Advancement of LED-Based Hazardous Gas Sensors for Space Applications

Prof. Subith Vasu

Mechanical and Aerospace Engineering,
University of Central Florida,
Orlando, FL, 32816

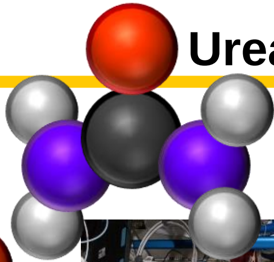
Team: A. Terracciano; A.Parupalli;
Z. Loparo; J. Urso;

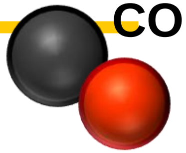
Agenda

- Motivation
- Technical Background
- High Altitude Balloon Flight
- Swept Grating Design
- Sensor Testing
- Laser Validation
- Conclusions
- Future Work
- Acknowledgements

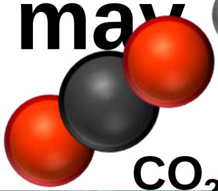
Need For Sensors & Design Theory

Motivation

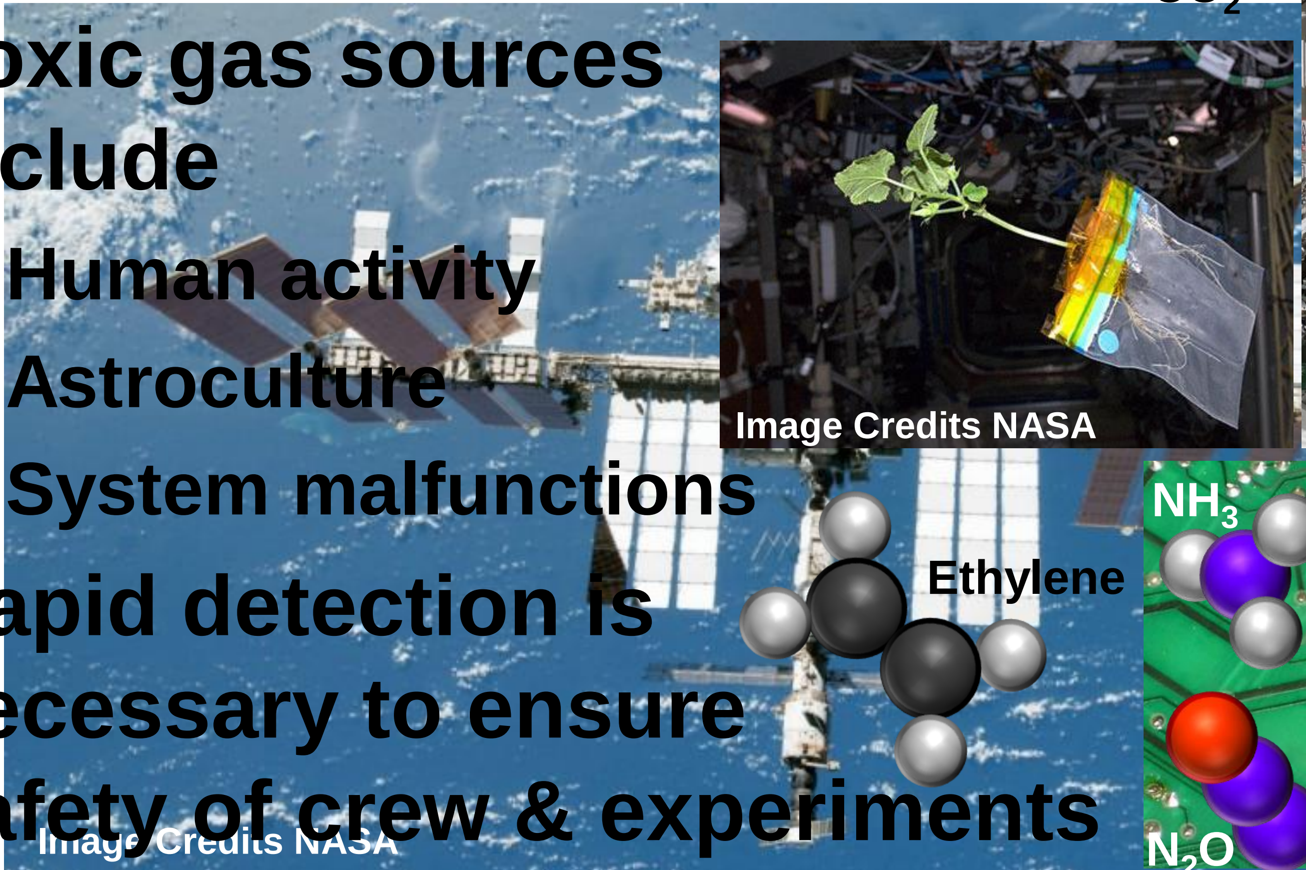


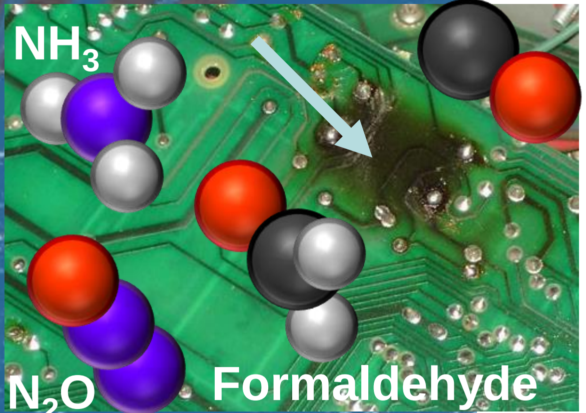


- **Cabin air is confined aboard spacecraft and toxic gases may accumulate**



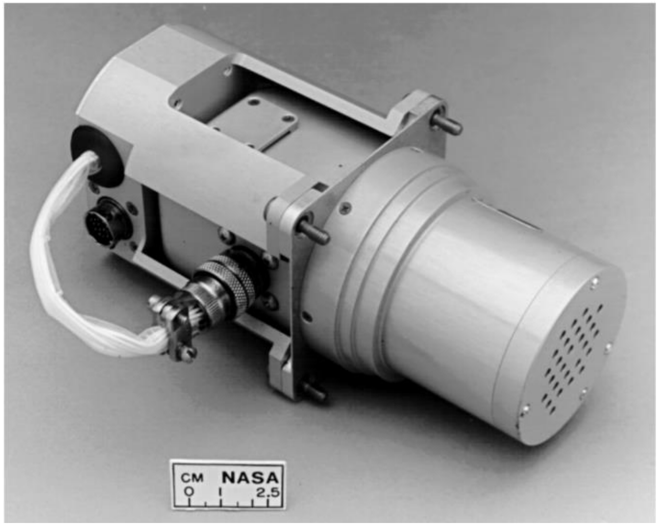
- **Toxic gas sources include**
  - **Human activity**
  - **Astroculture**
  - **System malfunctions**
- **Rapid detection is necessary to ensure safety of crew & experiments**





Motivation

- **Many current hazardous gas detection sensors are particle based**
  - **Particle ionization smoke detector**
  - **NIR laser forward scattering particle detector**
- **LEDs are more durable and less expensive than lasers**



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Absorption Spectroscopy & Beer's Law

- **Absorption Spectroscopy is an application of the Beer-Lambert Law:**

$$A(\lambda) = -ln\left(\frac{I_\lambda}{I_{\lambda,0}}\right) = \sum_i \int_{s_j}^{s_{j+1}} k_\lambda \cdot x_i \, ds$$

$A(\lambda)$ - **Spectral absorbance**

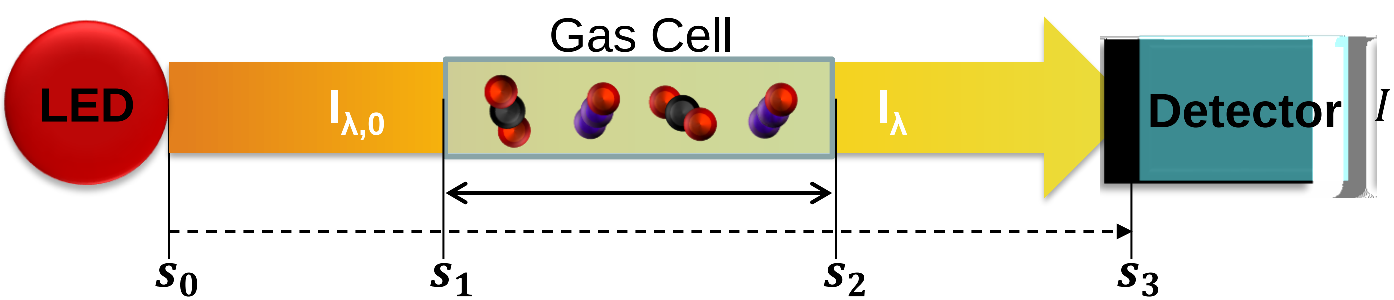
$I_{\lambda,0}$ - **Incident spectral intensity of electromagnetic radiation**

