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Engineering Integrated Sensing, Power, Telemetry, and Data Processing Systems for Complex Subsurface Environments: FY24 Progress

Daniel Deng, Hyunjun Jung, Xiaoqin Zang, Jun Lu, Xi Tan, Seunghwan Baek, Wonseop Hwang, Zhaocheng Lu

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U.S. DEPARTMENT OF ENERGY BATTELLE

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Presentation Outline

- Motivation & Objective
- Project Tasks
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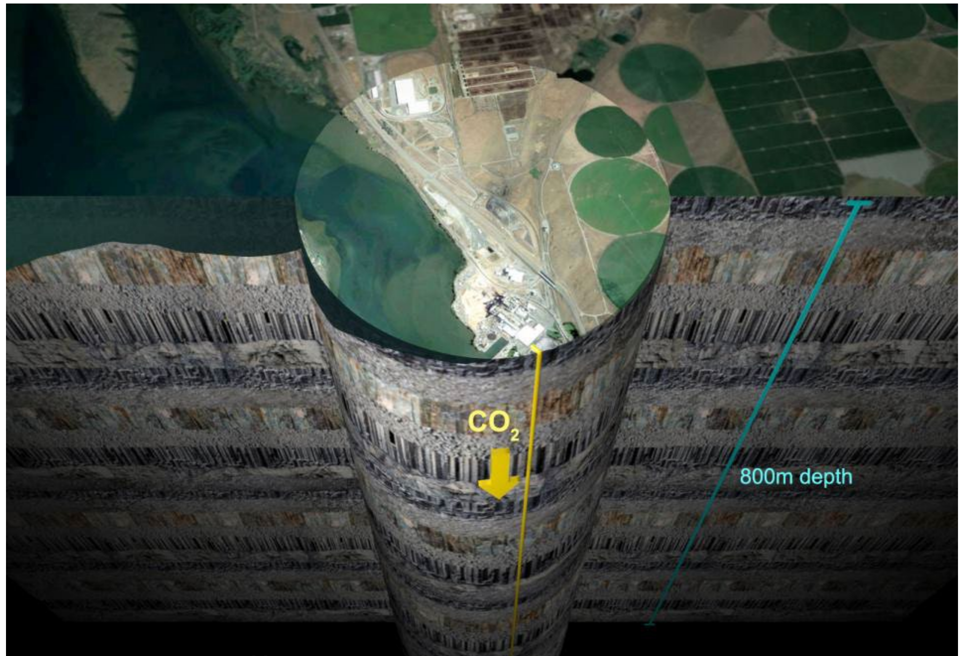
  - Task 2: Benchtop energy Harvesting System
  - Task 3: Sensor Development for Harsh Environments
  - Conceptual Design of the Integrated System
- Accomplishments
- Next Steps
- Acknowledgement

Motivation & Objective

Motivation: **Advanced monitoring tzechnologies** and **reliable wireless communications** to transmit data from the downhole to the surface can reduce measurement cost and uncertainties, ensure safe CO_2 injection, and provide more data for AI

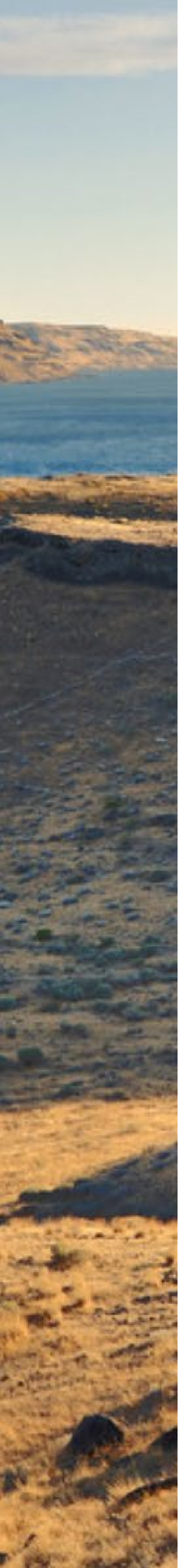


https://www.pnnl.gov/carbon-storage

Objective: Develop an **integrated self-powered sensing and telemetry system for monitoring subsurface environments**

- An acoustic telemetry system can potentially transmit data through the tubing from the downhole to the surface wirelessly in real time.
- An energy harvesting system can power the sensing and acoustic telemetry system reliably, leading to reduced operating cost.
- A sensing system can monitor data in harsh subsurface environment.

An integrated energy harvesting, sensing, and data communication system has not yet been developed for the CCS borehole environment



Project Tasks

Task 1: Data telemetry system

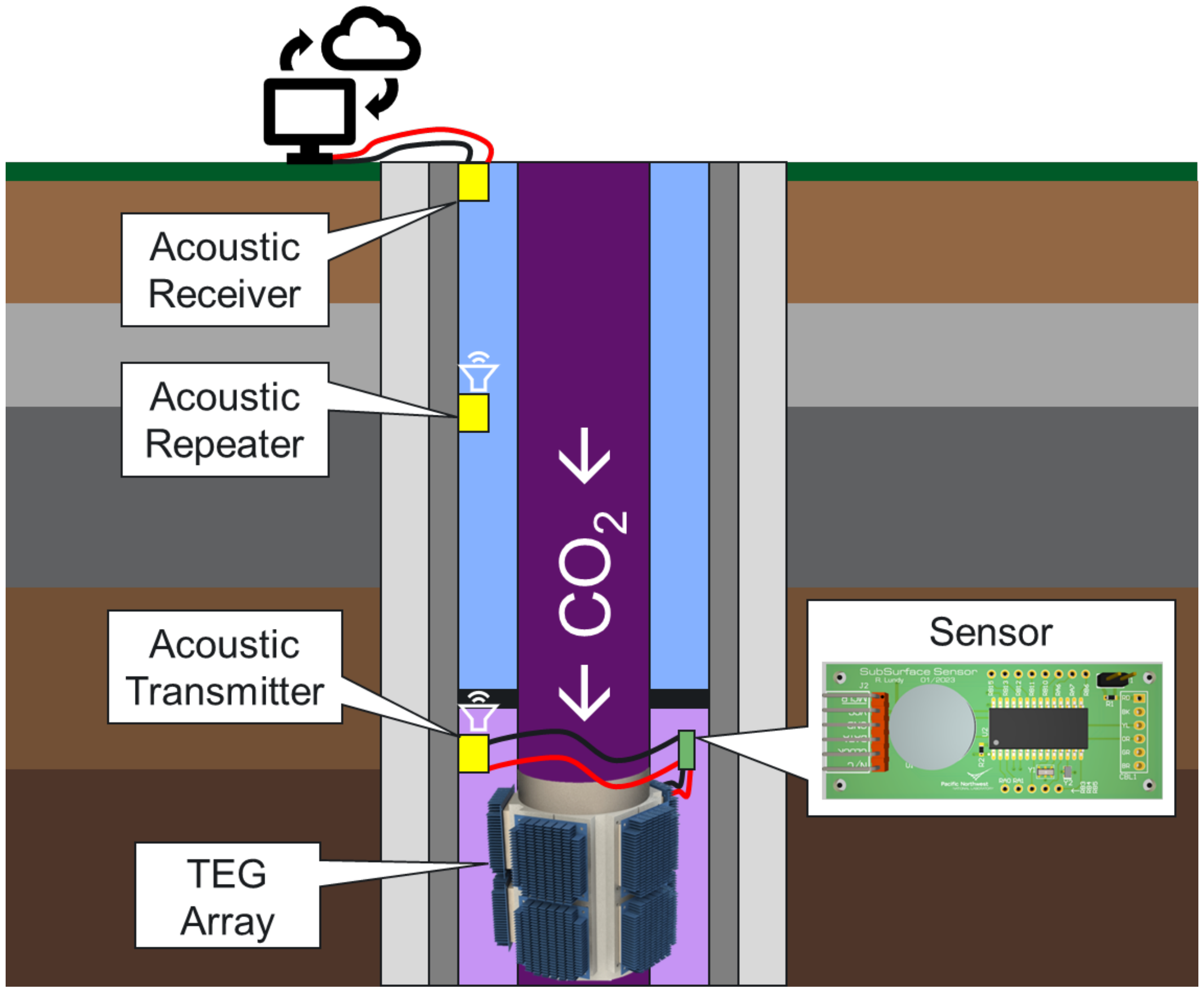
- Optimize the existing coding and decoding algorithms of Binary Phase Shifting Key (BPSK)
- Develop coding and decoding algorithms using differential phase shift keying (DPSK)

Task 2: Benchtop energy harvesting system

- Semi-analytical model of the downhole and Thermoelectric generator (TEG)
- TEG modules and power management circuit (PMC)
- Benchtop testing of the TEG system

