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PROPAGATION OF ULTRA-SHORT WAVES IN THE ATMOSPHERE OF VENUS

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SUMMARY

The results are presented of the analysis of decimeter and centimeter radiowave propagation in the atmosphere of Venus. The angles of refraction and the refractional attenuation of radiowaves are found. The fluctuations of field strength and the attenuation of the energy flux of radiowaves are analyzed.

INTRODUCTION

Radiowave propagation through the dense Venus' atmosphere takes place at spacecraft's position on the surface of Venus or at its motion along the trajectory shaded by the planet. The space station "Venera-4" was first to initiate radiocommunication between the Earth and the surface of Venus, whereupon the influence was noted of planet's atmosphere on the propagation of decimeter waves [1]. A strong influence of Venus' atmosphere was also observed during the motion of "Mariner-5" along the trajectory with setting behind the visible disk of the planet [2]. During radar location of Venus, a decrease was noted of effective scattering diameter in the centimeter wave band, this effect being also due to the influence of planet's atmosphere [3-6]. In connection with this, the analysis of the propagation of ultra-short waves in the atmosphere of Venus presents interest for two cases: the location of the source of radiowaves on the planet's surface, and the motion of the source near the visible planet's disk. For the analysis of the stated problem, we shall use the results of determination of pressure, temperature and composition of Venus' atmosphere obtained by means of the AIS "Venera-4" [7]. In the present work, we shall examine the propagation of ultra-short waves for source's location on the surface of Venus; moreover, according to [1], the ionosphere influence, may be disregarded. During computations we shall assume that the radius of Venus' surface is equal to 6060km.

1. DISTRIBUTION OF THE REFRACTIVE INDEX OF ULTRA-SHORT WAVES IN THE ATMOSPHERE OF VENUS

For the analysis of the propagation of radiowaves in the atmosphere, it is necessary to know the distribution with height of the refractive index n(h). According to data [7] it is possible to assume that the atmosphere of Venus has the following composition: CO_2) 95%, N) 4%, H_2O) (0.1-0.7)%. We assume the pressure on the planet's surface as being of 20 atm. The atmosphere must have the same composition to heights of the order of 60 km; at greater heights, a variation of percent content of gas composition is possible. If we disregard the water vapors' minor influence, the refractive index may be presented by relations of the form

$$\left.\begin{aligned} n(h) &= 1 + N(h), \\ N(h) &= \tau \frac{P(h)}{T(h)}. \end{aligned}\right\} \qquad (1)$$

Here P(h) and T(h) are the pressure and temperature as functions of altitude above the planet's surface. The quantity τ depends on gas composition; for the atmosphere of Venus $\tau = 0.145$ degree/atm.

Using (1) and dependences P(h) and T(h), brought out in the work [7], we shall obtain the dependence N(h), which basically determines the propagation of ultra-short waves. The numerical analysis of the function N(h) thus found has shown that it is well approximated by dependences of the form

$$N(h) = N_0 e^{-\beta h} \quad \text{for} \quad h \leqslant 30 \text{ км}, \qquad (2)$$

$$N(h) = N_0^{*} e^{-Ah^2 + Bh} \quad \text{for} \quad h \geqslant 30 \text{ км}.$$

Here

$$N_0 = 5{,}3 \cdot 10^{-3}; \quad \beta = 9{,}6 \cdot 10^{-2} \text{ км}^{-1};$$
$$N_0^{*} = 4{,}8 \cdot 10^{-4}; \; A = 4 \cdot 10^{-3} \text{ км}^{-2}; \; B = 0{,}1 \text{ км}^{-1}.$$

The refractive index in the Venus atmosphere must undergo fluctuations on account of temperature and humidity variations. According to data [1], the troposphere of Venus is turbulent up to heights of the order of 30 km, while the root-mean-square deflection of the refractive index $\sqrt{\overline{\Delta n^2}}$ is nearly $(5\text{-}10)\cdot 10^{-6}$. So far there are no data on the altitude propagation of $\overline{\Delta n^2}$ in the atmosphere of Venus.

2. REFRACTION EFFECTS IN THE ATMOSPHERE OF VENUS

The radial lines of radiowaves in the dense Venus atmosphere are strongly distorted. The analysis of refraction effects amounts to the determination of the angle of refraction, the calculation of radiowaves' refractive attenuation and the determination of conditions of ray capture by planet's atmosphere.

