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Approaches to Evaluating the Quality of Masking Noise Interference

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***Abstract*—The paper discusses the characteristics of spatial electromagnetic noise generators, as well as the formation of a broadband noise signal. A number of well-known methods for assessing the quality of masking noise interference and the approaches used in them have been described. Approaches to the measurement of masking noise were also determined in assessing their quality. In conclusion, additional methods are proposed for assessing the quality of masking noises, such as searching for correlation of noise in different frequency sub-bands and using statistical and (or) graphical methods (tests) for randomness.**

***Keywords*—noise generators, masking noise, TEMPEST, noise quality rating**

I. Introduction

THE aggravation of the situation on the world market increases the importance of ensuring national security. The basis in solving this problem is the protection of information in the field of optics, electronics, radio engineering, acoustics and other sciences. Spatial electromagnetic noise is used to prevent the possibility of interception of informative spurious electromagnetic radiation (TEMPEST) of technical means of processing and transmitting information. Spatial noise refers to active protection methods and is often used when passive methods cannot be used for any reason. By electromagnetic noise (electromagnetic interference, radio noise, radio interference, active masking interference) is meant a time-varying electromagnetic phenomenon that does not contain information and can be superimposed on or combined with a useful signal. In the context of this article, they are intended to worsen or distort the normal operation of the enemy's electronic equipment (EE). Active masking interference creates a background at the input of the enemy's receiver, which makes it difficult to detect informative TEMPEST, their recognition and determination of parameters [1, 2].

It follows that the use of spatial electromagnetic noise generators (NG) should prevent or lead to the impossibility of intercepting informative TEMPEST for their subsequent analysis and restoration of the initial information, or significantly complicating this process.

A large number of noise generators with various technical characteristics and type of execution are presented on the market [3, 4]. One of the most important requirements for a noise generator is the wide-width spectrum of the noise signal and the high uniformity of the spectral density of the noise power. For this reason, noise generators mainly use three schemes for generating a broadband noise signal [1]:

1. the classic method of generating direct noise interference. In this case, it is possible to use several noise sources operating in different frequency ranges. Noise resistors, diodes, transistors, Zener diodes and other elements forming noise similar in their characteristics to "white" can be used as the primary sources of noise in such noise generator;
2. the use of a digital noise generator, the "digital" noise of which is a temporary random process that is close in its properties to the process of physical noise and is called a "pseudo-random process". Such generators form chaotic (pseudorandom) sequences of binary symbols and convert them into a sequence of rectangular pulses of pseudorandom duration with pseudorandom intervals between them. Noise sources in such a noise generator can be microband elements, various integrated circuits, digital signal processors, programmable logic integrated circuits, and other elements [7-11];
3. the use of a stochastic or chaotic method of generating a noise signal. The signal from the harmonic signal generator is fed to a power amplifier operating in a non-linear mode and loaded onto a non-autonomous non-linear dynamic system in the form of a parallel non-linear oscillatory circuit in which the amplified signal is converted into stochastic noise.

At the same time, noisy informative TEMPEST can be filtered and in case of poor-quality masking, the enemy can gain access to the protected information [12]. In NG, a scheme for dividing the entire frequency range into subbands using a frequency multiplier can be used to generate a broadband noise signal [4, 13]. In such cases, the generated noise in different subbands will

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be correlated, i.e. have the same parameters except for the frequency.

This circumstance will allow the subtraction of noise in different ranges in which informative TEMPEST have large amplitude (power) and further restoration of the protected information. It should be noted that the presence of additional factors in the form of repeatability of the informative signal, the level of its amplitude (power), etc. [13] is also important.

In addition, in the absence of complete randomness of the generated noise, statistical analysis methods are used, through which it is possible to identify patterns of noise formation, including their frequency.

