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Influence of the lower region of the enhanced ionization produced by a space nuclear explosion on radio wave propagation

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[1] Propagation of radio waves through the region of enhanced (cold) ionization of the ionosphere formed below the ionospheric E layer by the X ray and penetrating radiation of a space nuclear explosion is considered. A method to calculate the field and the main radiophysical effects caused by this region is developed. The method makes it possible to calculate the above indicated effects for a wide range of the equivalents and altitudes of the nuclear charge explosions. Asymptotic formulae are obtained for the attenuation determining the conditions of radio wave propagation through the lower region of the enhanced ionization. The formulae make it possible to estimate the effects with the error not exceeding the error in the initial data on spatial-time distributions of the electron concentration. *INDEX TERMS:* 2403 Ionosphere: Active experiments; 2435 Ionosphere: Ionospheric disturbances; 2439 Ionosphere: Ionospheric irregularities; *KEYWORDS:* Lower ionosphere; Radio wave propagation; Nuclear explosions.

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1. Introduction

[2] It is widely known that the most effective and (under the current level of technical development) the only way to defend the Earth from the dangerous space objects (DSO) is using rocket nuclear technologies [see, e.g., *Simonenko et al.*, 2000]. Studying abilities of this way one should pay attention to the phenomena accompanying space nuclear explosions (SNE) and to the following limitations in its organization [*Batyr et al.*, 1996]. The matter is that SNE in the near-Earth space are accompanied by rather intense geophysical phenomena with their following strong impact on the operability of radio engineering systems of control and communication. Among the most large-scale consequences of SNE (together with the electromagnetic pulse (EMP) [*Lobolev*, 1997a, 1997b; *Semenov and Treckin*, 2000], the so-called lower region of the enhanced ionization (LREI) should be considered. The region is formed due to the action of the X ray and penetrating radiation from the explosion at altitudes below the ionospheric E region. The appearance of LREI impacts the radio wave propagation and disturbs normal operation of numerous radioelectronics systems located at a considerably large territory corresponding to the direct visibility from the nuclear charge explosion point.

[3] *Glasstone*'s [1962] book is one of the first that considered the effects of high-altitude nuclear explosions. It should be noted that in Glasstone's book (as well as in the work by the *Lobolev* [1997a, 1997b]) the description of the problems of radio wave propagation in the conditions of nuclear explosions is presented fairly briefly and is of a rather qualitative but nor quantitative character. In some publications the analysis of the impact of various SNE factors (X rays, gamma-quanta, neutrons, and beta particles) on the ionization of the lower atmosphere and absorption of radio waves is performed separately [see, e.g., *Latter and Lelevier*, 1963]. Such approach (being quite reasonable while studying EMP SNE [*Karzas and Latter*, 1965]) is verified only at the initial stage of the study of radio wave propagation in LREI. In his review dedicated to the impact of nuclear explosions on radio wave propagation, *Peterson* [1967] noted that during the 1962–1966 period very many papers have been published on

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this theme however the above indicated problem in no way may be considered as solved.

[4] The main defects of the studies performed earlier are (1) the absence of complex estimates of radiophysical effects (attenuation, elevation angle, and azimuth refraction, Doppler frequency shift) in the scope of a unite modern physical model of LREI; (2) the absence of the control of the performed calculations accuracy; and (3) very limited comparison of the results of calculations to the experimental data concerning both, various parameters of the lower ionosphere ionization and radiophysical effects.

[5] This paper, unlike the previous publications, is dedicated to complex simulation of the LREI impact on radio wave propagation with controlled accuracy of the calculations of the main radiophysical effects. The calculation of the parameters of the lower region of enhanced (cold) ionization is performed taking into account the entire radiation spectrum of the high-altitude explosion and fairly complete system of kinetic equations. The simulation is performed for SNE with rather large TNT equivalents (q) distanced from the Earth surface to considerable distances H (above the ionospheric E layer). This distance corresponds to general ideas on the use of rocket-nuclear technologies for the defense of the Earth from DSO. The propagation of radio waves through the magneto-conjugated regions and the ionized region in the explosion point (for ionospheric explosions both have much smaller dimensions than LREI [see, e.g., *Lobolev*, 1997a, 1997b]) is not considered in this paper.

[6] The need of developing of such model is due not only to the requirements in obtaining correct estimates of characteristics of radioelectronic systems in the conditions of a straggle against DSO. Such model is needed for a detailed analysis of the experimental data registered during high-altitude nuclear explosions.

2. Evaluation of the Impact of the SNE Regions

[7] The problems of evaluation of the impact of SNE artificial ionization regions on the operation of radioelectronic systems due to its complicity should be solved in two stages. At the first stage, as a rule, the parameters of the medium disturbed by the explosion are studied. First of all, fairly exact methods of solution of the nonstationary equation of the transfer of SNE ionizing radiation in the inhomogeneous atmosphere are developed [see *Lobolev,* 1997a, 1997b; *Kukhtevich and Mashkovich*, 1979]. Then the problems of ionization and kinetics of the plasma parameters of the lower atmospheric layers by the X ray and penetrating radiation are considered.

[8] The calculation of the LREI SNE parameters requires taking into account a large number of photochemical processes involving tens of chemical constituents. Variations in the electron concentration $N(t)$ and ion composition in time are looked for as a result of integration of the system of differential equations of continuity for each parameter. The initial conditions are formed under action of gamma quanta, neutrons, and X rays with the formation rates of the constituents determined by the fission fragments and beta particles. In the general case to take into account correctly the influence on $N(t)$ of minor neutral constituents one has to include into the equations (together with the chemical reactions) the transport terms. Integration of such a system of differential equations of a "rigid type" needs large resources of computer time, so for its solution sometimes one attracts special computing methods accelerating the computation process and introducing additional errors [see, e.g., *Kozlov et al.*, 1982]. The approach realized by *Kozlov* [1967, 1971], *Kozlov and Kudimov* [1969], and *Kozlov and Raizer* [1966] provided development of methods and calculation algorithms which made it possible to simulate numerically parameters of the lower atmosphere disturbed by the explosion. The parameters agree satisfactorily with the experimental data. Actually, for the frequency range from 100 to 1000 MHz and more where the vast majority of the radiolocation, radio navigation, and radio communication equipment operates, the method provides the accuracy of $N(t)$ calculations within LREI better than a few tens of percent. The problem of evaluation of the modeling accuracy of the disturbed by the explosion medium (where radio waves are propagating) is far from being trivial and we will come back to this problem at the end of the paper. Here we note that to provide a possibility to control the $N(t)$ simulation accuracy in the LREI on the basis of radiophysical measurements available one has to develop methods of calculation of radiophysical effects with the error less than a few percent.

[9] The studies of the second stage of the considered problem of evaluation of the SNE impact on operation of radioelectronics systems are reduced to solving of two problems. As a preliminary step one has to present the macroscopically continuous components of the dielectric permeability ε_{ik} in terms of parameters characterizing the plasma, that is in terms of the concentration of electrons (N), ions (N_i), and neutral particles (N_n), as well as the distribution of their velocities. The second step involves solution of the Maxwell equations with the given $\varepsilon_{ik}(r,t)$ functions and the range of the ω cyclic frequencies.

