USC University of Southern California

Reservoir Monitoring Consortium (RMC)

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Second Year Participation (Starting November 1, 2012)

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October 25, 2012

Reservoir Monitoring Consortium (RMC)

Executive Summary

The objective of the Reservoir Monitoring Consortium (RMC) is to develop new methods for dynamic reservoir monitoring. We will carry out a number of focused applied research projects in reservoir monitoring that are directly pertinent to the current and future needs of our industry sponsors. We will develop specific workflows for different types of reservoirs. These will include conventional reservoirs (e.g. carbonate, clastic, deep waters) and unconventional reservoirs (shales, tight sands, heavy oils, mature fields and geothermal). This will be preceded by the identification of the key technology gaps with input from the project sponsors. We will then focus on major issues such as integration of disciplines, data, information, and expertise. We will maintain a balance between short and long term, high impact research goals and the immediate and foreseen industry needs. One key distinguishing edge of RMC compared to other academic consortia is its focus on the multidisciplinary aspect of reservoir monitoring. This document highlights the current plans for second year participation, starting from November 1, 2012.

Introduction

Optimum reservoir management requires up to date information about different reservoir properties throughout the entire reservoir volume. Access to the latest data on fluid distribution in a reservoir and knowledge of how that distribution is changes with time, allows us to develop cost-effective strategies to optimize each field with the lowest possible risk. In the past, data used for reservoir monitoring and production optimization was limited to production and other well data. These included reservoir pressure and temperature, as well as oil water ratio. When a significant drop in reservoir pressure or oil production occurred, various enhanced oil recovery schemes were implemented. These methods, however, relied primarily on the production data that provided little information on the three dimensional distribution of the fluids inside the reservoir, making it difficult to devise an optimum strategy for the injection and production wells.

Dynamic reservoir characterization and more effective reservoir monitoring processes become even more important with major production declines in very large reservoirs or mature oil fields. Other important areas for reliable monitoring techniques include deep water reservoirs with expensive production platform and wells, shale oil and shale gas reservoirs, CO_2 injection processes, (both for EOR and sequestration) monitoring hydrofracking and well stimulation processes, revitalizing old or abandoned wells as well as heavy oil in-situ combustion and upgrading. Figure 1 shows a set of important practical problems and many tools that show promise to address these challenges.

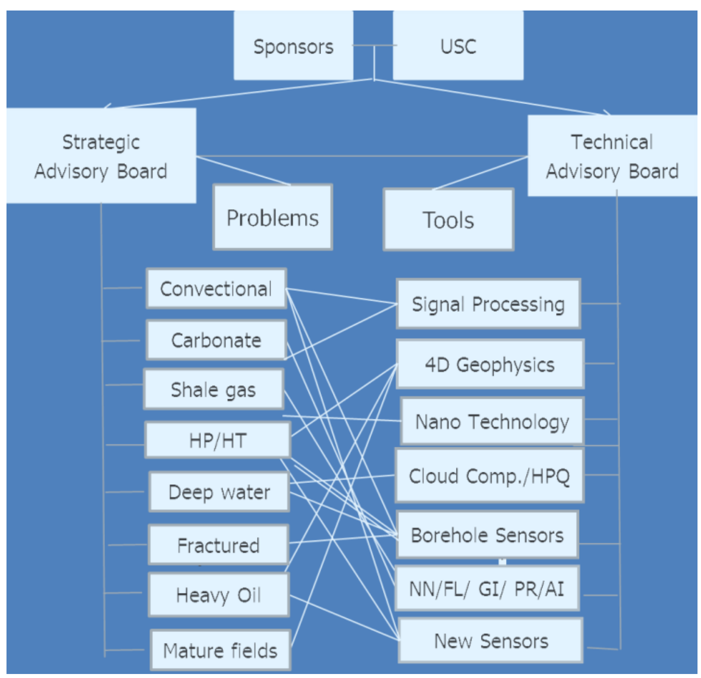


Figure 1- The Reservoir Monitoring Consortium Structure

In addition, we expect to have more direct industry sponsor involvement in different stages of the work. Every year, we will propose our Project Portfolio, comprised of a set of well-defined applied technology programs. The Project Portfolio Parts (PPP) will go through internal reviews, revisions, integration and ranking processes. We will then ask the sponsors, represented at the strategic and technical advisory boards, to further enhance the ranking of different projects. If particular sponsors, or a small group, have a keen interest in particular PPPs that are not selected for immediate funding by the entire RMC membership, they may consider funding them independently on an exclusive basis.

The main themes of our research plan are correlated with the technical expertise of our faculty and our ongoing general R&D focus areas. The following represent some of the main topics we expect to focus on:

Main consortium themes:
- 4D volumetric inversion for pressure, saturation, and permeability changes.
- Integrated reservoir model updating and history matching.
- Passive seismic monitoring.
- Seismic acquisition, processing and analysis for CO_2 sequestration & monitoring.
- Special issues for reservoir monitoring of mature oil fields, carbonate reservoirs or heavy oil.

When certain technical capability lacking from the tools available at USC is deemed necessary to address specific practical challenges, we will partner with others to supplement our capabilities. This may include involving our adjunct professors or other experts in a complementary fashion. We will also seek opportunities to collaborate with other universities, national laboratories as well as partners in industry to explore opportunities for technical cooperation. This would also include the possibility of an arrangement for visiting scientists or visiting scholars from both academia and industry.

Recent advances in sensor development and the introduction of new data types, as well as new data processing, analysis and integration methods have enabled more effective reservoir monitoring. Inclusive to this is the use of time lapse geophysical data (e.g. 4D seismic), passive seismic and borehole to borehole data.

Table 1- Different sensor measurements with sensitivity to specific physical properties correlated with reservoir properties

Geophysical technique	Physical property measured	Reservoir property inferred
Time lapse or 4D surface seismic,vsp, X-well seismic	Changes in amplitude, arrival time, seismic waveform	Fluid saturation, pressure changes
Microseismic continuous monitoring	Passive seismic waves from rock shear failure w/ stress perturbations	Fluid flow pathways Flow anisotropy
EM borehole and surface measurements	Electrical resistivity changes	Saturation 4D changes
ElectroSeismic (ES)	Seismic from electro-kinetic coupling changes Resistivity changes	Saturation 4D changes
Micro-gravity surface & borehole	Density differences Minute gravitational field change w/ fluid phase	Saturation 4D changes

Table 1 shows a list of different geophysical techniques, including time lapse or 4D seismic data, microseismic data, electromagnetic, electro-seismic, and micro-gravity data. In addition, Table 1 shows what type of data is most sensitive to specific physical properties and which reservoir properties can be inferred from the measurement of different physical properties through different sensing methods. For effective reservoir monitoring, or observing changes in the fluid and pressure, it is important to integrate different types of data on Table 1 with other data such as petro-physical and production data. Different Project Portfolio Parts (PPPs) that will be described below will elaborate further on how we will go through the process of data fusion to quantify changes in reservoirs on different practical settings and how the results will help us improve reservoir management.

Potential invited sponsors:
A broad base of organizations including major and large independent oil companies, national oil companies, and service companies are the key expected project sponsors. We will also encourage participation from companies who have strong technical ties with the oil and gas industry. These include companies who develop computer hardware, software or sensors and networks to address reservoir related problems. Our sponsors will have the flexibility to support our efforts through different means. They will include unrestricted gift contributions and fellowships sponsoring specific students. To fully benefit from ongoing technical developments in small software and service companies that may not be in a position to fully support RMC, we will encourage their participation through mutually agreeable manners. Such might include a voluntary payment, in kind contribution or providing hardware, software or manpower to assist with of our research work.

Benefits to sponsors:
In the following, we describe some of the benefits sponsors and project participants will receive.

- Access to low-cost, leading-edge research in an area of interest to sponsor.
- A mechanism to leverage contributions from multidisciplinary research that would otherwise be unavailable to some sponsors due to lack of internal expertise or infrastructure
- Staff training for manpower capabilities.
- Recruiting opportunities and access to potential hires with expertise in reservoir characterization and real time reservoir monitoring.

Consortium membership year: November 1st – October 30th

Sponsorship Fee- The annual fee to sponsor RMC is set at $50,000. The sponsorship fee can be paid in the form gift contribution (preferred, to reduce the university overhead charge) or contract research. The delivered results in both cases will be the same. For smaller oil and service companies alternative arrangements will be made for part of the fees to be paid in the form of in kind contribution, direct student support or fellowship. All companies will have to send the commitment letter by November 15th 2012. A late entry fee of 50% of the first year sponsorship fee will be applied to the new members, entitling them to receive the results of the first year.

For those companies who choose the gift contribution route, we request an email stating that they pledge to provide USC with a restricted gift for the amount to be paid, according to a given payment schedule. They also should express their preference that the funds to be used for RMC related research under the direction of Dr. Aminzadeh and the other CO-PIs. Those who choose to support the project under contract research should state their preference and we will send out the contract to be finalized.

Meetings: The inaugural meeting was held September 14-15, 2011, on the campus of the University of Southern California. We expect to conduct brief meetings during the annual SPE and SEG meetings. We tentatively plan to hold our annual meetings on November 16^{th}, 2012 at the USC campus.

Advisory Board: Strategic and Technical Advisory Boards (SAB and TAB) will provide general direction and schedule priorities regarding problems to be addressed and the tools considered. We expect the majority of our SAB will be comprised of the high level management from innovative sponsoring companies that can help guide RMC strategically. The TAB members are expected to be comprised mostly from the technical staff of the sponsoring companies (in many cases the main contact person from each company to RMC) and USC Co-Principal Investigators. We may invite to our SAB and TAB participation of selected people that can contribute to RMC and its leadership both from strategic and technical viewpoints. Each RMC sponsor is requested to provide us with one candidate for inclusion in our SAB and TAB

Project Portfolio

Here, we will highlight different components of our R&D project. We will refer to each as the particular Project Portfolio Part. To simplify references, we will regard each as PPP(n)(x), where n refers to the project number and x refers to the first principal investigator named in the project. Based on the feedback from both physical and remote participants in our inaugural meeting we have selected 6 out of the 17 projects for funding through the consortium. Other projects may be considered in the future and/or funded exclusively by some of the members of consortium or others.

The projects to be funded through “Base Membership” in the project are as follows. Projects are listed in order of combined ranking from the project evaluation. Some of the companies have expressed the desire to support the projects not included in the list below through “Individual Company” support. They should express their wishes via follow up communication in order to make the necessary arrangements.

Companies may select other projects from the Individual Company list provided below. Such projects could be supported by an individual company or a sub-group of companies. Furthermore, all the projects or an appropriately modified version of these projects could be considered as basis for proposals to be submitted to different government of funding agencies for external support.

Base Membership Project Portfolio

1. **PPP10BJ- Optimization of Hydraulic Fracturing in Unconventional Reservoirs:** Numerical optimization algorithms will be developed that can be combined with flow simulation to improve the design and implementation of hydraulic fracturing, so as to increase the productivity and net present value of unconventional assets.
2. **PPP7FA- Integration of Microseimic Data for Fracture Characterization:** Low permeability unconventional resources are typically produced through injection-induced stimulation (hydraulic fracturing). In this project, we plan to develop novel methodologies for integration of microseismic data into reservoir and fracture models for improved characterization and long-term production from unconventional reservoirs.

3. **PPP5CS- Using Microseismicity to Map Reservoir Structure:** The locations and magnitudes of small events will be used to determine the structure of the fracture network from which geothermal fluids are being produced. The observed structure and magnitude distribution also indicates whether the microsesmicity is triggered or induced. This project will be combined with the project PPP8MS: Development of Dynamic Models of Fractured Reservoirs based on Unstructured Grid and Discrete Fractures, and Their Up-scaling, in an attempt to develop flexible, accurate, and efficient models of fractured reservoirs in order to set aside double-porosity and similar models, incorporate recent advances in multi resolution computations in the model, and take into account the evolving nature of the models of fractured reservoirs that is based on 4D seismic characterization and dynamic history matching.

4. **PPP12SW- Understanding impact of reservoir fluid on seismic response using physical modeling-** Here, we conduct physical modeling experiments with the aim of predicting the impact of the reservoir fluid changes on the seismic response. Such physical modeling examines the effectiveness of time lapse seismic data in monitoring changes in reservoir fluid distribution in different geologic settings.

5. **PPP15DH- Time Lapse Petrophysical Reservoir Monitoring and Evaluation of Reservoir Characterization Sensitivity-** Using MWD, LWD and SWD, we would evaluate the sensitivity of various existing and potential reservoir petrophysical monitoring and characterization protocols to meet the reservoir monitoring needs of existing and future conventional and unconventional reservoirs.

6. **PPP16AO- Reservoir Modeling using Tomography based on Field Operation Data-** We propose to use novel injection (water, steam, etc.) schedules and to monitor gross fluid production in order to actively measure the response time between well-pairs without altering the average daily operations. With the well-pair response time, we will develop object-based algorithms to identify the heterogeneous structures. These object-based algorithms will be designed specifically to provide robust performance when high contrast structures are detected (e.g., high permeability channels).

For more details on these projects see Appendix 1.

Individual Company Project Portfolio

The following project could be considered for support by an individual company and/or used as a basis for proposals to government or other funding sources for external support.

1. **PPP1FA- Incorporating soft computing in time lapse monitoring:** Fuzzy logic and neural network will be used to detect subtle changes in the data for improved monitoring. The tools are expected to be applicable to time lapse monitoring on many data type. Numerical synthetic models (for example SEG SEAM Models) will be used to observe the impact of changes in the velocities, caused by changes in reservoir fluids on the seismic response, thus determine the effectiveness of time lapse data in a given situation.

2. **PPP2CA- Efficient data management for real-time reservoir monitoring and management:** To enable real-time reservoir management, efficient data management (i.e., effective processing, archival and querying and analysis of the reservoir data) is a requirement. The focus will be on three specific reservoir data management challenges: real-time processing of continuous reservoir data streams; rapid querying of archived reservoir data; dynamic reservoir characterization, and in particular, dynamic history matching; and cloud-based reservoir data management.

3. **PPP3JA- Inverse modeling and parameter estimation of nanoparticle transport in geological formations:** Obtaining operational data, including reservoir temperature, steam quality, solvent and catalysts concentration and reservoir pressure, both near the wellbore and far in the producing formations, is very essential to the optimal performance of the heavy oil recovery processes, such as steam-assisted gravity drainage (SAGD), vapor extraction (VAPEX), in situ combustion, air injection and in situ upgrading. Conventional approaches for managing heavy oil recovery process performance relies on measurements at or in the vicinity of the wellbores. This approach is insufficient for the delineation of anomalies that have been observed during these heavy oil recovery processes. This is particularly important, given the heterogeneous nature of the producing formations.

4. **PPP4JA- Applications of nanotechnology for reservoir monitoring:** The focus is on the investigation of the effects of various operational parameters on the success of engineered nanosensors injection into porous media for the specific purpose of in situ property measurements. We will determine the resolution of estimates of properties that can be obtained from various combinations of sensors and various specifications on sensor precision.

5. **PPP6BJ- Feature-based Reservoir Characterization:** Geologic formations and their physical properties often form spatially correlated and connected structures. Reconstructing a grid-based description of these structures from limited static and dynamic data poses the risk of losing spatial connectivity, which is critical for field development planning. We propose to develop featured-based property description and identification algorithms that respect and preserve natural and formation-specific geologic continuity.

6. **PPP8MS- Development of Dynamic Models of Fractured Reservoirs based on Unstructured Grid and Discrete Fractures, and Their Up-scaling:** The goal is to

develop flexible, accurate, and efficient models of fractured reservoirs in order to set aside double-porosity and similar models, incorporate recent advances in multiresolution computations in the model, and take into account the evolving nature of the models of fractured (or even unfractured) reservoirs that is based on 4D seismic characterization, dynamic history matching, and other time-dependent properties and information.

7. **PPP9BJ- Early Characterization of Reservoir Connectivity for Improved Field Development Planning:** Construction of reliable geologic models and early characterization of field-scale reservoir connectivity are critical for accurate assessment and effective development of producible hydrocarbon in a reservoir. A novel technology will be developed and applied for capturing large-scale reservoir continuity at early stages of field development to improve the prediction of future production and facilitate development strategies for increased recovery efficiency. This objective will be achieved by integration of reservoir dynamic response at early stages of development into low-dimensional parametric descriptions of large-scale field connectivity.

