AN INTERPRETATION OF DATA OBLIQUE-INCIDENCE SOUNDING USING THE CHIRP-SIGNAL

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1. Introduction

Diagnosing the ionospheric radio channel conditions is presently one of the "hottest" areas in current fundamental research into the ionosphere and radio wave propagation as well as in a wide range of practical purposes of securing reliable radio communications. Asuccessful resolution of this issue would be unfeasible without the organization of automatic processing and interpretation tools for diagnostic information about the ionospheric radio channel conditions. This generally necessitates implementation of a data treatment either on a mass scale or on a real-time basis. This report proposes a variant of the technique for automatic processing and interpretation of oblique-incidence ionospheric sounding ionograms obtained by using an ionosonde with a continuous chirp-signal.

2. The technique of ionogram processing

The basic challenge when tackling the problem of ionogram analysis is identifying traces on the ionogram that satisfy certain criteria, followed by a determination of points corresponding to arrival times of the signal (points with a significant amplitude). It is known that an important characteristic of ionograms is the presence of noise associated with the character of the process of image formation. In terms of the problem at hand, noise is an interfering factor that plagues the interpretation of the image. Therefore, it is necessary to have algorithms for smoothing out such noise in terms of corresponding statistical models of noise. Usually, in the theory of image processing a standard Rayleigh model of distribution is used. The use of more sophisticated models, such as the Rice model, is made difficult because of problems encountered when devising computational algorithms. Results of processing of images obtained through radar soundings of the terrestrial surface, showed a possibility of using a model for multiplicative noise, and it was invoked when developing a technique for processing of oblique-incidence sounding (OS) ionograms.

The chief approach to smoothing-out of noise is filtering with the aim to suppress noise, with the image structure being conserved. One can differentiate two alternative approaches to smoothing: one involves using global methods (Kalman, Wiener and other filters), and the other includes local methods enabling an estimate to be made by analyzing and processing restricted and reasonably small-sized fragments. The advantages of the local methods of smoothing are their higher computational effectiveness and the possibility of processing the image in real time. Checking the local filters against existing experimental oblique-incidence sounding ionograms obtained by an operational chirp-sonde [1] demonstrated efficiency in the use of the local filters for OS ionogram processing.

Results obtained along this line made it possible to set up the following processing scheme. The initial stage involves constructing a 'brightness' (amplitude) histogram of the entire image with the object to reduce information by dividing the image into two classes of points according to a threshold level (a class of background points, and a class of the object's points) and to subsequently filter out the background points. A nonparametric approach by discriminant criterion is used when selecting the threshold level. According to this approach, the best global threshold is provided by a threshold that maximizes the function of the ratio of the inter-class to total dispersion of the brightness levels.

At the second stage, an averaging filter plus filters based on order statistics (a sigma-filter, and a median filter) are used to remove noise from the image and to reconstruct the signal counts. The size of a fragment when processing the image is usually chosen from the requirement for ensuring a sufficient amount of sampled data and a minimum of computational expenditures as well as the nature of the problem being solved. For the sounding system used [1], the most suitable size of fragments for the filters employed when processing OS ionograms lie in the range 300-400 kHz in frequency and 20-50 km in group path, depending on ionogram resolution. Using fragments large in size leads to image

distortion as well as to an increase in computational expenditures. Experience gained by processing oblique-incidence sounding ionograms demonstrated inadequate proficiency in the use of any one of the types of filter. Thus, the sigma-filter makes it possible to achieve a higher quality discrimination of the lower modes, with a loss of data on the upper modes, whereas the averaging filter while leading to losses of lower modes on low frequencies adequately discriminates the upper modes. Therefore, an algorithm was developed, which take sadvantage of the combination of these filters with a sliding window. Filtering results in the identification on the ionogram of quasi-uniform regions corresponding to the signal modes.

