Adaptation of receiving channels to the spectrum of the received signal

A O Zhukov¹,²,³, I N Valyaev⁴, V P Kovalenko⁴, Z N Turlov⁴, A S Chebotarev⁴, I N Kartsan⁵,⁶,⁷ and N A Shumakova⁵

¹Institute of Astronomy of the Russian Academy of Sciences, 48, street Pyatnitskaya, Moscow, 119017, Russia
²Shternberg State Astronomical Institute of Lomonosov Moscow State University, 13, Universitetsky pr., Moscow, 119234, Russia
³Russian Technological University, 78, Vernadskogo Av., Moscow, 119454, Russia
⁴JSC «Special Design Bureau of the Moscow Power Engineering Institute»
⁵Reshetnev Siberian State University of Science and Technology, 31, Krasnoyarsky Rabochy Av., Krasnoyarsk, 660037, Russia
⁶Sevastopol state University, University str., 33, Sevastopol, Republic of Crimea, 299053, Russia
⁷V.I. Vernadsky Crimean Federal University, prospektVernadskogo 4, Simferopol, Republic of Crimea, 295007, Russia

E-mail: aozhukov@mail.ru, igorvalyaev@rambler.ru, kartsan2003@mail.ru

Abstract. The article deals with the implementation of optimal filtering in the correlation processing of random signals with a priori unknown characteristics of the spectrum. A scheme of the optimal processing device operating in a wide dynamic range of received signals is synthesized, adaptation to which requires the joint use of automatic gain control and automatic bandwidth adjustment.

1. Introduction
As is known from the theory of optimal reception, optimality is achieved by matching the characteristics of the receiver with the spectrum of the received signal [1]. In particular, it is necessary to coordinate the passband of the filter of the receiving channel and the width of the signal spectrum.

To adapt the characteristics of the optimal filter to the spectrum width of the processed signal, it is necessary to obtain an estimate of this parameter. For this, it is necessary to synthesize the structure of the discriminator of the signal spectrum width. Until now, the literature has not considered the estimation of the width of the spectrum as an independent task.

The logarithm of the likelihood function when receiving a random signal against a background of white noise has the following form [1].

\[
\ln(\Delta f) = \frac{1}{2} \int_{-\infty}^{\infty} \frac{S_0(f) / N_0 + S_0(f)}{N_0} |Y(f)|^2 df - T \int_{-\infty}^{\infty} \ln \left(1 + \frac{S_0(f)}{N_0}\right) df,
\]

(1)

where \(S_0(f)\) is a signal spectrum; \(N_0\) is noise spectral density; \(Y(f)\) is spectral density of the received implementation; \(T\) is averaging interval.
In general, it is impossible to obtain a solution to equation (1) and therefore it is possible to implement a receiver in the form of a series of parallel processing paths [2], where each path has a fixed value of the expected parameter, i.e. bandwidth equal to the expected width of the spectrum. A more acceptable technical solution can be found if we consider the estimate of the width of the spectrum of a signal having a spectrum of the following form

\[ S_0(f) = \frac{S_0}{1 + (f/\Delta f)^2}. \]  

(2)

For a given signal model, the expression of the logarithm of the likelihood function takes the following form

\[ \ln(\Delta f) = \frac{q}{2N_0} \int_{-\infty}^{\infty} \frac{|Y(f)|^2}{1 + (f/\Delta f)^2} \, df - T \int_{-\infty}^{\infty} \ln \left[ \frac{1+q+(f/\Delta f)^2}{1+(f/\Delta f)^2} \right] \, df, \]  

(3)

where \( q = \frac{S_0}{N_0} \).

We compose the maximum likelihood equation

\[ \frac{\partial \ln}{\partial \Delta f} = \frac{q}{(1+q)^2} \Delta f N_0 \int_{-\infty}^{\infty} \frac{(f/\Delta f)^2 |Y(f)|^2}{1 + \left( \frac{f}{1+q/\Delta f} \right)^2} \, df - \frac{2Tq}{(1+q)\Delta f} \int_{-\infty}^{\infty} \frac{(f/\Delta f)^2 df}{1 + \left( \frac{f}{1+q/\Delta f} \right)^2} \left[ 1 + (f/\Delta f)^2 \right], \]

if \( \Delta f = \Delta f^* \) is assessment of the signal spectrum width.

