Method for phase direction finding of signals with asymmetric spectra

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Abstract. The article deals with a new method of phase direction finding of broadband signals with asymmetric spectra. The authors propose a new definition of the signal frequency corresponding to phase measurements in correlation signal processing, such as the correlation-phase frequency.

1. Introduction

At present, methods of parametric spectral estimation of random processes, as well as a linear combination of real or complex exponents, have become common. These methods allow achieving very high resolution of signals, including harmonic ones, in frequency. However, these results can only be obtained with a very large signal-to-noise ratio in the analyzed sample at the input of the processing device (5-10 dB or more), otherwise the accuracy of the estimates is unsatisfactory, and a large number of false readings occur.

The method of broadband direction finding is known, in which digital signals characterizing spectra of received signals are extracted from output signals of each antenna array element, and for each selected frequency in the receiving band, using the phase of signals, direct calculation of Fourier spatial series is performed, which discretely describes angular spectrum of power at the selected frequency. After restoring the angular spectrum at all frequencies, the bearing of any source emitting signals at any of the frequencies within the current receiving band is determined. This method has low speed in determining the azimuthal bearing.
The real environment is not known to be strictly uniform, so that the path of propagation of radio waves will not be strictly straight. So, changes in humidity and density of the atmosphere with height cause vertical refraction. Under some weather conditions, changes in the humidity and density of the atmosphere and in the horizontal plane are possible, which will naturally cause horizontal refraction. The presence of the earth’s surface inhomogeneities and terrain irregularities also causes the path of radio waves to be curved. Various local objects, i.e. industrial and residential structures, trees, etc., located near the radio detector, cause a local change in the direction of propagation of radio waves.

All of these changes in the propagation path of the radio waves will cause corresponding radio modulation errors.

However, if the actual conditions of radio wave propagation are properly taken into account, these errors are such that they allow for radio modulation with practical accuracy.

To determine the direction to the radiation source, the phase tracker should measure two parameters at a known base direction finder, the phase difference of the signals received by spaced antennas, and the frequency of the signal [1, 2].

Before you can determine how to measure the frequency of a broadband signal, you need to figure out what frequency to measure.

Let the received signal be the sum of two harmonic oscillations of different frequency and amplitude with random phases [3].

\[ A_1 \cos(\omega_1 t + \varphi_1) + A_2 \cos(\omega_2 t + \varphi_2) \] 

(1)

where \( A_1 \) and \( A_2 \) are signal amplitude, \( \omega_1 \) and \( \omega_2 \) are signal frequency, \( \varphi_1 \) and \( \varphi_2 \) are signal phases.

The correlation function of the sum of random processes is equal to the sum of the correlation functions of these processes [4]. There is also an expression for the correlation function of a harmonic signal with a random phase. Therefore, the correlation function of the selected signal model takes the form

\[ R(\tau) = \rho_1 \cos \omega_1 \tau + \rho_2 \cos \omega_2 \tau \] 

(2)

where \( \rho_1 \) and \( \rho_2 \) are harmonic power, \( \tau \) is signal delay relative to each other.

If the harmonics powers are equal, the correlation function is converted to

\[ R(\tau) = 2\rho \cos \frac{\Delta \omega \tau}{2} \cdot \cos \omega_o \tau \] 

(3)

where \( \Delta \omega = \omega_1 - \omega_2 \) is the width of the signal spectrum, \( \omega_o = \frac{\omega_1 + \omega_2}{2} \) is the central frequency of the signal spectrum.

The first cofactor describes the envelope of the correlation function, and the second cofactor describes its high-frequency filling. As can be seen from the above expression (3), the measured parameter \( \tau \) is the delay of signals relative to each other, contained in the phase of high-frequency filling of the correlation function. To calculate it, it is necessary to measure the signal phase after correlation processing and the Central frequency of the signal spectrum

\[ \tau = \frac{\varphi}{\omega_o} \] 

(4)

where \( \varphi \) is the phase of the signal after correlation processing.

Let’s analyze the effect of spectrum asymmetry. To do this, specify the signal model. The central frequency of the spectrum is 3 GHz, the harmonics have frequencies of 3.002 GHz and 2.998 GHz, the
power of the harmonics in conventional units of 1 and 0.5, respectively. The correlation function of such a model has the form

\[ R(\tau) = 0.5 \cos 2\pi 2.998 \cdot 10^9 \tau + \cos 2\pi 3.002 \cdot 10^9 \tau \] (5)

The range of delay changes is limited to 150 ns based on the fact that the maximum delay of signals on the fifty-meter base of the direction finder is about 170 ns. Until now, it was believed that the frequency of filling the correlation function determines the phase relations during correlation processing.