[10] The plasma in LREI may be considered as a gas $((kT)/(e^2N^{1/3}) \gg 1)$, so to look for general expression for ε_{ik} one should use the method of the kinetic equation which includes also the terms taking into account variations of the distribution function due to the processes of ionization and recombination. As for the initial data for the plasma parameters, the results of the LRIE calculations for the wide range of explosion altitudes and TNT equivalents of nuclear charges obtained by *Kozlov* [1967, 1971], *Kozlov and Kudimov* [1969], and *Kozlov and Raizer* [1966] are used. Table 1 based on the results of these publications shows (for the case $q = 5000$ kT, $H = 150$ km and $\omega = 10^9$ s^{-1} close to the worst case) the calculations of the LREI plasma parameters along the vertical from the explosion epicenter for the time moment $t = 1$ s. Moreover, the vertical profiles of the effective collision frequencies of ions with neutral particles ($\nu_{\mathrm{eff},\,in}$), electrons with neutral particles ($\nu_{\mathrm{eff},\,en}$), and electrons with ions ($\nu_{\mathrm{eff},\,ei}$), are also shown. The corresponding absorption coefficients of radio waves (see equation (2)):

Table 1. Parameters of the LREI Plasma Along the Vertical From the Explosion Epicenter for the Time Moment $t = 1$ s for $q = 5000$ kT, $H = 150$ km, and $\omega \geq 109$ s^{-1}

	Parameters										
h, km	N, cm^{-3}	$\nu_{\mathrm{eff},en}$, s^{-1}	N_i, cm^{-3}	$\nu_{\mathrm{eff},ei}$, s^{-1}	$\nu_{\mathrm{eff},in}$, s^{-1}	μ_{en}, nep km^{-1}	μ_{ei}, nep km^{-1}	μ_{in}, nep km^{-1}	μ^*_{en}, nep km^{-1} (1 eV)	$K_{\varepsilon\, n}$, $\omega/\nu_{\mathrm{eff}}$	$K_{\sigma\, n}$, $\omega/\nu_{\mathrm{eff}}$
30	2×10^3	2×10^9	1.4×10^7		5×10^7	8×10^{-3}		2.4×10^{-4}	7.6×10^{-3}	1.19	1.02
40	5.3×10^5	5×10^8	5.6×10^7		1.2×10^7	2.7×10^0		2.3×10^{-5}	2.8×10^0	0.985	0.95
50	1.9×10^6	1.8×10^8	4.6×10^7		3.2×10^6	3.2×10^0			3.2×10^0	1.0	0.99
60	4×10^6	4×10^7	2.4×10^7			1.7×10^0			1.7×10^0	1.0	1.0
70	5.3×10^6	8×10^6	5×10^6			4.5×10^{-1}			4.5×10^{-1}	1.0	1.0
80	4.8×10^6	2×10^6	3.6×10^5	5.8×10^4		1.0×10^{-1}	2.8×10^{-3}		1.0×10^{-1}	1.0	1.0
90	3.7×10^6	5×10^5	1.8×10^4	3.9×10^4		2×10^{-2}	1.5×10^{-3}		2.0×10^{-2}	1.0	1.0
100	3.4×10^6	1.3×10^5	1.1×10^4	3.1×10^4		4.6×10^{-3}	1.1×10^{-3}		4.6×10^{-3}	1.0	1.0

$\mu \sim (\omega/c)\alpha S/(1+S^2)$ both for the Maxwell velocity distribution of particles (μ_{in}, μ_{en}, and μ_{ei}), characterized by the temperature T and for distributions different from the equilibrium distributions due to the ionization processes (μ^*_{en}) are also presented in Table 1. One can easily see in Table 1 that within the height interval 30–90 km the values of $\varepsilon_{\mathrm{ik}}$ are determined by the electron distribution $f_e(r, v, t)$, and the distribution of their velocities may be considered as a Maxwell distribution with acceptable accuracy. Taking into account that for $\omega \geq 10^9$ s^{-1} the input of LREI into the polarization distortions is negligibly small [*Batyr et al.*, 1996], to describe macroscopically continuous properties of the plasma, one can use the complex permeability $\varepsilon = \varepsilon' - i\varepsilon'' = 1/3Sp\varepsilon_{Ik}$ (under $\omega_H/\omega = |e|H_E/mc\omega \to 0$)

$$\varepsilon = 1 - K_{\varepsilon,\,n}(S^{-1})\frac{\alpha}{1+S^2} - iK_{\sigma,\,n}(S^{-1})\frac{\alpha S}{1+S^2} \qquad (1)$$

Here $K_{\varepsilon,n}$ and $K_{\sigma,n}$ are the functions obtained in the scope of the kinetic theory [see, e.g., *Ginzburg*, 1967, Figures 6.1 and 6.2];

$$S \equiv \frac{\nu_{\mathrm{eff},\,en}}{\omega} \qquad \alpha \equiv \frac{\omega_0^2}{\omega^2} = \frac{4\pi e^2 N}{m\omega^2} \qquad (2)$$

where e and m are the charge and mass of an electron, c is the light velocity, H_E is the Earth magnetic field, and

$$\nu_{\mathrm{eff},\,en} = 3.65 \times 10^{-10} N_n(T)^{0.5}$$

The results of the performed estimations (see Table 1) show that for $\omega \geq 10^9$ s^{-1} with the acceptable error not exceeding a few percent one can take $K_{\varepsilon,n} = K_{\sigma,n} \sim 1$ and limit the study by the consideration of the permeability in the scope of the elementary theory [*Ginzburg*, 1967].

[11] As the next step in the study of the problem of radio wave propagation in plasma one has to find solution of the Maxwell equations for the given spatial-time distributions of $\varepsilon(r, t)$ having certain scales of nonstationarity and spatial nonuniformity. One can show that for the LREI plasma the conditions of quasi-stationarity and quasi-uniformity are fulfilled already at $t \geq 1$ s and $\omega \geq 10^9$ s^{-1}. The characteristic scales of irregularities (z) of the artificial ionization regions for nuclear explosions are from a few kilometers to tens of kilometers, so in the λ wavelength range we are interested in the value of the λ/z ratio does not exceed portions of a percent. One can demonstrate [*Semenov*, 1974] that in our case the solution of the Maxwell equations in the zero approach of the geometric optics is reduced to integration of three equations: eiconal ψ

$$(\nabla\psi)^2 = 1 - \alpha \qquad (3)$$

of the transport for the electric field amplitude Φ ($k = \omega/c$)

$$\mathrm{div}\,(\Phi^2\nabla\psi) = -k\alpha S\Phi^2 \qquad (4)$$

and the rotation angle of the polarization plane which (as it has been noted above) one may not consider for the propagation through LREI of radio waves with $\omega \geq 10^9$ s^{-1}. Integrating equations (3) and (4), one can calculate the electromagnetic field and the main radiophysical effects with the accuracy up to the terms ~ 0 (λ/z), that is, the methodical error of the calculations of radio wave distortions is negligibly small.

