EXPERIMENTAL STUDIES OF THE SPECTRAL RESONANCE STRUCTURE OF THE ATMOSPHERIC ELECTROMAGNETIC NOISE BACKGROUND WITHIN THE RANGE OF SHORT-PERIOD GEOMAGNETIC PULSATIONS

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UDC 550.38

Results are presented from experimental studies into the spectral structure of the regular noise background of tangential magnetic-field components in the range 0.1-10 Hz. The regularly observed resonance structure of averaged spectra is detected and studied in detail; it appears as a sequence of maxima and minima with a frequency interval of $\Delta F \simeq 0.5$-2.8 Hz. The quantity ΔF exhibits a characteristic daily pattern which correlates with that of the critical F-layer frequency at the point of observation. The depth of spectral modulation may be as high as 50%. The daily seasonal pattern is studied, as is the relationship between the parameters of the resonance structure and solar activity. It is demonstrated that this regular noise background that we are considering exhibits the characteristics of a thunderstorm. The derived results are naturally explained in terms of the influence exerted by an ionospheric Alfvén resonator.

1. Introduction. The range of short-period geomagnetic pulsations (SPGP, $\Delta F \simeq 0.1$-10 Hz) has been drawn to the attention of researchers, primarily because the dynamics of many processes within the earth's magnetosphere is determined by the interaction of energy particles and the waves of this region. Interest in studying the SPGP increased markedly at the beginning of the 1960s, when it became clear that global electromagnetic resonators exist within this range. The global electromagnetic resonance of the cavity formed by the earth and ionosphere (Schuman resonance) [1, 2] has been studied in greatest detail. Systematic coverage of the contemporary state of research into Schuman resonances can be found in the monograph [3]. Another example of the appearance of resonance properties in the plasma near the earth in the SPGP range can be found in the existence of a waveguide for fast magnetosonic waves at the altitudes of the ionosphere [4, 6], governed by the nonmonotonic profile of the Alfvén index of refraction in the ionosphere (Fig. 1). Although the Q-factor of this

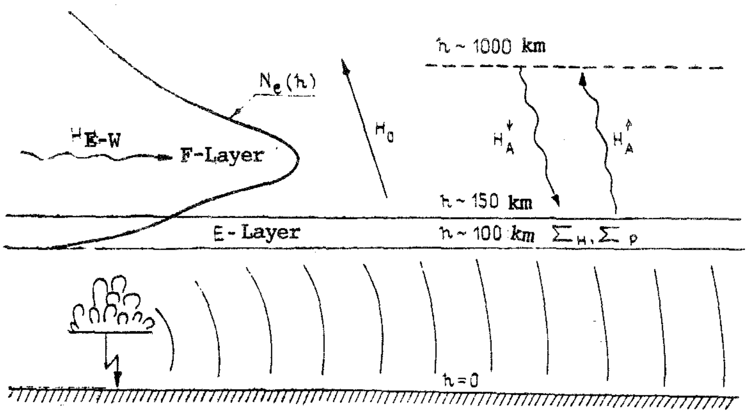


Fig. 1

Scientific Research Radiophysics Institute. Translated from Izvestiya Vysshikh Uchebnykh Zavedenii, Radiofizika, Vol. 32, No. 6, pp. 663-672, June, 1989. Original article submitted July 10, 1987.

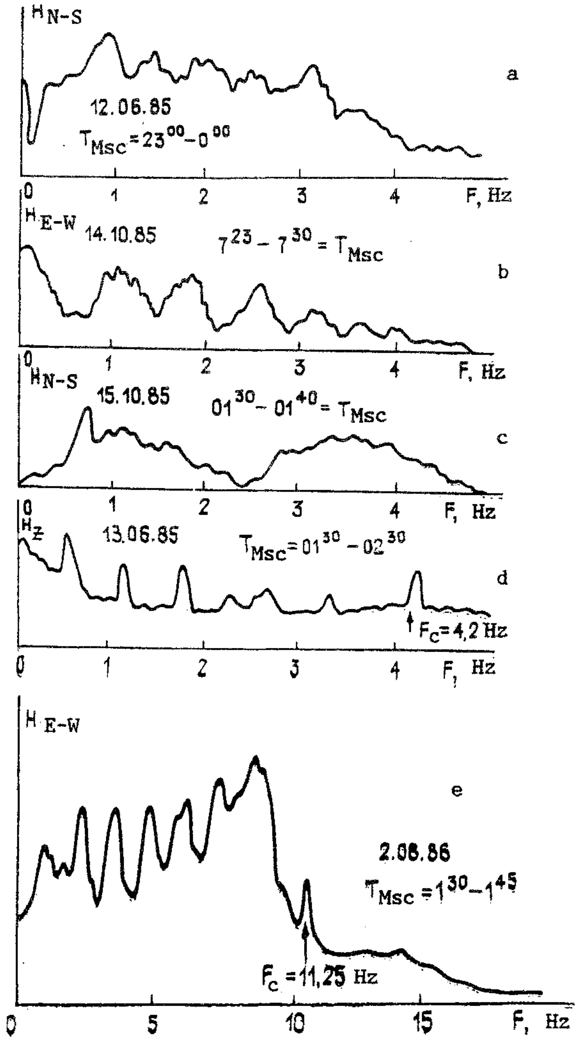


Fig. 2

waveguide is not large, nevertheless it plays an important role in the formation of the zone of SPGP reception from a local (magnetospheric) source.

