Chapter 10

MODIFICATION OF THE IONOSPHERE AS A METHOD OF ITS DIAGNOSTICS

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Among many of the problems of ionospheric physics there are ones associated with the definition of characteristic constants and the hierarchy of processes defining ionospheric properties under different geophysical conditions. In traditionally passive experiments their solution meets with sufficiently large difficulties. The aim of the present paper is to discuss briefly a range of problems of ionosphere diagnostics which can be solved using modern techniques and methods of ionosphere modification. The question deals with the use of weak ionospheric plasma disturbances, created by radio wave beams, to study its dynamics and define a number of its parameters. Here the basic differences of the methods based on the ionosphere modification from passive ones is in the possibility of regulation of the processes occurring and creation of controlled initial conditions. Briefly, the modification of the ionosphere by a powerful radio wave field is based on the following processes [*Ginzburg et al.*, 1979; *Gurevich and Shvartsburg*, 1973; *Gershman et al.*, 1984; *Grach et al.*, 1989]. An electron (with a charge e and mass m) in the radio wave field $E = E_\omega e^{i(\omega t - \mathbf{kr})}$ (for simplicity the wave frequency ω is much larger than the frequency of electron collisions with other particles ν_e and its gyrofrequency ω_H) receives the velocity

$$\mathrm{V}_\omega = i\,\frac{e\mathbf{E}_\omega}{m\omega}$$

in the result of which the function of the electron velocity distribution is changed $f(\mathrm{v}) \to f(\mathrm{v} + \mathrm{v}_\omega)$. Here phenomena of hydrodynamic character occur when the variations of the distribution function $f(\mathrm{v})$ as a whole are important, as well as the kinetic effects where variations of $f(\mathrm{v})$ only in the definite region of velocities play the main role. The role of hydrodynamic effects is convenient to show by an example of equations for the average velocity v, concentration N and temperature T of electrons

$$\frac{\partial \mathbf{v}}{\partial t} = \sum \nu_{e\beta}(T)(\mathbf{V} - \mathbf{V}_\beta) - (\mathbf{v}\nabla)\,\mathbf{v} - \frac{e}{mc}\left[\mathbf{v}_\omega\,\mathbf{H}_\omega\right] - \frac{1}{Nm}\nabla NT \qquad (1)$$

$$\frac{\partial T}{\partial t} = \frac{2}{3}\,\sigma'_\omega\,E_\omega\,E^*_\omega - \delta_{e\beta}\,\nu_{e\beta}\,(T - T_\beta) + \chi\Delta T \qquad (2)$$

$$\frac{\partial N}{\partial t} + div\,N_\omega\,\mathrm{v}_\omega = q(T) - \alpha^1(T)\,N_e^2 \qquad (3)$$

Here $\nu_{e\beta}$ is the frequency of electron collisions with other particles, $\mathbf{H}_\omega$ is the strength of the wave magnetic field, σ'_ω is the high frequency specific conductivity ($\sigma'_\omega = \frac{e^2\nu_e}{m\omega}$, $\nu_e = \sum \nu_{e\beta}$), $\delta_{e\beta}$ is the portion of energy transmitted by electrons to other particles in collisions, χ is the specific heat conductivity, q and α^1 are the functions describing ionization and recombination of particles, $N_\omega = \frac{k\mathrm{v}_\omega}{\omega}N$ is high-frequency oscillations of the density in the longitudinal wave field.

From (1)-(3) it is seen that nonlinearity manifests itself in all three equations. In a strongly collisional plasma the temperature effects play the main role: the occurrence of a nonlinear addition in the friction force, resulting in variation of the current in plasma, change of the motion in plasma due to the pressure force $F_T = \nabla NT$ of the gas heated by radio waves (see (2)), variation of the effective coefficients of electron disappearance (their recombination and attachment, etc.) which are described by (3). Collisionless processes are due to the force of the light pressure (striction force F_S) and in this case Equation (1) describes scattering and diffusion of the gas due to the light pressure and processes associated with the nonlinear component of the electron current (3). In all cases the variations in the ion plasma component are due to polarization fields induced by electrons.

Collisionless plasma escaping from the region of the strong field along the force lines of the geomagnetic field $\mathbf{h} = \frac{\mathbf{H0}}{H0}$ becomes essential if the scale of the field inhomogeneity L_E is smaller than the electron free path $l_e = \frac{v_{Te}}{v_e}$ (v_{Te} is the thermal velocity of an electron). If $l_e << L_{E\parallel}$, then at "large" times $t > (\delta v_e)^{-1}$ always $F_T > F_S$. When there is inhomogeneity of the field $L_{E\perp}$ in the direction orthogonal to $\mathbf{h}$, then due to small transverse heat conductivity of the plasma, F_S is always smaller than F_T, if $L_{e\perp} > \rho_e$ ($\rho_e = v_{Te}/\omega_H$ is the gyroradius of an electron, ω_H is the gyrofrequency). Really, from (2) it follows (time t is read from the moment of the field switching on):

$$T = \frac{2}{3} \frac{e^2}{m\omega^2\delta_1} \left(1 - e^{-\delta_1 v_e t}\right) E_0^2,$$

$$\delta_1 = \delta + \frac{\rho_e^2}{L_{E\perp}^2} + \frac{l_e^2}{L_{E\parallel}^2}$$

and

$$F_T = \begin{cases} \dfrac{F_S}{\delta_1 v_e} & , \quad t > (\delta_1 v_e)^{-1} \\ F_S & , \quad t < (\delta_1 v_e)^{-1} \end{cases}$$

where $F_S = \frac{\varepsilon - 1}{8\pi} \nabla |\mathbf{E}|^2 \simeq \frac{e^2 N}{2m\omega^2} \nabla |\mathbf{E}|^2$ is the striction force, and **E** is summarized from interacting fields of all modes among which there is not only the radio wave but the plasma mode induced by it. Chemical processes are important if their characteristic time τ_{ch} is smaller than the time of the plasma ejection from the region of inhomogeneous field

$$\tau_{ch} < L_E^2 / D_i , \quad D_i \simeq v_{Ti}^2 / v_{in}$$

(v_{Ti} is the thermal velocity of ions, v_{in} is the frequency of their collisions with neutrals).

The minimal scales L_E are evidently defined by the wavelength of the radiation inducing the nonlinearity. A standing electromagnetic wave which is formed by interfering incident and reflected from the ionosphere radio waves (Figure 1) [*Grach et al.*, 1989] can serve as an example. Its characteristic field scale $L_E = \frac{\lambda}{2}$. For the radio wave frequency $f = 6$ MHz, the value $\lambda/2 =$ 25 m. In the lower ionosphere ($Z = 50$–70 km) the frequency v_{in} is large, so, $\tau_{ch} << \tau_D$ and variation of free electron density due to heating by a powerful radio wave is controlled by the temperature dependence of the speed of electron attachment to oxygen molecules. The rate of this process varies from 15 s^{-1} at $Z = 55$ km up to 0.1 s^{-1} at $Z = 75$ km [*Belikovich et al.*, 1986]. Thus, the standing structure of the formed wave intensity induces the spatial periodic stratification of free electron density. At large altitudes where the time of the diffusional plasma ejection (due to the force F_T) becomes smaller than τ_{ch}, the formation of artificial periodic irregularities (API) occurs due to plasma ejection from the regions of the standing wave antinooks where the electron temperature is larger. Demolition of the plasma lattice after switching off the powerful radio transmitter creating the standing wave is explained by the same process of the molecular (and turbulent in the height region of 70-95 km) diffusion.

