Application of Kalman-Bucy filter for vessel traffic control systems in the northern sea route

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Abstract. The article considers the method of ice density concentration prediction based on the implementation of the Kalman-Bucy filter using geospatial data. The developed algorithm of data filtering allows us to assess the effective use of this approach in predicting the density of ice in the Arctic. The key aspects of the model application for the construction of optimal and safe routes of vessels in the waters of the Northern sea route are described.

1. Introduction

Currently, the development of the Northern sea route (NSR) is a priority for the development of the Russian transport system in the Arctic [1]. When developing a control system for such a long territorial object, it is necessary to mind about management of the natural risks in the conditions of climate change [2-4], including the influence of black carbon [5, 6]. It is also necessary to take into account the issues of environmental safety related to large sea objects [7, 8]. When solving these problems, it is natural to use advanced information technologies (IT) including the issues of information collection [9]. The development of such IT-technologies is the main goal of this study.

The Russian Federation transport systems are characterized by an enormous scale and developed infrastructure network. Current trends of information technology (IT) improvement together with scientific approaches determine one of the highest priority ways to develop the RF transport infrastructure and manage the optimal safe processes for organizing ship navigation in the Northern Sea Route waters.

To make managerial decisions on conducting business in the Arctic, the timely and relevant information is required that takes into account the regional climatic conditions, expressed in certain parameters. The operational ice information is needed to select the optimal sailing routes for ships, covering climate change and the ice area in the Arctic. For each of the indicators, our own mathematical calculation models were applied. The probability of the event occurrence can be estimated on the basis of known methods for assessing the probability processes characteristics.

With complete certainty of the initial data, the predicting problems of system changes are usually solved on the basis of classical statistics methods (ordinary least-squares method, maximum likelihood, etc.). Optimal filters are also part of these methods; among them, the most universal is the Kalman-Bucy filter. It is a recursive algorithm for weighted smoothing and time series forecasting. The Kalman-Bucy filter allows you to update the assessment of the current state and predict their future values as new data arrives. Let’s consider the implementing principle of the optimal Kalman-Bucy filter.
2. Methods and Materials

It is assumed that there are such time intervals at which the parameter under study (wind force) is a stationary random process. It may be considered as an accidental event that wind force does not exceed a given value of the Beaufort wind force scale. For the known random process, you can determine the probability of wind speed couldn’t exceed 11 Beaufort number (wind speed 28.5 - 32.6 m/s) using the following (1):

\[ P_i(t_3) = P\left[ S(t_i) / S(t_0) \right] = S_0 \leq \delta_i, \]

where, \( P_i(t_3) \) - probability of wind speed couldn’t exceed the i-th Beaufort scale number; \( \delta_i \) - boundary of the Beaufort scale number at the i-slice; \( S_0 \) - initial value of wind force; \( S(t_i) \) - random function of changing wind force at a given time \( t_3 \); \( S(t_0) \) - random function of changing wind force at the beginning of time \( t_0 \).

Using the estimates [10, 11] (2) was obtained:

\[ P_i(t_3) = \Phi \left\{ \frac{\delta_i - m_i - r_i(0,t_3) \times (s_0-m_0)}{\sigma_i \sqrt{1-r_i^2(0,t_3)}} \right\} - \Phi \left\{ \frac{-m_i - r_i(0,t_3) \times (s_0-m_0)}{\sigma_i \sqrt{1-r_i^2(0,t_3)}} \right\}, \]

where, \( m_i \) is the mathematical expectation of a random process; \( \sigma_i \) - standard deviation; \( r_i(0,t_3) \) - autocorrelation function.

