

High Order Stochastic Transport and Lagrangian Data Assimilation

by

Arkopal Dutt

B.Tech, Indian Institute of Technology Bombay (2015)

Submitted to the Department of Mechanical Engineering
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Signature redacted

Author

Department of Mechanical Engineering

January 18, 2018

Signature redacted

Certified by

Pierre F.J. Lermusiaux
Pierre F.J. Lermusiaux

Professor, Department of Mechanical Engineering

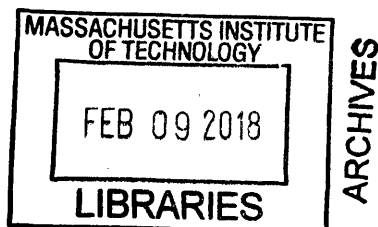
Thesis Supervisor

Signature redacted

Accepted by

Rohan Abeyaratne

Chairman, Department Committee on Graduate Theses



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Abstract

Ocean currents transport a variety of natural (e.g. water masses, phytoplankton, zooplankton, sediments, etc.) and man-made materials (e.g. pollutants, floating debris, particulate matter, etc.). Understanding such uncertain Lagrangian transport is imperative for reducing environmental damage due to natural hazards and for allowing rigorous risk analysis and effective search and rescue. While secondary variables and trajectories have classically been used for the analyses of such transports, Lagrangian Coherent Structures (LCSs) provide a robust and objective description of the important material lines. To ensure accurate and useful Lagrangian hazard scenario predictions and prevention, the first goal of this thesis is to obtain accurate probabilistic prediction of the underlying stochastic velocity fields using the Dynamically Orthogonal (DO) approach. The second goal is to merge data from both Eulerian and Lagrangian observations with predictions such that the whole information content of observations is utilized.

In the first part of this thesis, we develop high-order numerical schemes for the DO equations that ensure efficiency, accuracy, stability, and consistency between the Monte Carlo (MC) and DO solutions. We discuss the numerical challenges in applying the DO equations to the unsteady stochastic Navier-Stokes equations. In order to maintain consistent evaluation of advection terms, we utilize linear centered advection schemes with fully explicit and linear Shapiro filters. We then discuss how to combine the semi-implicit projection method with new high order implicit-explicit (IMEX) linear multi-step and multistage IMEX-RK time marching schemes for the coupled DO equations to ensure further stability and accuracy. We also review efficient numerical re-orthonormalization strategies during time marching. We showcase our results with stochastic test cases of stochastic passive tracer advection in a deterministic swirl flow, stochastic flow past a cylinder, and stochastic lid-driven cavity flow. We show that our schemes improve the consistency between reconstructed DO realizations and the corresponding MC realizations, and that we achieve the expected order of accuracy.

In the second part of the work, we first undertake a study of different Lagrangian

instruments and outline how the DO methodology can be applied to obtain Lagrangian variables of stochastic flow maps and LCS in uncertain flows. We then review existing methods for Bayesian Lagrangian data assimilation (DA). Disadvantages of earlier methods include the use of approximate measurement models to directly link Lagrangian variables with Eulerian variables, the challenges in respecting the Lagrangian nature of variables, and the assumptions of linearity or of Gaussian statistics during prediction or assimilation. To overcome these, we discuss how the Gaussian Mixture Model (GMM) DO Filter can be extended to fully coupled Eulerian-Lagrangian data assimilation. We define an augmented state vector of the Eulerian and Lagrangian state variables that directly exploits the full mutual information and complete the Bayesian DA in the joint Eulerian-Lagrangian stochastic subspace. Results of such coupled Eulerian-Lagrangian DA are discussed using test cases based on a double gyre flow with random frequency.

Thesis Supervisor: Pierre F.J. Lermusiaux
Title: Professor, Department of Mechanical Engineering

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