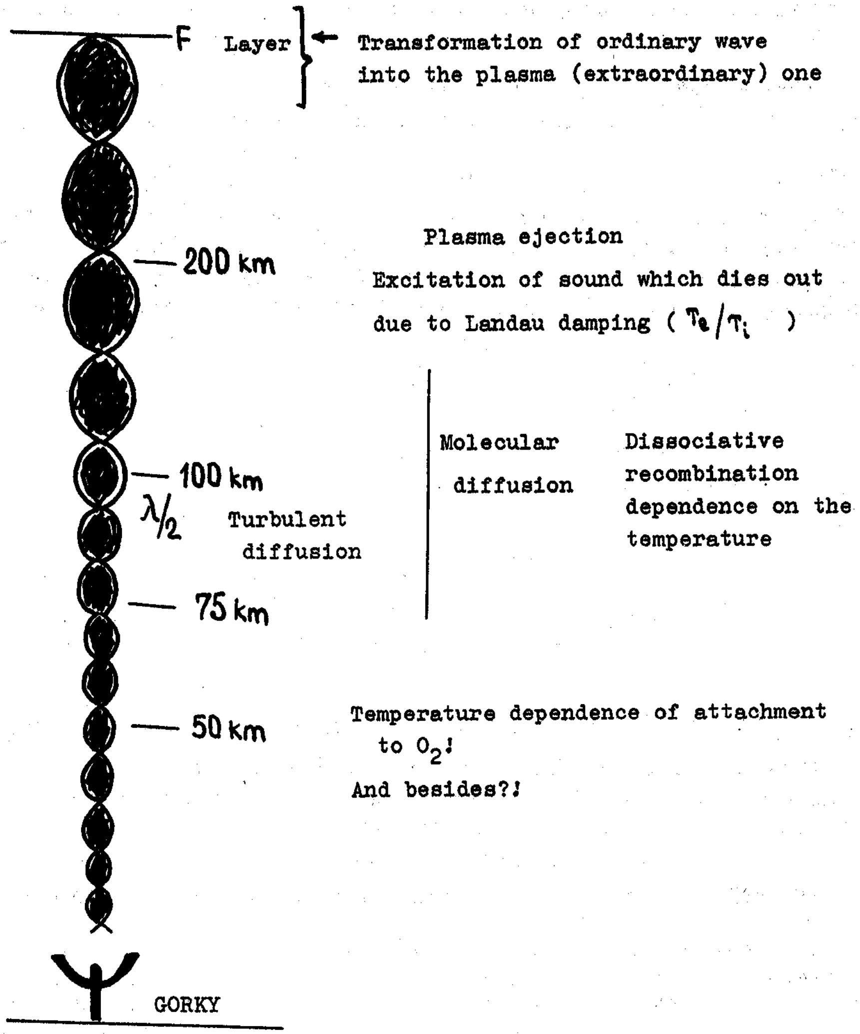


Figure 1. Nonlinear effects in the interference of incident and reflected radio waves.

At last, at altitudes where the wavelength of the standing structure becomes smaller than the free path, the API occurrence and relaxation is controlled by ejection processes due to the striction force. Here the ion acoustic waves are excited which are damped owing to collisionless Landau mechanism of themal ions. The rate of IAW damping depends on how their phase velocity $\left(v_{ph} = \sqrt{\frac{T_e+T_i}{M_i}}\right)$ is close to the ion thermal velocity $\left(v_{Ti} = \sqrt{\frac{T_i}{M_i}}\right)$ where the damping is maximal. In other words, the rate of damping depends on the relation T_e/T_i.

Figure 1 shows a possibility of one of the methods of ionospheric parameter study — scattering of probe radio waves by artificial periodic irregularities which is described below [*Gershman et al.*, 1984; *Grach et al.*, 1989; *Belikovich et al.*, 1975, 1977, 1986]. If in the interaction with plasma besides the radio wave, one more wave takes part with the wavelength λ_l smaller than the wave λ, then the scale L_E is defined by the length λ_l. This scale is minimal in the case of longitudinal plasma waves ($\lambda_l > r_{De}$, $r_{De} = \frac{v_{Te}}{\omega_{oe}}$ is Debye length, $\omega_{oe} = \left(\frac{4\pi e^2 N}{m}\right)^{1/2}$ is the Langmuir frequency). In the ionosphere λ_l can accept values from one centimeter up to dozens of meters. Excitation of plasma waves in the ionosphere by ground-based sources is realized because of the process of the wave transformation. Figure 2 illustrates schematically the dispersion curves of high-frequency ordinary and extraordinary waves in the plane "refraction index square n^2 — the relation square between plasma and operation frequencies" [*Ginzburg et al.*, 1979; *Gurevich and Shvartsburg*, 1973; *Gershman et al.*, 1984; *Grach et al.*, 1989; *Ginzburg*, 1967].

It is seen that a radio wave of extraordinary polarization sent vertically upwards to the ionosphere is reflected from its level of reflection out of the reach of the region where plasma waves exist. However, radio waves of ordinary polarization in the interval of altitudes from Z_1, where $\omega = \sqrt{\omega_{oe}^2 + \omega_H^2}$ up to Z_2 ($\omega = \omega_{oe}$) are present in this region. Thus, a transition can occur of a radio wave into a slower ($n > 1$) plasma one. Such transition is just called the mode transformation. It can occur by the diffraction way when dispersion curves draw closer to one another due to large-scale gradients in the medium, and it can take place due to the medium inhomogeneities (quasi-stationary in the given case) being polarized by the radio wave (scattering in plasma mode).

The plasma waves formed can be diagnosticated both by the method of incoherent scattering and by the artificial ionospheric radiation (AIR) which is the consequence of their back transformation into the radio wave. With a sufficiently large amplitude E_l which is equal to its maximal possible value

$$E_l = \delta N \frac{\omega}{v_e} E_0 \gg E_0$$

in a homogeneous medium they induce nonlinear forces F_S and F_T and form small-scale plasma irregularities with $l \sim \lambda_l/2$. These irregularities are created more easily when they are elongated along the geomagnetic field force lines, i.e., they are stratified in transversal to **h** direction, as in this case the processes of fast plasma transfer along **h** do not have fatal consequences. In this case they are just the low-frequency anisotropic plasma turbulence which induces the intensive aspect scattering of radio waves of decameter-meter ranges. These irregularities amplify the radio wave transformation into the plasma one and vice versa, making this process strictly nonlinear and the plasma state unstable. Excitation of plasma waves and low-frequency disturbances due to nonlinear transformation is possible in the case of the ionosphere modification by two high-frequency waves with a difference between frequencies equal, for example, to the frequency ω_l of the Langmuir wave.

