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IONOSPHERIC INFORMATICS - PART 1

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IONOSPHERIC INFORMATICS. 1. PROCEDURE FOR CALCULATING ELECTRON DENSITY PROFILES FROM VERTICAL-INCIDENCE SOUNDING IONOGRAMS

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"Method is more important than result
because a lot of results
can be obtained
with Method".

Academician L. D. Landau.

ABSTRACT

Simulation of the virtual heights of radio signal reflected from the different ionospheric regions allows to separate contributions of the different regions E, EF, and F into the trace observed at ionogram. Effects of the valley width and depth on the F region heights are demonstrated. Formulae relating the real height to the corresponding minimum virtual height at the E region via the peak parameters of the E layer allow to compensate for the EF valley and reduce the errors of electron density profile above the valley using only one magnetoionic component in an ionogram. Test examples of calculating the electron density profiles with the procedure proposed are given.

INTRODUCTION

Among the other available techniques for the scientific studies, the vertical-incidence sounding of the ionosphere have proved to be the best developed and widely used. There is a world-wide network of the ionosphere monitoring stations of the VI sounding providing annual flux of information about 10^{12} bit per year. This global network of ionosondes provides the real-time data for HF radio propagation predictions as well as accumulates ionograms and tables of conventional ionospheric characteristics which are widely available for the scientific research. However they suffer from the image disturbance at a mirror of ionogram so notwithstanding more than 40 years of efforts of many experts of the different countries, all available methods of solving the inversion problem of VI sounding data can not overcome all the problems involved /1,2/. Yet implementating numerical procedures for the ionogram analysis allows us to proceed from qualitative interpretation to quantitative building up of N-h profile.

This paper presents a system approach to development and implementation of methods of the ionospheric informatics. It is based on using the empirical ionospheric models which have been originated during 70th years and proved to develop successfully in a computer-accessible form. Involving a great deal of the ionospheric measurements and the VI sounding data as well, the modern models appeared to be an appropriate base for simulating the direct results of this experiment. Such feasibility allows us to carry out the cycle of studies from the model - to analysis of experimental data, then progress from the latter - to a renewed orbit of development of a model system based on synthesis of the data analysed. So the autonomous techiques of data analysis which were independent of the real model and suffered of appreciable errors and even ambiguity of results proved to be adapted to the model representations nowadays. In their turn, the mean background ionospheric models gained opportunity of updating or correction using operational data of regular observations /3,4/ compounding together a base of an Expert system on ionospheric informatics /5/.

CONTRIBUTION OF THE IONOSPHERIC REGIONS INTO THE VI SOUNDING SIGNAL RETARDATION

While algorithm for solving the inverse problems of radio physical experiments can not be developed straightforward owing to incomplete information, the integral character of the phenomena observed, signal/noice separation problems and so forth, the direct problem of simulating such the data is quite feasible to overcome with modern computers using current model representations. That is why in the ionospheric informatics a lot of attention has been given to development of systems of ray tracing in the ionosphere including the fine effects of spontaneous disturbances /6-9/. Many techniques of solving to the inverse problem of VI sounding employ directly or imply the simulation approach at the stage of preliminary interpretation of signal reflected by the ionosphere /10/.

Development of such simulation system not only makes us nearer to understanding and interpretation of results of observation but also provide a base for self-learning of an expert system on the ionospheric informatics. There is a special appeal to have such ability when the real time systems are being developed /11,12/. It would not be effective to build up such systems using the algorithms for data analysis as an iteration to the solution. On the contrary, a quick search for a solution /13/ allows to control a mode of operation of digital station by more frequent observations during the times of rapid changes in the ionosphere.

That is why numerical simulation presents a special importance for development of techniques of inversion of radio signal by studying the general regularities of reflection of the signal passing through the different ionospheric regions. To this end we consider a contribution of the underlying and interlayer regions of the ionosphere into the virtual heights of the VI sounding signal. Let us express the virtual height h'_k at any sounding frequency f_k above the interlayer EF valley as the sum of three integrals:

$$h'_k(f_k) = I_E(f_k) + I_v(f_k, f_v, w) + I_F(f_k) \qquad (1)$$

where

$$I_E(f_k) = \int_0^{h_m E} \mu'(f_k, f_N)\, dh$$

$$I_v(f_k, f_v, w) = \int_{h_m E}^{h_T} \mu'(f_k, f_N)\, dh$$

$$I_F(f_k) = \int_{h_T}^{h_k} \mu'(f_k, f_N)\, dh$$

$$(f_T \leq f_k \leq f_m F)$$

Here μ' is the group refractive index depending on the sounding frequency f_k, electron plasma frequency f_N and the geomagnetic field parameters (gyrofrequency and dip angle); $h_m E$ is minimum real height at the E layer plasma frequency $f_m E$ where the last signal reflection is observed in this layer near the critical frequency foE; $f_m F$ is the last frequency of reflection observed near the F region critical frequency, foF; h_T is the real height at the frequency f_T where the first signal reflected is observed in the F (F1) layer above the valley; $w = h_T - h_m E$ is the valley width; f_v is the minimum plasma frequency in the valley (the corresponding valley depth $\Delta f_v = foE - f_v$). Other legends are in common use.

