead of the track) should be obtained. However, if parameters of the MAF "last" point cannot be obtained, the use of the technique for calculation of $hmF2$ is impossible.

Adaptation of IRI using f_0F2 and $hmF2$

The international reference model IRI[14] allows determining the ionosphere parameters at any point of the Earth at any time. The obtained averaged parameters of the ionosphere can significantly differ from actual values, especially over the Russia territory. However, a possibility of adaptation of the model IRI makes it possible to compensate this disadvantage to some degree. Analysis of IRI adaptation possibilities using f_0F2 and $hmF2$ has shown that in this case only one parameter f_0F2 is sufficient to obtain values close to actual. The IRI adaptation using f_0F2 and $hmF2$ does not lead to a significant improvement in $N(h)$ calculation, because variations of the $hmF2$ height are small as compared to variations of f_0F2.

Conclusions

The prompt method for obtaining f_0F2 and $hmF2$ at the center point of the SS path using the modified Smith algorithm has been proposed and examined.

Experimental examination of the technique for obtaining f_0F2 and $hmF2$ at the center point of SS path from the observational data of 2003–2004 on the Norilsk–Tory path and at the ionospheric VS station Podkamennaya Tunguska (near the center point of the path) has shown that the absolute mean value of deviations of f_0F2 values at Podkamennaya Tunguska from the calculated f_0F2 values at the path center point obtained from SS data is 0.34 MHz. The mean relative deviation is about 8%, and the correlation coefficient is 0.96.

The proposed simple technique makes it possible to promptly and quite accurately calculate the critical frequencies and the heights of the electron density maximum of the $F2$ layer characterizing the ionosphere at the center point of the path. Recalculation of the SS data to the ionosphere parameters at the path center point can be useful for obtaining additional information on the medium in the regions, where the VS ionospheric stations are absent. The presence of reliable experimental SS data and the possibility of obtaining of the top beam parameters are necessary. This, in turn, can help in solving the problems of prompt diagnostics and forecast, producing the regional models of ionosphere, and adapting different models to actual conditions.

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