At the third stage, in the identified regions we determine times (points) of arrival of the signal which are represented by chosen local maximum for each of the identified regions. As a result, one obtains the image in the form of clouds of points with a significant amplitude in coordinates: group path -operating frequency, i.e. there is a matrix of experimental points P_{ij} corresponding to a two-dimensional set of values of the group path P_i on the grid of frequencies f_j.

3. The technique for ionogram interpretation

The technique for interpreting ionograms of oblique-incidence ionospheric sounding by chirp-signals is based upon using results derived by modelling OS ionograms on a given path under conditions of a longterm prediction and adiabatic relations between frequency and group-path characteristics of signals of different propagation modes. Model OS ionograms of chirp-signals are calculated from an operative algorithm for modelling characteristics of chirp-signals in terms of a normal mode approach[2]

By analyzing the frequency dependences of group characteristics of OS signals under different helio-geophysical conditions, it was possible to reveal the following relationships which slowly vary with a change of ionospheric parameters [3]:

- the ratio of the group path P_m, corresponding to the delay of the signal received at maximum usable frequency (MUF), to the range to the illuminated zone boundary D_m;
- the ratio of MUF modes of different radio paths.

The above ratios are confirmed by results of model calculations of oblique-incidence sounding signal characteristics in the case of a 20%-change of ionospheric parameters. In addition, this is also confirmed by the analysis of experimental OS data obtained from a chirp-sonde [1].

In doing model calculations of OS ionograms and analyzing experimental ionograms, it was also noted that the group path of the OS signal depends weakly on a change of ionospheric parameters on the relative frequency grid $\beta = f/f_m$, f_m -being a maximum usable frequency of the mode for a chosen range [4]. Especially strongly is this property manifested for signals that propagate along lower rays.

For the problem of interpreting oblique-incidence ionograms, it is possible to formulate the following basic assumptions. In the case of ionospheric parameter variations in the limits of the error of longterm predictions, there remain:

- the ratio of the group path P_m at the junction point of the lower and upper rays of any one of the modes to the path length;
- the ratio of the MUF modes (χ) of different multiplicities that propagate in one of the waveguide channels (their lower wall is represented by the terrestrial surface, and the upper layer is E, $F1$ or $F2$);
- group path of one mode, of multiplicity l, on the relative frequency grid $\beta = f/f_{m,l}$, where $f_{m,l}$ is the MUF mode for the range under consideration.

An algorithm for interpreting oblique-incidence ionograms under automatic conditions is constructed in the following manner. Model OS ionograms are calculated for a given path under longterm prediction conditions. Results of calculations are used to choose the reference propagation mode l_o on the path being analyzed for a given run. Usually, it is represented by the mode with a minimum number of reflections (l_{min}) from the $F2$-layer, whose maximum frequency does not exceed a limiting sounding frequency. A distinctive feature of this mode is a reasonably good coincidence of the dependence of the group path on the frequency of the modelled and experimental ionograms in the vicinity of MUF of this mode (on the relative frequency grid) for both the lower and upper rays. Based on this, a model mask is then constructed for the mode of multiplicity l_o, including two bands of a width of ΔP km (vertically) and of an extent in frequency from $0.7 f_{mp}$ to f_{mp}, where f_{mp} is the predicted MUF of the reference mode, for the lower ray and of an extent from $0.8 f_{mp}$ to f_{mp} - for the upper ray. The bandwidth ΔP can be varied within 50 km. The algorithm for identifying the reference trace on the

