ISSN 0016-7932, Geomagnetism and Aeronomy, 2022, Vol. 62, Nos. 1–2, pp. 58–65. © The Author(s), 2022. This article is an open access publication.
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Simulation of Medium Wave Propagation in the Magnetosphere

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Received August 3, 2021; revised September 23, 2021; accepted September 24, 2021

Abstract—A model of the medium of the ionosphere and magnetosphere, including the distributions of the concentrations and temperatures, collision frequencies, and magnetic field parameters, is described. The ray-tracing method was used to simulate the parameters of medium radio waves in this environment. The wave trajectories were calculated in the approximation of geometric optics. When the level of solar and geomagnetic activity and the location of the transmitter and the frequency are set, the parameters of the wave paths can be calculated. Numerical modeling of the characteristics of experimental echo signals has shown that the mechanism of magnetospheric propagation is of paramount importance. In this case, the main ionospheric trough turned out to be an unusual channel. Medium waves propagate inside the trough along the plasmapause. This is possible with sufficiently clear relationships between the positions of the trough, plasmapause, and transmitter. The considered effect of medium wave channeling can be used to diagnose the position of the trough and plasmapause.

DOI: 10.1134/S0016793222020049

1. INTRODUCTION

The modeling of processes occurring in the plasma of near-Earth space is one of the most important problems in modern solar–terrestrial physics. The development of this direction became possible only as a result of complex satellite, rocket, and ground experiments. A special place in the physics of the ionosphere and magnetosphere is occupied by the following issues: the obtainment of morphological information about various parameters of the ionosphere and magnetosphere; the identification of experimental factors influencing the behavior of waves; theoretical research and modeling of the processes of generation, interaction and propagation of waves; and a comparison of experimental and theoretical results.

To date, none of the above issues has been finally resolved. However, in the course of research, a large amount of theoretical and experimental material has been accumulated (Krinberg and Tashchilin, 1984; Lyatsky and Maltsev, 1983; Sergeev and Tsyganenko, 1980; Shafranov, 1983) and modern ideas about the environment and the process of radio wave propagation have been formulated (Alpert, 1972; Lichter, 1974; Sazhin, 1972; Budden, 1966). This makes it possible to create a unified model of the distribution process based on these representations.

The model of the medium should describe all of the parameters that affect wave properties: the distributions of concentrations and temperatures, which determine the refraction of waves; the collision frequencies, which determine collisional damping; and the distribution of the magnetic field, which determines the confinement of waves in the magnetosphere. The near-Earth plasma is a single, ionized region of space; however, to consider wave propagation within it, it is convenient to distinguish two regions: the ionosphere and the magnetosphere. Electrons have a significant effect on wave propagation in the former and on the magnetic field of the Earth in the latter (Ratcliffe, 1975).

In this work, the task is to describe the method and results of modeling of the process of the propagation of medium radio waves (MWs) in the Earth's magnetosphere. It is well known (Alpert, 1972; Shlionsky, 1979) that waves of various ranges can propagate in the near-Earth plasma. Traditionally, low-frequency waves are used for magnetospheric propagation, and high-frequency ones are used for ionospheric propagation. An intermediate midwavelength range (f = 1–3 MHz) is also predominantly associated with the ionosphere, although there is evidence of the magnetospheric propagation of MWs (e.g., Nagy et al., 2018). In this study, an attempt is made to assess the potential of MWs for the study, in particular, of the position of the main ionospheric trough and plasmapause in the magnetosphere.

