Distributed fiber sensing systems for 3D combustion temperature field monitoring in coal-fired boilers using optically generated acoustic waves
(DE-FE0023031)

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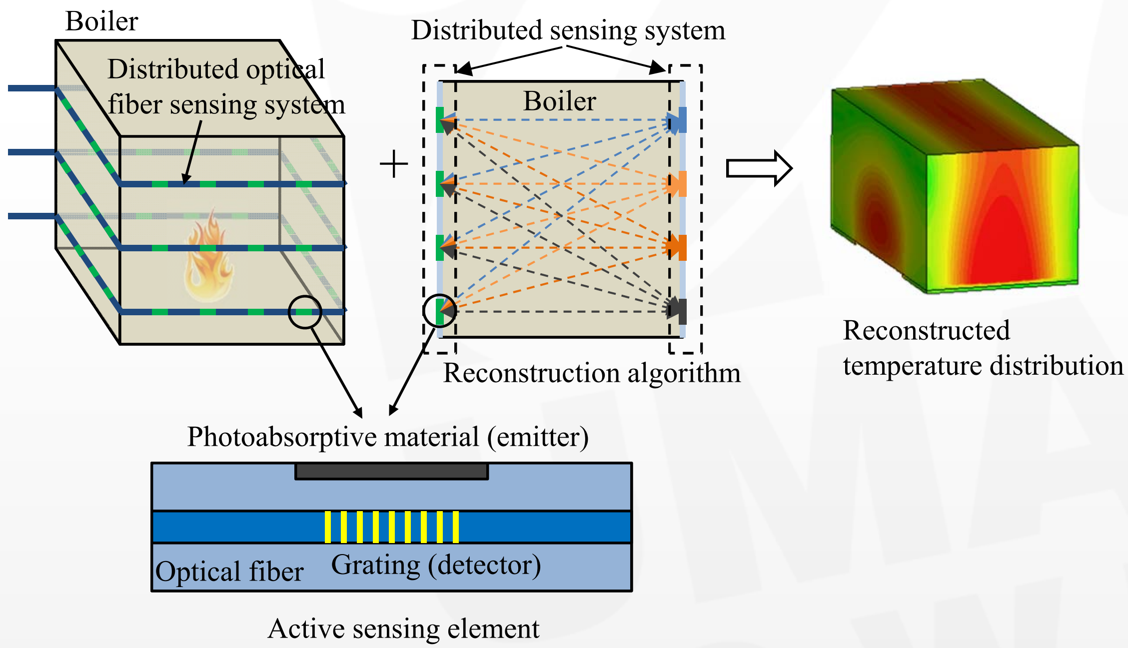
Outline

- Brief overview of DOE project
- Timeline and current status
- Experimental results
  1. Signal generator and receiver
  2. Water temperature measurement
  3. Steel plate temperature measurement
  4. Air temperature test and reconstruction
  5. Signal distance test
  6. Increase signal strength of generator
- Establish Simulation Model
- CDMA Modulation
- Temperature reconstruction algorithm with GRBF
- Future plan

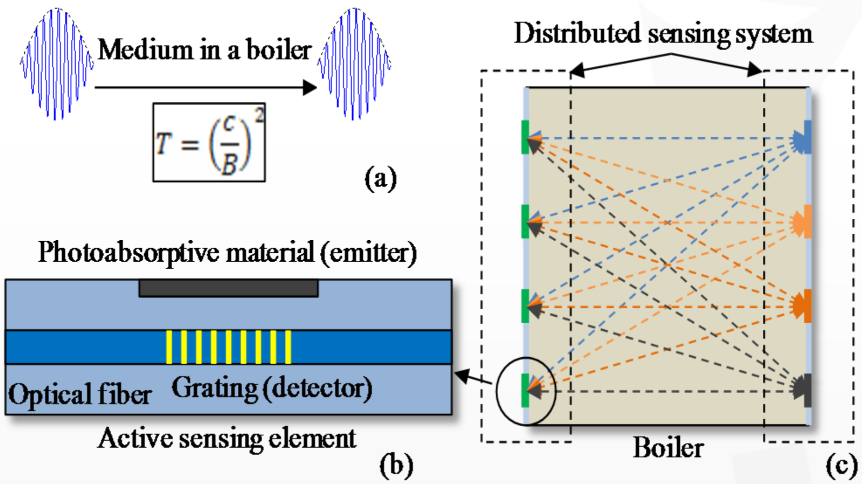
DOE project



Overview of DOE project.

- ❑ Reconstruct the 3D high temperature distribution within a boiler via a novel fiber optic distributed temperature sensing system using optically generated acoustic waves.

DOE project



Principle of DOE project.

- ❑ Speed of acoustic waves depend on the temperature of gaseous medium.
- ❑ The TOF (time-of-flight) of an acoustic signal over a propagation path can be calculated as:

$$TOF(l_j) = \int \frac{1}{C(x,y,z)} dl_j = \int \frac{1}{Z\sqrt{T(x,y,z)}} dl_j$$

$C(x,y,z)$ the velocity of sound at position (x,y,z)

z the ratio between the specific heats at constant pressure and volume of the gas

$d(x,y,z)$ the reciprocal of velocity

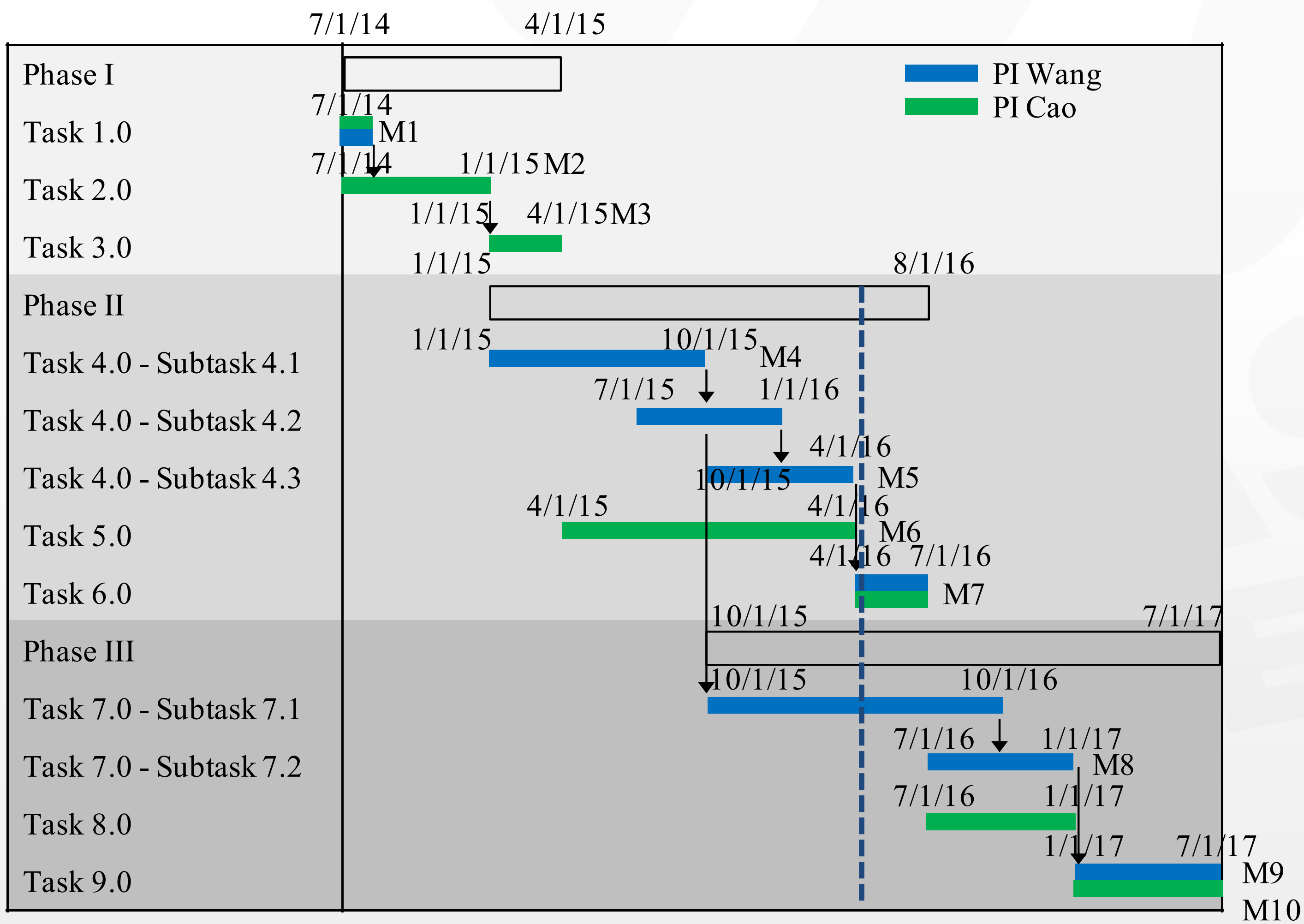
j the number of paths;

Timeline and current status

Table 1. Milestone Status Report

Milestone Title/ Description	Planned Completion Date	Actual Completion Date	Completion Percentage	Verification Method	Comments (Progress toward achieving milestone, explanation of deviation from plan, etc.)
M1/Develop Project Management Plan	July, 2014	July, 2014	100%	Plan Submission to DOE	This task is completed.
M2/ Establish a Simulation Model for Furnace Temperature Profile	January, 2015	January, 2015	100%	Simulation Program Files	This task is completed.
M3/Clarify Requirements for Distributed Sensing System Design	April, 2015	April, 2015	100%	Requirements Report	This task is completed.
M4/Develop Active Sensing Element	April, 2016	April, 2016	100%	Working Prototype	There is no variance from the original plan. All of the activities are progressing according to the original timeline.
M5/Characterize Distributed Sensing System I	April, 2016	April, 2016	100%	Working Prototype	There is no variance from the original plan. All of the activities are progressing according to the original timeline.
M6/Develop Reconstruction Algorithm	April, 2016	April, 2016	100%	2D and 3D simulations using Matlab	There is no variance from the original plan. All of the activities are progressing according to the original timeline.
M7/Field Test Distributed Sensing System I at Alstom	July, 2016		5%	Test Report	Plan the field test in April.
M8/Develop Distributed Sensing System II	January, 2017		0%	Working Prototype	Not started yet.
M9/Field Test Distributed Sensing System II at Alstom	May, 2017		0%	Test Report	Not started yet.
M10/Develop Final Report	June, 2017		0%	Deliver Final Report to DOE	Not started yet.

Timeline and current status

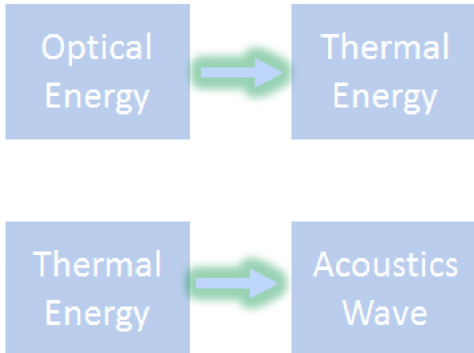


Project timeline (Gantt Chart).