Though the nominations are given for the E-F region everything below is equally valid for any other layers in the ionogram, with integral I_E including all retardation from the lower ionospheric boundary to the critical frequency of the layer under consideration. The integral I_v in the interlayer region can be expressed using the mean value theorem similar to that in /14, 15/:

$$I_v(f_k, f_v, w) = \bar{\mu}'(f_k, f_v^*)\, w \qquad (2)$$

where $\bar{\mu}'$ is some mean value of the group refractive index for either magnetoionic component $\mu'_{o,x}(f_k, f_N)$ /16/ at an intermediate plasma frequency in the valley:

$f_v < f_v^* < f_T$. Since by definition the group refractive index $\mu' > 1$ for every value of the frequencies f_v and f_T, from the expression (2) we obtain:

$$I_v > w \qquad (3)$$

This implies that at the vertical sounding the ionosphere at all frequencies of the F region, the integral of retardation in the valley, I_v, exceeds the valley width w. So, the interlayer region affects all the range of sounding frequencies $f_T \leq f_k \leq f_m F$ up to the main peak of the ionization rather than at a descending part of the h'f curve at the beginning of the reflecting F layer (or F1, F2) as it has been claimed earlier /15/.

Figure 1 illustrates that retardation in the lower ionosphere when the F layer is being sounded, I_E decreases with growing the sounding frequency from foE to foF, asymptotically approaching the value of hmaxE. The contribution of interlayer region, Iv is evident to be most just above the valley at the frequencies nearby foE = 4 MHz, then with growing the sounding frequency it decreases, asymptotically approaching w. Note the example shown here presents a monotonic electron density profile with no decrease of the electron concentration above the E layer peak just having inflection in the shape of N-h when transition from the E layer to the F layer occurs. So in this case the valley width is small, about w = 6 km /17/.

The shape of the virtual height curve in the F layer is basically determined by the shape of a mode of retardation I_F above the valley. Thus, location of the point of h'min(f_L) of zero slope of the trace in an ionogram dh'/df = 0 coincide with location of similar point at the frequency f_L at the curve of $I_F(f)$. This feature will be used below for determining the formulae of fitting the electron density profile from information available in the ionogram.

Not only width but also the valley depth affects all the following virtual heights in the F region above the valley. This is illustrated by Figure 2 at the test examples /17/ with deep and shallow valleys. Series of solutions to the inverse problem have been obtained in every case by successive deletion in the input data at the E layer profile those values nearby the critical frequency foE which contain one-side information on an assumed non-monotonic region so being contradictory with the data h'F reflected by the F layer, which involve retardation in the whole ionosphere below F included the interlayer EF region. Calculations have been carried out from the data of an ordinary component then the N-h solution yielded the X ray virtual numerical heights compared with those observed. The best coincidence (up to 1 km) has been achieved (circles in Figure 2) with the parent profile (solid line) for an effective minimum plasma frequency in the valley f_v corresponding to real valley depth of the parent model /17/. However this exact profile cannot be obtained sometimes using two component O and X data as it is seen in the diagram of descrepancies build in Figure 2.

To be stressed in particular that further increasing the valley depth assumed yields increasing real heights of the F layer (curves 2). This fact can be interpreted based on physical considerations: the deeper valley is assumed, the wider should be the interlayer region is order to contribute the same share into the signal retardation as a former narrow interlayer valley obtained with a shallow valley assumed. As a whole, Figure 2 illustrates a range of possible solutions to the inverse problem of N-h analysis of ionograms which requires a physical constraints to find out the non-ambiguent profile which could provide an evaluation of the underlying and interlying ionisation as accurate as possible.