In 1976 [7] one of the authors of this paper put forward the hypothesis that yet another natural resonator of Alfvén waves [8] must exist in the range 0.5-10 Hz at the altitudes of the ionosphere. It should be noted that the existence of such a resonator is by no means obvious, since in light of the specific dispersion of the Alfvén waves ($\omega = k_z v_A$, ω is the frequency, k_z is the projection of the wave vector onto the direction of the magnetic field) the nonmonotonic profile of the refractive index n_A which exists at the altitudes of the F-layer (Fig. 1) does not yet provide for the possibility of total internal reflection of the waves, and the geometric optics approximation must necessarily be disrupted. As is demonstrated by calculation [7, 8], this condition in the range 0.1-10 Hz can be satisfied both above and below the F-layer. The same unique features encountered in the dispersion of the Alfvén waves leads to yet another important consequence, namely, the absence of a group velocity component across the lines of force of the magnetic field. This indicates that in the presence of reflections above and below the maximum of the F-layer we have the formation of a local resonator of Alfvén waves in a direction that is transverse to that of the magnetic field, and the properties of this resonator are determined only by the characteristics of the medium along the chosen magnetic force line.

The studies conducted in recent times have demonstrated the important role of the ionospheric Alfvén resonator (IAR) in a number of geophysical phenomena. Thus it has been demonstrated in [9, 10] that the IAR may exert considerable influence on the formation of SPGP spectra in the magnetospheric Alfvén maser. The IAR serves, in considerable measure, to explain a number of auroral phenomena [11, 12].

In connection with the above, there arose the urgent need experimentally to observe the IAR, which is precisely the goal of the present study. The experiment to observe the IAR, independent of magnetospheric phenomena, can be based on the exploitation of the circumstance that the lower wall of the IAR serves simultaneously as the upper wall of the cavity formed by the earth and the ionosphere and, consequently, exerts influence on the formation of the frequency characteristics of its impedance in the corresponding frequency range. We are left only with the problem of finding the source of the electromagnetic field in the earth-ionosphere cavity with a given amplitude-frequency characteristic. As has been demonstrated in this study, we can use worldwide and local thunderstorm foci as such a source.

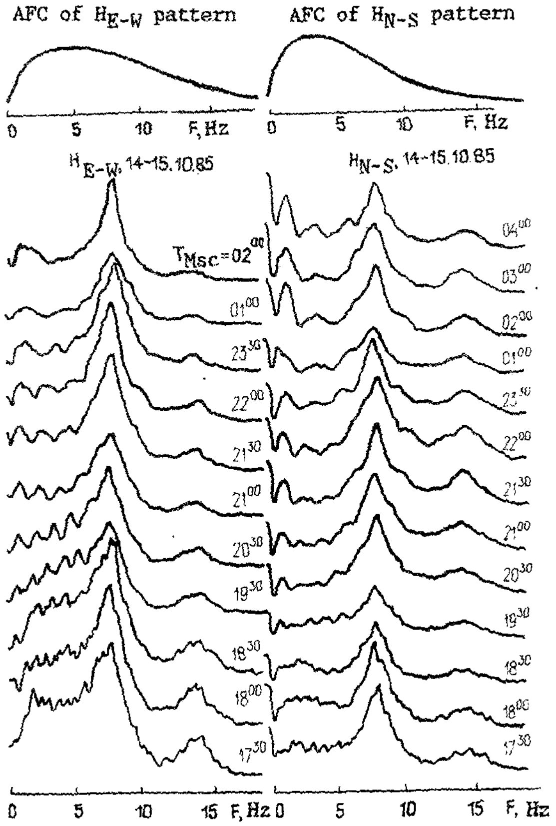
2. Measurement Technique and Method. The standard technique intended for geophysical studies in the range $\Delta F = 0.1$-10 Hz did not prove adaptable to the analysis of the fine spectral structure of the atmospheric noise background generated by the thunderstorm sources. A highly sensitive reception apparatus was developed at the Scientific Research Radiophysics Institute (NIRFI), which included induction sensors of the total vector $\boldsymbol{H}$ of the magnetic field and low-static preamplifiers. The level of intrinsic noise in the horizontal component (H_{N-S}; H_{E-W}) $5 \cdot 10^{-5}$ $\gamma/Hz^{1/2}$ and in the vertical component (H_z) $5 \cdot 10^{-6}$ $\gamma/Hz^{1/2}$. The difference in the H_τ and H_z antenna sensitivities is associated with the distinct structural designs. The H_τ antennas are fashioned in the form of coils (the number of turns is $N \simeq 350{,}000$) with a permalloy core $\mu_{eff} = 5000$. The H_z antenna was fashioned in the form of a frame ($N = 18$, $S = 4 \cdot 10^4$ m^2). The receiving station was situated near the city of Gor'kii, $L \sim 2.65$. The orientation of the H_{N-S} and H_{E-W} antennas was determined by means of a compass, without making any provision for magnetic declination correction factors.

The noise was processed on an SKCh-72/2 spectral analyzer (200 frequency channels on the band chosen for analysis) and this involved averaging independent successive spectral readings. Use was generally made of the following analysis band, i.e., 0.025-5 Hz and 0.1-20 Hz. The averaged spectra were recorded on a two-coordinate automatic recording instrument with continuous tape feed.

