Pressure-Based Inversion and Data Assimilation System for CO_2 Leakage Detection

Project # DE-FE0012231

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National Energy Technology Laboratory
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Transforming Technology through Integration and Collaboration
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  - Center for Subsurface Modeling: Mary Wheeler, Baehyun Min
- LBNL: Barry Freifeld, Paul Cook
- Sandia Technologies LLC: Kirk Delaune

Outline

- Benefit to the Program
- Project Overview
- Technical Status
- Accomplishments to Date
- Summary

Benefit to the Program

- Carbon program goal being addressed: ***Develop and validate technologies to ensure 99 percent storage permanence***

- Project benefits
  - The PIDAS project develops and demonstrates a ***pressure-based, pulse testing technology for leakage detection in carbon storage reservoirs*.**
  - Methodologies for **enhancing signal-to-noise ratio** for injection zone

Project Overview: Goals and Objectives

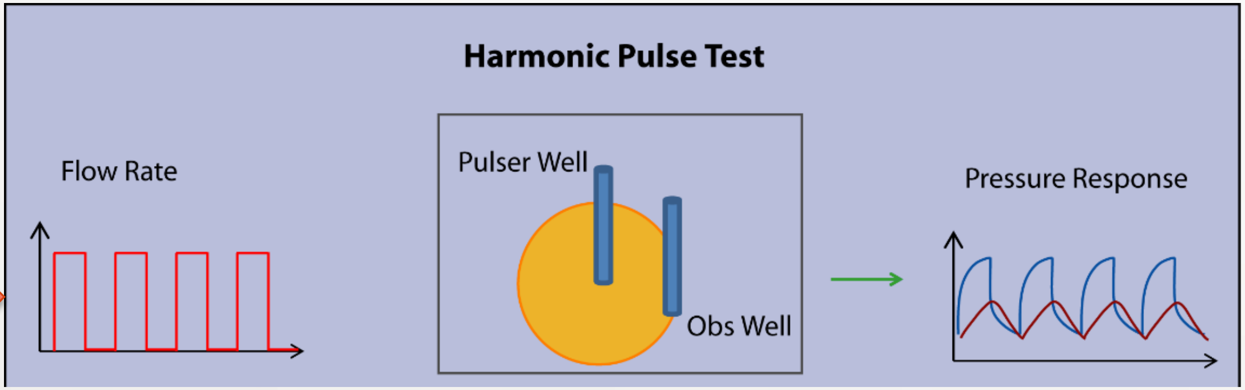
- Demonstrate the utility of pulse testing for leakage detection
- Develop relevant data analyses and inversion methodologies
- Provide an experimental design tool for CCS operators to apply the technology

Technical Status

- Task 2: Theoretical and numerical proof of concept studies
- Task 3: Laboratory experiments
- Task 4: Development of inversion and data assimilation algorithms
- Task 5: Field demonstration
- Task 6: Synthesis of results

Why Pulse Testing?

Coded injection pattern

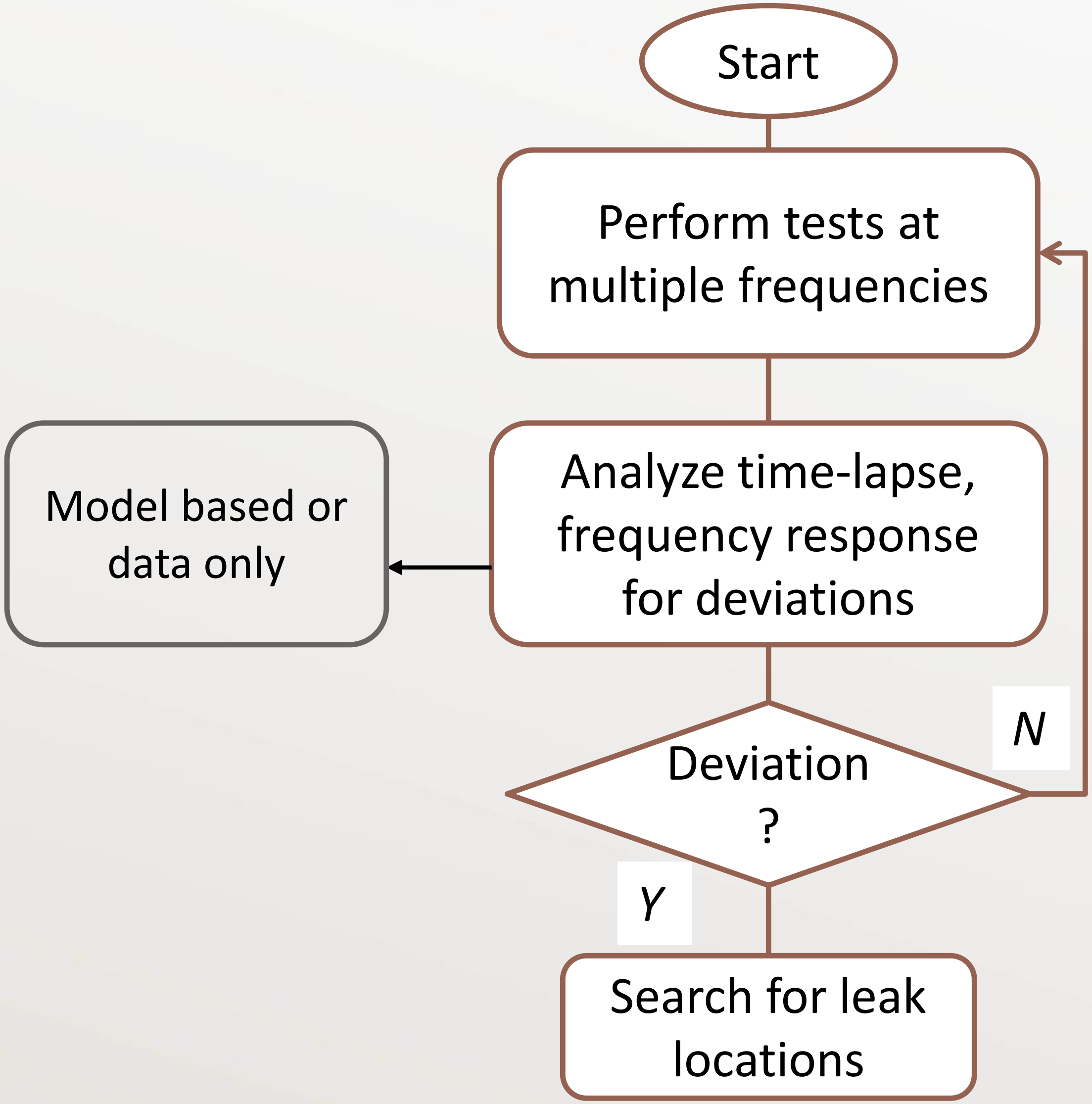


- Has been used for reservoir characterization since 1960s
- Hypothesis: pulse testing as a leakage detection technology for CCS
- Expected advantages over other pressure-based methods
  - An active monitoring method: enhanced signal-to-noise ratio, thus mitigating reservoir noise interference
  - No net injection rate change: little interruptions to nominal reservoir operations

Pulse Testing: A Renaissance?

Literature	Field	Use
• Johnson et al. (1966). Pulse-testing: A new method for describing reservoir flow properties between wells. J. Pet. Technol., 18. • Fokker, P. A., and F. Verga (2011). Application of harmonic pulse testing to water–oil displacement, J. Pet. Sci. Eng., 79(3), 125–134.	Reservoir	Site characterization
• Rasmussen et al., (2003). Estimating aquifer hydraulic properties using sinusoidal pumping at the Savannah River site, South Carolina, USA, Hydrogeol. J., 11, pp. 466–482. • Cardiff et al, (2013). Aquifer heterogeneity characterization with oscillatory pumping: Sensitivity analysis and imaging potential. WRR. • Guiltinan, E., & Becker, M. W. (2015). Measuring well hydraulic connectivity in fractured bedrock using periodic slug tests. Journal of Hydrology, 521, 100-107.	Aquifer	Site characterization
• Ferrante, M., and B. Brunone (2003). Pipe system diagnosis and leak detection by unsteady-state tests: 1. Harmonic analysis, Adv. Water Resour., 26(1), 95–105.	Water Industry	Water Leak

How Does It Work?

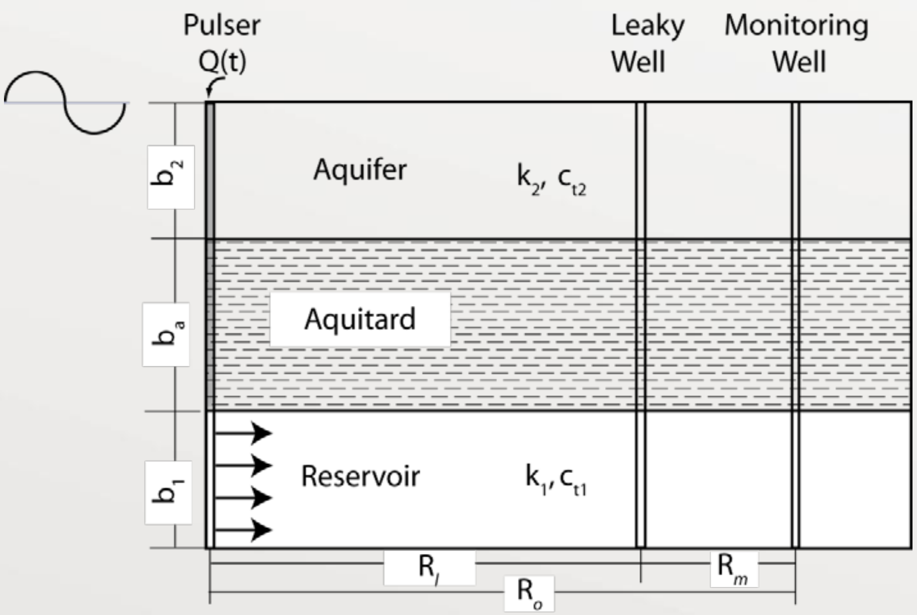


Frequency response function

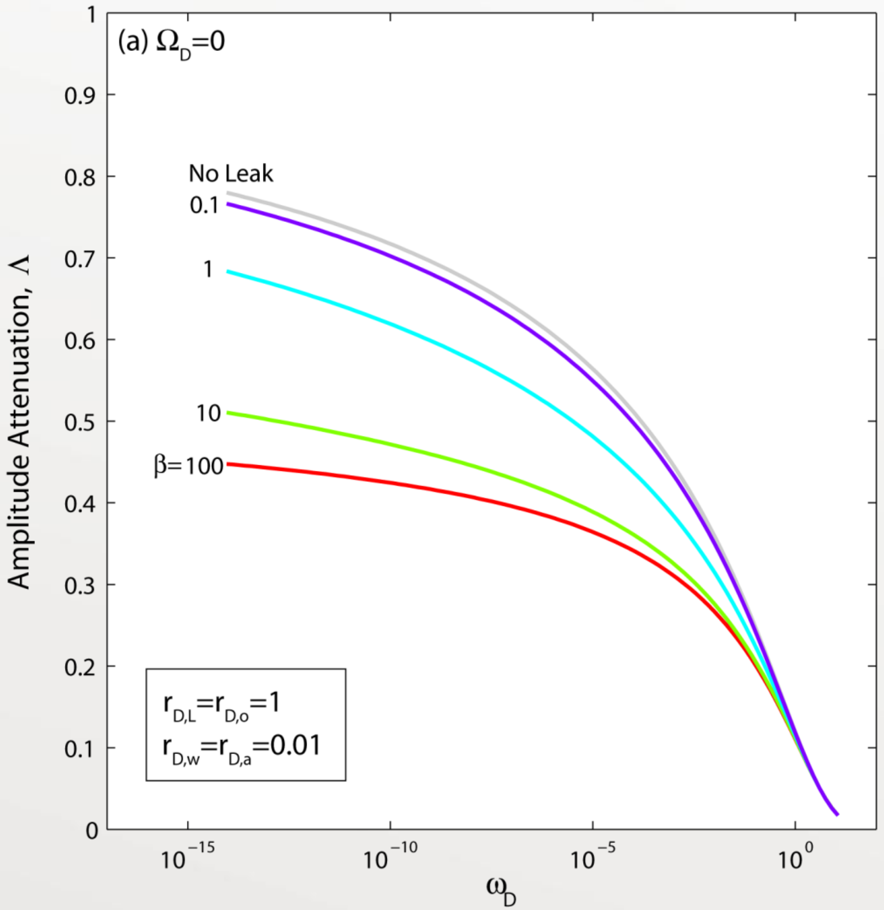
$$\hat{H}(w) = \frac{\hat{P}_{obs}(w)}{\hat{P}_{inj}(w)}$$

