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RESULTS OF COMPLEX GROUND-BASED AND ROCKET EXPERIMENTS AT DETERMINATION OF ELECTRON COLLISION FREQUENCY AND ELECTRON DENSITY PROFILES AT HEIGHTS 80÷500 KM OBTAINED FROM GEOPHYSICAL ROCKETS OF "VERTICAL" SERIES ACCORDING TO INTERCOSMOS-PROGRAM

Presented at the XIX Symposium COSPAR

Moscow

To Dr. E.K. Solomatina
with best regards

ACADEMY OF SCIENCES OF THE USSR
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In July and September, 1975 at middle latitudes of the European part of the USSR the complex measurements of the electron density and collision frequency were carried out at solar zenith angles 69° and 67°. The density was measured by the dispersion interferometer method on the rocket of "Vertical" series (including "Vertical-3" according to Intercosmos program). Simultaneously the vertical sounding and polarization measurements of the radiowave absorption at ten frequencies were also performed. In results of the joint processing of the graund-based and rocket data the profiles of the electron collision frequency were determined. The comparison of results of measurements with theoretical profiles is presented.

1. Introduction

The complex ground-based and rocket experiments were carried out to compare different methods for the measuring of the vertical variation of ionospheric parameters and to work out recomendations for ground-based methods.

Electron density profiles, $n_e(h)$ were measured in the height range 80 ÷ 500 km and effective electron collision frequencies were determined in the inner ionosphere.

The electron density n_e and the collision frequency ν_e in the ionosphere are two of most important parameters of the upper atmosphere from point of view of physical and chemical processes as well as from point of view of applied problems. However, while $n_e(h)$- profiles were repeatedly measured by different means, the reliable measurements of $\nu_e(h)$ were likely performed only at $h < 100$ km mainly by rocket methods. At > 100 km and especially at $h > 150 \div 170$ km the main data on ν_e were obtained by the well-known method by Appleton [1] in which some mean frequency ν_e is determined from the radiowave absorption measured by A1-method or a modification of this method (see the review in [2]). It is difficult to make direct rocket measurements of ν_e at these heights owing to low values of ν_e and in any case such measurements are unknown to authors of the present paper. The method by Appleton also has certain short comings [3] .

Recently methods for the determination of $\nu_e(h)$-profiles are developed on the base of multifrequency measurements of the radiowave absorption and from vertical sounding ionograms [4] . These measurements at present seem to be the only effective way to determine ν_e in the F-region. The main shortcoming of such measurements is some uncertainty of the $n_e(h)$-profile calculated from ionograms with taking into account of the interlayer ionization (the valley) between E and F - region of the ionosphere. That is why the measurements of $\nu_e(h)$- profiles are of great importance during rocket measurements of $n_e(h)$, when $n_e(h)$- profile and, in particular, the ionization in valley is measured sufficiently reliable. Such complex measurements were already performed at rocket launchings [5] .

However, the performance of such experiments presents certain difficulties. In the main the difficulties are due to the necessity to measure the reflection coefficient from F-region, besides the measurements by the usual method at one frequency do not give satisfactory results. Therefore it is necessary to use, first, multifrequency measurements and, second, polarization ones as only in this case one can be certain that in the frequency range 3÷6 Mc the interaction of signals of both magnetoionic components is absent which leads to the distortion of results of radiowave absorption measurements. Difficulties arise also in the interpretation of obtained results because the absorption measurements for the total removal of the influence of the long-termed fading are usually performed during about 90 min while the rocket measurement of the $n_e(h)$-profile is performed much more quickly. Moreover, a non-stationarity of the ionosphere in the period of the launching may be considerable and irregular through the frequency range. In the described experiment the majority of the mentioned difficulties was overcomed and $\nu_e(h)$-profiles were obtained at heights from 100 km to the F-region maximum.

The reliability estimation for the method of transformation ionograms into $n_e(h)$-profile is also of considerable interest. Having the rocket $n_e(h)$-profile and the data from the ionospheric sounder located near the rocket take-off one can easily make such an estimation [6].

2. Conditions of the experiment

The complex measurements were performed at middle latitudes of European part of the USSR during the flight of two geophysical rockets up to heights about 500 km conducted on July, 15 and September, 2, 1975 at solar zenith angles 69° and 67° respectively. $n_e(h)$-profiles were measured by the dispersion radiointerferometer method at frequencies 144 and 48 Mc [7] and were also calculated from the ionosond data. $\nu_e(h)$-profiles were determined from the data of O-component absorption measured by A1-method at ten fixed frequencies in the range $1 \div 7$ Mc [8].