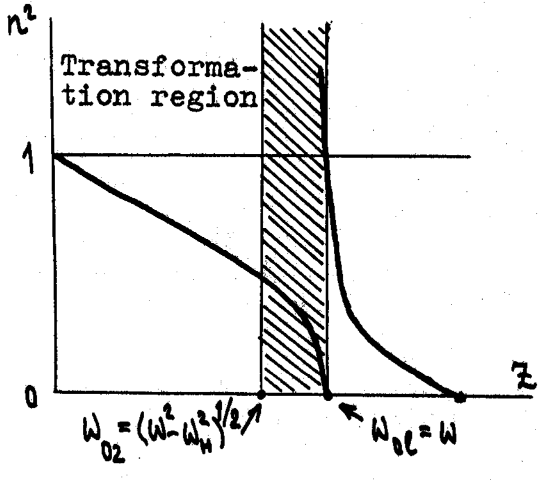


Figure 2. The region of radio wave transformation into plasma ones in the ionosphere.

Plasma waves are also subjected to decomposition processes. An example can serve their decomposition into a plasma wave of smaller frequency and a low-frequency wave, ion-acoustic, for instance

$$\omega_l = \omega_l' + \Omega_S ,$$

or a quasi-transversal helicon with $\omega \gtrsim \sqrt{\omega_H \Omega_H}$ (Ω_H is the gyrofrequency of ions).

In particular, frequencies of the artificial ionospheric radiation smaller than those of pumping waves are usually associated with the decomposition processes. Radiation with frequencies $\omega_{\mathrm{AIR}} > \omega_{PW}$ can be induced by processes of low-frequency and plasma wave coalescence, the vertical transfer of waves by accelerated electrons, particle radiation in fluctuating alternating electric fields, etc. (see Figures 3 and 4), in particular, with four-wave interaction.

Plasma waves induce particle acceleration which can transfer them not only in the vertical direction but also, by exciting the atmospheric components, induce the optical airglow of the atmosphere, as well as the artificial atmosphere ionization, at altitudes of the F-layer which are insufficient so far [*Grach et al.*, 1989].

Above we consider processes of spatial plasma stratification in the fields of powerful radio waves under the action of forces F_S and F_T giving the minimal scales of disturbance. There are a number of nonlinear processes (in particular, self-focusing instabilities) which lead to spatial stratifications of larger scales [*Gurevich and Shvartsburg,* 1973]. Processes not associated with the action of these forces are the above-mentioned chemical processes as well as those caused by variation of collision frequency ν_e. First of all these are the well-known effects of self-action and cross-modulation [*Gurevich and Shvartsburg*, 1973; *Gershman et al.*, 1984] and the effect of the generation of low-frequency ionospheric radiation-Getmatsev effect [*Gershman et al.*, 1984; *Grach et al.*, 1989; *Belyaev et al.*, 1987].

The sense of the Getmatsev effect is simple: by modulating the electron current structure due to the periodic variation of the friction force (electron conductivity), we can obtain alternating electric current which must radiate radio waves at the modulation frequency. The radiation received on the Earth is associated not only with the current value and its spatial structure but also with the conditions of low frequency Ω radio waves escaping from the ionosphere, which are defined by the depth of skin-layer of the ionosphere for the frequency Ω. By making measurements of the value and polarization of artificial low-frequency radiation at different frequencies one can investigate the radiation structure, the current structure at 70-80 km heights and hence, the parameters depending on them: the neutral gas motion speed $\mathbf{v}_n$ at midlatitudes and electric fields $\mathbf{E}_\perp$ in high latitudes. Variation of electron velocity transverse to geomagnetic field **h** due to the friction force by the neutral gas moving orthogonally to **h** with a speed $\mathbf{v}_n$ is equal to [*Gershman et al.*, 1984]

$$\mathbf{v}_1 = \frac{\nu_e^2}{\omega_H^2 + \nu_e^2}\,\mathbf{v}_n + \frac{\nu_e\,\omega_H}{\omega_H^2 + \nu_e^2}\,[\mathbf{v}_n\,\mathbf{h}]$$

The presence of the electric field $\mathbf{E}_\perp$ leads to electron motion with a speed

$$\mathbf{v}_2 = \frac{\nu_e}{\omega_H^2 + \nu_e^2}\,\frac{e}{m}\,\mathbf{E}_\perp + \frac{\omega_H}{\omega_H^2 + \nu_e^2}\,\frac{e}{m}\,[\mathbf{E}_\perp\,\mathbf{h}]$$

In the simplest case the low-frequency current component $j_\Omega = eN\mathbf{v}_\Omega \propto \dfrac{\Delta\nu_e\,\Omega}{\nu_e} = \dfrac{5}{6}\,\dfrac{\Delta T_\Omega}{T}$ where ΔT_Ω is the amplitude of periodic variations of the electron temperature under the action of a modulated radio wave. Here variations of an electron speed $\mathbf{v}_\Omega$ are maximal in the region where $\nu_e \sim \omega_H$. The modification of the lower ionosphere becomes more effective in operation with a high power as well as with approximation of the action frequency to the electron gyrofrequency. In this

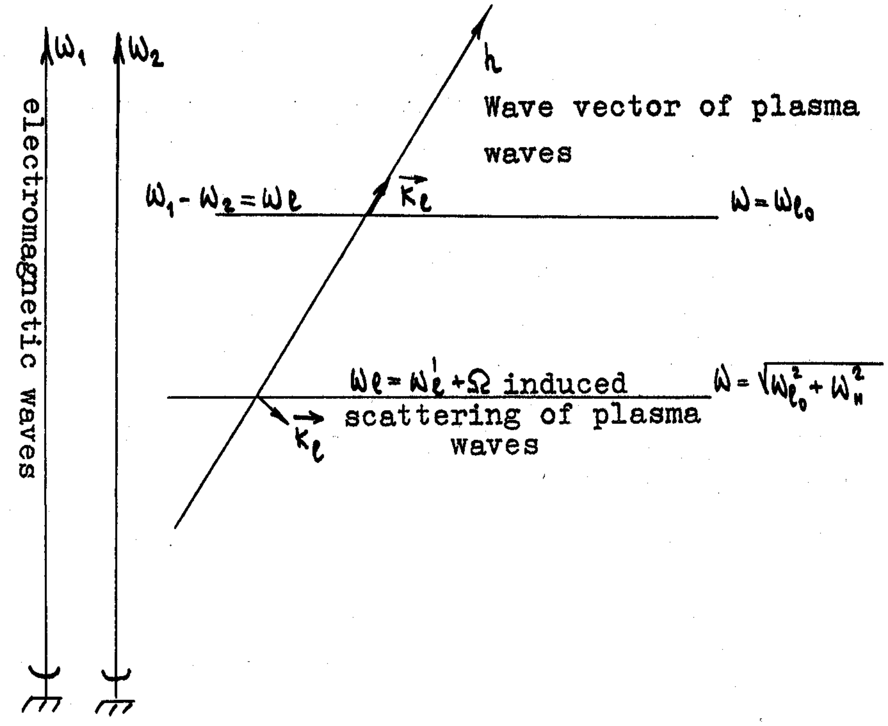


Figure 3. Generation of plasma and ion-acoustic waves in ionosphere.

