Chapter 10

Nonlinear ELF-VLF Effects Observed on ACTIVNY Satellite

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Abstract. It is reported that a powerful VLF generator on board the ACTIVNY (Inter-cosmos-24) satellite produced an effective nonlinear excitation of ion-sound electrostatic turbulence. This turbulence was then converted to lower hybrid resonance noise after the cease of the radiation, and the nonlinear increment of this conversion was proportional to the amplitude of the ion-sound wave. The interesting narrow-band signals with changing tone in the frequency range of low hybrid resonance were observed during the operation of low-power onboard generator with sweeping frequency from 0.5 to 19.5 kHz.

10.1 Introduction

Radiation from VLF antennas within the natural plasma was investigated in many theoretical papers based on a linear approximation to the problem (e.g., Wang and Bell, 1972). However, only a few experiments were carried out to prove these theoretical expectations. Two of them were conducted on rockets by Barrington (1969) and Beghin and Debie (1972), and the latter one was performed on a big satellite station "MIR", where

Nonlinear Waves and Chaos in Space Plasmas, 
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VLF signals from a transport satellite "Progress" with a transmitter at a fixed frequency of 5 kHz and a loop antenna, were received at distances from 1 km to 20 km (Armand et al., 1988). Results of these experiments were explained in terms of the linear excitation, but they found some inconsistency between the theoretical prediction and observational data. We will here mainly discuss the nonlinear effects observed by our onboard VLF radiation experiment.

Satellite ACTIVNY (Intercosmos-24) was launched on September 28, 1989 into the orbit with an apogee of 2500 km, a perigee of 500 km, an inclination angle of 82.5° and an orbital period of 116 minutes. The main purpose of the mission was to investigate the generation and propagation of VLF waves in the far, intermediate and near zones of the generator situated inside the natural upper ionospheric plasma. Following this intention, a powerful fixed-frequency VLF generator (VLF-G), loaded on a big loop antenna, was installed on board the satellite, together with the plasma and wave equipment to register the temporal behavior of the ionospheric medium near the satellite between the generator pulses. It was supposed to measure VLF signals and plasma perturbations in the near (distances \( d \leq 3 \) km) and intermediate zones (\( 3 < d < 100 \) km) from the generator, using a special subsatellite Magion-2 which was assumed to be detached from the main satellite after the first week of launching. It was also planned to observe VLF-G signals on other satellites and on the ground surface to analyze the far distance propagation and penetration of the signals through the lower ionosphere. Unfortunately, the subsatellite Magion-2 was spoiled just after the detachment and a possibility of observation in the near and intermediate zones was missed. Furthermore, the parameters of the output generator circuit after deployment of the loop antenna was drastically changed from pre-calculated values (Agafonov et al., 1991, see also the next section). As the result, the power output of VLF-G was essentially diminished and other satellite observations of ACTIVNY signals were unsuccessful (Sonwalkar et al., 1994).

In addition to VLF-G, a low-power generator PVP with sweeping frequency in a range 0.5-19.5 kHz, loaded on electric dipole antenna was placed on board the ACTIVNY satellite. Combining with a special registration device, PII, it was designed to measure the linear VLF impedance of plasma. However, the nonlinear effects were also observed during the operation of PVP, and they were sometimes rather similar to the effects observed during the VLF-G transmission. So, we will discuss both phenomena.

### 10.2 Short Description of Radiation and Reception Equipment

A VLF generator was connected with a loop antenna (20 m diameter) through a transformer and capacitor, which matched with antenna induc-
tance \( L_a \) of the circuit in resonance with the current near the generator frequency \( f_0 \). The capacity was chosen during the pre-launch tests, which showed that the quality of the circuit (Q) was about 50. In correspondence with the conventional theoretical expectations it was supposed that antenna impedance is not influenced by the plasma, and so we carried out the on-board tuning by changing either the frequency \( (f_0 = 9.8 \pm 0.7 \text{ kHz}) \) or the additional inductance \( (\Delta L \approx 0.05L_a) \). The values of antenna current \( J_a \), applied voltage and the phase between them were measured by a special device and they are telemetered to the ground station. They showed that the value of \( L_a \) during the flight was drastically decreased by about 3 times compared with that before launch and the resonant frequency became out of the tuning range. As the result, the antenna current diminished by about 30 times to 6.5 A even for the high tuning frequency \( f_0 = 10.5 \text{ kHz} \), and the output power was decreased to about 7 W instead of the planned 5 kW. The key on/off modulation of transmission was used, and the most popular were 1/1 s pulse/pause (regime G3), 0.5/3.5 s (regime G1) and 8/8 s (regime G8). Pulses in the last of them were additionally modulated with a frequency \( \Omega = 18.75 \text{ Hz} \). Duration of each sequence was 48 s with a big pause of 16 s. In every radiation session, 6 through 10 sequences were transmitted.