Proof of Concept [Task 2]

Problem Settings



Amplitude response



β =Transmissivity ratio between upper and lower aquifer

Ω = Resistance of leaky well to vertical flow

Analytical Solutions

Governing PDE:

$$\frac{\partial^2 p}{\partial r^2} + \frac{1}{r}\frac{\partial p}{\partial r} = \frac{\phi \mu c_{t,1}}{k_1}\frac{\partial p}{\partial t}$$

Boundary Conditions:

$$\frac{2\pi k_1 b_1}{\mu} r \frac{\partial p}{\partial r}\bigg|_{r=r_w} = -Q(t) \qquad \lim_{r\to\infty} p(r,t) = p_{init}$$

$$q_D = \frac{\dfrac{-K_0(\sqrt{i\omega_D})}{r_{D,w}\sqrt{i\omega_D}\,K_1(r_{D,w}\sqrt{i\omega_D})}}{\Omega_D + \dfrac{K_0(r_{D,a}\sqrt{i\omega_D})}{r_{D,a}\sqrt{i\omega_D}\,K_1(r_{D,a}\sqrt{i\omega_D})} + \dfrac{K_0(r_{D,a}\sqrt{\alpha i\omega_D})}{\beta r_{D,a}\sqrt{\alpha i\omega_D}\,K_1(r_{D,a}\sqrt{\alpha i\omega_D})}}$$

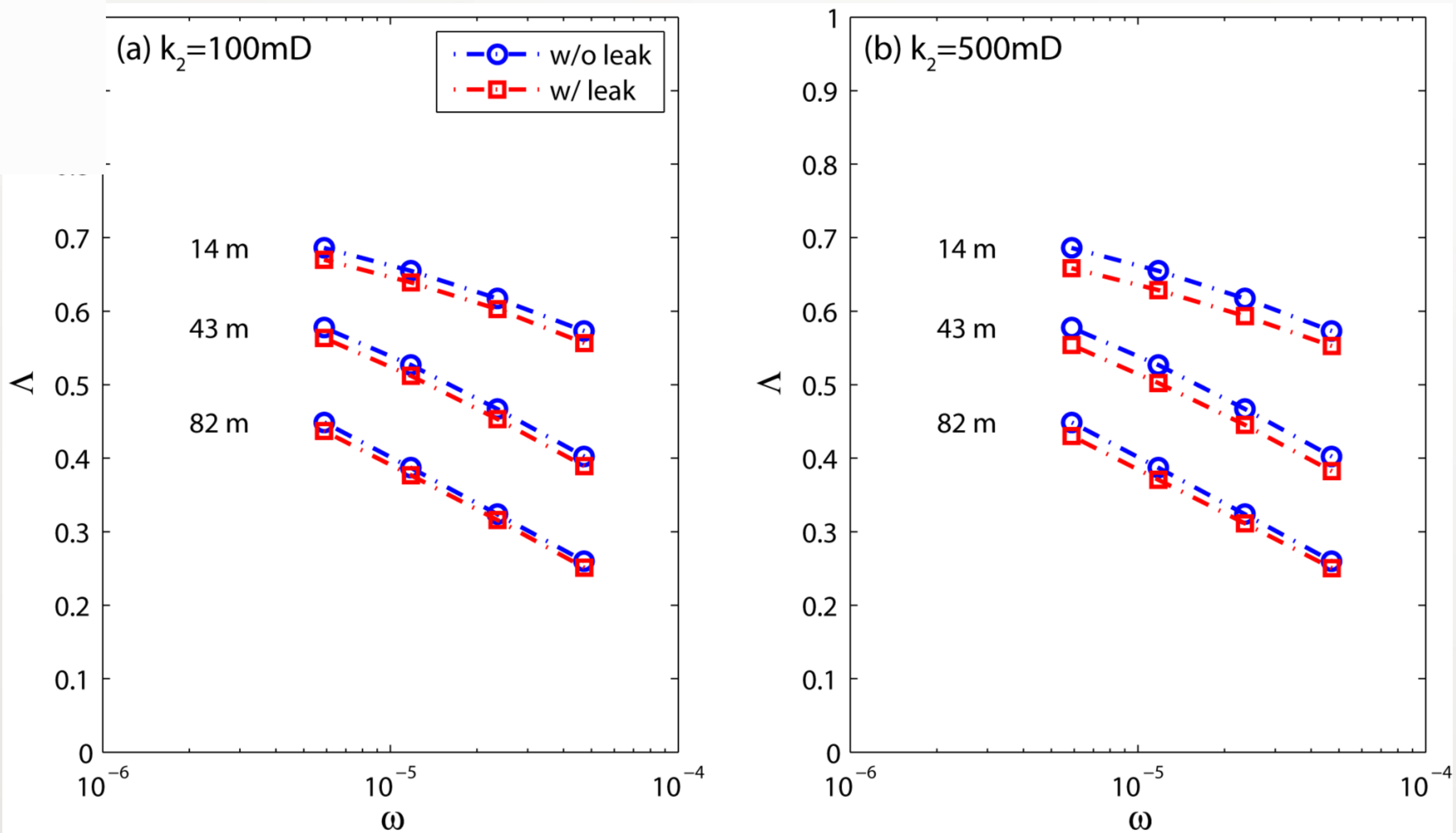
$$p_{D,1}^T = \frac{q_D}{r_{D,a}\sqrt{i\omega_D}}\frac{K_0(r_{D,L}\sqrt{i\omega_D})}{K_1(r_{D,a}\sqrt{i\omega_D})} + \frac{1}{r_{D,w}\sqrt{i\omega_D}}\frac{K_0(r_{D,O}\sqrt{i\omega_D})}{K_1(r_{D,w}\sqrt{i\omega_D})}$$

Transmissivity ratio: $\beta = k_2 b_2 / k_1 b_1$

Diffusivity ratio: $\alpha = \eta_1 / \eta_2$ $\qquad \eta = k / \phi \mu c_t \qquad \omega_D = \dfrac{\omega r_I^2}{\eta_1}$

Multiphase Flow Problem

CMG-GEM

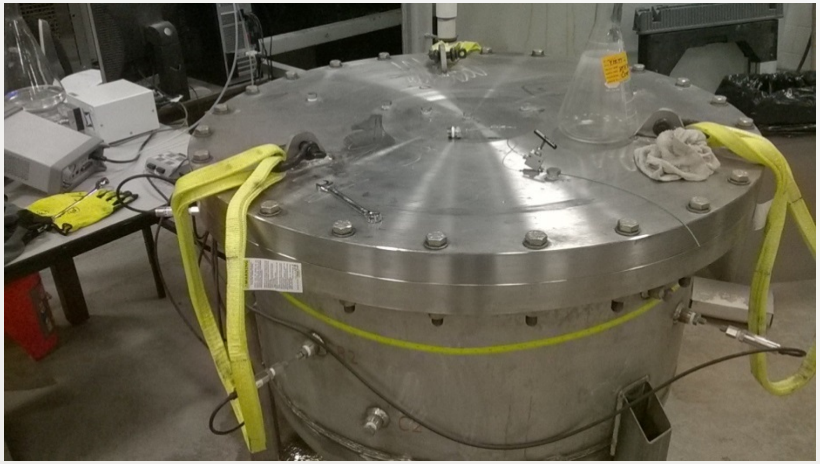


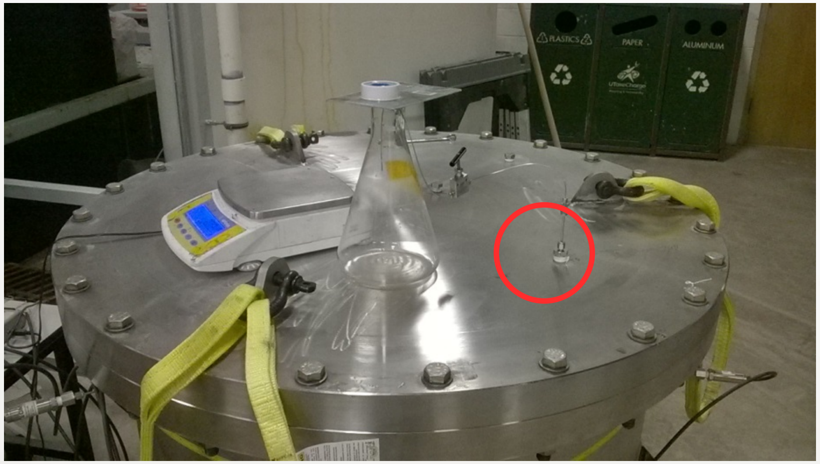
Amplitude response as a function of upper layer permeability

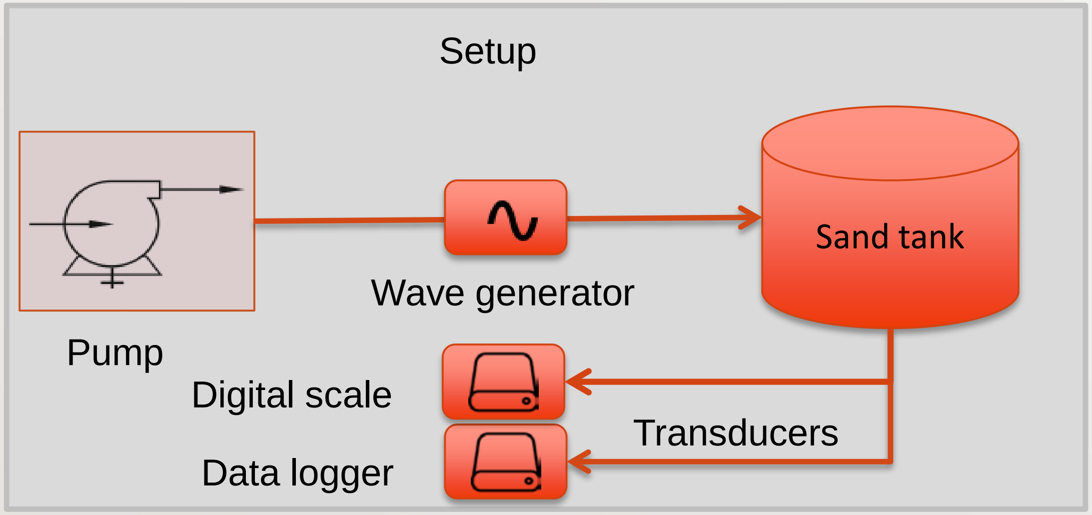
Sun et al., WRR, 2015

Laboratory Experiments [Task 3]