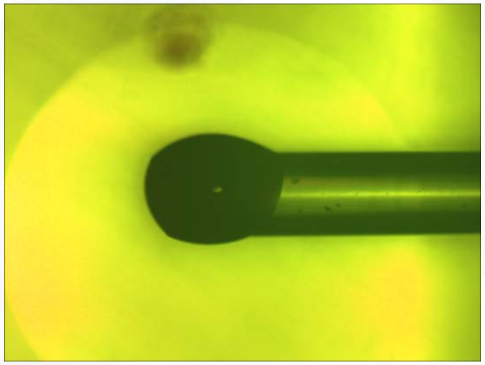
Learning with Purpose

Experimental results

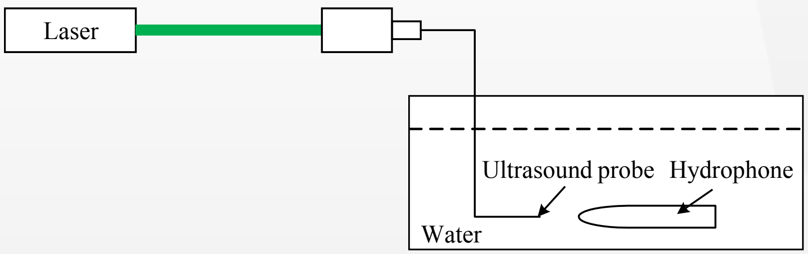
Signal generator (Fiber end)



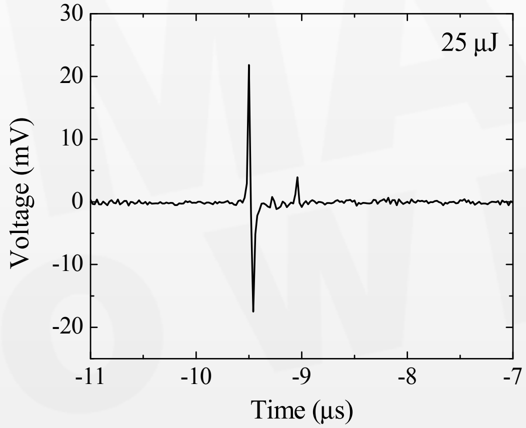
The photoacoustic principle [1].



The structure of the fiber optic ultrasound generator.



Experiment setup: test a fiber end generator.

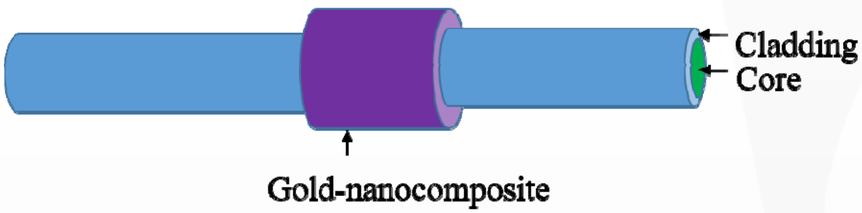


Profile of ultrasound signal [2].

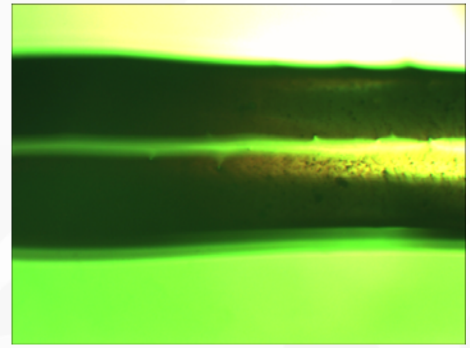
- Note: Gold-nanocomposite was coated on a 400μm fiber tip. A 532 nm Nd:YAG nanosecond laser (Surelite I-10, Continuum) was utilized as the source. A hydrophone (HGL-0200, Onda) was used as a receiver to collect the ultrasound signals.

Experimental results

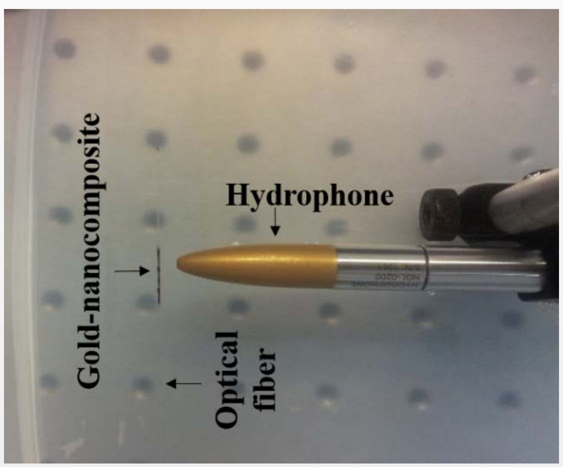
Signal generator (Sidewall configuration 1)



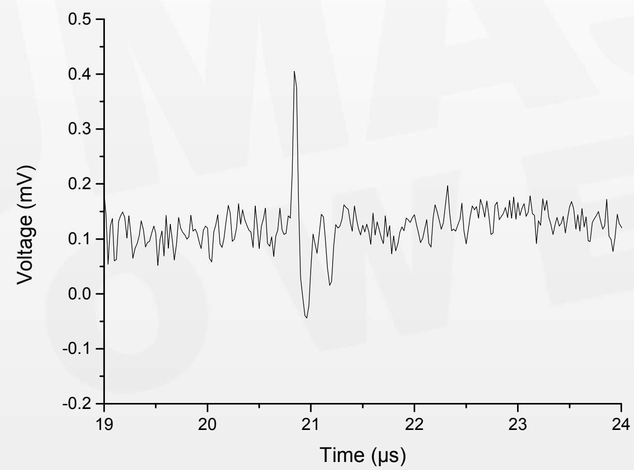
Coat gold nanocomposite on the sidewall of optical fibers[3].



Sidewall ultrasound generator configuration 1.



Experiment setup: test a sidewall generator.

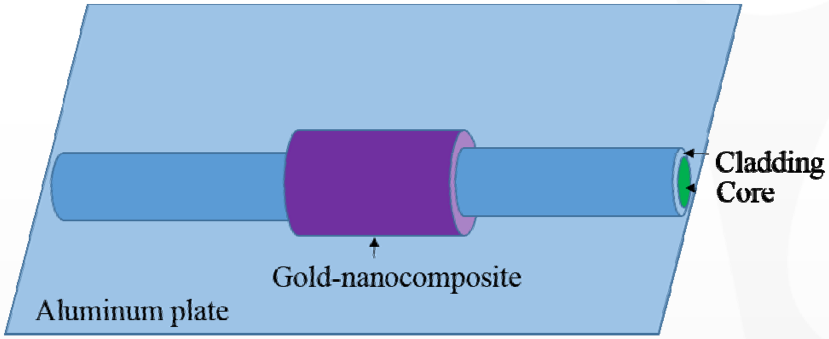


Acoustic signal generated from sidewall configuration 1.

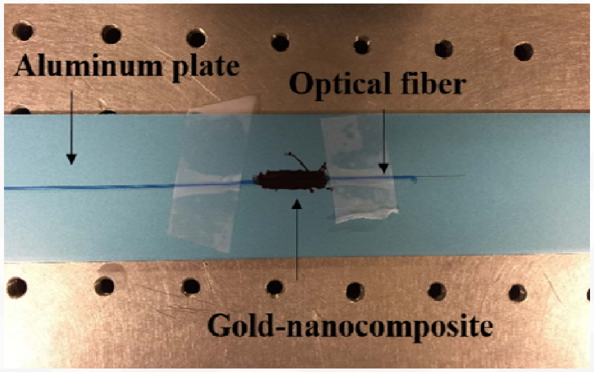
- Note: Generated ultrasound signal was from the sidewall of a 400μm fiber. A 532 nm Nd:YAG nanosecond laser (Surelite I-10, Continuum) was utilized as the optical radiation source. A hydrophone (HGL-0200, Onda) was used as a receiver to collect the ultrasound signals.

Experimental results

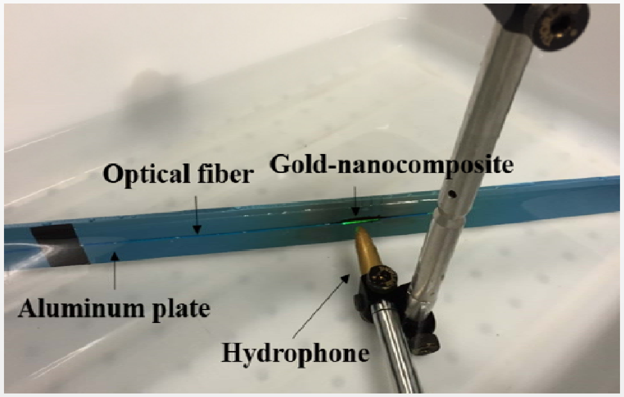
Signal generator (Sidewall configuration 2)



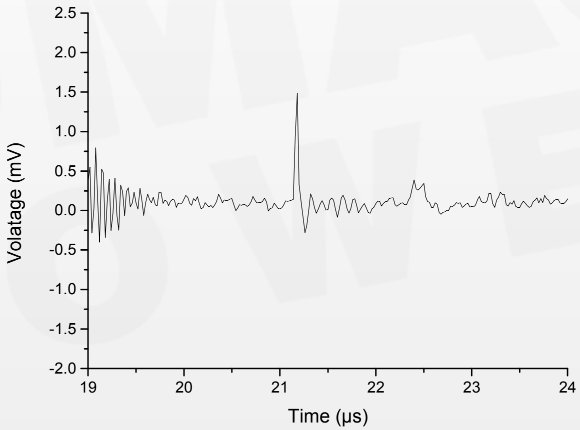
Sidewall fiber generator mounted on an aluminum plate [3].



Sidewall ultrasound generator configuration 2.



Experimental setup: test the sidewall ultrasound generator configuration 2.



Acoustic signal generated from sidewall ultrasound generator configuration 2.

- Note: Ultrasound signal generated from this configuration on the aluminum plate was much higher than pervious configuration when the laser power and detection distance is the same.