It follows that the adopted implementation after optimal filtering, quadratic detection, and averaging, is compared with the reference value, which is determined by the estimate of the expected parameter and the form of its spectrum. Setting a reference value when estimating the spectrum width of unknown signals is very difficult. Therefore, it is advisable to form the reference value also with the help of the adopted implementation. For this, we represent a part of the expression included in the second integral, as

\[ \frac{q}{1 + (f/\Delta f)^2} \approx \frac{|Y(f)|^2}{N_0}, \]  

(4)

and the whole equation of maximum likelihood as

\[ \int_{-\infty}^{\infty} |K_1(f)K_2(f)Y(f)|^2 \, df - k_s \int_{-\infty}^{\infty} |K_1(f)Y(f)|^2 \, df = 0, \]  

(5)

where \( K_1(f) = \frac{f/\Delta f}{\sqrt{1 + \left( \frac{f}{1+q/\Delta f} \right)^2}} \) is amplitude-frequency characteristic (AFC) of differentiating filter,

\[ K_2(f) = \frac{1}{\sqrt{1 + \left( \frac{f}{1+q/\Delta f} \right)^2}} \]

is AFC of optimal filter;

\[ k_s = 2T(1 + 1/q) \]

is a scaling factor.

The adopted implementation is pre-filtered using filter \( K_1(f) \). After that, the signal in one arm of the discriminator is subjected to additional filtering by the resonant circuit \( K_2(f) \), the passband of which corresponds to the estimated spectral width of the processed signal. Then there is a quadratic detection and averaging of signals over time. In other words, the signal is released before and after the filter \( K_2(f) \). The resulting stresses are compared with each other, and one of them with a scaling factor \( k_m \). The type of discriminatory characteristic is determined by the frequency response of the filters and the type of signal spectrum. The discriminator zero is determined by the value of the scaling factor. At zero discriminator voltage, which corresponds to the solution of the maximum likelihood equation, the discriminator filter passband corresponds to an estimate of the width of the spectrum of the input signal.
2. Correlation processing devices with adaptation of receiving channels to the signal spectrum width

The synthesized discriminator can be used both for measuring the spectrum width of various signals and for constructing adaptive receivers where the matching of the bandwidth of the selective devices with the spectrum width of the received signals is required.

If there are several receiving channels, it is advisable to use correlation signal processing to obtain an estimate of the width of the spectrum.

We consider the operation of the device under the following assumptions:

- the bandwidth of the preliminary filters is much greater than the width of the spectrum of the signal;
- the signal spectrum is described by expression (2);
- a bandpass filter is made in the form of a resonant circuit with a gain \( \sqrt{k_0} \) and a passband \( \Delta f \).

The adopted implementation after filtering in bandpass filters (BF) undergoes correlation processing in the first correlator, consisting of a multiplier and an integrator. The average voltage value of the first correlator will be proportional to the correlation function of the signal supplied to it

\[
U_{out} = \int_{-\infty}^{\infty} S_0(f) K_{BF}^2(f)e^{j2\pi f \tau} df = P_s k_0 \Delta f \frac{e^{-2\pi \Delta f \tau} - e^{-2\pi \Delta f_s \tau}}{\Delta f^2 - \Delta f_s^2},
\]

where \( K_{BF}(f) \) is the frequency response of bandpass filters;

\( P_s = \frac{3\pi \Delta f_s}{2} \) is input signal power.

The input signal also undergoes correlation processing in the second correlator without filtering by bandpass filters. In this case, the average value of the voltage at the output of the scaling amplifier (SA) will be equal to

\[
U_s = k_s \int_{-\infty}^{\infty} S_0(f) e^{j2\pi f \tau} df = P_s k_s e^{-2\pi \Delta f_s \tau}.
\]

The comparison unit generates the voltage difference from the outputs of the first correlator and the scaling amplifier

\[
U_\Delta = P_s k_s - \frac{P_s k_0 \Delta f}{\Delta f + \Delta f_s} = P_s \frac{\Delta f_s k_s - \Delta f(k_0 - k_s)}{\Delta f + \Delta f_s}.
\]

Upon receipt of the last expression, it was assumed that the spatial delay of the signals was compensated before the input of the device, so that \( \tau = 0 \). If the gain of the scaling amplifier is chosen equal to \( k_s = \frac{k_0}{2} \), then expression (8) is transformed to the form

\[
U_\Delta = P_s k_s \frac{1-x}{1+x}, \quad x = \frac{\Delta f}{\Delta f_s}.
\]

Therefore, the output voltage of the comparison unit is proportional to the difference in the passband of the bandpass filters and the spectrum width of the processed signals. If this voltage is equal to zero, which corresponds to the solution of the maximum likelihood equation (5), the passband of the bandpass filters will correspond to the estimate of the signal spectrum width. This voltage is used to automatically adjust the passband of bandpass filters to the spectrum width of the received implementation. The matching unit (MU) ensures the stability of the system of automatic adjustment of the passband and matching its output voltage with the adjustment characteristic of the bandpass filters.

