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Ship propagation as a harmonically bound particle

Using the Kramers equation for vessel traffic data

David W. Maybury
DRDC – Centre for Operational Research and Analysis

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Abstract

Understanding the statistical patterns of ship propagation along well-defined lanes increases domain awarness by giving security experts a clearer picture of the background in which targets of interest appear. I present a model which describes ship propagation in non-maneuvering modes, based on Kalman filtering with Brownian motion in the presence of a restoring potential. As a proof-of-principle demonstration of the algorithm, I use Automatic Identification System (AIS) data from a survey ship in the western Arctic Ocean. I find evidence for a non-vanishing potential along imputed non-maneuvering modes of operation. Imputed lanes from the AIS traffic data contain a potential degeneracy between drift and diffusion in the model calibration, which I break by fiat. Testing the model with ship traffic data along known shipping lanes will remove this ambiguity. The result in this paper, using the available data, successfully demonstrates the empirical model estimation technique, making the method available for further ship traffic analysis.

Significance for defence and security

Modelling the statistical properties of lane-bound ship traffic increases domain awareness by giving security experts a better understanding of the background in which suspicious activity may occur. Understanding the statistical properties of background ship movements provides a key to anomaly detection along shipping lanes.

This paper presents a model for describing ship propagation in lanes. The model differs from traditional approaches in that the ship sits in a potential well which restores the ship to its lane during propagation. I demonstrate the model through proof-of-principle concept development based on actual ship position data in the western Arctic Ocean. Through model estimation, I find evidence for a restoring potential. Implementing this model class with ship traffic data moving along known shipping lanes represents the next step in development. The result in this paper, using the available data, successfully demonstrates the empirical model estimation technique, making the method available for further ship traffic analysis.

I find:

- evidence for a restoring potential as ships move in non-maneuvering modes of operation;
- that the mathematical analysis follows from the solution of the Kramers partial differential equation;
- that the model estimation procedure generates reliable estimates based on Kalman filtering.

Résumé

La compréhension des tendances statistiques de propagation de navires dans des voies bien définies augmente la connaissance du domaine en donnant aux experts en sécurité une image plus claire du contexte dans lequel les objectifs d'intérêt apparaissent. Je présente un modèle qui décrit la propagation de navires en modes sans manIJuvre, selon le filtrage Kalman avec mouvement brownien en présence d'un potentiel de restauration. En tant que démonstration de principe de l'algorithme, j'utilise des données du système d'identification automatique (SIA) d'un navire hydrographique dans la partie ouest de l'océan Arctique. J'ai trouvé des preuves pour un potentiel sans chavirement dans des modes d'exploitation sans manIJuvre imputés. Les voies imputées des données sur le trafic maritime du SIA contiennent un potentiel de dégénérescence entre la dérive et la diffusion dans l'étalonnage du modèle, que je sépare de façon arbitraire. Le fait de soumettre le modèle à des essais avec des données sur le trafic maritime dans des voies de transport par eau connues éliminera cette ambigüité. Les résultats présentés dans ce document, à l'aide des données disponibles, démontrent avec succès la technique d'estimation de modèle empirique, ce qui rend la méthode disponible pour des analyses plus poussées du trafic maritime.

Importance pour la défense et la sécurité

La modélisation des propriétés statistiques du trafic maritime dans des voies augmente la connaissance du domaine en donnant aux experts en sécurité une meilleure compréhension du contexte dans lequel des activités suspectes pourraient survenir. La compréhension des propriétés statistiques du contexte des déplacements de navires est un élément essentiel pour la détection d'anomalies dans des voies de transport par eau. Ce document présente un modèle de description de la propagation de navires dans des voies. Le modèle diffère des approches traditionnelles, car le navire demeure en place dans un puits potentiel, ce qui restaure le navire dans sa voie durant la propagation. Je démontre le modèle au moyen d'un développement de concept de démonstration de principe fondé sur des données de position de navire réelles dans la partie ouest de l'océan Arctique. À l'aide d'une estimation de modèle, je trouve des preuves pour un potentiel de restauration. La mise en IJuvre de cette classe de modèle avec des données sur le trafic maritime dans des voies de transport par eau connues représente la prochaine étape du développement. Les résultats présentés dans ce document, à l'aide des données disponibles, démontrent avec succès la technique d'estimation de modèle empirique, ce qui rend la méthode disponible pour des analyses plus poussées du trafic maritime. J'estime :

- qu'il existe des preuves de potentiel de restauration lorsque des navires se déplacent en modes d'exploitation sans manIJuvre ;
- que l'analyse mathématique découle de la solution de l'équation différentielle partielle de Kramers.

