THE DEVELOPMENT OF METHODS OF THE SUPER WEAK INTENSITY RADIATIONS MEASUREMENT FROM PHYSICAL AND BIOLOGICAL OBJECTS

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Abstract — The measurement problem of super weak noise signals intensity in super-broad frequency band, which level is much lower than power of the inherent noises of measuring equipment and the external noises is urgent in many fields. The problem of this kind arises in radio astronomy, in radio thermal and plasma radiation measurements. Over last few years the electromagnetic radiation of biological objects, include humans, have been actively studied. Diagnostics of the human body is carried out from the values of radiation parameter proceeding [1]. The paper is devoted to the further development of measurement methods of super weak noise signal intensity in super-broad frequency band.

Keywords — super weak radiation, noise signal, radiometric equipment.

1. INTRODUCTION

Measured electromagnetic fields of the biological objects in the environment are stochastic. In the attempts to study it, some additional problems are arisen. The prevailing part of radiation is related to radio thermal component stipulated by equilibrium processes in a body occurring at temperature 35…40°C.

The frequency band of the most intensive thermal radiation lies mainly within the infrared domain, however, a radio wave component is also present. The power of radio-frequency emission from a human being and biological objects is extremely low. According to the data of experimental studies [2], the spectral power density of radiation lies within the range $10^{-20}…10^{-21}$ W/(Hz·cm^2).

To provide the possibility of the comprehensive analysis of radio-frequency emission and estimation of its parameters, it is necessary to have the equipment with fluctuation sensitivity threshold at the level 10^{-22} W/Hz or even less than that. As a rule, the inherent noises of the measuring devices considerably exceed this value (the signal/noise ratio is much less than unity). In this connection, the direct amplification of the signal being studied is inexpedient owing to still greater decrease of this parameter. Taking into account that the studied signal is non-determined, has a wide frequency spectrum and is statistically indiscernible against the background of wide band noises and interference's, it is possible to draw a conclusion about impossibility of selection under such conditions of its informative component with the use of classical methods [3].

2. DECISION OF THE PROBLEM

2.1. Basic information

For measurement of super weak noise signals intensity, the special radiometric devices (radiometers) are used. They help to realise scaling and functional transformations of the informative noise signal mixed with the noises. Then selection of the informative component characterising the structure and properties of the researched object takes place. Three basic methods of measurements are used for designing of radiometric equipment: compensation, correlation and modulation.

Using the compensation method, the amplified voltage of the inherent noises of the measuring track is compensated by the voltage of the additional stabilised source.

However, it is very difficult to attain the complete compensation of the background signal and respectively, to reach the required sensitivity threshold. This is caused by parameters fluctuation of the measuring track elements and instability of the background signal.

In radiometric equipment realising the correlation method of measurement, division of a measured signal into two anti-phase signals is carried out. Amplification each of them by independent amplifiers, multiplication and low-frequency filtration leads to suppression of non-correlated noises of amplifiers [4]. But all attempts to suppress in traditional way the inevitably arising correlated noises and voltage fluctuations of the multiplication scheme have failed.

Authors have considered the possibility of construction of a correlation radiometer providing the increased sensitivity and accuracy of measurements due to decreasing of the effect of both non-correlated

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and correlated noises and interference's from amplification channels [5].

The radiometer is constructed by two-channel structure and according to the suggested algorithm it provides the mutual subtraction of the correlated noises at the differential amplifier inputs.

From the point of view of providing the high sensitivity and accuracy of measurements, expansion of functionality and flexibility of the block diagram design, it is very advantageous to use a modulation method. It proves to be true by theoretical and experimental studies of the authors [6]. However, the large errors of the existing schemes of modulation radiometers do not allow to reveal the thin structure of electromagnetic field of biological objects.

Essential improvement of accuracy is obtained by the use of zero modulation method that envisages periodic connection of a measuring scheme to an output of a receiving antenna and its equivalent. However, instability and asymmetry of microwave keys constituting a component part of automated switch do not allow us to realise the potential accuracy of zero method.

