Competitive Academic Agreement Program

"Methane Detection from a UAV"

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"02/09/2018"

Main Objective

Natural gas leak detection can be labor intensive. Let's see if there's a better way.

- What if we automated a lot of it with drones?
- How expensive might it be to make a UAV-sized instrument?
- What are the physical drivers behind a next-generation sensor?

Project Team & Other Sponsors

- Professor: William J. Emery
- Students: Bill Tandy, Ashwin Yerasi
- Colorado University – Boulder
- Lots of mentorship from Ball Aerospace
  - Jarett Bartholomew, in particular

Defining a performance goal

- Talked with industry representatives, PHMSA managers, read proposal requests. Requests were fairly consistent:
  - Everyone would like to see an instrument capable of reliably finding 50 SCFH leaks in winds up to 10 mph.
  - Seeing 25 SCFH leaks would be even better, but not expected.
  - For sure have to find 100 SCFH leaks every time.
- Goal is to provide the 50 SCFH leak performance from a UAV flying no more than 500 feet above the target of interest.

Overview: Quick History of Methane Detection

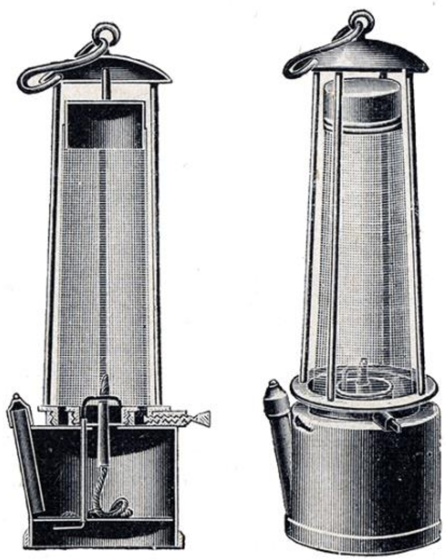
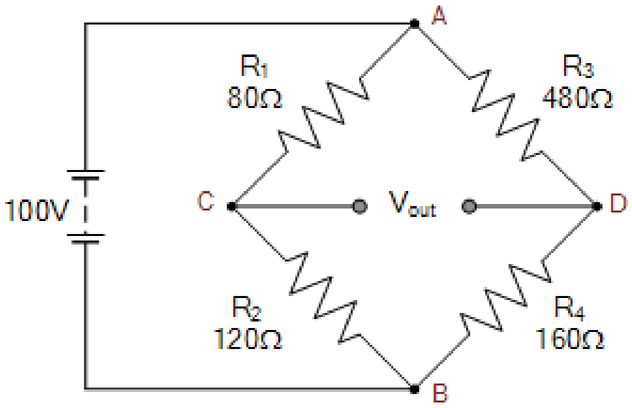


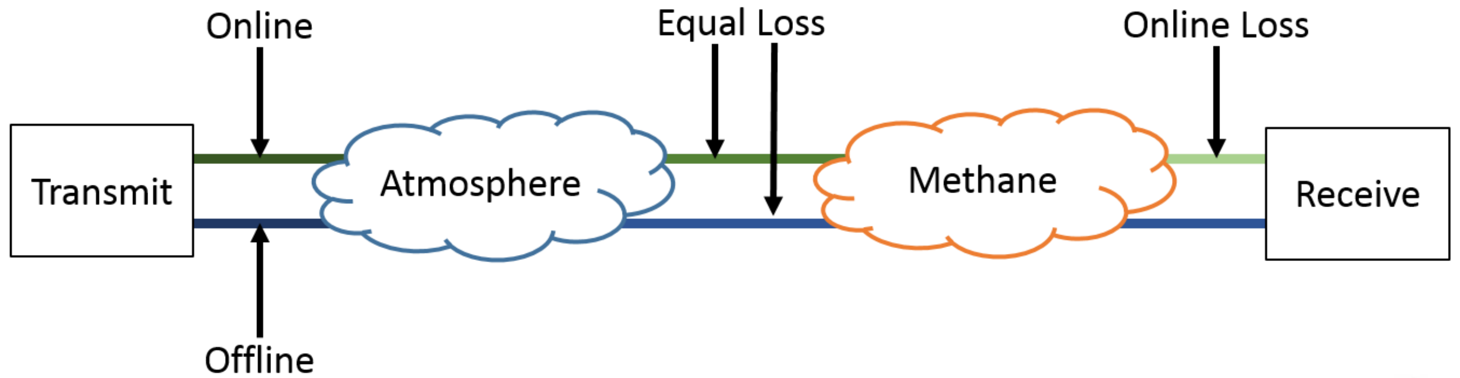
Fig. 192. Davysche Sicherheitslampe

<u>Figure</u> 8: The Davy Lamp burned brighter in the presence of methane and dimmer in the presence of CO2. [Davy,1816]



Overview: One page DIAL summary

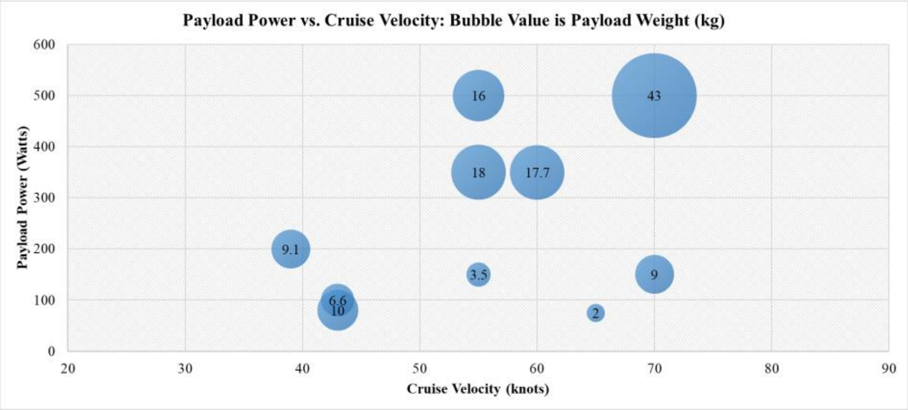
- Differential Absorption Lidar is a pretty good solution. There are challenges, but the technology is fairly robust and almost main stream.
- Hardest problem seems to be getting hardware for non-standard wavelengths

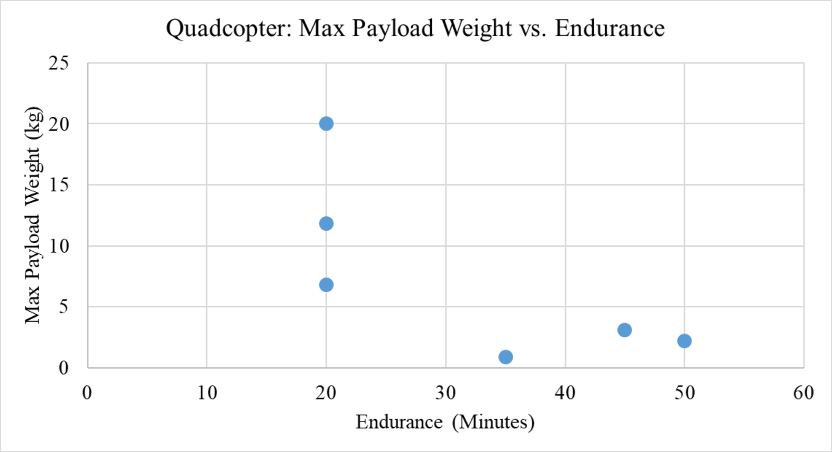


Overview: UAV Summary

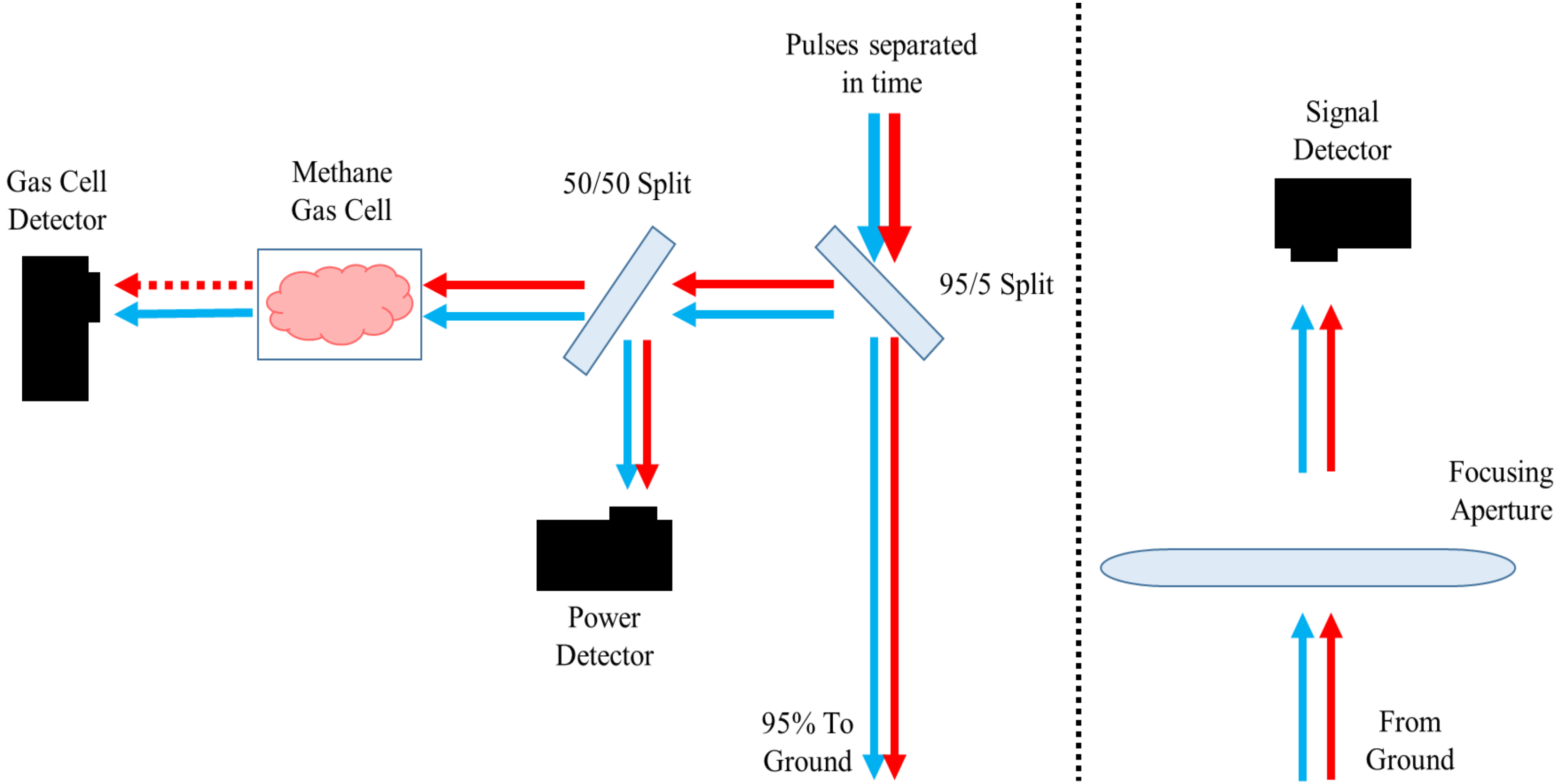
- Based on the data, a nominal fixed-wing UAV platform performance target is considered to be:
  1. A payload power of 350 W
  2. A cruise velocity of 55 knots (28.3 m/s)
  3. A payload weight of 16 kg (35 lbs.)

