Development of a Low-Cost Non-Dispersive Infrared Spectrometer for Real-Time Nitrous Oxide Detection

Zachary Holt[1], Dr. MD Shaad Mahmud[1], Dr. Wilfred Wollheim[2]

1) Department of Electrical and Computer Engineering, 2) Department of Natural Resources and the Environment, University of New Hampshire

Contact Information
Zachary.Holt@unh.edu

Introduction

- Nitrous oxide (N_2O) is the third-most problematic greenhouse gas [1]
- N_2O is a dominant ozone-depleting gas [2]
- Agricultural soils are responsible for 75% of U.S. N_2O emissions [1], [3]
- Monitoring soil N_2O emissions is vital to modeling climate change and for sustainable agriculture [4]
- N_2O emissions are highly variable, sometimes changing within hours and across single fields [3]
- Soil N_2O emissions are primarily driven by commercial fertilizer use [3]
- Current N_2O measurement devices are costly and limited in spatial and temporal resolution [3]

Project Motivation

This project has two distinct goals:

1. To enable real-time, *in-situ* N_2O flux measurement for soils and watersheds, enhancing understanding of emissions

2. For integration in a combustion-based total soil nitrogen device for precision fertilizer application

Technical Background

- N_2O uniquely absorbs IR light at 4.5 µm
- The absorption of 4.5µm in a cell is proportional to the concentration of N_2O

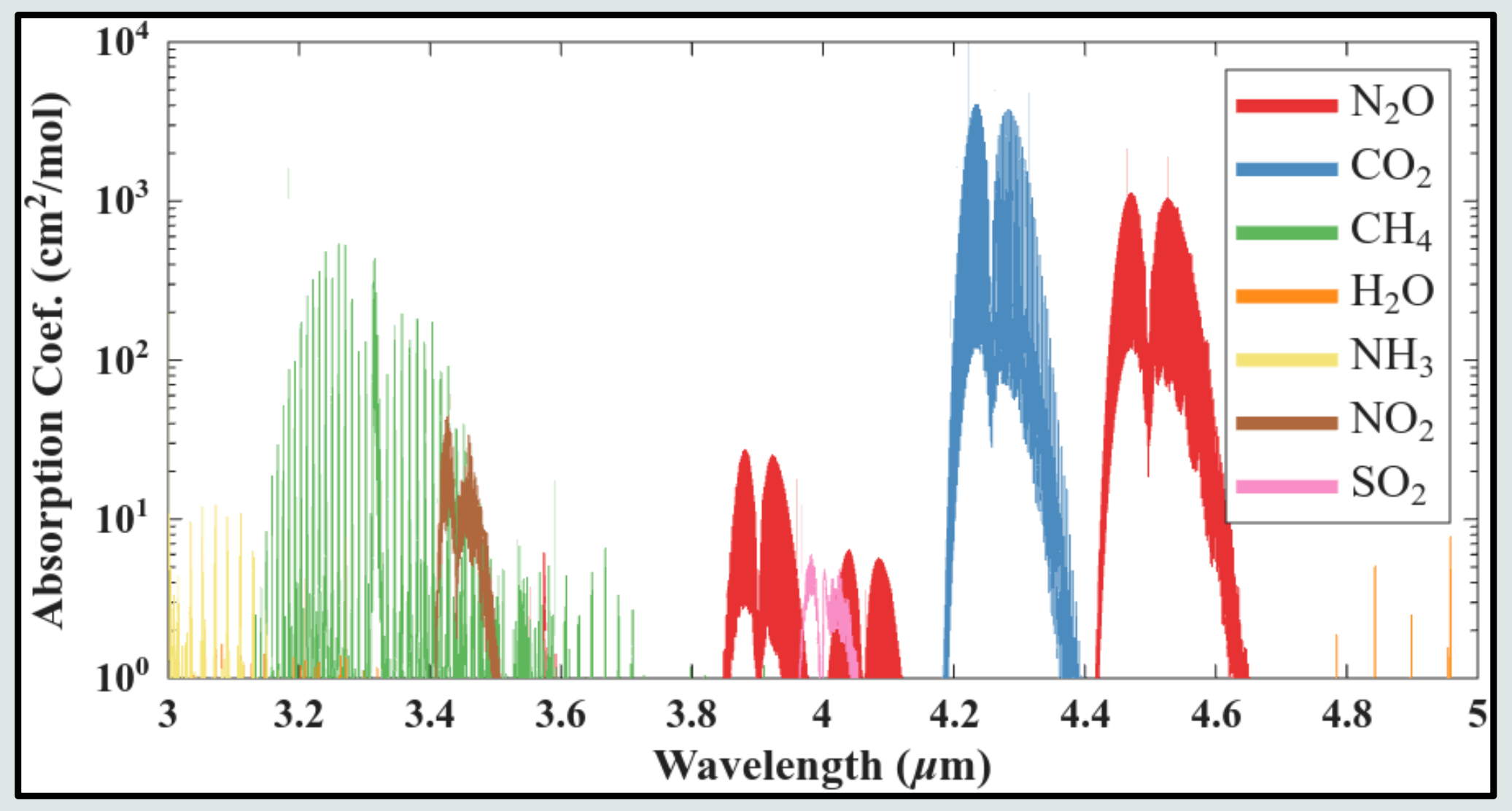


Figure 1: The log absorption spectra of common gases in the Mid-IR range.

The Beer-Lambert Law relates the absorption of light to the concentration of gas, given by:

$$I_o / I = \epsilon l c$$

where I = absorbed light intensity, I_o = reference intensity, ϵ = molar extinction coefficient, l = path length, c = gas concentration

In a dual-channel system (N_2O and Reference), the concentration is given as:

$$c = \frac{T}{T_{cal}} \frac{P_{cal}}{P} \left[\frac{\ln \frac{(N_2O)}{(Ref) * Zero}}{\epsilon l} \right]$$

where T_{cal} and P_{cal} are the temp. and pressure when ϵ was calculated and *Zero* is the zero-gas ratio between the channels