3. Algorithm Development

[12] To develop effective algorithms (realized at modern computers) of calculation of the field distortions appearing during the radio wave propagation in the medium disturbed by the explosion, it is reasonable to create an analytical model of this medium. This model should provide calculation of the medium parameters and their partial derivatives in terms of spatial coordinates and time required for integration of equations (2) and (3) in any points of the considered

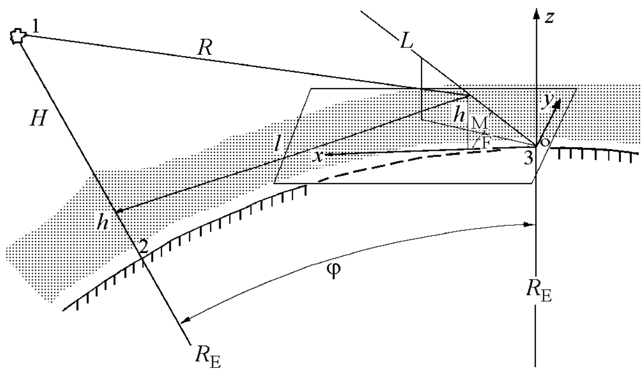

Figure 1. Geometry of the problem: 1 is the point of explosion, 2 is the explosion epicenter, 3 is the radio engineering device.

region. The analysis of development of such models (including the use of rigid methods of the function approximation theory) has shown that the most acceptable for practice is use, as approximating dependencies, of solutions of the simplified physical problems. Such problems make it possible to feel the main features of parameter distribution in the artificial ionization region (e.g., in LREI) and at the same time contain a small number of constants fitted to get the best agreement of the numerical simulation results (in our case by the methods described by *Kozlov* [1967, 1971], *Kozlov and Kudimov* [1969], and *Kozlov and Raizer* [1966]). Moreover, using fairly accurate methods of calculations of the main radiophysical effects, sometimes it is possible to estimate the unknown constants of the analytical model from the experimental data available.

[13] The distribution of the electron concentration in the lower atmosphere produced by the X ray and penetrating radiation of SNE is symmetrical relative the vertical axis. Therefore the LREI analytical model should depend on time and two spatial coordinates: the altitude h and distance l to the epicenter axis (Figure 1). For the approximation of the results of $N(t)$ calculations within LREI it is reasonably to use the dependencies which are obtained as a result of the solution of the simplified problem of falling of monochromatic emission at the angle θ to the vertical on a flat layer of the exponential atmosphere with constant scale height H_c containing particles of only one type ($N_n(h=0) = N_{n0}$)

$$N_n = N_{n_0} \exp\left\{-\frac{h}{H_0}\right\}$$

The number of the formed pairs of ionized particles is determined by the energy absorbed per second by the gas volume unit with the effective cross section σ is called the ionization rate J. To obtain the approximating dependence $N(t)$ we use the equations the Chapman layer [*Al'pert*, 1972], in particular (taking $N = N_i^+$) the ionization equation balance:

$$\frac{dN}{dt} = J_0 - \beta_0 N^2 \tag{5}$$

with the recombination coefficients β_0, cm^{-3} s^{-1} and ionization rate J_0, cm^{-3} s^{-1}. Then in the quasi-stationary conditions ($dN/dt \ll \beta_0 N^2$) the vertical distribution of the electron concentration takes the form

$$N(h) = N_M \exp\frac{1}{2}\left[1 - \frac{h-h_M}{H_0} - \exp\left(-\frac{h-h_M}{H_0}\right)\right] \tag{6}$$

The $N(h)$ maximum N_M is determined by the condition $dJ_0/dh = 0$ and is located at the altitude $h_M = H_0 \ln(N_{n0}\sigma H_0 \sec\theta)$. Thus, to describe $h_M(l)$, the dependence

$$h_M(l) = h_M(0) + (H_0/2)\ln\left(1 + \frac{l^2}{\Delta H^2}\right)$$

where $\Delta H = H - h_i(0)$, may be used. To take into account the deformation of the $N(h)$ vertical profile with time, we substitute the constants 1/2 and H_0 in equation (6) by the dependencies $\chi(t)$ and $h_m(t)$.

[14] Since the N level in LREI quickly decreases, the values of the effects caused by this region and by the ionosphere [see, e.g., *Kravtsov et al.*, 1983] become of the same order of magnitude. That is why one has to obtain a conjugation of the LREI analytical model to the ionospheric model. As the latter, the global phenomenological model [*Ching and Chiu*, 1973; *Chiu*, 1975] corrected for polar latitudes [*Vlaskov and Ogloblina*, 1981] is used. The N distributions within the altitude interval $h = 90 - 1000$ km obtained at 50 vertical sounding ionospheric stations present an experimental basis of the *Ching and Chiu* [1973] model. The observations were performed in 1957–1970, this interval including the time of carrying out nuclear explosions. The analytical expressions describing the polar part of the model were specified by *Vlaskov and Ogloblina* [1981] on the basis of 11 high-latitude stations of the Northern Hemisphere.

[15] We are interested in the intervals $t \leq 100$ s after the explosion moment. For these intervals one may neglect by the disturbance of the ionosphere by acoustic gravity waves propagating with a velocity less than 1 km s^{-1} [*Peterson*, 1967], because the region of their influence would not considerably exceed the dimensions of the ionized region of the explosion [see, e.g., *Lobolev*, 1997a, 1997b].

[16] The results of the calculations [*Kozlov*, 1967, 1971; *Kozlov and Kudimov*, 1969; *Kozlov and Raizer*, 1966; *Kozlov et al.*, 1982] show that a few minutes after the explosion moment independently on l the maximum in N_M is formed at a height of $h_M(0) \approx 70$ km. The performed studies show that the influence of the geometrical parameters of the medium on the values of the radiophysical effects is significantly (by about an order of magnitude) less than the influence of the gradients of the maximum electron concentration [*Misura*, 1973]. So taking into account the error in N calculations, taking into account of the h_m dependence on l looses sense. To describe the $N(l)$ distribution within LREI, it is enough to approximate the electron concentration distribution in the maximum $N_M(l)$. Neglecting the absorption of the radiation in the upper atmospheric layers down to the height of the nuclear explosion and taking into account the spherical divergence of the explosion radiation,

we obtain the dependence of J_0 at the height h_M

$$J_{M_0}(l) = \frac{J_M \Delta H}{(\Delta H^2 + l^2)^{3/2}} \equiv J_M F(l) \quad (7)$$

The initial distribution of the electron concentration at this height formed by the instant radiation will be $N_M(l) = N_{M_0}(0)\,F(l)$. If the ionization source is "switched off" ($J_0 = 0$), a solution of equation (5) with the found initial conditions is written in the form

$$N_M(l,t) = \frac{N_{M_0}(l)}{1 + \beta_0 N_{M_0}(l) t} \quad (8)$$

If one takes into account in equation (5) the variations with time of the intensity of gamma radiation of the fission fragments, it would lead to a substitution in equation (8) of the recombination coefficient β_0 by its effective value $\beta_{\mathrm{eff}}(l)$.