FORMULAE FOR THE CORRECTION OF ELECTRON DENSITY PROFILE FROM IONOGRAM

When a shape of an arbitrary N-h profile is analysed one could see that along the peaks of the ionospheric layers and the interlayer minima of electron concentration in the valleys between the regular ionospheric layers, the shape of a profile is also determined by location of maximum of the vertical ionisation gradient indicating the inflexion point within a layer. To fit the N-h profile to some calibration real height at the base of the F layer above the valley, a possibility should have been searched to detect a height in the real or modelled ionosphere through information available in ionogram. To this end the study has been carried out for such key point in the F layer which could serve as an orientation for fitting or calibrating the N-h profile /19/. This study has been carried out by comparing of numerical ionograms produced from available model distribution of N-h with parameters of these parent models.

Global model of electron concentration /20/ has been used as the initial data for constructing the numerical h'f curves at the latitudes of 0°, 20, 40, 60 and 80°, with the longitude step of 15° corresponding to hourly values in the diurnal variation of N-h, making the base of 120 profiles. The virtual heights h'f have been calculated with given accuracy of 1 km using the procedure /21/.

The virtual height at a fixed frequency is known to be equal to the real height at the plasma frequency of reflection f_N plus the magnetoionic delay in the ionosphere below this point /22/:

$$h'_{o,x}(f_N) = h(f_N) + \int_0^h (\mu'_{o,x} - 1)\, dh \qquad (4)$$

where the relationship of plasma frequency to radio frequency is $f_N^2 = f_o^2$ for the O ray and $f_N^2 = f_x(f_x - f_H)$. So it is natural to search for a relationship between the real height and the virtual height at some frequency f_L that could provide an evaluation of the integral on the right side of the expression (4).

In this respect the h'minF point with zero derivative dh'/df =0 holds a prominent, exceptional place in each ionospheric layer. It was noticed /23/ that the lower nonmonotonic parts of the ionization ceased affecting the virtual heights from this point, while the delay due to gradients dN/dh near the peak of the present layer is still negligible. As a rule, the real height $h_L(f_L)$ associated with h'minF is located below the inflexion point of the N-h profile and does not belong to the parabola fitting the peak of the layer /24/. It is this point that has been suggested for use in correcting the starting height of an N-h profile that uses only one value of h'_x in addition to the O ray data /25/. All these considerations lead to the conclusion of the necessity of comparing the values of h_L and h'min at the frequency f_L.

As a result of such a comparison the regression relations of the correction fac[tors] for the O and X ray data have been found /19/ as shown in Figure 3:

$$CoF = 0.172 + 0.110\, foE$$
$$CxF = 0.256 + 0.089\, foE \qquad (5)$$

Using these coefficients, the real height at the key point of the F region profile above the valley is expressed via the minimum virtual height and the E layer peak parameters:

$$h_L = h'minF - C_{o,x}F\,(h'minF - h_mE) \qquad (6)$$

Standard deviations of the real heights h_L defined by the formulae (5-6) does not exceed 15 km. Maximum spread around the regression lines (5) is observed at a geomagnetic DIP = 60°. This is due to features of the parent model of electron density prof[ile] at high latitudes /20/. In particular, the h'min F point is affected by two peaks of ionization when the critical frequencies of the E and F layers fall close together at the latitude of 60° (1.4 MHz ≤ foE ≤ 2.15 MHz, 2.45 MHz ≤ foF ≤ 3.95 MHz). It appea[rs] that formula (5) could be refined depending on the geomagnetic field parameters - gyr[o] frequency f_h and the geomagnetic DIP angle, using more extended base of the initial N-h profiles.

With the above limitations the correction formulae for the electron density prof[ile] relating the real and virtual height at a base of the F region proved to be a first real step of using information reticent in the ionograms for the inversion of the VI sounding data. Since then the regular variations in the ionosphere depicted in changi[ng] the virtual heights of the F layer in an ionogram, the relevant variations of the real heights of the electron density profile have been pronounced currently after the ionogram inversion.

SINGLE-COMPONENT ANALYSIS OF IONOGRAM WITH CORRECTING FOR UNOBSERVED IONIZATION.

The basic idea of the suggested method of correction of N-h profile when only one component is available in the ionogram is illustrated in Figure 4. Here we have an example of obtaining the N-h profile with a simple deep valley, for which the precise numerical ionogram has been calculated /19/. The upper lines are the virtual height curves h'o and h'x in the F layer, plotted against the plasma frequency at reflection. For foE = 4 MHz, we obtain from (5-6) the real height for the correction h_L from the O ray: h_{oL} = 166 km at frequency f_L = 4.3 MHz and, independently, from the X ray: h_{xL} = 176 km at frequency f_L = 4.4 MHz.

