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On the Accuracy Increase of Determining the Lower Ionosphere Parameters Using Amplitude Measurements of Partially Reflected Signals

A.M. Gokov

V. Karazin National University of Kharkov, 4, Svoboda Sq., Kharkov, 61077, Ukraine

Based on the experimental data and model calculations it is shown that the difference of experimental height dependences of the ratio of average (during the measurements of ~ 10 min) guadrates of amplitudes of the partially reflected signals of the extraordinary ("x") and ordinary ("o") polarizations $a(z,t)$ from the theoretical ones at the heights of $z >$ 80 km and $z <$ 70 km (which is frequently observed in the experiments and results to additional, frequently essential, errors in determination of the lower ionosphere parameters) is possible becose of simultaneous influence of the following factors: radio noise, the incomplete separation of the "o" and "x" components by receiving equipment and their transformation in the magnetoactive ionosphere, due to difference in their impulse volumes of the "o" and "x" components in space, their differential absorption in the scattering volume, and also due to the essential nonmonotonous of the height electron density and electron-neutral molecule collision frequency profiles (the presence of sharp layers and valleys).

1. Introduction. Statement of a problem

The partial reflection (PR) technique (see, e.g., [1-10]) is applied widely to study space-time variations of the main parameters of the ionospheric D-region. The PR technique allows to obtain the information on changes in the electron density N, the collision frequency of electrons with neutrals ν and on parameters of scattering irregularities with a rather small error (< 30-50 %).

As a rule, the space-time records of PR signal amplitudes of of the ordinary ("o") and extraordinary ("x") polarizations $A_{o,x}(z,t)$ at froquencies $f =$ 2-6 MHz (here z is the altitude over the Earth surface, t is the time) are used.

In order to determine a hight-altitude profile $N(z)$ there are used height dependences of the ratio of average amplitude guadrates of PR signals of the extraordinary and ordinary polarizations (usually for 8-15 minutes) $a(z) = \langle A_x^2 \rangle / \langle A_o^2 \rangle$, which is connected with N and ν as that in [11] (the known methods of differential absorption)

$$a(z) = R(z) \cdot P_1(z) \cdot P_2(z) \cdot \exp\left[-\int_{z_0}^{z} K(z') \cdot N(z) dz' \right], \tag{1}$$

where

$R(z) = \langle |\Delta\varepsilon_x|^2 \rangle / \langle |\Delta\varepsilon_o|^2 \rangle$ is the ratio of the reflection coefficients for "o" and "x" waves;

$\Delta\varepsilon_{o,x}$ is the fluctuations of the dielectric permittivity of ionospheric plasma;

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$P_1(z) = (y_o sh y_x)/(y_x sh y_o)$ describes the differential absorption of the "o" and "x" components in the scattering volume $L = c\tau_i / 2$;

c is the light velocity in vacuum,

τ_i is the duration of sounding pulses;

$y_{o,x} = \tau_i \omega \kappa_{o,x}$;

$P_2 = \exp\{-0,78[(n_x^2 - n_o^2) - (\kappa_x^2 - \kappa_o^2)]\}$ describes the difference between space fuctuations of the electron densities N, and

$n_{o,x}$ and $\kappa_{o,x}$ are the real and imaginary parts of $\varepsilon_{o,x}$.

$K = 8\omega_p^2 \omega_H \omega / c[(\omega + \omega_H)^2 + \nu^2][(\omega - \omega_H)^2 + \nu^2]$,

$\omega_p^2 = e^2 / m \cdot \varepsilon$, $\omega_H = eB_0 m \cos\chi$, $\omega = 2\pi f$,

B_0 is the induction of the Earth magnetic field,

χ is the angle between the direction of the vector B_0 and vertical,

ε is the dielectric permittivity of vacuum, and

e, m is the charge and mass of an electron.

It is supposed that the PR signals are stipulated by the electron dencity N fluctuations. The electron dencities N are obtined by a numerical solution of equation (1) (frequently disregarding of multipliers P_1 and P_2). In order to solve equation (1) (to have the $N(z)$ profiles) there is also used the model electron-neutral molecule collision frequency profile, $\nu(z)$ (for example, [1,2,12]).

In [13] this problem is reduced to solving the integral Volterra equation of the I kinds using the regularization Tikchonov method in the case when $a(z)$ and $\nu(z)$ are given with an error. In a general case with allowance for the multipliers P_1 and P_2, the problem is reduced to solving the integral linear inhomogeneous Fredholm equation of the II kind by the same methods

$$f(z) = N(z) - \lambda \int_{z_0}^{z} K(z') \cdot N(z') dz', \quad (2)$$

where

$\lambda = 1/g(z)$,

$f(z) = f'(z)/g(z)$,

$f'(z) = \ln[a(z)/R(z)]$,

$g(z) \cdot N(z) = \ln[P_1(z) \cdot P_2(z)]$,

z_0 is the initial altitude.

