LED-based Absorption Sensors for Early Fire and Hazardous Gases Detection for Flight Vehicles and Propulsion Engines

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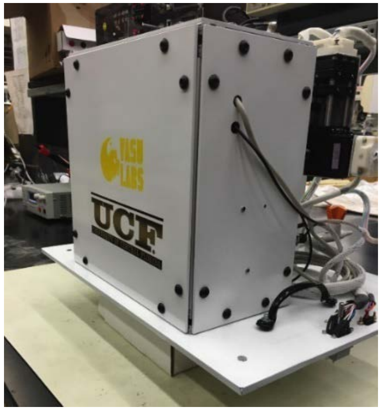
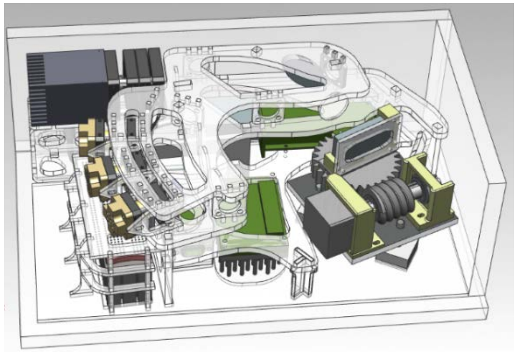
Organization

- **Fundamentals of spectroscopy and absorption technique**
- **LED sensor design and lab validation**
- **Demo fire sensor flight test results**





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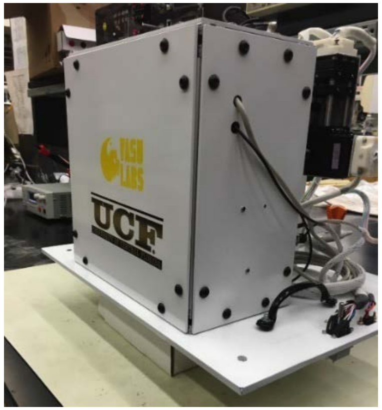
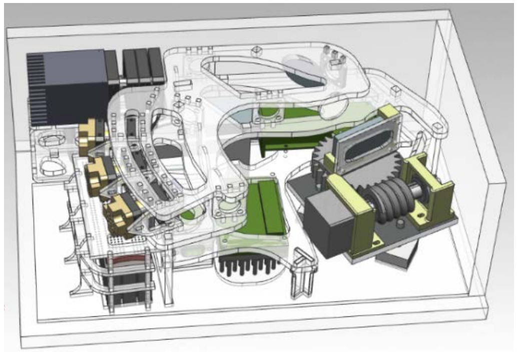
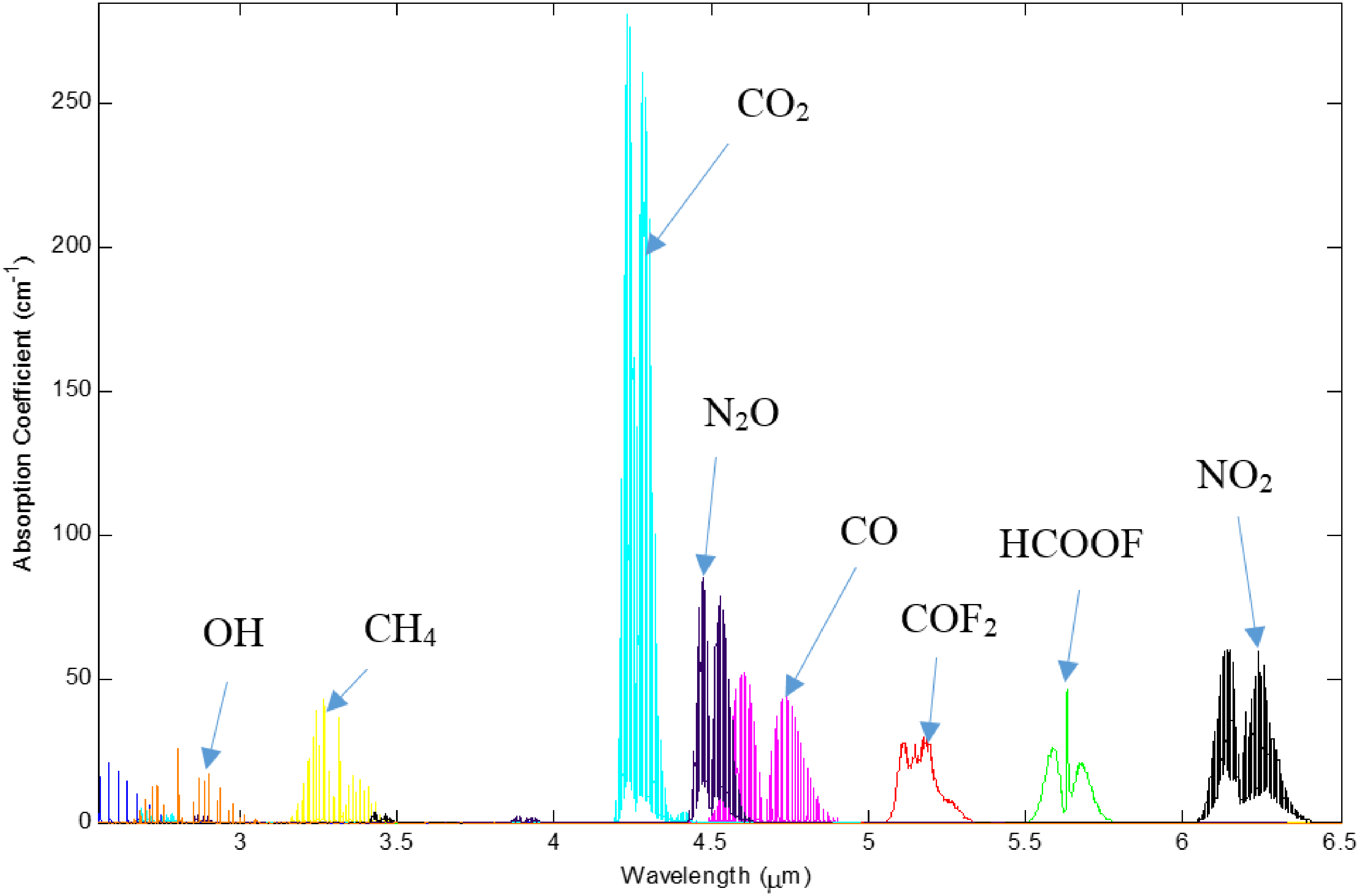




Mid-Infrared Absorption Spectra



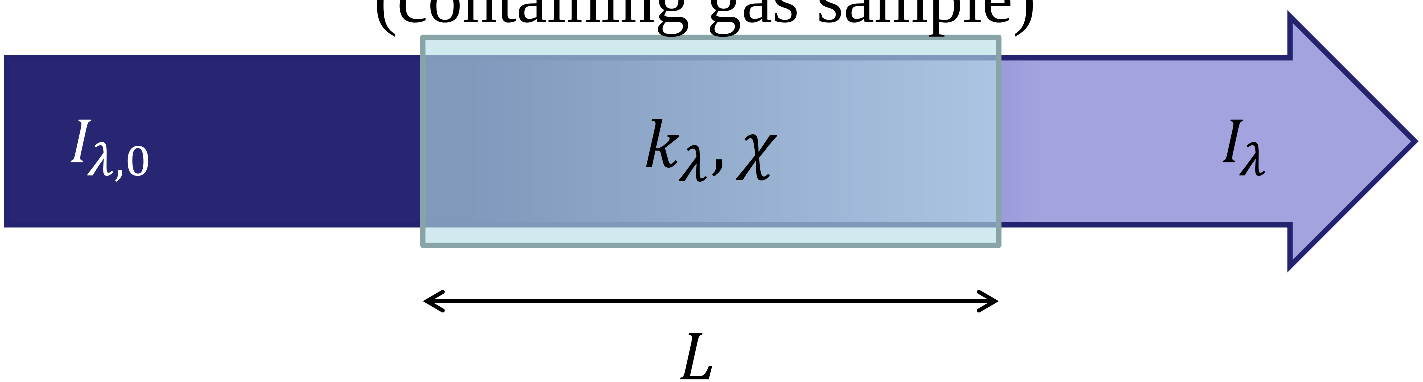
Absorption Spectroscopy and Beer's Law

Beer Lambert law of absorption

$$A_\lambda = -\ln\left(\frac{I_\lambda}{I_{\lambda,0}}\right) = k_\lambda L \chi$$

A_λ = spectral absorbance
I_λ = transmitted radiation at λ
$I_{\lambda,0}$ = incident radiation at λ
k_λ = spectral absorption coef.
L = path length
χ = mole fraction of target gas

Test Cell
(containing gas sample)



How Does Absorption Spectroscopy Work?

- ❖ 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

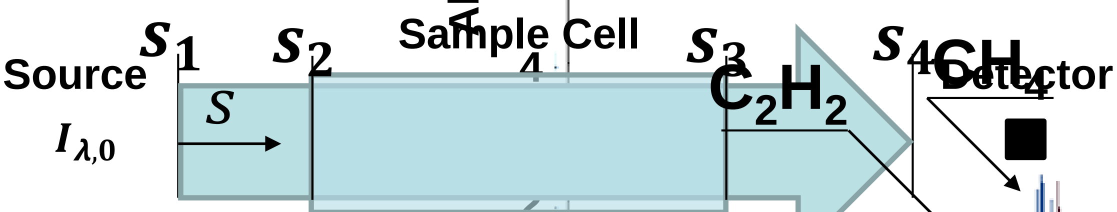
$I_{\lambda,0}$ - Incident spectral intensity of electromagnetic radiation

I_λ - Transmitted spectral intensity of electromagnetic radiation

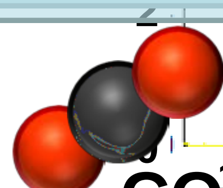
s - Path variable

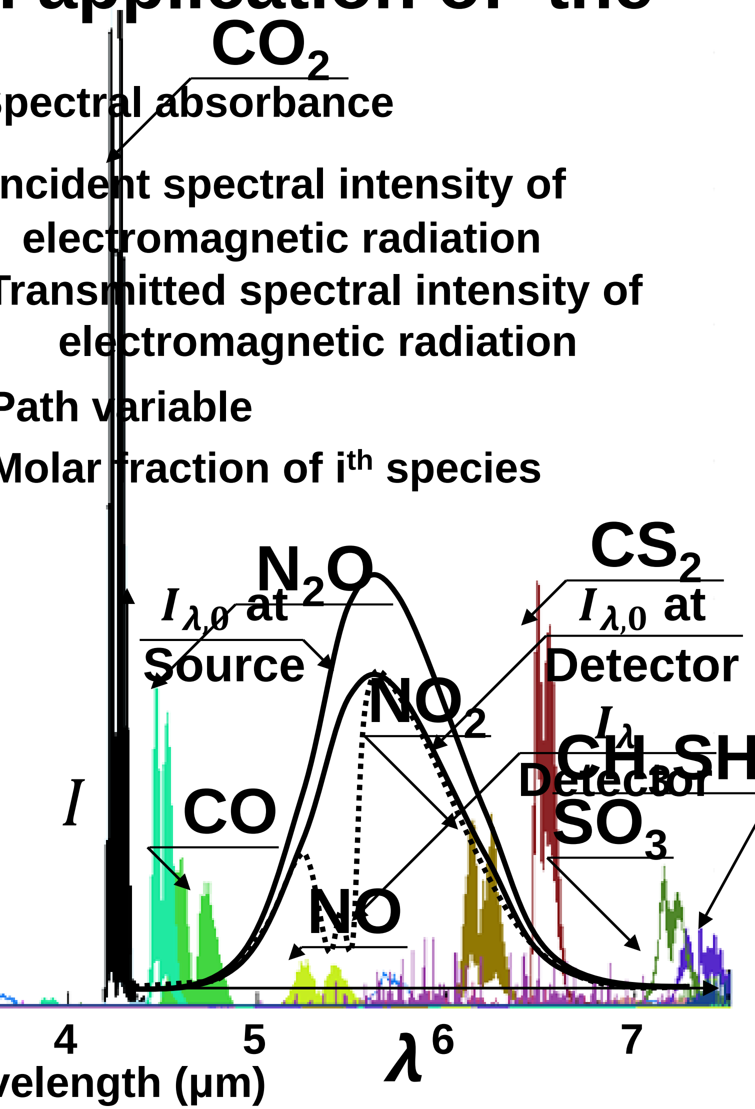
x_i - Molar fraction of i[th] species

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



- ❖ Many Near/Mid IR active pollutants





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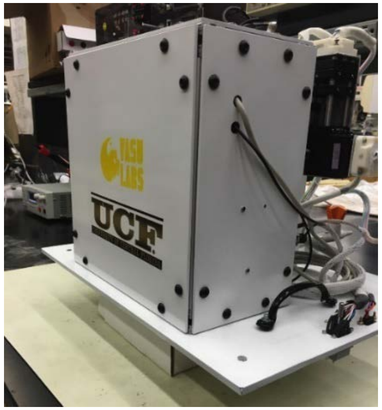
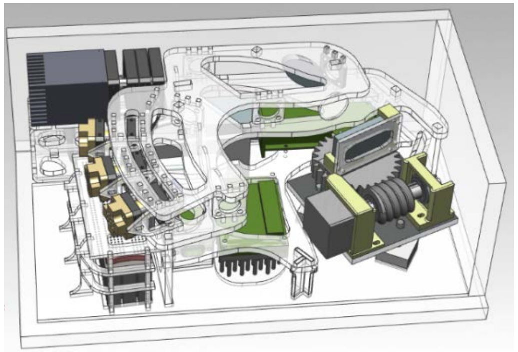
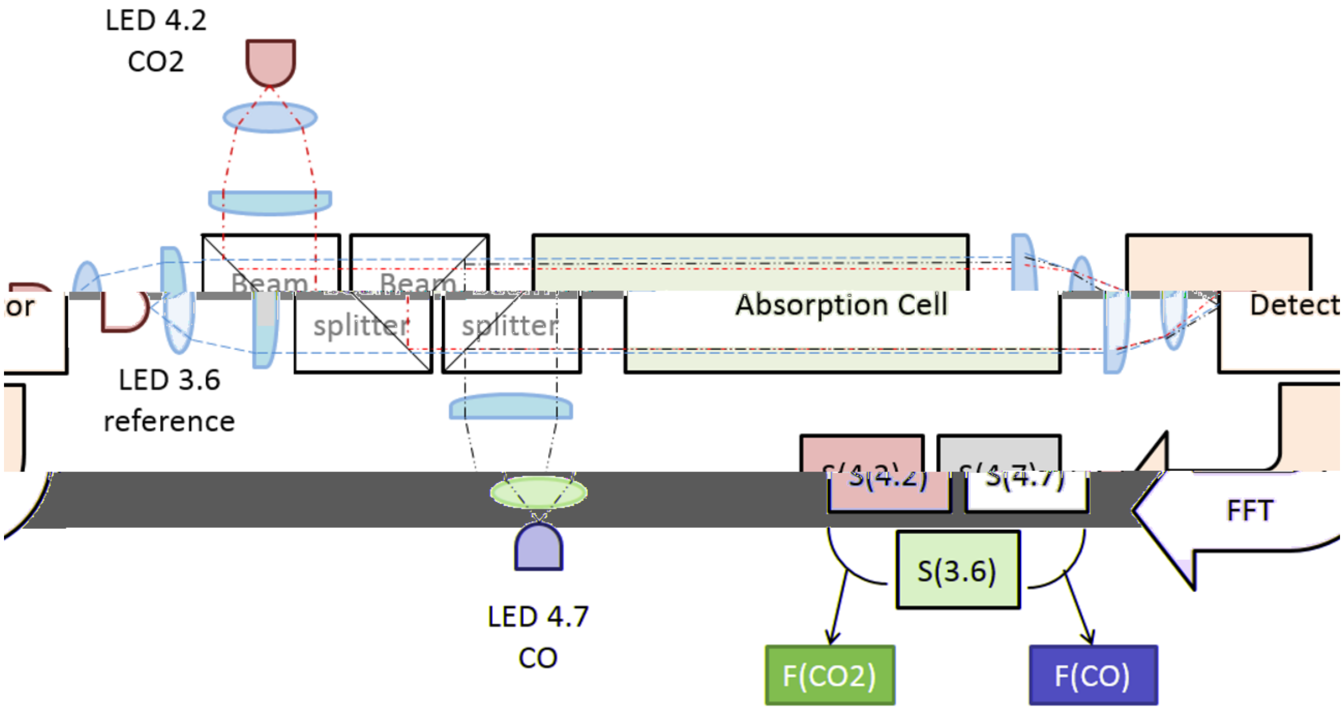