8. **PPP11KJ- Upscaling for Compositional Simulation of EOR Processes:** With a steadily increasing number of oil fields becoming candidates for enhanced recovery methods such a miscible gas injection and WAG processes, the need for effective and accurate upscaling techniques that are suitable for compositional simulation at large scale is now greater than ever.

9. **PPP13UM- Underwater Acoustic Communications Network Design for Reservoir Sensing Systems-** High performance reservoir monitoring will require a heterogeneous network of sensor systems with a combination of cabled and wirelessly communicating devices. Given the unique features of reservoir topology and underwater acoustic communication channels, a thoughtful sensing network design is required. We propose to determine network topologies and protocols suitable for such heterogeneous networks.

10. **PPP14UM- Acoustic Waveform Design for Joint Sensing and Communication-** We will examine jointly optimized waveforms for communication and sensing. In particular, communication and sensing metrics will be coupled so that a joint design can be enabled. Due to implementation considerations, we propose to focus on the use of modified orthogonal frequency division multiplexing (OFDM) waveforms.

11. **PPP17AO- Reservoir Data Visualization Using Graph Wavelets -** As tools for reservoir modeling advance, it becomes easier to obtain very high resolution simulations of reservoir characteristics. However, these 3D or 4D models are often difficult for end users (scientists, engineers) to visualize without access to high workstations and visualization software. Our goal is to make it possible for users to visualize this information using portable off-the-shelf devices, e.g., tablet computers. We aim to make complex geophysical simulation data easily available to remote users in order to facilitate interaction and team collaboration.

For more details on these projects see Appendix 2.

Appendix 1- Detailed Project Descriptions for Base Membership Projects

1- PPP10BJ

Key People: Behnam Jafarpour and Ph.D. Student (TBD)

Project Name: Optimization of Hydraulic Fracturing in Unconventional Reservoirs

Core Technical or Practical Problem(s) we are addressing

Production from low permeability unconventional reservoirs is accomplished through engineered hydraulic fracturing to generate pathways for gas flow from rock matrix to the production wells. While hydraulic fracturing technology has progressed considerably in the last thirty years, current practice in designing the fracture systems primarily involves subjective engineering decisions. We plan to develop numerical optimization algorithms that can be combined with flow simulation to improve the design and implementation of hydraulic fracturing to increase the productivity and net present value of unconventional assets.

Long term vision of how this impacts the industry

The ultimate goal of the project is to develop practical optimization tools to enhance production from unconventional gas resources. The significance of the proposed developments for optimization of unconventional reservoirs can be readily appreciated by observing the latest trends and emerging technologies in developing conventional reservoirs (e.g., smart fields, closed-loop reservoir management) and the limitations and challenges of the current practice in producing unconventional reservoirs. The main outcome of this project will be the development of a systematic approach to implement simultaneous optimization strategies for well trajectory and hydraulic fracture design in unconventional reservoirs in order to maximize production and realize better economic decisions.

Recent related activities in the industry/academia

During the past two decades, significant progress has been made in optimizing recovery from conventional resources. Model-based optimization strategies have been shown to outperform reactive control methods (opening and shutting wells) and improve on the recovery factor even when uncertain reservoir models are used. In addition, well placement decision has been largely facilitated by numerical optimization tools. Similar optimization developments can be developed to guide hydraulic fracturing by controlling the location and intensity of stimulation used to create fracture networks.

Brief Project Description

In this project, we will develop algorithms for fracture placement and optimization to facilitate the design of hydraulic fracturing systems. The main optimization problems are related to planning the best well trajectory for fracturing, designing the fracturing intervals for a selected trajectory, scheduling the fracturing sequence and adjusting the fracturing intensity at different locations, all based on an estimate of recovery potential in different regions of the reservoir as implied by flow and volumetric properties. As depicted in Figure 1, we will consider a hierarchical optimization approach with outer and inner loops. The outer loop of the hierarchical optimization deals with finding the best trajectory for drilling wells based on reservoir properties. The optimization will include constraints to ensure drilling feasibility of the well trajectory as well as geologic considerations including pay zones and spatial variability in reservoir properties. Each iteration of the outer loop is used to update the well trajectory and is followed by an inner loop optimization to optimize fracture interval and intensity (see Figure 1).

The sequence of outer and inner loop optimizations continue until no significant improvement in the objective function (i.e., project NPV) is observed or a stopping criterion such as maximum number of iterations is reached. The proposed optimization workflow described in this proposal is based on reliable knowledge of spatial distribution of reservoir properties such as porosity, permeability, and geo-mechanical properties. Reservoir property descriptions are, however, highly uncertain. Two important sources of information that can be used to improve reservoir property description are static data (such as well logs, core data and cross-well seismic) and dynamic data such as production and microseismic. The static data is often incorporated through geostatistical techniques while the dynamic data can be incorporated using non-linear inversion methods. While, these components are not within the scope of the current project, they can in general be used to provide information about reservoir property distribution.

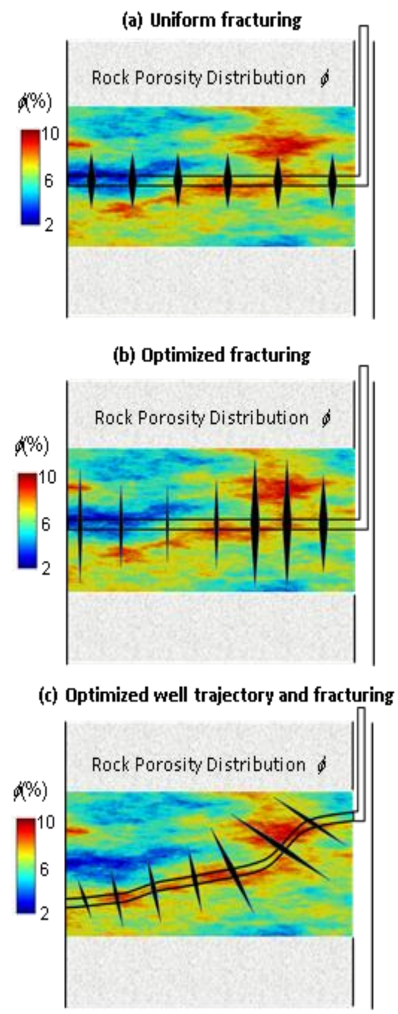


Figure 1. Demonstration of the proposed optimization workflow using a porosity map: (a) uniform fracturing; (b) inner loop optimization of fracture locations and intensity; (c) combined optimization of well trajectory and fracture design.

Immediate plans and goals for 2012-2014

The following tasks will be carried out in the first two years of the project.

- Development of fracturing well trajectory optimization algorithm (outer loop).
- Development of fracture optimization algorithms to identify fracture intervals and intensity for a fixed well trajectory (inner loop).
- Integration of fracture well trajectory optimization and fracture interval/intensity optimization to develop a hierarchical optimization algorithm.
- Fine-tuning and sensitivity analysis to evaluate the performance of the developed algorithms under geologic uncertainty.
- Preliminary test cases to evaluate the suitability of developed methodology before application to benchmark models and field data.

Deployment and testing plans

The developed framework will be validated using stimulation data from synthetic models as well as realistic field datasets provided by sponsor members.

Desired interactions with the sponsors

1. Technical interactions with sponsor members are essential for achieving planned milestones and ensuring satisfactory progress and completion of the project. We will work together with sponsor members to address specific issues encountered in their common practices and in benchmarking the developed strategies with realistic field data.

2. Sponsor members are welcome to provide field data to USC for our test cases. The case studies can be conducted either exclusively with each individual sponsor (to honor confidentiality) or with involvement of other sponsors. Depending on the sponsors' requirements, appropriate mechanisms will be designed for funding and other related logistics.

Key references

1. Brouwer D.R., Jansen J.D. (2004): Dynamic optimization of water flooding with smart wells using optimal control theory, SPE J. **9** (4), 391–402.
2. King G. (2010): Thirty years of hydraulic fracturing: what have we learned?, SPE-133456, presented in 2010 SPE Annual Technical Conference and Exhibition, 19-22 September, Florence, Italy.
3. Li L., Jafarpour B., Mohammad-khaninezhad M.R. (2011): A generalized simultaneous perturbation stochastic approximation algorithm for field development optimization: coupling well placement and control, Computational Geosciences, in revision.

2- PPP7FA

Key People: Fred Aminzadeh, Tayeb Tafti, and Debotyam Maity

Project Name: Integration of Microseismic Data for Reservoir Characterization

Core Technical or Practical Problem(s) we are addressing

We will study the use of microseismic data for monitoring changes in unconventional reservoirs. The aim is to better understand the complexity of the fracture networks in the subsurface and how they change with hydrofracing. Thorough understanding of the fracture network helps optimize the stimulation process and is of high importance to reservoir engineers. There are many useful tools which can be used for better understanding of the fractures created in the subsurface by injection induced stimulation. In addition to performing the traditional studies, we will look into relatively new approaches including:

1. Shear wave splitting (SWS) studies to determine fracture density/ orientations.
2. Multiplets analysis and fractal analysis to detect fracture patterns and movements which may differ from overall event distribution.
3. Integration of microseismic with conventional seismic data and other geophysical data types in an integrated interpretation approach.
4. Creating accurate fracture and property models from microseismic events to characterize time lapse anomalies.

These studies should reveal additional properties of the reservoir or enhance the resolution/ coverage of estimates being made. Our goal is to provide additional information to the reservoir engineer to allow for optimized field development especially in shale oil and gas reservoirs where sufficient microseismic activity is present during the hydraulic fracturing process for useful analysis. More importantly, monitoring changes in the velocity model and induced microseismicity over multiple stimulation stages along with establishing the cause and effect relationship between stimulation and observations can provide us a method for assessing the effectiveness of different stimulation methods and allow improved understanding of the stimulated area. Enhanced fracture network models should allow for better reservoir simulations studies and better field management over the long term.

Long term vision of how this impacts the industry

The proposed method should allow for *better reservoir property estimations* including *better fracture network modeling* which will help in improving reservoir management. It should enable reliable fracture network characterization including time lapse propagation and *improved long term production estimates*.

Recent related activities in the industry/academia

Passive seismic monitoring is a heavily used and necessary tool in most unconventional reservoir developments involving hydraulic fracturing or injection schemes. Because of the importance of unconventional resources in the US, this topic is receiving significant attention from both industry as well as academia. In the past, passive seismic data has been used extensively for fracture growth detection, fracture properties and stimulated zone estimation as well as rock property estimates. It has also been used for monitoring of injection processes over time. Most studies have used MEQ cloud location/ distribution to obtain useful fracture property estimates. Some also involve integrating conventional seismic data and advanced algorithms such as ant tracking schemes for better fracture characterization. Work has been done on 4D reservoir characterization using passive seismic data as part of hydraulic fracturing process.

Passive seismic tomographic inversion is a well understood technique and has been used for multiple property estimates. Microseismic data have also been combined with available fracture models using different concepts (see Figure 1 as an example) leading to improvements. Over the last few years, rapid progress has been made to better understand the reservoir and monitor for any divergent conditions or to take advantage of any additional information/ analysis in production optimization.

While full utilization of many capabilities is still limited, a holistic integrated approach is also missing in the way passive seismic data is being used today. Major issues include associated high costs, evaluation time as well as the approaches/ techniques used.

Brief Project Description

We discuss the project activities in the context of proposed workflow (Figure 2).

1. Advanced autopickers under development at USC are able to pick both compressional (p) and shear (s) wave arrivals with high accuracy. We will use these arrival times to generate event locations using tomographic inversion.
2. We will find the spatial structure and frequency-magnitude (Gutenberg-Richter) distribution of microseismicity to obtain additional information about the fracture network. Since events usually occur on the existing fracture network, fractal analysis can illuminate its underlying structure.

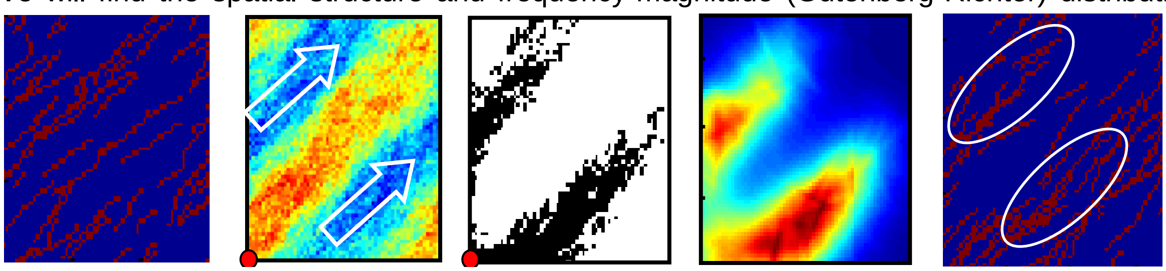


Figure 1: Example showing the workflow for integration of microseismic data into fracture model using fracture probability map concept: (a) prior fracture model; (b) rock criticality map showing the distribution of rock strength (a well is located on bottom left corner of the field, shown with red circle); (c) simulated microseismic data after hydraulic fracturing; (d) quantified fracture probability map generated from the microseismic data in (c); (e) updated fracture model after integration of microseismic data through fracture probability map. Notice that the updated fracture model is more consistent with the microseismic events indicating the location of high fracture density.

3. Compressional and shear wave velocity models will be generated from microseismic events and these will be integrated with other data such as borehole logs and core data to constrain models and to reveal properties of the reservoir such as porosity and fracture density.
4. We will ascertain fracture orientation, density maps and clusters using shear wave splitting phenomenon and multiplets analysis.
5. We will use seismic attribute analysis along with conventional seismic data to map fractures/ faults in an integrated fashion with MEQ's and reservoir properties derived from passive seismic data.
6. We will develop a fracture characterization framework for improved characterization of unconventional reservoirs. This will be accomplished by integrating microseismic data with production measurements into fracture model descriptions using advanced inverse modeling techniques.
7. We have the tools and the capability to tie the well logs with corresponding reservoir properties (e.g.: fracture density) and also to implement AI interpretation techniques (such as FL-ANN integrated learning schemes) to develop constrained reservoir property models.

3-- PPP5CS (combined with PPP8MS)

Key People: Charles Sammis, Muhammad Sahimi, and Fred Aminzadeh

Project Name: Dynamic Mapping of Fractured Reservoirs

Core Technical or Practical Problem(s) we are addressing

We use the locations and magnitudes of small events to determine the structure of the fracture network from which geothermal fluids are being produced. The observed structure and magnitude distribution also indicates whether the microsesmicity is triggered or induced. Despite decades of research, modeling of fractured reservoirs is still mostly based on the double-porosity model, even though its inadequacy for modeling of most of such reservoirs is well-documented. Some progress has been made, but the problem is still largely unsolved. At the same time, even if the geological model of a fractured reservoir can be adequately developed, up-scaling for use in reservoir simulation is still a major problem. Finally, with the advent of dynamic reservoir characterization, the development of a flexible model that can incorporate rapidly the newly arrived data and information and upscale the model has become paramount. Some of the major problems that one must address are:

1. How to adequately represent the widely disparate relevant length scales in a single model: Oil and gas reservoirs are highly heterogeneous at several distinct and widely separated length scales. Every relevant length scale may contain certain information that is useful, and even crucial, to the overall accuracy of the model.

2. How to represent the fracture and the matrix accurately, given the heterogeneous distribution of the former: As is well-known, fractures are not distributed as in the double-porosity model, which assumes a well-connected fracture network in the form of a cubic network, or some perturbations of it. They are distributed non-uniformly with the fractures' orientations and lengths following statistical distribution. If there are only a few dominating fractures that control most of the fluid flow, the problem is even more difficult.

3. How to model the interaction between the matrix and the fractures, given the large differences between the permeabilities of the two: A uniform grid cannot represent the interface between the two.

4. Even if an accurate geological model of a fractured reservoir is developed, the question of its up-scaling to a coarse, yet accurate level, is still a major challenge: Practically, all the current up-scaling methods are inadequate when it comes to fractured reservoirs. Thus, one must resort to empirical, semi-empirical, and curve fitting in order to develop the up-scaled model.

5. Given the advances in dynamic reservoir characterization, and in particular dynamic history matching, any model must be flexible enough to be able to handle new incoming information and data, incorporate them in the model, and up-scale it quickly, in order to maintain the model up to date.