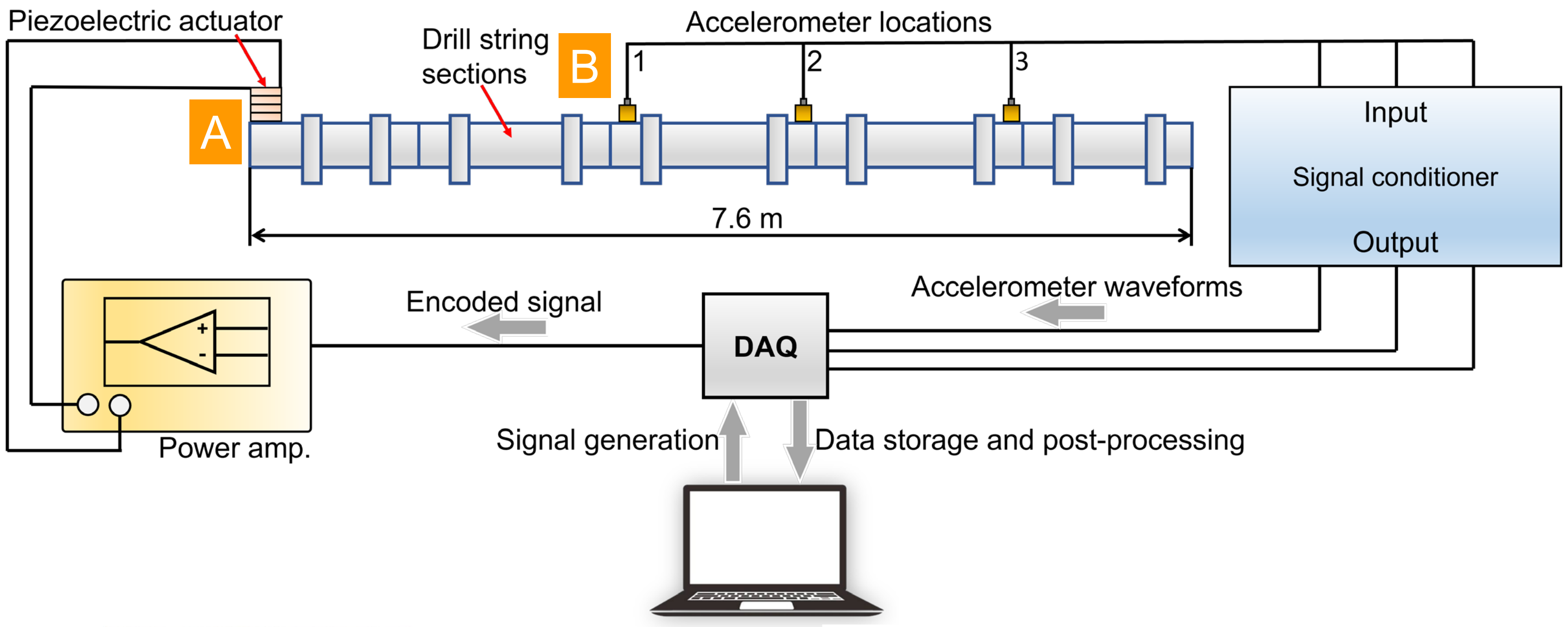
Task 3: Sensor development for harsh environments

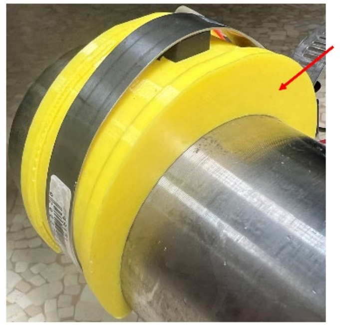
- Develop a benchtop environmental sensing platform



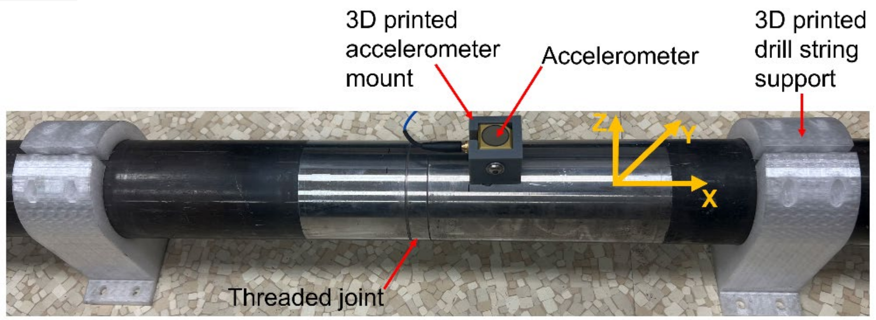
Task 1: Data Telemetry System

System Integration and Experiment Setup for Acoustic Data Telemetry Along Drill Strings