[17] Analysis of the fission fragments (e.g., after the "Starfish" explosion) shows [*D'Arcy and Colgate*, 1965] that since the first minutes the time decrease of the gamma radiation varies from $t^{-2.6}$ in the energy interval 9–13 MeV [see *D'Arcy and Colgate*, 1965, Figure 14] to t^{-2}, $t^{-1.5}$, and $t^{-1.2}$ for the energies 2.6–4, 0.9–2.6, and 0.02–0.9 MeV, respectively [*D'Arcy and Colgate*, 1965, Figure 9]. So in the simplified problem considered here we take the variation of the ionization source in the form $J_{M_0}(l)/t^2$, assuming

$$\sqrt{\frac{J_0}{\beta_0}} \ll N_{M_0}$$

In this case integrating (5) we obtain for $\beta_{\mathrm{eff}}(l)$

$$\beta_{\mathrm{eff}}(l) = \frac{2\beta_0}{(4\beta_0 J_M F(l) + 1)^{1/2} + 1} \quad (9)$$

As a basic spatial distribution of N at a height h_M it was more convenient to take not the initial distribution $N_{M_0}(l)$, but the $N_{M_{10}}(l)$ distribution for the 10 s time moment

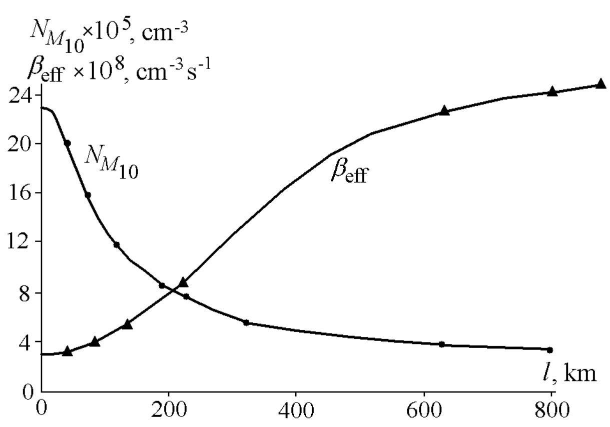

Figure 2. Approximation of the calculated (for q = 5000 kT, H = 150 km) distributions of $N_{M_{10}}(l)$ and $\beta_{\mathrm{eff}}(l)$ (points and triangles, respectively) by dependencies (10) and (9) (solid curves).

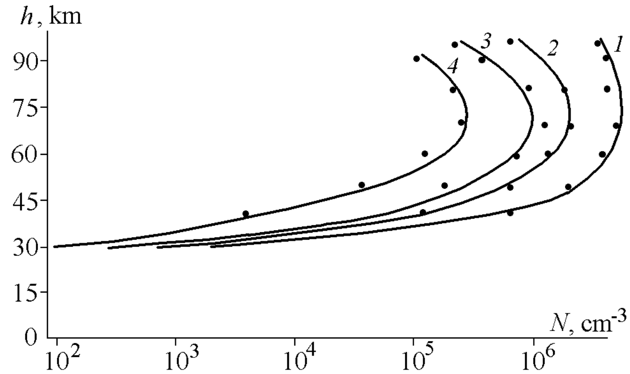

Figure 3. Approximation of the calculated (for q = 5000 kT, H = 150 km) distributions $N(h,t)$ (points) by dependence (11): curve 1, 1 s; curve 2, 10 s; curve 3, 30 s; and curve 4, 100 s.

$$N_{M_{10}}(l) = \frac{1}{20\beta_0}\left[(4\beta_0 J_M F(l) + 1)^{1/2} + 1\right] \quad (10)$$

Then the spatial-time distribution of the electron concentration in LREI may be described by

$$N(h,l,t) = \left\{N_{M_{10}}(l)\exp\left\{\chi(t) \times \left[1 - \frac{h-h_M}{h_m(t)} - \exp\left(-\frac{h-h_M}{h_m(t)}\right)\right]\right\}\right\} \Big/ \left[1 + \beta_{\mathrm{eff}}(l) N_{M_{10}}(l)(t-10)\right] \quad (11)$$

The values of the J_M constants in (9) and (10) we will further assume to be different $J_M \equiv J_{M_\beta}$ and $J_M \equiv J_{M_N}$, respectively.

[18] As an example, Figures 2 and 3 show the results of the approximation by dependencies (9)–(11) of the N calculations in LREI for the SNE with q = 5000 kT and H = 150 km. Points correspond to the numerical simulations [*Kozlov*, 1967, 1971; *Kozlov and Kudimov*, 1969; *Kozlov and Raizer*, 1966; *Kozlov et al.*, 1982]. The constants fitted for approximation are $J_{MN} = 13.16 \times 10^{11}$ s cm^{-1}, $J_{M\beta} = 35.36 \times 10^{11}$ s cm^{-1}, $\beta_0 = 2.9 \times 10^{-7}$ cm^3 s^{-1}, h_M = 70 km, and ΔH = 100 km. For χ and h_M the following dependencies are taken:

$$\chi(t) = \frac{t+8}{36} \qquad h_m(t) = 54.5\left(6.9 + \ln\frac{1+\frac{t}{700}}{t+7}\right)^{-1}$$

where t is measured in seconds.

4. LREI Model

[19] In the LREI model (11) the spatial coordinates are h and the distance to the epicenter axis l (see Figure 1).

To obtain the explicit solution of equations (3) and (4) by the method of variable separation [*Semenov,* 1974] in the analytical model (11), one is able only in the case of remote from the epicenter vertical sounding of LREI, or in the cases ($J_{M_\beta},\ J_{M_N} \ll \Delta H^2/4\beta_0$), when one can neglect the horizontal gradients. The latter situation takes place during SNE of relatively small equivalents occurring at considerable distances from the Earth when the LREI influence on the radio wave propagation is insignificant. We here are interested in cases of the strongest impact of LREI on the operation of radio systems when one cannot separate the variables in equations (3) and (4) for model (11). However, one can easily see (see, e.g., Table 1 and equations (2) and (11)) that under $t \geq 1$ s and $\omega \geq 10^9$ s^{-1} $\alpha_M = \max|\alpha(h,l,t)| \leq 10^{-2}$; so to obtain approximate solutions of this equations, one should use the small perturbation method [*Kravtsov et al.*, 1983]. Actually, even the first approximation of this method makes it possible to provide the needed accuracy of the calculations of the main radiophysical effects occurring at the propagation of the radio waves with $\omega \geq 10^9$ s^{-1} through LREI.

[20] To develop methods of calculations of radiophysical effects on the basis of the analytical models of $N(h,l,t)$, one has to obtain the dependence of its spatial coordinates h and l on the angular coordinates of the object observation (M and F) measured by a radio engineering device and on the current distance r ($0 \leq r \leq L$) under the given values of the geographical coordinates of the explosion epicenter (φ_1, λ_1) and the radio engineering device in question (φ_2, λ_2). In Figure 1, L designates the distance to the observed object, the elevation angle M and azimuth angle F are calculated from the horizontal plane in the point of the radio engineering device location and from the direction to the explosion in this plane, respectively. We have the following expressions for the above indicated dependencies

$$l^2 = R_E^2 \sin^2\varphi \sec^2\left(D + \frac{\varphi}{2}\right) + r^2$$

$$-2R_E r \sin\varphi \sec\left(D + \frac{\varphi}{2}\right)$$

$$\times\left[\cos\left(D - \frac{\varphi}{2} - M\right) - 2\sin^2\frac{F}{2}\cos M \cos\left(D - \frac{\varphi}{2}\right)\right]$$

$$h = (R_E^2 + r^2 + 2R_E r \sin M)^{1/2} - R_E \qquad (12)$$

where

$$\cos\varphi = \cos\varphi_1\cos\varphi_2\cos(\lambda_2 - \lambda_1) + \sin\varphi_1\sin\varphi_2 \qquad (13)$$

$$D \equiv \arctan\left(\frac{2R_E r \sin M + r^2}{4R_E^2 + 2R_E r \sin M + r^2}\cot\frac{\varphi}{2}\right)$$

and R_E is the Earth radius.

