Combination frequencies in the interaction between high-power short-wave radiation and ionospheric plasma

G. G. Getmantsev, N. A. Zuĭkov, D. S. Kotik, L. F. Mironenko, N. A. Mityakov, V. O. Rapoport, Yu. A. Sazonov, V. Yu. Trakhtengerts, and V. Ya. Éĭdman

Radiophysics Research Institute

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Emission due to quadratic nonlinearity in the ionosphere was observed at the modulation frequency of a high-power short-wave transmitter. The transmitter delivered an average power of 130 kW at 5.75 MHz to an antenna with a vertical directivity pattern. The antenna gain was $G \approx 150$. A signal with field intensity $E \sim 0.02$ μV/m was registered in daytime at transmitter modulation frequencies from 1.2 to 7 kHz at a distance 180 km. It is shown that the principal role in the formation of the combination-frequency signals is played by the heating nonlinearity in the ionosphere D layer.

In 1960, V. L. Ginzburg and A. V. Gurevich have shown that when two intense radio waves with frequencies f_1 and f_2 propagate in the ionosphere, a combination-frequency electromagnetic field should be produced.[1,2] To observe this effect, a land-based radio transmitter was used with a cw radiation power up to 150 kW, operating at $f = 5.75$ MHz. The transmitter was amplitude modulated (modulation depth ~95%) and fed a phased multidipole antenna with a vertical directivity pattern and with a gain $G = 150$.[3] The modulation frequency F was varied in succession and took on values 1259.45, 1773.03, 2525.27, 4000.04, and 7246.44 Hz. The receiving point was located at a straight-line distance 180 km to the north of the short-wave transmitter. The sensitivity of the receiving apparatus in the indicated frequency band was limited by the broadband atmospheric noise (under magnetic disturbance conditons) by the natural magneto-spheric VLF radiation. To increase the signal/noise ratio in the reception of a weak sinusoidal signal we used therefore a receiver with a narrow bandwidth. The signals were received at the indicated frequencies with a loop antenna having an effective area $nS \doteq 2500$ m^2. The réceived signals were amplified with a broadband amplifier (with bandwidth from 1 to 8 kHz) and fed to a synchronous detector, where the signal voltage was multiplied by that of an auxiliary oscillator whose frequency was 0.01—0.03 Hz lower than the signal frequency. The converted signal with difference frequency 0.01—0.03 Hz passed through a filter with bandwidth 0.25 Hz and was automatically plotted on a chart. A typical plot of the signal at 2525.27 Hz is shown in Fig. 1, where beats of frequency 0.019 Hz and of amplitude proportional to the signal field intensity are clearly seen after the transmitter is turned on at 11:01. After turning the transmitter off at 11:20, only random atmospheric noise was recorded on the chart.

The signals at the high-power transmitter modulation frequency F were observed for all the frequencies indicated above. A distinct diurnal variation of the signal field intensity was observed. As a rule, the intensity reached a maximum in the noontime. There were no signals during the dark time of the day. The frequency variation of the low-frequency signal field intensity is shown in Fig. 2. The maximum signal intensity is reached at the frequency $F = 2.5$ kHz. At the end-point frequencies ($F = 1.2$ and 7 kHz) the signal was rarely registered, whereas at $F = 2.5$ and 4 kHz the signals were observed regularly in the daytime. At 2.5 kHz, the field intensity varied from day to day between 2×10^{-2} and 25×10^{-2} μV/m. The low-frequency signal field intensity varied randomly during the day, with characteristic times 1—2 hr. The field intensity at the frequency F was linearly dependent on the change in equivalent transmission power. In October 1973, when the measurements were performed under magnetically quiet conditions, the changes of the field intensity during the day were smooth. In February 1974, some of the observations were made under magnetic-disturbance conditions against the background of intense natural VLF radiation. During that time, the signal field intensity at the frequency F varied considerably in time, and sometimes greatly exceeded the intensity of the signal in magnetically-quiet days. We note also that the signal field intensity at the low frequency was completely independent of the critical frequency of the ionosphere $\mathcal{F}$ layer and, in addition, no shifts of the frequency F of the received signals were observed, accurate to 10^{-3} Hz.

