From what was presented above it follows that in the case of $\omega_h < 2\omega_H$ the types of trajectories possible near the upper hybrid resonance are analogous to those examined earlier in the region of frequencies $\omega \approx \omega_p$ if $\omega_p > \omega_H$ [3, 12]. An important difference is that reverse waves propagate when $\omega \approx \omega_h$ and $\omega_h < 2\omega_H$, while the waves are direct when $\omega \approx \omega_p$ and $\omega_p > \omega_H$. Trajectories of the loop type are possible in both cases [3, 7, 12], however, and the criteria for the formation of such trajectories are analogous.

In conclusion, the author thanks B. N. Gershman for a discussion of the results.

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RESONANCE EFFECTS IN THE EARTH – IONOSPHERE CAVITY

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UDC 621.371.25

Natural oscillations of an electrical type in the earth – ionosphere cavity are analyzed with allowance for the height profiles of the plasma parameters of the lower ionosphere. Besides the well-known branch of natural frequencies corresponding to Schumann resonances (ones and tens of hertz) new resonance frequencies are obtained in the range of ones of kilohertz. The problem of forced oscillations of the cavity is solved within the framework of the same model of the ionosphere. The resonance parameters of the energy and cross spectra are compared with allowance for the suppression of interference.

The spherical cavity formed by the earth's surface (conductance on the order of 10^{10}) and the lower ionosphere (conductance on the order of 10^4) represents an electromagnetic resonator in a wide range of frequencies from ones of hertz to ones of kilohertz.

The resonance cavity is bounded below by the sphere $r = a$ at which the jump in conductance reaches values on the order of 10^{10}. The upper diffuse boundary is formed by the plasma of the lower ionosphere in which the particle concentration increases with height. The ionosphere is in the constant magnetic field of the earth and represents, generally speaking, a medium with double refraction [1, 2].

Institute of Radiophysics and Electronics, Academy of Sciences of the Ukrainian SSR. Translated from Izvestiya Vysshikh Uchebnykh Zavedenii, Radiofizika, Vol. 20, No. 4, pp. 501-509, April, 1977. Original article submitted November 17, 1975.

The solution of the problem of the natural or forced oscillations of the resonator with allowance for all its properties encounters insuperable difficulties. Therefore, simplified cavity models are usually used. The simplest of them has been the model of an ideal resonator [3], within the framework of which Schumann obtained the following spectrum of natural frequencies:

$$f_n = \frac{c}{2\pi a}\sqrt{n(n+1)}. \tag{1}$$

Here c is the velocity of light in a vacuum, a is the radius of the earth, and n is the number of the resonance mode. In particular, $f_1 = 10.6$, $f_2 = 18.3$, $f_3 = 26.0$ Hz, etc. A whole series of more complicated models allowing one to take into account one or another properties of the resonator, such as the gyrotropy of its upper wall, were suggested later [4-10].

In the present report we will not take into account the effect of the geomagnetic field and the angular nonuniformity of the ionosphere, which lead to removal of the degeneracy of the natural frequencies. Principal attention will be paid to oscillations of the E-type in a resonator bounded above by the ionosphere, isotropic and uniform over the angular coordinates, the parameters of which vary with height.

Even the first experimental studies showed that the observed resonance frequencies of 8, 14, 20, and 26 Hz [11-13] differ considerably from those predicted in the model of an ideal resonator. This discrepancy could be removed only through the use of models which allowed for the variation of the conductance of the ionosphere with height. Thus, for stepped models [13, 14] it was possible to connect the experimentally observed parameters with the characteristics of the ionization profile: the heights of the beginnings of the steps and their conductances. The parameters of the two-step model can be determined from the first four resonance frequencies or from the resonance frequencies and qualities of the first two modes of oscillations [13]. Attempts were made to analytically solve the eigenvalue problem within the framework of some sufficiently general smooth profile of the lower ionosphere. It was assumed that the parameters of the profile are determined from a comparison of the calculated and experimental data. The first work of this type was that of Galejs (see [9] and the bibliography to it).*

With such an approach the choice of a model of one type or another is arbitrary, generally speaking. The results of calculation and experiment are compared from the resonance parameters of not more than five modes, since the higher modes are not stably observed. It is not surprising that the "correct" values of the frequencies and qualities can be obtained within the framework of the most dissimilar models. (All the height profiles which allow one to solve the problem in known algebraic or transcendental functions are known for waves of the E-type in a spherical coordinate system with a permittivity $\varepsilon = \varepsilon(r)$ [15].)

