Application of a remote sensing data processing method for assessment ice cohesion in the Arctic navigation

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Abstract. Operational correct predictive information about an ice situation in the Arctic region is an important component in making strategic management decisions and planning the route of vessels, in this regard, the scientific work examines the application of a remote sensing data processing method for assessment ice cohesion in the Arctic navigation. The article presents a generalized model for assessment the state of a stochastic process using the Kalman filter in the environment of mathematical modeling Matlab. The algorithm of behavior of mathematical tools of the Kalman filter is considered. During the research the algorithm of filtration was corrected by adding recursion to the filtering algorithm. To simulate the method of processing spatially distributed data using the Kalman filter and to analyze the convergence of predictive data with actual data, we used hydrometeorological data for the sampling period from 01.01.2016 to 12.31.2018 according to remote sensing data. The obtained results illustrate the correctness of the hypothesis and show the possibility of using the described approach to solve problems of this kind. The proposed algorithm confirms the possibility of using combined prediction methods and causes perspectives of the development prospects of the research topic. Results of scientific activity allow to give the assessment to relevance of using such a prediction method. Based on the conducted research, we can conclude that, in the presence of sufficient and reliable data, the proposed method is suitable for further deeper consideration. Further development of scientific research is directed to improvement of quality of methods of prediction which gradual growth, will undoubtedly lead to expansion of the period of the useful predict.

1. Introduction
The effective development of marine activities in the Arctic requires not only special organization and strategic-spatial thinking, but also the use of economic-geographical and scientific-technical approaches to solving the problems that arise, especially those related to the development of navigation in one of the most perspective regions of the Russian Federation.

The changing ice situation of the Arctic region is one of the most pressing issues today. Ice sheet — very mobile environment and the magnitude of drift can reach 22 nautical miles and more. The application value of the ice density index is very important. Than more ices will disappear as a result of summer thawing, than vaster areas of the ocean and its seas will be cleared of ice, which will facilitate navigation. For example, if the area of residual ices in September is less than 5 million sq.km, then it means that the ice sheet was intensively destroyed during the summer period and the water area of the Russian Arctic seas will be completely free from ice. If the area of residual ices in September more than 5 million sq.km, then on the water area of some Arctic seas remains the ice sheet that will negatively affect the opportunity and safety of navigation of vessels [1].
According to measurements from 12.27.19 to 01.23.2020, from the Cryosat-2 satellite, provided by the Center for Polar Observation and Modeling in the UK, shown in Figure 1, the average observed ice thickness varies from 1 to 2 meters. Comparing with the indications of 10 years ago, we can confidently talk about changes in the ice situation in the Arctic region.

![Figure 1. Thickness map of arctic sea ice](image)

Operational data on the ice sheet in the marine environment and on glaciers allow to choose optimal strategic decisions for implementation of national projects of the country. The modern ice mapping technique is based on the experience of previous generations of ice observers. Since the end of the 80th and till present many scientists have been actively engaged in the issue of automatically determining the parameters of the ice sheet according to remote sensing data. Each new algorithm is developed for specific conditions here the connection is traced by geographical coordinates or seasonality. Certainly, competent application of methods of data processing gives analysts additional useful information that is taken into account when production predictive cards of the ice situation [2, [3].

In turn it should be noted that errors in long-term prediction are inherent to many models. At present, it is generally recognized that the arbitrarily small errors in specifying the initial data for calculating the predict transform into large ones over time. Outside of approximately two weeks, the errors of a detailed predict by days of a model grow to the level of errors of a random predict. Objective restrictions for the opportunity to precisely predict the specific course of processes on rather long intervals of time are so shown. Restriction is connected with the fact that initial conditions for calculation of the predict always contain errors and initial errors tend to increase during the predict period because of instability of processes. In certain cases, the development of weather processes is well traced for several days ahead, and it happens that the predict for tomorrow is very unreliable.
During the research, the actual current scientific problem of providing operational correct predictive information about the ice situation in the Arctic zone throughout the route of vessels is defined. The solution of the scientific problem posed is determined by the objectives of the development strategy of the Arctic zone of the Russian Federation and is aimed at implementing the foundations of the state policy of the Russian Federation in the Arctic, in order to ensure sustainable development of the region.