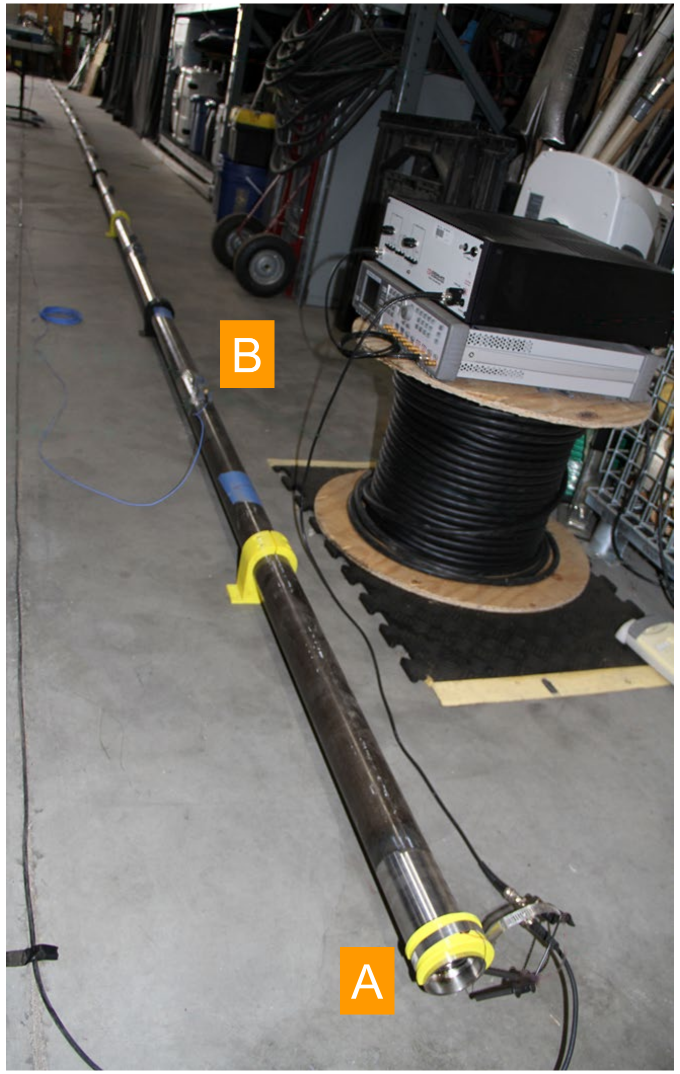




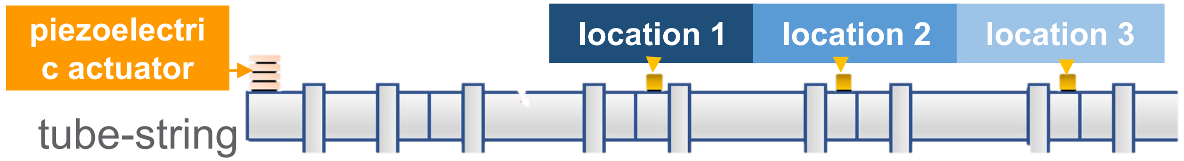
A Piezoelectric actuator

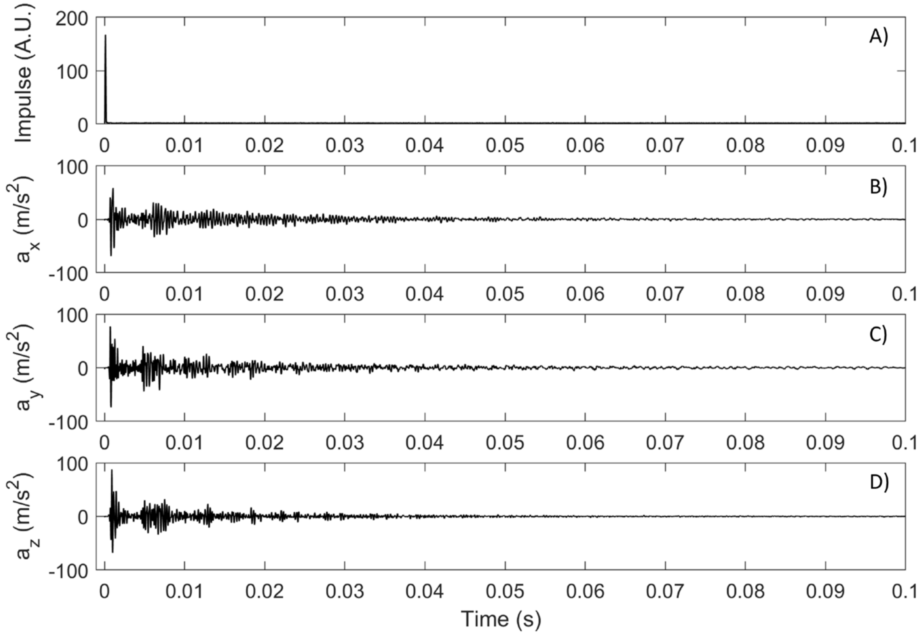


B Drill string and the accelerometers

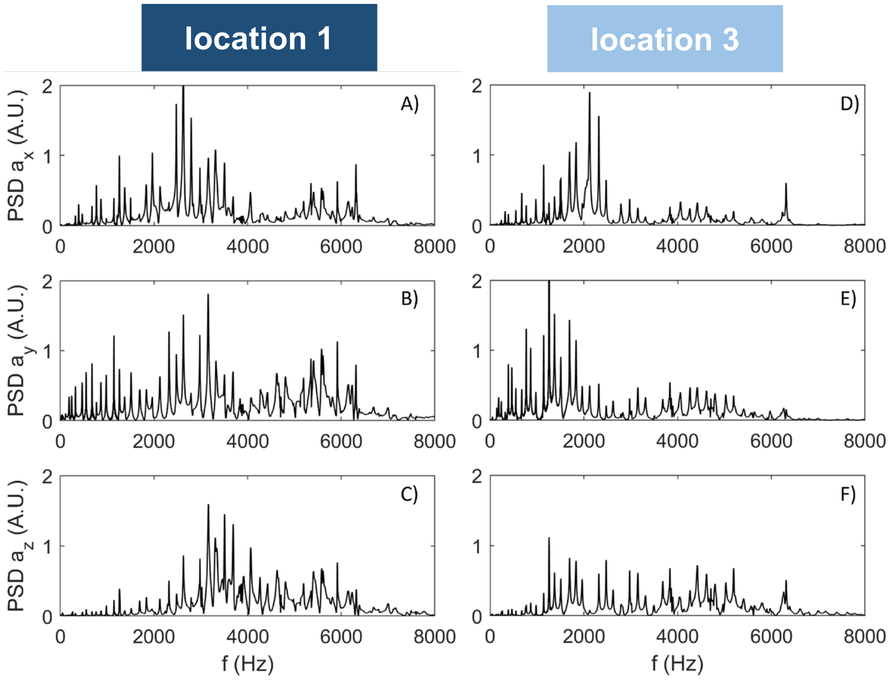


Task 1: Results - Channel Characteristics

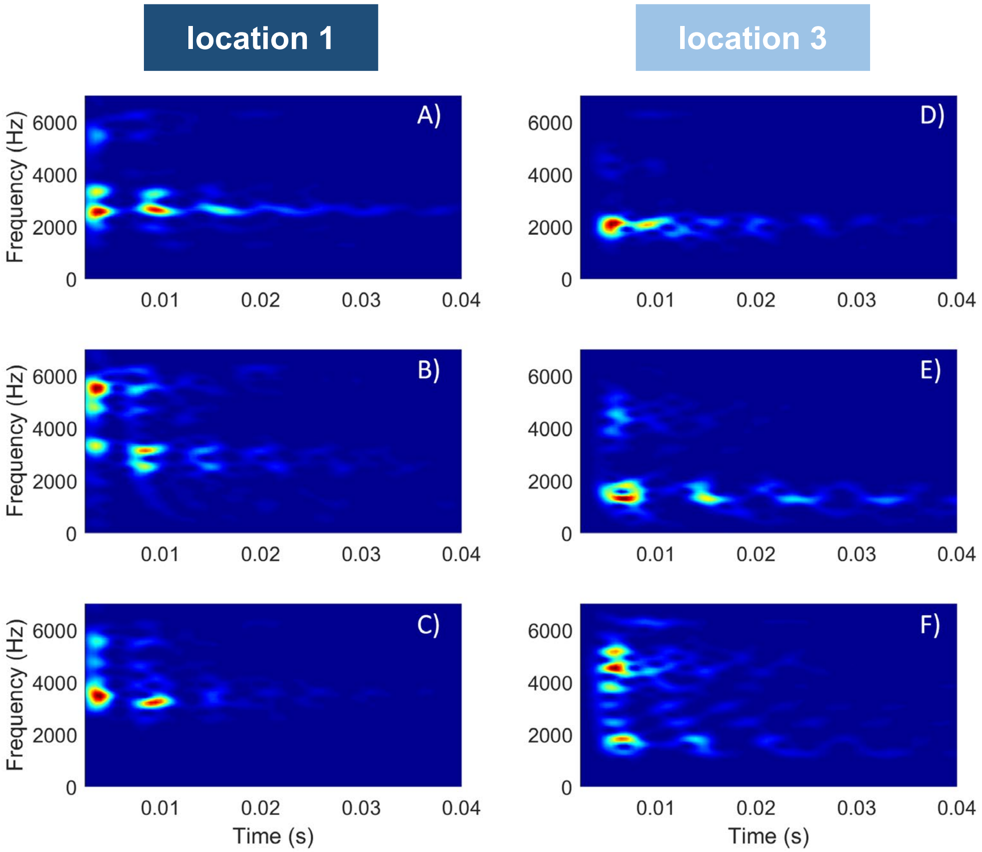




Impulse response time series



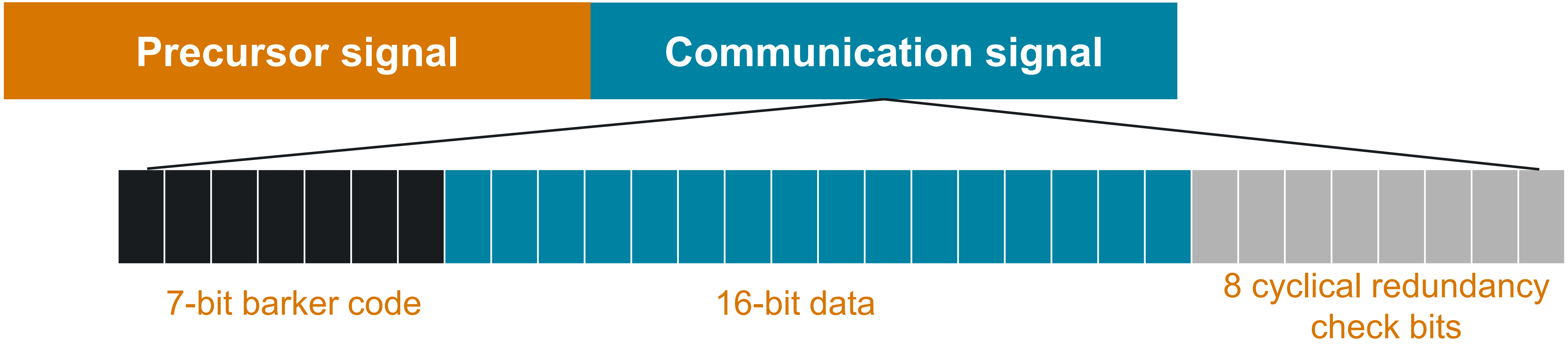
Impulse response PSD



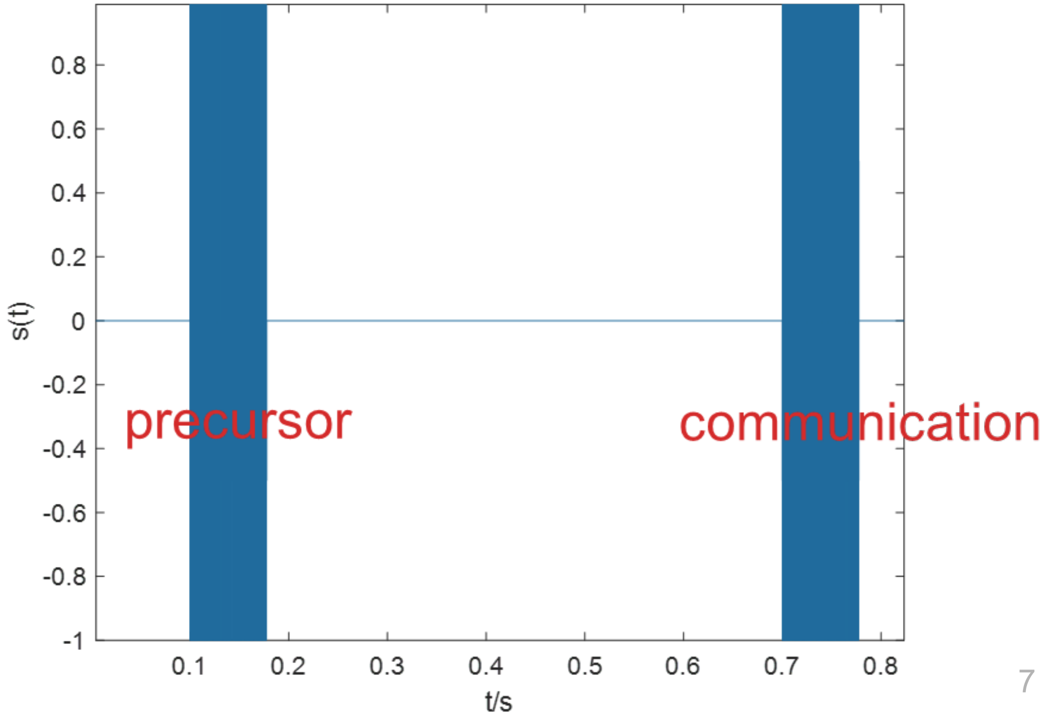
Impulse response spectrogram

- The power spectral densities of the impulse response function have **comb-like structures**, consisting of multiple passbands and stopbands; **careful selection of carrier frequency** is important to successful communication.
- Spectrograms show modal features, which indicate **strong dispersion** of the channel and pose **serious challenges** to signal processing.

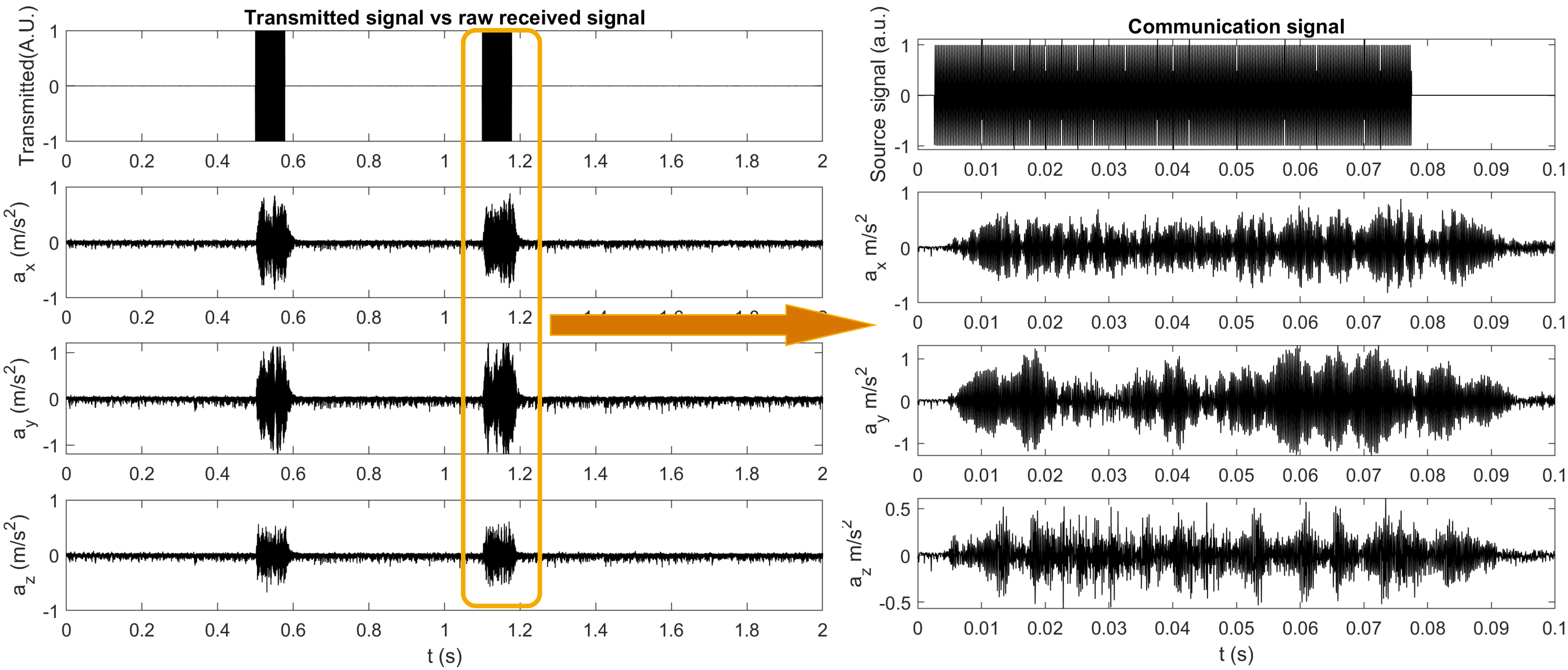
Task 1: Transmitted Signal



- Precursor signal (known to the receiver)
  - 31-bit M sequence, to **extract the impulse response function**
  - BPSK or DPSK modulated
- Communication signal (unknown to the receiver)
  - 31-bit per transmission
  - BPSK or DPSK modulated



