FORP

Fiber Optics Research Program

Fiber Optics Research Program

Gary Binder, Aleksei Titov, Kagan Kutun

COLORADO SCHOOL OF MINES
EARTH • ENERGY • ENVIRONMENT

FORP People:

Dr. Ali Tura – GP faculty, RCP director
Dr. Jennifer Miskimins – PE faculty, FAST director
Dr. Ge Jin – GP faculty, RCP co-director
Dr. Yilin Fan – PE faculty, flow expert

Dr. Gary Binder – GP Post-doc

Aleksei Titov – GP Ph.D. student
Kagan Kutun – PE Ph.D. student
Owen Huff – GP M.S. student
Dwaipayan Chakraborty – GP M.S. student

Associated members:

Lee Fronapfel – ME faculty,
Edgar Research Mine Manager
Dr. Alfred Eustes – PE faculty, drilling expert

Fiber Optics for Unconventionals

Exploration

- VSP
- DTS Warmback

Reservoir characterization

Completion

- Time-lapse VSP
- Microseismic
- Low frequency DAS
- Injection allocation

Completion and well spacing optimization

Production

- Gas lift monitoring
- Leak detection
- Production logging

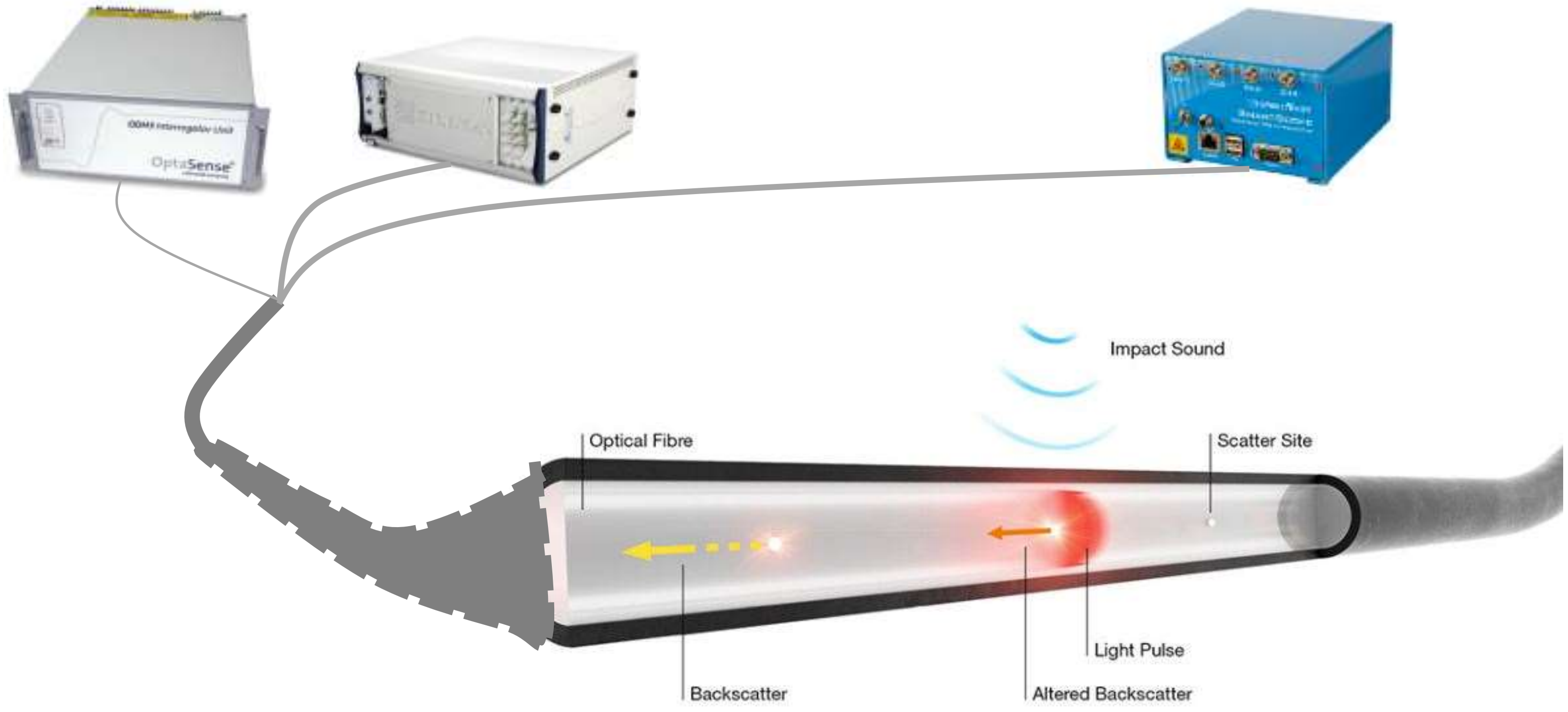
Reservoir management and production enhancement

Fiber Optic Sensing Introduction

Distributed Acoustic Sensing (DAS) Interrogator

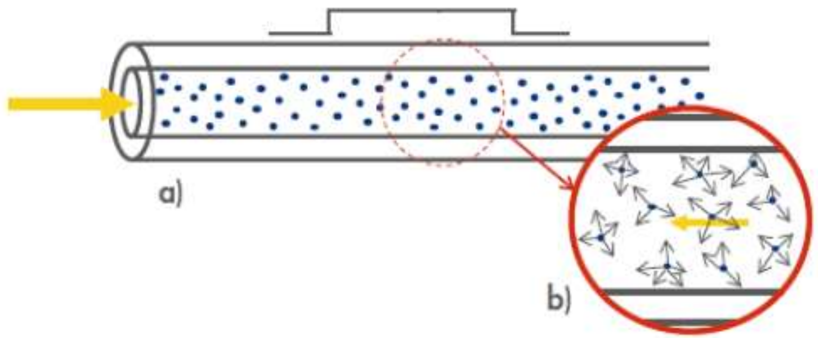
Distributed Temperature Sensing (DTS) Interrogator

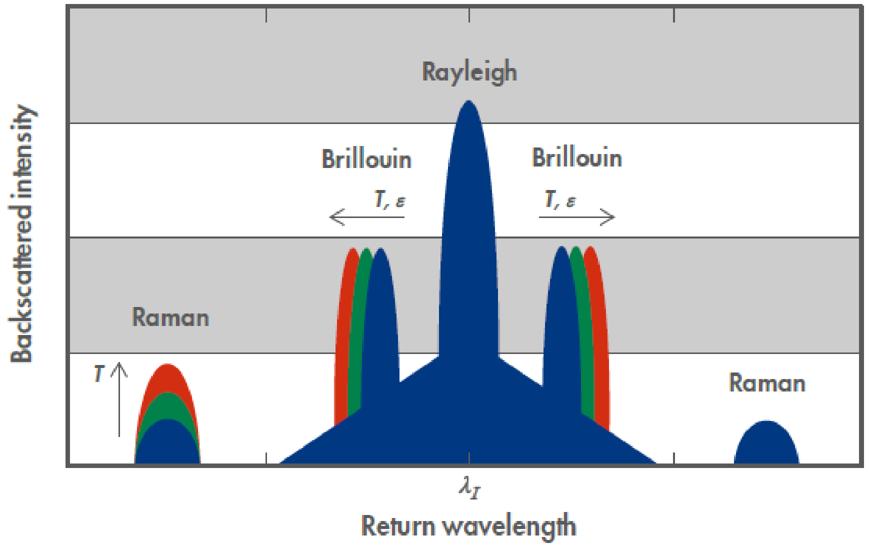
Distributed Strain Sensing (DSS) Interrogator



Modified from Frauscher, Optasense, Silixa, Smart Fibres

Fiber Optic Sensing Techniques





DAS - Distributed Acoustic Sensing

- Rayleigh phase change → strain

DSS - Distributed Strain Sensing

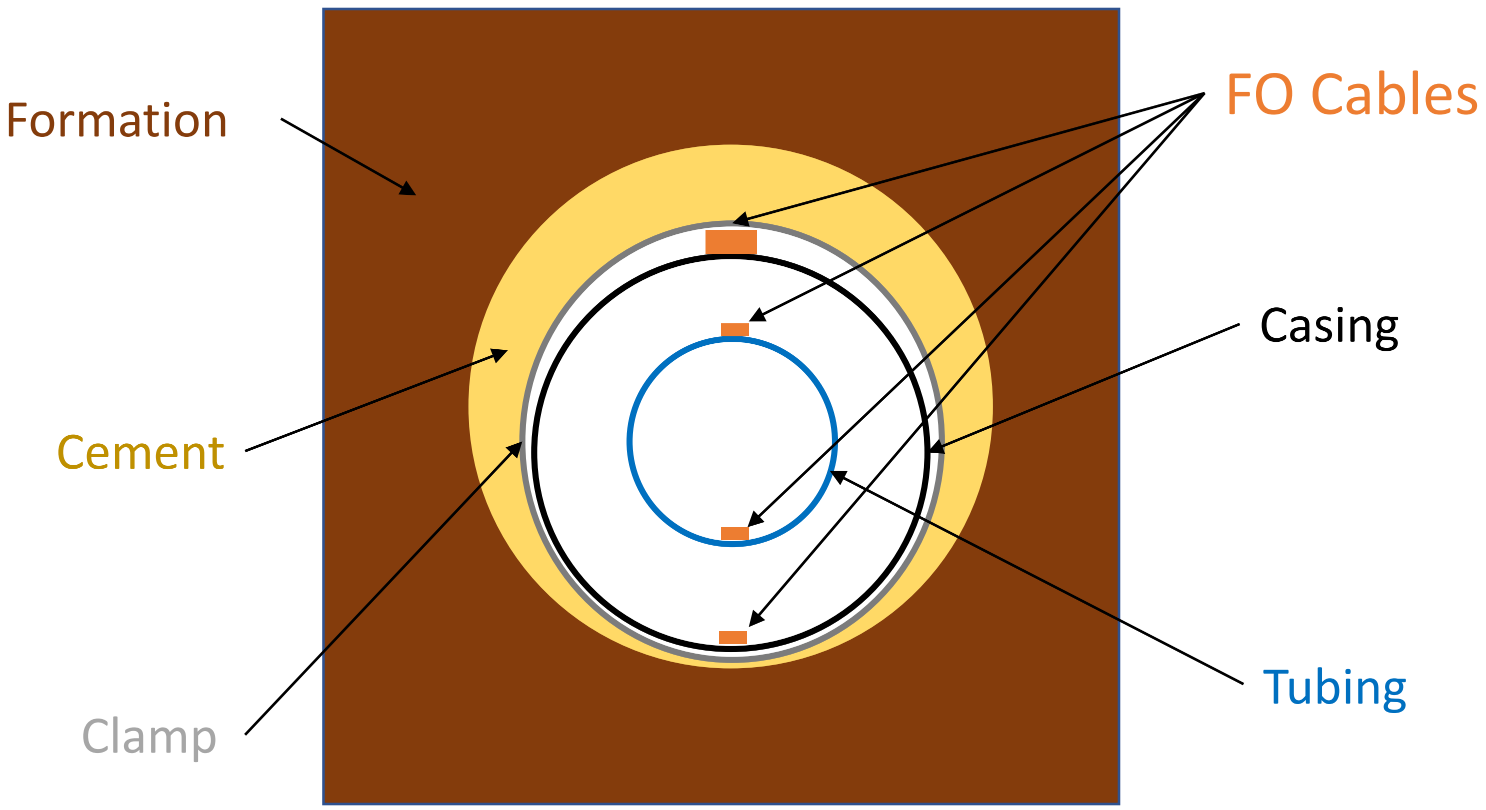
- Brillouin frequency shift → strain

DTS - Distributed Temperature Sensing

- Raman Anti-Stokes Peak Intensity → temperature

Fiber Optic Cable Deployment

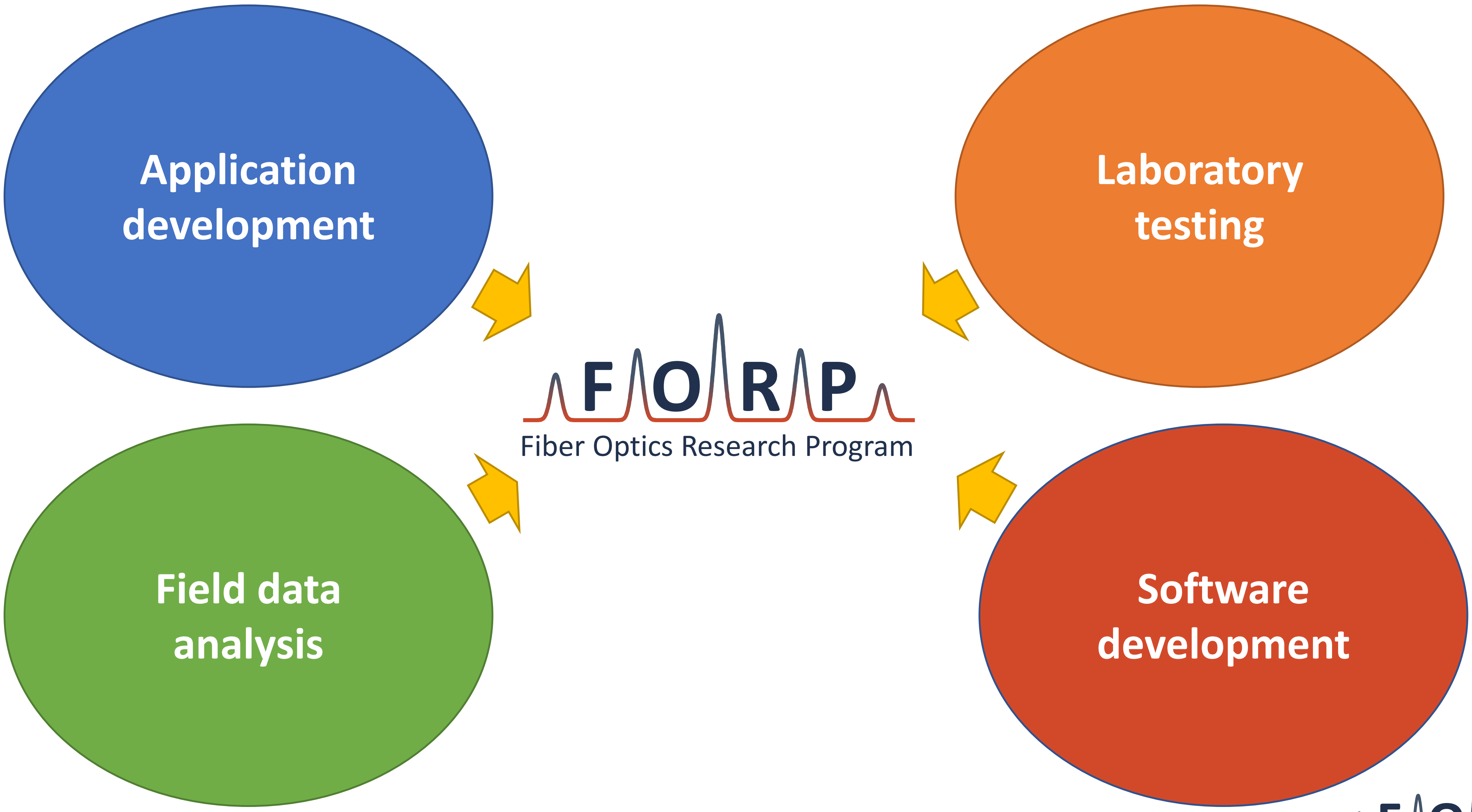
Borehole cross section:



Installation types:

- Cemented/clamped behind casing
- Clamped on tubing
- Free inside tubing
- Free inside casing

Fiber Optic Research Program Overview



RCP Field Projects with Fiber Optic Data

Chalk Bluff, HighPoint
- Completion and production monitoring with DAS/DTS
- Cross-well low-frequency DAS
- Interstage DAS VSP
- DAS microseismic

Midland Basin, Apache
- Interstage DAS VSP – engineered fiber

Eagle Ford, Devon/Penn Virginia
- DAS VSP
- DAS microseismic
- Completion and production monitoring with DAS/DTS

Wolfcamp, Apache
- Interstage DAS VSP

Laboratory Projects

High Bay Flow Loop

- 30 ft vertical flow loop on Mines campus
- Operating now
- Goals:
  - Discriminate multi-phase flow regimes
  - Flow velocity with thermal slugs
  - Detect liquid loading

Edgar Research Mine Flow Loop

- 130 ft horizontal borehole and flow loop underground
- Under construction
- Goals:
  - Multi-phase flow
  - Production logging
  - Injection allocation
  - Low-frequency strain with pressure cells
  - Testing fiber optic cable coupling methods

Fiber Optics for Unconventionals

Exploration
- VSP
- DTS Warmback

Reservoir characterization

Completion
- Time-lapse VSP
- Microseismic
- Low frequency DAS
- Injection allocation

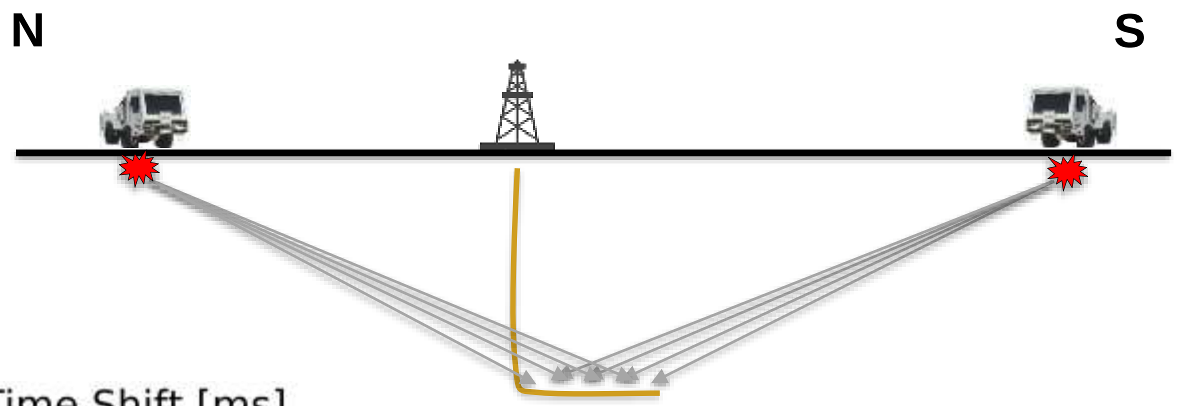
Completion and well spacing optimization

Production
- Gas lift monitoring
- Leak detection
- Production logging

Reservoir management and production enhancement

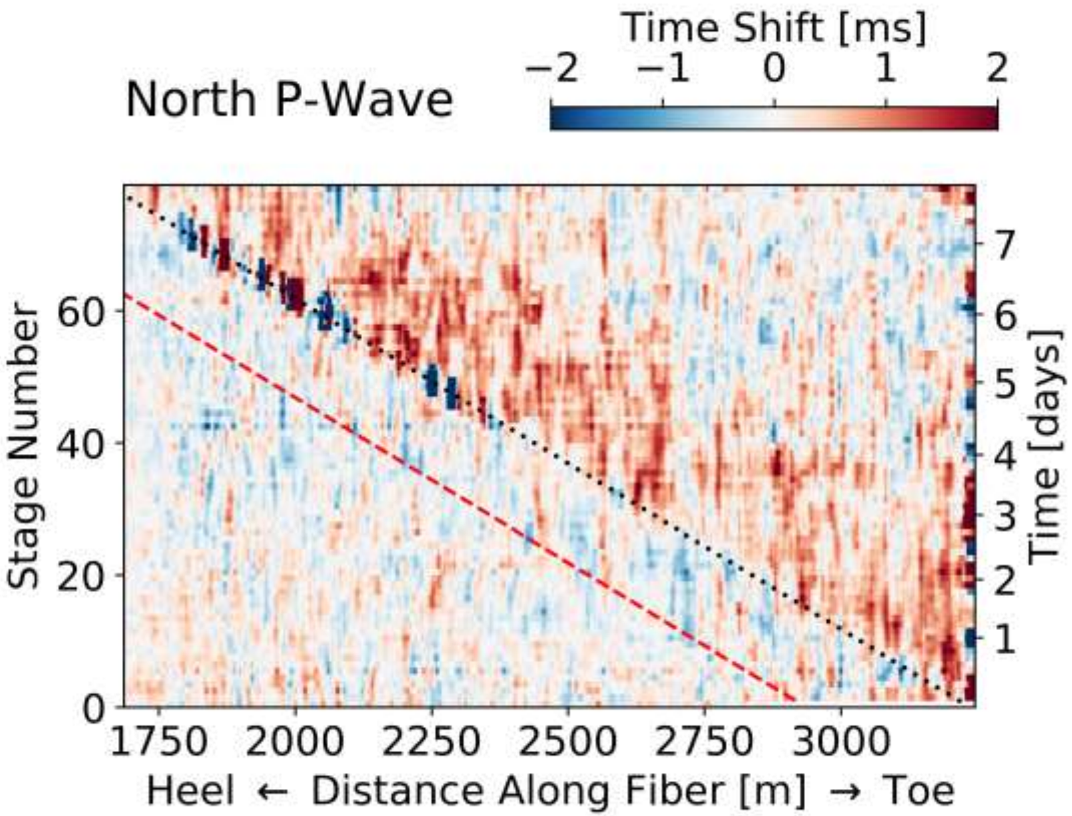
Apache Interstage DAS VSP

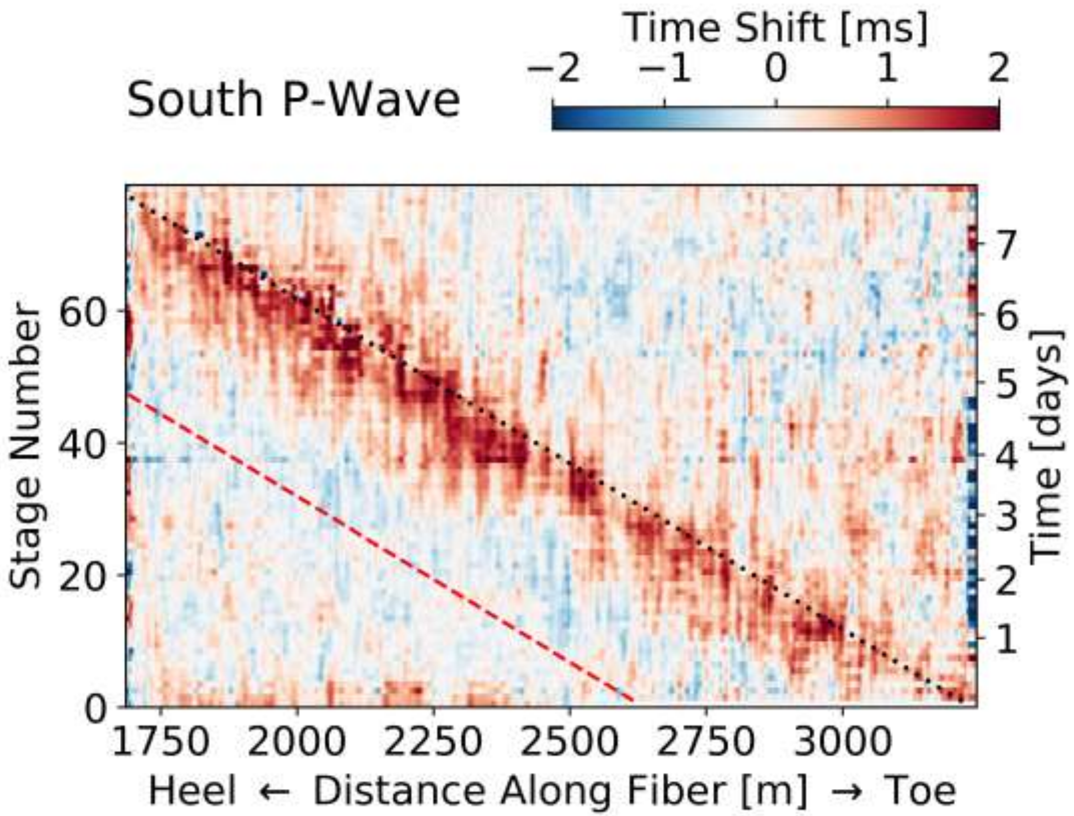
Time shifts observed after each stage moving from toe to heel



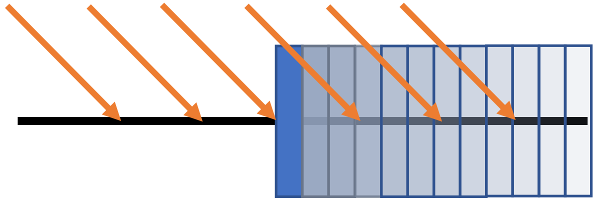
Byerley, G., et al. (2018). *The Leading Edge*, *37*(11), 802–810.