Long-term vision of how this impacts the industry

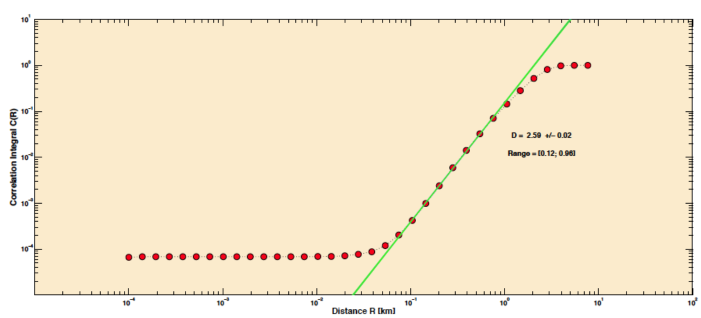
A detailed map of the fracture network can be used in formulating extraction strategies, as it is an improvement on the dual-porosity models commonly used to model fracture dominated reservoirs. A determination of whether the microseimicity is induced (event energy comes from the injection itself through pressure or thermal contraction) or triggered (energy comes from the release of stored tectonic stress) is important in assessing the risk of causing a large destructive earthquake. This risk is low for induced seismicity and higher for triggered seismicity.

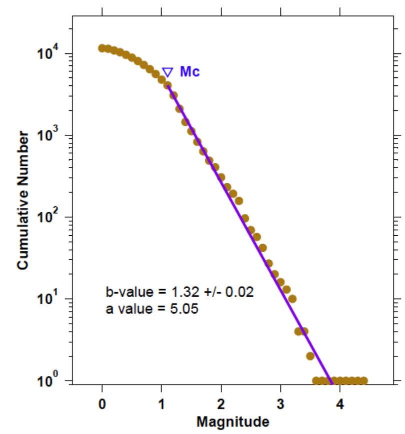
Recent related activities in the industry/academia

It has long been known that tectonically driven fault networks are self-similar (fractal) with a fractal dimension near D_f=2 in 3 dimensions. It is also known that the *b*-value (the slope of the Gutenberg-Richter frequency-magnitude relation) is near *b*=1 in tectonic regimes. Theoretical analysis of seismicity on a fractal network shows that the fractal dimension and b-value should be related as b=2D_f, which matches observation. It is also known that the b-value in volcanic and geothermal areas is significantly higher than *b*=1 as is the fractal dimension of the seismicity (if it is fractal, which is not always observed).

Brief Project Description

We are currently mapping microseismicity in The Geysers geothermal reservoir and measuring the fractal (correlation) dimension and *b*-value for selected clusters of activity. Our preliminary results find high b-values approaching *b*=1.3 and correspondingly high fractal dimension approaching D_f=2.6. The implication is that we are observing induced seismicity and the risk of triggering a large tectonic earthquake is low. Our working hypothesis is that tectonic seismicity is limited to the near-vertical faults in the network since they have lower normal stress and hence less frictional resistance to shear. Induced seismicity involves volume change and is not necessarily favored on vertical fractures. Since the entire fracture network is active, the observe dimension is near D_f=3 and the corresponding *b*-value approaches *b*=1.5.





1. To address the problem of incorporating all the relevant length scales in a single model, we have developed use of multiresolution wavelet transformation that is capable of addressing the multiscale nature of the problem.
2. To address the problem of incorporating a non-uniform spatial distribution of fractures, we have been working on the development of discrete fracture network models that are totally flexible and can represent practically any spatial distribution of fractures.
3. To address the problem of how to represent the interactions between the matrix and the fractures, we have been developing a method that combines three essential ingredients: (i) Use of a totally unstructured grid; (ii) representing the fracture as merely the high permeability paths, and (iii) use of multiresolution wavelet transformation to determine the density of the grid not just the in the matrix, but also around the interface between the matrix and the fractures. Two-dimensional models have been developed, and we have begun the development of 3D model based on advancing front technique and the aforementioned three ingredients.

4. To address the problem of up-scaling of the geological model of fractured reservoirs, we have been developing a method based on the use of wavelet transformation. The method has already been developed for the unfractured reservoirs and, in addition to its high precision, has been shown to be computationally more efficient than the best alternative by at least three orders of magnitude. Due to the nature of the wavelet transformations, its use for fractured reservoirs is natural, and the model
5. Due to its flexibility and extremely high efficiency, incorporation of new data that may become available dynamically poses no major problem with the models and methods that are developing.

We have extensive experience in developing techniques for addressing all the major problems that may arise. For example, we have been developing novel techniques for the analysis of cross-correlations between various types of data, including well logs. In addition, we have been studying elastic wave propagation in heterogeneous media and the effect that large-scale heterogeneities and long-range correlations have on the wave propagation and its localization, which are completely relevant to the interpretation of seismic data.

Here, we propose to develop an integrated method that addresses the five major problems listed above, and develop a flexible, accurate, and highly efficient technique for the development of models of fractured reservoirs that are also flexible enough to be able to be used in conjunction with dynamic reservoir characterization.

The model may also be easily integrated with what other members of the RMC are doing, or plan to do, such as the groups led by Fred Aminzadeh, and by Cyrus Shahabi, since in order to update the upscaled model one needs fast processing of the new data and their incorporation in the geological model, in order to efficiently upscale the model.

Immediate plans and goals for 2012-2014

We plan to enhance the fractal analysis by using the magnitude information. The idea is that larger events involve a larger fracture (or fault plane) so we can incorporate this information into our ultimate fracture map. This has, to our knowledge, never been done.

Deployment and testing plans

We would like to apply this analysis to other reservoir seismicity data.

Desired interactions with the sponsors

1. We expect the sponsors who are members of SEAM facilitate USC access to the models and the corresponding 3D synthetic seismic volumes developed under SEAM
2. Sponsors can suggest which models should be considered for our tests.
3. Any sponsor who may wish to provide real data can work directly with USC to test the results using their data. This part of the work can be either exclusive with that sponsor (if the results are to be kept confidential) or other sponsors can be involved in the tests. Accordingly, different funding mechanism for this part of the effort may be required.

Key references

1. Tayeb A. Tafti, Muhammad Sahimi, Fred Aminzadeh, and Charles G. Sammis, 2011, Using Microseismicity to Map the Fractal Structure of the Fracture Network at The Geysers Geothermal Field in California, Bull. Seism. Soc. Am., submitted for publication.
2. Wyss, M., C.G. Sammis, R.M. Nadeau, and S. Wiemer, 2004, Fractal dimension and b-value on creeping and locked patches of the San Andreas Fault near Parkfield, California, Bull. Seismol. Soc. Amer., 94, 410-421.

3. Sammis, C.G., L.-J. An, and I. Ershaghi, 1992, Determining the 3-D fracture structure in The Geysers geothermal reservoir, Proc.Seventeenth Workshop Geothermal Reservoir Engineering, Stanford University Publication SGP-TR-141, Jan 29-31. M.R. Rasaei and M. Sahimi, Upscaling of the permeability by multiresolution wavelet transformations and simulation of multiphase flow in heterogeneous porous media, *Computational Geosciences* 13, 187 (2009).
4. M. Sahimi, R. Darvishi, M.R. Rasaei, and M. Haghighi, Up-scaled unstructured grids for efficient simulation of flow in fractured reservoirs, *Transport in Porous Media* 83, 195 (2010).
5. H. Dashtian, G.R. Jafari, Z. Koohi Lai, M. Masihi, and M. Sahimi, Analysis of cross correlations between well logs of hydrocarbon reservoirs, *Transport in Porous Media* (in press, 2011).

4- PPP12KJ

Key People: Shangxu Wang, Fred Aminzadeh and Flora Sun

Project Name: Understanding impact of reservoir fluid on seismic response using physical modeling

Core Technical or Practical Problem(s) we are addressing

We propose to develop and conduct physical modeling experiments with the aim of predicting the reservoir fluid content in complex geologic settings. Time lapse seismic data is a vital tool in understanding the reservoir fluid distribution. However, there is still considerable scope for improvement when it comes to delineating the subtle differences between zones containing oil and water. Experiments have shown that the reflection characteristics of the resulting seismic response may differ based on the type of fluid present and these differences can either be directly predicted or indirectly obtained due to transmission effects. These differences should be useful in better interpretation of time lapse seismic data with a better delineation of different fluid zones of interest. We also plan on using these modeling experiments to develop and test fluid detection and inversion techniques for contemporary use. This project will allow us to demonstrate the effectiveness of different seismic attributes in observing fluid saturation impact as well as their diagnostics capability.

Long term vision of how this impacts the industry

Our proposed approach should allow for better physical models to be generated and should lead to more accurate fluid prediction in reservoirs. The tools developed should be useful in all those settings where multiple fluids are expected in the reservoir (water flooding and other multiphase flow scenarios) and should improve reservoir management in the long run. Moreover, if fluid properties can be deduced from seismic data, oil & gas exploration efficiency can be greatly improved.

Recent related activities in the industry/academia

Seismic modeling has been used extensively as a tool for exploration. Most of the efforts have been limited to numerical modeling. The main focus of such numerical modeling has been to test the impact of changes in the geologic structures on the seismic response. Till date, the applications have included examining the imaging approaches, analyzing the impact of reservoir fluid on the seismic response as well as many other reservoir property prediction problems such as pressure, porosity and permeability mapping. Physical modeling approaches have also been used to simulate both structural models and reservoirs with different properties. In the recent years, time-lapse seismic, AVO and prestack elastic inversion have been used extensively for hydrocarbon detection.

Brief Project Description

The project workflow can be summarized as follows:

1. The first step will involve the preparation of a reservoir model based on the geologic setting under investigation. An example of a typical model might involve overburden stratum and a series of thin reservoirs with interbedded shale layers (simulating shale setting). The design of such models is well understood and has been done in the past by the project team. Figure 1 shows this sample physical model setting in some detail.
2. The parameters of the designed model will be obtained through systematic examination of the same. At this point we will also devise the relation between the physical model and the actual geological setting in question.

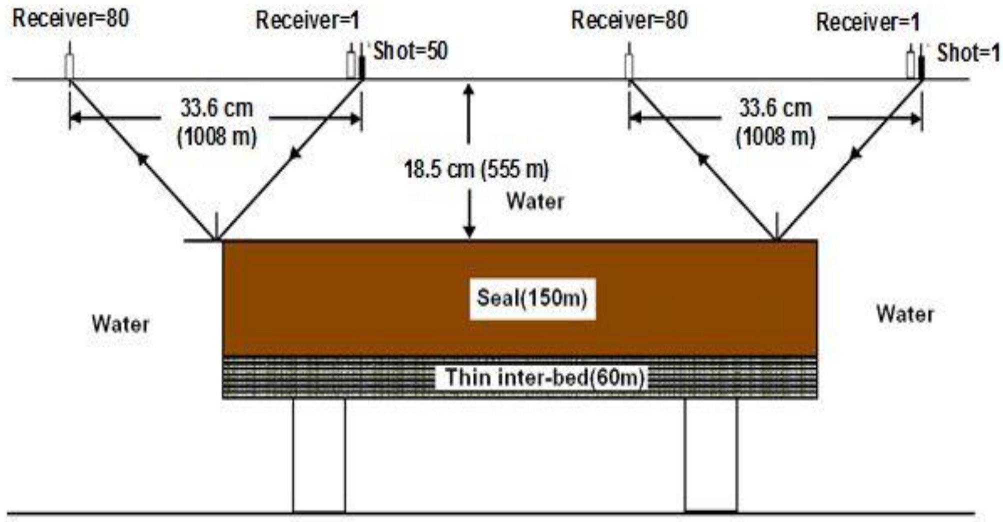


Figure 1: Experimental setup

3. The experimentation and data acquisition phase will follow. The acquisition parameters will be kept as close to the real reservoir setting as possible and repeatability will be used to keep the necessary parameters identical in all experiments with different fluids under study.
4. The next stage will involve experimental data processing. This involves upscaling the acquisition system to field level followed by filtering, stacking and migration.
5. A cross-equalization technique will be used to keep the non-reservoir reflections consistent and to focus the differences in the reservoir response. Differencing techniques such as mid-point amplitude difference, etc. will be then applied to analyze the attributes in a time lapse fashion.
6. Attributes other than amplitude will be tested including those associated with the spectra and the phase of the signals.
7. We will test for observable differences between different phases being present in the reservoir model. These reflection characteristics will be documented and developed further for possible use in real life scenarios to distinguish reservoir types, etc.
8. Results will be finally applied in a real test case reservoir setting and the designed attribute anomalies will be tested in the field case to monitor fluid changes in the reservoir (such as EOR processes using gas injection).

Immediate plans and goals for 2012-2014

The following tasks will be carried out in the first two years of the project.

- *Define reservoir setting as well as the attributes to be worked with.*
- *Design and develop physical models based on the actual reservoir under study.*
- *Design experimentation workflow based on defined project objectives.*
- *Design the acquisition scheme based on the actual reservoir and seismic data acquisition scheme being followed.*
- *Conduct necessary experiments in different settings as defined in the workflow.*

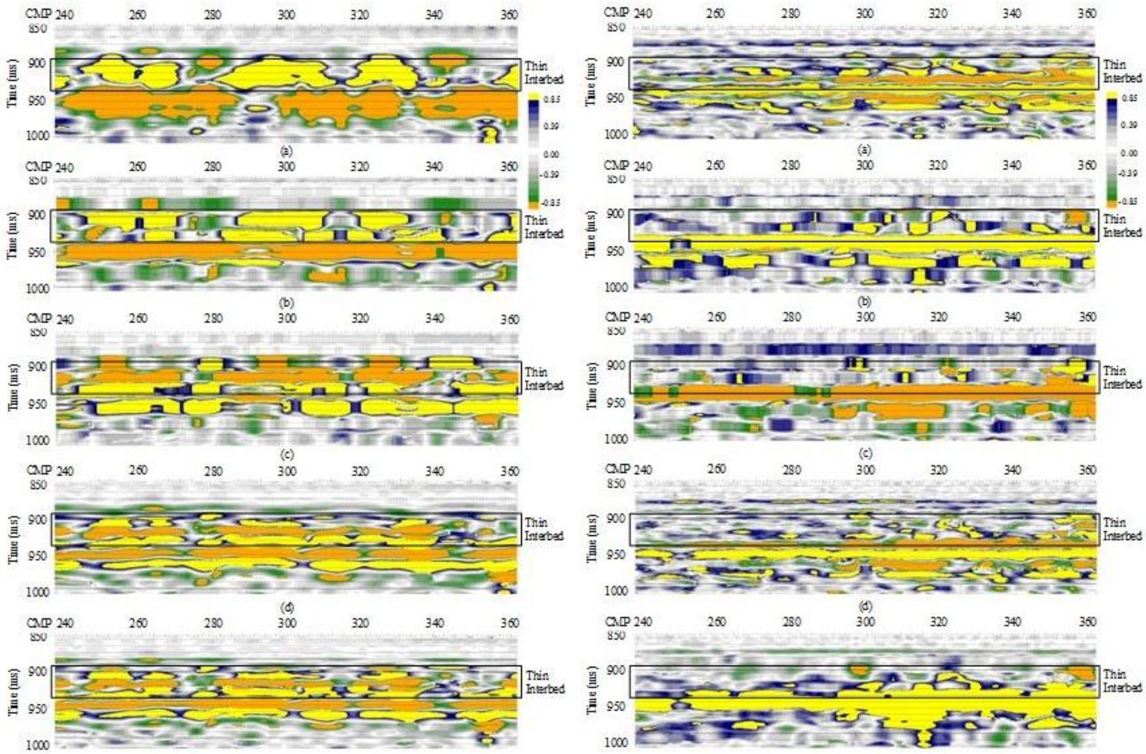


Figure 2: Differences in RMS, maximum, minimum, average and mid-point amplitudes for gas/ oil (left figure) and water/ oil (right figure) indicating fluid variations detected within the reservoir for gas/ oil combination and below the reservoir for water/ oil combination.

Deployment and testing plans

Upon the availability of time lapse seismic data from the sponsors, we will test our results on the real data case.

Desired interactions with the sponsors

Any sponsor or group of sponsors can suggest a particular physical model to be built. The characteristics of such model can be chosen to mimic a particular type of reservoir to test the impact of different structural settings or reservoir properties on the seismic response. This part of the work can be either exclusive with that sponsor (if the results are to be kept confidential) or other sponsors can be involved in the tests.