Sensor Design

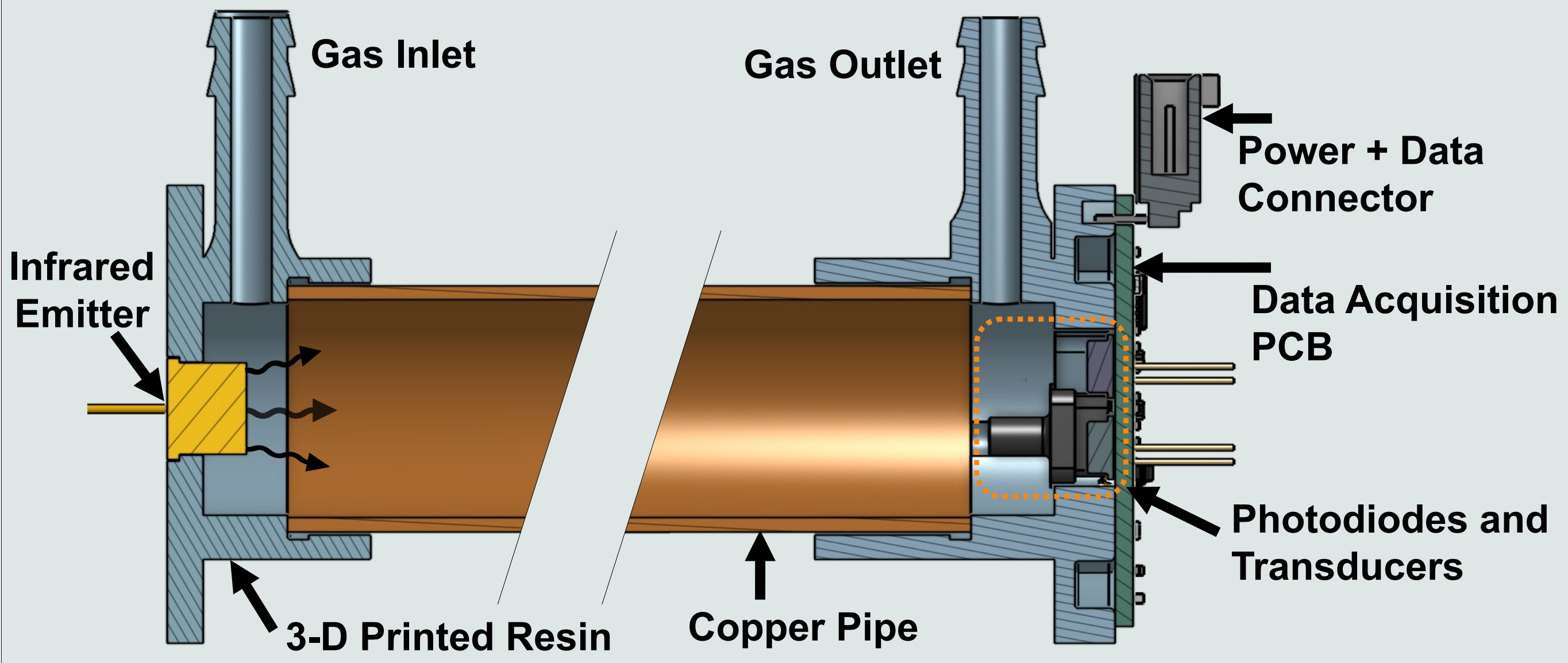


Figure 2: A cross-sectional view of the NDIR sensor. A custom copper gas cell reduces cost and while retaining high MIR reflectivity.

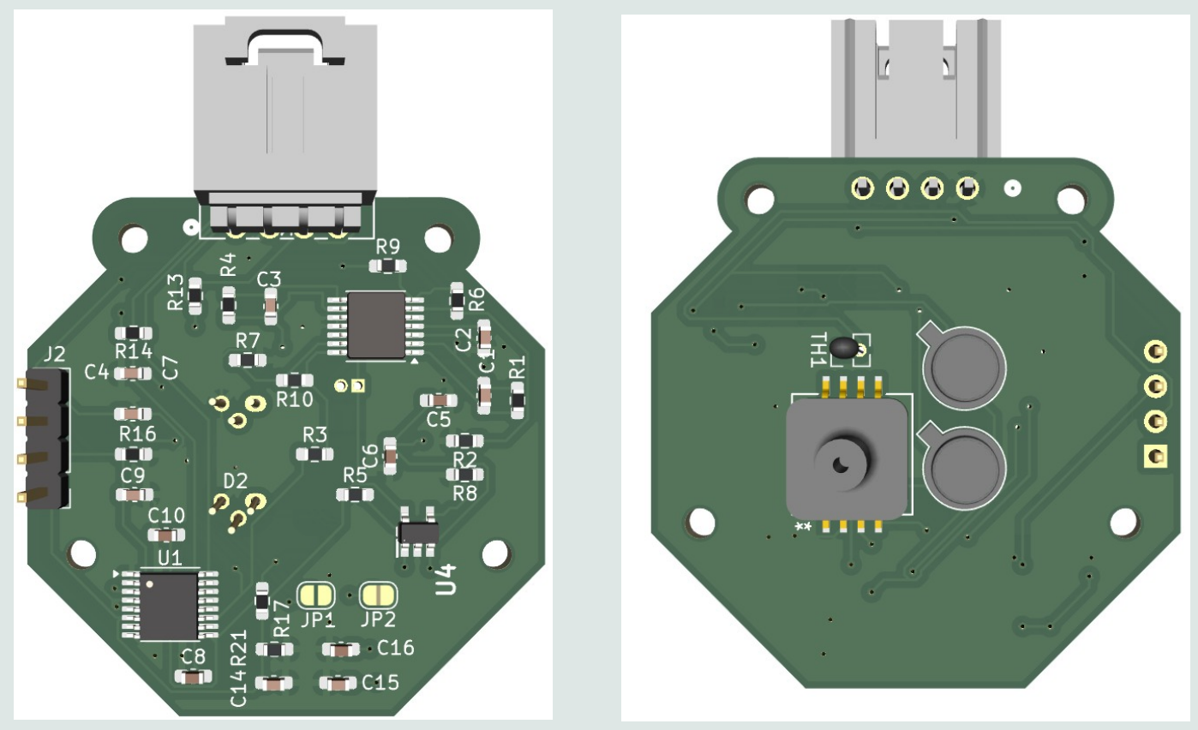


Figure 3: The data acquisition board. The left image shows the signal conditioning circuitry, while the right shows the sensor array.