- Quadcopters do not provide power and velocity is not the primary selling point.
  - Trade flight time for weight
  - Assumed 20 kg limit



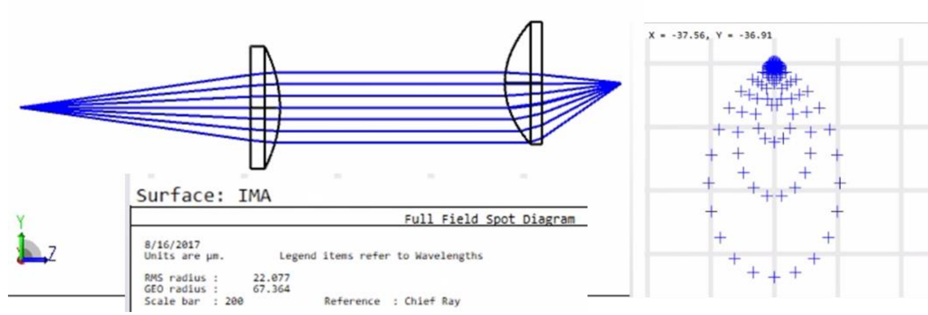


Example instrument design

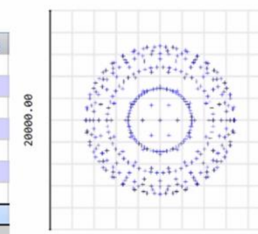


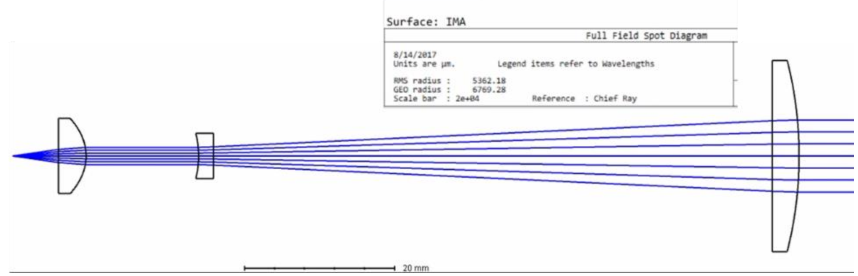
OpticStudio

- Zemax OpticStudio was used to do the optical analysis.
- Included nominal as well as sensitivity studies on displacement and rotation.
- Two hardest problems were:
  - Efficient beam expansion
  - Cost optimization on focus spot size
- Final output was transmission and receive optical efficiencies



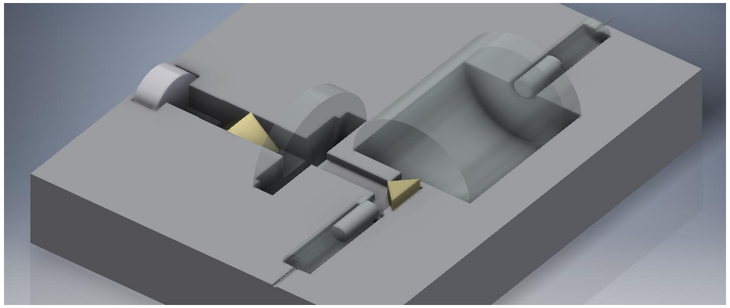
	Surf:Type		Comment	Radius	Thickness	Material	Coating
0	OBJECT	Standard		5.000E-03	6.093		
1	(aper)	Standard		Infinity	3.700	S-LAH64	THORC
2	STOP (aper)	Even Asphere	AL108	-6.215	15.000		THORC
3	(aper)	Standard	LC1975-C	-12.350	2.000	N-BK7	THORC
4	(aper)	Standard		Infinity	74.488 V		THORC
5	(aper)	Standard		Infinity	3.590	N-BK7	THORC
6	(aper)	Standard	LA1509-C	-51.500	1.500E+05		THORC
7	IMAGE	Standard		Infinity	-		THORC

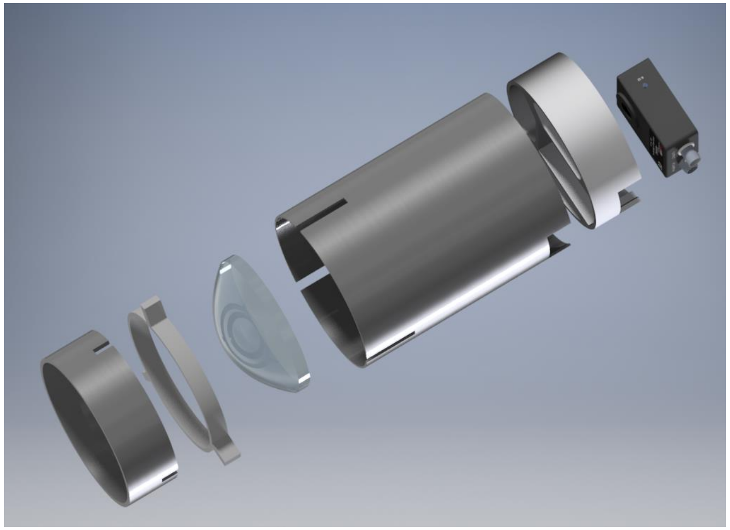




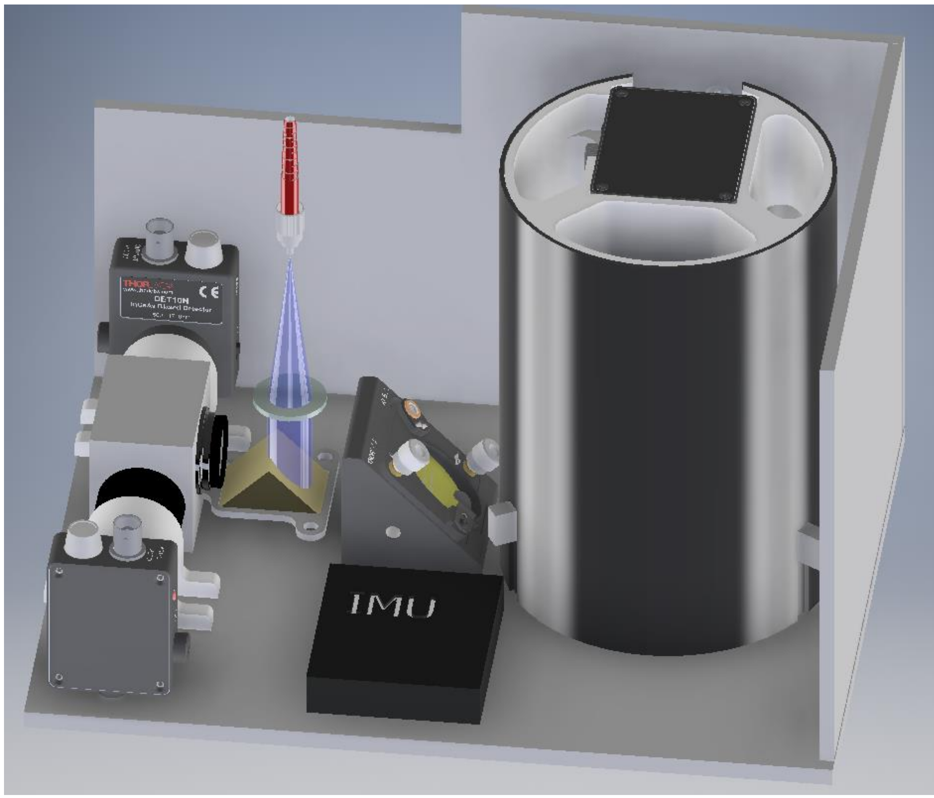
Autodesk Inventor

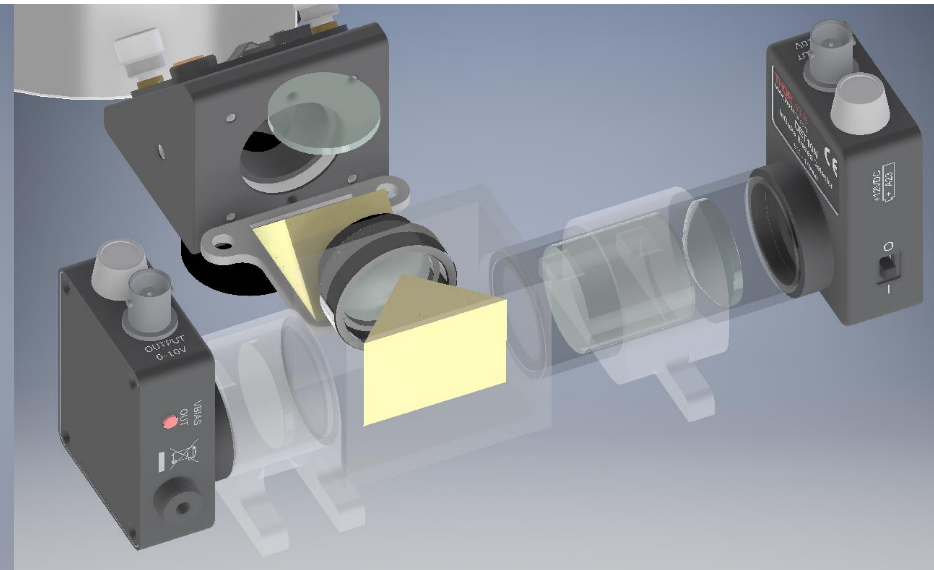
- Autodesk Inventor was used for the mechanical design.
- Pretty good program for the low price of free.
- Hardest challenges were:
  - Lots of little details to consider
  - Not as powerful as SolidWorks
  - A few times where I didn't figure out a design would not work until I had already invested several hours in setting things up
- Final outputs were weight and cost estimates