For the study, at least 2 such points \( x \) and \( y \) are taken, so that the mutual correlation between them is identically equal to zero \( r_{x,y} \equiv 0 \). If more points are taken, then the mutual double correlation is identically equal to zero \( r_{x,x} = r_{x,y} = r_{x,y} \cdots \equiv 0 \). According to the "minimization method \( \chi^2 \)", the values of unknown parameters were chosen so that Pearson’s distance would be the smallest. Once the parameters and the minimum distance have been determined, the question is whether it is small enough. Overall sequence of actions [12]:

1. Selecting the model (\( H_0 \) hypothesis).
2. Selecting number position and determining the vector of observed frequencies \( O_i \).
3. Assessing unknown model parameters and building confidence intervals for them (Pearson’s minimum distance).
4. Calculating the expected frequencies \( E_i \).
5. Comparison of Pearson’s found distance with the largest critical value \( \chi^2_{max} \), which is still considered plausible, and compatible with \( H_0 \). The value \( \chi^2_{max} \) determines from the known statistics, solving the equation \( P\left( \chi^2_n > \chi^2_{max} \right) = 1 - \alpha \), where \( \alpha \) - the "level of significance" or "criterion size" or "the magnitude of the error of the first kind" (typical value of 0.05).

If \( \chi^2 > \chi^2_{max} \), the \( H_0 \) hypothesis is rejected, otherwise it accepted. In \( \alpha \cdot 100\% \) of cases (i.e. rarely enough), this method of checking hypothesis \( H_0 \) will result in a "first kind error": the \( H_0 \) hypothesis will be rejected incorrectly.

3. Results and Discussion

A universal Kalman-Bucy filter is used to predict probabilistic values of ice density. The input data for the filter are a priori estimates of the mathematical expectations of the coefficients \( a_{ij} \) and their
covariance matrix. The mathematical expectation of the coefficients (formula 3) is defined at this case as follows: $a_0 \rightarrow -a_2 \rightarrow a_1 \rightarrow -a_1 \rightarrow a_2 \rightarrow -a_0$ (since the function returns values in this order):

$$
\begin{align*}
    n = 1; a_0 &= \frac{p_1(n) + p_2(n) + p_3(n)}{3}; \\
    n = 2; a_1 &= \frac{p_1(n) + p_2(n) + p_3(n)}{3}; \\
    n = 3; a_2 &= \frac{p_1(n) + p_2(n) + p_3(n)}{3}; \\
    Mx &= \begin{bmatrix} a_0 & a_1 & a_2 \end{bmatrix};
\end{align*}
$$

(3)

The coefficients $p_1, p_2, p_3$ are formed using the least-squares method. The covariance coefficient matrix (4):

$$
\begin{align*}
    AfK &= \begin{bmatrix} p_1; p_2; p_3 \end{bmatrix}; \\
    Kt &= \text{cov}(AfK); \\
    Kt_1 &= \text{cov}(AfK);
\end{align*}
$$

(4)

To construct the covariance matrix, it is necessary three- times to approximate the time dependence of the parameter in order to obtain estimates of the coefficients $a_{ij}$ using the methods of exponential smoothing or least squares [13].

The result of applying the Kalman-Bucy filter is shown in figure 1-4.

![Figure 1](image1.png)  
Figure 1. The indication of temperature on water surface coefficient.

![Figure 2](image2.png)  
Figure 2. The indication of wind speed coefficient.
4. Conclusions

Graphs 1-4 show that the forecast data using Kalman-Bucy filter is close to a priori values, except for outliers (zero values and data errors). Based on the study, it can be concluded that in the presence of sufficient and reliable data, the proposed method is suitable for further deeper consideration.

The implementation of the optimal Kalman-Bucy filter [14] to the vessel's motion control system will display the predicted value of spatially distributed hydro-meteorological data on the intended route of the vessel, using this algorithm to assess the probabilistic factors affecting the vessel and its position on the course. It will help to form an optimal-safe route.

In the future, the Kalman-Bucy filter will take into account the multi-parametric model of probability event assessment. Introducing this filter into the software module will automate the system control of the dynamic positioning and adjustment in accordance with the parameters of the particular vessel movement. Also, this control system should take into account manual commands from the remote control and data of on-board sensors. All of these factors are analyzed to ensure that the ship's trajectory is constantly updated.

Already, the results can help to lay an optimally safe route, which will allow making a rational and optimal decision on ship operations. The model under study can significantly reduce the risks of incidents and provide safer and more efficient navigation in the Northern Sea Route.

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