Obviously, it is not enough to require the simple coincidence of a finite number of calculated and experimental parameters; it is also necessary that the chosen model correctly describe the general laws of behavior of $\varepsilon(r)$ with variation in height, which are known from geophysics [10, 14, 19]. Unfortunately, not one of the analytical profiles [9, 15] satisfies this condition.

As a result, the problem of the resonance oscillations of the earth – ionosphere cavity within the framework of a smooth height profile $\varepsilon(r)$ must be solved numerically. Below we will describe an algorithm for such a solution with an arbitrary height profile of the concentration of both electrons and ions. In principle by having a set of solutions for different profiles based on some geophysical data or other and by comparing the results of the calculations with experimental data one can choose the most "realistic" profile. Such an approach to the solution of the stated problem was first applied in [10], where the earth – ionosphere resonator was modeled with a two-dimensional transmission line.

The use of the described algorithm within the framework of one of the realistic models made it possible, as will be shown in the first part of the present report, to obtain not only the Schumann resonance frequencies, but also the resonance parameters of higher types of oscillations.

The experimental data on the Schumann resonance, with which the results of the calculations are compared, are characterized by a certain error. It is connected not only with the apparatus, but also with the experimental method used. Therefore, when one and the same experimental installation is used the accuracy of the choice of a height profile of the ionosphere essentially depends on the method of the measurements and the analysis of the data. In the second part of the report the various methods of measurement are compared using computer modeling and the one which gives the most reliable results is indicated.

*A rather complete and detailed presentation of the results of work on the Schumann resonance can be found in the monograph [23].

In the solution of the problem of the natural frequencies the properties of the ionosphere will be taken into account with the help of the complex permittivity $\varepsilon(r)$, the values of which are determined by the electron and ion concentrations and by the frequency of collisions of electrons with other particles. For simplicity, we will consider the axisymmetric problem, i.e., $\partial/\partial\varphi = 0$. Then from the system of Maxwell's equations, after the introduction of the Hertz vector $\mathbf{\Pi} = \Pi \mathbf{e}_r$, where $\mathbf{e}_r$ is the radial unit vector, we obtain [16]

$$\frac{\partial^2}{\partial r^2}\Pi + \frac{1}{r^2 \sin\theta}\frac{\partial}{\partial\theta}\left(\sin\theta\frac{\partial\Pi}{\partial\theta}\right) + \left[k^2\varepsilon(r) - \sqrt{\varepsilon(r)}\frac{d^2}{dr^2}\left(\frac{1}{\sqrt{\varepsilon(r)}}\right)\right]\Pi = 0. \tag{2}$$

Here $k = \omega/c$ is the wave number and a time dependence of the type $e^{-i\omega t}$ is assumed. The scalar function Π must satisfy the following condition at the lower boundary of the resonator:

$$\frac{\partial}{\partial r}\Pi = -ik\delta\Pi\Big|_{r=a}, \tag{3}$$

where δ is the reduced surface impedance of the earth's surface, and it must satisfy the condition of emission as $r \to \infty$.

By separating the variables in Eq. (2) and introducing the spherical impedance $\delta_n(r)$ [17], which equals

$$\delta_n(r) = \frac{1}{k\sqrt{\varepsilon^3(r)}\,\rho_n(r)}\frac{d}{dr}\left[\sqrt{\varepsilon(r)}\,r_n(r)\right], \tag{4}$$

we arrive at an equation of the form

$$\frac{d}{dr}\delta_n(r) + ik\varepsilon(r)\delta_n^2(r) - ik - \frac{n(n+1)}{ikr^2\varepsilon(r)} = 0. \tag{5}$$

The radial function is designated as $\rho_n(r)$, while the quantity $n(n+1)$ is the separation constant. The index n is the number of the resonance mode (the zonal quantum number [4-14]).