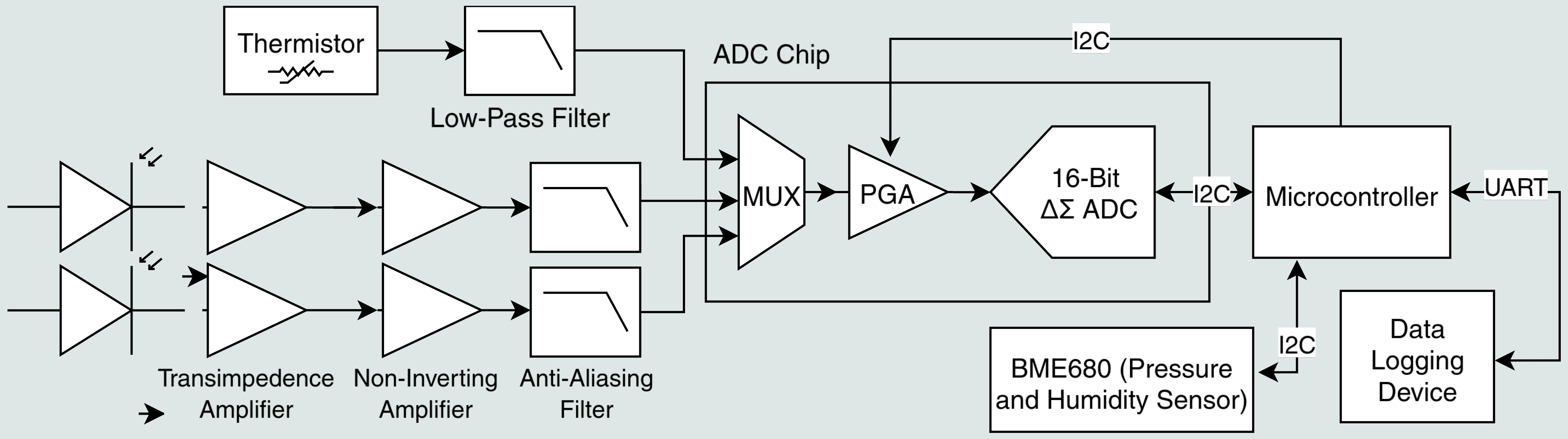


Figure 4: The block diagram of the signal conditioning circuitry.

Test Methods and Results

- A mixing system was built to create known N_2O concentrations
- 100 ppm N_2O calibration gas is injected using a syringe
- The gas is mixed and circulated through the NDIR sensor
- Sensor output is captured and analyzed
- A 1st order IIR filter used to filter photodiode signals
- ϵ was determined empirically using the first concentration step

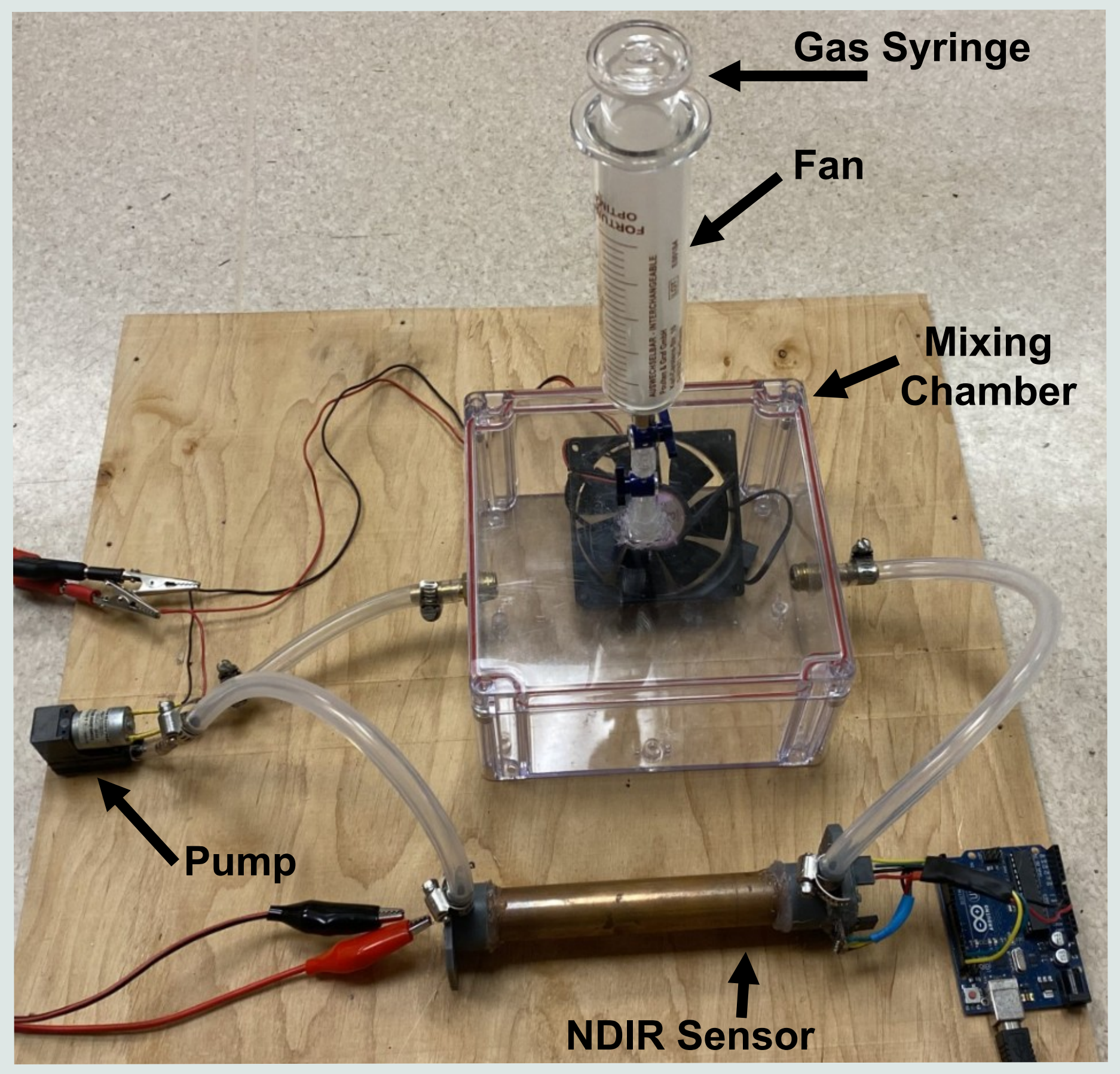


Figure 5: A mixing system to create a known N_2O concentration.