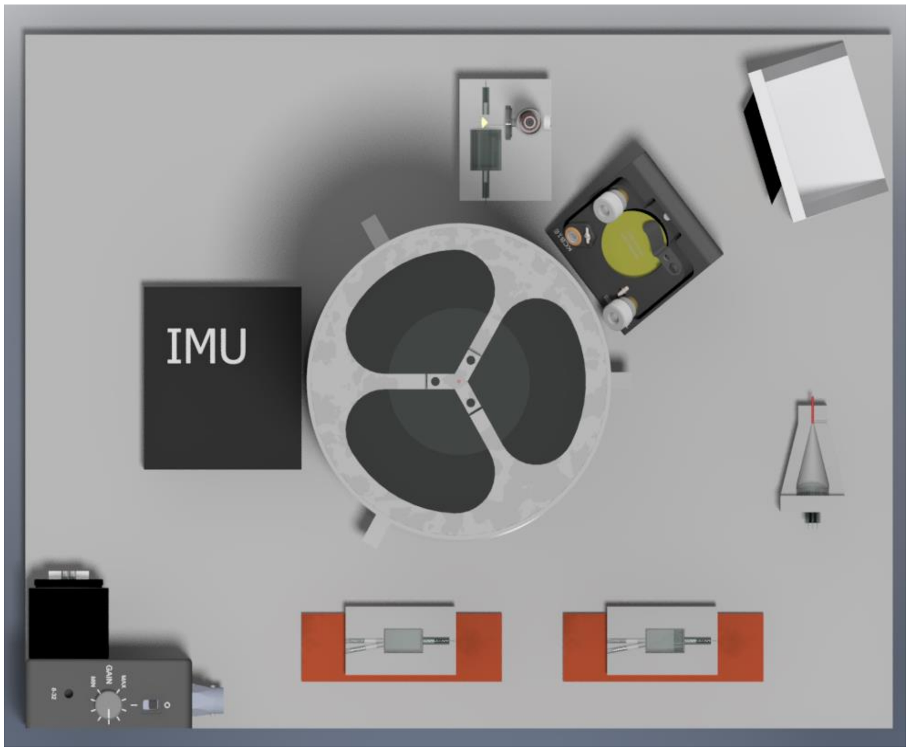


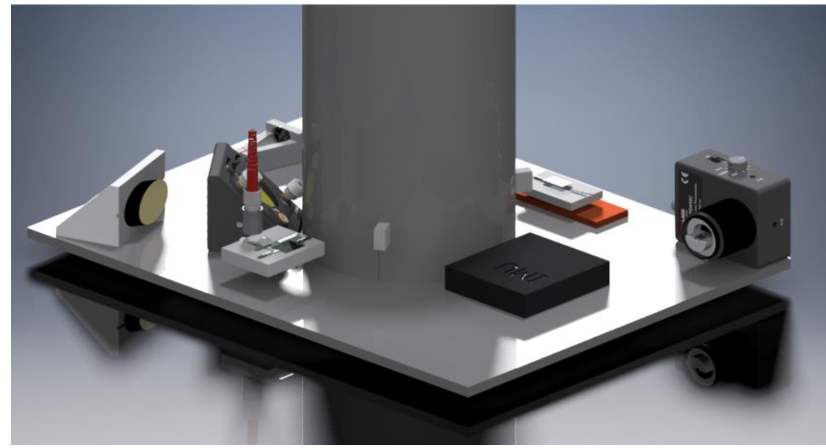
Example Layout 1

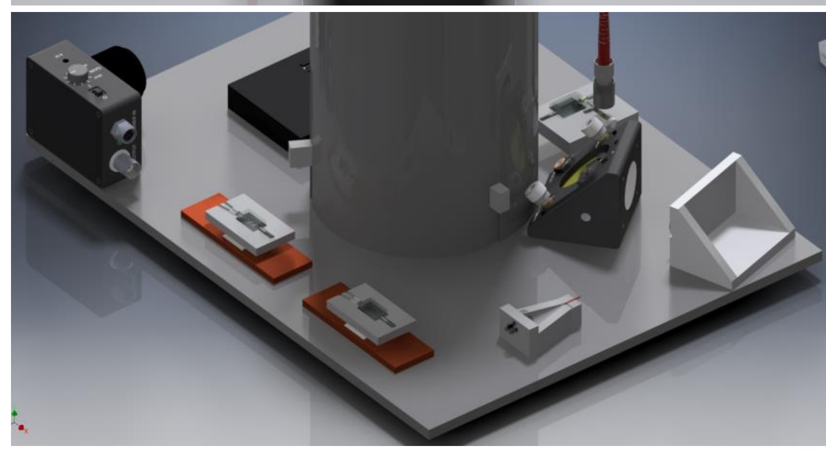




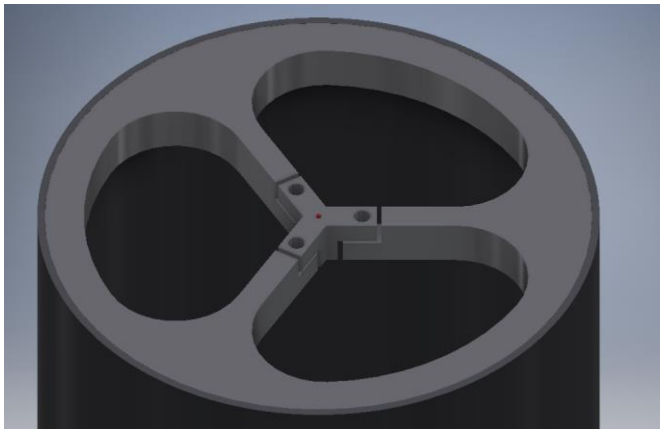
Example Layout 2

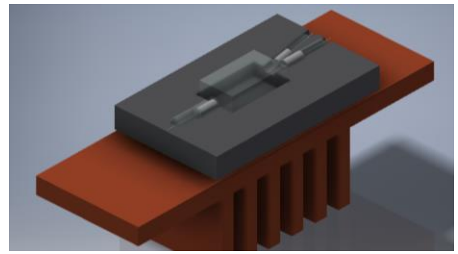


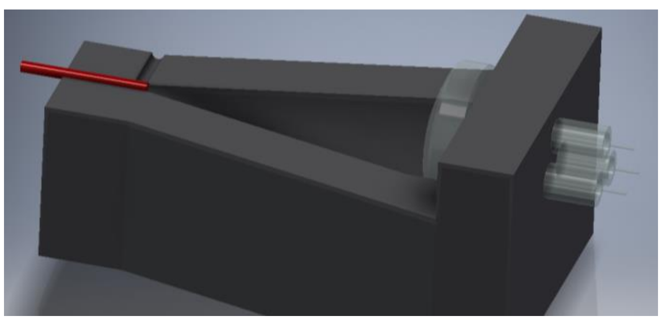


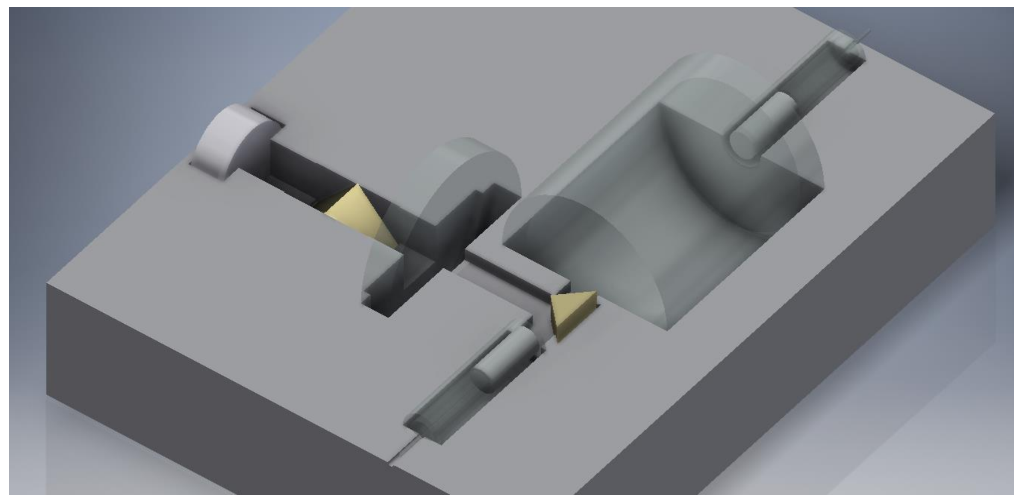


Component Examples









Optical Efficiency

- Top table is design 1.
- Bottom table is design 2.
- 2nd has roughly 40% of the optical efficiency

Optical Assembly	Efficiency (%)	Cumulative Efficiency (%)		
		Transmit Path	Gas Cell Path	Power Path
Fiber Input to Launch	93.5	93.5	-	-
Fiber Input to Gas Cell Fiber	86.0	-	86.0	-
Fiber Input to Power Fiber	91.5	-	-	91.5
Receive Optic to Detector	91.6	85.6	78.8	83.8
Detector Efficiency	70.0	60.0	55.1	58.6
Total Optical Efficiency		**60.0**	**55.1**	**58.6**