[21] Solving equation (3) by the perturbation method the following formulae were obtained for the refraction errors of the measurements of the observed object angular coordinates ($\Delta M = M - M_i$, $\Delta F = F - F_i$) [*Gdalevich et al.*, 1963]:

$$\Delta M = -\frac{1}{2}\int_0^L \left(\frac{1}{r} - \frac{1}{L}\right)\frac{\partial\alpha(h,l,t)}{\partial M}dr \qquad (14)$$

$$\Delta F = -\frac{1}{2\cos M_0}\int_0^L \left(\frac{1}{r} - \frac{1}{L}\right)\frac{\partial\alpha(h,l,t)}{\partial F}dr \qquad (15)$$

For the errors in the group delay ΔL_{gr} the phase path length ΔL_{ph} and the component of the Doppler frequency shift caused by the medium nonstationarity $\Delta\omega_n$ (they determine the error in the determination of the distance and velocity of the observed object) the following formulae are obtained in the first approximation:

$$\Delta L_{gr} = -\Delta L_{ph} = \frac{1}{2}\int_0^L \alpha(h,l,t)dr \qquad (16)$$

$$\Delta\omega_n = \frac{\omega}{2c}\int_0^L \frac{\partial\alpha(h,l,t)}{\partial t}dr \qquad (17)$$

The medium parameter distributions $\alpha(h,l,t)$ and their partial derivatives with respect to the spatial coordinates and time are determined by

$$\alpha(h,l,t) = \alpha_{M_{10}}(l)\frac{A(h,t)}{B(l,t)} \qquad (18)$$

$$\frac{\partial\alpha(h,l,t)}{\partial M} = \alpha_{M_0}(l)\frac{A(h,t)}{B^2(l,t)}$$

$$\times\left\{\left[N_{M_{10}}^{-1}(l)\frac{\partial N_{M_0}(l)}{\partial l^2} - N_{M_0}(l)\frac{\partial\beta_{\text{eff}}(l)}{\partial l^2}(t-10)\right]\frac{\partial l^2}{\partial M}\right.$$

$$\left.+\frac{r\chi(t)}{h_m(t)}B(l,t)N_{M_0}(l)\cos M\left[\exp\left(\frac{h-h_M}{h_m(t)}\right) - 1\right]\right\} \qquad (19)$$

$$\frac{\partial\alpha(h,l,t)}{\partial F} = -\alpha_{M_0}(l)\frac{A(h,t)}{B^2(l,t)}\left[N_{M_{10}}^{-1}(l)\frac{\partial N_{M_0}(l)}{\partial l^2}\right.$$

$$\left.-N_{M_0}(l)\frac{\partial\beta_{\text{eff}}(l)}{\partial l^2} - (t-10)\right]\frac{\partial l^2}{\partial F} \qquad (20)$$

$$\frac{\partial\alpha(h,l,t)}{\partial t} = -\alpha_{M_0}(l)\frac{A(h,t)}{B^2(l,t)}N_{M_{10}}(l)\beta_{\text{eff}}(l) \qquad (21)$$

One can neglect the terms proportional to $h'(t)$ and $\chi'(t)$ in equation (21) not exceeding the error of the order of a few percent. In equations (18)–(21),

$$\alpha_{M_{10}}(l) = \frac{4\pi e^2}{m\omega^2} N_{M_{10}}(l)$$

$$B(l,t) = 1 + \beta_{\text{eff}}(l) N_{M_{10}}(l)(t-10)$$

$$A(h,t) = \exp\left\{\chi(t)\left[1 - \frac{h-h_M}{h_m(t)} - \exp\left(-\frac{h-h_M}{h_m(t)}\right)\right]\right\}$$

$$\frac{\partial N_{M_{10}}(l)}{\partial l^2} = -\frac{3}{20} J_{M_N} \frac{F(l)}{\Delta H^2 + l^2} \left[4\beta_0 J_{M_N} F(l) + 1\right]^{-1/2}$$

$$\frac{\partial \beta_{\text{eff}}(l)}{\partial l^2} = \frac{6\beta_0^2 J_{M_\beta} F(l)}{\Delta H^2 + l^2} \left[4\beta_0 J_{M_\beta} F(l) + 1\right]^{-1/2} \times \left\{\left[4\beta_0 J_{M_\beta} F(l) + 1\right]^{1/2} + 1\right\}^{-2}$$

$$\frac{\partial l^2}{\partial M} = 2R_E \sin\varphi \sec\left(\frac{\varphi}{2} + D\right) \times \left\{\left[R_E \sin\varphi \tan\left(\frac{\varphi}{2} + D\right) - r\sin(M+\varphi) + 2r\sin\varphi\cos M \sin^2\frac{F}{2}\right] \times \sec\left(\frac{\varphi}{2} + D\right)\frac{\partial D}{\partial M} - r\sin\left(D - \frac{\varphi}{2} - M\right) - 2r\cos\left(D - \frac{\varphi}{2}\right)\sin M \sin^2\frac{F}{2}\right\}$$

$$\frac{\partial l^2}{\partial F} = 4R_E r \sin\varphi \cos M \sin F \sec\left(D + \frac{\varphi}{2}\right) \times \cos\left(D - \frac{\varphi}{2}\right)$$

where

$$\frac{\partial D}{\partial M} = \left(8R_E^3 r \cos M \cot\frac{\varphi}{2}\right) \Big/ \left[\left(4R_E^2 + 2R_E r \sin M + r^2\right)^2 + \cot^2\frac{\varphi}{2}\left(2R_E r \sin M + r^2\right)^2\right]$$

It should be noted that the Doppler shift of the frequency caused by the influence of the medium is due to both the motion of the object itself and nonstationarity of the medium along the radio wave propagation path. The first component of this shift is of the same order of magnitude as for the natural ionosphere [see, e.g., *Kravtsov et al.*, 1983], so here we consider only the second component (17). Calculating the integrals included to equations (14)–(17), each of them is split to two parts. The first is determined by the LREI parameters and integration is performed from r_1 to r_c. The calculation of the second part determined by the parameters of the natural ionosphere is performed from r_c to L. If the condition $L < r_c$ is fulfilled, integration in equations (14)–(17) is limited only by the boundaries of the lower region and is performed from r_1 to L. The values of r_1 and r_c are given by

$$r = R_E\left[\left(\sin^2 M + \frac{2h}{R_E} + \frac{h^2}{2R_E^2}\right)^{1/2} - \sin M\right] \tag{22}$$

into which either $h = 30$ km or the height of the conjugation of the lower region to the ionosphere $h = 90$ km is substituted, respectively.