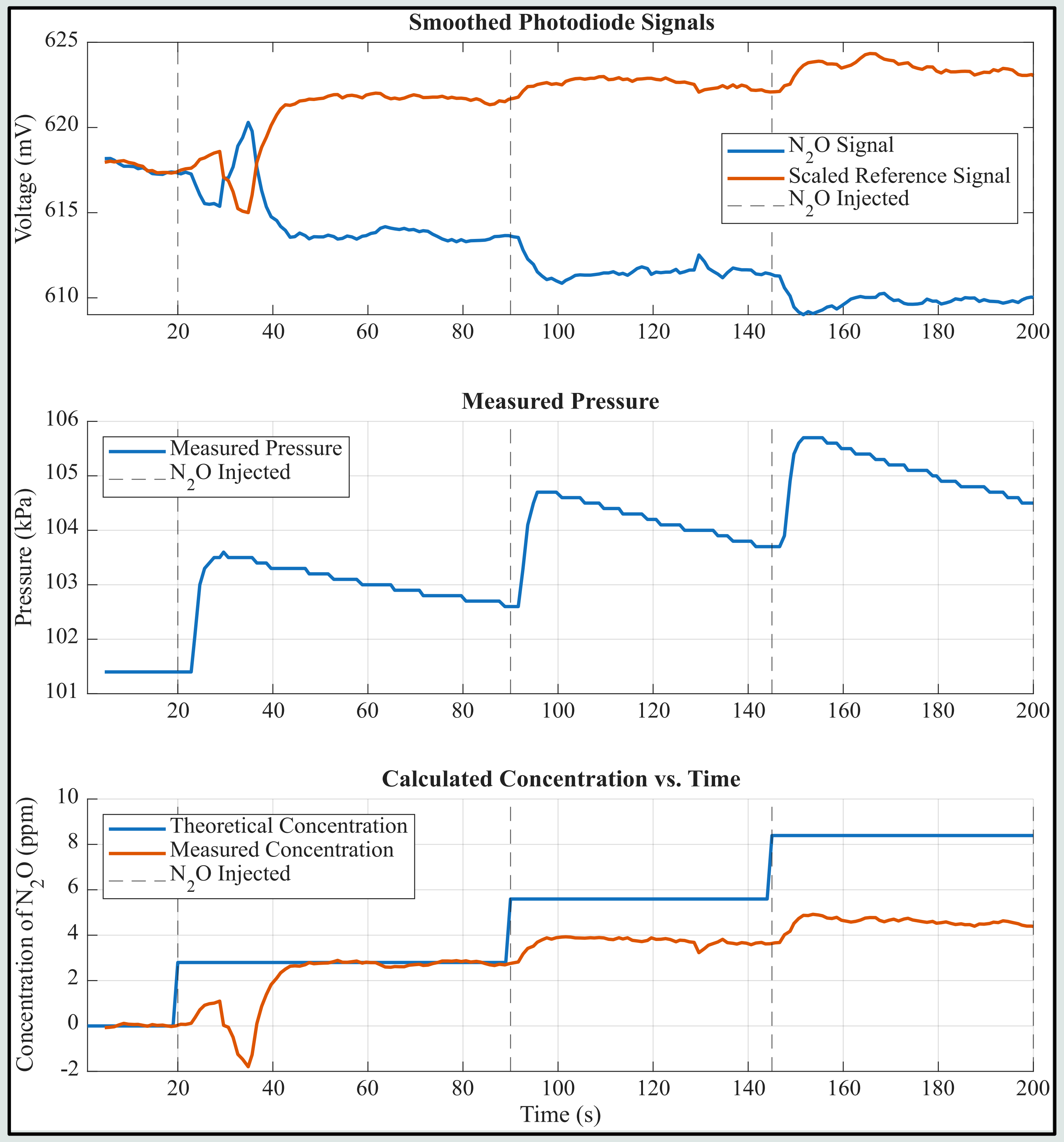


Figure 6: The results of the closed-system calibration tests.

Discussion

- Despite best sealing efforts, the system exhibited a 15-20 Pascal/sec leak
- Gas leakage may cause actual N_2O concentrations to be lower than theoretical, explaining sensor response
- The reference signal increase with each gas injection may be due to interference between the channels, but is unclear
- Significant noise limiting detection limits without time-domain filtering
- Calculations assume ideal Beer-Lambert law

Future Work

- Develop a new gas mixing system using flow controllers to eliminate pressure requirement
- Use a pulsed IR emitter to reduce the impact of 1/f noise and increase power efficiency
- Investigate behavior of reference channel
- Conduct field tests to determine real-world performance for flux measurements

Key Contributions

- Portable, low power (1.2 W continuous) N_2O sensor enables remote field measurements
- Sensor cost under $300, significantly less than than commercially available sensors
- Demonstrated sensitivity to sub-five ppm N_2O concentration
- Reference channel enables calibration-free measurements and eliminates drift
- Alternate designs using an adjustable path length maximize sensor measurement range
- Easily integrated into flux measurement systems

References

[1] US EPA, “Overview of Greenhouse Gases,” Greenhouse Gas Emissions. Accessed: Dec. 28, 2024. [Online]. Available: https://www.epa.gov/ghgemissions/overview-greenhouse-gases

[2]A. R. Ravishankara, J. S. Daniel, and R. W. Portmann, “Nitrous Oxide (N2O): The Dominant Ozone-Depleting Substance Emitted in the 21st Century,” Science, vol. 326, no. 5949, pp. 123–125, Oct. 2009, doi: 10.1126/science.1176985. .

[3] Z. Yao et al., “Comparison of manual and automated chambers for field measurements of N2O, CH4, CO2 fluxes from cultivated land,” Atmospheric Environment, vol. 43, no. 11, pp. 1888–1896, Apr. 2009, doi: 10.1016/j.atmosenv.2008.12.031.

[4]S. M. Ogle, K. Butterbach-Bahl, L. Cardenas, U. Skiba, and C. Scheer, “From research to policy: optimizing the design of a national monitoring system to mitigate soil nitrous oxide emissions,” Current Opinion in Environmental Sustainability, vol. 47, pp. 28–36, Dec. 2020, doi: 10.1016/j.cosust.2020.06.003.

Acknowledgments

Thank you to everyone in the Real-Time Sensing Lab and the CEPS Makerspace.

This project is funded by NHAES CREATE #11HN37.

