Detailed Syllabus

ISC5395-01 Data Assimilation Spring Semester 2014 Instructor: Prof. Ionel M Navon, DSL 483, phone 644-6560 or -1010 Meeting **Times**: WF, 09:30-10:45 am. 048 BEL.

Credit: 3 hours.

Prerequisites: Calculus I and II, Linear Algebra and a Programming language or consent of the instructor.

Intended audience: graduate students in computational science, mathematics, physics, meteorology, oceanography and engineering.

Course Description:

Data assimilation involves combining observations with model output to obtain a consistent, evolving 3-dimensional state of the model. In the last 20 years data assimilation has gained center stage in many computational disciplines at both universities and research centers starting with geoscience applications.

In this course, common methods of data assimilation (Kalman filtering, ensemble Kalman filter and variational methods) are introduced and derived in the context of both variational and estimation theory with emphasis on computational aspects.

Novel aspects of data assimilation using reduced order modeling will be introduced and examples presented.

A hands-on approach will be taken so that methods introduced in the lectures will be implemented in computer assignments using toy models and material of the research of the lecturer and other experts in the field.

Text books

No text is required to be purchased.

Lecture notes from books in preparation and from Dr Ricardo Todling (NASA) will be distributed during the class.

Alternate texts

Daley, R., 1991: Atmospheric Data Analysis, Cambridge University Press.

Todling, R., 1999: Estimation Theory and Foundations of Atmospheric Data Assimilation, DAO Office Note 1999-01.

Rodgers, C., 2000: Inverse Methods for Atmospheric Sounding, World Scientific Publishing.

Prasad S. Kasibhatla et al., 2000 Inverse Methods in Global Biogeochemical Cycles (Geophysical Monograph) (Hardcover). AGU

Enting, I., 2002: Inverse Problems in Atmospheric Constituent Transport, Cambridge University Press.

Swinbank, R., V. Shutyaev, and W. A. Lahoz, 2003: Data Assimilation for the Earth System, Kluwer Academic Publishers.

Kalnay, E., 2003: Atmospheric Modelling, Data Assimilation and Predictability, Cambridge University Press.

Gunzburger M. D., 2003: Perspectives in Flow Control and Optimization. Society for Industrial and Applied Mathematics, Philadelphia, 2003.

Dan G. Cacuci, Ionel Michael Navon, 2013: Data Assimilation and evaluation

CRC Press.

Geir Evensen, 2009: Data Assimilation: The Ensemble Kalman Filter. Springer

Verlag

John M. Lewis, S. Lakshmivarahan, and Sudarshan Dhall, 2006:

Dynamic Data Assimilation: A Least Squares Approach (Encyclopedia of Mathematics and its Applications). Cambridge University Press.

Olivier Talagrand, 2007: Data Assimilation in Meteorology and Oceanography.

Elsevier and Academic Press.

Data Assimilation for Atmospheric, Oceanic and Hydrologic Applications

Park, Seon K.; Xu, Liang (Eds.) 2009, XVIII, 475 p. 670 (recommended)

Objectives

The students should become able to implement basic variational and estimation methods in simple computer programs and to apply them to class projects.

Towards the end of the semester each student will be required to demonstrate his understanding by presenting a final project to the class. On the way to the goal that students use simple variational and Kalman filter, there will be few (4-5) projects.

In particular the assignments will include (but are not being limited to):

- Install and run TAMC automatic differentiation software for variational data assimilation
- Determine optimal initial conditions for toy model by minimizing a cost functional using adjoint code.
- perform parameter estimation using adjoint method
- implement a Kalman filter and smoother on a toy problem
- Use basic code on simple test problems (such as Lorentz 3 parameter problem) for ensemble Kalman filter (EnKF)
- Use model order reduction new techniques for data assimilation both variational and EnKF ensembles

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- Outline
- -Introduction to statistical concepts

- Probability density function
  - Basic probability concepts:
  - Bayes rule for probabilities
  - Expected value
  - -Variance and covariance
  - Concepts of optimal control
  - Optimal Interpolation
  - Nudging methods
  - Least square methods
  - Variational methods (e.g., 3D-VAR or 4D-VAR methods)
  - -Assimilation as an inverse problem
  - -Concepts of optimal control and optimization –
  - Adjoint based optimization methods -Illustration Examples:
  - Use of automatic differentiation: using TAMC code for automatic differentiation for adjoint code construction of simple models
  - -Tangent linear model -Toy model for sensitivity analysis
  - Basic gradient based minimization methods
  - -Algorithmic form of data assimilation -Model
  - -Cost functional
  - -Gradient of cost functional

- -Error statistics of the background fields and observations
- -Gradient based optimization algorithms using adjoint equations
- -Illustration via examples for time dependent problems in 1-D and 2-D.
- Computational aspects of data assimilation
- -Discretization of adjoint equations: first differentiate or discretize?
- Incremental method
- Check-pointing method: memory vs. CPU tradeoff -Estimation theory
- -The Kalman filter equations
- Examples:
- Damped harmonic oscillator
- A one dimensional advection problem
- The Kalman Smoother
- The extended Kalman filter for nonlinear models
- Computational Aspects of Kalman filter
- -Validation
- -Ensemble Kalman filter (EnKF) as a Monte Carlo alternative
- -Improved sampling strategies for EnKF
- -Reduced rank square root EnKF
- -Maximum likelihood ensembles

- -Computational aspects of flavors of EnKF
- -Particle filter ensembles (Bayesian ensembles)
- -Hybrid 3-D VAR and EnKF ensembles
- -Computational aspects of EnKF
- -State and parameter estimation with KF and EnKF
- New topics and open problems in data assimilation
- Model reduction methods :POD and balanced model reduction
- Model reduction and data assimilation
- Implementation examples using 1-D and 2-D models
- POD /DEIM for nonlinear problems
- - Quo Vadis in data assimilation: 4-D VAR or EnKF