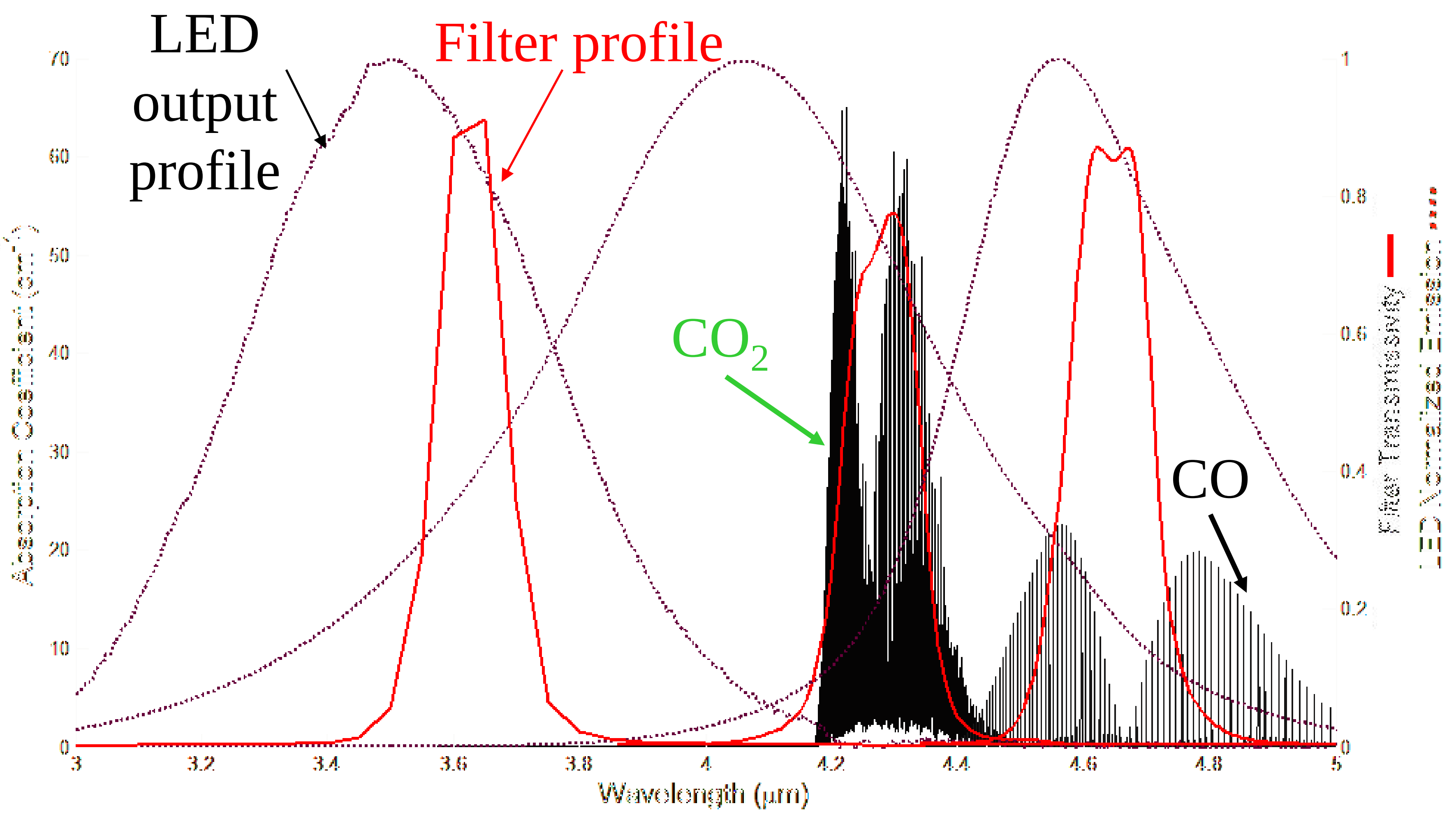
Sensor Design Using LEDs

- Three MIR LEDs centered at
  - 3.6μm (for reference)
  - 4.2μm (CO_2)
  - 4.7μm (CO)
- LEDs amplitude modulated at different frequencies

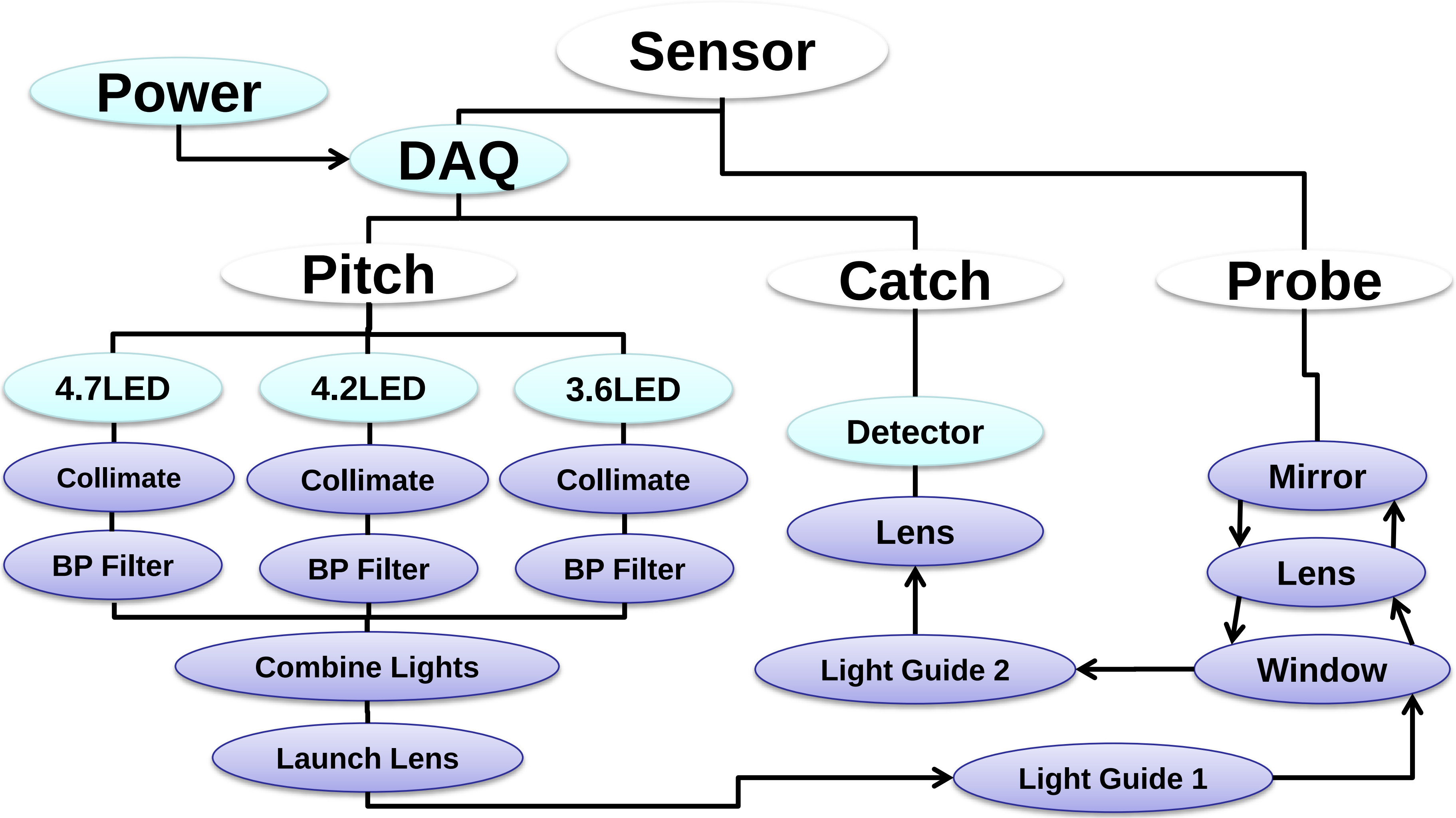
- Band pass filters
- Collimating lenses
- Pellicle beam splitters
- Thermo-electrically cooled photovoltaic detector



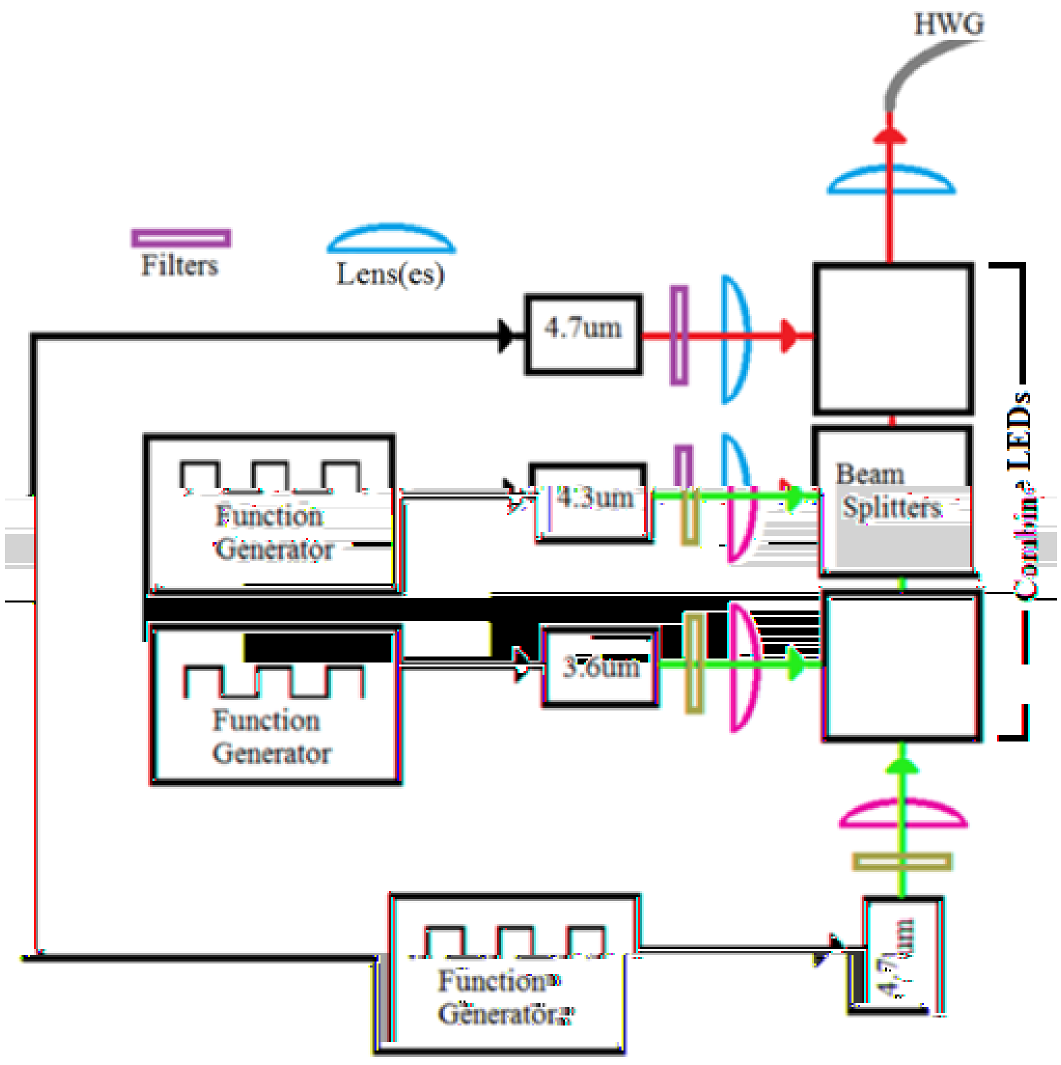
Broad spectrum of LEDs and absorption features of targeted gases



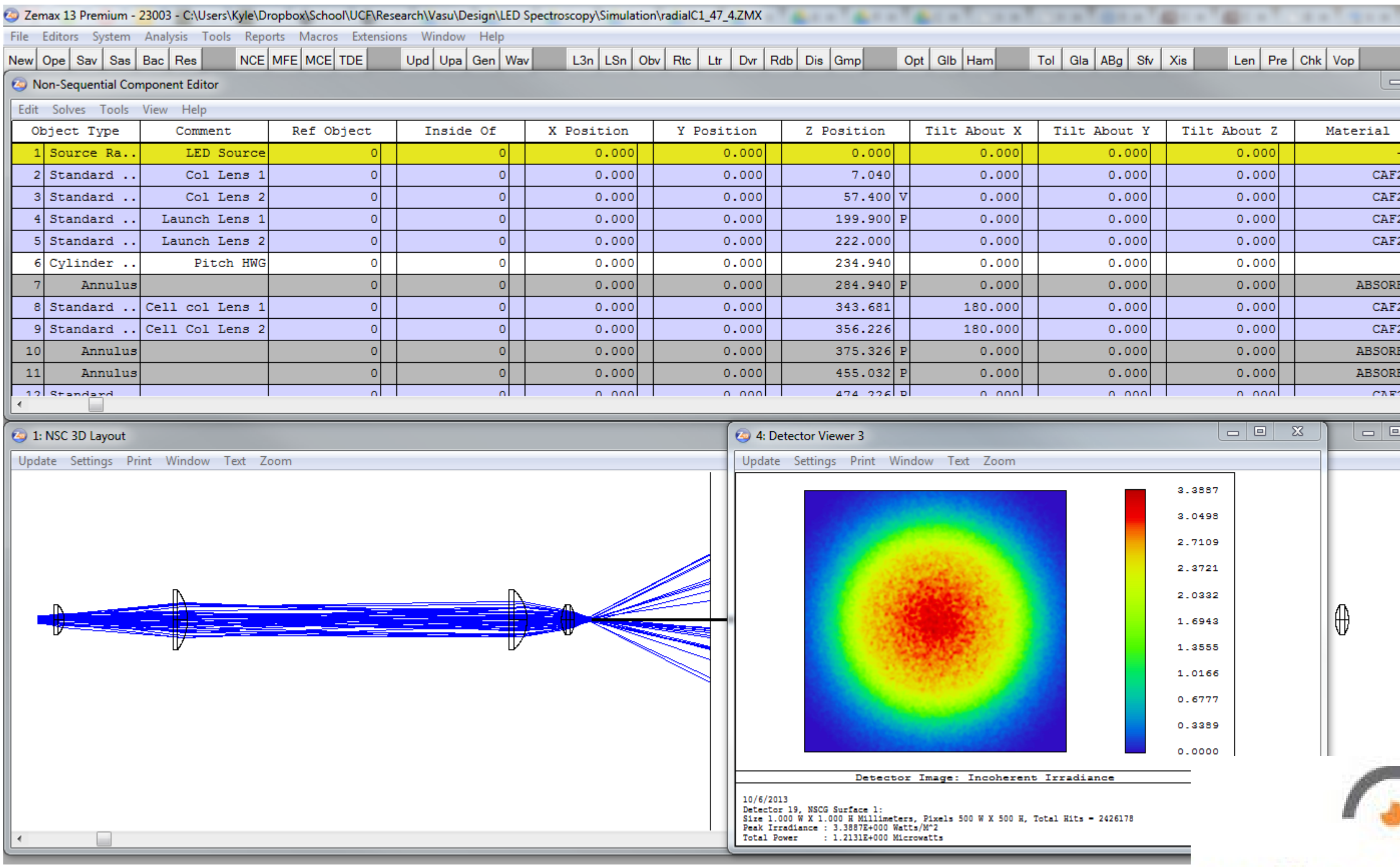
Sensor Overview and Operation



Pitch


HWG
Filters
Lens(es)
4.7um
Beam
Splitters
4.3um
3.6um
Combine LEDs
Function
Generator
Function
Generator
Function
Generator
4.7um

Simulations using Zemax (Optic Studio)