2. CIRCULAR PLASMA MODEL

The calculations of MW propagation are based on the results of an analysis of a series of experiments on

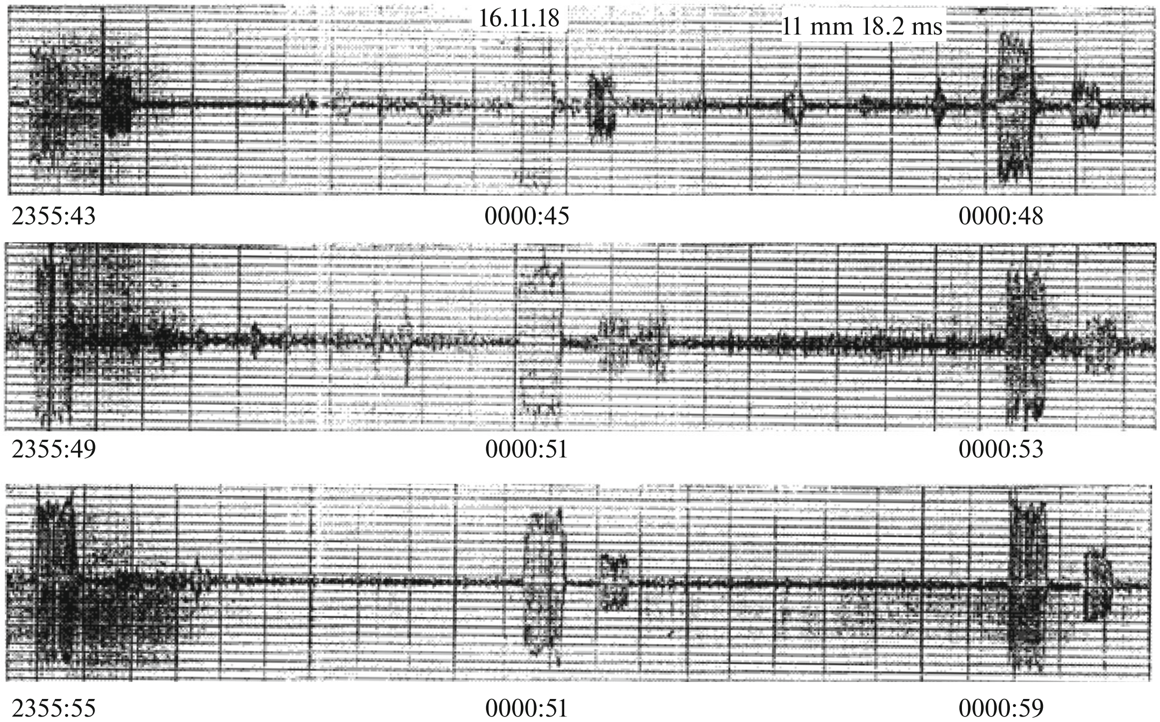

Fig. 1. Real photo recordings of echoes at a frequency of f = 1.8 MHz on November 16, 2018 (1 mm of record corresponds to 18.2 ms).

the observation of transmitter signals at a frequency of f = 1.8 MHz, which is combined with a receiver and is located near St. Petersburg (L = 3.2, where L is the shell, a parameter equal to the ratio of the distance from the center of the Earth to the line of force of the magnetic field above the equator R to the radius of the Earth R_O, i.e. $L = R/R_O$), in the winter of 2018. The experiments found echoes with average delays of t_{exp} = 0.28–0.29 s, with a low attenuation level and practically no Doppler shift. Figure 1 gives an example of recording echoes. It shows three consecutive time segments of 4 s each. The spacing between two adjacent vertical dashed lines is 200 ms. Each intense pulse, e.g., in the 57th s, corresponds to the transmitter signal, and there is an echo for each weak pulse located at a distance from transmitter pulse on t_{exp}. In the middle of the central figure, a third, unexpressed, impulse is recorded after the echo, which is a hindrance. The characteristics of such signals can only be explained by the mechanism of magnetospheric propagation, which is controlled by the position of the trough and plasmapause (Blagoveshchensky and Gladky, 2020).

There are certain conditions in the ionosphere and magnetosphere under which the channeling of MWs along the plasmapause was observed. At the moments when the echo signals appeared at the receiving point, the following information about the geophysical situation was obtained: (a) the observations were carried out during magnetospheric substorms; (b) the vertical sounding data of the station located near the point for the reception of echo signals indicate that the observation point was located deep inside the main ionospheric trough, closer to its southern border; (c) critical frequencies of the $F2$ layer for the considered sessions were within $foF2$ = 1.5–2.0 MHz in the region of the transmitter and within 4.0–6.0 MHz in the magnetically conjugated region (Blagoveshchensky and Dobroselsky, 1995, 1996). These results were used to construct a plasma model that was as similar as possible to the experimental conditions.