Speedup ← → Slowdown

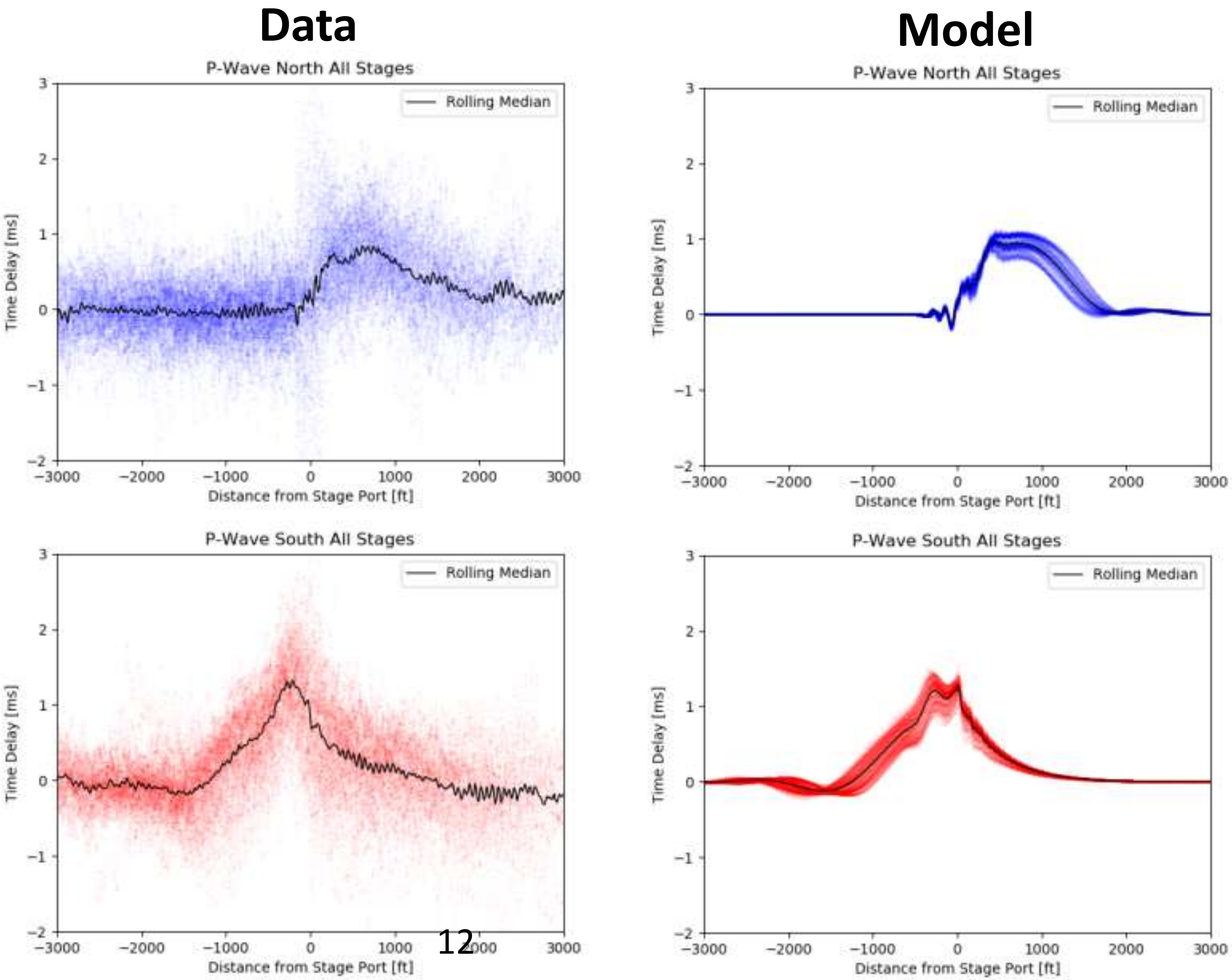




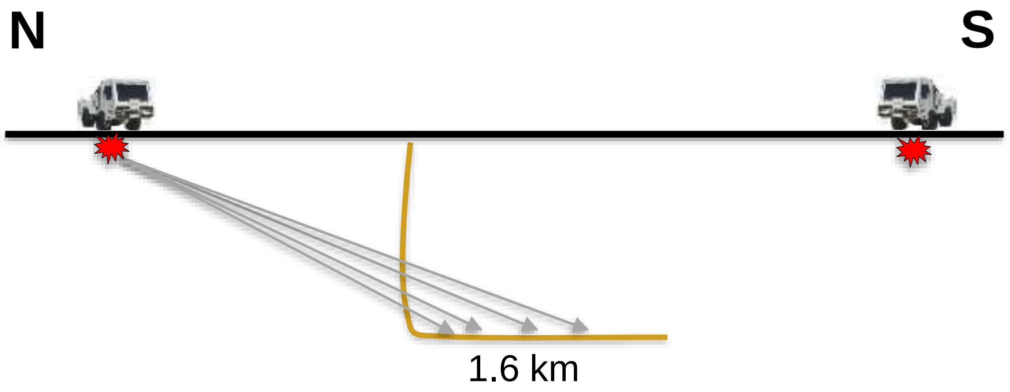
Apache Interstage DAS VSP



By fitting time shifts to a model, height, fracture compliance, and decay time can be found



Scattered Waves with Engineered Fiber



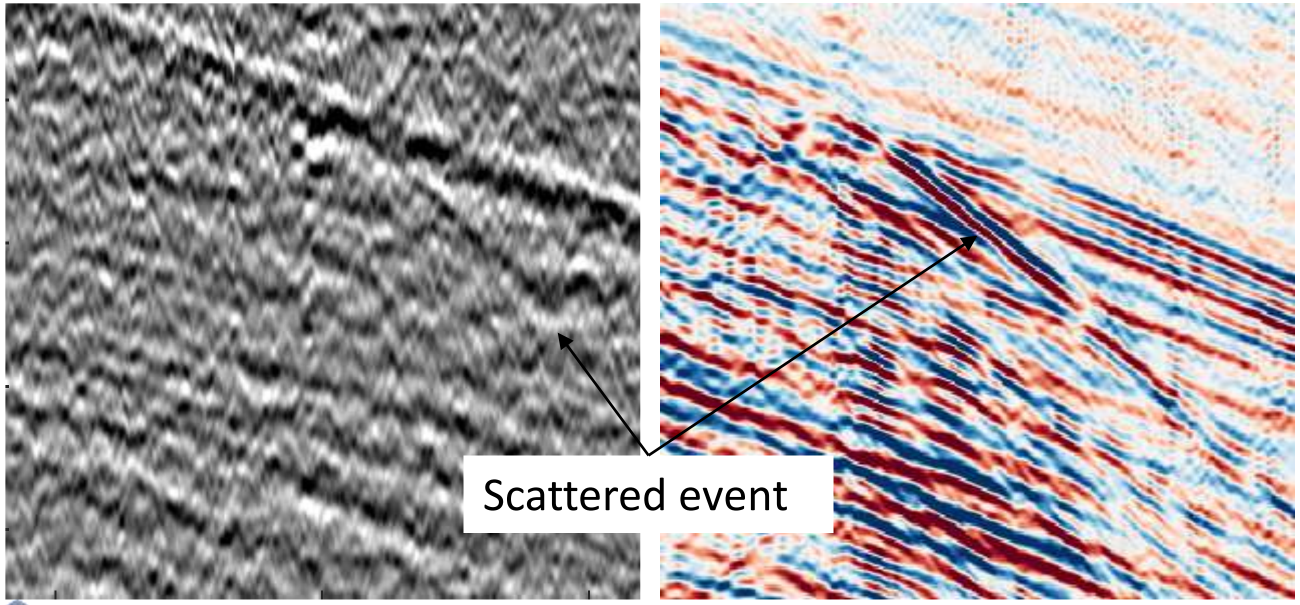
- Scattered waves are another path to height, fracture compliance, width, and decay time

- Weakly seen for some stages in first Apache dataset

- New survey with engineered fiber has improved SNR by a factor of ~100

- Scattered waves visible after almost every stage

Previous (stacked for 5 stages) New (single stage)



Fiber Optics for Unconventionals

Exploration
- VSP
- DTS Warmback

Reservoir characterization

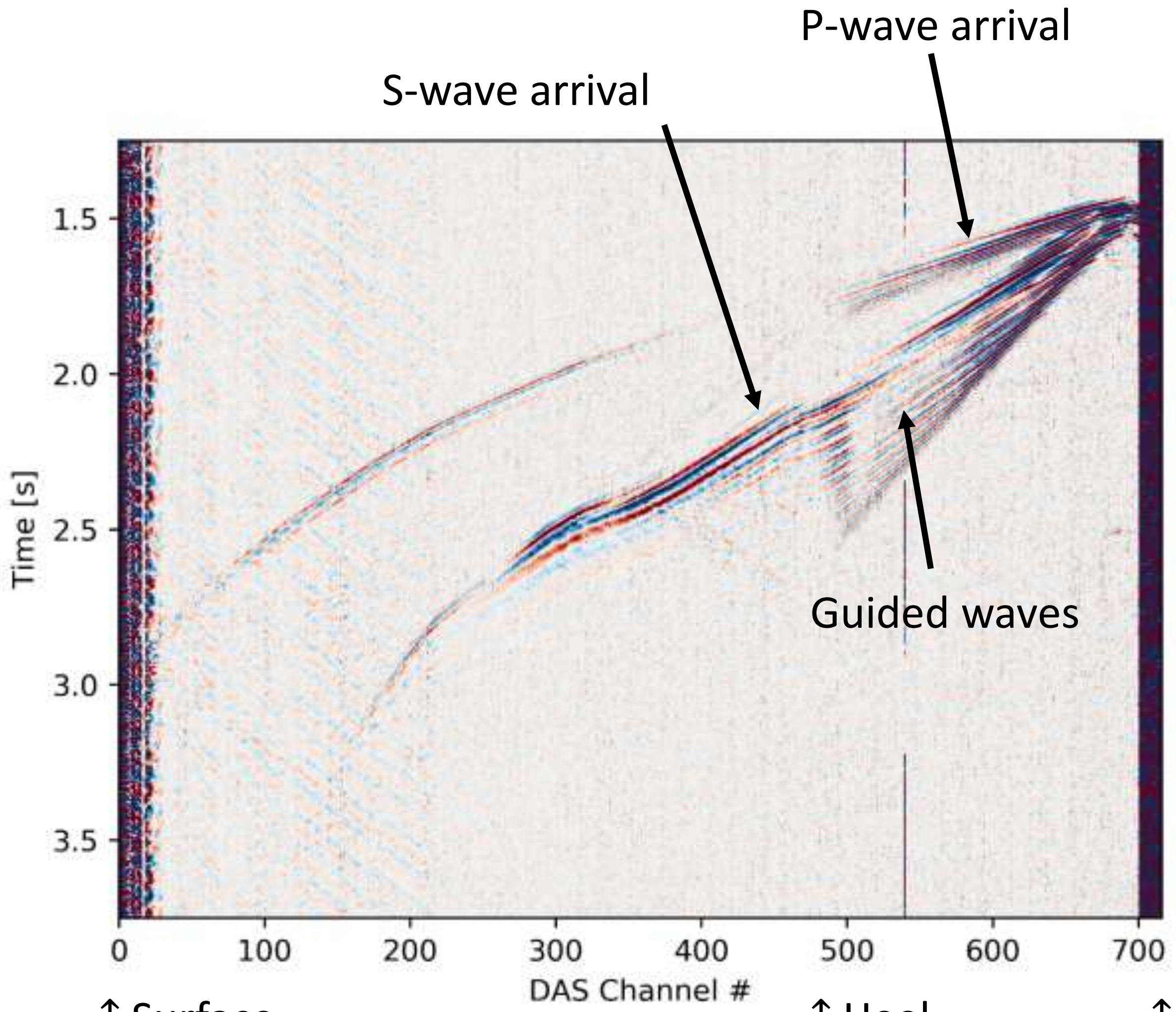
Completion
- Time-lapse VSP
- Microseismic
- Low frequency DAS
- Injection allocation

Completion and well spacing optimization

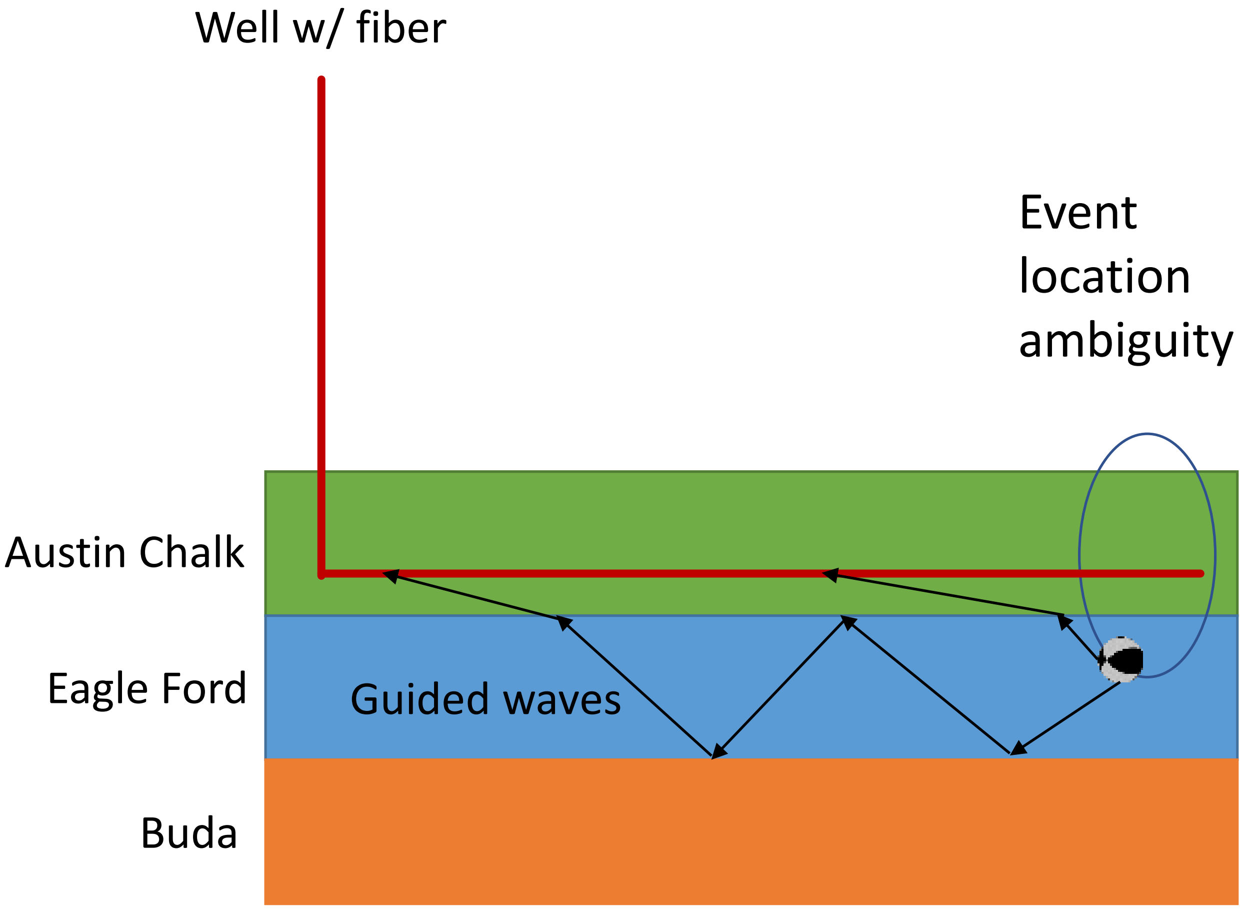
Production
- Gas lift monitoring
- Leak detection
- Production logging

Reservoir management and production enhancement

Eagle Ford DAS Microseismic



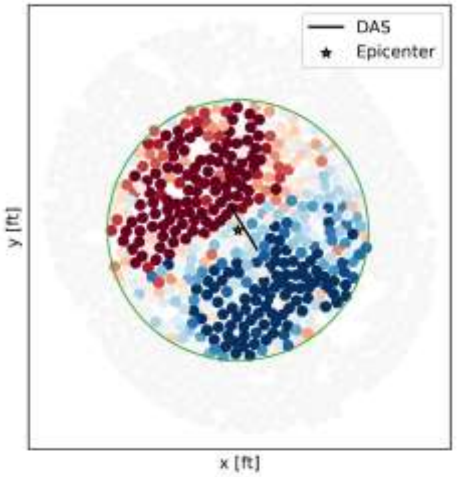
↑ Surface ↑ Heel ↑ Toe



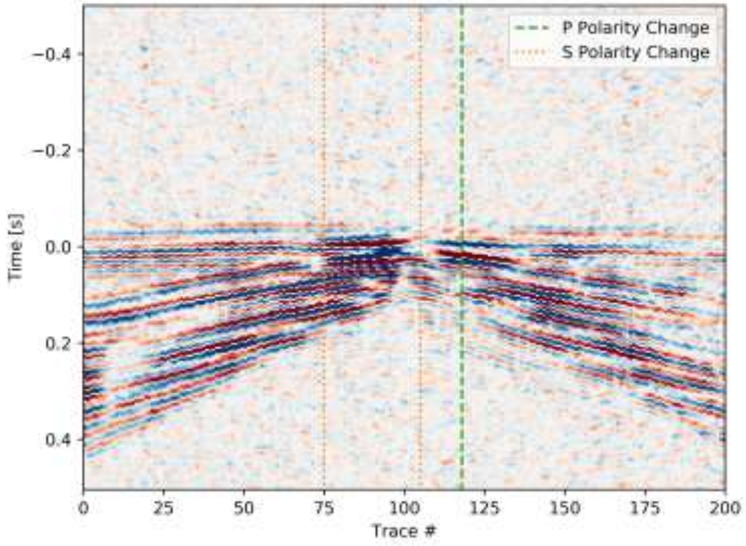
Surface/DAS Joint Inversion

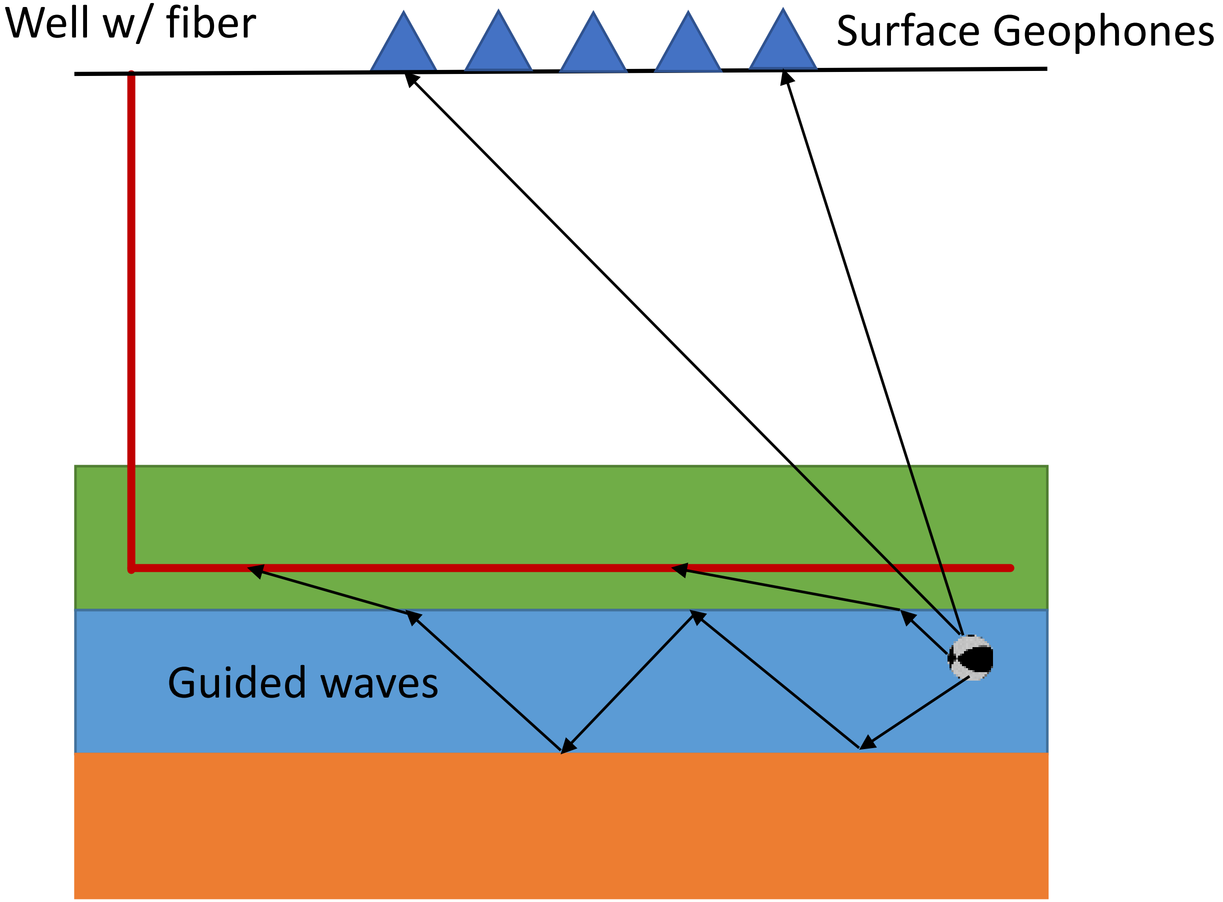
- Combine strengths of surface geophones and DAS for both accurate microseismic locations and source mechanisms