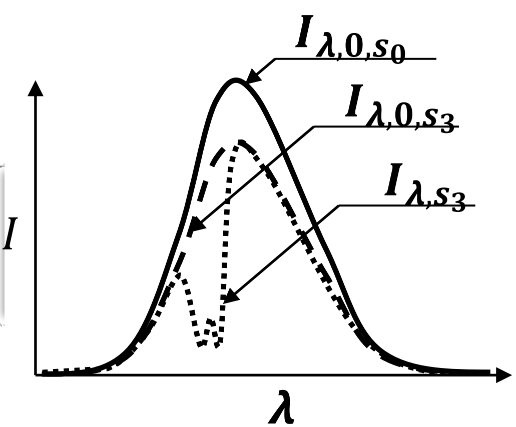
I_λ - **Transmitted spectral intensity of electromagnetic radiation**

x_i - **Molar fraction of i^th species**

k_λ - **Spectral absorbance coefficient (function of pressure, temperature, & species)**

s - **Path variable**

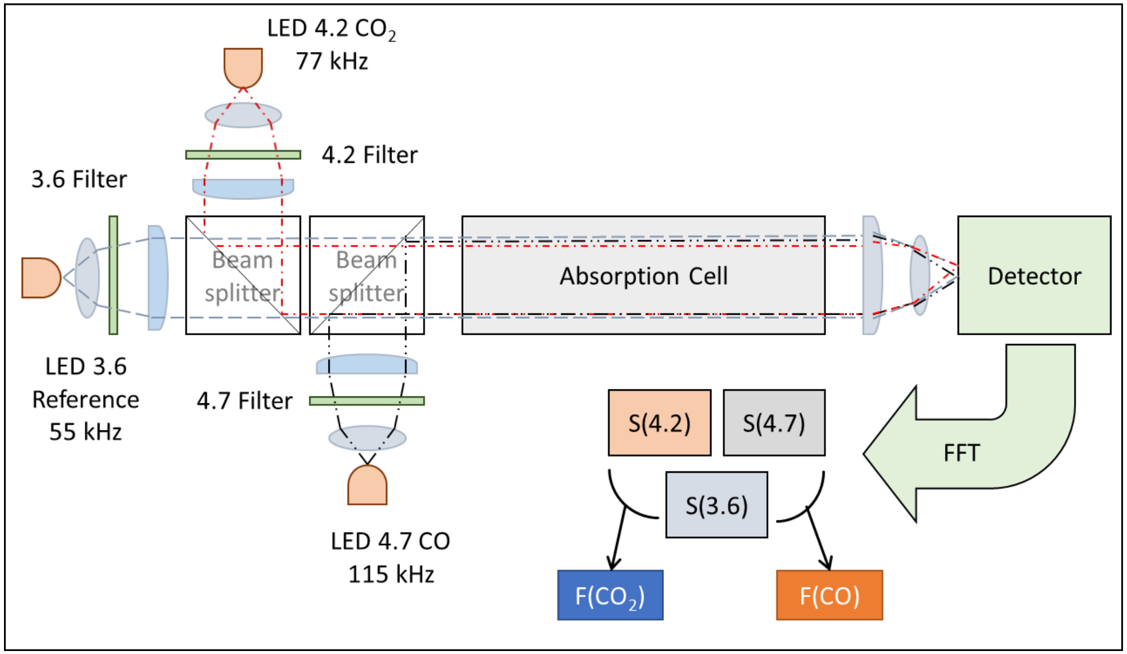




Sensor History

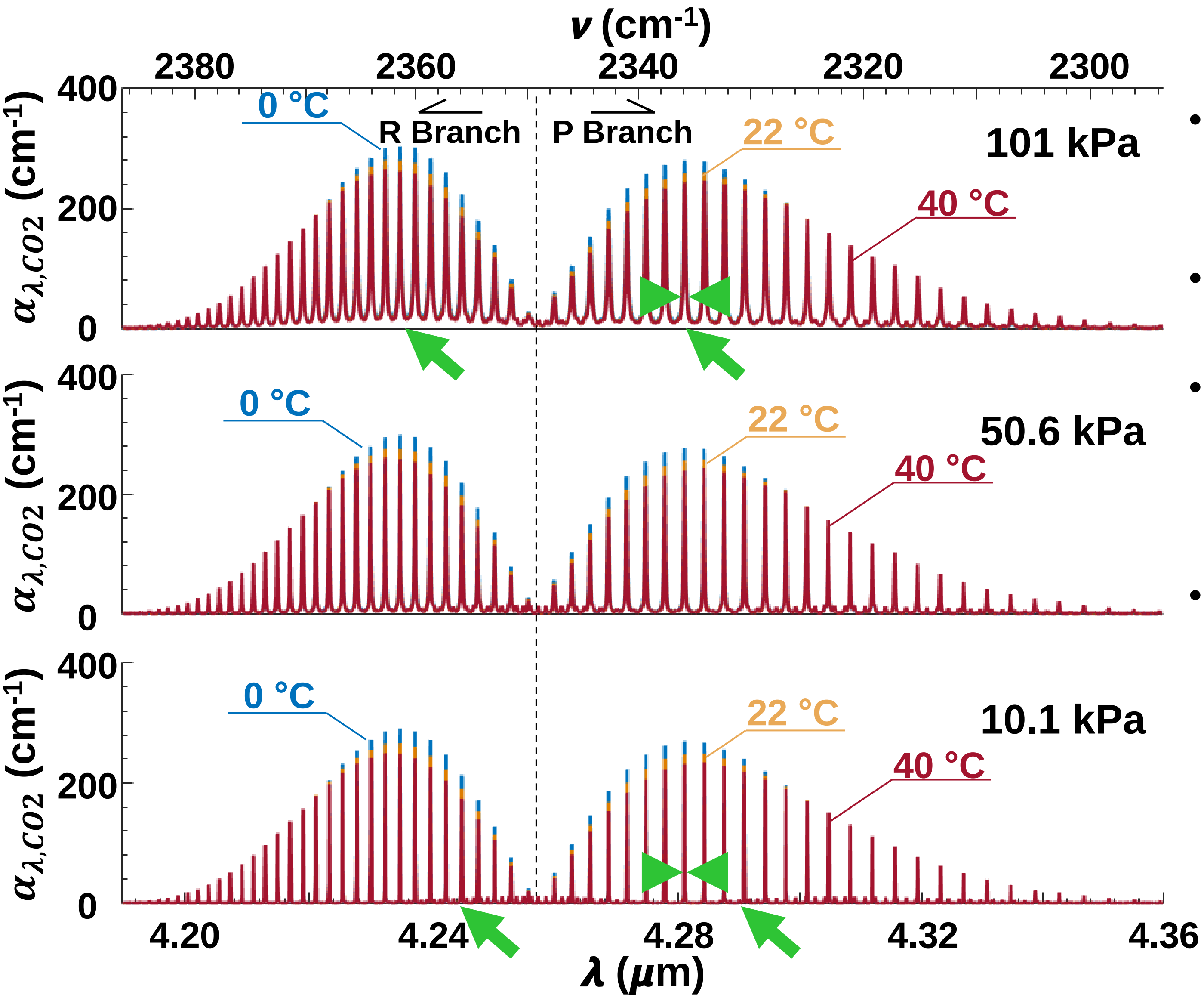
High Altitude Balloon Flight

Original Design



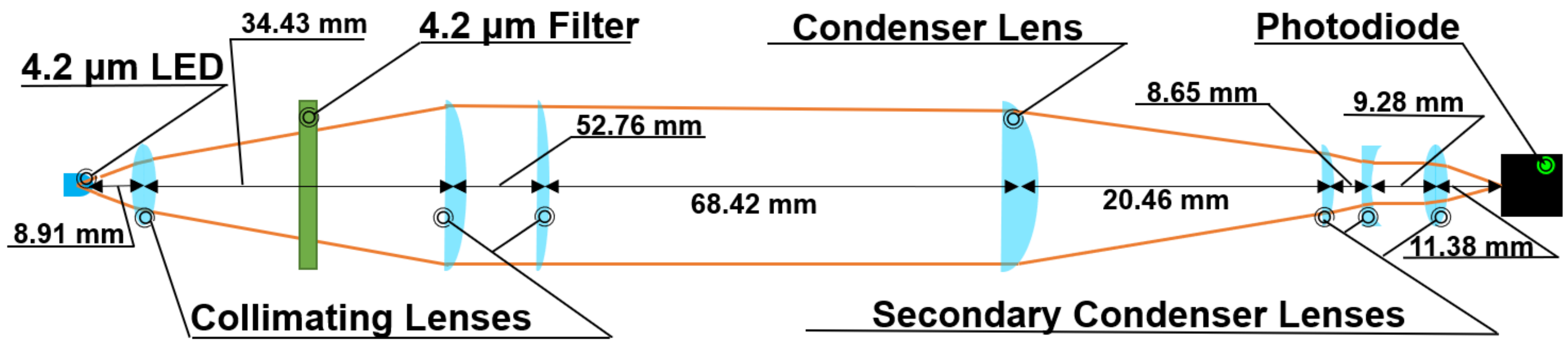
- **3 LEDs: CO_2, CO, and reference**
- **Modulated at different frequencies**
- **Separated signals via Fast Fourier Transform (FFT)**
- **Autonomous operation using a National Instruments cRIO DAQ**