To describe the distribution of the electron concentration $Ne(h)$, the so-called background, empirical models of the midlatitude ionosphere Ne^{mod} (Fatkullin et al., 1981) were used in a range of heights from the initial ionospheric height ho to the level of 1000 km, which is the basis for the diffusion equilibrium model (Maltseva and Molchanov, 1984). This describes the Ne distribution in the magnetosphere in the form of a power-law decrease in concentration with distance $Ne(r) \sim r^{-n}$ (Angerami and Thomas, 1964). To vary the background, for example, the multiplier div was added to $N_{e\max}F2$ in all models of Fatkullin et al. (1981), without changes to the profile view $Ne(h)$. With *div*, you can choose the $foF2$ (or $N_{e\max}F2$) values that correspond to the experimental $foF2$ (or $N_{e\max}F2$) values. The factor div is equal to the concentration ratio at the maximum of the layer $N_{e\max}F2$ for the model and the experiment:

$$\text{div} = \frac{N_{e\max}^{\text{mod}} F2}{N_{e\max}^{\text{exp}} F2}. \quad (1)$$

This multiplier determines the number of times that the values of the model profile should be changed Ne^{mod} to match the experimental data, It varies in the range div = 1.9–7.8 for *foF*2 = 1.5–2.6 MHz.

The increase in *foF*2 in the conjugate (southern) hemisphere with respect to *foF*2 in the transmitter hemisphere is modeled with additional altitude and latitude gradients described for simplicity based on two parameters: *ah* and *dr*.

The parameter *ah* is equal to the ratio of maximum concentrations $N_{e\max}F2$ in both hemispheres:

$$ah = \frac{N_{e\max}^{\text{conjug}} F2}{N_{e\max}^{\text{tr}} F2}, \quad (2)$$

where tr stands for transmitter.

The *dr* parameter characterizes the height of the profile area within which the concentration in the conjugate hemisphere differs from the concentration in the transmitter hemisphere, i.e., it is like the scale of the introduced difference in height.

The model of the concentration distribution in the magnetosphere includes such elements as the main ionospheric trough and plasmapause. These elements are taken into account with multipliers F_{th} and F_{pp}, so that

$$Ne = Ne \text{ background } F_{\text{th}}\, F_{\text{pp}}. \quad (3)$$

The midlatitude or main ionospheric trough (MIT) is known to represent a decrease in the electron concentration in the region of geomagnetic latitudes F_L = 50°–65° in a quiet time and F_L = 35°–50° during periods of disturbances generated by convection, high-speed outflow of ions and electrons, as well as due to the difference in the positions of the geographic and magnetic poles (Halperin et al., 1980; Kolesnik and Golikov, 1983; Mizun, 1985). The MIT is a feature of the behavior of the electron concentration in the range of heights from $h_{\max}F2$ up to 2000–3000 km and is most clearly manifested at night during the years of minimum solar activity. The shape of the trough depends on the longitude, season, local time, the level of geomagnetic disturbance, and other parameters, as shown in Fig. 2 taken from Karpachev (2003).

The factor describing the MIT is introduced in the form (Maltseva and Molchanov, 1984)

$$F_{\text{th}}(L) = 1 - a_{\text{th}} e^{\frac{-(L-L_{\text{th}})^2}{2d^2}}, \quad d = \begin{cases} \text{din}, & L \le L_{\text{th}} \\ \text{dout}, & L \ge L_{\text{th}} \end{cases}, \quad (4)$$

where L_{th} determines the position of the center of the hole, a_{th} is the drop in concentration at the center of the trough, and *d* is the value of the inner (din) and outer (dout) of walls of the hole. The coefficient a_{th} depends on the distance *r*, becoming equal to zero near the equatorial plane.