Surface:



DAS:





Fiber Optics for Unconventionals

Exploration → **Completion** → **Production**

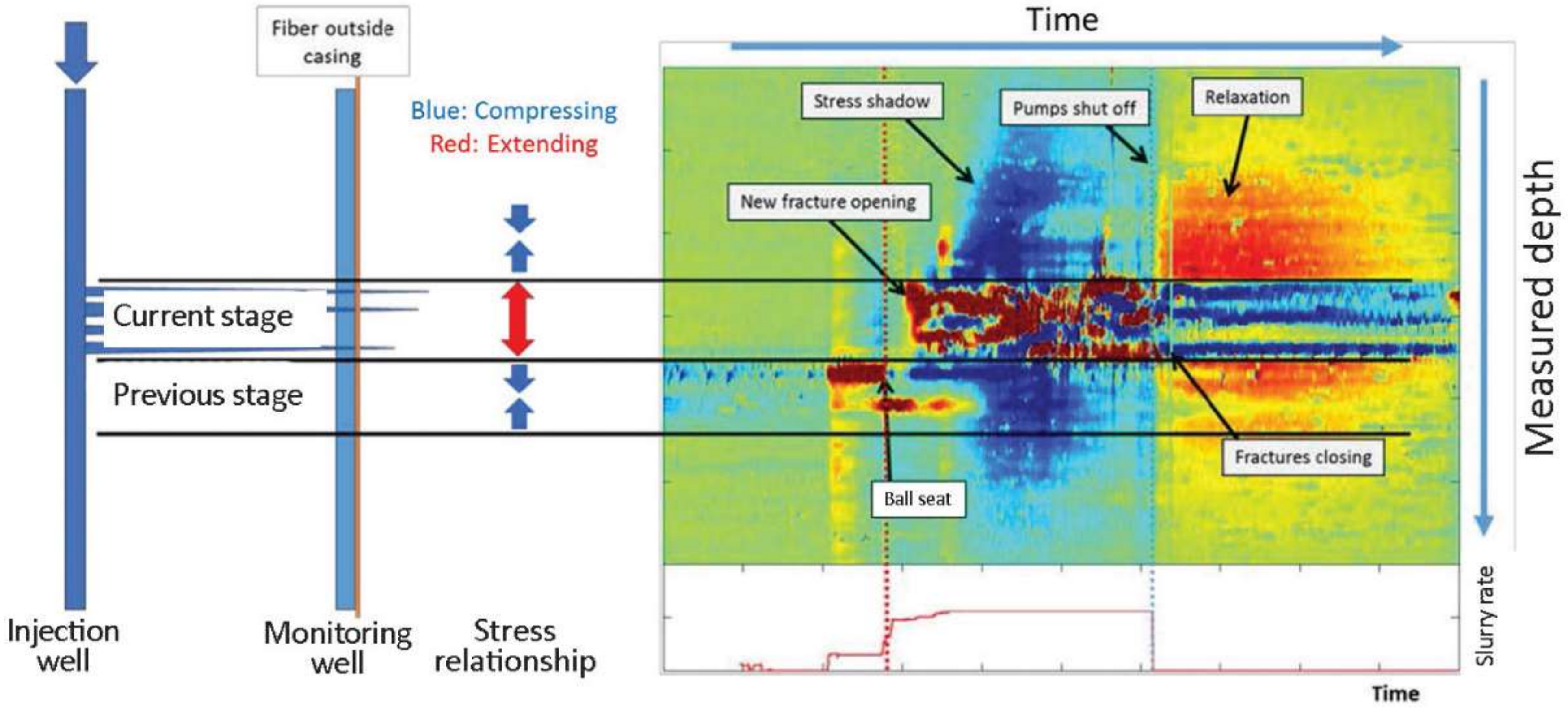
Exploration	Completion	Production
VSP	Time-lapse VSP	Gas lift monitoring
DTS Warmback	Microseismic	Leak detection
	Low frequency DAS	Production logging
	Injection allocation	
Reservoir characterization	**Completion and well spacing optimization**	**Reservoir management and production enhancement**

COLORADOSCHOOLOFMINES
EARTH • ENERGY • ENVIRONMENT

FORP
Fiber Optics Research Program

Cross-well Strain

- Low-frequency (<0.5 Hz) DAS data shows slow strain changes
  - Frac hits
  - Stress shadowing
  - Leak-off and fracture closure

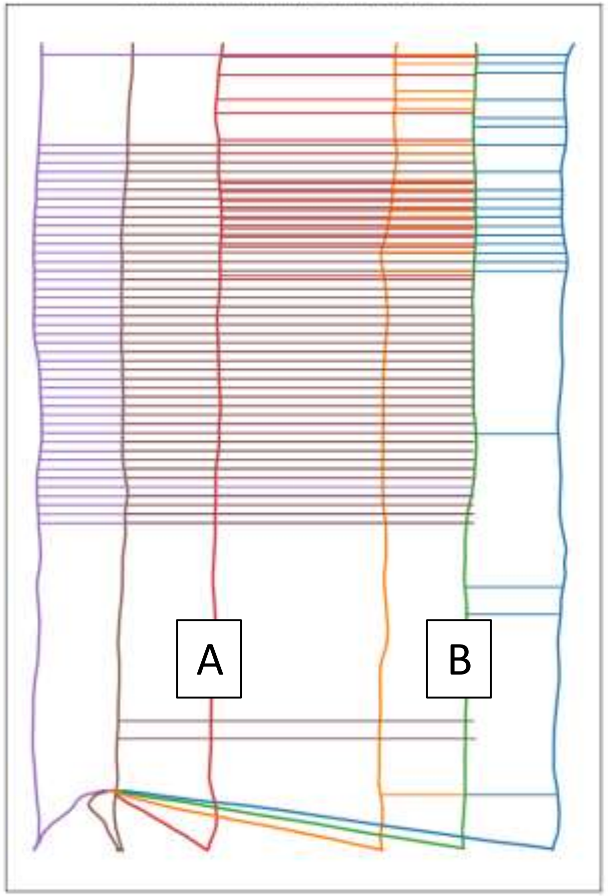


Jin, G., and B. Roy, 2017, Leading Edge, **36**, 975–980.

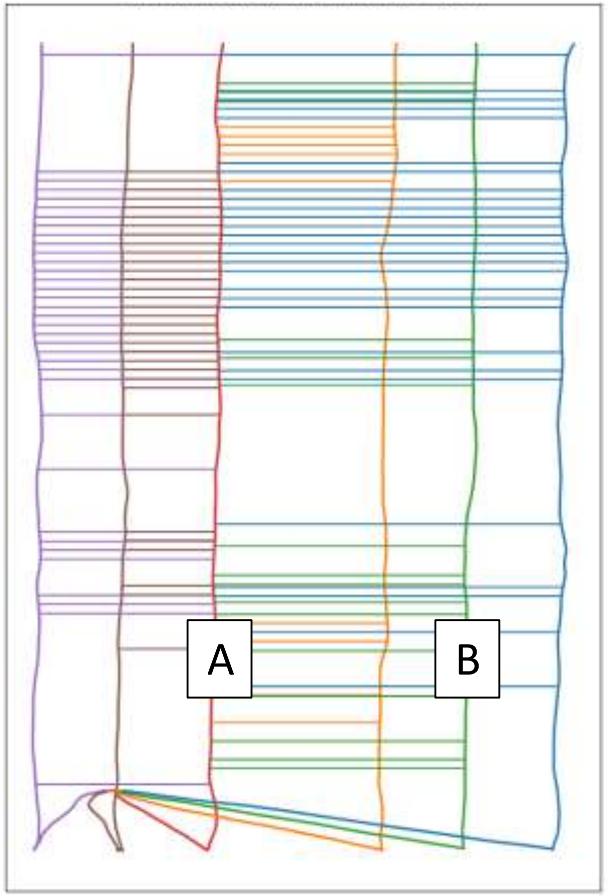
Chalk Bluff: Potential LF Signals

- LF DAS signals are observable for hundreds of stages in the Chalk Bluff project

Observable frac hits in Fiber Well A



Observable frac hits in Fiber Well B



Fiber Optics for Unconventionals

Exploration	Completion	Production
VSP	Time-lapse VSP	Gas lift monitoring
DTS Warmback	Microseismic	Leak detection
	Low frequency DAS	Production logging
	Injection allocation	

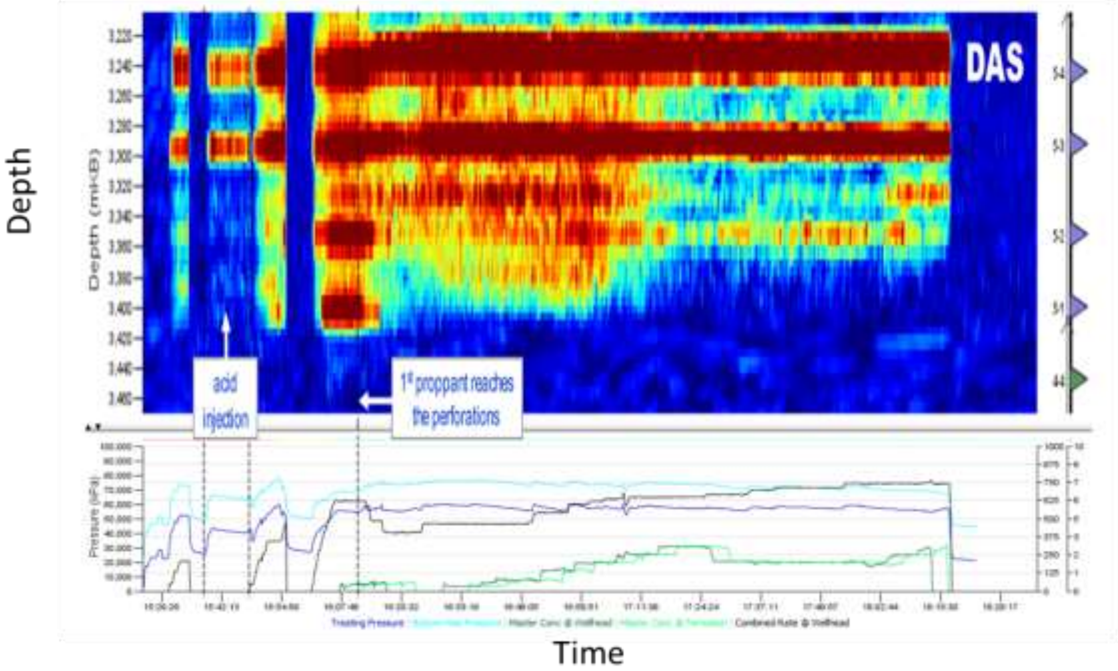
Exploration → **Reservoir characterization**

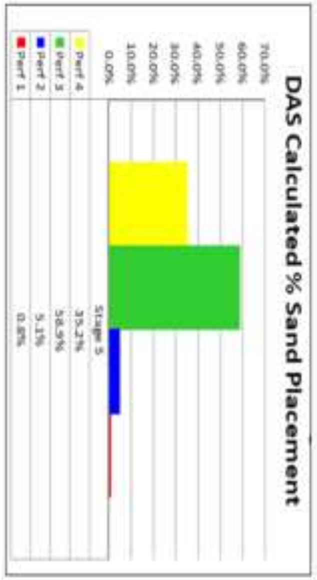
Completion → **Completion and well spacing optimization**

Production → **Reservoir management and production enhancement**

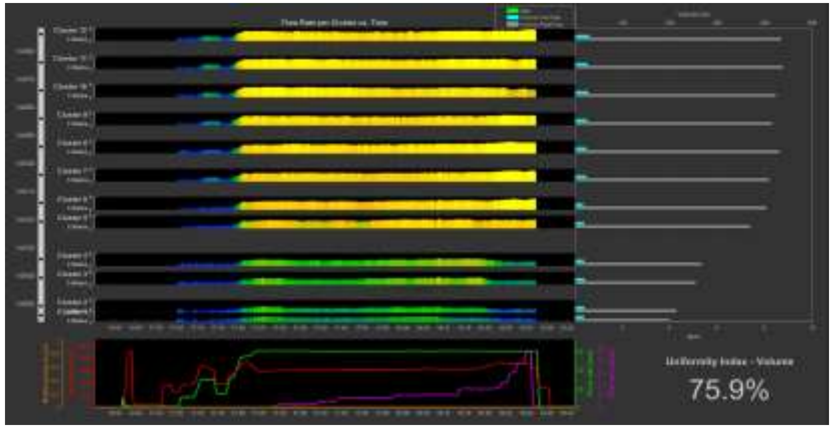
Injection Allocation

- Allocate fluid and proppant to each perf cluster using acoustic noise in DAS

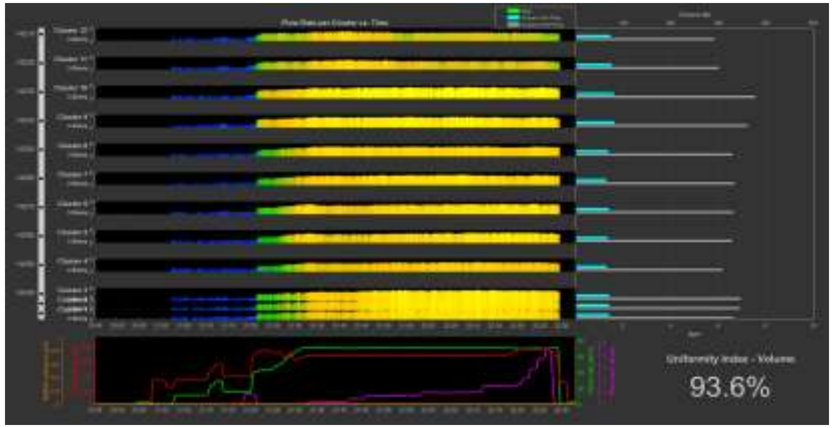




Webster et al. 2013



Completion design optimization



Fiber Optics for Unconventionals

Exploration → **Completion** → **Production**

Exploration
- VSP
- DTS Warmback

↓ **Reservoir characterization**

Completion
- Time-lapse VSP
- Microseismic
- Low frequency DAS
- Injection allocation

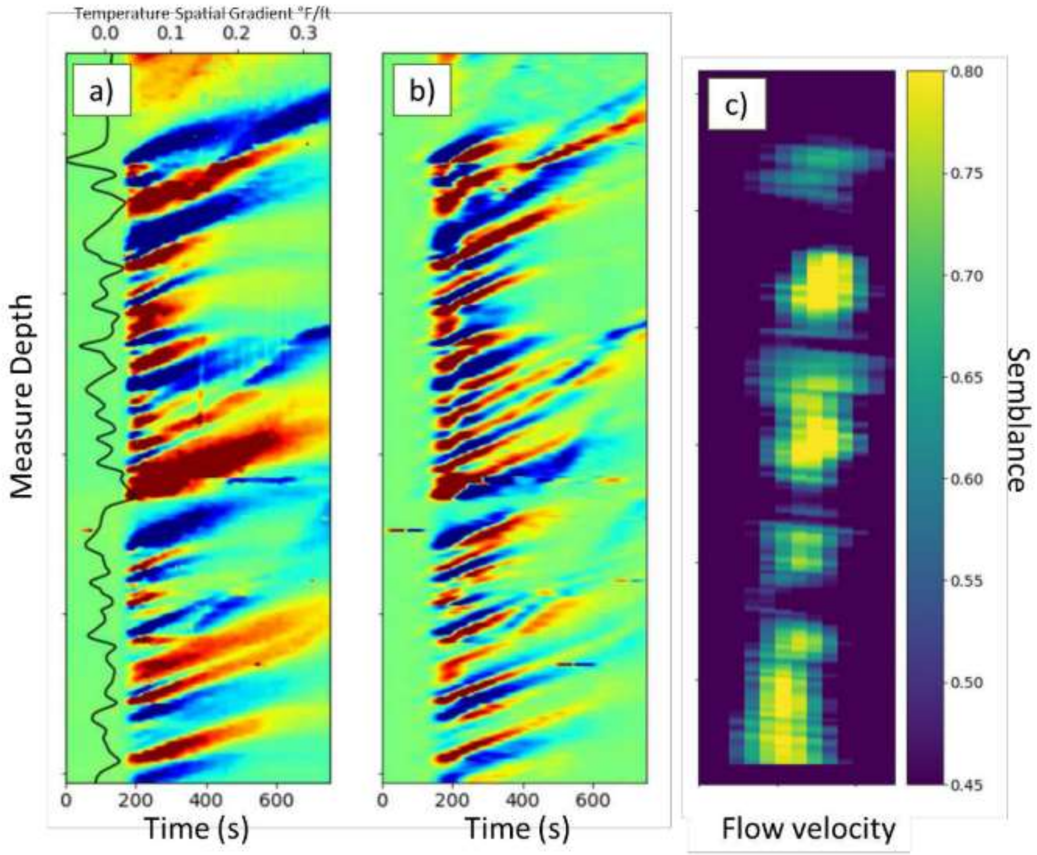
↓ **Completion and well spacing optimization**

Production
- Gas lift monitoring
- Leak detection
- Production logging

↓ **Reservoir management and production enhancement**

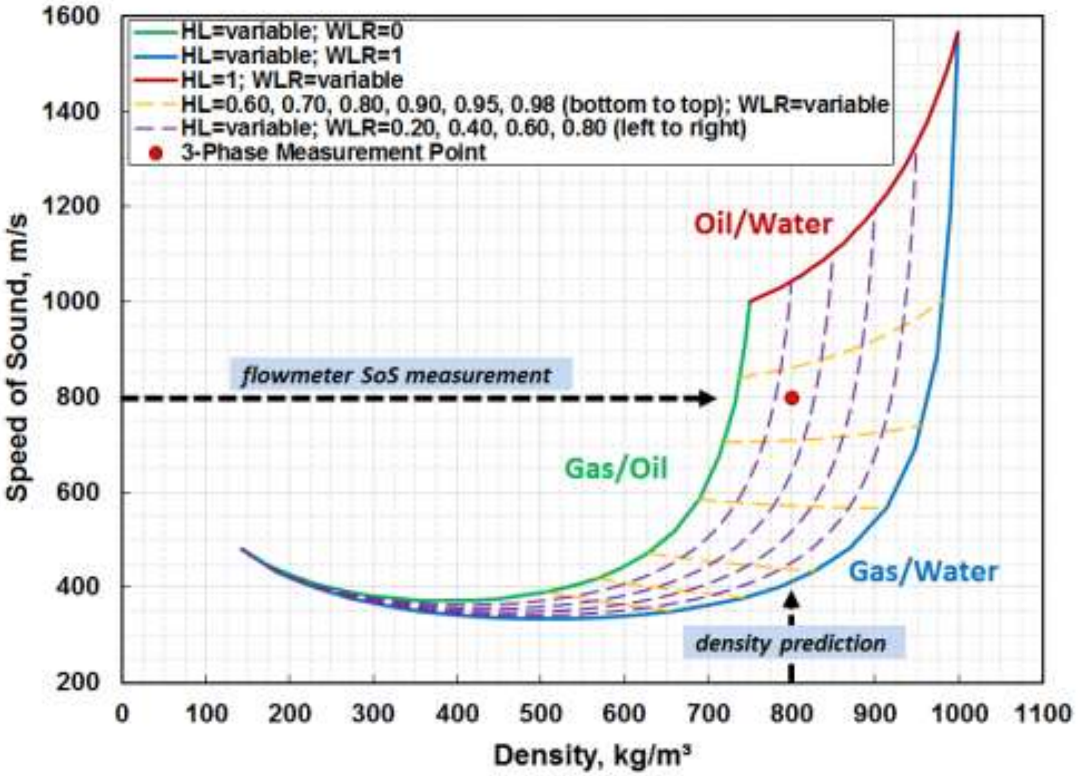
Production Logging

- Thermal slugs can be tracked to estimate flow velocity along well



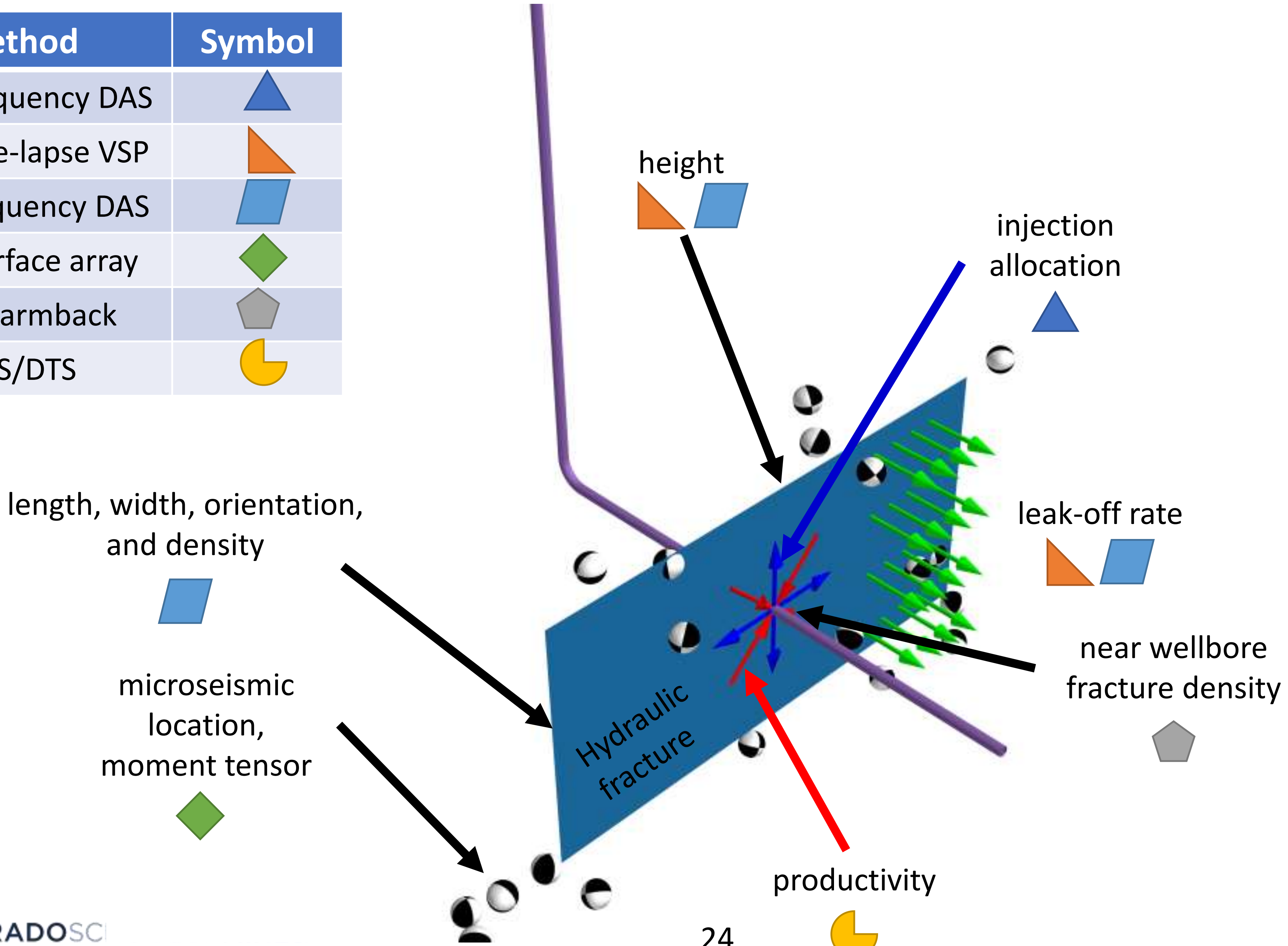
Jin et al., 2019, URTeC 2019, 943.