Abridged Sensor Overview

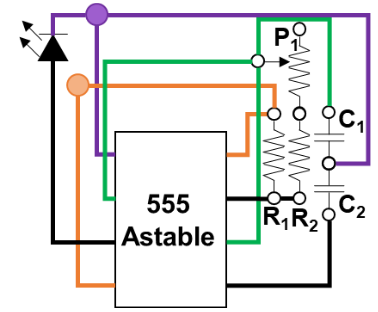


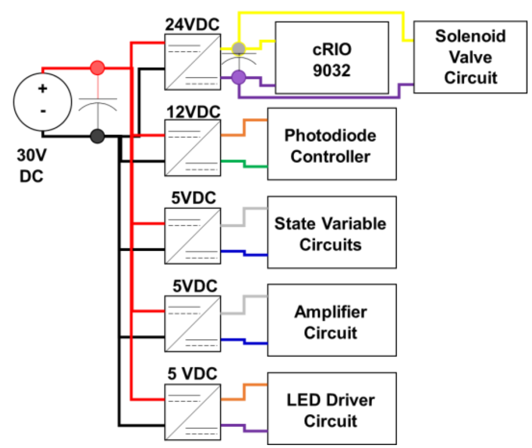
- Temperature dependent feature distribution
- As pressure ↓, peak width narrows
- As pressure ↑ baseline absorbance is present
- Baseline effects cause saturation when used in conjunction with broadband source

Abridged Sensor Overview



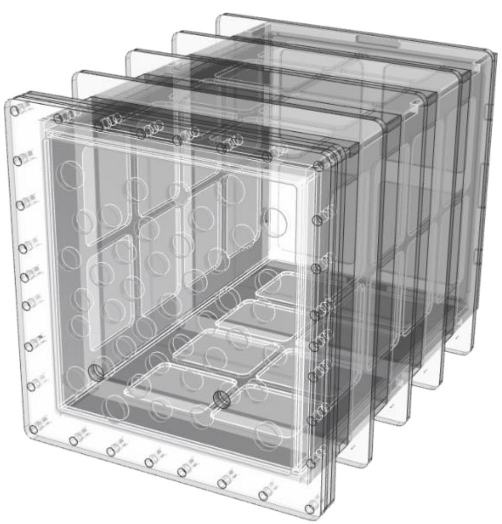
- Single LED used with filter for CO_2 detection
  - Reduction in complexity from previous design
  - Omitted reference LED
- Designed open-loop LED driver
  - Ceramic capacitor to allow temperature-dependent frequency changes
- Isolated power distribution channels
- Autonomous operation using a National Instruments cRIO DAQ

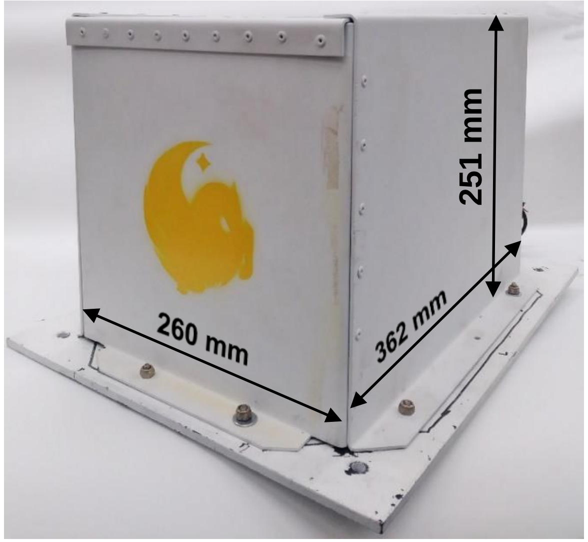




Sensor Enclosure & Packaging

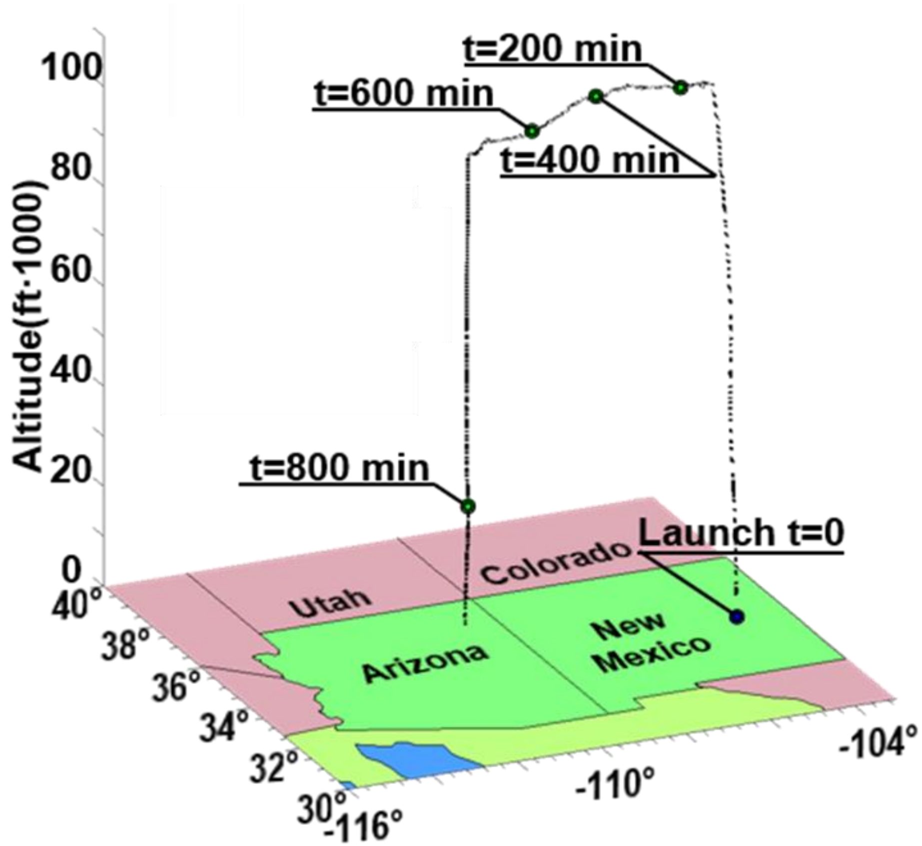
- **Components placed in acrylic enclosure**
  - **Panels cut using laser CNC & assembled using acrylic monomer**
  - **Ribs and layered design used to ensure lightweight construction**
- **Acrylic enclosure sealed using greased butyl gasket**
  - **Passthroughs on the enclosure for electrical signals & power**
- **Aluminum housing surrounding acrylic for protection**
  - **High altitude solar heating & μwave interference**





Balloon Flight

- NASA Columbia Scientific Balloon Facility Ft. Sumner, NM
- Sensor packaged and mounted on balloon payload
- Autonomous operation test
- Enclosure sealed with ambient air
- Power supplied via NASA HASP Platform



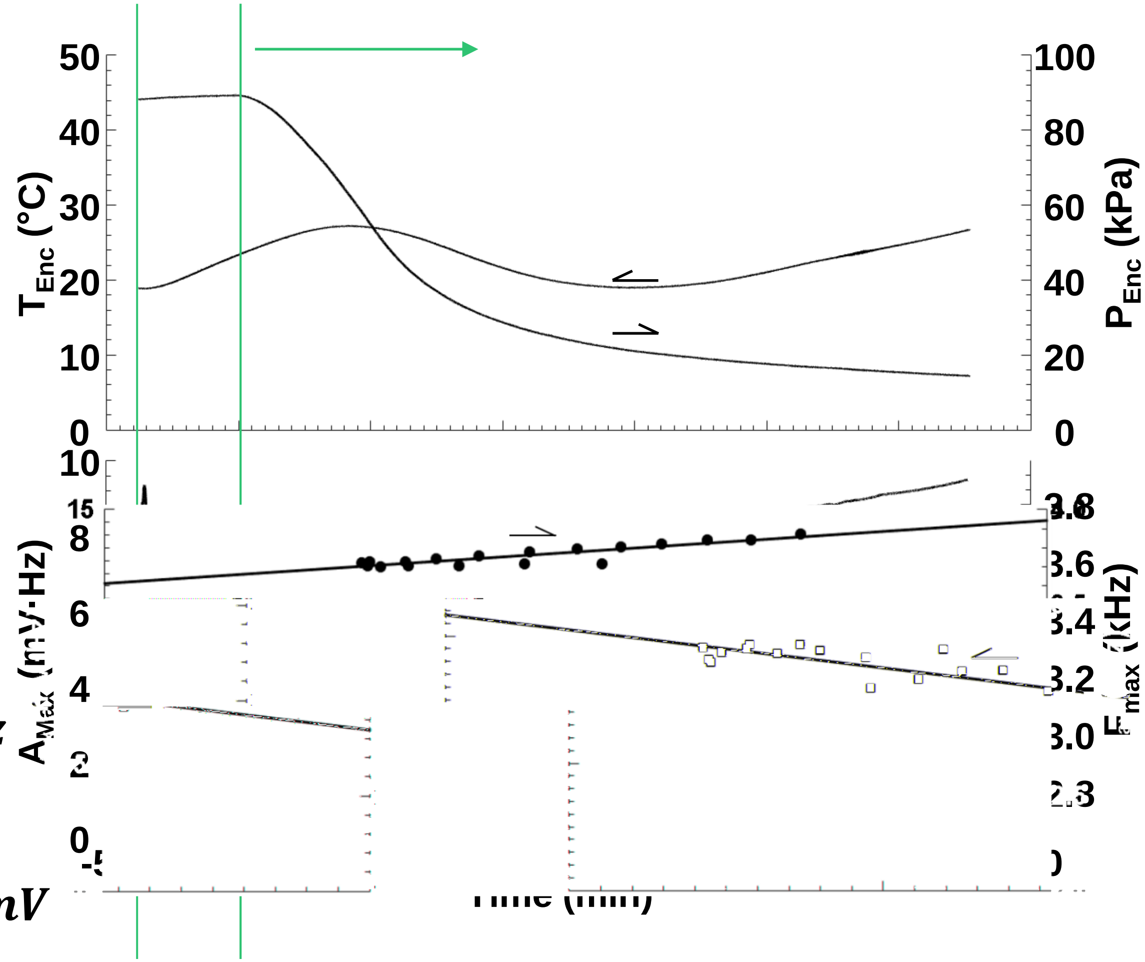
Max Altitude: 109,412 ft
Nominal Float Altitude: 105,000 ft
Launch Time: 9/4/2017 14:04:25 UTC
Duration: 776 min.