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1 Introduction

To detect anomalies in ship traffic data, we require an understanding of the statistical patterns of ship movements. In particular, understanding ship propagation along well-defined lanes in non-maneuvering modes of operation will help us generate a clear picture of the background in which potential targets of interest appear. I present a modelling technique, based on Brownian motion in a restoring potential, which describes ship propagation along lanes over long time frames.

Using Automatic Identification System (AIS) datasets, researchers in [1] analyze the statistical properties of route propagation through the application of Integrated Ornstein-Uhlenbeck (IOU) models (see [2] and [3] for details on IOU constructions). In this model class, vessels experience mean reversion in their velocity vectors, generating a well-defined velocity process with bounded variance. Since the IOU model does not possess a stationary distribution, the vessel's variance in position grows linearly with time. This property leads to the unrealistic feature that on long time frames, a ship cannot reliably maintain a lane—the vessel's position becomes increasingly less certain by dispersion around the lane. While estimation through moment matching of the ship movement data with the IOU model provides a good qualitative description of ship traffic [1], on timelines greater than 30 hours the non-stationarity of the solution limits predictivity.

In August 2015, Maritime Forces Atlantic Operations Research (MARLANT-OR)'s team lead asked me if I could extend the results in [1]. In particular, MARLANT-OR wanted to know if I could improve on the mean reverting stochastic process used in [1] and if I could improve on the estimation technique. MARLANT-OR provided ship tracking data in the western Canadian Arctic.

To solve the lane dispersion problem, I introduce a quadratic potential which harmonically bounds the ship to its lane. The potential ensures the existence of a stationary solution in which the variance of both velocity and position remain bounded for all times. This model belongs to an extension of the Ornstein-Uhlenbeck model class and Fokker-Planck equation [2] analysis of the transition probabilities results in kinematics that satisfy the Kramers equation [4]. While the mathematical analysis of the extension proceeds straightforwardly, solving the model in the presence of real data requires stochastic filtering. The underlying position and velocity of the model form the state space while AIS or ship reporting measurements form the observation process. Since the solution of the Kramers equation is a time dependent Gaussian, I use the Kalman filter [5], (see [6], [7], and chapter 13 of [8] for additional details) to estimate the model. As a proof-of-principle concept, I estimate the model using survey ship traffic in the western Arctic Ocean from September 2011 to October 2014.

I find evidence for a non-vanishing potential from ship traffic data. Unfortunately, the data I have on movements in the western Arctic Ocean do not contain routes between pre-determined ports. To estimate the model, I first impute lanes from estimated non-maneuvering trajectories. In principle, estimating the lane, followed by estimating the model leads to a degeneracy—the technique cannot distinguish between a ship tightly bound to an imputed lane from a loosely bound ship with a large lane-orthogonal drift. Since this paper focuses on the theoretical setup along with the numerical techniques for model estimation, I reserve the calibration issue for further studies.