- Speed of sound is sensitive to water/oil/gas mixture

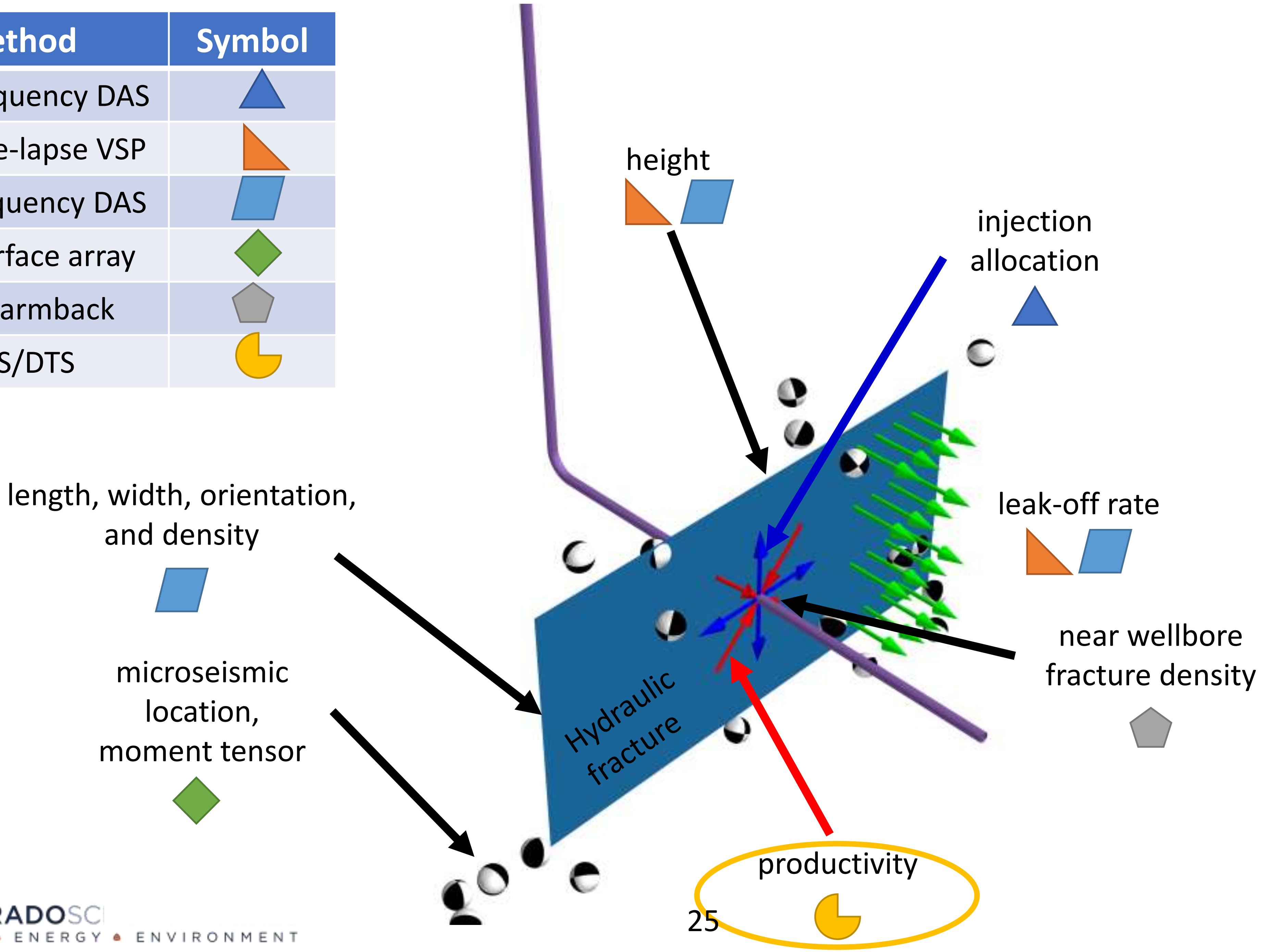


Haldun Unalmis, O., 2015, Proc. of Mtgs. on Acoustics, **23**, 045003.

Method	Symbol
High-frequency DAS	▲
DAS time-lapse VSP	◣
Low-frequency DAS	▱
DAS/surface array	◆
DTS warmback	⬟
DAS/DTS	◔



Method	Symbol
High-frequency DAS	
DAS time-lapse VSP	
Low-frequency DAS	
DAS/surface array	
DTS warmback	
DAS/DTS	



RCP FO Lab Equipment

- OptaSense: ODH-3.1 DAS interrogator
- Halliburton: SensorTran DTS interrogator
- AFL: fusion splicer/cleaver
- Pressure/temperature/flow sensors for calibration
- Compressed air injection for two-phase flow

RCP FO Lab Research

- Quantitative understanding of:
  - Single-phase and multi-phase flow
    - Flow Velocity; Flow Rate; Fluid Phase; Liquid Holdup; Flow Pattern
  - Acoustic and thermal energy propagation and attenuation
- Testing of installation methods, types of optical fiber, and interrogator settings to optimize measurements
- Low-frequency DAS measurements
- Development of physics-based modeling approaches

Flow Characterization Methods

Acoustic

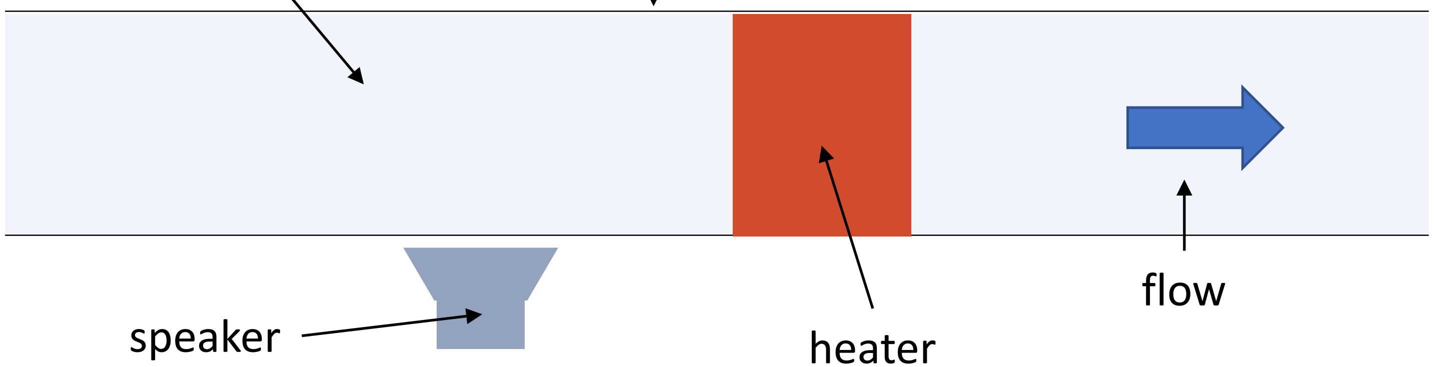
- Intensity-based
- Speed of sound
- Doppler effect
- Eddy tracking
- Slugging signal

Finfer et al., 2014; In’t Panhuis et al., 2014; Naldrett et al., 2018

Thermal

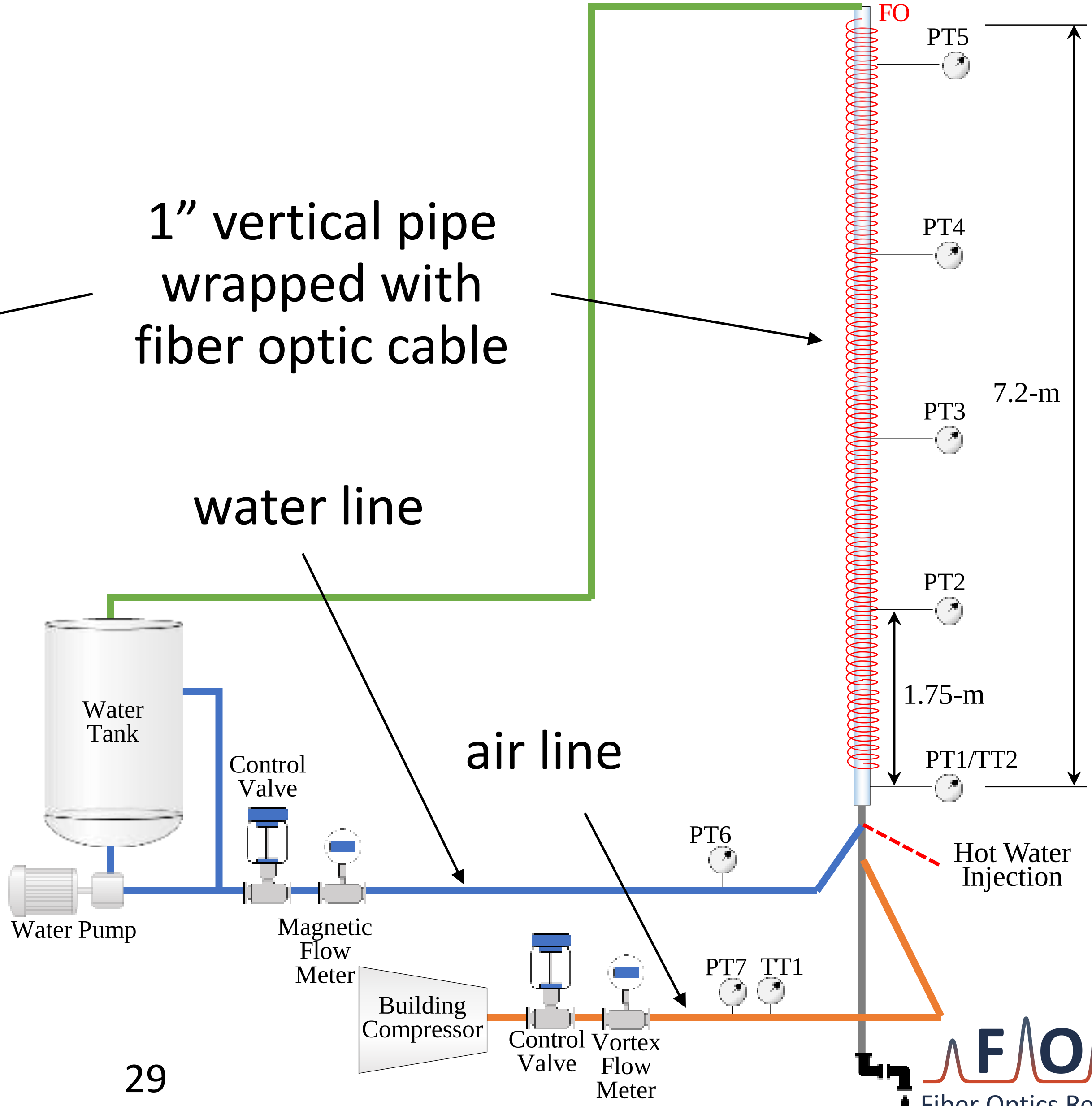
- Slugging signal
- Material and Thermal balance

Jin et al., 2019

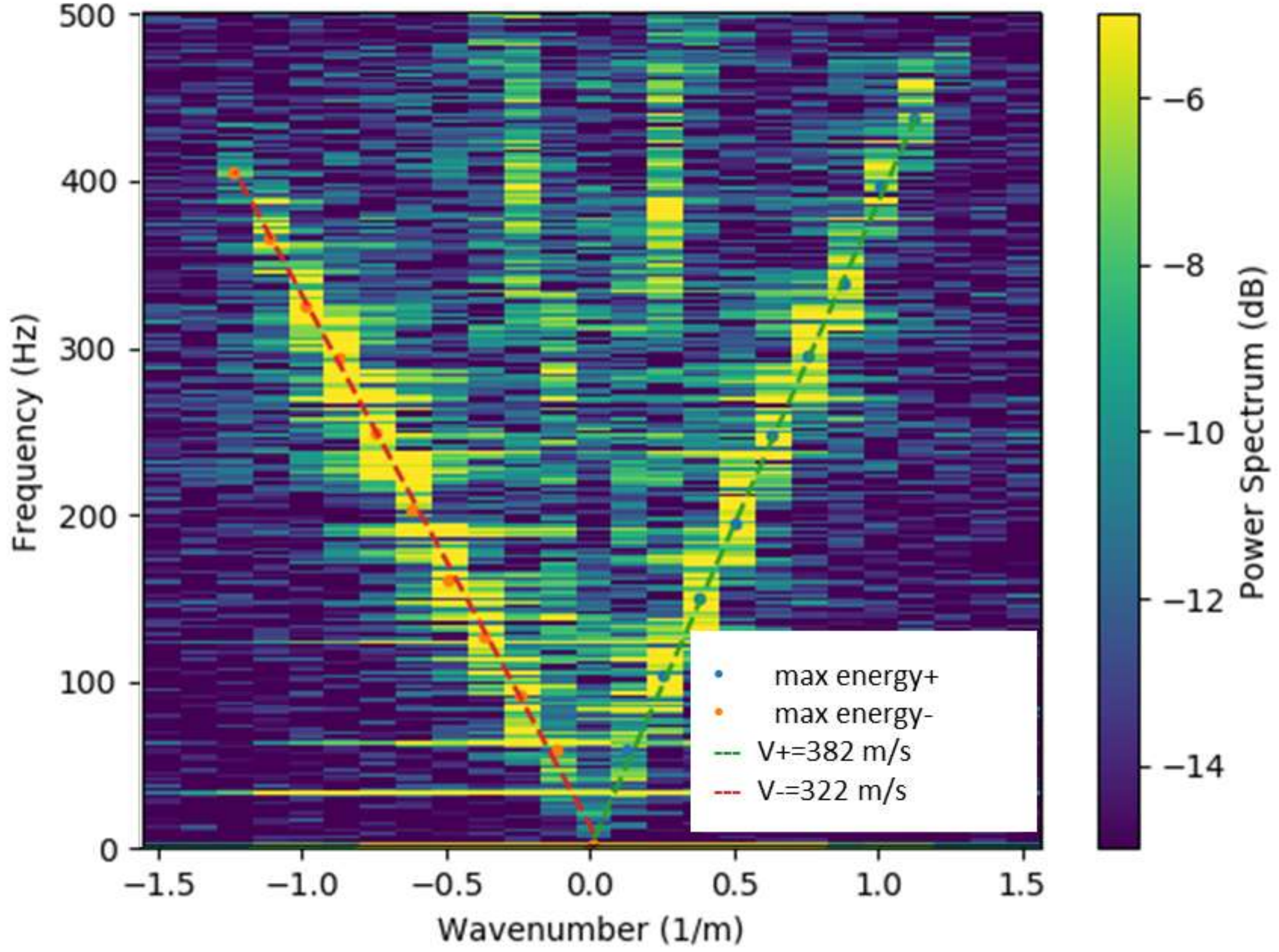


High Bay Vertical Flow Loop

1” vertical pipe wrapped with fiber optic cable



What fluid is flowing and how fast?



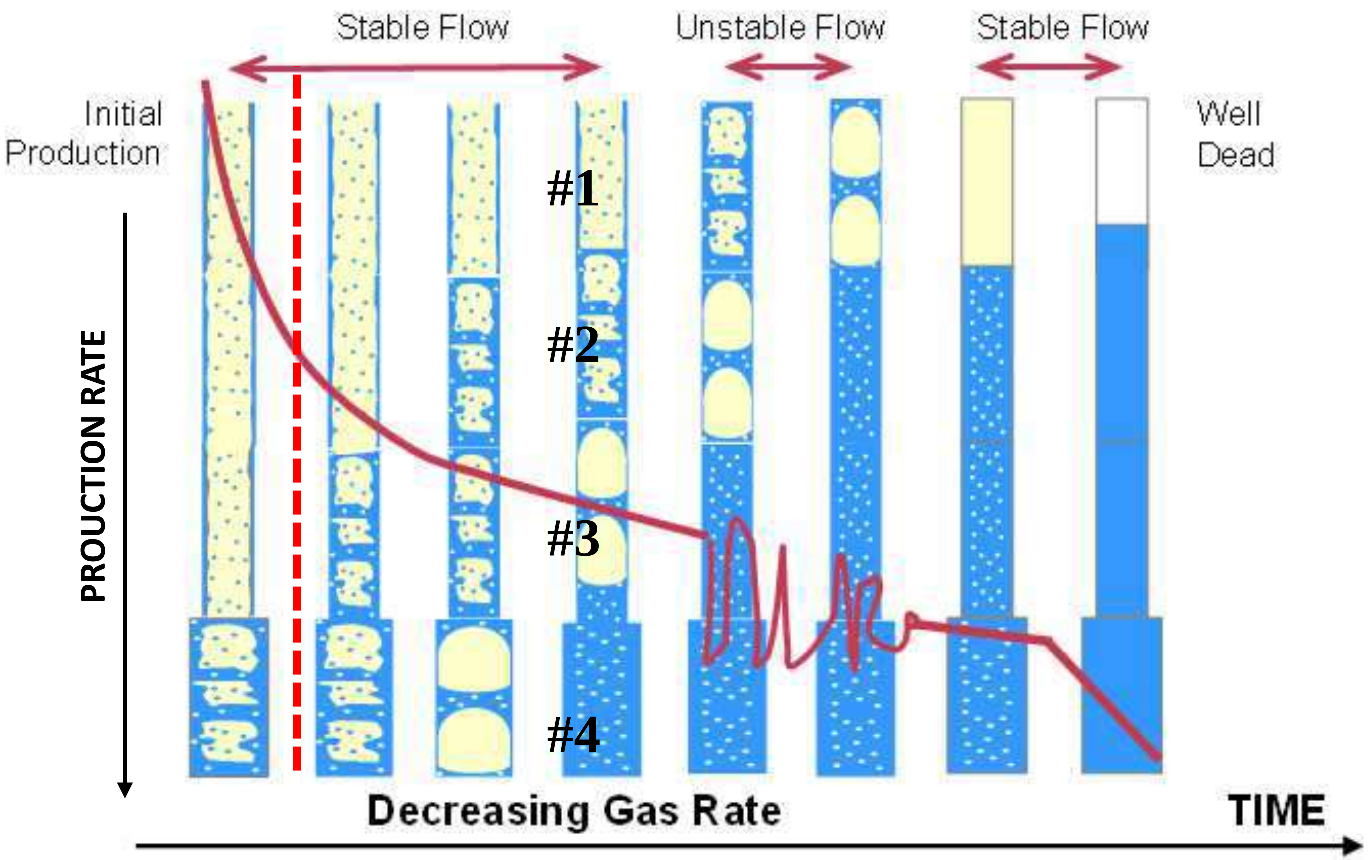
$$c = \frac{382 + 322}{2} = 352\, m/s$$

$$U = \frac{382 - 322}{2} = 30\, m/s$$

$U = 28\, m/s$ measured with flow meter

Air, 30 m/s

Two-Phase Flow and Onset of Liquid Loading

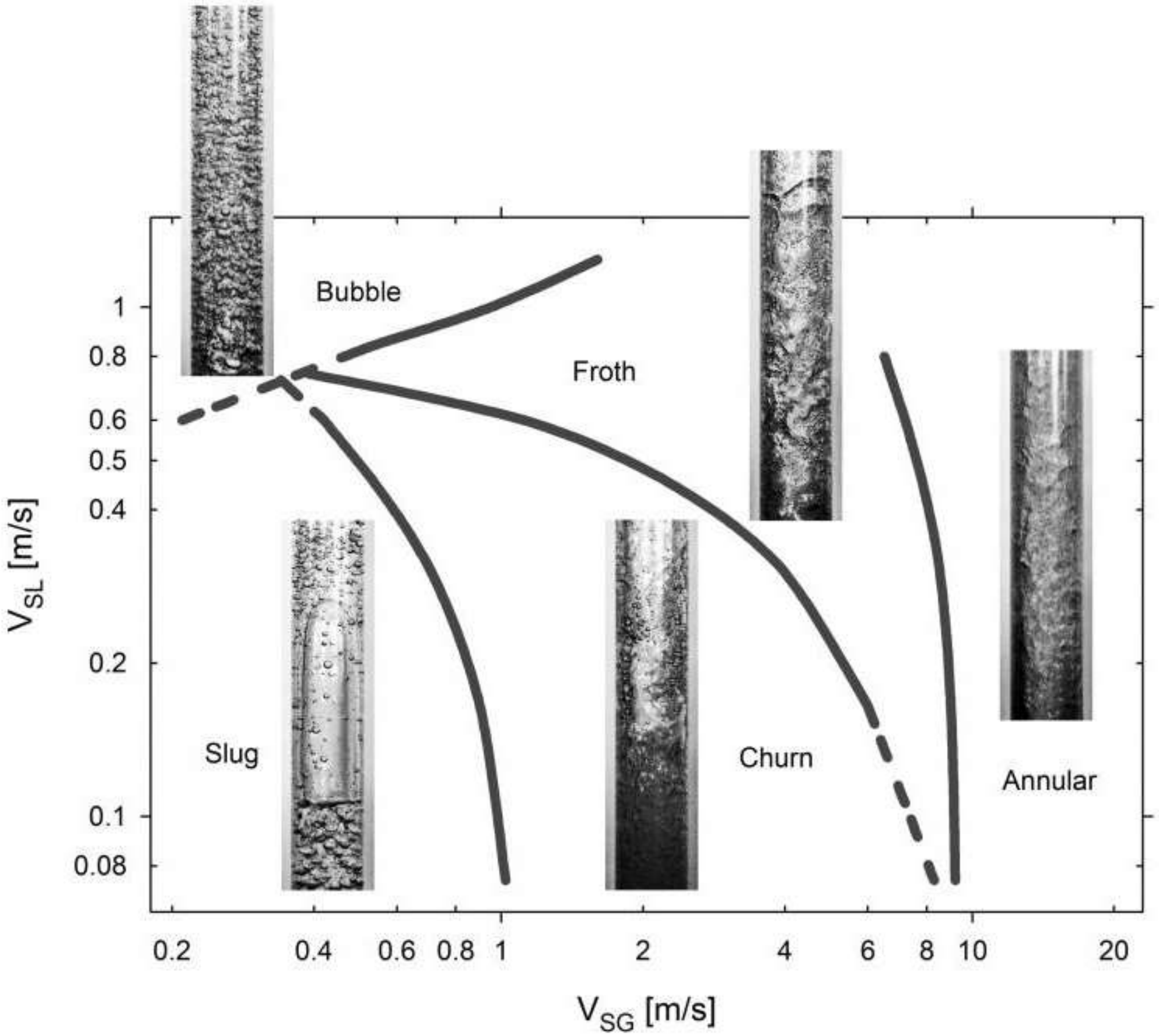


Hearn (2010)