Development of a Low-Cost Non-Dispersive Infrared Spectrometer for Real-Time Nitrous Oxide Detection

Zachary Holt[1], Dr. MD Shaad Mahmud[1], Dr. Wilfred Wollheim[2]

1) Department of Electrical and Computer Engineering, 2) Department of Natural Resources and the Environment, University of New Hampshire

Contact Information
Zachary.Holt@unh.edu

Introduction

- Nitrous oxide (N_2O) is the third-most problematic greenhouse gas [1]
- N_2O is a dominant ozone-depleting gas [2]
- Agricultural soils are responsible for 75% of U.S. N_2O emissions [1], [3]
- Monitoring soil N_2O emissions is vital to modeling climate change and for sustainable agriculture [4]
- N_2O emissions are highly variable, sometimes changing within hours and across single fields [3]
- Soil N_2O emissions are primarily driven by commercial fertilizer use [3]
- Current N_2O measurement devices are costly and limited in spatial and temporal resolution [3]

Project Motivation

This project has two distinct goals:

1. To enable real-time, *in-situ* N_2O flux measurement for soils and watersheds, enhancing understanding of emissions

2. For integration in a combustion-based total soil nitrogen device for precision fertilizer application

Technical Background

- N_2O uniquely absorbs IR light at 4.5 µm

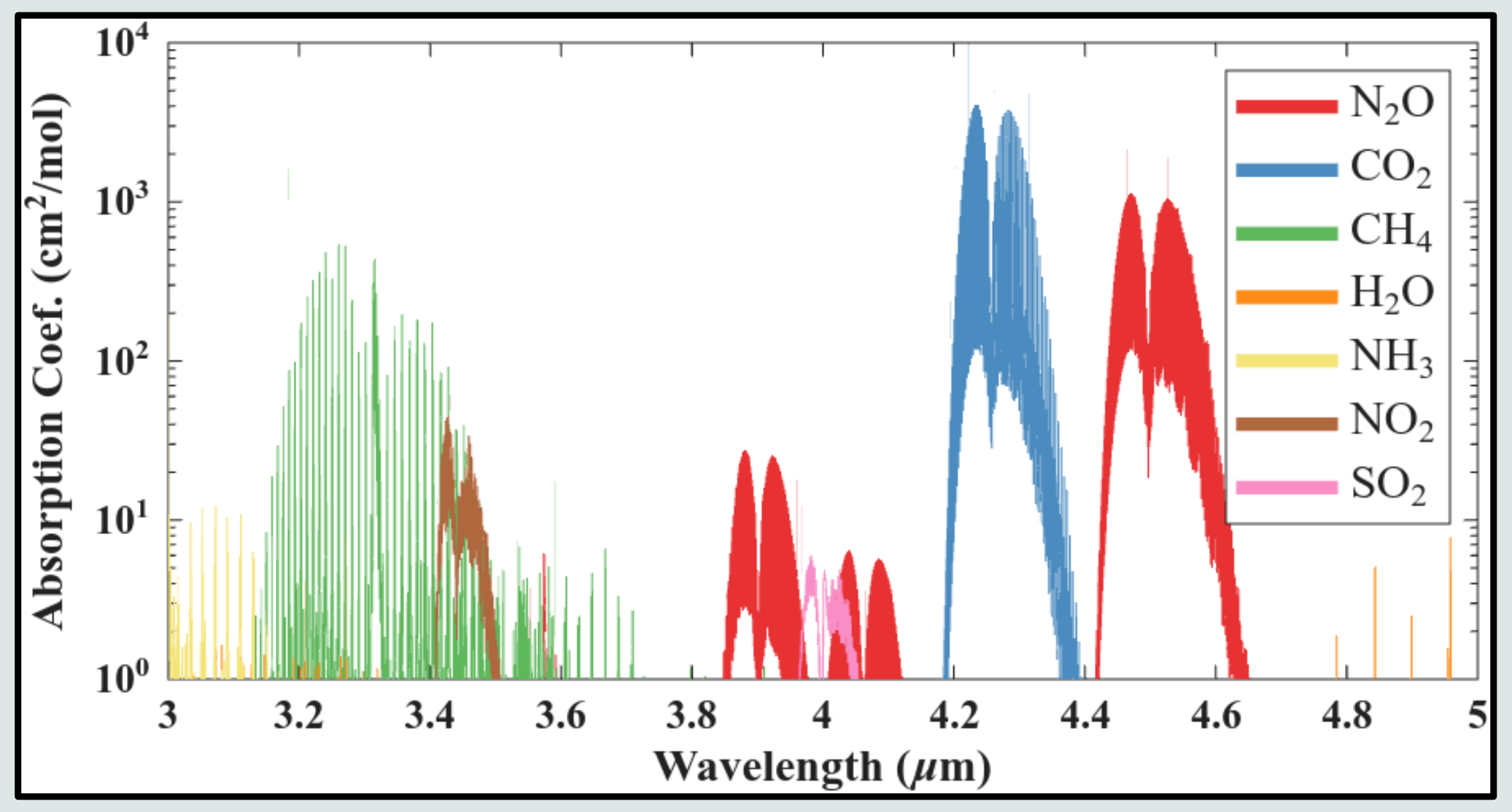


Figure 1: The log absorption spectra of common gases in the Mid-IR range.

The Beer-Lambert Law relates the absorption of light to the concentration of gas, given by:

$$I_o / I = \epsilon l c$$

Where I = experimental light intensity, I_o = reference light intensity
ϵ = molar extinction coefficient
l = gas cell path length
c = concentration of target gas

Solving for c and using the Ideal Gas Law in a dual-channel system yields:

$$c = \frac{T}{T_{cal}} \frac{P_{cal}}{P} \left[\frac{\ln \frac{(N_2O)}{(Ref) * Zero}}{\epsilon \, l} \right]$$