1-m diameter, 0.75 m tall

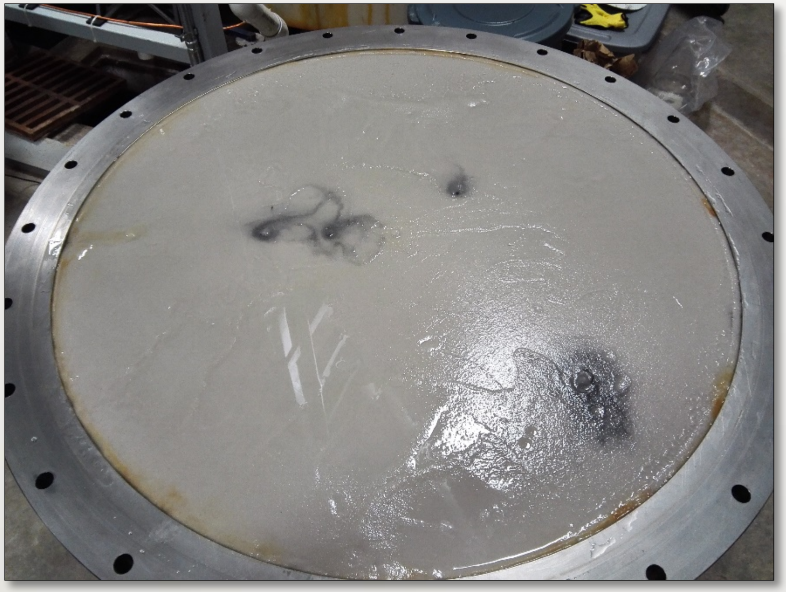




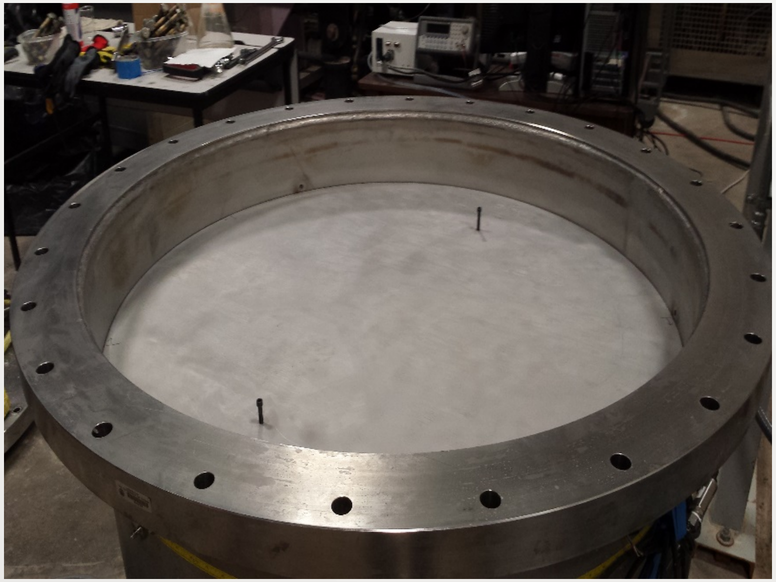


A Mini 3-Layer Repository

Clay as ‘caprock’



Aluminum plate as ‘caprock’

