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IDENTIFYING THE REGULARITIES OF THE SIGNAL DETECTION METHOD USING THE KALMAN FILTER

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Currently, it is more efficient to use LEO small spacecraft as radio control points to determine the compliance of the radiation parameters of electronic means with the relevant norms and conditions of permits for the use of the radio frequency spectrum. Such satellite radio monitoring systems make it possible to determine the parameters of signals and the location of radio-electronic means over a large area with a diverse terrain, which will increase the efficiency of radio monitoring systems. When performing such tasks, one of the most important parameters is the detection and isolation of a useful signal against the background of noise and interference. For such purposes, it is effective to use Kalman filters. It was found that the Kalman filter can detect and isolate useful signals against the background of noise and interference with very high accuracy. However, when solving such problems, problems arise related to the stability of the method to the choice of the initial state of the filter and the inevitable distortion of the frequency of the desired signal due to the presence of the Doppler effect. In the course of this study, it was found that the similarity coefficient depends on the noise level, but it does not actually depend on frequency distortion.

It was also found that when the SNR ratio is greater than 0 dB, the radio signal at the input of the on-board measuring receiver will be received with a reliability of more than 90 %. Therefore, it can be concluded that the signal detection method for satellite radio monitoring based on the use of the Kalman filter is resistant to possible frequency distortions of the desired signal due to the Doppler effect and does not affect the correctness and speed of decisions made

Keywords: Kalman filter, geolocation, Doppler measurements, low earth orbit satellite, radio monitoring

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1. Introduction

Currently, the radio frequency spectrum (RFS) is becoming an increasingly scarce natural resource due to the rapid development of new wireless technologies. Such development requires the improvement of the functions and mechanisms of regulation and management of RFS. However, radio monitoring is still one of the main tools in the RFS regulation, which is used to assess its load to solve the problems of long-term control of the radio frequency spectrum in the interests of the development of new wireless technologies. In radio monitoring, a special place is held by determining the location of radio emission sources, which is a complex task requiring the use of an automated complex of special equipment with specified technical characteristics to determine the location of the studied radio emission sources with maximum accuracy. However, it is practically impossible to perform all the functions and tasks of radio monitoring on the territory of even a small country without the use of modern radio monitoring systems. Therefore, it is important and necessary to improve the functions and mechanisms of radio monitoring. In addition, ground-based radio monitoring systems have a number of disadvantages, for example, a limited radio monitoring area, an insufficient number of radio monitoring points, the complexity of conducting radio monitoring procedures in difficult climatic conditions and in conditions of difficult terrain, etc. Therefore, to increase the efficiency of such systems, it is advisable to use low Earth orbit (LEO) small satellites as radio monitoring stations. Nevertheless, the implementation of this idea is fraught with a number of problems, one of which is the Doppler effect. When a signal is detected, the initial phase of the signal is unknown to the radio monitoring system, as well as when detecting and determining the location of the radio source, frequency component shifts may occur, which may lead to errors.

Therefore, it is important in solving such problems to study the problems associated with the stability of the method to the choice of the initial state of the filter and the inevitable distortion of the frequency of the desired signal due to the presence of the Doppler effect. Consequently, studies that are devoted to problems regarding the correctness and speed of decisions made by the system as a result of possible distortions of the frequency components of the desired signal due to the Doppler effect have scientific significance and relevance in detecting and recognizing radio signals from radio sources using satellite radio monitoring systems based on LEO small satellites.

2. Literature review and problem statement

In [1], an analysis of the signal levels at the input of the receiver of the radio monitoring system was carried out, which showed that for most of the considered ground-based radio electronic means, the SNR ratio is greater than 10 dB, which is acceptable for radio monitoring on the basis of a small satellite. However, it is noted in the work that for the effective operation of the radio monitoring system based on the small satellite it is necessary to apply special methods of processing weak signals, the use of on-board receivers with increased sensitivity and antennas with increased gain.

The possibilities of organizing such a system and their future architecture were also proposed in [2]. The paper notes the importance of developing such systems for effective management of the radio frequency spectrum in order to maximize the efficiency of spectrum use, minimize radio interference and eliminate unauthorized and improper use of the radio frequency spectrum. But nevertheless, it is also noted that further research is needed to overcome complex problems such as weak signal detection, signal delays, as well as security and privacy issues.

[3] focuses on the main platform and payload technology for such systems. There is also an assumption that such systems can be used not only to determine the location of ground-based electronic means, but also to control aircraft that are out of sight of ground-based controls. However, the stability of the system to the Doppler effect is not considered in the work.

[4] provides information on space and ground system technologies, services, as well as on the economic, political, regulatory, legal, business and social aspects of this growing field of space activities. Also, the paper does not sufficiently consider the effects of rapid fluctuations in the amplitude and phase of the received signals, known as fading, as well as distortions of the frequency components of the desired signal due to the Doppler effect on the satellite system.