Radiation was observed by electromagnetic receivers NVK-ONCH and ONCH-2. Only the data from filter banks connected with an electric field sensor will be discussed here. Sensors were a usual pair of carbon spheres (tip to tip, 2 m) placed at a distance of 15-18 m from the center of the antenna loop. The filter channels of NVK-ONCH were narrow-banded \( (\Delta f/f = 0.1) \) and were centered at 8, 20, 33, 50, 75, 150, 225, 430, 620, 970 Hz and 9.9, 15.0 kHz. The filters of ONCH-2 were more wide-banded \( (\Delta f/f = 0.25) \) than those of NVK-ONCH and their center frequencies were 35, 43, 75, 200, 300 Hz 1.04, 2.3, 3.45, 4.6, 5.75, 9.6, 19.2 kHz. The sensitivity of the both receivers are shown in Fig. 1. Protection from oversaturation of NVK-ONCH preamplifier was performed by switching on of special shunt during all the period of VLF-G operation. Estimated coefficient of shunting was \( K_{sh} \approx 0.02 \). Unlike it, ONCH-2 was simply switched off exactly during the pulses of the generator, but it could measure the signals during the pauses. Due to the limitations of on-board memory, NVK-ONCH counting rate \( 1/\Delta t \) was poor for ELF channels \( (f < 1000 \text{ Hz}, \ \Delta t = 1.3-5.1 \text{ s}) \) and was higher for VLF channels \( (\Delta t = 0.08-0.32 \text{ s}) \) with the total memory time of \( T = 0.5 - 2.0 \text{ hours} \). The same characteristics for ONCH-2 were as follows: \( \Delta t = 0.04 - 0.16 \text{ s}, T = 24 \text{ s} \) for each of the filter channels.

The sweeping frequency generator PVP was loaded on a dipole electric antenna (18 m tip to tip) and its applied alternative voltage changed from 50 V to 200 V in each of 20 second sequence. Its estimated output power
Figure 1: Sensitivity of NVK-ONCH receiver in the maximum (solid line with black circles) and minimum gain mode (dashed line with open circles) respectively. The lines marked with GAIN—the sensitivity of ONCH receiver (every 3 dB).

ranged from $6 \cdot 10^{-3}$ to $10^{-1}$ W. Similarly to the case of VLF-G, only electrostatic waves could be observed near the antenna. We registered them both on filter banks with memory and sometimes in wideband channels with direct telemetry transmission to the ground station.

### 10.3 Electric Field of VLF-G Signal Near the Antenna

The dynamic range of NVK-ONCH VLF filter 10 kHz, tuned close to the radiation frequency $f_0 = 10.5$ kHz, was 0.02–1 mV/m for the maximum gain and 0.4–40 mV/m for the minimum gain. This filter was usually oversaturated in the first regime of the gain, but showed variations of electric...
Figure 2: The response of NVL-ONCH receiver filters to the VLF generator emission in the G8 (8 sec. radiation, 8 sec. break) mode of operation. The top panel shows the signal supplied by the magnetic antenna (filter $f = 10$ kHz), and we notice the records received by the electric double boom pair at the frequency filter 15 kHz (middle panel) and 10 kHz (bottom). The increase of electric field intensity related to the switching of the input shunting is well manifested at 18.14.20.