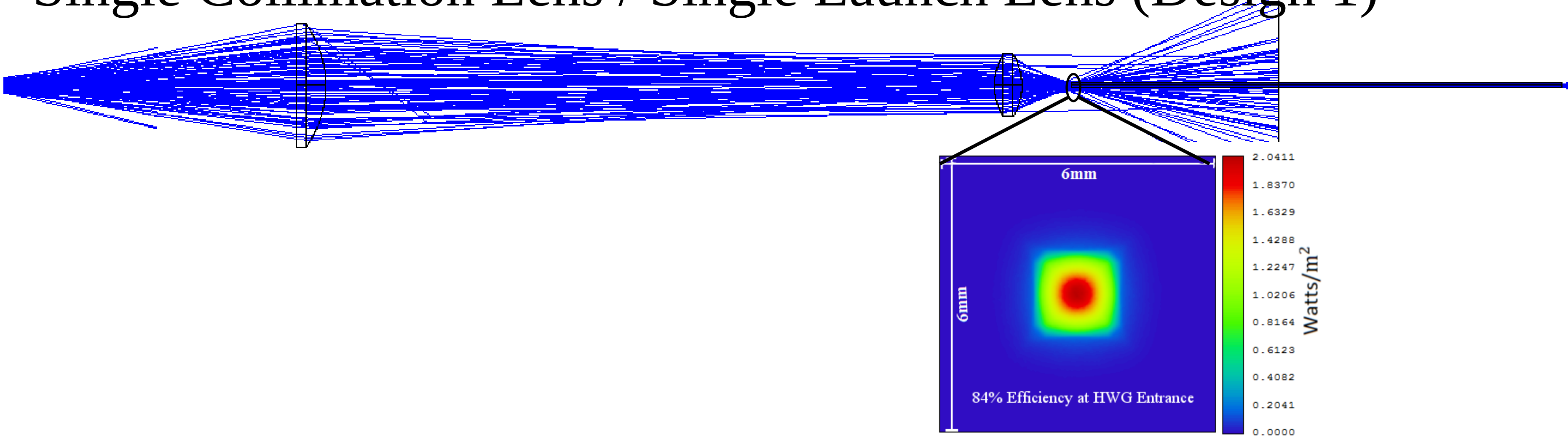


	Object Type	Comment	Ref Object	Inside Of	X Position	Y Position	Z Position		Tilt About X	Tilt About Y	Tilt About Z	Material
1	Source Ra..	LED Source	0	0	0.000	0.000	0.000		0.000	0.000	0.000	-
2	Standard ..	Col Lens 1	0	0	0.000	0.000	7.040		0.000	0.000	0.000	CAF2
3	Standard ..	Col Lens 2	0	0	0.000	0.000	57.400	V	0.000	0.000	0.000	CAF2
4	Standard ..	Launch Lens 1	0	0	0.000	0.000	199.900	P	0.000	0.000	0.000	CAF2
5	Standard ..	Launch Lens 2	0	0	0.000	0.000	222.000		0.000	0.000	0.000	CAF2
6	Cylinder ..	Pitch HWG	0	0	0.000	0.000	234.940		0.000	0.000	0.000	
7	Annulus		0	0	0.000	0.000	284.940	P	0.000	0.000	0.000	ABSORB
8	Standard ..	Cell col Lens 1	0	0	0.000	0.000	343.681		180.000	0.000	0.000	CAF2
9	Standard ..	Cell Col Lens 2	0	0	0.000	0.000	356.226		180.000	0.000	0.000	CAF2
10	Annulus		0	0	0.000	0.000	375.326	P	0.000	0.000	0.000	ABSORB
11	Annulus		0	0	0.000	0.000	455.032	P	0.000	0.000	0.000	ABSORB
12	Standard		0	0	0.000	0.000	474.226	P	0.000	0.000	0.000	CAF2

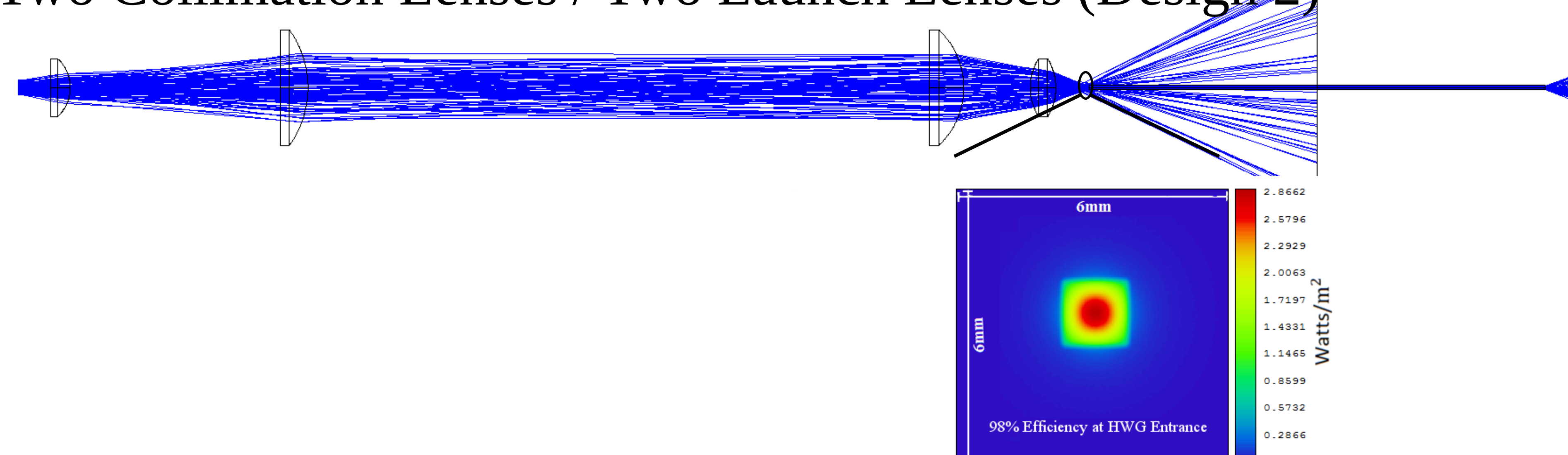
Radiant Zemax

Simulations: Collimation

Single Collimation Lens / Single Launch Lens (Design 1)

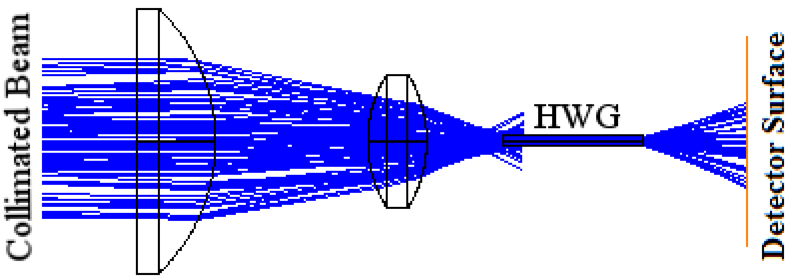


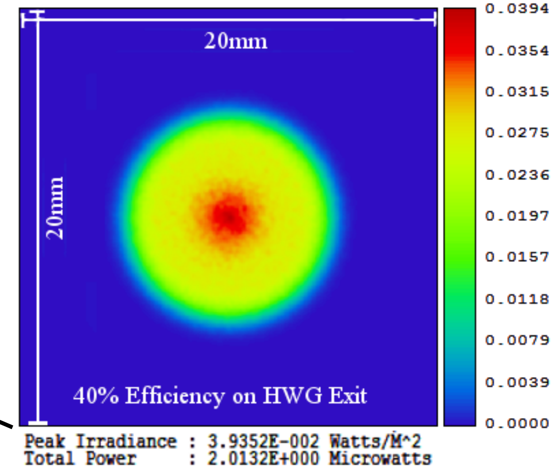
Two Collimation Lenses / Two Launch Lenses (Design 2)



