Обробка інформації в складних технічних системах

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I. Baryshev, M. Uss, Radhwan Mohammed Jawad Kadhim

National Aerospace University named after M.E. Zhukovsky “Kharkiv Aviation Institute”, Kharkiv

ROBUST ESTIMATION OF DOPPLER FREQUENCY AND ITS HIGHER-ORDER DERIVATIVES FOR A SIGNAL REFLECTED FROM VIOLENTLY MANEUVERING OBJECT

A robust estimation algorithm for the Doppler frequency and its derivatives is proposed based on the MLSAC algorithm. It is shown that it retains its working capacity when the probability of anomalous measurements reaches 0.9 (measurements of the Doppler frequency are abnormal in nine out of ten signal fragments) in comparison with 0.7 for the existing algorithm previously proposed by the authors. This may allow to measure the motion parameters of an object with less visibility at the same distance or an object with the same visibility at a greater distance.

Keywords: *Doppler frequency estimation, MLSAC algorithm, maneuvering object.*

Introduction

In modern pulse doppler radar (PDR) the measurement of the Doppler frequency shift of the reflected signal is performed in a block of Doppler filters, each of which is matched with a signal of a certain frequency. This type of radar encounters problems when accompanying maneuvering and subtle objects.

For effective tracking of objects of this kind, it is proposed to use complex signals with a long or extra-long (up to tenths of a second) coherent accumulation. However, the long-term coherent accumulation of a signal reflected from a maneuvering object is a complex, unsolved task to date. Its complexity is due to the fact that with an increase in the duration of observation, adequate acceleration of the maneuvering object is required to take into account its acceleration, as well as the derivative of acceleration, that is, the third derivative of the radial range. With violent maneuvering, the number of significant derivatives of the radial range may include fourth and higher derivatives.

The change in the Doppler shift in time causes frequency modulation of the reflected signals, the expansion of their spectrum and at the same time a decrease in the spectral density. In this case, the Doppler filters cease to be consistent, leading to the following negative consequences: the decrease in the quality of object detection due to the decrease in the signal component of the output effect of the Doppler filters; blurring the signal reflected from one object into several filters with the possibility of taking it as a group one; reducing the accuracy of measurement of the parameters of the reflected signal.

In this article the approach proposed by the authors in a work where signal splitting into small fragments is used, in which the influence of the Doppler frequency derivatives can be neglected is developed. In each of the fragments, due to the small signal-to-noise ratio, the probability of anomalous measurements is high. Under these conditions, the estimation of the Doppler frequency and its derivatives is implemented by joint processing of private measurements of the Doppler frequency in each fragment, in a manner that is resistant to anomalous measurements. The boundary probability of anomalous measurements is reached in 30–70 %, above which the reliability of measuring the Doppler frequency and its derivatives cannot be guaranteed. In this paper, the MLSAC (Maximum Likelihood Sample Consensus) algorithm was applied, which allowed us to raise the threshold probability of anomalous measurements to 90%.

Exposition of basic material

Robust measurement of the Doppler frequency and its derivatives in the presence of anomalous measurements

Suppose that in the observation interval the tracking object is a point target, the amplitude and phase of the complex reflection coefficient do not change. In the field of view of the radar is only one object. It is irradiated by the PDR signal of the form.

$$s_{\text{зонд}}(t) = A_{\text{зонд}} \cdot U(t) \cdot \cos(\varphi_{\text{зонд}} + 2\pi \cdot f_{\text{зонд}} \cdot t),$$

where $A_{\text{зонд}}$ – probing amplitude, $U(t)$ – probing envelope, $\varphi_{\text{зонд}}$ and $f_{\text{зонд}}$ – initial phase and frequency of the probing signal. For coherent burst:

$$U(t) = U_{\text{пачки}}(t) =$$
$$= \begin{cases} 1, \ t \in [l \cdot T_{\text{имп}}, l \cdot T_{\text{имп}} + t_{\text{имп}}), \ l = 0 \ldots n_{\text{пачки}} - 1, \\ 0, \ t \in [l \cdot T_{\text{имп}} + t_{\text{имп}}, (l+1) \cdot T_{\text{имп}}), \ l = 0 \ldots n_{\text{пачки}} - 1, \end{cases}$$

where $t_{\text{имп}}$ – single pulse length; $T_{\text{имп}}$ – pulse repetition period; $n_{\text{пачки}}$ – the number of pulses in a pack $T = n_{\text{пачки}} \cdot T_{\text{имп}}$ – the duration of the pack.

