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EVALUATION OF METHODS FOR CALCULATING MAXIMUM USABLE FREQUENCIES

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Summary

The accuracy of the calculation of maximum usable frequencies (MUF), employing methods which are most widely used in practice, was checked by comparing calculated and experimental values. The experimental figures were obtained from medium latitude radio lines extending over a distance of 1,500 to 7,000 km, and included simultaneous measurements of field strength and angles of arrival in a vertical plane. With the aid of mean deviation values between calculated and experimental MUF figures, it is possible to estimate the magnitude of the corrections which must be made when using the MUF calculation methods described here.

Introduction

The present study describes results obtained in evaluating the accuracy of the methods most widely used in practice for calculating maximum usable frequencies (MUF). The accuracy of these methods was evaluated by comparing calculated and experimental MUF values.

A number of methods for calculating MUF values have been published both in the Soviet and foreign literature. However, up to the present time, the accuracy of these methods has not been evaluated on the basis of experimental data, which include simultaneous measurements of the field strength and of the beam tilt angles in a vertical plane, with the aid of which it is possible to clarify the number of reflections occurring in radio lines and to determine experimental MUF values with a sufficient degree of reliability.

Data concerned with an analysis of individual methods have started to appear in a number of articles published during the past few years (1-8); these data, however, are of a scattered nature, since they are based on experiments of a short duration.

The MUF calculation methods used at the present time are based on a recalculation (conversion) of ionospheric data, obtained during a vertical sounding (probing) of the ionosphere, to the case of an oblique incidence; thus, these methods are actually indirect methods.

During the past few years, a number of studies have been published, which are concerned with the experimental determination of MUF's directly during the oblique incidence of radio waves (2; 5-13), for example, with the aid of return-oblique sounding (VNZ -Vozvratno-naklonnoye zondirovaniye - Back-scatter echo ?) and oblique sounding (NZ - Naklonnoye zondirovaniye). However, these methods have not yet found a wide field of application, and for this reason MUF's are usually determined by indirect methods.

In this study, the accuracy of the following calculation methods is checked: K. M. Kosikov's method; the method of "control points", developed at the Central Laboratory for Radio Wave Propagation (CRPL, USA); the method of "equal jumps" and the method of calculation based on altitude -frequency characteristics and the use of "transmission curves".

The experimental data, on which the analysis of the various MUF calculation methods is based, were obtained from 5 medium latitude radio lines running over a distance of 1,500 to 7,000 km. Simultaneous measurements of the field strength and of beam incidence angles in a vertical plane were also performed on these radio lines.

Characteristics of MUF Calculation Methods

The MUF calculation methods examined here have been published (14-16), and a detailed description of these methods is therefore not necessary. We shall merely point out the basic differences between these methods.

1. Different methods are used for determining the conversion factor used in converting data obtained in the vertical sounding of the ionosphere to data corresponding to an oblique incidence, whereby:

a. In the CRPL method (15) and in the method of "equal jumps" (16), these factors are determined with the aid of "transmission curves", starting from the assumption that the altitude distribution of the electron density in ionized layers is subject to the parabolic law.

b. In K. M. Kosikov's method (14), the conversion factors are obtained exprimentally by comparing the conditions under which the transmission of operating frequencies takes place in operating radio lines of different length with measured values of critical frequencies.

2. Different lengths of the maximum "jump" of the wave during its reflection from the F-2 layer are selected in the various methods: in K. M. Kosikov's method and in the method of "equal jumps", this magnitude is equal to 3,000 km, while in the CRPL method, it is equal to 4,000 km. During reflections from the F_1 and E layers, these magnitudes are equal to 3,000 and 2,000 km respectively in all methods.