The boundary conditions (3) take the form

$$\delta_n(a) = -\delta; \tag{6}$$

$$\delta_n(r_1) = \frac{1}{\varepsilon(r_1)}\sqrt{\varepsilon(r_1) - \frac{n(n+1)}{k^2 r_1^2}} \approx \sqrt{\frac{1}{\varepsilon(r_1)}}. \tag{7}$$

The condition (7) was obtained on the basis of the following physical considerations. Electromagnetic waves of the indicated frequencies penetrate into the ionosphere to depths of several tens of kilometers. It is therefore natural to expect that the properties of the plasma at heights considerably greater than the thickness of the skin layer do not affect the resonance frequencies. Consequently, starting with some $r \geq r_1$ one can set $\varepsilon(r) = \varepsilon(r_1) = \text{const}$, and then in this region the eigenfunctions become spherical Hankel functions of the first kind (the condition of emission), and since their argument $|kr\sqrt{\varepsilon(r)}| \gg 1$, one can also use an asymptotic representation to obtain (7) for the values of n of interest to us, which are not very large.

The eigenvalue problem was solved numerically by the method of successive approximations. Let k^l be the l-th approximation to the unknown eigenvalue k, and then the $(l+1)$-st approximation, according to Newton, equals

$$k^{l+1} = k^l - \frac{\delta_n(a; k^l) + \delta}{\frac{\partial}{\partial k}\left[\delta_n(a; k)\right]_{k=k^l}}. \tag{8}$$

The value of the spherical impedance $\delta_n(a; k^l)$ at the earth's surface required in (8) is found from Eq. (5), which is integrated numerically from the height $r = r_1$ to $r = a$. After the determination of k^{l+1}, Eq. (5) is again integrated numerically, as a result of which one finds $\delta_n(a; k^{l+1})$, from which k^{l+2} is constructed, etc. The iteration process is stopped when the values of k^l and k^{l+1} differ by less than a given amount. The values of the derivative $(\partial/\partial k)\delta_n(a; k)$ are found exactly like the values of $\delta_n(a; k)$, only the differential equation and the boundary conditions for it are obtained from (4), (6), and (7) by differentiation with respect to k. The initial height r_1 is chosen by examination; i.e., the problem is solved for several r_1 and then one settles on a value such that when it is varied the result of the solution remains constant within the limits of a given accuracy.

TABLE 1. Results of Solution of the Problem of Natural Frequencies of the Earth – Ionosphere Resonator and Their Comparison with Experimental Data

	n	1		2		3		4		5	
	p	f_{p1}, Hz	Q_{p1}	f_{p2}, Hz	Q_{p2}	f_{p3}, Hz	Q_{p3}	f_{p4}, Hz	Q_{p4}	f_{p5}, Hz	Q_{p5}
Theory	0	7,80	4,63	13,79	5,96	19,73	6,55	25,68	6,83	31,67	6,95
Theory	1	2005,70	9,04	2005,74	9,04	2005,81	9,04	2005,91	9,04	2006,02	9,04
Theory	2	4063,87	9,30	4063,89	9,30	4063,93	9,30	4063,97	9,30	4064,04	9,30
Theory	3	6116,76	10,37	6116,78	10,37	6116,80	10,37	6116,83	10,37	6116,88	10,37
	Reference	f_{01}, Hz	Q_{01}	f_{02}, Hz	Q_{02}	f_{03}, Hz	Q_{03}	f_{04}, Hz	Q_{04}	f_{05}, Hz	Q_{05}
Experiment	Balser and Wagner [11]	7,8	4—5,3	14,1	4,5	20,3	5	26,4	5,5	32,5	6
Experiment	Madden and Thompson [10]	8,0	4	14,0	5	20,0	5	26,5	6	—	—
Experiment	Jones [13]	7,96	—	14,1	—	20,2	—	26,1	—	32,7	—
Experiment	IRÉ AN UkrSSR*	7,85	4,86	13,82	4,95	20,0	4,89	26,1	5,26	31,9	5,34

*Institute of Radiophysics and Electronics, Academy of Sciences of the Ukrainian SSR.