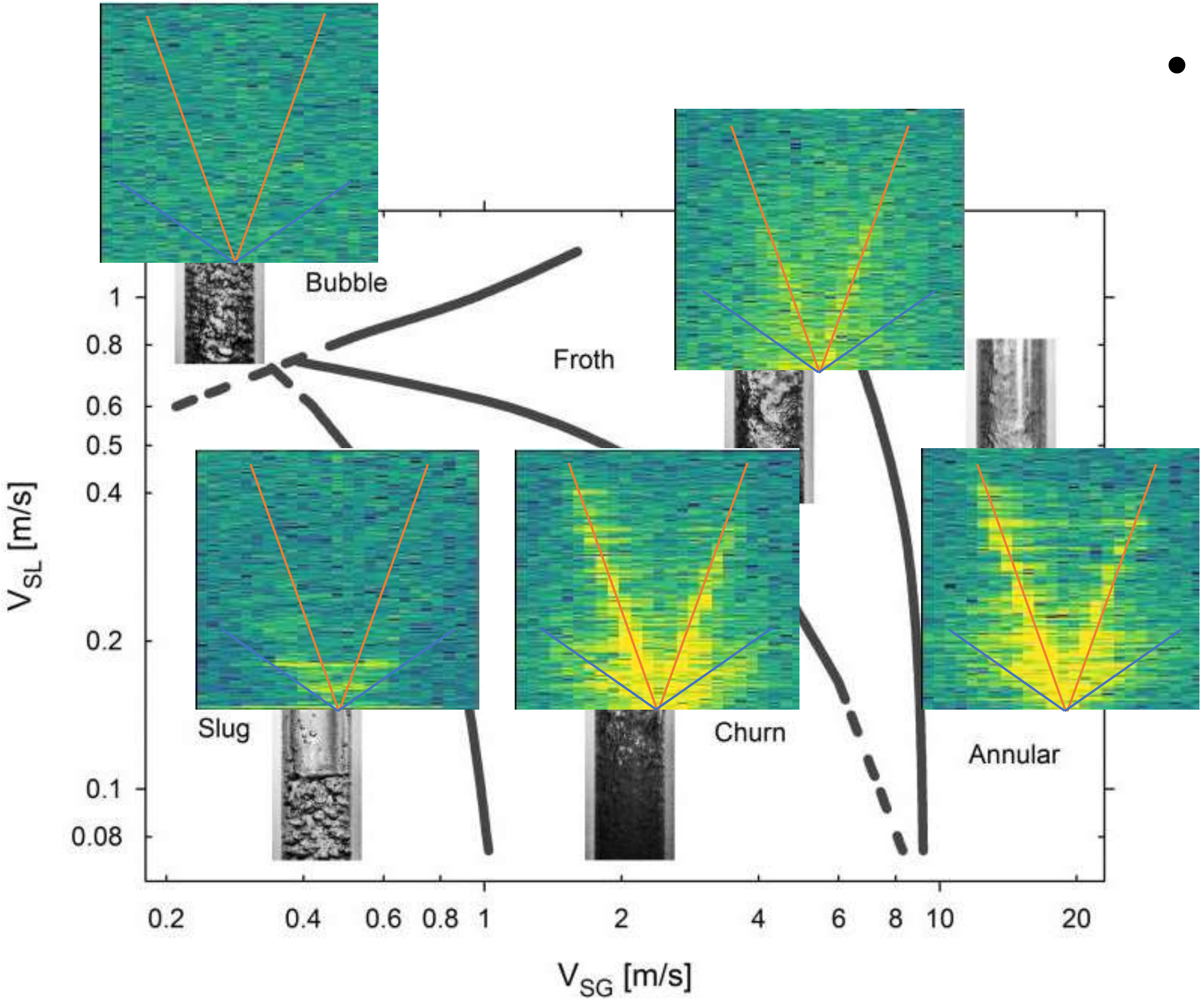
#1 Annular #2 Churn #3 Slug #4 Bubble

- Liquid loading detection will help to:
  - Put artificial lift
  - Understand the performance of artificial lift
  - Facilitate operational decision making
- Our objectives with vertical flow loop:
  - Characterize multiphase flow for different flow patterns with DAS
  - Detect flow pattern transition

Flow Patterns



Two-Phase Flow Observations

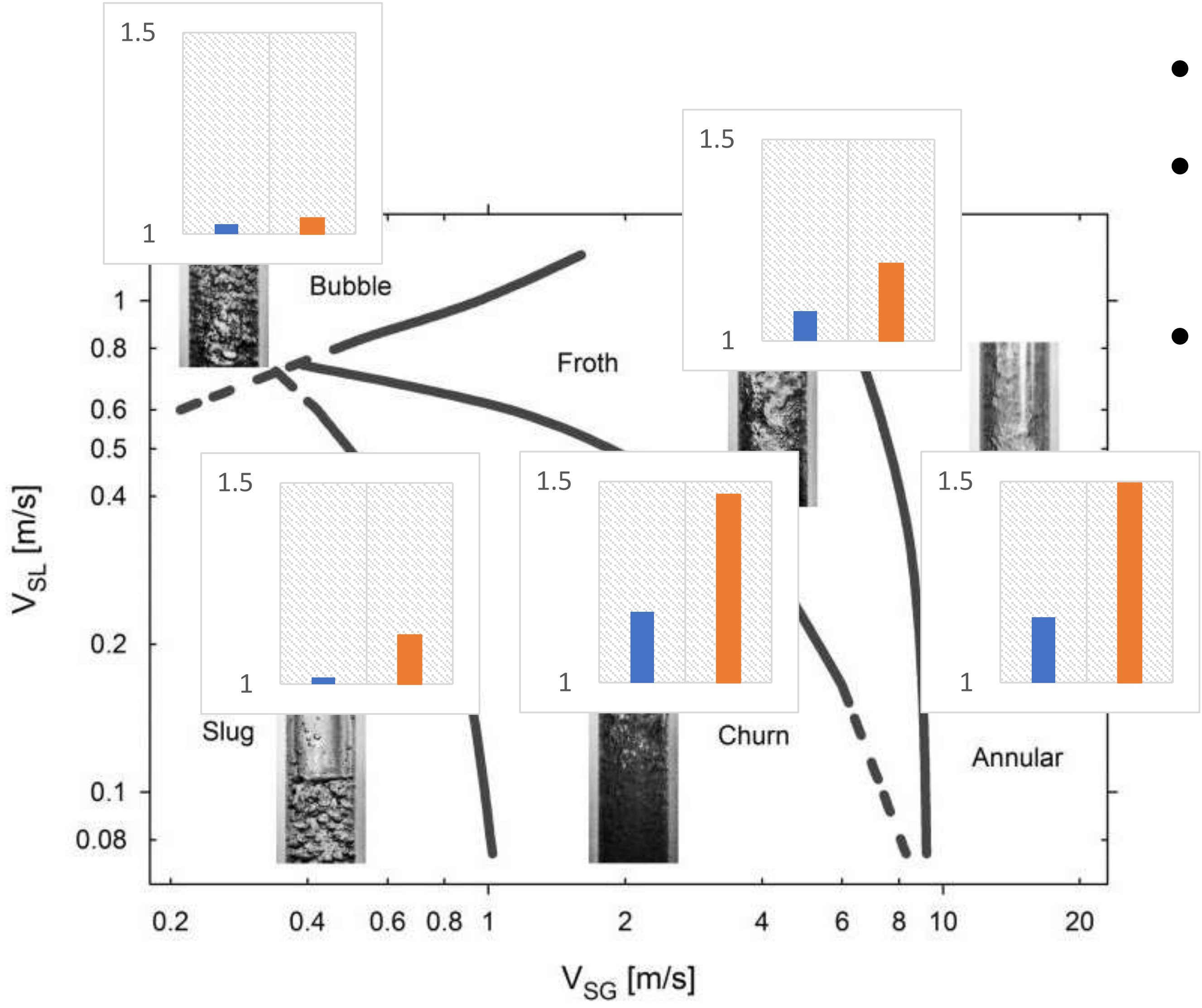


- We observe two modes

$c_1 = 350\, m/s$

$c_2 = 1500\, m/s$

Two-Phase Flow Observations



- We observe two modes
- The intensity of the modes varies with the flow pattern
- Normalized intensity can be used to distinguish between flow patterns

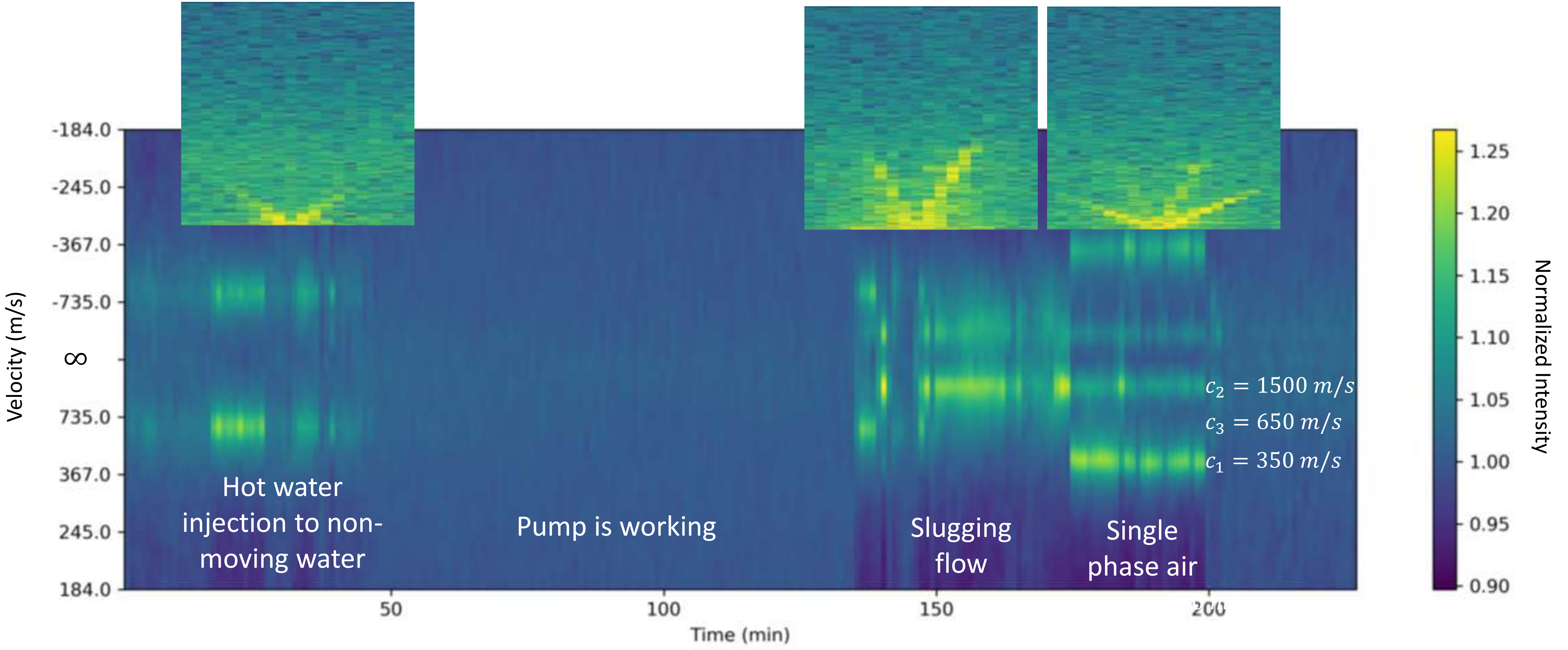
$c_1 = 350\ m/s$

$c_2 = 1500\ m/s$

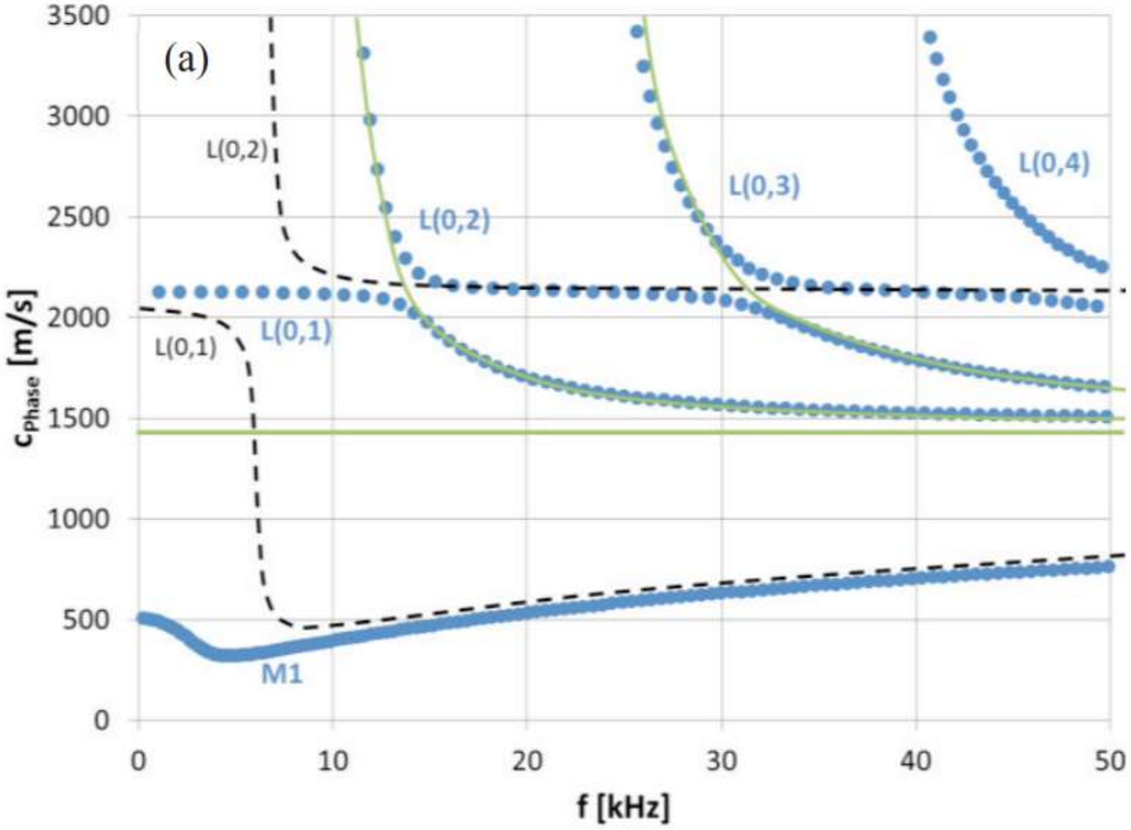
COLORADO SCHOOL OF MINES
EARTH • ENERGY • ENVIRONMENT

FORP
Fiber Optics Research Program

Tube Wave Complexity



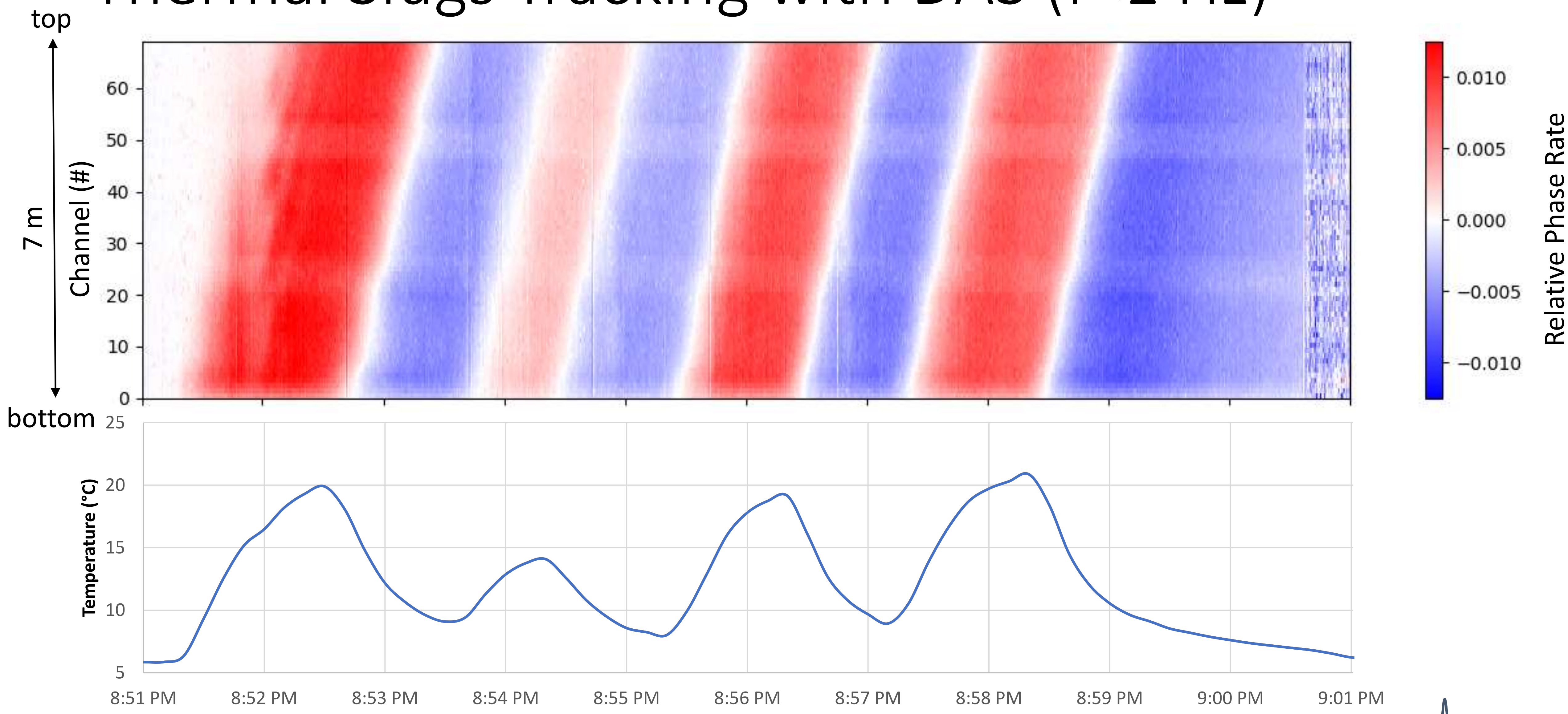
Tube Wave Complexity



Dispersion diagram of longitudinal modes L and the fluid mode M1 for water-filled 2” pipe
(from *Wöckel et al., 2015)*

- Different propagation modes exist in the filled-pipe system
- The modes are dispersive and change with pipe material, diameter, wall thickness, installation, and fluid properties
- To quantitatively analyze flow for lab and wellbore conditions we need to model them

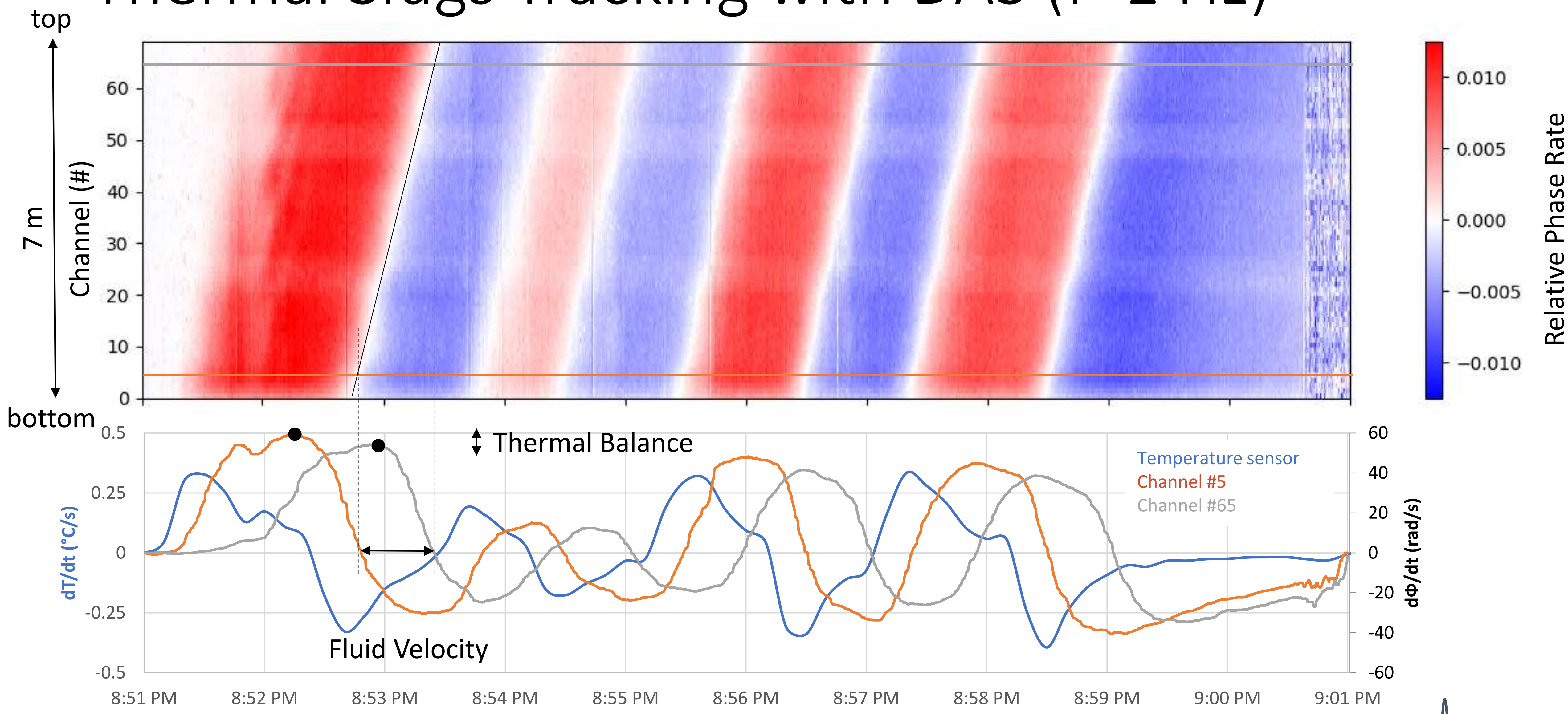
Thermal Slugs Tracking with DAS (f<1 Hz)