Key references (own or other's work)

1. Aminzadeh, F., Brac, J. and Kunz, T., "3-D salt and overthrust models in SEG/EAGE 3-D Modeling Series, No.1: Distribution CD of Salt and Overthrust Models (SEG Book Series, 1997).

2. Biot, M. A., 1956, Theory of propagation of elastic waves in a fluid saturated porous solid. I. Low frequency range and II. Higher-frequency range: J. Acoust. Soc. Am., **28**, 168-191.

3. Wang, S., Li, X., et al., 2007, Physical modeling studies of 3-D P-wave seismic for fracture detection: Geophys. J. Int., **168**, 745-756.

5- PPP15DH

Key People: Donald G. Hill, Fred Aminzadeh and Arman Khodabakhshnejad

Project Name: Time Lapse Petrophysical Reservoir Monitoring and Evaluation of Reservoir Characterization Sensitivity

Core Technical or Practical Problem(s) we are addressing
We would evaluate the sensitivity of various existing and potential reservoir petrophysical monitoring and characterization protocols to meet the reservoir monitoring needs of existing and future conventional and unconventional reservoirs.

Long-term vision of how this impacts the industry
It has been said that while a theory can be right or wrong, a model can be right, wrong, or irrelevant. Successful reservoir monitoring requires reservoir models. If the reservoir is inadequately characterized, the resulting model will be inadequate or irrelevant. The petrophysical parameters of reservoirs under production will change, with time. As a result, even those reservoirs which were properly characterized, initially, need to have their characteristics monitored, over time, as they are produced.

Seismic data that is used to monitor changes in reservoir for both conventional and unconventional reservoirs needs to be calibrated using well logs. Inversion of seismic data could not be performed without building precise time-equivalent petrophysical properties.

Some companies require wireline vendors to shut down all non-correlation logs outside of previously identified pay zones. While this practice obviously save the operator a few U$S/ft. in logging charges (depth charges would be unchanged), the incumbent and successor operators were left naked, once the primary drilling targets were depleted because this inadequate logging program offered no source rock and/or bypassed pay information.

Furthermore, many of the giant and super-giant Niger Delta fields were developed with a wireline program, which consisted of:

- Gamma Ray logs to differentiate between sands and shales.
- LateroLog 3, to determine if the sands were pay.
- Sidewall Cores to distinguish between gas and oil hydrocarbons.

While this logging program also saved on initial logging costs, it was totally inadequate for depletion planning and probably misidentified some high-energy Zircon rich beach sands as shales, because of the thorium content in the zircon.

Conventional wireline, Measurements while Drilling (MWD)/Logging While Drilling (LWD), and core analysis also appear to be inadequate for unconventional hydrocarbon resources, such as shale oil, Coal Bed Methane (CBM), Shale gas and complex reservoir rocks like the Monterey and Bakken Formations. If the reservoirs are inadequately characterized to begin with, any monitoring program becomes problematic.

With the decline in major new hydrocarbon discoveries, the importance of increasing recovery from existing reservoirs is equivalent to locating new reserves. Improving the efficiency and safety of stimulation and enhanced oil recovery (EOR), as well as monitoring technologies for these technologies are essential for increasing recoverable hydrocarbon reserves. Achieving this goal is only possible through accurate evaluation of petrophysical properties of reservoir for current and future development plan.

The most common EOR technologies are Water and Steam flooding. New technologies, which can deal with thief zones and tight formations, as well as those, which do not involve introducing foreign substances into reservoirs need to be evaluated. While there have been some evaluations of monitoring EOR activities, this need to be expanded.

Recent related activities in the industry/academia

The solutions to the problems listed above are obvious; make more measurements, but which ones? Wireline MWD/LWD and core measurement vendors are unlikely to recommend selective measurements if such would result in fewer services requested.

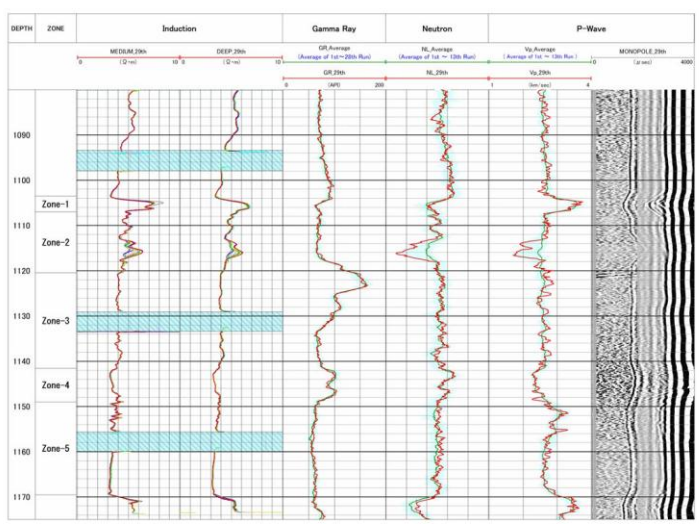
The unconventional reservoir characterization issue is even more complex. Recent unconventional reservoir workshops have moved from traditional Formation Evaluation (FE) volumetric (i.e., porosity and saturation) and flow (i.e., permeability) and Recoverability (i.e., capillary pressure) measurements, used to estimate total and recoverable reserves, to resource (i.e., Total Organic Content, or TOC) estimation with recovery based upon production decline curves.

Tilt-meter, and Microseismic monitoring have been utilized for monitoring stimulation and fluid flood EOR projects. Cross-well seismic and EM tomography have been utilized to monitor the advance of steam and water floods. These, and other, monitoring technologies need to be further evaluated and improved for monitoring stimulation and EOR projects, with time.

Brief Project Description

We will start by evaluating existing laboratory, wireline and MWD/LWD technologies for initial reservoir characterization and reservoir monitoring, with time, to identify which protocols appear to provide the most cost-effective benefits for reservoir monitoring and the situations where they work best. We will also look into integration of MWD and LWD with Seismic While Drilling (SWD), for further improvement in both drilling process and reservoir monitoring, Neill et al (1993).

Pulsed Neutron Capture (PNC) and Cased Hole Resistivity (CHR) techniques have both proven successful in some environments but not others. We will also evaluate potential new measurement technologies, which have not had sufficient time to develop any consistent "Track Record". We will also evaluate existing stimulation and EOR monitoring technologies in an effort to improve upon existing technologies or develop



new technologies.

Immediate plans and goals for 2012-2014

The following tasks will be carried out in the first two years of the project.

- *Evaluation of existing laboratory, wireline and MWD/LWD technologies for initial reservoir characterization and reservoir monitoring technologies.*
- *Evaluation of existing and mature experimental stimulation and EOR Technologies.*
- *Evaluation of surface-Borehole permanent monitoring arrays*

Deployment and testing plans

Upon the availability of field data from the sponsors, we will test our results on such real data cases.

Desired interactions with the sponsors

1- We expect the sponsors who are members of USC RMC to facilitate USC access to existing reservoir characterization and monitoring studies
2- Sponsors can suggest which models should be considered for our tests.
3- Any sponsor who may wish to provide real data can work directly with USC to test the results using their data. This part of the work can be either exclusive with that sponsor (if the results are to be kept confidential) or other sponsors can be involved in the tests. Accordingly, different funding mechanisms for this part of the effort may be required.

Key references

Hill, D. G., Iovenitti, J. L., and Wittle, J. K., 1999, "Enhanced Restoration of Contaminated Aquitards Using Electro-Osmotic Aided Remediation", USA/CIS Joint Conference—Hydrologic Issues for the 21st Century: Ecology, Environment and Human Health, American Institute of Hydrology, San Francisco, November.

Rynne, T. M., Spadaro, J. F., Iovenitti, J. L., Dering, J. P., and Hill, D. G., 1998, "Phased Array Approach to Retrieve Gases, Liquids, or Solids from Subaqueous Geologic or Man-Made Formations", US Patent 5,826,653.

Weiss, R. B. and Hill, D. G., 1997, "Acoustically Enhanced Petroleum Production", Los Alamos National Laboratory Oil and Gas Reservoir

Wittle, J. K., Hill, D. G., and Chilingar, G. V., 2011, "Direct Electric Current Oil Recovery (EEOR) – A New Approach to Enhancing Oil Production" Energy Sources, Part A. Recovery, Utilization, and Environmental Effects, vol. 33, No. 9, pp 805 – 822.

Neill, W. M., Aminzadeh, F., Sarem, A. M. S., and Quintana, J. M., 1993, Guided Oscillatory Well Path Drilling by Seismic Imaging, patent # 5242025, 1993

6- PPP16AO

Key People: Antonio Ortega and Yenting Lin

Project Name: Reservoir Modeling using Tomography based on Field Operation Data

Core Technical or Practical Problem(s) we are addressing

Identifying high contrast heterogeneous structures within a reservoir is always a challenging problem for reservoir modeling. A major limitation of conventional methods (seismic, tracer test) is that they require additional equipment, cost and time and cannot be used on a routine basis. Our goal is to identify these heterogeneous structures by using field operation data that is routinely available, for example injection/production rates in a waterflood. We propose to use novel injection (water, steam, etc.) schedules and to monitor gross fluid production in order to actively measure the response time between well-pairs without altering the average daily operations. With the well-pair response time, we develop object-based algorithms to identify the heterogeneous structures. These object-based algorithms are designed specifically to provide robust performance when high contrast structures have to be detected (e.g., high permeability channels).

Long term vision of how this impacts the industry

Real-time monitoring and identifying the heterogeneity for reservoir flow property is critical for prediction and production optimization. With the seismic or tracer test methods, it is possible to provide a map of reservoir flow properties but normal operations need to be interrupted for measurements to be obtained. Our active injection method provides a monitoring tool that does not disrupt normal operations and can estimate dynamic reservoir behavior, enabling the observation of changes in heterogeneous structures as they occur. Our long term vision is for the tools we develop to provide real time monitoring of reservoir characteristics with no impact on daily operations.

Recent related activities in the industry/academia

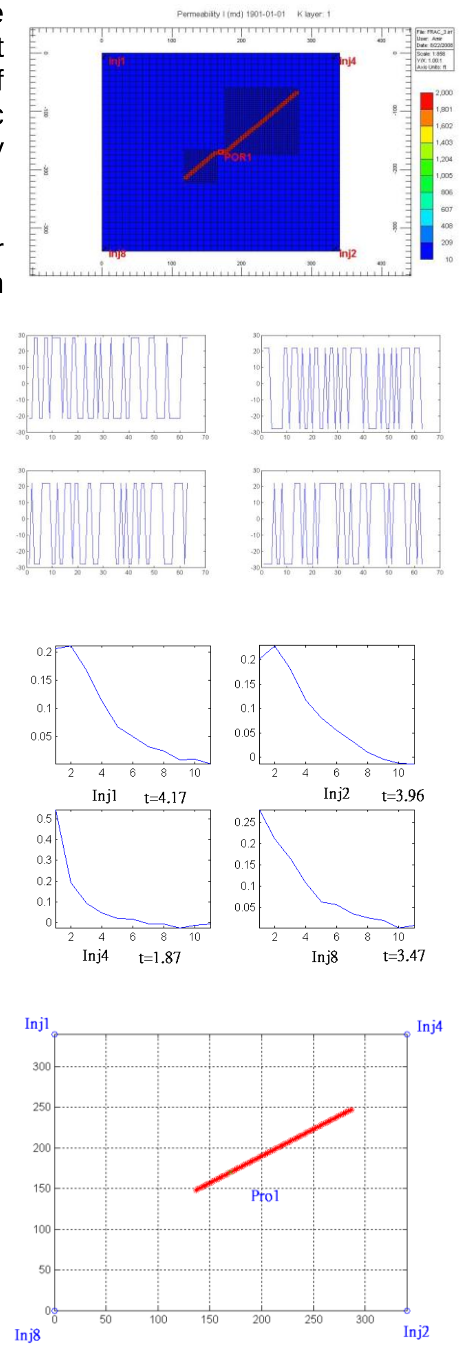
There has been significant interest in understanding highly heterogeneous reservoirs, which contain high contrast permeability structures that are likely to give rise to very fast flow paths. Grid-based inversion methods have been proposed that make use of tracer test or seismic data. To the best of our knowledge, we are the first to propose using injection/production rates to identify high contrast heterogeneous objects. We are also leveraging an emerging body of work on signal sparsity in the signal processing literature, in order to improve the reconstruction quality we can achieve.

Brief Project Description

With decreases in cost, multiple types of sensors can be found in modern reservoirs. These sensors record actions taken, such as rates (e.g., injection, steaming) or events (e.g., hydraulic fracturing, maintenance), while also recording production rates with different levels of granularity (e.g., bi-weekly). Even though increasing amounts of data are available, *a key challenge remains in modeling reservoirs in real time at a level of detail consistent with the amount of data available*. We propose to develop techniques based on two emerging signal processing techniques, namely sparsity and graph based representations, to achieve the best possible models, with accuracy adaptive to the amount of observed data, which sometimes can be very limited.

We consider tools for building object-based models to present high contrast heterogeneous structure by using sparseness constraints. This makes it possible (as in compressed sensing applications in signal processing) to identify likely models even when insufficient data is available. Compared to grid-based methods, we will be able to achieve better accuracy with limited data. We also use graph representation to model the relationship between heterogeneous objects. This concept enables us to apply the prior information and connectivity of these objects. Examples of application include tomographic techniques to estimate permeability and shale discontinuity between layers.

The proposed techniques can also incorporate prior information in order to favor solutions that match known reservoir characteristics. For example, prior seismic studies could be used in order to favor solutions with high permeability channels in certain orientations. Because the complexity of these algorithms is modest, it is possible to generate multiple solutions under different prior assumptions and present the end user (e.g., a reservoir engineer) with different alternative interpretations of the reservoir characteristics



perm estimation: (a) Testing case in simulator; (b) Injection schedule; (c) Retrieved well-pair response; (d) Estimation result of high perms.

Immediate plans and goals for 2012-2014

The following tasks will be performed in the first two years.

- Estimation of orientation of hydraulic fractures at producers and of shale breaker between layers using tomography

- Experimental design injection schedule techniques for modeling the reservoir as large scale MIMO systems

Deployment and testing plans

After completion of the development phase, the viability of the proposed approach can be evaluated using field data or apply a field trial by the sponsors.

Key references

Lin, Y. and Ortega, A. "Reconstruction algorithm for high contrast velocity travel time tomography". *In Proceedings of the 2010 IEEE International Acoustics Speech and Signal Processing Conference(ICASSP 2010),* Dallas, March 2010.

Lin, Y. and Ortega, A. and Nejad, A. and Ershaghi, I. "Waterflood Tomography: Mapping High Contrast Permeability Structures Using Injection/Production Data". *In Proceedings of the 2010 SPE Western Regional Meeting(SPE WRM 2010),* Anaheim, May 2010.

Appendix 2- Detailed Project Descriptions for Individual Company Support

1- PPP1FA

Key People: Fred Aminzadeh, Tayeb Tafti, Debotyan Maity, and Asal Rahimi

Project Name: Incorporating Soft Computing in Time Lapse Monitoring

Core Technical or Practical Problem(s) we are addressing
We would use fuzzy logic and neural network to detect subtle changes in the data for improved monitoring. The tools are expected to be applicable to time lapse monitoring on many data type and many

Long term vision of how this impacts the industry
Given the imprecise and fuzzy nature of many of the parameters involved in ADE conventional computing techniques may not be fully equipped to formulate and solve many practical problems.

Recent related activities in the industry/academia
Model perturbation to test the sensitivity of seismic response to different reservoir property and/or layer parameters has been an important tool for assessing the ability to detect changes in the reservoir properties. See References below for examples.

Brief Project Description
We will start with a number of recent models developed under the SEG Seismic Acoustic Modeling (SEAM) project. We will then create their counter-part sub-models using fuzzy velocity fields. We will conduct several tomographic inversions on the selected models. We will then run simulations and compare these results against the base models. We will examine their consistency and ability to observe small changes in the velocity fields through a number of validation and verification criteria, based on “fuzzy thresholding”. We will then test practical application of fuzzy differential equations in a realistic setting such as a fuzzified version of the industry standard SEG/EAGE and SEAM models. Subsequently, we will expand the concept to the elastic version of the SEAM models. We will then attempt to observe the sensitivity of tomographic inversion on both compressional (P) and shear (S) wave velocities. We will attempt to deduce information on the impact of the fluid flow in the reservoir, manifested by the changes in the Poisson ratio derived from the P and S wave tomographic inversion.

