Radiotomographic reconstruction of ionization dip in the plasma near the earth

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A two-dimensional cross section of the principal ionospheric dip has been reconstructed by satellite radiotomography for the first time. The dip was observed to have a complex structure, with many extrema, on several occasions. A new phase-difference radiotomographic approach is capable of reconstructing global sections of the plasma environment of the earth.

The principal ionosphere dip has been studied primarily by direct satellite measurements at altitudes far above the maximum density of the $F2$ layer. Much less frequently, it has been studied at the altitude corresponding to the $F2$ maximum or (by ionosondes) at altitudes below the $F2$ maximum.[1] Simultaneous observations of the structure of the dip both above and below the $F2$ maximum, i.e., a reconstruction of a two-dimensional section of the ionization in the ionosphere, are clearly of interest to the physics of the formation of the ionosphere. A radiotomographic experiment using the signals from navigation satellites is a comparatively accessible and inexpensive method for solving the problem of reconstructing a two-dimensional section of the plasma near the earth.

An arrangement with reception points near the cites of Murmansk, Kem' (on the White Sea, in the Karelian ASSR), and Moscow was selected for this radiotomographic experiment to reconstruct the dip structure. This arrangement was selected for the following reasons. First, these reception points lie near the projection onto the earth of the orbit of a satellite coming from the north. The projection of the orbit coincides with a geomagnetic meridian. Second, observations[2] on the satellite Interkosmos-19 under quiet conditions in the earth's ionosphere, at a period of high solar activity, have shown that the density minimum in the principal ionospheric dip at midnight lies approximately at the latitude of the city of Kem'—north or south of it, depending on the time of day.

A receiver of a passive navigation system, equipped with auxiliary output devices, namely, a system for discriminating amplitude-phase variations in a 150-MHz signal and apparatus for connecting the analog-digital-converters to a computer, was used in the radiotomographic experiment. These auxiliary devices made it possible to distinguish the ionospheric component of the Doppler frequency. A DVK-3M computer was used in the experiments. The reception points, separated by substantial distances, were synchronized by a trigger signal from a generator with a second marker tied to the on-board time scale on the satellite. A buffer area in the working memory made it possible to continuously record signals with a sampling frequency of 200 Hz for the 10

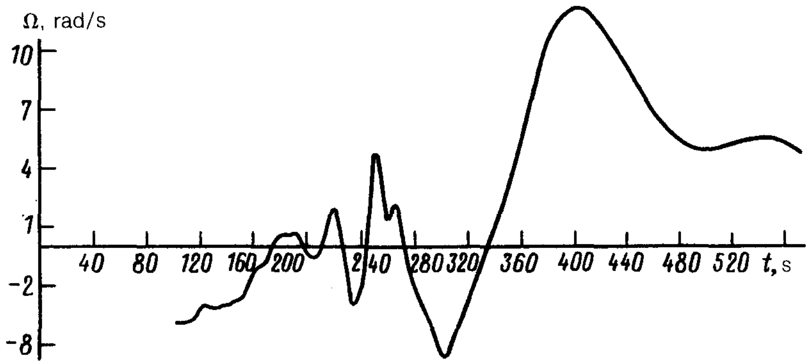

FIG. 1. Illustrative time evolution of the reduced Doppler frequency.

min required for an experiment. The time scales of the variations in the global structures are assumed here to be longer than the measurement time. An analysis of two quadratures yields the value of the phase ϕ, within an unknown constant. This phase value depends on the integral of the electron density (N) distribution along the propagation path of the radial wave.[3]

The two-dimensional distribution of the electron density can be reconstructed in the polar coordinate system (r,a) moving with the center of the earth. It is more convenient here to use the coordinates (h,τ), where $h = r - R$ is the height above the surface of the earth, whose radius is R, and $\tau = aR$ is the "transverse" coordinate, reckoned from the surface of the earth. Within some dimensional factors, the phase is then proportional to the line integral I:

$$\int_0^{h_0} \frac{N(h,\tau)(R+h)dh}{[R^2\sin^2\beta + 2Rh + h^2]^{1/2}} = I(\beta,\tau_i). \quad (1)$$

Here τ_i are the coordinates of the receivers, h_0 is the height, and β is the angular position of the satellite. If the phase were measured in absolute units, expression (1) would reduce to the standard problem of small-aspect-angle tomography. However, it is a complicated matter to measure phases in an absolute manner, i.e., to determine the unknown constant. Such measurements would require systems with many positions and many frequencies. In a radiotomographic experiment, a reduced Doppler frequency or phase difference is measured directly.

A method of phase-difference radiotomography has been developed for solving the problem of reconstruction for a reduced Doppler frequency. This problem corresponds to a reconstruction of the N distribution from the difference (D) between two line integrals of the type in (1) on nearby rays with a small difference in β. The difference system is reduced to a system of linear equations through a piecewise-planar approximation with triangular elements and higher-order approximations. In a reconstruction of the structure of regions with dimensions on the order of 10^3 km, the sparse

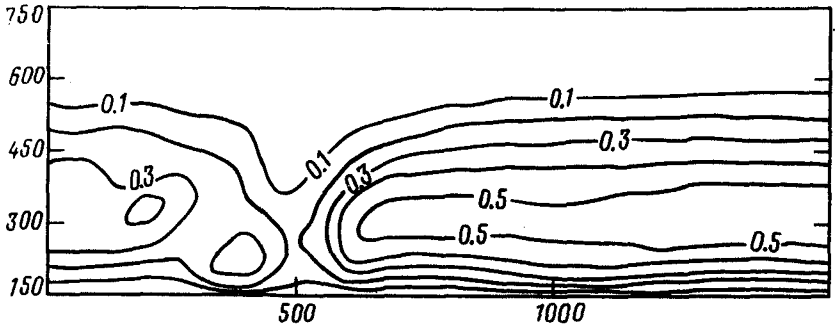

FIG. 2. Reconstruction of a section of the ionization dip at 22:05:26 on 7 April 1990.

square matrix of the system contains something on the order of 10^6–10^7 elements. Numerical simulations which were carried out showed that the global structure of the plasma near the earth can be reconstructed with a resolution of tens of kilometers by phase-difference tomography with three receivers. Good results were achieved with the help of several iterative algorithms and certain inverse-projection versions. The error of the reconstruction depends on the method, the number of iterations, and the initial approximation. As a rule, 10–20 iterations achieve a reconstruction error of 5–10%, and the basic qualitative features are reconstructed correctly. For inhomogeneities a few kilometers in size, it becomes necessary to resort to diffraction tomography.[4] Satellite radiotomography is also capable of reconstructing large anthropogenic inhomogeneities such as a defocusing ionospheric lens.[5]

Several experiments on the radiotomography of the principal ionospheric dip were carried out in March and April of 1990. The structures found as a result are

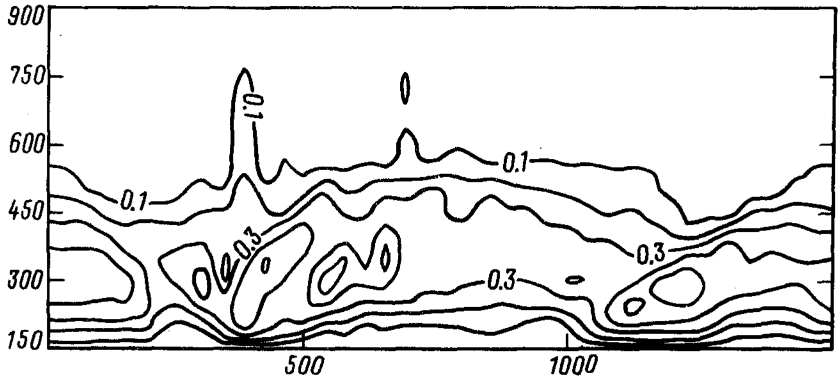

FIG. 3. Reconstruction of a section of the ionization dip at 5:37:10 on 28 March 1990.

extremely diverse; they vary significantly from day to day and also over the course of a day. Several fairly regular and smooth $N(h,\tau)$ sections were recorded; in such cases the Doppler frequency crossed zero only once. On the other hand, several dip sections had an extremely complex structure; in such cases the Doppler frequency had many extrema and crossed zero several times. Figure 1 shows an example of such a recording of the Doppler frequency Ω, at Murmansk on 7 April 1990 (the recording began at 22:05:26). Recordings of this type are a consequence of the complex structure of the dip, with several local extrema. Figure 2 shows the cross section of the dip reconstructed from this recording; the units here are 10^6 electrons/cm^3. The size of the image frame along height, h, is from 150 to 1000 km. The distance τ ranges from 0 to 1500 km. The coordinate τ of Murmansk is 10 km, that of Kem' is 433 km, and that of Moscow is 1475 km. The mesh size of the reconstruction if 50×60 km. Figure 3 shows a tomographic reconstruction of the cross section of the dip on 28 March 1990. Here again we see complex structure with many extrema.

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