In this case the hight-altitude profiles of $a(z)$ for frequencies f = 2-6 MHz are given in Fig. 1. These profiles were calculated for the impulse duration of τ_i = 25 mcs using model hight-saltitude profiles of $N(z)$ and $\nu(z)$ [14]. In practice at the middle and high latitudes when using the operation frequencies of f < 2-3 MHz in the experimental dependences of $a(z)$ at heights of z > 80-

85 km, one frequently observes a noticeable decrease (and even a change of a sign) in grad $a(z)$ (the so-called characteristic bend of the curve $a(z)$).

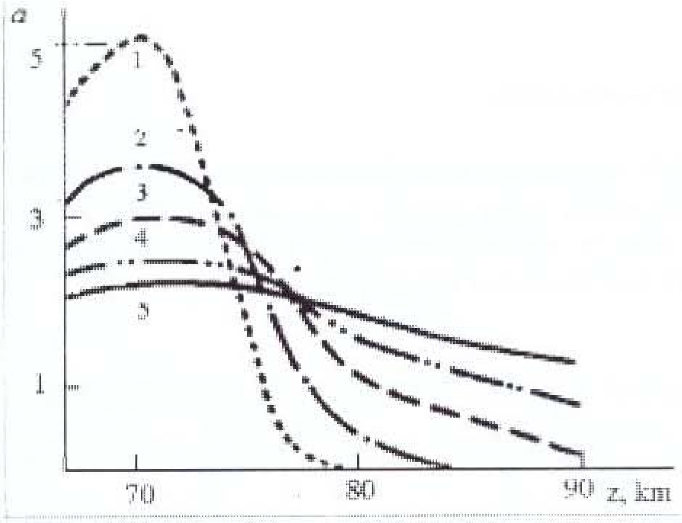

Fig. 1. Model dependences of $a(z)$ hight-altitude profiles for frequencies f = 2-6 MHz (curve 1-5 respectively)

The characteristic example is given in Fig.2: see experimental curve 1. Curves 2-3 are the model dependences of $a(z)$ for f = 2 and 3 MHz, obtained using formula (1). Curve 4-5 are the averaged for 10 minutes dependences of $< A_{o,x}(z) >$ obtained, as well as curve 1 in the measurements of 30.07.1981 at 09.30 LT for τ_i = 25 mcs and f = 2.583 MHz near the city of Kharkov. The feature marked in the $a(z)$ behaviour decreases a hight range in which it is possible to obtaine $N(z)$ by solving (1) or (2) as in this technique the N value ($N > 0$) are obtained under the condition of grad $a(z) > 0$.

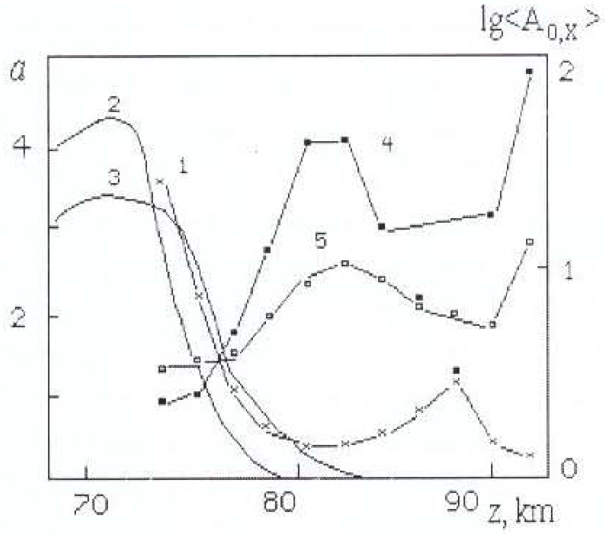

Fig. 2. Model and experimental dependences of $a(z)$ height-altitude profiles.

In the paper the possible causes of such behaviour of the experimental $a(z)$ dependences are analyzed and the recommendations for their account when determining hight-altitude profiles of $N(z)$ and $\nu(z)$ are adduced.

2. Analysis of experimental data

More than 5000 $a(z)$ experimental dependences obtained under various heliogeophysical conditions are analyzed. The experimental investigations were carried out in 1977-2003 by means of the complex equipment [15,16] using the PR technique at the V. Karazin Kharkiv National University Radiophysical Observatory situated near the city of Kharkiv (see Table 1).