Thus, it is assumed that in the future the satellite-ground integrated radio monitoring network will become a more efficient system for managing the RFS use [5]. Therefore, it is advisable to use such systems in order to increase the efficiency of the radio monitoring system for using the radio frequency spectrum as radio monitoring stations [6]. However, it is advisable to start performing radio monitoring functions at the initial stage using a single LEO small satellite, since this is the most attractive from an economic point of view [7]. Still, in order to implement radio monitoring systems based on small spacecraft, it is necessary to conduct a number of studies related to the evaluation and analysis of signals received by the onboard receiver. For such purposes, it is more efficient to use Kalman filters or and various forms of Extended Kalman filter (Extended Kalman filter– EKF) [8]. There are two algebraic solutions for such purposes:

1. It is intended for approximate initial estimates of the location and is based on the calculation of the point of closest approach.
2. Algebraically estimating the carrier frequency, and then using adaptive grid search to find an estimate for location determination [9].

The studies carried out in these papers have shown that for such purposes it is best to use a limited sigma-point Kalman filter (constrained Unscented Kalman Filter – cUKF). The authors conducted a comparative analysis that showed the effectiveness of the cUKF filter compared to EKF. Since in modeling, the cUKF filter demonstrates fast convergence, stability and accuracy of results with extreme simplicity of implementation [7]. In [10], errors in determining ephemerides and the influence of oscillator drift were taken into account. However, in these studies, the issues related to the distortions introduced due to the Doppler effect have not been fully investigated.

In [11], a Doppler discriminator based on the frequency domain and a Doppler tracking algorithm based on the Kalman filter are proposed. The proposed positioning method in this paper is of great importance for improving the performance of positioning systems in LEO orbit.

The errors of the orbital equivalent of the Doppler measurement error of LEO satellites were also simulated, taking into account the accuracy of the auxiliary information about the orbit. And according to this analysis of the model, a two-stage improved positioning method based on compensation of orbit and measurement errors is proposed to weaken the effect [12].

In [13], a method for determining the location of a mobile source using measurements of arrival time and Doppler frequency shift is considered. However, these papers do not consider the tasks of detecting and recognizing radio signals from radio sources with satellite radio monitoring. When solving such problems, issues arise related to the stability of the method to the choice of the initial state of the filter and the inevitable distortion of the frequency of the desired signal due to the presence of the Doppler effect. All this allows to assert the expediency of conducting a study on the question of how much the solution of the method based on the Kalman filter depends or not on the amplitude and initial phase of the desired signal, as well as on the distortion of its frequency that occurs on the receiving side due to the movement of the measuring satellite during satellite radio monitoring.

In [14], a scheme of a system for determining the location of ground-based wireless devices using a constellation of LEO satellite systems using only signal power and Doppler measurements is presented. However, the stability of the system to possible distortions of the frequency components of the signal due to the Doppler effect is not considered in the work.

Thus, as a result of the study and analysis of researches devoted to this area, it was found that currently there are few special studies devoted to the distortion of the frequency of the desired signal due to the presence of the Doppler effect, as well as studies related to the stability of the method to the choice of the initial state of the filter, as well as the speed of decision-making from the initial state of the filter and from distorted frequencies at different noise levels when detecting and recognizing radio signals from radio sources using satellite radio monitoring systems based on LEO small satellites.

3. The aim and objectives of the study

The aim of this study is identifying the stability of the signal detection method using the Kalman filter on the initial phase, amplitude, and frequency distortion of the useful signal due to the presence of the Doppler effect in LEO satellite radio monitoring.

To achieve the aim, the following objectives were set:

– to investigate the dependence of the similarity coefficient on the initial states of the Kalman filter;

– to investigate the dependence of the decision-making speed on the initial state of the filter at different noise levels;

– to investigate the dependence of the similarity coefficient on the distorted frequencies of the useful signal at different noise levels;

– to investigate the dependence of the decision-making speed on the distorted frequencies of the useful signal at different noise levels.

4. Materials and methods of research

The objects of research of this work are the following two issues related to the method of signal detection using the Kalman filter:

– Does the speed of decision-making and the accuracy of the method depend on the initial phase of the desired signal?

– Does the speed of decision-making and the accuracy of the method depend on the frequency distortion of the desired signal caused by the Doppler effect?

The main hypothesis of the study is that the Kalman filter is inherently adaptive, so it was assumed that the accuracy of the signal detection method using this filter should not depend on the initial phase of the desired signal. Even if there is such a dependence, it should be weak. It was also assumed that small frequency distortions would not have a serious impact on the accuracy and speed of decision-making of the considered signal detection method. In order to answer the questions posed, the following simplifications were adopted:

– the desired signal of a certain frequency can be represented as the result of some kind of oscillatory process, which corresponds to the mathematical model described in formula (1);

– the amplitude of the desired signal remains unchanged during the process of its detection.