The reflected signal is observed against the background of a normally distributed uncorrelated interference with zero expectation and variance σ_η^2 on a discrete time interval $\Delta\mathbf{t} = \left\{\Delta t_l = \Delta t \cdot l \mid l = 0..N_{\text{д}}\right\}$, where Δt – discretization step; $N_{\text{д}} = T / \Delta t + 1$ – the number of samples of the sampled reflected signal.

To resolve the contradiction between the duration of observation of the signal and the presence of anomalous measurements, it is proposed to measure the Doppler frequency shift in blocks of short duration and form an estimate of the Doppler frequency shift and its derivatives by robust processing of private measurements. In this case, the presence of anomalous measurements in each of the blocks. In our work, for evaluating the Doppler shift in each block, we take the most plausible frequency estimate. At the same time, a reliable estimation of the Doppler frequency shift and its derivatives was provided with the probability of anomalous measurements $P_{\text{аном}}$ <0,3–0,7. In this paper, it is proposed to use a more sophisticated algorithm for detecting anomalous measurements, the application of which achieves a reliable estimation of the Doppler frequency shift and its derivatives at higher values $P_{\text{аном}}$ up to 0.9. Consider the details of the algorithm.

The dependence of the Doppler frequency shift on time is described by a polynomial n of the order $f(t) = g(t, \boldsymbol{\theta}) = \sum_{i=0}^{n} \frac{1}{i!} f_i \cdot t^i$, where f_0 – Doppler frequency shift at the initial time, and $f_1, f_2, \ldots$ – its derivatives of the first, second and higher orders. Required to measure the parameter vector $\boldsymbol{\theta} = (f_0, f_1, \ldots, f_n)$.

Let the time of observing the signal T is divided into $N_{\text{бл}}$ fragments of duration $T_{\text{бл}} = T / N_{\text{бл}}$. In each i block the most plausible Doppler frequency measurement algorithm measures the Doppler frequency f_{0i}, corresponding to the maximum maximum likelihood function. Let us denote the variance of the Doppler frequency measurement error σ_f^2. Probability of anomalous measurements $P_{\text{аном}}$ in each block and potential value σ_f^2 can be estimated according to the algorithm given in. Additionally set the range of the maximum possible change in the Doppler frequency $[f_{0.\min}, f_{0.\max}]$.

To measure the vector of parameters $\boldsymbol{\theta}$ we use the maximum likelihood method. Measurement likelihood function $\left(f_{01}, f_{02}, \ldots, f_{0N_{\text{бл}}}\right)$ has the following form:

$$p\left(f_{01}, f_{02}, \ldots, f_{0N_{\text{бл}}} / t_1, t_2, \ldots t_{N_{\text{бл}}}, \boldsymbol{\theta}\right) = \prod_{i=1}^{N_{\text{бл}}} p(f_{0i} / t_k, \boldsymbol{\theta}),$$

$$p(f_{0i} / t_k, \boldsymbol{\theta}) = \sum_{\mathbf{z}_k} p(f_{0i}, \mathbf{z}_k / t_k, \boldsymbol{\theta}) =$$

$$= P_{\text{норм}} N\left(f_{0i} - \mathbf{g}(t_k, \boldsymbol{\theta}), \sigma_f^2\right) + P_{\text{аном}} / L_{\text{поиск}}(k),$$

where $L_{\text{поиск}}(k) = f_{0.\max}(k) - f_{0.\min}(k)$; $\mathbf{z}$ – vector of hidden variables, each element of which indicates a normal or anomalous measurement in this fragment; $P_{\text{норм}} = 1 - P_{\text{аном}}$.