The plasmapause (PP), in contrast to the MIT, is a feature of the concentration distribution in higher regions up to the equatorial plane. The structure is also different: in particular, the plasmapause has only one wall, and the concentration falls by one to two orders of magnitude at a distance ΔL = 0.1–0.3. The trough and plasmapause are not on the same *L*-shell; in particular, the trough lies inside the plasmapause and moves to the equator faster during disturbances at a small *Kp* (Halperin et al., 1990). The factor describing the change in concentration near the PP has the form (Maltseva and Molchanov, 1984)

$$F_{\text{pp}}(L,r) = \begin{cases} \left(\frac{r_0}{r}\right)^n + \left[1 - \left(\frac{r_0}{r}\right)^n\right] e^{\frac{-(L-L_{\text{pp}})^2}{w^2}}, & L \ge L_{\text{pp}} \\ 1, \quad L \le L_{\text{pp}} \end{cases}, \quad (5)$$

where L_{pp} is the position of the plasmapause; parameter *w* is the half-thickness of the plasmapause, which is measured in units *L* and depends on *Kp* ($w = w^0 - C\,Kp$); and *n* is an indicator of the degree of radial decrease in the concentration behind the plasmapause.

As for the MIT, the specified model of the trough has the same depth ($1 - a_{\text{th}}$) along the entire channel. Although such cases are not rare (Blagoveshchensky and Zherebtsov, 1987), it is known that the trough has a certain spatial extent (Rodger and Dudeney, 1987; Rodger et al., 1992). To take into account the influence of this factor, it is advisable to introduce the spatial dependence of the coefficient a_{th}, which gives a decrease in the depth of the trough towards the equatorial plane. In this case

$$F_{\text{th}}(L) = 1 - a_{\text{th}} e^{\frac{-(R-R_{\text{th}})^2}{2(dR)^2}} e^{\frac{-(L-L_{\text{th}})^2}{2d^2}}, \quad dR = \begin{cases} \text{drin}, & R \le R_{\text{th}} \\ \text{drout}, & R \ge R_{\text{th}} \end{cases}. \quad (6)$$

By varying the parameter *dR*, one can change the length of the trough, i.e., its structure.

The longitudinal dependence *Ne* it was not considered here due to its low significance.

The range of variation of each of the above model parameters (div, *ah*, *dr*) was set in accordance with the experimental data. Thus, the distribution of plasma frequencies f_{Ne} are characterized by *foF*2 values in the hemisphere of the transmitter *foF*2 = 1.5–2.6 MHz, which gives a variation of div = 1.9–7.8. The critical frequencies *foF*2 = 4.0–6.0 MHz in the conjugate hemisphere determine the range of changes *ah* = 2–10. The distribution statistics *Ne* contain no lines of force between the asymmetric hemispheres, but the parameter *dr* can vary in the range of 1000–10000 km according to some data (Berger and Barlier, 1981; Brace et al., 1988; Brace et al., 1967; Strangeways, 1982).