To solve the problems of studying the stability of the signal detection method using the second order linear Kalman filter, computer modeling was used. The simulation was performed using the filterpy.kalman library of the Python programming language. Below is a fragment of the code for using the Kalman filter to detect a signal with a certain frequency and visualize the results:

```
import math
import filterpy.kalman
import filterpy.common
import matplotlib.pyplot as plt
import numpy as np
from Simulator import simulateSensor # modeling sensors

F=1000                          # Frequency of the desired signal
Fs=50000                        # Sampling frequency
dt=1/Fs                         # Sampling step
w02=(2*math.pi*F)**2 # Cyclic frequency of the desired signal
measurementSigma = 0.1          # Standard deviation of the sensor
noiseSigma = 0.9                # Standard deviation of noise
processNoise = 1e-3             # Model error

# Modeling the data from sensors
trajectory, measurement, noise=simulateSensor(F,Fs,noiseSigma)

# Create an object KalmanFilter
filter=filterpy.kalman.KalmanFilter(dim_x=2, dim_z=1)

# F – a process matrix
filter.F = np.array([ [1, dt], [-w02*dt, 1]])

# an observation matrix
filter.H = np.array([[1.0, 0.0]])

# Model error covariance matrix
filter.Q = filterpy.common.Q_discrete_white_noise(dim=2, dt=dt, var=processNoise)

# Measurement error covariance matrix
filter.R = np.array([[measurementSigma*measurementSigma]])

# Initial state
filter.x = np.array([1.0, 0.0])

# Covariance matrix for an initial state
filter.P = np.array([[0.111, 0.0], [0.0, 4.4e+6]])

filteredState = []
stateCovarianceHistory = []

# data processing
for i in range(0, len(measurement)):
    z = [ measurement[i] ] # vector of measurement
    filter.predict() # predicting phase
    filter.update(z) # updating phase

    filteredState.append(filter.x)
    stateCovarianceHistory.append(filter.P)

filteredState = np.array(filteredState)
```

```
stateCovarianceHistory = np.array(stateCovarianceHistory)
# Visualisation
plt.figure(0)
plt.title(“Kalman filter (2nd order)”)
plt.plot(measurement, label=”Measurement”, color=”#99AAFF”)
plt.plot(trajectory[0], label=”True value”, color=”#FF6633”)
plt.plot(filteredState[:, 0]/2, label=”Filter evaluation”, color=”#224411”)
plt.legend()
plt.show()

# Calculation of the similarity coefficient
n = int(len(filteredState)/2)
x1 = filteredState[n:,0]/2
x2 = trajectory[0, n:]
S = 1-np.std(x2-x1)
```

The following is the code of the program with which the sensor operation was simulated (the contents of the file Simulator.py):

```
import numpy as np
import math
import numpy.random

# Modeling data from the sensor
def simulateSensor(F, Fs, noiseSigma):
    dt = 1/Fs # Sampling step

    Nper = 30 # Number of complete signal periods
    tmax = Nper*(1/F) # Maximal time
    tmin = 0 # Minimal time
    # Number of signal values
    samplesCount = int(np.fix((tmax-tmin)/dt))
    x = 1 # Initial value of signal
    y = 0 # Initial value of the signal change rate
    w02 = (2*math.pi*F)**2 # cyclic frequency of the desired signal

    # Noise with normal distribution
    noise = numpy.random.normal(loc = 0.0, scale = noiseSigma, size = samplesCount)
    # Desired sinusoidal signal
    realSignal = np.zeros((2, samplesCount))
    # Noise as signal
    noiseToRet = np.zeros((2, samplesCount))

    for i in range(1, samplesCount):
        x = x + y*dt
        y = y - w02*x*dt

        realSignal[0][i] = x
        realSignal[1][i] = y

    noisedSignal = realSignal[0] + noise
    noiseToRet[0] = noise
    noiseToRet[1] = numpy.random.normal(loc = 0.0, scale = noiseSigma, size = samplesCount)
    # The true value, the data of the “sensor” with noise and the noise itself
    return realSignal, noisedSignal, noiseToRet
```

In order to increase the reliability of detection and recognition of radio signals from radio sources, measurement works were carried out on the basis of the National Company “Kazakhstan Gharysh Sapary” of the telemetry signal from the satellite of the Earth remote sensing (ERS) space system in the period from September 5 to October 19, 2022. The technical characteristics of the remote sensing space system are given in Table 1. From the ground transmitter, the signal was transmitted with a power of about 47 dBW.

Table 1

Parameters of the remote sensing space system

Name of the Earth remote sensing space system	**KazEOSat-2**
Frequency of the ground transmitter, MHz	2060
Frequency of the onboard transmitter, MHz	2226.666
Ground transmitter power, dBW	13
Onboard transmitter power, dBW	–7.5
Antenna gain (ground), dBi	39.5
Antenna gain (onboard), dBi	0
Satellite altitude, km	630
The type of orbit	Sun-synchronous
Inclination, degree	98

Fig. 1 shows a graph of signal levels from a ground transmitter at the input of a satellite receiver at an altitude of 630 km. As can be seen from the graph, the signal level is in the range from – 85 dBm to – 120 dBm. At the same time, the average signal level at the input of the on-board receiver is 100 dBm.