The interferometer receiver was located near the rocket take-off, the ionospheric sounder was at the distance about 40 km from the rocket take-off in such a way that the reflection of the O-component occured near the rocket trajectory. To estimate a typicalness of the conditions in the ionosphere during launchings of rockets the ground-based measurements were conducted several days before and after the rocket launchings. The rocket $n_e(h)$-profiles were obtained in the height range 80 ÷ 480 km during both experiments at the rocket descent.

For determining of the reflection coefficients reflected pulses amplitudes continious registration was performed at ten frequencies by means of pulse sounding device. Then values of amplitudes were averaged over 2.5 min intervals. In this case at ten frequencies at which the radiowave absorption was measured ("knot" frequencies) the effective height was registered more exactly by means of the electronic altimeter and this gave the possibility to exclude errors inherent to the usual ionograms. Polarization ionograms in the period of measurements were registered one every 5 min.

3. Calculation of $n_e(h)$-profiles from ionograms

In the used method of the $n_e(h)$ -profile calculation (from the base of the ionosphere up to the height of the ionization maximum) from the vertical sounding data the most suitable sources of the additional information are taken for the given height range at different stage of the calculation.

V

At the first stage the calculation is made of the lower ionization (D -layer and the base of F -layer) from the absorption and effective height data, as well as the ionization correcting in the valley is made from the data of X-component in the ionogram and the calculation of the ionization above the valley mainly with the use of O-component with taking into account of the above-determined lower and valley ionization. The h_{max} determination is made with the use of the parabolic approximation of the ionosphere. The rocket profile was used only at certain limitation of the valley depth. In the model profile calculation of the lower ionization the modified method was employed [9] in which the absorption $L_{2.0}$ at the fixed frequency near 2 Mc was used with the reflection from the flat boundary of E-layer and several values of effective heights $h'_e(f)$ from f_{min} to this first knot frequency. The ionization model $n_e(h) = n_o \exp(h-h_o)\alpha$ is used, where α and h_o (at n_{eo} =100 cm^{-3}) are determined through the minimization of the sum of squares of difference between calculated and measured values of $h'_E(f)$ and $L_{2.0}$ which are measured and calculated with the use of the model. The height dependence $\nu_m(h)$ in this range is well-known, $\nu_m = kp$ (k =7.8$\cdot 10^5$ $N^{-1} m^{-2} sec^{-1}$ and the pressure p model is taken from [10]).

All calculations for this height range are performed in term of the generalized magnetoionic theory [11] .

For the valley the single-layer approximation of $n_e(h)$ is taken and it is considered that the electron density there not less than 0.9 n_{emaxE}. Near the F2 maximum, as it was mentioned the parabolic approximation of the ionosphere is used. Parabolic parameters are determined by two methods. In first method (1) the conjugation of the parabolas is made by the derivative at the boundary of latest reliable recovered interval. In second method (2) parabolic parameters are determined from the coincidence of the parabola with parts of the

$n_e(h)$ -profile determined at values $(0.8 \div 0.9)n_{e\,max\,E}$ and the known value of $n_{e\,max\,E}$.

4. Discussion of obtained $n_e(h)$ -profiles

In Fig.1, 2 all main results of calculations of $n_e(h)$ -profiles obtained during both launchings are presented. Solid curves (without circles) are $n_e(h)$ -profiles measured by the rocket interferometer. Curves with blacked circles are monotonic $n_e(h)$ -profiles calculated from the O -component of ionograms and the data on absorption at f =2 Mc. Curves with unblacked circles are non-monotonic $n_e(h)$ -profiles calculated with taking into account of both magnetoionic components and the absorption at f =2 Mc. Dashed lines, $h'(f)$, are curves obtained just before the rocket launching. Circles indicate the location of the ionization maximum according to different methods of the calculation from ionograms. On the left from each curve the part corresponding to the interlayer ionization is given (in calculation of this part the influence of the sporadic E_s -layer was taken into account).

Let us consider the results of $n_e(h)$ -profiles determination separately for each ionospheric region.

4.1. D -region and the base of E -layer

During first and second rocket launchings the electron density measurements were performed from $n_e = 10^4 cm^{-3}$ and $n_e = 2 \cdot 10^3 cm^{-3}$ respectively (Fig.1,2). That is why model distributions of $n_e(h)$ are represented by values of the density more than $10^4 cm^{-3}$ and $10^3 cm^{-3}$. The comparison of model and rocket profiles in the height range $h <$ 100 km shows that during the first launching the height difference is on average about 1 km. During the second launching in the height range h =87 ÷ 100 km the model $n_e(h)$ gives more values and at $h < 87$km less ones of n_e than those obtained in rocket measurements. Maximum height-difference between profiles in the range h =87 ÷ 100 km is about 3 km. At the conjugation point ($h \approx 100$ km) of the model $n_e(h)$ and the profile from ionograms the height difference is less than 1 km.

