PTE505: Inverse Modeling for Subsurface Flow Data Integration

(3 Units)

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Class Hours: Wednesdays 11:00 – 13:40 **Office Hours:** TBD

Teaching Assistant: TBD

Catalogue Description:
Introduction to fundamentals of deterministic and stochastic inverse modeling for calibration of hydrocarbon reservoirs and groundwater models, iterative and recursive integration of dynamic data into predictive flow and transport models, reservoir parameterization and adjoint methods.

Extended Course Description
This is a graduate course designed to introduce the fundamentals of inverse modeling and its application to integration of dynamic flow data into heterogeneous subsurface flow and transport models. The objective of the course is to provide students with inverse modeling tools that can be used to combine of dynamic data with prior knowledge of subsurface property models to construct reliable predictive subsurface flow and transport models. The course covers a broad range of topics including introduction to concepts in forward and inverse modeling, linear inverse problems, deterministic and probabilistic inversion methods, linear and nonlinear least-squares, gradient-based iterative methods, adjoint models, parameterization and regularization techniques, sequential estimation and Kalman filtering, ensemble data assimilation and forecasting, uncertainty quantification, and stochastic search methods.

Course Vision and Objectives
This course is designed to develop a fundamental understanding of how concepts in inverse modeling theory can be applied to integrate uncertain dynamic data into predictive models of subsurface flow and transport systems. Each topic of the course first introduces the related inverse modeling principles followed by a discussion of their importance and applications to characterization of subsurface systems.

Prerequisites
The material in this course would require basic familiarity with linear algebra, differential and integral calculus, and general reservoir engineering. Familiarity with MATLAB is useful but not essential.

Text Book
There is no required textbook for this course. Relevant reading material for each topic will be provided to students. The following is a list of textbooks that are closely related to the topics covered in this course.

1. Oliver S.D., Reynolds C.A., and Liu N. (2008): *Inverse Theory for Petroleum Reservoir Characterization and History Matching*, Cambridge University Press.
2. Tarantola A. (2004): *Inverse Problem Theory and Methods for Model Parameter Estimation*, Philadelphia, PA, Society for Industrial and Applied Mathematics.
3. Aster R.C., Brochers B., Thurber C.H. (2005): *Parameter Estimation and Inverse Problems,* Elsevier.
4. Evensen G. (2006): *Data Assimilation: The Ensemble Kalman Filter*, Springer.
5. Gelb A. (1974): *Applied Optimal Estimation*, MIT Press.

Course Grading Policy

Letter grade

Grade	A	B	C	D	F
Score	90-100	80-90	70-80	60-70	<60

Homework = 20%   Exam 1 = 50%   Project = 30%

Class Project

Each student is required to choose a topic for class project and confirm it with the instructor before week 6 of the class. A list of potential topics will be handed out to students during the first lecture to help with topic selection; however, students are also welcome to choose a topic that is of interest to them as long as it is approved by the instructor. Students are expected to provide two progress reports (weeks 8 and 12) that each carry 10% of the project grade, a 15-minute presentation (30% of the project grade), and a final project report (50% of project grade). Total contribution of the class project to final grade is 30%.

Lectures and Labs

Lectures are scheduled for Wednesdays 11:00–13:40. A number of computational lab sessions will also be scheduled for hands-on introduction to the required software packages that will be used in this course.

Homework

There will be a total of 9 homework assignments that contribute to 20% of the final grade. Problem sets will be provided at the end of the lecture on the specified dates in the tentative schedule sheet (to be distributed during the first lecture) and are due before lecture begins on the due date. Late homework submissions will not be accepted unless prior arrangement is made with the instructors. In addition to carrying 20% of the final grade, problem sets are a crucial part of the learning and will invariably have a major impact on understanding of the material and largely contribute to performance in the exams. In undertaking the problem sets, moderate collaboration in the form of joint problem solving with one or two classmates is permitted provided each student will write up their work and answers independently. Also, some of the problem sets may involve use of computers and software packages to provide students with an opportunity to explore different aspects of the lecture material and for gain hands-on experience. The two software packages that will be used in this course are ECLIPSE and MATLAB. Tutorial material on these packages will be made available for practicing and carrying out homework assignments.