ionogram implies counting the number of points of arrival times of the matrix P_{ij} signals as the model mask moves on the ionogram. Methods of displacing the mask on the ionogram and counting the number of points of arrival times depend substantially on whether there is absolute referencing of the group path scale in experiment. In the presence of absolute referencing in group path one may take advantage of one of adiabatic invariants: the ratio of the group path P_m, corresponding to the MUF mode, to the range. Hence one selects on the ionograms a rectangle, in which the model mask will be displaced, centered on a point, corresponding to the frequency f_{mp}, and the predicted value of the group path on this frequency P_{mp}. The size of the rectangle is $[f_{mp}-\gamma f_{mp}, f_{mp}+\gamma f_{mp}]$ horizontally and $[P_{mp} -\alpha \Delta P, P_{mp} +\alpha \Delta P]$ vertically, where α and γ are some numerical parameters. P_{ks} points of the entire set of points P_{ij} fall winside a given rectangle. By displacing the mask through a parallel transfer until the junction points of the lower and upper rays match with P_{ks} points, the number of P_{ij} matrix elements inside the mask is calculated. In this case the mask starts its displacement from the right-hand side of the rectangle, and at every step the mask bands are scaled by the factor f_s/f_{mp} along the horizontal axis. A maximum on the histogram of the distribution of the number of experimental points depending on the position of the mask makes it possible to determine the real values of MUF, f_{mr}, and of the group path at this frequency, P_{mr}, for the propagation mode of multipicity l_o. If a maximum number of points corresponding to the mask is less than a certain number (four, for example), it is presumed that the mode of multiplicity l_o is not identified, and the procedure is repeated for the mode of multiplicity l_o+1. It is also to use the mode of multiplicity l_o+1 when the reference mode leaves the right-hand edge of the ionogram. Therefore, preliminary before identifying the reference mode, it is necessary to 'scan' the right-hand edge of the ionogram by a rectangular mask, with the size of 1000 kHz horizontally and ΔP vertically. When determining f_{mr} and P_{mr}, the remaining experimental points, corresponding to the mode of multiplicity l_o, are identified by extending the mask bands into the region of low frequencies along a model OS ionogram, scaled by the factor f_{mr}/f_{mp}, and by looking for P_{ij} elements corresponding to these bands.

The adiabatic character of the ratio of MUF of modes of different multiplicity $\chi_k=f_{m,k}/f_{m,s}$, $k=s\pm1$ is used to calculate the tentative values of MUF of other modes of multiplicity l: $f_{m,l}=f_{mr}\,\chi_l$, $l=l_o\pm1$. Values of the group path $P_{m,l}$ can be taken to be equal to predicted values. The values determined in this way serve as the center of the rectangle, inside which to look for the real values of $f_{mr,l}$ and $P_{mr,l}$ following the above procedure of constructing a histogram of the number of points, corresponding to the mask as it is displaced. Subsequently, a sequence of experimental points is formed, which correspond to the neighborhoods of the scaled model ionogram of the modes of multiplicity l. Modes of multiplicity l_o+2 etc. are identified in a similar manner.

If there is no absolute referencing of the group path scale, one has to look for the junction point of the upper and lower rays by scanning a model mask throughout the entire ionogram. In this case two variants of displacement of the model mask exist: one is when the mask moves from the right-hand lower corner upward along a group path at steps ΔP and to the left in frequency at steps Δf (of about 500 kHz); the other variant is when the mask moves through the points of the matrix P_{ij} by making the 'nose' match with the point $P_i(f_j)$. In the former method of displacing the mask, for each current frequency f_k we construct a histogram of distribution of points P_{ij} which fall within the mask during its parallel transfer along the vertical axis at steps ΔP. A maximum value of the number of experimental points n_k, and also the corresponding (to this position of the mask) value of the group path for the junction point of the upper and lower rays $P(f_k)$ are memorized. After passage of the entire operating frequency range, we construct a histogram of distribution of n_k-values in frequencies f_k. An absolute maximum of this distribution makes it possible to determine the center of the rectangle, i.e. the frequency f_m and the group path P_m, inside which more accurate values of f_{mr} and P_{mr} are looked for in the same manner as done in the presence of referencing to the common timing system. If the number of experimental points in the distribution maximum is larger than four, then the mask for the mode of multiplicity l_o+1 is used, and the whole procedure is repeated.