[22] Solution of equation (4) for the field amplitude is written as [*Semenov*, 1974]

$$\Phi^2 = \Phi_0^2 \frac{D(0)}{D(\tau)} \exp\left(-k\int_0^L \alpha S d\tau\right) \equiv \Phi_0^2 \frac{D(0)}{D(\tau)} \exp(-\delta)$$

Expanding the Jacobian $D(\tau)$ in terms of the small parameter α_m, one can show [*Kravtsov et al.*, 1983] that for a regular inhomogeneous ionosphere the correction of the first order $D_1(\tau)$ is small as compared to the zero approximation $D_0(\tau)$. Therefore calculating the field amplitude Φ in our case it is enough to take into account only the spherical divergence of the rays and calculation of the attenuation δ in the first approximation ($d\tau \approx dr$)

$$\delta = \frac{\omega}{c}\int_0^L \alpha(h,l,t)\frac{S(h)}{1+S^2(h)}dr \tag{23}$$

Here expression (18) is used for $\alpha(h,l,t)$. Writing equation (23), we did not neglect S^2 in comparison to 1 in the imaginary part of ε (see equation (1)) because at heights of 30–40 km the inequality $\nu_{\text{eff},\,en}/\omega \ll 1$, generally speaking is not fulfilled for $\omega \geq 10^9$ s^{-1}. According to the experimental data [*Al'pert*, 1972; *Gringauz*, 1966] obtained by different methods for $h \leq 100$ km the effective collision frequency ν_{eff} fairly well is described by the exponential dependence (see Figure 4)

$$\nu_{\text{eff},en}(h) = \nu\exp\left(-\frac{h}{H_0}\right) \tag{24}$$

where the values $\nu_0 = 1.1 \times 10^{11}$ s^{-1} and $H_0 = 7.1$ km are fitted for the ν_0 and H_0 parameters. Calculating the attenuation the usage of the LREI analytical model (11) does not

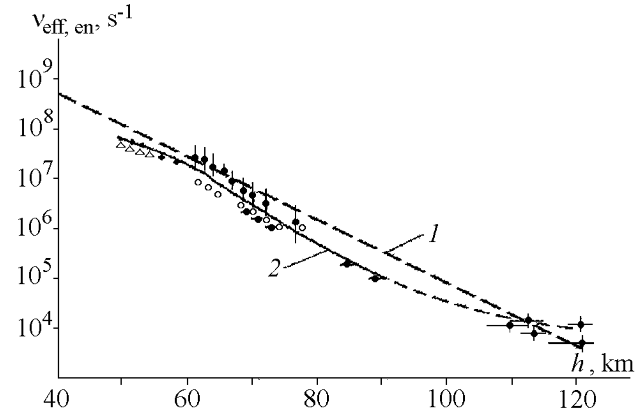

Figure 4. Dependence of the effective collision frequency on altitude: curve 1, $\nu_{\text{eff},en}(h) = \nu_0 \exp(-h/H_0)$, where $\nu_0 = 1.1 \times 10^{11}$ s^{-1} and $H_0 = 7.1$ km; and curve 2, calculation by the formula obtained by *Phelps and Pack* [1959] on the basis of laboratory measurements.

provide the relative error required because its value is determined not only by the accuracy of the $N(h,l,t)$ approximation, but depends on the quality of the approximation of the product $N(h,l,t)\nu(h)$. To provide the methodical error of the order of a few percent while calculating the attenuation one should model the N values by the methods described by *Kozlov* [1967, 1971], *Kozlov and Kudimov* [1969], and *Kozlov and Raizer* [1966] along the ray connecting the radio-engineering device and the observed object. In other words, the initial electron concentrations are determined along the ray in question and then the decrease of N in these points is calculated up to the time moment needed. Doing this one has to obtain the distance R_i from the explosion point to the points with the coordinates M, F, and r_i at the ray having a height of h_i,

$$R_i = \left[(H-h_i)^2 + l_i^2 \frac{R_E + H}{R_E + h_i}\right]^{1/2}$$

where l_i is determined by equations (22) and (12). Further calculation of the attenuation (23) is performed in a similar way to the calculation of the integrals in equations (14)–(17). Such approach provides the required methodical error in simulation of the wave attenuation in LREI, however increases the time needed for the calculations.

[23] Using the method described above, the calculations of the attenuation, group delay, Doppler frequency shift and azimuthal refraction as functions of the radiotechnical coordinates of the object in the wide range of H and q were performed. The results show that the main radiophysical effect influencing propagation of the radio waves with $\omega \geq 10^9$ s^{-1} through LREI is the attenuation. For the Doppler systems operating at frequencies $\omega \gg 10^9$ s^{-1}, the Doppler frequency shift reaching at $\omega = 10^9$ s^{-1} at $t \approx 1$ s the value of $\Delta\omega_L \leq 1$ kHz may present an exception. As an example, Figures 5–8 show the values of these effects at the working frequency $\omega = 10^9$ s^{-1} for the explosion with $q = 5000$ kT at $H = 150$ km, distanced from the radio engineering device by $b = 335$ km, at different elevation angles of the observed object M and $F = 10°$. The value of b was found by

$$b = [H^2 + 2R_E(R_E + H)(1 - \cos\varphi)]^{1/2}$$

5. Asymptotic Estimates of the Attenuation

[24] Since the conditions of the radio wave propagation through LREI are determined mainly by the attenuation, the main amount of calculations falls on the calculation of the latter, the simulation of the attenuation with the relative error of the order of a few percent takes a lot of time. It should be noted that such a high accuracy of calculations is needed to provide a control of the errors of the numerical simulation of the electron concentration in LREI on the basis of the physical measurements. At the same time, to perform mass calculations of the attenuation with the errors not exceeding the accuracy of the N simulation in LREI [*Kozlov*, 1967, 1971; *Kozlov and Kudimov*, 1969; *Kozlov and Raizer*, 1966], one can obtain simple asymptotic formulae making possible to evaluate the attenuation value with the accuracy of the order of a few tens of percent.

[25] To do that, neglecting the terms of the order of h^2/R_E^2, we integrate equation (23) with respect to h and (taking into account equation (2)) rewrite the integrand in the full form

$$\delta = \frac{4\pi e^2}{mc} \int_{h_1}^{h_c} \frac{N(h,l,t)\nu_{\text{eff},\,en}(h)}{\omega^2 + \nu^2_{\text{eff},\,en}(h)} K(h)dh \qquad (25)$$

where $N(h,l,t)$ and $\nu_{\text{eff},\,en}(h)$ are determined by equations (11) and (24), respectively, and

$$K(h) = \frac{1}{\sqrt{\sin^2 M + 2h/R_E}} \qquad (26)$$

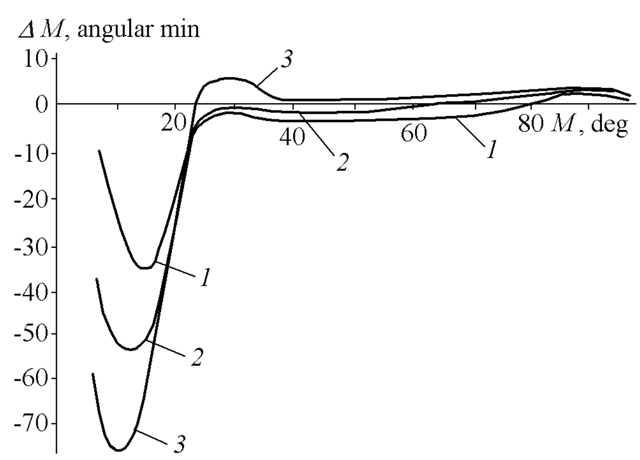

Figure 5. Dependence of the elevation-angle refraction error on the elevation angle M at the time moment $t = 3$ s (for $q = 5000$ kT, $H = 150$ km, and $F = 10°$): curve 1, $L = 500$ km; curve 2, $L = 1000$ km; and curve 3, $L = 2000$ km.