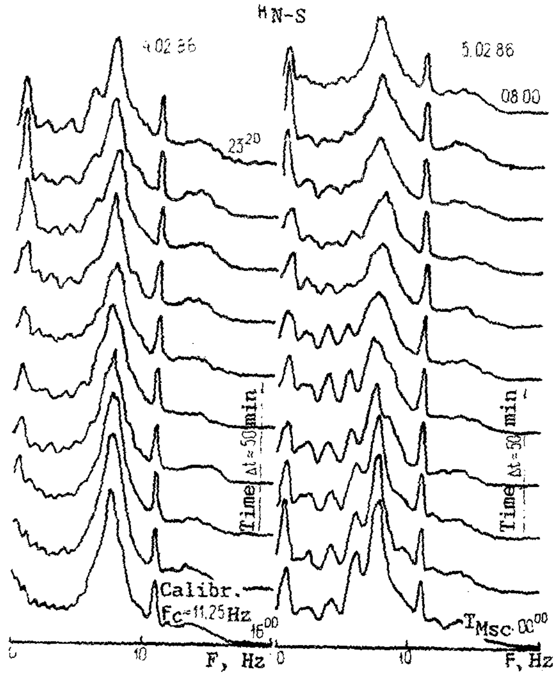
3. Detection of the Spectral Resonance Structure (SRS). The first recordings of resonance structure were obtained in 1985, approximately around midnight, by averaging ~100 independent spectral readings. An example of the first recording is shown in Fig. 2a, where we can see the relatively weakly expressed resonance structure with a frequency interval of $\Delta F \sim 0.5$ Hz between the maxima (minima). Figure 2e shows a typical example of such a recording in the band $\Delta F = 0$-20 Hz, obtained in some of the later experiments. The spectral maxima at frequencies of $F \sim 8$ Hz and 14 Hz correspond to the first and the second Schuman resonances. The narrow spectral line between the Schuman resonances represent the frequency calibration ($F_c = 11.25$ Hz). The zero level near the upper edge of the range is governed by the high-frequency filtration of the input signal. The spectral resonance structure under consideration is concentrated in the frequency band $\Delta F \simeq 10$ Hz. By its nature the spectral resonance structure is quite similar to sporadic radiation of the "hydromagnetic hissings" type [13]. According to [13] this type of radiation is only rarely observed at geomagnetic observatories and is associated with the generation of Alfvén waves in the magnetosphere during the process of cyclotronic instability development. The results of episodic observations of the spectral structure, similar to that shown in Fig. 2, are also contained in [3, 14-16]. Unlike these cited references, it is our contention that the spectral resonance structure, similar to that shown in Fig. 2, is, in addition to the Schuman resonances, a regularly observed fundamental characteristic of the noise in the SPGP range.

The foregoing pertains to the spectra of the horizontal components of the magnetic field H_τ. No spectral structure was observed with sufficient clarity in the H_z component, similar to that of H_τ, if we ignore the first recordings of the averaged spectra obtained in the summer of 1985 when cases of extremely specific spectral resonance structures were recorded in the H_z component, and these contained a number of narrow maxima. An example of such a recording is shown in Fig. 2d. For more detailed conclusions relative to H_z we require additional morphological studies.

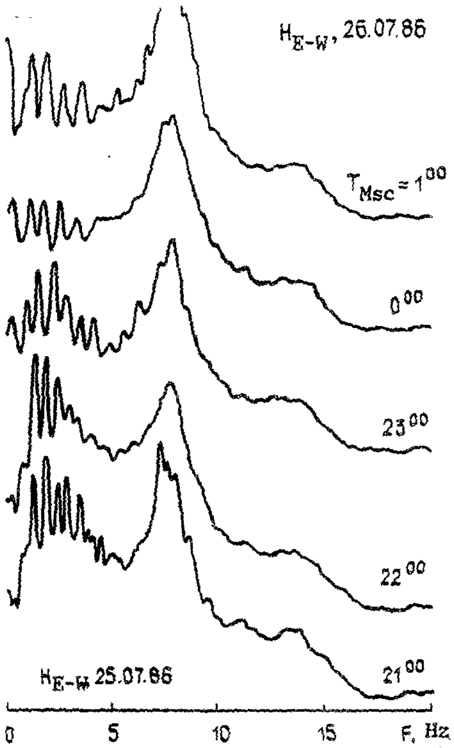
4. Tracking the SRS Parameters on a Daily Basis. A total of 36 daily scans were conducted in the 1985-1987 period (6 scans in October, 10 in December 1985, 2 in February, 6 in March, April, 3 in July, and 3 in September 1986, and 6 in January, 1987) to record the averaged spectra in the 20-Hz frequency band (with a frequency resolution of 0.1 Hz). It required 15 min to record each averaged spectrum (averaged over 128 spectral recordings). Typical examples of these daily scans or fragments of these can be found in Fig. 3a-f. In


AFC of H_{E-W} pattern
AFC of H_{N-S} pattern
F, Hz
H_{E-W}, 14-15.10.85
H_{N-S}, 14-15.10.85
T_{Msc} = 02⁰⁰
F, Hz