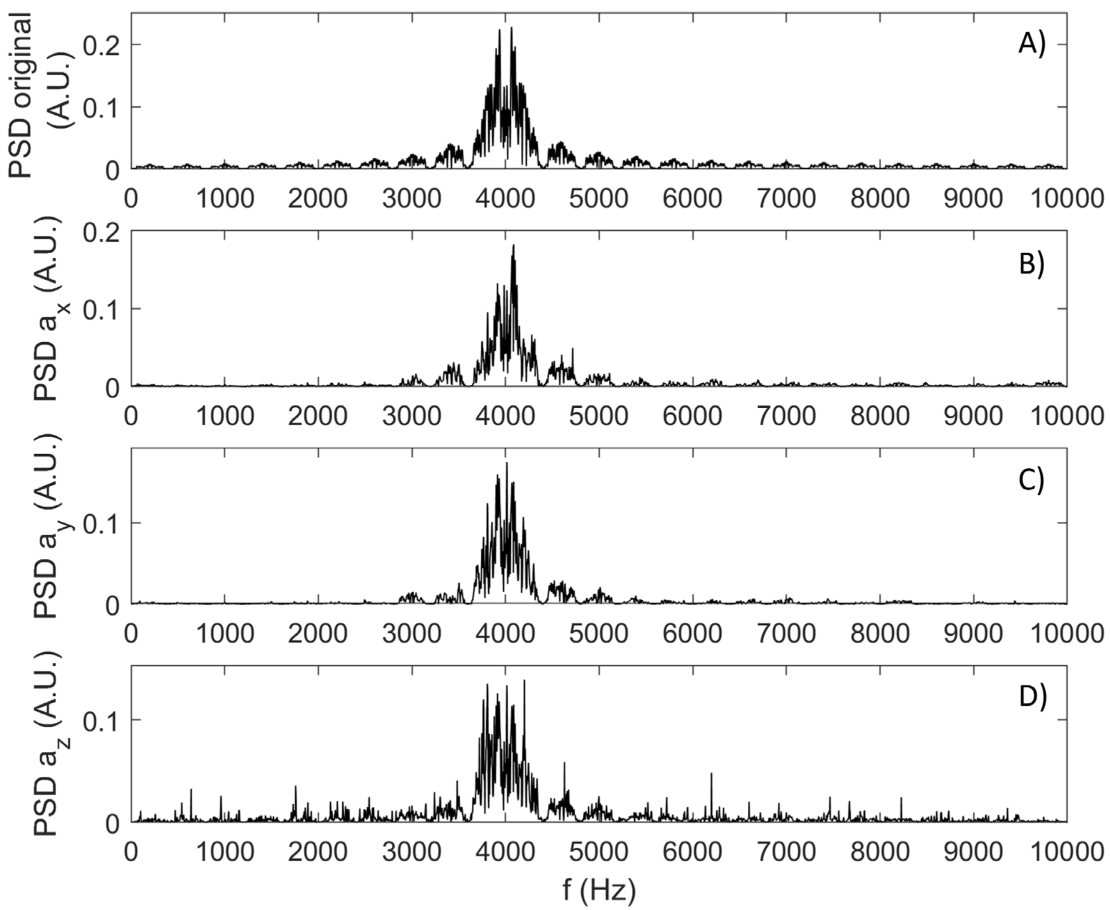
Task 1: Received Signals

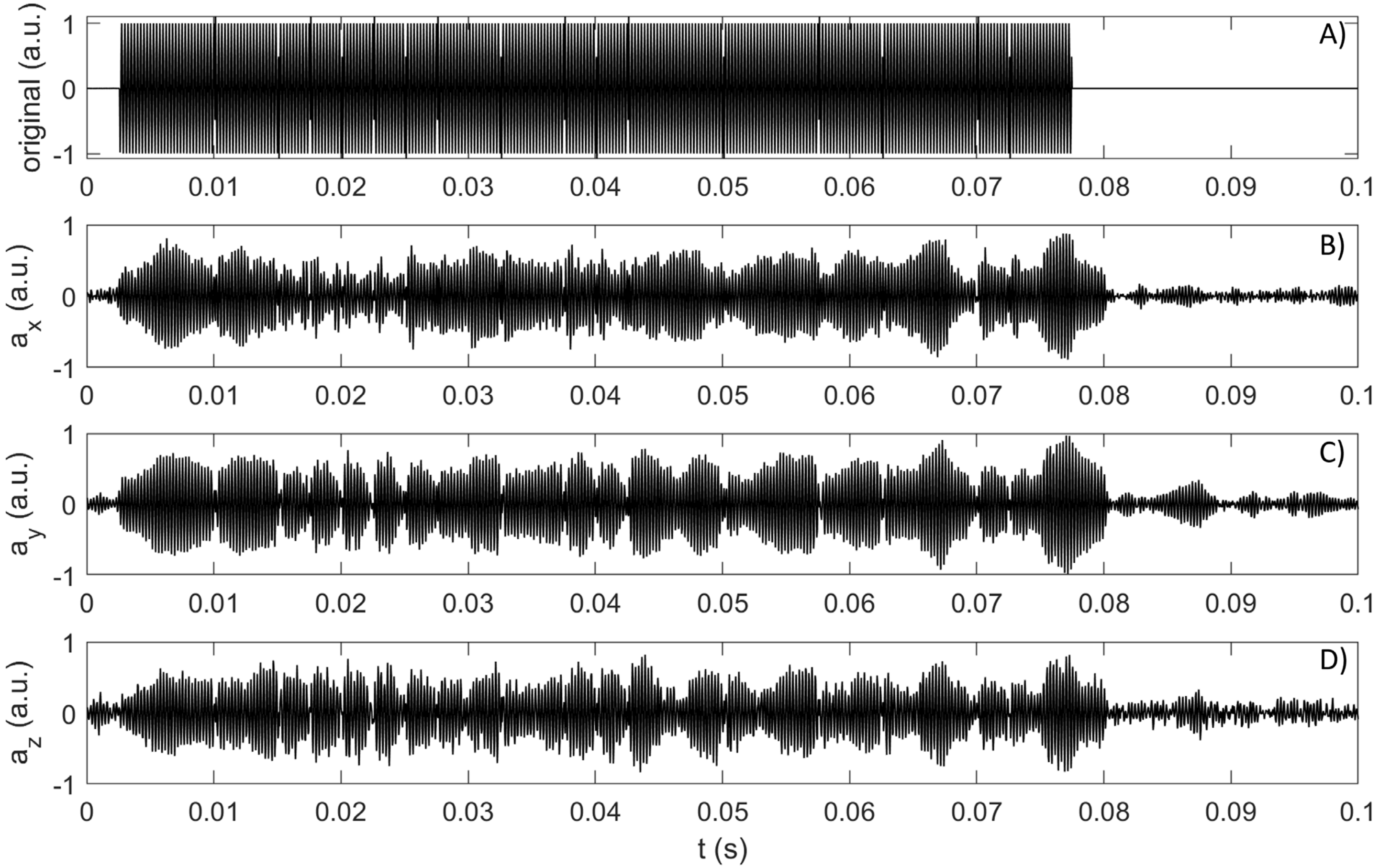


Task 1: Results - Signal Processing Protocols

$$S_c(\omega) = \frac{R_c(\omega)}{G(\omega)} = \frac{R_c(\omega)S_m(\omega)}{R_m(\omega)} \approx \frac{R_c(\omega)R_m(\omega)S_m(\omega)}{|R_m(\omega)|^2 + \varepsilon^2}$$

Inverse filter processing for communication signal recovery





- PSDs of the original and recovered communication signals
- Waveforms of the transmitted and recovered communication signals, with clear phase shift between bits 1s and 0s