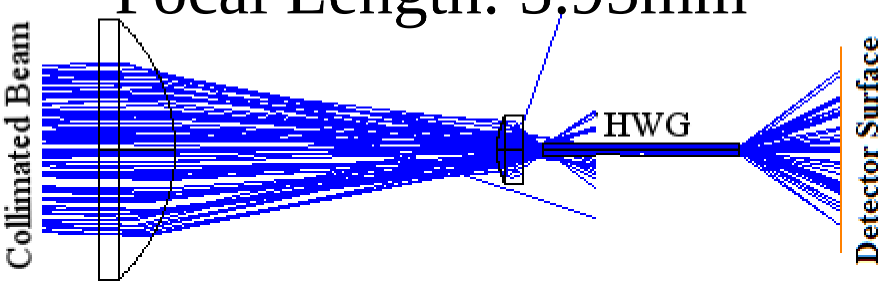
Simulations: Launch Lens FL

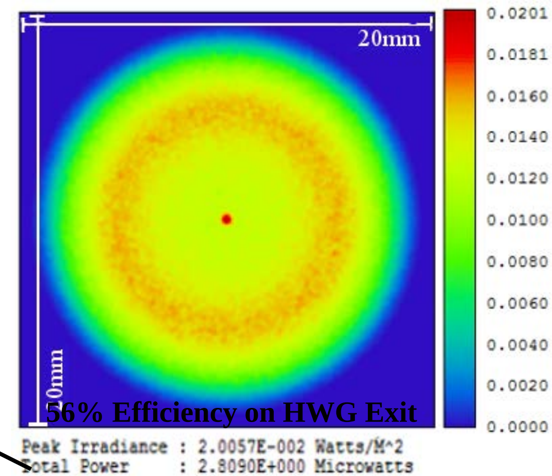
Focal Length: 15mm



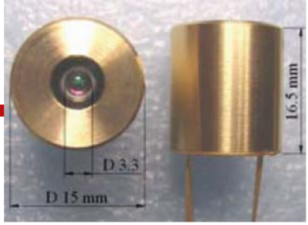


Focal Length: 5.95mm

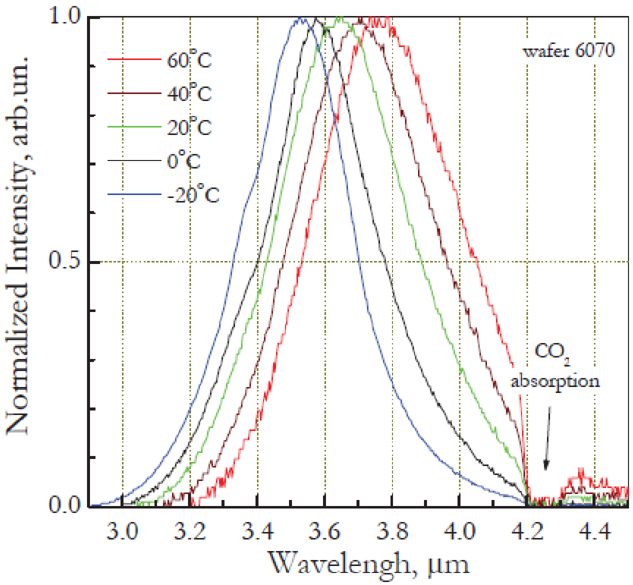


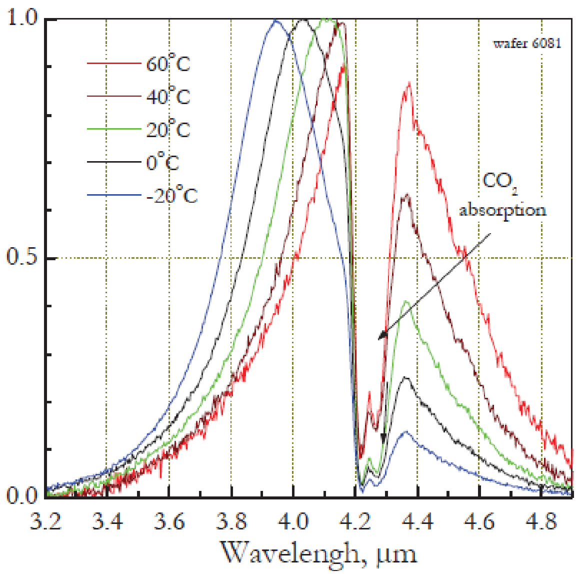


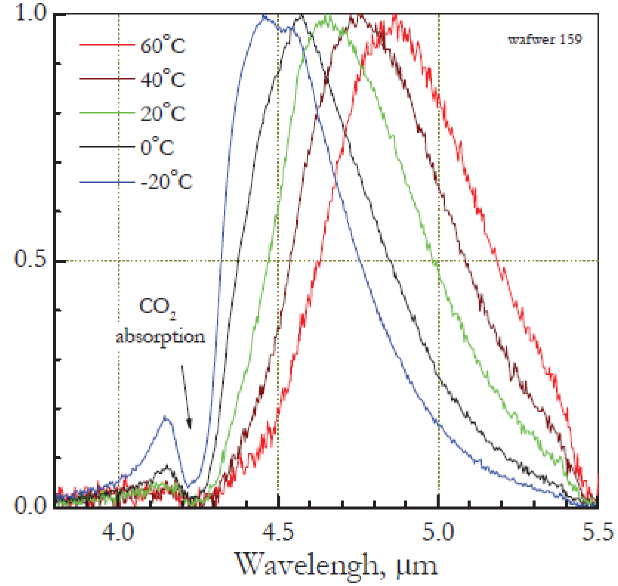
LED temperature control



3.6μm LED w/TEC 4.2μm LED w/TEC 4.7μm LED w/TEC

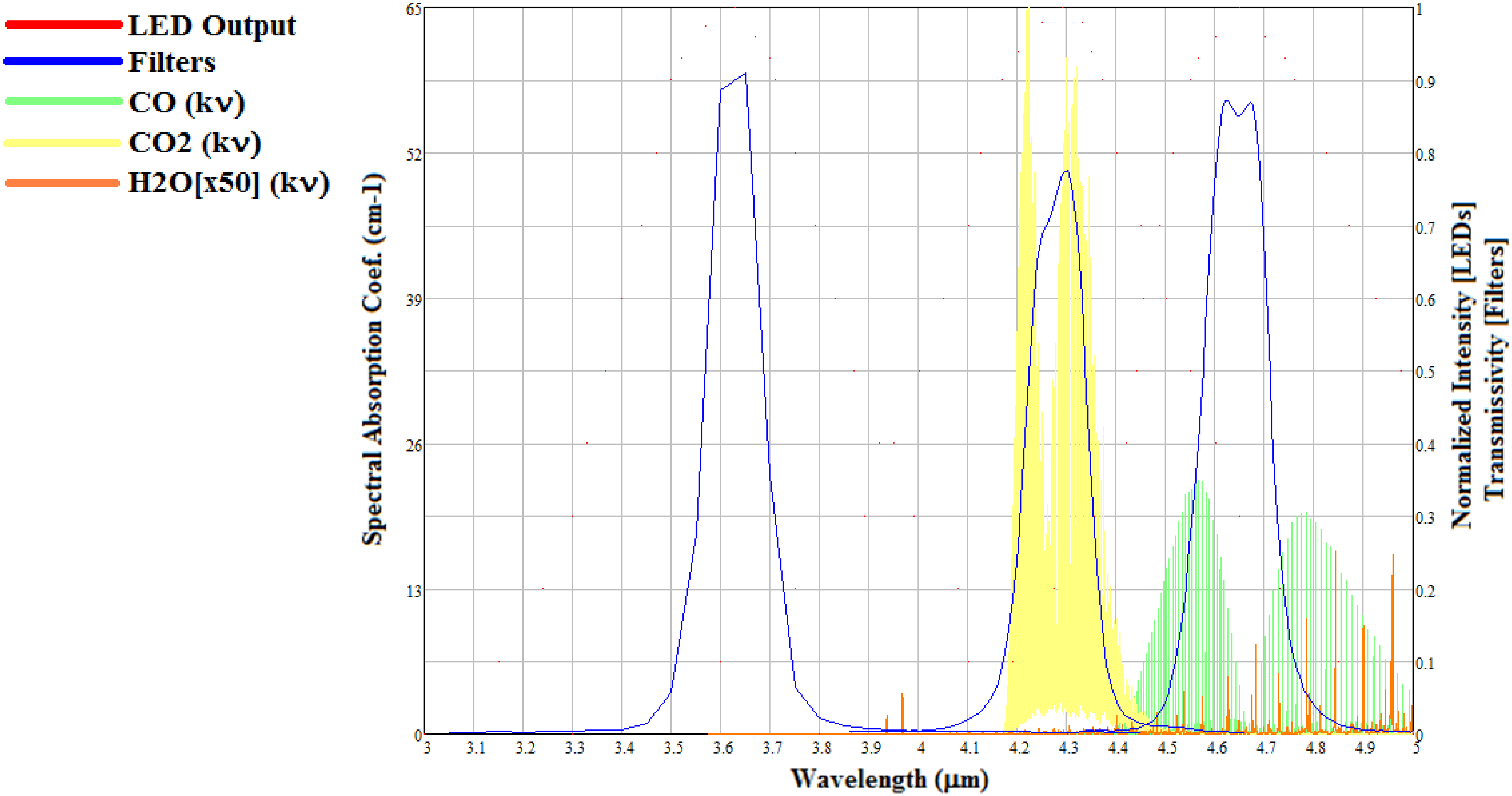




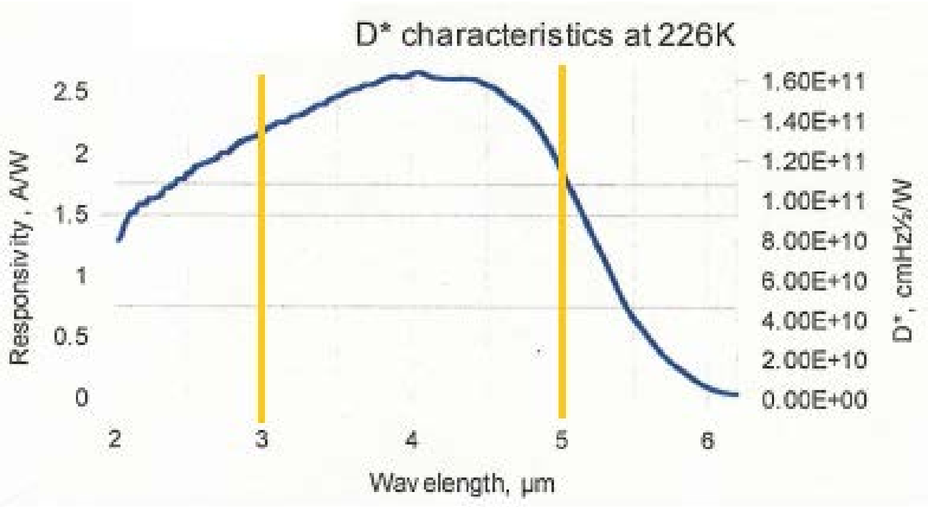


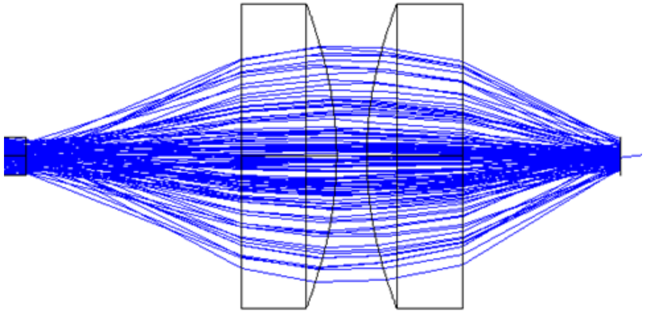
Features	Far-Field Pattern	Axis Deviation	Emissions Size
All 3 LEDs	≤20, deg	≤7, deg	3.3mm (radius)

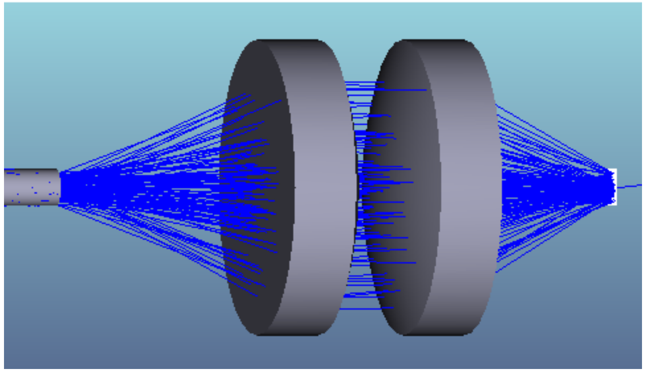
Filters Selection

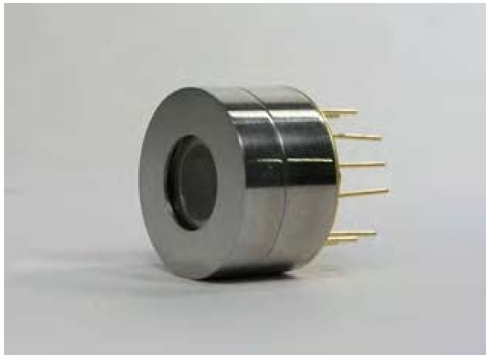


Detector & Catch Optics





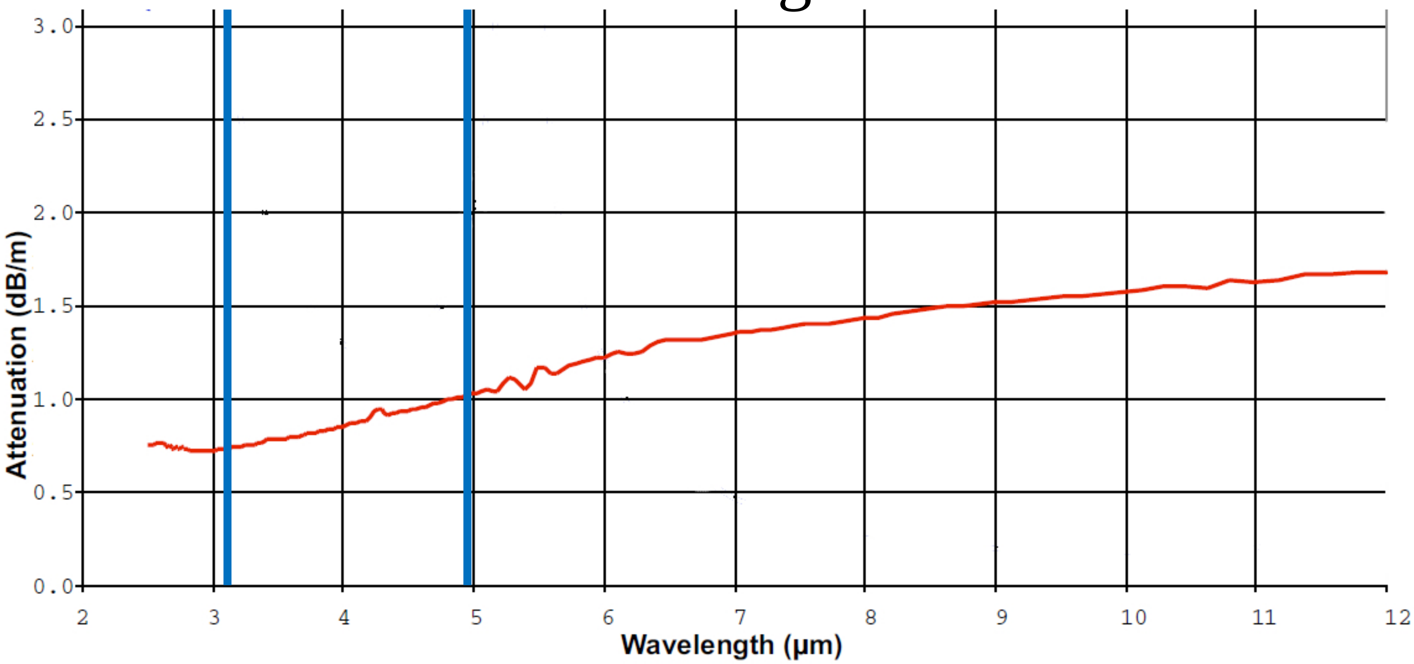




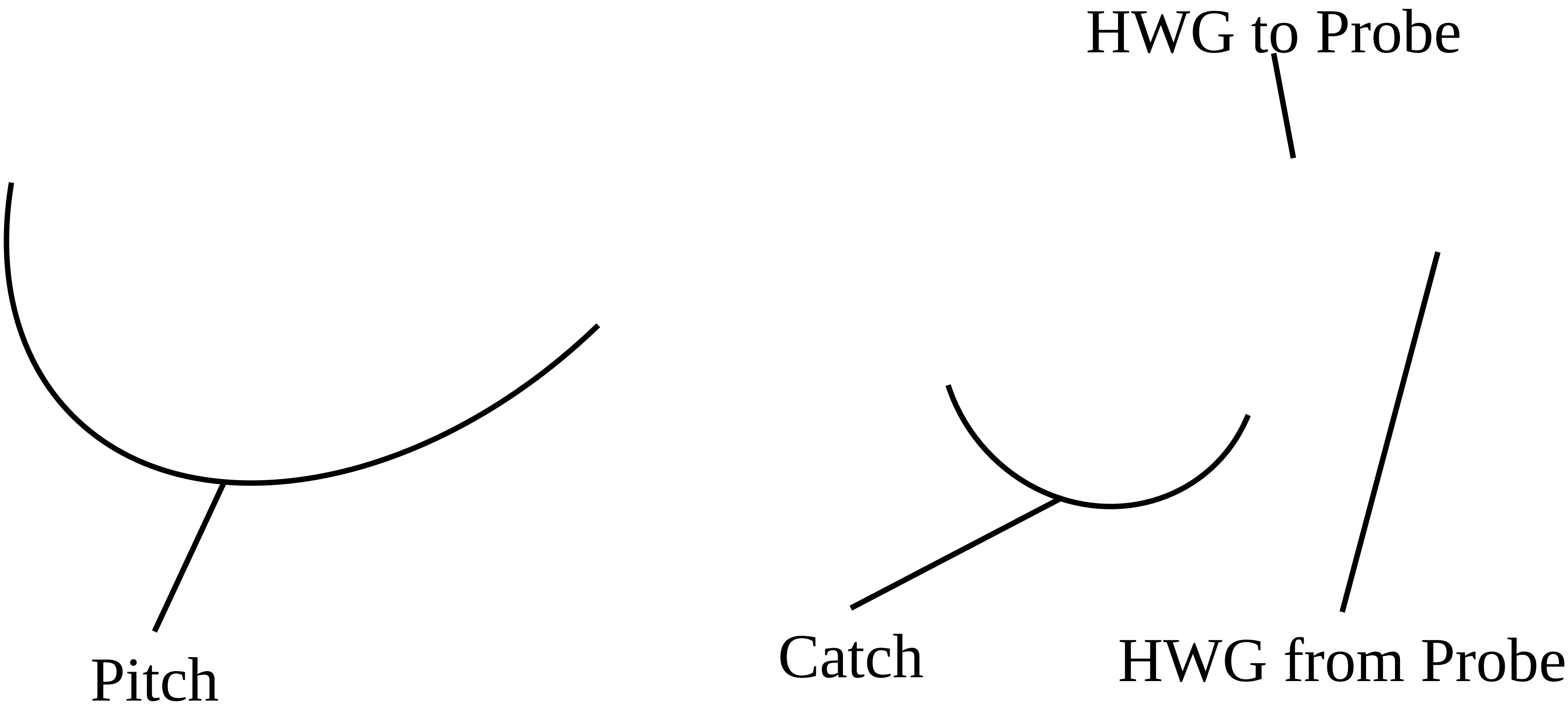
- Lenses: 2x BD-2 Aspheric Lens
  - Effective Focal Length: 5.95mm
- Detector: VIGO Systems PVI-2TE-5
  - Two stage, thermoelectrically cooled