At small angles of the spot θ, radiowaves may not emerge beyond the limits of the atmosphere. Let us determine the value of the critical angle θ_k at which the waves envelop Venus, without emerging beyond the limits of its atmosphere. For the determination of θ_k it is possible to use relation (2) for then the influence of the region $h \leqslant 30$ km is important. According to [9] and taking into account (2) the curvature radius of the ray at an arbitrary point of troposphere is expressed by a relation of the form

$$R = (1 + N_0 e^{-\beta h}) / \sin\gamma(h) N_0 \beta e^{-\beta h}. \qquad (3)$$

Here γ is the angle between the normal to the planet surface and the radial line. For the ray having emerged at the critical angle of the spot θ_k, at the point of ray capturing $\gamma = 90°$ and $R = a + h_k$. Here $\underline{a}$ is the radius of Venus, h_k is the altitude above the planet at the point of ray capturing. From (3) for the critical ray we have

$$N_0 \beta e^{-\beta h_\kappa}(a + h_\kappa) = 1 + N_0 e^{-\beta h_\kappa}. \qquad (4)$$

Expression (4) allows us to determine h_k. From the law of refraction in a spherically-stratified layer we have for the determination of θ_k the following formula:

$$(1+N_0)\cos\theta_к = (1+N_0 e^{-\beta h_к})\left(1+\frac{h_к}{a}\right). \tag{5}$$

From (4) and (5) we obtain the approximation relations

$$\bar{h}_к \simeq \frac{1}{\beta}\ln(N_0 a\beta), \tag{6}$$

$$\theta_к \simeq \sqrt{2\left[N_0(1-e^{-\beta h_к})-\frac{h_к}{a}\right]}. \tag{7}$$

It follows from (6) and (7) that $\theta_k \simeq 3.3°$ and $h_k \simeq 12$ km. Therefore, for an angle of the spot $\theta < 3.3°$ capture of radiowaves takes place; the radiowave cannot emerge beyond the planet's atmosphere.

For $\theta > \theta_k$, the radial lines, being distorted by the angle of refraction ξ, emerge beyond the limits of Venus' atmosphere. The refraction angle ξ is determined by a well known expression for the refraction integral [9].

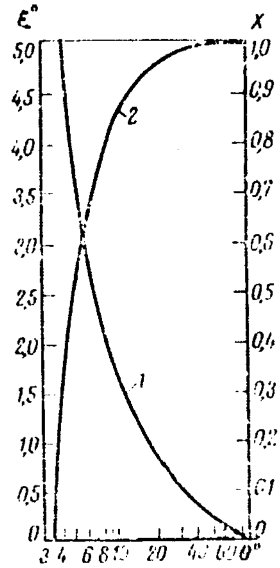

Fig.1.

Dependences of the angle of refraction ξ (curve 1) and of the refractive attenuation X (curve 2) on the angle of the spot θ.

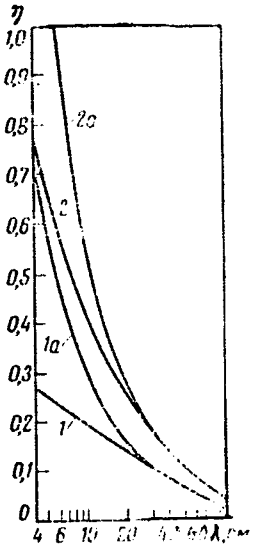

Fig.2.

Dependence of average depth of **rapid fluctuations of field** strength on wavelength for two angles of the spot. Curves 1 and 1a for θ = 90°, curves 2 and 2a for θ = 15°.

In the investigated problem this expression has the form

$$\xi = N_0(1+N_0)\cos\theta \int\limits_0^{\beta h} \frac{e^{-x}dx}{(1+N_0e^{-x})\sqrt{\left(1+\frac{x}{a\beta}\right)^2(1+N_0e^{-x})^2-(1+N_0)^2\cos^2\theta}} +$$

$$+\frac{N_0^{*}(1+N_0^{*})\cos\theta}{\sqrt{A}} \int\limits_{\sqrt{A}h}^{\infty} \times$$

$$\times \frac{(2\sqrt{A}x-B)\,e^{-x^2+(B/\sqrt{A})x}\,dx}{(1+N_0^{*}e^{-x^2+(B/\sqrt{A})x})\sqrt{\left(1+\frac{x}{a\sqrt{A}}\right)^2(1+N_0^{*}e^{-x^2+(B/\sqrt{A})x})^2-(1+N_0^{*})^2\cos^2\theta}}. \qquad (8)$$

Using a computer, expression (8) permits us to obtain the value of the angle of refraction. Shown in Fig.1 is the dependence of the angle of refraction ξ on the angle of the spot of the ray θ. The refraction effects in the atmosphere of Venus are strongly expressed. Thus, for $\theta = 15°$, $\xi = 1.15°$; for $\theta = 5°$, $\xi = 4.1°$.