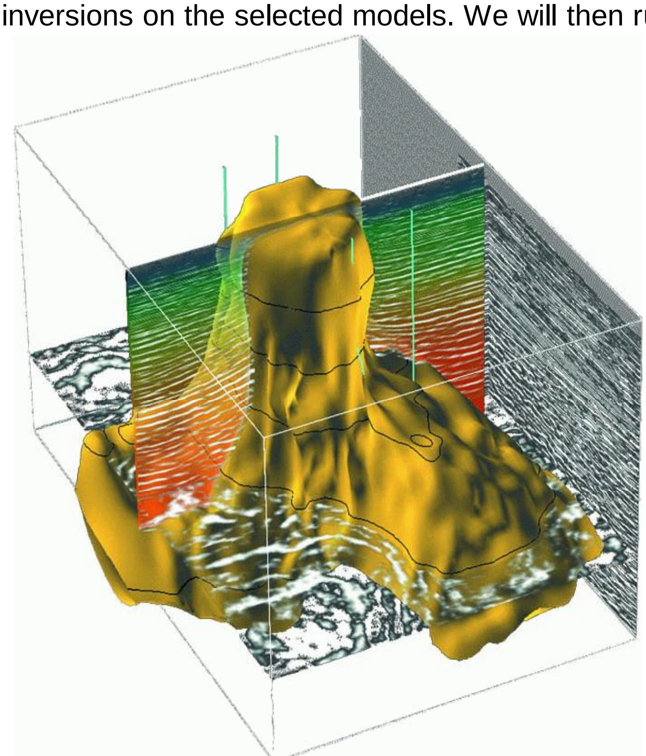
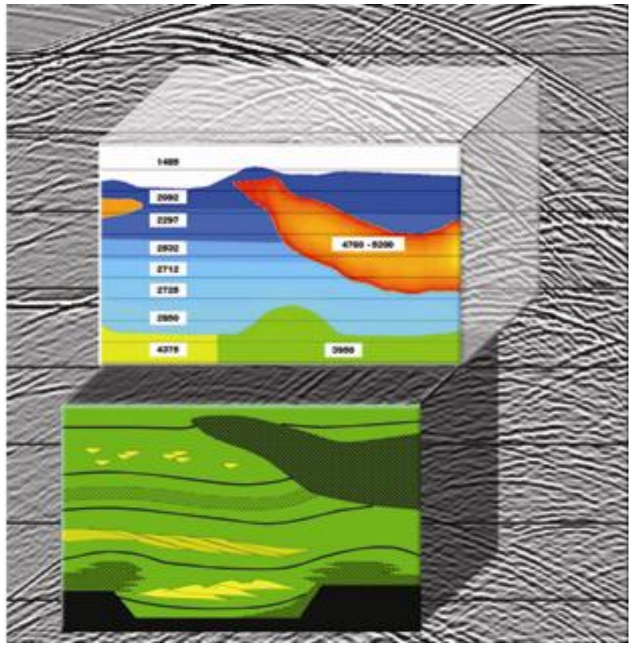


Figure 1-1 A Realization of structure based on a given velocity model

Immediate plans and goals for 2012-2014

The following tasks will be carried out in the first two years of the project.



- Seismic Modeling with Fuzzy Velocity Field
- Velocity Field Perturbation and Model Sensitivity Analysis
- Using Fuzzy Velocity Field to Conduct Model Sensitivity Analysis
- Establishing Fuzzy Compressional and Shear Wave Velocity Relationship
- Analyzing impact of changes in the velocity field on the seismic response
- Assessing the effectiveness of the method in monitoring the fluid flow in the "reservoir"

Deployment and testing plans

Upon the availability of field data from the sponsors, we will test our results on such real data cases.

Desired interactions with the sponsors

- We expect the sponsors who are members of SEAM facilitate USC access to the models and the corresponding 3D synthetic seismic volumes developed under SEAM
- Sponsors can suggest which models should be considered for our tests.
- Any sponsor who may wish to provide real data can work directly with USC to test the results using their data. This part of the work can be either exclusive with that sponsor (if the results need to be kept confidential) or other sponsors can be involved in the tests. Accordingly, different funding mechanism for this part of the effort may be required.

Key references

1. Aminzadeh, F. and Xu, W., 2001, Hybrid Reservoir Characterization, US Patent # 6,236, 943
2. Aminzadeh, F., 2009, State of the Art of Soft Computing for Intelligent Oil Field Applications, The Recent Advances and the Road Ahead Session. Annual SEG Meeting, Houston, October 26, 2009
3. Li Y., and Krahenbuhl, R.A., 2009, Hybrid optimization for lithologic inversion and time-lapse monitoring using a binary formulation, GEOPHYSICS, Vol. 74, NO. 6

2- PPP2CS

Key People: Cyrus Shahabi and Farnoush Banaei-Kashani

Project Name: Efficient Data Management for Real-Time Reservoir Monitoring and Management

Core Technical or Practical Problem(s) we are addressing

To enable real-time reservoir management, efficient data management, i.e., effective processing, archival, querying and analysis of the reservoir data, is a requirement. In particular, we focus on three specific reservoir data management challenges:

1. Real-Time Processing of Continuous Reservoir Data Streams: Real-time reservoir monitoring and, in particular, dynamic reservoir characterization (DCR) require real-time pre-processing and processing of continuous streams of data collected from the reservoir, e.g., to cleanse, smooth, interpolate the input data, to re-compute/update the reservoir characterization based on the continuous input data, and to visualize the results of dynamic reservoir characterization in real-time. In all these and similar use-cases, the main data management challenge is to process a large set of heterogeneous, high-rate and virtually infinite input data streams in real-time given constrained computing resources.
2. Rapid Querying of Archived Reservoir Data: Dynamic reservoir characterization, and in particular dynamic history matching[1], requires frequent access, querying and analysis of the past reservoir characterizations to enhance future predictions. Given the potentially very large size of the dataset that includes all past characterizations for a reservoir, rapid access, querying and analysis of the past data is only made possible by utilizing *intelligent data transformation methods* that allow for effective data archival.
3. Cloud-based Reservoir Data Management: Real-time reservoir management typically involves handling massive quantities of data, which in turn requires significant computational resources (CPU cycle, storage space, and network bandwidth). However, such extensive resources are often not cost-effective for the IT infrastructure of typical enterprises to provide. Recently cloud computing has emerged as a new technology that allows for providing such computational resources as services over the Internet. Enabling *cloud-based reservoir data management* remains a challenge.

Long term vision of how this impacts the industry

Our proposed efficient data management solutions to address the aforementioned challenges reduce the data-collection to decision-making time in order to improve *the cost-benefit of oil recovery* as well as the *safety*.

Recent related activities in the industry/academia

We discuss the related activities in the context of the three challenges discussed above:

1. Real-Time Processing of Continuous Reservoir Data Streams: While one can always throw more resources at this problem (e.g., utilizing high performance computing (HPC) and cloud), this only delays the problem, as the resource requirements are virtually infinite (e.g., the required storage space for infinite data streams).
2. Rapid Querying of Archived Reservoir Data: Unfortunately, the state of art solutions for data archival and data access fall short of handling the reservoir datasets. In particular, managing the sheer size of these reservoir datasets is well beyond the capabilities of the typical data visualization and analysis tools (such as Microsoft Excel). On the other hand, the existing

[1] History Matching is the act of adjusting a model of a reservoir until it closely reproduces the past behavior of a reservoir.

database management systems (such as Oracle 11g DBMS) as well as custom-built data historians are designed for generic use and are not customized for efficient archival of such reservoir datasets.

3. Cloud-based Reservoir Data Management: To the best of our knowledge, cloud-based reservoir data management is new to the oil industry, not only for reservoir management but also for other oilfield management tasks.

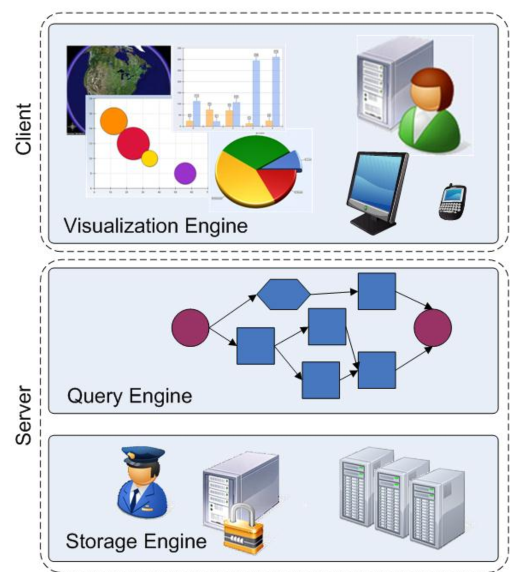
Brief Project Description

We discuss our activities in the context of the three challenges discussed above:

1. Real-Time Processing of Continuous Reservoir Data Streams: In practice, on top of cloud and HPC, *novel data-stream summarization techniques/ algorithms* must be developed and used to address this challenge [1]. Such techniques maintain a *sketch* of the infinite data (i.e., a data summary that captures the "essence" of the data while fitting the limited space) that allows for real-time data/query processing with guaranteed error-bounds.

2. We have extensive experience in developing and deploying data-stream summarization techniques in the context of various applications. For example, in the context of oilfield applications, in collaboration with CiSoft[2] we have developed algorithms and tools for *real-time waterflood optimization* as well as *real-time oilfield sensor data cleansing*[3]. We work very closely with all three industry leaders (Microsoft, IBM, and Oracle) in the area of stream data processing and regularly use their corresponding products (respectively, Microsoft StreamInsight, IBM InfoSphere-Streams and Oracle CEP Engine) as part of our solutions for stream data processing. Also in academia, we are recognized as leaders in this area and we regularly organize research forums for advancement of stream data processing techniques (e.g., ACM International Workshop on GeoStreaming (IWGS) in 2010 and 2011).
3. Here we propose to develop novel data summarization techniques that allow for real-time processing of continuous reservoir data streams, in particular to enable real-time reservoir monitoring and dynamic reservoir characterization.

4. Rapid Querying of Archived Reservoir Data: Over the past half-decade, we have designed, developed, and matured an end-to-end system, dubbed ProDA (short for Progressive Data Analysis) for rapid and efficient execution of the basic and complex queries on massive datasets[4] [2]. ProDA leverages the excellent energy-compaction properties of the *wavelet transform*. As compared with other wavelet-based solutions for rapid data access, our innovation is in transforming the query in addition to transforming the data. Since queries are often more patterned than data, they are also more compactable when transformed into the wavelet domain. With a highly compact yet accurate query representation, in addition to a compact data representation, we can effectively select and retrieve the high-energy data coefficients relevant to the query with exponentially less data access when compared to previous



[2] Center for Interactive Smart Oilfield Technologies (CiSoft): http://cisoft.usc.edu/
[3] For more information about our project under CiSoft, dubbed DOR (short for Data-Driven Oil Recovery), please see http://infolab.usc.edu/projects/DOR/
[4] ProDA Project Website: http://infolab.usc.edu/projects/proda/

approaches that only transform data. As a result, we can approximate the query result accurately with an exponentially improved response time.

5. In the past, ProDA has been sponsored by both governmental agencies (NSF and NASA) as well as the industry (Chevron/CiSoft and Microsoft). Accordingly, so far ProDA has been customized, extended and deployed for various applications of interest, including oilfield data management and earth science data management. Here we propose to extend ProDA to support efficient access, querying and analysis of the reservoir data, in particular for archival of the reservoir characterization datasets to enable dynamic reservoir characterization and dynamic history matching.

6. Cloud-based Reservoir Data Management: Recently cloud computing has emerged as a new technology that allows for providing computational resources as services over the Internet. Various features of cloud computing makes it a desirable choice of computing platform to implement real-time reservoir management: 1) computational resources of the cloud are abundant, 2) the cloud services are provided on a flexible *on-demand* and *pay-per-use* basis, which lets one avoid under- and over-provisioning of the resources for cost-efficient reservoir management, and 3) the cloud enables *off-site* reservoir data management that allows for distributed and collaborative reservoir management.

   Accordingly, we propose developing a cloud-based reservoir management framework that provides the services (or a proper subset of the services) required for reservoir management over the cloud. This framework can provide reservoir management services on a proprietary basis to corporations individually, and/or can serve as a common suite of reservoir management services shared by a set of partner corporations (e.g., an oil company and its partner company that provides consultancy on reservoir management).

   We are well-positioned to take on the development of the proposed cloud-based reservoir management framework. In academia, we are among the leading group of researchers that study effective approaches to adopt the cloud as the desired data management platform for various data-intensive applications [3]. We also have the experience of developing and deploying large-scale cloud-based data management tools for real-world applications. For example, in partnership with Microsoft we are currently developing a comprehensive cloud-based tool for LA-MTA (Los Angeles Metropolitan Authority) to manage the real-time and historic transportation data collected from the entire Southern California. We are developing this tool on top of Microsoft Azure, which is the cloud platform provided by Microsoft for academic projects.

Immediate plans and goals for 2012-2014

Our plans are flexible to the sponsors' interests.

Deployment and testing plans

Upon the availability of field data from the sponsors, we will test our results on such real data cases.

Desired interactions with the sponsors

We are open to define the preferred interaction mode according to sponsors' interests.

Key references

1. C. Aggrawal, Data Streams: Models and Algorithms, IBM T. J. Watson Research Center, Yorktown Heights, NY 10598. Kluwer Academic Publishers.

2. C. Shahabi, M. Jahangiri, and F. Banaei-Kashani, ProDA: An End-to-End Wavelet-Based OLAP System for Massive Datasets, IEEE Computer Magazine, Vol.41, No.4, Pages 69-77, ISSN: 0018-9162, April 2008.
3. Akdogan, U. Demiryurek, F. Banaei-Kashani and C. Shahabi, Voronoi-based Geospatial Query Processing with MapReduce, IEEE CloudCom 2010. (Note: This paper received **Best Paper Award** from CloudCom)

3- PPP3JA

Key People: Jalal Abedi, Hassan Hassanzadeh, and Mohsen Zirrahi

Project Name: Inverse Modeling and Parameter Estimation of Nanoparticle Transport in Geological Formations

Core Technical or Practical Problem(s) we are addressing

Obtaining operational data, including reservoir temperature, steam quality, solvent and catalysts concentration and reservoir pressure, both near the wellbore and far in the producing formations, is very essential to the optimal performance of heavy oil recovery processes, such as steam-assisted gravity drainage (SAGD), vapor extraction (VAPEX), in situ combustion, air injection and in situ upgrading. Conventional approaches for managing heavy oil recovery process performance rely on measurements at or in the vicinity of the wellbores. This approach is insufficient for the delineation of anomalies that have been observed during these heavy oil recovery processes. This is particularly important, given the heterogeneous nature of the producing formations.

Long term vision of how this impacts the industry

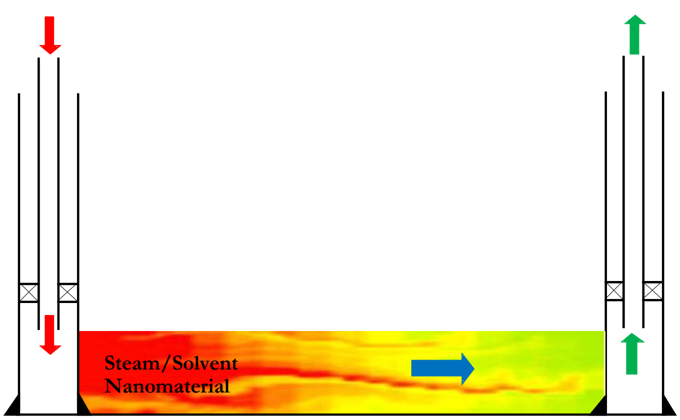
If it becomes possible to acquire in situ reservoir data, the oil and gas industry could find ways to improve recovery efficiency.

Recent related activities in the industry/academia

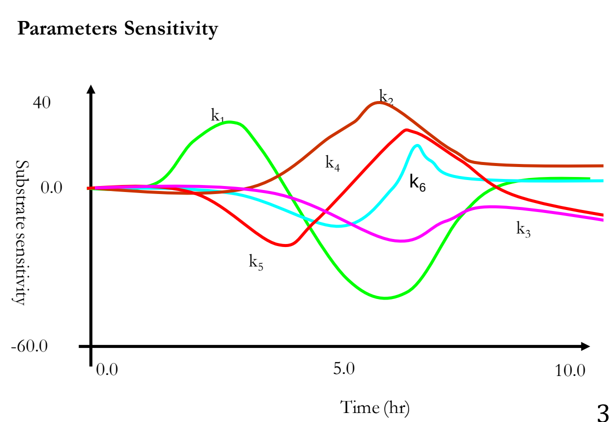
While applications of nanomaterials in oil recovery are in their infancy and relatively little research has been reported on the fate of nanoparticles in geological formations. To our knowledge, research works related to transport of nanoparticles in geological media are limited. A number of groups are currently working in this area. See References below for examples.