Table 1.

Coordinates of V. Karazin Kharkiv National University Radiophysical Observatory

	Geographic		Geomagnetic				
Elevation (m)	Latitude (N)	Longitude (E)	Latitude (N)	Longitude (E)	Inclination	Declination (W)	L
156	49° 38'	36° 20'	45.37°	118.7°	66° 36.8'	6° 19.6'	~2.0

In experiments the main parameters of the PR technique complex equipment were as follows: operating frequencies $f = 2.1$-3 MHz, the sounding pulse length $\tau_i = 25$ mcsec, the repetition rate $F = 1$ Hz, the peak pulse power $P = 100$ kW, the antenna gain coefficient $G = 40$.

In the experiment there were recorded height-time dependences of the mixture amplitudes of the partially reflected signal and radio noise, $A_{so,x}(z,t)$, (where t is the time, "o" and "x" correspond to the ordinary and extraordinary polarizations, respectively) from 14 or 22 height levels, beginning from 45 or 60 km with a step of $\Delta z = 3$ km. In order to select the amplitudes of partially reflected signals, $A_{o,x}(z,t)$, there were also recorded those of only radio noise, $A_{no,x}(t)$, (2-6 samples in a 50 kHz frequency band) at the time moments preceding a sounding pulse radiation. The measurements of $A_{so,x}(z,t)$ and $A_{no,x}(t)$ were made by sessions with duration of unit-ten of hours. Estimating of the mean values of PR signal intensities, $< A^2_{o,x} >$, and those of the noise, $< A^2_{no,x} >$, were made by means of 60 realizations over a time interval of 60 sec. A statistical error in this estimating was not more than 10%. Height-time dependences of $< A^2_{o,x} > (z,t)$ and $< A^2_{no,x} > (t)$ were calculated. Using the $< A^2_{o,x} >$ values calculated previously, there was calculated their ratio, $a(z) = < A^2_x > / < A^2_o >$, (at the fixed heights with a step of $\Delta z = 3$ km) used further to obtain height-altitude profiles of the electron density, $N(z)$, by means of the differential absorption methods [1,2,8]. The height $a(z)$ profiles were calculated over the average intervals of $\Delta t = 10$ min, then being smoothed using three points. The $a(z)$ dependences obtained in such a way were used in order to construct $N(z)$ profiles (the $N(z)$ profiles were corrected by means of a technique in [13]). When calculating the $N(z)$ profiles, there was used a profile model of the electron-neutral molecule collision frequencies, $\nu(z)$ [12].

The error in the $N(z)$ profile calculation over the average intervals of 10 min was not more than 30% - 50%.

The analysis of the experimental data has allowed to find that the second maxima in the hight variarion of $a(z)$ (see Fig. 2), pointed by the authors in [14], is stipulated by reflections from sporadic layers or mirror reflections. It is confirmed by the examples in Figs.2,3. In the first case (Fig. 2) the partial reflection signals took place at the heights of z = 75-87 km, and at z > 87 km the mirror reflection signals were registered. In the second case (see Fig. 3) the partial reflection signals were registered from the hight levels of z = 69-83 km, and at the z > 85 km there were registered the mirror reflections (the data were obtainededed in the experiment of 30.07.1981 at 14.00 LT).

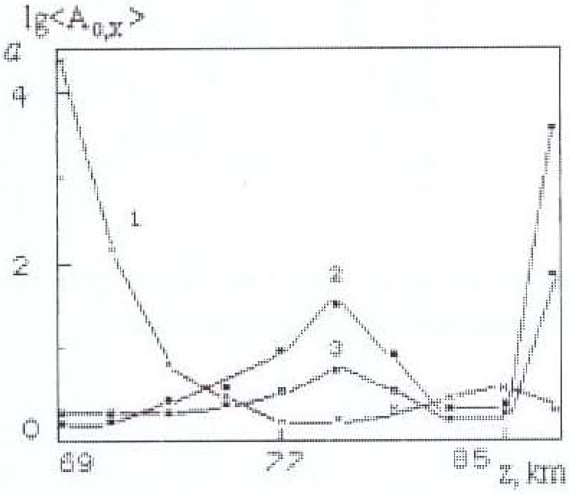

Fig. 3. Height profiles of $<A_{o,x}>$ (curve 2,3) and $a(z)$ (curve 1) obtained in the experiment of 30.07.1984.