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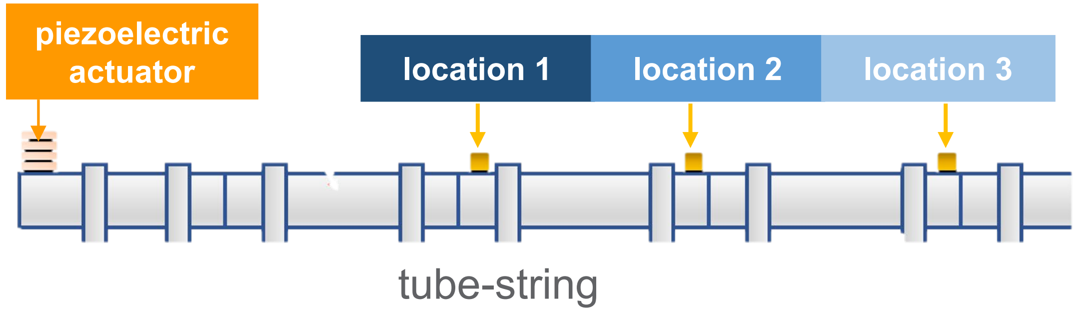
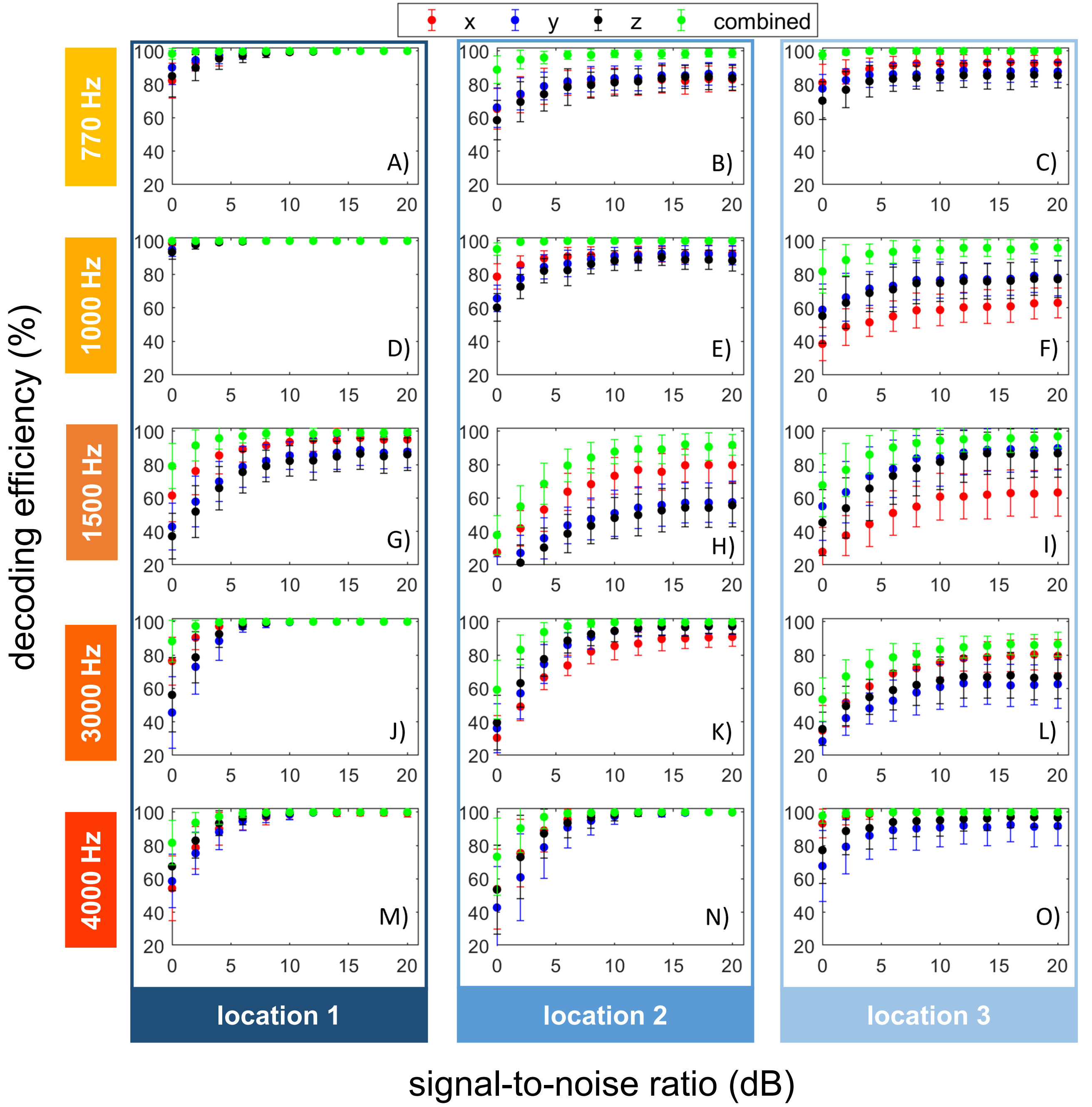
Task 1: Results - Decoding Efficiency of BPSK Scheme

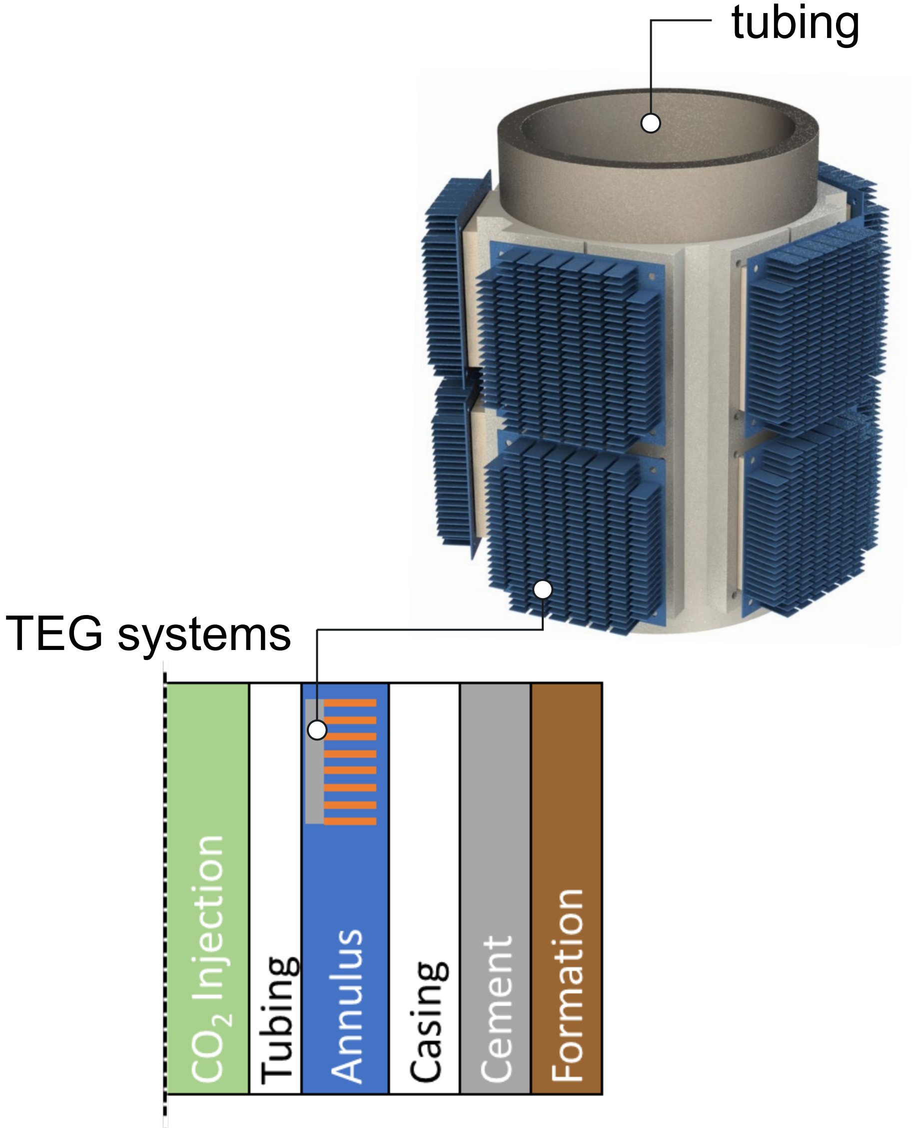


- Carrier frequencies of 770 and 1000 Hz have better decoding efficiencies than other testing frequencies.
- At 770 Hz, 100% decoding efficiencies were achieved at all three locations when the SNR was 2 dB.
- The decoding efficiency at 2000 Hz (not shown in the figure) is less than 1%.



Task 2: Benchtop Energy Harvesting System

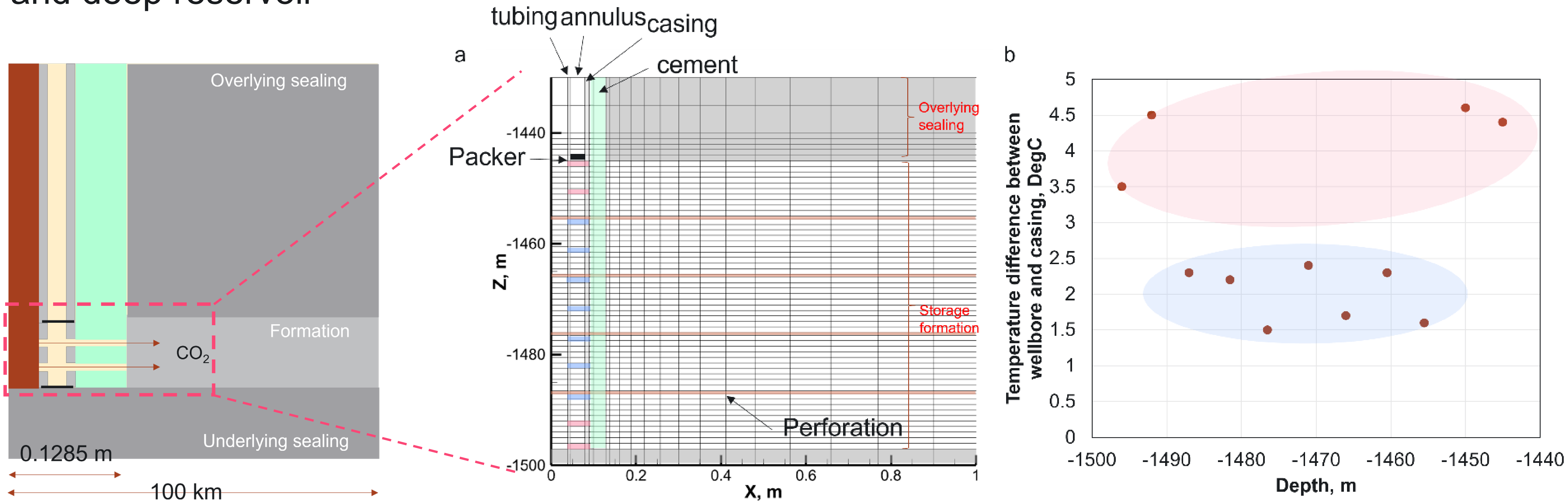
- TEGs will be mounted around the tubing in annulus to harvest thermal gradient energy between casing and tubing
- Range of available temperature difference is from 1.5 to 10 °C[1-5]
- Field data from MRCSP (Northern Michigan)[6] shows that temperature difference is around 3 °C (Max: 4 °C)
- Our energy generation target is 1 kJ/day under high-temperature and high-pressure conditions (harsh downhole environment)