Autonomous Flight Data

- **Intensity, temperature & wave center changing**
- **Following warmup**
  - **Signal intensity & Frequency correlate with temperature**
- **Curve fits for baseline detection were then fit**
  - **Temperature dependent**

$$F_{max}(T°C) = 0.022\,{}^{kHz}/_{°C} \cdot T(°C) + 3.283kHz$$

$$A_{max}(T°C) = -0.299\,{}^{mV}/_{°C} \cdot T(°C) + 15.313mV$$



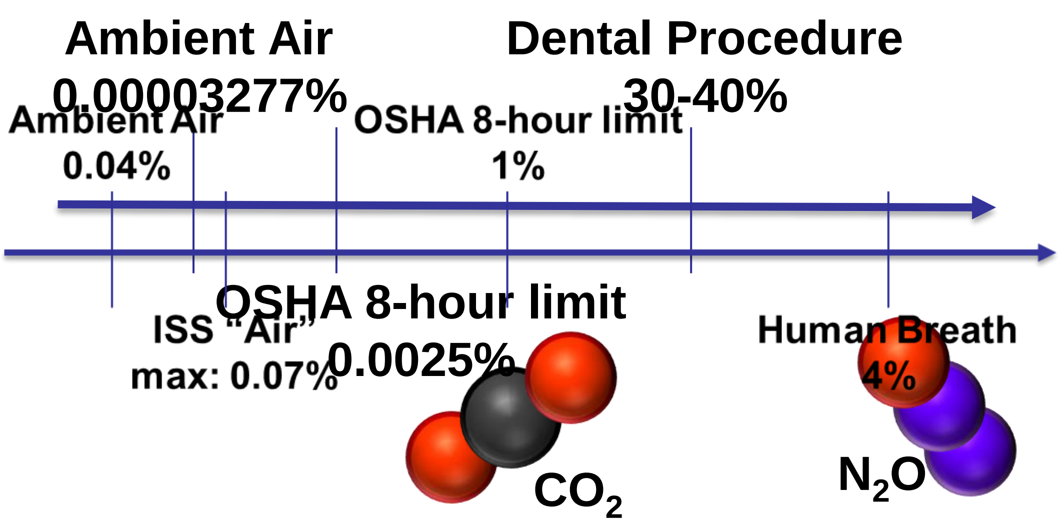
Balloon Flight Conclusions

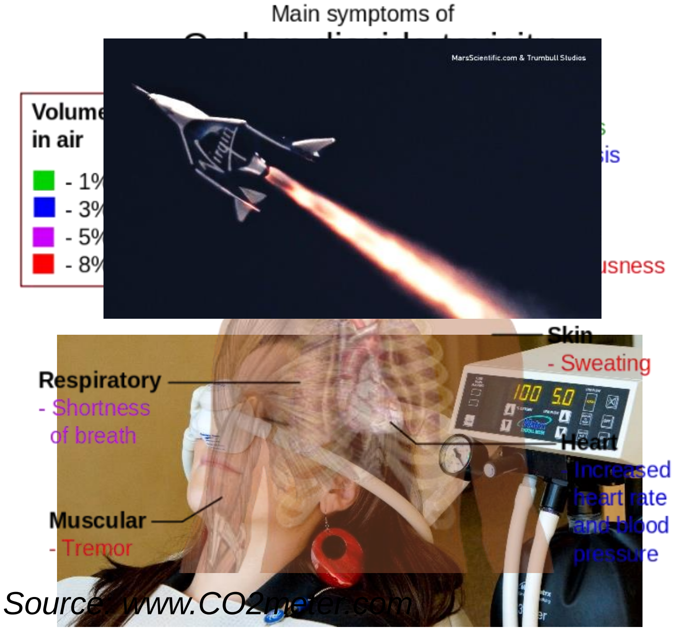
- Simplified design requiring less power and optical space
- Proved functional and able to withstand high-altitude balloon flight
- Established effect of temperature on modulated frequency
- Expand detection range without greatly increasing optical complexity

Swept Grating Sensor

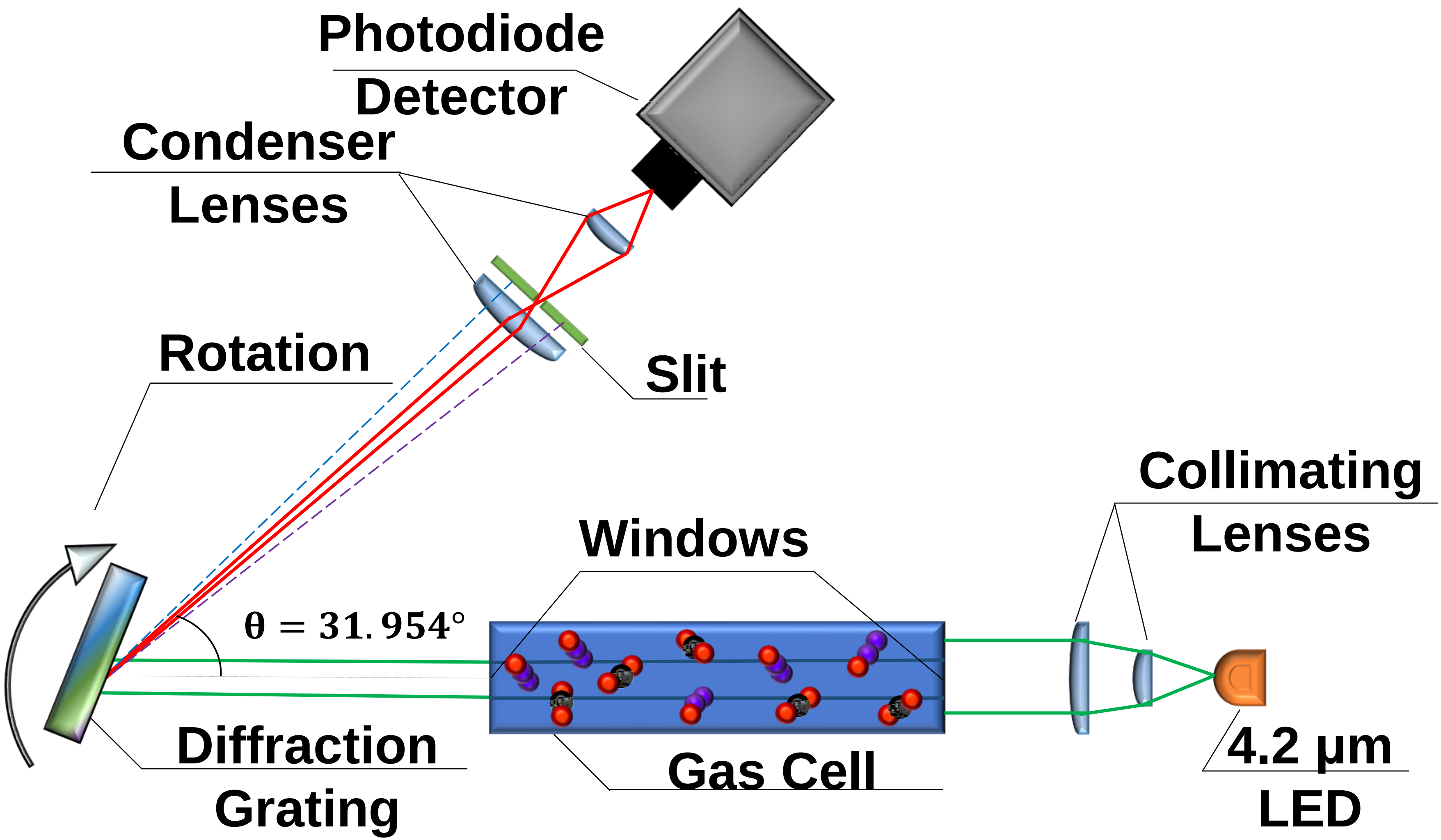
Sensor Target Gases

- CO_2
  - Released during combustion and smoldering events
  - Impairs cognitive capacity in large concentrations
- N_2O
  - Oxidizer in hybrid rockets
  - Sedative and affects critical thinking