As the refraction angle ξ depends greatly on the angle θ, the refraction attenuation of radiowaves should be observed. For its determination let us examine two rays with the close spot angles θ and $\theta + d\theta$. Beyond the limits of the atmosphere, the angle between the two considered rays will be greater by $d\xi$. The refractive attenuation of radiowaves' energy flux is equal to the ratio of angles $d\theta$ and $d\theta + d\xi$, which is

$$X = \frac{1}{1+|d\xi/d\theta|}. \qquad (9)$$

Expressions (8) and (9) enable us to find by means of the computer the refractive attenuation of radiowaves for various angles of the spot (Fig.2). Since at $\theta = 15°$ we have $X = 0.92$, for $\theta > 20°$ we may neglect the refractive attenuation. At small θ the refractive attenuation is strongly expressed; thus, for $\theta = 5°$, $X = 0.47$. The true angle α of the spot in the direction toward the receiver is linked with the spot angle of the ray θ and, the angle of refraction ξ by a well known relation

$$\alpha = \theta - \xi.$$

3. FLUCTUATIONS OF FIELD STRENGTH

In the atmosphere of Venus the radiowaves' refractive index fluctuates, which leads to the fluctuation of radiowaves' energy flux. Since the altitude distribution of index of refraction fluctuations is unknown, let us represent in the first approximation the troposphere of Venus as a statistically inhomogenous medium of thickness L_0 with uniform distribution of $\overline{\Delta n^2}$ with height. According to [10] the depth of radiowave fluctuations is expressed by a relation of the form

$$\overline{B^2} = \frac{35\overline{\Delta n^2} b L_0}{\lambda^2}\left(1 - \frac{1}{D}\operatorname{arc\,tg} D\right). \qquad (10)$$

Here

$$\overline{B^2} = \overline{\left(\ln\frac{|E_0 - E_i|}{E_0}\right)^2},$$

$\underline{b}$ is the conditional scale of inhomogeneities with Gaussian from of autocorrelative fluctuation function of the refractive index, $D = 2L\lambda/\pi b^2$ is the wave parameter. Expression (10) is valid for an angle of the spot equal to 90°. As the latter decreases, the fluctuation depth should rise on account of effective length increase of the course L in the turbulent part of Venus' atmosphere. The relationship of the effective length with the angle of the spot is expressed by the relation

$$L = \frac{L_0}{\sin\theta}\left(1 - \frac{L_0}{2a\sin^2\theta}\right) \qquad (11)$$

Expressions (10) and (11) allow us to determine the fluctuation depth for various wavelengths and spot angles; they are valid for $\theta > \theta_k$. For spot angles close to the critical ones, these relations are invalid, for then, minor profile variations of the refraction index may result in strong fadings on account of the inconstancy of refractive attenuation and ray capture.

It is shown in work [1] that at propagation of radiowaves of the $\lambda = 0.3$ m band through the Venus atmosphere at $\theta \simeq 90°$, rapid scintillations with a depth

$$\eta_1 = \sqrt{\overline{\Delta E_1^2}}/E_0 \sim 0{,}1$$

and slow variations of field strength $\eta_2 \simeq 0.2$ were observed. Inasmuch as, so far, the scales of inhomogeneities b are unknown, we may postulate in the first approximation $D \gg 1$. At the same time, the term $(1 - (1/D)\ \mathrm{arctg} D)$ in (10) will be close to unity and therefore may be neglected. Since $\overline{B^2} = \eta^2$, it follows from (10), that for $\eta_1 = 0.1$ and $\lambda = 0.3$ m the parameter of inhomogeneities, responsible for rapid scintillations, is equal to $\overline{\Delta n^2} b L_0 = 2.5 \cdot 10^{-5}$ m^2 for $D \gg 1$. More precise calculations of the depth of rapid fluctuations may be conducted taking into account the true value of the wave parameter D. This accounting is beset with difficulties, as the knowledge of parameters L_0 and b is prerequisite. The quantity L_0 may be estimated according to the experimental data, for according to [1], perceptible fluctuations in the atmosphere of Venus were observed only at the height of 20 km. According to data [7], at the height of 30 km the pressure is equal to 0.5 atm. Therefore, the contribution of inhomogeneities, disposed above 30 km, is not great, so that one may postulate $L_0 = 30$ km. Parameter b could be set by analogy with inhomogeneities of the Earth's troposphere $b = 50$m, whereupon for $\lambda = 0.3$ m and $\eta = 0.1$ we shall obtain that $\overline{\Delta n^2} b L_0 = 5.1 \cdot 10^{-5}$ m^2.