field amplitude in the second gain regime due to switching on of the shunt. An example of electric field variation is presented in Fig. 2. Magnetic field amplitude at 10 kHz filter (upper panel) is not changed and directly proportional to the antenna current, but the electric field amplitude at 10 kHz filter (bottom panel) and at 15 kHz filter (middle panel) did change during the flight. Relative attenuation of the wideband 15 kHz filter was about 0.3 at $f_0$ and relation of its response with 10 kHz filter one is understandable. The variation of electric field with geomagnetic latitude is shown in Fig. 3.
There is a clear decrease of amplitude with increasing latitude and also with increasing height (compare the curves 1 and 4, 3 and 7). The latter dependence is connected with diminishing of the plasma density, but an explanation of latitudinal dependence is not so evident. The most probable one is that the excitation factor \( A(f_0) \) of electric field at frequency \( f_0 \) increases approximately as an inverse function of the difference between \( f_0 \) and \( f_{LHR} \) (frequency of low hybrid resonance) as discussed by Beghin and Debie (1972). They showed that \( A(f_0) \approx (f_{LHR} - f_0)^{-1/2} \) by neglecting thermal dissipation. If so, electric field has a maximum amplitude in the situation when \( f_0 \approx f_{LHR} \) (curve 5 in Fig. 3) and the latitudinal variation reflects dependence on ion composition along the satellite trajectory. It is
well known from the observation by low-orbital satellites at heights \( \sim 1000 \) km that the low-latitude values of \( f_{LHR} \) is in a range \( 10-12 \) kHz, but it is smaller for the high latitudes, sometimes \( 3-4 \) kHz. As concerned with the characteristic values of the signal \( A_s \), they can be estimated directly from Fig. 3, with taking into consideration \( K_{sh} \approx 0.02 \), and as the result, \( A_s = 0.5 - 0.8 \) V/m. By a magnetostatic approximation \( A_s \approx Z_0 k_0 a H \), where \( Z_0 \) is free space impedance, \( k_0 = w_0/c \), \( a \) is antenna radius and \( H \) is the value of magnetic field which is approximated by \( J_a/a \). Assuming \( J_a = 6.5 \) A, \( f_0 = 10.5 \) kHz, \( Z_0 = 3.77 \cdot 10^2 \) Ohm we have \( A_s = 0.39 \) V/m, which is in a good agreement with the observational values.

10.4 Excitation of ELF Turbulence by VLF-G Signal

Responses of ELF filters \( (f < 1000 \text{ Hz}) \) were observed simultaneously with the radiation of a quasi-monochromatic signal at frequency \( f_0 \). An example is shown in Fig. 4. It is evident from the figure that an appearance of ELF responses is related with the intensification of VLF signal intensity. The normalized ELF spectra for the four sessions of 1/1 s regime are shown in Fig. 5(a). Normalization of the intensity by a factor \( f/f_1 \) is convenient because of the sensitivity of the receiver and also the ordinary spectra of natural noises are horizontal lines in this presentation. \( (f_1 = 8 \) Hz is frequency of the first filter). The spectra exhibited \( f^{-2} \) dependence in the frequency range \( f < 100 - 200 \) Hz and approximately \( f^{-1} \) dependence at high ELF region. Other spectra for the three sessions of 8/8 s regime with modulation frequency \( \Omega = 18.75 \) Hz are shown in Fig. 5(b). Then, the relationship between the average ELF amplitude and VLF signal for the first three filters is depicted in Fig. 6(a). The same dependence of ELF amplitude near the modulation frequency for the regime 8/8 s is shown in Fig. 6(b). The simplest idea is to suppose that ELF response \( E(f) \) is connected with the imperfectness of filters or non-linearity of NVK-ONCH chains. In both cases, however, \( E \) should be much less than \( A_s \) if \( A_a \) falls in the linear part of amplifier characteristic. For example, in the case of quadratic nonlinear detection,

\[
E = \beta A_s^2(\Omega)
\]