2 The Model

The original IOU model of [1] estimates ship propagation in two dimensions on a coordinate patch of the Earth's surface using uncorrelated Brownian motions in each basis direction. Thus, the model in [1] naturally decomposes into two orthogonal estimation problems. The authors of [1] solve the orthogonal problems through moment matching. Since I am interested in the possibility of a restoring potential perpendicular to a lane, I restrict the analysis to one spatial dimensional—the orthogonal displacements relative to the imputed shipping lane. My model specification takes the form,

$$\begin{bmatrix} dx \\ d\dot{x} \end{bmatrix} = -\begin{bmatrix} 0 & -1 \\ \omega^2 & \gamma \end{bmatrix} \begin{bmatrix} x \\ \dot{x} \end{bmatrix} dt + \begin{bmatrix} 0 & 0 \\ 0 & \sqrt{2\gamma\nu^2} \end{bmatrix} \begin{bmatrix} 0 \\ dW(t) \end{bmatrix}, \tag{1}$$

in which $dW(t)$ denotes the usual one-dimensional Weiner increment (Brownian motion) and x measures the orthogonal[1] displacement relative to a non-maneuvering track. The models has three parameters, $\{\omega, \gamma, \nu\}$, and the kinematics of eq.(1) match the model of [1] except for the inclusion of ω, which represents the effect of the restoring potential. The model yields the following coupled stochastic equations,

$$\begin{cases} dx = \dot{x}\, dt \\ d\dot{x} = (-\omega^2 x - \gamma\dot{x})\, dt + \sqrt{2\gamma\nu^2}\, dW(t) \end{cases} \tag{2}$$

Using the Fokker-Planck equation (see [2] and [3] for details) with eq.(2), I derive the transition probability density in the form of the Kramers partial differential equation. Dotted variables denote time differentiation throughout. Defining the initial state as $(x_0, \dot{x}_0, t_0)$ with the conditional transition probability, $p = p(x, \dot{x}, t | x_0, \dot{x}_0, t_0)$, the Fokker-Plank equation yields the Kramers equation, namely,

$$\frac{\partial p}{\partial t} = -\dot{x}\frac{\partial p}{\partial x} + \frac{\partial}{\partial \dot{x}}[(\omega^2 + \gamma\dot{x})p] + \gamma\nu^2 \frac{\partial^2 p}{\partial \dot{x}^2}. \tag{3}$$

The solution of eq.(3) permits the construction of a state space process for the ship dynamics orthogonal to the lane propagation. In particular, by defining $\mathbf{X} = [x, \dot{x}]^T$, the solution to eq.(3) reads,[2]

$$p(\mathbf{X}, t | \mathbf{X}_0, t_0) = \frac{1}{2\pi[\mathrm{Det}(\sigma(t - t_0))]^{1/2}} \cdot \exp\left(-\frac{1}{2}(\mathbf{X} - \mathbf{G}(t - t_0)\,\mathbf{X}_0)^T (\sigma(t - t_0))^{-1} (\mathbf{X} - \mathbf{G}(t - t_0)\,\mathbf{X}_0)\right), \tag{4}$$

[1]In this analysis, I define "orthogonal displacement" to mean the shortest great circle distance from a point to an arc.

[2]Boldfaced variables represent vectors and matrices. $\mathbf{X}$ is a 2×1 column vector throughout.

in which

$$\mathbf{G} = \exp\left(-\boldsymbol{\Gamma}(t-t_0)\right), \tag{5}$$

$$\boldsymbol{\Gamma} = \begin{bmatrix} 0 & -1 \\ \omega^2 & \gamma \end{bmatrix}, \tag{6}$$

$$\sigma(t) = 2\int_0^t \mathbf{G}(s)\begin{bmatrix} 0 & 0 \\ 0 & \gamma\nu^2 \end{bmatrix}\mathbf{G}^T(s)\,ds. \tag{7}$$

The matrix $\boldsymbol{\Gamma}$ has eigenvalues,

$$\lambda_{1,2} = \frac{1}{2}\left(\gamma \pm \sqrt{\gamma^2 - 4\omega^2}\right) \tag{8}$$

which affords the solution to $\mathbf{G}(t)$ and $\sigma(t)$:

$$\mathbf{G}(t) = \begin{bmatrix} \frac{\lambda_1 e^{-\lambda_2 t} - \lambda_2 e^{-\lambda_1 t}}{\lambda_1 - \lambda_2} & \frac{e^{-\lambda_2 t} - e^{-\lambda_1 t}}{\lambda_1 - \lambda_2} \\ \frac{\omega^2 (e^{-\lambda_2 t} - e^{-\lambda_1 t})}{\lambda_1 - \lambda_2} & \frac{\lambda_1 e^{-\lambda_1 t} - \lambda_2 e^{-\lambda_2 t}}{\lambda_1 - \lambda_2} \end{bmatrix}; \tag{9}$$