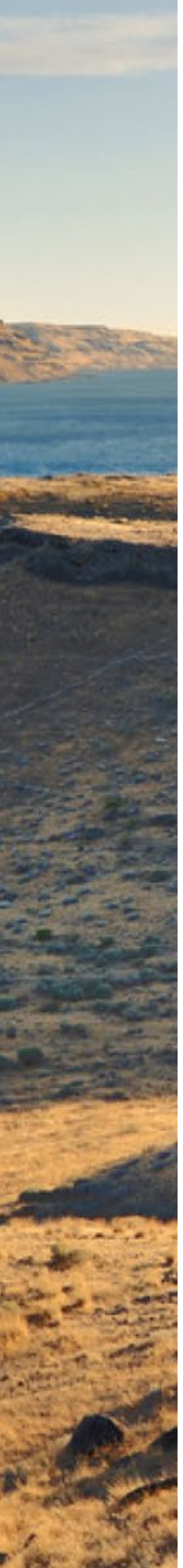
[1] X. Lyu, S. Zhang, X. Ma, F. Wang, and J. Mou, "Numerical investigation of wellbore temperature and pressure fields in CO2 fracturing," *Appl. Therm. Eng.*, vol. 132, pp. 760–768, Mar. 2018, doi: 10.1016/j.applthermaleng.2017.12.095.
[2]X. Zang *et al.*, "Real-time, wireless access to sensor data using telemetry for monitoring the deep subsurface," Pacific Northwest National Laboratory, PNNL-32162, Sep. 2021.
[3]X. Li *et al.*, "A unified model for wellbore flow and heat transfer in pure CO2 injection for geological sequestration, EOR and fracturing operations," *Int. J. Greenh. Gas Control*, vol. 57, pp. 102–115, Feb. 2017, doi: 10.1016/j.ijggc.2016.11.030.
[4]B. Ruan, R. Xu, L. Wei, X. Ouyang, F. Luo, and P. Jiang, "Flow and thermal modeling of CO2 in injection well during geological sequestration," *Int. J. Greenh. Gas Control*, vol. 19, pp. 271–280, Nov. 2013, doi: 10.1016/j.ijggc.2013.09.006.
[5]X. Lyu, S. Zhang, Y. He, Z. Zhuo, C. Zhang, and Z. Meng, "Numerical Investigation on Wellbore Temperature Prediction during the CO2 Fracturing in Horizontal Wells," *Sustainability*, vol. 13, no. 10, Art. no. 10, Jan. 2021, doi: 10.3390/su13105672.
[6]N. Gupta, S. Mawalkar, and A. Burchwell, "Distributed Temperature Sensing (DTS) to Monitor CO2 Migration in an Enhanced Oil Recovery Field in Northern Michigan," Battelle Memorial Inst., Columbus, OH (United States), DOE-BATTELLE-42589-DTS, Sep. 2020. doi: 10.2172/1773169.

Task 2: Reservoir Modeling by STOMP-CO2

Performed large-scale reservoir simulation to study thermal behavior of the injected CO_2 and deep reservoir

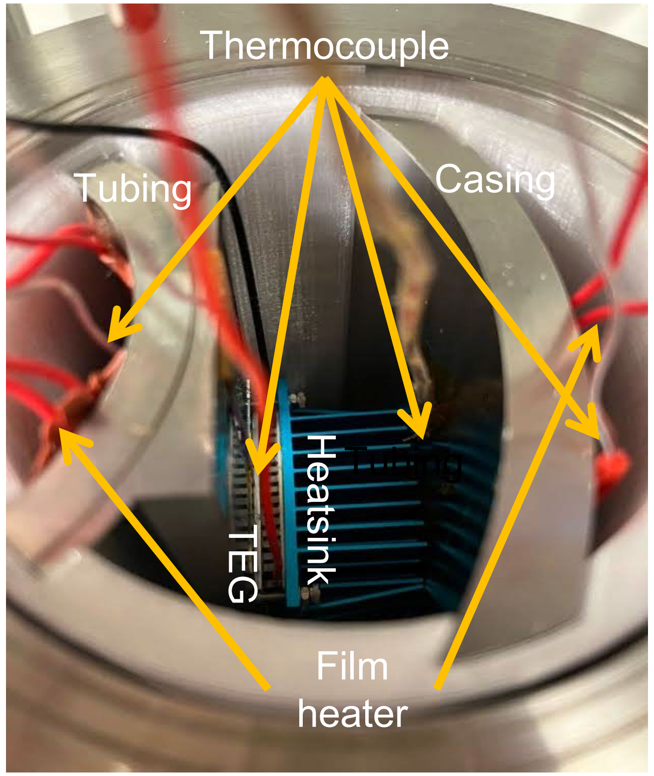


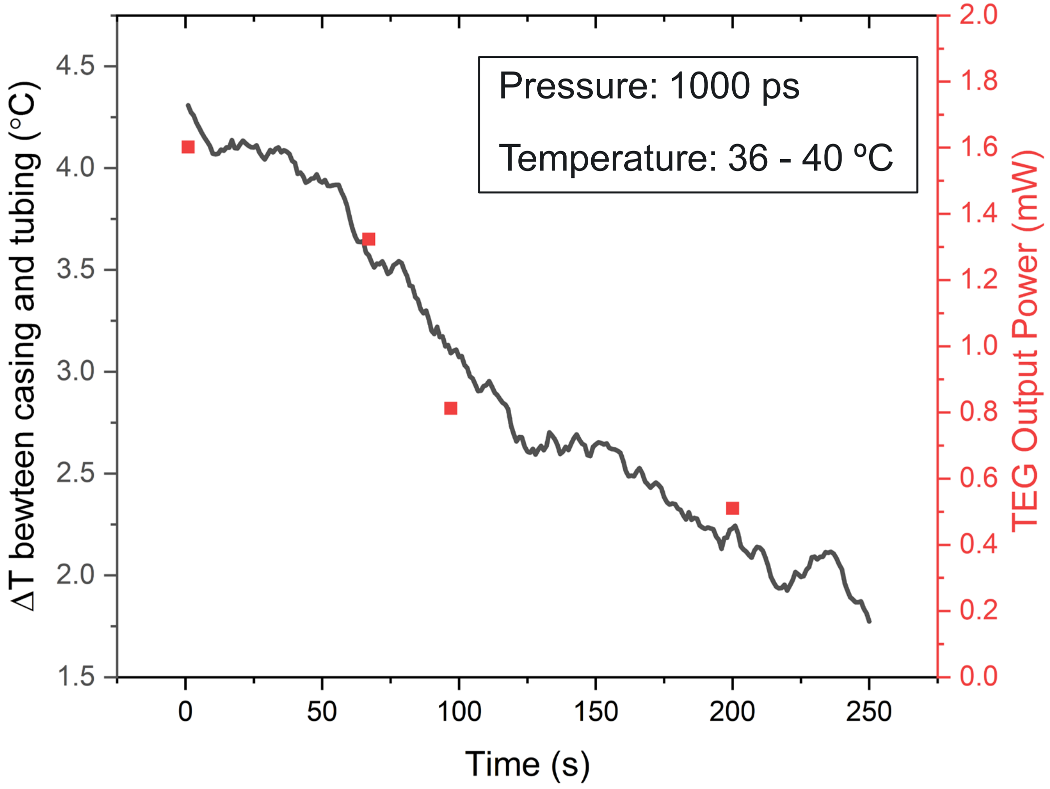
- Temperature gradient across well structures (wellbore to outer casing) were analyzed.
- TEG placement study was conducted to analyze theoretical energy production. A range of available temperature difference is between **1.5 °C to 5 °C**.



Task 2: High-Pressure Testing of Single TEG

- High pressure (≤5000psi) TEG testing setup to mimic the downhole environment.





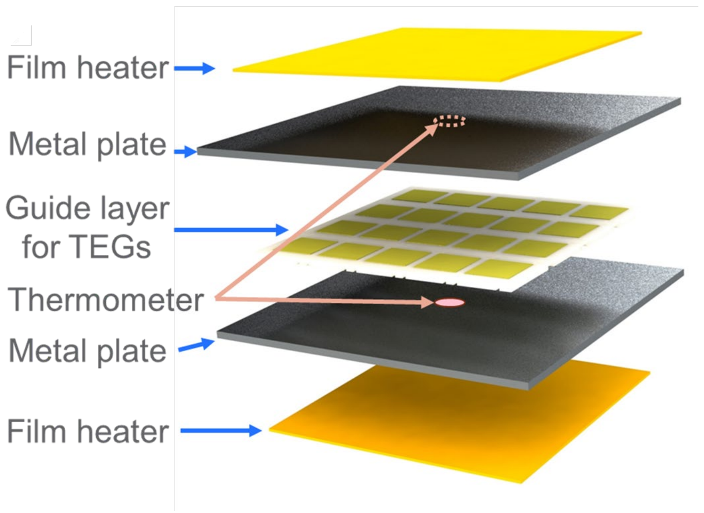
Average power: **1.06 mW** from single TEG

