Nonlinear phenomena in the ionosphere

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In 1930, Tellegen and Lbov discovered that the transmission of a strong radio station could be heard at another frequency in the radio band. It was found that the radiation from the strong station gave rise to considerable disturbances in the ionosphere and this was why its modulation was transmitted to other radiowaves propagating in the disturbed region. This nonlinear phenomenon, now known as cross modulation or the Luxemburg-Gor'kov effect, was investigated in detail in the nineteen-thirties and nineteen-forties.[1] It was interpreted by Bailey and Martin in a fundamental paper published in 1934.[2] In 1948, V. L. Ginzburg proposed a different and more rigorous approach to the description of cross modulation, based on the kinetic theory of Boltzmann.[3] This approach was extensively developed by subsequent workers and forms the basis of the theory of nonlinear thermal phenomena in the ionosphere.[4,5]

The rapid increase in the power and directivity of radio stations in recent years has resulted in the availability of very high intensity radio waves producing strong disturbances in the lower ionosphere (D and E layers at 60–120 km) and effectively modifying the upper ionosphere (the F layer at 200–350 km). This has given rise to a new stage in the investigation of nonlinear phenomena in the ionosphere which began in 1960–1970.

The characteristic quantity that determines nonlinear thermal effects is the plasma field[4,5]

$$E_p = \sqrt{3Tm\delta}\,\frac{\omega}{e} \qquad (1)$$

where e, m are the electron charge and mass, T is the electron temperature, δ is the mean fraction of energy lost by an electron per collision, and ω is the radiowave frequency. If the radiowave field amplitude is $E_0 \ll E_p$, it can give rise to only weak disturbances in the ionosphere. Conversely, when $E_0 \gtrsim E_p$, the properties of the ionospheric plasma are strongly modified by the incident radiowaves.

In the lower ionosphere, the plasma field E_p is relatively low (for example, $E_p \sim 0.05$ V/m when $\omega = 10^6$ sec^{-1} and $E_p \sim 0.3$–0.5 V/m when $\omega = 10^7$ sec^{-1}). Modern transmitters can produce fields E_0 exceeding E_p by an order of magnitude. At the same time, we know that nonlinearity has a determining influence on the propagation of such strong radiowaves. The electrons in the ionosphere are rapidly heated by the radiowaves, and their effective temperature can increase by factors of 20–40.[6,7] There is a corresponding increase in the electron collision frequency, and this leads to an increase in the nonlinear absorption of radiowaves. The result of all this is a sharp attenuation or even the effect discovered by Shlyuger *et al.*[6] whereby the intensity of the radio signal reflected from the ionosphere decreases with increasing radiated power. Under these conditions, nonlinear absorption may reach 25–30 dB. There are also strong wave-interaction effects, namely, the "suppression" of a weak wave by a strong radiowave (nonlinear attenuation up to 30 dB) and the reverse effect of induced transparency of ionospheric plasma (reduction by 10–15 dB in the attenuation of a weak wave under the influence of a strong wave). The interaction of amplitude-modulated waves was found to be accompanied by a considerable distortion of the modulation waveform and the doubling of the modulation frequency (overmodulation).

The observed nonlinear effects in the lower ionosphere are, in general, in reasonable agreement with the predictions of the theory based on the simultaneous analysis of the kinetic equation for the plasma electrons and the Maxwell equations for the radiowave field.[4,5] More precise quantitative analysis requires particular details of electron kinetics in ionospheric plasma. One must know the specific characteristics of the various inelastic processes such as, for example, the cross sections for the excitation by electrons of rotational, vibrational, and optical levels of the main molecular components of the ionosphere. Detailed comparison of ionospheric experiments with the theory can be used to determine the kinetic parameters of the lower ionosphere.[7]

Substantial changes in the ionization in the lower ionosphere produced by high-power radiowaves have also been established experimentally.[8] The fact that artificial ionization of the ionosphere was possible was pointed out by Bailey as far back as 1938.[9] Various specific mechanisms for changing the ionization were subsequently discussed theoretically, including high-frequency breakdown, changes in the recombination coefficients, and isothermal ionization.[10] There are also some interesting phenomena connected with the heating of the neutral atmosphere and the appearance of the sporadic E layer.[11]

The "detecting" effect of the ionosphere, discovered by Getmantsev *et al.*,[12] must be particularly noted. Thus, low-frequency radiowaves with $F = 2$–8 kHz are observed in the earth-ionosphere waveguide and are generated as a result of the nonlinear detection in the ionosphere of high-power, high-frequency radio signals with amplitude modulation at the frequency F. The possibility of this important phenomenon, which appears as a result of the nonlinear generation of the difference combination frequencies in the ionosphere, was pointed out by Ginzburg *et al.*[4,13] Detailed theory connects the detecting effect with the modulation of ionospheric currents.[14] Considerable enhancement of the detecting effect is expected when the ionosphere is disturbed in the regions near the poles or near the equator, where the ionospheric currents are particularly strong. The nonlinear generation in the ionosphere of other combination frequencies is also possible.[15]

The modification of the upper ionosphere achieved for the first time by Utlaut *et al.* in 1970[16] has played a fundamental role in the development of studies of nonlinear phenomena. The fact that radiowaves could be a means of modifying the ionosphere, i.e., of altering the plasma temperature and concentration distribution in the F layer, was originally noted by Ginzburg *et al.*[4,17] Such changes in the temperature and concentration of electrons have, in fact, been confirmed experimentally and were found to be in accordance with the theoretical predictions.[18] Moreover, a whole series of new and important phenomena has been discovered and found to be connected with the excitation of instabilities in the ionosphere under the action of radiowaves. They include, above all, the large-scale stratification of ionospheric plasma resulting in the appearance of the artificial sporadic F layer.[19] The spectrum of inhomogeneity scales ranges from about 100 m to about 10 km, and the concentration perturbations in these inhomogeneities are of the order of a few percent. Theory associates this stratification with thermal self-focusing instability which develops in the region from which the radiowaves are deflected.[20]

Small-scale stratification of ionospheric plasma with the formation of inhomogeneities that are highly elongated in the direction of the geomagnetic field, discovered by Fialer *et al.*,[21] are found to develop in the region from which the ordinary radiowaves are reflected. The characteristic scales of these inhomogeneities at right-angles to the magnetic field range from 10 cm to 1 m, and their longitudinal size is of the order of a few hundred meters or even kilometers. Such inhomogeneities are very effective scatterers of VHF radiowaves (frequencies up to 100 MHz or even 500 MHz). They are very effective as a means of VHF radiocommunication between points on the earth surface three to four thousand kilometers apart (artificial ionospheric mirror)[22] and for the excitation and deexcitation of the ionospheric wave channel with a view to ensuring ultralong-range and global propagation of short radiowaves.[23] The small-scale stratification also appears to be connected with anomalous absorption of ordinary radiowaves in the upper ionosphere, found by Cohen *et al.*[24] Theory associates this small-scale stratification with nonlinear resonance instability.[25] Parametric dissipative and drift instabilities may be important during the initial stage.[26]

Finally, Gordon *et al.*[27] have discovered strong excitation of plasma waves in the ionosphere and emission due to accelerated electrons. Theory relates these phenomena to parametric instability of Langmuir oscillations in the field of a high-power radiowave.[28] Self-modulation of a strong radiopulse reflected from the F layer, reported in[6,29], is probably also connected with the excitation of this parametric instability.[30]

It is also important to note the enhanced nonlinear scattering of the extraordinary wave, which is probably connected with strictional expulsion of plasma.[31]

Both theoretical and experimental studies of nonlinear effects in the ionosphere are currently developing very rapidly.

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