Light Guiding

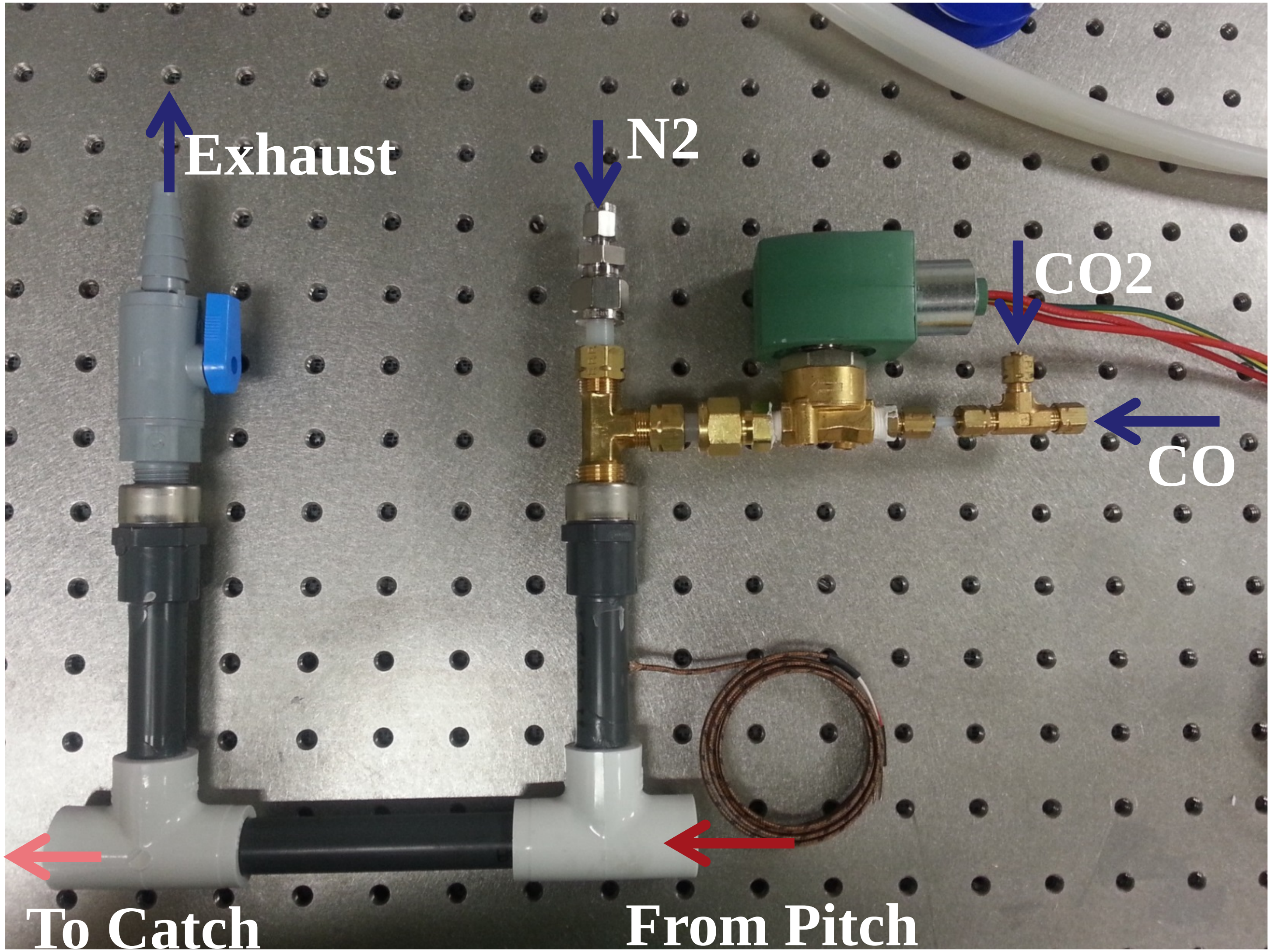
Hollow Silica Waveguide from Molex



Assembly

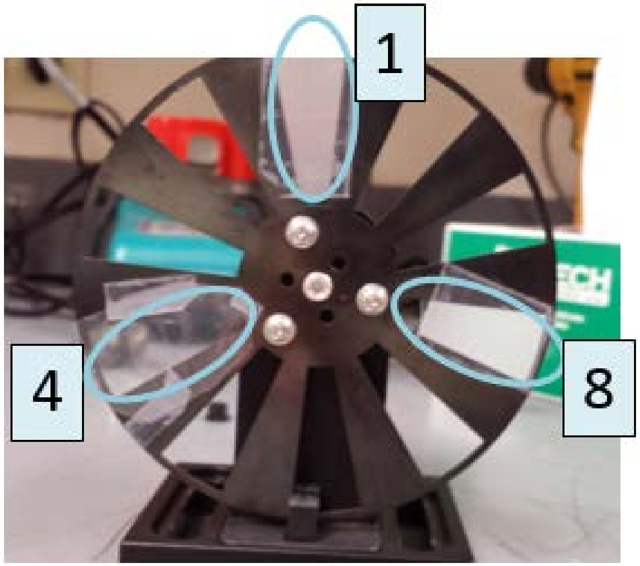


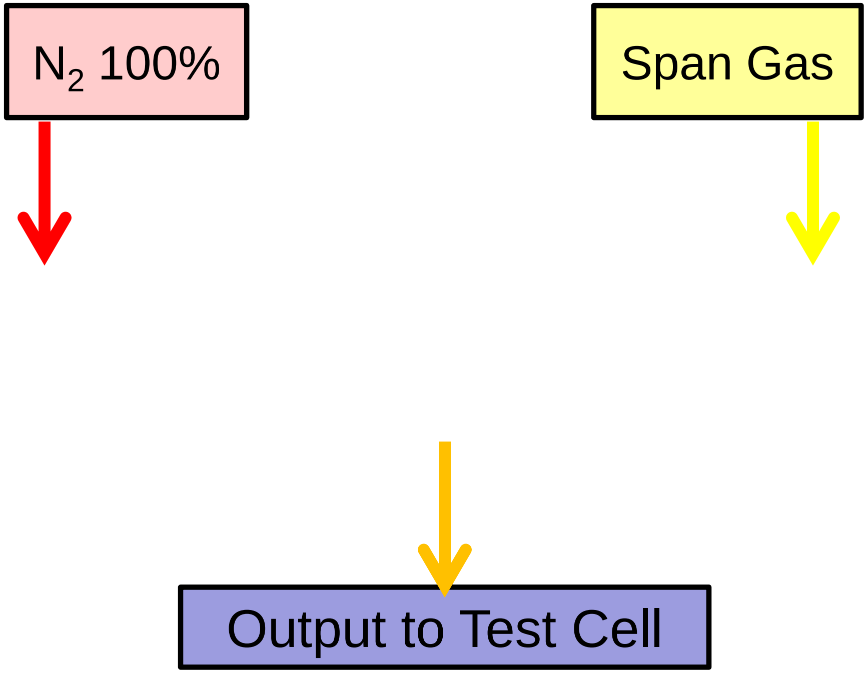
Validating



Detection limit and time resolution characterization

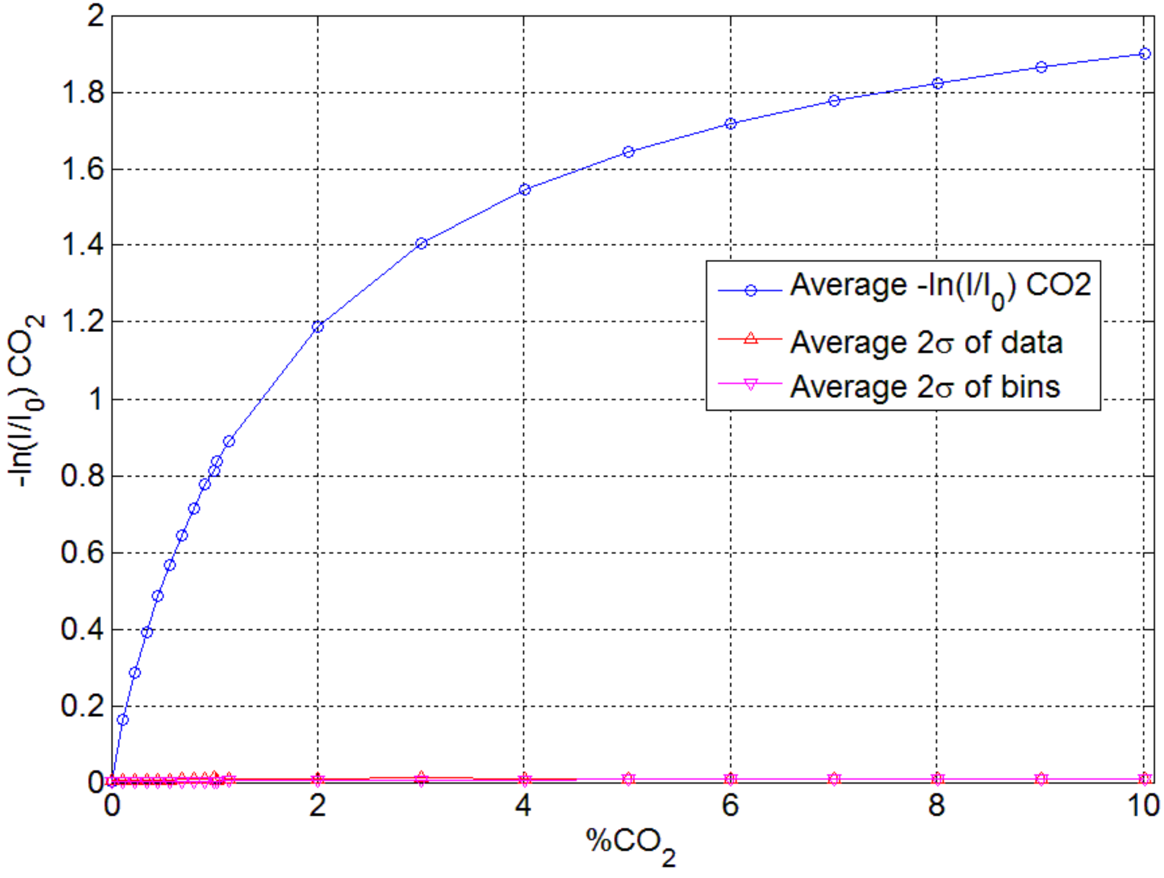
- Early evaluation testing done at ORNL
- Measurements were taken using a flow cell with a path length of 8cm
  - Neat CO_2 measurements
  - Neat CO measurements
  - Simultaneous measurements/evaluation of cross-interference
- Time resolution testing
  - Chopper wheel with plastic to simulate absorption





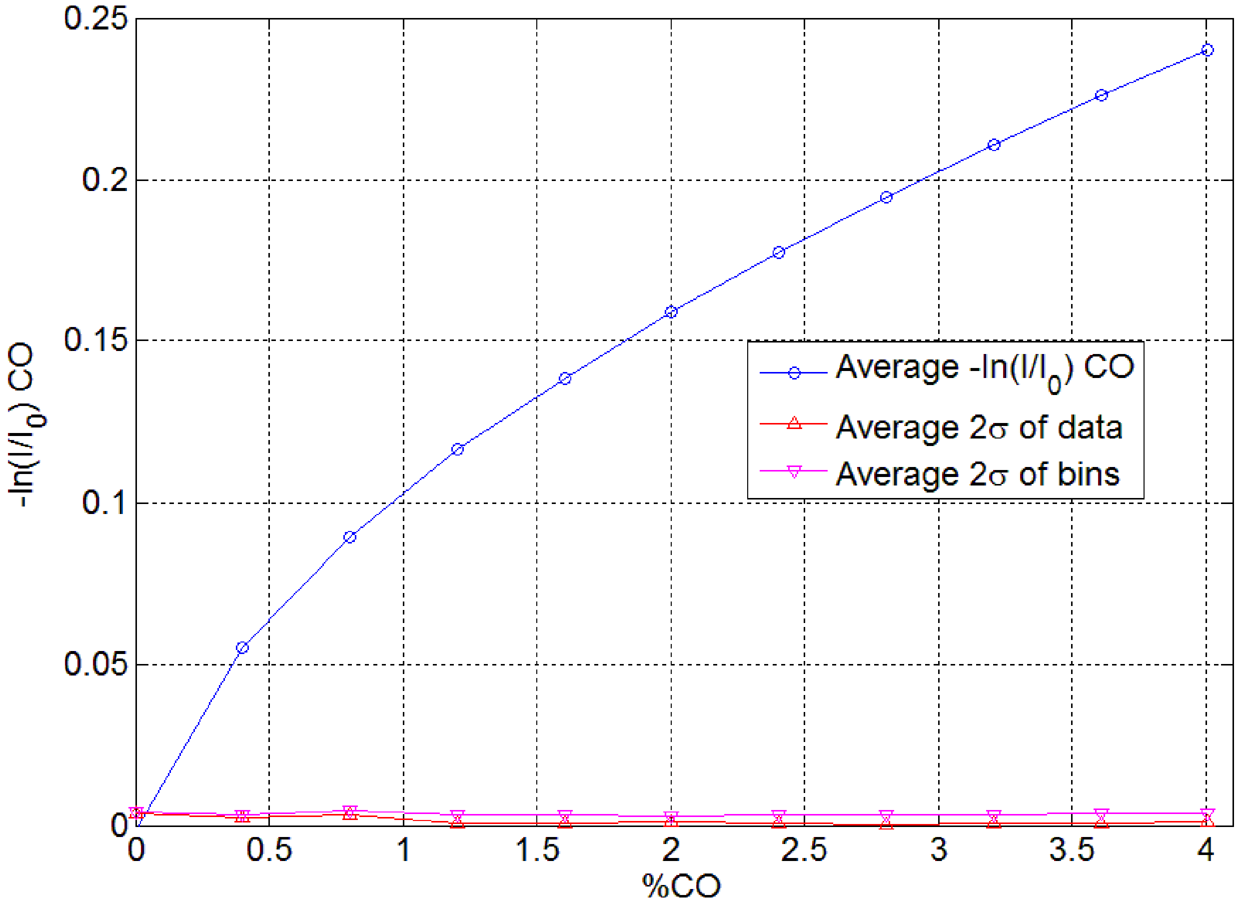
Neat CO_2 Results: 30ppm

$$-\ln\left(\frac{I}{I_0}\right) = kL\chi$$



Detection Limit: 30ppm (function of path length L)

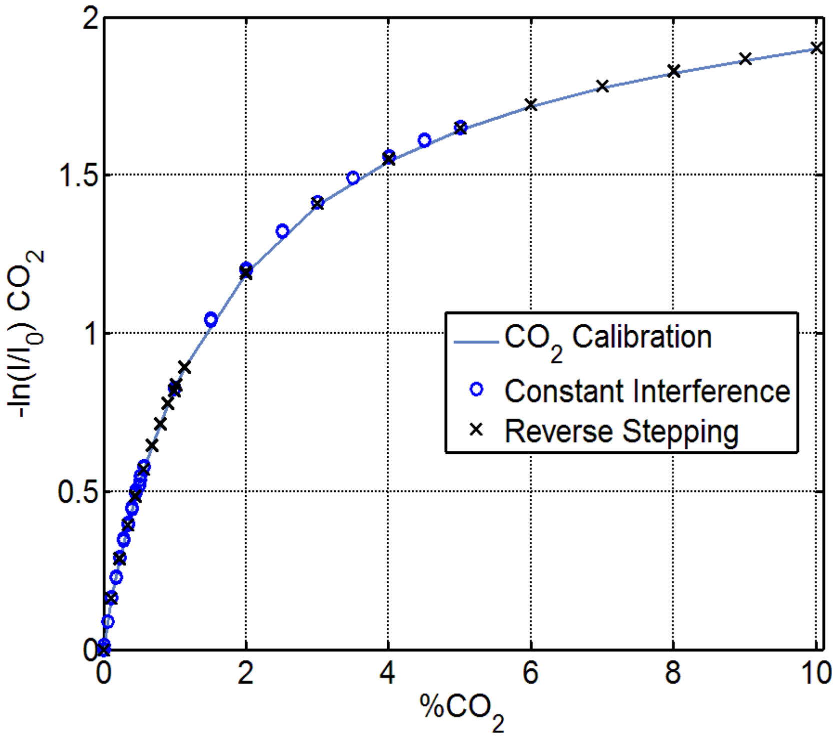
Neat CO Results: 400ppm

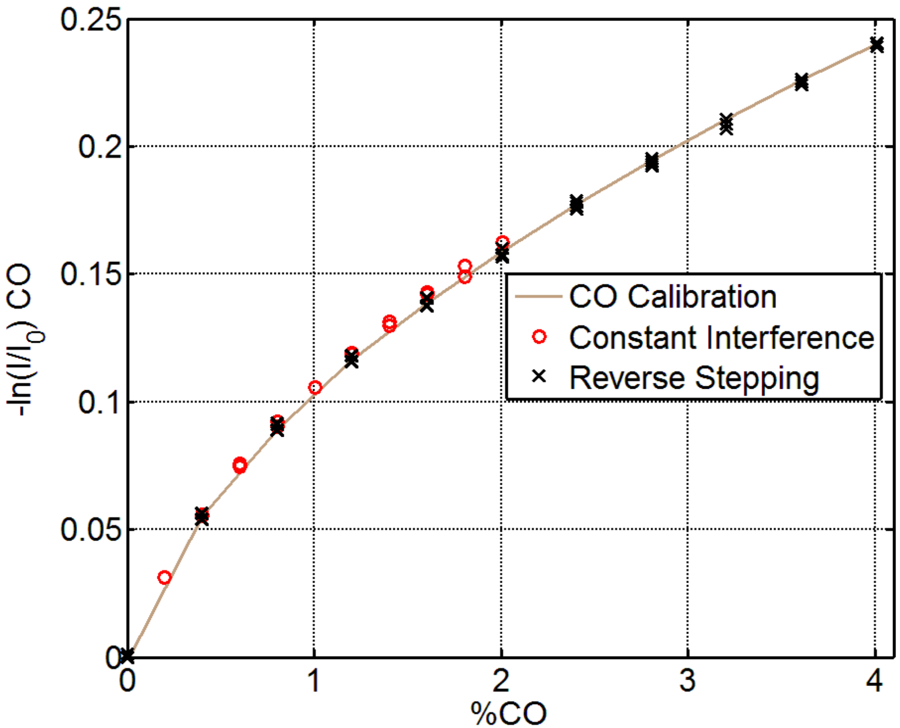


Detection Limit: 400ppm (function of path length L)

No cross-interference observed

Simultaneous measurements of CO and CO_2





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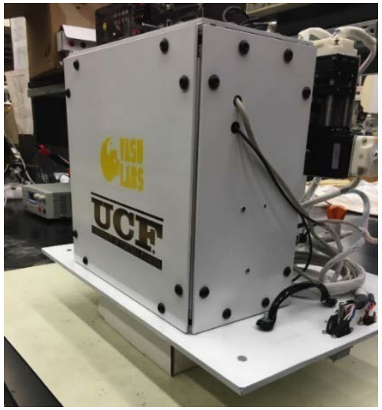

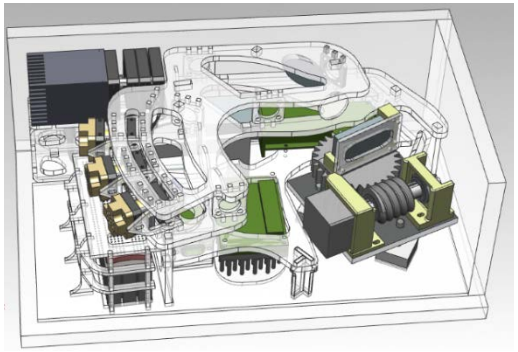

Team Members & Sponsoring Organizations

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Sponsoring Organizations

UCF

CATER

OAK RIDGE
National Laboratory

COE CST
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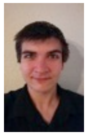

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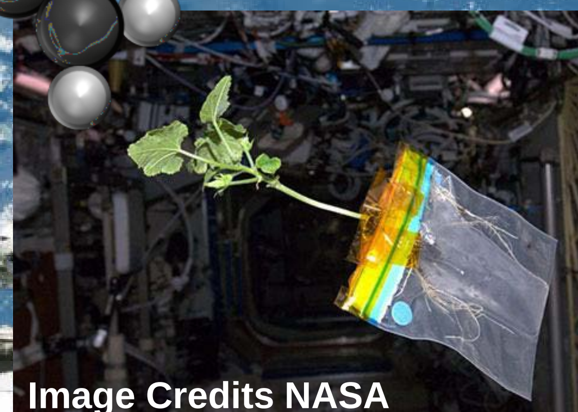
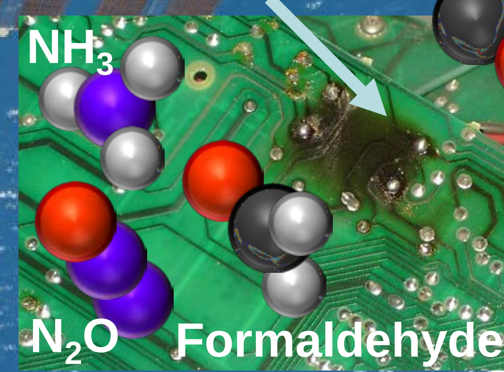
Akshita Parupalli
University of Central Florida