3. A different concept of the trajectory of radio wave propagation is assumed in the various methods for distances exceeding the maximum length of a single jump. Starting from this concept, a method of calculation is elaborated, whereby:

a. In the method of "equal jumps", it is assumed that propagation takes place in "equal jumps", with a maximum jump length equal to the maximum length or somewhat smaller than this length. In such cases, the MUF magnitudes are calculated for all points where reflection occurs (whereby the number of these points is the same as the number of jumps), while the smallest magnitude obtained in this manner is selected as the final MUF value for the route.

b. In K. M. Kosikov's method and in the CRPL method, the trajectory along which the propagation of radio waves takes place is not specified, and MUF's are calculated:

Either at two points separated from each end of the route by a distance equal to one half of the maximum jump length, whereby the shortest distance is selected as the final MUF value for the route (15);

Or at one point, located on the sector of an arc extending between the two points mentioned above; the smallest critical frequency value among all magnitudes observed in the route sector under examination should correspond to this point (14).

Prior to examining the results obtained in establishing the accuracy of MUF calculation methods, we shall examine the methods used in determining experimental MUF values.

Experimental Data Used in Case of Oblique Incidence and Initial Ionospheric Data

An evaluation of the accuracy of indirect MUF calculation methods is given on the basis of experimental data derived from measurements performed on separate days and from median monthly MUF values in medium latitude radio lines. Pulse operations were used on some of these radio lines. Measurements of the field strength and of the beam incidence angles were performed once every 5 minutes. The measuring sessions lasted for 2 hours and more. During these sessions, work was conducted on the same operating frequency, which was selected in such a manner that it was smaller than the MUF during a certain time interval, then equal to the MUF at a certain moment, and finally higher than the MUF.

The initial (original) experimental ionospheric data, used during MUF calculations, gave a sufficiently good picture of the condition of the ionosphere along the route only in case of certain radio lines; for the majority of radio lines, the calculation was performed on the basis of charts listing critical frequencies and MUF factors, since no ionospheric stations were located directly along the path of radio wave propagation. These charts, in case of the F-2 layer, were compiled separately for each hour of the day (24-hour period), i.e. they constituted a geographical distribution of the parameters of the layer in one physical moment of time. This type of representation, as specially conducted comparisons have shown, results in a greater accuracy than the one obtained with the aid of widely used charts showing geomagnetic zones. Standard type critical frequency charts were used for the F_1 and E layers, since the parameters of these layers exhibit a more regular geographical distribution than those of the F-2 layer.

Methods for Determining Experimental MUF Values

The trustworthiness of the evaluation of MUF calculation methods depends on the reliability with which experimental MUF values are determined.

First, we shall examine methods for determining experimental MUF values during a specific day and hour, and then methods used to obtain median monthly values.

It is usually assumed that a MUF is the highest frequency which is still reflected from the ionosphere. However, an analysis of experimental data with simultaneous measurements of field strength and beam incidence angles in a vertical plane has shown that such a definition of MUF's cannot be unambiguous. It was found that, on operating frequencies higher than the frequency at which reflection still takes place, the reception of signals did not always stop, although it was accompanied by a sharp reduction in field strength. The "residual" signal observed in this case was no longer due to a normal reflection from the ionosphere, but may have been caused by other phenomena, such as, for example, diffusion by irregularities in the ionosphere; in such cases, the possibility of detecting the signal depends on the efficiency of technical means.

It is possible to conclude from the above statements that experimental MUF values during a specific day and hour should be derived not from the highest frequency which is still capable of returning from the ionosphere, but rather from the highest frequency above which a 2-fold or greater reduction of field strength is observed.

A clear example, which confirms the accuracy of such an MUF definition, is shown in Figure 1 (a_1 and a_2). The top part of this figure shows the variation in the ratio between operating frequency and MUF which occurred during the course of a measuring session (see the solid line). Measured field strength values (measured once every 5 minutes) are shown in the central portion of the graphs, and measured values of angles in a vertical plane are shown at the bottom. The following magnitudes are plotted along the ordinate axis: in the upper graph, the ratios between operating frequencies and MUF's; in the central graph, the ratios between the field strengths, measured during the course of the session, and the maximum field strength value obtained during the same session; in the bottom graph, the ratios between the magnitudes of the angles, measured during the course of the session, and the value of the incidence angle observed at the time when the operating frequency was equal to the MUF.