So the use of the absorption and effective height data for the O -component leads to better recovery of the inter-layer ionization profile than the use of both magnetoion components [12] which are reflected at E -layer.

4.2 Valley ionization and E -layer

The ionization drop above the E -layer maximum was insignificant during launchings of both rockets and it is well seen in Fig.1, 2. Let us compare profiles for each launching separately.

The experiment on July, 15, 1975. Fig.1 shows that the valley in this case is a rectangular plateou about 30 km wide at which increases of the ionization are observed at two places. The lower part, as it follows from the ionogram, has sporadic semi-transparent structure. The calculation of the whole $n_e(h)$-profile (with taking into account of the absorption and X -component) shows a good agreement with the rocket curve. Particularly it should be noted that the width of the valley was found correctly. The difference in the density at the E -layer maximum (h =110 km) between results of rocket and ground-based experiments one can explain by the presence of E_s-layer.

Really it is impossible to find the difference between regular and sporadic layers by means of the rocket method while in the ionogram this difference is usually seen. However if it is taken in the $n_e(h)$ -profile calculation that E_s -layer brings in also group delays essential in the calculation of the upper ionization then, as one can see from Fig.1, the difference of rocket and calculated curves in the width of the valley abruptly increases, i.e. in this type of the calculation the width of the valley is determined incorrectly. So in results of the comparison of the valley for the measurements on 15 July, 1975 one can conclude that, first, the total calculation of $n_e(h)$ -profile from vertical sounding ionograms with taking into account of the absorption and X -component gives the results comparable to the rocket data and, second, the semi-transparent E_s -layer of c -type does not influence on group delays from the F -region.

The experiment September, 2, 1975 (Fig.2). It is seen, that the pronounced valley is absent. The analysis of the ionogram shows that there were sporadic E_s -layers of c and ℓ -types. However, the E_{sc} -layer is screening one as opposed to the layer observed in the preceding experiment. The $E_{s\ell}$ -layer is located below the E -layer maximum. The presence of these layers makes difficult the determination of f_oE from the ionogram. In the interpretation of the ionogram presented in Fig.2 the frequency f_oE value is taken to be 2.8 Mc based on the studing of the low-frequency end of the reflection from the F -region. During the rocket flight considerable changes of the E -layer electron density occured in particular, the blanketing frequency of E_s -layer ($f_B E_s$)

increased from 2.9 Mc to 3.1 Mc for 10 min. A slight height difference between maxima of two laminations in the E -region equal to 12 km (according to the rocket curve) is presented by two E_s -layers in the ionogram. These layers are of ℓ -type with the limiting frequency 2.65 Mc corresponding to the lower lamination with $n_e = 9 \cdot 10^4 cm^{-3}$ and -type of which maximum is located by 12 km higher and the limiting frequency is about 3.0 Mc corresponding to $n_e = 1.15 \cdot 10^5 cm^{-3}$. The type of the valley follows also from $n_e(h)$ -profile calculations, namely, the calculation of the monotonic $n_e(h)$ -profile gives the under-estimation of the ionization height on average by 10 ÷ 15 km everywhere above E_{max}. The calculation of the nonmonotonic $n_e(h)$ -profile without taking into account of sporadic formations gives the results practically coincident with the rocket curve at $h > 150$ km but naturally in this calculation the ionization due to the lamination in the valley is taken into account satisfactorily. The full calculation of the $n_e(h)$-profile with mentioned sporadic formations (the picture on the left from the main curve in Fig.2) makes it possible to take into account the ionization in the valley in a better way and gives values practically coincident with rocket curve up to the F -region maximum.

The ionization measurements in the E -layer and in the valley shows:

a) in the presence of complex laminations it is impossible to determine the critical frequency of the regular E - layer from one rocket curve,

b) in the presence of screening E_s -layers the curve with taking into account of these layers gives the better agreement with the rocket profile.

So the analysis of both launching gives the possibility to make following recomendations for routine calculations of $n_e(h)$ -profiles from ionograms in the E -layer, the valley and the lower part of the F -region:

a) the maximum electron density in the E -layer is determined from $f_B E_S$ -values rather than $f_o E_S$ -values,

b) in the calculation of the $n_e(h)$-profile above E_{max} in the presence of the screening thick E_S -layer it would be sound practice to take into account group delays with $f > f_o E$ due to E_S . In the case of the semi-transparent E_S -layer the group delays may be ignored.