Exams and Quizzes

There will be one exam for this course that takes place in Week 11 of the course. The exam will be designed to require 90 minutes of effort, but you will be given 120 minutes to reduce time pressure. The exam will be closed book. The required formulas and equations will be provided with the exam booklet.

EXAM DATES

Exam: (Week 11 of the class)

Statement for Students with Disabilities

Any student requesting academic accommodations based on a disability is required to register with Disability Services and Programs (DSP) each semester. A letter of verification for approved accommodations can be obtained from DSP. Please be sure the letter is delivered to me (or to TA) as early in the semester as possible. DSP is located in STU 301 and is open 8:30 a.m.–5:00 p.m., Monday through Friday. The phone number for DSP is (213) 740-0776.

Statement on Academic Integrity

USC seeks to maintain an optimal learning environment. General principles of academic honesty include the concept of respect for the intellectual property of others, the expectation that individual work will be submitted unless otherwise allowed by an instructor, and the obligations both to protect one's own academic work from misuse by others as well as to avoid using another's work as one's own. All students are expected to understand and abide by these principles. *Scampus*, the Student Guidebook, contains the Student Conduct Code in Section 11.00, while the recommended sanctions are located in Appendix A: http://www.usc.edu/dept/publications/SCAMPUS/gov/. Students will be referred to the Office of Student Judicial Affairs and Community Standards for further review, should there be any suspicion of academic dishonesty. The Review process can be found at: http://www.usc.edu/student-affairs/SJACS/

Detailed Syllabus , Lecture Topics, Class Discussion, Reading and Homework Assignments

Week 1

Lectures: Course introduction, objectives, and expectations*;* An overview of the course content and topics

Reading Assignment: Review of probability/statistics and liner algebra; Probabilistic representation of reservoir models; Static and dynamic production data integration (geostatistics and history matching);

Week 2

Lectures: Basic concepts in probability and statistics; Review of linear algebra and vector calculus;

Class Discussions: Uncertainty in subsurface reservoirs, deterministic versus probabilistic reservoir descriptions;

Reading Assignment: Chapter 1 of Aster et al.; Chapter 1 of Tarantola;

Homework Assignment 0: practice with probability, statistics, linear algebra, and vector calculus with example problems related to reservoir engineering; Statistical analysis of reservoir petro-physical data;

Week 3

Lectures: Deterministic methods for inverse modeling and production data integration; Linear inverse problems; Inverse modeling components: data, models, and algorithms; Least-squares formulation of inverse problems; Undertermined, overdetermined and even-determined inverse problems; Solution of ill-posed inverse problems: instabilities and ill-conditioning;

Class Discussions: Least-square formulation of history matching inverse problems; available data ill-posedness in reservoir history matching;

Reading Assignment: Chapters 2 & 3 of Asters et al; Chapter 1 of Tarantola;

Homework Assignment 1: Least-squares inversion for reservoir characterization; Regularization methods and solution of regularized inverse problems in reservoir engineering; Geophysical tomography;

Week 4

Lectures: Solution of ill-posed inverse problems; Singular value decomposition (SVD); Regularization techniques: objectives, forms, and formulations of regularized inverse problems; Tikhonov regularization; Total variation regularization; Determining regularization level (parameter)

Class Discussions: Regularization of reservoir history matching problems; regularization and geologic formations

Reading Assignment: Chapter 4 of Asters et al;

Week 5

Lectures: Nonlinear models and inverse problems; reservoir simulation as nonlinear forward model; non-linear least-squares; iterative solution techniques; gradients and sensitivities;

Class Discussions: Nonlinearity of reservoir dynamic data integration problems; solving history matching inverse problems with iterative techniques;

Reading Assignment: Chapters 9 and 10 of Aster et al.; Reading material on history matching problems