Experimental results

Signal receiver (Fiber Bragg Grating)

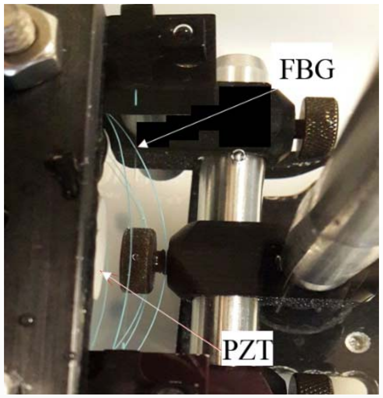


Photo of FBG test setup (FBG as the receiver)

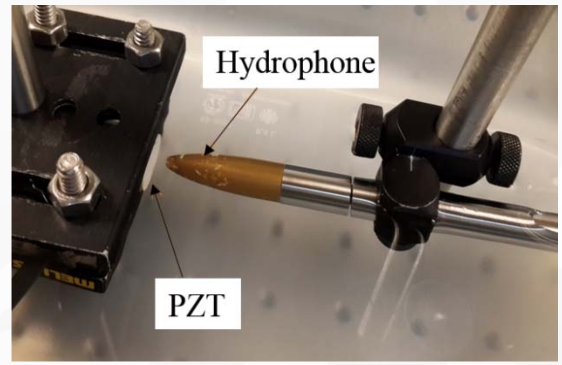
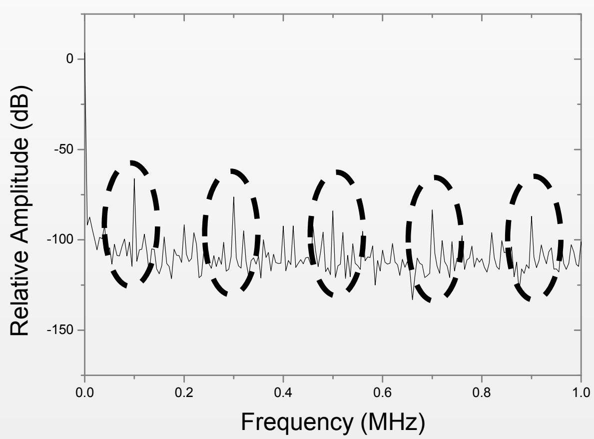
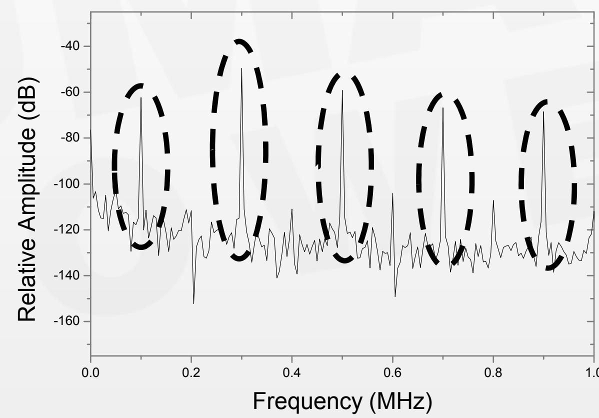


Photo of FBG test setup (Hydrophone as receiver)



The ultrasound signal received by FBG in frequency domain

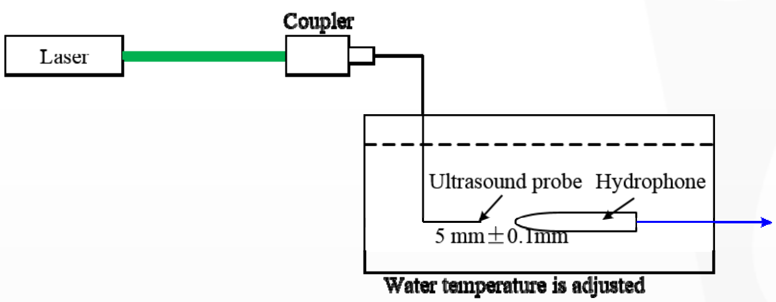


The ultrasound signal received by Hydrophone in frequency domain

- Note: FBG receiver got same results as hydrophone in frequency domain.

Experimental results

Water temperature measurement



Schematic diagram of the water temperature measurement setup [1].

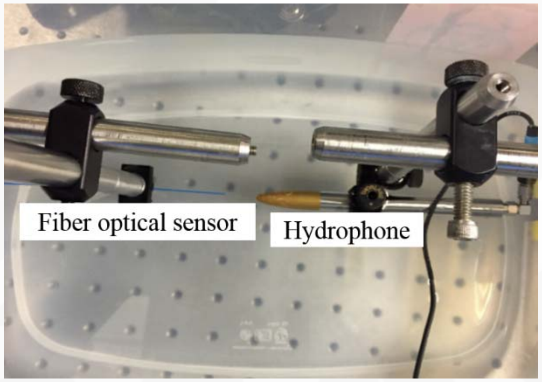
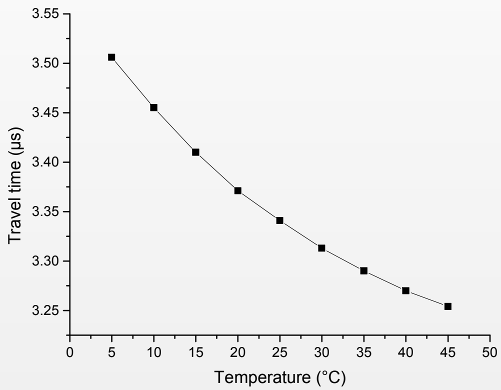
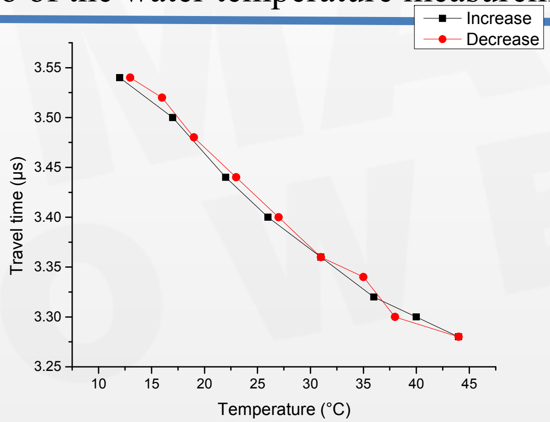


Photo of the water temperature measurement setup.



Travel time V.S. water temperature based on Marczak equation. (Range of validity: 0 - 95 ˚C at atmospheric pressure)



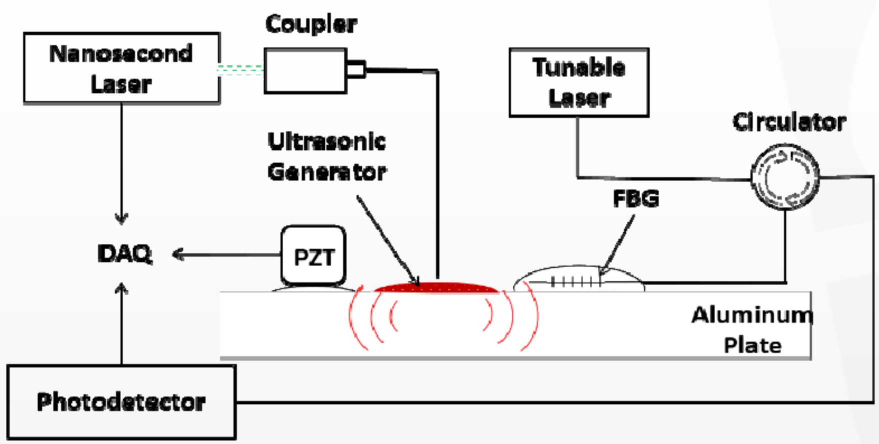
Experimental results: water temperature V.S. travel time

$$C = 1.402385 \times 10^{3} + 5.038813\,T - 5.799136 \times 10^{-2}\,T^{2} + 3.287156 \times 10^{-4}\,T^{3} - 1.398845 \times 10^{-6}\,T^{4} + 2.787860 \times 10^{-9}\,T^{5}$$

- Note: It demonstrated the temperature measurement capability of the fiber optic ultrasound transducer system.

Experimental results

Aluminum plate temperature measurement



Schematic diagram of steel plate temperature measurement [4].

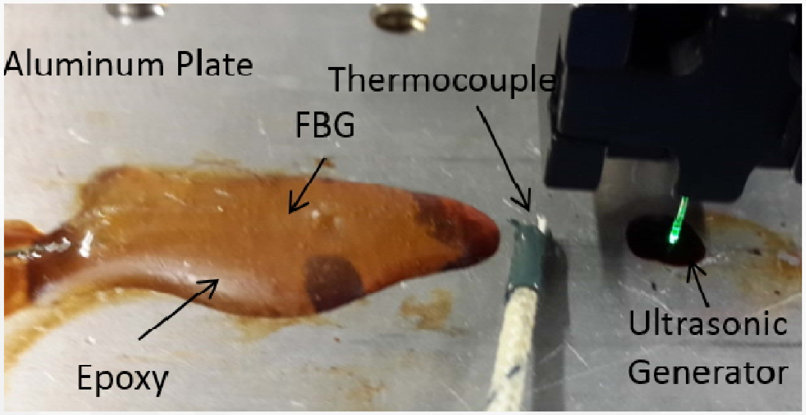
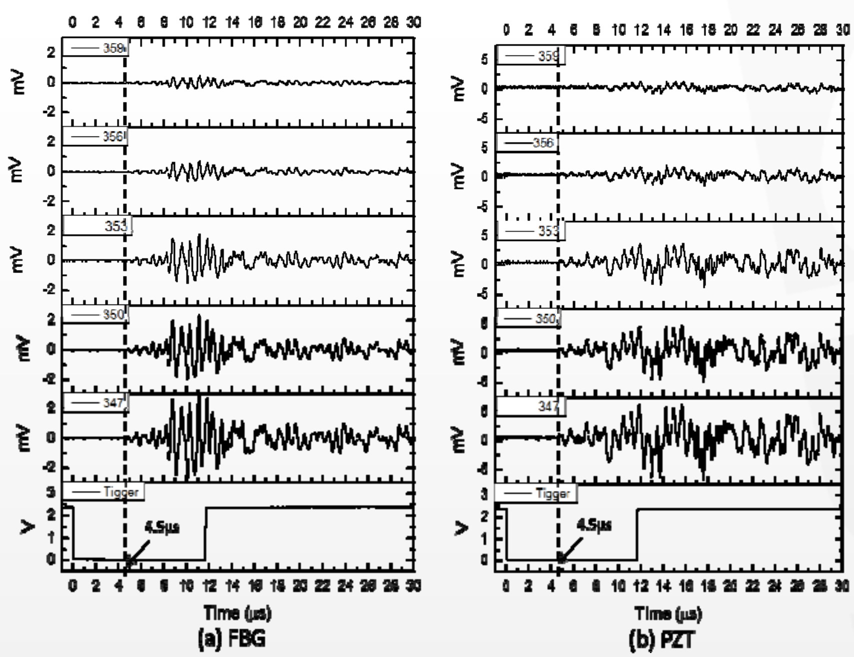


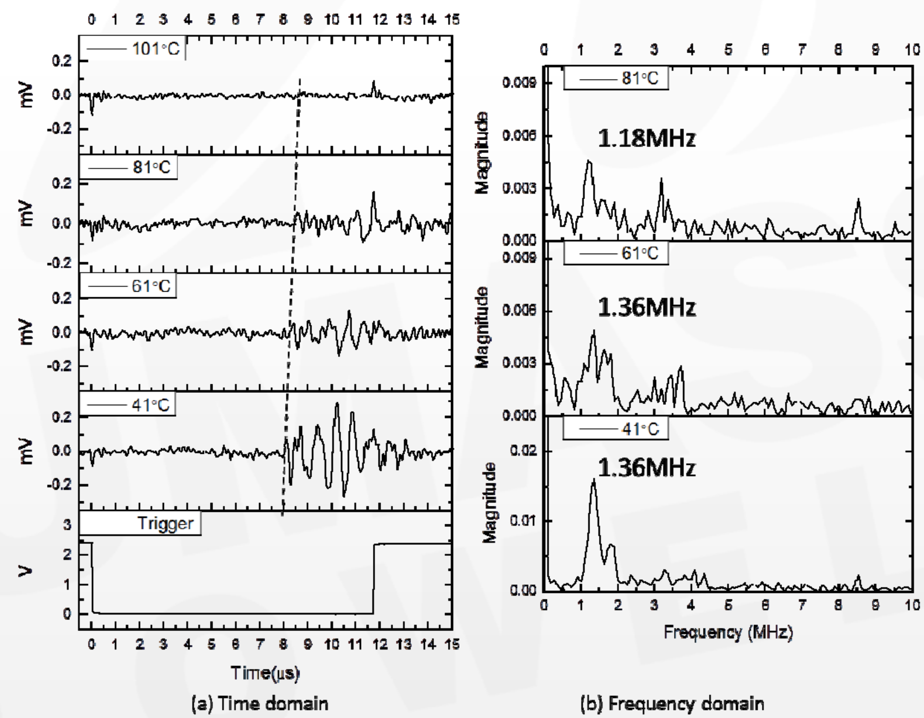
Photo of the Aluminum plate temperature measurement.