The new approaches to construction of zero modulation radiometers are considered below. They allow us to reach the higher accuracy and to lower fluctuation threshold of sensitivity.

2.2. Zero modulation radiometer without periodic switching-off of antenna

One of the drawbacks of modulation systems is the necessity to periodically switch off the antenna receiving the studied noise signal. It results in occurrence of commutation noises in a receiving channel and spurious modulation of the inherent noises of a radiometer. The block diagram is given below (Fig. 1) allowing to remove this drawback.
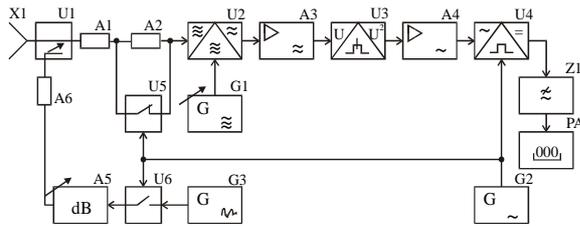

Fig. 1. Structure of zero modulation radiometer without periodic switching-off of antenna.

The noise signal from the researched object is received by the antenna X1 and is fed to the mixer U2 through the basic channel of the directed branching unit U1 and attenuators A1, A2. Mixing of a noise signal with a harmonic signal of heterodyne G1 results in formation of signal of intermediate frequency. This signal is amplified by intermediate frequency amplifier A3 and detected by the quadrature detector U3. The output voltage of the quadrature detector is proportional to power P_X of the signal received by the antenna and is determined by the relation

$$U_1 = S_1^2 S_2^2 K_1^2 \left[(1+\gamma) P_X + \Delta P \right], \qquad (1)$$

where S_1 and S_2 are transfer coefficients of attenuators A1, A2; K_1 is the total transfer coefficient of the units U2, A3 and U3; γ is the relative multiplicative error of the channel; ΔP is the absolute additive error.

The scheme functions in two commutation steps. At the first step the key U5 is turned on and key U6 is turned off. In this way the attenuator is shunted and its transfer coefficient is equal to 1. And here the absolute additive error assumes the value ΔP_1, and it is determined by output resistance of the attenuator A1. The relative multiplicative error which is defined by mismatch of the mixer U2 and the attenuator A1 assumes the value γ_1.

At the second step, key U5 is turned off and key U6 is turned on. In this case the signal from the reference noise generator G3 is admitted to a receiving channel of a radiometer through attenuators A5, A6 and the second channel of the directed branching unit U1. And here, summation of the powers of two noise signals takes place at the output of the directed branching unit U1. The output voltage of the quadrature detector is as follows

$$U_2 = S_1^2 S_2^2 K_1^2 \left[(1+\gamma_2)\left(P_X + S_3^2 S_4^2 S_5^2 P_E \right) + \Delta P \right], \qquad (2)$$

where S_3, S_4 and S_5 are transfer coefficients of the directed branching unit U1, attenuators A5 and A6; P_E is the power of the reference noise generator; ΔP_2 is the level of the inherent noises determined by output resistance of the attenuator A2; γ_2 is a mismatch error of the mixer U2 and the attenuator A2.

With periodic switching of the keys U5 and U6, which are controlled by the signals from low-frequency generator G2, the voltage of low-frequency envelope curve is formed at the quadrature detector output U3. The obtained low-frequency voltage is amplified by A4 amplifier and rectified by synchronous detector U4. The rectified voltage is smoothed out by lower frequencies filter Z1 and is registered by an indicator PA.

If the choice is made of the attenuators A1 and A2 with identical parameters ($S_1 = S_2 = S$), then they will have identical output resistances. So the level of inherent noises will not change ($\Delta P_1 = \Delta P_2 = \Delta P$) when the key U5 is switched. The degree of mismatch of the mixer U2 and attenuators A1 and A2 ($\gamma_1 = \gamma_2 = \gamma$) will also remain unchanged.