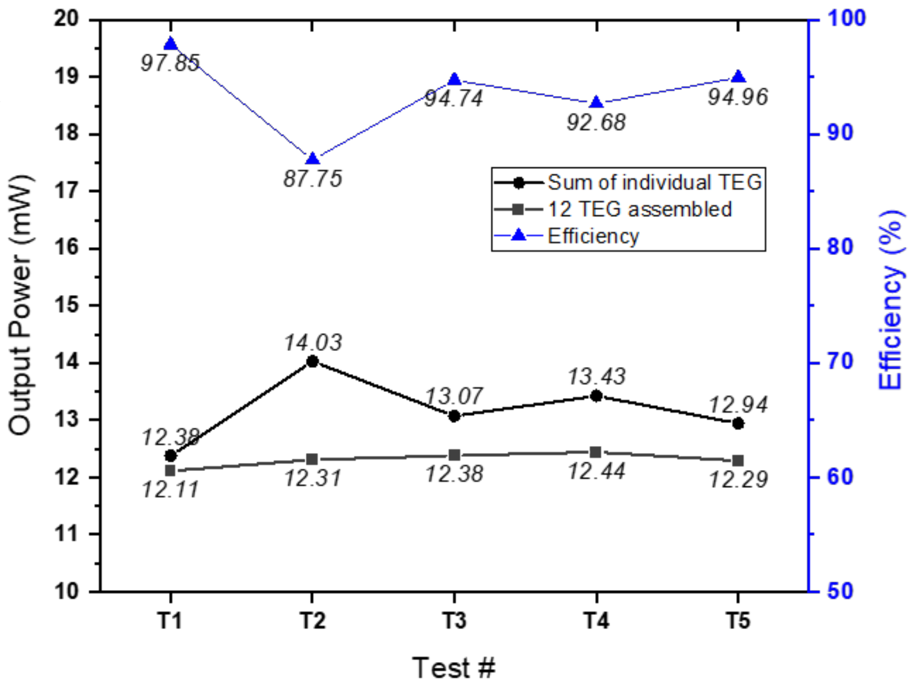
12 TEGs are needed to power the system

Task 2: TEG Modules and Power Management Circuit (PMC) Testing

Multi-array TEG modules

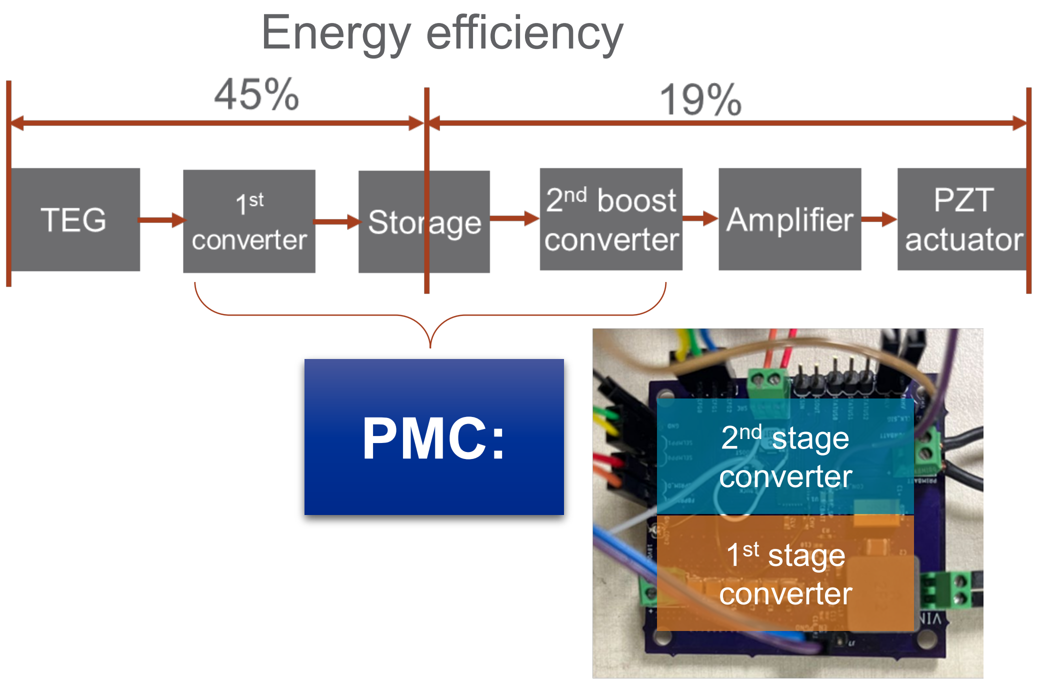
- 12 TEGs are assembled in series and in parallel
- Under 3°C difference, >12 mW power is generated by the multi-array TEGs, retain 93.6% (average) of power output compare with single TEG.



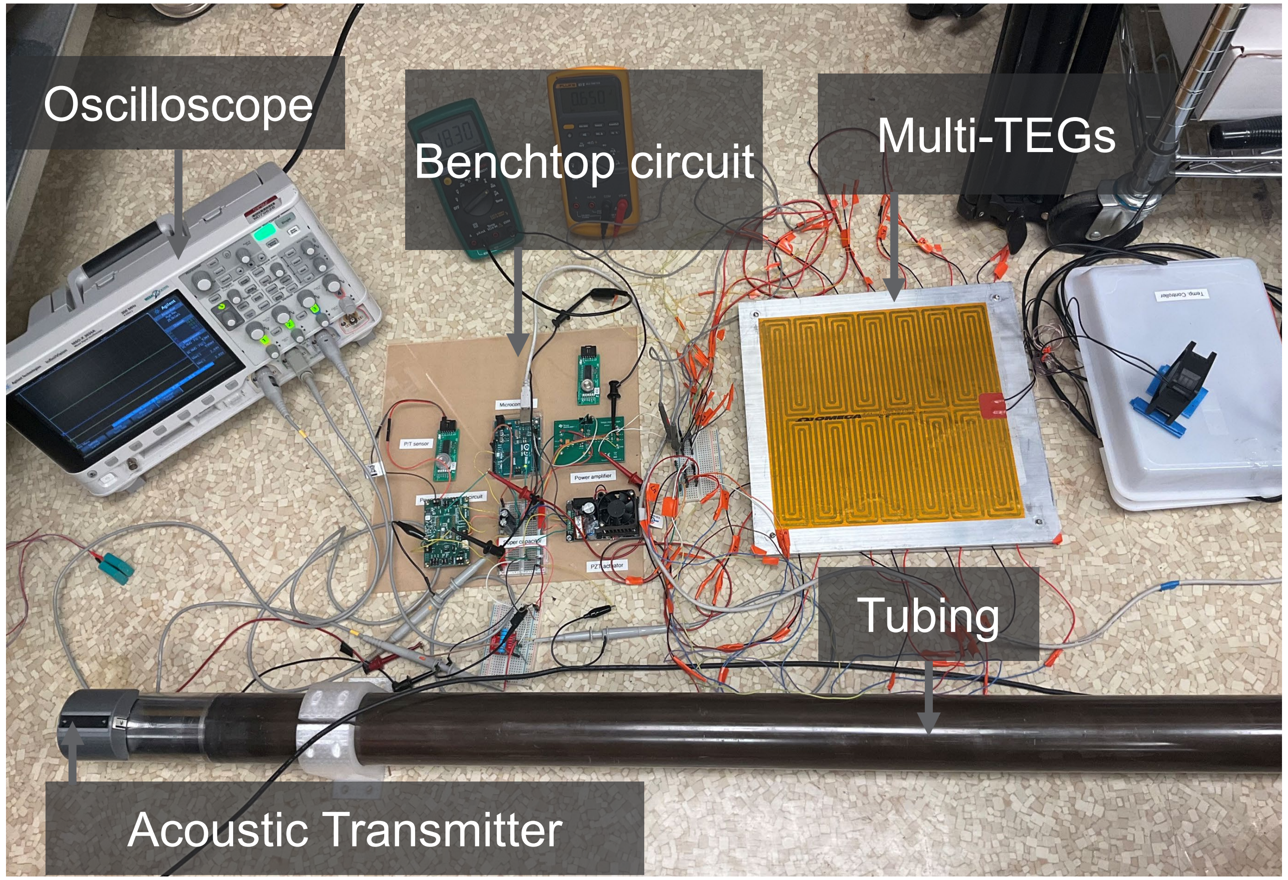


PMC

- PCM consists of two dc/dc converters.
- The energy efficiencies from TEG modules to storage (40%) and from storage to signal transmission (19%) are obtained.



Task 2: Benchtop System with Multi-Array TEGs



- Multi-array TEG system with benchtop circuit **successfully supply power to acoustic transmitter**.
- Our TEG module (with **12 mW power output**) can generate approximately **1.036kJ of energy per day.**
- Acoustic transmitter can transmit data **every 15 mins** using TEG output under lab conditions.
- Estimated transmission **distance of acoustic transmitter: 1448 m** under lab conditions.

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Task 2: Benchtop System with Multi-Array TEGs

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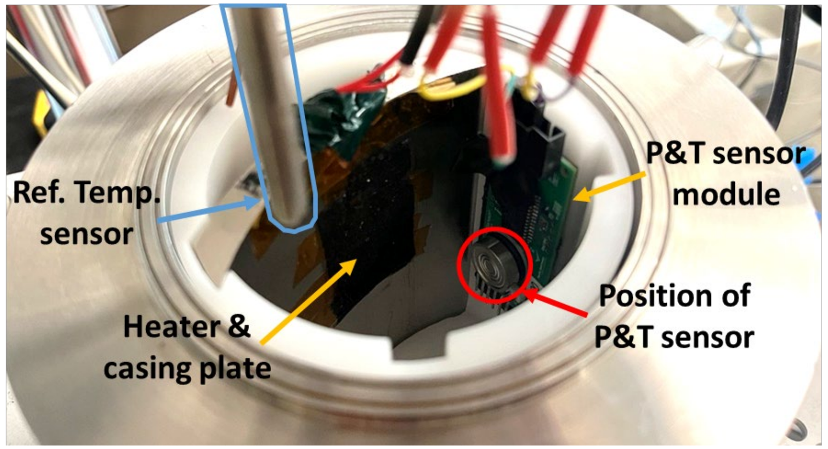
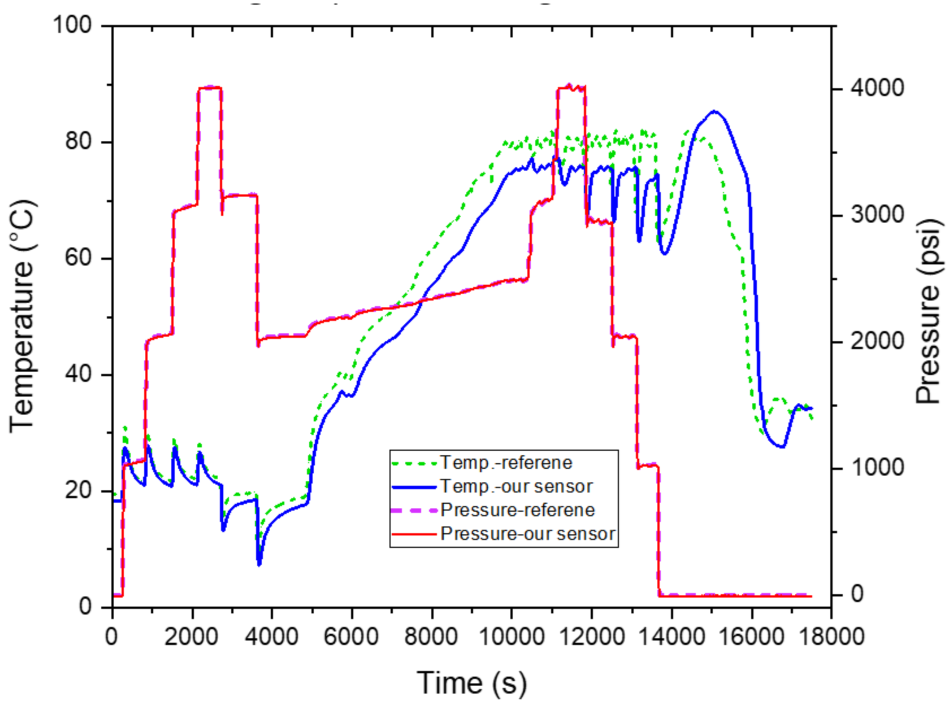
- Acoustic transmitter can transmit data **every 15 mins** using TEG output under lab conditions.
- Estimated transmission **distance of acoustic transmitter: 1448 m** under lab conditions.