Graphs a_1 and a_2 in Figure 1 confirm the fact that, if the MUF is determined on the basis of the maximum frequency still returning from the ionosphere, a frequency of too high magnitude may be selected as the MUF; at this frequency the conditions corresponding to a normal reflection are not fulfilled, and for this reason, the field strength is lower by several orders of magnitude than it would be at a lower frequency.

If one follows the variations in the beam incidence angles in a vertical plane, one can easily notice that the angles increase smoothly as the operating frequency approaches the MUF (in view of a greater depth of penetration into the layer); on the other hand, when the operating frequency exceeds the MUF, the incidence angles remain unchanged in case a "residual" signal is present (since the depth of penetration remains constant). This fact confirms the assumption that the return of the "residual" signal is not due to reflection processes.

At the same time, it is also interesting to note that a diffusion (scattering) may take place when a "residual" signal is present: at the level of the layer which determines the MUF (see Figure 1, a_2, and Figure 1, a_1, second beam), and at the level of the layer immediately below this layer (first beam in Figure 1, a_1).

Results of an experimental study have shown that cases may occur in which no "residual" signal can be observed, as can be seen from the examples listed in Figure 1 b_1 and b_2. In such cases, the determination of MUF's becomes unambiguous.

The median monthly MUF values selected were equal to the operating frequency reflected from the ionosphere during 50% of the measuring days, whereby those operating frequencies which were higher than the MUF were reflected during a smaller percentage of days, and frequencies lower than the MUF were reflected during a larger percentage of days.

Comparison of Calculated and Experimental MUF Values

Experimental MUF values were obtained on radio lines extending over a distance of 1,500, 3,000, 4,200, 6,000 and 7,000 km, primarily during periods of twilight and darkness along the routes. There were few data obtained during daylight hours, in view of the fact that measurements were performed during a period of high solar activity, and daytime MUF values exceeded in most cases the upper limit of the transmitter frequency band.

Along with a determination of experimental MUF values, on the basis of measured magnitudes of incidence angles in a vertical plane and altitudes of reflecting layers, the types and number of reflections (signal trajectories) were also determined. These data are of interest, since it is important to know, for practical and calculation purposes, what is the minimum possible number of reflections on radio lines of various length, and what types of reflection may take place. An analysis of measurement data obtained on the above-mentioned radio lines has shown that, in case of operating frequencies close or equal to MUF's and a minimum number of jumps, the following types of reflections were mostly observed:

$1F_2$ - on radio lines having a length of 1,500 and 3,000 km.

$2F_2$ - " " " " 4,200 km.

$2F_2$ and $3F_2$ - on radio lines having a length of 6,000 and 7,000 km.

The probability of the appearance of a given type of reflection, in case of a minimum number of jumps, is listed in Table 1.

Table 1

Length of Radio Line (km)	Number and Type of Reflection	Length of Jump (km)	Number of Cases (%)
6,000	2 F_2	3,000	62
	3 F_2	2,000	38
7,000	2 F_2	3,500	40
	3 F_2	2,300	60

All reflecting layers were taken into account during the calculation of MUF's, but the F-2 layer was found to be the principal layer determining the values of MUF's.

In order to estimate the accuracy of a given MUF calculation method, the magnitude of the deviation (discrepancy) between calculated and experimental MUF values was determined.

As a result of a statistical processing of deviations, both for median and individual daily values, histograms showing the distribution of these deviations, shown in Figure 2, were calculated and plotted. Mean arithmetic values are shown in each histogram (designated by the latter "c").