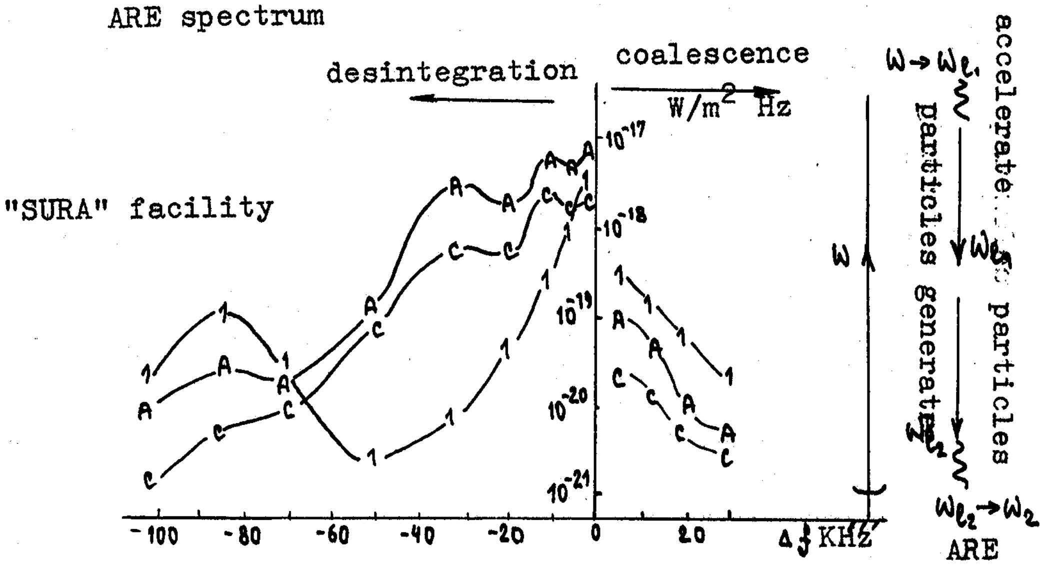


Figure 4.

connection a new stage began in the investigation of the Getmatsev effect in the eighties when in Tromsø (Norway) and Vasil'sursk powerful wide-band heating facilities were introduced [*Stubbe et al.*, 1985; *Belov et al.*, 1983]. A broadening of the frequency wave range and an increase of the heating facility power permit one to essentially increase the signal-to-noise ratio and obtain the stability for the combination frequency signal (CFS) reception in the frequency range of modulation current systems 0.5 kHz ÷ 10 Hz. This gives a possibility to investigate the fine structure and dynamics of the neutral component (at midlatitudes) as well as study a wider class of geophysical problems including methods of action on the magnetospheric plasma instabilities. Figure 5 presents CFS spectra at small displacements of the observation point over the horizontal from the current source (the dependence of the field magnetic component on the low-frequency radiation). From the figure it is seen that maxima are well distinguished in the near field which are associated with the fact that in the Earth-ionosphere waveguide there is an integer of half-waves of artificial low-frequency radiation. There is a shift of the first maximum from 2.2 kHz at midday to 1.6 kHz in the evening which corresponds to the diurnal variation of the upper waveguide wall height during the day (from 68 km in daytime up to 88 km at night). Note that the CFS method permits using the swinging of the powerful radiator directivity pattern (or simultaneous radiation in three directions) to measure over the well-known three-point method — in the given case from three CFS sources — the value and direction of the neutral wind velocity v_n in the horizontal plane of its variations. Information on vertical velocities is obtained in CFS reception at two different frequencies Ω_1 and Ω_2, since their sources are spaced over the height. In the case of one-point reception, the information on the velocity v_n variation is obtained from the polarizational variations of CFS.

One of the perspective directions for the Getmatsev effect development is connected with the generation of ultra-low-frequency electromagnetic fields $\left(\frac{\Omega}{2\pi} < 10 \text{ Hz}\right)$ (geomagnetic pulsations) especially in the frequency region corresponding to the frequencies of the ionospheric Alfven resonator [*Belyaev et al.*, 1987].

Further CFS investigations are expected to be related to the total exploitation of geomagnetic pulsation wave range (up to 10^{-3} Hz), with excitation of Alfven ionospheric and magnetospheric resonators by the modulation of their lower edge conductivity, especially in the region of auroral latitudes [*Belyaev et al.*, 1987; *Bespalov and Trakhtengerts*, 1986], that must result in strong variations of precipitating particle streams. Of great interest are CFS observations from the F region, in particular, under the condition of developed parametric instabilities.

Let us consider again the artificial periodic irregularities. Figure 6 shows the characteristic dependences of the relaxation time τ on altitude for three periods of observation. The variety of the given curves $\tau(Z)$ is striking both at small altitude, i.e., in the region of chemical processes dominating and in the altitude region where turbulent diffusion prevails and where the method can be the tool for its investigation. From this viewpoint a good illustration for the possibility of the vertical motion diagnostics serves Figure 7 where the time dependence is given for the amplitude of a signal scattered by the "lattice" in the periodic creation of it by impulses of 2 s duration. It is seen that in the repeated switching on of the powerful radio transmitter (at places indicated by a dotted semicircle) the rapid lattice breakdown occurs. The latter is associated with the fact that due to the vertical component of the turbulent and regular wind speed transporting the lattices, the breaking down of the preceding lattice occurs by "unphaseable" heating. On the basis of the given effects it is easy to develop a method for definition of the turbulent vortices of different scales as well as coefficients of the turbulent diffusion so necessary for constructing lower ionosphere models.

Figure 8 illustrates the altitude profiles of electron density obtained by the given method [*Belikovich et al.*, 1986]. The electron density N is defined from the requirements of spatial synchronism of the scattered wave and the artificial periodic irregularity — "lattice." It results in equality

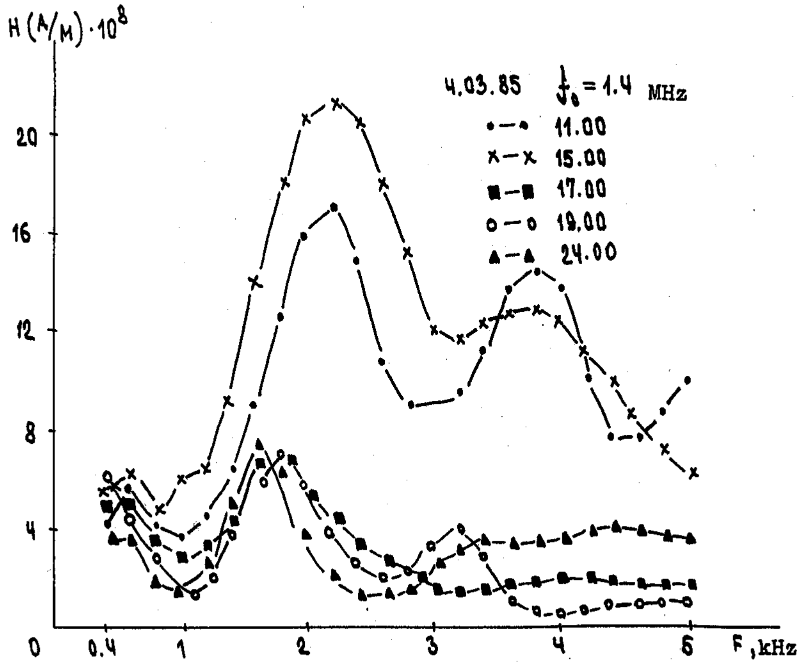


Figure 5. Spectra obtained by "SURA" facility in different times of day.