II. Assessing the Quality of the Noise Signal Generated

One of the most important requirements for noise generators is the wide-width spectrum of the noise signal and the high uniformity of the spectral density of the noise power. For this reason, noise generators mainly use three schemes for generating a broadband noise signal [1]:

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2) the use of a digital noise generator, the “digital” noise of which is a temporary random process that is close in its properties to the process of physical noise and is called a “pseudo-random process”. Such generators form chaotic (pseudorandom) sequences of binary symbols and convert them into a sequence of rectangular pulses of pseudorandom duration with pseudorandom intervals between them. Noise sources in such generators can be microband elements, various integrated circuits, digital signal processors, programmable logic integrated circuits, and other elements [5, 6];

3) the use of a stochastic or chaotic method of generating a noise signal. The signal from the harmonic signal generator is fed to a power amplifier operating in a non-linear mode and loaded onto a non-autonomous non-linear dynamic system in the form of a parallel non-linear oscillatory circuit in which the amplified signal is converted into stochastic noise.

At the same time, noisy informative TEMPEST can be filtered and in case of poor-quality masking, the enemy can gain access to the protected information [5].

In NG, a scheme for dividing the entire frequency range into subbands using a frequency multiplier can be used to generate a broadband noise signal [3, 8]. In such cases, the generated noise in different subbands will be correlated, i.e. have the same parameters except for the frequency.

This circumstance will allow the subtraction of noise in different ranges in which informative TEMPEST have a large amplitude (power) and further restoration of the protected information. It should be noted that the presence of additional factors in the form of repeatability of the informative signal, the level of its amplitude (power), etc. is also important.

In addition, in the absence of complete randomness of the generated noise, statistical analysis methods are used, through which it is possible to identify patterns of noise formation, including their frequency.

III. Assessing the Quality of the Noise Signal Generated

In this regard, an important problem arises related to assessing the quality of the noise signal generated by NG.

To determine the estimated characteristics of masking noise, information (non-energy or statistical) and energy methods are used. Information methods consider the statistical parameters of noise signals in the time domain and directly determine the numerical coefficient of noise quality. Based on the calculation of the mathematical expectation, variance and entropy of the instantaneous values of time samples and their envelopes, the degree of approximation to some reference distributions is calculated. They are aimed at finding the degree of uncertainty in the instantaneous values of noise signals, expressed, for example, through the entropy coefficient of quality of masking noise. When using this method of active masking, a noise generator emits a special masking signal (interference) with a spectrum similar to that of informative TEMPEST. In this case, the spectral density of the masking noise should be higher than the spectral density of the TEMPEST, and its level should not exceed the levels of the TEMPEST.

The energy method for protecting information uses the postulate of the need for excess noise energy over PEMI in the entire frequency range. Therefore, in order to check the noise quality, integral indicators are used that take into account the excess of the noise level over the level of the informative signal [7, 9].

A. *Methods for assessing the quality of masking noise*

Currently, a number of methods for assessing the quality of masking noise are known:

1) a method for assessing the quality of masking frequency-modulated noise interference;

2) a method for assessing the quality of masking amplitude-modulated noise interference;

3) a method for assessing the quality of masking direct noise interference;

4) a method for assessing the quality of masking acoustic (vibro-acoustic) noise;

5) a method for assessing the quality of masking noise [10];

6) the use of a universal indicator for assessing the effectiveness of masking and imitation radio interference [12].

B. *Entropy coefficient of quality of masking noise*

The main criterion for evaluating the quality of noise in all these methods is the entropy coefficient of quality of masking noise (interference). The entropy coefficient is calculated based on the results of reception (measurement) for a certain period of time of the noise signal (for statistics) and its conversion to voltage with further mathematical operations.

The proposed methods accept instantaneous voltage values of the noise signal with their discretization in time. Further, to calculate the entropy coefficient of quality of the masking noise, the rms value of the voltage of the electric signal, the second moment of the distribution law of the voltage values of the amplitude of the electric signal, the mathematical expectation of the natural logarithm of the voltage values of the electric signal and other parameters are used.

Thus, the following basic parameters are used to calculate the entropy quality factor of masking noise (interference):

- the rms value of the voltage of the electrical signal;
- the entropy of the law of distribution of instantaneous voltage values of an electrical signal (its envelope);
- the second moment of the law of distribution of the voltage values of the electrical signal (its envelope);
- the mathematical expectation of the natural logarithm of the voltage values of the electrical signal (its envelope).