On the basis of the results listed in Figure 2, it is possible to draw the following conclusions:

1. Certain methods yield lower MUF values, while others yield higher values, whereby:

a. In radio lines with one reflection (D = 3,000 km), MUF values calculated by K. M. Kosikov's method are, on the average, 30% higher than experimental values; while MUF values calculated by the CRPL method, by the method of "equal jumps", and on the basis of altitude-frequency characteristics, are 4-8% lower than the experimental value.

b. In radio lines with two and more reflections (D = 3,000 km), MUF values calculated by K. M. Kosikov's method exceed experimental values by an average of 20 or 30% in a radio line having a length of 4,200 km and in radio lines having a length of 6,000-7,000 km. MUF values calculated by the CRPL method are, on the average, 12% or 24%

higher than the experimental values on a radio line having a length of 4,200 km, and lower by 2-4%, on the average, on radio lines having a length of 6,000-7,000 km. The MUF values calculated by the method of "equal jumps", and on the basis of altitude-frequency characteristics, are, on the average, 8-13% lower than the experimental values.

2. In radio lines with two or more reflections, the spread of deviations in regard to average values obtained by each method is greater than in radio lines with one reflection. In case of a comparison between the various methods, one finds that, in radio lines extending over long distances, the spread of deviations resulting from the application of the Kosikov and CRPL methods is 1.5-2.0 times greater than in the case of the other two methods examined here. In radio lines with a single reflection, the error spread for all methods lies approximately within the same range.

Thus, the method of "equal jumps" and the method of calculation based on altitude-frequency characteristics give the smallest errors, which do not vary greatly with the distance, and the lowest spread of deviations. This is probably due to the fact that these methods reflect the physical picture of radio wave propagation more closely than do other methods. However, the calculation based on altitude-frequency characteristics is more laborious, and for this reason it is more expedient, from a practical standpoint, to use the method of "equal jumps".

On the basis of the average magnitude of deviations between calculated and experimental MUF values, it is possible to compute the corrections which must be introduced into the calculation of MUF's by these various methods and to estimate the deviations which may occur during these calculations.

The correction factor, by which it is necessary to multiply the MUF values calculated for various distances by the method of "equal jumps", can be derived from the curve shown in Figure 3. Corrections for figures published in various articles (1, 2, 8) are also plotted in this figure. There is satisfactory agreement between these figures and the results obtained in the present study.

Conclusion

The accuracy of the calculation of maximum usable frequencies (MUF) by means of methods most frequently used in practice was checked in this study. The accuracy of the calculation was checked by comparing calculated and exprimental MUF values. In this connection, the following methods were examined: K. M. Kosikov's method, the method developed at the Central Radio Wave Propagation Laboratory (CRPL, USA) the method of "equal jumps", and the method of calculation based on altitude-frequency characteristics using "transmission curves".

The experimental data, used in this study, were obtained on medium latitude radio lines having a length of 1,500 to 7,000 km, and included simultaneous measurements of the field strength and of beam incidence angles in a vertical plane. With the aid of these measurements, it was possible to clarify the method of determining experimental MUF values for a specific day and to obtain the data required for checking the accuracy of MUF calculation methods.

The results obtained from a comparison of calculated and experimental MUF values have shown that, out of all the methods examined here, the smallest errors, which do not vary greatly with the distance, and the lowest spread of deviations are obtained by using the method of "equal jumps" and the method based on altitude-frequency characteristics. However, in view of the laborious nature of the latter method, the most effective method is the method of "equal jumps".

On the basis of the average deviations between calculated and experimental values, it is possible to estimate the magnitude of corrections which must be introduced when using the above-mentioned MUF calculation methods.