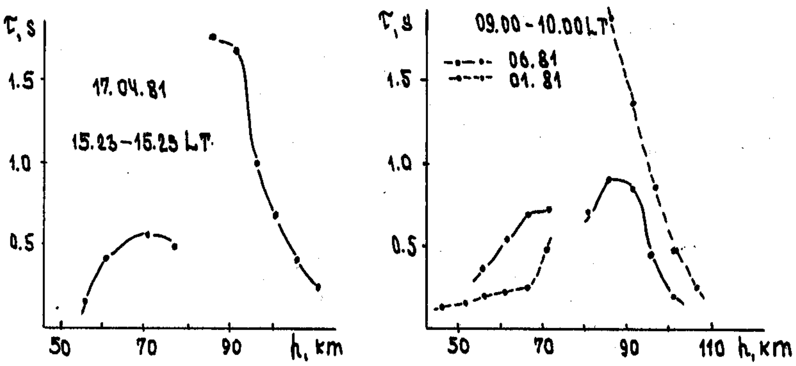


Figure 6. The dependence of relaxation time of API on altitude ("SURA" facility).

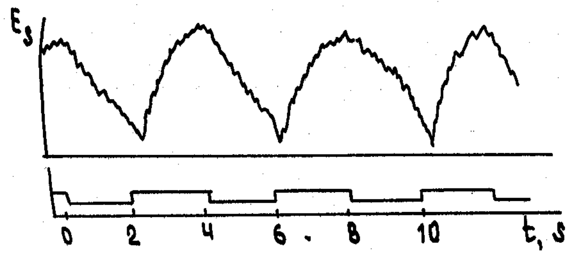


Figure 7. Breakdown of periodic irregularities at repeated switching of the SURA transmitter.

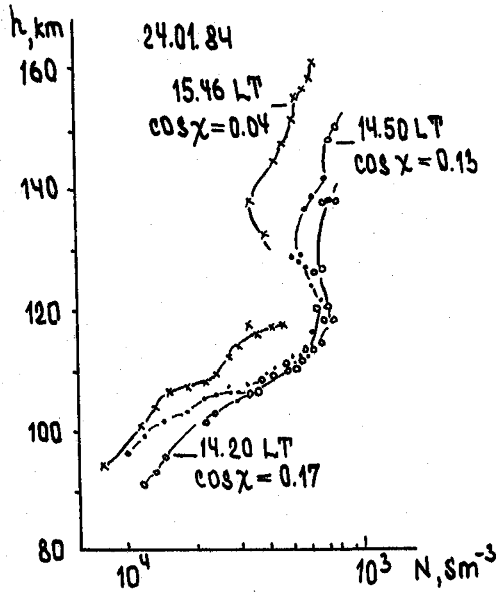


Figure 8. Altitude profiles N(h) obtained by the method of resonance scattering.

$$f_{PW}\, n^{\pm}\left(f_{PW}\right) = f_{Pr}\, n^{\mp}\left(f_{Pr}\right),$$

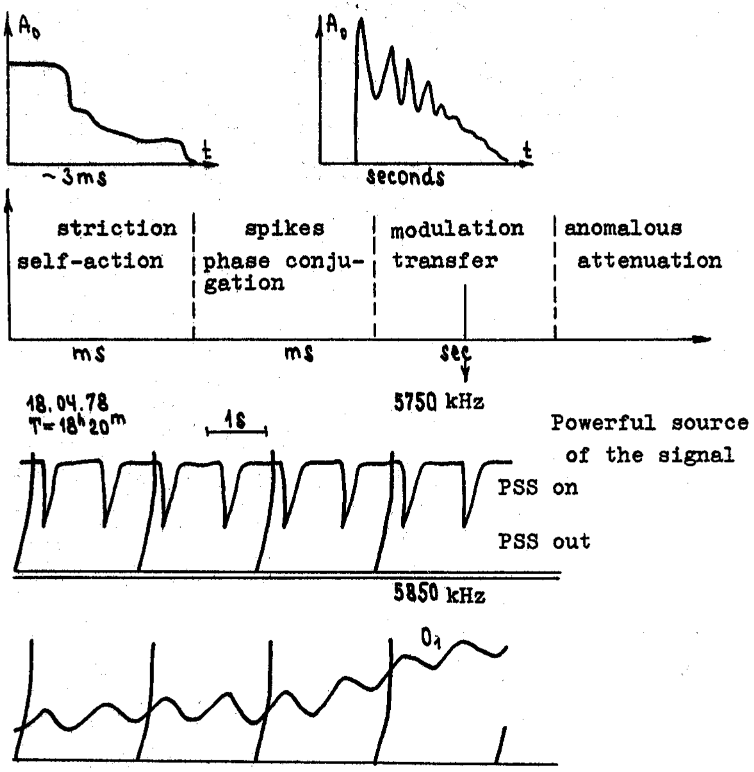
where $n^{\pm}\left(f_{PW}\right)$ and $n^{\mp}\left(f_{Pr}\right)$ are refraction indices of the medium for frequencies of the pumping wave $\left(f_{PW}\right)$ and the probe wave referred to different normal polarizations (+ – is the ordinary component). $N(Z)$ is measured by changing the frequency of one of the transmitters and definition of the acting altitude of the backscattering over the strobed signal. API relaxation in the upper ionosphere is defined by the plasma ejection. The API formation in the F region of the ionosphere is accompanied by excitation of long wavelength quick damping ion-acoustic oscillations. For them the frequency $\Omega = kv_S$, where $v_S = \sqrt{\frac{T_e+T_i}{M_i}}$, and damping is determined by collisionless Landau damping, the decrement of which is defined by the ratio T_e/T_i (high altitudes) or collisional absorption determined by the frequency of collisions ν_{in} between ions and neutrals. This permits one to estimate the values T_e, T_i and ν_{in}.

In perspective, of interest is excitation of APIs which are elongated along the force lines **h**; they must be considerably more intensive due to small transfer coefficients in the direction orthogonal to **h**.

Let us discuss the experimental data on artificial ionospheric turbulence. The scenario of the development process of plasma turbulence from small to large times of development can be presented in the following way (Figure 9). At the exceeding of threshold values of the striction parametric instability development at times of the order of 1-3 ms, the anomalous attenuation of pumping waves due to striction excitation of plasma waves begins. This process is mainly developed near the level of PW reflection (Figure 2) due to the known effect of the field amplification near the reflection level. Then, since times of the development are inversely proportional to the square PW amplitude, the striction plasma wave excitation occurs at smaller altitude in the interval between the reflection level and the level of the upper hybrid resonance. Here, in the region of (UHR) the plasma waves are already orthogonal to **h**, and at the level of reflection $\mathbf{k}_l \parallel \mathbf{h}$ the excitation of plasma waves with $\mathbf{k}_l \perp \mathbf{h}$ (in the region of UHR) can be accompanied by the formation of low-frequency waves with $\mathbf{k}_\Omega$ approximately orthogonal to **h**.

