Applied problems of information systems operation

UDC 004.9621.396.96 **doi:** https://doi.org/10.20998/2522-9052.2025.2.12

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IMPROVING THE ACCURACY OF EXPONENTIAL SMOOTHING IN SECONDARY INFORMATION PROCESSING IN MODERN INFORMATION LOCATION SYSTEMS

Abstract. The quality of tracking location objects (LO) depends not only on their ability to perform complex maneuvering, but also on the influence of external conditions of the primary processing of location information (LI). These external conditions can be defined as the state of the atmosphere and the influence of the earth (sea) surface. The quality of secondary processing of LO, in particular, the stability of tracking depends on the accuracy of the current measurement of the radial velocity of the observation object (OO), which is largely determined by the influence of the external conditions of the primary processing means of LI (radar) performing its intended tasks. **The subject** of study in the article is the possibility of improving the quality of secondary processing of the LI, namely, the accuracy of tracking the LO by radial velocity. **The aim** is to study the possibilities of increasing the accuracy of exponential smoothing in the secondary processing of the LI by considering the correlated phase fluctuations of the signal at the stage of current measurement of its Doppler frequency. **Objective:** to consider the information on correlated phase fluctuations of radio pulses of the packet signal when tracking the LO by radial velocity**. Methods** used: maximum likelihood and Kalman filtering of trajectory parameters. **The following results** were obtained. The influence of correlated phase fluctuations of the received packet signal radio pulses on the decrease in the accuracy of the discrete tracking measurement of its Doppler frequency is estimated. The possibilities of increasing the accuracy of exponential smoothing in the steady-state filtering mode in the discrete tracking measurement of the radial velocity of an OO by considering the correlated phase fluctuations of the received packet signal radio pulses, which are described by a known correlation function, are determined. Recommendations for constructing a block diagram of a trajectory parameter filtering device for tracking measurement of the radial velocity of an OO with the implementation of an improved exponential smoothing procedure in it are given. **Conclusions.** Proposals are presented to improve the accuracy of exponential smoothing by considering information on the correlated phase fluctuations of the received radio pulses at the stage of current Doppler frequency measurement, which contributes to the efficiency of secondary processing of the LI in difficult conditions of performing the radar's intended tasks. **A promising direction** for further research may be to identify ways to improve the accuracy of joint tracking measurement of the range and radial velocity of the OO.

Keywords: secondary processing, exponential smoothing, location information, location object, radial velocity, radar, tracking measurement, trajectory processing, phase fluctuations, Doppler frequency.

Introduction

The problem definition. In modern information systems, ensuring the continuity of obtaining location information (LI) and increasing its reliability is associated with the combination of data coming from different sources, considering their location and the nature of the movement of the observation object (OO).

The system of LI secondary processing provides obtaining the trajectory of location objects (LO). In other words, this system ensures the solution of the task of trajectory processing of LI and OO support.

The output information stream of the secondary processing system is the estimated values of co-ordinates and parameters, considering the possible prehistory of the OO movement.

The input data for this system are the results of the primary processing system of the LI, namely the coordinates and parameters of the OO movement obtained by a single LI source during a one-time space survey. The results of the secondary processing system are the input data for the tertiary processing of LI, which solves the problem of identifying information obtained from different sources and estimates the parameters of the combined trajectories.

The ability of the LO to maneuver and use low and extremely low flight altitudes requires ensuring the highest possible accuracy of the current measurement of its radial velocity at the stage of primary processing, since this directly affects the quality of the stages of secondary and tertiary processing of the LI.

The quality of OO tracking by radial velocity depends on the accuracy of estimating the Doppler frequency of the received signal at the stage of primary processing of the LI, which is determined by the degree of its coherence. The presence of tropospheric inhomogeneities and reflection of radio waves from the ground or sea surface led to a violation of the coherence of the received signal and the occurrence of fluctuations in its phase. An additional factor in the emergence of Doppler noise of the OO is the possibility of its sudden and complex maneuvering.

Thus, the presence of a fluctuating component of the error in measuring the Doppler frequency of the received signal can lead to a deterioration in the quality of the trajectory processing of the LI, which is especially important when it is necessary to ensure reliable tracking of the OO at long ranges.

The above indicates the relevance of research aimed at considering the correlated phase fluctuations of the signal during the tracking measurement of its Doppler frequency and, thus, improving the efficiency of secondary processing of the LI, particularly the accuracy of tracking the OO by radial velocity.

Analysis of recent research and publications. Consideration and comparative analysis of the main stages of LI processing are described in [1].

In particular, the signal processing issues in the implementation of the primary processing of the LI are considered in [2, 3].

The conditions of radio wave propagation, in particularly, the influence of tropospheric inhomogeneities, the underlying surface, and the nature of the OO movement, were analyzed in [4].

In these works, it was noted that due to the influence of the above factors, the phase front of the signal wave undergoes distortions, whose nature is random. The characteristics of phase fluctuations that can occur during the observation of modern OO due to the influence of the above conditions are given in [5]. At the same time, it was determined that their influence causes a decrease in the accuracy of measuring the coordinates and parameters of the movement of the OO, which is especially relevant when they are observed at small angles [6].