(1)

where \( \beta \) —general coefficient of nonlinear conversion, \( A_s(\Omega) \approx A_s^0/(1 + \Omega/\Omega_0) \), \( \Omega_0^{-1} \) is the repetition period of the meander pulses, \( A_s^0 \) is the amplitude of the signal at current frequency \( f_0 \). It is obvious that the dependence of ELF response on \( \Omega \) \( (E \approx \Omega^{-2}) \) and \( A_s \) is described by Eq. (1). But, nonlinearity of the equipment, calculated from the tests either before launching or during flight calibration, is small, and \( \beta_{eq} \cdot A_s < 10^{-2} \) (eq means equipment) if \( A_s \) did not exceed the saturation level. However, in
Figure 4: The response of NVK-ONCH receiver filters to the VLF-G signal in the G3 mode of operation (1/1 s) with a duration of radiation sequence of 48 sec. and big pause of 16 sec. between them. The response along the orbit to the VLF-G signal itself (filter 10 kHz) is presented at the bottom. The response of other filters showed the excitation of ELF electrostatic turbulence.

reality $\beta A_s \approx 1$, and this means that nonlinear element is situated outside of the equipment and there is strong nonlinear conversion or induced excitation in ELF frequency range. It is very probable that ion-sound electrostatic waves (ISW) were induced. First of all, the VLF generator produced strong heating of the plasma, and its evidence was observed for every session of generation. An example of registration from temperature and electron density analyzer KM-6 is shown in Fig. 7. Increase in effective electron temperature $T_e$ is more enhanced for the direction close to the magnetic field line (bottom panel in Fig. 7) and is about 10–40 times the
background temperature $T_0 \sim 10^3$ K.

The simple estimations show that

$$\frac{T_e}{T_0} \approx \frac{c_0 A_s^2 \omega_{pe}^2}{N_e T_e \omega^2} \approx 10 - 10^2$$  \hspace{1cm} (2)

if $A_s \approx 0.1 - 0.3 \text{ V/m}$, $N_e \approx 10^4 \text{ cm}^{-4}$, $\omega$-wave angular frequency and $\omega_{pe}$, electron plasma frequency. The increase in $T_e$ leads to the ion heating and to the excitation of ISW with the following dispersion relation,

$$\omega = kV_s/(1 + k^2 d_i^2)^{1/2}$$  \hspace{1cm} (3)

where $d_i = V_{Ti}/\omega_{pi}$ is the Debye length, $V_{Ti}$ is the average thermal velocity of ions, $\omega_{pi}$ is the ion plasma frequency and $V_s = V_{Ti}(T_{eff}/T_i)^{1/2}$. We can assume that $k \max \approx 1/a$ in the inhomogeneous radiation field and due to $d_i \ll a$ the phase and group velocities $V_{ph}$ and $V_g$ of the induced ISW are $\sim V_s$ and there is a high-frequency cutoff in their spectrum,

$$f_{\max} \sim V_s/2\pi a.$$  \hspace{1cm} (4)
For the ordinary ionospheric parameters $V_{Ti} \simeq 1.5 - 5$ km/s depending on ion composition and for $V_s \simeq 3V_{Ti}$ we have $f_{\text{max}} \simeq 75 - 200$ Hz. After the cease of radiation, during the period between pulses, the perturbed particles disappear very quickly from the satellite environment due to thermal movement along magnetic field lines or simply due to movement of the satellite itself with velocity $V_0 \simeq 7$ km/s. Supposing a dimension of the heated region $L \approx 10a$, the elapsed time $\Delta t \approx L/V_0 \approx 15$ ms $\ll \tau_p$ ($\tau_p$ is a duration of pause, $\tau_p = 1, 3, 5, 8$ s or $\tau_p = 16$ s between sequences). However, ISW could exist near the satellite for a much long time if

$$V_g \simeq V_0 \cos \alpha$$

(5)

where $\alpha$-angle between the vector of group velocity and direction of the satellite movement. Outside the heated zone $V_g \sim V_{Ti}$ and Eq. (5) could be easily fulfilled. Indeed, this type of ELF turbulence relaxation was usually observed. It was especially evident, using the data by ONCH-2 receiver, because its chains did not undergo the saturation effects during the pulse radiation. An example is shown in Fig. 8 for regime G3. In this case the relaxation time of ELF turbulence is $\sim 1$ s or like so, and it is evident that
after some time a new and higher frequency response ("echo") has taken place.