Experimental results

Aluminum plate temperature measurement



Signals of FBG (a) and PZT (b)



Experimental results of aluminum plate temperature test in (a) time domain and (b) frequency domain by FBG

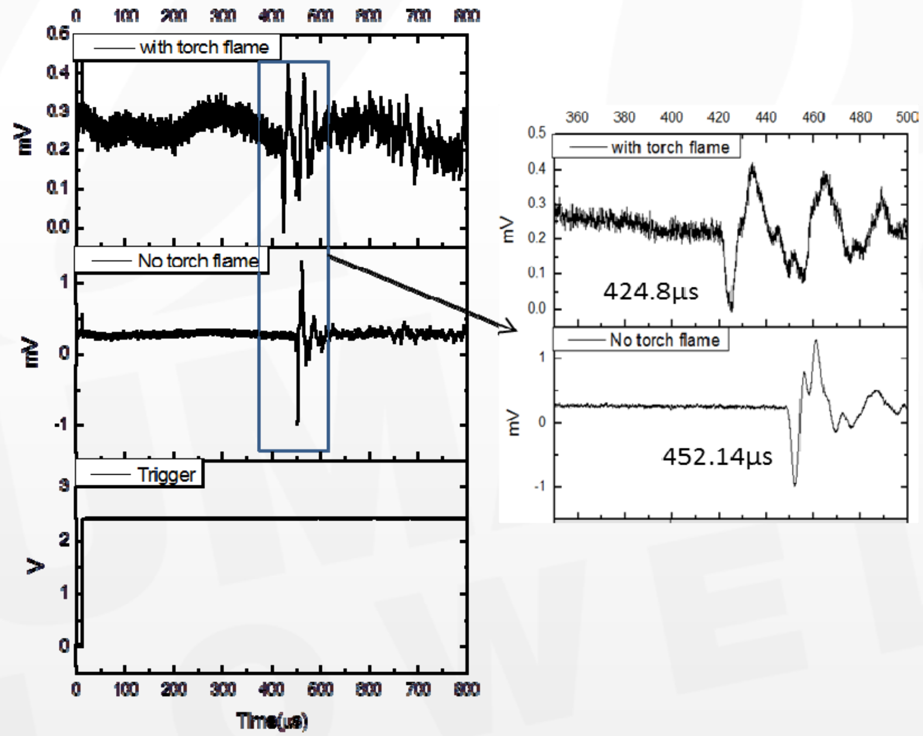
- Note: It proved that the FBG could be used as the signal receiver and also proved the fiber optic ultrasound transducer system.

Experimental results

Air temperature test

Experimental setup: Measure the temperature of a torch flame [4].

Experimental results of air temperature test in frequency domain.



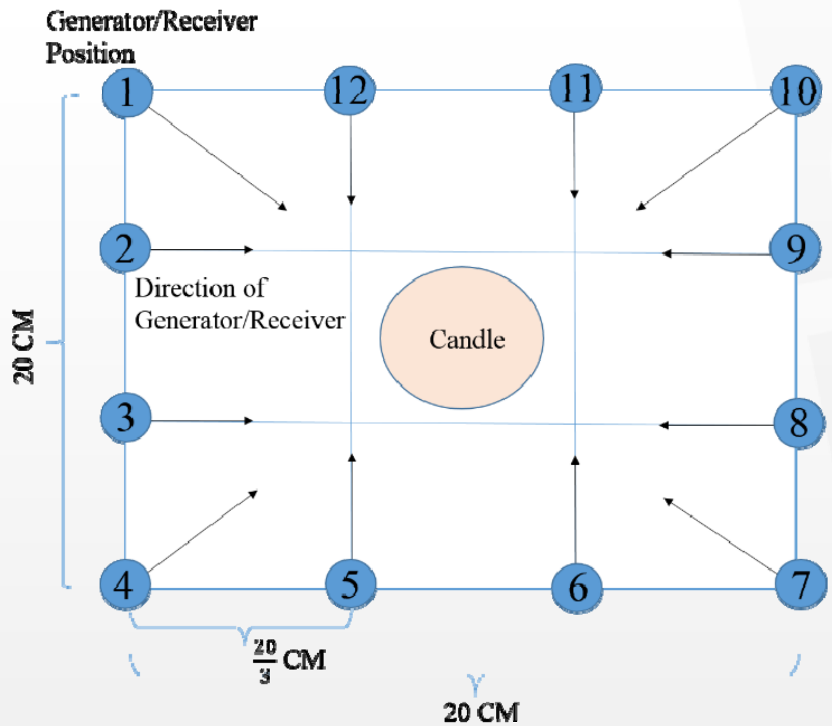
Experimental results of air temperature test in time domain.

- Note: It demonstrated that fiber optic ultrasound transducer system can be used to measure the air temperature.

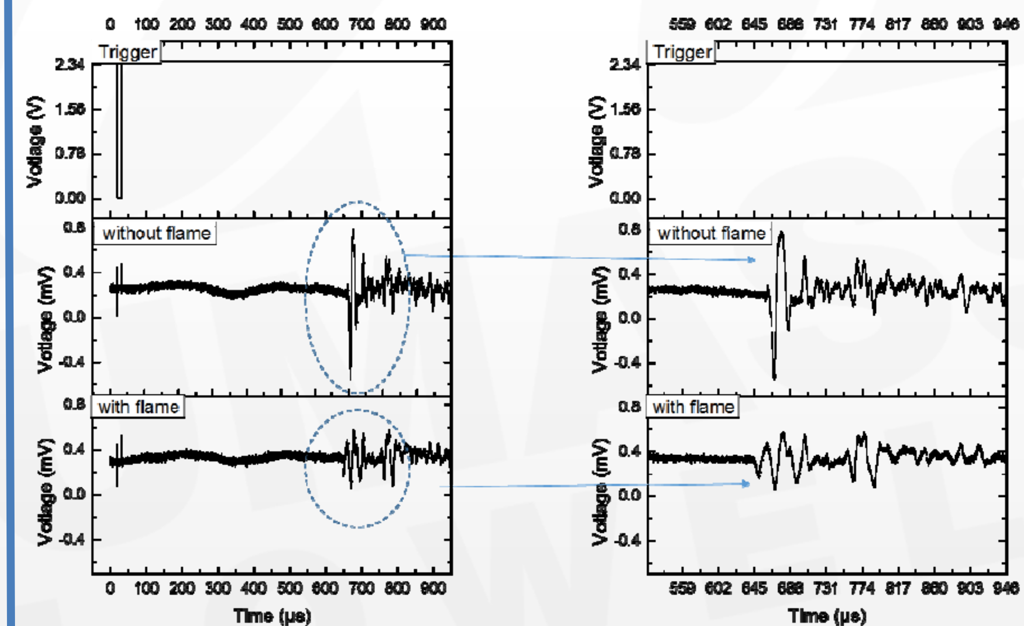
UMASS LOWELL

Experimental results

Air temperature reconstruction



Air temperature test experimental setup. (Top view)

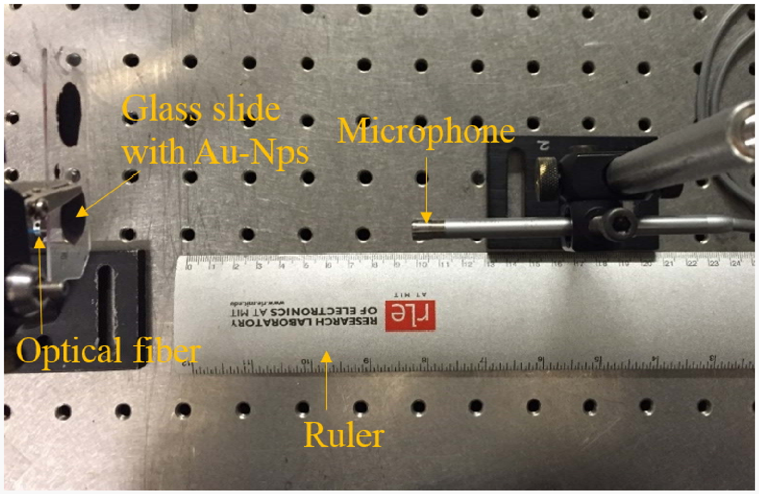


The ultrasound signal between positions 2 and 8.

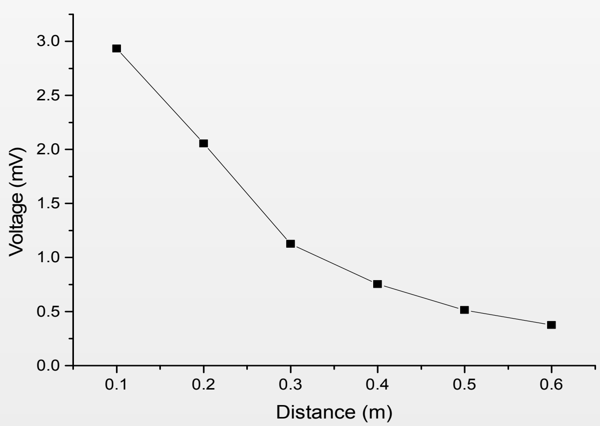
- Note: The air temperature test can be reconstructed by using this fiber optic ultrasound transducer system.

Experimental results

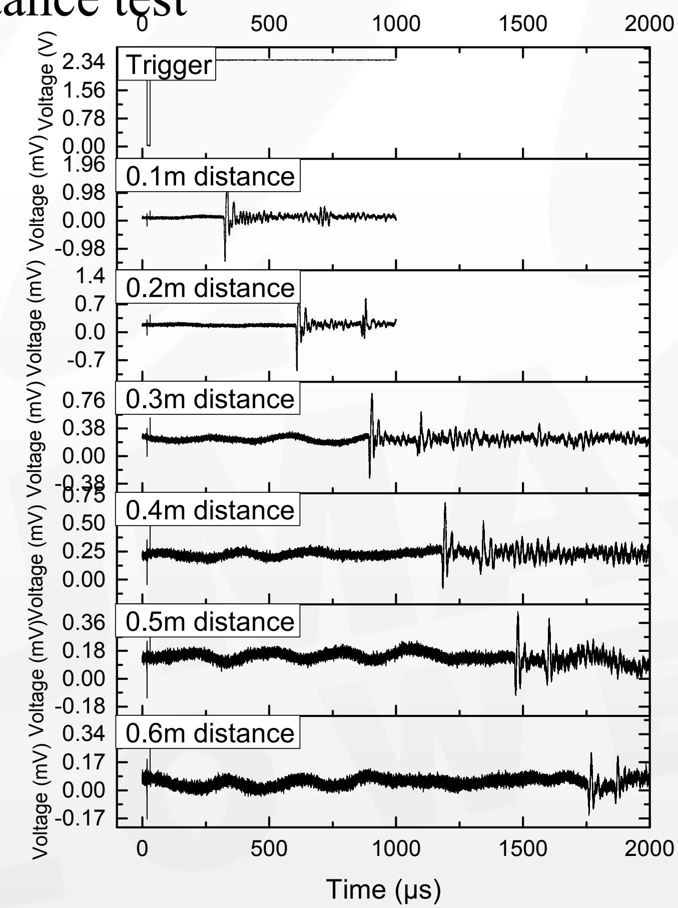
Signal distance test



Signal distance test experimental setup.