Optical Assembly	**Efficiency (%)**	**Cumulative Efficiency (%)**		
		Transmit Path	**Gas Cell Path**	**Power Path**
Fiber Input to Launch	93.6	93.6	-	-
Fiber Input to Gas Cell Fiber	85.6	-	85.6	-
Fiber Input to Power Fiber	90.1	-	-	90.1
Receive Optic to Fiber	88.45	82.7	75.7	79.7
3-Fiber Input to Single Fiber	96.0	79.4	72.6	76.5
Fiber Input to VBG to Fibers	69.8	55.4	50.6	53.4
Fibers to Detector	96.0	53.1	48.5	51.2
Detector Efficiency	70.0	37.2	34.0	35.8
Fiber Optics	98.6/92.9/96.0	36.6	31.6	34.4
Total Optical Efficiency		**36.6**	**31.6**	**34.4**

SNR and Error Calculation

- Properties of the instrument were fed into the SNR equation.
- Followed both Dr. Chu's lecture notes and the paper "Performance evaluation of a 1.6 micron methane DIAL system from ground, aircraft, and UAV platforms"
- Final error is based strongly on SNR value as most atmospheric terms drop out. Left with:

$$\varepsilon_R \cong \frac{\sqrt{SNR_{on}^{-2} + SNR_{off}^{-2}}}{dOD_{mn}}$$

Parameter	Value	Comment
Flight Altitude	150 m	~500 ft.
Optical Properties		
Fiber Input MFD	10 µm	Single Mode Fiber
Beam Area	.005 m^2	80 mm diameter
Receive Telescope Area	.008 m^2	100 mm diameter
Transmit Efficiency	93.5%	
Receive Efficiency	64.1%	
Solar Filter Width	10 nm	
Laser Properties		
Laser Pulse Energy	150 µJ	
Pulse Length	80 ns	
Detector Properties		
Efficiency	70%	
Responsivity	17 A/W	at 1.645 µm
Bandwidth	10 MHz	
Noise Equivalent Power	0.13 $pW/Hz^{1/2}$	
Dark Current		No Reverse Bias
Ground Properties		
Reflectivity	50%	
Height Difference	5 m	
Atmosphere Properties		
Background Methane	1.8 ppm	
Solar Irradiance	5 $mW/(m^2 \cdot nm \cdot sr)$	Vegetation
Transmittance - Online	92%	Background methane, HITRAN w/ 1 km path
Transmittance - Offline	99%	Background methane, HITRAN w/ 1 km path

Performance Result

1st Concept

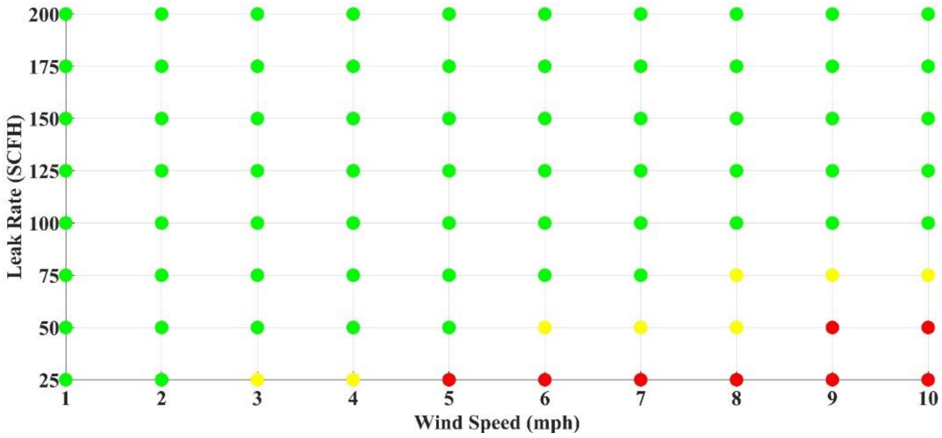
Parameter	Value
Fiber Properties	
Allowable Pulse Power	2.25 KW
Expected Pulse Power	1.88 KW
Percent of Damage Threshold	83.6%
SNR Terms	
SNR Online	969
SNR Offline	1,006
Differential Optical Depth	0.019
Error Terms	
SNR/dOD Error	7.5%
Reflectance Error	1.0%
Speckle Error	2.5%
Total % Error	11%
Absolute Error (of 1.8 ppm)	0.20 ppm

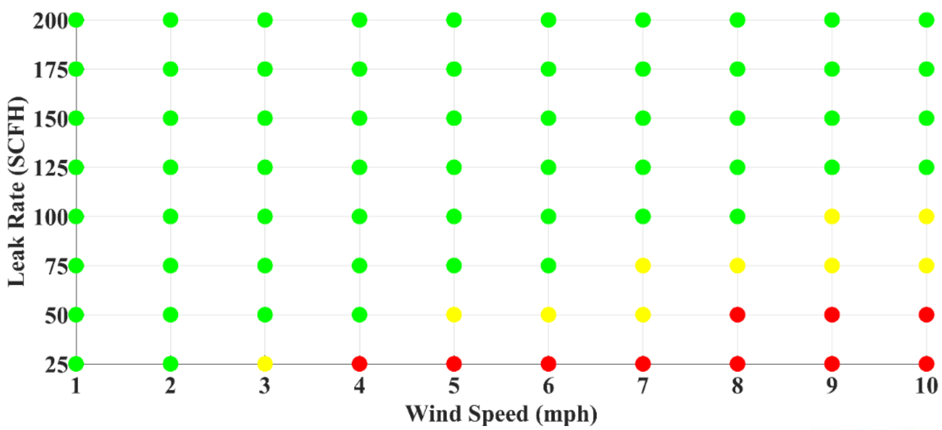
2nd Concept

Parameter	Value
Fiber Properties	
Allowable Pulse Power	2.25 KW
Expected Pulse Power	1.88 KW
Percent of Damage Threshold	83.6%
SNR Terms	
SNR Online	749
SNR Offline	778
Differential Optical Depth	0.019
Error Terms	
SNR/dOD Error	9.7%
Reflectance Error	1.0%
Speckle Error	2.5%
Total % Error	13.2%
Absolute Error (of 1.8 ppm)	0.24 ppm

Expected Performance

- End-to-end simulation with plume models allowed plume detection performance estimates.
- Top image is the traditional concept. Bottom image is the VBG filtering concept.
- Green means excellent chance of seeing the plume, yellow means marginal, and red means unlikely.
- Don’t quite make it to the goal of seeing a 50SCFH plume in 10 mph winds
- But pretty good performance overall





Cost and Weight Estimates

- Cost and weight estimates are for the transceiver.
- No estimates for the laser, scan mechanism for the fixed-wing version, processing electronics.

Cost		Weight (lbs.)	
1st Design	2nd Design	1st Design	2nd Design
$9,119	$16,376	15.20	25.45

- 2nd Design costs $7,000 more and weighs 10 pounds more while returning worse performance
- Reminder: Goal was a weight of around 35 pounds for the fixed-wing, 45 pounds for the quadcopter.

Hardware Conclusions

- Right on the threshold of being able to fly an advanced DIAL system from a UAV
- Primary problem is the instrument is much more expensive than the UAV. Would like to have the instrument about the same or less cost.
- New things coming out all the time. Could be ready in a couple of years.

PLUME SIMULATION

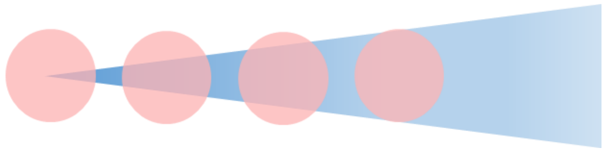
Gaussian Plumes: Introduction

- Gaussian plume equations have been around since the 1920's
- $C(x,y,z) = \frac{Q}{U}\frac{1}{2\pi I_y I_z x^2} e^{\frac{-y^2}{2\sigma_y^2}} \left(e^{\frac{-(z-H)^2}{2(I_z x)^2}} + e^{\frac{-(z+H)^2}{2(I_z x)^2}} \right)$
- Used by just about every paper trying to find leak sources
  - Easy to forward-solve
  - Easy to invert
- My extension is to integrate the equations and solve for path-averaged ppm values using
  - Instrument height
  - Beam diameter (or beam divergence and height)
  - Leak rate
  - Sample density
  - Atmosphere properties

Gaussian Plumes: Integration Considerations

- Leak rate in equations is in kg/s. Want leak rate in Standard Cubic Feet per Hour
  - $1\frac{kg}{s} = 1\frac{kg}{s}x\frac{1\,m^3}{0.668\,kg}x\frac{1ft^3}{0.028317\,m^3}x\frac{3600s}{1\,hr} = 190{,}320\,SCFH$

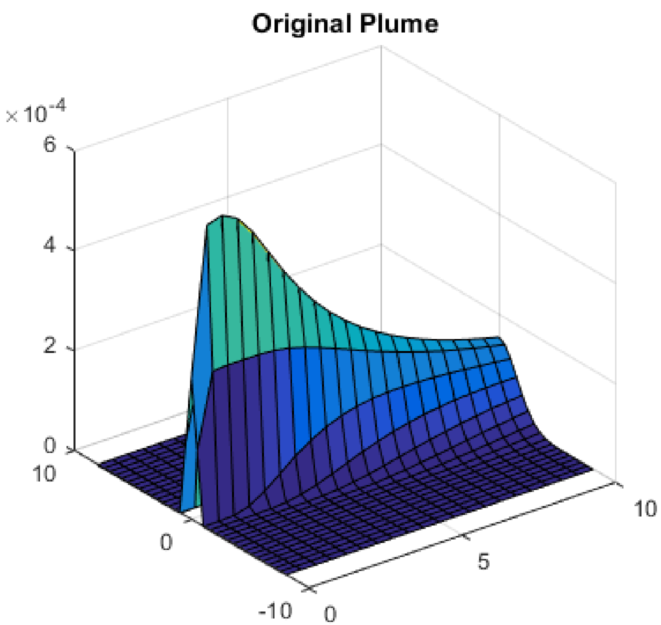
- Beam diameter drives integrated volume. The highest measurement is not at the leak source.

