Narrow-band correlation processing of signals in a phase direction-finding

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Abstract. The article deals with the phase method of direction finding, based on the dependence of the phase difference of the signals received by the antennas, as well as the correlation signal processing in the phase direction finding, which will assess the possibility of signal direction finding of the "Spectrum-RG" spacecraft, derived in the neighborhood of the L2 Lagrange point located at a distance of one and a half million kilometers from Earth.

1. Introduction
Monopulse phase direction finders with antenna systems in the form of arrays of weakly directed elements are widely used in radio monitoring systems. The reason for this is that they are angle-free, i.e. they are able to locate a radio source located in the viewing area by a single radiated signal. The disadvantage of phase direction finders built according to known schemes is the lack of angular resolution, which is manifested in the impossibility of bearing radio sources whose signals simultaneously fall into the bandwidth of the receivers. Obviously, giving phase direction finders this capability is an urgent scientific and technical task [1].

The operation of the phase direction finder is based on measuring the phase difference of signals received on two antennas spaced apart [2]. The correlation processing method is widely used in the formation of measurement signals [3, 4].
2. Correlation signal processing with fork heterodine

Consider the correlation processing of signals with a fork heterodine [5, 6].

A block diagram of correlation signal processing with a fork heterodine is presented in figure 1. The scheme works as follows.

The inputs of the device receive signals received by separated antennas, characterized by a phase difference. Consider the operation of the device with harmonic signals

\[ u_{v1} = \cos(2\pi f_c t + \varphi_1) \quad \text{and} \quad u_{v2} = \cos(2\pi f_c t + \varphi_2) \]

where \( f_c \) is signal frequency, \( \varphi_1 \) and \( \varphi_2 \) are signal phases.

Here and further, for simplicity, we will consider the signal amplitudes as individual, since their level does not affect the principle of operation of the device.

After conversion in mixers using a fork heterodine, the frequencies of which have a predetermined spacing \( f_c - F \) and \( f_c \), and filtering by bandpass filters, the signals take the form

\[ u_{v1} = \cos(2\pi f_{np} t + \varphi_1) \quad \text{and} \quad u_{v2} = \cos[2\pi(f_{np} + F) t + \varphi_2], \]

where \( f_{np} = f_c - f_c \) is the value of the intermediate frequency. The specified frequency difference of the fork heterodine is formed by applying a reference harmonic signal to its input \( u_o = \cos 2\pi F t \).

After multiplying the output signals of the bandpass filters and using the multiplier (X), we obtain a harmonic signal whose frequency corresponds to the spacing of the fork local heterodine, and the phase to the phase differences of the input signals

\[ u_{vp} = \cos(2\pi F t + \Delta\varphi), \text{ where } \Delta\varphi = \varphi_2 - \varphi_1. \]

This signal is then fed to a narrow-band filter. When working with signals from dynamic radiation sources, the Doppler effect occurs, which can be divided into two components. Absolute Doppler, which is expressed in a change in the carrier frequency of the received signals depending on the radial speed and direction of movement of the radiation source. And the relative Doppler caused by a change in the angle of arrival of the signals, which is expressed in a change in the phase difference of the signals received over time. This is equivalent to changing the frequency of the signal at the output of the multiplier \( \Delta\varphi(t) = 2\pi F_d \). The output signal of the multiplier takes the form

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Figure 1. Correlation signal processing device with fork heterodine.
\[ \Phi_{np} = \cos 2\pi (F + F_d) t . \]

The resonant frequency of the narrow-band filter corresponds to the separation frequency of the fork local heterodine and is equal to \( F \). The passband of the narrow-band filter should be selected based on the expected dynamics of the radiation source, i.e. taking into account \( F_d \). The high dynamics of the radiation source leads to the need to significantly expand the passband of the narrow-band filter, which increases the noise error of measuring the phase difference of the processed signals.

To eliminate this drawback, a new technical solution is proposed, protected by a patent for the invention “Narrow-band device for correlation signal processing” [5]. The block diagram of this device is shown in figure 2.

![Figure 2. Narrow-band correlation signal processing device.](image)

In the present invention, the frequency of the fork heterodine spacing is fed to the fork heterodine not directly, but through a digital phase shifter. The functional purpose of the digital phase shifter is to adjust the phase of the fork heterodine reference signal \( \Phi_{np} \) to the phase of the output signal of the multiplier, i.e. to compensate for the relative changes in the phases of the signals at the input of the multiplier.

For this, a phase-locked loop system consisting of a phase detector and a phase locked loop is used. The output signal of the phase locked loop is fed to the control input of the phase shifter. Automatic tuning of the frequency of the reference signal of the fork local heterodine provides compensation using the phase shifter of the phase incursion of the signal at the output of the multiplier, as a result of which the reference signal of the fork local heterodine takes the form

\[ \Phi_{np} = \cos 2\pi (F - F_{dk}) t , \]

where \( F_{dk} \) is a compensating frequency shift of the reference signal.

After changing the frequency of the reference signal of the fork local heterodine, the output signal of the multiplier takes the form \( \Phi_{np} = \cos 2\pi (F - F_{dk} + F_d) t . \) The operation of the phase-locked frequency provides the following ratio \( F_{dk} = F_d \), the frequency of the output signal of the multiplier corresponds to the resonant frequency of the narrow-band filter.

This allows you to significantly narrow the passband of the narrow-band filter and improve the accuracy of measuring the phase difference of the processed signals. The compensating phase shift introduced by the phase shifter is equal to the phase difference of the processed signals. This information comes from the information output of the phase shifter, which is the output of a narrowband correlation signal processing device.
In 2008, a mock-up of a five-channel receiver was produced that implements this principle of correlation signal processing. The bandwidth of the bandpass filters was 100 Hz. The bandwidth of narrowband filters was 0.2 Hz. Such parameters of the receiver made it possible to significantly increase its sensitivity. In November 2008, this receiver was used as part of the Rhythm phase direction finder at the Bear lakes test site when working on the Indian lunar vehicle Chandrayang-1. The signal from the device was received by antennas with a diameter of 2.5 meters at a frequency of 2.2 GHz. The narrow bands of the receiver provided sufficient sensitivity, since a significant part of the signal energy was radiated at the carrier frequency \([7]\). At the same time, the narrow passbands of bandpass filters required constant tuning of the direction finder local oscillator frequency to the continuously changing frequency of the direction, finding signal due to the Doppler effect. During the sessions, automatic tracking by angular coordinates and manual tracking by frequency were performed. The signal-to-noise ratio of the measuring signal at the receiver output averaged 30 dB.

In August 2019, the upgraded correlation-phase direction finder “Rhythm-M” was used for trajectory measurements during the launch of the “Spektrum-RG” spacecraft. A fairly confident signal reception was recorded at distances up to 450 thousand kilometers. In November of the same year, work began on the inclusion of this five-channel narrowband receiver in the correlation-phase direction finder "Rhythm-M".

3. Conclusion
Correlation signal processing for phase direction finding allows for the direction finding of the “Spectrum-RG” spacecraft signal output in the vicinity of the L\(_2\) Lagrange point, located at a distance of one and a half million kilometers from Earth.

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