Optimization can be performed using the EM algorithm (Expectation-Maximization algorithm), which transforms the problem into an iterative maximization of the expectation of the logarithmic likelihood function:

$$Q(\boldsymbol{\theta}, \hat{\boldsymbol{\theta}}) = \sum_{i=1}^{N_{\text{бл}}} \left[-\frac{P_i^{\text{норм}}(\hat{\boldsymbol{\theta}})}{2\sigma_f^2} (f_{0i} - \mathbf{g}(t_k, \boldsymbol{\theta}))^2 - \right.$$
$$- \ln\left(\sigma_f^2\right) P_{ip}^{\text{норм}}(\hat{\boldsymbol{\theta}}) + \ln(P_{\text{норм}}) P_i^{\text{норм}}(\hat{\boldsymbol{\theta}}) +$$
$$\left. + \ln(P_{\text{аном}}) \left(1 - P_i^{\text{норм}}(\hat{\boldsymbol{\theta}})\right) + \ln(1 / L_{\text{поиск}}(k)) \right].$$

The EM algorithm consists of iteratively repeating two steps: (E) calculating the expected likelihood function value, while the hidden variables are treated as observable and (M) the maximum likelihood estimate is calculated. In step E of the algorithm, posterior estimates of the probabilities of measurement normality are calculated f_{0i} according to the formula:

$$\hat{P}_i^{\text{норм}} = \frac{P_{\text{норм}} N\left(f_{0i} - \mathbf{g}(t_k, \hat{\boldsymbol{\theta}}), \sigma_f^2\right)}{P_{\text{норм}} N\left(f_{0i} - \mathbf{g}(t_k, \hat{\boldsymbol{\theta}}), \sigma_f^2\right) + \hat{P}_{\text{аном}} / L_{\text{поиск}}(k)}.$$

Further, the probability of anomalous measurements is specified as

$$\hat{P}_{\text{аном}} = 1 - \frac{1}{N_{\text{бл}}} \sum_{i=1}^{N_{\text{бл}}} \hat{P}_i^{\text{норм}}.$$

At step M of the algorithm, the estimates obtained at the previous stage are fixed and the parameter vector is refined $\boldsymbol{\theta}$ by optimization. This task reduces to a weighted polynomial approximation of measurements f_{0i} by function $g(t, \boldsymbol{\theta})$ with the weight of each dimension is directly proportional to the probability $\hat{P}_i^{\text{норм}}$.

Steps E and M are repeated until the convergence of the algorithm is reached. The convergence of the algorithm depends on the selected initial approximation. According to the MLSAC algorithm, the initial approximations are chosen by randomly searching the subsets of measurements f_{0i}. Each subset is assumed to be normal, on the basis of which the initial value of the parameter vector is calculated $\boldsymbol{\theta}$ and it is being optimized. The optimal decision is an estimate for the one of the subsets that minimizes the loss function.

Experimental part

To test the proposed algorithm, we consider a fixed PDR with the following parameters: pulse duration – $10 \mu s$, the duty cycle –10, the number of pulses in a pack –30,000, the duration of a pack – 0.3 s, and the probing frequency – 10 GHz.

The Doppler frequency and its first 3 derivatives are subject to evaluation, i.e. $n = 3$.

Consider the situation when the Doppler frequency shift of the aircraft on the observation interval T changes with parameters:

$$\boldsymbol{\theta} = \left(10^4 \text{Hz}, 180 \cdot 10^3 \text{Hz}^2, \text{-}500 \cdot 10^3 \text{Hz}^3, 500 \cdot 10^3 \text{Hz}^4\right).$$

Let these parameters be known before the measurements with errors specified by the following standard deviations: $\left(3 \cdot 10^3 \text{Hz}, 100 \cdot 10^3 \text{Hz}^2, 200 \cdot 10^3 \text{Hz}^3, 200 \cdot 10^3 \text{Hz}^4, 200 \cdot 10^3 \text{Hz}^5\right)$. The maximum and minimum values of the Doppler shift are set equal to $0\,\text{Hz}$ and 10^5Hz (taking into account the frequency of the stand, which shifts the negative Doppler shifts into a positive area).