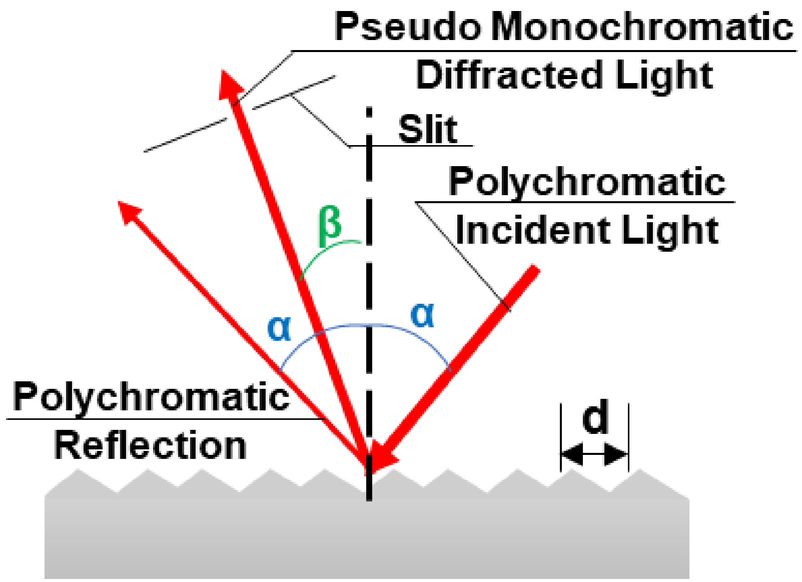
Optical Path



Diffraction Grating

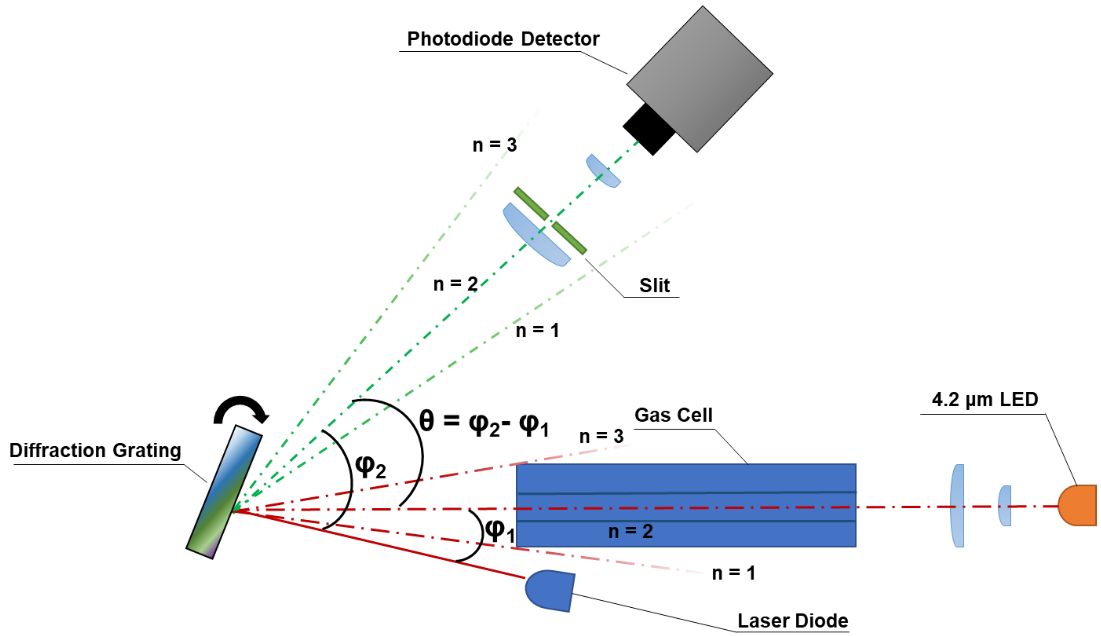
- **Detected wavelength calculated using grating equation:**

$$n\lambda = d[sin(\alpha) \pm sin(\beta)]$$



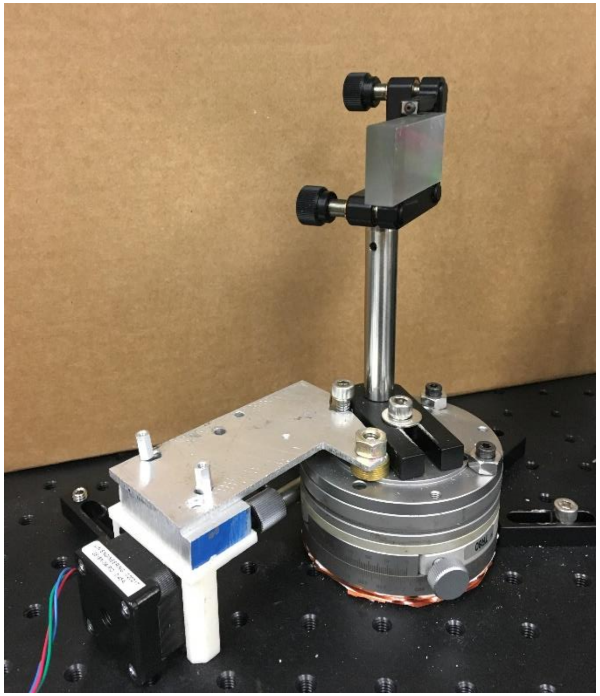
Grating Calibration

- **Grating "zero" reference**
  - **Laser diode placed perpendicular to grating**
  - **Measuring distance between adjacent modes**
  - $n\lambda = d[sin(\alpha) \pm sin(\beta)]$



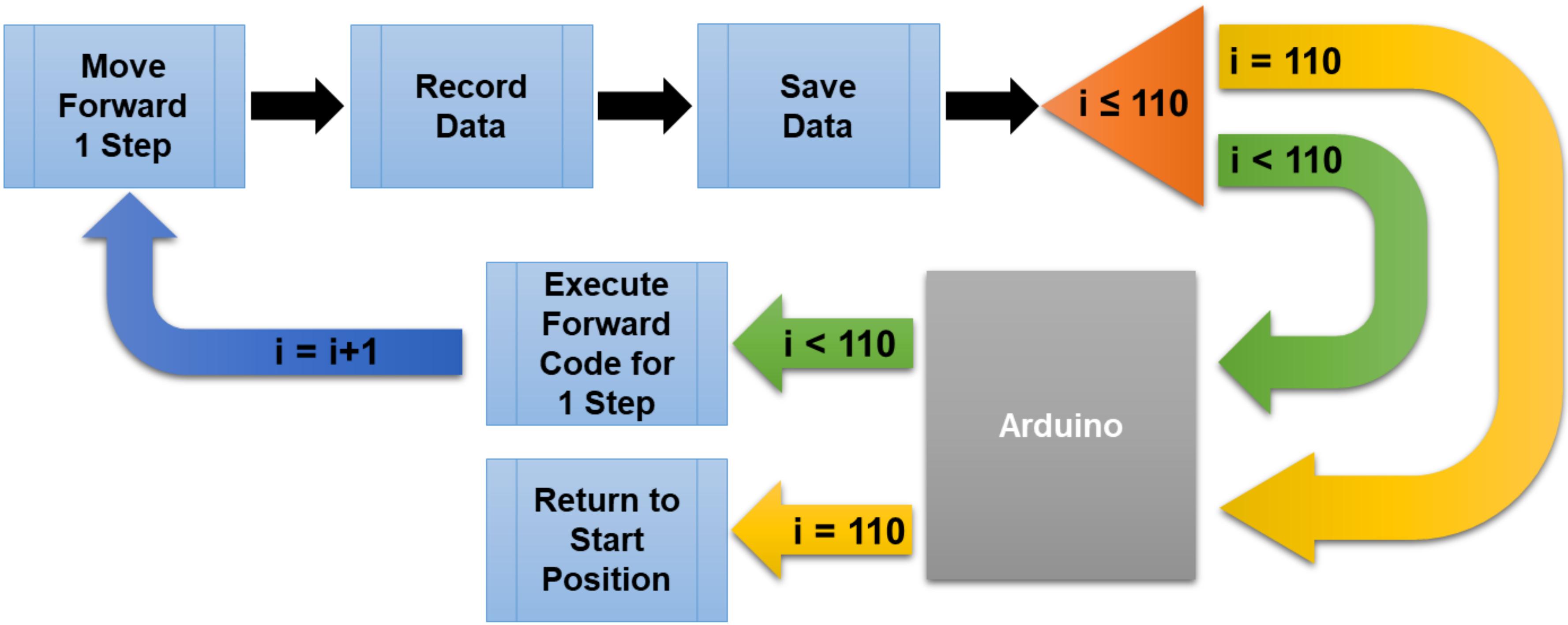
Grating Calibration

- For valid measurements, a repeatable grating position is necessary
  - Stepper motor used for actuation
  - Motor driving function parametrically investigated for minimal drift