Sensor Design

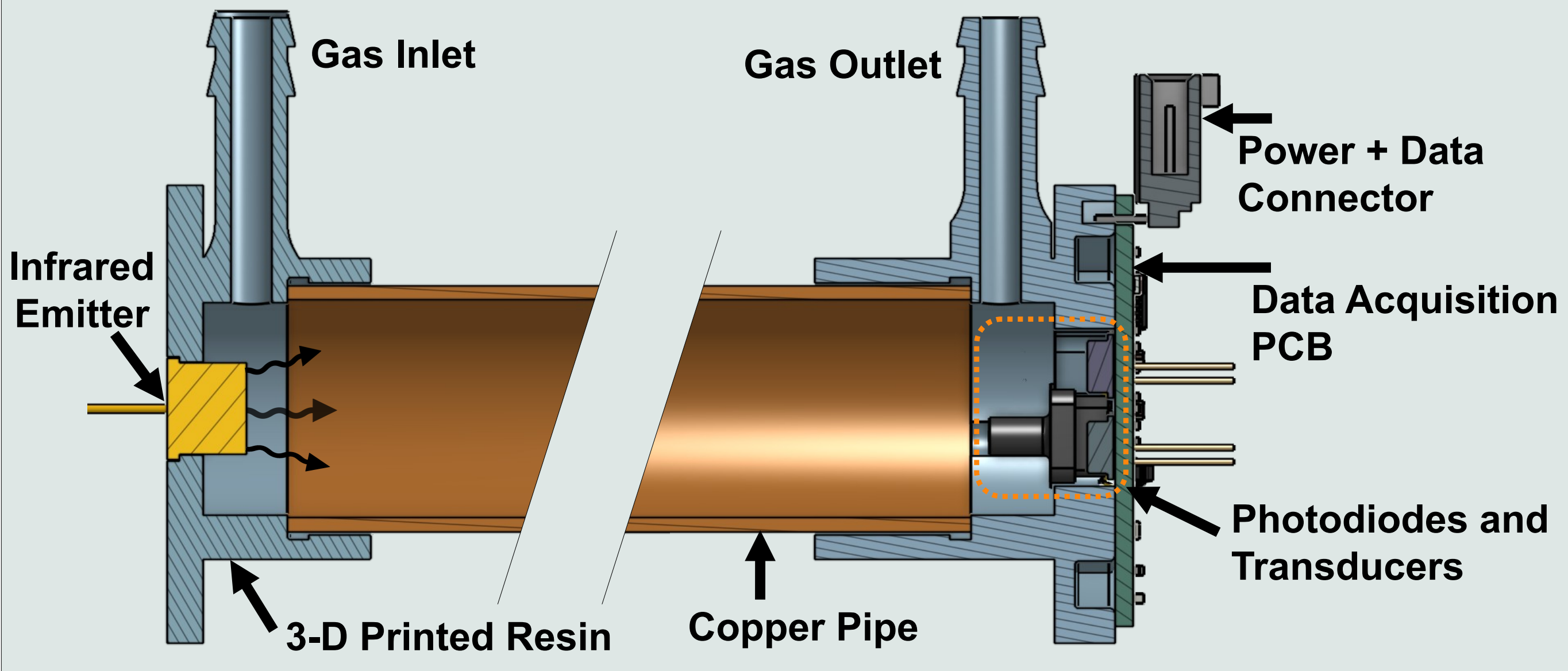


Figure 2: A cross-sectional view of the NDIR sensor. A custom copper gas cell reduces cost and while retaining high MIR reflectivity.

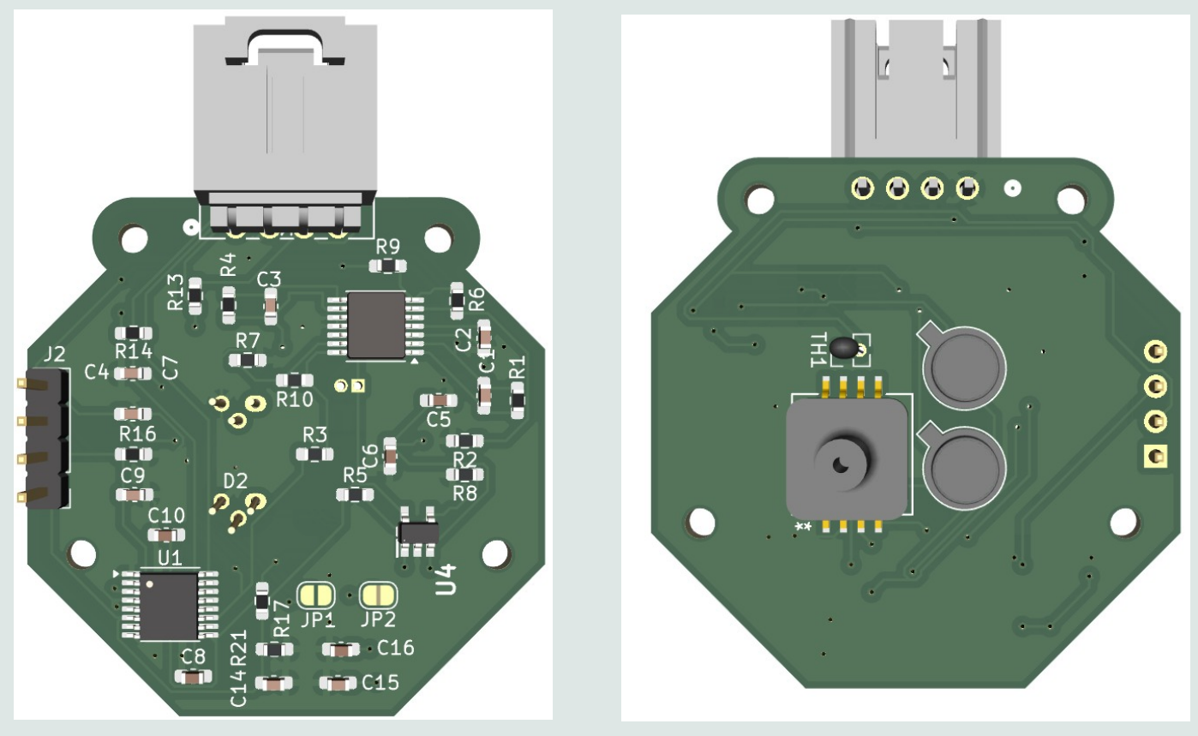


Figure 3: The data acquisition board. The left image shows the signal conditioning circuitry, while the right shows the sensor array.