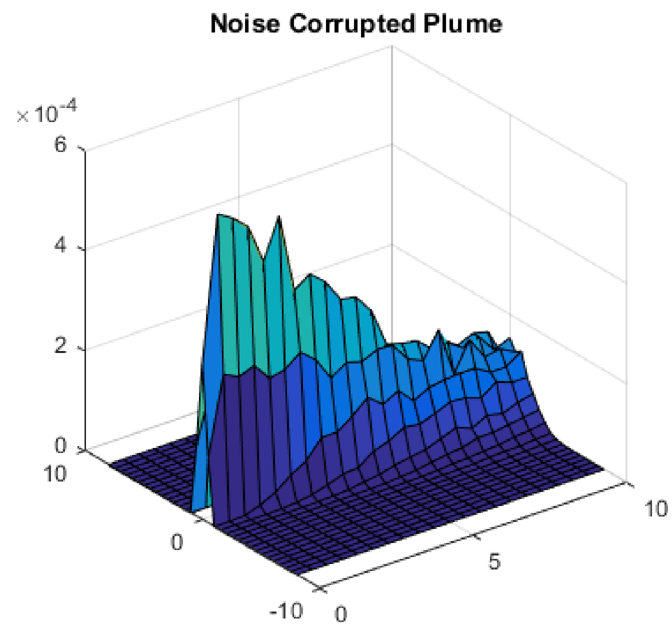


- Equation returns mass density and we want number density
  - Input atmospheric pressure, temperature, and the masses of air and methane
  - Output is the number of methane molecules per million air molecules per meter
  - Can multiply by range to get ppm-m value

Gaussian Plumes: Optional Noise Simulation

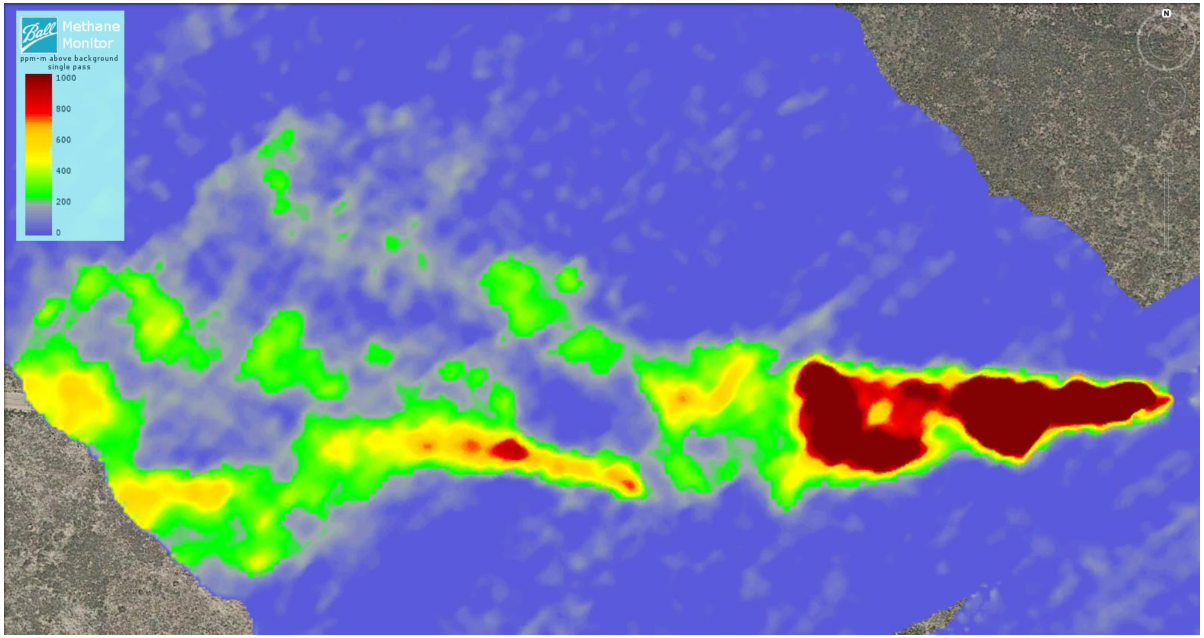
- Shot to shot noise is simulated with a Poisson distribution
- Can be turned on and off as needed





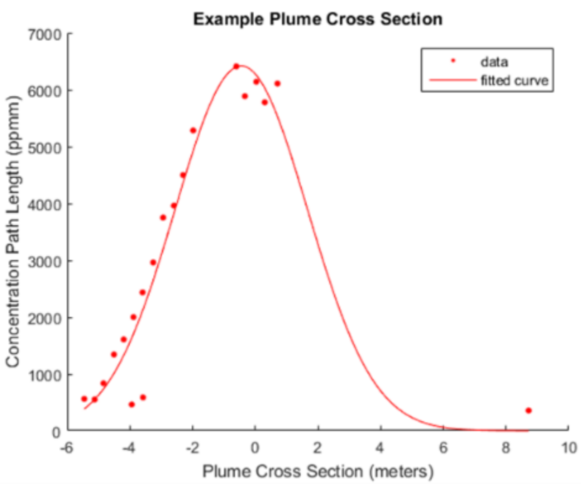
Gaussian Plumes: Data Correlation

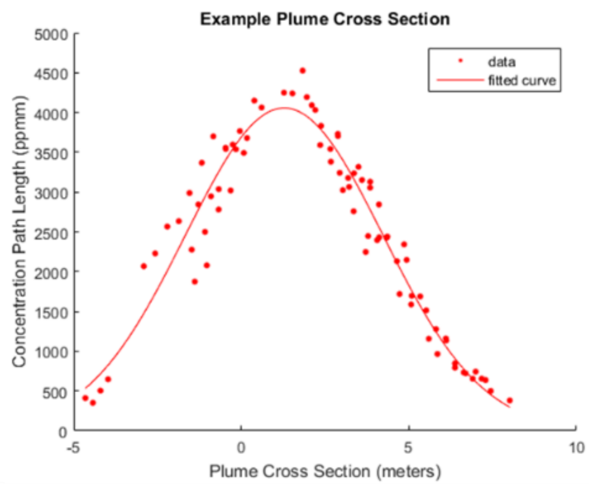
- Ball's 10 kHz laser provides lots of dense data for plume correlation

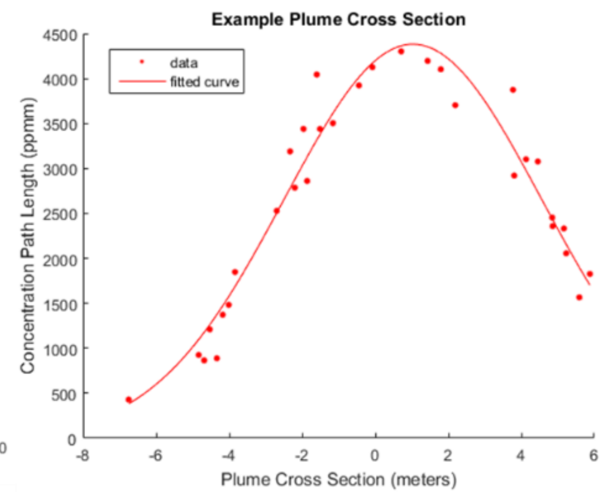


Gaussian Plumes: Cross-Section Analysis

- Three example fits of real data are shown below.
- The fits are surprisingly good, given the visually noisy nature of the plumes







SIMULATION STUDIES

Simulation Studies: Choosing a Beam Diameter

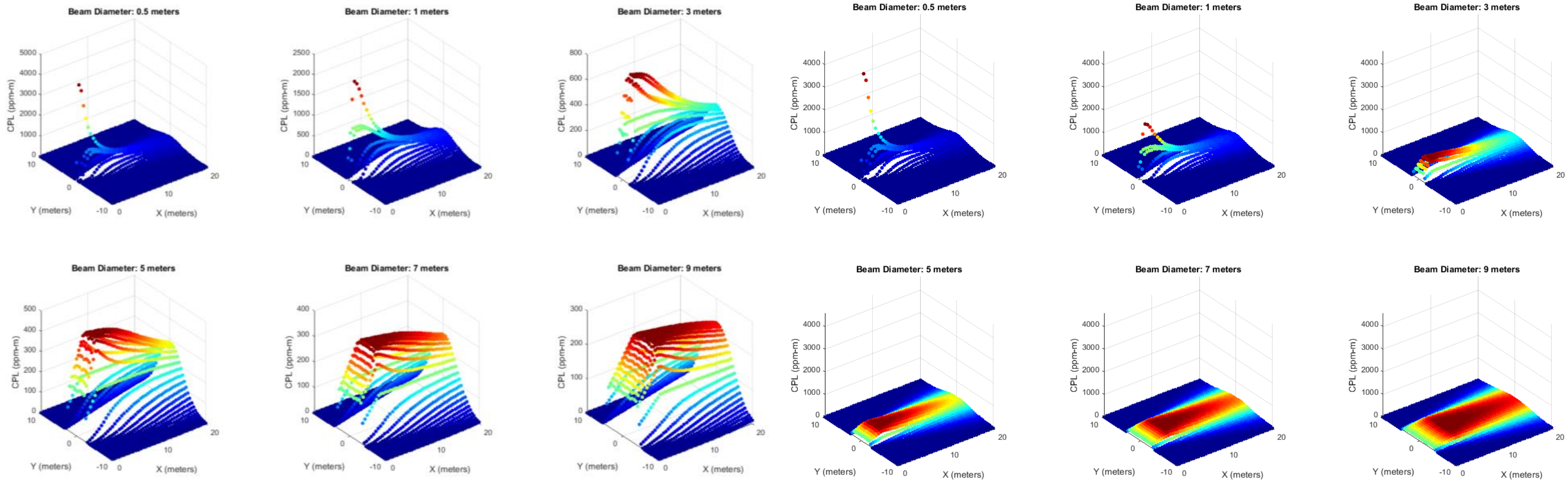
- Big beams mean better chance of landing on a plume, but integrated volumes return lower results

- Next slide simulates various beam sizes:
  - 1,000 meter altitude
  - 0.5 meter spatial resolution
  - Leak rate of 300 SCFH