Homework Assignment 2: Iterative solution of nonlinear production data integration inverse problems; History matching optimization methods with Matlab; Derivation of gradients for reservoir simulation;

Week 6

Lectures: Iterative solution of non-linear history matching inverse problems; first and second order optimization methods; Adjoint method for calculating gradients and sensitivities in history matching problems

Class Discussions: Gradient calculation in history matching of reservoirs;

Reading Assignment 5: Chapter 9 of Oliver et al.; reading material handouts

Week 7

Lecture: Probabilistic inversion with Bayesian formulation; Probabilistic descriptions of data and models; Prior, likelihood, and posterior distributions; Bayesian inversion formulation;

Class Discussions: The need for probabilistic approaches to subsurface modeling; From theoretical constructs to practical applications: reservoir prediction and management under uncertainty;

Reading Assignment: Chapter 11 of Aster et al.; Chapter 1 of Tarantola; Chapters 4 and 7 of Oliver et al.

Homework Assignment 4: Practice with Bayesian inversion; Linear Gaussian case; Reservoir data integration example;

Week 8

Lecture: Analytical solutions for Bayesian inversion: the linear Gaussian case; Nonlinear problems; Point statistical estimate: Maximum Likelihood (ML) and Maximum A-Posteriori (MAP) estimates; Gaussian posterior approximation; Introduction to Monte-Carlo solution methods

Class Discussions: Bayesian formulation of history matching problems; ML and MAP estimates in history matching

Reading Assignment: Chapter 7of Oliver et al.; Chapter 3 of Tarantola;

Week 9

Lectures: Sequential state estimation; linear and nonlinear state-space models; Properties of estimators: bias and variance; Unbiased minimum-variance estimators; Derivation of Kalman filter for recursive estimation for linear models; Properties of the Kalman filter;

Class Discussions: Batch and sequential data processing in history matching; Modeling error and reservoir simulation; reservoir parameter estimation and balance equations;

Reading Assignment: Chapters 3 and 4 of Gelb; Reading material handouts;

Homework Assignment 5: Recursive linear estimation practice with reservoir examples; Kalman-filter algorithm for a simple linear model; Extended and ensemble Kalman filter for parameter estimation in linear models; Ensemble kalman filter for history matching;

Week 10

Lectures: Sequential estimation for nonlinear dynamical models; The extended Kalman filter; Limitations of extended Kalman filter; The ensemble Kalman filter: Monte-Carlo implementation of KF for nonlinear problems; Ensemble Kalman filter for reservoir history matching; Implementation issues of ensemble Kalman filter;

Class Discussions: Reservoir history matching with ensemble Kalman filter: advantages and challenges; Gaussianity and reservoir history matching;

Reading Assignment: Chapters 2,4,16 of Evensen; Chapter 11 of Oliver et al.; Reading material handouts;

Week 11

Exam

Week 12

Lectures: The need for reservoir model parameterization; Parameterization methods for history matching; Spatial parameterization methods: zonation and adaptive zonation methods

Class Discussions: Geologic continuity and parameterization of reservoir formations;

Reading Assignment: Reading material handouts on spatial zonation and adaptive form of zonation;

Homework Assignment 3: Practice with spatial zonation; Basis construction for transform domain parameterization methods; history matching problem formulation and solution with Matlab;

Week 13

Lectures: Transform-domain parameterization techniques; Generic and learned compression bases; Image compression transforms: Fourier and Wavelets; Principle component analysis (PCA) and truncated singular value decomposition;

Class Discussions: Transform-domain parameterization in history matching; Application of PCA, Fourier, Wavelet methods to history matching problems;

Reading Assignment: Reading material handouts on transform-domain parameterization methods: PCA, Truncated SVD, Fourier and Wavelets;

Week 14

Lectures: Advanced topics in inverse modeling and reservoir history matching: stochastic global search methods for history matching; simulated annealing and genetic algorithm; Markov Chain Monte-Carlo methods for history matching;

Class Discussions: Global and local search methods for history matching (pros and cons); computational notes on global search methods;