4.3. The region near the F -maximum

The height of the F -region maximum, $h_{max}F$, and the density in it, $n_{e\,max}F$, can be determined from the ground-based sounding data either by one of routine methods recommended by the URSI instruction [13] , or from the $n_e(h)$-profile calculation with the use of the parabolic approximation near the maximum. The results of the h_{max} determination are given in Tabl.1. They obtained by different methods during rocket flight under consideration (the numerator - h_{max}- value during the launching July, 15, 1975; the denominator - the data corresponding to the launching September, 2, 1975). The table show the following:

a) the difference of h_{max}-values calculated from ionograms by different methods (see section 3) reaches 12 km. The difference between these values of $h_{max}F$ and the rocket data is within 0 ÷ 23 km. Calculations performed under the assumption of a non-monotonous profile with taking into account

Table 1

The height of the ionization maximum (km)

	Monotonous profile		Non-monotonous profile	
	not including Es	including Es	not including Es	including Es
Method 1	247/233	255/235	252/236	260/242
Method 2	256/234	259/242	260/239	262/245
Method 3 $h=h(0.834 \cdot f_0F2)$ The URSI-guide	No data/290			
Rocket experiment		270/242		

The numerator - the data obtained in the experiment on 15 July, 1975

The denominator - the data obtained in the experiment on 2 September, 1975 of the E_s -layer give better agreement. The value of h_{maxF} calculated for the profile on 15 July, 1975, by the method 1 coincides with the rocket data while the profile obtained on 2 September, 1975 gives the better agreement with the rocket data in the calculation by the method 2 (the difference is 8 km). The fact that the better agreement in these two launchings is obtained by different methods can be explained by the point that the $n_e(h)$ -distribution near h_{maxF} is not stritly parabolic.

b) the h_{maxF} -value defined according to the URSI instruction for the case of a rough determination from ionograms ($h_{max} = h'(f = 0.834 f_oF2)$, where f_oF2 - the critical frequency of the $F2$-region) differs from the rocket data by 48 km in the experiment on 2 September, 1975 but can not be determined in the experiment on 15 July, 1975 since the corresponding frequency lies near the critical frequency of the $F1$ -layer.

5. The method and results of the $\nu_e(h)$-profile calculations

The determination of $\nu_e(h)$-profiles was carried out by the numerical reversion of the integral equation

$$L(f) = 2\int_{h_o}^{h_r(f)} \varkappa[f, n_e(h), \nu_e(h)]\, dh,$$

relating the frequency dependence of the absorption $L(f)$ to the height dependence of the collision frequency $\nu_e(h)$. The solution of the equation is performed in the geometrical optics approximation and $h_r(f)$ means the height of the radiowave reflection.

The registration of polarization ionograms and simultaneous measurements of the O -component absorptions at ten frequencies were carried out in days of rocket experiments as well as in control days before and after the rocket launchings by the method A1 in the range 2.0 - 6.0 Mc. The determination of the radiowave absorption was made trough 25 min averaging of amplitudes and following calculation of the reflection coefficients. The suppression of the long-termed fading was reached through the following averaging of reflection coefficients determined over 2.5 min intervals. It was established that in the experiment on 15 July, 1975 the period of the averaging should be taken 30 min and in the experiment on 2 September, 1975 - 20 min.

To choose the suitable values of knot frequencies for the correct determination of the $\nu_e(h)$ -profile, the study of the time variability of the ionosphere was made during several days before the rocket launching.

The knot frequencies were determined based on the necessity to receive reflections from levels defining the character of the $\nu_e(h)$ -profile as well as from the ionospheric situation. In spite of such a careful choice of knot frequencies results for some frequencies proved to be unsuitable for the calculation of the $\nu_e(h)$ -profile.

In Tabl.2 all measured absorption values are presented

Table 2

Date	f Mc	f Mc	2.0	2.25	2.5	2.75	3.0	3.25	4.0	4.25	5.0	5.25
15.7.75		L,dB	22.7	26.1	22.3	25.2	20.6	25.3	12.8	20.3	-	-
Interval 30 min		Region	E	E	E	E_sF	E_sF	E_sF	F	F		
2.9.75		L,dB	22.3	22.1	20.8	15.6	16.2	14.2	10.2	10.3	11.0	13.5
Interval 20 min.		Region	E	E	E	E_s	E_s,F	F	F	F	F	F

From the analysis of these data one can see the following:

The absorption at the frequency 2.0 Mc during measurements on 15 July 1975 was less than that at frequency 2.25 Mc and this phenomenon was continuously observed over 3.5 hours. The cause of this phenomenon is apparently the presence of an additional ionization maximum in the E-region at the level of the reflection of radiowaves with the frequency f =2.25 Mc. This maximum is displayed in the ionogram in the form of the lamination and leads to the increase of the deviative absorption. Since this lamination was not registered in the rocket experiment and it was impossible to recover it from ionograms the $\nu_e(h)$ determination was made without taking into account of the absorption at the frequency 2.25 Mc. The further analysis showed that in the period of measurements the sporadic E_s -layer appeared and its influence led to the erroneous determination of the absorption at knot frequencies 2.75, 30.0 and 3.25 Mc as gate pulses of the device were set for the reflection from the F -region. So in the calculation of the $\nu_e(h)$-profile the data obtained at following frequencies were used:

15 July, 1975 - 2.0; 2.5; 4.0; 4.25 Mc;

2 September, 1975 - 2.0; 2.25; 2.5; 3.25; 4.0; 4.25; 5.0; 5.25 Mc

The calculation of $\nu_e(h)$ -profiles at heights $h > 100$ km includes two stages. At first from the model $n_e(h)$ -profile (see section 3) the part of the absorption is determined in the height range up to the level of the reglection of radiowaves with the frequency 2.0 Mc. Such a procedure is necessar, to take into account the contribution of the height region with the low electron density and high collision frequency to the absorption. After the estimation of the frequency dependence of the radiowave absorption in the E and F -regions the calculation of the $\nu_e(h)$-profile is made. For the estimation of a calculated profile error the accuracy of measured absorption values is settled to be 10% (the method of the error estimation is described in 14). Calculated $\nu_e(h)$ -profiles and their errors are given in Fig.3. In this figure the solid curve with circles gives the results of gas-kinetic calculations of ν_e performed for the corresponding time of day, season and latitude [15] . The error of the $\nu_e(h)$ -profile recovery corresponding to the experiment on 15 July, 1975 does not exceed 20%, in the case of the experiment on 2 September, 1975 the error is less than 20% at heights 100÷145 km, about 25% at heights 188-208 km and reaches 100% at heights 145÷188 km. The latter is related to the point that at low collision frequencies ν_e (the heights interval 145 ÷ 188 km in the experiment on 2 September, 1975) the mentioned error of the absorption measurement leads to considerable deflections of ν_e .

The distinctive feature of both $\nu_e(h)$ -profiles is the presence of the collision frequency minimum. Experimental errors do not allow to determine exactly the height of the minimum. In the experiment on 15 July, 1975 the minimum is located within 150 ÷ 200 km in the experiment on 2 September, 1975 - within 150 ÷ 180 km. Let us also note that on both cases at heights $h > 180$ km the values of collision frequencies determined in our experiments are essentially higher than the theoretical values [15] . Another peculiarity is the difference of ν_e -values at $h < 125$ km: on 2 September, 1975 collision frequencies were on average 1.3 times higher than those on July, 15, 1975.

Let us consider the discrepancy between theoretical and experimental curves $\nu_e(h)$ at heights more than 150 km. Such a discrepancy was observed formerly too [16] . It should be found out whether or not high values of ν_e are related to measurement errors and how one can explain such a variation of the $\nu_e(h)$-profile.

In the present method of the determination of the frequency ν_e some shortcomings inherent to other methods are remouved. Nevertheless this method is not free of shortcomings. Thus, for instance the rocket $n_e(h)$-profile is measured during about 10 min while the absorption measurement takes about 1.5 hours. The complex rocket and ground-based experiment cannot be stoped after the rocket launching although at this time (as it was in described experiments) the E_s -layer can appear or abruptly increase. During the rocket flight and the absorption measurement session the limiting frequency $f_o E_s$ and blanketing frequency $f_B E_s$ can sharply change and this can lead to essential errors in absorption measurements at certain knot frequencies. As to the interval difference it is necessary to average the reflected signals over about 90 min [17] to take into account the influence of large-scale inhomogeneities on the reflection coefficient value. This period of averaging is about 10 times greater than the rocket $n_e(h)$-profile measurement time and here we are faced with difficulties in the joint interpretation of the data. The decrease of the period of the averaging leads, with the rare exeption, to the incomplet removal of the long-termed fading. In the discussed experiment these both causes took place but their influence was weakened by the excluding of a number of knot frequencies "spoilt" during the rocket flight and by the choice of the averaging time at which the fading was practically excluded and the time of the receiving of $n_e(h)$ and $\nu_e(h)$-profiles differed only by two times. This gives the ground to suppose that $\nu_e(h)$-profiles presented in Fig.3 are reliable and really during the rocket flight there were high values of at heights more than 180 km.