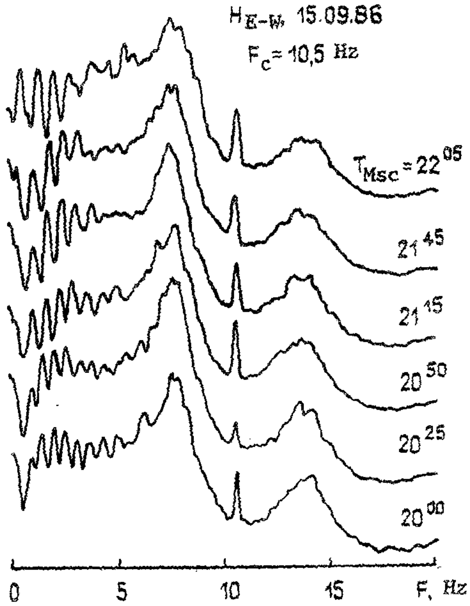
a


H_{N-S}
4.02.86
5.02.86
Time Δt = 50 min
Calibr.
F_c = 11.25 Hz
T_{Msc} 00⁰⁰
F, Hz

b


H_{E-W}, 26.07.86
T_{Msc} = 1⁰⁰
H_{E-W} 25.07.86
F, Hz

c


H_{E-W}, 15.09.86
F_c = 10,5 Hz
T_{Msc} = 22⁰⁵
F, Hz

d

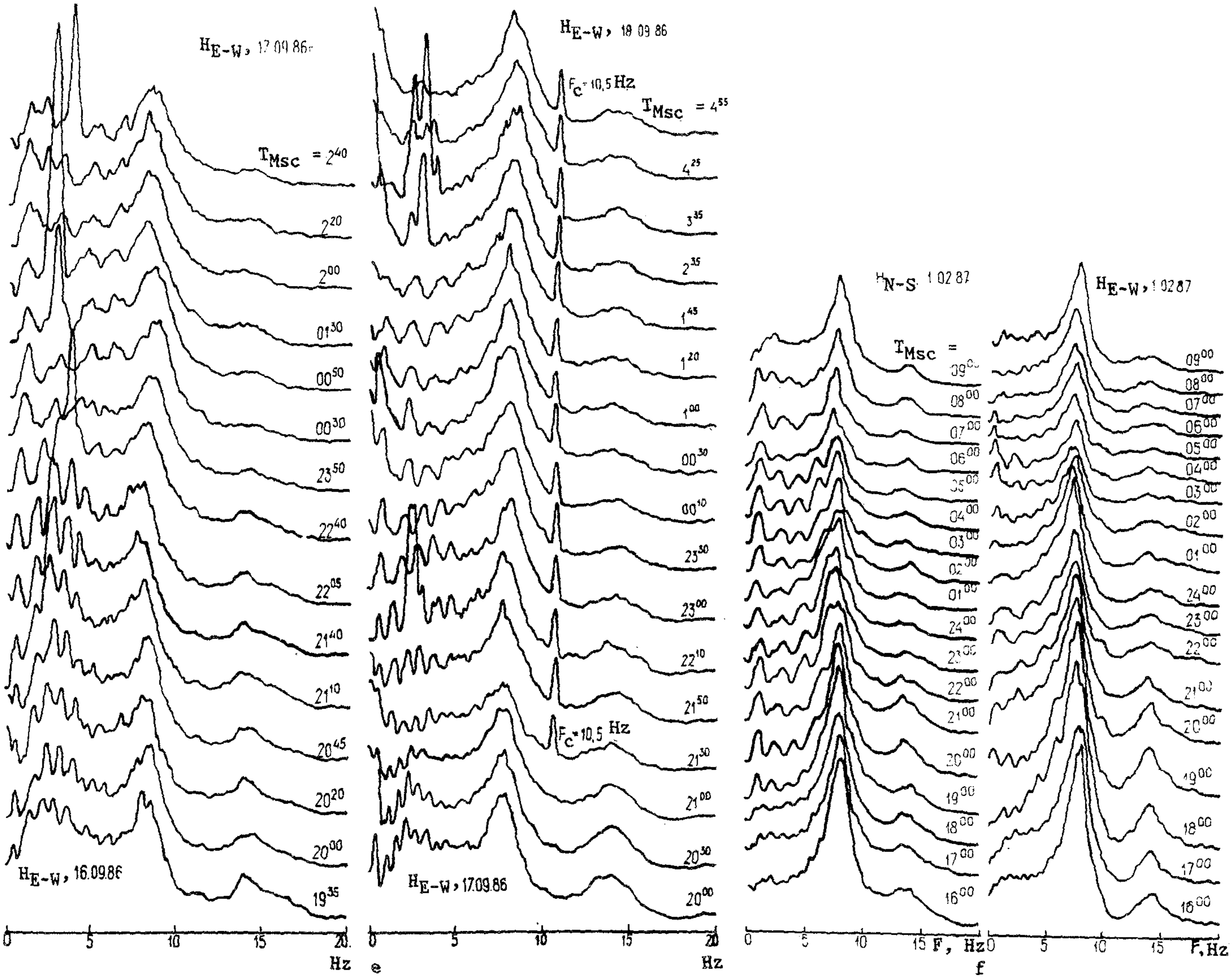


Fig. 3. a-f) Examples of SRS recordings in 1985-1987. a) At the top we show the amplitude-frequency characteristics of the reception patterns obtained with an external calibration frame which served as the source of the calibration field; b) at a frequency F_c = 11.25 Hz the calibration signal generated by the external frame (in analogy with d, e); beginning with T_{Msc} = 23.00 we noted a pronounced deformation in the generatrix of the spectrum in the region of the first Schuman resonance (F_{Schu} = 8 Hz) with a frequency scale characteristic for SRS (compare with f); c) general rise in spectral amplitudes at frequencies of 1-5 Hz during the evening hours is associated with local thunderstorm activity (Fig. 3e; 8).