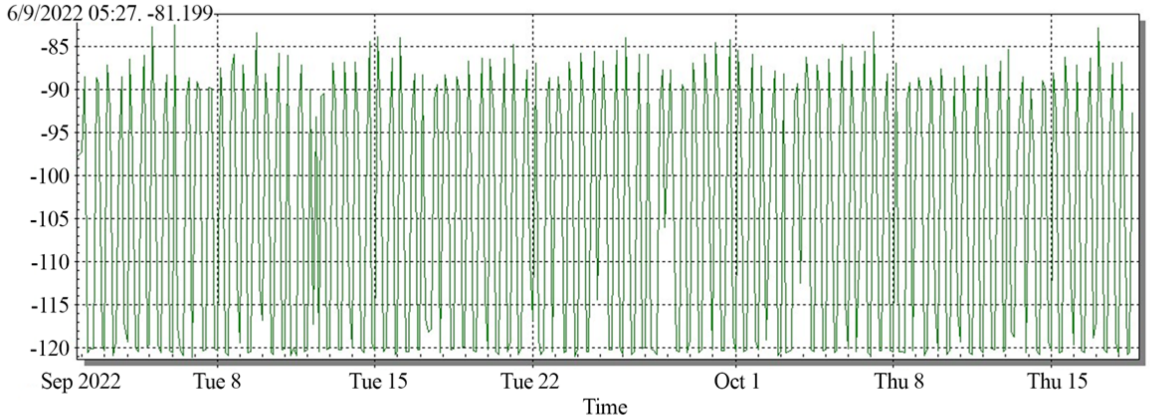

Fig. 1. The maximum value of the signal level at the input of the on-board receiver

Fig. 1 shows that when registering a signal on board a LEO satellite, the SNR ratio can be quite small. Accordingly, the method of detecting a useful signal should work on such values of the SNR ratio.

The studies carried out in [15] showed that the application of the Kalman filter to the implementation of the signal detection task turned out to be a successful solution. However, if this solution is used for radio monitoring using LEO satellites, a couple of questions arise related to the stability of the method to the selection of the initial state of the filter and the unreliable distortion of the frequency of the desired signal due to the presence of the Doppler effect. In this regard, in this paper let's aim to clarify the question of how much the solution of the method based on the Kalman filter depends or does not depend on the amplitude and initial phase of the desired signal, as well as on the distortion of its frequency that occurs on the receiving side due to the movement of the measuring satellite. As the basis of our research work, the method proposed in [15] is considered. According to this method, the desired sinusoidal signal should be the result of a dynamic process described by the equation**:**

$$\ddot{x} + \omega_0^2 x = 0, \tag{1}$$

where x – is some dynamic variable, $\omega_0=2\pi f_0$, f_0 – is the frequency of the desired signal in Hertz.

(1) is a second-order differential equation. If to lower its order, it get the following system of first-order differential equations:

$$\begin{cases} \dot{x} = v(t), \\ \dot{v} + \omega_0^2 x = 0. \end{cases} \tag{2}$$

Further, the system of equations (2) can be rewritten in the form of difference equations:

$$\begin{cases} x_{k+1} = x_k + v_k * dt, \\ v_{k+1} = v_k - \omega_0^2 x_k * dt. \end{cases} \tag{3}$$

In this case, a signal z is registered on the receiving side, defined as:

$$z_k = x_k + \eta_k, \tag{4}$$

where η_k is the total error obtained due to the effect of noise and imperfections of measuring equipment.

In the numerical study of the signal detection method using the Kalman filter, the desired signal (x_k) is obtained as a result of solving the system of equations (3). When solving the system of equations (3), f_0=1000, was set, and the initial conditions were set as follows: x_0=1, ν_0=0. The recorded signal (z_k) is obtained by adding noise of varying intensity to the desired signal. Thus, the task of detecting the desired signal is reduced to the possibility of isolating the desired signal from a highly noisy signal.

First of all, let's check how the choice of different initial conditions affects the result of the Kalman filter. To do this, it is first necessary to configure the Kalman filter. Based on equations (3), the filter process matrix is defined as follows:

$$F = \begin{bmatrix} 1 & dt \\ -\omega_0^2 \nu dt & 1 \end{bmatrix}. \tag{5}$$

The initial state of the filter is set as the following matrix:

$$x = x_i \quad \nu_i \ , \tag{6}$$

where x_i and ν_i vary from –1 to 1 in increments of 0.1.

Let's assume that as a result of applying the Kalman filter to the signal z_k a filtered signal y_k is got Then, according to [15], the similarity coefficient of the filtered signal with the desired signal is determined as follows:

$$S = 1 - std\left(y_k - x_k\right), \tag{7}$$

where $std(y_k - x_k)$ is the standard deviation of two signals (the original and filtered signals).

5. Results of the stability study of the signal detection method using the Kalman filter

5. 1. Investigation of the dependence of the similarity coefficient on the initial states of the Kalman filter

By changing the initial state of the filter according to the matrix (6), it is possible to obtain a set of similarity coefficients, respectively, it is possible to determine its dependence on these values of the initial state. Fig. 2 shows a three-dimensional graph of the dependence of the similarity coefficient on the initial states of the Kalman filter.