In view of equality of additive and multiplicative components of an error the voltage on PA indicator will be defined by the expression

$$U_3 = \frac{1}{2} K_1^2 K_2 (1+\gamma)\left[S^2 P_X - S^4 \left(P_X + S_3^2 S_4^2 S_5^2 P_E \right) \right], \qquad (3)$$

where K_2 is a transfer coefficient of low-frequency part of the scheme.

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By variation of weakening brought about by alternating attenuator A5, zero values of the indicator PA ($U_3 = 0$) are set. The value of power of the received signal is obtained from the expression (3)

$$P_X = \frac{S_3^2 S_4^2}{1 - S^2} S_5^2 P_E .$$ (4)

If transfer coefficients of the attenuators A1, A2 and A6 are chosen such that condition $\frac{S_3^2 S_4^2}{1 - S^2} = 1$ would be satisfied, then we'll finally obtain the expression for estimation of power of the received signal

$$P_X = S_5^2 P_E .$$ (5)

From relation (5) it follows that the measured power P_X is unequivocally defined by the level of the reference power of a noise generator at an output of graduated attenuator A5.

2.3. Zero modulation radiometer with equilibration of the antenna's signal by the noises of the microwave amplifier

It was noted above that the main problem of measurement of super weak radiation intensity consists in the fact that the inherent noises of measuring devices exceed the level of the friendly signal. One of the basic elements of a measuring scheme is the high-frequency amplifier.

Time and temperature instability of the amplifier exerts determinant influence on the measurement result. To provide the possibility of carrying out the measurements and estimation of the inherent noises of an amplifier, the authors have suggested the structure and operation algorithm of a radiometer with positive feedback in a high-frequency track. The block diagram of the radiometer is shown in Fig. 2.
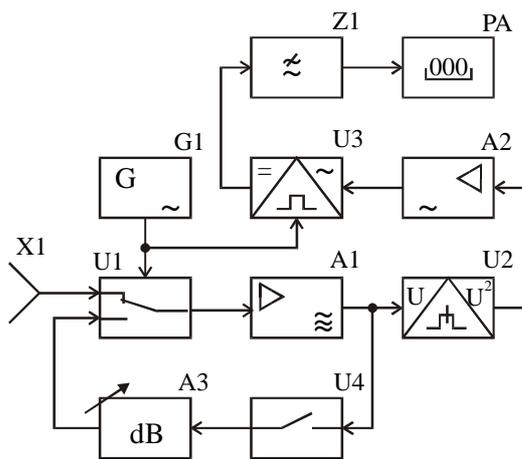

Fig. 2. The structure of zero modulation radiometer with equilibration of the antenna's signal by the noises of the microwave amplifier.

In its initial state, an antenna is directed to an object whose radiating ability approaches O. With the disconnected key U4, the antenna's output signal determined by the level of its inherent noises is fed to microwave amplifier A4 through the switchboard U1. The dispersion of the amplifier's output signal is determined by the sum of output noise signal of the antenna X1 and inherent noises of the amplifier A1. The amplified total signal is detected by quadrature detector U2, and the voltage U3 is formed at its output.

$$U_3 = S_1 K_1 \left(\overline{U}_1^2 + \overline{U}_2^2 \right),$$ (6)

where S_1 is steepness of transformation of quadrature detector U2; K_1 is amplification coefficient of the amplifier A1; $\overline{U}_1^2$ and $\overline{U}_2^2$ are dispersions of output noise signal of the antenna X1 and inherent noises of the amplifier A1, respectively.

On changing the position of a switchboard U1, the amplifier's A1 input becomes connected to the output of attenuator A3. If output resistance of attenuator A3 coincides with output resistance of antenna X1, the level of inherent noises of the amplifier A1 will not change. Dispersion of output signal of the amplifier A1 is determined only by the level of its inherent noises. Respectively, output voltage of the quadrature detector will change up to the value of U_4

$$U_4 = S_1 K_1 \overline{U}_2^2 .$$ (7)

At periodic switching of a switchboard U1 controlled by generator G1, the alternating voltage of commutation frequency with the amplitude U5 is formed at the quadrature detector output.