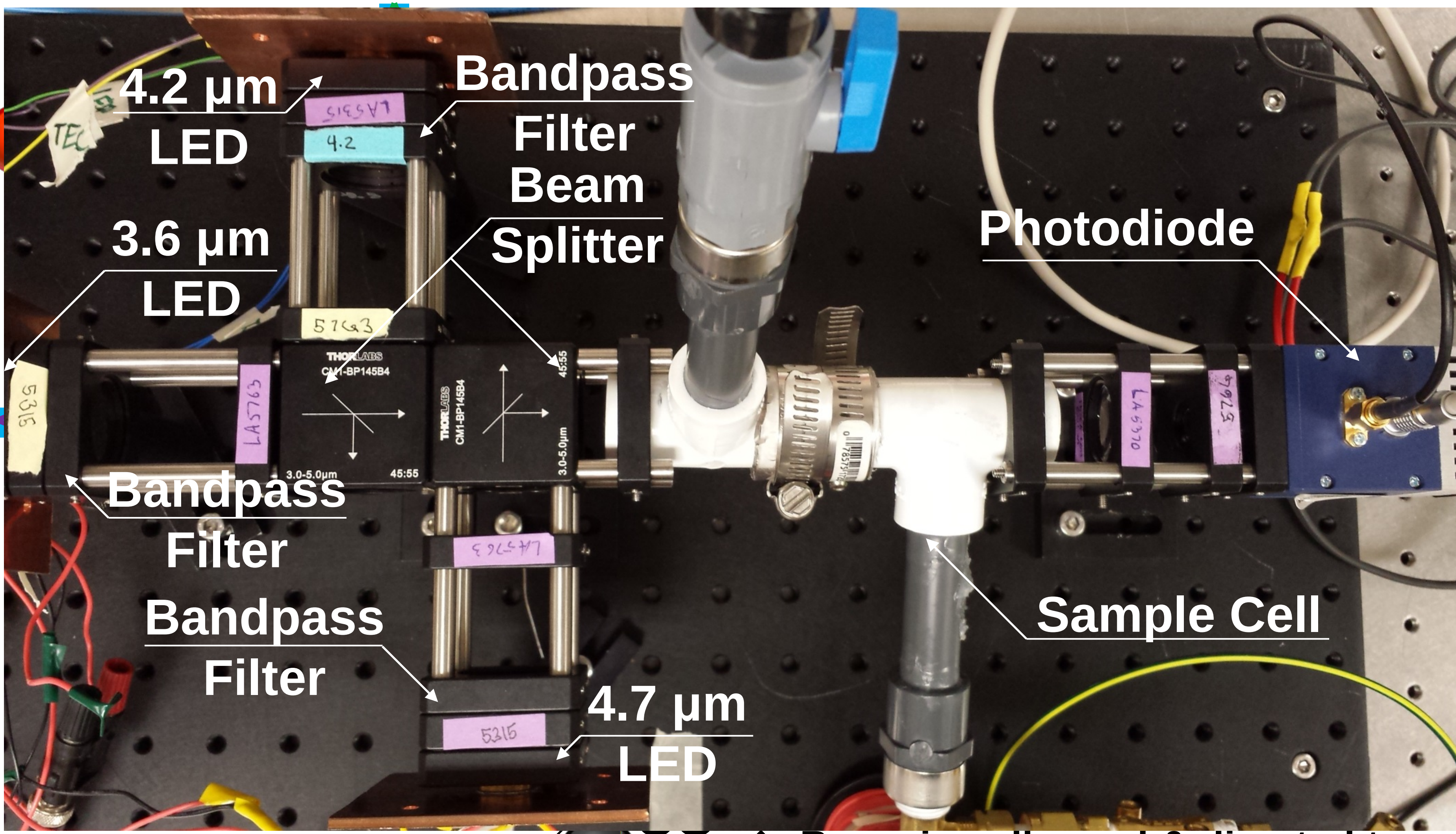
Need for Gas Sensors on Spacecraft

- ❖ **Spacecraft 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**





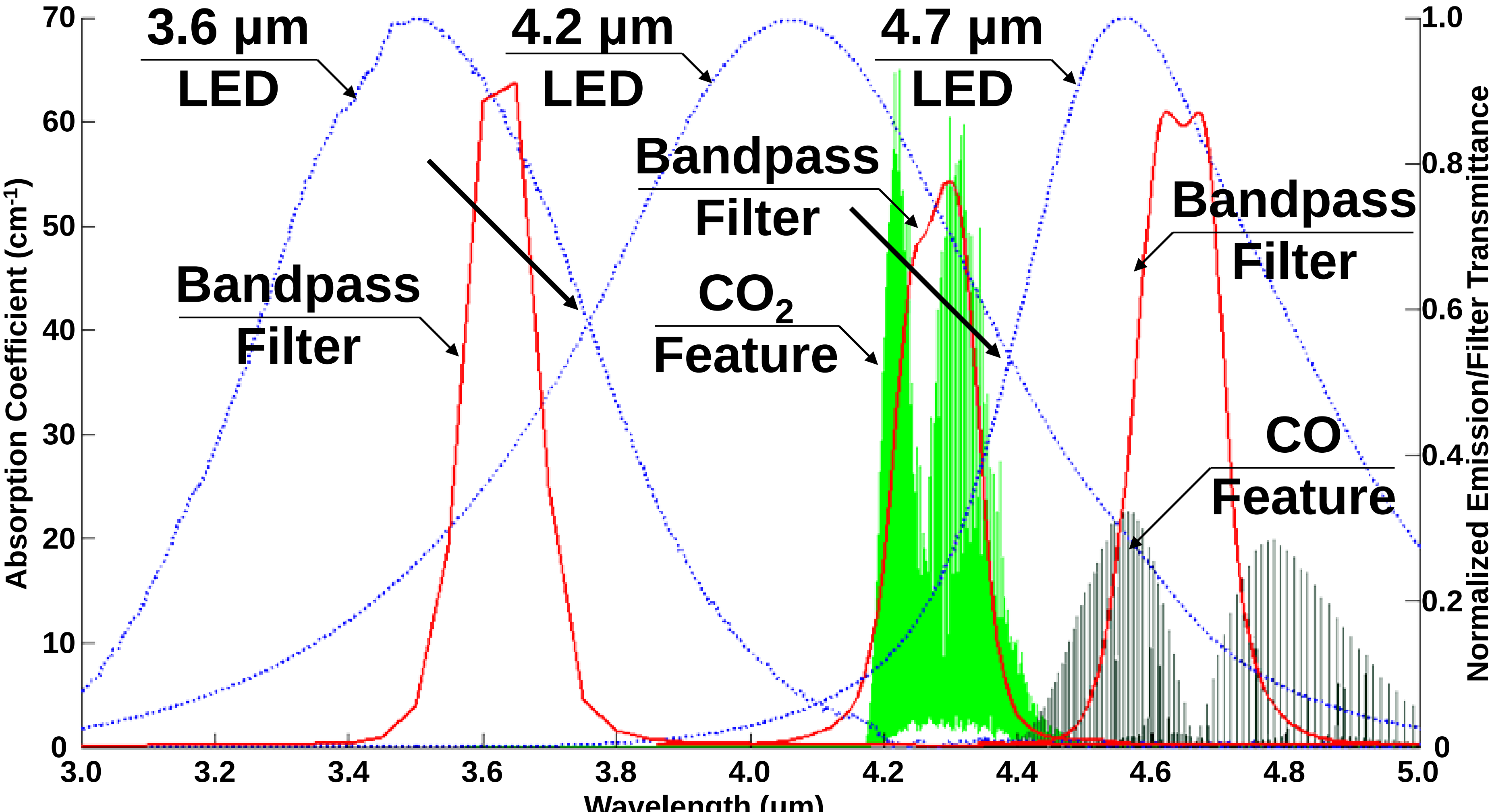
Tabletop Sensor



LED

❖ Beam is collapsed & directed to a photodiode

Spectral Considerations of Tabletop Sensor

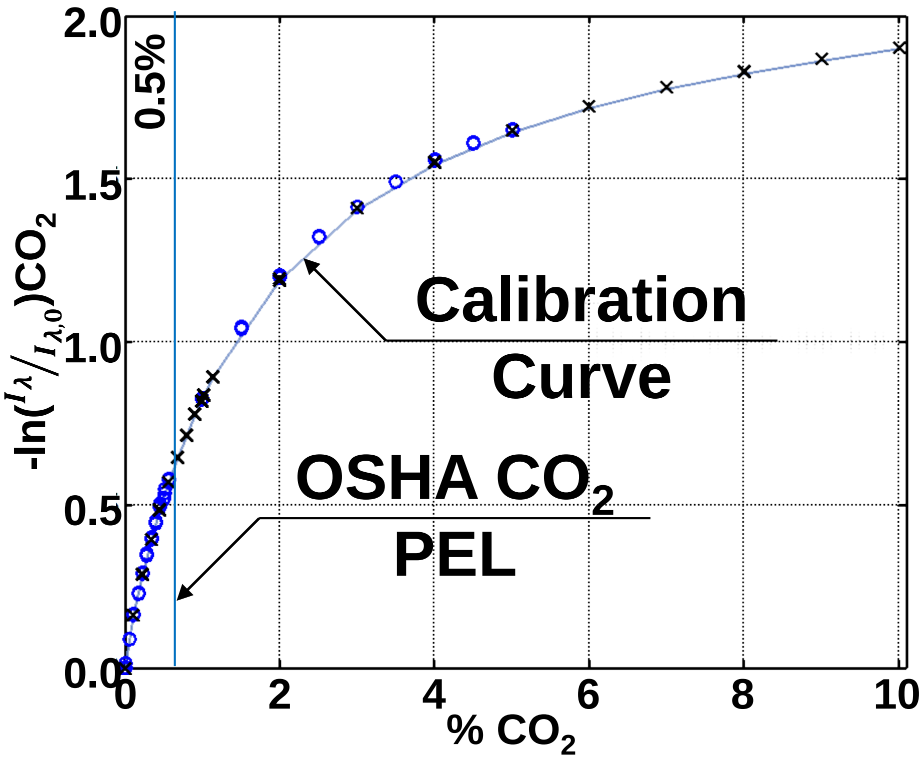


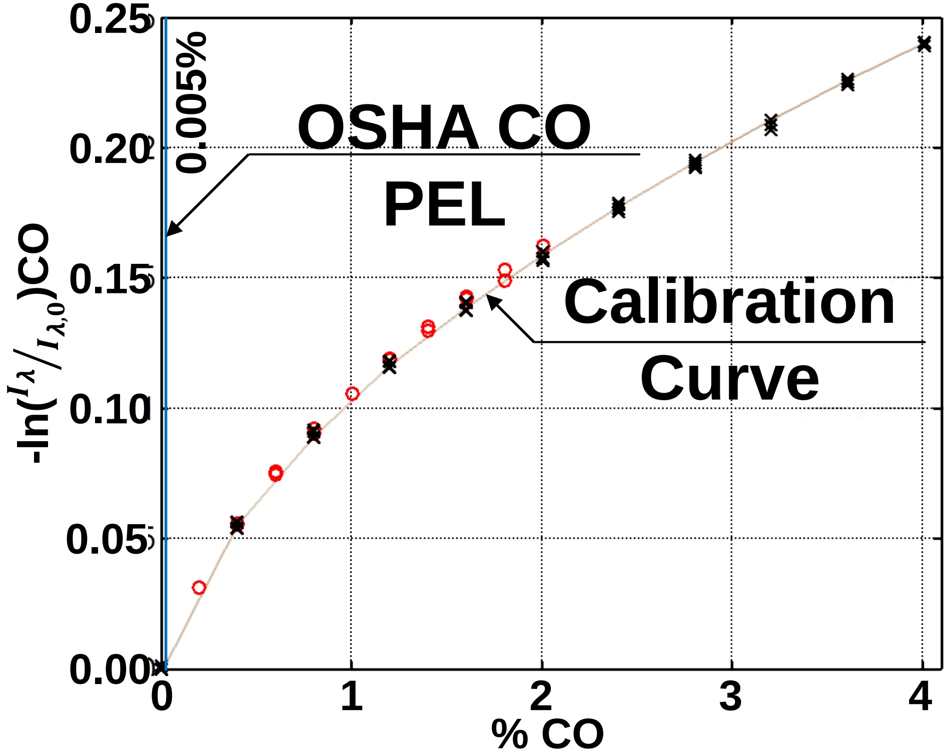
❖ [illegible] to

[illegible] - 5±1 μW

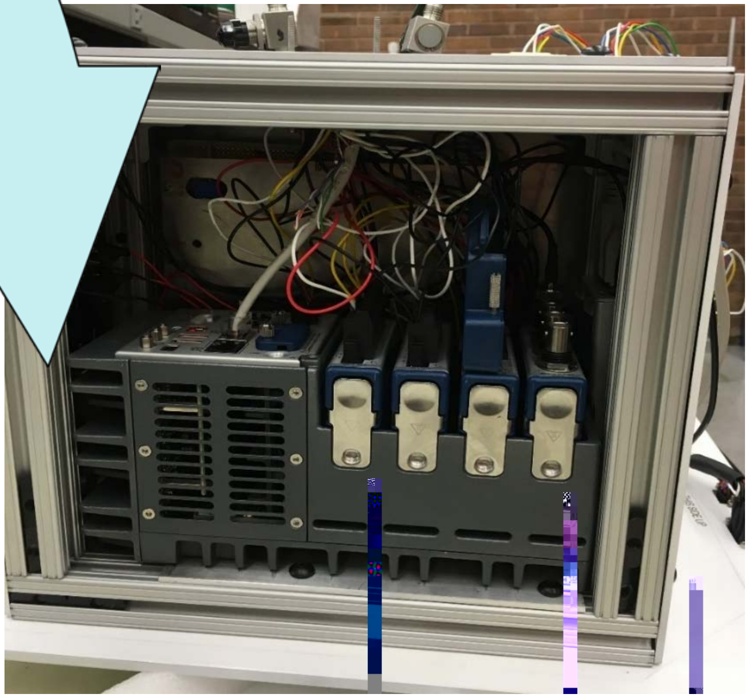
Calibration of Tabletop Sensor

- Calibration study performed while CO and CO_2 were flowed through a test cell
  - Test was performed with simultaneous CO/CO_2 test gas
  - No interference was observed
- Calibration Curves as shown
  - OSHA permissible exposure limits (PEL) shown for reference