Thus decreasing in grad $a(z)$ and one change in its sign were only really observed.

As has shown in the analysis of the experimental data, the increase in the experimental $a(z)$ values, with respect to their model values at heights z > 80 km, frequently took place in cases when the differential absorption of ordinary and extraordinary components at these heights is insignificant. It is possible in the case when the electron density in this height range is small ($N \leq 10^2$ см$^{-3}$). Such an event in the middle latitude ionospheric D-region is observed rather frequently: the so-called valley in the $N(z)$-profile at the mesopause heights. The similar changes in the experimental $a(z)$-dependences are also observed at the lower heights ($z \leq$ 70 km) when over the height range of z= 60-70 km there exist increased ionization layers with the electron density of $N \sim 10^3$см$^{-3}$. Such layers of increased ionization are caused, for example, by flows of charged particles (electrons, protons) during perturbations of various natures, both natural and artificial characters (see, for example, [17-21]).

As an illustration of it, shown in Fig. 4 arethe experimental profiles of $< A_{o,x}(z) >$ and $a(z)$, obtained over a period of charged particle precipitation during a strong thunderstorm of 03.06.1987 (f = 2.31 MHz).

Note, that at the low heights (near the maximum of $a(z)$) there also takes place a change (decrease) in grad $a(z)$.

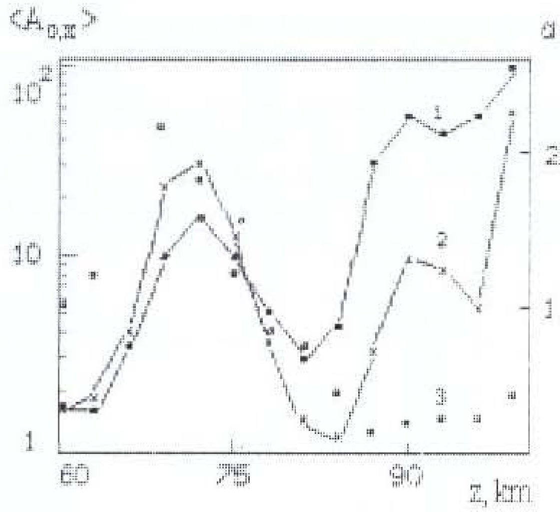

Fig. 4. Height profiles of $<A_{o,x}>$ (curve 1,2) and $a(z)$ (curve 3) obtained in the experiment during a strong thunderstorm of 03.06.1987

In order to analyze the possible causes of such a difference of the experimental $a(z)$ profiles from the theoretical ones we use expression (1) connecting $a(z)$ with the parameters of the ionospheric plasma, the equipment and the measurement errors. Main possible causes of the "anomalous" behaviour of $a(z)$ may be:

1) incomplete separation of "o" and "x" magneto-ionic components by the receiving equipment;
2) transformation of magneto-ionic components in the magnetoactive ionosphere;
3) divergence of impulse volumes of the magneto-ionic components in space, and influence of their differential absorption in the scattering volume (the multipliers P_1 and P_2 in formula (1));
4) nonmonotonic change in the $N(z)$ and $\nu(z)$ - height-altitude profiles (influence of the exponential multiplier in formula (1));
5) radio noise and other factors (for example, inclined reflections).

Let us analyze the effects of each of the factors mentioned above.

3. Calculation results. Discussion

The incomplete separation of "o" and "x" magneto-ionic components in the receiving system results to noticeable decreasing in grad $a(z)$ at $z \geq 80$ km and $z \leq 70$ km [22].

In order to decrease the influence of this effect, we tested the receiving equipment, and the technique of accounting incomplete separation of components (in the joint measurements by a PR technique and impedance probe on rockets, carried out near the Volgograd city) was developed [23].

The analysis of the partial reflection signal records with allowance for the real construction of the receiving equipment of [15,16] has shown that the effect of incomplete separation of "o" and "x" magneto-ionic components in the receiving system does not provide any observable change in $a(z)$.

The transformation effect of the magneto-ionic components in the magnetoactive ionosphere for f = 2-3 MHz at the heights of z = 80-90 km is rather insignificant [24], making units of percents.

Therefore its influence on $a(z)$ is insignificant; it is difficalt to evaluate and exclude one.

In our experiments the half-power width of the main lobe of the receiving antenna pattern is no more than $\theta \approx 30^{\circ}$, therefore sloping reflections caused by the spherical divergence of a sounding wave can ones not explain observable difference of the experimental $a(z)$ dependences from the theoretical ones [14].