Simulation Studies: Choosing a Beam Diameter

- 300 SCFH plume simulation

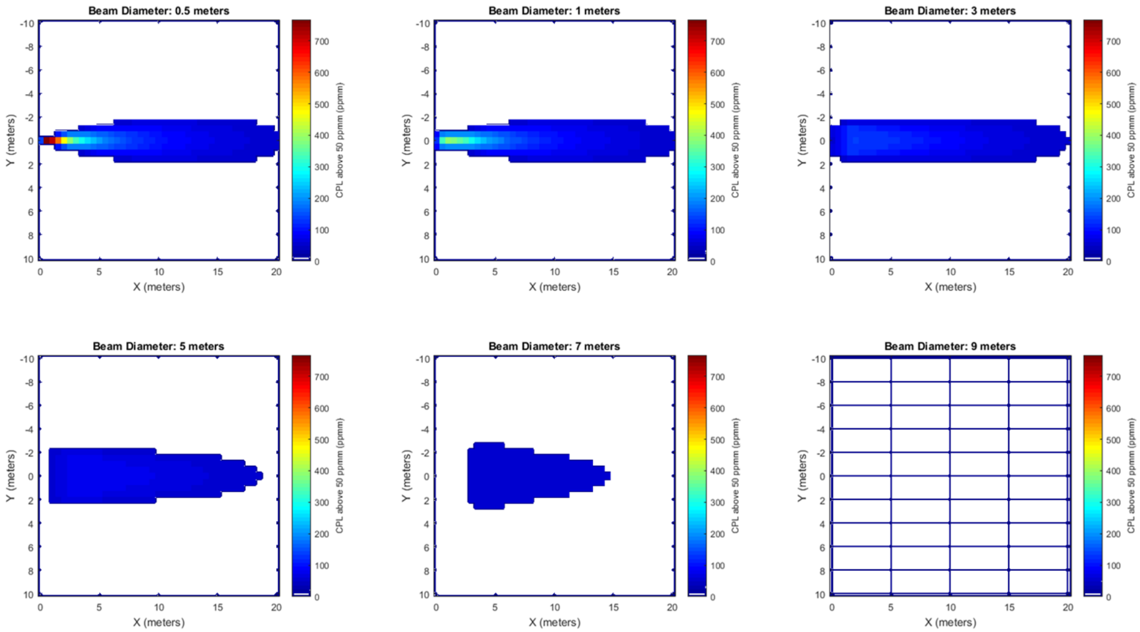
0.5 m beam | 1 m beam | 3 m beam | 0.5 m beam | 1 m beam | 3 m beam



5 m beam | 7 m beam | 9 m beam | 5 m beam | 7 m beam | 9 m beam

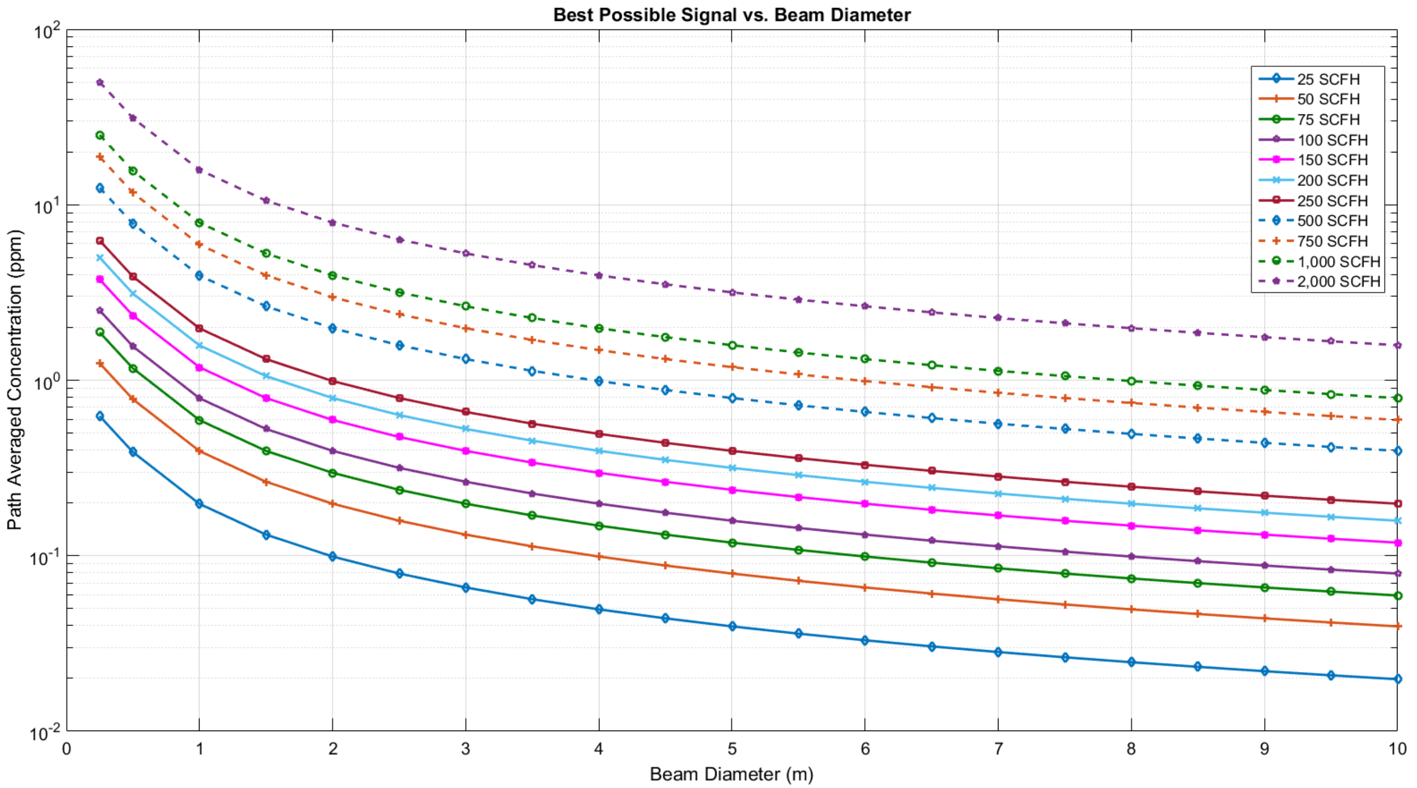
Simulation Studies: Choosing a Beam Diameter

- These types of simulations can be combined.
  - Beam diameter sets maximum thresholds of ppm
  - Noise floor sets minimum thresholds
  - Where they cross, plumes become invisible to the sensor
- Example below uses the same plumes with a noise floor of 50 ppm-m



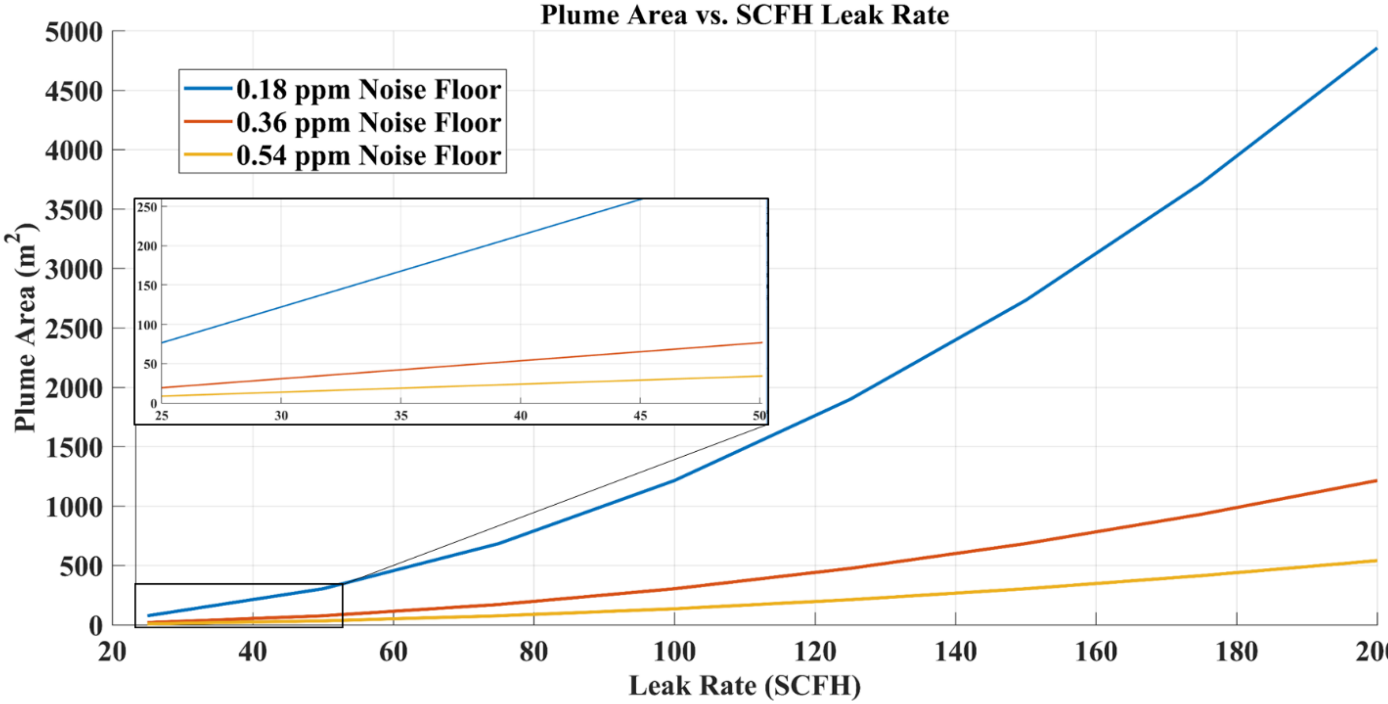
Simulations Studies: Instrument Agnostic Beam Diameter Plot

- Plot below is useful for estimating your maximum allowable beam diameter for wind speeds of 1 m/s, regardless of any other parameters.