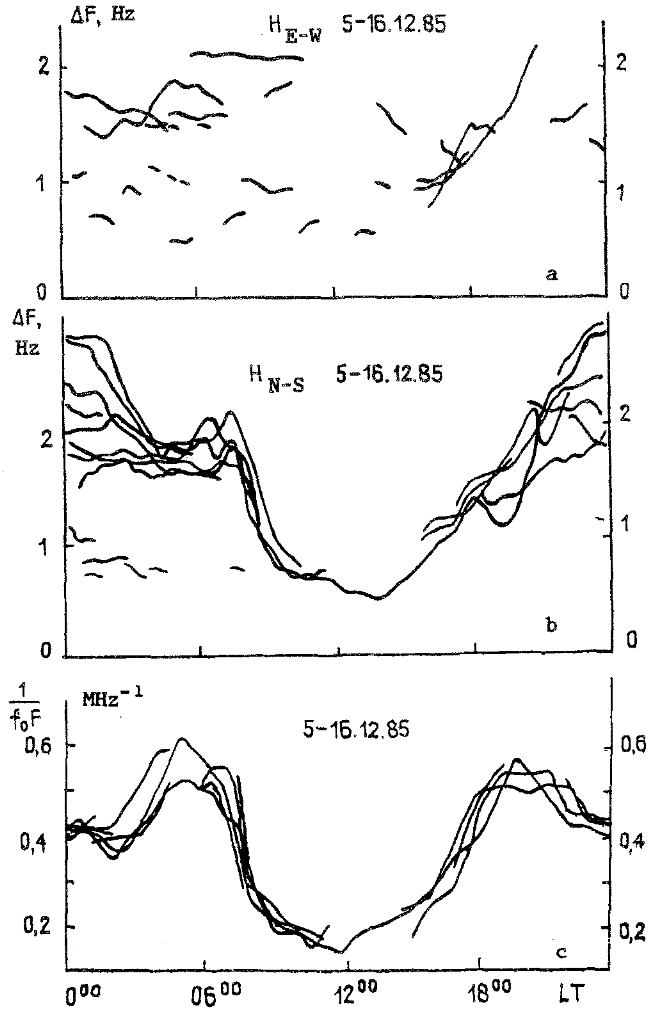


Fig. 4

the frequency region ΔF ~ 1-10 Hz we can clearly observe the resonance structure for all of the scanning procedures with a frequency interval between the resonance frequencies within limits of ΔF = 0.5-2.8 Hz. The quantity ΔF exhibits a characteristic daily track: ΔF attains a maximum during the nighttime hours and diminishes rather rapidly both in the morning and in the evening (see Fig. 2). The depth of spectral modulation is at its maximum at night (up to 50%) and diminishes sharply in the morning and evening hours. During the daytime the SRS is only rarely observed. During the nighttime hours this structure is imposed on the first maximum of Schuman resonance and leads to its "disintegration," which had apparently been observed earlier [3]. Figure 4a, b shows ΔF as a function of the time of day, these functions having been constructed on the basis of the data obtained from the daily scans over the period from November 5-16, 1985. Let us note that in individual cases there exists a double resonance structure which contains two frequency intervals ΔF_1 and ΔF_2 [$\Delta F_1 \approx (1/2)\Delta F_2$; see Fig. 4]. The unique features involved in the polarization of the signals are noteworthy. It is characteristic that if the resonance structure is clearly expressed in the H_{N-S} component, then it will be absent or weakly expressed in the H_{E-W} component, and conversely (see Fig. 4a, b). In our observations the most clearly defined resonance structure was noted in the H_{N-S} component during the winter months, and in the H_{E-W} component in the fall months. We should take note of the fact that within the indicated period of observation, the strong sporadic magnetospheric signals were observed only rarely and this, possibly, was responsible for the results which we obtained above. By the way, the spectral maxima shown in Fig. 3e for the frequency F ~ 3 Hz apparently correspond to the Pc1-type magnetospheric emissions (in analogy with the F ~ 1 Hz maximum in Fig. 3b).

5. Relationship between the SRS Parameters and the State of the Ionosphere and Solar Activity. Let us compare the daily changes in ΔF with the behavior of the critical frequency of the F layer, i.e., f_0F. Figure 4c shows the daily variations in $f_0^{-1}F$ over the same