The first four methods for assessing the quality of noise involve the evaluation of a certain type of noise interference (frequency-modulated, amplitude-modulated, direct noise, acoustic (vibro-acoustic)). Below we consider the frequency-modulated, amplitude-modulated and direct noise interference.

C. Frequency-modulated, amplitude-modulated and direct noise interference

The voltage of the frequency-modulated noise interference at the input of the receiver can be represented as follows:

$$u_N(t) = U_N \cos\left[2\pi f_0 t + 2\pi \int_0^t \Delta f(\xi) d\xi + \varphi_0\right] \quad (1)$$

where U_N is the oscillation amplitude; f_0 is the average value of high frequency; $\Delta f(t)=k_F \Delta U_{mod}(t)$ is the random change in vibration frequency; k_F is the steepness of modulation characteristic.

One of the main parameters of frequency-modulated oscillations is the effective value of the frequency deviation index, equal to the ratio of the effective value of the frequency deviation to the effective value of the spectrum width of the modulating voltage. The quality factor of the frequency-modulated noise interference to a large extent depends on the ratio between the width of the interference spectrum and the passband of the receiver of the suppressed electronic means.

Amplitude-modulated noise interference is an undamped harmonic vibration, amplitude-modulated noise. The interference signal at the input of the receiver can be recorded as follows

$$u_N(t) = U_N[1 + k_a \Delta U_{mod}(t)]\cos\omega_0 t \quad (2)$$

where k_a is the steepness of transmitter's modulation characteristic; $\Delta U_{mod}(t)$ is the modulating voltage that comes from the noise generator.

The interference spectrum includes oscillations at the carrier frequency and side components.

Forward noise is closer to normal noise. Two ways of creating noise interference can be applied. The first of these is the use of a microwave generator. The oscillations formed at the output of such a generator are amplified in power and radiated into space. Microwave discharge lamps, for example, are suitable as primary noise sources. The noise generator consists of a gas discharge tube, a segment of a transmitting high-frequency line and a matching device. Depending on the type of high-frequency line used, the generators are coaxial and waveguide. Waveguide-type noise generators are created for waves from 0.2 to 10cm, and coaxial noise from 10-12 to 120-140cm. Gas discharge tubes are very wide-range sources of high-frequency noise and are characterized by high uniformity of the spectrum.

The second way to create direct noise interference is to use the heterodyning method to transfer the noise of a low-frequency generator to the high-frequency region. At low frequencies, the role of primary noise sources is played by direct-heating diodes, thyristors in a magnetic field, and photomultipliers.

The quality factor of direct noise interference would be equal to unity if it were not for the amplitude-limited oscillation that occurs in any physically feasible amplifier path. The amplitude limitation leads to a change in the interference spectrum and the law of distribution of its instantaneous values, as a result of which the quality of the interference decreases.

The fifth method, when calculating the entropy coefficient, considers the uniformity coefficient obtained by a set of spectral components of masking noise in a given limited frequency band.

The sixth method involves taking into account the energy, probabilistic and information-energy properties of interference by applying indicators that take into account useful signals and standard white Gaussian noise.

It should be noted that some parameters and indicators in the considered methods have differences in their designation or name, however, they mean the performance of identical operations or vice versa, the same designations are used for different parameters.

The method for evaluating the quality of masking noise takes into account the influence of the shape of the envelope of the frequency spectrum on the quality of noise interference, as well as the influence of uneven amplitude spectrum of masking noise in a certain (final) frequency range when calculating the entropy coefficient [10].

For clarity, the application of the method for assessing the quality of masking noise generator Fig. 1 shows the histograms of the distribution of amplitudes of the noise signal. For the left histogram, the entropy quality factor is 0.9, and for the right, 0.7. The X-axis corresponds to the number of intervals, and the Y-axis corresponds to the number of sample elements in the interval.

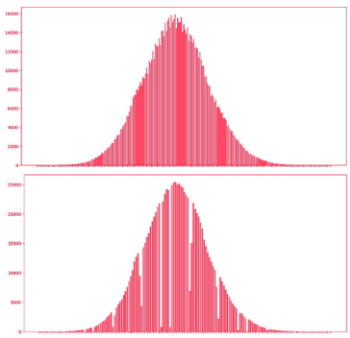

Fig. 1. Histograms of the distribution of amplitudes of the noise signal

Each of the above-mentioned methods for assessing the quality of masking noise interference has some drawbacks. It is also necessary to indicate that in the first three methods for evaluating the quality of masking noise interference, it is proposed to use an X6-4 type correlation characteristics meter (Fig. 2).