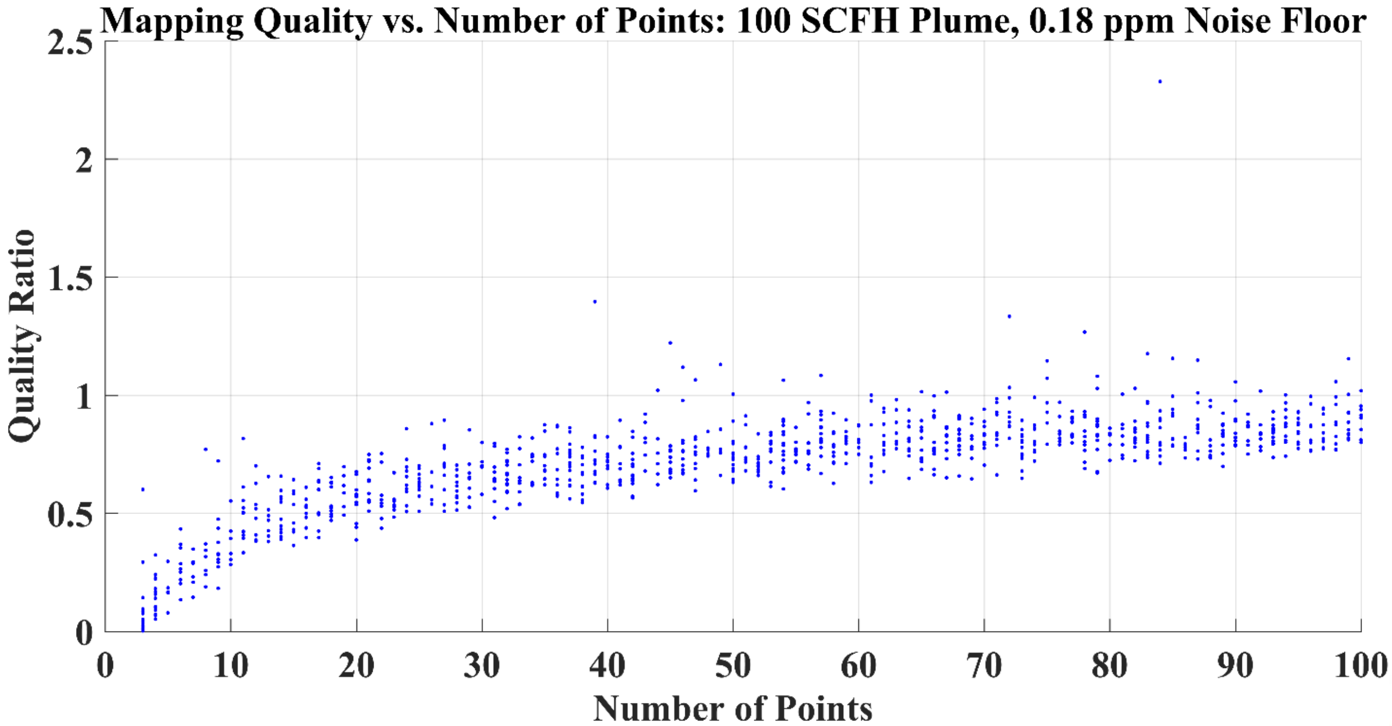
Simulations Studies: Towards scan density analysis

- The first step was to determine how much area of a plume would be visible for various noise floors



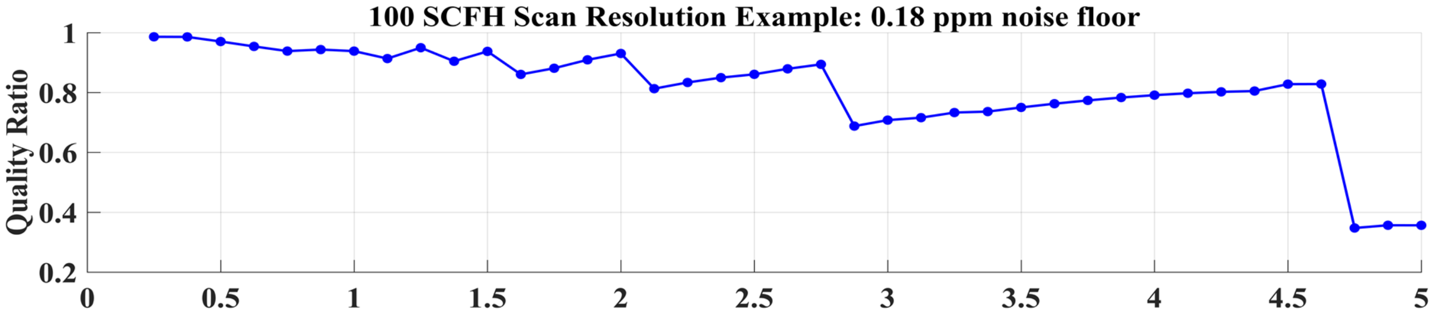
Simulation Studies: Scan Density on a Quadcopter

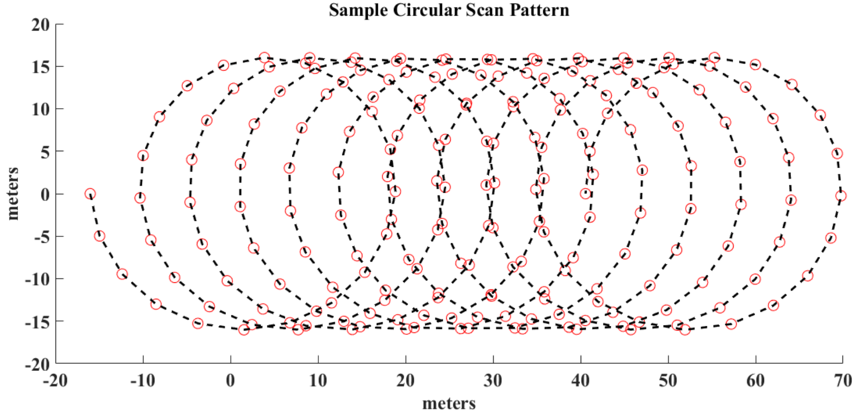
- Quadcopter concept assumes tip/tilt scanning of the vehicle. A Monte Carlo type analysis was run to map the probability curves.
- Quality Ratio is the ratio of the captured plume volume to the actual plume volume.



Simulation Studies: Fixed Scan Resolution Analysis

- Scan points are "worst case" placement on a plume for a given resolution. (No points on the plume axis, for instance.)
- Jagged nature is due to "modes" of the resolution within the plume boundary.





REFLECTIVITY

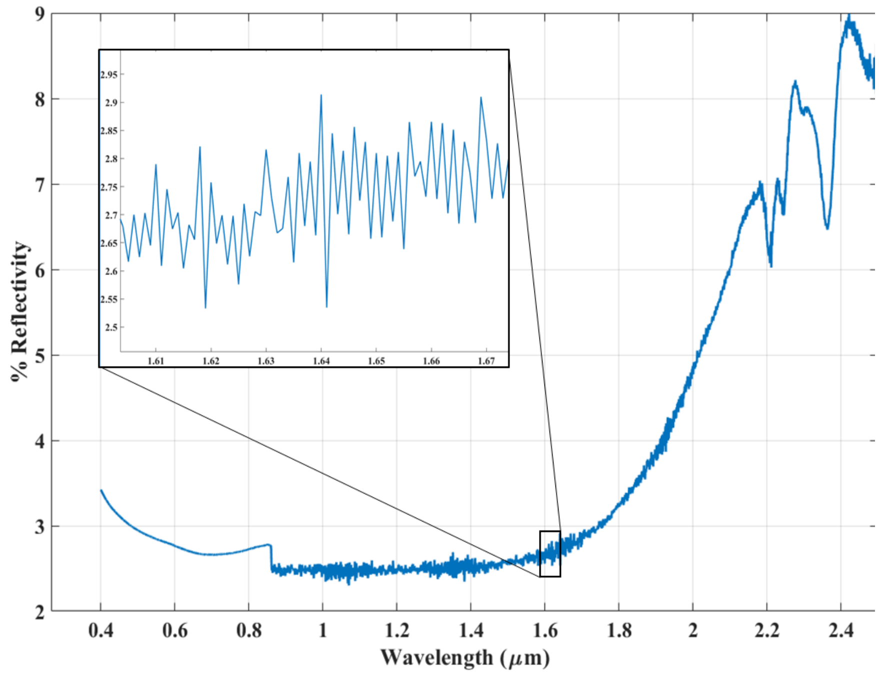
Overview

- The number density has a number of natural log terms.
- Assume the argument goes to zero and life gets simpler
- Started out trying to find papers talking about reflectivity so I could understand deeper theory.
  - But I couldn't find any

