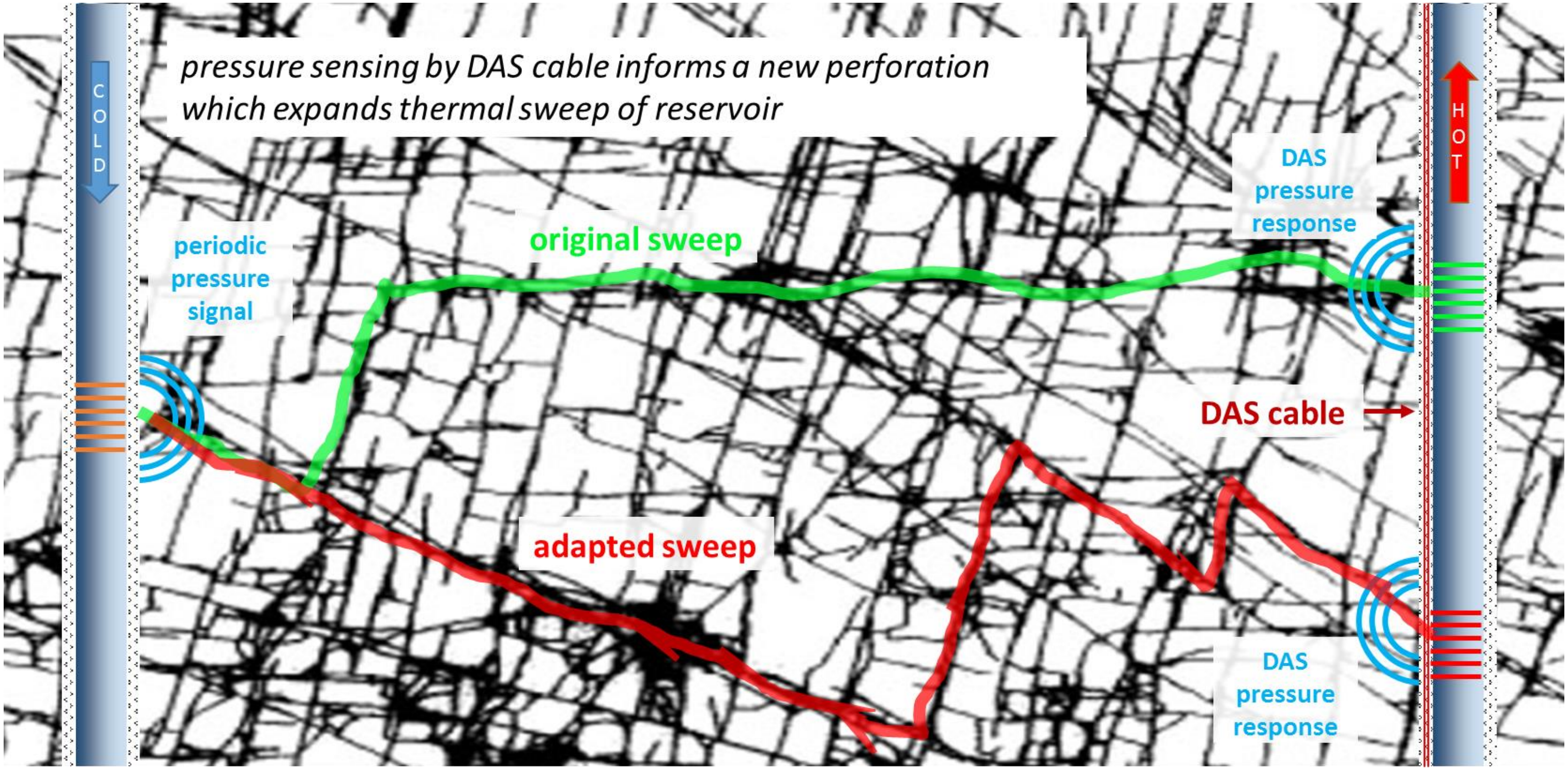


Phase I Project: Fiber Optic Distributed Acoustic Sensing for Periodic Hydraulic Tests

Project Officer: William Vandermeer
Total Project Funding: $505,829 (Fed Share $449,994)
May 13, 2015

Matthew W. Becker
California State University Long Beach

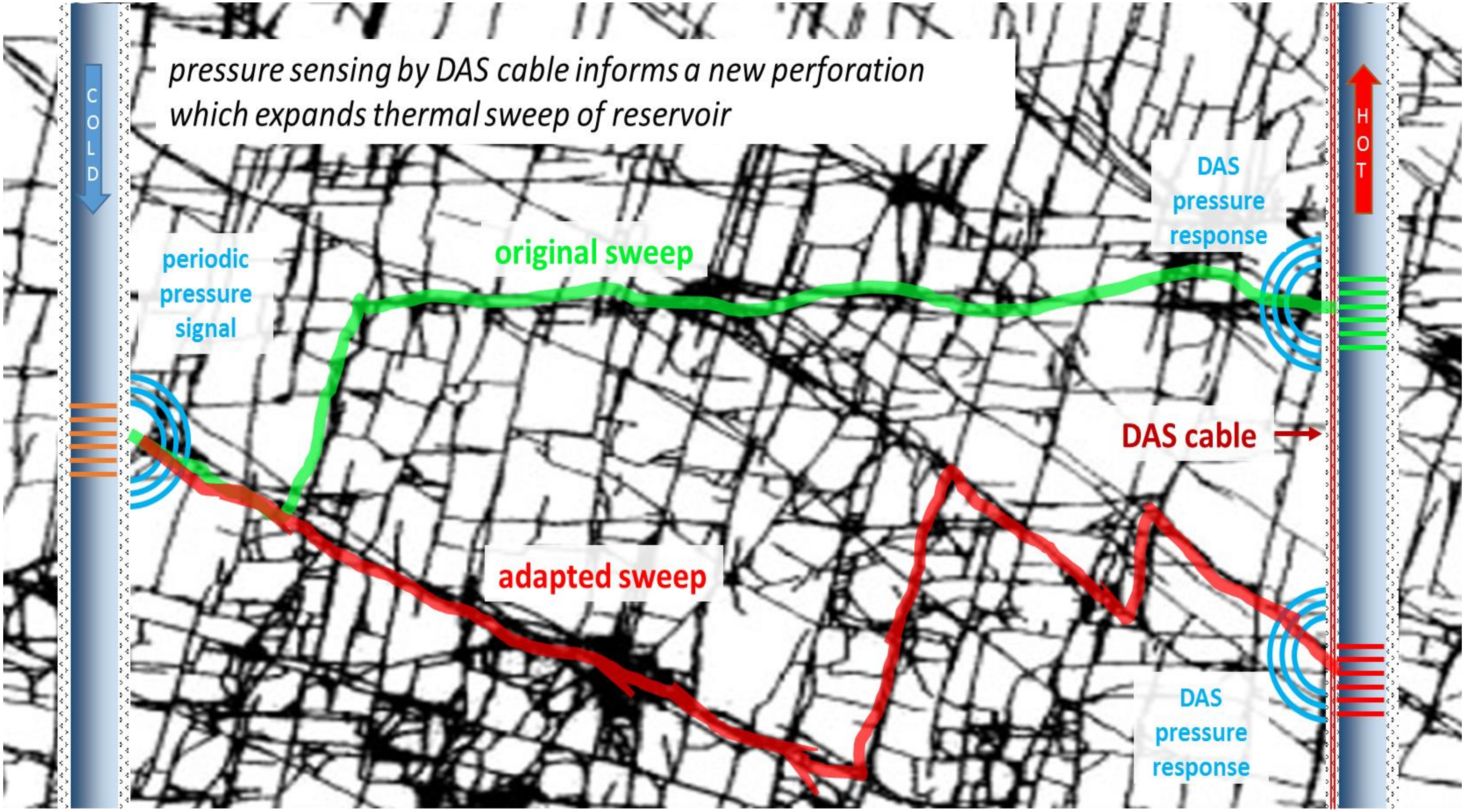
EGS Track

Relevance/Impact of Research

Objectives:

- Optimal hydraulic connectivity between wells is the key to geothermal reservoir efficiency. Tracer tests are expensive, result in operational downtime, and can only evaluate connectivity between existing perforations.
- We develop and test periodic hydraulic tests that can be conducted during operations and provide greater spatial information than constant rate or pulse injection tests.
- We develop distributed acoustic sensing (DAS) technology that will allow periodic pressure signals to be evaluated the entire length of a geothermal well.
- The combination of periodic hydraulic tests and DAS will allow for adaptive recompletion of geothermal wells which will improve efficiency and lifetime of heat extraction.

Relevance/Impact of Research



Scientific/Technical Approach

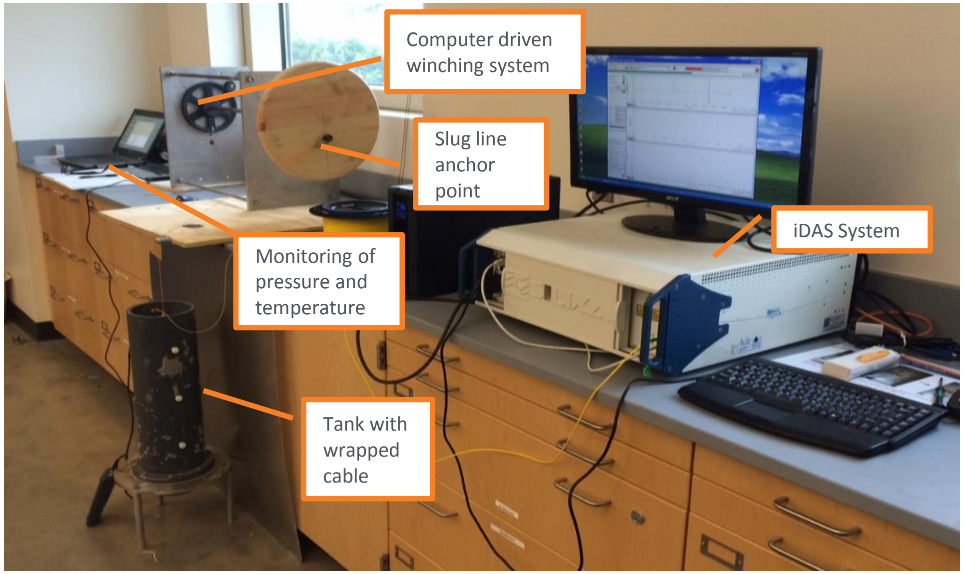
- The project is organized into four major Tasks:
  - Task 1: Prove in the laboratory that DAS can be extended from the seismic kHz range to periodic testing mHz range in frequency. **Silixa** is subcontractor for this technology.
  - Task 2: Demonstrate the technology in a geothermal analog field site. DAS will be deployed in wells completed in the well-characterized Mirror Lake Fractured Rock Hydrology site.
  - Task 3: Perform numerical modeling to elucidate the sensitivity of periodic hydraulic signals to hydraulic connectivity and interpret the field results obtained in Task 2.
  - Task 4: Document, report, and publish the results.
- There is a go-no/go decision point following Task 1, prior to performing field tests.

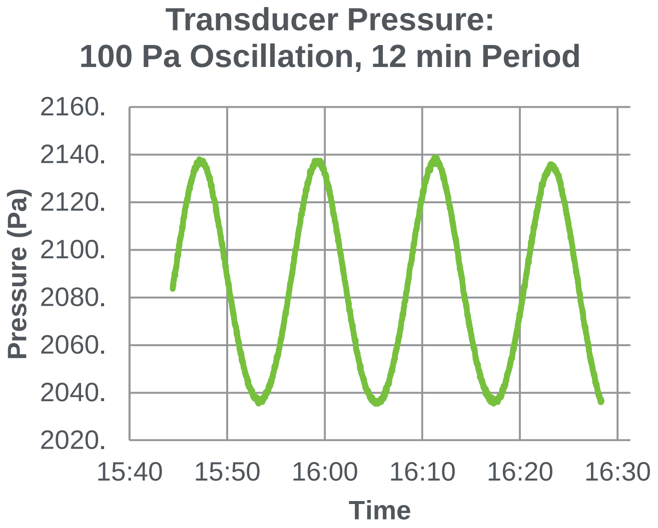
Accomplishments, Results and Progress

- Task 1 Laboratory Tests:
  - Experiments were performed in the CSULB laboratory in which an oscillating pressure signal was sensed using the Silixa iDAS™ system.
  - The go-no/go milestone of measuring at least100 Pa (1 cm water) pressure at periods of at least 10 min was achieved.
  - We have submitted our decision point D1 report which is under review at this writing
- Task 2 Numerical Models
  - Hypothetical models of periodic hydraulic tests were created in COMSOL in frequency domain
  - Sensitivity of amplitude and phase change to hydraulic structure was tested.
  - Periodic tests were simulated in measured aperture field from Altona Flat Rock.

Original Planned Milestone/ Technical Accomplishment	Actual Milestone/Technical Accomplishment	Date Completed
M1.1 Construct Pressure Vessel	Completed ahead of schedule	11/1/2014
M1.2 Lab DAS Tests	Completed ahead of schedule	2/28/2015
D1 Lab Target (100 Pa, T=10 min)	Completed ahead of schedule	3/18/2015

- Task 1 Laboratory Tests:
  - Oscillating pressure was generated by moving a “slug” attached to a rotating disc, controlled by a stepper motor. High-resolution transducer measured pressure.
  - The iDAS system measured laser backscatter as a function of strain rate along a coiled 100 m cable at 0.25 m intervals.
  - iDAS reports longitudinal strain in the fiber optic as nm/m. Strain must be converted to pressure through physics (i.e. Poisson ratio) and calibration.





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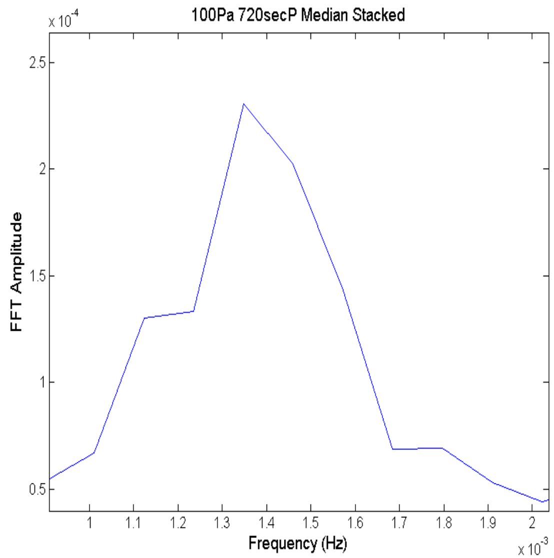
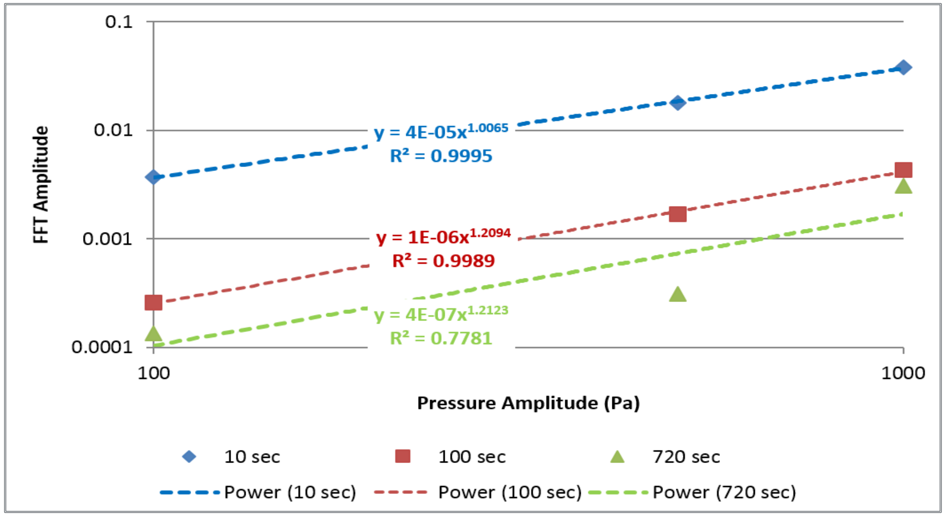
- Task 1 Laboratory Tests continued:
  - Strain is measured in frequency domain. A Fast Fourier Transform (FFT) algorithm is used to extract strain amplitude over a range of frequencies.
  - FFT amplitude and transducer amplitude show a power-law relationship which is linear for short periods of oscillation. At larger periods relationship becomes poorer and regression degrades
  - More work with signal processing and instrument tuning is necessary to improve long-period response.



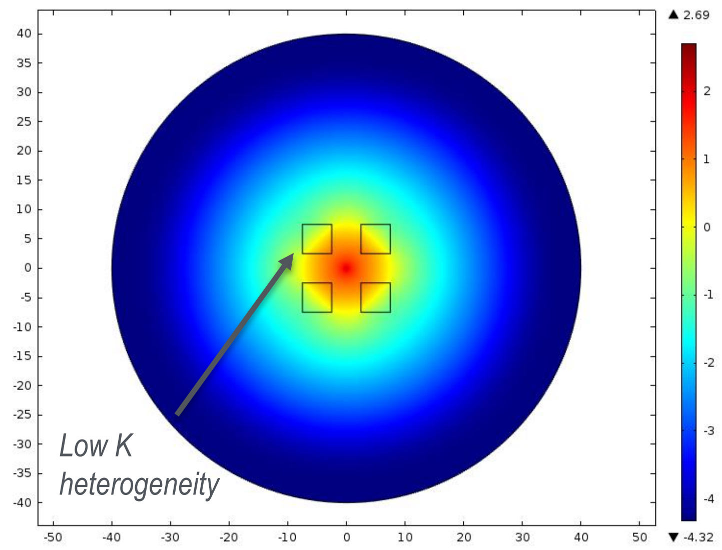
FFT processing of experiment with 100 Pa oscillation amplitude and 12 min (720 sec) period



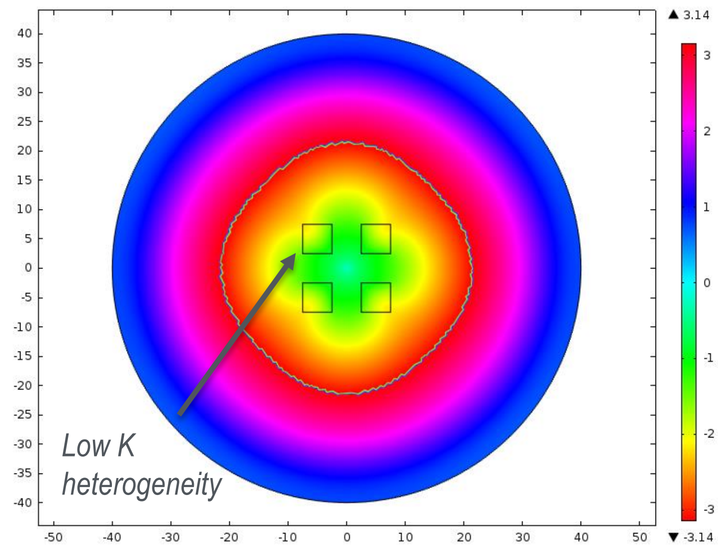
FFT peak amplitudes as a function of transducer-measured pressure amplitudes.
A power law regression is shown for each period of oscillation.

- Task 2 Numerical Models
  - COMSOL Multiphysics was chosen as a modeling platform for its ability to work in time and frequency domain and to couple flow, heat, and geomechanics.
  - Simulations of periodic pressure propagation were developed for the frequency domain and tested for various structures of permeability.
  - Phase shift appears to be more sensitive to heterogeneity in permeability (and therefore connectivity) than amplitude.

Log of pressure amplitude in response to oscillating head at center of the field



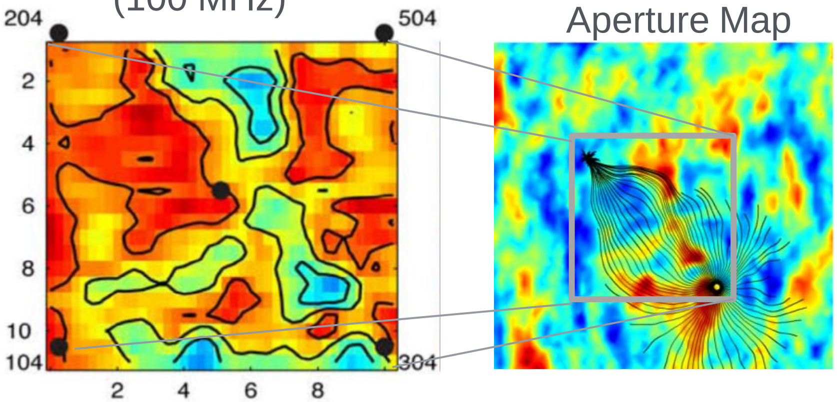
Phase shift (rad) in response to oscillating head at center of the field



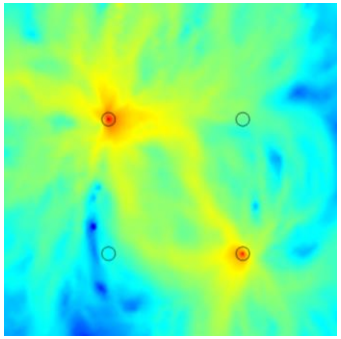
- Task 2 Numerical Models
  - Simulations in a single fracture with a realistic aperture distribution. Aperture derived from GPR imaging for previous EERE project.
  - Sensitivity studies show
    - Phase more sensitive to heterogeneity than amplitude
    - Higher frequencies are best for discerning local connectivity
    - Frequency can be use to “tune” hydraulic test to scale of interest

GPR Amplitude (100 MHz)

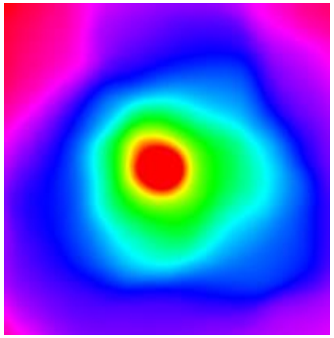
Particle Paths in Extrapolated Aperture Map



Magnitude of Specific Discharge Vector



Periodic Pressure Test Phase



Future Directions

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Project start October 1, 2014

Milestone or Go/No-Go	Status & Expected Completion Date
Task 2: Prep field equipment/tracer	Underway but need to pass decision point to purchase equipment / supplies
Task 2: Field hydraulic/tracer tests	July 15-Aug 8,2015: collaborating with Cornell on tracer work at Mirror Lake Fractured Research Site
Task 2: Complete field DAS testing	8/15 completion: will monitor six bedrock wells and use flexible liners to observe individual fracture zones
Task 2: Interpret field results	1/16 completion: signal processing to improve long period resolution will be important
Task 3: COMSOL modeling	6/16 completion: 2-D cross-section representations of tracer and hydraulics field tests in COMSOL
Task 3: Numerical sensitivity study	8/16 completion: evaluate ability to measure connectivity in fracture network using PHT
Task 4: Publications / Reporting	Final report 9/16: 1 paper sensitivity to heterogeneity (in draft), 1 paper PHT field, 1 paper PHT/Tracer comparison

Future Directions

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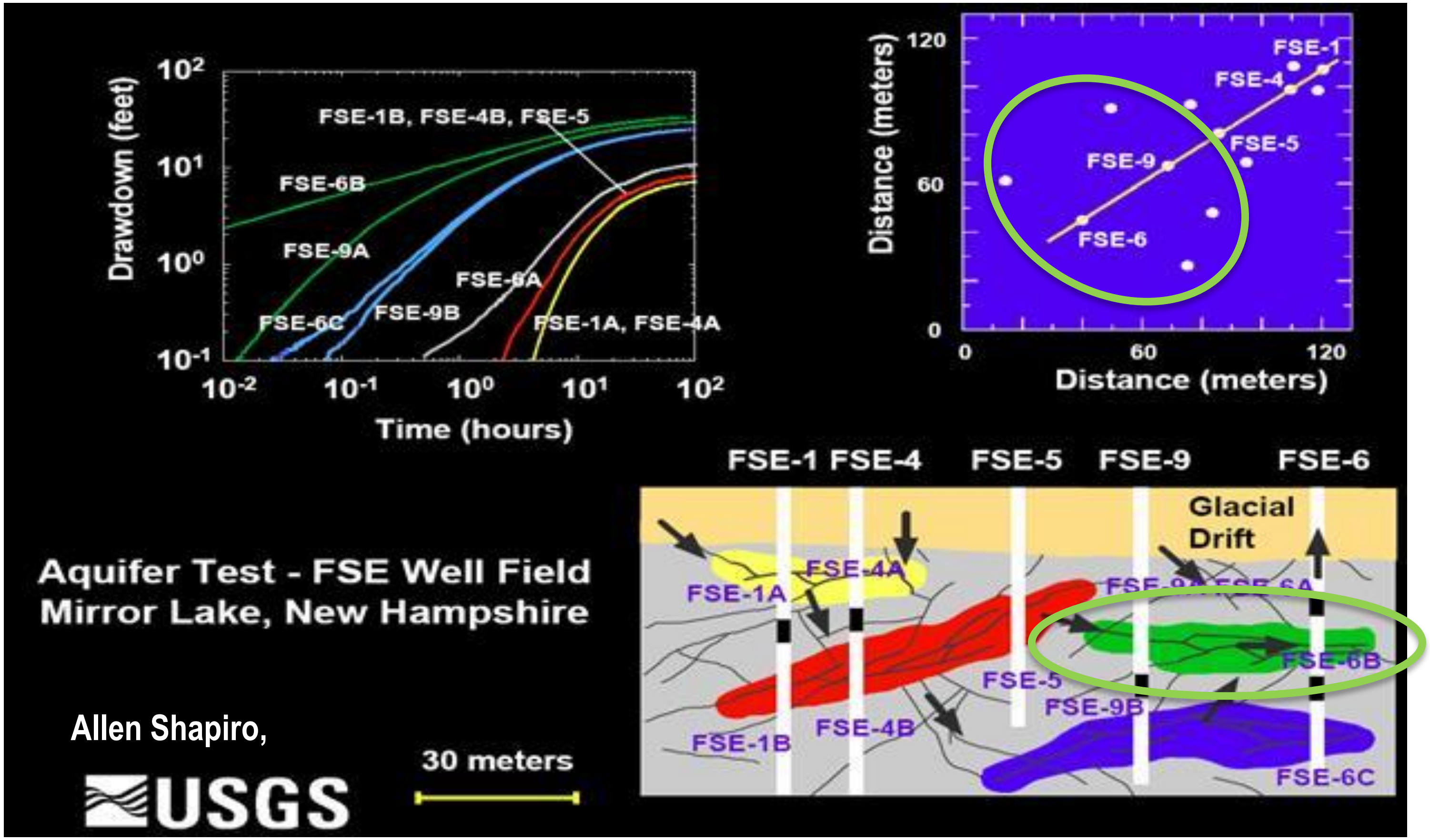
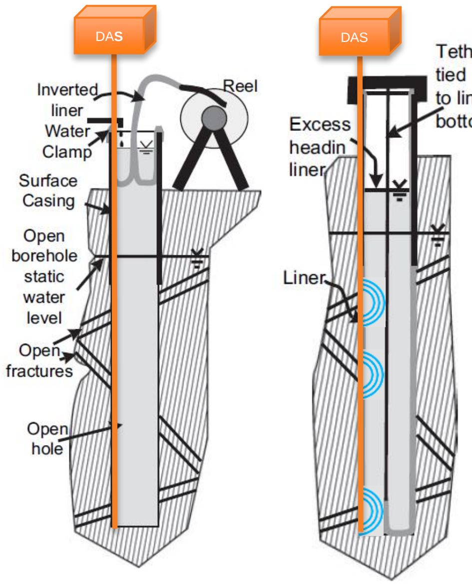
Field tests will be conducted this summer at the Mirror Lake Fractured Rock Hydrology Site, Grafton, County, NH.



Future Directions

- Revised field design:
  - Original proposal was to deploy FO cable in open borehole to sense PHT response
  - To get response from individual fractures, we will push cable against borehole wall using a flexible liner (FLUTe™)
  - We will compare open hole to lined response to evaluate ability to measure local signals
  - The revised field design will better mimic conditions in a grouted well
  - FLUTe liners will cost about $2000 per well, in 5 wells, which will be diverted from cost savings in the laboratory



After Cherry, et al. (2007), Ground Water Monitoring & Remediation, 27(2), 57-70

Mandatory Summary Slide

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- We have demonstrated for the first time that distributed *acoustic* sensing (DAS) can be utilized as distributed *pressure* sensing (DPS)
- We have adopted the Silixa iDAS technology for DPS but instrument tuning and improved signal processing is still needed to measure long period pressure oscillations
- Numerical simulations suggest that observing phase shift is best for measuring hydraulic connectivity, and frequency should be tuned to resolve target features
- Field experiments are set to start this July once we obtain permission to proceed past decision point