Reading Assignment: Chapter 2 of Tarantola; Reading material handouts;

Week 15

Class project presentations and evaluation;

Tentative Course Topics and Schedule

Week	Date	Lecture	Reading	Out	In
I. Course Introduction and Review Material					
Topic 1: Introduction					
1	28-Aug	T1L1: Course Information, Objectives, and Expectations	T1L1		
		T1L2: Course Overview	T1L2		
Topic 2: Probability/Statistics, Linear Algebra, Vector Calculus					
2	04-Sep	T2L1: Review of Probability, Statistics	T2L1	HW1	
		T2L2: Review of Linear Algebra and Vector Calculus	T2L2		
II. Deterministic Inversion					
Topic 3: Linear Inverse Problems					
3	11-Sep	T3L1: Inverse Modeling Elements: Data, Model, Algorithm	T3L1	HW2	HW1
		T3L2: Linear Least-Squares/ Under- & Overdetermined Problems	T3L2		
		T3L3: Generalized Least-Squares Problems	T3L3		
Topic 4: Regularization of Ill-posed Inverse Problems					
4	18-Sep	T4L1: Rank Deficiency and Regularization	T4L1	HW3	HW2
		T4L2: Regularization Forms (Tikhonov, Total variation)	T4L2		
5	25-Sep	T4L3: Regularization Parameter (L-Curve and Cross-Validation)	T4L3	HW4	HW3
		T4L4: Singular Value Decomposition	T4L4		
Topic 5: Nonlinear Inverse Problems					
6	02-Oct	T5L1: Solution of Nonlinear Least-Squares Problems	T5L1	HW5	HW4
		T5L2: Gradients, Sensitivities, and Iterative Linearization	T5L2	**Project Proposal Due**	
		T5L3: Gradient Calculation with Adjoint Model	T5L3		
III. Probabilistic Inversion					
Topic 6: Bayesian Inversion: Linear Case					
7	09-Oct	T6L1: Probabilistic Inversion: Prior, Likelihood and Posterior PDFs	T6L1	HW6	HW5
		T6L2: Bayesian inversion – The Linear Gaussian Case	T6L2		
Topic 7: Nonlinear Models					
8	16-Oct	T7L1: Nonlinear Bayesian Inversion	T7L1	HW7	HW6
		T7L2: Linearization of Nonlinear Inverse Problems	T7L2	**Progress Report 1 Due**	
		T7L3: Approximate Solutions: Point Estimates & Monte-Carlo	T7L3		
Topic 8: Sequential Linear Estimation					
9	23-Oct	T8L1: Properties of Estimators: Bias and Variance	T8L1	HW8	HW7
		T8L2: Derivation of Kalman Filter as Optimal Linear Estimator	T8L2		
Topic 9: Sequential Nonlinear Estimation					
10	30-Oct	T9L1: The Extended Kalman Filter (EKF)	T9L1	HW-HM	HW8
		T9L2: The Ensemble Kalman Filter (EnKF)	T9L2		
		T9L3: Properties and Implementation of EnKF	T9L3		
Topic 10: Application of EnKF to Reservoir Engineering					
11	06-Nov	T10L1: History Matching with EnKF	T10L1		
		T10L3: Implementation Issues and Challenges	T10L2	**Progress Report 2 Due**	
12	13-Nov	**MIDETRM EXAM**			
IV. Effective Model Description					
Topic 11: Parameterization					
13	20-Nov	T11L1: Parameterization of Subsurface Properties	T11L1		
		T11L2: Spatial Parameterization Methods	T11L2		
		T11L3: Transform Domain Parameterization	T11L3		
	27-Nov	**THANKSGIVING RECESS**			
Topic 12: Case Studies					
13	04-Dec	T12L1: Case Study 1	T12L1		HW-HM
		T12L2: Case Study 2	T12L2		
V. Project Presentation and Report					
14	**11-Dec**	**In Class Project Presentations**			
	13-Dec	**Final Project Report Due**			