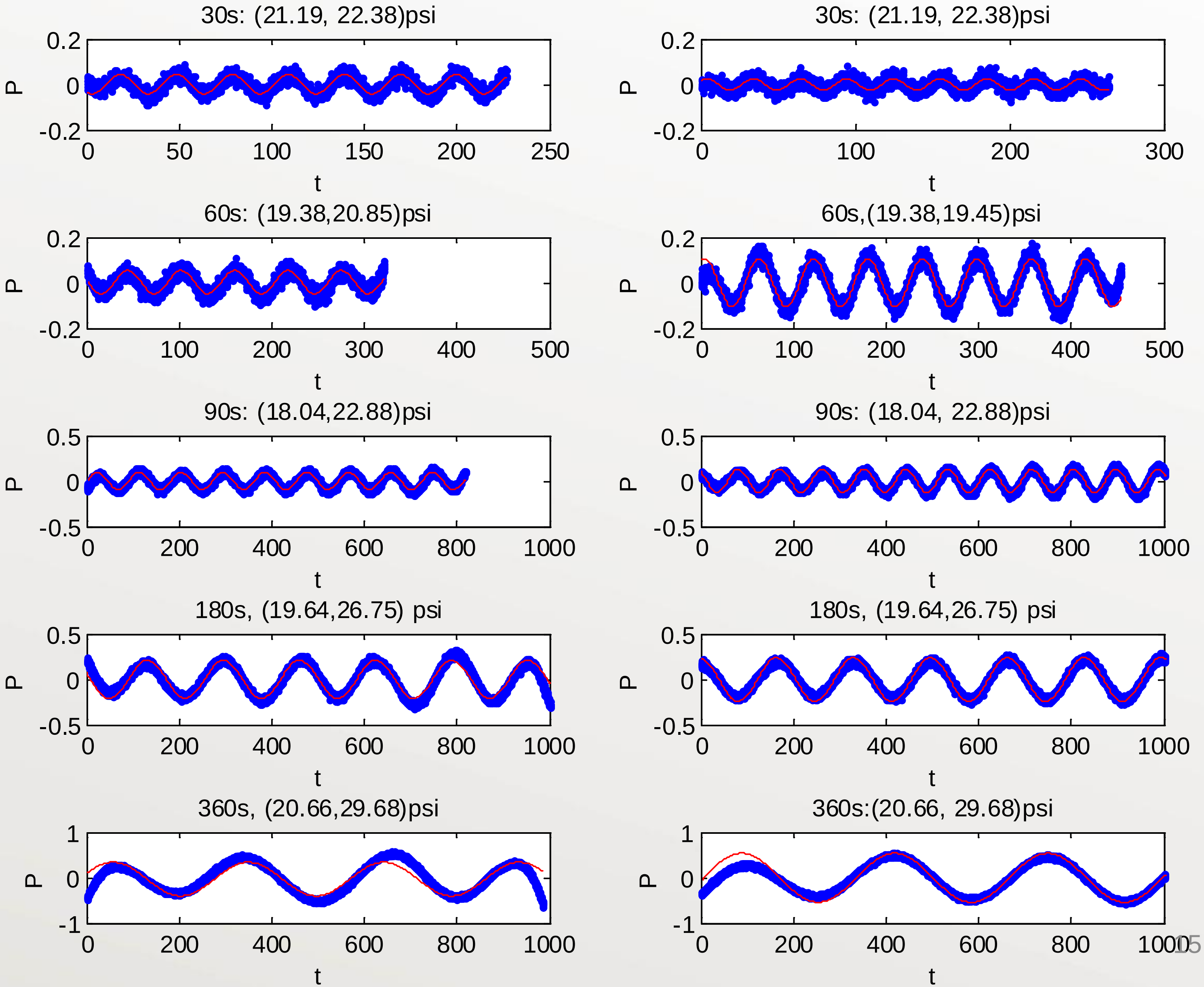


Time domain

Pulse period↑

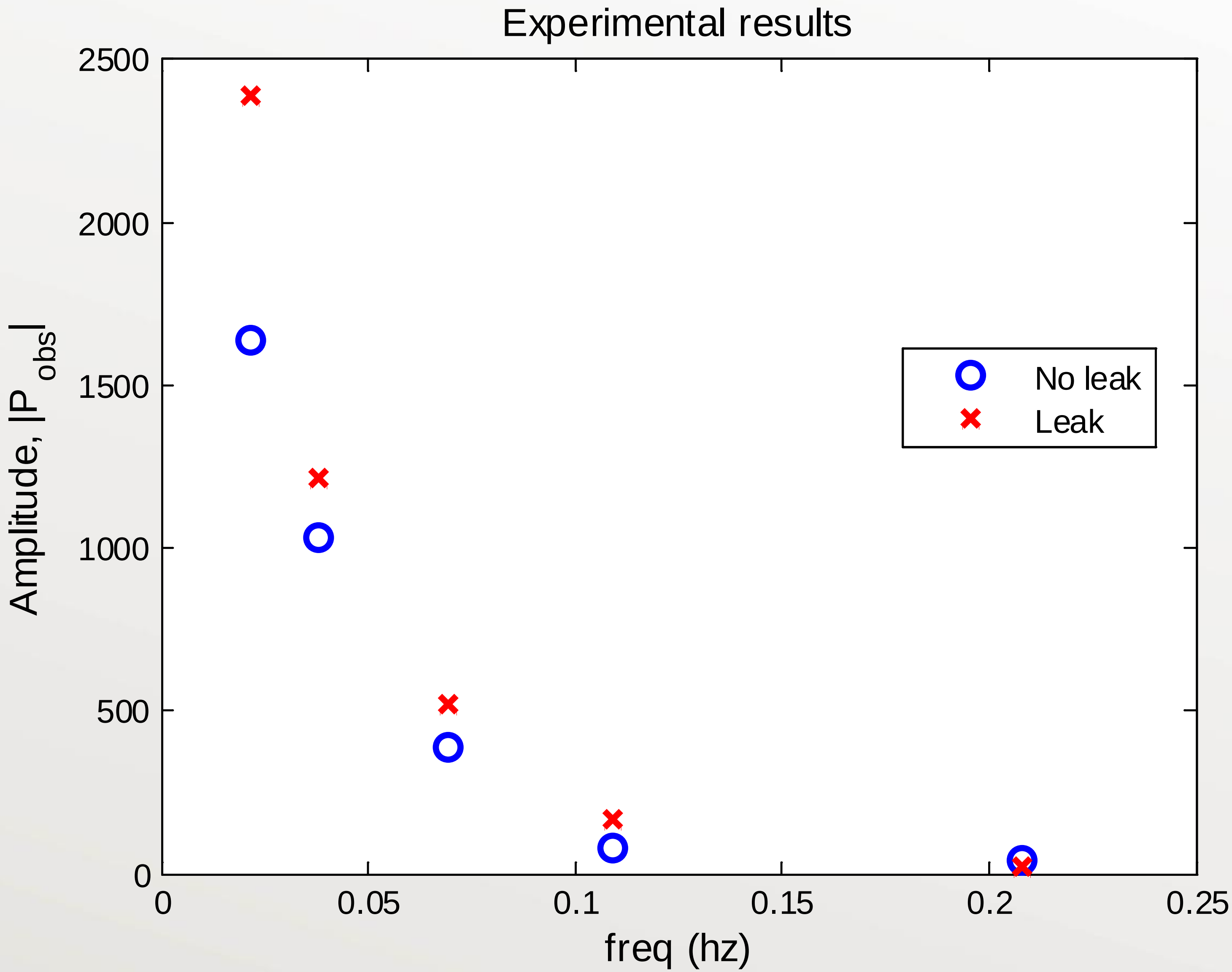
Oscillation ↑

No Leak | Leak

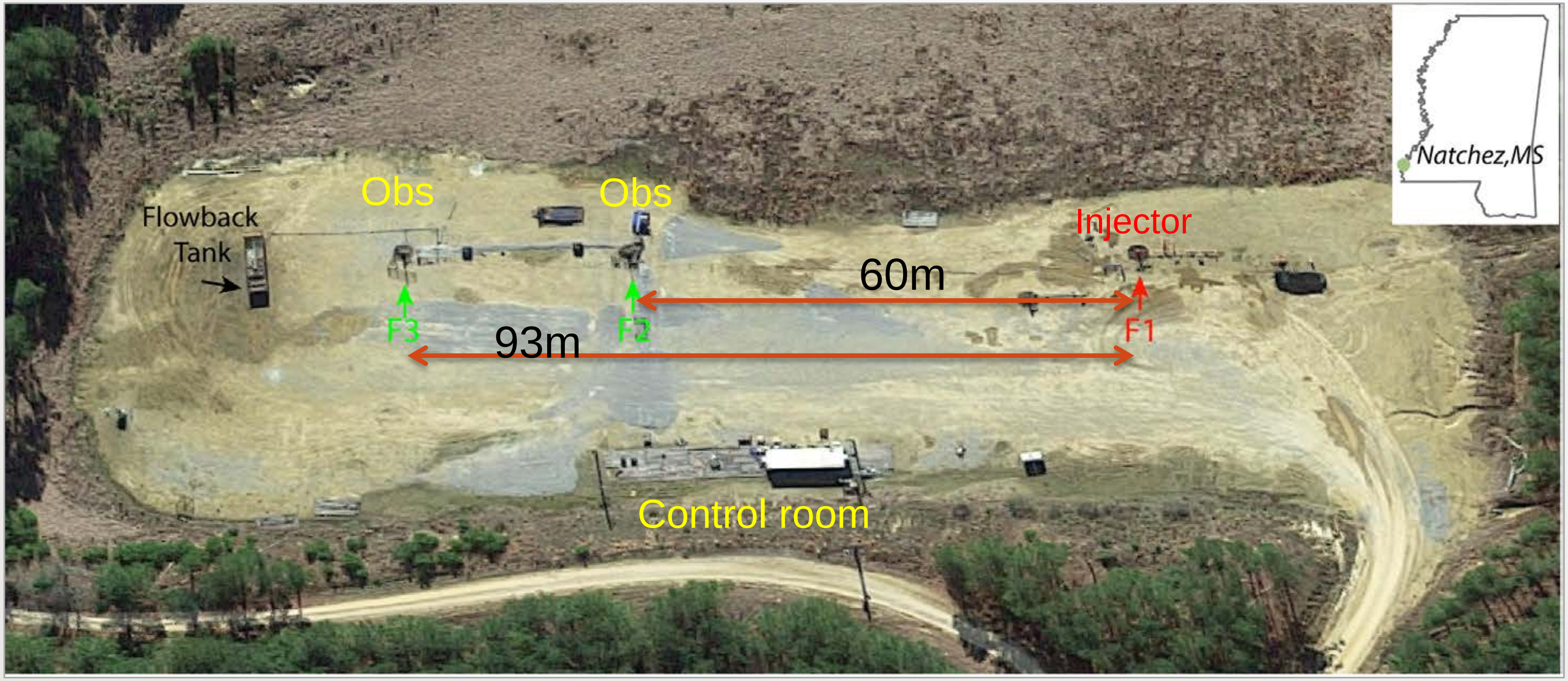


Amplitude shifts due to leak

$$\hat{H}(w) = \hat{P}_{obs}(w)$$



Field Experiments [Task 5]

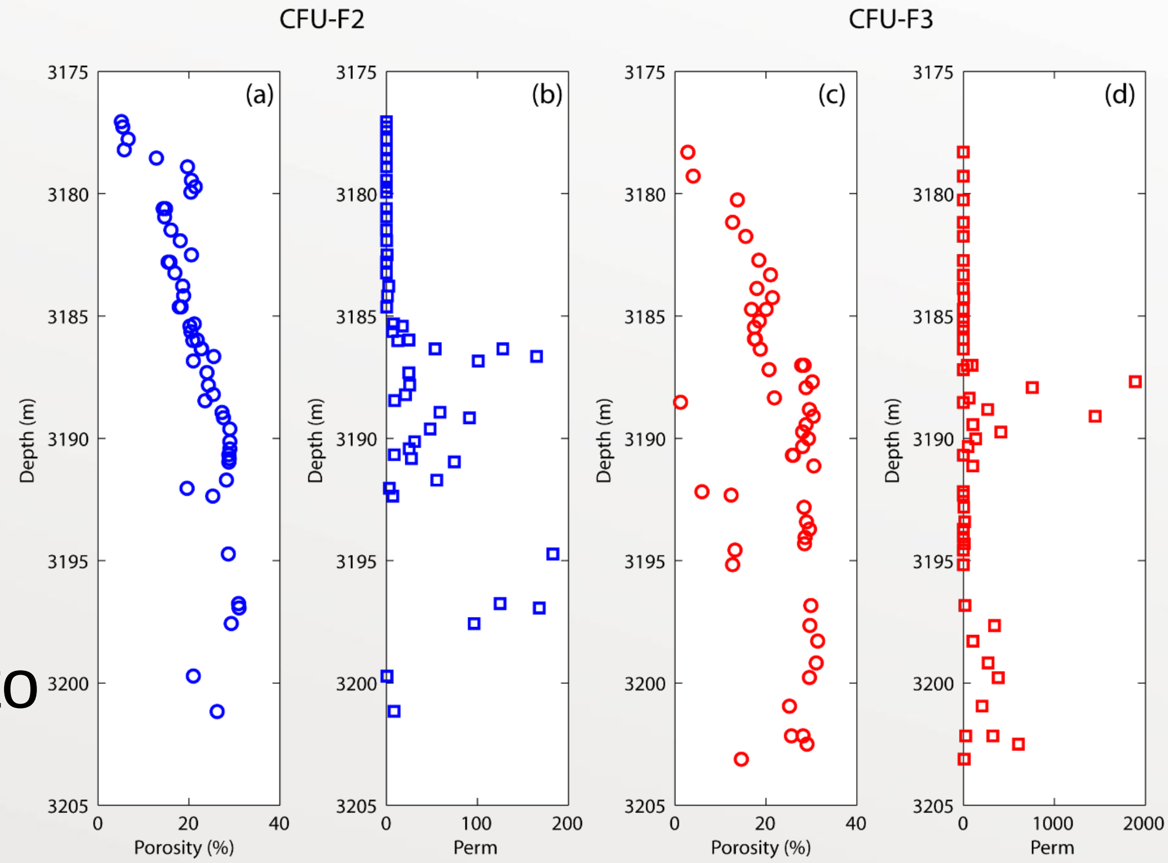


Detailed Area of Study @ Cranfield, MS, January 19-31,2015

Cranfield, MS, Lon:-91.141º, Lat: 31.564º

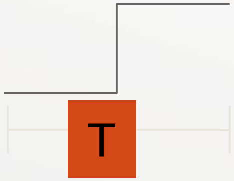
DAS Site

- Lower Tuscaloosa formation
  - Depth 3176 m (10420 ft)
  - Thickness14-24 m (46-80 ft)
- Heterogeneous fluvial strata
  - Permeability: 10^{-3} to 10^{4} mD
  - Porosity: 5-35%