Now let us discuss the causes of such values of ν_e. First of all note that high values of ν_e were not obtained in this experiment for the first time. The presence of them was only confirmed by more careful measurements. The discrepancy between theoretical values of ν_e and those determined in radiowave absorption experiments was also noted in the case of the E-region [18] and F-region [16]. There are two explanations of the obtained high values of ν_e. First, this is standard absorption mechanism where an additional absorption takes place due to the increased cross-section of electron collisions with atomic oxigen [2]. Second, the increased absorption may be caused by the resonance absorption in the developed plasma turbulence of the ionosphere. In this case exept usual collisions of electron-neutral and electron-ion types the collisions of electron-plasmon type play the part [19].

6. Conclusion

6.1. The comparison of the results of the $n_e(h)$-profile measurement obtained by the ground-based sounding and the rocket interferometer allows to give following recommendations fro routine calculations of $n_e(h)$-profiles from ionograms:

a) maximum electron density in the E-layer should be found from $f_b E_s$ -values rather than $f_o E_s$ -values.

b) In the calculation of the $n_e(h)$-profile above E_{max} in the presence of the screening thick E_s -layer the group delays should be taken into account with $f > f_o E$ due to E_s . In the case of the semi-transparent E_s -layer the group delays may be ignored.

c) The height h_{max} should be determined under the assumption of at non-monotonic $n_e(h)$ -profile with taking into account of E_s .

6.2. In the result of both experiments the high values of the collision frequency ν_e are obtained at heights more than 180 km and these values essentially differ from those obtained from the gas-kinetic theory.

6.3. The ground-based sounding and the radiowave absorption data are a valuable suplemented method to the rocket study of the upper atmosphere. The impulse sounding device used in described experiments has a number of essential dignities due to the polarization selection of the received signal and multifrequency measurement of the radiowave absorption.

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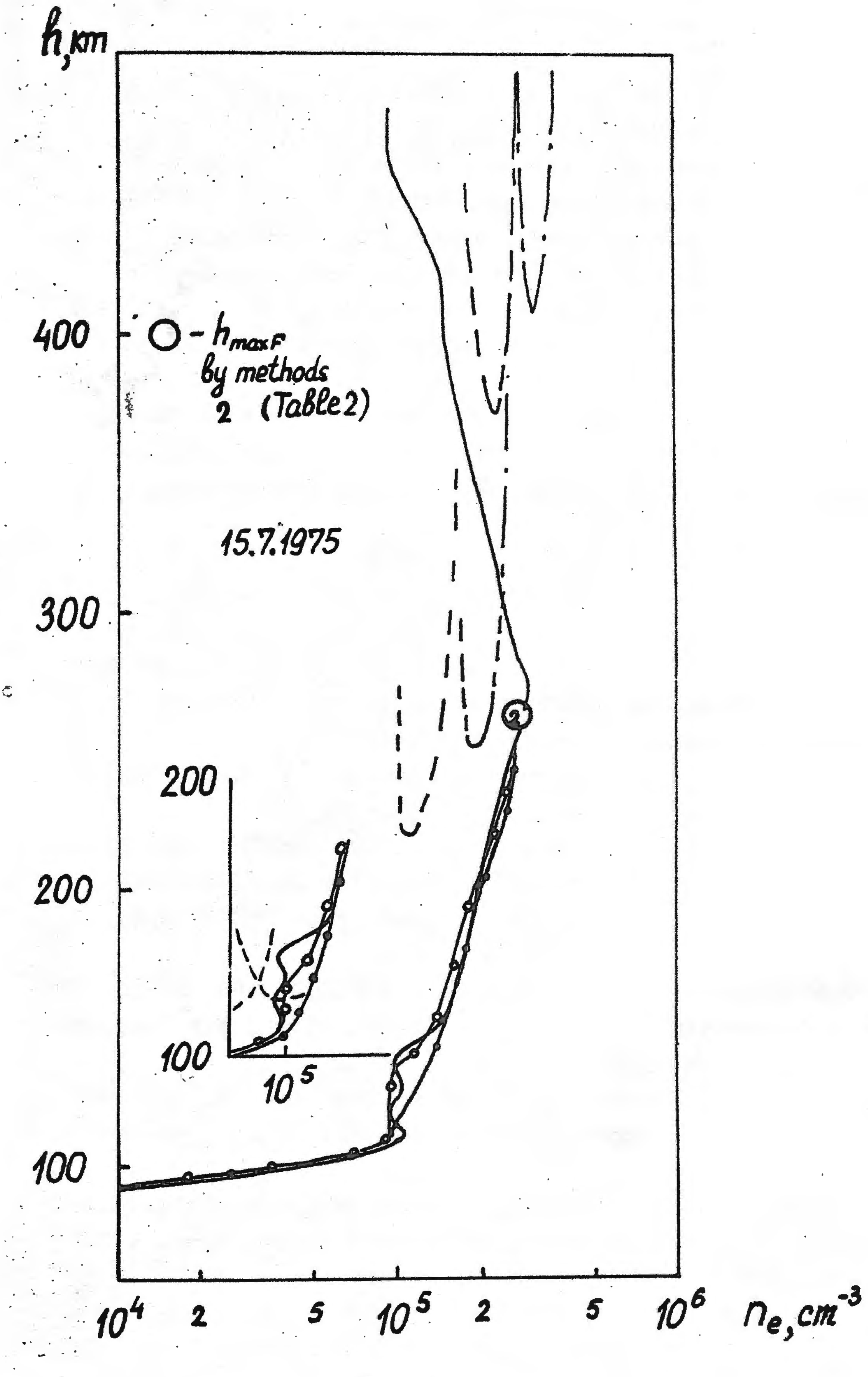
h, km
400
300
200
100
O - h_{maxF}
by methods
2 (Table 2)
15.7.1975
200
100
10^5
10^4
2
5
10^5
2
5
10^6
n_e, cm^{-3}