$$\sigma_{1,1}(t) = \frac{\gamma\nu^2}{(\lambda_1 - \lambda_2)^2}\left[\frac{\lambda_1 + \lambda_2}{\lambda_1\lambda_2} + \frac{4(e^{-(\lambda_1 - \lambda_2)t} - 1)}{\lambda_1 + \lambda_2} - \frac{e^{-2\lambda_1 t}}{\lambda_1} - \frac{e^{-2\lambda_2 t}}{\lambda_2}\right], \tag{10}$$

$$\sigma_{1,2}(t) = \sigma_{2,1}(t) = \frac{\gamma\nu^2}{(\lambda_1 - \lambda_2)^2}(e^{-\lambda_1 t} - e^{-\lambda_2 t})^2, \tag{11}$$

$$\sigma_{2,2}(t) = \frac{\gamma\nu^2}{(\lambda_1 - \lambda_2)^2}\left[\lambda_1 + \lambda_2 + \frac{4\lambda_1\lambda_2(e^{-(\lambda_1 - \lambda_2)t} - 1)}{\lambda_1 + \lambda_2} - \lambda_1 e^{-2\lambda_1 t} - \lambda_2 e^{-2\lambda_2 t}\right]. \tag{12}$$

In the limit that $\omega^2 \to 0$, we recover the moments of the free particle case in [1]. The stationary solution takes the form of the familiar Boltzmann distribution,

$$p(x, \dot{x}, t \to \infty) = \frac{\omega}{2\pi\nu^2}\exp\left[-\frac{\dot{x}^2 + \omega^2 x^2}{2\nu^2}\right], \tag{13}$$

leading to bounded variances at all times.

The state space dynamics given by eq.(4) has the form of a linear Gaussian model and thus the Kalman Filter represents the optimal Bayesian filter for this problem, provided that noise term in the observation dynamics follows a Gaussian process as well. I approximate the noisy observation of the ship's position and velocity, denoted by $Y = [y, \dot{y}]^T$, under the Gaussian/linear assumption. In discrete time, the solution eq.(4) with the observation assumption reads,

$$p(\mathbf{X}_k|\mathbf{X}_{k-1}) = N(X_k; \mathbf{G}_k X_{k-1}, \sigma_k), \tag{14}$$

$$p(\mathbf{Y}_k|\mathbf{X}_k) = N(\mathbf{Y}_k; \mathbf{X}_k, \mathbf{R}_k), \tag{15}$$

in which $N(\mathbf{x};\mu,\Sigma)$ denotes the multivariate Gaussian density function with mean and variance of μ and Σ respectively, k labels the time index, $\mathbf{Y}_k$ represents the ship observation data and $\mathbf{R}_k$ denotes the covariance matrix associated with the noise in the observation process. I assume that $\mathbf{R}_k \to \mathbf{R}$ is time independent and diagonal through this analysis. Using eq.(4) and the multivariate Gaussian densities for $X = [x,\dot{x}]^T$ and $Y = [y,\dot{y}]^T$, the Kalman filter for the lane-orthogonal component of the harmonically bound ship reads,

$$\hat{\mathbf{X}}_{k|k-1} = \mathbf{G}_k\hat{\mathbf{X}}_{k-1}, \tag{16}$$

$$\mathbf{P}_{k|k-1} = \mathbf{G}_k\mathbf{P}_{k-1|k-1}\mathbf{G}_k^T + \sigma_k, \tag{17}$$

$$\hat{\mathbf{Y}}_{k|k-1} = \mathbf{X}_{k|k-1}, \tag{18}$$

$$\mathbf{S}_k = \mathbf{P}_{k|k-1} + \mathbf{R}, \tag{19}$$

$$\mathbf{K}_k = \mathbf{P}_{k|k-1}\mathbf{S}_k^{-1}, \tag{20}$$

$$\hat{\mathbf{X}}_{k|k} = \hat{\mathbf{X}}_{k|k-1} + \mathbf{K}_k(\mathbf{Y}_k - \hat{\mathbf{Y}}_{k|k-1}), \tag{21}$$

$$\mathbf{P}_{k|k} = \mathbf{P}_{k|k-1} - \mathbf{K}_k\mathbf{P}_{k|k-1}. \tag{22}$$