Discrepancies between the calculated and correct real height at the frequency f_L for the test examples /17/ do not exceed 12 km. They testify that equations (5) are not specific to the collection of parent model profiles /20/. Though the values of foE for this model do not exceed 3.6 MHz (see Figure 3), the accuracy of the real height h_L obtained for the critical frequency foE = 4 MHz in the tests /17/ is quite acceptable.

Having the N-h profile in the E layer and using one-parameter model of valley ionization, a simple iterative algorithm is constructed for fitting the N-h profile in the F layer to one given point of the real height $h_L(f_L)$. This adjustment is performed automatically in several steps by a computer program /26/. As a result we obtain solution such as that shown in Figure 4 by circles in a case when only O ray echoes are used or by crosses in a case of the X ray data. The dashed lines show the effective distribution of the valley ionisation adopted in the present method of N-h analysis.

The same scheme can also be used for the correction of nighttime electron density profile in the F layer. Actually all the points in Figure 3 at foE ≤ 1 MHz and the corresponding part of the approximating lines of $C_{o,x}F$ refer to nighttime conditions. If there is h'min F point with a zero gradient dh'/df = 0 in the nighttime F layer, the correction factor is found easily from (5). In this case, the E layer peak parameters unobserved in the ionogram can be given, say, from morphological models of nighttime ionization in the E layer /3/. In an absence of such data, one can use a mean values at nighttime: CoF = 0.246, CxF = 0.316, and hmE = 110 km in (6).

Standard deviation of these coefficients is the same as in a case of the formulae (5-6). The greater errors appear when the ionogram in the F layer includes only an increasing branch of h'f - as a rule, in such cases the N-h profile yields over-estimated real heights, i.e. an uplifted base of the F region and increased EF valley width.

CONCLUSION.

A correction method has been suggested for calculation of an N-h profile with allowance for unseen ionisation when only one mode of reflection is available in the ionogram. The correction is based on the deduced regularity of the relationship between the real and virtual heights at the key point in the F layer where the slope dh'/df equals zero in the ionogram. This permits an estimate of the real height h_L for calibration of N-h profile in the F region above the valley using the value of h'min F and the peak parameters of the E layer. Such calibration can be successfully applied with every existing procedure for N-h analysis of ionograms.

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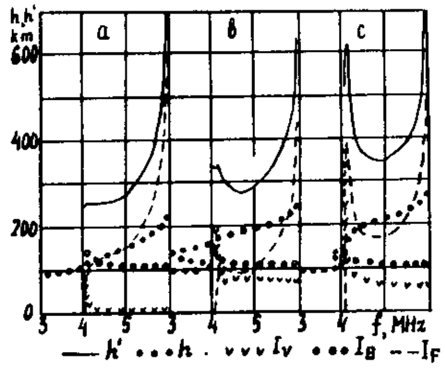

Fig. 1. Decomposition of virtual height into three components of retardation.

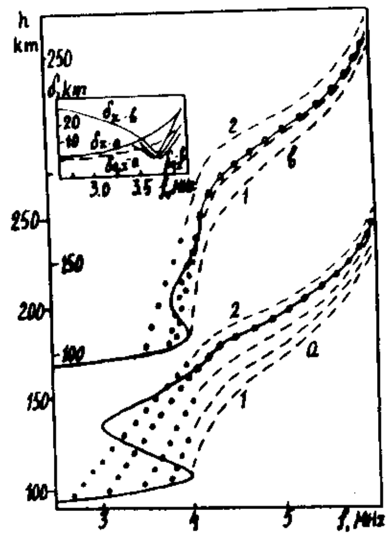

Fig. 2. Effect of the valley depth assumptions on the F region heights. 1 - monotonic profile without valley.

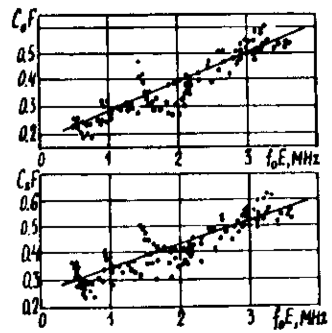

Fig. 3. Linear approximation of the correction factor of Nh profile for the O ray (top section) and X ray (bottom section) versus the E layer critical frequency.

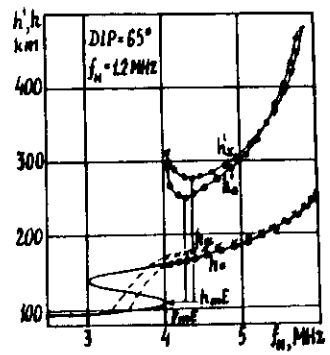

Fig. 4. Example of Nh profile calculation with the valley ionization taken into account. Parent model - solid line, o o O-ray results, x x X-ray results.