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INVESTIGATING SMALL SCALE IRREGULARITIES IN THE HIGH LATITUDE IONOSPHERE FROM AMPLITUDE DATA OF SATELLITE RADIO PROBING

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Abstract. The use of satellite amplitude data in studies of small scale irregularities in the high latitude ionosphere is considered. A new method is described for determining the parameters of 3-dimensionally-anisotropic irregularities from single-point measurements. The method works if the spectrum of irregularities obeys the power law and the irregularities are evenly distributed within the ionospheric layer. If spatial distribution of electron density fluctuations is not even, a tomographic approach can be applied for reconstruction of the irregularities from multipoint amplitude data. As the first step, multipoint experimental amplitude curves were simulated using a simplified model of irregular density distribution. A good agreement between experimental and fitted curves is obtained, which proves the applicability of tomographic approach to the analysis of satellite amplitude data.

Satellite radio probing is an effective method for investigating the irregular structure of the ionospheric electron density. The method makes use of satellite radio signals scattered by ionospheric irregularities. Ground based measurements of these signals give information on the parameters of scattering irregularities. The interaction of the radio wave with large scale inhomogeneities (of sizes exceeding the Fresnel radius) mostly results in phase fluctuations of the radio signal. Small scale irregularities of order of the Fresnel radius (in the experiments carried out in PGI - about 700 m) mainly contribute to the amplitude scintillation of a satellite radio wave.

Ionospheric volumes of different shapes and sizes can be filled by small scale irregularities. These irregularities produce a chaotic scattered field since it depends on a large set of aggregated small scale scatters. Therefore it is impossible to find out the parameters of each separate inhomogeneity. A statistical approach can be a success in this situation, instead. In this approach, the ionosphere is considered as a statistical medium and one finds a relationship between statistical properties of the ionosphere and statistical properties of the scattered radio wave.

Using this approach, we obtained the relation between the variance of the logarithmic relative amplitude of the scattered radio wave and the parameters of scattering irregularities in the high latitude ionosphere. This equation takes into account the three-dimensional anisotropy of high-latitude small-scale irregularities. It is assumed that the spectrum of the irregularities obeys the power law. We found that the variance of the amplitude σ_χ^2 is proportional to the integral of the variance of electron density fluctuations σ_N^2 multiplied by some function f. This function depends on the Fresnel radius R_F, the anisotropy parameters α, β, Ψ, p and the angle Θ between the geomagnetic field and the line-of-sight from the radio source to the receiver

$$\sigma_\chi^2 \sim \int_{Z_L}^{Z_U} \sigma_N^2(z) \cdot f\{R_F(z)\,, \alpha, \beta, \Psi, p, \Theta(z)\}\, dz\,.$$

Here α is the elongation of the irregularities in the direction of the geomagnetic field, β is the field-perpendicular elongation, p is the power index and Ψ is the orientation angle of the perpendicular anisotropy (the angle between the horizontal projection of the perpendicular anisotropy and the geographical North measured eastward). Z_L and Z_U are the lower and the upper boundaries of the layer of irregularities.

The above equation means that three different reasons may cause changes in the amplitude. They are (*i*) spatial changes in electron density, (*ii*) spatial changes of the spectrum and (*iii*) the behaviour of the function f. Let us assume that the spectrum of the irregularities is spatially constant. In the simplest case of constant density fluctuations, changes in amplitude are due to the function f only, which gets its maximum close by the geomagnetic zenith of the receiving site. The peak is caused by geometrical enhancement of the amplitude scintillation (so called "aspect-effect") which takes place at some specific position of the ray from the radio source to the receiver. The shape and the location of the aspect peak depend on the parameters of irregularities and the angle Θ. Calculating Θ and varying α, β, Ψ while fitting the model to the experimental σ_χ^2 curve, the anisotropy parameters can be determined from the best fit.

In order to verify the applicability of this theoretical approach to the experiment, we processed a large set of amplitude data measured at high latitudes. Indeed, it turned out that a lot of experimental curves contained a single maximum that could be properly reproduced by fitting the theoretical curve calculated from (1).