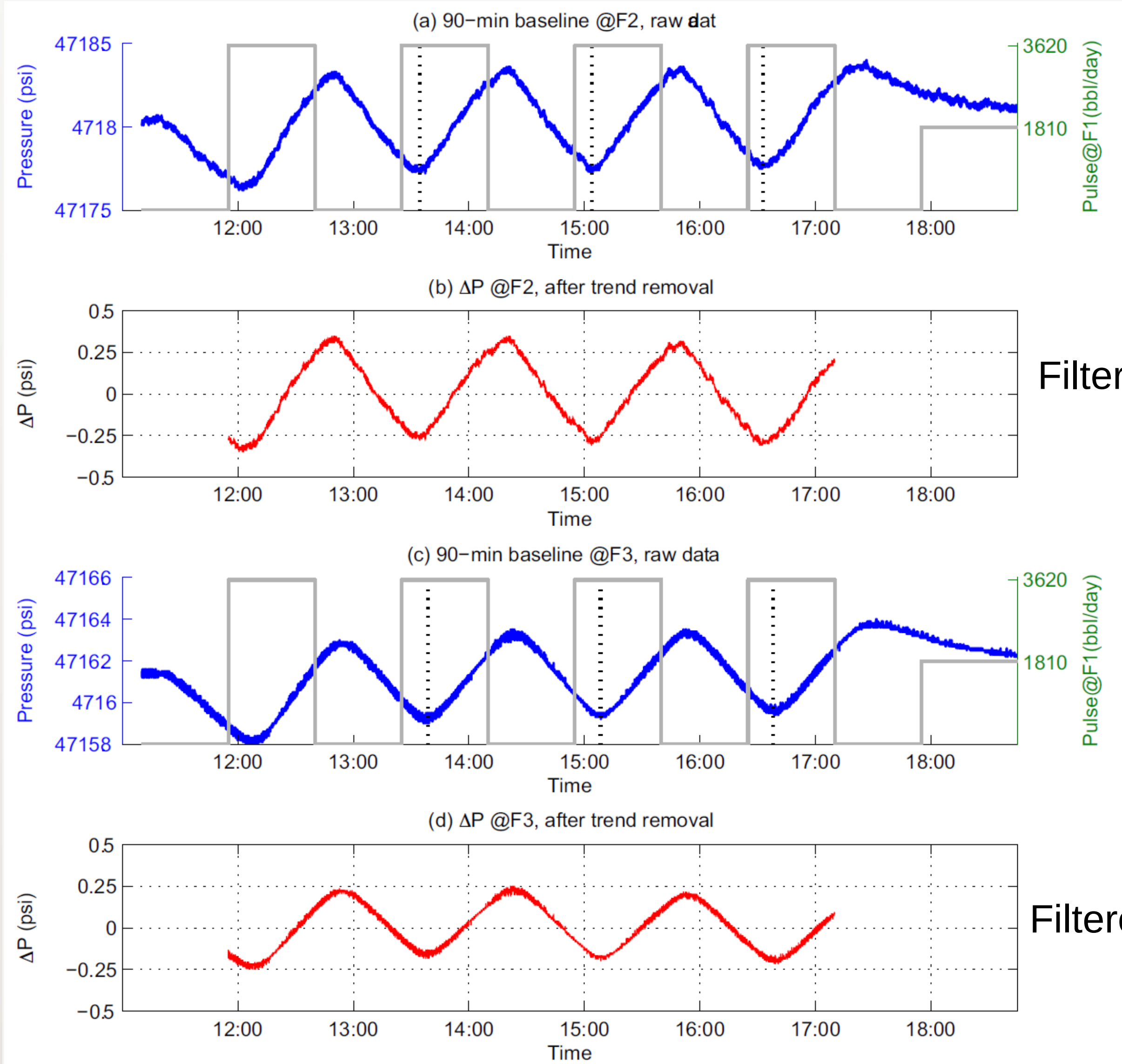


Lu et al, 2012

Baseline Tests



Pulsing Cycle
= 90min



Filtered Time Series

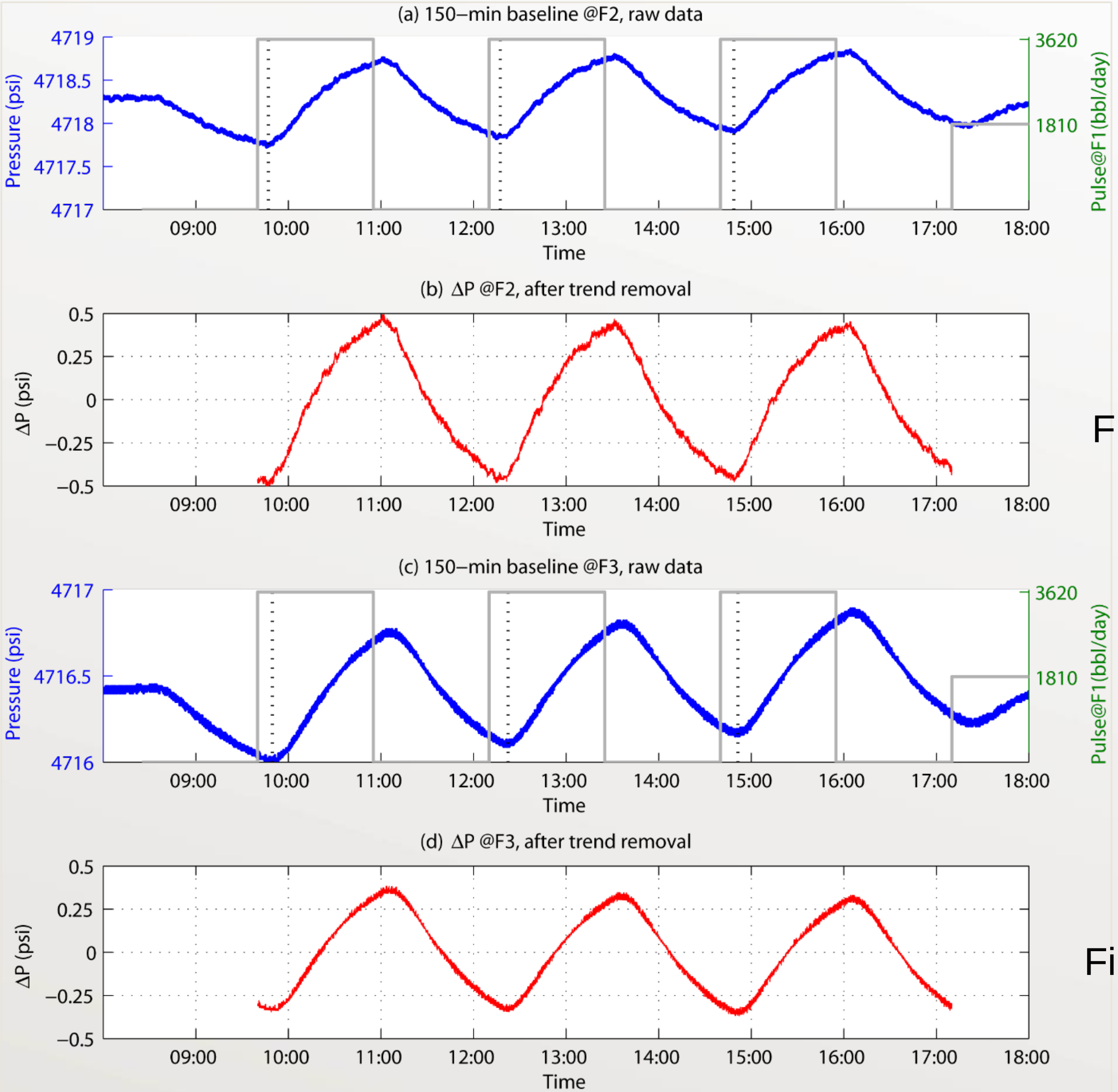
Filtered Time Series

Reservoir temperature ~ 128.8 C
Gauge res: 0.01psi

Pulsing Cycle
T = 150min

Pulse period↑

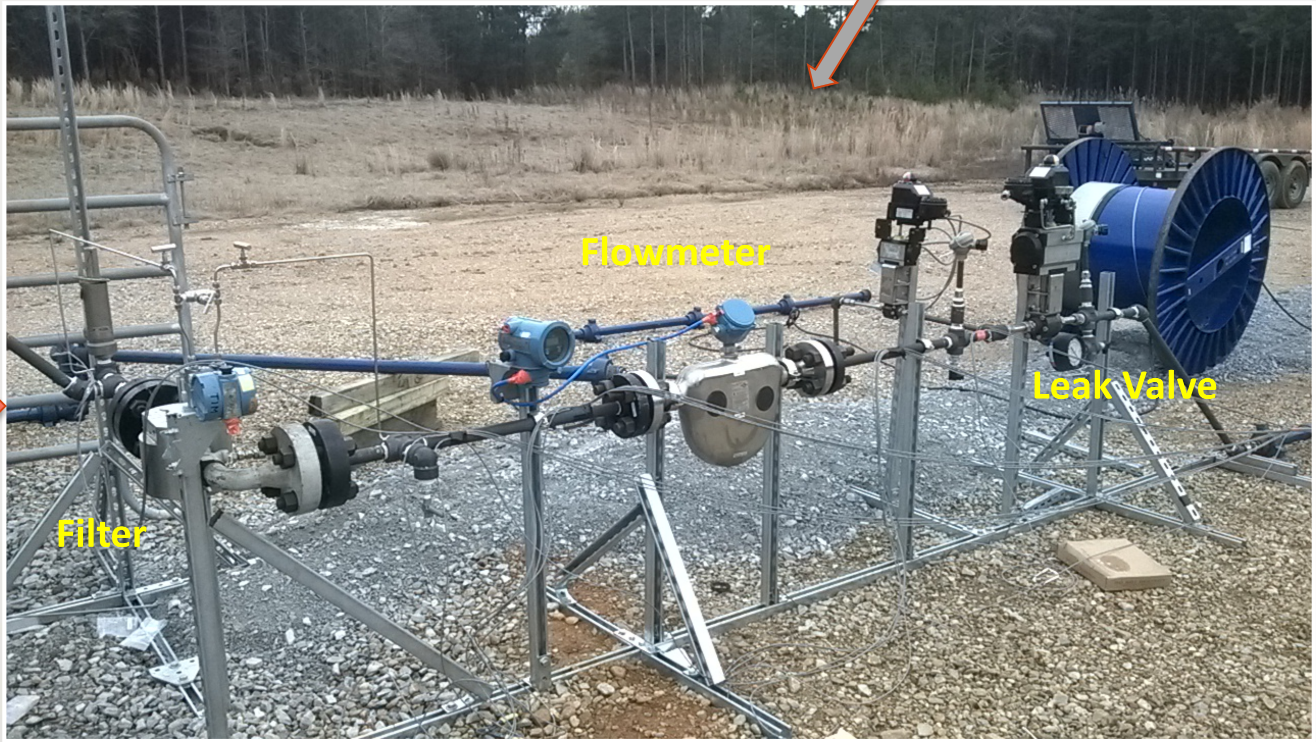
Oscillation ↑



Filtered Time Series

Filtered Time Series

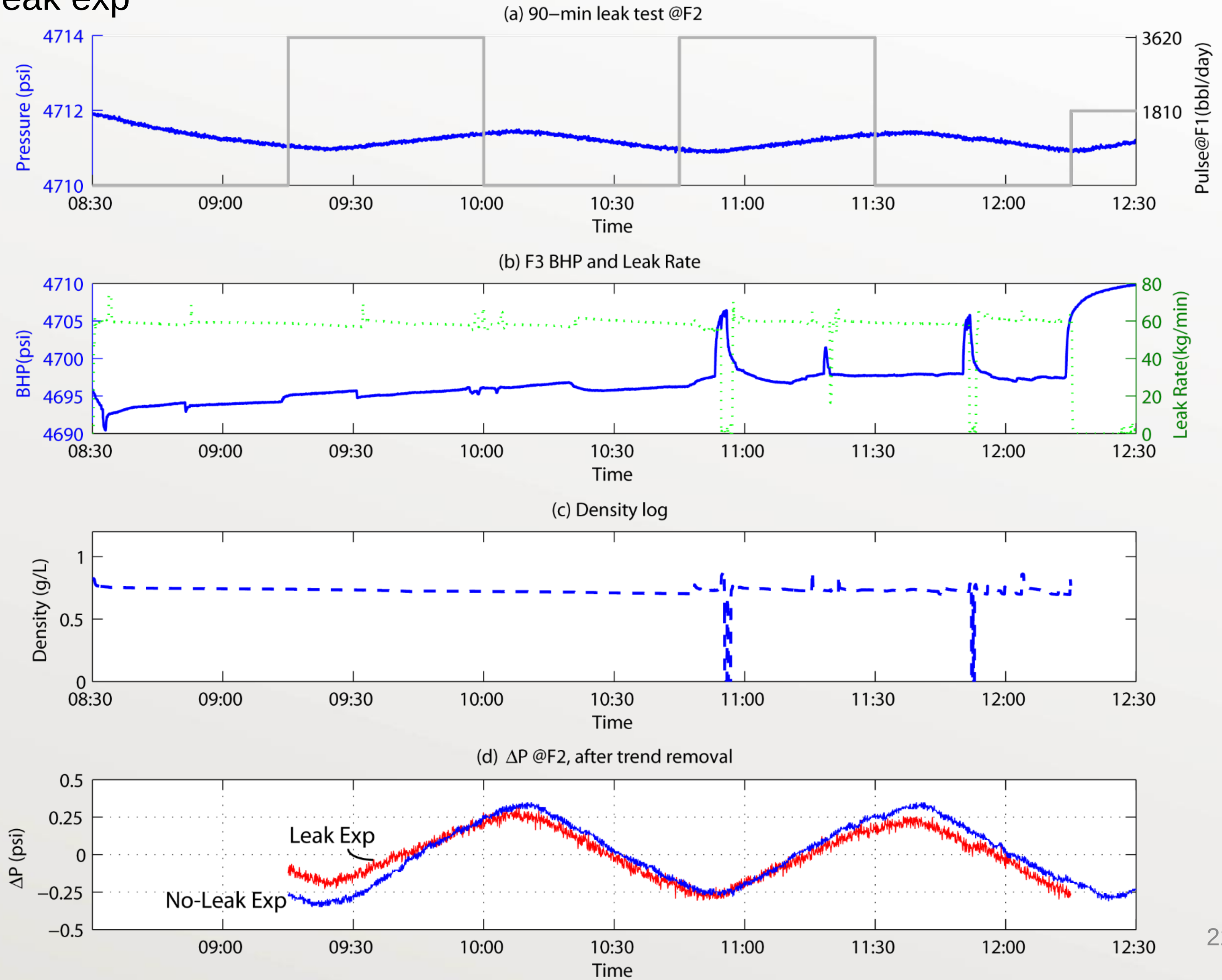