Shown in Fig.2 are the results of calculation of the quantity η, characterizing the rapid fluctuations of field strength for various wavelengths. The curve 1a is constructed in the assumption that $D \gg 1$. The curve 1 corresponds to $b = 50$ m, when D is comparable with the unity. From Fig.2, it follows that for $\lambda > 10$ cm the calculations yield in both cases close values of η; in the centimeter band divergences are great. With the decrease of spot angle, the effective length L and the fading depth increase. The curves 2 and 2a in Fig.2, describe the dependence of the depth of rapid field strength fluctuation on wavelength for $\theta = 15°$. The curve 2a corresponds to $D \gg 1$, and the curve 2 is constructed in the assumption that $b = 50$ m, when D is comparable with the unity in the centimeter band. From the comparison of curves 2 and 2a it follows that for $\lambda > 7$ cm the calculations yield close values of η in both cases.

4. ATTENUATION OF RADIOWAVES IN THE ATMOSPHERE OF VENUS

The attenuation of radiowaves in the atmosphere of Venus may be conditioned by molecular absorption and radiowave scattering on the statistical inhomogeneites of the refraction index

$$S = S_0 \exp\left[-\int_0^\infty \alpha_1(h)\,dl - \int_0^\infty \alpha_2(h)\,dl\right]. \tag{12}$$

Here α_1 and α_2 are respectively the absorption and scattering coefficients as a function of altitude above the planet's surface. According to [1] the absorption coefficient is expressed by the relation

$$\alpha_1 = C\frac{P^2(h)}{\lambda^2 T^5(h)}, \tag{13}$$

where

$$C = 1{,}52\cdot 10^4(5{,}7f^2_{CO_2} + 3{,}9f_{CO_2}f_{N_2} + 2{,}64f_{CO_2}f_{Ar} + 0{,}085f^2_{N_2} + \\ + 1330f_{H_2O})\ \text{cm}^{-1}. \tag{14}$$

In (13) and (14) P is the pressure in atmospheres, T is the temperature in °K, λ is the wavelength in cm, f is the relative content in CO_2, N_2, Ar, H_2O of the atmosphere. Formulas (13) and (14) describe with a precision to several percent the attenuation of radiowaves in CO_2, N_2, Ar. The influence of water vapors is described by these formulas with lesser accuracy. Another expression is given in the work [8] for the accounting of water vapor influence on the attenuation of radiowaves. According to [8] the attenuation by water vapors is somehow greater than what follows from (13) and (14). The altitude dependence of the attenuation factor α(h) is basically determined by the dependence P^2/T^5, therefore

$$\gamma_1 = \frac{C}{\lambda^2}\int_0^\infty \frac{P^2(h)}{T^5(h)}\,dl. \tag{15}$$

Here γ_1 is the integral absorption coefficient. According to the dependences P(h) and T(h), given in [7], it is possible to show that the following approximation is feasible in the form

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$$\frac{CP^2(h)}{\lambda^2 T^5(h)} = \frac{M}{\lambda^2} e^{-mh}, \qquad (16)$$

where $M = C(P_0{}^2/T_0{}^5)$ and P_0 and T_0 are the near-surface values of pressure and temperature, $m = 1.24 \cdot 10^{-4}$ cm^{-1}. From (15) and (16) taking into account the relation $dh = dl \sin \theta$, follows

$$\gamma_1 = M / m\lambda^2 \sin \theta = \Delta_1 / \lambda^2 \sin \theta. \qquad (17)$$

This expression allows us to determine the absorption of radiowaves for spot angles $\theta > 10°$. For the 0.4% content in H_2O it follows from (17) that $\Delta_1 = (2-4) \cdot 10^{-4}$ m^2. Here the first value in parentheses corresponds to the computations according to formula (14), and the second is obtained when accounting for the water vapors' influence according to data of the work [8].