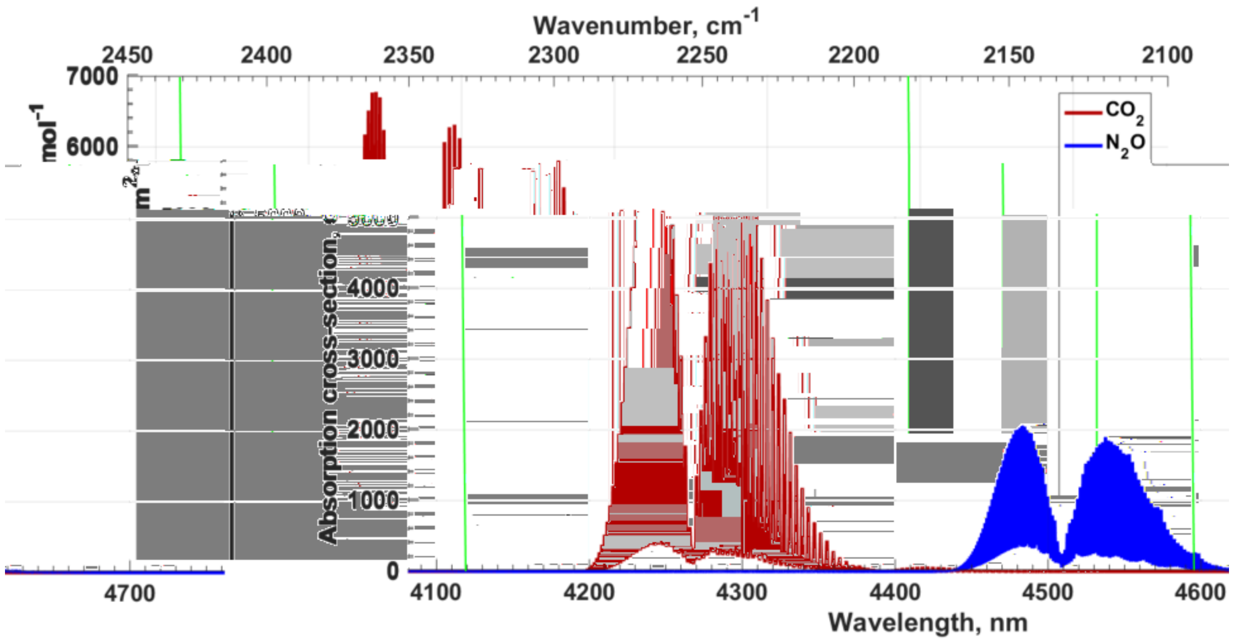
Grating Calibration

- DAQ controls the movement of the grating in a uniform manner



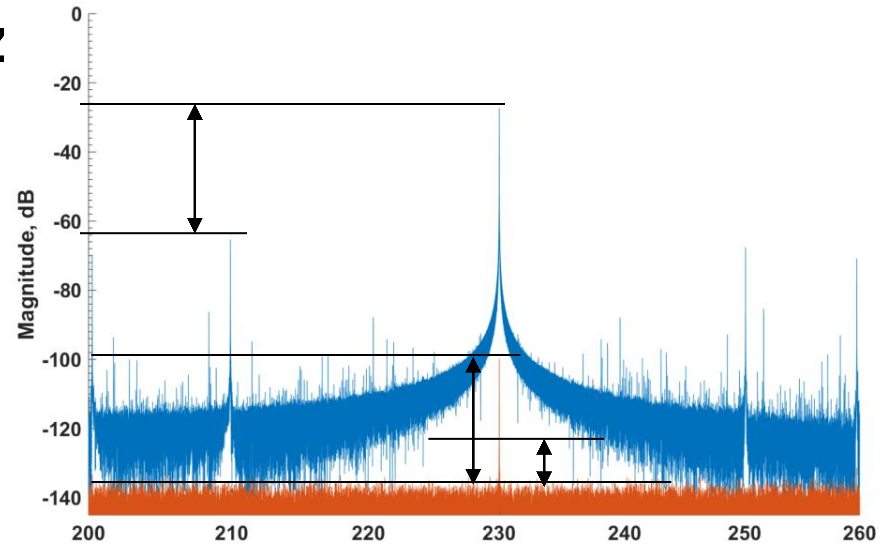
Measurement Sweep Range

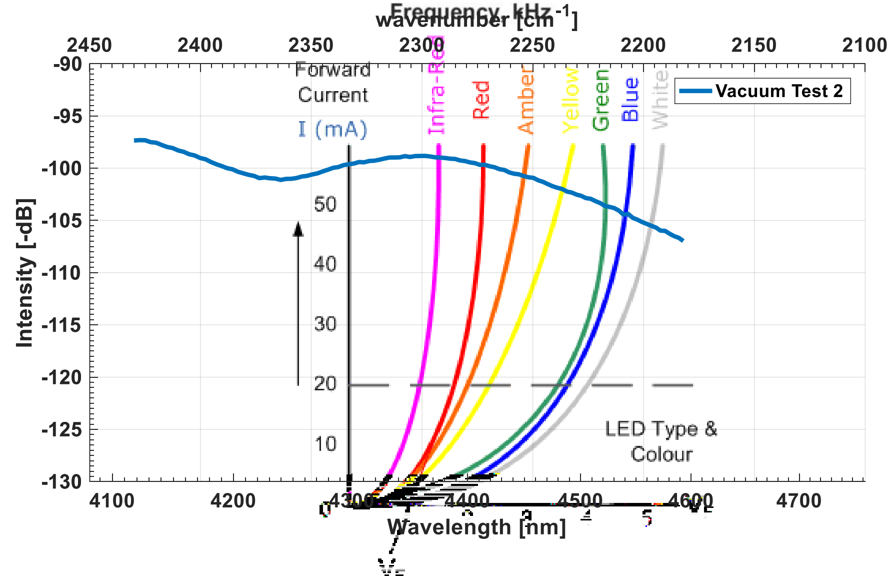
- **Wavelength Range: 4117nm – 4592nm**
  - **Split into 110 discretizations**
  - **Step size of 4.318nm**



Signal Collection & Interpretation

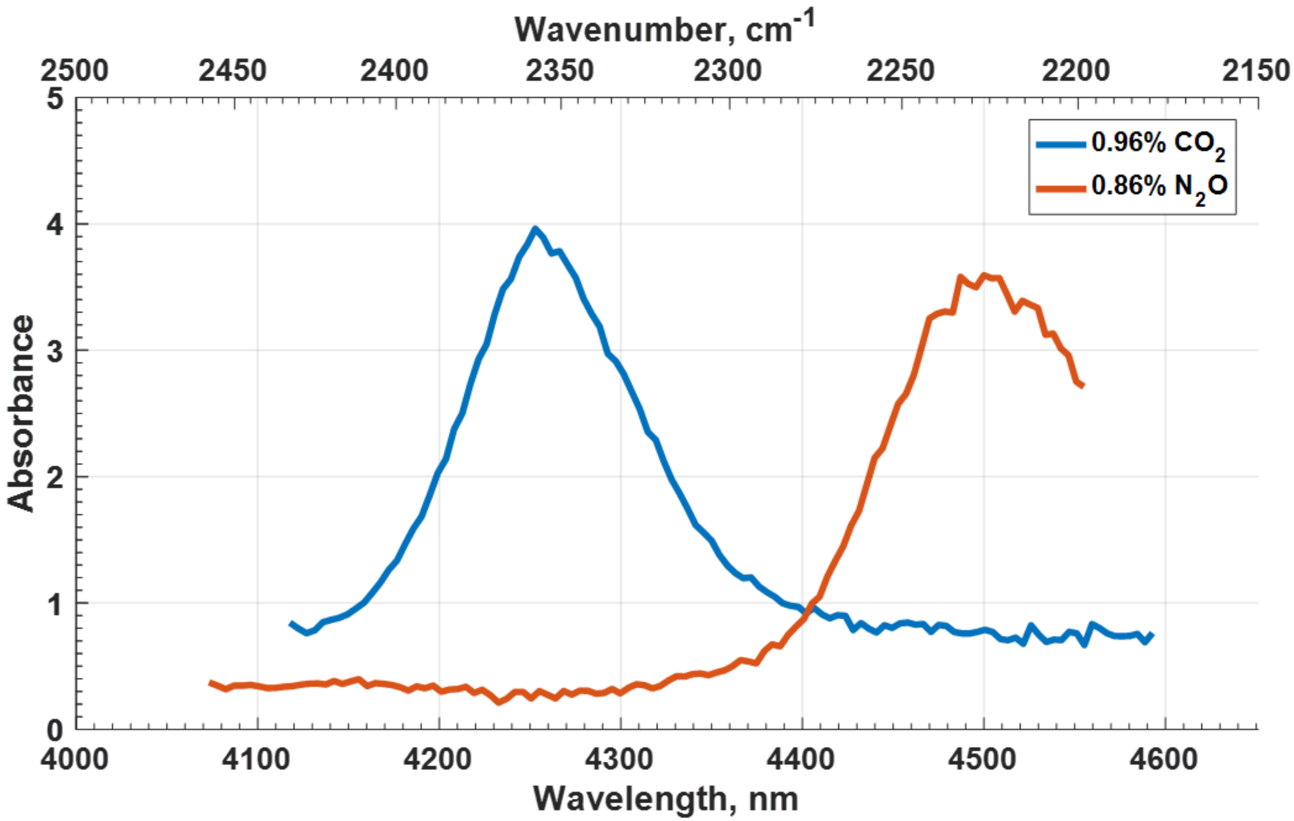
- LED modulated at 250 kHz to reduce noise
- FFT & Absorbance
  - Figure shows FFT at 4185nm for vacuum
  - Save peak signal and reference data (110)
  - $P_{signal,dB} = 10log_{10}\left(\frac{P_{signal}}{P_{ref.}}\right)$
  - $A(\lambda) = -ln\left(\frac{I_{\lambda}}{I_{\lambda,0}}.\right)$
    - I_{λ} = test detector signal
    - $I_{\lambda,0}$= vacuum detector signal
- $SNR_{dB} = P_{signal,dB} - P_{noise,dB}$
  - $SNR_{dB,ref} = 37dB$
  - SNR ... $= 39dB$





Cross-Interference Study

- Interference between the two species must be studied before making combined mixtures
- False baseline absorbance is present