Evaluating integral (25) by the mountain pass method, we obtain for the radio waves with $\omega \geq 10^9$ s^{-1} the value of the attenuation in LREI expressed in decibels

$$\delta(t) = 1.153 \times 10^3 \frac{h_m}{\sqrt{\chi}} K(h_0)$$

$$\times \frac{N(h_0, l_0, t)\, \nu_{\mathrm{eff},\, en}(h_0)}{\omega^2 + \nu^2_{\mathrm{eff},en}(h_0)} \exp\left(\frac{h_0 - h_M}{2h_m}\right) \qquad (27)$$

Here

$$h_0 = h_M - h_m \ln\left(1 + \frac{h_m}{\chi H_0}\right)$$

$$\Delta H = H - h_0$$

and l_0 with the given coordinates (M, F) of the observed object, geographic coordinates of the explosion (φ_1, λ_1) and the radio engineering device (φ_2, λ_2) are calculated for $h = h_0$ using formulae (12) and (13), where

$$r = R_E \left[\left(\sin^2 M + \frac{2h_0}{R_E}\right)^{1/2} - \sin M\right]$$

$$D = \arctan\left(\frac{h_0}{2R_E + h_0} \cot\frac{\varphi}{2}\right)$$

[26] The parameters entering equation (27) and other formulae and used to calculate attenuation are fitted to provide the best approximation of the LREI calculation results obtained on the basis of the Kozlov method [*Kozlov*, 1967, 1971; *Kozlov and Kudimov*, 1969; *Kozlov and Raizer*, 1966]. These values for a wide range of equivalents $q = 300 \div 10{,}000$ kT and explosion altitudes $H = 150 \div 500$ km are shown in Table 2. Moreover, the interpolation formulae are obtained for the values J_{M_β}, s cm^{-1}; J_{M_N}, s cm^{-1}; and h_m, km:

$$J_{M_\beta} = 1.8 \times 10^{11} \left(\frac{q}{5000}\right)\left(\frac{300}{H}\right) - 0.64 \times 10^{11} \qquad (28)$$

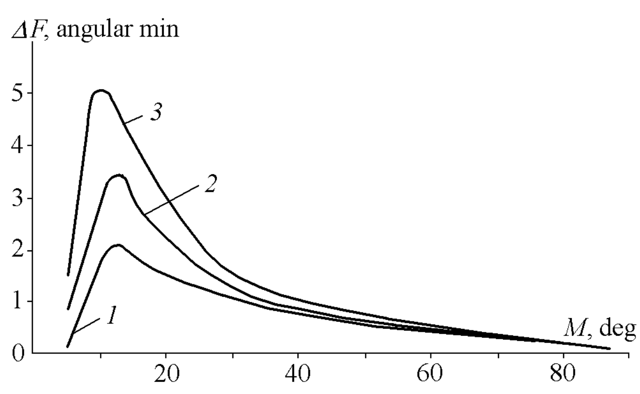

Figure 6. Dependence of the azimuthal refraction error on the elevation angle M at the time moment $t = 3$ s (for $q = 5000$ kT, $H = 150$ km, and $F = 10°$): curve 1, $L = 500$ km; curve 2, $L = 1000$ km; and curve 3, $L = 2000$ km.

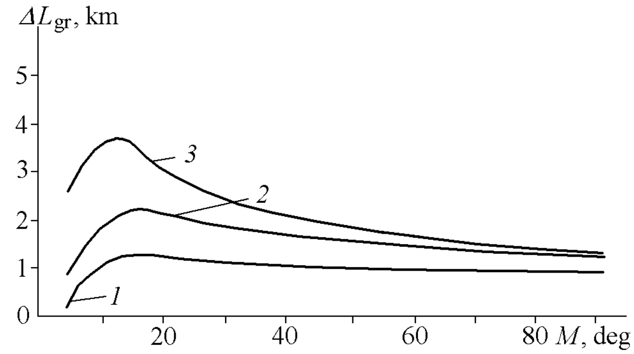

Figure 7. Dependence of the group delay on the elevation angle M at the time moment $t = 3$ s (for $q = 5000$ kT, $H = 150$ km, and $F = 10°$): curve 1, $L = 500$ km; curve 2, $L = 1000$ km; and curve 3, $L = 2000$ km.

$$J_{M_N} = 6.7 \times 10^{11} \left(\frac{q}{5000}\right)\left(\frac{300}{H}\right) - 0.24 \times 10^{11} \qquad (29)$$

$$h_m = \Theta\left(\xi + \ln\frac{1 + t/\gamma}{1 + \zeta}\right)^{-1}$$

$$\chi = \frac{H(t + 8)}{5400} \qquad (30)$$

where $\theta = 47 + 0.05H$, $\gamma = 625 + 0.5H$, $\xi = 7.1 - 0.00133H$, and $\zeta = 8.5 - 0.01H$. The values of t, H, and q are measured in sec, km, and kT, respectively.

[27] As an example, the asymptotic estimates of the attenuation in LREI are calculated using equation (27) and formulae for the values included into equation (27). The calculations were performed for the working frequency $\omega = 10^9$ s^{-1} for the explosion with $q = 5000$ kT conducted at

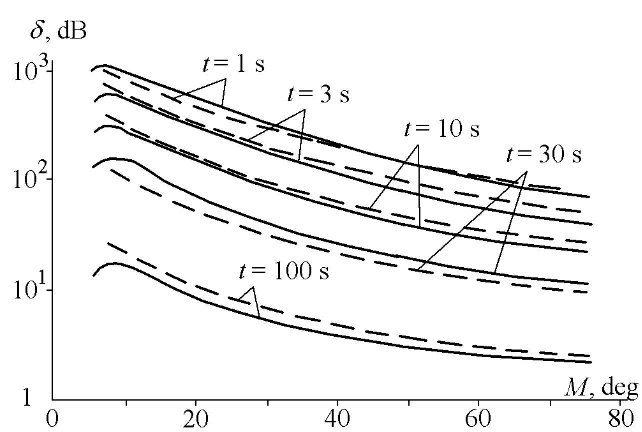

Figure 8. Dependence of the attenuation on the elevation angle M (for $q = 5000$ kT, $H = 150$ km, and $F = 10°$): calculations with the methodical error of a few percent (solid curves); asymptotic estimates with the error of the order of tens of percent (dashed curves).