According to [9], the attenuation of radiowaves' energy flux on account of scattering on statistical inhomogeneities of the refraction index is representable in the form

$$S = S_0 e^{-\gamma_2}, \qquad (18)$$

where $\gamma_1 = \Delta_2/\lambda^2 \sin \theta$. The expression (18) is obtained from [9], if we are to assume that the wave parameter $D \gg 1$. As in the case of the analysis of fluctuations, we do not account for the distriubtion of $\overline{\Delta n^2}$ with altitude. Therefore, according to [10], $\Delta_2 = 70[\overline{\Delta n_1{}^2 b_1 L_0}]$. The quantities $\Delta n_1{}^2$ and b_1 correspond to the small-scale part of the fluctuation spectrum of the refraction index, responsible for radiowave scattering. It was shown above, that $\overline{\Delta n^2} b L_0 = 2.5 \cdot 10^{-5}$ m^2. This value follows from the data on field strength fluctuations; it imparts to $\Delta_2 = 1.7 \cdot 10^{-3}$ m^2 a knowingly overrated value.

The presented Δ_1 values and the rough estimates of Δ_2 are found by means of the absorption computations and estimates of radiowave scattering according to limited data on wateriness and inhomogeneities of the refraction index of Venus atmosphere. In connection with this it is of interest to determine $\Delta_1 + \Delta_2$ according to radar data, from which it follows that for $\lambda = 0.4-0.7$ m, the effective cross-section σ_0 does not depend on the wavelength and is on the average equal to $\sigma_0/\pi\alpha^2 = 0.15$. It is pointed out in [4,5,12] that for

$\lambda = 12.5$ cm, the effective cross-section decreases to the value $\sigma/\pi\alpha^2 = 0.11$; this decrease is particularly strong near $\lambda = 3.7$ cm, where $\sigma_1/\pi\alpha^2 = 0.01$-$0.015$ [2,3]. The attenuation at single passage of radiowaves through planet's atmosphere may be determined by these data, since

$$\frac{S}{S_0} = \sqrt{\frac{\sigma_1}{\sigma_0}\frac{F_0}{F_1}}. \tag{19}$$

Here F_0 and F_1 are the reflection factors according to the power of radiowaves of 0.4-0.7 m and 3.7 m bands. If we assume that at $\lambda = 3$-70 cm there is no substantial frequenc dependence $F(\lambda)$, then $S/S_0 = 0.3$ for $\lambda = 3.7$ cm, and, consequently, $\Delta_1 + \Delta_2 = 1.6\cdot10^{-3}\ \mathrm{m}^2$. This is the estimate of the maximum value of $\Delta_1 + \Delta_2$. It is possible, that in $\lambda = 40$-70 cm band, the reflection stems from rocky grounds with dielectric constant $\varepsilon = 4.7$ (this follows from the value $\sigma/\pi\alpha^2 = 0.15$), but for $\lambda = 3.7$ cm it originates from a sandy layer with $\varepsilon = 2.4$ [12]. In this assumption, $\Delta_1 + \Delta_2 = 0.3\cdot10^{-3}\mathrm{m}^2$. The latter assumption seems to us as being more probable; however, the determination of the quantity $\Delta_1 + \Delta_2$ then depends on the accepted value of ε for $\lambda = 3.7$ cm. According to data [2,3] the effective radar cross-section of Venus varies considerably from day to day; this may be explained by the variation of radiowave scattering. From the conducted analysis it follows that for $\theta > 10°$, the attenuation of radiowaves in Venus' atmosphere is described by the expression of the form

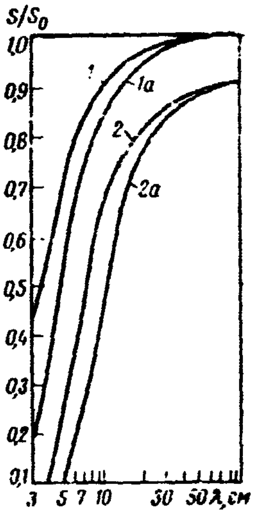

Fig.3.