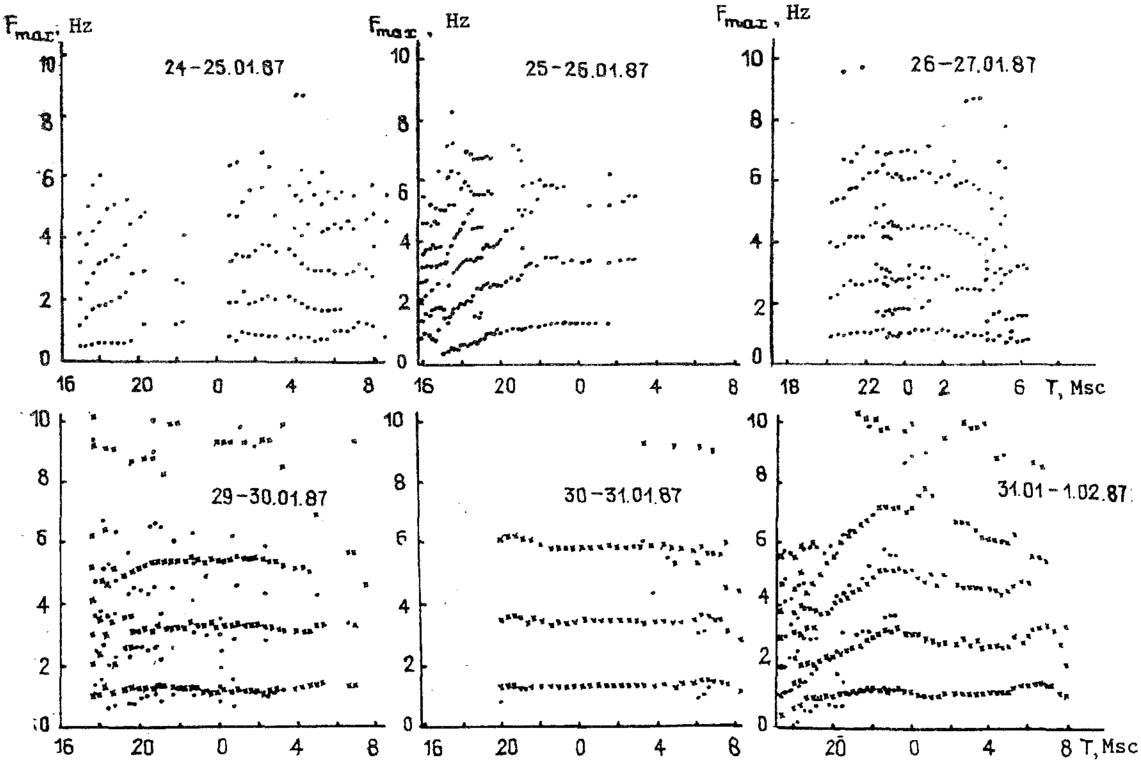


Fig. 5

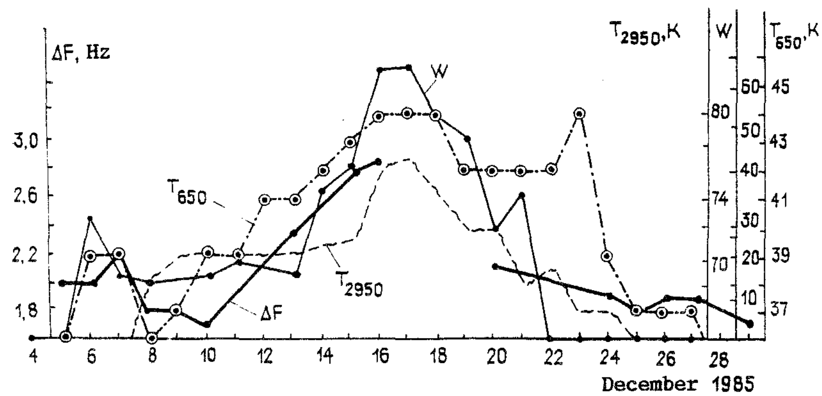


Fig. 6

observation period as in Fig. 4a, b, constructed on the basis of data from an ionosphere station (Zimenki, Gor'kii Oblast), situated 100 km from the point of observation. It follows from a comparison of Fig. 4b and Fig. 4c that the daily variations in ΔF during the morning and evening hours is close to the local daily course of the quantity $f_0{}^{-1}F$. Nevertheless, significant differences are observed during the nighttime hours in the time relationships ΔF and $f_0{}^{-1}F$. Figure 5 shows the results obtained in processing the daily changes in the frequencies which correspond to the maxima of the spectral resonance structure for the period from January 24-31, 1987. The data presented in Fig. 4 on the daily changes in ΔF for the SRS during the period from December 5-16, 1985 are remarkable in yet another regard. This interval of time is characterized by the increasing solar activity beginning on December 13, 1985 through December 20, 1985 (see [17] for additional details). Figure 6 shows the comparative day-to-day changes in the ΔF structure of the period, averaged over the late-night hours 00.00-02.00 LT, as well as the changes in the number W of sunspots and in the brightness temperatures T_{650} and T_{2950} at frequencies of 650 and 2950 MHz, constructed on the basis of the data from [17]. (Unfortunately, no data exists for the period from December 14-17, 1985 on the local critical frequency of the ionospheric F layer during the

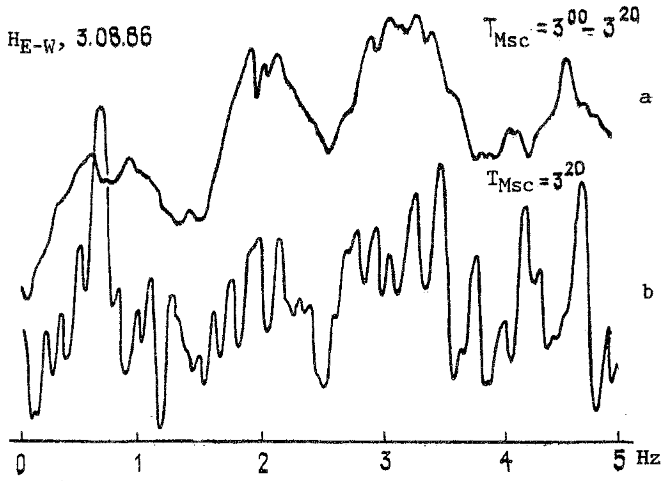


Fig. 7

nighttime hours as a consequence of increased radio wave absorption.) The figure shows the correlation between the time variation of ΔF and solar activity. From the cited experimental data we see that the SRS parameters are controlled to a considerable extent by the structure of the ionosphere near the point of observation.