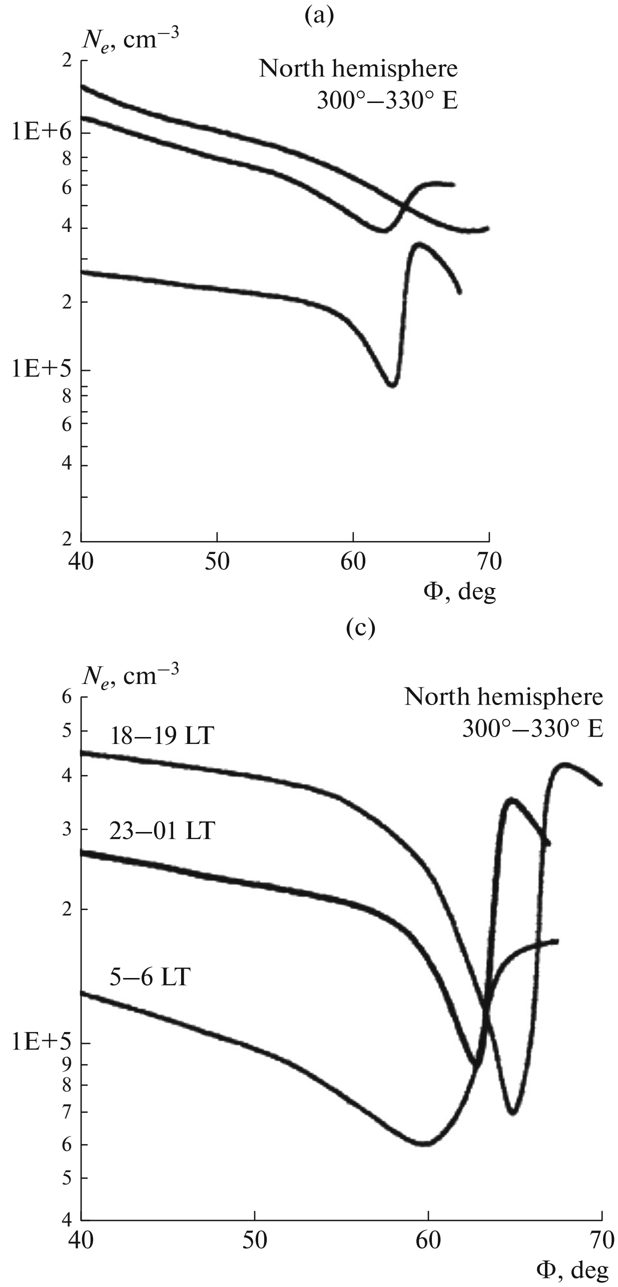

Fig. 2. Changes in the shape of the main ionospheric trough according to data from the Kosmos-900 satellite: (a, b) by season in longitudinal sectors 300°–330° E and 210°–240° E with upper curves showing the summer, middle curves showing the equinox, and lower curves showing the winter; (c) by local time (*LT*); (d) by solar activity.

The parameters of the MIT (the *L*-shell of its center L_{th}, depth factor a_{th}) and the plasmapause correspond to disturbed conditions (L_{th}, L_{pp} = 3.2–3.6, a_{th} = 0.6–0.9). In addition, the value of the difference was set as $\Delta L_{th} = L_{pp} - L_{th}$ in the range 0–0.6 based on the fact that the average value ΔL_{th} is 0.2–0.3 (Rycroft and Burnell, 1970; Rycroft and Thomas, 1970) and that this difference can reach 0.6 (Titheridge, 1976) or more (Smith et al., 1987) during disturbances.

3. METHOD TO CALCULATE RADIO-WAVE TRAJECTORIES

A traditional version (Maltseva and Molchanov, 1984) of the ray-tracing method was used to simulate the characteristics of waves (*L*-shells of observation points of waves L_k, distribution times t_{gr}, and others). In the determination of L_k and t_{gr}, it is necessary to set the position of the source and the angles of wave emission. In accordance with the experimental data, the source was located at L_{tr} = 3.23. To obtain more general results, other values were also used in the model calculations. The angles of the "start" of waves δ between the wave vector **k** and the vertical were set in the range of $-20° \le \delta \le 60°$. These angles determined the corresponding starting angles ψ between vector **k** and the vector of the Earth's magnetic field $\mathbf{B_0}$. The analysis of this behavior plays an important role in the trajectory calculations. Table 1 summarizes the values of the parameters used in the calculations.

4. DISTRIBUTION MECHANISMS

The experimental group delays of echo signals, as indicated above, were on the order of 0.28–0.29 s. Three physical mechanisms can correspond to such delay values: the propagation of medium waves in the upper ionosphere, the circumnavigation of MWs, and magnetospheric propagation.

The first mechanism is propagation with the reflection of waves from the upper ionosphere. Here, *O* mode converts to *X* mode at heights of $h < h_{max}F2$; it then propagates in the upper ionosphere ($h > h_{max}F2$), is reflected in this area, and comes back. Near $h_{max}F2$, *X* mode converts to *O* mode and reaches the Earth.

The second mechanism is circumnavigation. It enables waves to penetrate the conjugate hemisphere. There, the wave can be reflected, return to the transmitter and, repeating this process several times, gain a large delay.