Accuracy of measuring the Doppler frequency and, accordingly, the radial velocity of the OS when using a packet of radio pulses as a sensing signal was carried out in [7]. It was assumed that the law of distribution of phase fluctuations is normal, and the correlation function can be described by the variable dependence [8].

The results obtained in these works can be used to study the issues of ensuring the required quality of secondary processing of LI. The peculiarities of assessing the stability of tracking LO capable of sudden maneuvering are discussed in [9]. However, the issue of considering the influence of signal parameter fluctuations on the quality of secondary processing of LI was not studied in these works. Therefore, the analysis of these sources indicates the relevance of finding ways to improve the quality of OO tracking, by optimizing the current measurement of the Doppler radar signal frequency at the stage of primary processing of the LI.

In [10], the problem of optimal estimation of the Doppler frequency is presented, considering the correlated phase fluctuations of the received radio pulses, and in [11], the corresponding optimal algorithm is proposed and its effectiveness is proved in comparison with the measurement algorithm against the internal noise of the radar receiving device alone.

The obtained results could be used to improve the quality of exponential smoothing when tracking the LO by radial velocity under the influence of correlated phase fluctuations of the received signal.

The aim of the article is to study the possibilities of increasing the accuracy of exponential smoothing in the secondary processing of the LI by considering information about correlated phase fluctuations of the signal at the stage of current measurement of its Doppler frequency.

Summary of the main material

The estimation of the current coordinates of the OS in information localization systems with pulsed radiation is carried out discretely. About all-round radars, the data of primary information processing are issued practically equally discrete with the viewing period T_0. In the case of tracking the LO, for example, by range, data can be issued in each period of pulse passage [12].

The trajectories of the OO do not belong to the class of deterministic ones. When analyzing the trajectories of such objects, their maneuverability, altitude, and flight speed are essential. The choice of certain motion parameters is influenced by several random factors. For example, those related to the need for maneuvering, uneven density and current state of the atmosphere, inaccuracy of the object's control, etc.

The above factors lead to the need to attribute the trajectory of the OO movement to the implementation of a random process. Knowledge of the statistical characteristics of such processes allows us to introduce a stochastic model of the OO movement [13]. However, there are certain a priori difficulties in specifying the characteristics of trajectories. It is only possible to specify the limits of the permissible change in time of individual parameters of the radar observations objects. Such restrictions include the limits of change in radial velocity.

The implementation of secondary processing of LI requires timely receipt of information on the coordinates and parameters of the movement of the object in each survey period. Pulsed circular view radars provide this information with a discreteness of $T_{0.}$

The parameter to be evaluated when implementing a discrete tracking measurement is the Doppler frequency and, consequently, the radial velocity, which has random deviations from cycle to cycle of inspection due to both the performance of a random manoeuvre by the OO and the influence of correlated phase fluctuations. The process of exponential smoothing in the steady-state filtering mode under different degrees of influence of correlated phase fluctuations is subject to study.

To effectively process the obtained data, it is necessary to determine a mathematical model of the OO movement, i.e., to accept the hypothesis about the nature of changes in the parameters of its trajectory. Motion models with a constant structure have a sufficient simplicity of mathematical description and ease of use in the systems of secondary processing of the LI.

For a linearized model of changes in the parameters of the OS trajectory, the optimal estimate of the state vector $\bar{a}_{k+1}$ can be described in general by the following expression [2]:

$$\hat{\bar{a}}_{k+1} = \bar{B}_k \hat{\bar{a}}_k + \bar{C}_{k+1}^{-1} \bar{C}_{Y(k+1)} \left[\hat{\bar{a}}_{Y(k+1)} - \bar{B}_k \hat{\bar{a}}_k \right], \quad (1)$$

where $\bar{B}_k$ – is a square non-random matrix of dynamic recalculation of the state vector from the k-th to the (k+1) step; $\hat{\bar{a}}_k$ – s the state vector estimate based on measurement data during k survey cycles; $\bar{C}_{k+1}^{-1}$ – the correlation matrix of errors of the (k+1) state vector estimate based on measurement data for all (k+1) survey cycles; $\bar{C}_{Y(k+1)}$ – the accuracy matrix of the state vector estimation based only on the data of the current radar measurement; $\hat{\bar{a}}_{Y(k+1)}$ – the current state vector estimation based on the radar measurement data on the (k+1) view cycle.

That is, on the (k+1) cycle of the radar survey, the state vector $\hat{\bar{a}}_{k+1}$ is subject to evaluation, considering the entire set of received signals.

The state vector is assumed to be represented by a single parameter - the Doppler frequency F_d of the radar signal. Fluctuations in the parameters of the radar signal cause the difference between the estimate of the state vector $\hat{\bar{a}}_{k+1}$ and its actual value. Therefore, the Doppler frequency acquires random deviations (fluctuations) with each survey cycle, which may be caused by the sudden maneuver of the vehicle and the influence of the conditions of propagation and reflection of the radar signal.

To build tracking meters, it is necessary to define a model of the OO movement, which should consider both deterministic and random movement [14].