Thus, in the considered device, the bandwidth is adapted to the spectrum width of the processed signal, i.e. optimized processing is achieved. In addition to increasing the accuracy of processing, this device allows you to get additional information about the signal, namely, information about the width of its spectrum. This information can be removed from the output of the matching unit.
With relatively large input signal-to-noise ratios, to ensure optimal processing, it is not enough to adapt the passband of the bandpass filter to the spectral width of the received signal. In addition, it is necessary to take into account the input signal level. Indeed, for large signal-to-noise ratios, i.e., when there is no need to select a signal from noise, any filtering leads to a weakening of the energy of the received signal and a decrease in the beneficial effect. In the limit at $q \gg 1$ the optimal filter has an infinitely large passband.

To substantiate this situation we consider a signal-to-noise ratio at the output of the correlation processing unit, namely the known expression $[3, 4]$

$$q_{out} = \Delta f T \frac{q_{in}^2}{1 + 2q_{in}}$$  \hspace{1cm} (10)

$$q_{in} = \frac{p_{in}}{p_n}$$ \hspace{1cm} (11)

Where

$\Delta f$ is a band pass filter;
$T$ is an averaging time;
$p_{in}$ is signal power at the input of the correlator;
$p_n$ is noise power at the input of the correlator.

We write the signal power at the input of the correlator taking into account the influence of the bandpass filter

$$p_{in} = \frac{P_s k_0 \Delta f}{\Delta f + \Delta f_s} = \frac{P_s k_0 x}{1 + x}$$ \hspace{1cm} (12)

and we’ll transform the noise power to the form

$$p_n = N_0 k_0 \frac{n \Delta f}{2} = N_0 k_0 \frac{n \Delta f_s}{2} x = P_{ns} k_0 x,$$ \hspace{1cm} (13)

where $P_{ns}$ is noise power normalized in the signal band.

With this approach, expression (11) takes the form

$$q_{in} = \frac{P_s k_0 x}{(1 + x) P_{ns} k_0 x} = \frac{q_n}{1 + x},$$ \hspace{1cm} (14)

where $q_n$ is an input signal-to-noise ratio normalized in the signal band.

Taking into consideration expression (14), expression (10) takes the following form

$$q_{out} = \Delta f T q_{in}^2 \frac{1}{1 + x} \frac{(1 + x)}{(1 + x + 2q_n)}.$$ \hspace{1cm} (15)

For small values $q_n = 0,1$ the maximum value of the output signal-to-noise ratio after correlation processing corresponds to $x = 1$, i.e. when the filter passband is equal to the signal spectrum width. Increasing the input signal-to-noise ratio ($q_n = 1,10$) requires expanding the filter bandwidth to maximize $q_{out}$.

Therefore, when constructing optimal processing devices operating in a wide dynamic range of input signals, adaptation requires the joint use of automatic gain control (AGC) and automatic passband adjustment (APA) signals.

The processing structure under consideration differs from the structure of correlation processing with adaptation to the signal spectrum width by the presence of broadband amplifiers (BA) covered by AGC. As can be seen from the figure, the voltage from the output of the AGC block is used not only to adjust the gain of the BA, but also to control the passband of bandpass filters. For this, the AGC voltage is summed with the output voltage of the discriminator of the signal spectrum width.

If we represent the output voltage of the automatic gain controller (AGC) block in the form $U_{AGC} = k_A q$, where $k_A$ is the transfer coefficient of the AGC circuit, and take into account expression (9), the
control voltage for adjusting the passband of the bandpass filters (output voltage of the adder) takes the form:

\[ U_\Delta = U_{AGC} + U_{APA} = k_A q + S(1 - x), \]  

where \( S \) is the steepness of the discriminator of the signal spectrum width.

The steady state of the automatic direction finder (ADF) system corresponds to the equation \( U_\Delta = 0 \). Solving this equation for bandpass filters \( \Delta f \), we get

\[ \Delta f = \left(1 + \frac{k_A}{S} q\right) \Delta f_s. \]  

This shows that the appropriate choice of coefficients \( k_A \) and \( S \) you can realize the optimal passband of bandpass filters.

3. Conclusion

The problems of implementing optimal filtering in the correlation processing of random signals with a priori unknown characteristics of the spectrum are considered. The structures of correlation processing devices with the adaptation of the receiving channels to the width of the signal spectrum are developed.

Acknowledgements

Project № 2686.2020.8 "Models, methods and means for obtaining and processing information about space objects in a wide spectral range of electromagnetic waves"

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