6. The Spectral Structure of the Primary Source of the Observed Noise. Apparently, it is thunderstorms that serve as the sources of the regular noise background being studied here. We are drawn to this conclusion by the following experimental facts. First of all, the resonance structure which we are investigating is situated on the frequency axis in the immediate vicinity of the first Schuman resonance (and is even superimposed on it), and the fact that a thunderstorm serves as the source of this resonance is generally recognized. Second, the resonance structure is observed on a regular basis, at least under nighttime conditions, under conditions of diverse geophysical and solar activity. And, finally, observation of the dynamics of the noise spectrum in real time demonstrates that the variation of the spectrum is accompanied by regularly repeated bursts (lightning discharge), with the resonance structure most clearly apparent at individual noise peaks. An example of the simultaneously recorded averaged spectrum and of a single instantaneous dynamic spectrum is shown in Fig. 7a, b. Two factors may play a significant role in the formation of the SRS, i.e., the unique characteristics of the spectral source and the response of the natural resonance systems. The presence of SRS in the spectral source (lightning discharge) is highly improbable. At the very least, existing literature contains no specific indications to this effect (see, for example, [3]). We were able to obtain direct data in the summer of 1986 regarding the structure of the nighttime spectrum of the thunderstorm focus as it passed near the point of observation. A recording of this event is shown in Fig. 8a-f. We can see from the figure that the SRS makes its appearance when the distance to the source (the thunderstorm focus) becomes significant (greater than the altitude from the earth to the ionosphere). At these distances the ionosphere (reflected sources) plays a significant role in the formation of the field at the point of observation. In the immediate vicinity of the center of the thunderstorm, basically quite close, we observe a field of lightning discharges whose spectrum, according to Fig. 8, contains no resonance structure.

7. Mechanism of SRS Formation. The most probable factor responsible for the formation of the observed resonance structure is the effect exerted by the properties of the ionosphere, in particular, by the ionospheric Alfvén resonator, on the electromagnetic thunderstorm noise. As was mentioned earlier, the possibility of the existence of an IAR was predicted and theoretically validated in [7, 8]. Numerical calculations are given in [18] for the passage of short-period geomagnetic pulsations from the magnetosphere to the surface of the earth, confirming the conclusions of [7, 8]. The IAR exists due to the presence, in the ionosphere, of two regions (vertical) in which the geometric optics for the Alfvén waves of the SPGP range are disrupted: in the lower ionosphere and in the region above the maximum of the F-layer at the drop in the Alfvén refractive index (see Fig. 1). According to [8] the distance between the harmonics of the IAR can be estimated by means of the formula

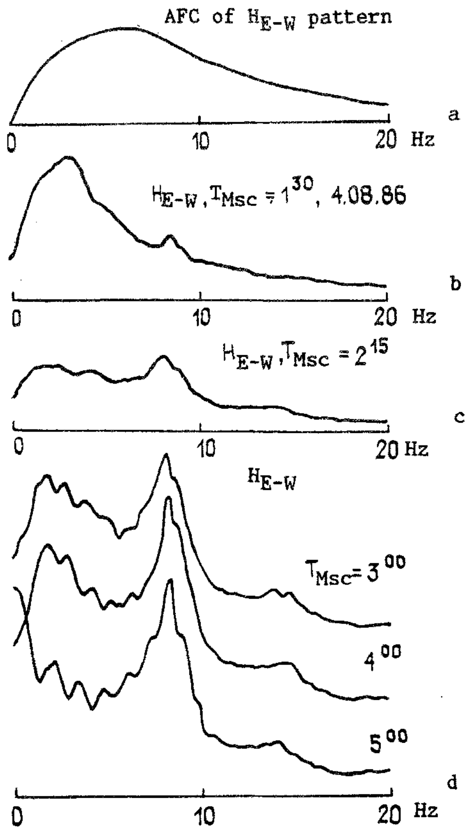


Fig. 8. a) Amplitude-frequency characteristic of the H_{E-W} pattern; b) T_{Msc} = 1 h 30 min: nearby thunderstorm activity and lightning within the field of view; c) T_{Msc} = 2 h 15 min: thunderstorm activity moving away, lightning on the horizon; d) T_{Msc} = 3 h: quiet, with summer lightning; T_{Msc} = 5 h: clear starry sky. The scale has been enlarged by a factor of 2.5 relative to b) and c).