Given the above assumptions, the model of the change in the state vector is the following scalar value:

$$\alpha_{k+1} = \alpha_k + \delta_k + \mu_k , \tag{2}$$

where α_k – the previous value of the state vector (Doppler frequency); δ_k – a random increase in the Doppler frequency on the k-th inspection cycle due to the influence of correlated phase fluctuations; μ_k – a random increase in the Doppler frequency on the k-th inspection cycle due to the OO maneuver.

In the trajectory parameter filtering equation (1), the accuracy matrix $\bar{C}_{k+1}^{-1}$ is generally defined by the following expression [15]:

$$\bar{C}_{k+1} = \bar{C}_{0(k+1)} + \bar{C}_{Y(k+1)} , \tag{3}$$

where $\bar{C}_{0(\mathrm{K}+1)}$ – the matrix of forecast accuracy (extrapolation) for the (k+1) view cycle.

In this case, the matrix $\bar{C}_{0(k+1)}$ can be determined by the following relationship:

$$\bar{C}_{0(k+1)} = \left[\bar{B}_k \bar{C}_k^{-1} \bar{B}_k^T + \bar{C}_{\mu_k}^{-1} \right]^{-1} . \tag{4}$$

where $\bar{C}_{\mu_k}^{-1}$ – is the correlation matrix of errors of the discrete Doppler frequency measurement arising from the OO maneuver.

Given that only the Doppler frequency is subject to monitoring, the above matrices are scalar values:

$$\bar{B}_k = 1,\ \bar{C}_{\mu_k}^{-1} = D_{\mu_k} ,\ \bar{C}_{Y(k+1)} = 1/D_{Y(k+1)} , \tag{5}$$

where D_{μ_k} – is the dispersion of the Doppler frequency measurement error component caused by the OO maneuver; $D_{Y(k+1)}$ – is the dispersion of the current Doppler frequency measurement on the (k+1) view cycle.

Thus, for the case of tracking measurement of only a single parameter (in this case, the Doppler frequency), expressions (1) and (3) can be represented as follows:

$$\hat{\alpha}_{k+1} = \hat{\alpha}_k + \frac{D_{k+1}}{D_{Y(k+1)}} \left(\hat{\alpha}_{Y(k+1)} - \hat{\alpha}_k \right) ; \tag{6}$$

$$\frac{1}{D_{k+1}} = \frac{1}{D_k + D_{\mu_k}} + \frac{1}{D_{Y(k+1)}} . \tag{7}$$

where D_{k+1} and D_k – are the error dispersions of the resulting discrete Doppler frequency measurement at the (k+1) and k-th steps, respectively.

According to expression (6), it can be argued that the k+1 estimate of Doppler frequency is the sum of the previous estimate and the corresponding difference in estimates, balanced with the dispersions D_{k+1} and $D_{Y(k+1)}$.

In the steady-state mode, the value of the dispersion D_{k+1} practically does not change from cycle to cycle. At the same time, $D_{Y(k+1)} = D_Y$ and $D_{\mu_k} = D_\mu$ - are constant values in each of the inspection cycles at the same manoeuvre intensity.

Provided that $D_{\mu_k} = \upsilon D_Y$, for the value of $D_{k+1} = D$, we can state the following:

$$\frac{1}{D} = \frac{1}{D + \upsilon D_Y} + \frac{1}{D_Y} . \tag{8}$$

One solution to the quadratic equation:

$$D^2 + \upsilon D_Y D - \upsilon D_Y^2 = 0 ,$$

which relates to D with D_Y, is following:

$$D = \frac{\sqrt{\upsilon^2 + 4\upsilon} - \upsilon}{2} D_Y . \tag{9}$$

The dispersion of the current Doppler frequency measurement D_Y is determined by the following components [11]:

$$D_Y = \sigma_\Omega^2 + \sigma_{\Omega fl}^2 , \tag{10}$$

where σ_Ω^2 – is the error dispersion of the current Doppler frequency measurement, which is caused by the influence of only the internal noise of the radar receiving device; $\Omega = 2\pi F_d$ – is the index denoting the cyclic Doppler frequency; $\sigma_{\Omega fl}^2$ – is the error dispersion of the current Doppler frequency measurement, which is caused by the predominant influence of correlated phase fluctuations of the radar signal $\left(\sigma_{\Omega fl}^2 >> \sigma_\Omega^2 \right)$.

The components of expression (10) σ_{Ω}^2 and $\sigma_{\Omega fl}^2$ can be considered constant values since they do not undergo significant changes during the radar survey cycle.

A radar with coherent pulse radiation is considered as a system of primary processing of the LI, the sensing signal of which is a packet of *n* radio pulses, the phases of which have fluctuating components φ_{i} ($i = 1, 2...n$) due to the influence of real conditions of propagation and reflection of radio waves.

The component σ_{Ω}^2 or a packet of radio pulses with a rectangular envelope can be determined by the following expression [11]:

$$\sigma_{\Omega}^2 = \frac{12}{q^2 T^2 (n^2 - 1)}, \tag{11}$$

where q^2 is the signal-to-noise ratio in terms of power provided by the radio pulse of the packet; T is the period of the packet radio pulse tracking.