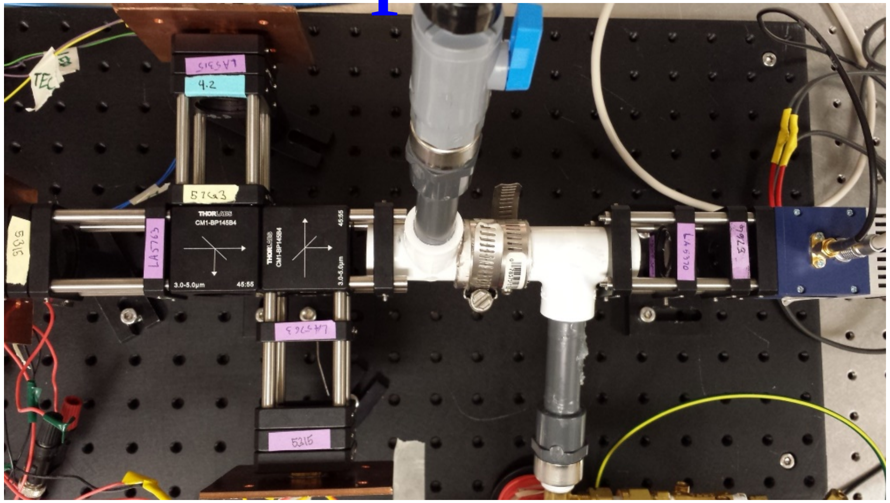




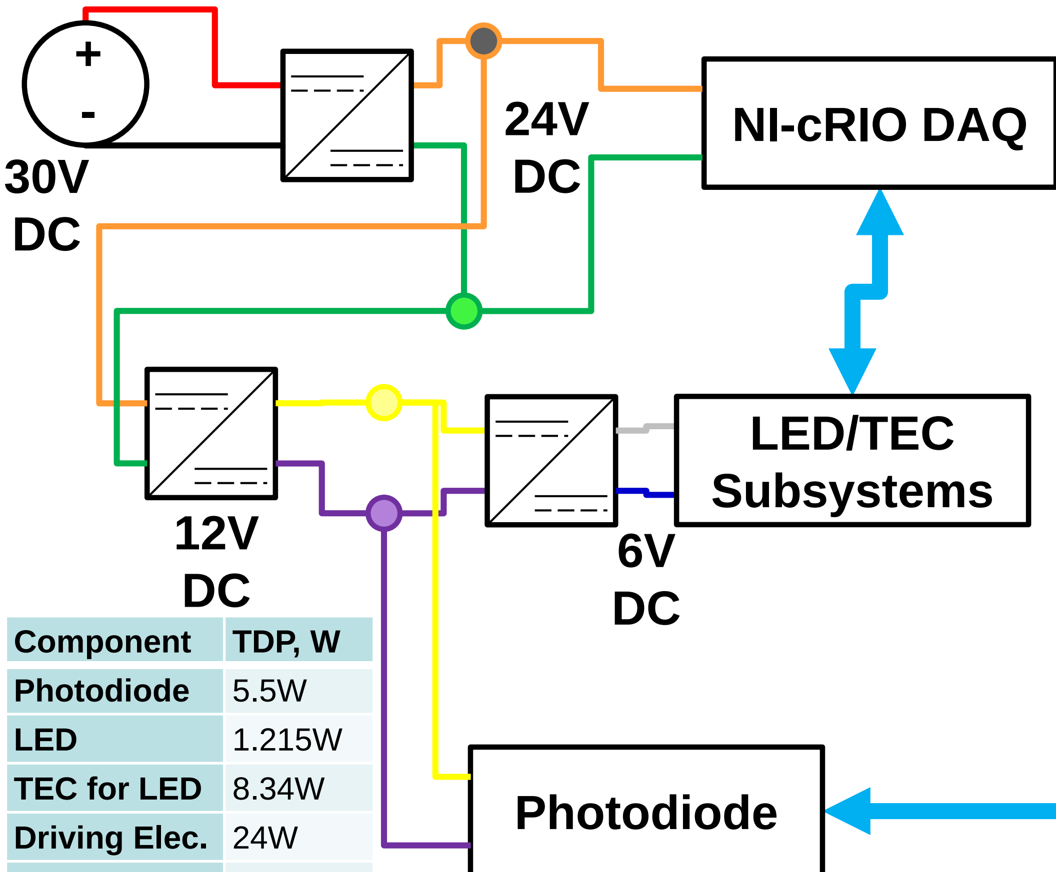
Flight Test



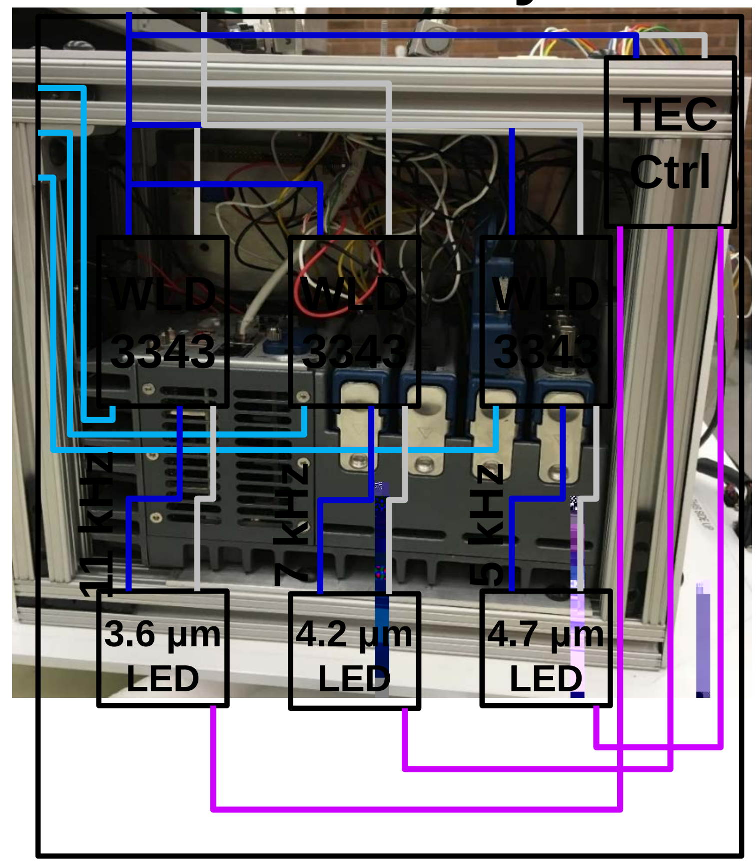
Tabletop Model



Flight Test Sensor Electrical System



LED/TEC Subsystems



Component	TDP, W
Photodiode	5.5W
LED	1.215W
TEC for LED	8.34W
Driving Elec.	24W
cRIO-9031	10W
Total	49.055W

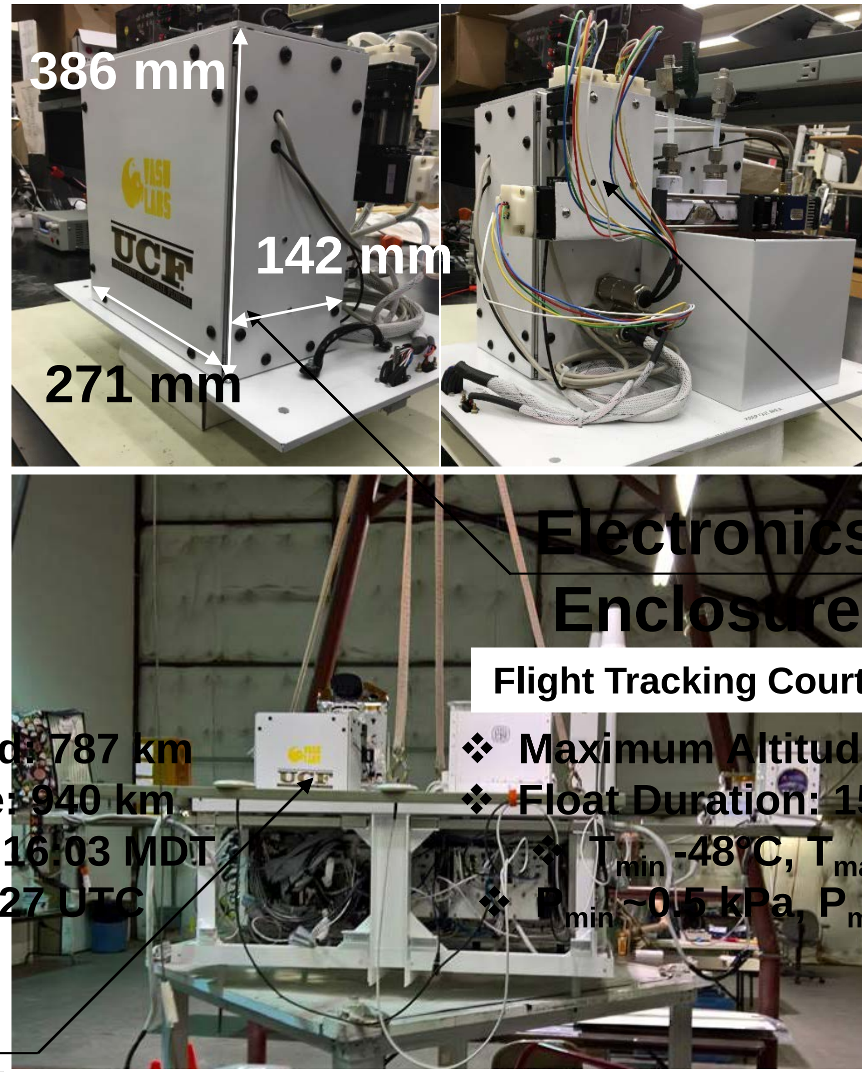
- Thermal Design Power 49 W ... controller

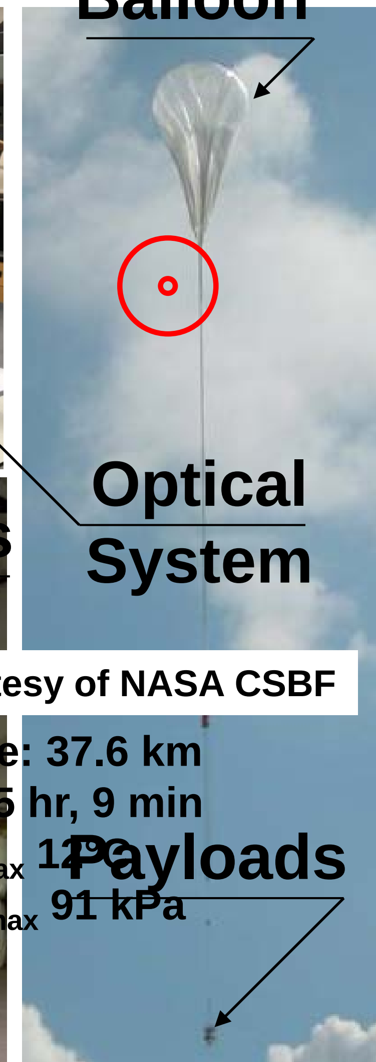
Pre Flight Testing at the UCF Environmental Chamber Testing

- Test Conditions
  - Duration 4 hours
  - T_{min} -20°C
  - T_{max} 23°C
  - P_{min} 0.27 kPa
  - P_{max} 101 kPa
- No observed issues with operation

High Altitude Balloon Flight Test

- NASA Columbia Scientific Balloon Facility Ft. Sumner, NM
- Sensor packaged and mounted
  - Aluminum enclosure for sensor electronics
  - Sensor mounted externally
- Autonomous operation test
- Fixed gas composition
  - N_2 89.51%
  - CO 4.97%
  - CO_2 5.52%



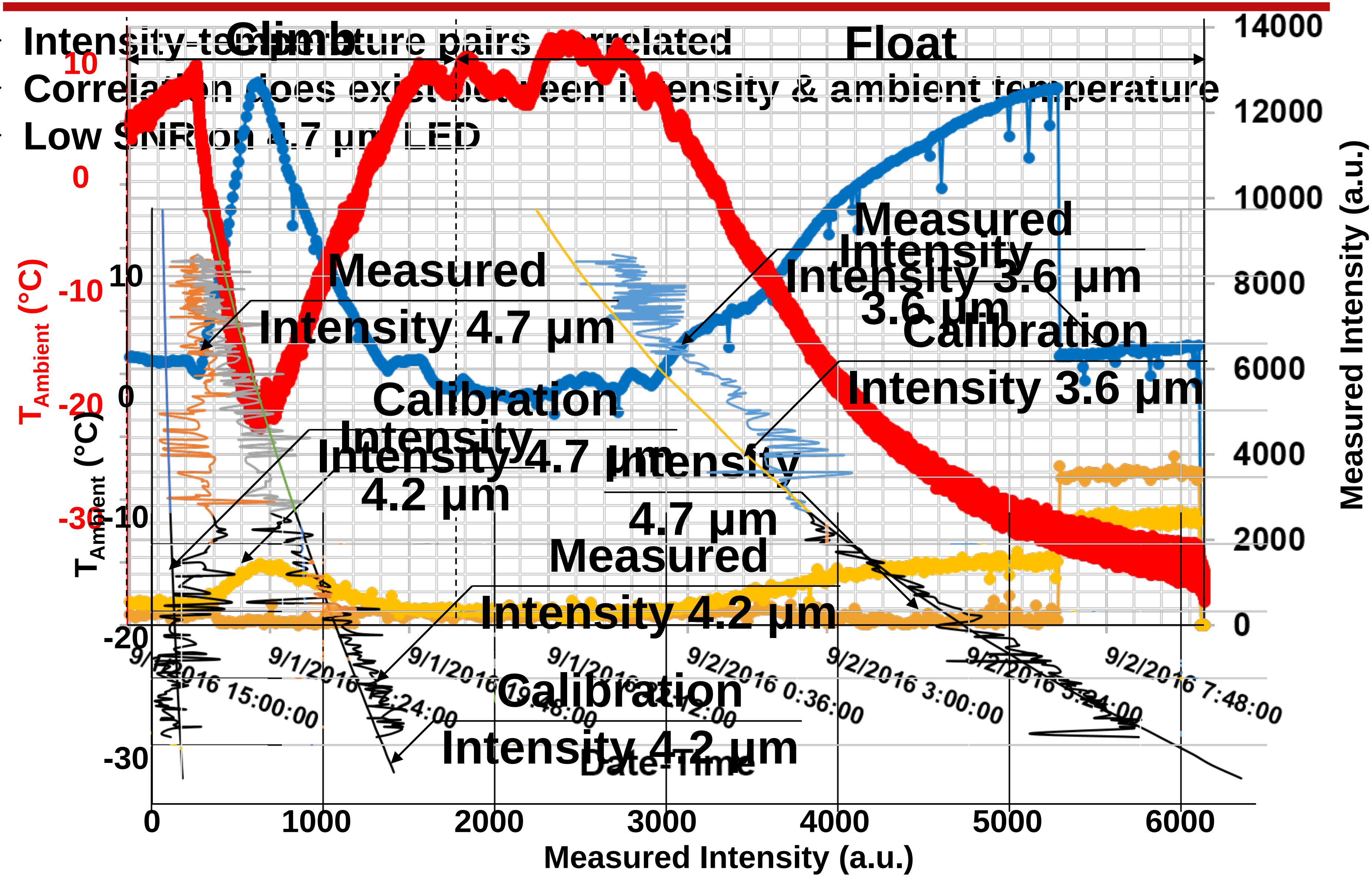


Flight Tracking Courtesy of NASA CSBF

- Distance Over Ground: 787 km
- Total Flight Distance: 940 km
- Launch Time: 9/1/2016 16:03 MDT
- Impact: 9/2/2016 10:27 UTC
- Maximum Altitude: 37.6 km
- Float Duration: 15 hr, 9 min
  - T_{min} -48°C, T_{max} 12°C
  - P_{min} ~0.5 kPa, P_{max} 91 kPa

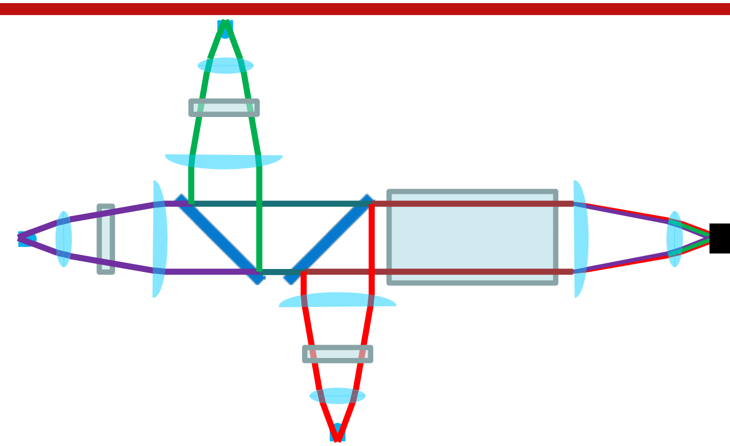
High Altitude Balloon Flight Results

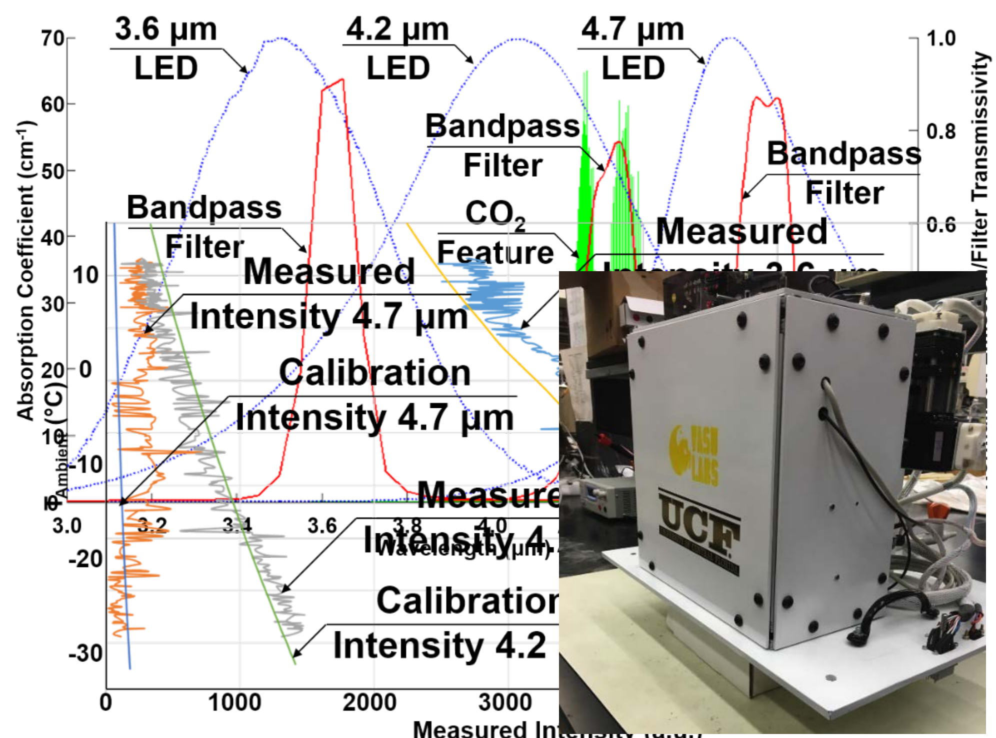
- Intensity-temperature pairs correlated
- Correlation does exist between intensity & ambient temperature
- Low SNR on 4.7 µm LED