The third mechanism is magnetospheric propagation, i.e., the passage of waves into the conjugate hemisphere and back through the magnetosphere.

Blagoveshchensky and Gladky (2020) showed that experimental echo signals are due only to MW propagation in the magnetosphere. Here, this circumstance is proved once again in modeling. Three mechanisms were studied via numerical simulation:

(1) the propagation of waves in the upper ionosphere of the hemisphere in which the transmitter is located, and their return to the transmitter after reflection; (2) wave propagation via circumnavigation; and (3) magnetospheric propagation.

The choice of the most probable mechanism is based on a comparison of the measured and calculated values of group delays based on information about the behavior of other characteristics. Let us consider each of the mechanisms separately.

The main data are delays τ and localization of the observation point *Lk*, and the additional data include absorption and Doppler shifts.

The first mechanism gives group delays in a wide range, including those equal to the experimental range, but the measured values lie in a narrow range. In addition, the wave may experience a large attenuation as a result of two conversions from *O* mode from *X* mode and back. This conflicts with the measured low attenuation values.

Table 1. Range of changes in the parameters used to calculate the trajectories of radio waves

Parameters	Change area
*foF*2	1.5–2.6
div	1.0–7.8
ah	1.0–10.0
L_{pp}	3.3–3.6
L_{th}	3.0–3.6
L_{tr}	3.23
a_{th}	0.6–0.9
D_r	1000–10000
δ	20°–60°

The second mechanism provides $Lk \approx L_{tr}$ and a small attenuation with a constant delay of 0.25 s, but this value is lower than the experimental value. According to the calculations, a single case could provide the required τ for several reflections from the Earth; however, signals with intermediate delays should be observed in this case, but they are not.

The third mechanism, magnetospheric propagation, includes two cases: reflection from the Earth and from the ionosphere. If we choose the first case, then the measured values should be compared with the 2τ values. Calculations show that the value of 2τ for all minimum delays is greater than the measured values. Consequently, the wave should be reflected from the conjugate ionosphere, and only this second case should be used to explain the experimental values.

All model calculations in the second case were carried out with allowance for the corresponding geophysical environment. There are two main circumstances (Ben'kova et al., 1985; Galperin et al., 1990).

(1) Under conditions of long-term, moderate magnetic disturbances ($Kr \ge 2$), the northern border of the trough at the ionospheric *F*-layer maximum coincides with the position of the plasmapause, i.e., the MIT at night is located inside the plasmapause.

(2) In stationary, calm conditions in the evening and near-midnight sectors, the northern boundary of the sinkhole is located outside *L*-shells of the plasmapause.

The simulation of magnetospheric propagation for all ranges of the parameters indicated in Table 1 showed that the experimental values τ can be obtained in a fairly wide range of background plasma (div = 3.5–7.8).

(a) Moderately perturbed conditions (L_{pp} = 3.6; L_{th} = 3–3.6; L_{tr} = 3.2; f = 1.8 MHz). The calculation result is shown in Fig. 3.

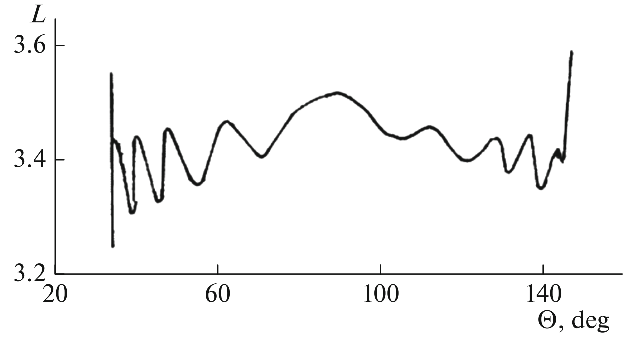

Fig. 3. Trajectory of the beam during the passage of MW radio waves into the conjugate hemisphere for specific parameters of the main ionospheric trough and plasmapause: $L_{pp} = 3.6$, $L_{th} = 3.4$, $a_{th} = 0.9$, div = 5.0, $Lk = 3.41$.