It is assumed that the phase fluctuations of the received radio pulse packets are distributed according to a normal law, and their correlation coefficient can be described by an oscillating dependence, which is confirmed by the results of experimental research [16]:

$$R_{\varphi} = e^{-T/\tau} \cos(\gamma T), \tag{12}$$

where τ – is the phase fluctuation correlation interval; $\gamma = 2\pi / T_{fl}$ – is the oscillation frequency of the phase fluctuation correlation coefficient; T_{fl} – is the oscillation period of the phase fluctuation correlation coefficient.

At the same time, the oscillation frequency of the correlation coefficient (12) shall be chosen according to the following condition:

$$T_{fl} / \tau = 3,$$

that is consistent with the results of experimental studies [16]. For the correlation coefficient of phase fluctuations (12), the component $\sigma_{\Omega fl}^2$ can be determined by the following expression [11]:

$$\begin{aligned} \sigma_{\Omega fl}^2 = {} & \frac{72\sigma_{\varphi}^2}{n^2 (n^2-1)^2 T^2} \cdot \Bigg[\sum_{j=1}^{n/2} (2j-1)^2 \times \\ & \times \Big(1 - \exp\big(-T(2j-1)/\tau\big) \cos\big((2j-1)\gamma T\big) + \\ & + 2 \cdot \sum_{l=1}^{(n/2)-j} \exp\big(-Tl/\tau\big) \cdot \sum_{j=1}^{(n/2)-1} (2j-1)(2j+2l-1) \times \\ & \times \Big(\cos(j\gamma T) - \exp\left(-\frac{T}{\tau}(2j-1)\right) \cos\big((2j+l-1)\gamma T\big)\Big)\Bigg], \end{aligned} \tag{13}$$

where σ_{φ}^2 – is the dispersion of phase fluctuations.

Assuming that the weighting factor is included:

$$D / D_Y = \xi, \tag{14}$$

then, considering (14), expression (6) can be written as follows:

$$\begin{aligned} \hat{\alpha}_{k+1} = \xi \Big[& (1-\xi)^{k+1} \hat{\alpha}_{Y_0} + (1-\xi)^k \hat{\alpha}_{Y_1} + \ldots + \\ & + (1-\xi) \hat{\alpha}_{Y_k} + \hat{\alpha}_{Y_{(k+1)}} \Big]. \end{aligned} \tag{15}$$

The more compact form of equation (15) is as follows:

$$\hat{\alpha}_{k+1} = \sum_{m=0}^{k+1} W_{k+1-m} \, \hat{\alpha}_{Y_m}, \quad W_m = \xi (1-\xi)^m \tag{16}$$

and is a convolution operation performed by a discrete linear filter with impulse response W_m.

For values of $\xi << 1$, the normalized impulse response can be determined by the following relation:

$$W_{Hm} = \frac{W_m}{W_{max}} = (1-\xi)^m \approx \exp(-m\xi). \tag{17}$$

According to (17), the parameter ξ is the exponential smoothing coefficient.

The exponential smoothing procedure is realized in the steady-state mode of filtering the trajectory parameters. However, the contribution of the previous results of the current measurement to the smoothed trajectory estimate is reduced according to the exponential function.

The exponential smoothing coefficient should be considered for the following cases, based on the influence of correlated phase fluctuations.

The first case corresponds to the condition of insignificant influence of correlated phase fluctuations compared to the impact of internal noise ($\sigma_{\Omega fl}^2 << \sigma_{\Omega}^2$) as follows:

$$D / \sigma_{\Omega}^2 = \xi_{sh}. \tag{18}$$

The second case corresponds to the condition of the predominant influence of correlated phase fluctuations compared to the impact of internal noise ($\sigma_{\Omega fl}^2 >> \sigma_{\Omega}^2$) as follows:

$$D / \sigma_{\Omega fl}^2 = \xi_{fl}. \tag{19}$$

According to (18) and (19), the relationship between ξ_{sh} and ξ_{fl} can be described as follows:

$$\xi_{fl} = \xi_{sh} \cdot \sigma_{\Omega}^2 / \sigma_{\Omega fl}^2. \tag{20}$$

Likewise, the relationship between the corresponding normalized impulse responses $W_{Hm_{sh}}$ and $W_{Hm_{fl}}$ can be determined:

$$W_{Hm_{fl}} = \left(W_{Hm_{sh}}\right)^{\sigma_{\Omega}^2 / \sigma_{\Omega fl}^2} = \left[\mathrm{e}^{-m\xi_{sh}}\right]^{\sigma_{\Omega}^2 / \sigma_{\Omega fl}^2}. \tag{21}$$

Fig. 1 shows the values of $W_{Hm_{sh}}$ for different values of $\xi_{sh} = 0{,}1 \; 0{,}3 \; \textit{and} \; 0{,}5$.

According to the obtained graphs, we can state that at smaller values of ξ_{sh}, which correspond to larger values of the error dispersion of the current Doppler frequency measurement, the function $W_{Hm_{sh}}$ decreases more slowly. This indicates that the previous estimates are considered with more weight.