The second method of displacing the mask of the reference mode is used to count from the points P_{ij} the number of points corresponding to the mask and a maximum of the histogram of the distribution in points corresponds to values of f_{mr} and P_{mr}. By determining f_{mr} and P_{mr} for the reference mode taking into account the adiabatic group path on the relative frequency grid, it becomes possible to accomplish referencing of the group path scale of the ionogram by shifting the origin by an amount equal to the difference between the predicted value of P_{mp} and P_{mr}. Subsequently, the sequences of

experimental points corresponding to the neighborhood of the scaled model ionograms of other modes are identified and formed in much the same way as done in the case described previously when signal delays are recorded.

In some cases the algorithm for automatic identification of oblique-incidence sounding ionograms does not make it possible to identify reliably the points of arrival times of signals on the experimental sounding ionogram. This is associated with the presence of severe geophysical conditions on the sounding path (disturbances, interferences, ionosphere stratification) and with errors inherent in longterm predictions. In such a case it is possible to employ the semi-automatic ionogram identification approach. Identified points of arrival times of signals are also the input ones. Ionogram traces are interpreted based on a longterm prediction and experience in interpreting oblique-incidence sounding ionograms.

4. Results of ionogram interpretation

Our developed algorithms for processing and interpreting ionospheric OS ionograms were tested against experimental ionograms obtained on the Magadan-Irkutsk path 3000 km long. Fig. 1(a-b) illustrates the operation of the algorithms for the case of a one-layer winter ionosphere. Fig. 1a presents the results of a pretreatment of signals with identification of experimental points on the ionogram with significant amplitudes (dark squares). The figure also gives the results of numerical simulation OS ionogram for the same path under longterm prediction conditions. For the ionogram concerned, the result of matching in the automatic operation is shown in Fig. 1b. The mode with minimum multiplicity is identified as *1F*. Besides, the modes *2F* and *3F* are identified on the ionogram.

By testing our developed identification algorithm, we have demonstrated its suitability for winter

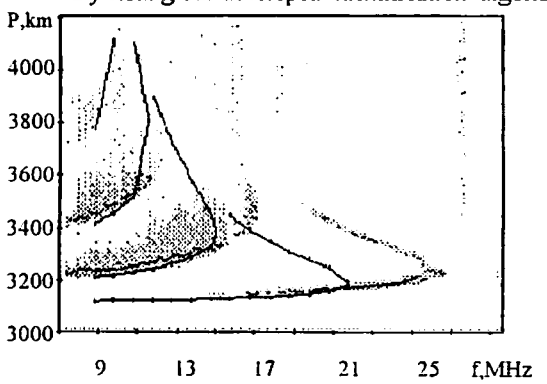

Fig. 1a. Experimental OS ionogram, and longterm prediction results for February, 15, 1989.

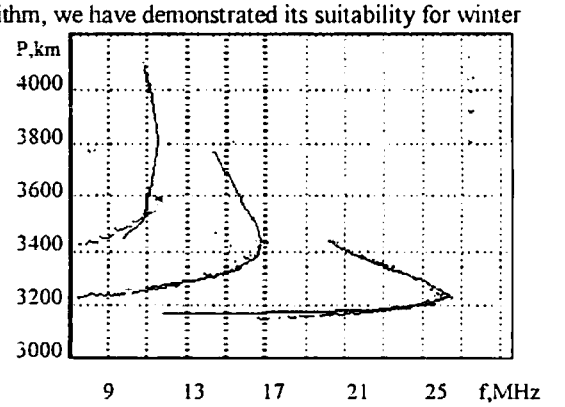

Fig. 1b. Processing and identification results on the OS ionogram for February, 15, 1989.

and night-time summer conditions. In this case the speed and accuracy of ionogram interpretation depend seriously on the presence of referencing of the diagnostic system to the common timing system. Summer daytime ionograms present the greatest problems when accomplishing automatic ionogram interpretations when the propagation of signals takes place under ionosphere stratification conditions.

5. Conclusions

Our developed program package, useful for accomplishing the ionogram pretreatment, detection of traces and identification of modes, can be used as a component part of the system for automatic selection of radio frequencies for a communication radio link based on results of ionospheric channel sounding by the chirp-signal.

6. References

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