Learned Lessons from Beamspliter Balloon Flight

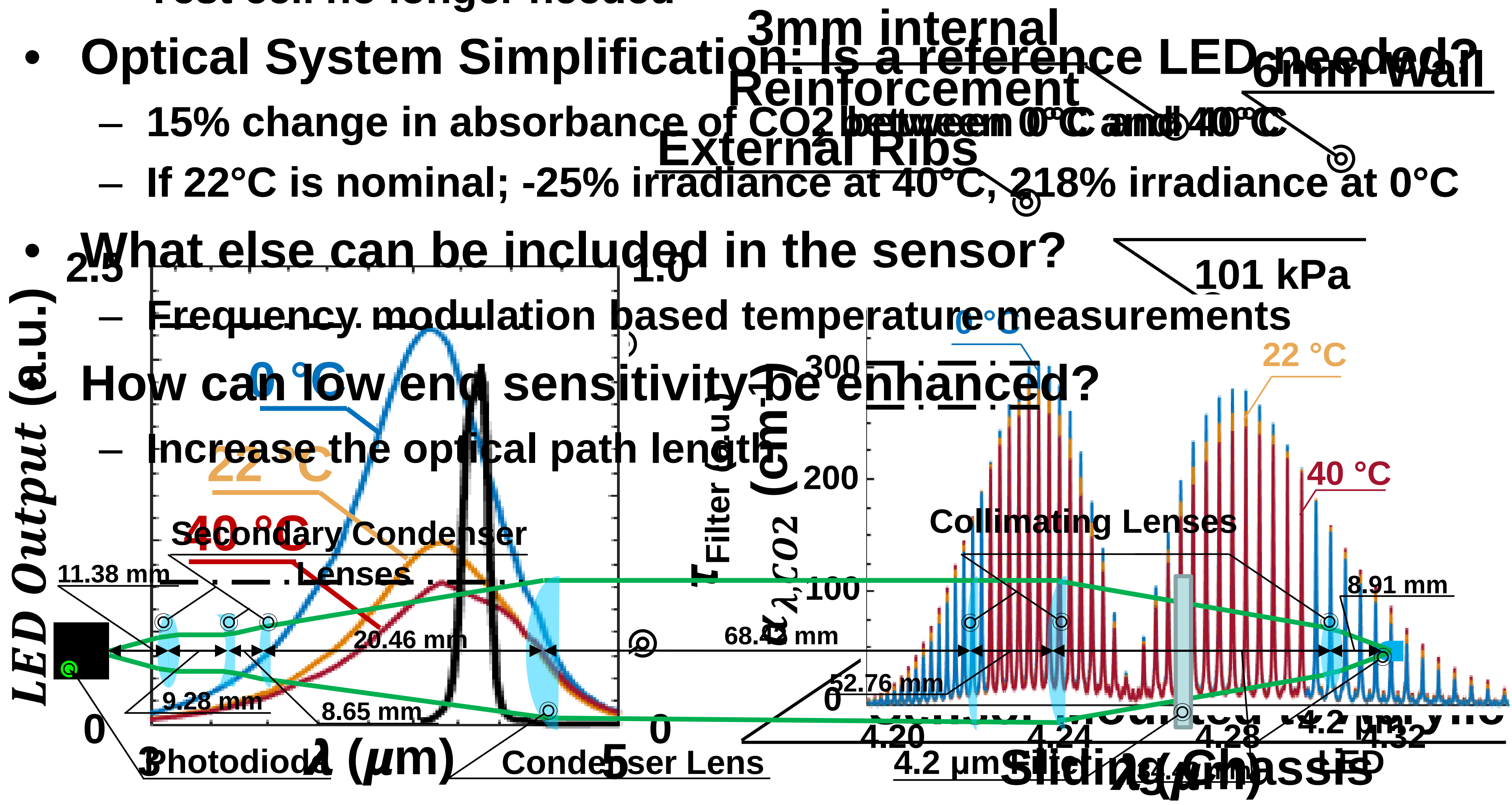
- Low SNR
  - 45% Intensity loss at each beamsplitter
  - Test cell is too small
- Band pass filters limit versatility
  - Poor overlap of CO feature with 4.7 µm filter
  - Gases outside of bands are nondetectable
- High signal variance from calibration
  - LED temperature regulation was sub par
  - Nested ground loops caused increased noise
- Sensor is too big
  - High TDP
  - Large volume
  - Heavy



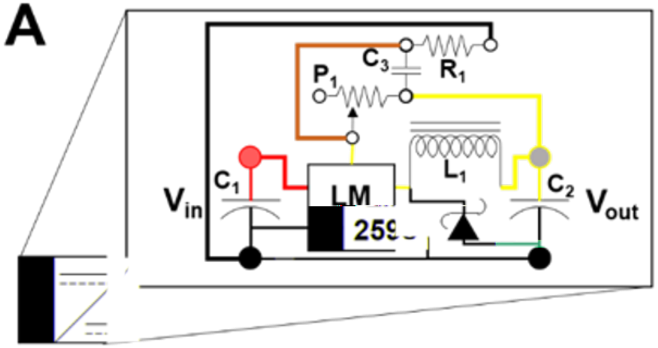


Rethinking & Improving the Sensor Design

- Weight Reduction: Laser cut acrylic enclosure
  - Test cell no longer needed
- Optical System Simplification: Is a reference LED needed?
  - 15% change in absorbance of CO_2 between 0°C and 40°C
  - If 22°C is nominal; -25% irradiance at 40°C, 218% irradiance at 0°C
- What else can be included in the sensor?
  - Frequency modulation based temperature measurements
- How can low end sensitivity be enhanced?
  - Increase the optical path length



Condensed Electrical Systems



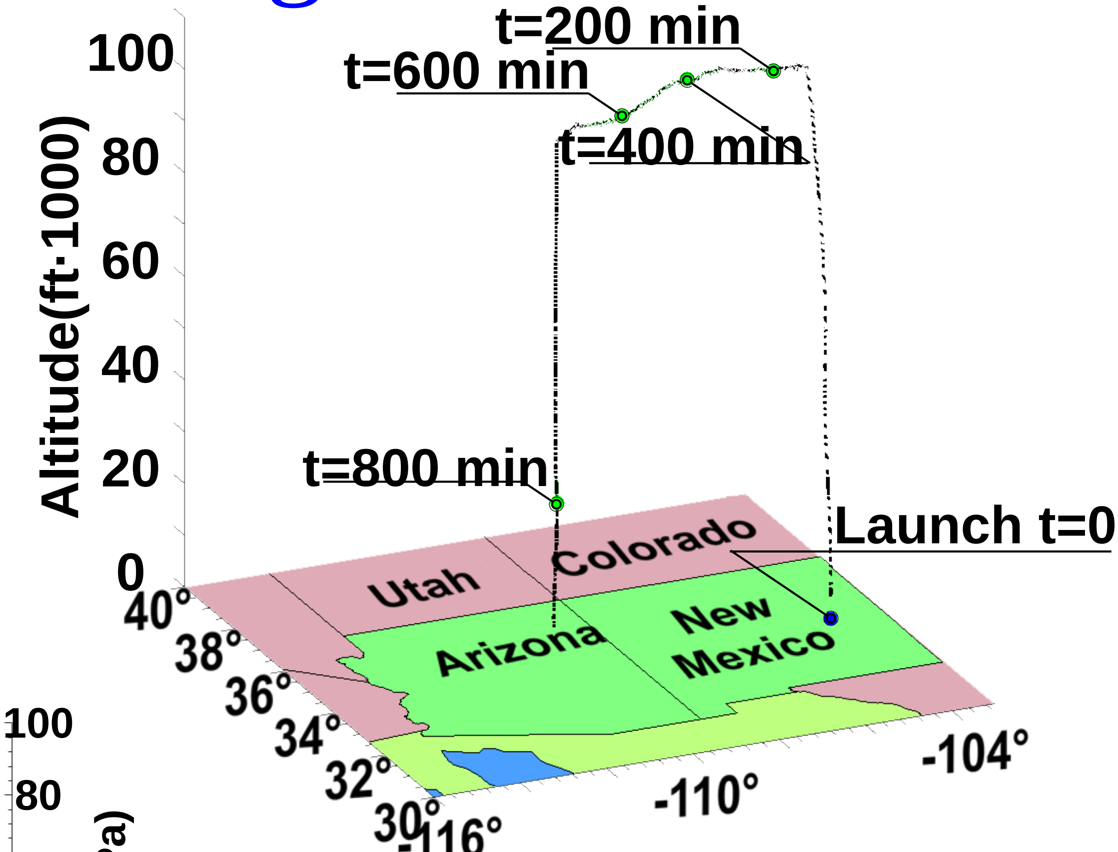
Legend

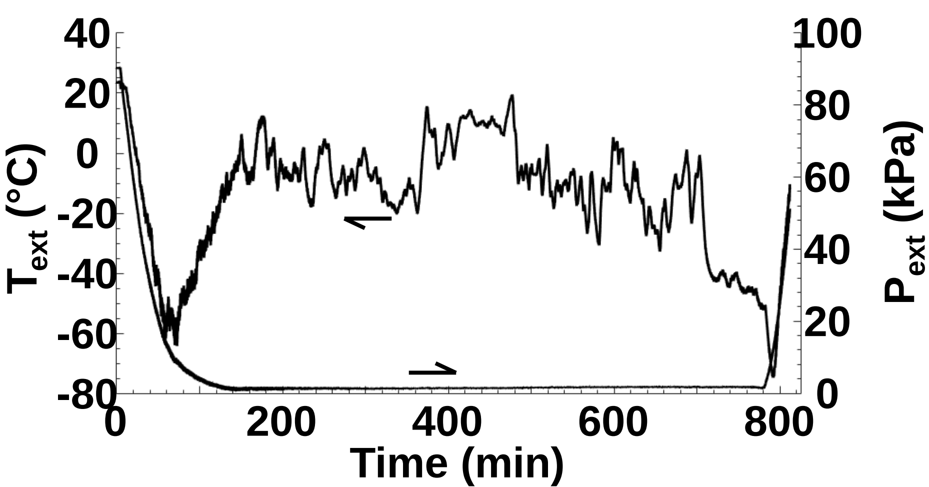
C_1	100 µF	C_5	3.3 mF	L_1	33 µH	P_1	30 kΩ
C_2	220 µF	C_6	10 nF	R_1	1 kΩ	P_2	50 kΩ
C_3	33 nF	C_7	1 nF	R_2	200 kΩ		
C_4	330 µF	C_8	100 nF	R_3	100 Ω		

Maximum power draw reduced to 17W, 10.6 of which is cRio

High Altitude Balloon Flight Test

- Launch at Ft. Sumner 9/4/17
  - 138 min ascent to Alt_{Avg} 105,000'
  - Float for ~10.5 hrs
  - Alt_{Max} 110,000'
  - Total fight time 820 min
  - P_{min} 1.6 kPa, P_{max} 90 kPa
  - T_{min} -64°C, T_{max} 23°C





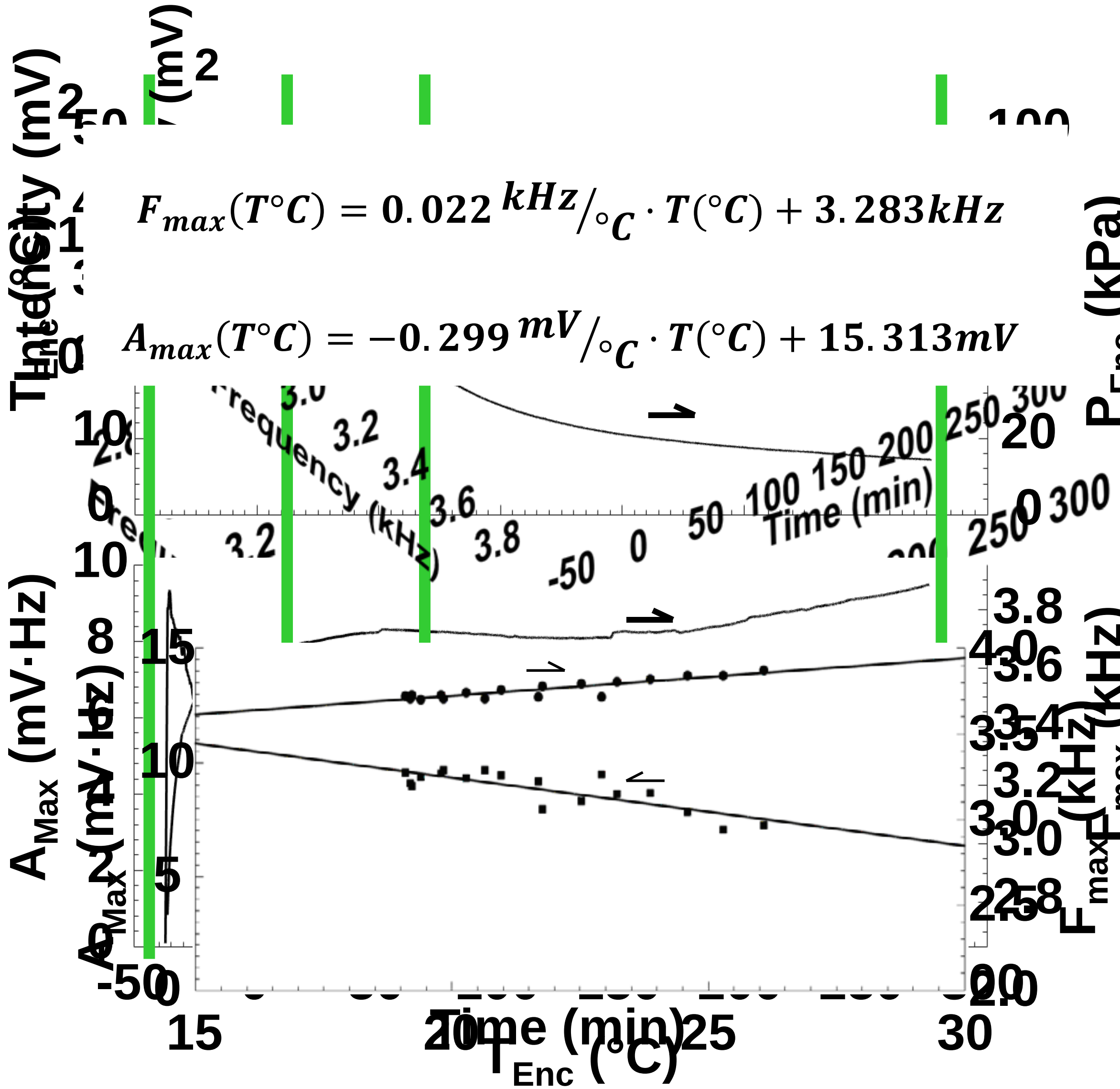
- Air at 90 kPa packaged into the enclosure with sensor
  - Fixed CO_2 concentration
- Flight testing examines signal drift and noise floor under real conditions

Condensed Flight Data

- Photodiode output spectrums
  - 2^{16} data points sampled at 100 kHz
  - FFT applied to each sample set
- Locus of maxima corresponds to CO_2 measurements
- F_{max} and A_{max} are both temperature dependent
  - F_{max} transient at startup
- After, ↑ F_{max} and T_{Enc} ↑
  - ↓ A_{max} envelope and T_{Enc} ↑
- Linear relations are found for F_{max} and A_{max} under constant CO_2

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

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



Conclusions & Future Work

- **LED based gas sensor is to be used for the detection of toxic compounds in spacecraft air**
- **Both amplitude and frequency modulation are simultaneously used in the sensor**
- **Next iteration will use multiple LEDs and variable path optical system to enhance species selectivity and LDL**
  - **MHz modulation instead of kHz**
- **Sounding rocket test**

Acknowledgements

Vasu Lab

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Publications for further reading

- Anthony Terracciano; Kyle Thurmond; Michael Villar; Justin Urso; Erik Ninnemann; Akshita Parupalli; Zachary Loparo; Nick Demidovich; Jayanta S. Kapat; William P. Partridge, Jr.; **S. Vasu, "**Hazardous das detection sensor using broadband LED based absorption spectroscopy for space applications", ***New Space,*** 2018, 6 (1), 28-36. **Cover Page Article.**
- Kyle Thurmond; Zachary Loparo; W.P. Partridge Jr.; **Subith S. Vasu;** "A Light-Emitting-Diode (LED) Based Absorption Sensor for Simultaneous Detection of Carbon Monoxide and Carbon Dioxide", ***Applied Spectroscopy***, 2016, 70 (6), 962-971.

Questions?