$$U_5 = \frac{U_3 - U_4}{2} = \frac{S_1 K_1}{2} \overline{U}_1^2 .$$ (8)

After amplification of voltage U_5 by low-frequency amplifier A2, rectification by synchronous detector U3 and selection of constant component by the filter Z1, the voltage U6 is applied to the measuring device PA:

$$U_6 = \frac{1}{2} S_1 K_1 K_2 K_3 U_1^2 = S_0 U_1^2 ,$$ (9)

where K_2 is amplification coefficient of low-frequency amplifier A2; K_3 is transformation coefficient of synchronous detector U3 with due regard for transfer coefficient of the filter Z1; $S_0 = S_1 K_1 K_2 K_3 / 2$ is sensitivity of a radiometer with respect to power.

Then the key U4 is turned on. Thus, in the bottom position of a switchboard U1, there arises a positive feedback in the amplifier A1.

In the top position of a switchboard U1, output signal of the amplifier A1 remains the same. With the key U4 turned on and periodic operation of a switchboard U1, the amplitude of a variable component of output voltage of the quadrature detector U2 will constitute

$$U_7 = \frac{S_1 K_1}{2} \left(\overline{U}_1^2 + \overline{U}_2^2 - \frac{\overline{U}_2^2}{1 - K_1 \beta} \right),$$ (10)

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where β is a transfer coefficient of the attenuator A3 with respect to power.

The transfer coefficient of attenuator A3 is being changed up to the value β_1 thereby zero indications of the indicator PA are set. So the following relation becomes valid

$$\overline{U}_1^2 + \overline{U}_2^2 - \frac{\overline{U}_2^2}{1 - K_1\beta_1} = 0. \qquad (11)$$

Having fulfilled the condition (11), the researched object is placed in front of the antenna X1. In a condition of radio thermal radiation from the object the signal dispersion at antenna's output will increase by the value $\Delta\overline{U}_1^2$. Indications of the indicator PA therewith will differ from 0. By changing a transfer coefficient of the attenuator A3 up to the value β_2 we again obtain zero indications of the indicator PA. Thus the new condition is fulfilled

$$\overline{U}_1^2 + \Delta\overline{U}_1^2 + \overline{U}_2^2 - \frac{\overline{U}_2^2}{1 - K_1\beta_2} = 0. \qquad (12)$$

The expression for determination of dispersion of radio thermal radiation of the researched object $\Delta\overline{U}_1^2$ can be easily obtained from equation (12).

In view of the relation (11) we obtain the value of the relative power of radio thermal radiation of the researched object reduced to the level of inherent noises of the antenna X1

$$\eta = \frac{\Delta\overline{U}_1^2}{U_1^2} = \frac{\beta_2 - \beta_1}{\beta_1} \frac{1}{1 - K_1\beta_2}. \qquad (13)$$

Taking into account that the depth of a positive feedback is set small ($K_1\beta_2 \ll 1$), so a part $K_1\beta_2$ can be neglected as compared to 1. Then, finally, relation determines the relative radiation power of an object

$$\eta = \frac{\beta_2 - \beta_1}{\beta_1}. \qquad (14)$$

From the obtained expression (14), it can be seen that the value of the relative power does not depend on a radiometer parameters and is defined only by the values of a transfer coefficient of the attenuator A3 connected to the feedback channel.

2.4. Zero modulation radiometer with periodic weakening of the reference noise

The radiometer scheme considered above assumes that microwave signal is amplified prior to its detection. It narrows essentially the frequency band of the received radiation, which is defined by the amplifier pass band.