Leak Experiments



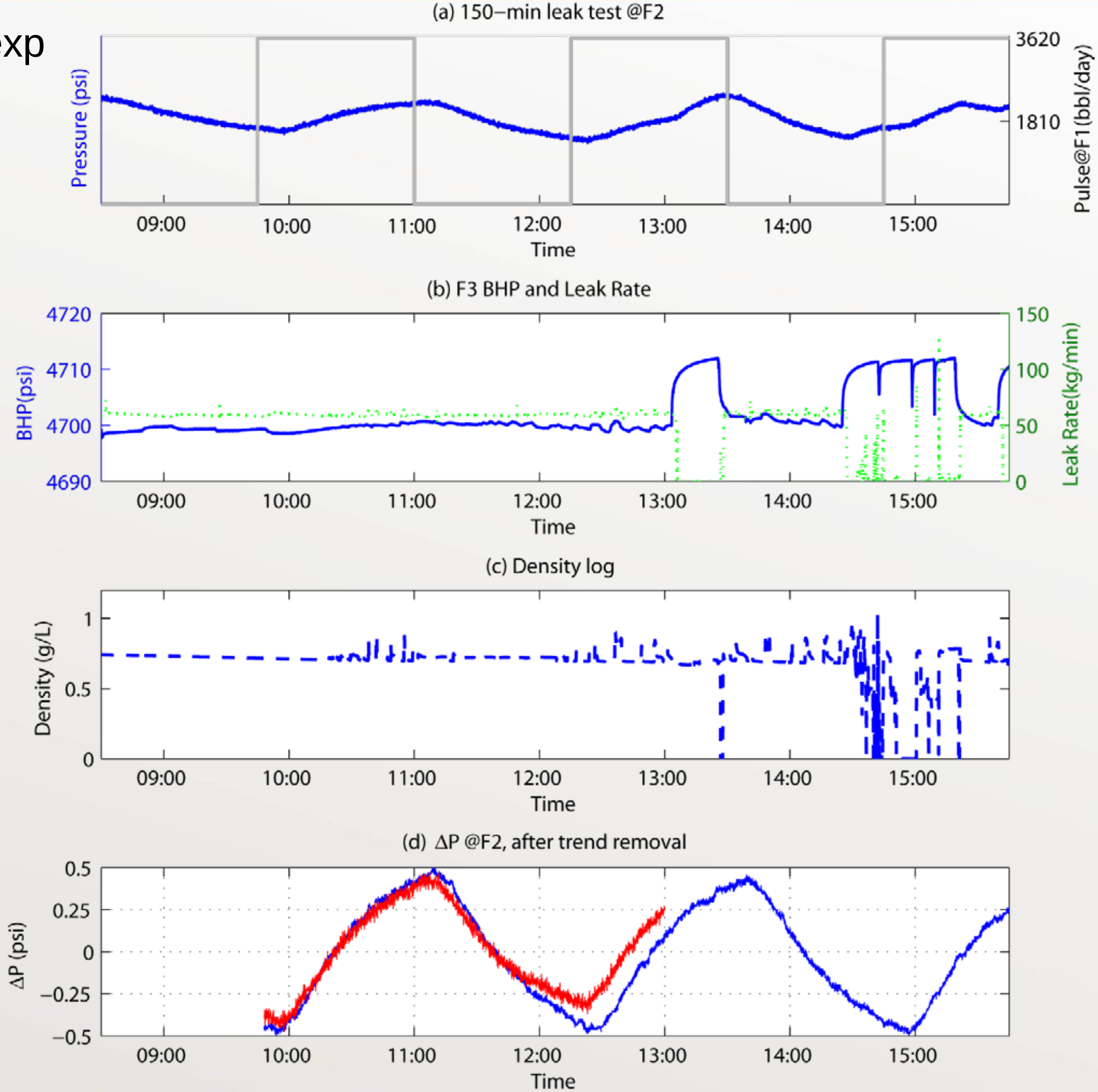
Leak control

F3

90-min, leak exp



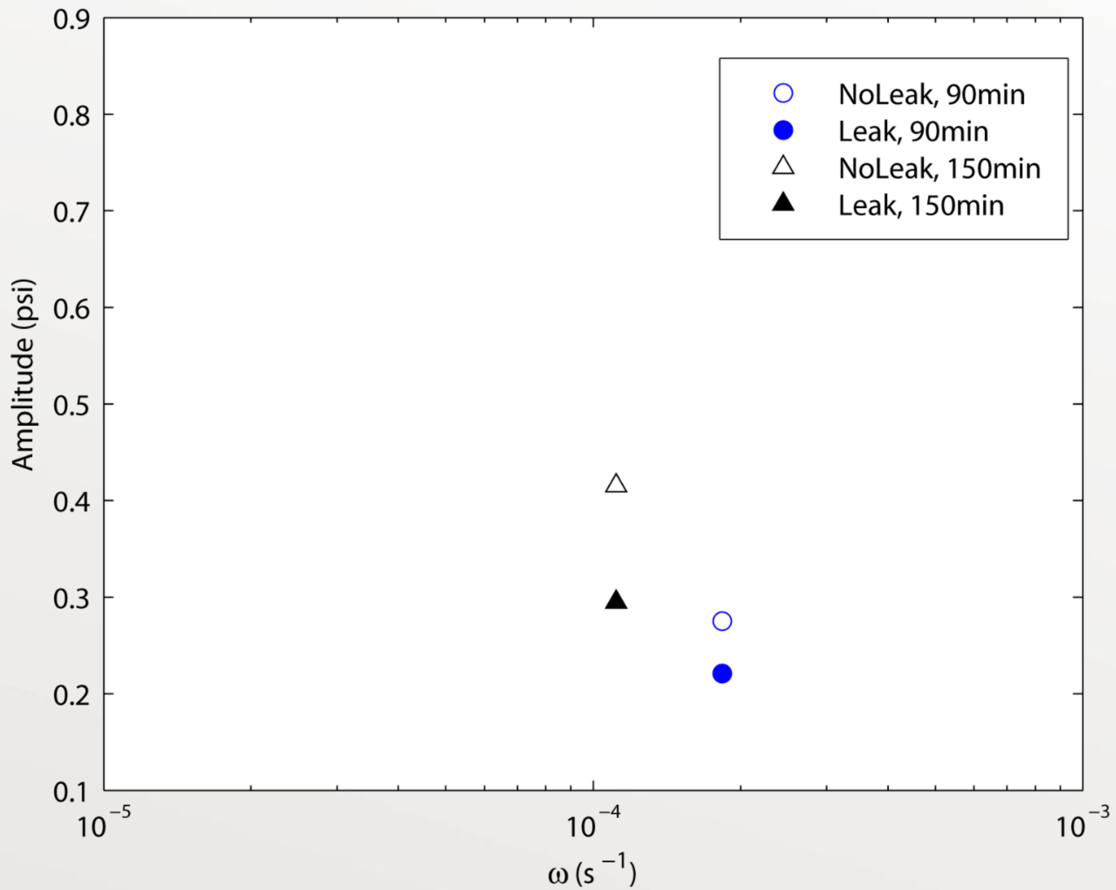
150-min, leak exp



Data Only Diagnosis

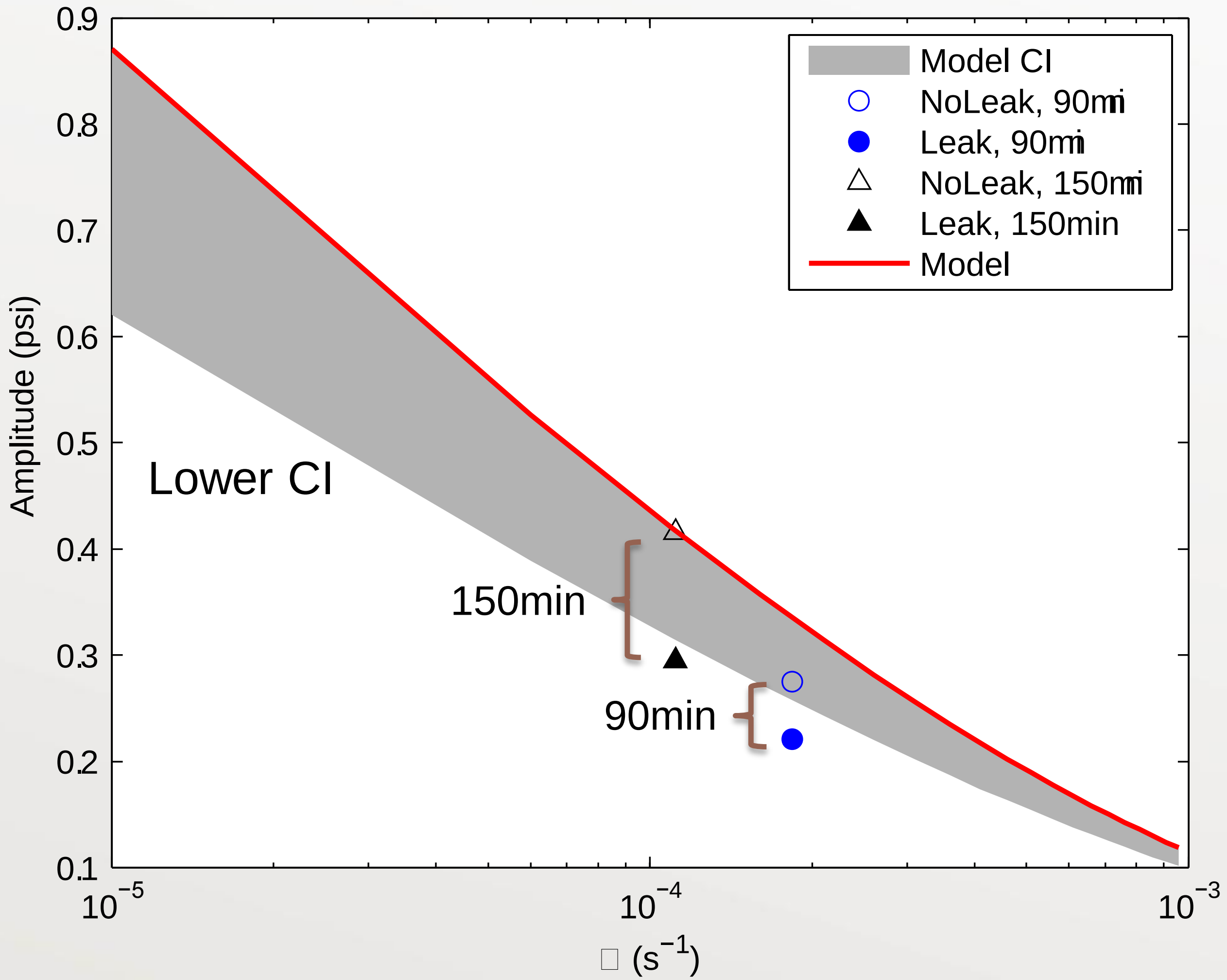
Amplitude vs. Frequency

Leaks caused deviations in signal amplitudes



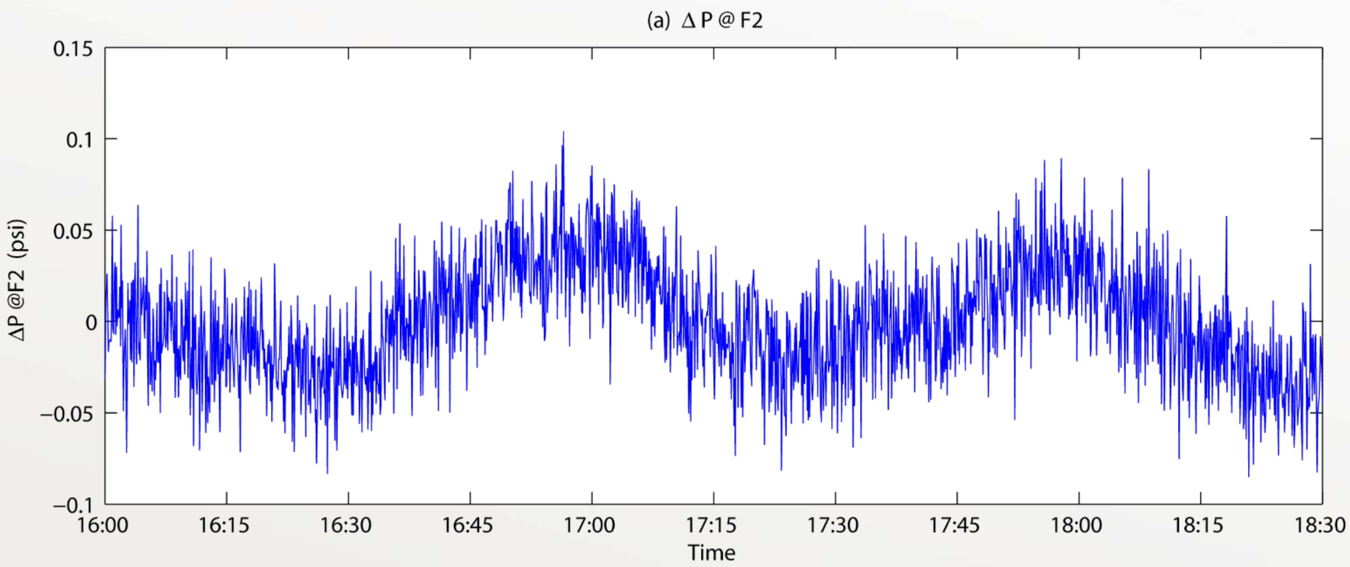
Each experiment yields one data point on the plot