The amplitude of the reflected signal at the receiving side is conventionally taken equal to one $\tilde{A} = 1$, and RMS the interference $\sigma_\eta = 3$.

At the first stage of the algorithm, according to the method described in the work, the minimum size of the observation interval fragment is determined, in which the expected probability of anomalous measurements does not exceed the specified threshold $P_{\text{аном.max}}$. In this work the threshold $P_{\text{аном.max}}$ is set to 0.3, since with a greater probability of anomalous measurements, the algorithm for detecting anomalous measurements is unable to correctly divide normal and anomalous measurements. With $P_{\text{аном.max}} = 0.3$, the calculated number of blocks is 789.

We fix this number of blocks and consider how it will affect $P_{\text{аном}}$ reduction of the signal-to-noise ratio (this experiment corresponds to the consideration of a less noticeable object at the same range or an object with the same visibility at a greater range) for the algorithm and the proposed algorithm based on MLSAC. The results of numerical simulation are shown in tabl. 1.

It is seen that the algorithm maintains performance for values $P_{\text{аном}}$ significantly higher than the 0.3 threshold: for $P_{\text{аном}} = 0.7$ 100% measurements of the Doppler frequency and its derivatives are correct. However, with a further decrease in the signal-to-noise ratio, the probability of correct estimation drops sharply, and the algorithm loses its operability. Thus, for the algorithm the critical value $P_{\text{аном}}$ is a value of 0.7. The proposed algorithm based on MLSAC retains its performance even with a further decrease in the signal-to-noise ratio: with increasing σ_η up to 8 when $P_{\text{аном}}$ reaches 0.9, the proposed algorithm correctly estimates the Doppler frequency and its derivatives in 100% of cases. For MLSAC algorithm critical value $P_{\text{аном}}$ is a value of 0.9, when the simulation shows the presence of incorrect measurements.