3 Analysis

The data I work with come from the the Royal Canadian Navy (RCN) Global Positioning Warehouse [9] and contains ship traffic data on 823 vessels in the western Arctic Ocean spanning dates from 2011 to 2015. These data do not contain traffic patterns on well-defined shipping routes, but rather on irregular traffic legs reported through AIS or other self reporting data channels.

To demonstrate the model class and estimation procedure, I select the traffic data of the of 1328 deadweight tonnage ocean research/survey vessel Zephyr I. In the western Arctic Ocean, from Septemer 2011 to October 2014 the Zephyr I performed movement patterns consistent with surveying, which closely resemble propagation along a shipping lane. For the demonstration purposes of this paper, I use 23 shipping tracks segments cut from all the movement patterns and which correspond to non-maneuvering modes. I isolate these separate non-maneuvering tracks from the dataset by cutting track segments based on the deflection angle between reported positions. If the deflection angle exceeds 10° I cut the track into a new segment, making the assumption that the ship maneuvered onto a new trajectory. My method of imputing "shipping lanes" represents a crude technique for isolating non-maneuvering modes—analysis of future datasets based on actual shipping lane traffic will remove the need to impute lanes from track data. Figure 1 shows the imputed lanes from data in the western Arctic Ocean. The 23 track segments range in length from 12 km to 288 km with between five and 32 observations associated with each track.

I use R's[3] *geosphere* library to calculate ship bearings and great circle distances. With each track, I fit the best great circle arc through the data in a least squared error sense, which forms the imputed track. Minimum great circle distances of each data point from the imputed lane form the orthogonal displacements. The position data reports latitude and longitude to six significant figures which I represent in the observation error matrix as a standard error of one metre. The data do not contain useful velocity information in regards to the orthogonal displacement analysis. I estimate the velocity in the orthogonal direction using differenced displacements in conjunction with the time stamp data. Unfortunately, the estimation procedure results in velocity estimates that contain a high level of observational noise. In the observation error matrix, I capture the noise by using the variance of orthogonal velocity estimates as the standard error of the velocity component, $\text{var}(\hat{v}_{\perp}) = (200\,\text{metre}/\text{hour})^2 = \mathbf{R}_{2,2}$. Each track represents a separate observation or experiment for estimation purposes. Using R's *dynamic linear model (DLM)* library, I estimate the model parameters of eq.(2) for each of the 23 isolated non-maneuvering tracks and compute the average of the parameters with standard errors. I display the results in Table 1.

We see evidence for a non-vanishing potential, ω, in Table 1 and it is statistically different

[3]R is a programming language and software environment for statistical computing and graphics.

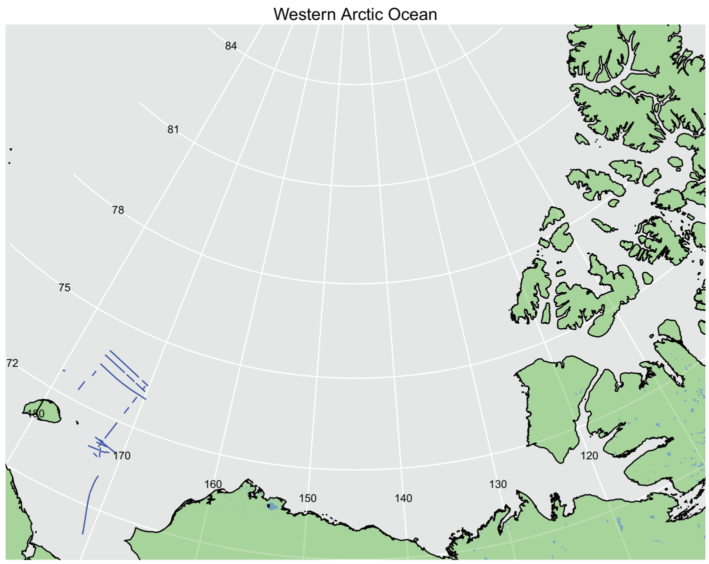

Figure 1: Imputed non-maneuvering tracks of the Zephyr I, SEP 2011—OCT 2014.