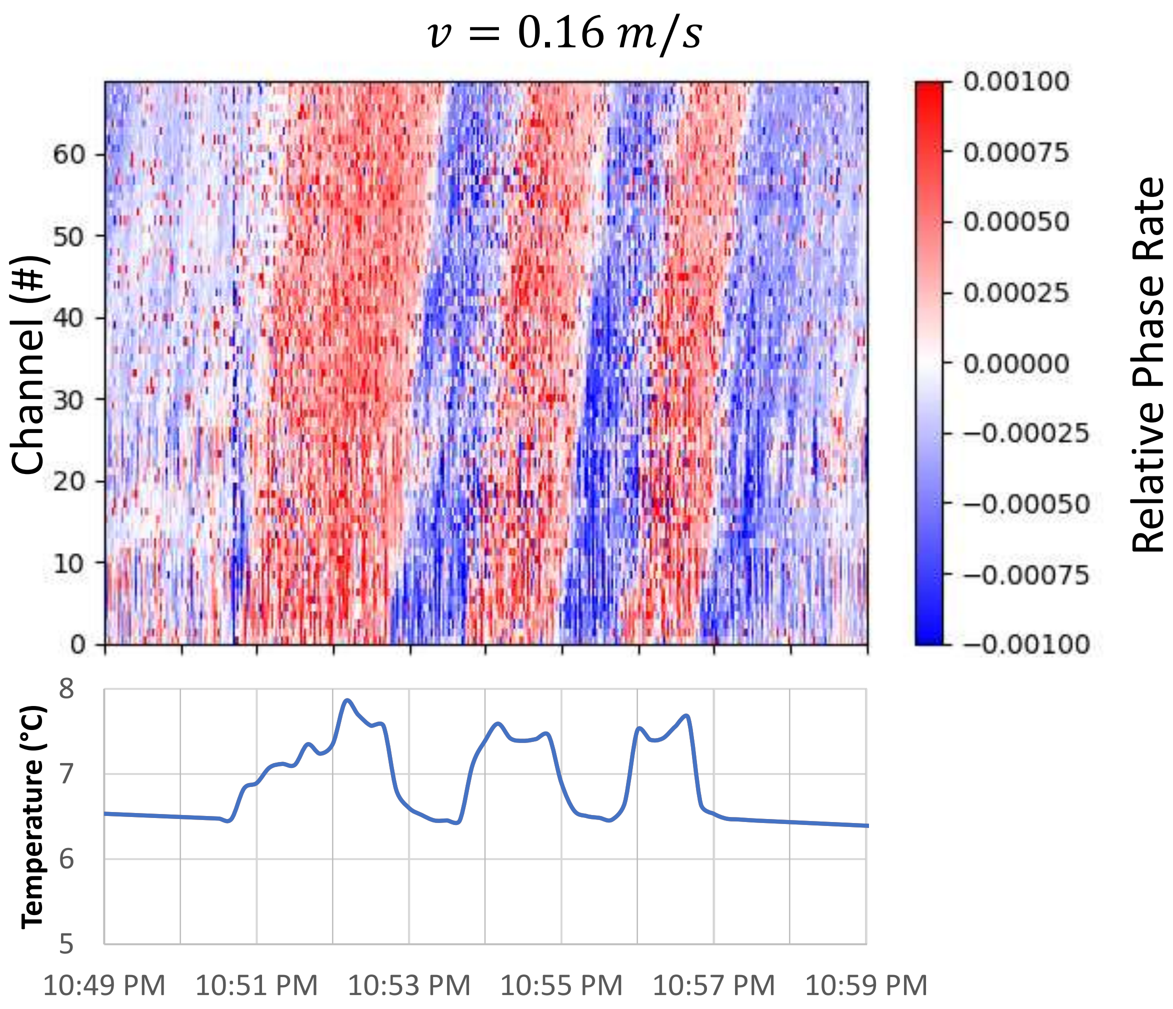
COLORADO SCHOOL OF MINES
EARTH • ENERGY • ENVIRONMENT

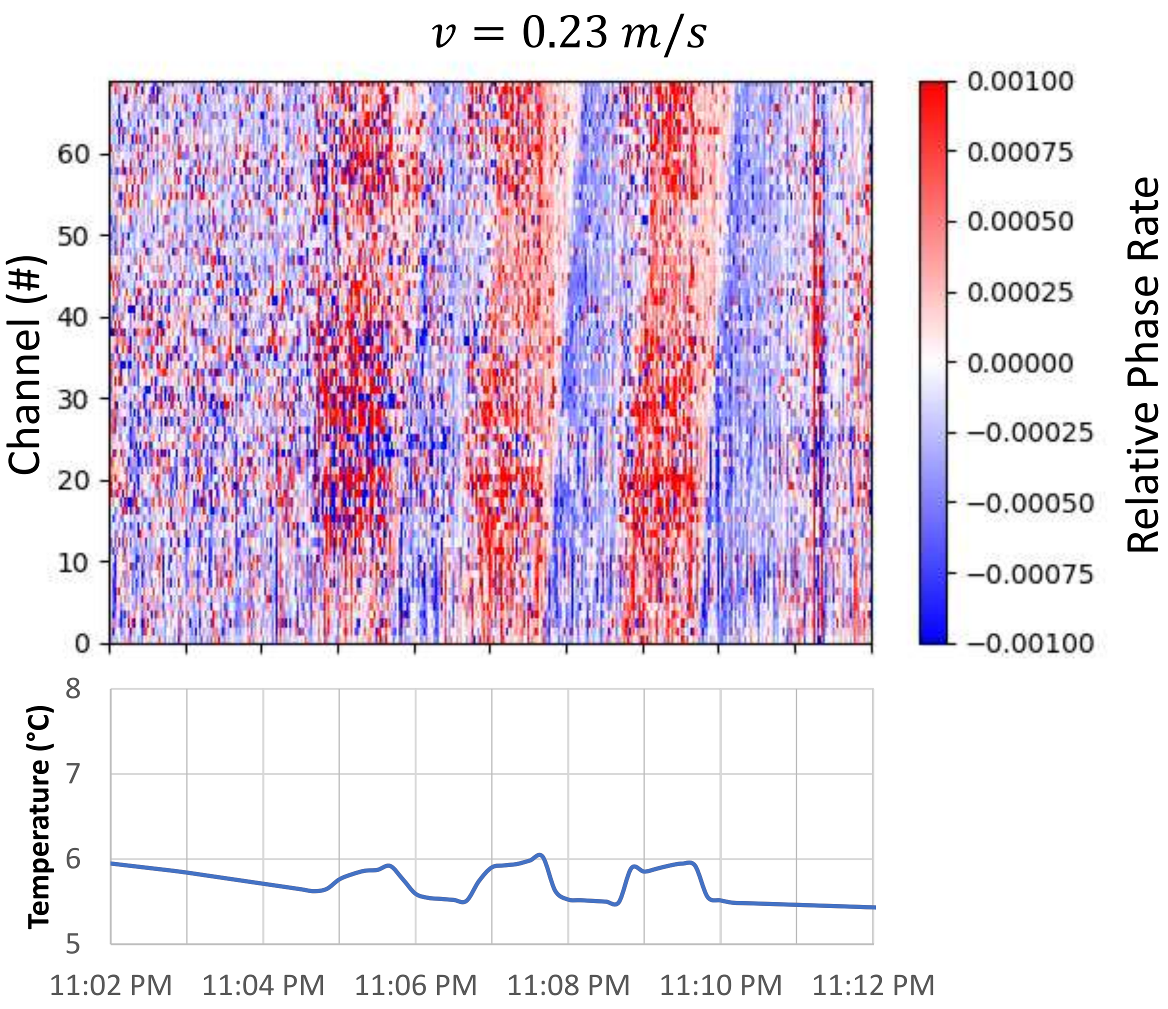
FORP
Fiber Optics Research Program

Thermal Slugs Tracking with DAS (f<1 Hz)



Thermal Slugs Tracking with DAS (f<1 Hz)





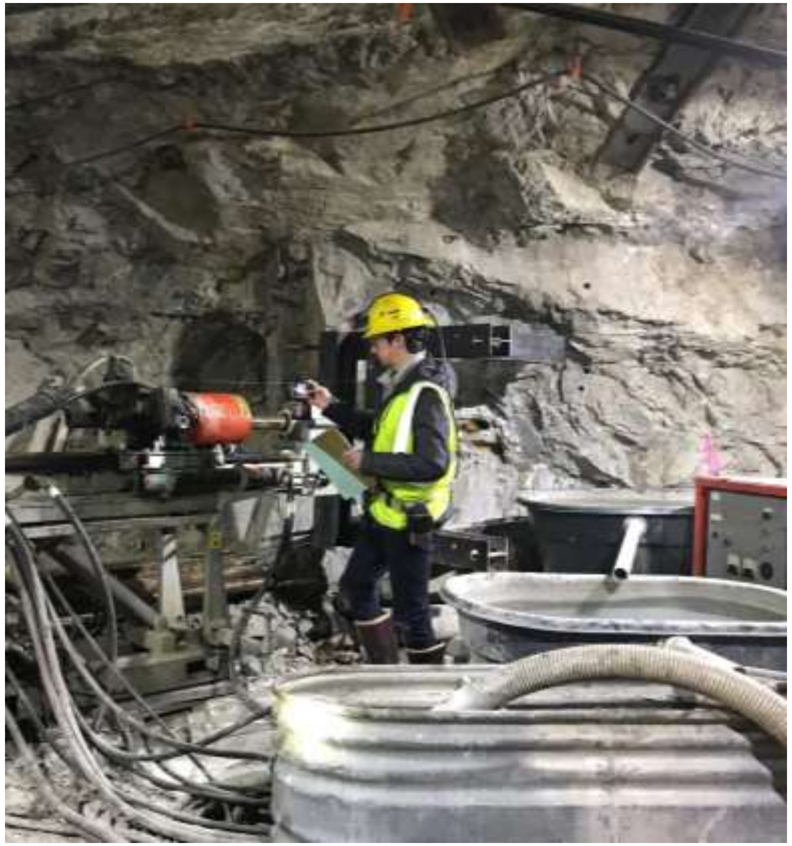
Findings and Future Plans

We can:

- Determine the phase of fluid
  - water vs. air
- Estimate flow velocity
  - Doppler effect
  - Eddy tracking
  - Slugs tracking
  - Thermal slugs tracking
- Distinguish between various flow patterns

We plan:

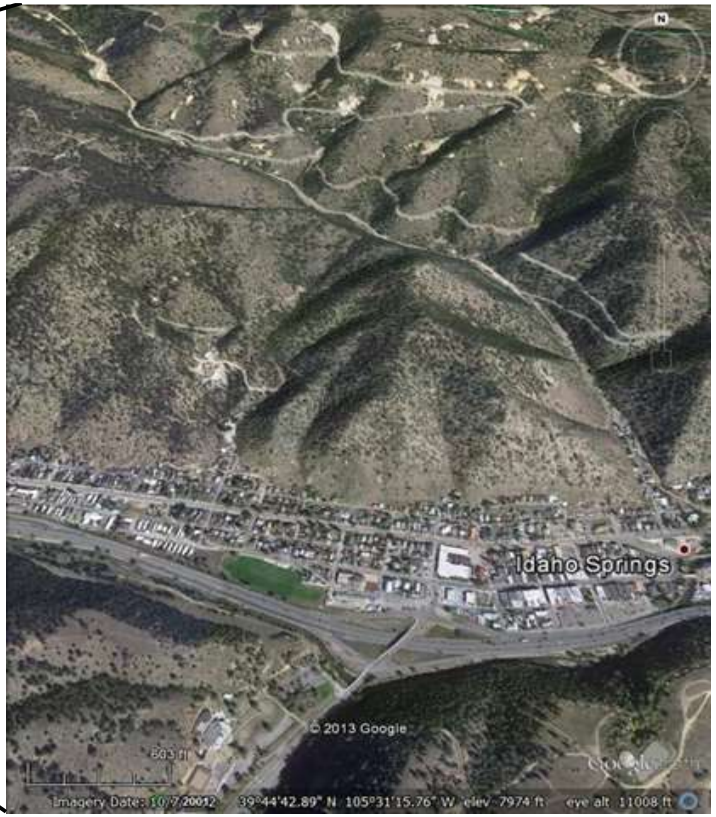
- Model structural and fluid tube waves modes for flow loop and borehole
- Estimate the uncertainty of velocity determination
- Develop other quantitative attributes for different flow patterns



Edgar Mine Flow Loop

Edgar Mine – Introduction

- Active mine in the 1870's
- Originally leased to Mines in 1921
- More than 10,000 ft of underground drifts
- Used for teaching, research, and mine rescue training



https://mining.mines.edu/edgar-experimental-mine/

Edgar Mine – The Why

Modeling

Experimentation

Data Analysis

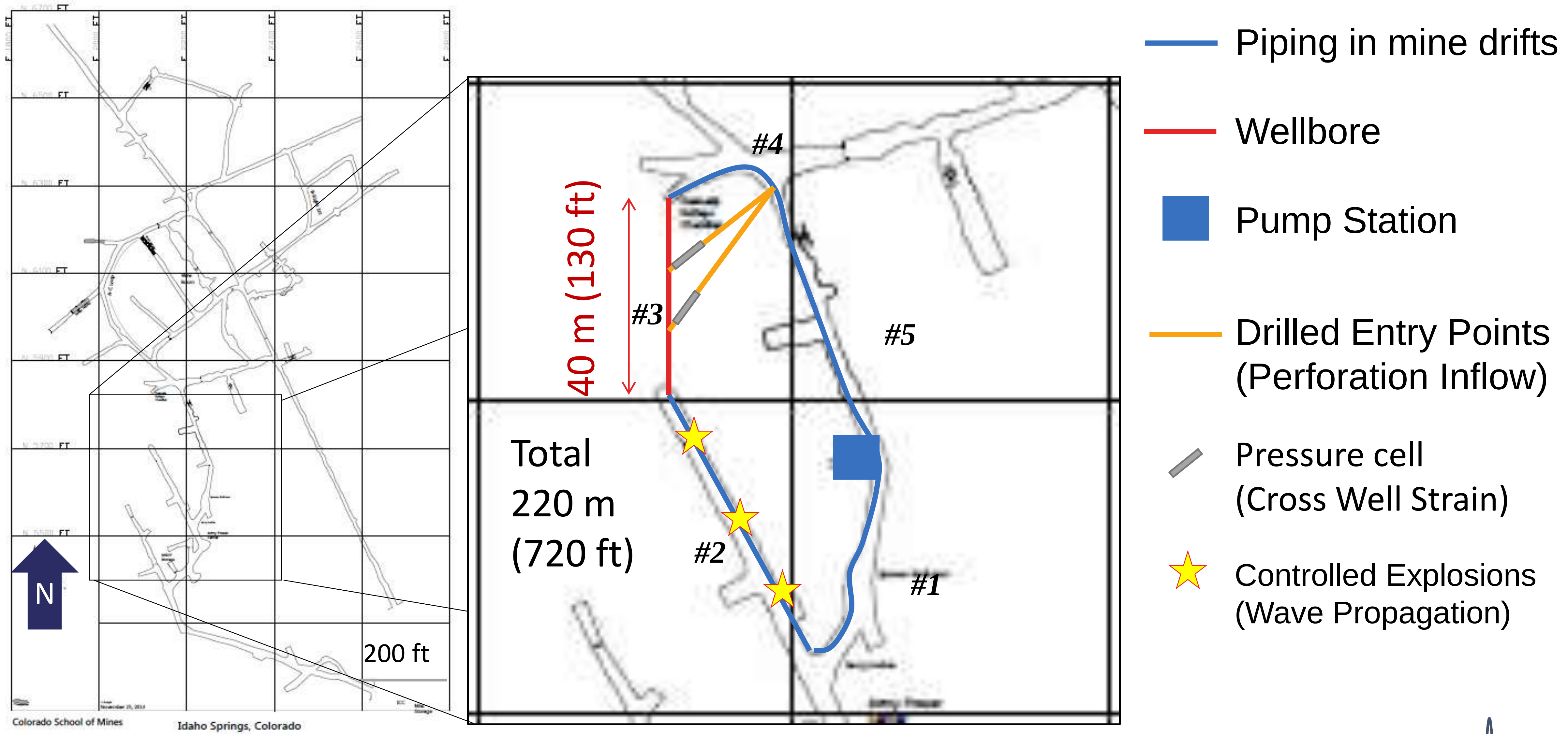
Lab Limitations
- Scale
- Environment
- Material

Edgar Mine Flow Loop
- Larger
- Quiet / Temperature Stable
- Real Cable / Casing / Rock

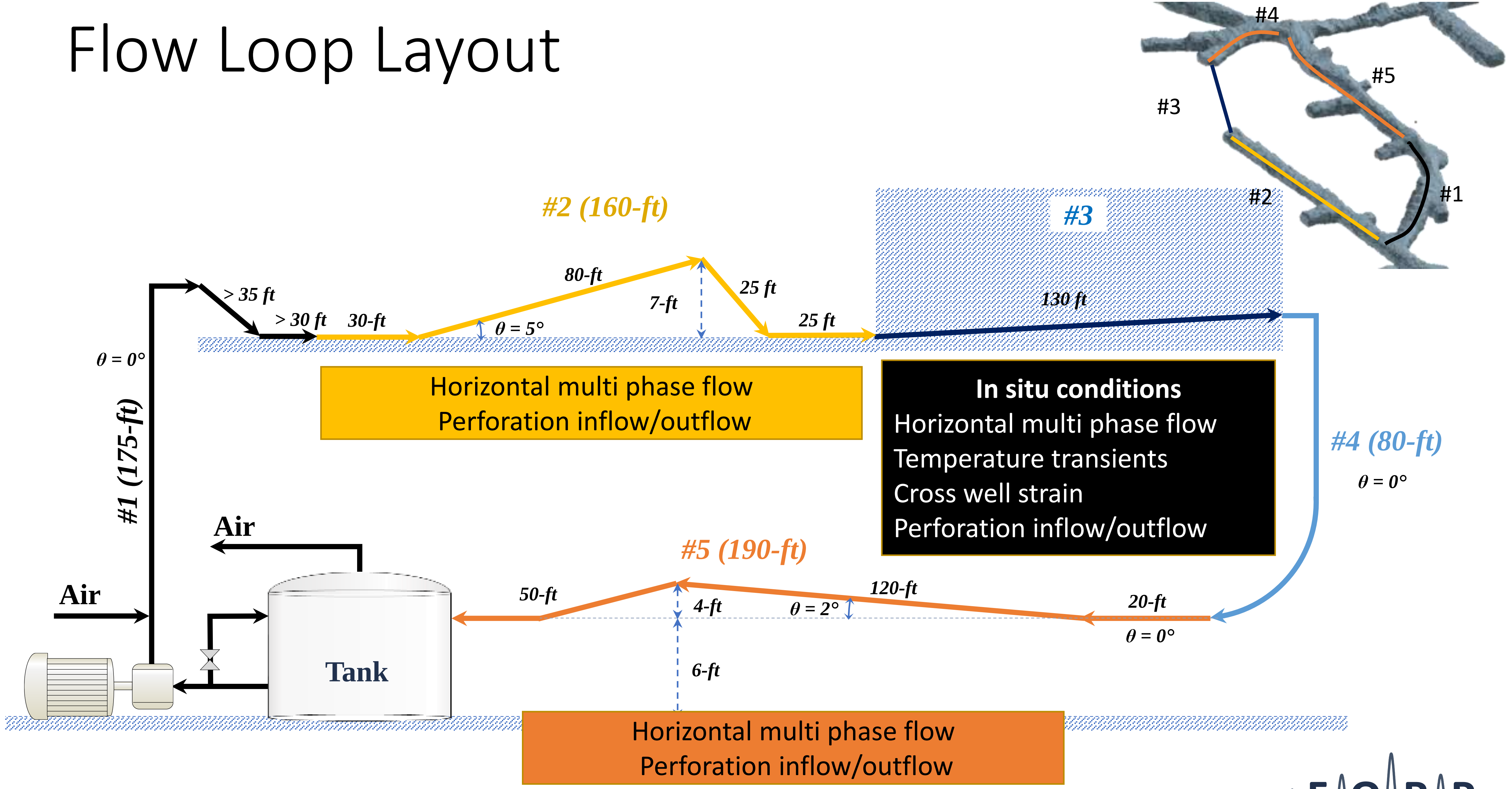
Improve Understanding Fluid Physics / Geomechanics Interacting with F.O. Sensing