The formation of low-frequency waves damping slower than the ion sound must lead to the decrease of excitation thresholds and correspondingly to larger times of the process development. It is natural to expect that initially the plasma waves must be excited in maxima of a standing electromagnetic field. However, even small shifts of the reflection point leads to a shift of the field maxima. The latter can be one of the reasons (others will be discussed below) of the breakdown of the effect of self-action at times of dozens and hundreds of milliseconds resulting in the observing oscillation regime (the effect of "spikes") of the pumping wave and probe one. Here, the slower the process develops, the larger interval of altitude it occupies and the more wide-band it is. If the PW is switched on and off periodically the effect of the modulation transfer is observed for probe waves at this intermediate phase. As Figure 9 shows, a phase shift can be observed (in time) of oscillations being transferred to probe waves. Even at this duration (dozens of milliseconds) the thermal effects begin to develop. The minimal time of their development is defined by ν_e^{-1} and the next over the rank is the time of longitudinal heat conductivity $\tau_D = \frac{l_\parallel^2}{4D_{e\parallel}}$, $D_{e\parallel} = \frac{T}{m\,\nu_e}$ (here T is in the energetic units), $l_\parallel$ is the scale of the temperature variations along **h**. The value τ_D amounts 0.05-0.2 s and depends on the longitudinal scale [*Erukhimov et al.*, 1987]. But it is convenient for irregularities to be developed self-consistently ejecting the ions in transverse to **h** directions, so that a considerable spatial charge cannot occur. The latter takes place if $\frac{l_\parallel^2}{D_{e\parallel}} \sim \frac{l_\perp^2}{D_{i\perp}}$, $D_{i\perp} = \frac{T_i\,\nu_{in}}{M_i\,\Omega_H^2}$. It

"Spikes" and the anomalous attenuation



The modulation depression effect

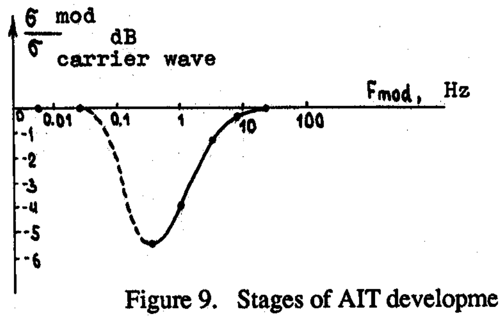


Figure 9. Stages of AIT development.

is not excluded that for this reason the time of "expectation" in the process of formation of thermal irregularities elongated along **h** increases with the growth of $l_\perp$.

Of interest is the scattered signal spectrum dynamics in the process of irregularity development. Initially, the narrow spectrum broadens gradually and that testifies to a nonlinear mechanism of formation of irregularity scale spectra at initial stages of artificial turbulence development due to interference of small-scale irregularities.

Then, larger irregularities stabilize the smaller ones at a lower level and the initially inverse spectrum $\phi_N(æ)$ of the turbulence which has a maximum in the region of small scales ($l_\perp < 1 \div 2$ m) becomes quasi-exponential as shown in Figure 10, where the spectrum $\phi_N(æ_\perp)$ is given, $æ_\perp$ is the transverse wave number $\left(æ_\perp = \frac{2\pi}{l_\perp}\right)$ obtained at the stationary phase by the method of the aspect scattering and the satellite signal scintillations.

Striction effects, "spike" effects, and that of modulation transfer vanish due to a stronger effect of the anomalous absorption of the pumping wave and plasma waves at upper hybrid resonance (UHR) levels. The energy of the pumping wave does not achieve the reflection level, practically completely damping at the UHR level. The period of the aspect scattering, scintillations, F_{spread} phenomenon, the occurrence of large-scale stratifications in the F layer, etc. take place.

After the powerful radio transmitter is switched off, the artificial ionospheric turbulence is relaxed; first small scales decrease and then larger ones decrease. Figure 11 shows the characteristic dependences of irregularity relaxation time τ_r of the stationary level of their transverse to **h** dimension. It is seen that there is a characteristic scale $l_\perp^*$ where there is a break in the character of the dependence $\tau_r\,(l_\perp)$: on $\tau_r \propto l_\perp^2$ for $l_\perp < l_\perp^*$ up to $\tau_r \propto l_\perp^{1/4}$ for $l_\perp > l_\perp^*$. For the second case the relaxation is defined by the longitudinal ion diffusion, and in the first case the diffusion coefficients are close to the transverse electron ones, $D_{e\perp} = \frac{2T\,\nu_e}{m\,\omega_H^2}$. It is not excluded that for $l_\perp < l_\perp^*$ the longitudinal scale of irregularities is proportional to $l_\perp$ and the relaxation proceeds with approximate "self-correlation" between the times of transverse electron and longitudinal ion diffusion. The relaxation is of two-step character. Its rate considerably decelerates after the intensity of artificial irregularities decreases by ten-fifty times (the upper part of Figure 11). The second step can be associated with the nonlinear pumpback of the turbulent energy by large scales. A problem on the mechanism of natural plasma turbulence formation is one of the keys in the physics of ionosphere and cosmic plasma physics. Since the artificial turbulence in the scale region $l_\perp < 1$–10 km is close in its properties to the natural one, its investigation serves for understanding the natural processes leading to the formation of different scales of irregularities and helps to solve key problems in the building of inhomogeneous structure models of the upper ionosphere. So, for example, a tremendous impression is made because of how easy F_{spread} is excited at low latitudes (Dushanbe), while under natural conditions it almost never appears.

It was noted long ago that irregularities caused by short-period action radio waves continue to develop after the powerful transmitter is switched off. The temperature fluctuations excited in the ionosphere, forgotten by their creator, form the plasma inhomogeneities which relax and reach the maximal value. But the time of the maximum and the velocity of inhomogeneity destruction depend on the pause between the successive radio wave switching, i.e., on the presence of inhomogeneities of other scales. This can also testify to the role of direct and inverse nonlinear pumping over the turbulent spectrum into the formation of definite scales of inhomogeneities and the characteristic lifetime. The dynamics of the frequency spectrum of the scattered signal in the turbulence relaxation is also informative.

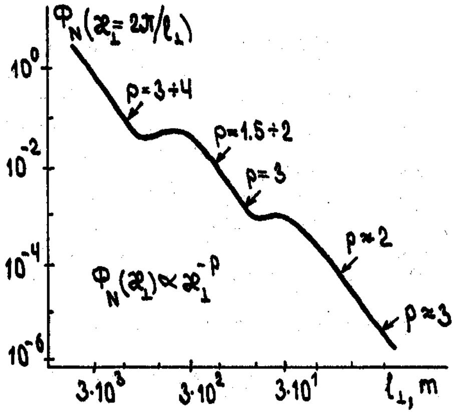
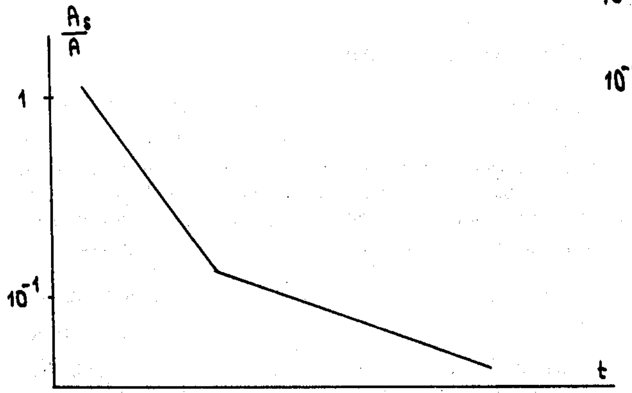


Figure 10. The spectrum of scales of artificial ionospheric turbulence.