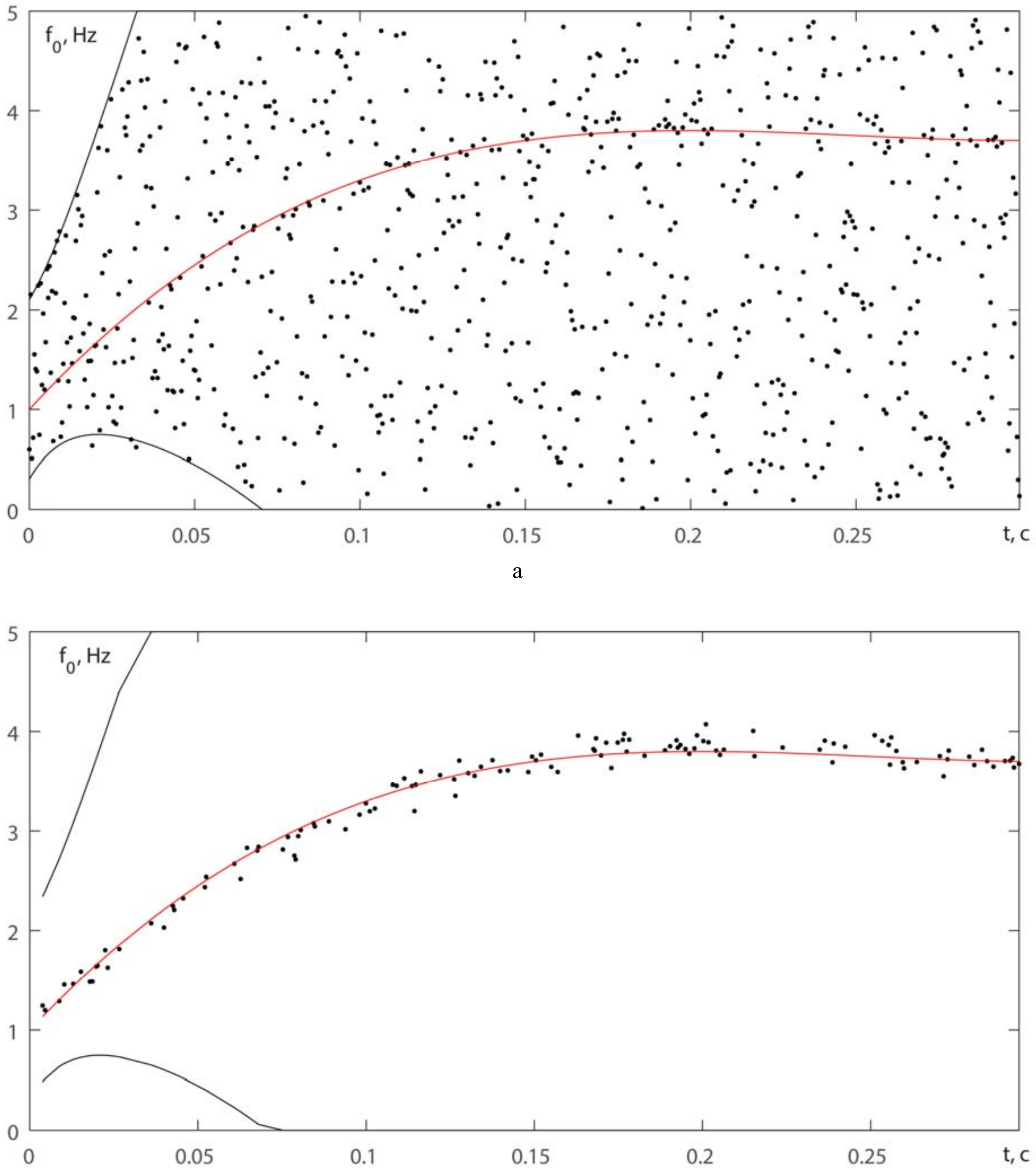
Fig. 1, a shows the results of estimating the Doppler frequency shift in each block with $\sigma_\eta = 6$. Normal measurements are marked with a red solid curve, which corresponds to the true value of the instantaneous Doppler shift of the reflected signal. The result of the proposed algorithm is shown in fig. 1, b, where only the detected normal measurements are shown. It can be seen that they are consistent with the true value of the instantaneous Doppler shift for the entire observation time of the signal.

In fig. 1 the grey curves correspond to the true value of the instantaneous Doppler frequency. Solid black lines show the search range of the Doppler frequency, taking into account its a priori uncertainty and predetermined top and bottom limits.

Table 1

The probability of correct estimation of the Doppler frequency and its derivatives

Algorithm	$\sigma_\eta = 3$	$\sigma_\eta = 4$	$\sigma_\eta = 5$	$\sigma_\eta = 6$	$\sigma_\eta = 7$	$\sigma_\eta = 8$
	$P_{\text{аном}} = 0{,}3$	$P_{\text{аном}} = 0{,}6$	$P_{\text{аном}} = 0{,}7$	$P_{\text{аном}} = 0{,}8$	$P_{\text{аном}} = 0{,}84$	$P_{\text{аном}} = 0{,}87$
	100%	100%	100%	20%	10%	0%
MLSAC	100%	100%	100%	100%	100%	100%



а

б

Fig. 1. The result of the detection of anomalous measurements: a – initial estimates;
b – evaluation after elimination of detected anomalous measurements

Conclusions

This article deals with the problem of estimating the Doppler frequency and its higher-order derivatives using a coherent block of long duration pulses. An approach to measure the Doppler frequency and its higher-order derivatives by crushing a burst of pulses into smaller fragments has been developed. When estimating the Doppler frequency shift by a signal fragment with a low signal-to-noise ratio, the probability of anomalous measurements in each of the fragments is high. A robust estimation algorithm for the Doppler frequency and its derivatives is proposed based on the MLSAC algorithm. It is shown that it retains its working capacity when the probability of anomalous measurements reaches 0.9 (measurements of the Doppler frequency are abnormal in nine out of ten signal fragments) in comparison with 0.7 for the existing algorithm previously proposed by the authors. This may allow to measure the motion parameters of an object with less visibility at the same distance or an object with the same visibility at a greater distance.