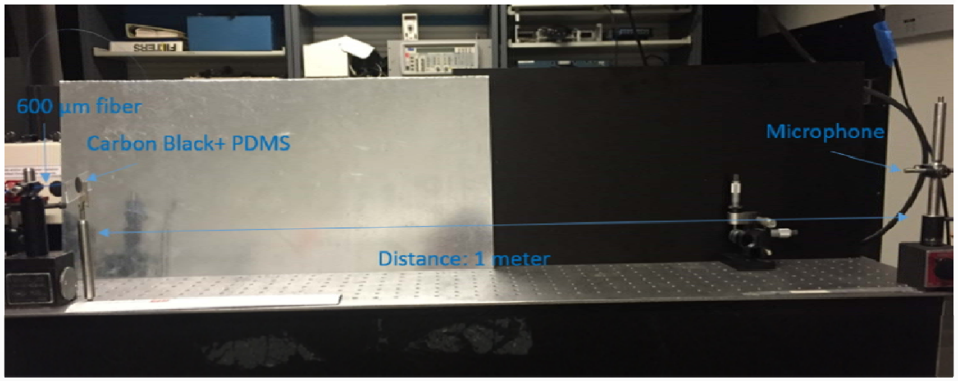
The ultrasound signal attenuation with distance.



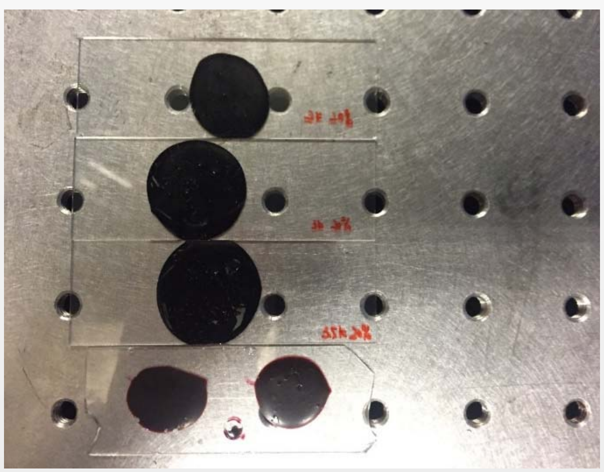
The ultrasound signal at different distance.

- Note: This fiber optic ultrasound transducer system can work at a distance of 0.6 meter. A 532 nm Nd:YAG nanosecond laser (Surelite I-10, Continuum) was utilized as the optical radiation source.

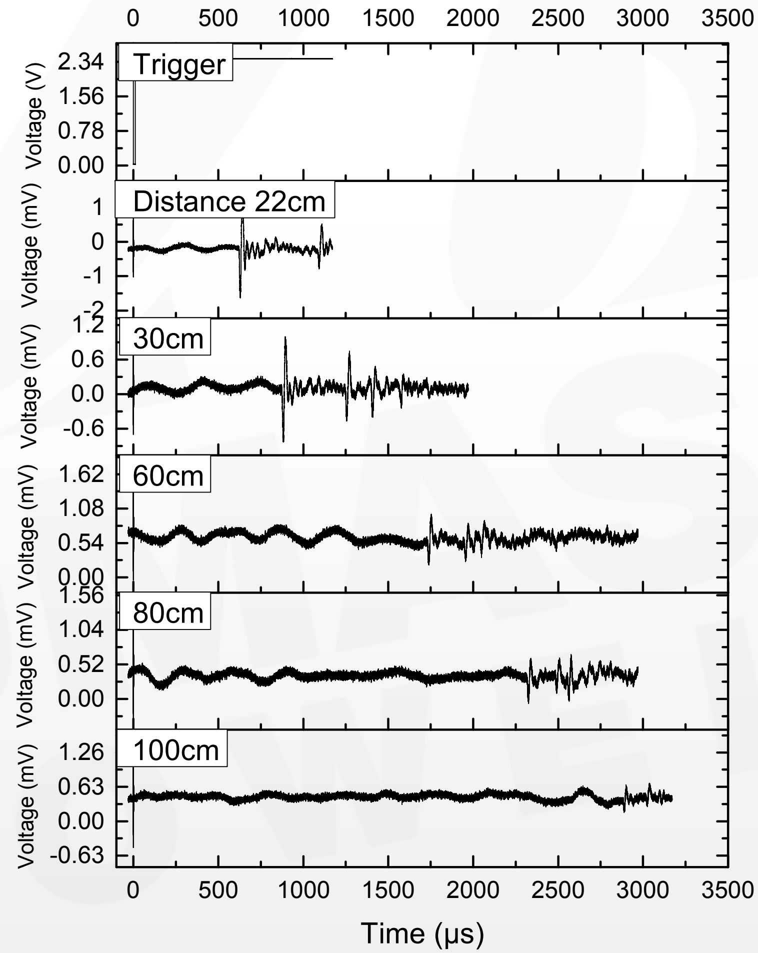
Increase signal strength of generator



Experimental setup.



Carbon black + PDMS and gold-nanocomposite



The ultrasound signal at different distance.

- Note: This fiber optic ultrasound transducer system could work at a distance of 1 meter. 600 um fiber and Carbon black + PDMS was used in this system.

Establish Simulation Model

1. Develop furnace temperature field model

   Governing Equation:

   - 2D case : unimodal symmetric, unimodal deflection and bimodal distribution
   - 3D case : unimodal symmetric and unimodal deflection distribution

   Alstom: 3D temperature distribution in field test stage.

2. Develop acoustic propagation model and specify the sensor locations

   Sensors location

   - Reconstruction algorithm will be affected by propagation paths.
     - Geometry of the tested field (uniformly distributed)
     - Temperature distribution (regions with more temperature variations should have more weights)

Establish Simulation Model

1. Traditional sensors location for power plant boilers (**Fig. 1**)

All acoustic sensors can both generate and receive signals

n sensors will generate signals along n(n-1)/2 paths, effective paths will be less due to infeasible ones between some sensors.

1. Nonlinear Programming (NLP) for optimization of sensor locations

An initial choice is given in **Fig. 2**.

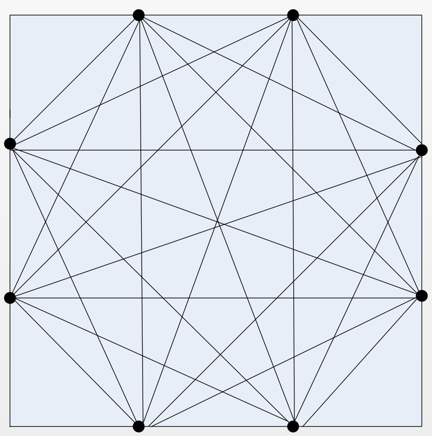


Fig. 1.

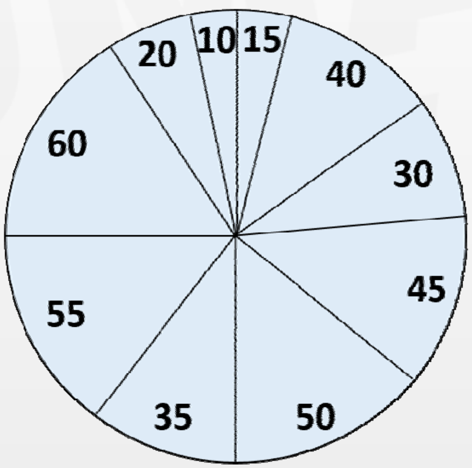
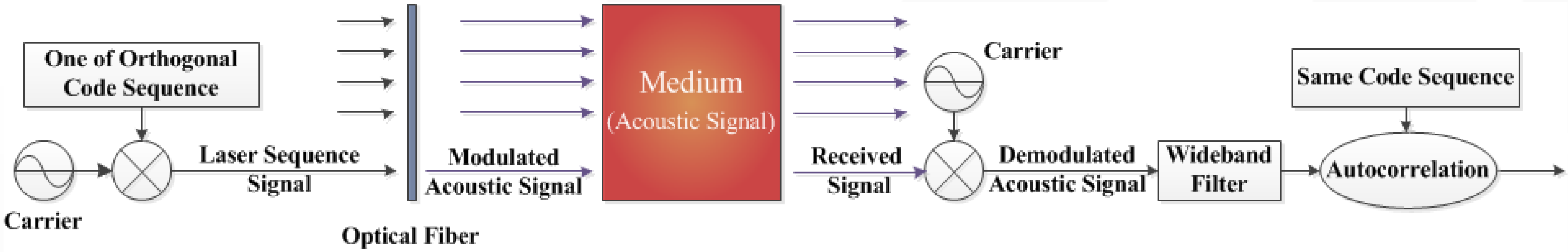


Fig. 2.