Previous works on direction finding of broadband signals also offered technical solutions for measuring the frequency of the energy center of gravity of the signal spectrum [5, 6, 7]. It was believed that the frequency of the energy center of gravity of the signal spectrum corresponds to the phase measurements for direction finding of broadband signals with asymmetric spectra. The analysis shows that this is not entirely true. The modern mathematical apparatus allows us to offer a new solution to this problem.

2. Phase direction finding method that takes into account the effect of spectrum asymmetry on the value of the correlation-phase frequency

A new definition of the frequency of a broadband signal, namely, the frequency corresponding to phase measurements in the correlation processing of signals, is proposed. We call this frequency the correlation-phase frequency.

This frequency is defined as the ratio of the phase of the correlation function to a given delay. The frequency of filling the correlation function, and the frequency corresponding to the phase measurements, depend on the delay.

The lower the power of the second harmonic, the smaller the deviation of the correlation-phase frequency from the frequency value of the fundamental. A power imbalance of 20% leads to a deviation of the correlation-phase frequency from the center frequency of the spectrum to 3 MHz. Even the presence of the second harmonic in the spectrum of the signal only 1% of the power of the fundamental harmonic shifts the correlation-phase frequency from the fundamental frequency to 43 kHz. For any ratio of harmonic power, the correlation-phase frequency corresponds to the frequency of the main harmonic at 3.002 GHz. At this point, the relative delay of the signals is 125 ns, which is correlated with the signal spectrum width of 4 MHz and is equal to half the period of the envelope correlation function.

For a direction finder with a base of 50 meters, the optimal receiver band is about 1 MHz.

The correlation-phase frequency is weakly dependent on the delay, since the delay corresponding to half of the period of the envelope correlation function is outside the working zone for delays.

A simulation was performed to determine the effect of absolute values of harmonic powers on the correlation-phase frequency. Calculations have shown that the value of the correlation-phase frequency depends only on the power ratio of harmonics and does not depend on their absolute value.

Consider a model of a signal with modulation. This model has three spectral harmonics, a carrier and two lateral harmonics.

\[ R(\tau) = 0.4 \cos 2\pi 2.9995 \cdot 10^9 \tau + \cos 3 \cdot 10^9 \tau + 0.5 \cos 2\pi 3.0005 \cdot 10^9 \tau \] (6)

The width of the spectrum is 1 MHz, i.e. lateral harmonics are 0.5 MHz behind the carrier. Carrier frequency 3 GHz. The asymmetry of the spectrum is 20%.

The analysis showed that the deviation of the correlation-phase frequency increases with increasing delay. With an increase in the carrier power, both the absolute value of the deviation of the correlation-phase frequency and the dependence of this deviation on the delay decrease. The higher the carrier power, the smaller the deviation of the correlation-phase frequency from the center frequency of the spectrum. An increase in the carrier power from 0.7 to 3 conventional units leads to a decrease in the deviation of the correlation-phase frequency from 31 kHz to 13 kHz.

Consider a signal with a more full spectrum. The signal model has a spectrum consisting of a carrier harmonic and five side harmonics on each side.
Analysis of a signal with a spectrum width of 1 MHz shows the independence of the correlation-phase frequency from the delay. More precisely, the change in the correlation-phase frequency from the delay affects the level of units of Hertz. However, the absolute deviation of the correlation-phase frequency from the Central frequency of the spectrum has a sufficient value that must be taken into account to ensure the specified accuracy.

The proposed method makes it possible to increase the accuracy of trajectory measurements in the direction finding of broadband signals with an arbitrary spectrum shape. At the same time, this method works successfully with direction finding of narrow-band signals and signals with symmetric spectra, since in this case the Central frequency of the spectrum corresponds to the correlation-phase frequency.

3. Conclusion
The main result of this work is the determination of the correlation-phase frequency corresponding to the phase measurements in correlation signal processing. The analysis made it possible to propose a new phase direction finding method that takes into account the effect of spectrum asymmetry on the value of the correlation-phase frequency. The implementation of the proposed phase direction finding method will improve the accuracy of trajectory measurements of radiation sources of signals with an arbitrary spectrum shape.

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