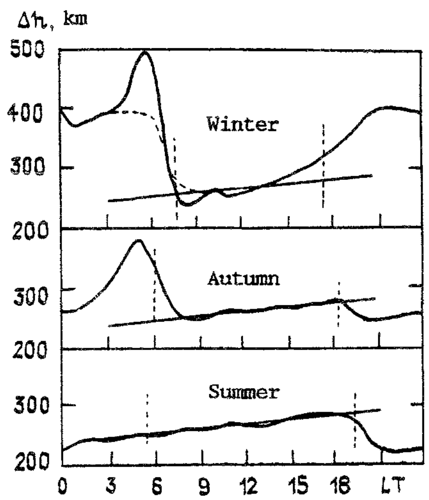


Fig. 9

$$\Delta F = \frac{c}{2 n_A L}. \tag{1}$$

Here c is the speed of light; L is the characteristic scale of the decline in the Alfvén refractive index above the maximum of the ionospheric F-layer, n_A is the Alfvén refractive index at the maximum of the F-layer,

$$n_A = \frac{c\sqrt{4\pi\rho}}{H_0} \propto N_e^{1/2}, \tag{2}$$

where H_0 is the strength of the earth's magnetic field, ρ is the density of the plasma, N_e is the electron concentration. The characteristic quantity $\Delta F \approx 0.5$ Hz ($n_A = 10^3$, L = 300 km) is in good agreement with the period of the resonance structure observed experimentally.

The relationship between ΔF and the electron concentration ($\Delta F \propto N_e^{-1/2}$) corresponds to the quantity $f_0^{-1}F$ as a function of N_e. This fact naturally explains the relationship between the SRS parameters and the state of the ionosphere and the daily variations in ΔF. From the standpoint of the interpretation presented here, the individual differences in the daily variations in ΔF and $f_0^{-1}F$ are associated with the relationship between ΔF and the characteristic vertical scale L of the ionosphere (in addition to its dependence on n_A). Figure 9 shows the ionospheric thickness $\Delta h = \int N_e dz / N_{e\,max}$ as a function of the time of day, taken from [19]. Comparison of Figs. 4 and 9 shows similarity of the functions under consideration. Particularly evident is the presence in both cases of a predawn maximum.

Because of the influence of the IAR, the input impedance of the ionosphere at its lower boundary must exhibit a resonant nature that is similar to the input impedance of the long-line segment with a mismatched load at the end. In qualitative terms, the mechanism of SRS formation as a direct consequence of the influence exerted by the IAR, in our opinion, consists in the transformation of the TH-polarization field (the field of the vertical electric source in an ideal waveguide) into the field of TE-polarization (the field of the vertical magnetic source) as a result of the Hall current excited by the descending field in the lower ionosphere. The level of transformation is determined by the magnitude of the horizontal electric field of the source in the lower ionosphere, which in turn is proportional to the input impedance of the ionosphere, the latter exhibiting a resonance structure. The attenuation and even disappearance of the SRS during daylight hours is explained by the weakening of the resonance structure of the input impedance as a consequence of the large ohmic attenuation of the waves in the daytime lower ionosphere.

8. Conclusions. The totality of all of the above experimental data allows us to formulate the following conclusions. We have observed and investigated the regularly noted spectral resonance structure of the atmospheric electromagnetic noise background in the frequency range 0.1-10 Hz, and this, together with the Schuman resonances, is a fundamental characteristic of the low-frequency electromagnetic field in the cavity formed by the earth and the ionosphere. Apparently, the ionospheric Alfvén resonator is responsible for the formation of the resonance structure, since it affects the frequency characteristic of the impedance of the upper wall of the cavity formed by the earth and the ionosphere. This is borne out by the parameters of the resonance structure (the frequency interval ΔF between the maxima, as well as by the unique features of polarization), by its daily variations, and by the dynamics of the resonance structure in the reception of electromagnetic signals generated by the isolated focus of local thunderstorms. The estimates cited above confirm the conclusion drawn.

Finally, the authors regard it as their pleasant duty to express their gratitude to Yu. V. Smirnov for his assistance in the development of the equipment and to L. V. Grishkevich for his assistance in providing the ionospheric data.

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FLUCTUATIONS IN THE IMAGE CENTER OF GRAVITY WHEN SOUNDING IN A TURBULENT ATMOSPHERE

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UDC 535.317

We have obtained experimental values for the mean square displacement in the image center of gravity under conditions of light-flux scintillation attributable to the finite dimensions of the receiver and the reflector. It is demonstrated that the magnitude of the displacements depends significantly on the type of artificial relfector (disk, corner, corner array) and does not agree with the calculation that corresponds to the conditions of the experiment.

In optical tracking systems and in trajectory-measurement systems, operating in the atmosphere, some contribution to the error in the operational measurements of the angular coordinates is introduced by atmospheric turbulence. As a rule, measurements of this type are carried out with a monopulse method [1, 2] or on the basis of the position of the instantaneous image center of gravity $R_{x,y}$ of the sounding target in the analysis plane Σ of the receiving telescope [3, 4]:

$$R_{x,y} = \frac{\iint\limits_{\Sigma} \{x, y\}\, I(x, y)\, dxdy}{\iint\limits_{\Sigma} I(x, y)\, dxdy} = \frac{P_{x,y}}{P}, \tag{1}$$

where {x, y} are Cartesian coordinates calculated from the optical axis of the system, I(x, y) is the instantaneous distribution of intensity, P is the flux through the aperture, $P_{x,y}$ is the image moment relative to the x and y axes, respectively.

The groundbreaking monograph [5] examines the fluctuations of the image center of gravity for the source of light when the emission is propagated in a turbulent atmosphere under conditions in which the fluctuations in the flux P can be neglected. To perform experiments

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Translated from Izvestiya Vysshikh Uchebnykh Zavedenii, Radiofizika, Vol. 32, No. 6, pp. 673-678, June, 1989. Original article submitted July 14, 1987.