The change in $\operatorname{grad} a(z)$ is possible under the influence of the factors described by the multipliers P_1 and P_2 in formula (1). According to the calculations in [11] for $f < 2$ MHz and $\tau_i = 25$, 50 mcs, $P_1 \approx$ 1-100 for $z >$ 70 km ($P_2 \approx$ 1-2 for $f =$ 2-6 MHz). Note that the main contribution to $a(z)$ in formula (1) is introduced by an exponential multiplier, where $K(z) = K(N, \nu)$. Our calculations have shown that this multiplier is differently changed for monotonic and nonmonotonic $N(z)$ and $\nu(z)$ -profiles. For example, for $N(z)$-profile with a valley $\operatorname{grad} a(z)$ noticeably decreases at the heights the valley if compared with the monotonic one (the calculation results will be given later).

The model calculations [25] have shown that the incomplete subtraction of radio noise $A_{no,x}(t)$ essentially distorts the $a(z)$-profile, which results in large errors (~ 10-100 %) in $N(z)$ (especially noticeably the $\operatorname{grad} a(z)$ changed at the small ($z < 70$ km) and the large ($z >$ 80 km) altitudes).

Thus the factors mentioned above can result in changes in the $\operatorname{grad} a(z)$. They practically always (besides the nonmonotonic height change in the $N(z)$ and $\nu(z)$-profiles) take place simultaneously. The calculation results are given further.

Using formula (1) the model $a(z)$ calculations are made for $f =$ 2.5 MHz and τ_i = 25 mcs. Curve 1 in the above mentioned Fig. 5 is obtained for the model profiles of $N(z)$ and $\nu(z)$ (curves 3 and 4, respectively) disregarding of listed factors, and curve 2 - for the nonmonotone $N(z)$ (curve 5) and $\nu(z)$-profiles (curve 4) with their account. We used the formula $< A_{no,x} > = 0.5 < A_{o,x} >_{\min}$ ($< A_{o,x} >_{\min}$ is the minimum value of $< A_{o,x} >$ during the measurement time); the transformation of magneto-ionic components in the magnetoactive ionosphere was set under the linear law from 0,5 % up to 7 % with $z =$ 80 km up to $z =$ 90 km; incomplete separation of the "o" and "x" components by the receiving equipment was 15%.

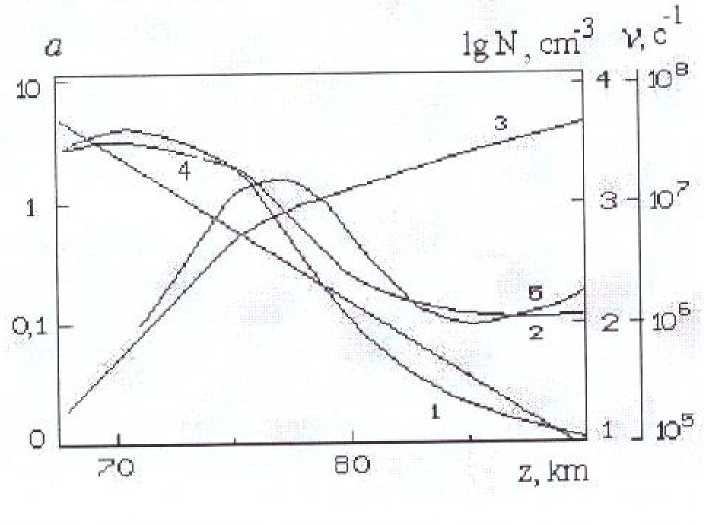

Fig. 5. Model dependences of $a(z)$ height-altitude profiles.

The calculation results show that the simultaneous influence of the above-mentioned factors results in a noticeable distortion of the experimentally obtained height-altitude profiles of $a(z)$. In order to decrease such effect in each experiment, it is necessary to control initial data of ($A_{o,x}(z,t)$, $A_{no,x}(t)$) and introduce appropriate corrections.

4. Conclusion

Thus, the "anomalous" changes in the $a(z)$-profile in the height ranges of $z \geq$ 80 km and $z \leq$ 70 km, frequently observed in the experiments, are possibly the result of simultaneous influence of the following factors: incomplete subtraction of radio noise; incomplete separation of the "o" and "x" components by the receiving equipment and their transformation in the magnetoactive ionosphere; due to the divergence of the pulse volumes of the magneto-ionic components in space and the influence of their differential absorption in a scattering volume; the nonmonotonic height change in the $N(z)$ and $\nu(z)$-profiles (availability of sharp layers and valleys which frequently take place, especially during the disturbances of various natures).

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