Fig. 1

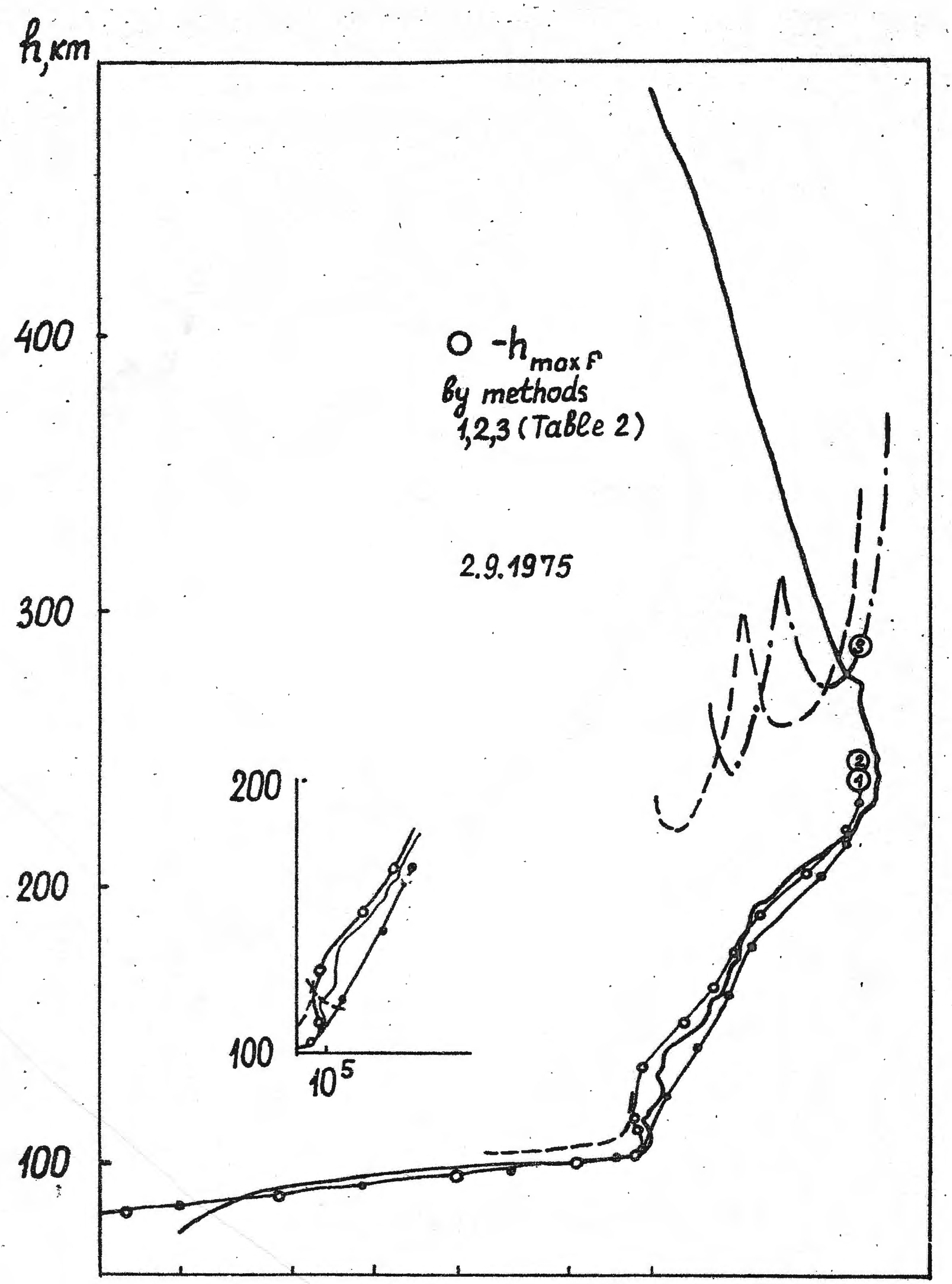
h, km
400
300
200
100
o - $h_{max F}$
by methods
1,2,3 (Table 2)
2.9.1975
200
100
10^5
10^3
2
5
10^4
2
5
10^5
n_e, cm^{-3}