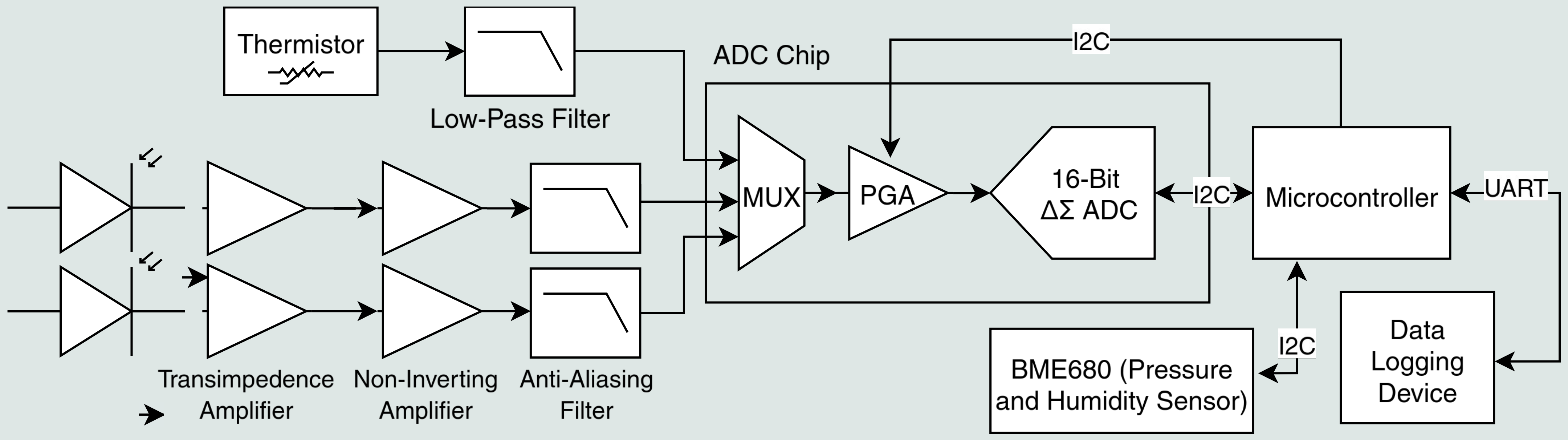
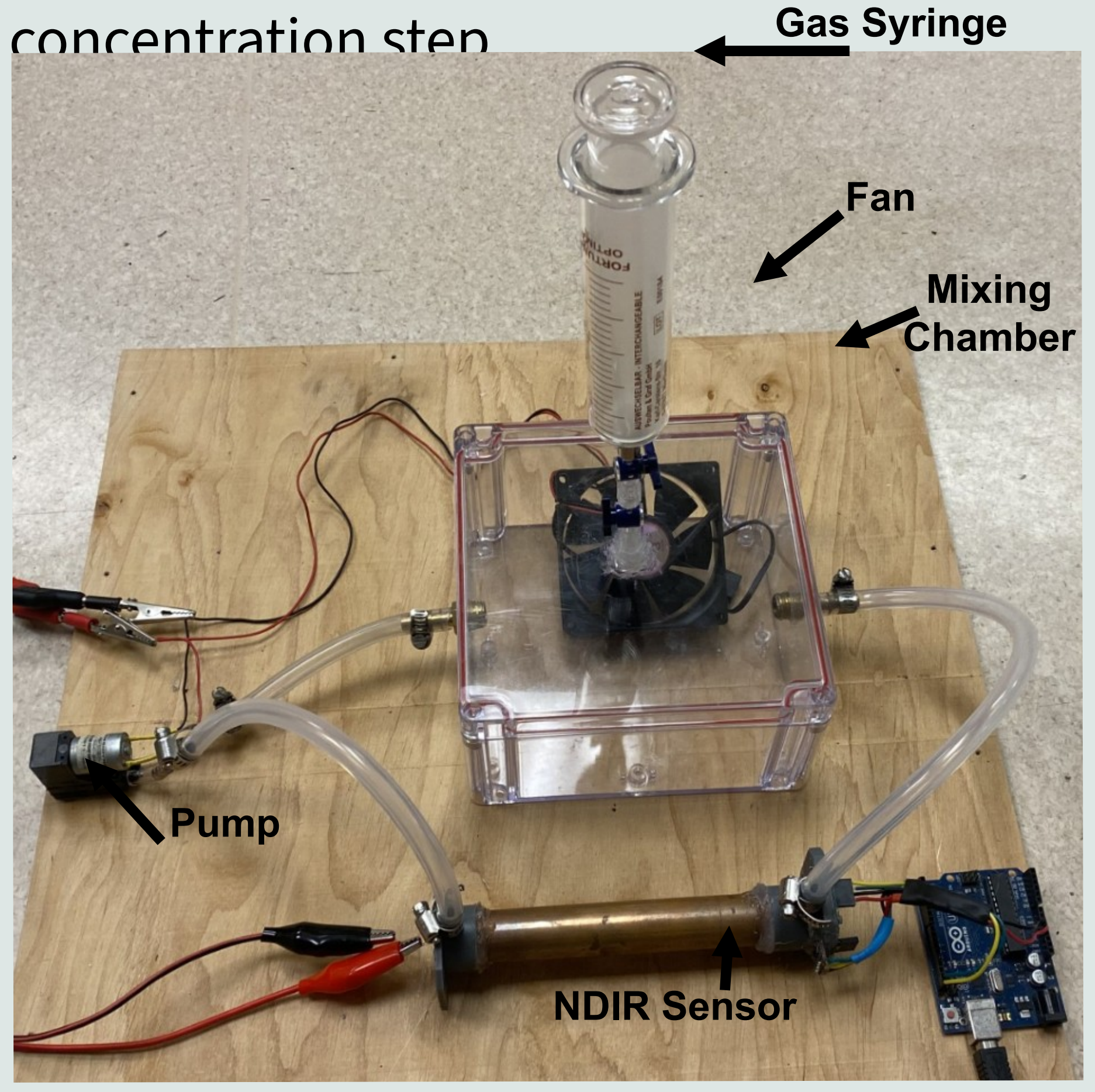
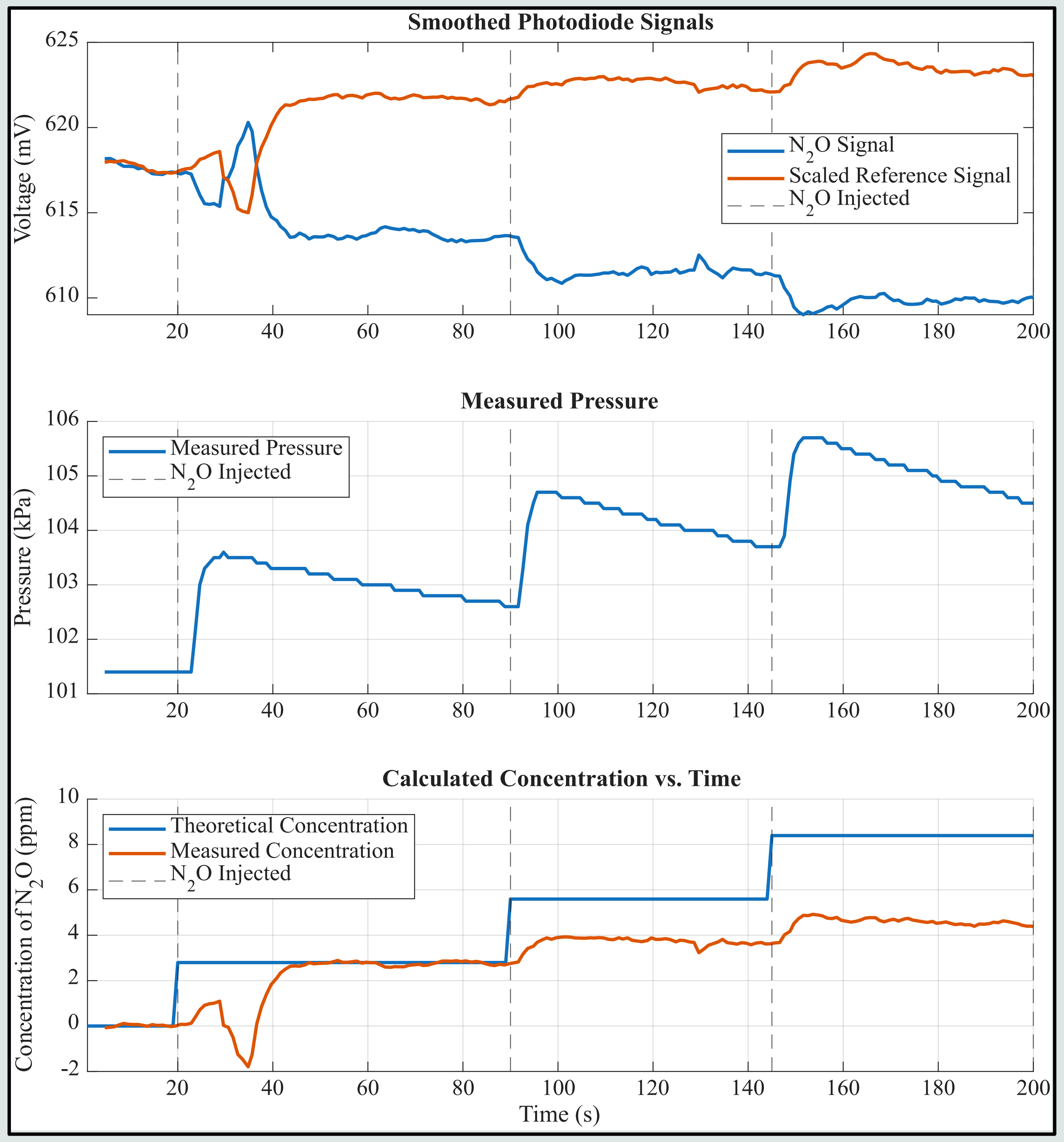