2. Methods and Materials
Operational correct predictive information about the ice situation in the Arctic region is the important component in making strategic management decisions and planning the route of vessels; in this regard in the research examines application of the method of data processing of remote sensing for assessment of ice cohesion in the Arctic navigation [4].

For calculate the predicted value of the ice cohesion index for subsequent periods, various models were considered. Having carried out the multicriteria analysis of remote sensing data processing methods based on linear and recursive data filtering, a data processing method using the Kalman filter (KF) was determined. The Kalman filter according to the criterion of the minimum of the mean square error and its generalization to the case of Gaussian nonlinear continuous and discrete dynamic systems is the most famous result of modern control theory. KF is also used to predict possible trends in the development of dynamic systems that cannot be managed [5].

The mathematical toolkit of the Kalman filter consists of two phases. The first phase is the extrapolation or prediction of the value of the system at the next point in time. In mathematical form, the first phase is an equation of matrix form, which in turn is divided into two equations: the equation for directly predicting the state of the system (formula 1) and the equation for predicting the covariance error (formula 2).

\[
\hat{x}_k = F_k \hat{x}_{k-1} + B_k u_{k-1}, \tag{1}
\]

where \(\hat{x}_k\) — the predicted state on \(k\) step; \(F_k\) — dynamic transition matrix system state; \(\hat{x}_{k-1}\) — the value of the system in the previous step; \(B_k\) — matrix of managing influence; \(u_{k-1}\) — managing influence on the previous step.

\[
P_k = F_k \bar{P}_{k-1} F_k^T + Q_k, \tag{2}
\]

where \(P_k\) — error prediction covariance matrix; \(F_k\) — dynamic matrix transition state of the system; \(\bar{P}_{k-1}\) — covariance matrix that displays the error in the previous step; \(Q_k\) — the covariance matrix of the noise value.

Due to the fact that in our research managing influences are not defined, that is, they are absent, their value will be zero (\(B_k = 0\)), or managing influence can be referred to noise.

The second phase — the phase of correction of the system. At this stage, actual data are compared with received predicted, after which the values are adjusted. In the same way as in the first phase, the equations are a matrix form that can be represented in several stages [2].

As the first stage, we consider the Kalman gain equation (formula 3):

\[
K_k = P_k H^T \left( HP_k H^T + R \right)^{-1}, \tag{3}
\]

where \(K_k\) — Kalman gain coefficient; \(P_k\) — covariance matrix of error prediction; \(H^T\) — state matrix of the obtained values in relation to the actual data; \(R\) — covariance matrix for measuring noise.

Further using the calculated data, we correct the system taking into account the actual state of \(z_k\) and obtain an equation of the following type (formula 4):

\[
\hat{x} = \hat{x}_k + K_k \left( z_k - H \hat{x}_k \right), \tag{4}
\]

where \(z_k\) — measurement of actual state at the moment.
At the last stage, the equation of the covariance matrix of the updated state of the system (formula 5):

\[ P_k = \left( I - K_k H \right) P_{\bar{x}}, \]  

where \( I \) — identity matrix.

The theory of the Kalman filter algorithm is to predict the future state of the system, based on previous indications, adjustments to the resulting state, noise, and actual indications. During the experiment, it is possible to check the filter's operability by comparing the predicted state with real indications. Due to the recursive form, the filter is relatively easy to implement on a computer, and its estimates are consistent, efficient and not displaced [6-9].

For the solution of the set scientific task it is offered to use the method of processing a priori data. During the research an analysis was made of the spatial distribution of sea ice in the Arctic based on its cohesion (the ratio of the area of ice floes in the zone where they are distributed to the total area of this zone) for the sampling period from 01/01/2016 to 12/31/2018 according to the platforms DMSP-F08, DMSP-F10, DMSP-F11, DMSP-F13, DMSP-F14, DMSP-F15, DMSP-F17, NIMBUS-7. Actual information on the density of ice is collected from four points lying along the Northern Sea Route. The points are located in latitude and longitude coordinates (50.80), (135.85), (173.95), (193.132), as shown in Figure 2.