CDMA Modulation

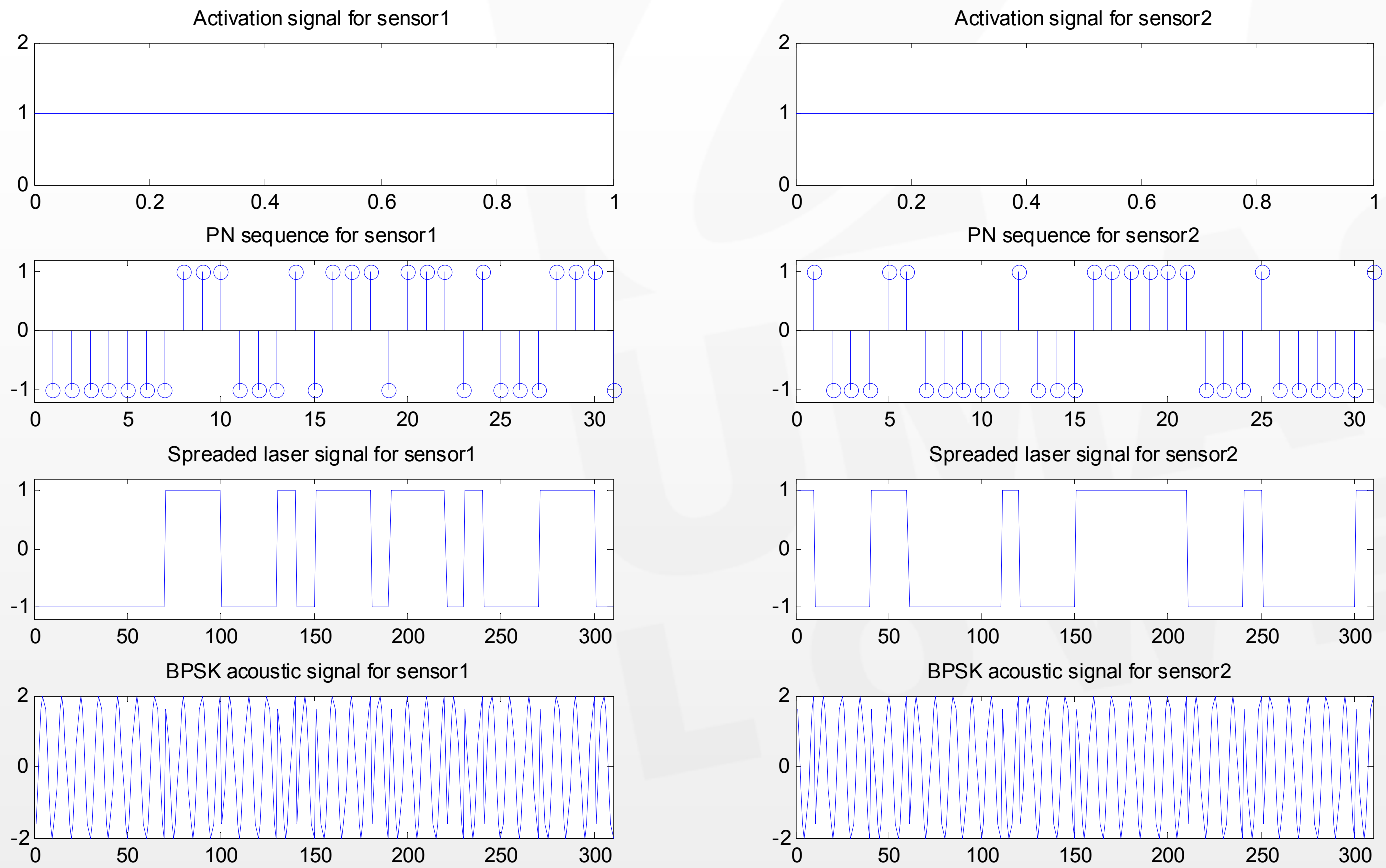


Example: 2-transmitter-1-receiver scenario

- Address Codes : 31-bit pseudo-noise sequences
- Binary Phase-shift Keying (BPSK) modulation:
  simulate the acoustic signals activated by PN laser signals
- Background Noise: additive Gaussian white noise (SNR = - 10db)
- Flight delay: different path
- Signal detection: sliding correlation

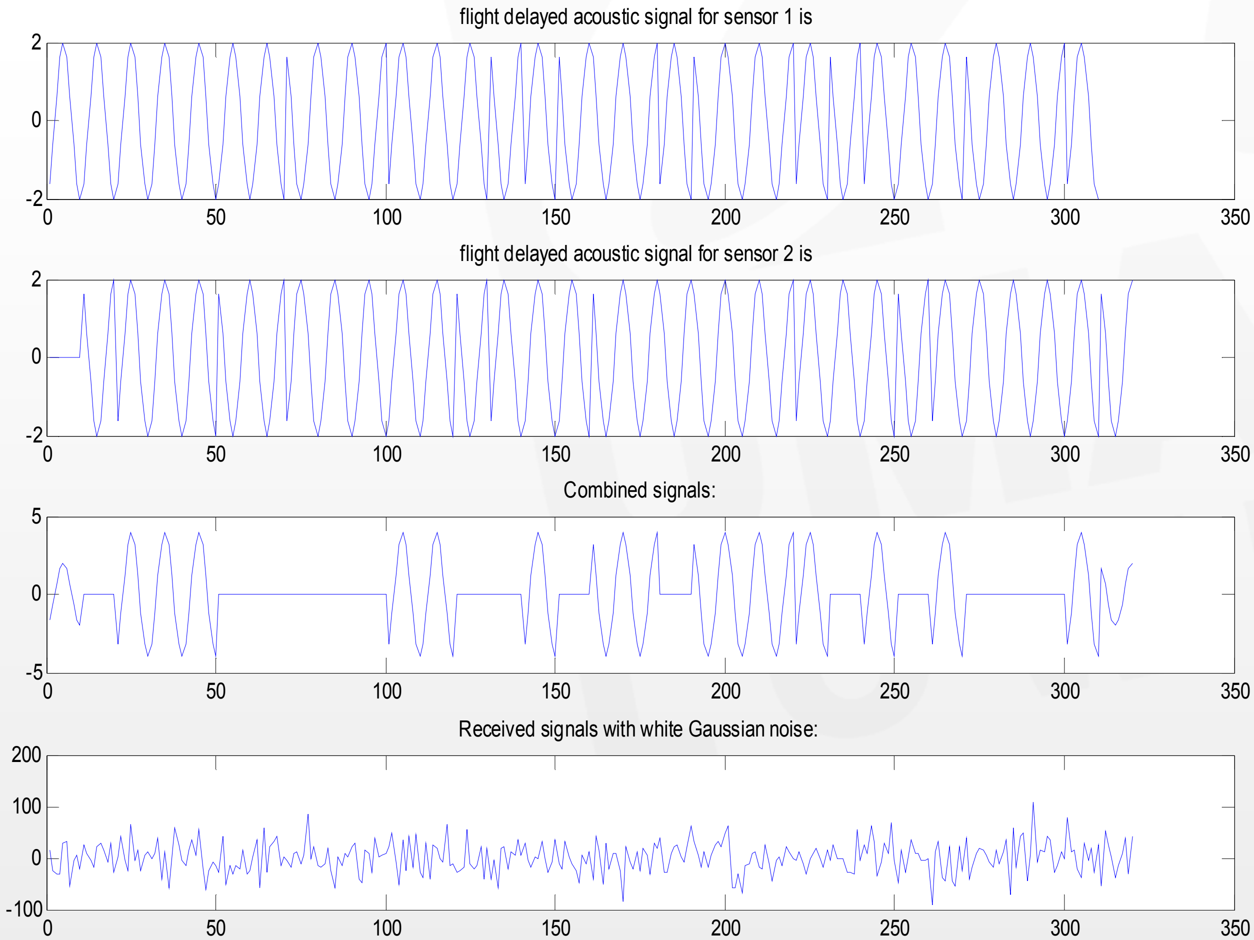
CDMA Modulation

- Transmitters : Modulation for Signals



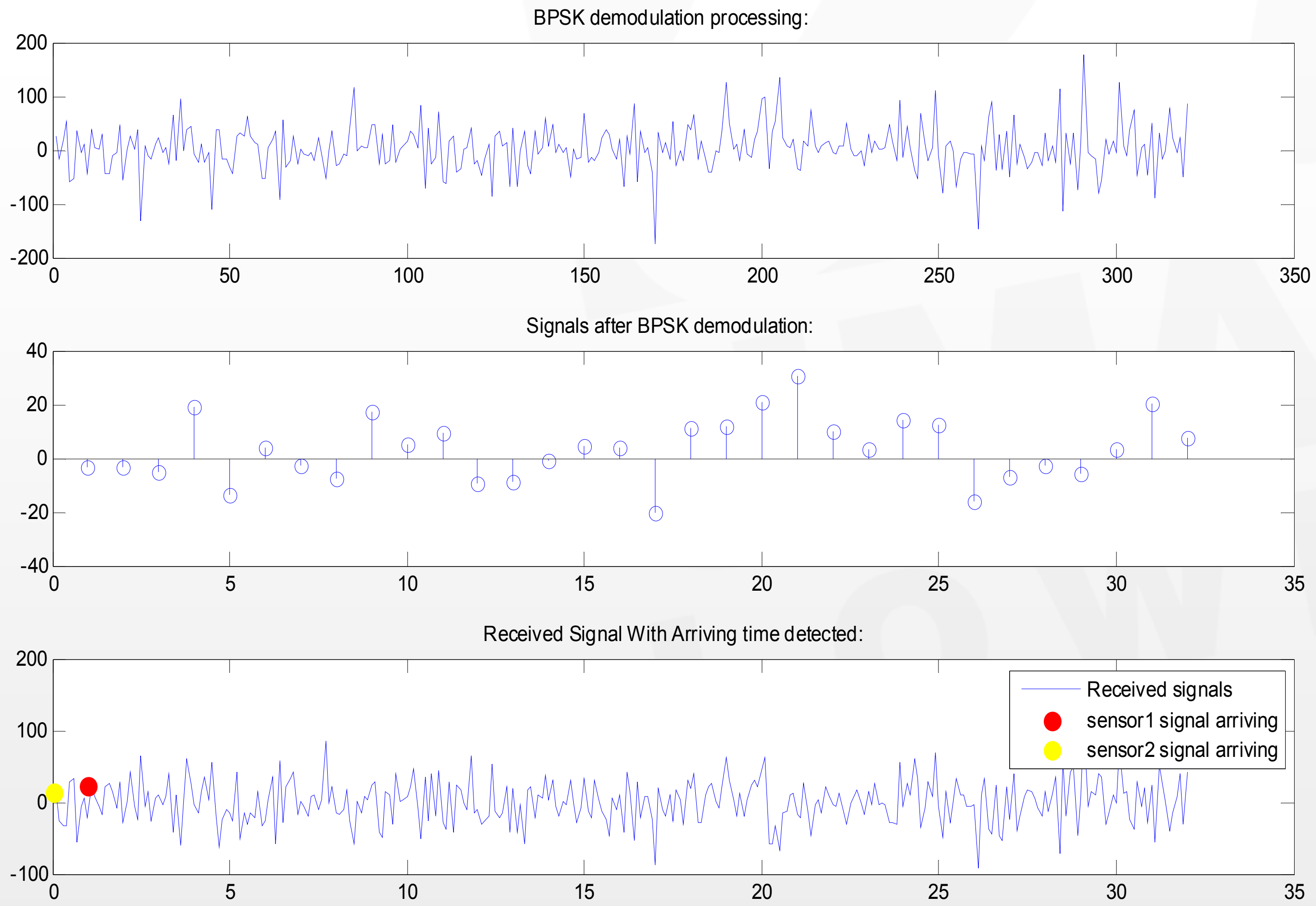
CDMA Modulation

- Boiler : Signals Transmission



CDMA Modulation

- Receiver: Demodulation and Flight Time Detection

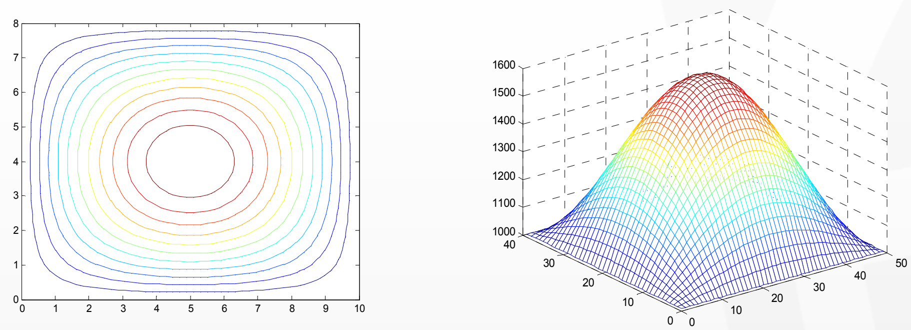


Temperature Reconstruction Algorithm with GRBF

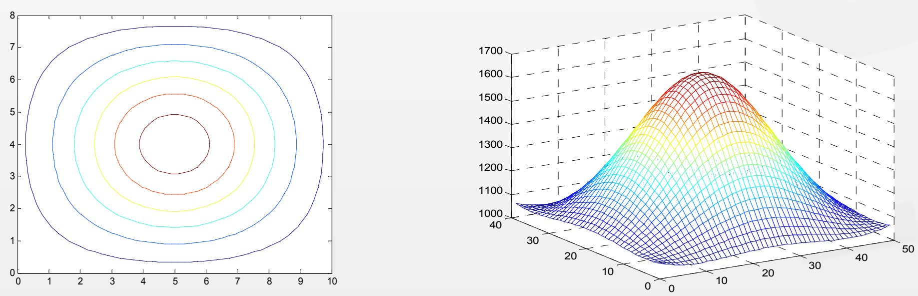
- 2D temperature field case I:

Unimodal symmetric

$$T(x, y) = 1000 + 600\sin(\pi x / length)\sin(\pi y / height)$$



Real Temperature Field



Reconstructed Temperature Field

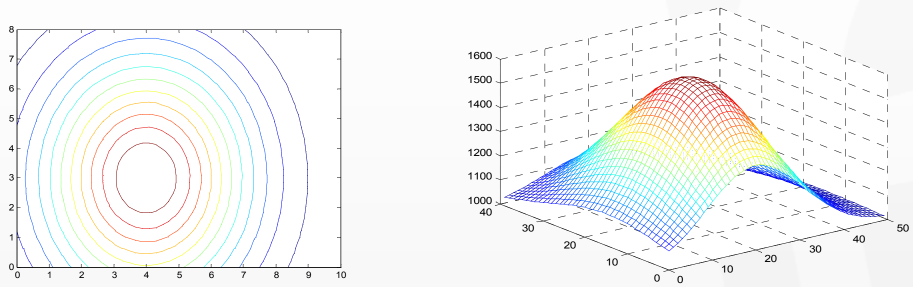
Notes: In the simulation, 10 sensors were evenly distributed, 10 basis functions were used and 24 paths are chosen. The matching error was 1.95%.

Temperature Reconstruction Algorithm with GRBF

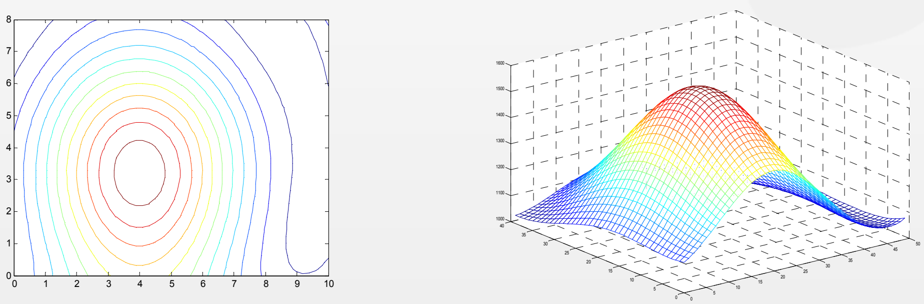
- 2D temperature field case II:

Unimodal deflection

$$T(x,y) = 600\exp((-(x-4)^2)/length - ((y-3)^2)/(2*height)) + 1000$$



Real Temperature Field



Reconstructed Temperature Field

Notes: In the simulation, 10 sensors were evenly distributed, 10 basis functions were used and 24 paths were chosen. The matching error was 0.8%.

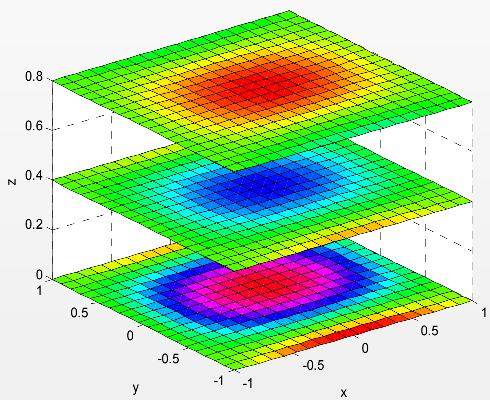
Temperature Reconstruction Algorithm with GRBF

- 3D temperature field case I:

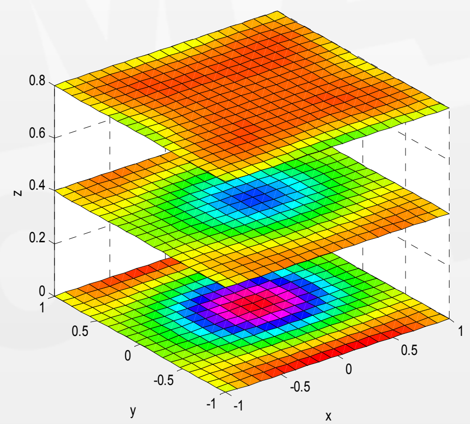
3D Unimodal symmetric model:

$$T(x,y,z)=1000+500\cos(1.5x)\cos(2y)\cos(2.5z)$$

Notes: In this model, 24 sensors are distributed and 30 Gaussian basis functions are used; the compact set is 2 × 2 × 1; the average approximation error is 10.14 °C over the entire region.



Z slice of the real temperature field



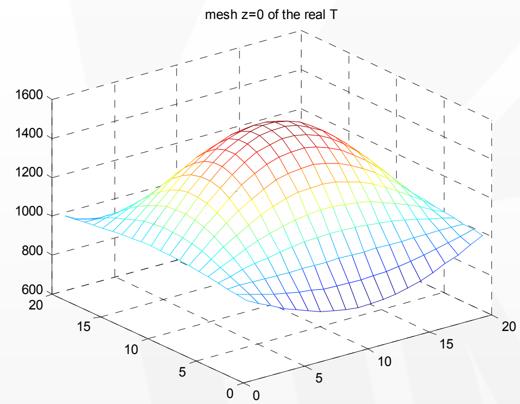
Z slice of the reconstructed

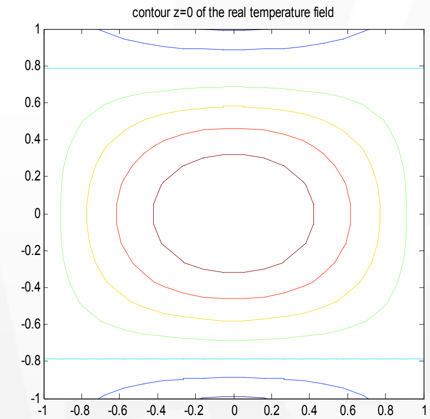
Temperature Reconstruction Algorithm with GRBF

- 3D temperature field case I:

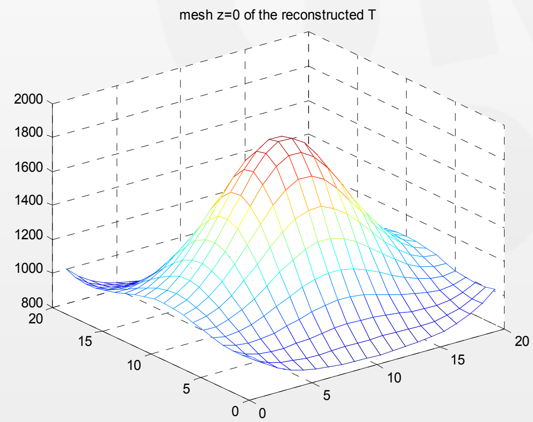
3D Unimodal symmetric model:

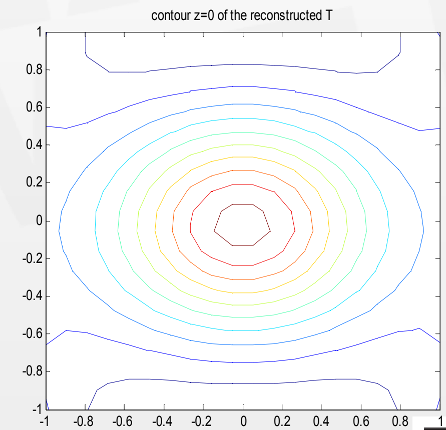
Z=0 of the real temperature field





Z=0 of the reconstructed temperature field

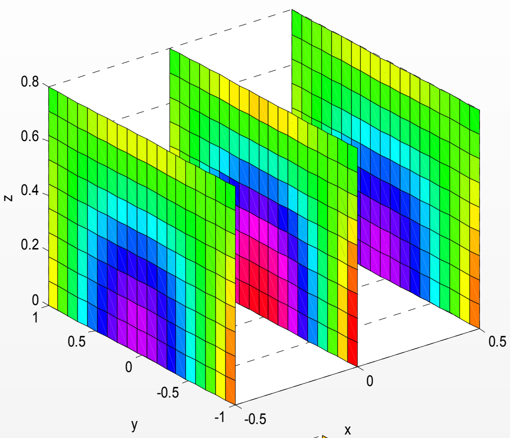




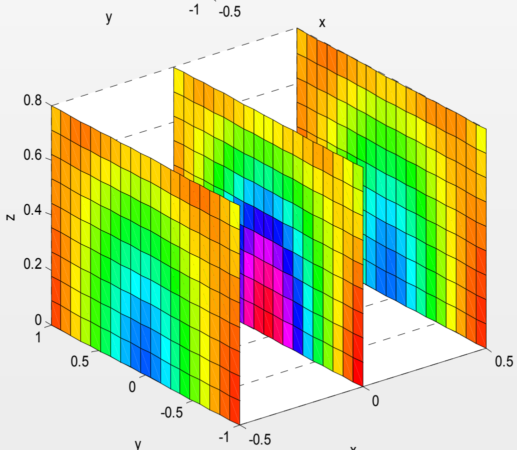
Temperature Reconstruction Algorithm with GRBF

- 3D temperature field case I:

3D Unimodal symmetric model:



X slice of the real temperature field



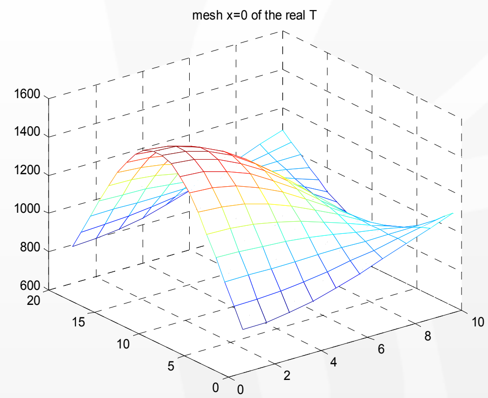
X slice of the reconstructed temperature field

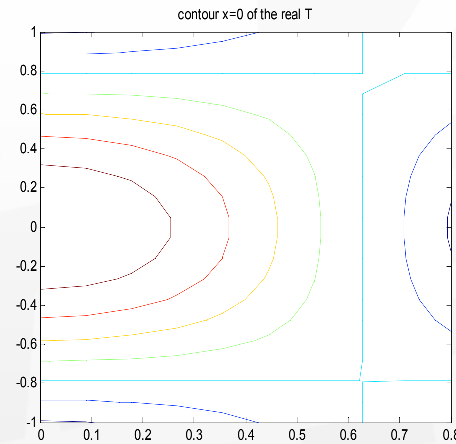
Temperature Reconstruction Algorithm with GRBF

- 3D temperature field case I:

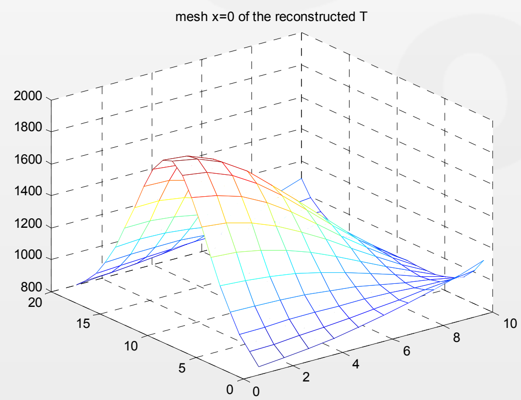
3D Unimodal symmetric model:

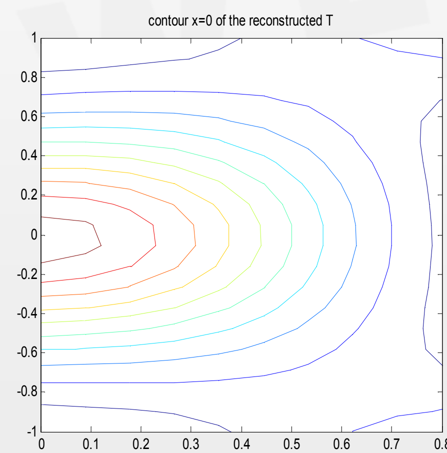
X=0 of the real temperature field





X=0 of the reconstructed temperature field





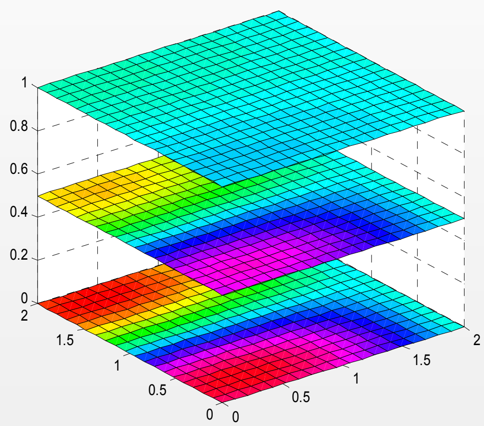
Temperature Reconstruction Algorithm with GRBF

- 3D temperature field case II:

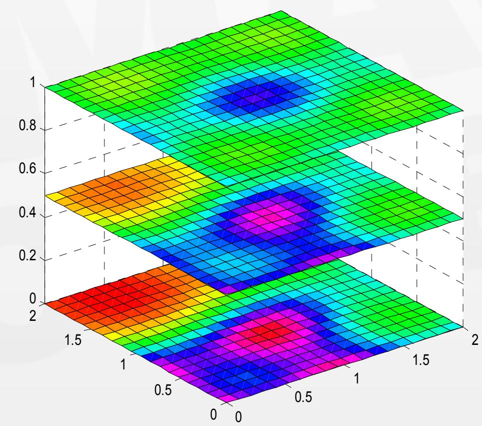
3D unimodal deflection model:

$$T(x, y, z) = 800 + 600\cos(x - 0.3)\cos(2y - 0.4)\cos(1.5z)$$

Notes: In this model, 24 sensors are distributed and 30 Gaussian basis functions are used; the compact set is 2 × 2 × 1; the average approximation error is 14% over the entire region.



Z slice of the real temperature field



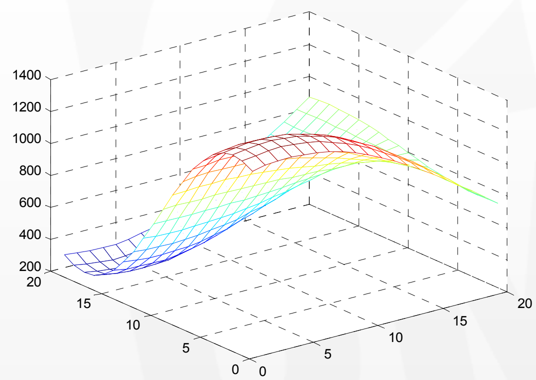
Z slice of the reconstructed

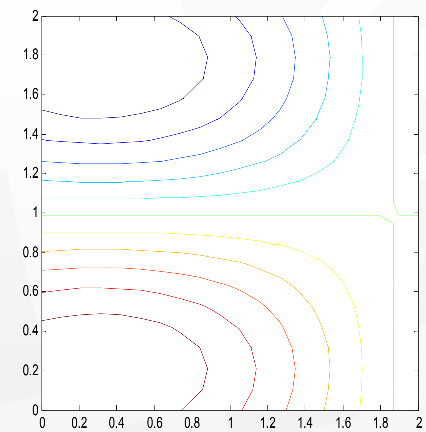
Temperature Reconstruction Algorithm with GRBF

- 3D temperature field case II:

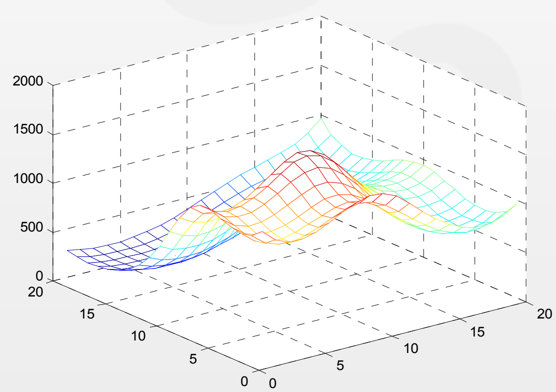
3D unimodal deflection model:

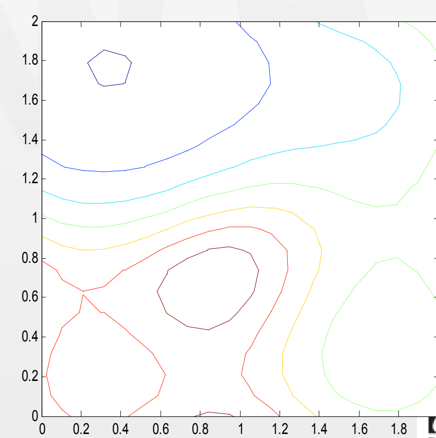
Z=0 of the real temperature field





Z=0 of the reconstructed temperature field



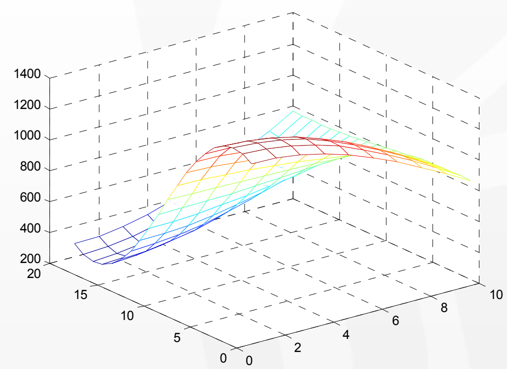


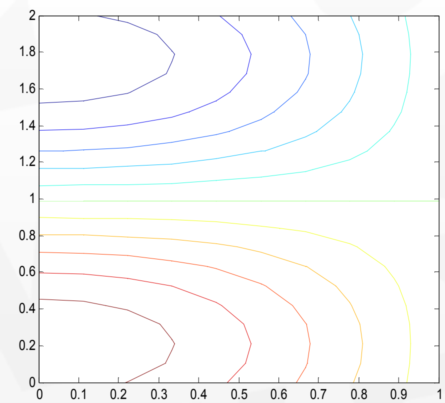
Temperature Reconstruction Algorithm with GRBF

- 3D temperature field case II:

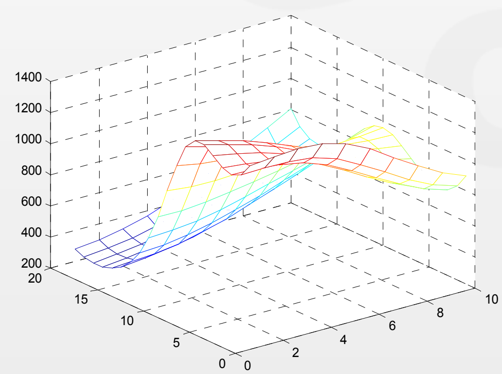
3D unimodal deflection model:

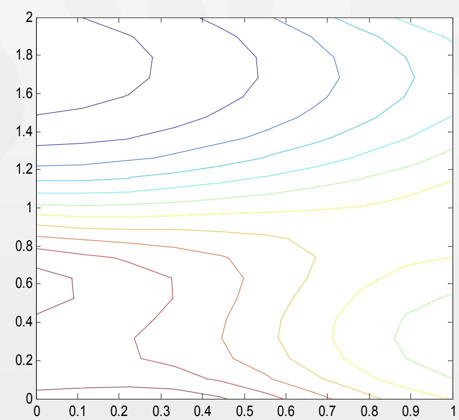
X=0 of the real temperature field





X=0 of the reconstructed temperature field





Future plan

- ❑ M7/Field Test Distributed Sensing System I (One point) at GE (Start in April)
- ❑ M8/Develop Distributed Sensing System II (Multiple points)
- ❑ M9/Field Test Distributed Sensing System II at Alstom

Publications

- [1] Jingcheng Zhou, Nan Wu, Xingwei Wang, Yuqian Liu, Tong Ma, Daniel Coxe, Chengyu Cao, “Water temperature measurement using a novel fiber optic ultrasound transducer system”, IEEE International Conference on Information and Automation, Lijiang, China, August 8-10, 2015.
- [2] Xiaotian Zou, Nan Wu, Ye Tian, and Xingwei Wang, "Broadband miniature fiber optic ultrasound generator", Virtual Journal for Biomedical Optics, 9(9), 18119, 2014
- [3] Jingcheng Zhou, Nan Wu, Siwen Bi and Xingwei Wang, ”Ultrasound generation from an optical fiber sidewall” SPIE Smart Structures/NDE 2016, Accepted
- [4] Siwen Bi, Nan Wu, Jingcheng Zhou, Xingwei Wang, Tong Ma, Yuqian Liu and Chengyu Cao, “Ultrasonic temperature measurements with fiber optic system” SPIE Smart Structures/NDE 2016, Accepted
- [5] Nan Wu, Xiaotian Zou, Jingcheng Zhou and Xingwei Wang, "Fiber optic ultrasound transmitters and their applications", Measurement, Volume 79, 164-171, 2016
- [6] Nan Wu, Ye Tian, Xiaotian Zou, Vinicius Silva, Armand Chery, and Xingwei Wang, "High-efficiency optical ultrasound generation using one-pot synthesized polydimethylsiloxane-gold nanoparticle nanocomposite", Journal of the Optical Society of America B, 29(8), 2016-2020 2012
- [7] Ye Tian, Nan Wu, Kai Sun, Xiaotian Zou, and Xingwei Wang, “Numerical simulation of fiber-optic photoacoustic generator using nanocomposite materials”, Journal of Computational Acoustics, 21(2), 1350002, 2013
- [8] Xiaotian Zou, Nan Wu, Ye Tian, Yang Zhang and Xingwei Wang, "Polydimethylsiloxane thin film characterization using all-optical photoacoustic mechanism", Applied Optics, 52(25), 6239-6244, 2013
- [9] Xiaotian Zou, Tyler Schmitt, David Perloff, Nan Wu, Tzu-Yang Yu, and Xingwei Wang, "Nondestructive corrosion detection using fiber optic photoacoustic ultrasound generator", Measurement, Volume 62, 74-80, 2014


Thanks