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FIGURE APPENDIX

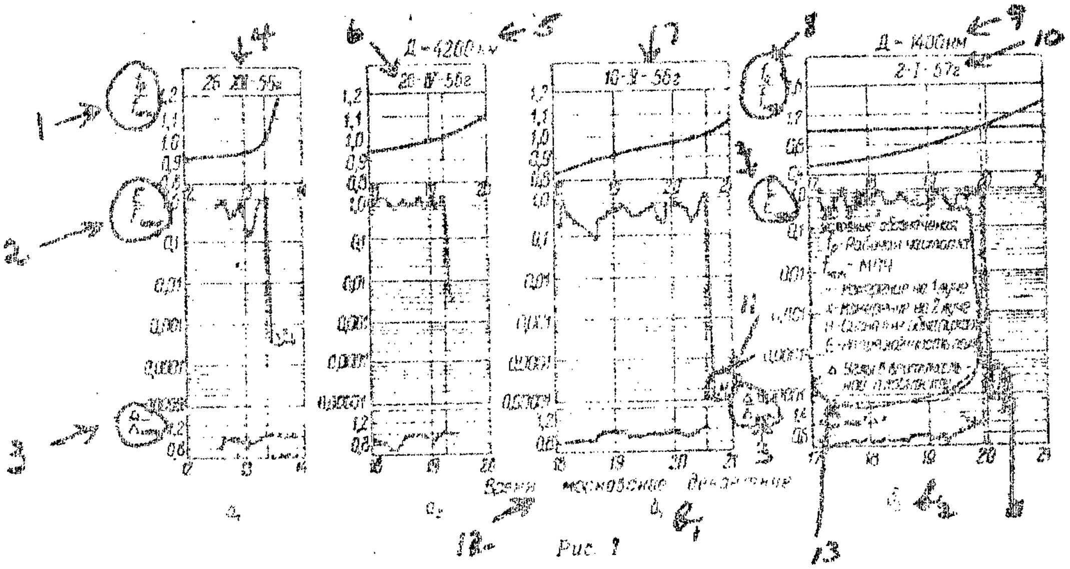

Рис. 1

Figure 1.

Legend:

1. $\frac{f_p}{f_{MUF}}$
2. $\frac{E}{E_{MUF}}$
3. $\frac{\Delta}{\Delta_{MUF}}$
4. 26 December 1956
5. D = 4,200 km
6. 20 April 1956
7. 10 May 1956
8. $\frac{f_o}{f_{MUF}}$

Figure 1, Legend (continued)

9. D = 1,400 km

10. 2 January 1957

11. H (see definition below)

12. Statutory Moscow time

13. Conventional designations;
f_p - Operating frequency

f_{MUF} - MUF

o - Measurement on first beam

x - Measurement on second beam

H - Signal was not detected

E - Field strength

Δ - Angles in a vertical plane.