Figure 4: The block diagram of the signal conditioning circuitry.

Test Methods and Results

- A mixing system was built to create known N_2O concentrations
- 100 ppm N_2O calibration gas is injected using a syringe
- The gas is mixed and circulated through the NDIR sensor
- Sensor output is captured and analyzed
- A 1st order IIR filter used to filter photodiode signals
- ϵ was determined empirically using the first concentration step





Discussion

- Despite best sealing efforts, the system exhibited a 15-20 Pascal/sec leak
- Gas leakage may cause actual N_2O concentrations to be lower than theoretical, explaining sensor response
- The reference signal increase with each gas injection may be due to interference between the channels, but is unclear
- Significant noise limiting detection limits without time-domain filtering
- Calculations assume ideal Beer-Lambert law

Future Work

- Develop a new gas mixing system using flow controllers to eliminate pressure requirement
- Use a pulsed IR emitter to reduce the impact of 1/f noise and increase power efficiency
- Investigate behavior of reference channel
- Incorporate non-ideal Beer-Lambert law factors

Key Contributions

- Portable, low power (1.2 W continuous) N_2O sensor enables remote field measurements without power requirements
- Sensor cost under $300, significantly less than commercially available sensors
- Demonstrated sensitivity to sub-five ppm N_2O concentration
- Reference channel enables calibration-free measurements and eliminates drift
- Alternate designs using an adjustable path length maximize sensor measurement range
- Easily integrated into flux measurement systems

References

[1] US EPA, "Overview of Greenhouse Gases," Greenhouse Gas Emissions. Accessed: Dec. 28, 2024. [Online]. Available: https://www.epa.gov/ghgemissions/overview-greenhouse-gases
[2]A. R. Ravishankara, J. S. Daniel, and R. W. Portmann, "Nitrous Oxide (N2O): The Dominant Ozone-Depleting Substance Emitted in the 21st Century," Science, vol. 326, no. 5949, pp. 123–125, Oct. 2009, doi: 10.1126/science.1176985. .
[3] Z. Yao et al., "Comparison of manual and automated chambers for field measurements of N2O, CH4, CO2 fluxes from cultivated land," Atmospheric Environment, vol. 43, no. 11, pp. 1888–1896, Apr. 2009, doi: 10.1016/j.atmosenv.2008.12.031.
[4]S. M. Ogle, K. Butterbach-Bahl, L. Cardenas, U. Skiba, and C. Scheer, "From research to policy: optimizing the design of a national monitoring system to mitigate soil nitrous oxide emissions," Current Opinion in Environmental Sustainability, vol. 47, pp. 28–36, Dec. 2020, doi: 10.1016/j.cosust.2020.06.003.
[5] O. Mathieu, J. Lévêque, C. Hénault, M.-J. Milloux, F. Bizouard, and F. Andreux, "Emissions and spatial variability of N2O, N2 and nitrous oxide mole fraction at the field scale, revealed with 15N isotopic techniques," Soil Biology and Biochemistry, vol. 38, no. 5, pp. 941–951, May 2006, doi: 10.1016/j.soilbio.2005.08.010
[7]K. M. T. S. Band

Acknowledgments

Thank you to everyone in the Real-Time Sensing Lab and the CEPS Makerspace.

This project is funded by NHAES CREATE #11HN37.