Radiowaves' energy flux as a function of the wavelength. The curves 1 and 1a are given for $\theta = 90°$, 2 and 2a for $\theta = 15°$ (1 and 2 is the average attenuation, 1a and 2a is the maximum possible attenuation).

$$S = S_0 e^{-(\Delta_1+\Delta_2)/\lambda^2 \sin\theta}, \tag{20}$$

where $\Delta_1 + \Delta_2 = (0.8 \pm 0.4)\cdot10^{-3}\mathrm{m}^2$.

Presented in Fig.3, is the attenuation of radiowaves as a function of wavelength for two angles of the spot; at $\theta = 15°$, the refractive attenuation of radiowaves is taken into account additionally.

CONCLUSIONS

The refraction effects in Venus atmosphere are strongly exprèssed. For ray spot angles $\theta < 3.3°$, capture of radiowaves takes place; the radial line, then, however, does not emerge beyond the limits of Venus' atmosphere. For $\theta > 3.3°$ the radial line emerges beyond the atmosphere limits, after being distorted by a big refraction angle; for example, at $\theta = 7°$ the angle of refraction is equal to 2.7°. Refractive attenuation of radiowaves for $\theta > 20°$ is immaterial. For $\theta < 10°$ the refractive attenuation is great.

Rapid fluctuations of field strength, due to the influence of statistical inhomogeneities of the refractive index must be observed during the propagation of radiowaves in the atmosphere of Venus. The depth of these fluctuations may be computed for $\lambda > 10$cm. With smaller wavelengths the fluctuations of field strength should be great, but their computation is difficult, since the information on statistical parameters of the refractive index' inhomogeneities is not sufficient.

The attenuation in Venus atmosphere is conditioned by the molecular absorption and radiowave scattering; the contributions of these factors to the general attenuation are comparable. The frequency dependence of attenuation on account of the indicated causes is expressed by an identical law. or $\lambda > 3$ cm the attenuation may be computed according to formula (20); it is particularly great for $\lambda < 3$ cm; however, in this case, the inaccurate determination of $\Delta_1 + \Delta_2$ parameters leads to great errors in the determination of attenuation.

The numerical results of this paper are given for the near-surface pressure of 20 atm. It is possible that the pressure on the surface of Venus is somewhat higher. With great pressure P_0, the effects of refraction are easily determined with those of the data presented here. From the structure of formulas (6) and (7) it follows, that the critical angle θ_k and altitude h_k hardly depend on the near-surface value of the presented refractive index N_0, and consequently on P_0 and T_0 also. According to (8) the angle of refraction is proportional to N_0, and consequently, to ratio P_0/T_0. The attenuation of radiowaves depends greatly on pressure. Parameter $\Delta_1 \sim P^2$, therefore the increase of pressure may augment Δ_1, and decrease the role of scattering in the general attenuation of radiowaves.

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REFERENCES

1. M.A. KOLOSOV, O.I. YAKOVLEV, A.I.YEFIMOV, Dokl. AN SSSR, 1968, 182, 1, 93.
2. NEW SCIENTIST, 1968, 37, 579, 66.
3. J.V. EVANS, R.P. INGALLS, L.P. RAINVILL, R.R. SILVA, Astron. J., 1966, 71, 9, 902.
4. D. KARPER, W.E. WORROW, W.B. SMITH, Incarus, 1964, 3, 3, 473.
5. W.K. VICTOR, R. STEVENS, IRE Trans., 1962, SET-8, 84.
6. R.L. CARPENTER, Astron. J., 1966, 71, 2, 142.
7. V.S. AVDUEVSKIY, N.F. BORODIN, V.V. KUZNETSOV, A.I. LIFSHITZ, Sch.Ya. MAROV, V.V. MIKHNEVICH, M.K. ROZHDESTVENSKIY, V.A. SOKOLOV, Dokl. AN SSSR, 1968, 179, 2, 310.
8. D.H. STAELIN, J. Geophys. Res., 1966, 71, 12, 2875.
9. Ya.L. AL'PERT, V.L. GINZBURG, E.L. FAYNBERG, Rasprostraneniye radiovoln, GITTL, 1953
10. L.A. CHERNOV, Rasprostraneniye voln v srede so sluchaynymi neodorodnostiyami, Izd-vo AN SSSR, 1958."Propagation of waves in the medium of random inhomogeneities."
11. A.I. KAUFMAN, P. THADDEUS, J. Geophys. Res., 1966, 71, 21, 5091.
12. G.M. STRELKOV, Astron. vestn., 1968, 2, 1, 74.

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