Devices of type X6-4 are designed for:

- measurement of normalized functions of autocorrelation and cross-correlation;
- selection of a periodic signal from noise;
- measurement of probability distribution density, probability distribution function and characteristic function;
- measuring the relations of levels that make up the power spectrum of stationary ergodic random processes.

Fields of their application:

- study of the identity of two complex signals;
- study of nonlinear distortions of complex waveforms;
- separation of periodic signals from noise;
- study of power spectra of random signals.

However, X6-4 type meters, as well as other instruments designed to study the correlation characteristics (X6-3, X6-5, X6-8, X6-11 / 1 and X6-11 / 2) have long been discontinued. Accordingly, their use is not possible.

In the fifth and sixth measurement methods, the use of spectrum analyzers is proposed. However, the measurement process itself is not described.

In this regard, taking into account the impossibility of using the X6 series instruments for the necessary measurements, it is considered advisable to use spectrum analyzers (or other measuring receivers), digital storage oscilloscopes, or mixed-signal oscilloscopes.

In this case, you should pay attention to the parameters of the selected measuring instruments: the range of operating frequencies and bandwidth.

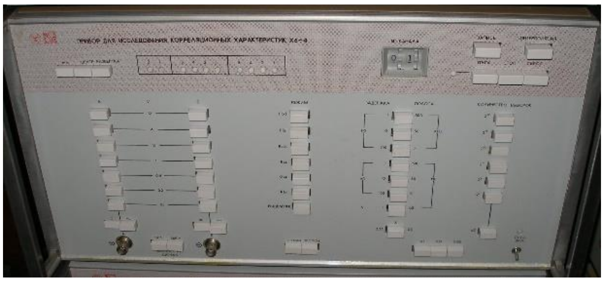

Fig. 2. The device for research of correlation characteristics X6-4

If you select an oscilloscope with the necessary bandwidth of 2-3 GHz (the operating frequency range of the NG) is possible, then for measurements on the air this will be an almost impossible task. This is due to the fact that even premium spectrum analyzers with the best features have less bandwidth. For example, Keysight UXA spectrum analyzers (N9040B) have a maximum bandwidth of 1 GHz (510 MHz in real-time), and the R&S FSW 800MHz (expandable to 5 GHz with RTO2064 oscilloscope). However, the cost of such devices is very high. In this regard, in order to carry out measurements on the air using a spectrum analyzer, the noise generator operating frequency range will need to be divided into equal sub-bands that fit into the passband of the spectrum analyzer.

IV. Carrying out Measurements with a Further Calculation of the Entropy Noise Quality

Carrying out measurements with a further calculation of the entropy noise quality can be carried out in two ways:

1. using a digital storage oscilloscope (a measurement stand diagram is shown in Fig. 3). During measurements, the oscilloscope is connected to a special noise generator connector designed to measure the instantaneous values of the amplitudes of the noise signal or, in its absence, to the noise generator antenna output;
2. using a spectrum analyzer and a digital storage oscilloscope (a measurement stand diagram is shown in Fig. 4). The electromagnetic noise signals received by the spectrum analyzer are transmitted to the oscilloscope at an intermediate frequency.

In the first method, oscilloscope probes (probes) with a voltage divider must be used to avoid undue stress on the measuring instrument.

The oscilloscope must meet the following requirements:

- compatibility of the oscilloscope probe with the oscilloscope;
- the bandwidth of the oscilloscope probe (probe) and the oscilloscope must be at least the operating frequency range of the NG;
- the dynamic range of the oscilloscope probe must be sufficient to measure the values of the output voltage level at the noise generator connector.
- the oscilloscope memory size must be at least 1 million samples (counts);
- the presence of the fast Fourier transform (FFT) function in the oscilloscope;
- the ability of the oscilloscope to save the screenshot and the obtained sample values to an external USB flash drive.

