MODELLING OF HF WAVE PROPAGATION IN THE VICINITY OF QUASICRITICAL RAYS IN THE DISTURBED IONOSPHERE

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The results of experimental studies of the fine structure of a signal in the vicinity of the maximum observed frequency (MOF) on the Khabarovsk—Nizhny Novgorod path of oblique chirp sounding (OCS) are presented. Additional tracks were observed in the region between the high-angle and low-angle rays during magneto-ionospheric disturbances. Under strong disturbances the ionograms were of a spreading type in the vicinity of the MOF. The observed effect was modelled in the presence of travelling ionospheric disturbances (TID) with different parameters. It is shown that the stratification of the high-angle ray into several additional tracks is a maximum for TID with vertical scales \( t_s \approx 20-40 \) km whose wave fronts make angles about \( 0-10^\circ \) with the horizontal line. The possibilities of using the Pedersen mode as a probing wave for diagnostics of the fine structure of the ionosphere in the vicinity of the F-layer maximum are discussed.

1. INTRODUCTION

The upper-angle ray (Pedersen mode) was studied in a large number of experimental and theoretical papers (see, e.g., [1] and references therein). This interest is due to the specific propagation of quasicritical rays in the vicinity of the permittivity minimum. Theoretically [2], the Pedersen mode is damped exponentially with distance in the regular ionosphere. However, it is known from the literature that the upper-angle ray can propagate in one jump to distances over 5,000 km [3]. Studies [4, 5] on paths of different length and orientation show the possibility of amplification of the upper-angle ray and broadening of its frequency range \( \Delta f_p = \text{MOF}_p - \text{LOF}_p \) (due to reduction of the LOF) in the period of magneto-ionospheric disturbances when the inhomogeneous structure is amplified. All these data indicate that under favorable conditions the radio wave field of the upper-angle ray can be localized in the vicinity of the F2 layer maximum. This can lead to both the flattening of the electron density profile, which decreases the leakage of radio waves, and the formation of large-scale stratification structures capable of guiding a sliding beam of rays to considerable distances. The nature of such irregularities can be due to acoustic-gravity waves (AGW) [6]. Ionospheric stratifications near the reflection region were confirmed by the measurements of the absolute time of SW signal propagation on oblique sounding (OS) paths when the fine structure of the signal was observed with high resolution of separate components [7]. In [8] we modelled the amplification effect of the upper-angle ray in the disturbed ionosphere for an ionospheric model consisting of a parabolic layer with superimposed medium-scale irregularities extended along the layer and having dimensions from hundreds of meters to several kilometers in the vertical direction and from tens to hundreds of kilometers in the horizontal direction. According to calculations in the approximation of a parabolic equation of diffraction theory, the anisotropic structures in the vicinity of the F2 layer maximum can contribute to the localization of the wave field in the vicinity of quasicritical rays through interference of multiply reflected waves by such irregularities. In the present paper, the fine structure of the Pedersen mode was modelled on the...
mid-latitude Khabarovsk–Nizhny Novgorod path in the period of magneto-ionospheric disturbances, using
the model of large-scale wave-like disturbances.

2. EXPERIMENT

The characteristics of the upper-angle ray were studied on the mid-latitude Khabarovsk–Nizhny Nov-
gorod path in the period from March 21 to April 2, 1988. The OCS probe of power 200 W was operated
in the mode of continuous radiation of chirped signals in the frequency range 6–28.4 MHz. The frequency
tuning rate amounted to 350 kHz/s. For the radiation and reception of signals we used horizontal rhombic
antennas oriented in opposition to each other. At the signal reception point we recorded the ionograms
and amplitude–frequency characteristics of each mode of the signal. The magnetic storm, which occurred
in the period of observations, allowed the dependence of some characteristics of the upper-angle ray on
the magneto-ionospheric disturbance to be examined. The experiment began under the conditions of the
quiet ionosphere: in March 21, 22, 23, 24, and 25 the total (diurnal) magnetic activity index \( \sum K_p \) was
3, 6, 10.3, 9.3, and 17.7, respectively. A magnetic storm began in March 26, and the increased magnetic
activity also took place in the subsequent days of observation. In March 26, 27, 28, 29, and 30 and in
April 1 and 2 the total index \( \sum K_p \) amounted to 36.7, 32.7, 30, 33.7, 32.7, 22.3, and 26.7, respectively. The
analysis of experimental data showed the broadening of the frequency range of the upper-angle ray at the
expense of LOF reduction. The frequency range was increased by about two or three times compared with
quiet conditions [5]. Processing of the normalized (with respect to the lower-angle ray) amplitude of the
upper-angle ray signal showed that the amplitude–frequency dependence is different in quiet and disturbed
ionosphere [9]. Under quiet conditions, the amplitude of the upper-angle ray decreased quickly on both
sides of the connection frequency \( f_c \), whereas in the disturbed ionosphere a moderate-amplitude (\( \sim 10\% \)
of the maximum signal of the upper-angle ray), almost constant signal was observed against the background
of the Pedersen mode in the low-frequency part of the frequency range of the upper-angle ray. The high
resolution of the OCS ionospheric probe allowed us to study in more detail the fine structure of the signal
in the vicinity of the MOF. We are speaking about the MOF of the 3F2 mode for which the largest vol-
ume of data was received. This is because rather often, and in the daytime in particular, the MOF of the
2F2 mode exceeded the upper frequency of the sounding range. Moreover, the radiation patterns of the
receive–transmit antennas were optimal for the 3F2 mode on this path.

Characteristic examples of ionograms are shown in Fig. 1. The fine structure of the signal was man-
ifested in the form of stratifications (Fig.1c), diffusivity (Fig.1d), and other distortions of the ionograms
(Fig.1b). The analysis of data showed that these features are manifested most clearly at the time of mag-
netic disturbance. Under quiet conditions, the frequency of such events was three or four times smaller and
those events were recorded mainly in the daytime hours 12–14 MT). During the magnetic disturbance, the
time interval of these events was broadened: they were recorded from 10 to 17 MT and in the morning hours
4–6 MT during the sunrise when the terminator passed along the propagation path. We will not describe all
the features of the fine structure of the signal which were registered in the experiment. We only note that
most likely these features are due to the transmission of TIDs at the time of the ionospheric disturbance.
Attention is drawn to the fine structure of the Pedersen ray in the form of quasiregular tracks (Fig.1c, d). It
should be mentioned that additional reflections were also recorded in the quiet ionosphere. Characteristics
of disturbed conditions were the broadening of the transmission frequency range of the upper-angle ray
and the increase of the ray intensity. However, the recording of splitting of the upper-angle ray even in
the presence of weak disturbance was made possible due to the higher sensitivity and higher resolution of
the ionospheric probe with a continuous OCS signal. The modelling of this effect is interesting for study
of the fine structure of the ionosphere in the vicinity of the F2 layer maximum and determination of the
parameters of the ionospheric structures responsible for the observed phenomenon.

3. RESULTS OF MODELLING

As mentioned above, the features of OS ionograms in the vicinity of the MOF were manifested most