Brief Project Description

Accurate numerical modeling is essential in order to correctly interpret experimental measurements of the in situ processes, leading to developing a better understanding and design of field scale processes. This project will present a framework for mathematical modeling of in situ property estimation in hybrid oil recovery.



There are currently several barriers to the application of nanotechnologies in reservoir engineering. One of the great challenges is the construction of a nanomaterial for the specific purpose of in situ rock and fluid property measurements. The other great challenge is the design of the operational conditions of nanomaterial injection into oil reservoirs. The focus of this proposal is on the investigation of the effects of various operational parameters on the success of engineered nanoparticle injection



into porous media for the specific purpose of in situ property measurements.

Numerical and analytical models will be developed to study the flow and transport of nanoparticles in porous media under various operational conditions. These analytical and numerical models will be used as forward models for parameter estimation and inverse modeling.

Immediate plans and goals for 2012-2014

The following tasks will be carried out in the first two years of the project.

- Development of analytical models
- Development of numerical model
- Testing and validation of the numerical model
- Development of the parameter estimation methodologies and inverse modeling
- Development of the benchmark problems

Deployment and testing plans

Upon the availability of field data from the sponsors, we will test our results on such real data cases.

Desired interactions with the sponsors

Any sponsor who may wish to provide real data can work directly with USC to test the results using their data. This part of the work can be either exclusive with that sponsor (if results are to be kept confidential) or other sponsors can be involved in the tests. Accordingly, different funding mechanism for this part of the effort may be required.

Key references

1. Hassanzadeh, H. and Abedi, J.:2010, Modeling and parameter estimation of ultra dispersed insitu catalytic upgrading experiments in a batch reactor, Fuel, 2010, 89(10) 2822-2828. doi:10.1016/j.fuel.2010.02.012.
2. Cullen, E.A., D.M. O'Carroll, E. Yanful and B.E. Sleep.: 2010, Simulation of the Subsurface Mobility of Carbon Nanoparticles at the Field Scale. Advances in Water Resources, 33 (4), 361-371. doi:10.1016/j.advwatres.2009.12.001.
3. Yu, J, Berlin, J. M., Lu, W., Zhang, L., Kan, A.T., Zhang, P. , Walsh, E.E., Work, S. N., Chen, W., Tour, J. M., Wong, M. S. and Tomson, M. B.: 2010, Transport study of nanoparticles for oilfield application," SPE 131158, 2010 SPE International Conference on Oilfield Scale, Aberdeen, UK, May 26-27, DOI: 10.2118/131158-MS.

4-PPP4JA

Key People: Jalal Abedi and Fred Aminzadeh

Project Name: Applications of Nanotechnology for Reservoir Monitoring

Core Technical or Practical Problem(s) we are addressing

We would focus on applications of nanotechnology for reservoir monitoring. Nanosensors will be developed and injected into the porous media to provide data on reservoir characterization, fluid-flow monitoring, and fluid-type recognition. We will investigate the effects of various operational parameters on the success of engineered nanosensors injection into porous media for the specific purpose of in situ property measurements. The resolution of estimates of properties that can be obtained from various combinations of sensors and various specifications on sensor precision will be determined.

Long term vision of how this impacts the industry

Nanosensors will ultimately have an enormous impact on our ability to comprehend the reservoir. They are the critical enablers that will allow mankind to perform in-situ measurements within the reservoir. Data collected could enable more efficient exploitation of hydrocarbon resources.

Recent related activities in the industry/academia

Inspired by the rapid growth in integrated semiconductor-based devices, autonomous biological and chemical nanosensors have emerged as an ubiquitous method both to perform fundamental science and to monitor industrial processes and detect bio warfare agents (Hunt et al., 2010). While there are many different methods of performing detection, they all rely on detecting a change in a fundamental physical property of the device, such as a change in electrical current or a change in optical input power. As expected, the concept of applying nanosensors to monitoring and characterizing reservoirs was straightforward. However, even though the fundamental sensing unit is at the nanoscale, the entire sensing unit is much larger, as it requires a power source, a transmitter, and packaging to protect the system. This limitation is a direct result of the “top-down” nanotechnology methods which are used to fabricate these devices (Timp, 1998). Therefore, these sensing units are unable to accurately probe the nanostructure of the reservoir.

Nanosensors have been an important tool for assessing the ability to detect changes in the reservoir properties. They can migrate into pores of the surrounding geological structure to collect data about the physical and spatial characteristics of hydrocarbon reservoirs. A number of groups are currently working in this area. See References below for examples.

Brief Project Description

There is currently no practical way to measure in situ rock and fluid property beyond the wellbore region. A variety of new types of sensors are being developed for improved imaging of the state of the reservoir and for improved estimation of reservoir rock properties. As the goal is to inject these sensors into reservoir rock, they will out of necessity be extremely small and consequently of limited functionality.

We hope to overcome several barriers to the application of nanotechnologies in reservoir engineering. One of the great challenges is the construction of nano sensors for the specific purpose of in situ rock and fluid property measurements. The other great challenge is the design of the operational conditions of nanosensors injection into oil reservoirs. The focus of the study is to determine the resolution of estimates of properties that can be obtained from various combinations of sensors, various frequencies of observations, and various specifications on sensor precision.

To genuinely probe such nano features, it is necessary to develop a nanosensor where the entire sensing package is at the nanoscale. To achieve this requires moving away from "top-down" nanotechnology methods, in which devices are fabricated from bulk materials, and applying "bottom-up" principles, in which sensors are self-assembled from individual atomic units (Timp, 1998). One approach is based on functional nano materials which respond and react to their environment (Xu et al., 2006). For example, materials which degrade upon exposure to extreme pressure, temperature and pH have already been developed (Chen et al., 2009). While it is possible to determine this information at the entrance of a reservoir, this type of information is currently inaccessible in the interior.

By creating nano-onions, which comprise of layers of these functional materials, it will be possible to determine these parameters within the reservoir. Figure 1 shows a rendering of the proposed nano-onion structure, where the colors indicate different functional layers and the core is a high temperature ceramic.

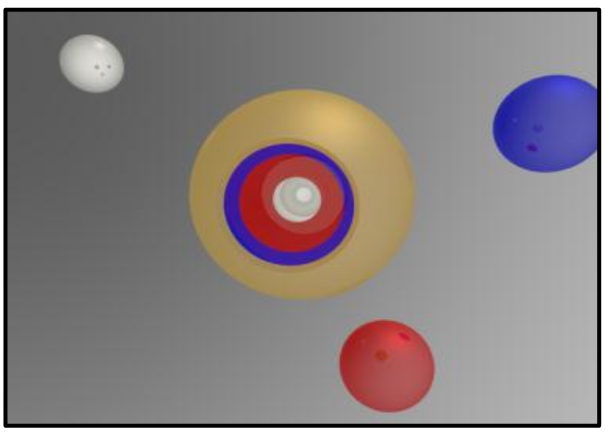


Figure 1. *Rendering of nano-onion sensor. The center nano-onion is cut away to highlight the layered nature of the nano-sensor material and the ceramic core. Layers degrade upon exposure to pH, temperature and pressure changes in the reservoir.*

For simplicity, the figure shows a structure with only three layers; however, it is envisioned that these sensors will have at least 20 layers. As the nano-onions transverse a reservoir, they will degrade according to their exposure. Once collected, it will be possible to determine what types of materials and environments they have interacted with. Additionally, because this nanosensor will be made using synthetic chemistry, instead of classic semiconductor fabrication methods, it will be inexpensive to inject vast quantities of nano-onions into a single reservoir, greatly improving data collection and analysis.

Immediate plans and goals for 2012-2014

The following tasks will be carried out in the first two years of the project.

- Nanosensors will be developed and tested in the petroleum laboratory.
- They will be injected into the core sample to provide data.

- The forward modeling of nanosensor pressure and location for a nanosensor that is passively transported with the flow in a 1-D porous medium and a 2-D porous medium will be developed.
- The sensitivity of the observations to flow properties of the porous medium will be computed (how the change in permeability or porosity at a point would affect the location of the sensor or the pressure on the sensor).
- The resolution of the estimates of porosity and permeability from measurements of pressure alone, or from measurements of pressure in conjunction with location will be estimated (these estimates of resolution are based on linearization of the data relationship and an assumption that the pressure can be observed with Gaussian errors).

Deployment and testing plans

Upon the availability of field data from the sponsors, we will test our results on such real data cases.

Desired interactions with the sponsors

We will define the preferred interaction mode according to sponsors' interests.

Key references

1. Timp G., Editorial. *Nanotechnology*, 1998, p. 696.
2. Waldhauser F. *hypoDD - A program to comppute double difference hypocenter locations.* Menlo Park: U.S. Geological Survey, 2001.
3. Chen X. C. et al., Control of Morphology and Its Effects on the Optical Properties of Polymer Nanocomposites. *Langmuir* , 2009, 3659-3665.

5- PPP6BJ

Key People: Behnam Jafarpour and Lianlin Li

Project Name: Feature-based Reservoir Characterization

Core Technical or Practical Problem(s) we are addressing

Geologic formations and their physical properties often form spatially correlated and connected structures. Reconstructing a grid-based description of these structures from limited static and dynamic data poses the risk of losing spatial connectivity, which is critical for field development planning. We propose to develop featured-based property description and identification algorithms that respect and preserve natural and formation-specific geologic continuity.

Long term vision of how this impacts the industry

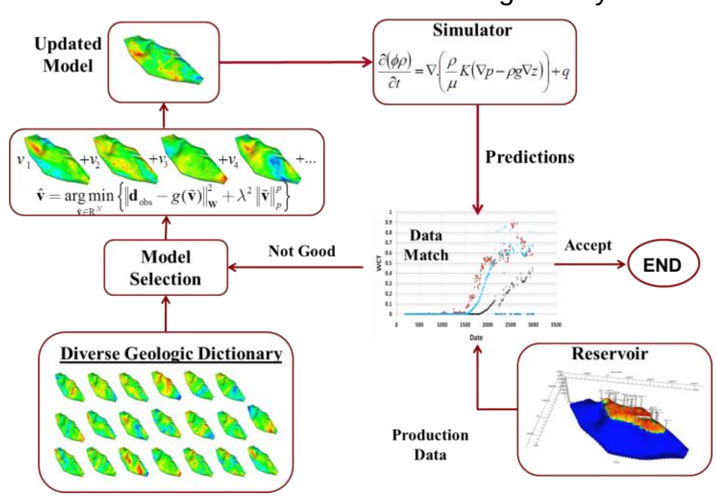
Realistic representation of the connectivity in reservoir flow property distribution is critical for reliable prediction of reservoir performance and ultimately for designing sound reservoir development practices. While grid-level reservoir characterization methods provide a flexible approach for model parameter identification, they face several challenges in preserving the expected geologic continuity in reservoir properties. Featured-based methods that are geologically defensible provide a more suitable description and estimation framework for reservoir characterization.

Recent related activities in the industry/academia

Characterization of connectivity in reservoir flow properties has always been a fundamental challenge for reservoir engineers. In particular, correct representation of connectivity in turbidite and fluvial formations can have a large impact on fluid displacement patterns and reservoir performance prediction and management.

Brief Project Description

Many geologic formations consist of connected patterns with distinct flow properties (e.g., preferential flow paths/barriers) that constrain the global fluid displacement patterns. A feature-based history-matching approach (instead of gridblock property estimation) is more appropriate for capturing the field-scale connectivity from low-resolution fluid flow data. In this project, we develop a novel and geologically-inspired feature estimation method for solving history-matching problems more consistently. The method relies on using uncertain prior information to generate a diverse geologic dictionary that compresses the main information in the prior models. Just as a few words from a large dictionary are combined to construct a sentence, only a small subset of elements from the diverse geologic dictionary are needed to construct a history-matched model. This property leads to a compressed formulation of the history matching problem that is quite robust against prior uncertainty. The overall history



matching workflow is summarized in the following figure. The impact of the proposed approach for history matching under geologic uncertainty is significant as geologic uncertainty is one of the most challenging aspects of reservoir characterization.

Immediate plans and goals for 2012-2014

The following figure shows the proposed featured-based history matching workflow that combines a diverse prior geologic dictionary with production data to update dynamic reservoir models. The following tasks will be performed in the first two years.

- Effective description of reservoir properties through construction of geologic dictionaries from diverse uncertain prior models
- Development of efficient sparsity-based feature estimation for history matching
- Integration of sparse inversion with geologic dictionaries for history matching
- Two dimensional numerical experiments for testing developed algorithms
- Fine-tuning and improving the performance of the overall framework
- Application to 3D benchmark problems as a feasibility study for field application

Deployment and testing plans

After completion of the development phase, the viability of the proposed approach will be evaluated using field data that will be provided by the sponsors.

Desired interactions with the sponsors

- The sponsor members of SEAM are expected to facilitate USC access to field data and models for feasibility studies.
- We encourage collaborations with and suggestions from the sponsor members throughout development and application phases of the project.
- Sponsor members are welcome to provide field data to USC for our test cases. The case studies can be conducted either exclusively with each individual sponsor (to honor confidentiality) or with involvement of other sponsors. Depending on the sponsors' requirements, appropriate mechanisms will be designed for funding and other related logistics.

Key references

1. Jafarpour B., McLaughlin D. B., 2009. Reservoir characterization with discrete cosine transform, part-1: parameterization, part-2: history matching, *Soc. Pet. Eng. Journal*, 14(1), 182-201.
2. Jafarpour B., Goyal V.K., McLaughlin D.B., Freeman W.T., 2010. Compressed history matching: exploiting transform-domain sparsity for regularization of nonlinear dynamic data integration problems. *Mathematical Geosciences*, vol. 42, no. 1, pp. 1-27, 2010.
3. Mohammad-khaninezhad M.R., Li L., Jafarpour B., History Match- ing with Learned Sparse Dictionaries", SPE-133654, Society of Petroleum Engineers Annual Technical Conference and Exhibition, 20-22 September 2010, Florence, Italy.

6- PPP8MS

Key People: Muhammad Sahimi and students

Project Title: Development of Dynamic Models of Fractured Reservoirs based on Unstructured Grid and Discrete Fractures, and Their Up-scaling

Core Technical or Practical Problem(s) that we are addressing:
Despite decades of research, modeling of fractured reservoirs is still mostly based on the double-porosity model, despite its well documented inadequacy in modeling most such reservoirs. Some progress has been made, but the problem is still largely unsolved. At the same time, even if the geological model of a fractured reservoir can be adequately developed, up-scaling for use in reservoir simulation is still a major problem. Finally, with the advent of dynamic reservoir characterization, the development of a flexible model that can rapidly incorporate the newly arrived data and information and upscale the model has become paramount. Some of the major problems that must be addressed are

1. How to adequately represent the widely disparate relevant length scales in a single model: Oil and gas reservoirs are highly heterogeneous at several distinct and widely separated length scales. Every relevant length scale may contain certain information that is useful, and even crucial, to the overall accuracy of the model

2. How to represent the fracture and the matrix accurately, given the heterogeneous distribution of the former: As is well-known, fractures are not distributed as in the double-porosity model, which assumes a well-connected fracture network in the form of a cubic network, or some perturbations of it. They are distributed non-uniformly with the fractures' orientations and lengths following statistical distribution. If there are only a few dominating fractures that control most of the fluid flow, the problem is even more difficult.

3. How to model the interaction between the matrix and the fractures, given the large differences between the permeabilities of the two: A uniform grid cannot represent the interface between the two.

4. Even if an accurate geological model of a fractured reservoir is developed, the question of its up-scaling to a coarse, yet accurate level, is still a major challenge: Practically, all the current up-scaling methods are inadequate with regard to fractured reservoirs. Thus, one must resort to empirical, semi-empirical, and curve fitting in order to develop the up-scaled model.