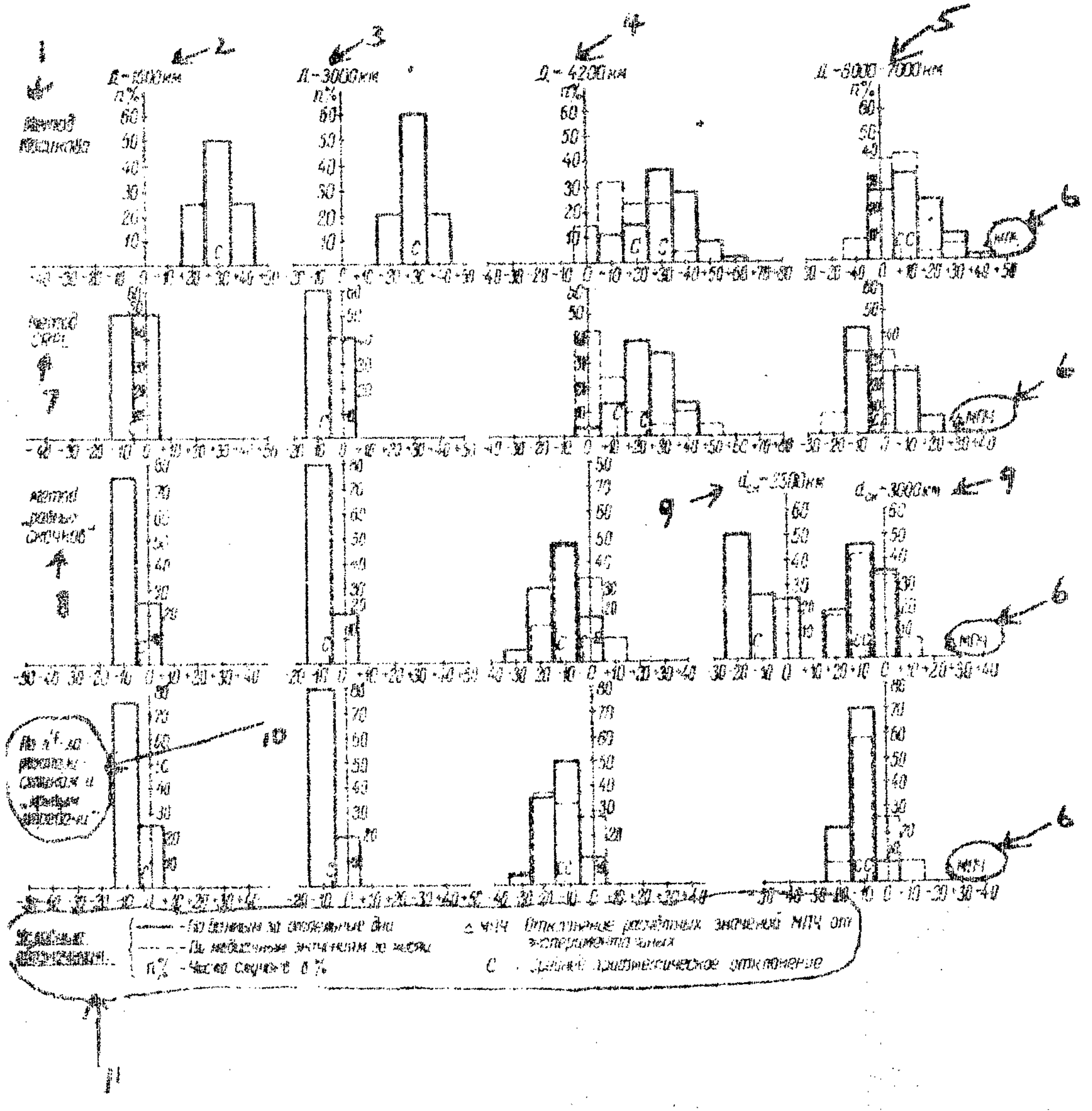
1
2
3
4
5
6
7
8
9
10
11
Д~1500км
Д~3000км
Д~4200км
Д~6000-7000км
n%
dск~2500км
dск~3000км
МПЧ
С
Δ МПЧ - Отклонение расчётных значений МПЧ от экспериментальных
n% - Число случаев в %
С - Среднее арифметическое отклонение

Figure 2.

Figure 2, Legend:

1. Kosikov's method
2. $D = 1{,}500$ km
3. $D = 3{,}000$ km
4. $D = 4{,}200$ km
5. $D = 6{,}000 - 7{,}000$ km
6. △ MUF
7. CRPL method
8. Method of "equal jumps"
9. $d_j = 2{,}300$ (3,000) km (d_j - Maximum jump length)
10. Method based on h'f (altitude-frequency) characteristics and "transmission curves"
11. Conventional designations:

———————— Based on figures for individual days

-------- Based on median monthly values

n % - Number of cases in %

△ MUF - Deviation of calculated MUF values from experimental values

C - Mean arithmetic deviation.

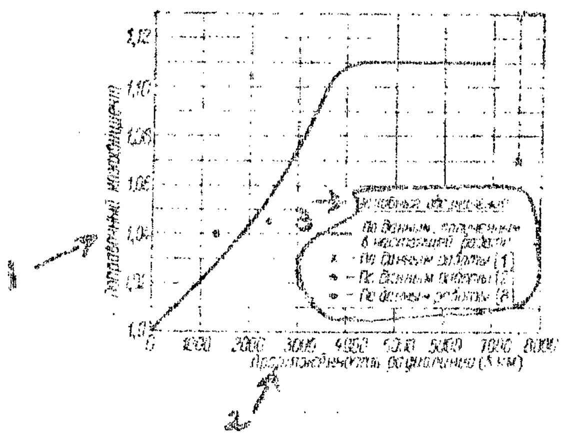

Figure 3.

Legend:

1. Correction factor

2. Length of radio line (in km)

3. Conventional designations:

—— - Based on figures obtained in the present study

x - Based on data published in (1)

● - Based on data published in (2)

• - Based on data published in (8)

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- E N D -