— Low background plasma gives mostly overestimated values of τ. Here, the center of the MIT should not be far south of the transmitter.

— A high background plasma requires deeper troughs ($a_{th} = 0.8–0.9$). There is good agreement for τ^{exp} and τ^{model} when the transmitter is located slightly south of the center of the MIT.

— Moderate background plasma (div = 5) forms the most favorable conditions for the interpretation of experimental data and for clearly limited relative positions of the trough and the transmitter ($\Delta L = 0.1$) and moderately deep troughs ($a_{th} = 0.6–0.7$).

— Waves are not channeled and do not pass into the conjugate hemisphere at $L_{pp} = L_{th}$.

(b) Significant disturbance ($L_{pp} = 3.3–3.5$, $L_{th} = 3.0–3.5$, $L_{tr} = 3.2$, $f = 1.8$ MHz). Here, the calculation results did not greatly change the picture described in point (a), but the propagation of waves into the magnetically conjugated region and their reflection in it become unlikely for $L_{pp} - L_{th} \geq 0.3$ and absolutely incredible at $L_{pp} < L_{th}$. The last inequality is physically unrealizable for $L_{pp} = 3.3–3.4$.

This can be interpreted in terms of physical concepts. The channel for propagation is not formed, and the channeling of waves along the plasmapause will be absent in two situations:

(1) the position of the trough is far south of the plasmapause ($L_{pp} - L_{th} > 0.5$), i.e., the trough is almost completely inside the plasmasphere;

(2) the trough center is close to the position of the plasmapause ($L_{pp} \cong L_{th}$), i.e. The southern part of the trough is located in the plasmasphere, the northern border is outside the plasmasphere and is blurred.

To create the optimal conditions for wave channeling, the center of the MIT must be slightly south of the position of the plasmapause ($L_{pp} - L_{th} \leq 0.2$) and the transmitter must be located near the center of the trough ($-0.1 \leq L_{th} - L_{tr} \leq 0.1$). Wave propagation occurs along the ionization step formed by the MIT center and plasmapause.

5. CONCLUSIONS

1. A model of the medium (ionosphere and magnetosphere), including the distributions of concentrations and temperatures, collision frequencies, and magnetic field parameters, is described. The ray-tracing method was used to simulate the MW parameters in this environment. The wave trajectories were calculated in the approximation of geometric optics. The use of this method turned out to be the most justified, since it is quite developed and widespread. A specific program has been created and can be used to calculate the parameters of wave trajectories when the level of solar and geomagnetic activity, the location of the transmitter, and the frequency are set.

2. Numerical modeling of the signal characteristics showed that, under the conditions of the experiment described by Blagoveshchensky and Gladky (2020), signals can return to the transmitter in at least three cases: (a) when they are reflected in the upper ionosphere at heights both below and above $h_{max}F2$, (b) during propagation around the globe, and (c) as a result of magnetospheric propagation (channelization of waves). Comparison of the measured and calculated values of the signal group delays, together with an analysis of other characteristics, made it possible to give preference to the mechanism of magnetospheric propagation. In contrast to the traditional channeling of waves in ducts, in this case, the MIT turned out to be an unusual channel. Medium waves propagate inside the trough along the plasmapause during moderate and strong disturbances.

3. Medium-wave canalization is possible with sufficiently clear relationships between the positions of the trough, plasmapause, and transmitter:

— the relative position of the transmitter and the trough is determined by the condition $\Delta L = L_{th} - L_{tr} = 0.0 \pm 0.1$;

— the limitation on the position of the trough and plasmapause is given by the equality $L_{pp} = L_{th} + (0.1 - 0.3)$.

The most favorable conditions for the existence of echoes are the following:

— critical layer frequencies *F* the ionosphere that are close to the sounding frequency;

— low altitude gradients *Ne* along the lines of force of the magnetic field.

4. The considered effect of the channeling of MWs along the plasmapause provides a basis for the possible use of MW signals (both for the observation of echo signals and for wave propagation into the magnetically conjugated region) to determine quickly the position of the trough and plasmapause, as well as to identify the phenomena associated with these areas.

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