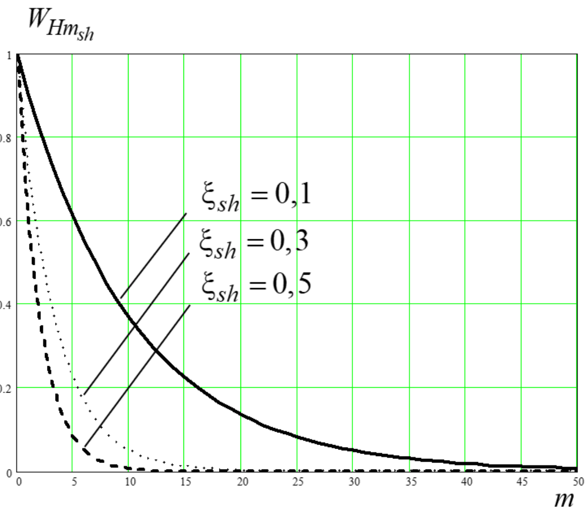

Fig. 1. Dependence of $W_{Hm_{sh}}$ for different ξ_{sh}

Thus, the closer ξ is to zero, the slower the results of current measurements age because they require a longer consideration in the algorithms of secondary processing of the LI until a stable mode of OO tracking is achieved.

The analysis of the above data indicates that the error dispersion is established. That is, the stabilization of the ξ value at a level different from zero.

A discrepancy between the value of the exponential smoothing coefficient and the required one will lead to a decrease in the quality of OO tracking. Therefore, to ensure close to optimal quality indicators, it is advisable to evaluate this coefficient at each cycle of measuring the radial velocity of the OO and timely adjust the tracking algorithm.

As it was proved in [16], for modern radars under regular measurement conditions, the accuracy of estimating the Doppler frequency of a radio pulse packet is much more influenced by the statistical characteristics of the phase fluctuations of its radio pulses than the signal-to-noise ratio. The values of the dispersion and the correlation interval of the phase fluctuations of radar signals can be within the following limits:

$$\sigma_\varphi^2 = (0,01...10)\,rad^2, \quad \tau = (0,1...1)\,s.$$

According to [17], with the predominant influence of correlated phase fluctuations over internal noise, i.e., when $\sigma_\varphi^2 = (1...10)\,rad^2$ and the ratio $T/\tau = 10^{-2}$ or more, the fluctuation component of the Doppler frequency measurement error can exceed the corresponding noise component by tens to hundreds of times.

Many modern coherent-pulse radars implement coherent processing of sequences of (8...16) radio pulses. Therefore, below is an analysis of the decrease in the quality of exponential smoothing when implementing coherent processing of packets of 8 and 16 radio pulses due to the presence of the predominant influence of correlated phase fluctuations with a phase correlation coefficient of (12).

Therefore, it is initially advisable to analyze the same effect of correlated phase fluctuations on the quality of exponential smoothing at different values of the coefficient ξ_{sh}.

Fig. 2 shows graphs corresponding to the following cases:

1) $W_{Hm_{fl}}$ for n=8, q^2=1000, σ_φ^2=1 rad^2, $T/\tau = 10^{-3}$ with $\xi_{sh} = 0,1$ and $\xi_{sh} = 0,5$;

2) $W_{Hm_{sh}}$ for $\xi_{sh} = 0,1$ and $\xi_{sh} = 0,5$.

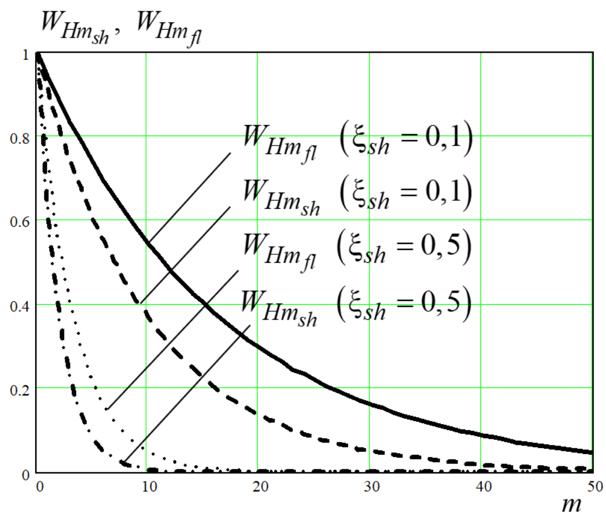

Fig. 2. Dependencies $W_{Hm_{sh}}$ and $W_{Hm_{fl}}$ for different ξ_{sh}

According to the graphs in Fig. 2, the influence of correlated phase fluctuations reduces the accuracy of the current Doppler frequency measurement, which requires an increase in the number of tracking measurement steps to achieve a stable mode of the OO.

Thus, at $\xi_{sh} = 0,1$, the value that $W_{Hm_{sh}}$ takes at, for example, m=30, the value of $W_{Hm_{fl}}$ approaches only at m=50.

That is, the influence of the fluctuating component of the Doppler frequency measurement error requires 20 additional steps of tracking measurement.

If the primary processing of the LI results in a higher accuracy of the Doppler frequency measurement ($\xi_{sh} = 0,5$), then under the similar influence of correlated phase fluctuations, the number of corresponding steps to approximate the values of $W_{Hm_{sh}}$ and $W_{Hm_{fl}}$ decreases.