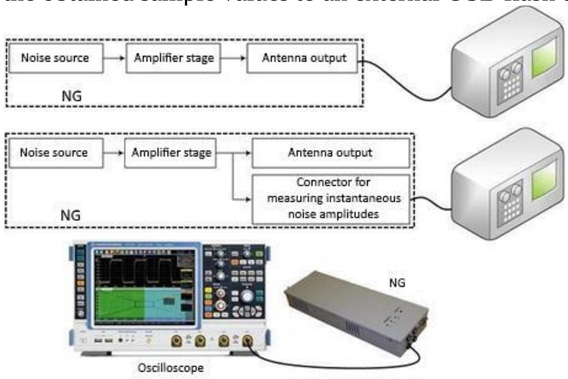

Fig. 3. Schematic of a measuring bench using a digital storage oscilloscope

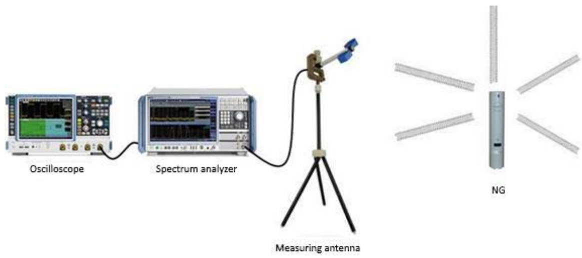

Fig. 4. Schematic of a measuring stand using a spectrum analyzer and a digital storage oscilloscope

Using the controls on the vertical scale of the oscilloscope, you need to adjust the volt-on-division (V/div) parameter to a level sufficient to correctly display the signal amplitude. Next, need to set the oscilloscope bandwidth equal to the operating frequency range of the NG.

Use the oscilloscope horizontal controls to set the appropriate capture settings for the input signal - sampling rate and record length (positioning and scaling the waveform). It should be noted that the higher the sampling rate, the better the resolution and the more detail of the waveform is visible.

To display the signal spectrum, need to switch to the FFT analysis mode, select a span equal to the operating frequency range of the noise generator (the centre frequency should be equal to half of the range). In this case, the parameters for displaying the signal by the oscilloscope will be selected automatically.

To obtain the largest number of instantaneous values of the amplitude of the noise signal, it is possible to set the maximum duration of the time interval according to the formula:

$$\text{Memory depth} = (\text{sampling rate}) \times (\text{time interval duration}) \quad (8)$$

However, if you set the maximum time interval, saving the obtained values will take a long time and will require a large amount of oscilloscope memory or a USB flash drive.

The obtained values of the instantaneous values of the amplitude of the noise signal are written to a USB-stick (file of the *.csv format) for further calculations of the quality assessment of masking noise interference.

In the second method, the use of a spectrum analyzer in conjunction with a digital storage oscilloscope (with analogue-to-digital converters) is proposed as a means of measuring instantaneous values of the amplitudes of a noise signal. Fig. 5 shows a measuring stand, which includes:

- broadband measuring antenna with a range of operating frequencies not less than the range of operating frequencies of the noise generator;
- measuring cable;
- spectrum analyzer with a range of operating frequencies not less than the range of operating frequencies of the noise generator and a bandwidth of at least 10 MHz;
- digital storage oscilloscope with an analogue-to-digital converter with a bandwidth of at least the range of operating frequencies of the noise generator and a memory capacity of at least 1 million MVsamples/s).

Fig. 5 shows a laboratory bench for measuring instantaneous values of the amplitudes of a noise signal using a spectrum analyzer and an oscilloscope.

Fig. 5. Laboratory stand 1 for measuring instantaneous values of noise signal amplitudes a spectrum analyzer and an oscilloscope

Taking into account that the bandwidth of the spectrum analyzer is much less than the operating frequency range of the NG, it is considered advisable to measure the noise signal in several ranges.

The noise signals received by the analyzer are transmitted at the intermediate frequency to the oscilloscope. Then, instantaneous values of the amplitude of the noise signal (in volts) in the *.csv format are obtained from the oscilloscope for further calculation of the masking noise quality factor.