10.5 Excitation of VLF Turbulence ("Echo" Signal)

A weak echo-signal was observed for about 30% of ONCH-2 registrations. This effect was sometimes observed also by NVK-ONCH, when the signal was rather strong and had a long duration. An example of echo-response on the VLF filters is shown in Fig. 9, and this is the result in the regime of 1/1 s transmission of generator and maximum gain of receiver. The responses were saturated, and we found the signal relaxation between pulses due to time constant of the filter. Appearance of "echo" is evident especially after the last pulse in this sequence (in a big pause 16 s). The time delay of "echo" was about 0.5-0.8 s and its duration was about 0.5 s in this case. Note that observation was made in the high-latitude region ($L = 9.9$, see orbital information in Fig. 9). The results of observations for the session 1163 are presented in Fig. 10. There were 8 sequences, each of which had a
Figure 8: The example of response of ONCH-2 receiver filters in the G3 mode of VLF-G operation (L=1.6, H=844 km). Each segment between dotted vertical lines, duration .92 s, represents the recording after termination of transmission pulse. (The receiver was switched on with time delay 0.08 s after pulse termination and was switched off just before beginning of pulse). The slow relaxation of ELF turbulence below 200 Hz is noticed, and the “echo” response appeared at the higher frequency filters.
Figure 9: An example of "echo" response registered in G3 mode of VLF-G operation by NVK-ONCH VLF filters. The data refer to the session 940 on Dec. 12, 1989. The level of radiation signal is limited due to the dynamic range of NVK-ONCH receiver (maximum gain).
duration 48 s and 16 s pauses between them. Echo response is clearly seen on the ELF higher frequency filters \((f > 150 \text{ Hz})\) and on the VLF filters during the pauses. On the contrary, low frequency ELF filters exhibited only relaxation of the signal. It looks that disappearance of ELF turbulence in the frequency range less than 150 Hz leads to the generation of the wideband high frequency turbulence. In other words, ISW turbulence, leaving the heated region, converts to VLF turbulence with some time delay. Note that VLF turbulence is not likely connected with radiation signal itself, because the turbulence level in the pause exceeds its level during the pulse. Efficiency of ISW conversion obviously depends on geomagnetic
latitude which becomes maximal at the auroral zone region \((L = 5 - 9)\) as evident from Fig. 10. We tried to estimate the statistical characteristics of this conversion using the data of ONCH-2 as presented in Fig. 8. The time difference between the appearance of echo-signal and stoppage of pulse as a function of ISW intensity at the beginning of the pause, calculated as the sum of amplitude squares at the filters with \(f < 100 \text{ Hz}\), is shown in Fig. 11, which provides us with the approximate relation of \(\tau \sim (E^2)^{-1/2}\) indicating a nonlinear increment of conversion \(\gamma \sim \tau^{-1} \sim E\). The typical spectra of VLF turbulence are presented in Fig. 12. Unfortunately due to the limitations of ONCH-2 memory, it was possible to analyze data only in a short time intervals during only a few seconds at the beginning of the transmission session, and this is why we could not estimate the turbulence evolution.

There are at least two possibilities to explain the conversion of ISW turbulence to VLF electrostatic noise. The first is diffusion of ISW turbulence in the k-space that leads to an increase in frequency in correspondence with

![Figure 11: The relation between the delay time of the “echo” response and ELF amplitude square observed in the break between 1 sec. pulses with ONCH-2 receiver (see text for details).](image-url)
Figure 12: The examples of delayed VLF spectra observed with ONCH-2 receiver.

Eq. (3). The final frequency will be about \( \omega_{\text{max}} \simeq V_s/d_i \simeq \omega_{\text{pi}} \), which is close to 3-5 kHz for the ionospheric plasma. However, in this case, the coefficient of diffusion is given by \( D_k \sim E^2 \) and \( \tau \sim (\Delta k)^2 E^{-2} \sim \omega^2 E^{-2} \) for \( \Delta k \gg a^{-1} \). This relation does not coincide with the experimental results. The second is parametric wave-wave interaction with the excitation of LHR electrostatic waves. This possibility does not contradict with our results, because nonlinear increment \( \gamma_n \sim E \), the spectrum maximum roughly corresponded to the ionospheric values of \( \omega_{\text{LHR}} \) and extension of observed frequency range below \( \omega_{\text{LHR}} \) might be explained by a Doppler-shift of short-wave part of the turbulence.