![Spatial distribution of sea ice in the Arctic.](image)

**Figure 2.** Spatial distribution of sea ice in the Arctic.

3. Results and Discussion

To model the data processing method using the Kalman filter and to analyze the convergence of predictive data with actual data for previous periods, the mathematical modeling system Matlab was chosen as the basis of the software environment. The algorithm for assessment the state of a random process by the Kalman filter in the modeling environment is presented in Figure 3.
Figure 3. A generalized model for assessment the state of a random process with a Kalman filter

Having conducted the further research, it was revealed that the basic algorithm of the Kalman filter does not satisfy to characteristics of the objective as has no opportunity to manage two conditions of the system, and within advance unknown dependence between them, also in the algorithm there is no possibility of managing impacts on model, as a result — completion of the algorithm with implementation of recursive process is necessary.

The result of processing ice cohesion data using the corrected Kalman filter is presented in Figure 4-6.

Figure 4. A priori data of drift ice cohesion
Figure 5. Indication of drift ice cohesion by Kalman filtering

Figure 6. Comparison of a priori data and processed by Kalman filtering

The graph shows two indicators: a priori values and processed data of remote sensing using the Kalman filter. The predict data using the Kalman filter are close to a priori values, with the exception of a number of errors that are caused by the following possible factors: lack of managing impacts on model, the absence of ice sheet measurements during a certain period, zero satellite measurements, and the Kalman filter algorithm structure, which at its core is linear in nature, where for the smallest mean square error too limited conditions (hypotheses) are required [3].

Having obtained information for the bigger period of time and having applied methods of the system analysis, it will be possible to predict indicators of density of ice in future season. It will reduce risk of passing of vessels on the sea route in the Arctic, wreck and stuck in sea ices, works on their release and
other rescue operations, the system of pass of flights will also be debugged, vessels traffic and economic component will be increased.

Implementation of the Kalman filter in traffic control system of the vessel will allow to display the predicted value of the space distributed hydrometeorological data on estimated route of the movement of the vessel, using this algorithm for assessment of the probabilistic factors influencing the vessel and its situation on course. It will help to create optimum and safe route.

In the future, the Kalman filter will take into assessment the multi-parameter model for evaluating probabilistic events. Introduction of this filter to the program module will allow to automate control system of dynamic positioning and adjustment according to parameters of the specific movement of the vessel. Also this control system has to consider tame teams from remote control panel and data of on-board sensors. All these factors are analyzed for ensuring continuous updating of trajectory of the movement of the ship.

The received results of research can be basis for the analyst when laying optimum safe route of vessels. The model under study allows us to significantly reduce the risks of incidents and ensure safer and more efficient navigation on the Northern Sea Route [10].

4. Conclusions
Within this research, the Kalman filter is shown as one of the data processing methods for assessment ice cohesion in Arctic navigation. The task of prediction the ice situation is an important component in the strategic planning of the movement of sea vessels, therefore this approach can be used as an alternative to existing solutions or in addition to them. Change of basic algorithm has allowed to consider multidimensional conditions of system, increasing the accuracy of the predict.

On the basis of the conducted research, we can conclude that, in the presence of sufficient and reliable data, the proposed method is suitable for further deeper consideration. The results obtained illustrate the correctness of the hypothesis put forward and show the possibility of using the described approach to solve problems of this kind. The offered algorithm has number of the shortcomings specified in scientific work, which only confirms the possibility of using combined prediction methods and determines the development prospects of the research topic.

Further development of scientific research is aimed at improving the quality of prediction methods, the gradual growth of which will undoubtedly lead to an extension of the useful predict period.

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геоданных для принятия управленческих решений по прокладке оптимальных маршрутов следования судов в Арктике. Эстественные и технические науки 4(130) 130-133