Table 2. Parameters Included in Equation (27) and Other Formulae Fitted to Provide the Best Approximation of the LREI Simulation Results by the Kozlov Method †

q, kT	$J_{M_\beta},\ J_{M_N}$					
	$J_{M_\beta} \times 10^{-11}$			$J_{M_N} \times 10^{-11}$		
	$H = 150$ km	$H = 300$ km	$H = 500$ km	$H = 150$ km	$H = 300$ km	$H = 500$ km
300	1.52	0.44	0.008	0.564	0.162	0.001
1000	6.56	2.96	1.52	2.44	1.10	0.564
5000	35.36	17.36	10.16	13.16	6.46	3.78
10,000	71.36	35.36	20.96	25.56	13.16	7.80

† The Kozlov method is from *Kozlov* [1967, 1971], *Kozlov and Kudimov* [1969] and *Kozlov and Raizer* [1966].

$H = 150$ km and distanced from the radio engineering device by $b = 335$ km and are presented in Figure 8 (dashed curves).

6. Conclusions

[28] Concluding, we emphasize once more that the estimation of the accuracy of numerical simulation of the N distribution in LREI is a rather complicated problem. It may seem that the simplest way to determine the error ΔN is a comparison of the N simulation results to its values measured by rockets. However, the errors in measurements of local values of N during the first tens of seconds after an explosion may reach unacceptably large values (up to an order of magnitude) due to the increase in the radiation level (if probe methods of measurements are used) and the medium nonstationarity along the radio wave propagation path (if the dispersion interferometer is used).

[29] In these conditions a special attention should be drawn to the measurement methods based on radiolocation of the ionospheric plasma and analysis of the parameters of radio wave propagating in the ionosphere [see, e.g., *Al'pert*, 1972; *Galkin et al.*, 1971]. It is worth noting that many very popular methods (the methods of pulse radiosounding, partial reflection, incoherent scatter and others) are not acceptable for studying LREI at $t \leq 100$ s after the explosion due to the high level of the radio wave absorption. In the short-wave range (used for radiophysical measurements of the medium parameters) at the first seconds after the explosion according to equation (1) the condition $\varepsilon' \sim \varepsilon''$ is fulfilled in LREI. In this case it is impossible to find if the exponential depletion of the field is due to the absorption or to the exit into the caustic shadow. Irregularity of the absorption in such medium initiates the emission diffusion into the regions with the stronger absorption [*Kravtsov*, 1967]. One can show that the trajectory of the electromagnetic energy of the SW range waves in LREI is influenced by the distribution in it of not only real but imaginary part of the plasma permeability as well.

[30] It follows from the performed studies that the conditions of radio wave propagation though LREI are mainly determined by the attenuation. Therefore evaluating the accuracy of the N numerical simulation in the lower ionosphere one should concentrate attention on methods of absorption measurements. Such methods are [*Galkin et al.*, 1971] the method of the vertical sounding of the ionosphere (A1), method of registration of the extraterrestrial sources (A2), method of registration of the field strength of the signal from a remote radio station operating in permanent regime (A3), and others. We note that the A1 method is not acceptable for measurements of the radio wave attenuation in LREI because of a high level of the attenuation and the most suitable and often used is the A2 method (see, for example, the review by *Belikovich and Benediktov* [1969]).

[31] The remote measurements of the $N(h)$ vertical profile within LREI on the basis of the absorption $\delta\omega$ measured by the A2 method are based on the solution relative to $N(h)$ of integral equation (25). *Belikovich et al.* [1964] reduced equation (25) to the Fredholm equation of the first type with the residual kernel and obtained a general formula for calculation of $N(h)$ from the $\delta(\omega)$ curve. It follows from this solution that to find N at some height h_i, it is enough to know $\nu_{\rm eff}$, $d\nu_{\rm eff}/dh$ and the attenuation function $\delta(\omega)$ with its frequency derivatives $\omega = \nu_{\rm eff}(h_i)$. To obtain the $N(h)$ profile within the height interval $h = 40 - 80$ km one has to have measurements of these values in the frequency range from a few megahertz to hundreds of megahertz. Unfortunately, there are no experimental values of the radio wave absorption in the needed amount and with acceptable accuracy [*Belikovich and Benediktov*, 1973; *Zhulin*, 1964].

[32] At the same time, the available measurements of attenuation at various frequencies make it possible not only to estimate the errors of the simulation results of the absorption in LREI but to check the errors in simulation of N. Actually, the errors in measurements of radio wave attenuation $\Delta\delta/\delta$ are of a few percent [see, e.g., *Belikovich and Benediktov*, 1973, Figure 1], so we principally are able to control the errors in the attenuation calculations with very high accuracy. Using the algorithm developed above (the methodical error of which does not exceed a few percent), we may the entire discrepancy between the calculated and measured values of the attenuation explain by the error in N simulation in the conditions of SNE. At the same time, asymptotic estimates (27) show that at correct enough ap-

proximation of the values of $\nu_{\text{eff}}(h)$ (see curve 2 in Figure 4) the relative error $\Delta N/N \sim \Delta\delta/\delta$. Thus the method of attenuation measurements used during the experimental SNE makes it possible to check the error in simulation of N with the accuracy of a few percent. However, as far as the radio wave absorption within LREI is determined by integral (25), to provide such error in simulation of the $N(h)$ profile one needs the corresponding accuracy of agreement between the simulation results and the measured values of attenuation within the entire frequency range (from a few megahertz to a thousand and more megahertz). For the frequencies from a few megahertz to hundreds of megahertz one has to take into account fairly correctly the level of the synchrotron radioemission of the high-energy electrons of the artificial radiation belt formed during SNE [*Peterson*, 1967; *Zhulin*, 1964].

[33] It has been mentioned above that the results of the numerical simulation of N in the frequency range from 100 to 1000 MHz [*Kozlov*, 1967, 1971; *Kozlov and Kudimov*, 1969; *Kozlov and Raizer*, 1966] have an error of tens of percent. For the lower boundary of this range the calculated values of the attenuation by 50–90% exceed the experimental values. For the upper boundary the simulation results are by about the same value lower than the experimental data. Therefore the $N(h,t)$ profile from *Kozlov* [1967, 1971], *Kozlov and Kudimov* [1969], and *Kozlov and Raizer* [1966] strictly speaking is not able to explain the frequency dependence of $\delta(\omega)$ in the frequency range from a few megahertz to 1000 MHz obtained experimentally.

[34] For the sake of objectivity, one has to note that during the recent years a series of papers has appeared [*Kozlov*, 1987a, 1987b; *Kozlov et al.*, 1982, 1988, 1990; *Smirnova et al.*, 1984; *Vlaskov et al.*, 1983]. These papers in our opinion make it possible to improve considerably the method of numerical simulation of the spatial-time distribution of N in LREI of SNE and achieve an agreement between the simulation results and experimental data in the entire frequency range. The decrease of the considered interval down to a few megahertz provides a need to study the electron-ion balance kinetics of the ionosphere disturbed by the explosion up to F region heights [see, e.g., *Dyadichev and Kozlov*, 1976]. Development of a specified mode on the basis of these publications requires more attentive choice of the reaction rate constants currently determined within a rather broad interval, specification of the initial data on the explosives, atmospheric state etc. Specifying this model in the regions located at the periphery of the direct visibility from the explosion point, one should consider in more detail the problem of propagation of penetrating radiation in the inhomogeneous atmosphere [*Lobolev*, 1997a, 1997b; *Kukhtevich and Mashkovich,* 1979]) and provide taking into account the voluminous character of this radiation source and its motion in space.

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