It should be noted that the sampling frequency of the instantaneous values of the amplitude of the noise signal affects the accuracy of the calculations. However, the resulting sample size significantly increases the size of the resulting file and the time it takes to perform the necessary calculations. Experiments have shown that using a sample of more than 40 MVsamples/s is impractical.

The most reliable will be the results of measurements on the air (using a spectrum analyzer). In measurements using only an oscilloscope, the voltage values will be obtained from the noise generator connectors bypassing the antenna system, which makes its own changes to the generated noise. Figures 10 and 11 show the waveforms of masking noise interference. In the left image, the oscillogram was obtained using a digital storage oscilloscope from the noise generator antenna output. In the right image, the waveform is obtained from a digital storage oscilloscope connected to a spectrum analyzer.

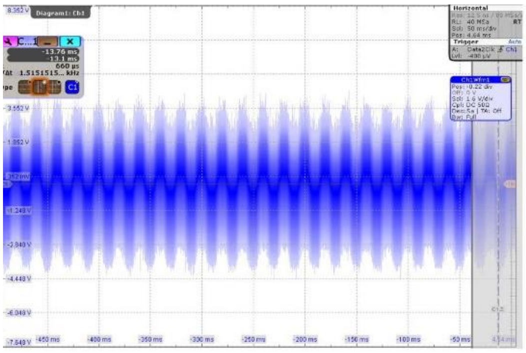

Fig. 6. Oscillograms of masking noise interference

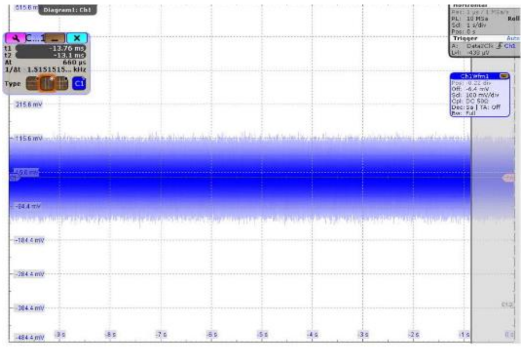

Fig. 7. Oscillograms of masking noise interference

The following is the procedure for calculating the entropy coefficient of noise quality according to the statistics of instantaneous amplitudes of the noise signal generated by noise generator using one of the above measurement methods.

1. Statistics are collected on the instantaneous values of the amplitudes of the noise signal with a volume of at least 10 million elements.

2. Based on the collected statistics $X = \{x_1, x_2, \dots x_n\}$, a statistical series is constructed $\{x_{(1)} \leq x_{(2)} \leq \cdots \leq x_{(k)} \leq \cdots \leq x_{(n)}\}$ and calculated: mean ($\bar{X}$), variance (σ^2) and standard deviation (σ) by the formulas:

$$\bar{X} = \frac{1}{n}\sum_{i=1}^{n} x_i \tag{3}$$

$$\sigma^2 = \frac{1}{n-1}\sum_{i=1}^{n}(x_i - \bar{X})^2 \tag{4}$$

$$\sigma = \sqrt{\frac{1}{n-1}\sum_{i=1}^{n}(x_i - \bar{X})^2} \tag{5}$$

3. The values of the statistical series $x_{(k)}$ are grouped by the selected non-overlapping intervals $(x_{(j-1)}; x_j)$, $j = 1, 2, \dots, m$, where m is the number of obtained intervals, and x_j are the upper boundaries of the intervals. When choosing the width of the interval, it is recommended to use the rule:

$$\Delta \leq \frac{(x_{(n)} - x_{(1)})}{2^r} \tag{6}$$

where Δ is the maximum width of the interval; $x_{(1)}$ and $x_{(n)}$ are the minimum and maximum elements of the statistical series respectively; r is the capacity of the used analogue-to-digital converter of the measuring instrument.

The width of the interval Δ_j is:

$$\Delta_j = x_j - x_{j-1} \tag{7}$$

where $j = 1, 2, \dots, m$.

It is recommended that all spans be equal in width.