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Відомості про авторів:

Баришев Ігор Володимирович
доктор технічних наук професор
завідувач кафедри Національного аерокосмічного
університету ім. М.Є. Жуковського
"Харківський авіаційний інститут",
Харків, Україна

Information about the authors:

Igor Baryshev
Doctor of Technical Sciences Professor
Head of Department of National Aerospace
University named after M.E. Zhukovsky
"Kharkiv Aviation Institute",
Kharkiv, Ukraine

Усс Михайло Леонтійович
кандидат технічних наук
викладач Національного аерокосмічного
університету ім. М.Є. Жуковського
“Харківський авіаційний інститут”,
Харків, Україна

Mykhailo Uss
Candidate of Technical Sciences
Instructor of National Aerospace
University named after M.E. Zhukovsky
“Kharkiv Aviation Institute”,
Kharkiv, Ukraine

Радван Мухамед Жавад Кадім
аспірант Національного аерокосмічного
університету ім. М.Є. Жуковського
“Харківський авіаційний інститут”,
Харків, Україна

Radhwan Mohammed Jawad Kadhim
Doctoral Student of National Aerospace
University named after M.E. Zhukovsky
“Kharkiv Aviation Institute”,
Kharkiv, Ukraine

РОБАСТНЕ ОЦІНЮВАННЯ ДОПЛЕРІВСЬКОЇ ЧАСТОТИ ТА ЇЇ ПОХІДНИХ ВИЩОГО ПОРЯДКУ ДЛЯ СИГНАЛУ, ВІДБИТОГО ВІД ІНТЕНСИВНО МАНЕВРУЮЧОГО ОБ'ЄКТУ

І.В. Баришев, М.Л. Усс, Радван Мухамед Жавад Кадім

У статті розглянуто оцінювання доплерівської частоти та її похідних вищого порядку по когерентній пачці імпульсів великої тривалості. Отримав розвиток підхід вимірювання доплерівської частоти та її похідних вищого порядку за допомогою дроблення пачки імпульсів на фрагменти меншої довжини. При оцінюванні доплерівського зсуву частот за фрагментом сигналу з малим відношенням сигнал / шум висока ймовірність аномальних вимірювань в кожному з фрагментів. Запропоновано алгоритм робастного оцінювання доплерівської частоти та її похідних на основі алгоритму MLSAC. Показано, що він зберігає свою працездатність, коли ймовірність аномальних вимірювань досягає 0,9 (вимірювання доплерівської частоти є аномальними в дев'яти з десяти фрагментів сигналу) в порівнянні з 0,7 для існуючого алгоритму, раніше запропонованого авторами. Це може дозволити вимірювати параметри руху об'єкта з меншою помітністю на тій же дальності або об'єкта з тією ж помітністю на більшій дальності.

Ключові слова: *оцінка доплерівської частоти, алгоритм MLSAC, об'єкт, що маневрує.*

РОБАСТНОЕ ОЦЕНИВАНИЕ ДОПЛЕРОВСКОЙ ЧАСТОТЫ И ЕЕ ПРОИЗВОДНЫХ ВЫСШЕГО ПОРЯДКА ДЛЯ СИГНАЛА, ОТРАЖЕННОГО ОТ ИНТЕНСИВНО МАНЕВРИРУЮЩЕГО ОБЪЕКТА

И.В. Барышев, М.Л. Усс, Радван Мухамед Жавад Кадим

Предложен алгоритм робастного оценивания доплеровской частоты и ее производных на основе алгоритма MLSAC. Показано, что он сохраняет свою работоспособность, когда вероятность аномальных измерений достигает 0,9 (измерения доплеровской частоты являются аномальными в девяти из десяти фрагментов сигнала) в сравнении с 0,7 для существующего алгоритма, ранее предложенного авторами. Это может позволить измерять параметры движения объекта с меньшей заметностью на той же дальности или объекта с той же заметностью на большей дальности.

Ключевые слова: *оценка доплеровской частоты, алгоритм MLSAC, маневрирующий объект.*