Completions / Production / Characterization

Edgar Mine Flow Loop Layout



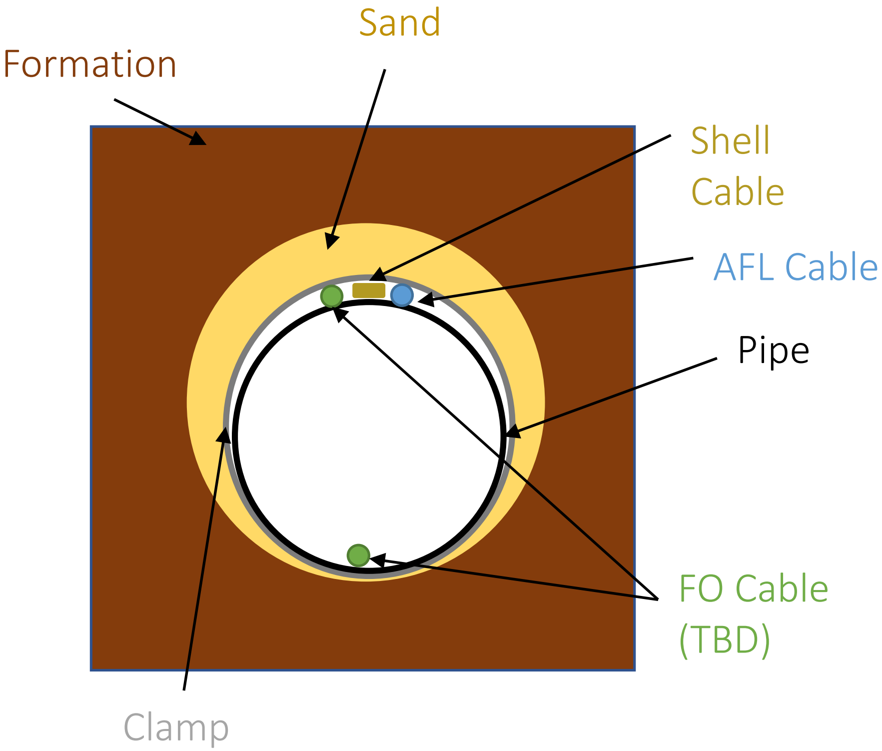
Flow Loop Layout



COLORADO SCHOOL OF MINES
EARTH • ENERGY • ENVIRONMENT

FORP
Fiber Optics Research Program

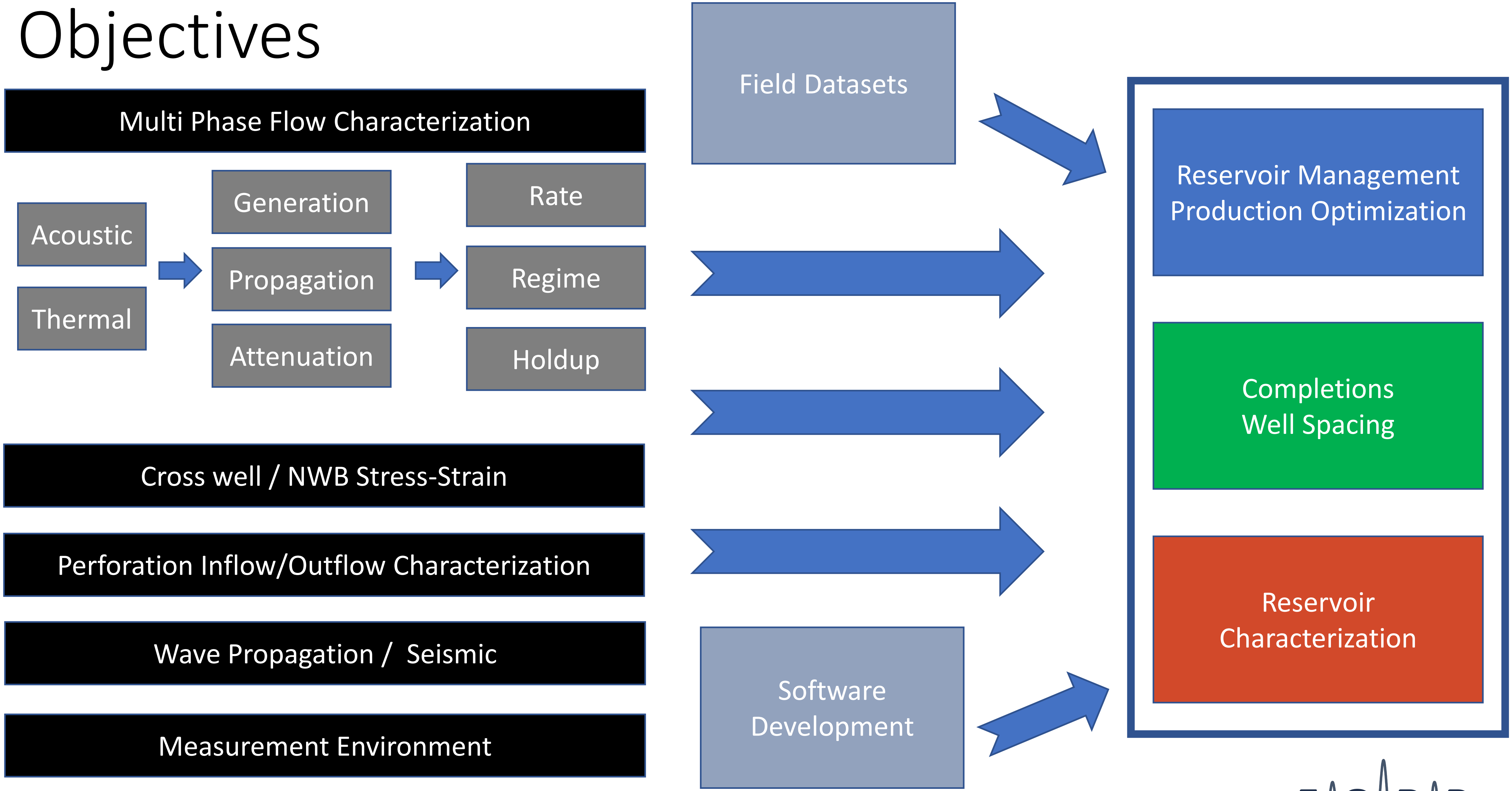
Cable Deployment



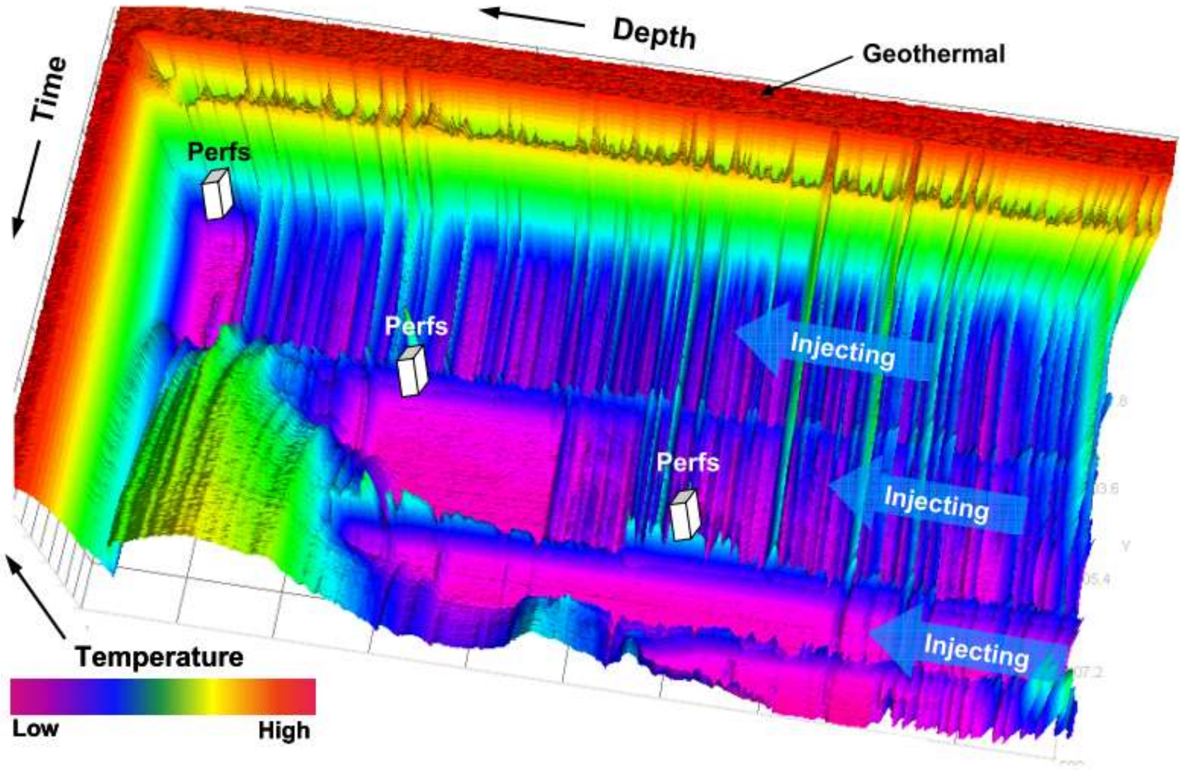
Current Status

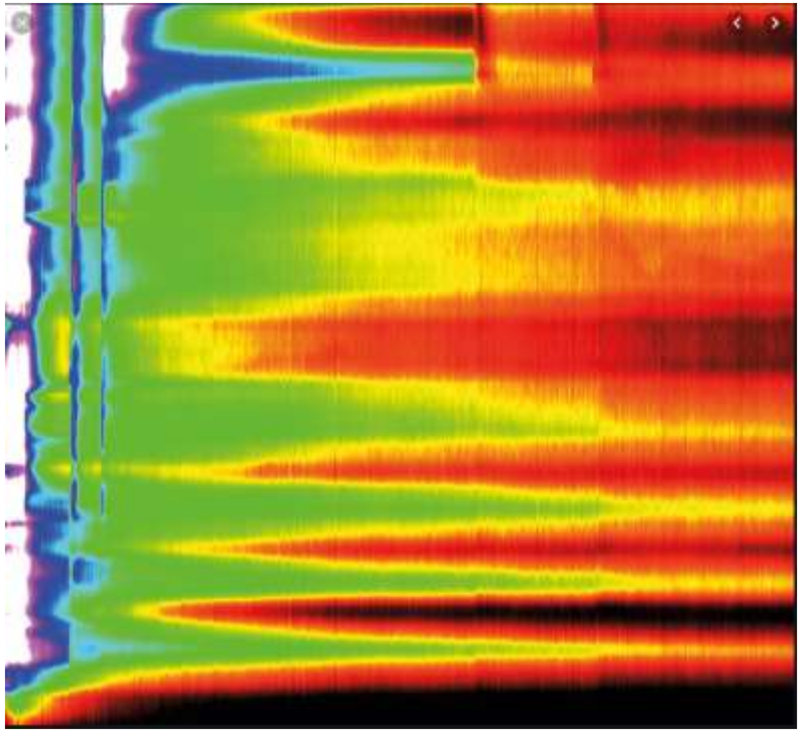
- 3” pilot hole is completed
- 6” back-reaming is in progress
  - Bit problems encountered
- 300’ of 4.5” casing ordered
- Compressor
  - Ingersoll Rand – 125 psi, 688 scfm
- Pump
  - AMT Self-Priming Pump
    50 GPM, 1HP, 93’ head

Objectives



Multi Phase Flow Characterization
Acoustic
Thermal
Generation
Propagation
Attenuation
Rate
Regime
Holdup
Cross well / NWB Stress-Strain
Perforation Inflow/Outflow Characterization
Wave Propagation / Seismic
Measurement Environment
Field Datasets
Software Development
Reservoir Management
Production Optimization
Completions
Well Spacing
Reservoir Characterization



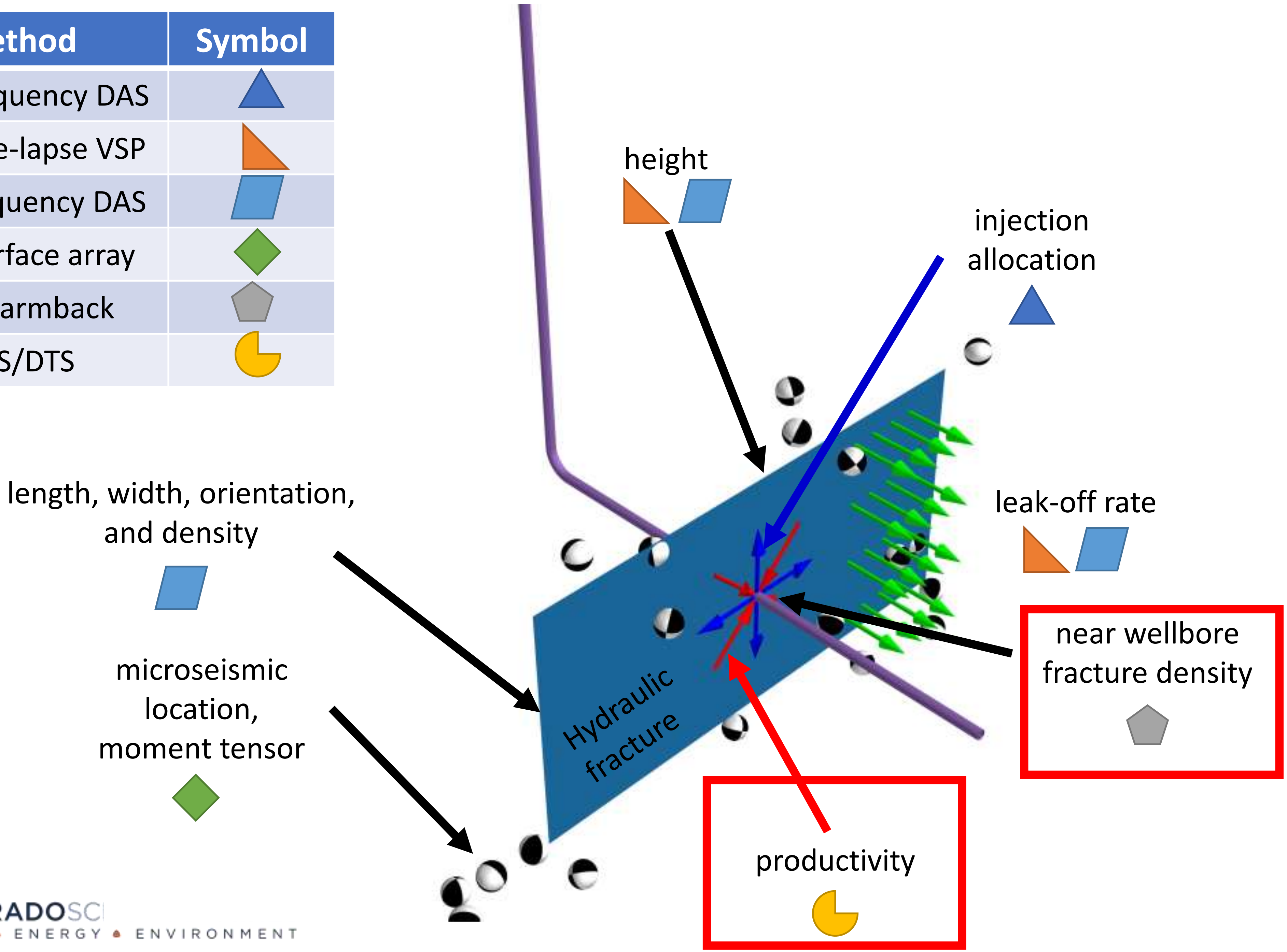


(Sierra et.al., 2008)

DTS Modeling

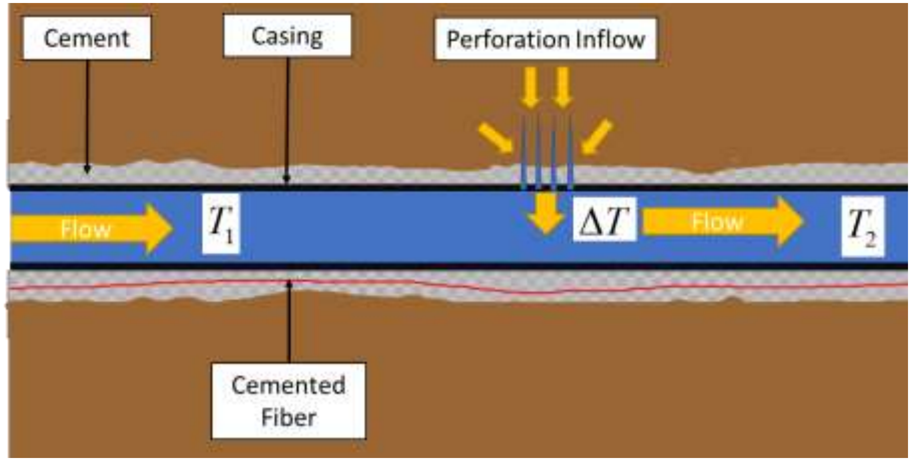
(Raterman et al. 2019)

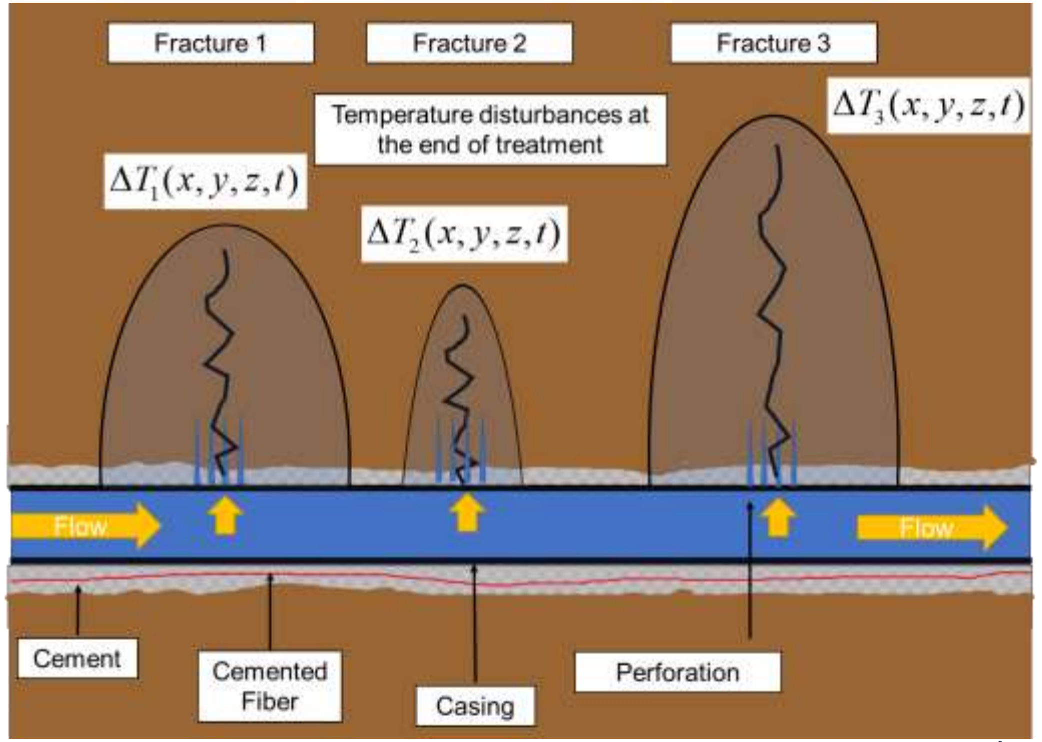
Method	Symbol
High-frequency DAS	
DAS time-lapse VSP	
Low-frequency DAS	
DAS/surface array	
DTS warmback	
DAS/DTS	



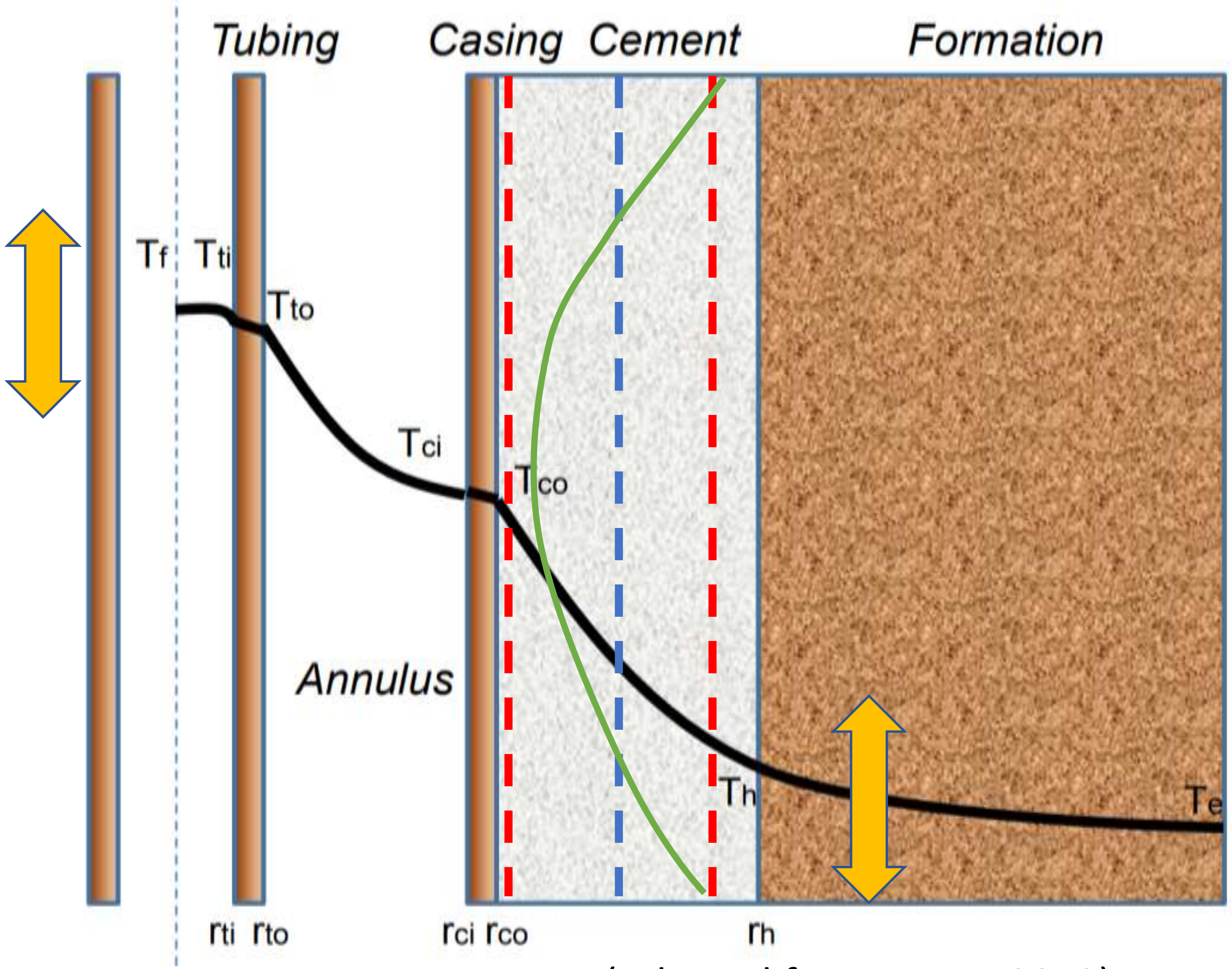
Motivation

- Production
  - Varying formation/inflow temperature
  - Joule-Thompson effects
- Completions
  - NWB Fracture Characterization
  - Cluster efficiency
- Cement Integrity
- Response is a function of:
  - Cable location
  - Location/magnitude/duration of heat anomaly





NWB Temperature in Relation to Fiber



(Adapted from Wang, 2012)