Table 1: Model parameter estimates
with standard error.

parameters	estimates
ω	$(1.4 \pm 0.3) \times 10^1$ hour^{-2}
γ	$(5 \pm 2) \times 10^1$ hour^{-1}
ν	$(1.6 \pm 0.4) \times 10^3$ metre/hour

from zero. The presence of the potential ensures that the ship maintains a desired route over long distances and as a proof-of-principle concept we see that the model captures the correct statistical behaviour. The ship traffic in the western Arctic Ocean does not contain the type of detailed routing information available in [1]. Ideally, to make a comparison in predictions and in statistical properties, we would need to perform this analysis on the same data. The greatest limitation in the current analysis rests in the imputed lane estimation. Since the data contain only ship position reports, we do not know the crew's intent. While the data seem to suggest routing along a tightly bound survey lane, we may in fact be observing a track along a low noise trajectory but with a substantial biased drift relative to the intended route. As an analogy, the method cannot distinguish a drunkard walking in a valley with steep walls from sober priest walking sideways down a hill. The lane imputation method *assumes* that the ship behaves as the confined drunkard, thereby turning the analysis into wall height estimation problem. Since Zephyr I is a survey vessel which travelled along well-defined tracks, it is almost certainly the case that the vessel was maintaining a constant course for survey work. Ship routing data in an established lane environment breaks the degeneracy—in such circumstances, we know for sure that the ships are sailing between predetermined points.

4 Discussion

Using a potential model based on the Kramers partial differential equation, I extend the work of [1] by introducing a restoring force along ship propagation routes. I address MARLANT-OR's request for improvements on the techniques used in [1]. Application of the Kalman filter with imputed shipping lane data in the western Arctic Ocean reveals the presence of a restoring potential for the survey vessel Zephyr I. Unfortunately the data does not contain routes between pre-determined ports which leads to a degeneracy between types of non-maneuvering modes. This paper focuses on the theoretical setup along with the filtering techniques for model estimation, reserving lane calibration to future studies involving shipping lane data of the type found in [1].

Under the lane imputation method, I discover evidence for a restoring force in ship propagation data. To further test these ideas and empirically determine suitability for anomaly detection, we need to:

- obtain the ship routing data available in [1];
- compare the results in [1] to the free particle and harmonically bound cases on that dataset;
- obtain new shipping data along well-defined shipping lanes.

Abbreviations and Acronyms

AIS Automatic Identification System

CORA Centre for Operational Research and Analysis

DND Department of National Defence

DRDC Defence Research and Development Canada

IOU Integrated Ornstein-Uhlenbeck

MARLANT-OR Maritime Forces Atlantic Operations Research

RCN Royal Canadian Navy

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Understanding the statistical patterns of ship propagation along well-defined lanes increases domain awarness by giving security experts a clearer picture of the background in which targets of interest appear. I present a model which describes ship propagation in non-maneuvering modes, based on Kalman filtering with Brownian motion in the presence of a restoring potential. As a proof-of-principle demonstration of the algorithm, I use Automatic Identification System (AIS) data from a survey ship in the western Arctic Ocean. I find evidence for a non-vanishing potential along imputed non-maneuvering modes of operation. Imputed lanes from the AIS traffic data contain a potential degeneracy between drift and diffusion in the model calibration, which I break by fiat. Testing the model with ship traffic data along known shipping lanes will remove this ambiguity. The result in this paper, using the available data, successfully demonstrates the empirical model estimation technique, making the method available for further ship traffic analysis.

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