Before discussing the results of the calculations, which are presented in Table 1, we note that the frequencies of the three-dimensional earth – ionosphere cavity must have three indices: ω_{pnm}. Here m is the azimuthal number, which plays an important role in the absence of angular symmetry of the resonator [5-8]. In our case $\partial/\partial\varphi = 0$ and the eigenvalues do not depend on m, and therefore one can take m = 0 and drop the index itself; n is the zonal eigenvalue, equal to the number of waves of the oscillations which fit along the earth's equator; p is the "longitudinal" number, equal to the number of half-waves which fit along a radius between the points a and the effective point of reflection of the radio waves from the ionosphere.

For Schumann resonance frequencies the index p = 0, while the index n, not equal to zero, is called the mode number. In this case the radial functions $\rho_n(r)$ vary very slowly with r, and therefore the waves are called null E-waves or quasi-TEM-waves [10, 18]. Other oscillations must exist in the earth – ionosphere cavity besides the solutions with p = 0. The lowest natural frequency with p = 1 corresponds to half the length of the wave which fits along the height of the resonator, on the order of 100 km, from which we get $\omega_{1n}/2\pi = 3\cdot10^5/200 = 1500$ (Hz). These oscillations differ in physical nature from Schumann resonances in that it is not "obligatory" for them to run around the earth. The resonances have a "transverse" character when the waves run along the radius and are reflected from the earth and the ionosphere. On the strength of this the eigenvalues ω_{pn} are almost independent of n when $p \neq 0$ (see Table 1).

The method of calculation presented allows one to obtain not only the Schumann frequencies, but also the frequencies of higher types of oscillations with $p \neq 0$, which have not yet been detected experimentally.†

Strictly speaking, besides the resonances of E-type waves, in the earth – ionosphere cavity one should also observe resonances of H-waves whose polarization is horizontal. The natural frequencies $\tilde{\omega}_{pnm}$ of these waves also lie in the kilohertz range, with $p \neq 0$ always for them. The complete sequence of resonance frequencies of the earth – ionosphere cavity with fixed n and m satisfies the following condition, which is well known from electrodynamics:

$$\omega_{0nm} < \tilde{\omega}_{1nm} < \omega_{1nm} < \tilde{\omega}_{2nm} < \omega_{2nm} < \cdots \tag{9}$$

The first frequency in this sequence corresponds to the Schumann resonance, while the rest correspond to the "transverse" resonances of H- and E-waves.

Graphs of the height profiles of the electron and ion concentrations of the lower ionosphere which we used in the calculations are presented in Fig. 1. On the one hand, the graphs agree with the well-known models of the lower ionosphere [1, 2, 10, 19], while on the other, they give values of the frequencies and qualities

†It is possible that such resonances were detected in experiments of the Scientific-Research Institute of Radiophysics (Gor'kii) on nonlinear effects in the lower ionosphere in which powerful radiation of the SW range modulated with a frequency of from 2 to 7 kHz was incident on the ionosphere [24]. Then the maximum of the received lf signal at a frequency of 2.5 kHz can be explained by the excitation of "transverse" resonators of the cavity.