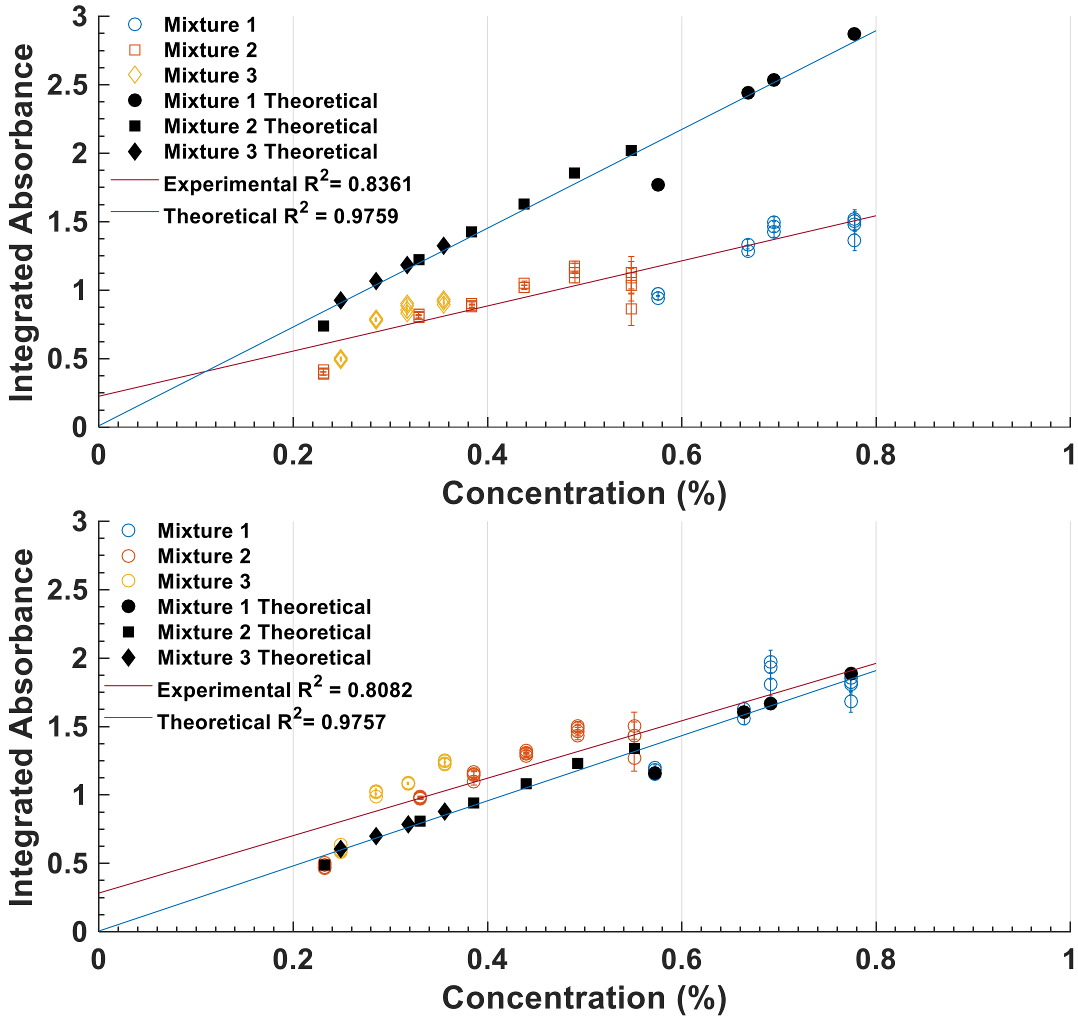


Test Mixtures

- Mixtures were prepared in a manifold using an MKS Baratron
- All mixtures contained equal concentrations of CO_2 and N_2O
- The gas cell was filled with the specific mixture and diluted with N_2 to reach different concentrations
- Each test was completed 3-4 separate times
- The gas cell was vacuumed to 0.30 Torr in between experiments

Mixture	Percentage of CO_2 (%)	Percentage of N_2O (%)	Percentage of N_2 (%)
1	0.778	0.774	98.5
2	0.548	0.551	98.9
3	0.355	0.356	99.3

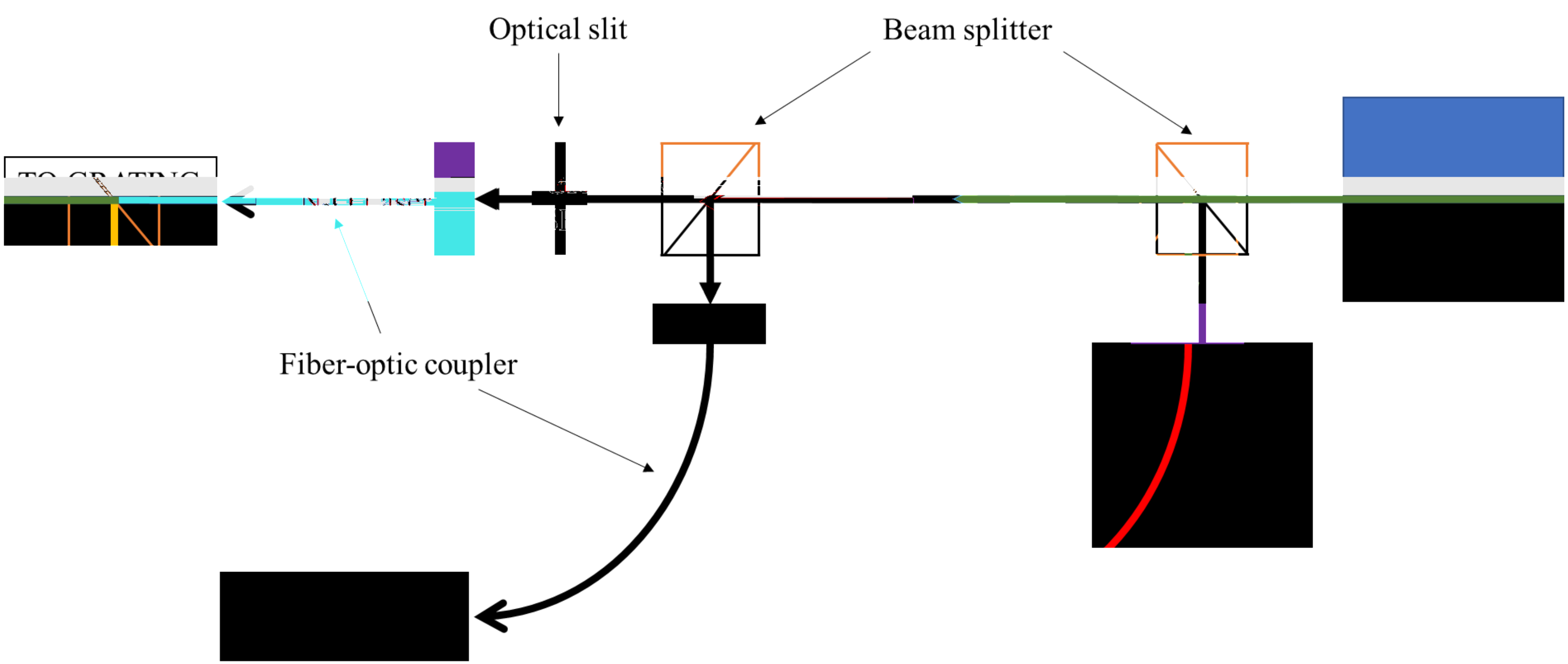
Integrated Absorbance



- Top figure shows CO_2 integrated from 4150 to 4350nm
- Bottom figure shows N_2O integrated from 4420 to 4585nm
- HITRAN absorption cross-section modeled using a Gaussian App. Function with an App. Resolution of 35 cm^{-1}
- Error bars show standard deviation at each concentration value

Laser Validation Setup

- **Validation with 2 Distributed Feedback Quantum Cascade Lasers (QCL)**
- **“CO_2 Laser” : 4.256 – 4.266μm**
- **“N_2O Laser” : 4.583 – 4.596μm**