Fig. 2

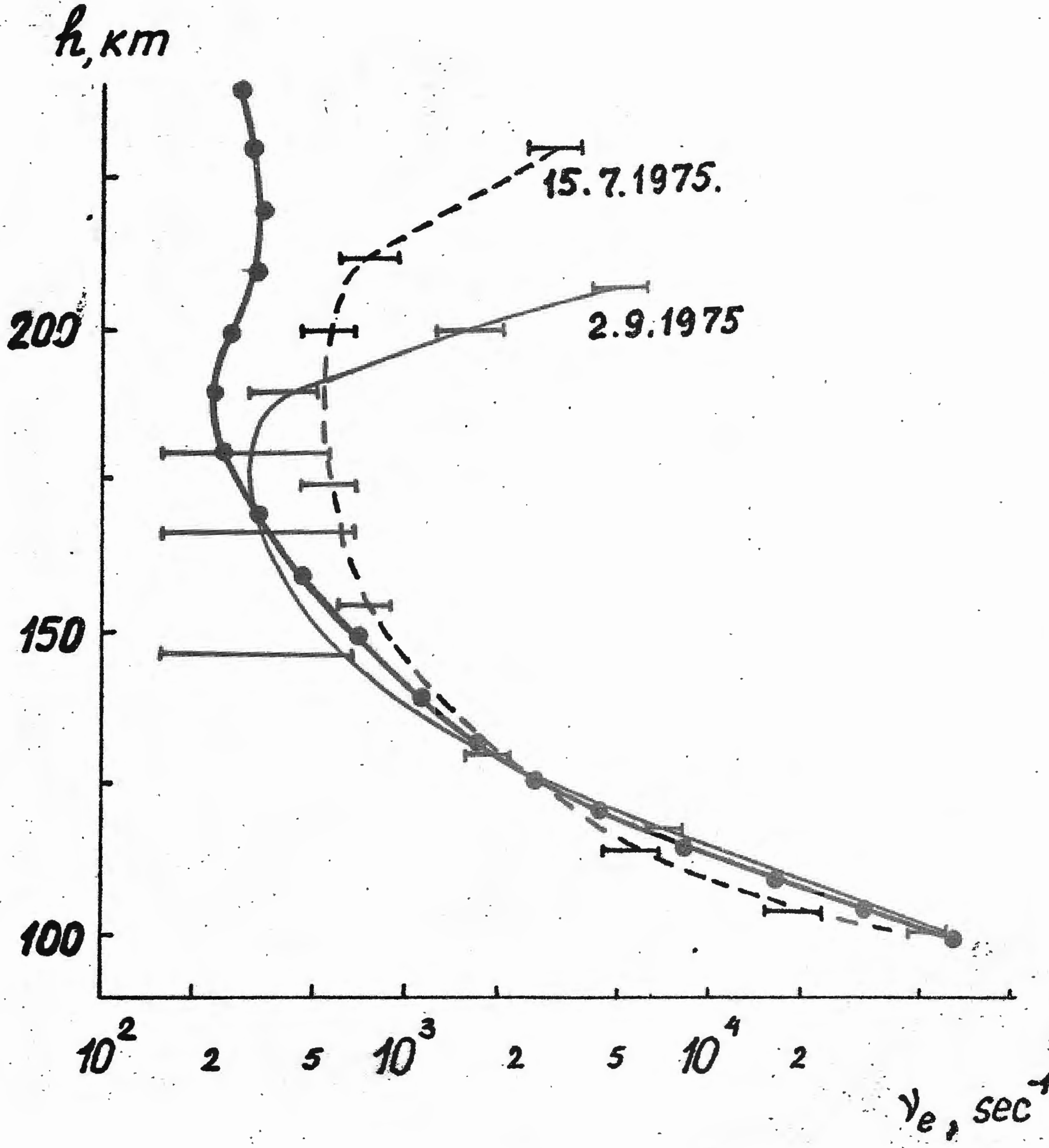

Fig 3

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