Several examples of this kind are shown in Fig. 1.

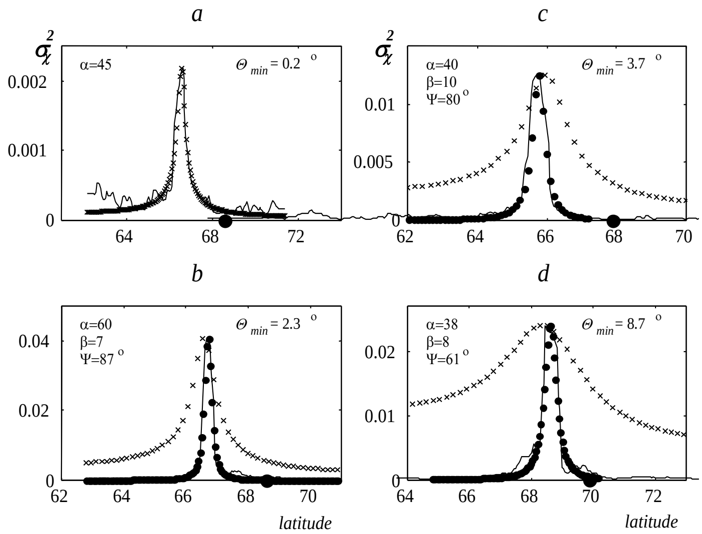

Fig.1. Fitting the model to the experimental amplitude curves.

The horizontal axis here is the satellite latitude; the vertical axis is the variance of the amplitude σ_χ^2 . Each curve contains a single maximum due to the aspect-effect somewhere close to the geomagnetic zenith of the receiver site. If the satellite passes very close to the local magnetic zenith or crosses it (Fig.1a), then the minimal angle between the magnetic field and the ray from the radio source to the receiver reaches zero. In this case the variance of relative amplitude is insensitive to the perpendicular anisotropy and the experimental curve can be fitted well using the model of spectrum symmetric around the geomagnetic field.

If the satellite flies at some distance from the local magnetic zenith, the minimal Θ is higher than zero. In this case the σ_χ^2 curve becomes sensitive to the field-perpendicular anisotropy. Examples of such a situation are portrayed in Fig.1 b, c, d. for the minimal Θ = 2.3°, 3.7° and 8.7°, respectively**.** The model curves shown by crosses are calculated for the spectra symmetric around the geomagnetic field. Dots are model curves calculated for the perpendicularly anisotropic spectra. A good agreement between the experimental and fitted curves is observed in all cases if the perpendicular anisotropy is taken into account.

The above examples show that the parameters of small scale irregularities can be obtained from ground-based measurements of the amplitude by a single receiver. Using this scintillation method, we have analyzed more than a thousand records in order to study the anisotropy parameters of small scale irregularities in the high latitude ionosphere. It was found that the relative elongation of the irregularities along the geomagnetic field made from 7-10 to 70-100, the field-perpendicular elongation was from 2-3 to 15-25. Various orientations of the perpendicular anisotropy (from 50-60° to 140-160°) were encountered. It was established that the orientation of perpendicular anisotropy does not necessarily coincide with the magnetic east-west direction, as it was thought to be previously.

However, spatial uniformity is not typical for high latitude ionospheric plasma. Spatial changes in density fluctuations may produce complicated amplitude curves with more than one maximum. Indeed, the analysis shows that many experimental curves contain several maxima of different shape and magnitude. Some of these extrema are due to the aspect-effect; another indicate spatial variations of electron density fluctuations.

Reconstruction of the spatial distribution of density fluctuations is a subject of statistical tomography. In a tomographic experiment satellite radio signals are measured by several receivers. The receiving chain is arranged along the ground projection of the up-going or down-going satellite passages. With this geometry, the rays from the moving satellite to the receivers consecutively crosses the ionosphere in a plane containing satellite path. When the satellite consecutively passes the local magnetic zeniths of the receiving sites, the corresponding "zenith" rays come through separate not-intersecting volumes in the ionosphere (see Fig.2, a). Therefore the set of aspect-produced maxima do not suit for tomographic reconstruction of density fluctuations. When the satellite flies above some ionospheric irregularity, then a set of intersecting rays is coming through this volume from the receivers to the moving satellite (see Fig.2, b). The spatial distribution of electron density fluctuations within the volume can be reconstructed by means of tomography from the set of amplitude data at several receivers.

The structure of integral relation (1) is similar to the basic integral equation of phase tomography $\phi \sim \int N\,ds$, where N is the electron density, ds is the ray element and ϕ is the phase. In contrast to the phase tomography, the integrand in (1) contains weighting factor f due to the aspect effect, which acts as a masking factor in the reconstruction of the spatial distribution of density fluctuations. However, its influence is significant only within a narrow cone around the local geomagnetic zenith of the receiving site. Hence, in tomographic reconstruction of the amplitude data the weighting factor should be taken into account only if the irregularity lies close to the geomagnetic zeniths of receiving sites.

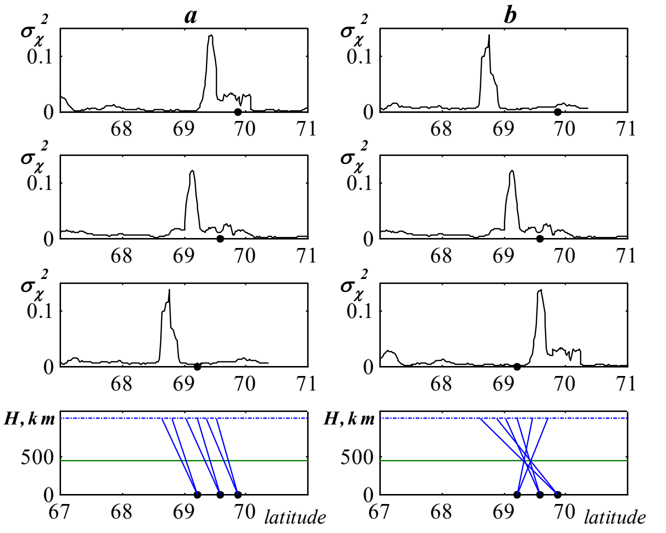

Fig.2. A set of "aspect" peaks (a) and a set of "tomographic" peaks in multipoint amplitude data.

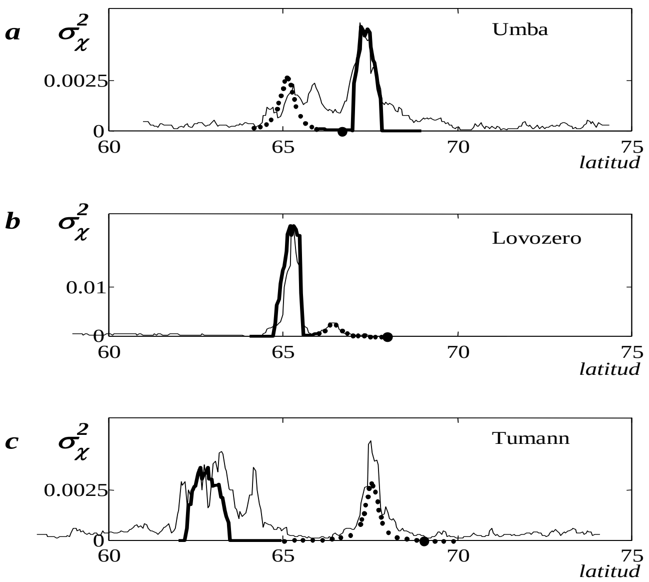

Fig.3. Experimental σ_χ^2 curves fitted by the model of irregular σ_N^2 distribution.

The first step towards implementation of amplitude tomography is simulating irregular structure of density fluctuations. The purpose is to find a model of irregular σ_N^2 to fit the set of experimental curves of σ_χ^2 measured at several receiving sites during the same satellite passage. This model could be next used in regularization in tomographic reconstruction of the variance of density fluctuations. An example of such simulation is shown in Fig.3.

The experimental data were measured at 18:20-18:30UT 2.02.1997 at three receiving sites - Umba, Lovozero and Tumanny (Murmansk region). Each experimental σ_χ^2 curve contains several extrema. In all three curves a set of maxima each lying close and somewhat southward of the corresponding receiving site are due to the aspect-effect. The locations and the shapes of these "aspect" peaks can be reproduced by the model of irregularities evenly distributed within a horizontal layer 200km thick, centered at 180 km height. The fitted parameters of irregularities are $\alpha = 40$, $\beta = 9$ and $\Psi = 100$ °. Theoretical maximum in Umba does not match exactly any of experimental peaks but it falls well into the interval of increasing amplitude variance. Absolute levels of the theoretical and experimental maxima are close to each other. The aspect-produced experimental peak in Lovozero is properly reproduced by the theoretical curve. Similarly shaped experimental and theoretical aspect maxima in Tumanny are nearly collocated, however, their absolute values do not match quite well. This difference may imply density variations within the region of aspect effect.

A set of another maxima can also be seen in experimental data. Scattering from the same ionospheric volume produces these 'tomographic' peaks. The spatial structure of density fluctuations within this volume was modeled as a cylinder of enhanced density fluctuations embedded into the background ionospheric layer. It was assumed that irregularities of the same spectrum form both the background layer and the cylinder. The center of the cylinder lies at 67.09°N and 33°E at 290 km height within the ionospheric layer. The radius of the cylinder is 15 km, its length is 180 km. The cylinder is oriented close to the local magnetic field. Within the cylinder the variance of density fluctuations varies from $(\sigma_N^2)_1 = 1500 \cdot (\sigma_N^2)_0$ in the bottom third of the volume (where $(\sigma_N^2)_0$ is variance of density fluctuations within the background layer), to $(\sigma_N^2)_2 = 600 \cdot (\sigma_N^2)_0$ in the middle third; in the top third of the structure the variance of density fluctuations is 870 times as high as its background level.

Theoretical curves are shown in Fig.3 by crosses within aspect peaks and by solid lines within 'tomographic' maxima. These curves show the summary scattering by a layer with evenly distributed irregularities and a cylinder of enhanced σ_N^2 embedded into this layer. The good agreement between theoretical and experimental curves is seen in Umba and Lovozero. A worse fit is obtained in Tumanny where the fine structure of experimental 'tomographic' peak cannot be properly reproduced by the model of a simple cylinder. However, general agreement between experimental and fitted curves even in this case is still satisfactory. It is quite natural that detailed reproduction of amplitude curves can hardly be a success if only simplified models of spatial distribution of σ_N^2 are used. Nevertheless, the shown general agreement between experimental data and modeling results prove tere is a possibility of tomographic approach in reconstruction of the variance of density fluctuations from satellite amplitude data.

The results of the paper can be summarized as follows

1. A theory is developed accounting for experimental amplitude data of satellite radio probing in the high latitude ionosphere. It is assumed that the scattering irregularities are 3-D anisotropic and their spectrum obeys the power law. Applicability of the developed approach to the analysis of experimental data is proved by numerous investigations.

2. A method is proposed for determining the anisotropy parameters of irregularities from amplitude measurements of satellite radio signals at a single ground based receiver. The method is based on the assumption of constant spatial distribution of density fluctuations. The method allowed for the first time to find the orientation of perpendicular anisotropy of small scale irregularities. It was shown that the orientation does not necessarily coincide with the geomagnetic west-east direction as it was thought to be previously.

3. Tomographic approach can be applied to reconstruct irregular distribution of density fluctuations from the amplitude data. As a first step, a modeling of experimental amplitude data is made in the case of irregular σ_N^2. The irregularity was simulated as a cylinder of enhanced electron density fluctuations, embedded into the layer of evenly distributed irregularities. Even this simplified model gives a satisfactory agreement between experimental and fitted curves at all receiving sites. Hence, it can be well hoped that the fine structure of spatial distribution of density fluctuations will be successfully mapped by means of amplitude tomography.

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