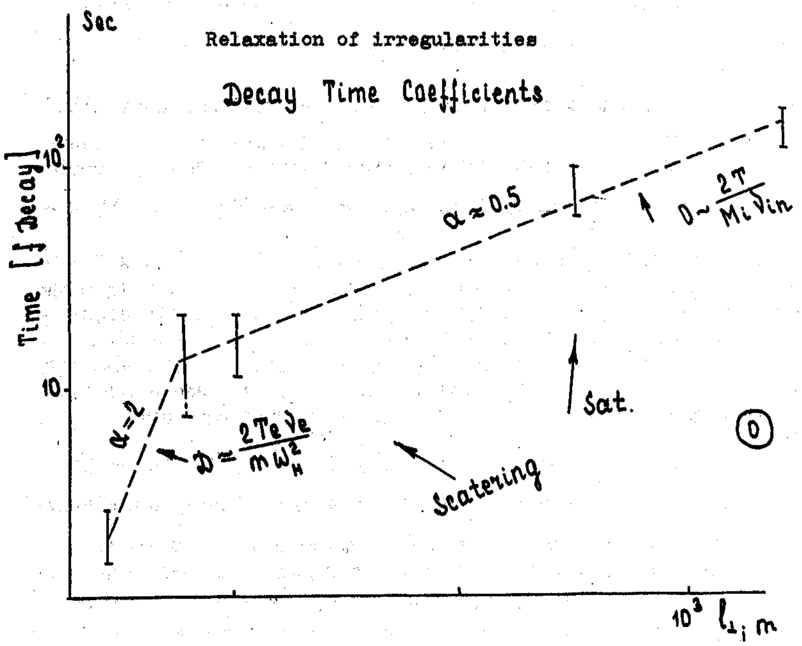


Figure 11. Illustration of two-step relaxation of the amplitude of the aspect signal and the dependence of the decay-time on the irregularity scale.

Of interest is the fact that, after the inhomogeneity relaxation, they can again occur in ($\sim$30 s), which is much larger than the time of their relaxation [*Belenov et al.*, 1977]. As shown in *Yampol'skij* [1989], this effect has a brightly expressed resonance nature, i.e., the ionosphere here serves as a memory device. Processes which are investigated in the ionosphere modification, especially when the question deals with the dynamics of small-scale plasma structures with the wave transformation, are of great interest in the cosmic plasma. Again, the atmosphere similarity parameters of a number of cosmic objects are close to those of the Earth. The solar chromosphere can serve as an example. Thus, at present, the ionosphere can already be presented as the most close to our cosmic laboratory, equipped with different diagnostic methods and possibilities of excitation of different types of instabilities.

Facilities of the Ionosphere Modification by Powerful Radio Waves

The heating nonlinearity is of importance for ionosphere modification. It is defined by the ratio of the wave field amplitude $E \sim 0.3\, R^{-1} \sqrt{PG}\ (V/m)$ to the characteristic plasma field E_P, where R is the distance from the source in km, P is the power of the transmitter in kW, G is the antenna amplification coefficient relative to the isotropic emitter. The nonlinear effects sharply increase when the wave frequency coincides with one of the plasma resonance frequencies — Langmuir ω_{oe}, gyrofrequency ω_H of electrons or with the frequency of the upper hybrid resonance $\sqrt{\omega_{oe}^2 + \omega_H^2}$. The duration of the ionospheric plasma modification effects for the heat nonlinearity amounts $\sim(\delta\nu)^{-1}$, where ν is the effective frequency of collisions of electrons and ions or molecules, and δ is the portion of energy losses by an electron in one collision. At last, the pumping wave polarization must correspond to the polarization of normal waves in the ionosphere (ordinary or extraordinary). All this permits one to formulate some general principles of building of investigation facilities for the modification of the ionosphere by radio waves. First of all, the facility must have the equivalent power $PG \gtrsim 10$ MW to provide the ratio $\frac{E^2}{E_P^2} \gtrsim 10^{-2}$ for the vertical radio wave beam in the interval of altitude 80–250 km. Since the characteristic time $(\delta\nu)^{-1}$ sharply increases with altitude, from 10^{-4} s up to 10 s, the duration of radiating radio pulses must change in the same limits. This means that the facility transmitter must operate both in the impulse regime and in the regime of continuous radiation. If the gyrofrequency $\frac{\omega_H}{2\pi} \simeq 1.4$ MHz is practically constant, the plasma frequency ω_{oe} (and hence, $\sqrt{\omega_{oe}^2 + \omega_H^2}$) is defined by the critical frequency of the ionosphere, diurnal and seasonal variations of which in midlatitudes are in the limits of 2–10 MHz. From here it is clear that the range of operating frequencies of the facility in the ideal case must approximately amount to 1.3–10 MHz. The limiting polarization of normal waves in the ionosphere in the vertical radio wave beam incidence is close to the circular one, practically at all latitudes apart from a narrow region of approximately ± 10° near the geomagnetic equator. So, the antenna must receive radio waves with right (or left) circular polarization.

The power of standard SW transmitters does not exceed 100–200 kW. To provide a sufficient ($\sim 10^2$) amplification coefficient of the antenna $G = \frac{4\pi S}{\lambda^2}$ the antenna systems are used with the maximally large area S. The potential of the facility can be increased if we use several *(N)* synchronously operating modula, each consisting of the transmitter loaded for a separate antenna section. The equivalent power of the facility in this case is equal to $PG = P_N G_N N^2$, where $P_N G_N$ is the equivalent power of each modulus. As the antenna, a horizontal phased antenna lattice is used. In the synphase lattice feed, the vertical directivity pattern is formed with a width $\Delta\theta \simeq \frac{\lambda}{D}$, where D is the dimension of the antenna field. By varying the separate lattice elements, one can control the directivity pattern in the limits ± 40° from the zenith. A separate element of the lattice is two horizontally crossed wide-band vibrators located at the height $\frac{\lambda}{4}$ above the Earth (λ is the mean wavelength over the range). The crossed vibrators are fed with a phase shift $\pm\frac{\pi}{4}$, to provide the wave radiation with right (or left) circular polarization. The coefficient of the frequency overlapping of a wide-band vibrator does not exceed two magnitudes. So, for broadening of the frequency range the facilitiy uses two (or three) independent antenna systems.

All facilities for modification of the ionosphere by radio waves are built over the given scheme and differ by the frequency range and equivalent radiation power. The facility parameters are given in Table I where we give the name and location of the facility as well as references.