Anomaly Detection

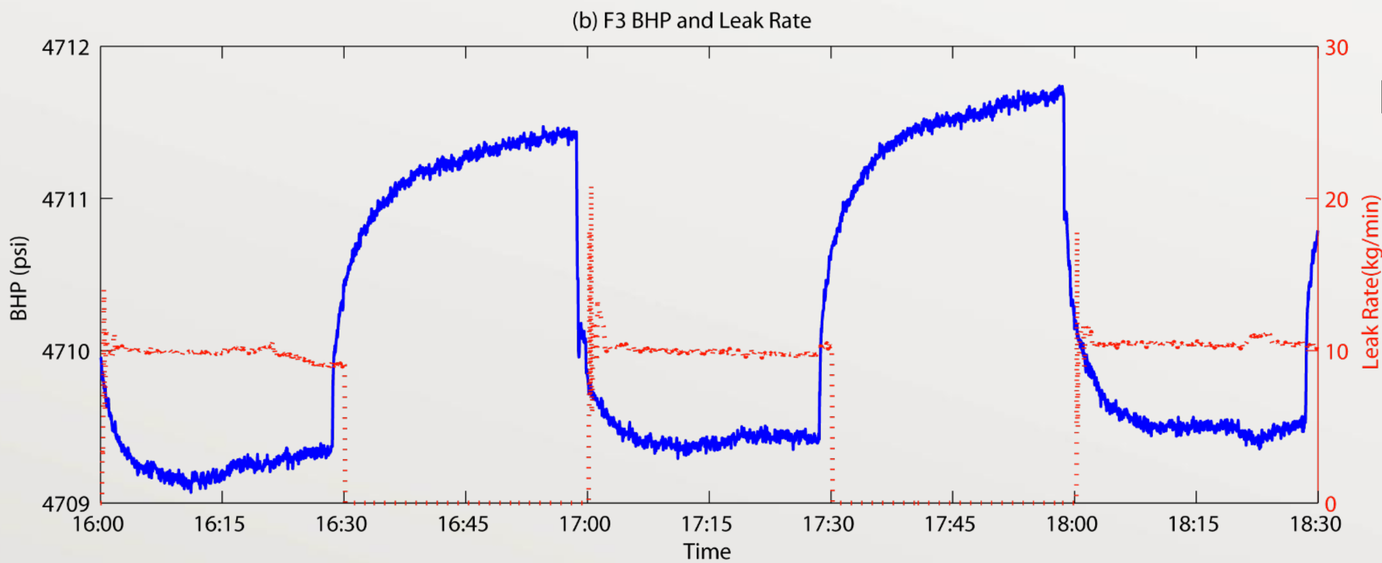


Sun et al., IJGGC, 2016

Sensitivity Exp



Monitoring well

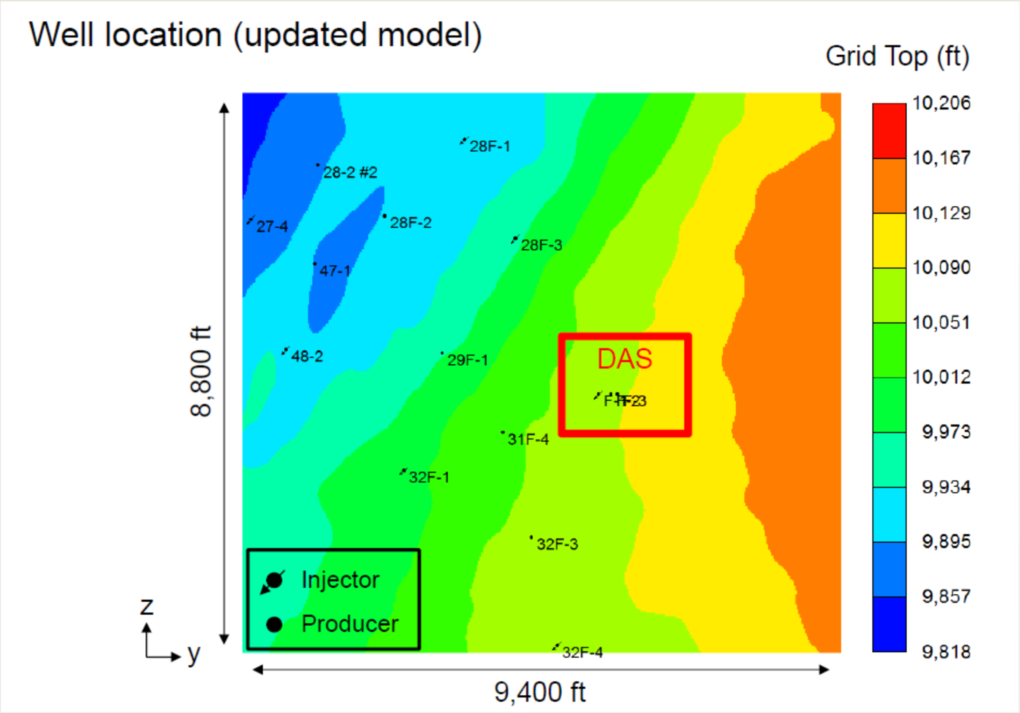


Leak Rate 10 kg/min

Model-Based Analysis

- Can Cranfield site-scale model reproduce the DAS pulse testing experiments?
  - Updated the existing model by including more wells
  - History matching
  - Refined mesh around DAS

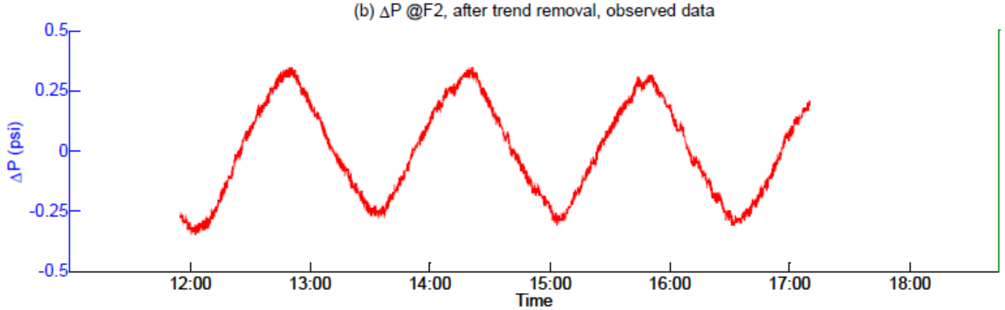
UT IPARS (Integrated Parallel Accurate Reservoir Simulator) Simulation