4. After choosing the intervals Δ_j for the sample $X = \{x_1, x_2, \dots x_n\}$, the number n_j^* of the sample values $x_{(i)}$ that fall into the

corresponding intervals is calculated. The obtained values of n_j^* are used to calculate the corresponding relative frequencies (p_j^*) and relative densities of sample values in each interval (σ_j^*):

$$p_j^* = \frac{n_j^*}{n} \quad (8)$$

$$\sigma_j^* = \frac{p_j^*}{h_j} \quad (9)$$

The sum of the relative frequencies (p_j^*) must equal one:

$$\sum_{j=1}^{m} p_j^* = 1 \quad (10)$$

5. For cases when in any of the intervals n_j^* turns out to be equal to 0, you should combine this interval with the interval (j-1) or (j+1), recalculating the relative frequencies and relative densities in the newly formed intervals, or change Δ so that with a new partition, each of the intervals contains at least one sample value *(x_j)*.

6. Based on the obtained values, a histogram of the distribution of the instantaneous voltage values of the noise signal is constructed.

7. For each bit of the histogram, the entropy *(H_j)* is calculated by the formula:

$$H_j = p_j^* \cdot \ln \sigma_j^* \quad (11)$$

8. Next, the entropy of the noise signal *(H)* is calculated by the formula (18), the entropy power of the noise signal *(P_E)* by the formula (19) and the entropy quality factor of the instantaneous values of the masking noise voltages *(K_N)* by the formula (20):

$$H = -\sum_{j=1}^{m} H_j \quad (12)$$

$$P_E = \frac{e^{2H}}{2\pi e} \quad (13)$$

$$K_N = \frac{P_E}{\sigma^2} \quad (14)$$

The proposed technique has been tested when measuring the entropy quality factor of the noise generator installed at the objects of informatization. Figures 8 and 9 show oscillogram and spectrograms of masking noise signals of the generator.

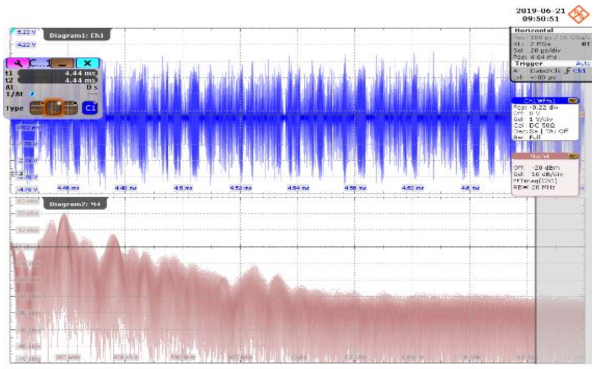

Fig 8: The oscillogram and spectrum of masking noise created by a noise generator

Taking into account the rather large dimensions of the measuring instruments (spectrum analyzer, oscilloscope, measuring antenna with a tripod, computer for measuring control), the proposed methods for measuring noise quality are more applicable in laboratory conditions. For offsite events with measurements at the installation site of the main power supply (in real operating conditions), a compact tool will be acceptable.

Such a tool can be made based on digital SDR receivers. For example, SDRplay RSPduo, KerberosSDR, Coherent Multi-Tuner-Receivers or other similar.

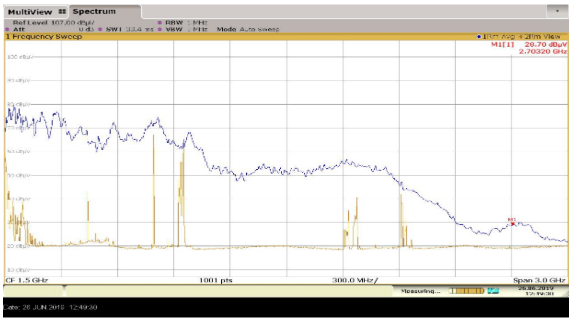

Fig. 9. The spectrum of masking noise created by a noise generator

V. Conclusions

On the basis of the described receivers, it is possible to manufacture a universal device for evaluating the quality of the generated noise. Such a device will be able to implement the following methods for assessing the quality of noise interference:

- calculation of the entropy coefficient of quality according to the proposed combined method;
- search for noise correlation in different frequency subbands;
- use statistical and (or) graphical methods (tests) for randomness.

Prospects for further research are related to the manufacture of universal devices for assessing the quality of noise.

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