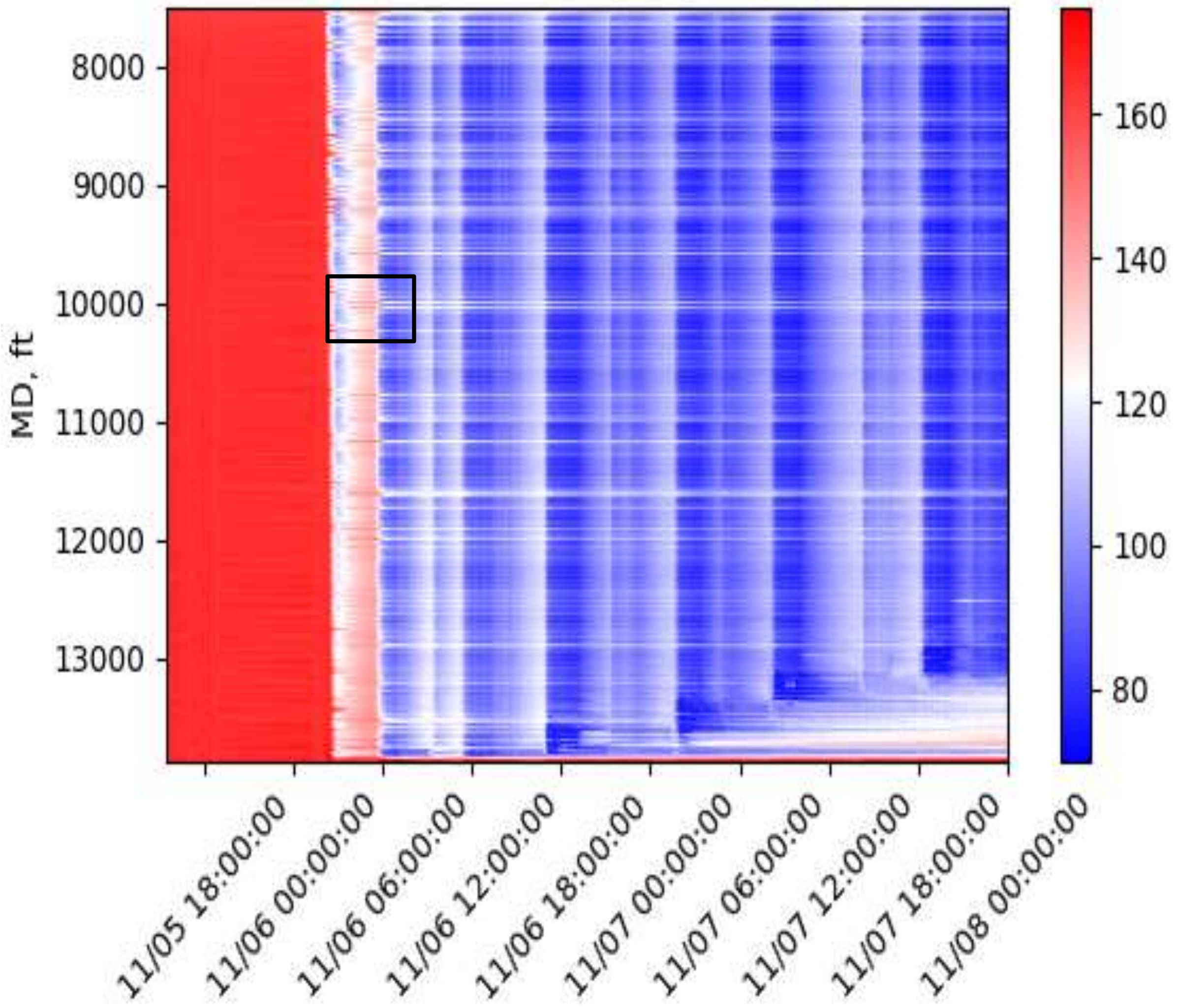
Idealized fiber location

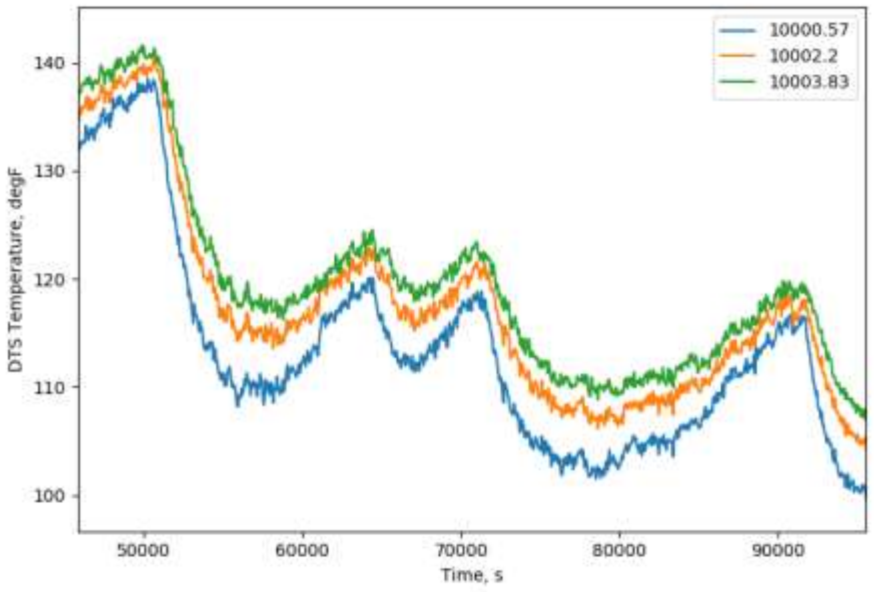
Possible fiber location

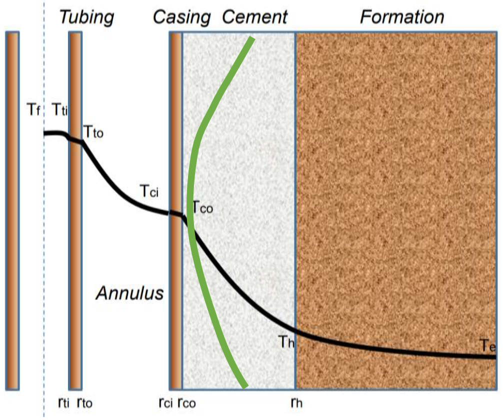
Error in inverted temperature

Realistic fiber location

NWB Temperature in Relation to Fiber







(http://mseel.org/research/research.html)

DTS Warmback Modeling

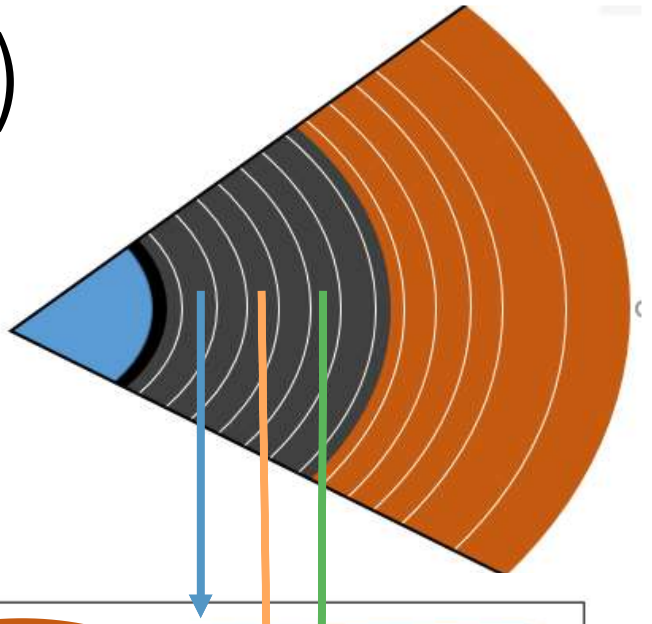
- Simple, 1D, conduction only model
- Determine temperature response of different points within the cement
- Locate the cable, filter the location effect out
- Lay the groundwork for 2D, 3D NWB temperature inversion

(http://mseel.org/research/research.html)

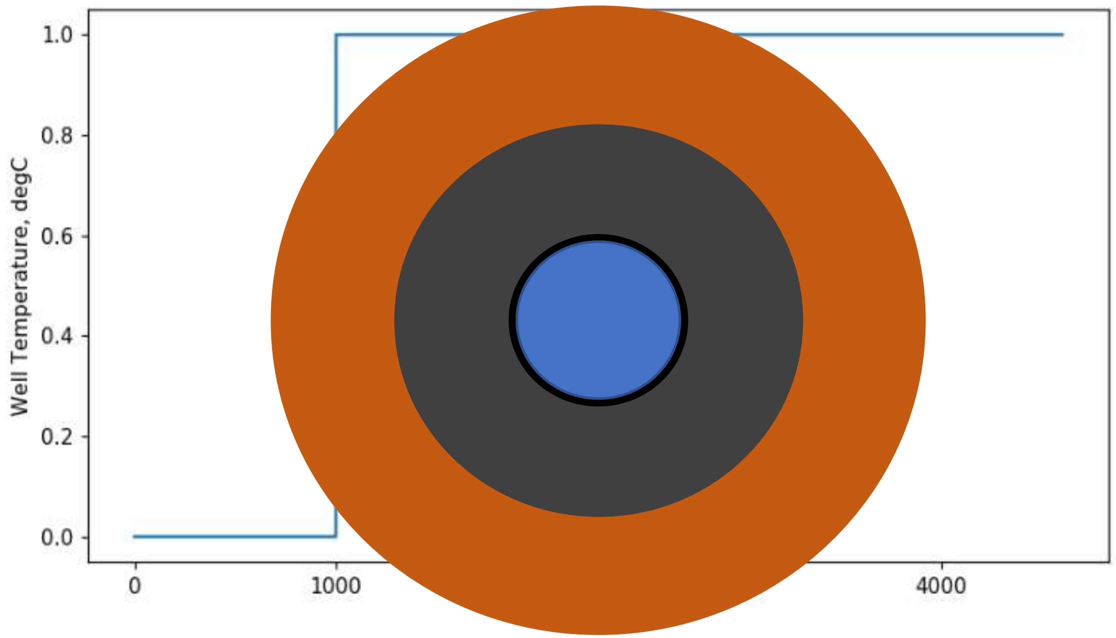
DTS Warmback Modeling (Workflow)

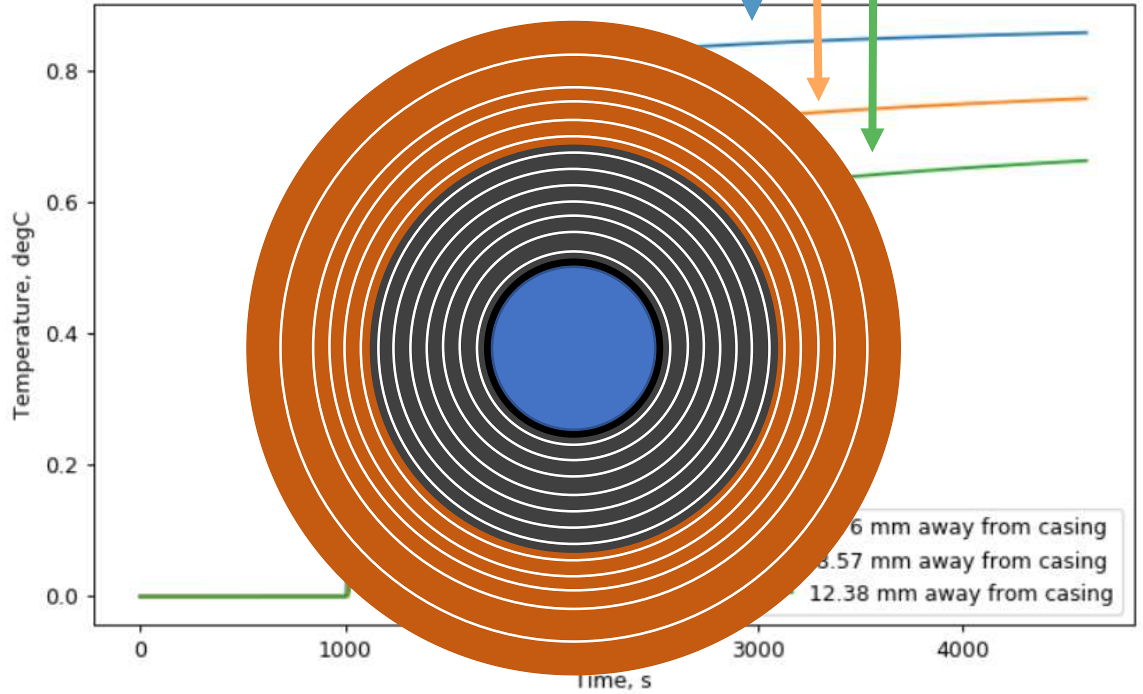
- 1D – Radial Conduction

$$\rho C_p \frac{\partial T}{\partial t} = \frac{1}{r}\frac{\partial}{\partial r}\left(Kr\frac{\partial T}{\partial r}\right)$$



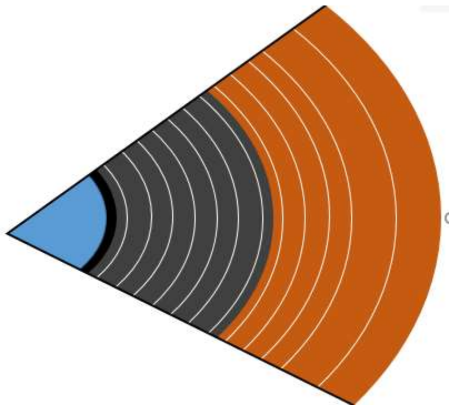
Wellbore Fluid (B.C.) → Casing Steel (0.205") 5 grids → Cement (0.75") 10 grids → Formation (300 ft) 86 grids

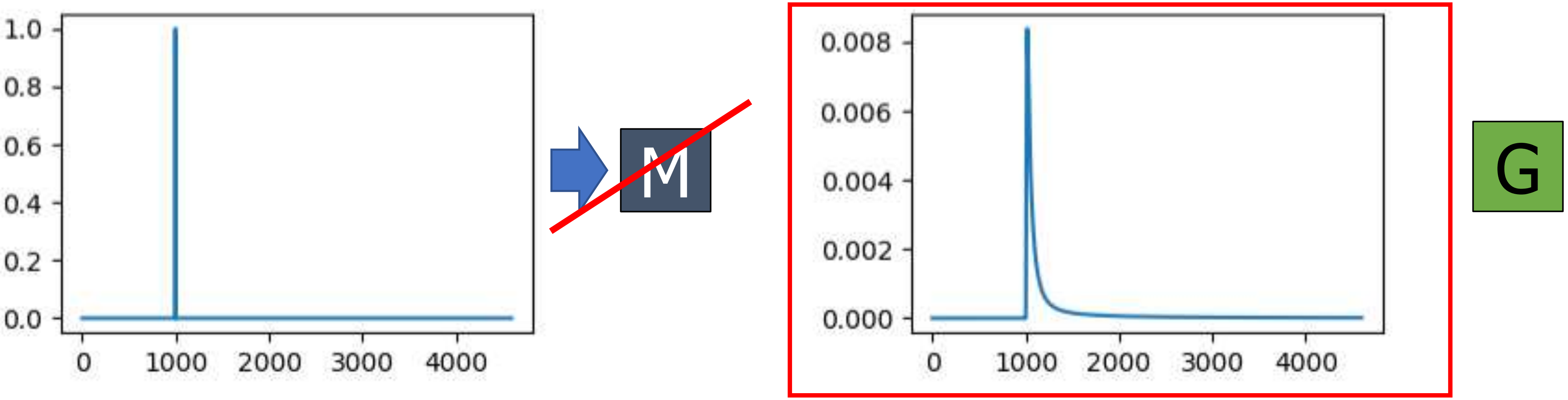




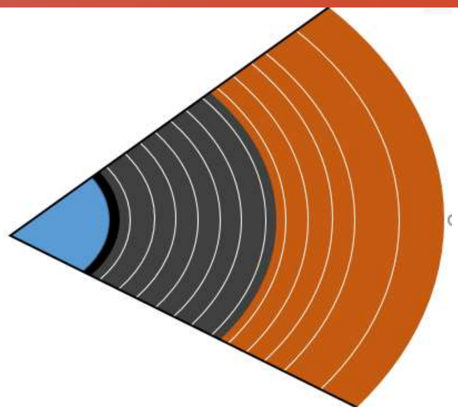
DTS Warmback Modeling (Workflow)

- Numerically extract Green's functions for the entire system

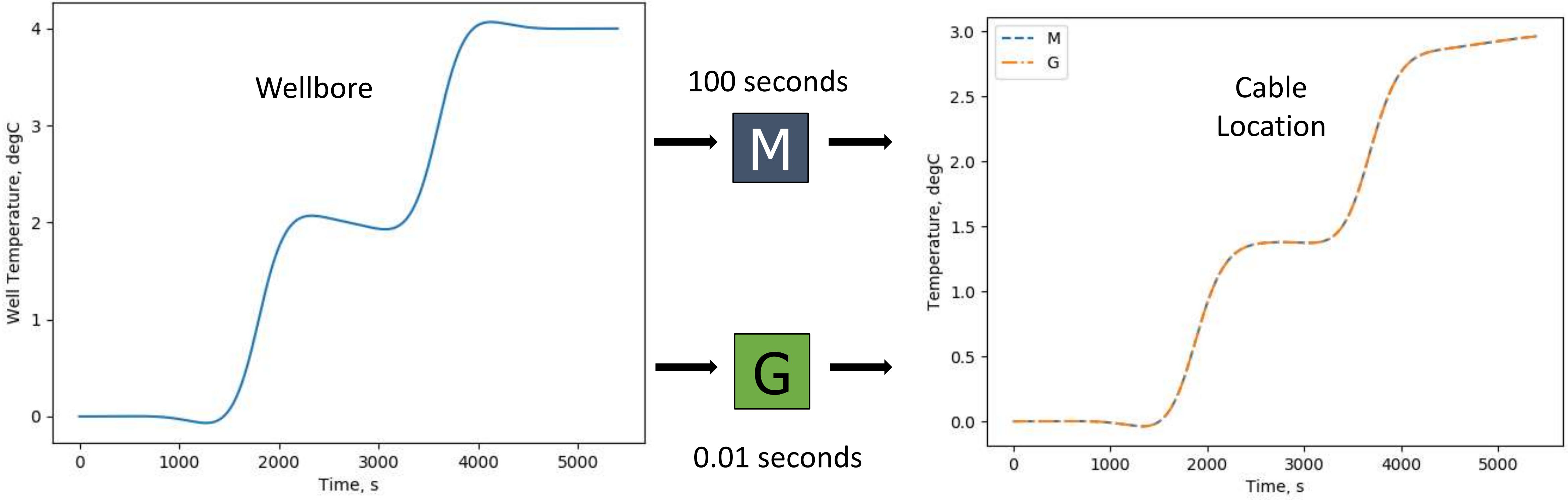




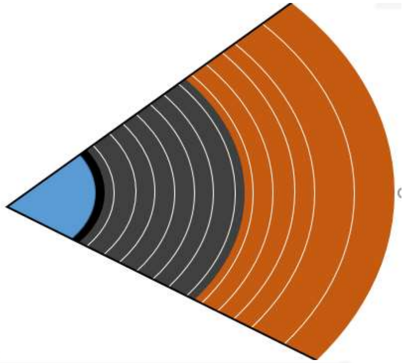
DTS Warmback Modeling (Workflow)



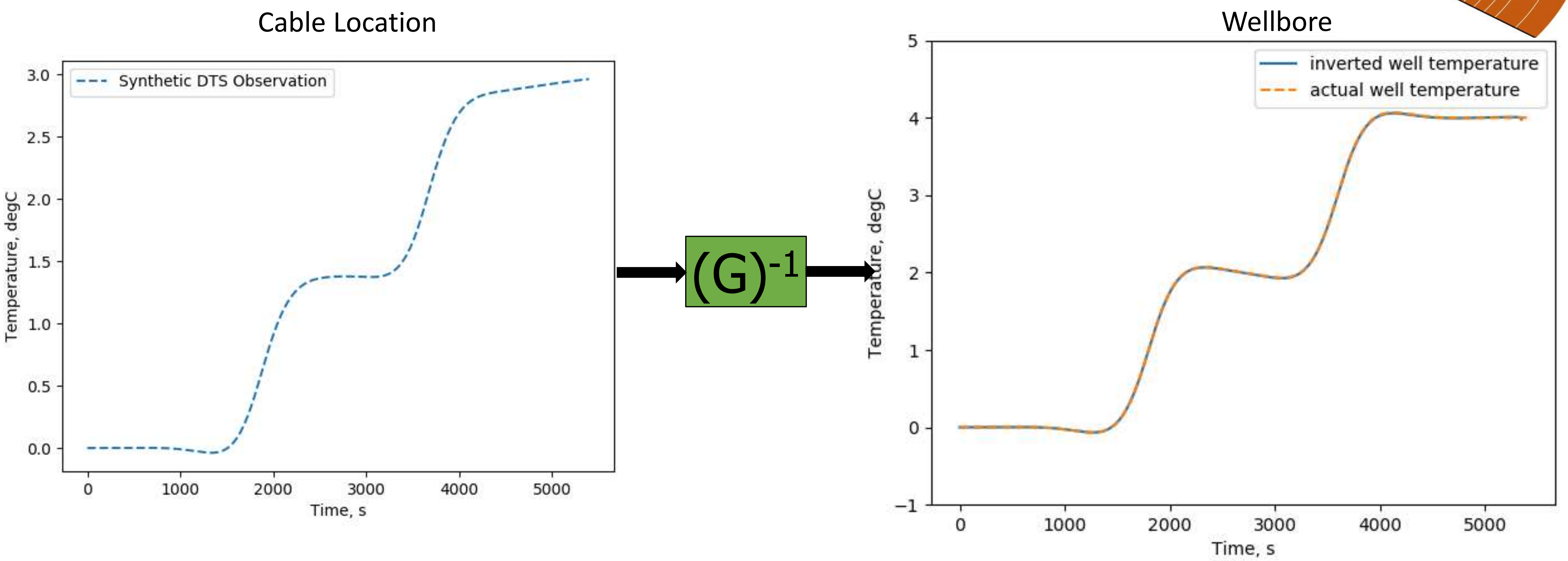
- Model results can be replicated via convolution
- Numerically much faster



DTS Warmback Modeling (Workflow)



- Inversion for the wellbore temperature



Future Work

- Fiber location mapping (1D Model)
  - Filter the cable effect out
- Production logging modeling (Wellbore model)
- Temperature Tomography (2D and 3D models)
  - NWB Fracture density
- Cement setting and integrity
- Applications on field data

Special thanks to OptaSense, Shell, Halliburton, and AFL for supporting the Fiber Optics Research Program

Thank you RCP industry sponsors: