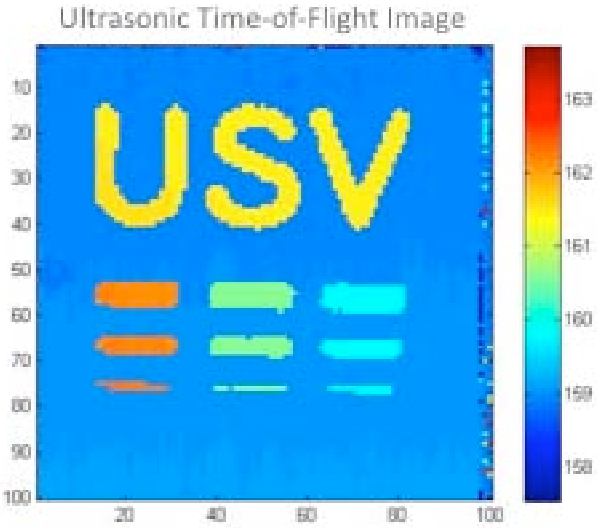
U.S. DEPARTMENT OF ENERGY | Energy Efficiency & Renewable Energy



Waveguide-based Ultrasonic and Far-field Electromagnetic Sensors for Downhole Reservoir Characterization

May 19, 2010

Shuh-Haw Sheen
Argonne National Laboratory

Chemistry, Reservoir and Integrated Models

Project Overview

U.S. DEPARTMENT OF ENERGY | Energy Efficiency & Renewable Energy

- Timeline
  - Project start date – November, 2009
  - Project end date – January, 2011
  - Percent complete – 40%
- Budget
  - Total project funding – $550K
  - Received in FY09 – $330K
  - Received in FY10 – $220K
- Barriers – None
- Partners – None

Relevance/Impact of Research

- **Objective** – To develop waveguide-based ultrasonic and far-field electromagnetic sensors to measure key Enhanced Geothermal Systems (EGS) reservoir parameters, including directional temperature, pressure, fluid flow, fracture imaging, and flow/rock interaction.

- **Impact** – The proposed sensors for reservoir characterization and flow measurement can improve the EGS performance.

Scientific/Technical Approach

- Proposed first-year tasks:
  - *Task 1: Knowledge capture*
  - Task 2: Development and evaluation of microwave (MW) radiometer
  - Task 3: Development and evaluation of ultrasonic waveguide (UW) sensors (temperature profile, flow instrument)
  - Task 4: Construction of a bench-top hot-rock test facility
  - Task 5: Annual report
- Milestone:

  A go/no-go decision will be made on 09/30/2010

Accomplishments, Expected Outcomes and Progress

- Completed the knowledge-capture report that surveys logging tools and measurement techniques being used in gas/oil and geothermal wells and identifies the measurement needs for enhanced geothermal systems.
- Completed antenna design evaluation, helix and spiral antenna designs operating in 10 -100 MHz are proposed.
- Completed design and tests of ultrasonic time-of-flight (TOF) probes for temperature profile measurement.
- Completed ultrasonic waveguide design evaluation.

Project Plan and Schedule

- Project management plan: Three-phase work plan
  - Phase I: Development of microwave radiometer and ultrasonic waveguide sensors.
  - Phase II: Laboratory prototype development and evaluation.
  - Phase III: Field prototype development and field tests.

1st-year Schedule:

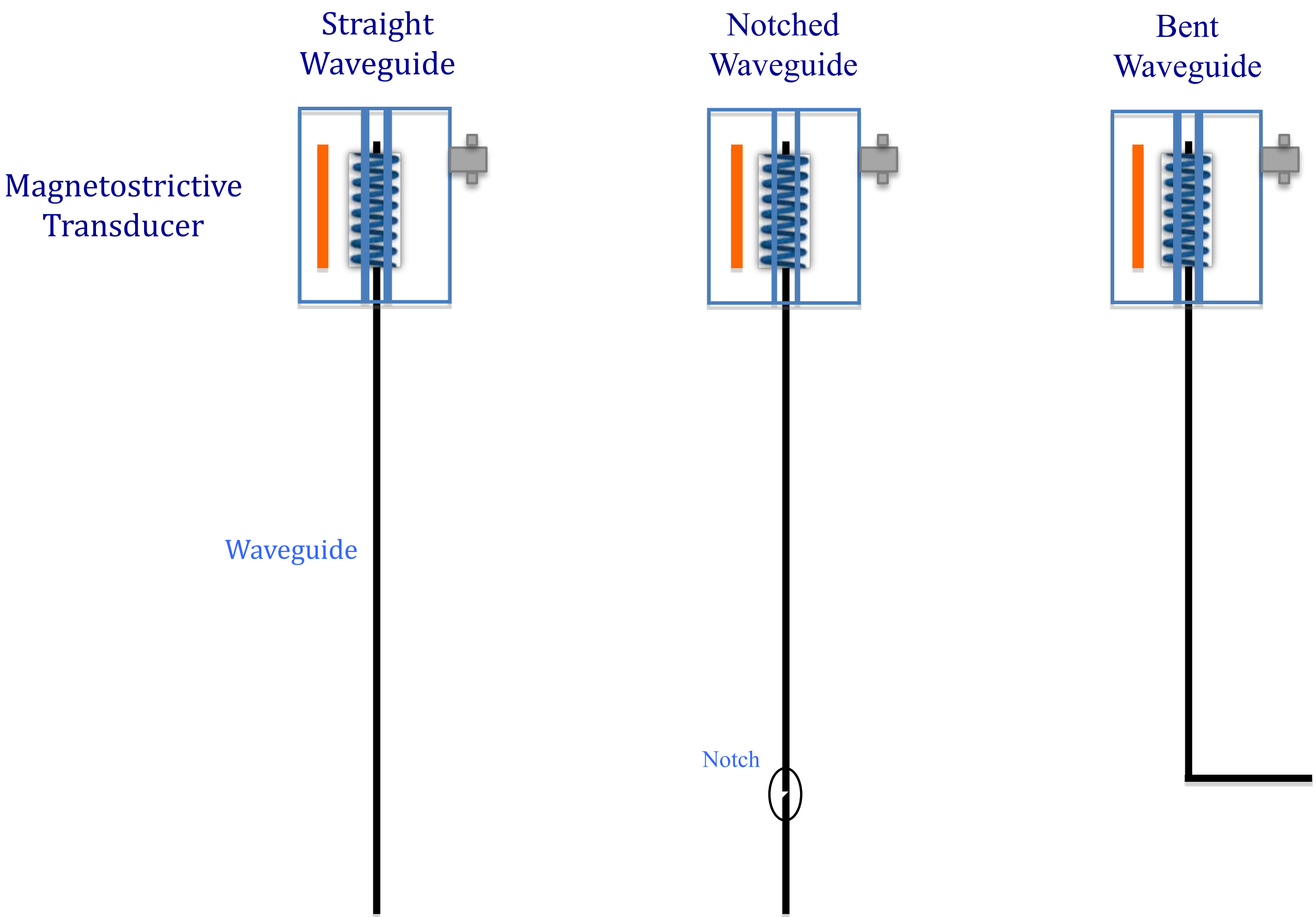
Task	FY2010			
	Q1	Q2	Q3	Q4
1	→	→		
2			→	→
3			→	→
4				→
5				→

Future Directions

U.S. DEPARTMENT OF ENERGY | Energy Efficiency & Renewable Energy

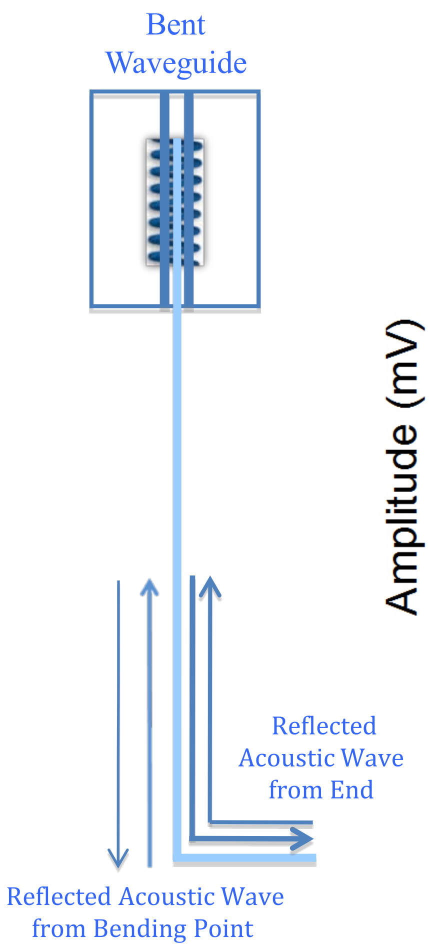
- Complete development of
  - Microwave radiometer (FY2010)
  - Ultrasonic temperature-profile probe (FY2010)
  - Microwave pressure sensor (Future proposed work)
  - Ultrasonic flow enthalpy sensor
    - Flow measurement (FY2010)
    - Enthalpy sensor (Future proposed work)
  - Passive acoustic sensor for flow/rock interaction (FY2010 – feasibility study)
  - Ultrasonic waveguide sensor for fracture imaging (Future proposed work)
- Complete a bench-top hot-rock test facility for sensor evaluation and demonstration (FY2010)

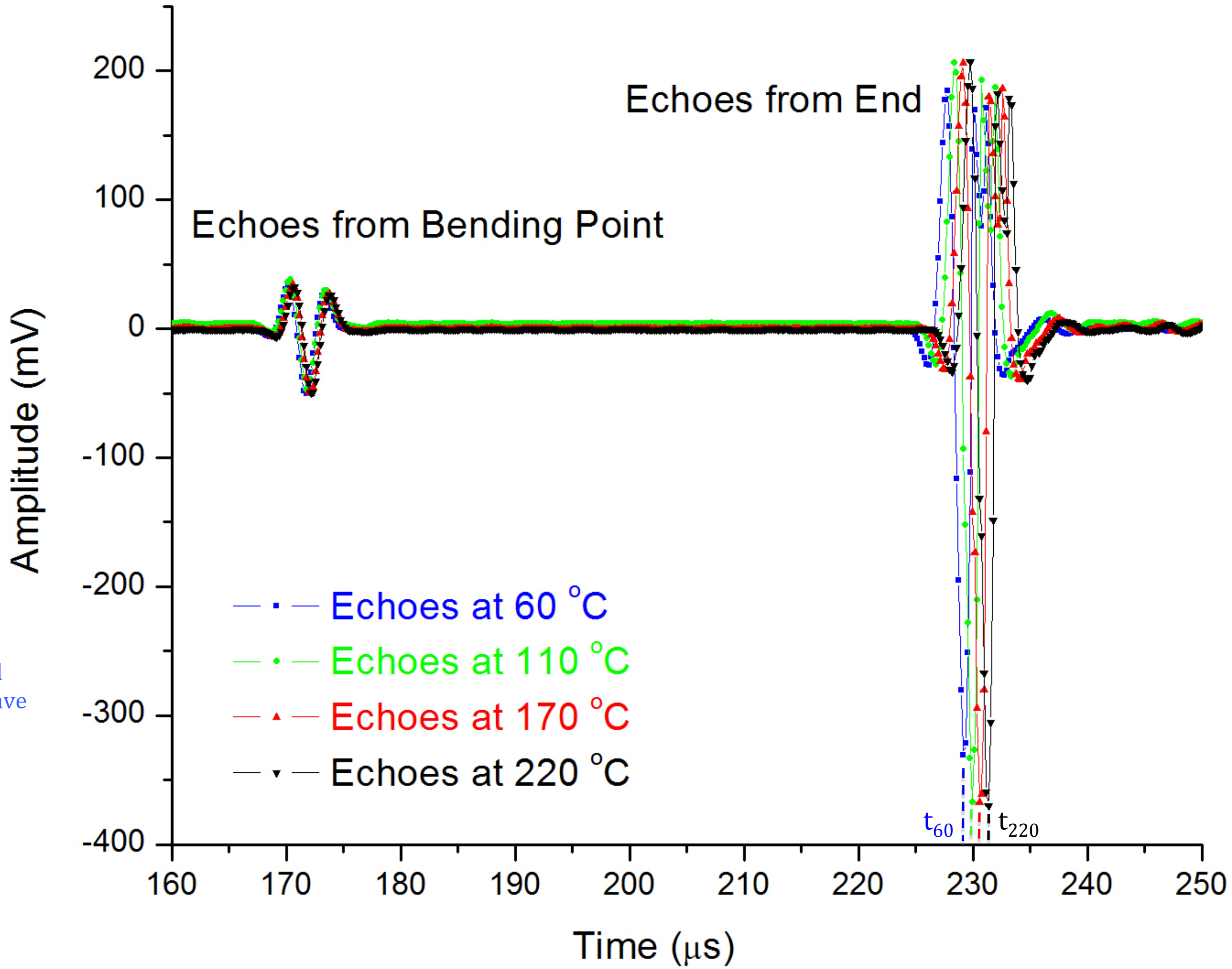
Ultrasonic Waveguide Designs for Temperature Profile Measurement



Temperature Measurement Using Bent Waveguide

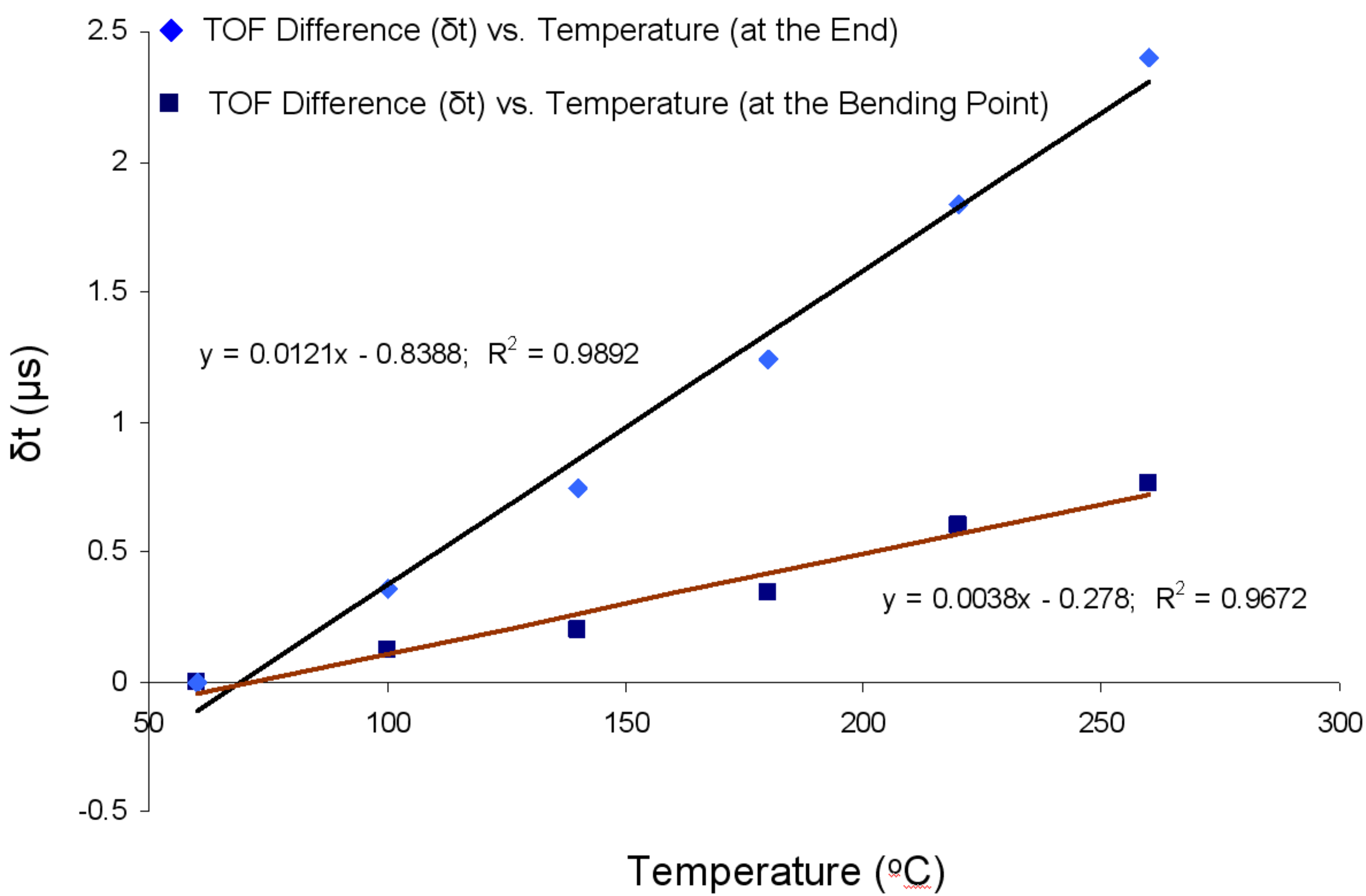
U.S. DEPARTMENT OF ENERGY | Energy Efficiency & Renewable Energy





TOF Changes of Bent Waveguide

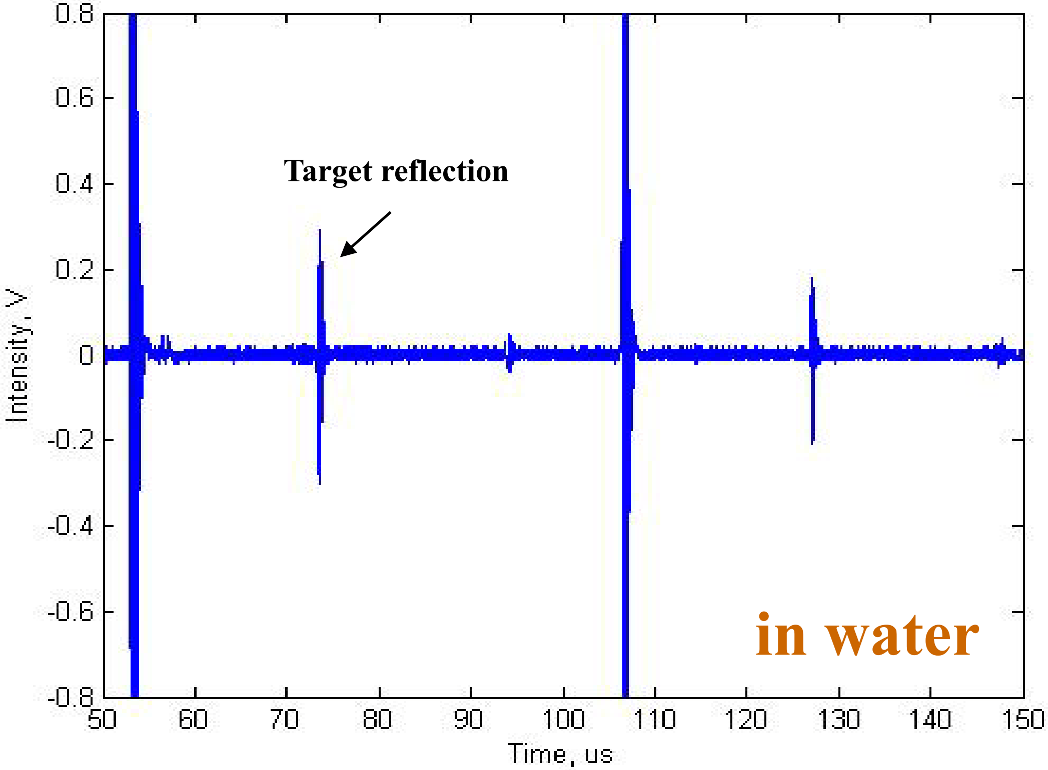
U.S. DEPARTMENT OF ENERGY | Energy Efficiency & Renewable Energy

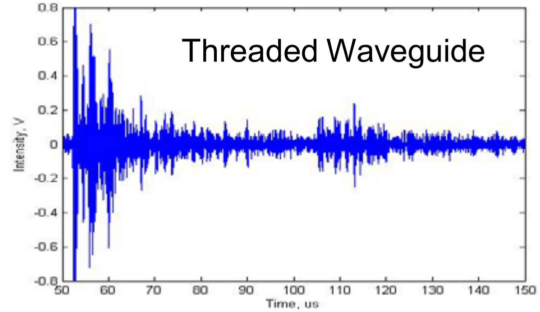


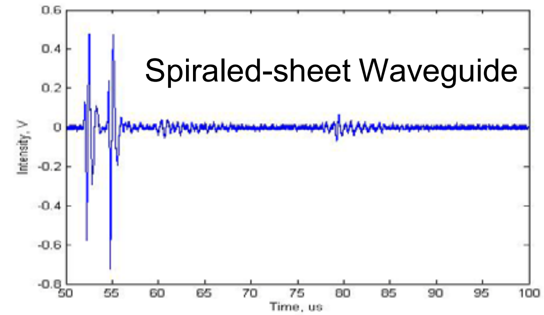
Waveguide Design Evaluation

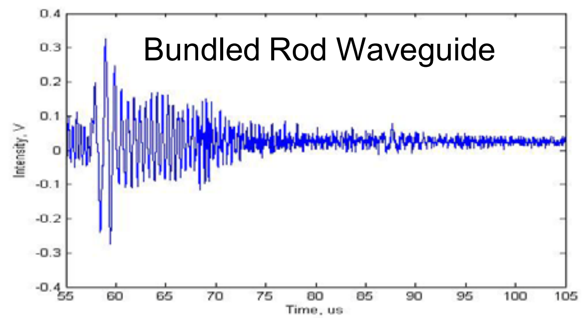
U.S. DEPARTMENT OF ENERGY | Energy Efficiency & Renewable Energy

Bundled-rod with Spiraled-Sheet Waveguide
(d = 0.5", l = 5.75")









Geothermal Passive MW Sensing Principle

Black-body Radiation (Planck's formula)

$$B(T) = \frac{2h\nu^3}{c^2}\frac{1}{e^{\frac{h\nu}{kT}} - 1} \sim \frac{2kT}{\lambda^2}$$

- ν Frequency
- T Temperature
- h Planck's Constant
- k Boltzmann's Constant

Antenna Effective Area and Received Power

$$A_{antenna} = \frac{\lambda^2}{4\pi}G \Rightarrow P_{received} = B(T)A_{antenna}B \propto kTGB$$

- λ Wavelength
- G Gain
- B pre-detection bandwidth
- τ post-detection integration time

Signal to Noise Ratio (SNR) vs. Antenna Bandwidth B

$$SNR \equiv \frac{P_{received}}{P_{noise}} \propto \frac{kTGB}{\frac{1}{\sqrt{\tau}}} = kT\left[GB\sqrt{\tau}\right]$$

High Gain !
Wide Bandwidth!

MW Antennas for Passive Underground Geothermal Sensing from 10 MHz to 200 MHz

U.S. DEPARTMENT OF ENERGY | Energy Efficiency & Renewable Energy

Helix Antenna

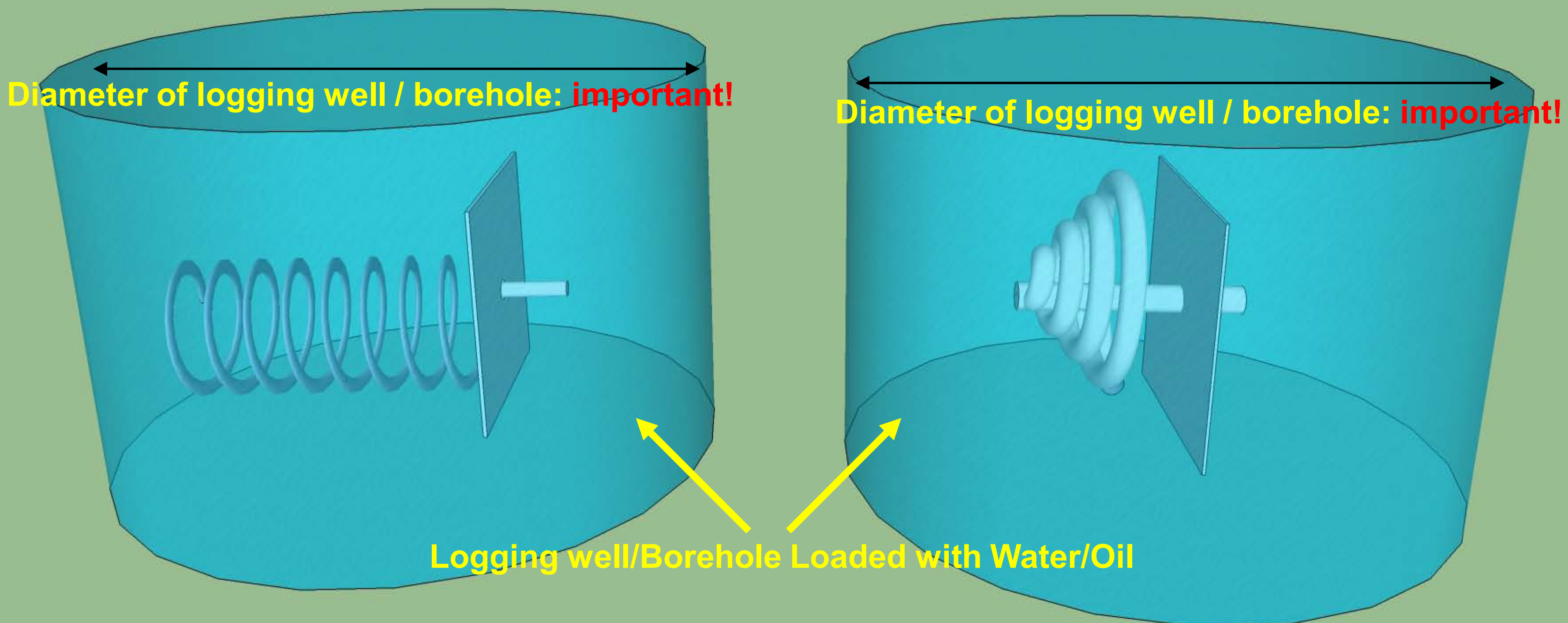
Pros: High gain (>10) and wide bandwidth: ~50%

Cons: Larger size compared with conical spiral antenna

Conical Spiral Antenna

Pros: Compact size and ultra-wide bandwidth: ~150%

Cons: Low gain (<10)



Water/Oil (high dielectric constant) loaded antennas reducing the size to fit small dimension of logging well or borehole

Summary

- Ultrasonic waveguide sensors have been developed for high-temperature applications (>600^{O}F demonstrated).
- Ultrasonic temperature–profile probe with magnetostrictive transducer has been developed.
- Microwave radiometer with helix or spiral antenna operating at 10-100 MHz has been designed.
- The Team:
  - Dr. A. C. Raptis --- Project management
  - Dr. Shuh-Haw Sheen – Principal Investigator
  - Drs. H. T. Chien and K. Wang – Ultrasonic tasks
  - Drs. N Gopalsami, S. Bakhtiari, A. Heifetz, and Shaolin Liao – Microwave tasks
  - D. Miranda and X. Xu (Summer students)