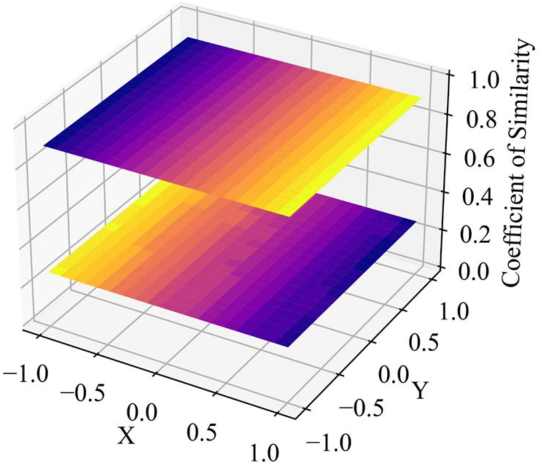

Fig. 2. Dependence of the similarity coefficient on the initial states of the Kalman filter

Fig. 2 shows two planes almost parallel to each other, the lower of which corresponds to the area of similarity coefficient values in the absence of the desired signal in the received signal, and the upper plane corresponds to the case when the desired signal is present in the received signal. From this figure it is also clear that the planes still have a certain angle of inclination. To illustrate this angle of inclination more clearly, Fig. 3 shows a graph of the upper plane on a small scale.

It should be noted that this angle of inclination is quite small, accordingly, it can be assumed with great confidence that the similarity coefficient calculated by formula (7) does not actually depend on the choice of the initial state of the filter.

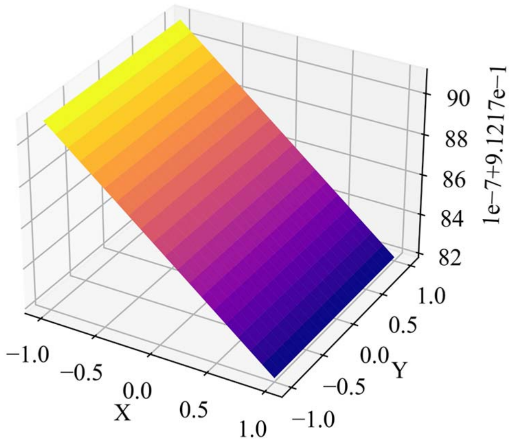

Fig. 3. Illustration of the angle of inclination of the plane of the similarity coefficient values in the presence of the desired signal in the received signal

It is also necessary to remember that the final result is strongly influenced by the noise level available in the received signal. Accordingly, in order to be completely sure that the solution of the Kalman filter does not depend on the choice of its initial values, it is necessary to carry out appropriate calculations for different noise levels. Fig. 4 shows graphs of the dependence of the similarity coefficient on the initial values of the filter for only one component.

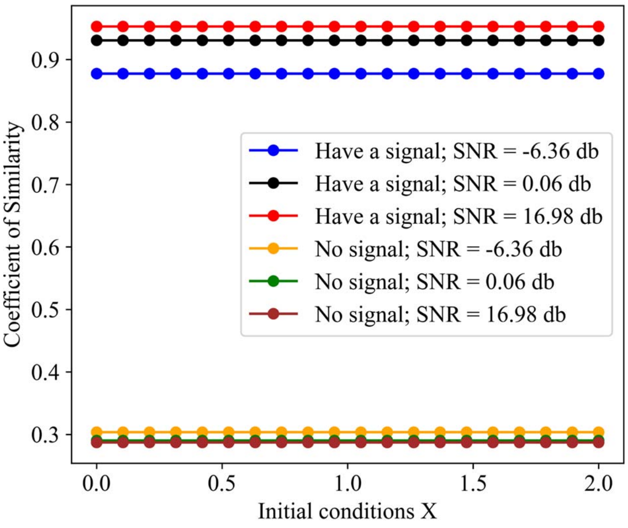

Fig. 4. Dependence of the similarity coefficient values on the initial state of the filter at different noise levels

As it is possible to see from Fig. 4, the similarity coefficient for both cases (in the presence and absence of the desired signal in the received signal) does not actually depend on the choice of the initial state of the filter. Based on these results, it can now be argued that the method of detecting the desired signal in a noisy signal using a Kalman filter is resistant to the choice of initial filter conditions. In addition, also one of the important aspects of using this method is the speed of decision-making by the method. It is known that the Kalman filter is based on an adaptive algorithm, so it takes some time to make a decision about the presence or absence of the desired signal in a noisy signal, after which the method can make the right decision.

5. 2. Investigation of the dependence of the decision-making speed on the initial state of the filter at different noise levels

To estimate the required time to make a decision, it is best to use the number of periods of the desired signal. This will make it possible to apply the results obtained for signals of different frequencies. Fig. 5 shows graphs of the dependence of the speed of decision-making by the method depending on the choice of the initial state of the filter.

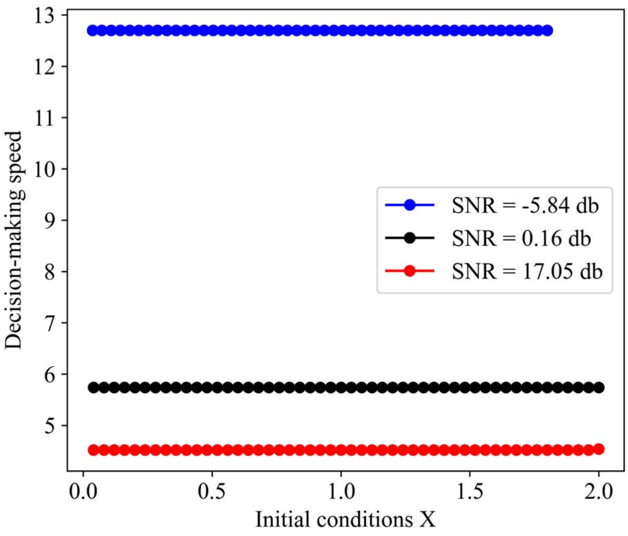

Fig. 5. The dependence of the decision-making speed on the initial state of the filter at different noise levels

Fig. 5 shows that the speed of decision-making does not actually depend on the initial state of the filter. In this case, it depends only on the noise level in the received signal. The stronger the noise level, the longer the method takes to make a decision.

5. 3. Investigation of the dependence of the similarity coefficient on the distorted frequencies of the useful signal at different noise levels

Another important aspect to pay attention to is that this method, based on the use of the Kalman filter, is proposed to be used for radio monitoring of the Surface of the Earth by a LEO satellite. Since the satellite is in constant motion at a fairly high speed, the actual frequency of the desired signal will differ slightly from the set value due to the effect of the Doppler effect. In this regard, before applying this method on board a LEO satellite, it is necessary to assess the effect of a small distortion of the frequency of the desired signal on the correctness and speed of decisions made.

Numerical studies were carried out to assess the effect of frequency distortion of the desired signal on the receiving side due to the Doppler effect. For this purpose, the filter process matrix takes the same values as in the previous calculations. Thus, let's fix the frequency of the desired signal on the filter side. And the distortion of the signal frequency will be set through equations (3). The change in the frequency of the desired signal on the receiving side will be determined using the relativistic formula of the Doppler effect:

$$\omega=\omega_0\frac{\sqrt{1-\left(\frac{v}{c}\right)^2}}{1-\frac{v}{c}\cos(\theta)}, \tag{8}$$

where c is the speed of light, ν is the speed of the radiation source relative to the receiver, θ – is the angle between the direction to the receiver and the velocity vector in the reference frame associated with the receiver. It is obvious that the angle θ in extreme cases takes the values 0 or π. Note that the satellite is moving at the first cosmic velocity, which is ν=7.91 km/s. The speed of light is approximately equal to c =300 000 km/s. Calculations show that if the frequency of the desired signal is f_0=1000 Hz, then the maximum frequency distortion due to the Doppler effect is equal to $\Delta f=\pm 0.03$ Hz. This is a fairly small distortion.

So, to assess the effect of the Doppler effect, it is necessary to generate signals with different frequencies using the system of equations (3). In our work, the frequency change within $f=f_0\pm 0.03$ is considered. Fig. 6 shows a picture of the dependence of the similarity coefficient on the distorted frequencies of the desired signal at different noise levels.

Fig. 6 shows that the similarity coefficient significantly depends on the noise level, but it does not actually depend on the "distortion" of the frequency. It is also possible to notice that the values of the similarity coefficient fluctuate greatly. Such a noticeable fluctuation is due to the fact that Fig. 6 shows graphs for a one-time calculation. But if the calculations are averaged over a variety of calculations, then it is possible to a smoother picture. Just in Fig. 7, graphs of the dependence of the similarity coefficient on "distorted" frequencies averaged over 50 independent calculations are presented.

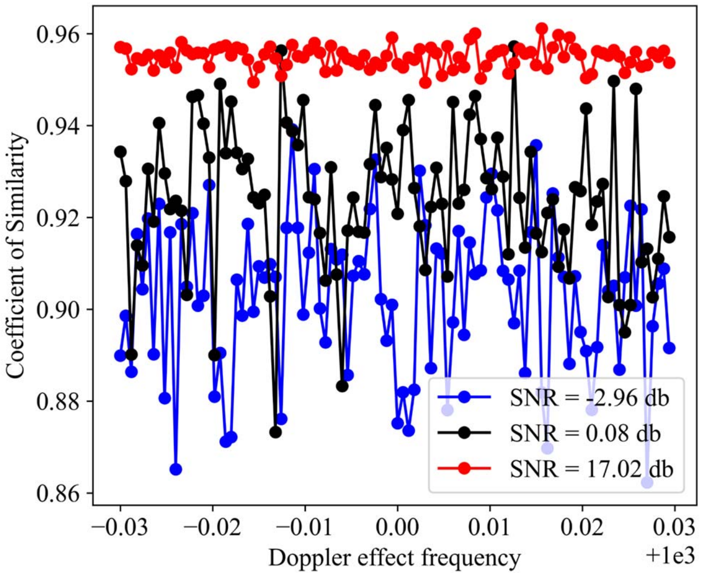

Fig. 6. Dependence of the calculated similarity coefficients on the distorted frequencies of the desired signal at different noise levels

As it is possible to see from Fig. 7, with average calculated data, fluctuations have become smaller. It is also possible to notice that the level of fluctuations depends on the noise level. The higher the noise level, the higher the level of fluctuations. Nevertheless, it is possible to see that the similarity coefficient within the limits of acceptable frequency distortions practically does not depend on them. This suggests that the signal detection method based on the use of the Kalman filter turns out to be resistant to possible "distortions" of the frequency of the desired signal due to the Doppler effect.