Further, it is advisable to perform a comparative analysis of the different degrees of influence of correlated phase fluctuations on the quality of exponential smoothing at a given value of ξ_{sh}.

Fig. 3 shows the graphs constructed for n=8, q^2=1000, $\xi_{sh} = 0,1$ which correspond to the following cases:

1) $W_{Hm_{fl}}$ for $\sigma_{\phi}^2 = 1$ rad² with $T/\tau = 10^{-3}$ (graph 1) and $T/\tau = 10^{-2}$ (graph 2);

2) $W_{Hm_{fl}}$ for $\sigma_{\phi}^2 = 10$ rad² with $T/\tau = 10^{-3}$ (graph 3);

3) $W_{Hm_{sh}}$ (graph 4).

The relevant graphs shown in Fig. 4, are plotted for n = 16.

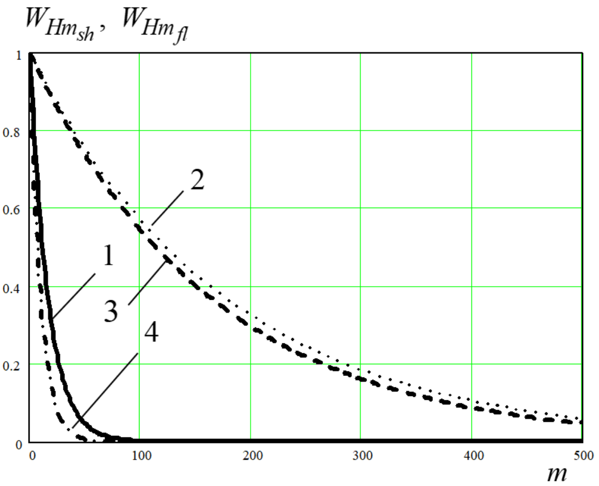

Fig. 3. Dependencies $W_{Hm_{sh}}$ and $W_{Hm_{fl}}$ for n = 8

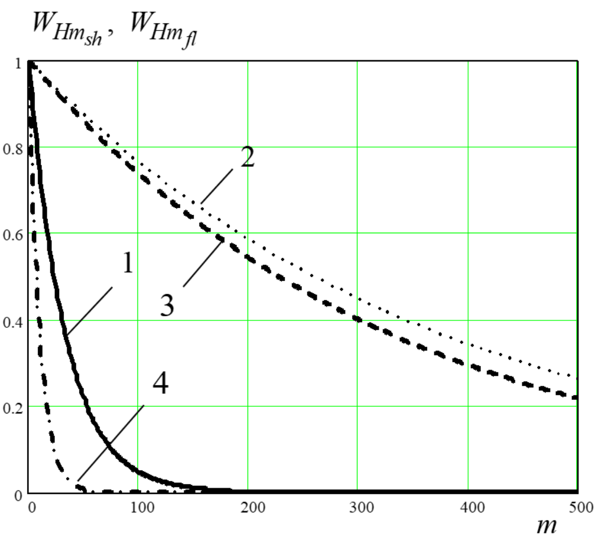

Fig. 4. Dependencies $W_{Hm_{sh}}$ and $W_{Hm_{fl}}$ for n = 16

Comparison of Fig. 1 and 4 indicates that the usual influence of phase fluctuations requires only tens of additional steps of tracking measurement to achieve a steady state mode of OS tracking at the Doppler frequency.

Comparison of Fig. 1 with Fig. 2 and 3 indicates that an increase in the ratio T/τ from 10^{-3} to 10^{-2} is close to the effect of increasing the dispersion of phase fluctuations σ_{φ}^2 from 1 rad² to 10 rad². This means that a significant influence of phase fluctuations leads to an increase in additional steps of the Doppler frequency tracking measurement to a thousand or more, which indicates the possibility of a danger of disruption of the tracking of the OC by radial velocity.

Thus, it is of practical use to evaluate the possibilities of improving the accuracy of exponential smoothing by considering the correlated phase fluctuations of the received radio pulses at the stage of primary processing of the current Doppler frequency measurement [18].

The following study investigates the possibility of using the optimal current estimate of the Doppler frequency, obtained considering the statistical characteristics of the correlated fluctuations of the initial phases of the received radio pulses, in the algorithm for filtering the parameters of the OO trajectory [19].

The corresponding algorithm for the optimal accurate measurement of the Doppler frequency is given in [20].

