ENVE5704: Data Assimilation and Uncertainty Quantification

Department of Civil and Environmental Engineering
Course Syllabus, Fall 2022

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Course Description (Calendar):

Fundamentals of data assimilation; forward and inverse techniques; optimal interpolation; variational techniques (3DVar and 4DVar); various implementations of Kalman filtering; Bayesian approach to uncertainty quantification; Monte Carlo techniques.

Course Description (Informal):

What is data assimilation? It is the science (and sometimes art) of combining a prior understanding of a dynamical system with observed data to obtain the best possible description of the system. It has myriad applications in engineering, from structural mechanics to hydrology to building occupant behaviour to transportation to disease dynamics to meteorology. All share a common fundamental framework that is rooted in Bayesian statistics.

Think of a problem in your field where you have a good idea of the governing equations; you can probably write out a simple mathematical model of your system and how it evolves in time. Now imagine you have a physical model of this system and take measurements of it – how can you combine those measurements with the equations you wrote? Do you approach the problem all at once, or sequentially? Do the measurements have the same weight as your prior knowledge? Are there any parameters in the equations that you might be able to refine using the new information, and if so, how do you do that? How do you evaluate how good your model was before and after incorporating the measurements? What assumptions have you made about your data?

In parallel to the lecture content that will explore all of the above questions, I propose to use this course as a venue for students to develop implementations of various data assimilation methods on a simple model of their choice. A term project will have students implement and evaluate several data assimilation methods on the same system to test their strengths and weaknesses. Example systems will be offerred, but students who bring their own relevant research questions will be encouraged to explore them.

Prerequisite Knowledge:

Students are expected to have background in multivariate ordinary and partial differential equations, probability and statistics, and linear algebra.

Student Learning Outcomes:

At the end of this course, students will be able to:

- Implement various formulations of a data assimilation (DA) system for a simple model;
- Select appropriate DA method based on system, method strengths and weaknesses; and,
- Evaluate the performance of a DA system.

Course Week-by-Week Outline:

Contents of the course or the length of time spent on a given topic may change based on interest in the class.

Week 1: Formulating the Problem: Bayes theorem. Defining the prior, posterior, and conditional probability density functions.

Week 2: Maximum A Posteriori Solution: Gaussian random variables and the Gauss-Newton iteration method.

Week 3: Smoother Formulation: Kalman smoother. MCMC and Metropolis-Hastings sampling methods.

Weeks 4-5: Variational Methods: 4D-Var with strong constraint, Lagrangian form. Deriving an adjoint model. Euler-Lagrange update equations. Weak constraint 4D-Var.

Week 6: Tangent Linear Approximation: 3D-Var, Kalman filter, optimal interpolation, and Extended Kalman filter.

Weeks 7-8: Ensemble Methods: Ensemble Kalman filter and sampling strategies, ESMDA, En4DVar.

Weeks 9-10: Non-linear Data Assimilation: Particle filters, improved proposals, localization and inflation.

Week 11: Analysis Characterization: Chi-squared, cross-validation, Desroziers diagnostics, and internal consistency.

Week 12: Design of Observation Systems: Information content, error characterization, well-posedness.

This list and order of topics is tentative at this stage, and may be appended, reduced, rearranged, or otherwise modified.

Textbook:

The following textbook will be followed in the course, although not always in order. The electronic version is available in the MacOdrum Library.

- Evensen, G., F. C. Vossepoel, and P. J. van Leeuwen (2022). *Data Assimilation Fundamentals: A Unified Formulation of the State and Parameter Estimation Problems*, Springer Nature, ISBN 978-3030967086.

Additional Reading:

Students are encouraged to read widely on the subject. Some relevant sources include:

- Law, K., A. Stuart, and K. Zygalakis (2015). *Data Assimilation: A Mathematical Introduction*, Springer Cham, Texts in Applied Mathematics, ISBN 978-3319203249.
- Rodgers, C. D. (2000). *Inverse Methods for Atmospheric Sounding: Theory and Practice*, World Scientific, ISBN 978-9810227401.
- Research articles from Roger Daley, Olivier Talagrand, Kikuro Miyakoda and many others.

Assessment:

Carleton University uses the twelve-point system for letter grades as follows:

90 – 100 %: A+	73 – 76 %: B	60 – 62 %: C-
85 – 89 %: A	70 – 72 %: B-	57 – 59 %: D+
80 – 84 %: A-	67 – 69 %: C+	53 – 56 %: D
77 – 79 %: B+	63 – 67 % C	50 – 52 %: D-

The final grade for the course will comprise a term-long project with submissions roughly every two weeks. Weightings are as follows:

Project Submissions (best 5 of 6)	50
Project Presentations	10
Final Exam	40

Course Policies

Communications

Course materials will be distributed through the course's Brightspace page. Students are responsible for ensuring they are correctly registered through Brightspace, and for checking the Brightspace course management site regularly. Lecture slides will be made available; however, material will be presented in class that is not accessible through the slides alone.

All electronic communications with the instructor must be through official Carleton email accounts. Effort will be made to respond to inquiries as quickly as possible, but please expect delays of up to 48 hours for a response. Complex technical questions should be addressed during office hours or by appointment.

Lateness

A 10% per day penalty will be applied to deliverables submitted after the deadline. Accommodation may be made for valid reasons, requirements for which are outlined below.

Final Exam

The final exam is for evaluation purposes only and exam papers will not be returned to the student. A minimum mark of 40% on the final exam is required to pass the course.

Appeals

All grade appeals in this course must be made to the instructor within one week of the posting date.

Course Material Copyright

Classroom teaching and learning activities, including lectures, discussions, presentations are copy protected and remain the intellectual property of the instructor. All course materials, including Powerpoint presentations, outlines, videos, and other materials are also protected by copyright and remain the intellectual property of the instructor. Students registered in the course may take notes and make copies of course material for their own educational use only. Students are not permitted to reproduce or distribute lecture notes and course materials publicly for commercial or non-commercial purposes without express written consent from the copyright holder(s). Students are not permitted to upload these copyrighted materials to any online repositories.

Academic Integrity:

Academic integrity is essential to the pursuit of learning and scholarship in a university, and to ensure that a degree from Carleton University is a strong signal of each student's individual academic achievement. As a result, the University treats cases of cheating and plagiarism very seriously. Carleton University's Policy on Academic Integrity (https://www.carleton.ca/registrar/academic-integrity) outlines the behaviours that constitute academic dishonesty and the processes for addressing academic offences. It is your responsibility to be familiar with these policies. Any students who do not act with academic integrity will face severe consequences including immediate referral to Associate Dean of Student Affairs.

Academic Accommodation:

Students with diverse learning styles and needs are welcome in this course. You may need special arrangements to meet your academic obligations during the term. For an accommodation request, the processes are as follows. For more information, please consult: https://students.carleton.ca/course-outline

Pregnancy Obligation

Please contact the instructor with any requests for academic accommodation during the first two weeks of class, or as soon as possible after the need for accommodation is known to exist. For more details, please consult: https://students.carleton.ca/course-outline

Religious Obligation

Please contact the instructor with any requests for academic accommodation during the first two weeks of class, or as soon as possible after the need for accommodation is known to exist. For more details, please consult: https://students.carleton.ca/course-outline

Accommodations for Students with Disabilities

The Paul Menton Centre for Students with Disabilities (PMC) provides services to students with Learning Disabilities (LD), psychiatric/mental health disabilities, Attention Deficit Hyperactivity Disorder (ADHD), Autism Spectrum Disorders (ASD), chronic medical conditions, and impairments in mobility, hearing, and vision. If you have a disability requiring academic accommodations in this course, please contact PMC at 613-520-6608 or pmc@carleton.ca for a formal evaluation. If you are already registered with the PMC, contact your PMC coordinator to send me your **Letter of Accommodation** at the beginning of the term, and no later than two weeks before the first in-class scheduled test or exam requiring accommodation (if applicable). **Requests made within two weeks will be reviewed on a case-by-case basis.** After requesting accommodation from PMC, meet with me to ensure accommodation arrangements are made. Please consult the PMC website (https://www.carleton.ca/pmc) for the deadline to request accommodations for the formally-scheduled exam (if applicable).

Carleton University has launched a new academic accommodation management system, Ventus. With Ventus, course instructors can view up-to-date information on their student's academic accommodation requirements, and submit and manage exam booking requests with the McIntyre Exam Centre. Ventusprovides students with more control over their accommodations on a per-course and per-test basis, and creates an improved user experience for students and faculty with real-time data in one shared web location. Students can request and manage their academic accommodations via the Ventus Student Portal (https://ventus.carleton.ca/student). More information on using Ventus, with overviews of the student and faculty portals, can be found on VentusHelp.

Survivors of Sexual Violence

As a community, Carleton University is committed to maintaining a positive learning, working, and living environment where sexual violence will not be tolerated, and survivors are supported through academic accommodations as per Carleton's Sexual Violence Policy. For more information about the services available and to obtain information about sexual violence and/or support, please visit: https://www.carleton.ca/sexual-violence-support

Accommodation for Student Activities

Carleton University recognizes the substantial benefits, both to the individual student and for the university, that result from a student participating in activities beyond the classroom experience. Reasonable accommodation must be provided to students who compete or perform at the national or international level. Please contact the instructor with any requests for academic accommodation during the first two weeks of class, or as soon as possible after the need for accommodation is known to exist. For more information, please consult: https://students.carleton.ca/course-outline

Special Information for Pandemic Measures

It is important to remember that COVID-19 is still present in Ottawa. The situation can change at any time and the risks of new variants and outbreaks are very real. There are a number of actions you can take to lower your risk and the risk you pose to those around you including being vaccinated, wearing a mask, staying home when you're sick, washing your hands and maintaining proper respiratory and cough etiquette.

Feeling sick? Remaining vigilant and not attending work or school when sick or with symptoms is critically important. If you feel ill or exhibit COVID-19 symptoms do not come to class or campus. If you feel ill or exhibit symptoms while on campus or in class, please leave campus immediately. In all situations, you must follow Carleton's symptom reporting protocols.

Masks: Carleton has paused the COVID-19 Mask Policy, but continues to strongly recommend masking when indoors, particularly if physical distancing cannot be maintained. It may become necessary to quickly reinstate the mask requirement if pandemic circumstances were to change.

Vaccines: Further, while proof of vaccination is no longer required as of May 1, 2022 to attend campus or in- person activity, it may become necessary for the University to bring back proof of vaccination requirements on short notice if the situation and public health advice changes. Students are strongly encouraged to get a full course of vaccination, including booster doses as soon as they are eligible, and submit their booster dose information in cuScreen as soon as possible. Please note that Carleton cannot guarantee that it will be able to offer virtual or hybrid learning options for those who are unable to attend the campus.

All members of the Carleton community are required to follow requirements and guidelines regarding health and safety which may change from time to time. For the most recent information about Carleton's COVID-19 response and health and safety requirements please see the University's COVID-19 website (https://www.carleton.ca/covid19) and review the Frequently Asked Questions (FAQs). Should you have additional questions after reviewing, please contact covid-info@carleton.ca.