Proceeding to the interpretation of the experimental results, we emphasize that the appearance of combination-frequency signals is due to processes in the lower atmosphere. This is evidenced by the absence of a frequency shift in the received signal, the absence of any connection between the measurement results and the critical frequencies of the ionosphere $\mathcal{F}$ layer, and the characteristic diurnal course of the field intensity at the difference frequency F.

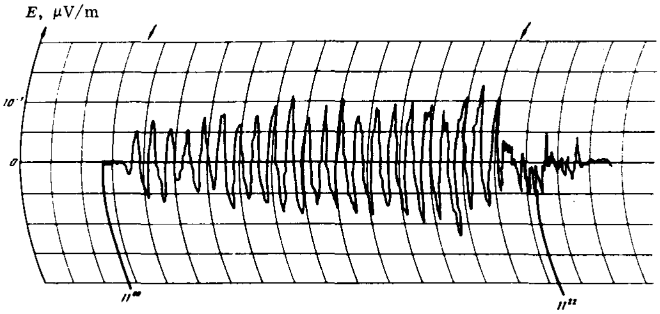

FIG. 1. Typical signal at 2.5 kHz. The arrows indicate the instants when the high-power transmitter was turned on and off.

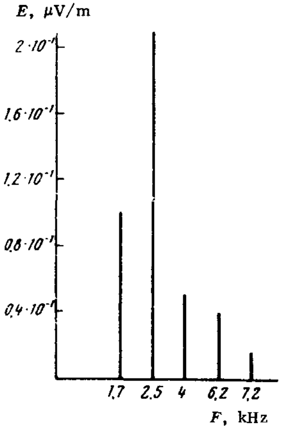

FIG. 2. Typical amplitude spectrum of the field at the combination frequencies at noontime hours.

A theoretical estimate of the field intensity above the signal reduces to a calculation of the nonlinear current excited in the D layer of the ionosphere by the field of the high-power earth-based transmitter. Comparison of the nonlinear currents due to the heating and striction effects shows that the heating currents are $(\omega + i\nu)/(\Omega + i\delta\nu)$ times stronger than the striction currents (here $\Omega = 2\pi F$, $\omega = 2\pi f$, $\nu \sim 10^{-7}$ is the electron collision frequency, and $\delta \sim 10^{-3}$ is the relative fraction of the energy transmitted by the electron to the molecule in one collision).

The density of the nonlinear current due to the thermal effects in the homogeneous plasma¹⁾ is

$$\mathbf{J} = \frac{ie\omega_{0e}^2(\Omega + 2i\nu)(i\vec{\kappa} + \nu\mathbf{V}_0/V_{Te}^2)E_{\omega 1}E_{\omega 2}^*}{12\pi m(\Omega + i\nu)(\Omega + i\delta\nu)(\omega_1 + i\nu)(\omega_2 - i\nu)}\, e^{-i(\Omega t - \vec{\kappa}\mathbf{r})}, \tag{1}$$

where $\vec{\kappa} = \mathbf{k}_1 - \mathbf{k}_2$ is the difference wave vector, $\Omega = \omega_1 - \omega_2$, ω_{0e} is the Langmuir frequency of the electrons, V_{Te} is the thermal velocity of the electrons, e and m are the charge and mass of the electrons, and $V_0 = V_{0e} - V_{0m}$ is the difference between the translational velocities of the electrons and of the molecules.

The first term in the numerator of J is connected with the thermal pressure of the electrons, and the second with the presence of regular motions of the electronic component relative to the molecules.

A rough estimate based on (1) shows that even at $\mathbf{V}_0 = 0$ the field intensity at the reception point can amount to 10^{-2} μV/m under the experimental conditions. In magnetic-disturbance days, when an increase of the velocity $\mathbf{V}_0$ can be expected, nonlinear currents can be governed by the second term of (1) and the field intensity increases.

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(1) The characteristic pressure gradient ∇NT in an inhomogeneous plasma may be governed not by κ, but by the scale L^{-1} of the inhomogeneous layer.

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