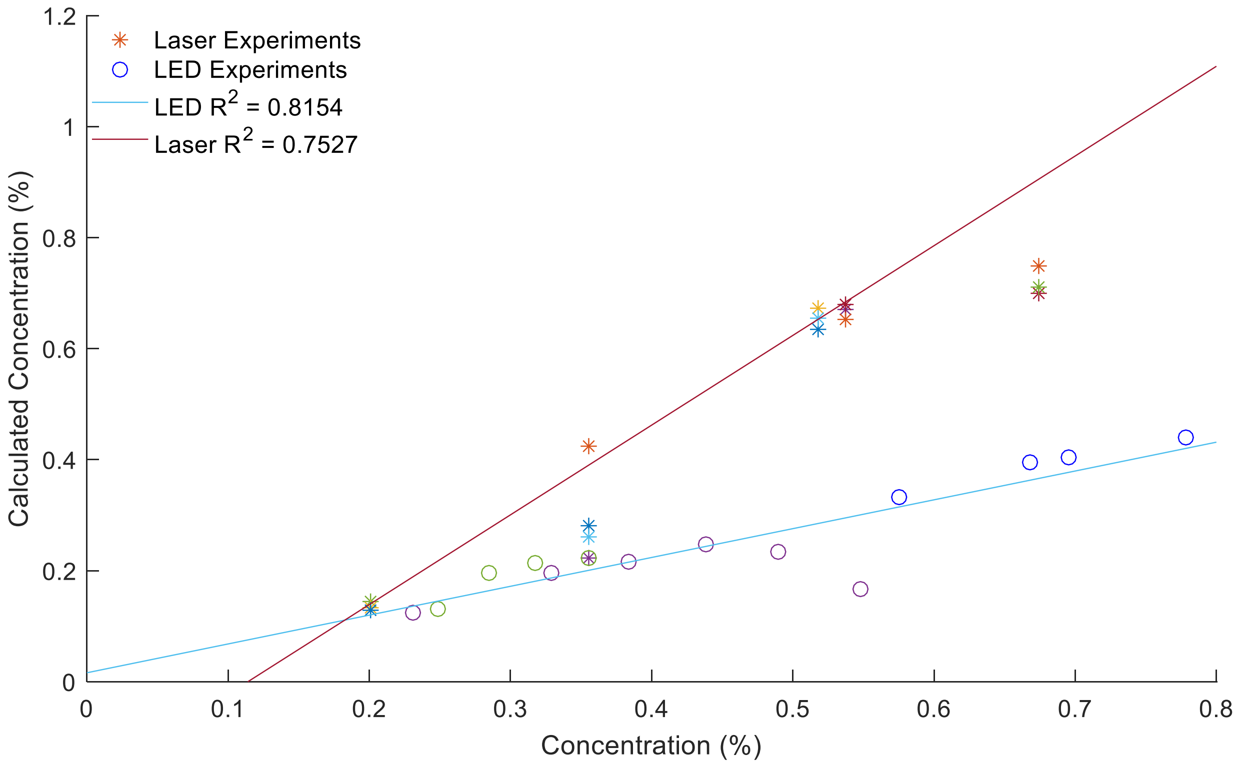
Laser Test Mixtures

- Mixtures were prepared in the same manner as the LED experiments

Mixture	Percentage of CO_2 (%)	Percentage of N_2O (%)	Percentage of N_2 (%)
1	0.355	0.356	99.29
2	0.674	0.654	98.67
3	0.518	0.503	98.97
4	0.537	0.521	98.94
5	0.201	0.195	99.60

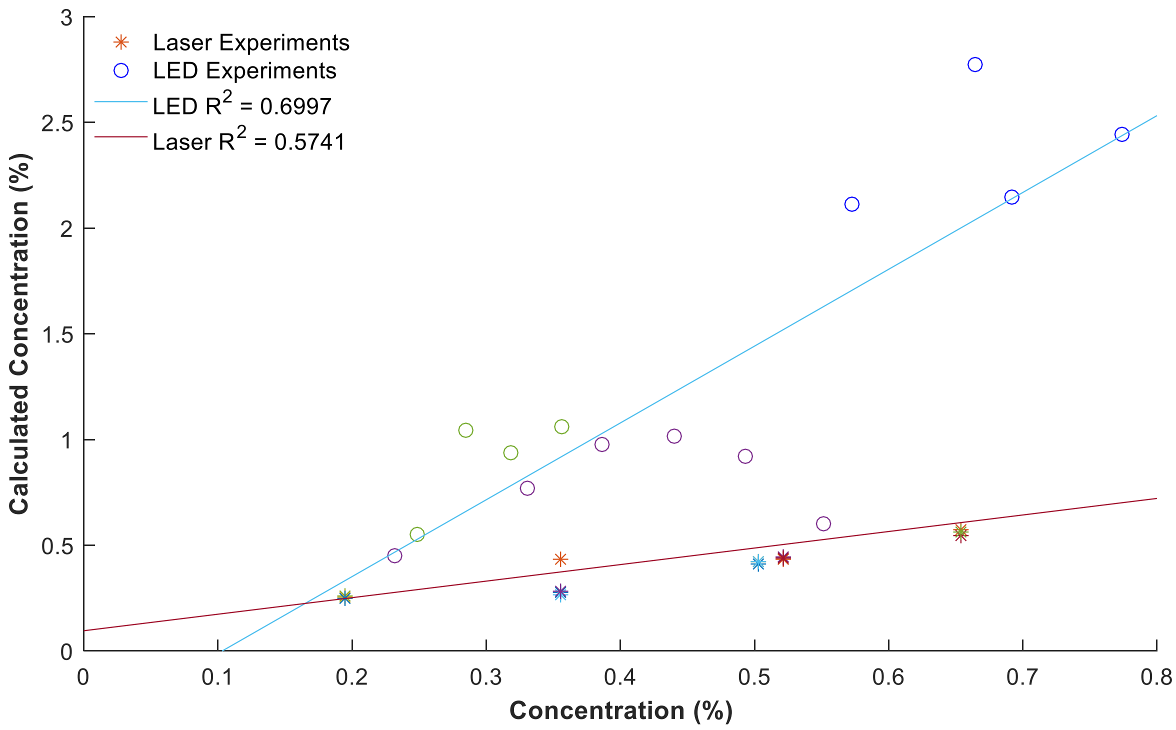
Concentration Comparison

- **CO_2 laser at 4264.314 nm**
- **LED data at same wavelength**
- **Calculated concentration values from Beer-Lambert Law**



Concentration Comparison

- N_2O laser at 4589.699 nm
- LED data at same wavelength
- Calculated concentration values from Beer-Lambert Law

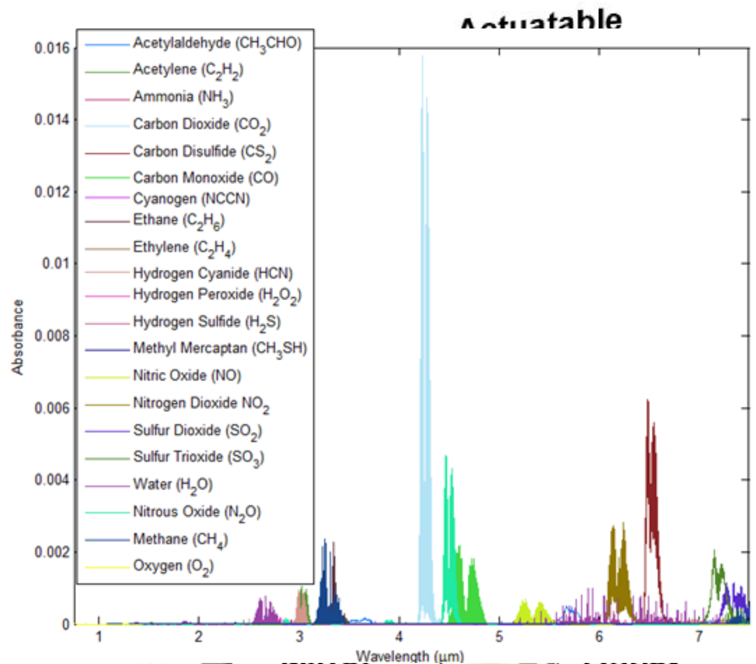


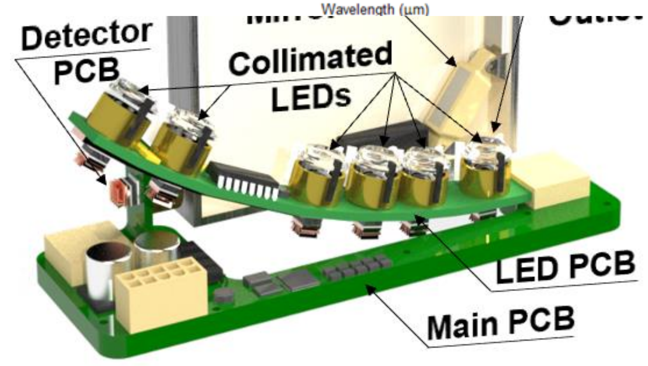
Conclusions

- An LED based gas sensor was tested for its abilities to detect toxic compounds
- Grating design proved functional for detection of both CO_2 and N_2O with a single LED
- Comparison with laser-based measurements validates the sensor at lower concentrations
- Show potential for greatly reducing complexities of gas detection systems
- Lead to increased safety in space vehicles

Future Work

- **Focus on increasing wavelength test range**
- **Detect more hazardous gases, such as CO**
- **Conduct tests in harsher environments**
- **Partner with Commercial Space companies**
- **Seek other applications and resources (e.g., NASA planetary sensing, enrionmental applications, etc.)**





Presentations & Publications

- **Journal Publications**
  - Akshita Parupalli, Anthony Carmine Terracciano, Zachary Loparo, Justin Urso, S.S. Vasu, “Multi-Species Single-LED Gas Sensor for Space Habitats and Vehicles”, New Space, 8(2), 2020.
  - Published in Anthony Carmine Terracciano, Kyle Thurmond, Michael Villar, Akshita Parupalli, Justin Urso, Erik Ninnemann, S.S. Vasu, “Hazardous Gas Detection Sensor Using Broadband Light-Emitting Diode-Based Absorption Spectroscopy for Space Applications”, New Space, 6(1), 28-36, 2018.
- **Presentations**
  - A.Terracciano, A. Parupalli, Z. Loparo, J. Urso, S.S. Vasu, "Advancement of LED-based hazardous gas sensors for space applications." *2018 AIAA SPACE and Astronautics Forum and Exposition*. 2018.
  - A. Terracciano, K. Thurmond, M.S. Villar, J. Urso, A. Parupalli, E. Ninnemann, Z. Loparo, N. Demidovich, J. Kapat, W. Partridge, S.S. Vasu, “Flight Test Demonstration of LED-based Fire Sensors for Space Propulsion Vehicles”, presented at the ESS/CI Spring Technical meeting, State College, PA, 3/2018.

Acknowledgements

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Questions?

Vasu Lab 2016