### 10.6 Possible Excitation of Narrow-Band Emissions from PVP-Generator

A schedule of operation of PVP low-frequency generator is demonstrated in Fig. 13. Voltage applied to the electric dipole antennas, was changed from 50 V (regime 1) to 200 V (regime 4). Approximately on about 10% of sessions, rather strange and narrow-band signals were observed. The examples are shown in Figs. 14, 15 and 16. The frequency range of analyzes was from 0 to 10 kHz, because there were no any signals but radiation pulses above this range. The signals were observed in the regime 2 on the upper panel and in the regime 3 on the middle panel of Fig. 14 and in the regime 4 on the bottom panel. The characteristics...
of the signals with changing tone were very variable, such that depending on regime they changed from rising to falling tones and then to constant frequency response with "echo". The example in Fig. 15 is for the regimes 1, 2, 3 and the example in Fig. 16 is again for the sequence of regime 2, 3, 4. All of these examples were received on the orbit 947 during 5 minutes when the satellite was inside the high-latitude ionosphere ($L = 5.9 - 6$) at the altitudes 1320–1600 km. Estimated $f_{LHR}$ was about 7-8kHz in this case and the response on the sweeping frequency in Fig. 14 (bottom panel) is similar to the results of rocket experiment by Beghin and Debrie (1972) (their Fig. 7). Note also that the time delays of "echo" signals in Fig. 14 and Fig. 15 (upper panel) are the same as shown in Figs. 8 and 11, but in this case it is an excitation of quasimonochromatic LHR wave by the fixed-frequency radiation signal. However, the excitation of changing tone signals, like rather well-known triggered emissions from the ground VLF transmitters (see e.g. Helliwell, 1965), is not easily understandable. There is some probability that they are the results of malfunction of the equipment. The only arguments against it is that these signals were not observed during the complex tests of the equipment before launching, that they were observed not very often during the flight and their frequency
Figure 14: Dynamic spectrum of the signals observed with NVK-ONCH receiver during the operation of PVP generator. Upper panel refers to mode 2 ($E_0 = 100 \text{ V}$), middle panel to mode 3 ($E_0 = 150 \text{ V}$), and bottom panel to mode 4 ($E_0 = 200 \text{ V}$). The data refer to the session 947 at the high latitude region ($L = 6.0, H = 1320-1360 \text{ km}$).
Figure 15. The same as in Fig. 14, but 1 minute later. Modes of PVP-operation are 1, 2, and 3 from the upper to bottom panel, respectively. L = 5.95 and H = 1400-1470 km.
Figure 16: The same as in Fig. 15, but 3 minute later. Modes of PVP-operation 2, 3, 4 from the upper to bottom panel, respectively and $L = 3.9$, $H = 1550-1600$ km.
range was concentrated near $f_{LHR}$. So, the origin of these signals is not clear at present.

10.7 Conclusions

There were a lot of discussions before the realization of ACTIVNY project such as how to reach a high efficiency of radiation from an on-board VLF transmitter. The general opinion, based on the results of theoretical calculations, was that using our magnetic antenna with current $J_a \geq 100$ A we can obtain the propagating signal comparable to the radiation from a powerful ground transmitter ($P \sim 1$ MW or so) and we can receive this signal at far distances and below the ionosphere. However, our experiment showed that efficiency of radiation is determined not only by matching of antenna with plasma, but also by nonlinear excitation of wideband electrostatic turbulence. More than 50% of input power were spent to this excitation even for the rather moderate antenna current $J_a = 6.5$ A and intensity of turbulence ($E(\sim A^2)$) was proportional to $J_a^2$. It means that the level of our current was not very below a critical value, above which the current increase have no sense at all. This conclusion might be important for the future active experiments in the natural plasma.

Then, conversion of ISW turbulence to the LHR noise, observed in the our experiment, may not be so an exotic phenomenon, as seems at the first sight. Indeed there were many satellite observations at high-latitude ionosphere, which demonstrated that strong low-frequency emissions, "lion roar" type ($f < 100$ Hz), were accompanied by simultaneous LHR-noise. At least sometimes the origin of LHR-noise might be explained in the manner discussed here.

Acknowledgments. The authors would like to thank Dr. Matsumoto of Kyoto University for useful discussion of the results and L. Turivnenko for assistance in preparation of this paper.

References