The error variance of the optimal measurement of the Doppler frequency of the packet, considering the predominant influence of the phase fluctuations of its radio pulses with an oscillating correlation coefficient, is as follows [21]:

$$\sigma_{\Omega opt}^2 = \frac{2\sigma_{\varphi}^2\left[1+e^{-\left(\frac{T}{\tau}\right)}\cos(\gamma T)\right]}{T^2\left[1-e^{-\left(\frac{T}{\tau}\right)}\cos(\gamma T)\right](n-1)} \times$$
$$\times\left[1-e^{-\left(\frac{T}{\tau}\right)}\cos(\gamma T)\right]^2 \times$$
$$\times\left\{\left[4(n-1)^2-1\right]\left[1-e^{-\left(\frac{T}{\tau}\right)}\cos(\gamma T)\right]^2 + \right.$$
$$\left. + \left[n-1-(n-3)e^{-\left(\frac{T}{\tau}\right)}\cos(\gamma T)\right]\right\}^{-1}. \qquad (22)$$

Given (22), we consider the third case, which meets the condition of accounting for the predominant influence of correlated phase fluctuations compared to the influence of internal noise:

$$\frac{D}{\sigma_{\Omega opt}^2} = \xi_{opt}. \qquad (23)$$

The normalized impulse response $W_{Hm_{opt}}$, which, by analogy with (17), is determined by the following expression:

$$W_{Hm_{opt}} = \left(W_{Hm_{ш}}\right)^{\sigma_{\Omega}^2/\sigma_{\Omega opt}^2}. \qquad (24)$$

Fig. 5 shows the graphs obtained for the above conditions (n=8, q^2=1000, $\xi_{sh}=0{,}1$), which correspond to the following cases:

1) σ_{φ}^2=1 rad² and $T/\tau=10^{-3}$ for $W_{Hm_{fl}}$ (graph 1) and $W_{Hm_{opt}}$ (graph 2);

2) σ_{φ}^2=1 rad² and $T/\tau=10^{-2}$ для $W_{Hm_{fl}}$ (graph 3) and $W_{Hm_{opt}}$ (graph 4);

3) σ_{φ}^2=10 rad² and $T/\tau=10^{-2}$ для $W_{Hm_{fl}}$ (graph 5) and $W_{Hm_{opt}}$ (graph 6).

Fig. 6 shows the corresponding graphs for n=16.

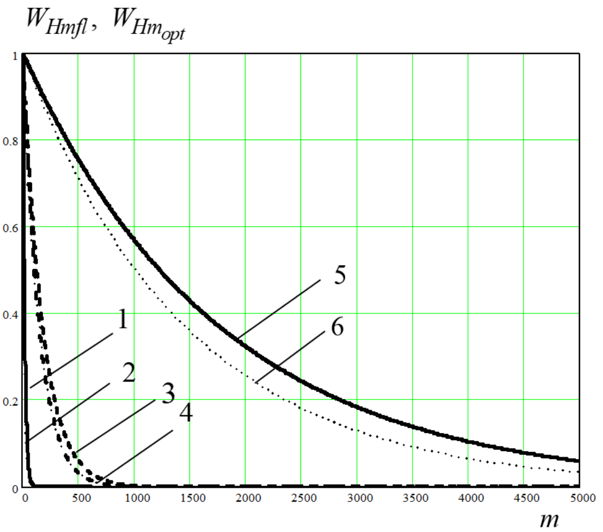

Fig. 5. Dependencies $W_{Hm_{fl}}$ and $W_{Hm_{opt}}$ for n = 8

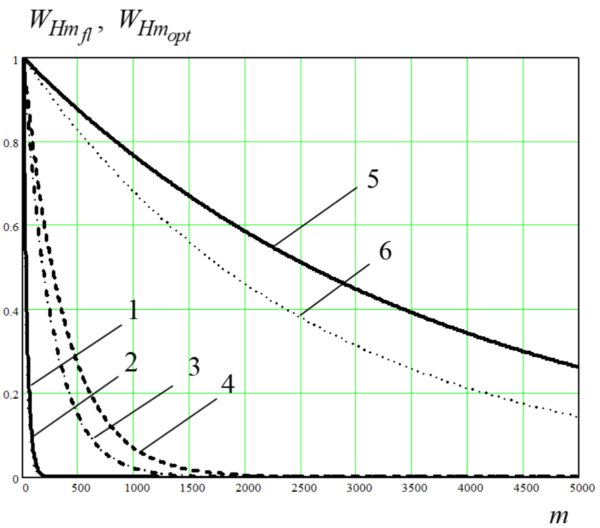

Fig. 6. Dependencies $W_{Hm_{fl}}$ and $W_{Hm_{opt}}$ for n = 16

From graphs 1 and 2, it can be concluded that considering the insignificant influence of correlated phase fluctuations in the current measurement allows reducing the process of tracking Doppler frequency (radial velocity) measurement by only a few to a dozen steps. Therefore, curves 1 and 2 practically coincide.

According to the obtained graphs 3 and 4, it can be concluded that with an increase in the influence of correlated phase fluctuations (increasing T/τ from 10^{-3} to 10^{-2}), their consideration provides a reduction in the process of tracking Doppler frequency measurement by tens to hundreds of steps.

Comparison of Fig. 5 and 6 indicates that with significant phase fluctuations (σ_{φ}^2=10 rad² and $\frac{T}{\tau}=10^{-2}$) he number of steps of the tracking measurement before reaching a steady-state Doppler frequency tracking mode can reach many thousands, but their reduction when optimizing the Doppler frequency measurement can be hundreds to thousands of steps.

Thus, for example, the reduction in the number of these steps when $W_{Hm_{fl}}$ and $W_{Hm_{opt}}$ reach the level of 0.1 is:

– from graphs 1 and 2 - 3 steps (by 8%) for n=8 and 12 steps (16%) for n=16;

– from graphs 3 and 4 - 70 steps (17%) for n=8 and 265 steps (31%) for n=16;

– from graphs 5 and 6 - 700 steps (17%) for n=8 and 2310 steps (31%) for n=16.