5. Given the advances in dynamic reservoir characterization, and in particular dynamic history matching, any model must be flexible enough to be able to handle new incoming information and data, incorporate them in the model, and up-scale it quickly, in order to maintain the model up to date.

Long term vision of how this impacts the industry
The goal is to develop flexible, accurate, and efficient models of fractured reservoirs in order to set aside double-porosity and similar models, incorporate recent advances in multiresolution computations in the model, and take into account the evolving nature of the models of fractured (or even unfractured) reservoirs that is based on 4D seismic characterization, dynamic history matching, and other time-dependent properties and information.

Recent related activities in the industry/academia

This problem has been studied for years, however though no definitive solution has yet been developed.

Brief Project Description

We have been working on the aforementioned problems for the past several years:

1. The problem of incorporating widely disparate and relevant length scales in a single model has remained unsolved.

2. Though the inadequacy of double-porosity and similar models has been recognized for years, the industry still relies heavily on such models. Discrete fracture modeling has been used by the groundwater community, and has begun to find its way in the petroleum literature.

3. New methods of modeling the transfer functions for representing the exchange between the fractures and the matrix have been developed, including some by us. These are based on the analogy between fluid flow and electrical currents. The development of a flexible grid for adequately representing the interface region between the two is under study.

4. Accurate up-scaling methods for unfractured reservoirs have been developed. However, many, if not all, of them are not yet computationally efficient enough for use in very large geological models, and use parallel computing or supercomputer is necessary. The problem of development of an up-scaling method for fractured reservoirs, at least by a fundamentally sound scientific method, remains unsolved.
5. Incorporation of dynamic reservoir characterization in models of fractured reservoirs is in its infancy.
6. To address the problem of incorporating all the relevant length scales in a single model, we have developed use of multiresolution wavelet transformation that is capable of addressing the multiscale nature of the problem.
7. To address the problem of incorporating a non-uniform spatial distribution of fractures, we have been working on the development of discrete fracture network models that are totally flexible and can represent practically any spatial distribution of fractures.
8. To address the problem of how to represent the interactions between the matrix and the fractures, we have been developing a method that combines three essential ingredients: (i) Use of a totally unstructured grid; (ii) representing the fracture as merely the high permeability paths, and (iii) use of multiresolution wavelet transformation to determine the density of the grid not just the in the matrix, but also around the interface between the matrix and the fractures. Two-dimensional models have been developed, and we have begun the development of 3D model based on advancing front technique and the aforementioned three ingredients.
9. To address the problem of up-scaling of the geological model of fractured reservoirs, we have been developing a method based on the use of wavelet transformation. The method has already been developed for the unfractured reservoirs and, in addition to its high precision, has been shown to be computationally more efficient than the best alternative by at least three orders of magnitude. Due to the nature of the wavelet transformations, its use for fractured reservoirs is natural, and the model
10. Due to its flexibility and extremely high efficiency, incorporation of new data that may become available dynamically poses no major problem with the models and methods that are developing.

We have extensive experience in developing techniques for addressing all the major problems that may arise. For example, we have been developing novel techniques for the analysis of cross-correlations between various types of data, including well logs. In addition, we have been studying elastic wave propagation in heterogeneous media and the effect that large-scale heterogeneities and long-range correlations have on the wave propagation and its localization, which are completely relevant to the interpretation of seismic data.

Here, we propose to develop an integrated method that addresses the five major problems listed above, and develop a flexible, accurate, and highly efficient technique for the development of models of fractured reservoirs that is also flexible enough that can be used in conjunction with dynamic reservoir characterization.

The model may also be easily integrated with what other members of the RMC are doing, or plan to do, such as the groups led by Fred Aminzadeh, and by Cyrus Shahabi, since in order to update the upscaled model one needs fast processing of the new data and their incorporation in the geological model, in order to efficiently upscale the model.

The model may also be used in the emerging computational technologies, such as cloud computing that has emerged as technology that allows for providing computational resources as services over the Internet. The essential features of cloud computing makes it a method of choice for implementing real-time reservoir management, because the computational resources of the cloud are abundant, and the cloud enables *off-site* reservoir data management that allows for distributed and collaborative reservoir management. In the past, our work has been supported by the DOE, as well as the National Iranian Oil Company.

Immediate plans and goals for 2012-2014

While we continue our work in this area, our plans are also flexible to the sponsors' interests.

Deployment and testing plans

Upon the development of the 3D model and the availability of data from the sponsors, we will test our results on such real data cases. The 2D model has been developed to a large extent.

Desired interactions with the sponsors

We are open to define the preferred interaction mode according to sponsors' interests.

Key references:

1. M.R. Rasaei and M. Sahimi, Efficient simulation of water flooding in three-dimensional heterogeneous reservoirs using wavelet transformations: Application to the SPE-10 model, *Transport in Porous Media* 72, 311 (2008).
2. M.R. Rasaei and M. Sahimi, Upscaling of the permeability by multiresolution wavelet transformations and simulation of multiphase flow in heterogeneous porous media, *Computational Geosciences* 13, 187 (2009).
3. M. Sahimi, R. Darvishi, M.R. Rasaei, and M. Haghighi, Up-scaled unstructured grids for efficient simulation of flow in fractured reservoirs, *Transport in Porous Media* 83, 195 (2010).
4. H. Dashtian, G.R. Jafari, Z. Koohi Lai, M. Masihi, and M. Sahimi, Analysis of cross correlations between well logs of hydrocarbon reservoirs, *Transport in Porous Media* (in press, 2011).

5. M. Sahimi, M.R. Rahimi Tabar, A. Bahraminasab, R. Sepehrinia, and S.M. Vaez Allaei, Propagation and location of acoustic and elastic waves in heterogeneous rock: Renormalization group analysis and numerical simulation, *Acta Mechanica* 205, 197 (2009).

7- PPP9BJ

Key People: Behnam Jafarpour, M. Reza, and M. Khaninezhad

Project Name: Early Characterization of Reservoir Connectivity for Improved Field Development Planning

Core Technical or Practical Problem(s) we are addressing

Construction of reliable geologic models and early characterization of field-scale reservoir connectivity are critical for accurate assessment and effective development of producible hydrocarbon in a reservoir. We propose to develop and apply a novel technology for capturing large-scale reservoir continuity at early stages of field development to improve the prediction of future production and facilitate development strategies for increased recovery efficiency. We will achieve this objective by integration of reservoir dynamic response at early stages of development into low-dimensional parametric descriptions of large-scale field connectivity. We compactly describe field connectivity by combining signal processing principles with generic characteristics of geologic formations (such as spatial continuity) and/or specific attributes of a given formation type (e.g., fluvial channels).

Long term vision of how this impacts the industry

The long-term vision of the proposed work is that construction of predictive reservoir models to guide future field development should inherently begin with identification of large-scale reservoir connectivity from low-resolution and limited field-scale measurements at early stages and proceed with successive refinements as additional data become available at later stages of the production phase. Therefore, reservoir characterization should be performed in a multi-scale framework, starting from characterization of large-scale connectivity followed by a series of successive refinements down to a scale supported by the highest data resolution. Several critical field development decisions (e.g., number and locations of wells to be drilled) are made at initial stages of field development when little information is available about reservoir flow properties and spatial connectivity. Therefore, early characterization of reservoir connectivity is imperative to planning successful long-term production strategies.

Recent related activities in the industry/academia

Since connectivity of flow properties governs fluid displacement and distribution in a reservoir, accurate characterization of reservoir connectivity, particularly at the early stages of development, is a key design parameter in production planning and management strategies. Hence, development of methodologies for reliable characterization of reservoir compartments to capture fluid flow connectivity has always been an important area of research in the industry and academia. Variants of zonation and reduced-order methods such as principle component analysis have been developed for estimation of field connectivity. While these methods have their strength, they are mainly limited by the subjectivity introduced through prior knowledge. The proposed methods in this project would rely on generic and natural attributes of geologic formations (such as natural facies continuity) to characterize large-scale connectivity using signal processing principles.

Brief Project Description

Data limitation at the early stages of reservoir development can seriously degrade the quality of reservoir characterization and modeling efforts, and lead to ineffective development decisions such as costly infill drilling at low-pay locations. *Effective and early characterization of global reservoir connectivity* is of paramount importance in improving field development strategies. We propose to build on our past work to develop novel methodologies for early identification of reservoir connectivity and optimal infill well placement. The proposed method will reconcile the low resolution of limited dynamic data at early stages of production with high resolution of geologic models through an effective reduced-order description by focusing on identification of reservoir connectivity. The early characterization of field-scale reservoir connectivity will be accomplished by developing flexible large-scale basis functions, derived from model grid-connectivity that can be linearly combined to construct the field connectivity from early exploratory dynamic data. Identification of reservoir connectivity is then used to facilitate field development planning such as well placement to improve recovery and reduce development uncertainties, risks, and costs. The proposed global field characterization and optimal development workflow consists of the following steps:

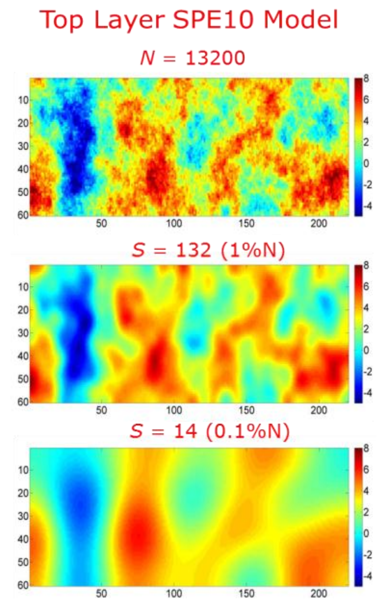


Figure 1. Reduced description of connectivity in reservoir permeability field using frequency-domain analysis. Top: original model with 13200 gridblocks, Middle: reduced representation with 132 parameters, Bottom: further reduced description with only 14 parameters (*note that the global connectivity can still be represented with very few parameters in the frequency domain*).

- Characterization of the *global geologic continuity* from limited *field-scale* exploratory and flow data using novel connectivity-based parameterization techniques.
- Model refinement to capture *local variability* in properties using phase fluid flow data.
- Testing and validation using realistic datasets.
- Systematic production forecasting and uncertainty assessment by accounting for multiple plausible geologic models.

Immediate plans and goals for 2012-2014

The proposed connectivity-driven reservoir characterization research will be a multidisciplinary effort as it will combine signal processing principles with physical insight from the properties of geologic formations and fluid flow dynamics. The following tasks will be performed in the first two years.

- Development of effective parametric descriptions of reservoir connectivity using the continuity in geologic formations and fundamentals of signal/image processing
- Integration of early dynamic data to identify field connectivity by estimating a small number of parameters used to represent flow connectivity in the reservoir
- Combining the early characterization of field connectivity with development optimization (to illustrate the real impact of improved knowledge about connectivity on overall recovery efficiency)
- Extension of methodology into a multi-scale framework for integration of additional dynamic data at later stages of field development for increased model resolution
- Synthetic numerical experiments for testing and verification, followed by application to benchmark problems and feasibility study for field application

Deployment and testing plans

Upon completion of the development phase, suitability of the developed methods will be assessed through application to field data that will be provided by the sponsors.

Desired interactions with the sponsors

1. Technical interactions with sponsor members are essential for achieving planned milestones and ensuring satisfactory progress and completion of the project. Therefore, we encourage and expect collaborations with and suggestions from the sponsors throughout the development and application phases of the project.
2. Sponsor members are welcome to provide field data to USC for our test cases. The case studies can be conducted either exclusively with each individual sponsor (to honor confidentiality) or with involvement of other sponsors. Depending on the sponsors' requirements, appropriate mechanisms will be designed for funding and other related logistics.

Key references

1. Bhark E., Jafarpour B., Datta-Gupta A. (2011): A generalized grid-connectivity-based parameterization for subsurface flow data assimilation, Water Resources Research, accepted.
2. Bhark E., Jafarpour B., Datta-Gupta A. (2011): An adaptively scaled frequency-domain parameterization for history matching, Journal of Petroleum Science and Engineering, 75(3-4), 289-303.
3. Jafarpour B., McLaughlin D. B. (2009): Reservoir characterization with discrete cosine transform, part-1: parameterization, part-2: history matching, *Soc. Pet. Eng. Journal*, 14(1), 182-201.

8- PPP11KJ

Key People: Kristian Jessen, Hasan Shojaei, and Mohammad Evazi

Project Name: Upscaling for Compositional Simulation of EOR Processes

Core Technical or Practical Problem(s) we are addressing

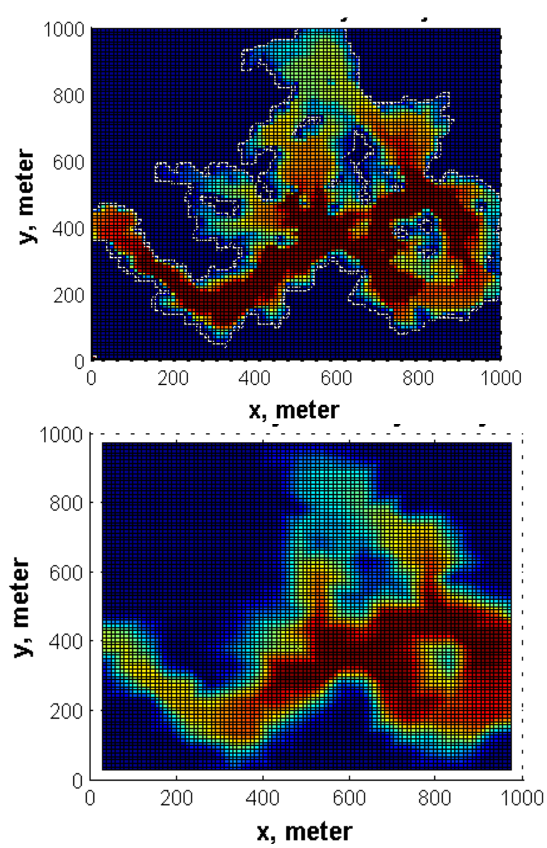
We are currently working on novel solutions to the last frontier of upscaling: Compositional simulation of enhanced recovery processes. With a steadily increasing number of oil fields becoming candidates for enhanced recovery methods such a miscible gas injection and WAG processes, the need for effective and accurate upscaling techniques that are suitable for compositional simulation at large scale is now greater than ever.

Long term vision of how this impacts the industry

Compositional simulation on reservoir models that are sufficiently fine-scaled to resolve the relevant physics of enhanced recovery processes is currently not feasible. Our vision is to bridge the gap between the need for resolution in compositional simulation and the need for timely management of reservoirs during operation and to allow for more efficient work flows for integration of uncertainty in the design and development of enhanced recovery projects.

Recent related activities in the industry/academia

Various techniques have been developed for displacement processes that are less complex (e.g. water flooding) than enhanced recovery techniques that rely on the interplay between flow and phase behavior to drive down the residual oil saturation and maximize recovery. These include novel works that integrate local and/or global flow information in the upscaling (Wen *et al.,* 2006). These approaches are, however, still not suitable for compositional simulation due to the additional complications associated with volume averaging and equilibrium assumptions that result in over-estimation of sweep and underestimation of local displacement efficiency.



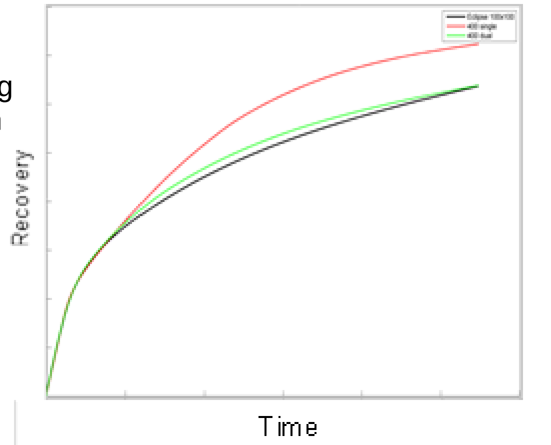
Fine-scale (100x100) single-porosity simulation (top) of multicontact miscible displacement. Up-scaled (20x20) dual-

Brief Project Description

We combine streamline derived information with local/global flow information to upscale complex multicontact miscible displacement processes in heterogeneous reservoirs. The upscaling technique converts the model for an N porosity formation into an N+M porosity model where M>0. This allow us to upscale these complex displacement processes by more than an order of magnitude while maintaining a good representation of the process sweep and recovery predictions. We have successfully applied our technique to structured and unstructured reservoir models for two-phase gas-oil multicomponent displacement processes.

Immediate plans and goals for 2012-2014

The following tasks will be carried out in the first two years of the project.



- Extend and test the application of our upscaling framework in 3D displacement calculations on structured and unstructured reservoir models.
- Improve mass transfer modeling between passive and active porosities in the upscaled volumes.
- Extend and test upscaling technique for WAG and thermal recovery processes.
- Initiate full automation of the upscaling framework.

Deployment and testing plans

With input from interested industry members, we will test our technique for upscaling on displacement processes and reservoir settings of relevance in day to day operations. The upscaling framework will be designed to work with existing simulation technology.

Desired interactions with the sponsors

1. We envision a close collaboration with industry to facilitate the technology transfer based on problems of relevance to the industry.
2. Specific input from participating sponsors will ensure that development and implementations are directly useful to the industry via existing simulation tools.7

Key references

1. Wen, X.H., Chen, Y., Durlofsky, L.J.: “Efficient three-dimensional implementation of local-global upscaling for reservoir simulation,” SPE Journal, 11, 443-453 (Dec. 2006).
2. Jessen, K., Gerritsen M.G. and Mallison, B.T: “High-Resolution Prediction of Enhanced Condensate Recovery Processes”, SPE Journal, Vol. 13(2), p. 257-266, 2008.
3. Jessen, K., Stenby, E.H. and Orr, F.M. Jr. “Interplay of Phase Behavior and Numerical Dispersion in Finite Difference Compositional Simulation”, Society of Petroleum Engineers Journal, 9(2), p. 193-201, 2004.

9- PPP13UM

Key People: Urbashi Mitra

Project Name: Underwater Acoustic Communications Network Design for Reservoir Sensing Systems

Core Technical or Practical Problem(s) we are addressing

High performance reservoir monitoring will require a heterogeneous network of sensor systems with a combination of cabled and wirelessly communicating devices. Given the unique features of reservoir topology and underwater acoustic communication channels, a thoughtful sensing network design is required. We propose to determine network topologies and protocols suitable for such heterogeneous networks.

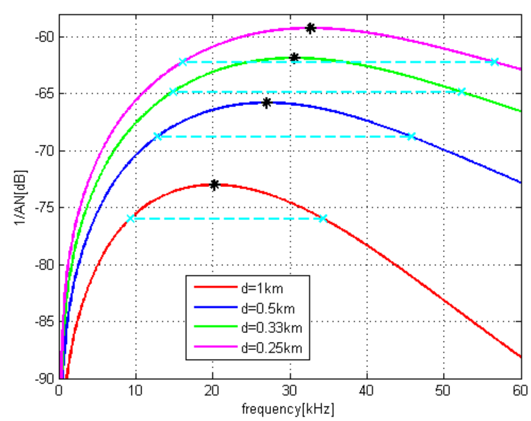
Long term vision of how this impacts the industry

Increasing the real-time flow of information and sensed data could have a dramatic impact on reservoir management. Given the immense expense and complexity of sensor instrumentation and deployment, a careful network design can provide the optimal performance/cost tradeoff in terms of both deployment and daily operation.

Recent related activities in the industry/academia

While design of acoustic communication systems has persisted since the 1970s, there has been a recent interest in the design and analysis of acoustic communication networks; however, most studies have been for ad hoc environmental sensing and have been speculative in nature. There has been some suggestion of the use of acoustic telemetry for signaling in petroleum/reservoir applications, but the scope of the system has been limited. Herein, we propose the design of acoustic communication networks specific to reservoir monitoring.

Brief Project Description



Challenges to be overcome in the design of underwater acoustic communication systems include a severely limited range-dependent bandwidth, extensive time-varying multipath propagation, and long propagation delays caused by the low speed of sound underwater (1500 m/s). The poor quality of the physical link and the high channel latency combine in this channel to produce the worst properties of land-based and satellite radio channels. Due to the very nature of signal propagation, underwater acoustic channels differ fundamentally from the terrestrial radio channels. The decay in signal energy due to absorption is exponential in a monotonically decreasing function of the signal frequency. The frequency-dependent attenuation and the spectral characteristics of (non- white) ambient noise in the ocean result in a range-dependent and frequency-dependent SNR as shown in the figure. Thus, the usable channel bandwidth is range-dependent. This is not the case in terrestrial radio channels, and as such it is not accounted for in any of the available methods for network topology optimization, message routing, or capacity assessment. From the network design point of view, propagation delays are also an issue–low speed of sound implies high latency. Propagation delay over the same distance in an acoustic network is five orders of magnitude higher than in a radio network.

Thus, the characteristics of the acoustic communication channel, the desired data rates, the sensor node locations (in three dimensions) all play a significant role in determining where to place acoustic communication transducers and how the communication nodes should interact with each other. Questions to answer are: (1) what multiple access technology should be employed (2) are repeaters (relays) required and (3) what are the power constraints of the system?

Immediate plans and goals for 2012-2014

The following tasks will be performed in the first two years.

- Candidate network designs and deployments will be proposed.
- Analysis of communication protocols such as time-division multiple-access, code-division multiple-access, random access, etc. will be examined. Parameter optimization for the network design will be conducted.
- Extensive simulation studies to validate network design.

Deployment and testing plans

The proposed network architectures and protocols will be evaluated via analysis and simulation. System parameters and requirements will be determined in cooperation with the sponsors.

Desired interactions with the sponsors

- Field sensor data rates, sensor descriptions and reservoir topology information from the sponsors will greatly facilitate system design.

Key references

1. W. Zhang, U. Mitra, and M. Chiang, **Optimization of Amplify-and-Forward Multicarrier Two-Hop Transmission**, IEEE Transactions on Communications, vol. 59, no.5, May 2011, pp.1434-1445.

2. W. Zhang, M. Stojanovic, and U. Mitra, **Analysis of a Linear Multihop Underwater Acoustic Network**, IEEE Journal on Oceanic Engineering, vol. 35, no. 4, October 2010, pp. 961-970.

3. C. Carbonelli, S.-H. Chen, and U. Mitra, **Error Propagation Analysis for Underwater Cooperative Multihop Communications**, Elsevier Journal on Ad Hoc Networks, invited submission, vol. 7, no. 4, June 2009, pp. 759-769.

4. M. Vajapeyam, S. Vedantam, U. Mitra, J. Preisig, and M. Stojanovic, **Distributed Space-Time Cooperative Schemes for Underwater Acoustic Communications**, IEEE Journal of Oceanic Engineering, vol. 33, no. 4, October 2008, pp. 489 - 501.

10-PPP14UM

Key People: Urbashi Mitra

Project Name: Acoustic Waveform Design for Joint Sensing and Communication

Core Technical or Practical Problem(s) we are addressing

We will examine jointly optimized waveforms for communication and sensing. In particular, communication and sensing metrics will be coupled so that a joint design can be enabled. Due to implementation considerations, we propose to focus on the use of modified orthogonal frequency division multiplexing (OFDM) waveforms.

Long term vision of how this impacts the industry

Acoustic sensor systems that can be exploited for both communication and sensing have the potential to dramatically reduce energy consumption and thus system life over having two dedicated systems (one for communication and one for sensing). Furthermore, such systems can be designed to be adaptive to environmental conditions and user needs: focusing more on sensing or more on communication as dictated by the application.

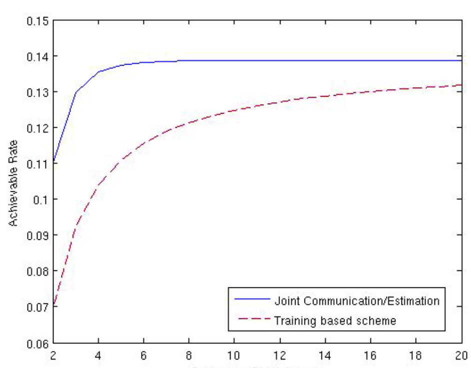
Recent related activities in the industry/academia

Orthogonal Frequency Division Multiplexing (OFDM) has been actively researched for wireless terrestrial communications; there has been recent concentrated interest in the use of OFDM for radar signaling; however, to our knowledge, there is no clear work on the use of optimized OFDM signaling for sensing purposes; nor is there research on the use of optimized OFDM signaling for both communication and sensing. Thus, contributions in this area would represent a significant novelty.

Brief Project Description

Orthogonal Frequency Division Multiplexing (OFDM) is emerging as a popular signaling choice for underwater acoustic communication systems. OFDM systems are of interest when there is limited mobility in the transmitters and receivers as will be true for many of the acoustic transducer devices envisioned for reservoir monitoring.

Given the recent interest in the use of OFDM signaling for radar sensing, we propose the novel design of OFDM waveforms for both communication and sensing.   The goal is to use the OFDM signal opportunistically and adapting the use for more communication or sensing as the environment dictates. Radar signal distortion shares many properties with that for underwater acoustic communication, thus the success of OFDM radar suggest that OFDM acoustic sensing would also be high performance. To this end, we propose to investigate the use of OFDM-LFM (linear frequency modulated chirps) which has been employed in radar systems and high resolution imaging signals based on OFDM-LFM waveforms in the current context. We shall examine both single transmitter/receiver systems as well as multiple transmit antennae/multiple receive antennae systems. Cost functions such as mean-squared error and mutual information will be examined. We have made significant contributions in determining the limits of joint communication and sensing from a theoretical point of view and will apply our lessons learned to the practical instantiation of these concepts.   The



theoretical results strongly suggest how joint designs should be undertaken. In particular, the signal should **not** be divided into two orthogonal parts: a sensing portion and a communication portion. This fact can be clearly seen in the information rate curves shown in the figure. The information rate is maximized subject to a sensing metric constraint: the joint design achieves a higher rate over the design that separates communication from sensing (training).

Immediate plans and goals for 2012-2014

The following tasks will be performed in the first two years.

- Determine per-carrier power allocations to optimize sensing performance for OFDM signaling in underwater acoustic communication.
- Characterize sensing performance for optimized signaling.
- Compare optimized underwater acoustic sensing OFDM to other sensing waveforms to characterize performance gains.
- Begin cost function design for joint communication and sensing.

Deployment and testing plans

The proposed signaling methods will be evaluated via analysis and simulation. System parameters and requirements will be determined in cooperation with the sponsors.

Desired interactions with the sponsors

- Acoustic sensor system specifications and communication requirements will be needed from the sponsors.

Key references

1. N. Michelusi , B. Tomasi, U. Mitra,J. Preisig and M. Zorzi, **An Evaluation of the Hybrid Sparse/Diffuse Algorithm for Underwater Acoustic Channel Estimation**, *IEEE/OES OCEANS Conference*, Big Island, HI, November 2011, to be presented.

2. S. Vedantam, W. Zhang, and U. Mitra, **A Constrained Channel Coding Approach to Joint Communication and Channel Estimation**, IEEE Transactions on Information Theory, accepted
3. June 2011.

4. W. Zhang, U. Mitra, and M. Chiang, **Optimization of Amplify-and-Forward Multicarrier Two-Hop Transmission**, *IEEE Transactions on Communications*, vol. 59, no.5, May 2011, pp.1434-1445.

5. S. Yerramalli and U. Mitra, **Optimal Resampling of OFDM Signals in Multi-Scale Multi-Lag Underwater Acoustic Channels**, *IEEE Journal on Oceanic Engineering*, vol. 36, no. 1, January 2011, pp. 126 - 138.

6. S. Vedantam, U. Mitra, and A. Sabharwal, **Distortion Bounds for the Estimation of Time-Varying Channels in Multihop Sensor Networks**, ACM Transactions on Sensor Networks, vol. 6, no. 4, July 2010, pp. 33:1–33:33.

7. S. Yerramalli, M. Stojanovic, and U. Mitra , **Analysis of Partial FFT Demodulation for Doppler Distorted OFDM Signals**, *Asilomar Conference on Signals, Systems and Computers*, Pacific Grove CA, November 2010, **invited paper**.

8. G. Leus, T. Xu, and U. Mitra, **Block Transmission over Multi-Scale Multi-Lag Wireless Channels**, *Asilomar Conference on Signals, Systems and Computers*, Pacific Grove CA, November 2010, **invited paper**.

11- PPP17AO

Key People: Antonio Ortega

Project Name: Reservoir Data Visualization Using Graph Wavelets

Core Technical or Practical Problem(s) we are addressing

As tools for reservoir modeling advance, it becomes easier to obtain very high resolution simulations of reservoir characteristics. However, these 3D or 4D models are often difficult for end users (scientists, engineers) to visualize without access to high workstations and visualization software. Our goal is to make it possible for users to visualize this information using portable off-the-shelf devices, e.g., tablet computers. We aim to make complex geophysical simulation data easily available to remote users in order to facilitate interaction and team collaboration.

Long term vision of how this impacts the industry

The long term vision is for users (e.g., experts in a cross-disciplinary team evaluating a reservoir) to collaborate with each other in real time while interacting with high quality, high resolution 3D and 4D datasets. This can make it possible for top area experts to share their ideas and input with others in geographically distributed teams.

Recent related activities in the industry/academia

Most work on visualization in the oil industry has focused on high end platforms (e.g., control rooms). We think that there is an opportunity in considering off the shelf mobile platforms, such as tablet computers. Work on remote visualization has been taking place in both academia and industry but has not considered special characteristics of reservoir data. For example, it is likely that 3D datasets will be structured in layers and so remote visualization techniques that exploit this structure will tend to be more efficient.

Brief Project Description

We propose to develop the first truly interactive volumetric data browsing system for mobile computing devices. Examples of volumetric datasets include medical imagery (e.g. CT scans), simulated or measured geophysical data, and artificially generated 3D models. Users will be able to navigate 3D data by moving a tablet and by using the tablet's native touchscreen capability. Our system will allow its users to interact with these data sets remotely, in real time via off-the-shelf mobile computing devices (e.g., an Apple iPad). This type of interaction is currently not possible due to insufficient capacities of network bandwidths and computing power of mobile devices. Furthermore, transferring the complete datasets requires excessive delays, while interaction is mostly optimized for high-end computing platforms with sophisticated visualization capabilities. As a result, the system we plan to develop will facilitate new forms of collaboration, as users of this system will no longer need to be tied to either the high-end computing platforms or specialized computing devices. In the oil/gas exploration industry this is particularly important since sophisticated 3D simulations of reservoirs are widely used but are not easily accessible on the field, e.g., near the actual well drilling operations.

From a research perspective this work leverages off work on redundant representations for volumetric datasets [1,2], which has developed novel techniques to reduce overall bandwidth utilization by making use of additional server storage. We are currently in the process of implement an iPad prototype of this idea to demonstrate its feasibility. Moreover, some of our recent work on signal processing using graph wavelets [3] will serve as the basis for new ways of representing complex geophysical datasets. In particular, graph wavelets can represent sets of pixels/voxels of arbitrary shape, making it possible to display only important parts of a dataset. For example, we can describe a volumetric geophysical dataset in terms of layers, of arbitrary shape, each of which can be encoded, retrieved, decoded and displayed independently.

Immediate plans and goals for 2012-2014

The following tasks will be performed in the first two years.

- We are currently developing an iPad prototype to illustrate 2D visualization of 3D volumetric data

- We are studying how graph transforms can be used to represent data with arbitrarily shaped boundaries (e.g., data that is represented in layers)

Deployment and testing plans

We plan to test a simple iPad app internally and use it to generate some data about usability. We plan to extend this to a broader group testing.

Desired interactions with the sponsors

Once an initial app is in place we would seek advice about the quality/usability of the users interface from domain experts, so that changes can be made accordingly.

Key references

[1] Z. Fan, A. Ortega, “Optimization of Overlapped Tiling for Efficient 3D Image Retrieval”. Full paper in Proc. of IEEE Data Compression Conference (DCC), Snowbird, UT, March 2010

[2] Z. Fan, A. Ortega, , “Mapping data on rotated grid in high-dimension for lossless compression” to appear in IEEE International Conference on Image Processing (ICIP), Sept. 2011

[3] S.K. Narang and A. Ortega, "Local Two-Channel Critically Sampled Filter-Banks On Graphs",Intl. Conf. on Image Proc. (ICIP'10)

[4] G. Shen, W.-S. Kim, S. K. Narang, A. Ortega, J. Lee, and H. Wey, "Edge-adaptive transforms for efficient depth-map coding," in Proc. Of 28th Picture Coding Symposium (PCS ‘10), Nagoya, Japan, Dec. 2010