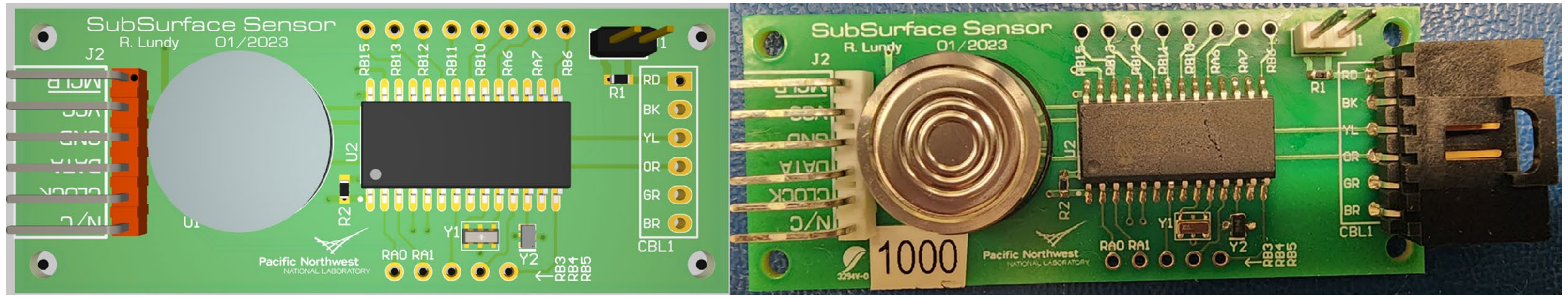
Subsurface Benchtop System Test

Task 3. Sensor Development for Harsh Environments

- The custom pressure and temperature (P&T) sensor has been designed, which can sustain up to 1000 bar (40 MPa).
- The prototype P&T sensor's performance was evaluated in a pressure chamber under extreme pressure of 4000 psi (27 MPa) and temperature up to 80°C.
- Bothe pressure and temperature sensors demonstrate consistent tracking of data fluctuations, under extreme environment.







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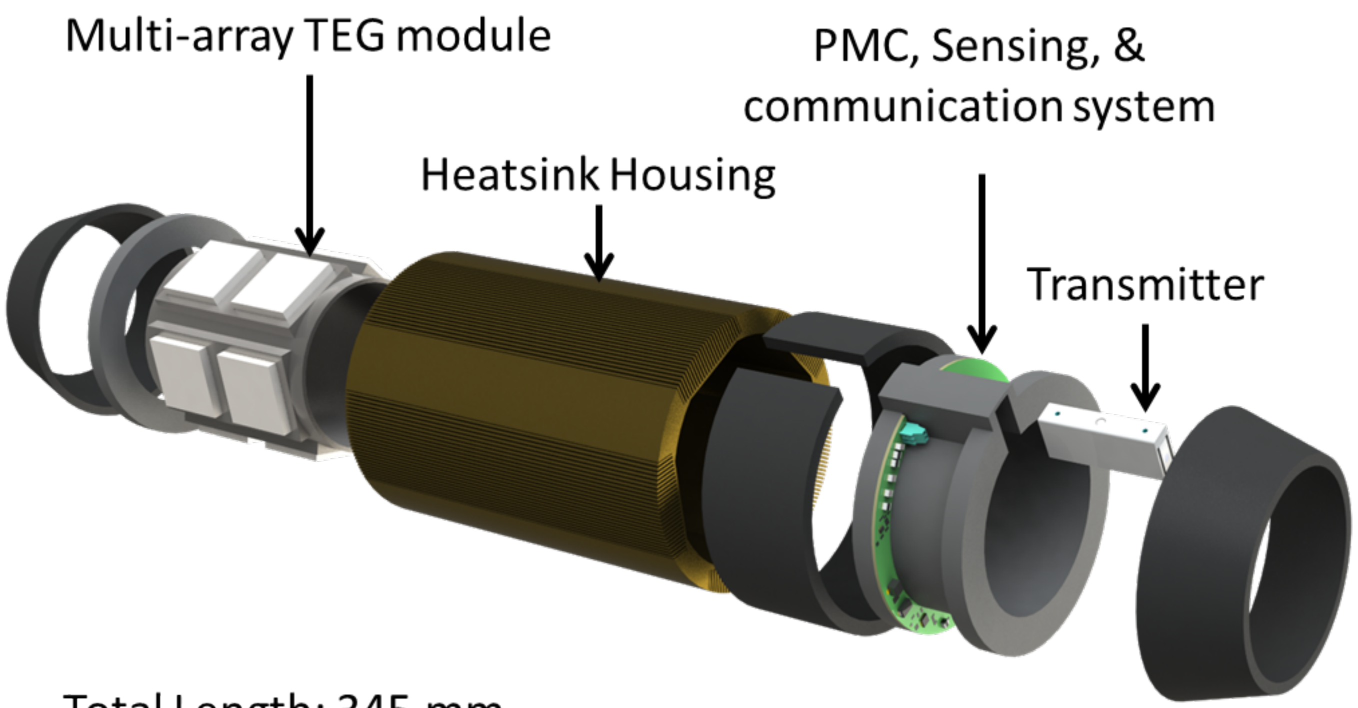
Conceptual Design of the Integrated System



Total Length: 345 mm
Max Diameter: 140 mm

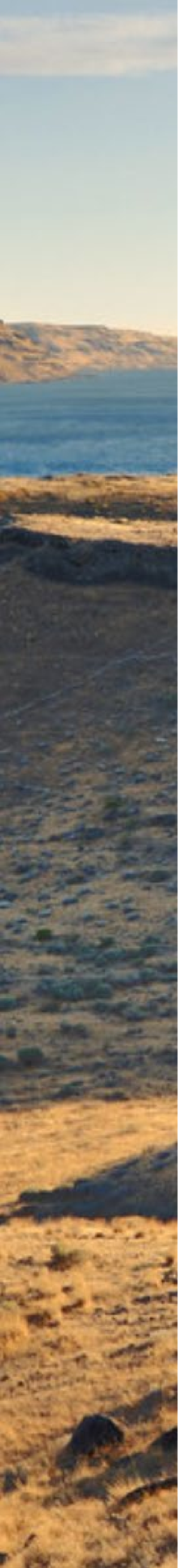
Accomplishments

- ✓ Integrated an acoustic data telemetry system in the lab and investigated the acoustic properties of the tubing string.
- ✓ At 770 Hz, 100% decoding efficiencies were achieved at all testing locations where the SNR was 2 dB.
- ✓ Tested TEG and sensing system in a high-pressure vessel.
- ✓ Demonstrated that the benchtop multi-array TEG systems can power the acoustic transmitter.
- ✓ Our benchtop prototype system can transmit data every 15 minutes using TEG output under laboratory conditions

❖ 1 journal publication, 2 conference presentations, two provisional patents

Next Steps

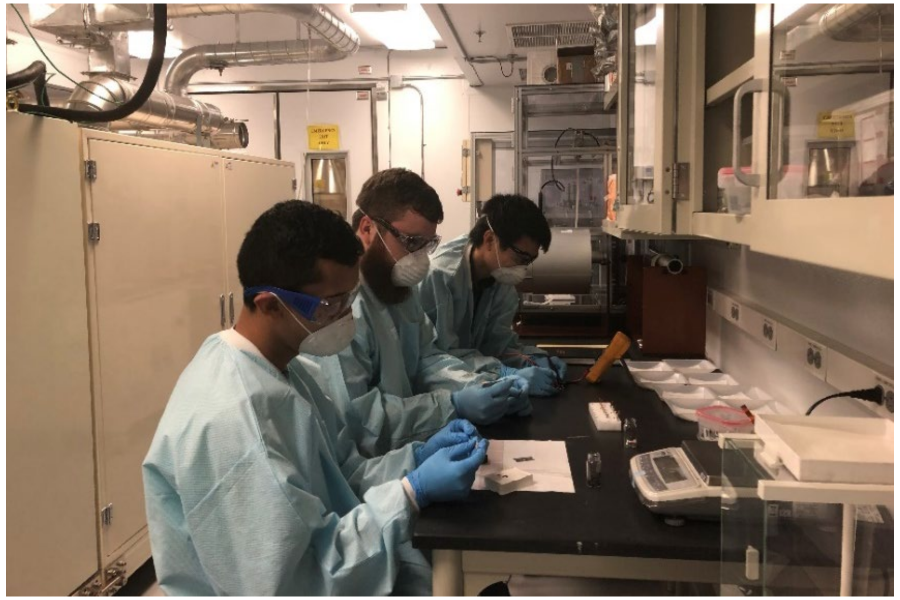
- Optimize the coding and decoding schemes of DPSK
- Optimize the design of multi-array TEG systems and PMC; build and conduct full-scale prototype benchtop testing
- Miniaturize the sensing system
- Evaluate the integrated system in a relevant environment



Acknowledgments

DOE FECM for funding opportunities

Neeraj Gupta's team at Battelle for the field data



Zhiqun.deng@pnnl.gov