With further complication of the radar operation conditions ($\mathrm{T}/\tau=(10^{-2}...10^{-1})$), i.e., a significant influence of the disturbed state of the atmosphere, earth (sea) surface and maneuvering of the OO, the useful effect of the proposed optimization in the secondary processing of the LI will only increase.

Thus, the optimization of the current Doppler frequency measurement can provide an additional increase in the stability of the tracking of the LO in difficult conditions of performing the intended tasks by the means of primary processing of the LI.

The corresponding device for optimal filtering of the tracking measurement parameters should be supplemented with an additional optimal Doppler frequency meter.

In case of insignificant influence of correlated phase fluctuations, parameters corresponding to the usual mode of trajectory processing of the LI should be used. In case of significant influence of correlated phase fluctuations, it is recommended to switch to tracking the LI using estimates of the Doppler frequency and their error dispersions, which are determined in the optimal Doppler frequency meter, considering the statistical characteristics of correlated phase fluctuations.

Conclusions

Thus, the impact of correlated phase fluctuations requires an increase in the number of tracking measurement steps to achieve a stable radial velocity tracking regime. In particular, the significant influence of correlated phase fluctuations leads to the necessity of performing up to several thousand of these additional steps.

Consideration of the influence of correlated phase fluctuations in the primary processing of the LI and the measurement of the Doppler frequency allows to reduce the process of tracking radial velocity measurement by 17 % for a packet of 8 radio pulses and by 31 % for a packet of 16 radio pulses.

The complication of the conditions of functioning of the means of primary processing of LI will lead to an increase in the beneficial effect of the proposed optimization during the secondary processing of LI.

The study indicates the feasibility of using an additional optimal Doppler frequency meter in devices for filtering the OO trajectory parameters, which implements obtaining current estimates of the Doppler frequency and their error variances, determined by the optimal measurement algorithm, considering the statistical characteristics of correlated phase fluctuations.

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Received (Надійшла) 13.01.2025
Accepted for publication (Прийнята до друку) 09.04.2025

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Підвищення точності експонентного згладжування при вторинній обробці інформації у сучасних інформаційних локаційних системах

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Анотація. Якість супроводження локаційних об'єктів (ЛО) залежить не тільки від можливостей здійснення ними складного маневрування, а також і від впливу зовнішніх умов функціонування засобів первинної обробки локаційної інформації (ЛІ). Такими зовнішніми умовами можливо вважати стан атмосфери та вплив земної (морської) поверхні. Якість вторинної обробки ЛО, зокрема, стійкість супроводження залежить від точності поточного вимірювання радіальної швидкості об'єкта спостереження (ОС), яка у значному ступені визначається впливом саме зовнішніх умов виконання засобом первинної обробки ЛІ (радіолокатором) завдань за призначенням. **Предметом** вивчення у статті є можливості підвищення якості вторинної обробки ЛІ, а саме – точності супроводження ЛО за радіальною швидкістю. **Метою** є дослідження можливостей підвищення точності експонентного згладжування при вторинній обробці ЛІ за рахунок врахування корельованих фазових флуктуацій сигналу на етапі поточного вимірювання його частоти Допплера. **Завдання:** врахування інформації про корельовані фазови флуктуації радіоімпульсів пачкового сигналу при супроводженні ЛО за радіальною швидкістю. Використані **методи:** найбільшої правдоподібності та Калманівської фільтрації параметрів траєкторії. Отримано наступні **результати**. Здійснено оцінку впливу корельованих фазових флуктуацій радіоімпульсів прийнятого пачкового сигналу на зниження точності дискретного слідкуючого вимірювання його частоти Допплера. Визначено можливості підвищення точності експонентного сгладжування у сталому режимі фільтрації при дискретному слідкуючому вимірюванні радіальної швидкості ОС за рахунок врахування корельованих фазових флуктуацій радіоімпульсів прийнятого пачкового сигналу, які описуються знакозмінною кореляційною функцією. Наведено рекомендації щодо побудови структурної схеми пристрою фільтрації параметрів траєкторії при слідкуючому вимірюванні радіальної швидкості ОС з реалізацією у неї покрашеної процедури експонентного сгладжування. **Висновки.** Наведено пропозиції щодо підвищення точності експонентного згладжування за рахунок врахування інформації про корельовані фазови флуктуації радіоімпульсів прийнятої пачки на етапі поточного вимірювання частоти Допплера, що сприяє підвищенню ефективності вторинної обробки ЛІ у складних умовах виконання радіолокатором завдань за призначенням. **Перспективним напрямком** щодо подальших досліджень може бути визначення шляхів підвищення точності сумісного слідкуючого вимірювання дальності та радіальної швидкості ОС.

Ключові слова: вторинна обробка; експонентне згладжування; локаційна інформація; локаційний об'єкт; радіальна швидкість; радіолокатор; слідкуюче вимірювання; траєкторна обробка; фазові флуктуації; частота Допплера.