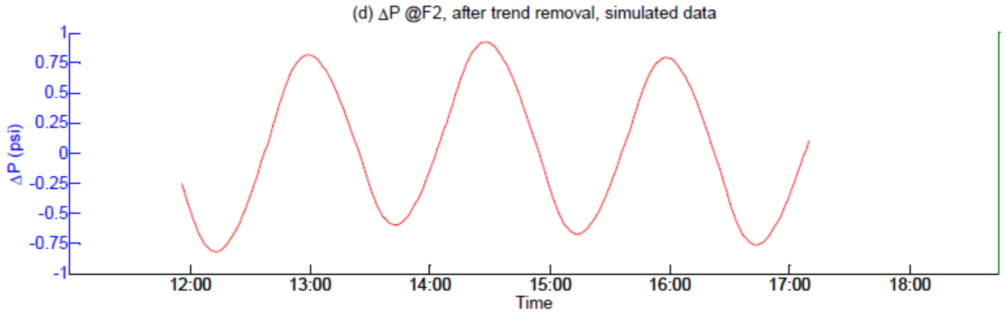
By Baehyun Min

- Day 1 (Jan 19, 2015): BHP@F2: 90-min. experiment without leakage

❑ Observed

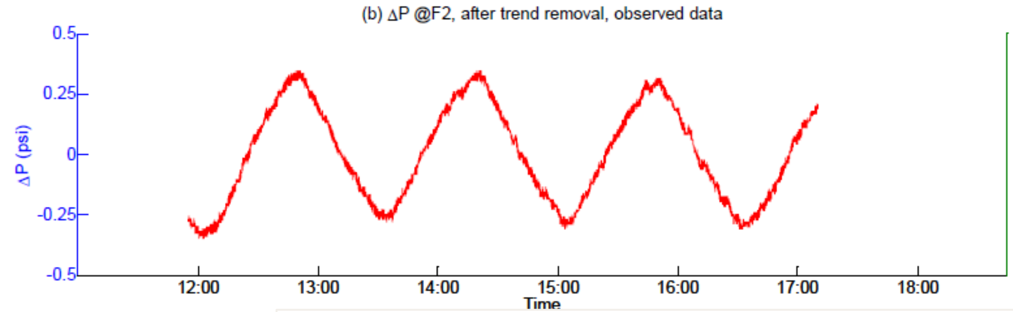


❑ Simulated

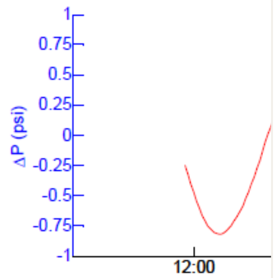


- Day 1 (Jan 19, 2015): BHP@F2: 90-min. experiment without leakage

❑ **Observed**

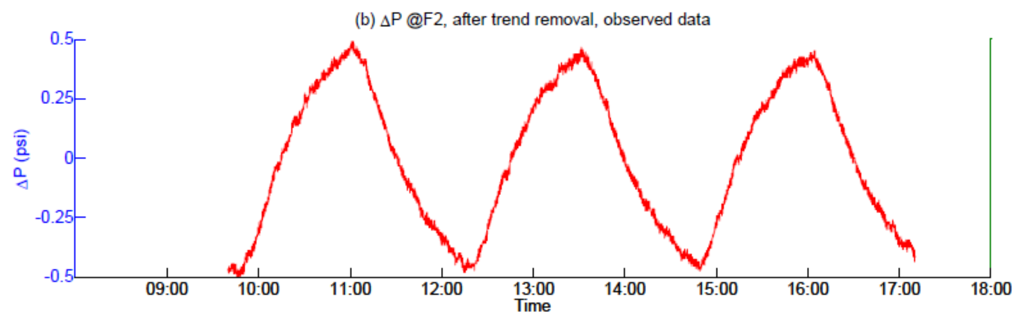


❑ **Simulated**

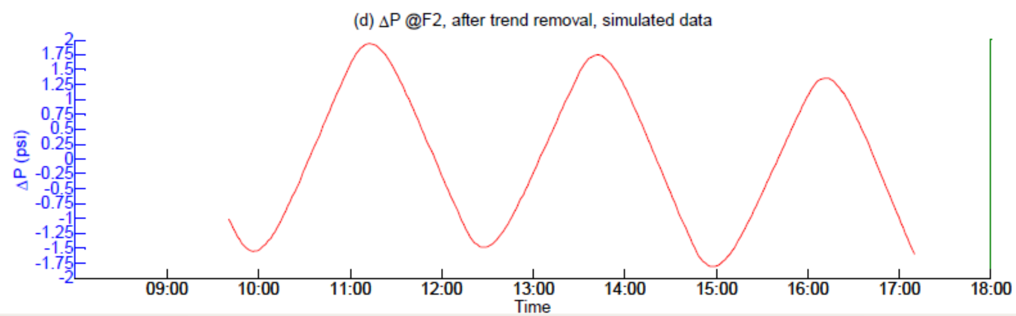


- Day 2 (Jan 20, 2015): BHP@F2: 150-min. experiment without leakage

❑ **Observed**

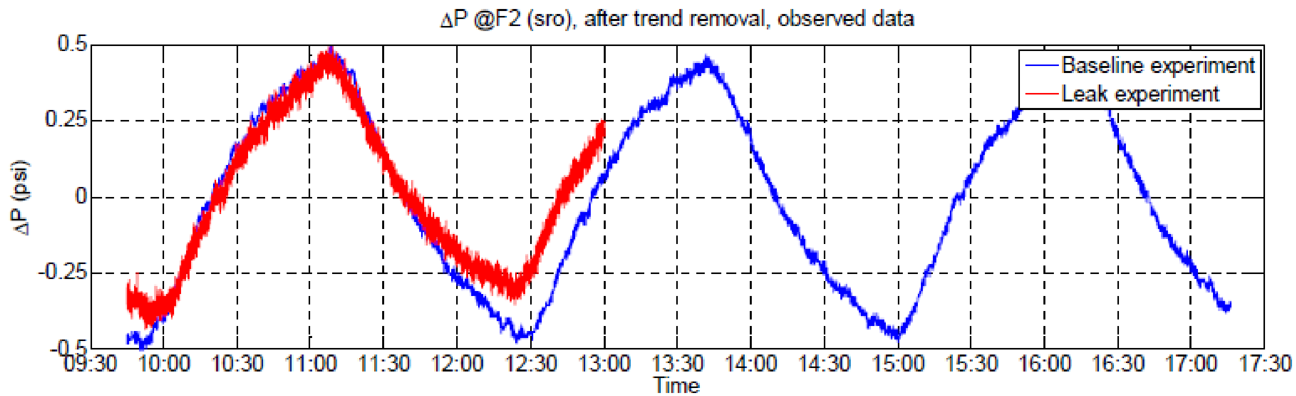


❑ **Simulated**

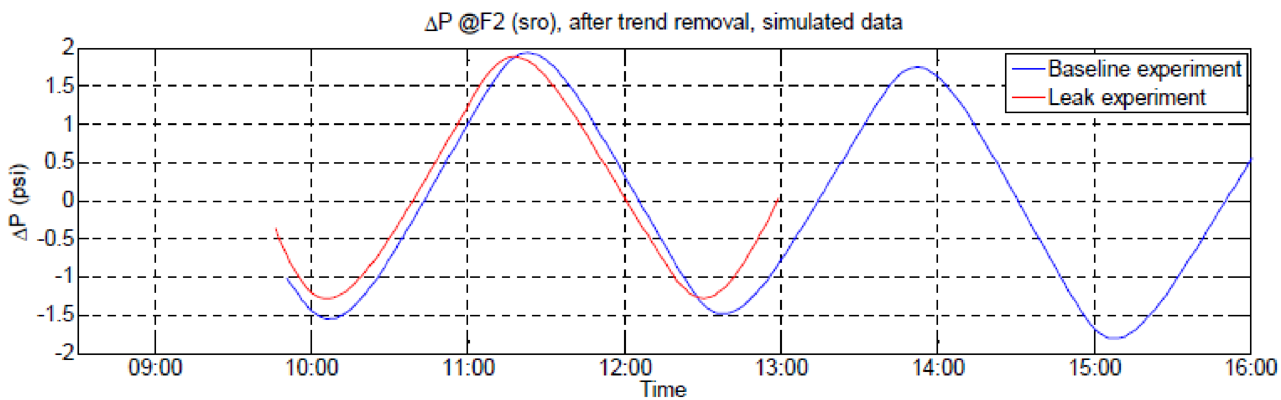


▪ 150-min. experiment

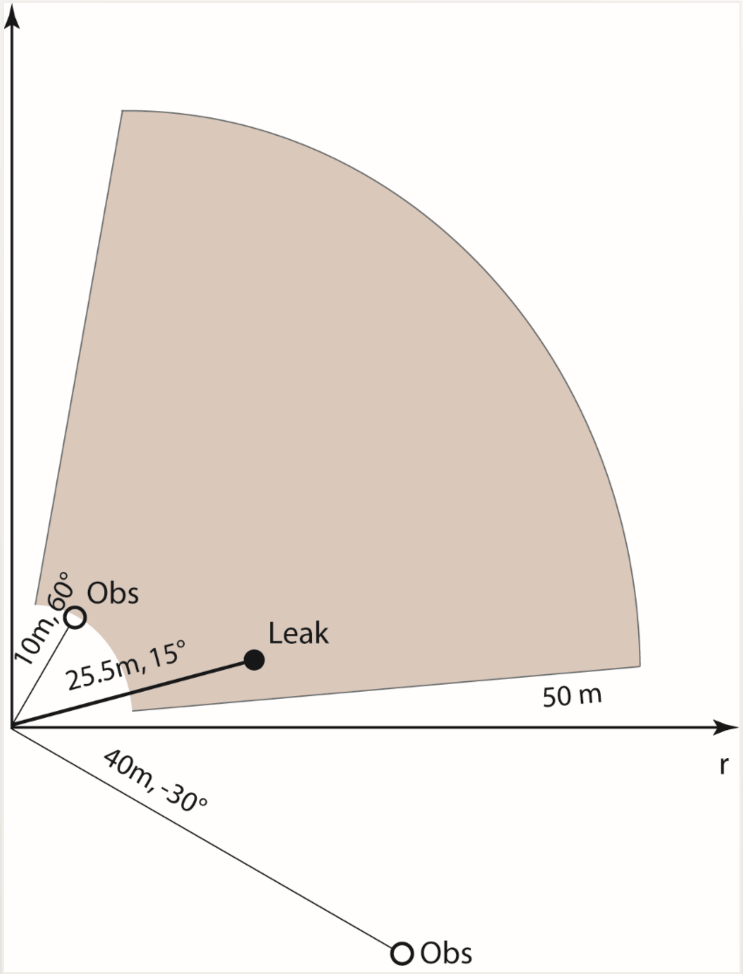
❑ Observed



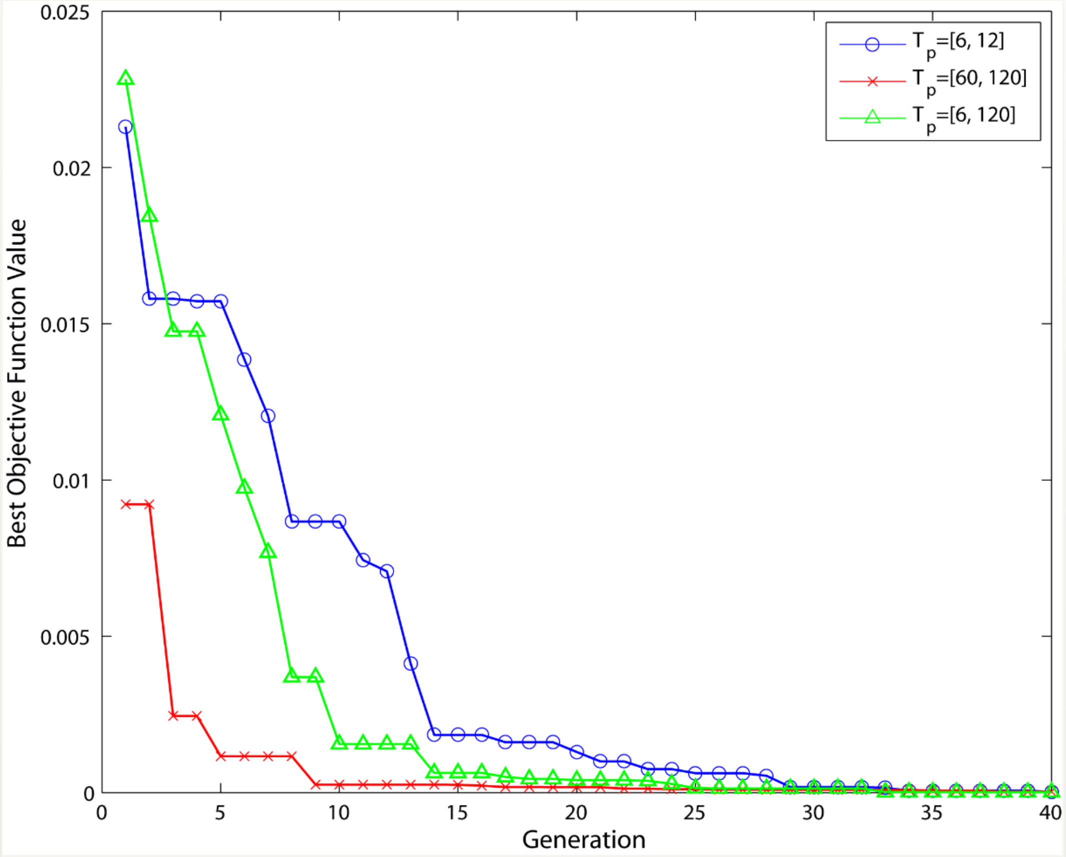
❑ Simulated



Leak Location: Global Search



Convergence History



Genetic Algorithm

Conclusions

- Leaks will modify the system frequency response function and can be detected if an appropriate pulsing period is used
- Longer HPT pulsing periods increase coverage area
- Lower reservoir permeability or, equivalently, higher upper aquifer permeability, favors detection of leakage, if all other parameters are fixed
- The amplitude and phase of frequency response function provide independent information regarding the current system status and can be combined to locate leaky well locations

Accomplishments to Date

- Task 2: Theoretical and numerical analyses
  - Year 1: Established theoretical basis and validated the concept of pulse-testing-based leakage detection numerically
- Task 5: Field experiments
  - Year 2: Demonstrated viability of the pulse testing leakage detection technique in the field
- Task 3: Laboratory experiments
  - Year 2&3: Performed additional validation tests
- Task 4: Data assimilation algorithms
  - Year 2&3: Developing and testing algorithms

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Future Work

- Complete laboratory experiments
- Complete remaining modeling and data analyses
- Provide a toolbox for designing pulse testing experiments

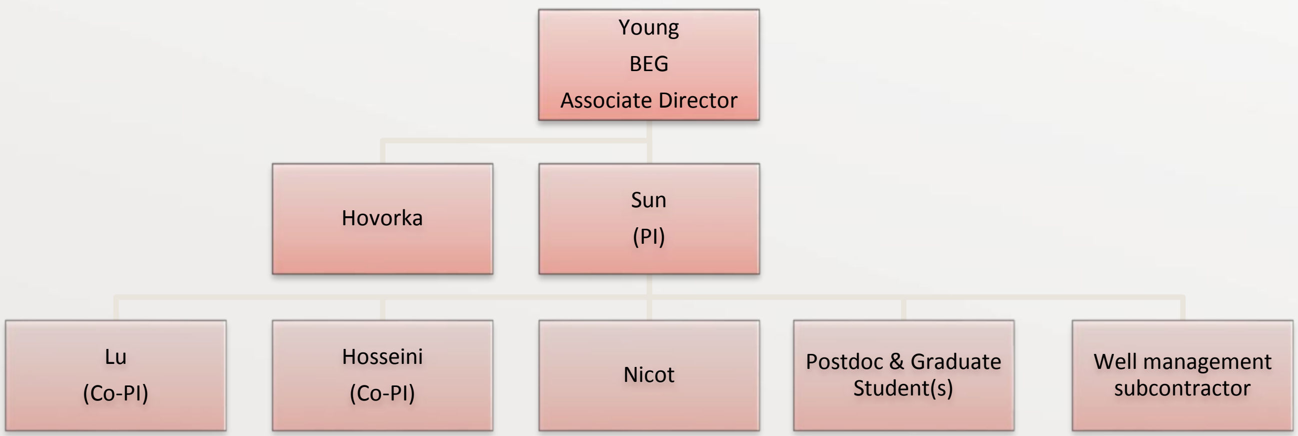
Synergy Opportunities

- The project developed a cost-effective, pressure-based leakage detection technique that can be incorporated into commercial CCS monitoring plans
- Collaboration with Center for Subsurface Modeling at UT

Appendix

Organization Chart

Bureau of Economic Geology, UT Austin
Gulf Coast Carbon Center



Gantt Chart

Table 2. Project Gantt chart
(Numbers in table rows indicate milestones).
(Phase I ; Phase II)

Task	Description	Year 1				Year 2				Year 3			
		1	2	3	4	1	2	3	4	1	2	3	4
1	Update project management plan												
2	Modeling of harmonic pulse tests		1										
3	Lab experiment												
3.1	Experiment design and assembling				2								
3.2	Single-phase experiment												
3.3	Multiphase experiment								5				
4	Algorithm development												
4.1	Inversion technique												
4.2	Data assimilation										6		
5	Field demonstration												
5.1	Field site selection												
5.2	Site access & NEPA determination												
5.3	Field experiments						3	4					
6	Synthesis of results												
6.1	Tool user interface development												
6.2	Technology transfer												

Bibliography

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