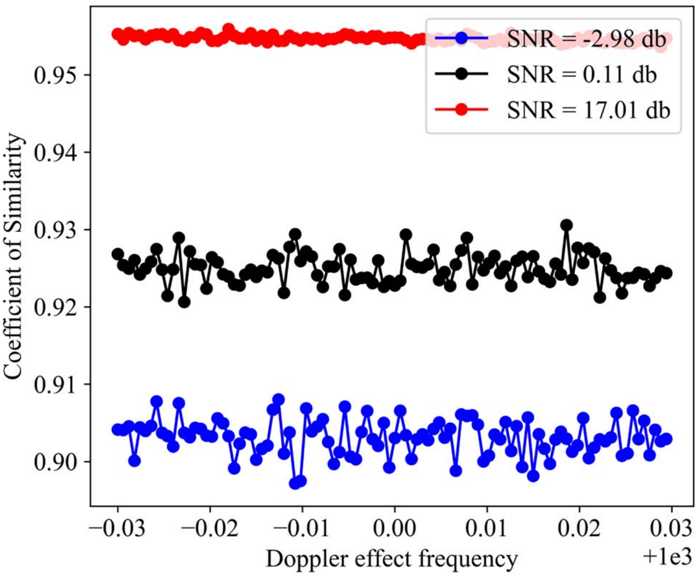

Fig. 7. The dependence of the calculated similarity coefficients on the distorted frequencies of the desired signal at different noise levels from the averaged data

5. 4. Investigation of the dependence of the decision-making speed on the distorted frequencies of the useful signal at different noise levels

Just as in the previous case, here it is necessary to assess the influence of frequency distortions on the speed of decision-making. Fig. 8 shows a graph of the dependence of the decision rate on the "distorted" frequencies at different noise levels. It should also be noted that Fig. 7 shows the graphs of a single calculation.

As it is possible to see from Fig. 8, with a single calculation, the values of the decision-making speed fluctuate greatly. Fig. 9 shows graphs of the same dependence, but averaged over 50 different calculations.

From Fig. 9, it is possible to see that, as in the previous case, the level of fluctuations decreases noticeably when averaging. But it remains dependent on the noise level. As it is possible to see in the last Fig. 7, the higher the noise level, the higher the level of fluctuations. However, it is not noticeable here that the speed of decision-making in any way depends on the "distorted" frequencies of the desired signal. Thus, it is possible to definitively assert that frequency distortions of the desired signal due to the Doppler effect in no way affect the correctness and speed of decisions made by the method based on the use of the Kalman filter.

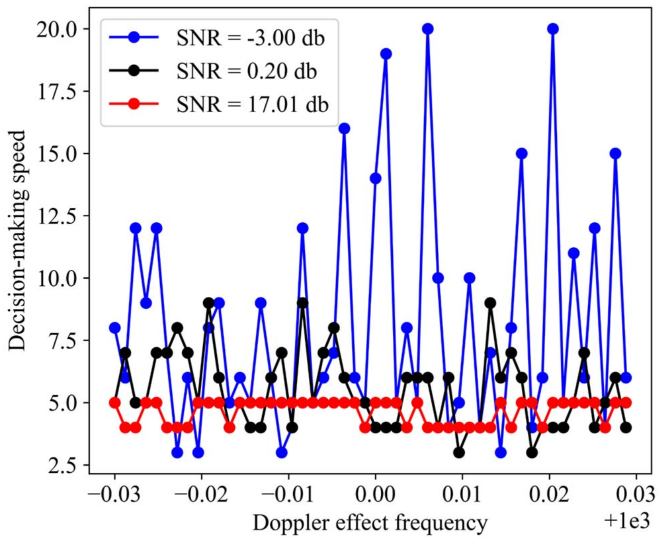

Fig. 8. The dependence of the decision-making speed on the distorted frequencies of the desired signal at different noise levels in a single calculation

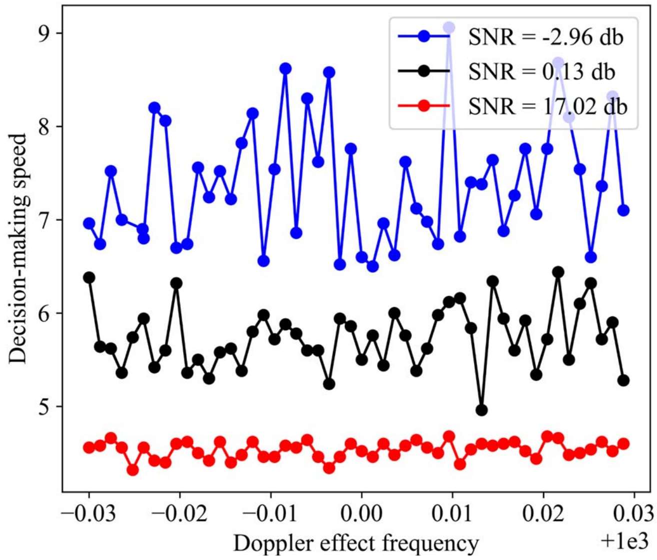

Fig. 9. The dependence of the decision-making speed on the distorted frequencies of the desired signal at different noise levels according to the averaged data

6. Discussion of the results of the stability study of the signal detection method using the Kalman filter

The fact of detecting the desired signal is established using the similarity coefficient determined by the formula (7). From this formula it follows that the value of this coefficient is calculated as the difference between the desired signal and the predicted signal at the filter output. Calculating the similarity coefficient through the difference of these two signals could give an ambiguous result, because in real conditions, the initial phase of the desired signal and the initial conditions of the Kalman filter will not actually coincide. However, the results obtained by us, which are shown in Fig. 2–4, show that, as a result, the values of the similarity coefficient do not depend on the initial phase of the desired signal and the initial conditions of the Kalman filter. This, of course, is due to the adaptability property of the Kalman filter, which sooner or later can detect the regularity of the process generating the desired signal.

At the beginning of the study, it was assumed that the process of adapting the Kalman filter might take too long, as a result of which this method of signal detection would not be very attractive for practical application. Indeed, the greater the difference between the initial phase of the desired signal and the initial conditions of the Kalman filter, the longer the filter adaptation process can take. However, our calculations, the results of which are shown in Fig. 5, have shown that the decision-making speed (the duration of the filter adaptation process) of this method does not actually depend on the difference between the initial phase of the desired signal and the initial filter conditions.

It is assumed that this method of signal detection can be used on board low-orbit satellites when organizing and conducting radio monitoring procedures. In this case, the application of this method in practice would face another problem related to the distortion of the frequency of the desired signal caused by the Doppler effect due to the movement of satellites at high speed. The frequency distortion of the desired signal on the receiving side is calculated by the formula (8), and, according to our calculations, its maximum value is about 0.003 % of the frequency of the signal itself. It follows from this that the distortion of the frequency of the desired signal is of little importance, however, it was necessary to determine whether this distortion could have a noticeable effect on the result of the method. According to the results shown in Fig. 7, 9. Doppler frequency distortions do not actually affect the values of the similarity coefficient and the speed of decision-making by this method.

Thus, it can be concluded that the signal detection method using the Kalman filter can be used on board a LEO satellite. In this case, the accuracy of the method and the speed of decision-making may depend only on the signal-to-noise ratio.

However, the conducted research and the application of its results in practice have some limitations. These limitations are primarily due to the fact that if it is impossible to describe mathematically the process generating the desired signal, then it becomes impossible to use the Kalman filter. Also a weak link is the similarity coefficient, which has proven itself very well for the processes described by equation (1). But in the considered process, it was assumed all the time that the amplitude of the desired signal does not change. Accordingly, for processes where the signal amplitude is not a constant value and can change rapidly, the considered signal detection method is likely to show a poor result. In this regard, in the future it will be necessary to find a characteristic that does not depend not only on the initial phase and frequency distortions of the desired signal, but also on changes in the amplitude of the signal during the detection process.

In addition, the disadvantage of the study is the lack of real physical experiments. All the results obtained in this work are achieved exclusively with the help of computer modeling and numerical solutions of the process equation.

7. Conclusions

1. In the course of the conducted research, it was revealed that the similarity coefficient does not actually depend on the choice of the initial state of the filter.

2. As numerical calculations have shown, the speed and correctness of decision-making by the signal detection method, based on the Kalman filter, depends only on the noise level. I. e., this method turned out to be resistant to the choice of the initial state of the filter and frequency distortions arising from the Doppler effect. Moreover, for any positive SNR value, the decision time on the presence of the desired signal in the registered signal does not exceed 5 periods of the desired signal. This means that this method works very fast.

3. It should also be noted that the main characteristic of the method is the similarity coefficient remains above the value of 0.8 in the presence of the desired signal in the received signal, even with a sufficiently large negative SNR value. And in the absence of the desired signal in the received signal, the similarity coefficient does not rise above 0.35 up to SNR=–6 dB. Accordingly, it can be argued that this method is able to make the right decision about the presence or absence of the desired signal in highly noisy signals. Thus, it is possible to say that this method can be successfully applied to solving problems of radio monitoring of the Surface of the Earth using LEO satellites.

4. The calculations performed in this paper have shown that the decision-making speed of the method does not actually depend on small frequency distortions that can be caused by the Doppler effect during the movement of the measuring satellite. The time required to make a decision about the presence or absence of the desired signal in a noisy signal does not exceed ten periods of the desired signal. The maximum decision time corresponds to a very low signal-to-noise ratio of about –3 dB. Accordingly, it can be concluded that the speed of decision-making remains very high and suitable for the application of this method in practice.

Conflicts of interest

The authors declare that they have no conflicts of interest in relation to the current study, including financial, personal, authorship, or any other, that could affect the study and the results reported in this paper.

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Data availability

All data are available in the main text of the manuscript.

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