Improvement of Signal Reception Reliability at Satellite Spectrum Monitoring System

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ABSTRACT Extensively increasing numbers of radio electronic devices significantly complicate the electromagnetic situation under conditions of radio frequency spectrum deficiency and require improvement in the functions and mechanisms of spectrum monitoring systems. Today, in the framework of the existing ground-borne spectrum monitoring system, it is impossible to qualitatively perform the functions and problems of spectrum monitoring. Spectrum (radio) monitoring is one of the main techniques for spectrum load estimation to solve problems of perspective management of the radio frequency spectrum with the purpose of developing new radio technologies. Therefore, the problem of improving the effectiveness of spectrum monitoring does not lose relevance. When solving such problems, one of the most important factors is the extraction of an effective signal with background noise and interference. Therefore, the effectiveness of the Kalman filter application for satellite-based radio monitoring systems is considered in this study. The proposed method for detecting radio signals using Kalman filters makes it possible to make correct decisions with high accuracy. The simulation results show that Kalman filters work effectively even at a negative signal-to-noise ratio (90% and higher), adapting to the original signal at different noise dispersions in a noisy signal. It can be concluded that this method can be successfully applied to solve problems of detecting sources of radiation of a certain frequency according to the signal registered by the onboard receiver of the satellite spectrum monitoring system. The influence of the Kalman filter decision-making speed on the results of radio signal processing was estimated.

INDEX TERMS Kalman filter, low-orbit small spacecraft, satellite spectrum monitoring radio-frequency spectrum, radio monitoring.

I. INTRODUCTION Wireless technology has gained immense popularity in recent years. However, owing to the policy of fixed distribution of the radio frequency spectrum (RFS), RFS has become an increasingly deficient natural resource. Under such conditions of deficiency, RFS requires improvement in the functions and mechanisms of regulation and management [1], [2], [3], [4], [5], [6], [7]. At present, new approaches to RFS management have appeared, including dynamic/opportunistic spectrum access, spectrum sharing and licensed/unlicensed spectrum aggregation, cognitive radio, and software-defined networks. All these methods are directed toward achieving the best and most scientific use of RFS [7], [8], [9], [10]. Radio control of RFS use (spectrum radio monitoring) is one of the ways of estimating its load for solving problems of perspective management of the radio frequency spectrum, with the aim of developing new wireless technology [11]. Radio monitoring of the radio frequency spectrum is a collection, treatment, analysis, and storage of information about the state of the radio frequency spectrum and identification of violations of the rules of spectrum use. However, at present,
spectrum monitoring is performed based on ground-borne means of radio control systems [12], [13], [14]. Using ground-borne radio control means the provision of complete operative information about the real state of RFS use in conditions of megapolis is a difficult problem, and the management of RFS on the scale of the country is much more difficult. Therefore, it is necessary to improve the functions and mechanisms of spectrum monitoring. In addition, ground-borne systems have a range of drawbacks, for instance, a limited zone of radio monitoring, insufficient quantity of radio control sites, the labor-consuming procedure of radio control in adverse climatic conditions, and the condition of complex relief of the sites. In the framework of the existing ground-borne means of radio monitoring, it is impossible to qualitatively carry out the functions and problems of radio monitoring. One of the directions for improving the effectiveness of radio monitoring systems is to study the possibility of using low-orbiting small spacecraft (SS) as radio monitoring stations [15], [16], [17], [18], [19], [20]. Such systems possess a range of advantages, including high efficiency, a global view, and total coverage of the territory.

The use of Kalman filters is proposed to improve the reliability of the results of the satellite spectrum monitoring system when receiving radio signals. According to the studies and calculations of the reliability, the proposed method for detecting a radio signal using Kalman filters enables us to make correct decisions with high accuracy, increasing the reliability of the results of the satellite monitoring system. The obtained results are of practical importance for organizations engaged in the regulation of the radio frequency spectrum. It can also be used to assess the compliance of the radiation parameters of ground-based electronic means with the norms of permits for the use of the radio frequency spectrum as well as to identify illegally operating ground-based electronic devices and improve the electromagnetic environment.

The rest of the paper is organized as follows: in Section II the analysis of the radio channels of a low-orbit satellite system to assess the real signal levels is presented; in Section III signal evaluation using the Kalman filter in a satellite monitoring system, influence assessment of the decision-making speed and clarifying the position of the small spacecraft in orbit using the Kalman filter are considered. The conclusions are drawn in Section IV.

II. METHOD

In [15], an analysis of the energy budget of radio lines was carried out, and the analysis showed the possibility of applying a low-orbiting small spacecraft to fulfill radio monitoring. The analysis of the signal level at the input of the measuring onboard receiver of the radio monitoring system showed that for most ground-borne radio-electronic means, the signal-to-interference ratio is more than 10 dB, which is acceptable for satellite radio monitoring systems. However, to increase radio monitoring quality, effective methods for improving the detection reliability and recognition of radio signals from radio emission sources are required [21], [22], [23], [24], [25], [26], [27]. To estimate the detection reliability of radio signals from radio emission sources there has been carried out an analysis of telemetry signal levels of the Earth distance probing satellite system KazEOSat-2 (Figure 1), the signals were obtained as a result of measurements in a period from September, the 5th to October, the 20th, 2020 and from January to June 2021 on the base of national company "Kazakhstan Garysh Sapary".

![KazEOSat-2](image-url)

**FIGURE 1. Space system of distance probing of the Earth KazEOSat-2, the Republic of Kazakhstan.**

The technical parameters of the distance probing of Earth space system KazEOSat-2 are listed in Table 1.

| Designation                             | Parameters of space system         |
|-----------------------------------------|------------------------------------|
| Frequency of ground transmitter, MHz    | 2060                               |
| Frequency of on-board transmitter, MHz  | 2226,666                           |
| Power of ground transmitter, dBWt       | 13                                 |
| Power of on-board transmitter, dBWt     | -7,5                               |
| Factor of antenna gain (ground), dBi    | 39,5                               |
| Factor of antenna gain (on-board), dBi  | 0                                  |
| Satellite altitude, km                  | 630                                |
| Type of orbit                           | Heliosynchronous                   |
| Inclination, deg                        | 98                                 |
| Speed of data transmission, Mbit/s      | 160                                |
| Size of spacecraft, m x m x m           | 7,0 x 8,0 x 9,0                    |
| Mass of spacecraft, kg                  | 180                                |
| Term of active existence, years         | 7                                  |

The receiving and data treatment equipment of ground complex was used to monitor the radio channels of the satellite system KazEOSat-2 for signal levels assessment. The power of the ground signal transmitter was 47 dBWt.

Measurements of the telemetry signal levels in the zone of radio visibility at the input of the on-board measuring receiver range from $-85$ dBm to $-120$ dBm, and the altitude of the average resolution satellite KazEOSat-2 was 630 km.
Such a signal level is optimal from the point of view of satellite radio monitoring.

To increase the quality of radio monitoring, it is necessary to carry out an analysis of the existing methods of detection of determined signals in the background of noise and to choose the most effective method. At this point, one can orient to the real level of the signals (in the range from $-85$ dBm to $-120$ dBm) (Figure 2).

When performing the functions and tasks of a satellite monitoring system based on a single low-orbit small spacecraft, the detection of a useful signal against the background of noise and interference is required. This was performed to increase the signal-to-noise ratio. These problems are solved using matched filters, Wiener filters, Kalman filters, optimal detection of signals according to the Neumann-Pearson criteria, the least squares method, etc. [28], [29].

In addition, to determine the coordinates of radio emission sources using low-orbit small satellites based on the Doppler effect, the least squares method and various forms of the extended Kalman filter (EKF) are used [30], [31], [32], [33], [34]. Studies carried out in [20] and [35] have shown that for such purposes, it is best to use a constrained unscented Kalman filter (cUKF) because the cUKF filter demonstrates fast convergence, stability, and accuracy of results in simulation with extreme ease of implementation.

Thus, it is easier to apply restrictions to cUKF filters, which are natural when performing the tasks of determining the location of radio emission sources. In [36], the errors in determining the ephemeris and the influence of oscillator drift were considered. However, all the considered works do not take into account the rotation of the Earth, which can affect the accuracy in determining the location of radio emission sources.

In a satellite spectrum monitoring system to determine parameters and the current position of radio emission sources it is suggested to use radio receiving equipment placed onboard a small low-orbit satellite. It is assumed that at a specific time on the input of the onboard measuring receiver, the observation is fixed, which is the measured value ($z$). At this point, a useful signal ($x$) distortion owing to interference $n$ (noise) is observed. Here, $n$ is a random variable that appears in the measurement and when transmitted through the connection channel. Therefore, on the input of the measuring on-board receiver, one defines not the true values of the signal parameters (by which the radio emission source parameters are determined), but the distorted ones. The task of the on-board measuring receiver is to determine the useful signal ($x$) most reliably. However, one can only approximate the values of the radio emission source signal parameters ($x$), denoting the values as $\hat{x}$.

When receiving a signal from an on-board receiver, it is suggested that it is a product of a certain dynamic process, and correspondingly, a mathematical model of the system is in the following form:

$$\dot{x} = \frac{dx}{dt} = F(x, t)$$  \hspace{1cm} (1)

where $x$ is the vector of states of the system and $F(x, t)$ is the function describing the evolution of the system.

If the dynamics of the observed signal can be represented in the form $\dot{x}$, then the Kalman filter can be applied to extract the signal from the noises one can apply the Kalman filter [20], [36], [37].

### III. RESEARCH RESULTS

When determining radio emission source parameters using a satellite spectrum monitoring system on the basis of one low-orbit small spacecraft, let us suppose that one deals with the problem of detecting a harmonic signal (carrying oscillation), which has the following form:

$$x(t) = U\cos(\omega_0 t + \varphi_0)$$  \hspace{1cm} (2)

However, this form does not satisfy the requirements of the Kalman filter. Let us represent this in differential form. To achieve this, one needs to find differential equations that have a solution in the form of (2). Before applying Kalman filters, it is necessary to solve a transitional problem – to find a system of differential equations. Solving these differential equations, one can find function (2), and if this requirement is true, then one can use these differential equations in the logic of the Kalman filter application. Furthermore, we write an equation that describes the dynamics of the harmonic oscillator:

$$\ddot{x} + \omega_0^2 x = 0$$  \hspace{1cm} (3)

Then, the differential equation order is reduced. To reduce the order, one should introduce additional parameters, such as

$$\begin{cases}
\dot{x} = v \\
\dot{v} + \omega_0^2 x = 0
\end{cases}$$  \hspace{1cm} (4)

where $\dot{x} = v$ – speed of signal modification.

Hence,

$$\frac{dx}{dt} = v(t)$$

Here the speed is variable.
Thus, the mathematical model of the process generating a harmonic oscillator has the following form:

\[
\begin{align*}
\frac{dx}{dt} &= v(t) \\
\frac{dv}{dt} &= -\omega_0^2 x(t)
\end{align*}
\] (5)

Here \( x \) is represented as a set of discrete values.

From (5), it is necessary to obtain a differential equation that has the following form:

\[
\begin{align*}
\frac{x_{k+1} - x_k}{dt} &= v_k \\
\frac{v_{k+1} - v_k}{dt} &= -\omega_0^2 x_k
\end{align*}
\] (6)

From equation (6), one obtains a final solution that provides the possibility of defining each subsequent value of the signal. Hence, to apply the Kalman filter, one should write the equations of the signals’ real values in the following form:

\[
\begin{align*}
x_{k+1} &= x_k + v_k dt \\
v_{k+1} &= v_k - \omega_0^2 x_k dt
\end{align*}
\] (7)

Thus, the signal to be defined is represented in accordance with equation (7) in the form

\[
\begin{align*}
x_{k+1} &= x_k + v_k = k + \varepsilon_k \\
v_k &= v_k - \omega_0^2 x_k dt
\end{align*}
\] (8)

where \( \varepsilon_k \) – the model error, which is related to the mathematical model accuracy; \( \eta_k \) is a technical error related to the noise presence and imperfection of the measuring device, including errors that occur during the rotation of the Earth (\( \eta_k = \eta_k^{(1)} + \eta_k^{(2)} \); \( \eta_k^{(1)} \) - noise, \( \eta_k^{(2)} \) - error of the measuring equipment).

If the condition \( \eta_k^{(2)} \ll \eta_k^{(1)} \) is true, then \( \eta_k \) is the actual noise effect.

Hence, \( x_{k+1} = x_k + v_k dt + \varepsilon_k \) – is a mathematical model, \( z_k = x_k + \eta_k \) – measured value.

Here, \( v_k dt \) is a term that controls the evolution of the system, \( \varepsilon_k \) – model error, \( x_k \) is the real value of the signal, \( z_k \) is the value obtained from the output of the board measuring receiver, \( \eta_k \) – the noise. Where \( \varepsilon_k \) and \( \eta_k \) are random values.

The mathematical expectations of the random values \( \varepsilon_k \) and \( \eta_k \) are assumed to be as follows:

\[ E\varepsilon_k = E\eta_k = 0 \] (9)

Thus, it is assumed that the noise does not possess any constant components. Further one needs the values of dispersions of the random values \( \sigma_\varepsilon^2 \) and \( \sigma_\eta^2 \).

The Kalman filter algorithms then follow. For this, one needs to find the optimal value of signal \( y_k \) which is unknown.

If values \( x_k \) and \( z_k \) are available, then \( y_k \) is an optimal value of the golden mean between \( x_k \) and \( z_k \), and here, \( U_k = v_k dt \).

\[ x_{k+1} = x_k + U_k + \varepsilon_k \] (10)

Hence, to find the optimal value of the golden mean it is necessary to introduce weight coefficient \( k \) (optimal value of the golden mean will depend on the coefficient), here \( x_k \rightarrow 1 - k_k, z_k \rightarrow k_k \), then:

\[ y_{k+1} = k_k z_{k+1} + (1 - k_k) \cdot (y_k + U_k) \] (11)

Further one should minimize \( \varepsilon_{k+1} = x_{k+1} - y_{k+1} \). This is done in the following way:

\[
\frac{d}{dk} \sum (x_{k+1} - y_{k+1})^2 = 0
\] (12)

Having solved the equation, one obtains the following:

\[ \varepsilon_{k+1} = (1 - k) \cdot (\varepsilon_k + \eta_k) - k\eta_{k+1} \] (13)

Finally, for Kalman filter coefficient the following expression is obtained:

\[ k_{k+1} = \frac{E\varepsilon_k^2 + \sigma_\eta^2}{E\varepsilon_k^2 + \sigma_\xi^2 + \sigma_\eta^2} \] (14)

In Figures 3 and 4, graphs of the measured signal depending on time with the effect of different noise levels are illustrated. In the figure, along the horizontal axis, the numbers of signal counts are shown, the counts measure and make calculations at discrete time moments, and along the vertical axis, the model values of the signal are given. Thus, in the figures, graphs of the dependence of the signal levels on different noise levels are represented. In the graphs, the red curve denotes the initial signal, and the blue curve denotes the initial signal with noise addition.

FIGURE 3. Form of model measured signal depending on time for various noise dispersion values (\( \sigma = 0.1 \)).

When the magnitude of the root-mean-square deviation of the noise is equal to \( \sigma = 0.1 \), the level of noise generated is significantly less than the level of the initial signal. At this point, the resulting oscillation (blue curve) was similar to the initial signal. At \( \sigma = 0.5 \), the level of noise generated is insignificantly less than that of the initial signal. At this point, the resulting oscillation (blue curve) was greater than the initial signal. At \( \sigma = 1 \), the resulting oscillation (blue curve) becomes greater than the initial signal, that is, the signal-to-interference ratio decreases to a minimum value. At \( \sigma = 2 \), the resulting oscillation (blue curve) became...
FIGURE 4. Form of model measured signal depending on time for various noise dispersion values ($\sigma = 2$).

significantly greater than the initial signal, that is, the signal-to-interference ratio decreased to a negative value. Hence, the greater the root-mean-square deviation of the generated noise, the smaller the signal-to-interference ratio.

FIGURES 5 and 6 show graphs of the detection and recognition of radio signals from radio emission sources (for increasing radio monitoring quality) using the Kalman filter. When applying the Kalman filter to determination (establishing) an effective signal out of noisy signals (blue curve), the Kalman coefficient adapts quite rapidly between $x_k$ and real signal value and $z_k$ – measured value.

FIGURE 5. Representation of signals depending on time according to results of Kalman filter application at various values of noise dispersion in case of initial signal availability ($\sigma = 0.1$).

Thus, as can be seen in the graphs, the signal on the output of the Kalman filter (green line) at initial counts at value $\sigma = 0.1$ differs from the true value of the existing signal (red curve); further, in subsequent iterations, it is rapidly stabilized to the initial signal. Hence, at $\sigma = 0.5$, in the case of initial signal availability, the Kalman coefficient adapts rapidly to the initial signal, which is the detection of the initial signal. At this point, the signal on the output of the Kalman filter and initial signal coincide. At $\sigma = 1$, in the noisy signal, where the signal-to-interference ratio is significantly smaller, the Kalman filter adapts to the initial signal. At $\sigma = 2$, in the noisy signal, where the signal-to-interference ratio has a negative value, the Kalman filter adapts to the initial signal.

In Figure 7, the result of the Kalman filter works with an absent initial signal on the filter input. When an effective determined signal in the noisy signal is absent, the Kalman filter defines the absence of the initial signal by stochastic oscillation with a level close to zero. This means that the Kalman coefficient is successfully applicable when radio monitoring of radio emission sources is used to detect the effective signal availability.

FIGURE 6. Representation of signals depending on time according to results of Kalman filter application at various values of noise dispersion in case of initial signal availability ($\sigma = 2$).

FIGURE 7. Result of Kalman filter work when the initial signal is absent on the input of the filter.

For this purpose, we introduce the concept of the similarity coefficient of the filtered signal using a Kalman filter for the initial signal.

Similarity coefficient is calculated in the following way:
- the difference between the two signals is calculated (filtered and initial);
- The root-mean-square value of the difference signal was calculated.
The root-mean-square value of the difference signal is subtracted from the initial signal amplitude.

Figure 8 shows the graphs of the dependence of the similarity coefficient on the noise level. As can be seen from Figure 8, the similarity coefficient has a value greater than 0.9 at any positive value of the signal-to-interference ratio. Correspondingly, the value of 0.9 can be taken as a threshold value for deciding the availability of the initial signal in the measured signal; if in the result of calculations, the similarity coefficient is greater than 0.9, and it is decided that the initial signal is present.

From Figure 8, it is obvious that the similarity coefficient has a value not greater than 0.3 at any positive values of the signal-to-interference ratio. Correspondingly, the value of 0.3 can be taken as a threshold value for the decision about the absence of the initial signal in the measured signal; if in the result of the calculations, the similarity coefficient occurs to be less than 0.3, it is decided that the initial signal is absent.

The advantage of this method is that the similarity coefficient when the initial signal is available has a value greater than the threshold (0.9), even at negative signal-to-interference ratios.

In Figure 8, by unifying the two above-mentioned graphs of similarity coefficients, one can demonstrate the method of verification of the effective signal availability, where it is possible to introduce the upper and lower thresholds of making decisions when monitoring radio emission sources. The lower threshold excludes false alarms. The upper threshold is for the exclusion of the target dropout. Thus, at a similarity coefficient greater than 90%, one can confidently confirm the availability of an effective signal at a signal-to-interference ratio greater than zero.

As shown in Figure 9, the method reliability index has a very high value of 1 for all positive values of the signal-to-interference ratio. However, at negative values of the signal-to-interference ratio, the index sharply approaches zero and at −6 dB it achieves its possible minimum value.

In Figure 8, one can see that the method reliability index with an unavailable initial signal has virtually its maximum possible value, which means that the method works ultra-reliably in this case.

Thus, at a negative signal-to-interference ratio value, the signal level at the input of the filter was greater than 0.85 (85%). Hence, when the signal-to-interference ratio is greater than zero, the signal on the input of the on-board measuring receiver is taken with a reliability of more than 0.9 (90%). Thus, one can conclude that the probability of the signal to exist and the signal to be taken by the on-board
measuring receiver is more than 0.9 (90%) at zero and a greater signal-to-interference ratio.

We estimated the operating speed of the proposed method. As can be seen from Figure 11, when the signal-to-interference ratio is greater than 0 dB, the correct decision regarding signal availability is made during the same time interval equal to four periods of the initial signal. However, it is worth noting that if the signal level is less than 0 dB, then the correct decision about signal availability is approximately equal to five periods of the initial signal or more, depending on the signal-to-interference ratio.

Furthermore, we consider the problem of defining the emission source location using similarity coefficients. For this purpose, the satellite motion trajectory and emission source position coordinates can be represented by two parallel straight lines. This assumption is appropriate for low-orbiting satellites. In Figure 12, this assumption is illustrated.

In Figure 12, the satellite position during its motion is denoted as point A, and the emission source location corresponds to point B. At this point, the satellite moved along the OX-axis direction. To simulate the problem of defining the coordinates of the emission source for the purpose of this discussion, BC = 1, and the distance from it to the current satellite position can be found by the following formula:

\[
AB = r = \sqrt{AC^2 + BC^2} = \sqrt{1 + (X_A - X_B)^2} \tag{15}
\]

where \(X_A, X_B\) – coordinates of the satellite and emission source respectively.

Suppose that the attenuation of the signal from the emission source obeys the exponential law. Then, the root-mean-square deviation of noise at a satellite location is defined by the following formula:

\[
\sigma = \sigma_0 \exp(\alpha |1 - r|) \tag{16}
\]

where coefficient \(\alpha\) is defined by the boundary data of the problem. For instance, if we consider the following:

\[
\sigma = 0, \quad 1 at r = 1 and \sigma = 2, \quad 0 at r = 10 \tag{17}
\]

then the coefficient \(\alpha\) is equal to:

\[
\alpha = \frac{\ln 20}{9} \tag{18}
\]

Thus, the further away the satellite is from the emission source, the lower the signal-to-interference ratio will be. Correspondingly, the maximum similarity coefficient corresponds to the satellite position at point C (Figure 12). Hence, by fixing the satellite coordinates at which the similarity coefficient has its maximum values, one can define the emission source location coordinate as well.
Figure 13 shows the results of the calculations according to this algorithm in the form of graphs of the dependence of the similarity coefficient on satellite coordinates. In this diagram, the satellite coordinates are along the horizontal axis and the respective similarity coefficients are along the vertical axis. From Figure 13, the similarity coefficient has a functional dependence on the satellite coordinates. This dependence can be used to define emission source coordinates. In the example shown in Figure 13, the maximum similarity coefficient corresponds to a value of 3.6. This value 3.6 was fixed as the coordinate of the emission source in the numerical experiment. Thus, it can be concluded that this algorithm can be applied to increase the accuracy of the determination of emission source coordinates, defining the peak value of the similarity coefficient when measuring at several points in orbit.

IV. CONCLUSION
With the purpose of confirming theoretical conclusions about the creation of a satellite spectrum monitoring system and to improve the reliability of detection and recognition of radio signals due to ground-based radio emission sources, the levels of real radio signals of the distance-probing satellite KazEOSat-2 were estimated. The measurements showed that the maximum level of radio signals on the input of the onboard measuring receiver was in the range of −85 dB to −120 dB, which is acceptable for a satellite-based spectrum monitoring system. To improve the validity of the satellite spectrum monitoring results at radio signal reception, a Kalman filter is proposed for application. The representation of signals in the time domain based on the results of applying the Kalman filter at different noise dispersions in the presence of the desired signal shows that the Kalman coefficient quickly adapts to the original signal. Simultaneously, the signal at the output of the Kalman filter and the desired signal practically coincide.

Studies and calculations of the reliability index showed that the proposed method of radio signal detection using the Kalman filter offers the possibility of making correct decisions with a high degree of accuracy. It can be concluded that the probability of signal existence and the signal to be received by the onboard receiver is greater than 90% at zero and a positive value of the signal-to-interference ratio.

To improve the efficiency of the satellite spectrum monitoring system, further research will be directed toward the development of efficient antenna systems (Active Phased Array Antenna - APAA) for onboard receivers, to reduce satellite location errors, and to assess the impact of pulsed and concentrated interference when receiving weak signals.

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VOLUME 10, 2022

101407