The modulation radiometer structure shown in Fig. 3 allows to carry out measurements within wide frequency band. It is achieved due to the fact that detection of the received signal is carried out without its preliminary amplification.
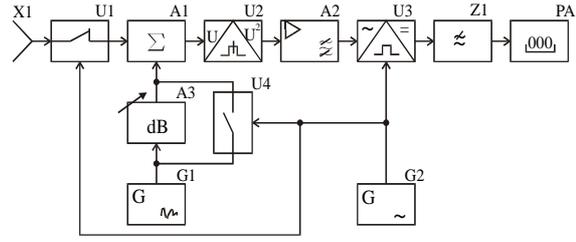

Fig. 3. The structure of zero modulation radiometer with periodic weakening of the reference noise

In the first step, the wide-band radiation from the researched object is received by microwave antenna X1 and is directed to the first input of wave guide summator A1 via wave guide key U1. The reference noise from the generator G1 weakened by graduated attenuator A3 is applied to the second input of wave guide summator A1 with the key U4 being turned on. The summarised signal is received at the quadrature detector U2 input where its detecting and averaging takes place. Output power P_E of the reference noise generator is set at the level sufficient for its direct detection by the quadrature detector U2 over the linear portion of its characteristic. And here, output voltage of the quadrature detector is determined by the expression

$$U_1 = S(1 + \gamma_1)(P_X + \alpha P_E + \Delta P), \qquad (15)$$

where S is steepness of transformation of the quadrature detector U2; P_X is power of the received microwave radiation; α is a transfer coefficient of the attenuator A3; ΔP is power of the inherent noises of the quadrature detector U2; γ_1 - is the relative error of sensitivity of the quadrature detector U2 caused by the influence of destabilising factors.

In the second step, by a signal from the generator G2, a change of position of the keys U1 and U2 takes place. Only one signal from the reference noise generator G1 having power P_E (the attenuator A3 is shunted by the key U4) is received at the input of the quadrature detector U2. Output power of the generator G1 and the level of the inherent noises of the quadrature detector U2 thereby define the output voltage of the quadrature detector.

At periodic operation of the keys U1 and U4 at the output of a quadrature detector there is formed a variable component of low-frequency voltage with the following amplitude

$$U_2 = \frac{S}{2}(1 + \gamma_1)[P_E(1 - \alpha) - P_X]. \qquad (16)$$

Low-frequency voltage (16) is amplified by the narrow-band amplifier A2 adjusted to frequency of commutation of the generator G2 and is rectified by synchronous detector U3 controlled by low-frequency voltage of the generator G2. After filtration the rectified voltage is registered by measuring unit PA. Its value is determined by relation

$$U_3 = \frac{S}{2}(1+\gamma_1+\gamma_2)K_1 K_2 K_3 [P_E(1-\alpha)-P_X], \quad (17)$$

where K_1, K_2 and K_3 are transfer coefficients of the selective amplifier A2, synchronous detector U3 and filter Z1, respectively; γ_2 is the relative error of sensitivity of the selective amplifier A2.

Then a transfer coefficient α of the attenuator A3 is changed for the sake of getting zero indications at the indicator PA ($U_3 = 0$).

And here, expression (17) is reduced to

$$P_X = (1-\alpha)P_E. \quad (18)$$

In this way, the measured power of the received microwave radiation P_X at a constant power level of the reference noise generator ($P_X = const$) is determined only by transfer coefficient α of the attenuator A3 and is independent of the level of inherent noises of a radiometer and instability of parameters of its elements.

3. CONCLUSIONS

The suggested schemes of modulation radiometers possess the essential advantages as compared to the traditional zero method. They allow for incomplete replacement of the signal received by the antenna by the signal of the reference generator. Due to this fact the super weak input signal is not interrupted completely but relatively big power of the reference noise generator is commuted.

The considered schemes make it possible to avoid the operation of interruption of output signal of a receiving antenna (Fig. 1), the intensity of the given signal is much less than the intensity of the inherent noises of a microwave amplifier and a mixing unit. This adds to the increase of accuracy of measurement of low radiation levels owing to the absence of commutation noises.

If the reference noise generator (Fig. 2) is not present, the absence of fluctuation sensitivity threshold can be essentially reduced due to the absence of the direct passing of a signal of the reference noise generator onto the receiver's input owing to spurious connections.

Removal of the preliminary microwave amplifier at the quadrature detector input (Fig. 3) substantially expands the reception band of a radiometer and helps to reduce the fluctuation sensitivity threshold.

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