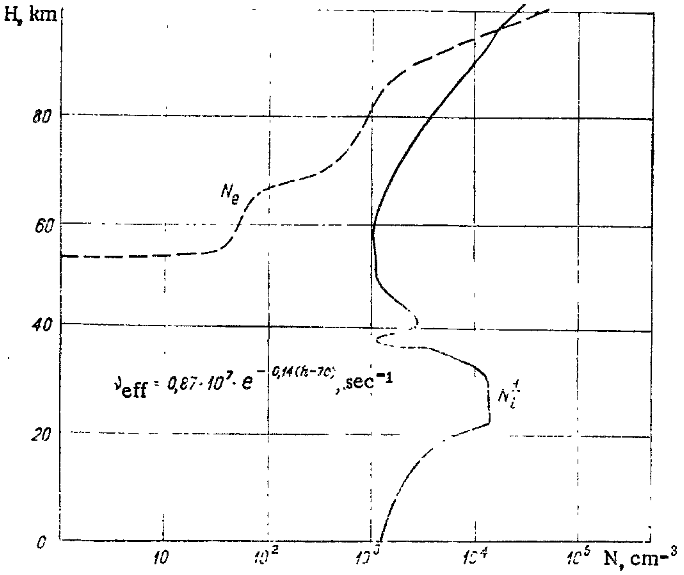

Fig. 1

which are close to the experimental values [10-14] (see Table 1, where the results of the calculations and the experimental data are presented).

FILTRATION OF LOCAL INTERFERENCE

Because of the large losses in the earth – ionosphere cavity, periodic oscillations of the resonance frequencies are not observed. The resonances are usually detected from maxima of the spectral density of natural radio noise excited by the electromagnetic radiation of thunderstorm discharges. In this case the frequencies of the maxima in the energy spectrum of slf noise are identified with the resonance frequencies, while the relative widths of the resonance peaks are connected with the quality of the resonator.

With such a determination of the resonance parameters an important role can be played by the interference [10, 20, 21], i.e., natural or artificial slf signals not connected with resonance effects. Such interference includes induction from electrical transmission lines and telegraph lines, oscillations of the antenna charge produced by wind, various electrostatic inductions, etc. [20, 21]. The interference incident on the receiver input is recorded together with the resonance signal:

$$S(t) = u(t) + n(t). \tag{10}$$

Here S(t) is the recorded signal, u(t) is the resonance signal, and n(t) is the interference.

It is easy to see that in this case the energy spectrum of the signal consists of the sum of the spectra of the interference and the resonance signal,*

$$G(f) = G_{res}(f) + N(f), \tag{11}$$

where the energy spectrum of the resonance signal equals

$$G_{res}(f) = \int_{-\infty}^{\infty} \overline{u(t)\,u(t+\tau)}\; e^{2\pi i f\tau}\, d\tau, \tag{12}$$

while the energy spectrum of the interference is

$$N(f) = \int_{-\infty}^{\infty} \overline{n(t)\,n(t+\tau)}\, e^{2\pi i f\tau}\, d\tau. \tag{13}$$

The bar above signifies averaging over time t.

Usually the interference comprises from 0.5 to 0.8 of the level of the resonance signal [6, 10, 20, 21]. Calculated spectra are shown in Fig. 2: Curve 2 is the resonance spectrum $G_{res}(f)$, curve 3 is the interference spectrum N(f), and curve 4 is the resultant spectrum G(f).

*Here and later the subject concerns Schumann resonances.