The facilities are equipped with diagnostic complexes which are rather different. They contain both the traditional facilities, for example, ordinary impulse ionosonde, and more contemporary analogies (kinesonde, chirpsound) as well as such unique facilities as stations of incoherent scattering. These stations by which the facilities in Arecibo, Tromsø and Khar'kov are equipped are the most informative diagnostic facilities, since they permit the direct study of the plasma and ion acoustic waves (with wave vectors having a projection in the direction of the sounding radio ray), to obtain the height profiles of the density and temperature [*Schlegel et al.*, 1987]. So, considerable plasma displacements (plasma holes) have been studied in modification of the night F-layer of the ionosphere [*Duncan et al.*, 1988]. Again, such effects were also detected in Dushanbe at the beginning of the eighties under definite regimes of modification producing a rather specific picture on the ionograms (of the type of a blossomed-out bed). The chirpsound permits one to obtain a very informative picture of the ionosphere modification (see, for example, *Erukhimov et al.* [1987]). We have mentioned above the method of resonance scattering which permits the observation of a sufficiently large set of ionospheric parameters. We add that this method requires the use of facilities with the impulse power of several hundreds of kW and receiving-transmitting antenna with $G \approx 10^2$. To study the ionospheric turbulence of mean scales, of interest is the method of the signal scintillations from the board transmitters and transit and geostationary spacecrafts. They helped to obtain the basic data discovered in the latter decade on the dynamics of irregularity spectra at different heights from the level of energy release in the modification; in particular, the presence of large vertical velocities (up to 0.5–1 km/s) is shown for the turbulence source propagation from the heating level. Recently, of particular attention regarding the method of the aspect scattering is the investigation of the frequency spectrum scattered by artificial signal irregularities. One can hope that these measurements alone make it possible to determine the character and the values of the motions induced by the modification of both regular and wave (in particular, variations of the electrodynamic drift due to variations of the plasma density in the region of heating) and to find the mechanism of the turbulence spectrum formation (see *Belenov et al.* [1987]). The investigation of peculiarities of the frequency spectrum of combination frequency signals, its polarization and the fine time and spatial structure can be the real method of diagnostics of the natural current system as well as the study of effects associated with their essential modification. In reality, all methods of diagnostics (except for the resonance scattering and CFS) are used, to a certain degree, in the ionospheric investigations. In the case of the ionosphere modification they are applicable; but only as methods of the diagnostics of the modification effects which in their turn can be effective methods for the experimental investigations of the ionosphere.

TABLE I

NN	Name, location geographical latitude	Frequency range MHz	*G*	*PG* MW	Year of operation start	Reference
1.	Moscow, 56°	1.35	100	1000 (in pulse)	1961	Shlyuger, 1974
2.	Boulder, 40°	4.5–9 2.7–3.3	60–80 30	120–160 60	1970	Utlaut, 1970
3.	Arecibo, 18°	3–12	200–400	160–320	1971	Gordon et al., 1971
4.	Gorky, 56°	4.6–5.75	100–150	15–22.5	1973	Getmatsev et al., 1973
5.	Monchegorsk, 68°	3.3	130	10	1976	Kapustin et al., 1977
6.	Tromsø, 70°	2.5–8	240	360	1980	Stubbe et al., 1981
7.	Sura(Gorky), 56°	4.5–9	240	150–320	1981	Belov et al., 1981
8.	Gissar (Dushanbe), 38°	3.7–6	60–80	6–8	1981	Erukhimov et al., 1985
9.	Khar'kov, 50°	6–12	150	15	1987	Bogdan et al., 1980

REFERENCES

Belenov, A. F., L. M. Erukhimov, N. A. Mityakov, E. N. Myasnikov and V. L. Frolov, In. Sb. Instabilities and wave phenomenon in ionosphere-thermosphere system, 1987, Gorky, IPF, AN USSR.

Belenov, A. F., V. A. Bubnov and L. M. Erukhimov et al., *Izv. VUZov, Radiofizika, 20*(12), 1805, 1977.

Belikovich, V. V., E. A. Benediktov, G. G. Getmatsev et al., *Pis'ma v ZhETF, 22*(10), 497-799, 1975.

Belikovich, V. V., E. A. Benediktov, M. A. Itkina et al., *Izv. VUZov, Radiofizika, 20*(12), 1821-1826, 1977

Belikovich, V. V., E. A. Benediktov, G. I. Terina, *J. Atmos. Terr. Phys., 48*(11-12), 1247-1253, 1986.

Belov, I. F., V. V. Bychkov, G. G. Getmatsev et al., Experimental facility SURA and the first results of investigations on the ionosphere heating, In sb. XXII All-Union Conference on Propagation of Radio Waves, Gorky. Theses of papers. Nauka, M.: 1981, pp. 103-104, June 1981.

Belov, I. F., V. V. Bychkov, G. G. Getmatsev, N. A. Mityakov and G. R. Pashkova, Experimental complex SURA for investigation of artificial ionospheric disturbances, preprint, N167, *NIRFI*, Gorky, 1983.

Belyaev, P. P., D. S. Kotik, S. N. Mityakov, S. V. Polyakov, V. O. Rapoport and V. Yu. Trakhtengerts, *Izv. VUZov, Radiofizika, 30*(2), 248-267, 1987.

Bespalov, V. I., and V. Yu. Trakhtengerts, Alfven masers, *AN USSR*, Applied Physics Institute, Gorky, 1986.

Bogdan, A. P., A. N. Gridin and A. V. Levkov, Decametric heating facility, in *Investigation of the Ionosphere by the Method of Incoherent Scattering*, no. 170, pp. 44-48, Vestnik, Khar'kov Polytechnical Institute, Kar'kov, 1980.

Duncan, L. M., J. P. Sheerin and R. A. Behnke, *Phys. Rev. Lett., 61*(2), 239-334, 1988.

Erukhimov, L. M., V. A. Ivanov, N. A. Nityakov, V. P. Uryadov, V. L. Frolov and V. V. Shumaev, *Izv. VUZov, Radiofizika,, 30*(9), 1055-1066, 1987.

Erukhimov, L. M., V. Ya. Kovalev, E. P. Kurakin et al., *Izv. VUZOv, Radiofizika, 28*, 658-662, 1985.

Erukhimov, L. M., S. A. Metelev, E. N. Myasnikov, N. A. Mityakov and V. L. Frolov, *Izv. VUZov, Radiofizika,, 30*(2), 208-225, 1987.

Gershman, B. N., L. M. Erukhimov, Yu. A. Yashin, *Wave Phenomena in Ionospheric and Cosmic Plasma*, M.: Nauka, 1984.

Getmatsev, G. G., G. P. Komrakov, Yu. S. Korobkov et al., *Pis'ma v ZhETF, 18*, 621-624, 1973.

Ginzburg, V. L., *Propagation of Electromagnetic Waves in Plasma*, M.: Nauka, 1967.

Ginzburg, V. L., and A. A. Rukhadze, *Waves in Magnetoactive Plasma*, M.: Nauka, 1979.

Grach, S. M., N. A. Mityakov and S. N. Mityakov, Ionosphere disturbance by powerful waves. The results of science and technology. VINITI. ser. *Geomagnetism and High Layers of the Atmosphere*, M.: 1989.

Gordon, W. E., R. L. Showen and N. C. Carlson, *J. Geophys. Res., 76*(31), 7808-7813, 1971.

Gurevich, A. V., and A. B. Shvartsburg, *Nonlinear Theory of Radio Wave Propagation in the Ionosphere*, M.: Nauka, 1973.

Kapustin, I. N., R. A. Pertsovskij, A. N. Vasil'ev et al., *Pis'ma v ZhETF, 25*, 248-251, 1977.

Schlegel, K., M. Rietveld and A. Maul, *Radio Sci., 22*(6), 1063-1072, 1987.

Shlyuger, I. S., *Pis'ma v ZhETF, 19*(5), 247-251, 1974.

Stubbe, P., H. Kopka and R. L. Dowden, *J. Geophys. Res.* , *86*(11), 9073-9078, 1981.

Stubbe, P., et al., *J. Atmos. Terr. Phys., 47*(12), 1151-1163, 1985.

Utlaut, W. F., *J. Geophys. Res., 75*(31), 6402-6405, 1970.

Yampol'skij, Yu. N., *Izv. VUZov, Radiofizika, 32*(4), 519, 1989.