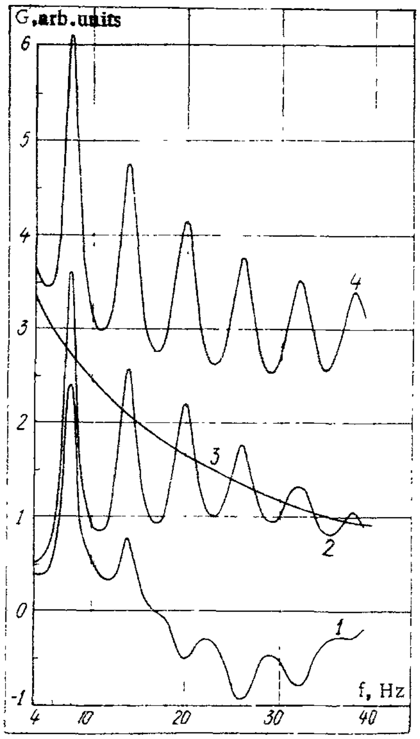

Fig. 2

The following model was adopted in the solution of the problem of excitation of the resonator. The parameters of the earth – ionosphere cavity are the same as for the uniform problem (see Fig. 1). Vertical, mutually independent, random thunderstorm discharges, uniformly distributed over the surface of the planet, were chosen as the sources of the electromagnetic radiation of the slf range. The spectrum of the sources did not depend on frequency. It was assumed that the interference spectrum is smooth, while the following relation is satisfied at the resonance frequencies:

$$N(f) \approx 0.8 \cdot G_{\text{res}}(f). \tag{14}$$

As seen from Fig. 2, the presence of interference "elevates" the energy spectrum $G_{\text{res}}(f)$ of the resonance signal above the frequency axis, which leads to errors in the determination of the qualities Q_{0n} (see Table 2). To suppress the interference and increase the reliability of the experimental results one can use the difference in the correlation radii of the interference and the resonance signals [6, 10]. Actually, the resonance signals have a correlation radius comparable with the length of the earth's equator, while the interference, having a nonresonance nature, has a considerably smaller correlation radius. Therefore, in the reception of signals over distances larger than the correlation radius of the interference but smaller than the wavelength of the highest mode being studied, we obtain

$$S_1(t) = u_1(t) + n_1(t); \tag{15}$$

$$S_2(t) = u_2(t) + n_2(t). \tag{16}$$

Here $u_1(t)$ and $u_2(t)$ are the resonance signals, while $n_1(t)$ and $n_2(t)$ are the mutually independent interferences at the first and second points.

TABLE 2. Resonance Parameters Found from Spectra of Fig. 2

Type of model $p = 0$	$n=1$		$n=2$		$n=3$		$n=4$		$n=5$	
	f, Hz	Q	f, Hz	Q	f, Hz	Q	f, Hz	Q	f, Hz	Q
Initial model	7,8	4,63	13,8	5,96	19,7	6,56	25,7	6,83	31,7	6,95
Energy spectrum without interference	7,8	4,30	13,8	5,35	19,9	5,80	25,9	6,27	32,0	6,03
Energy spectrum with interference	7,8	3,40	13,8	3,31	19,9	3,98	25,9	4,48	31,9	4,70
Cross spectrum, interference suppressed	7,8	4,73	13,8	5,40	20,0	5,72	25,9	6,30	32,0	6,35

By making a correlation analysis of the signals, i.e., constructing their cross spectrum [22], we obtain

$$G_{12}(f)=\int_{-\infty}^{\infty}\overline{S_1(t)S_2(t+\tau)}\,e^{2\pi if\tau}\,d\tau\equiv\int_{-\infty}^{\infty}\overline{u_1(t)u_2(t+\tau)}\,e^{2\pi if\tau}\,d\tau. \tag{17}$$

It is seen from Eq. (17) that the interference is completely suppressed in the cross spectrum.

In contrast to the energy spectrum, the cross spectrum is, generally speaking, a complex function of the frequency. In the excitation model which we chose it turns out to be real but not positive-definite. For a separation of 5000 km between the observation points the cross spectrum has the form shown in Fig. 2 (curve 1). The change in the sign of $G_{12}(f)$ at $f \approx 17$ Hz means that in the chosen model at frequencies greater than 17 Hz the oscillations at the first and second points take place in antiphase.

The data presented allow one to draw the following conclusions. Resonance oscillations of several types can exist in the earth – ionosphere cavity. The lowest branch of the natural frequencies is the Schumann resonances. The natural frequencies of higher types lie in the range of ones of kilohertz and are practically independent of the zonal quantum number n.

In a comparison of calculated and experimental data on a Schumann resonance one must allow for the distorting effect of interference, which can be reduced through the coherent reception of signals at remotely separated points and a subsequent correlation analysis.

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