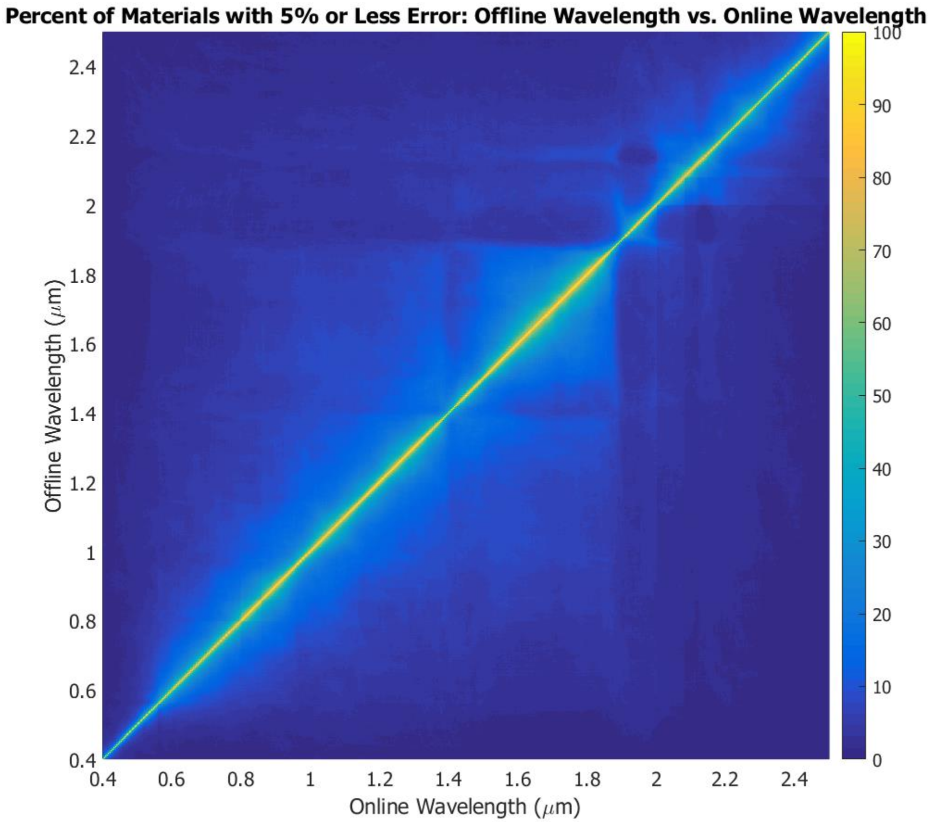
$$
\begin{aligned}
n_c &= \frac{1}{2\Delta\sigma_C(R)}\frac{d}{dr}ln\left[\frac{N_S(\lambda_{off},R) - N_B(\lambda_{off},R)}{N_S(\lambda_{on},R) - N_B(\lambda_{on},R)}\right] \\
&- \frac{1}{2\Delta\sigma_C(R)}\frac{d}{dr}ln\left[\frac{\eta_d(\lambda_{off})\cdot\eta_r(\lambda_{off},R)}{\eta_d(\lambda_{on})\cdot\eta_r(\lambda_{on},R)}\right] \\
&- \frac{1}{2\Delta\sigma_C(R)}\frac{d}{dr}ln\left[\frac{\rho(\lambda_{off})}{\rho(\lambda_{on})}\right] \\
&- \frac{1}{\Delta\sigma_C(R)}\left[\alpha(\lambda_{on},R) - \alpha(\lambda_{off},R)\right]
\end{aligned}
$$

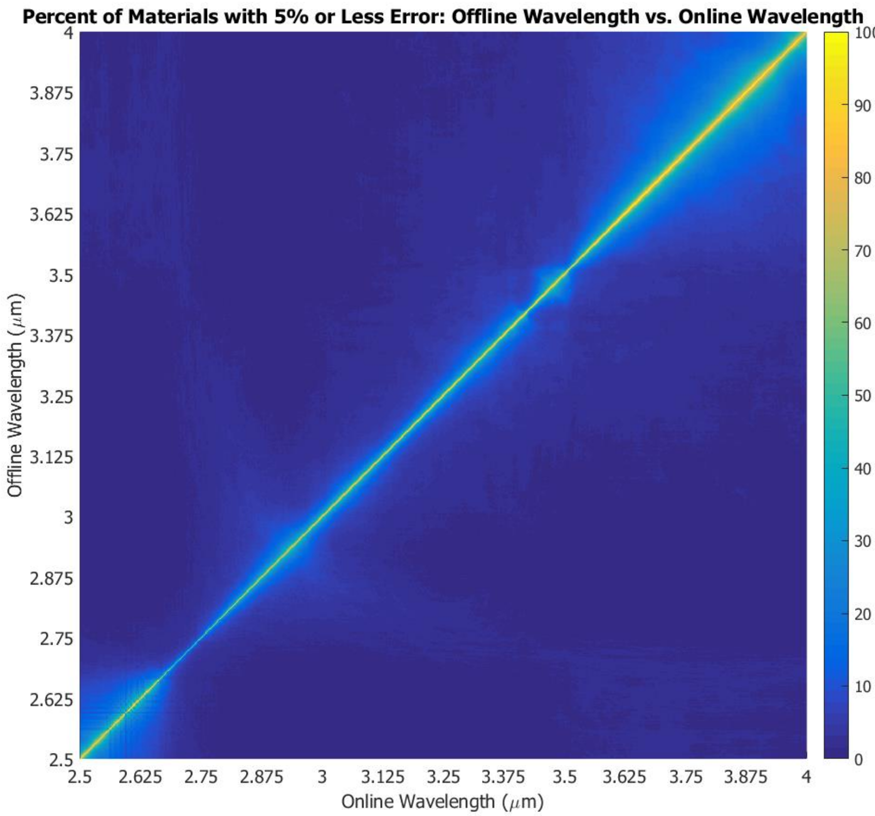
Reflectivity: Why things fail

- Most problems are from a low reflective and noisy material. Crystal structures, such as the Tourmaline below, are often culprits.
- All materials have regions of low reflectivity.

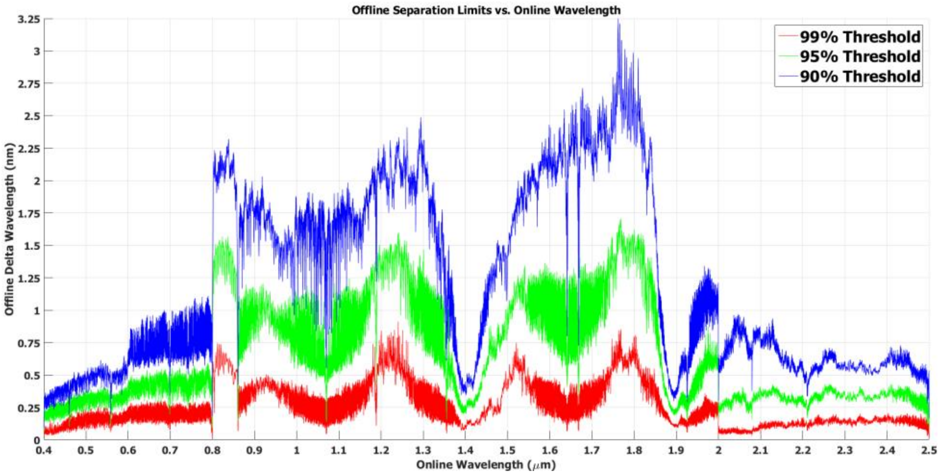


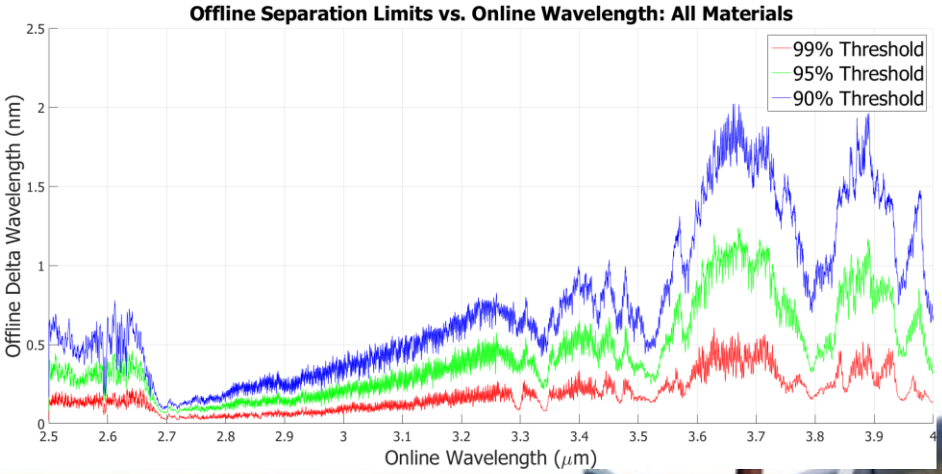
Reflectivity: Full analysis





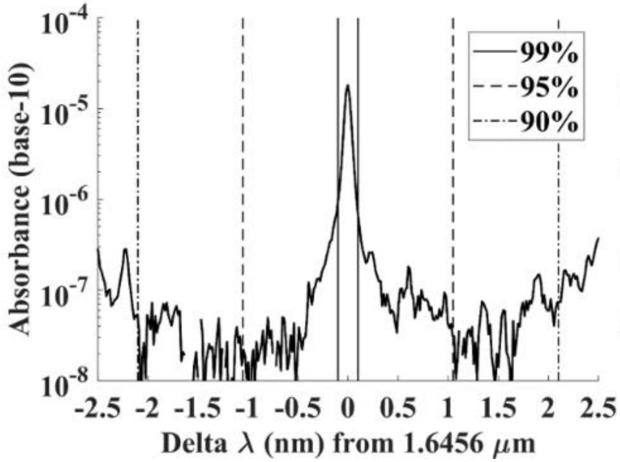
Reflectivity: All materials zoomed in

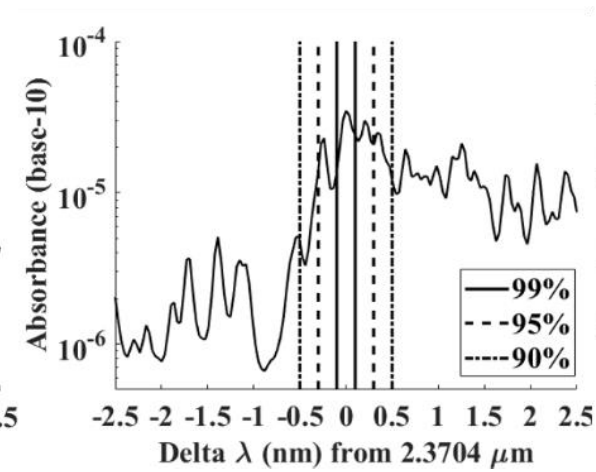


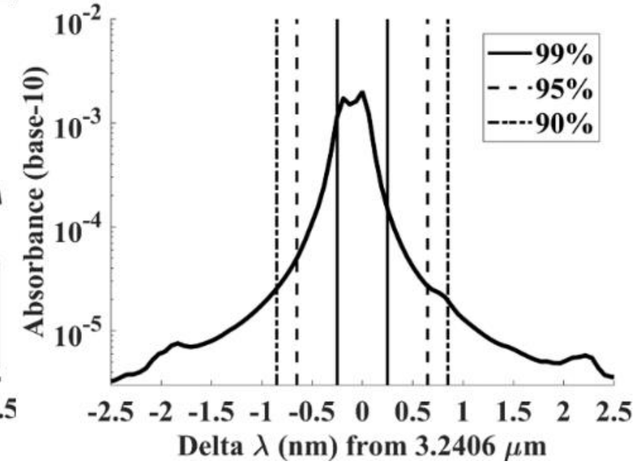


Example Application

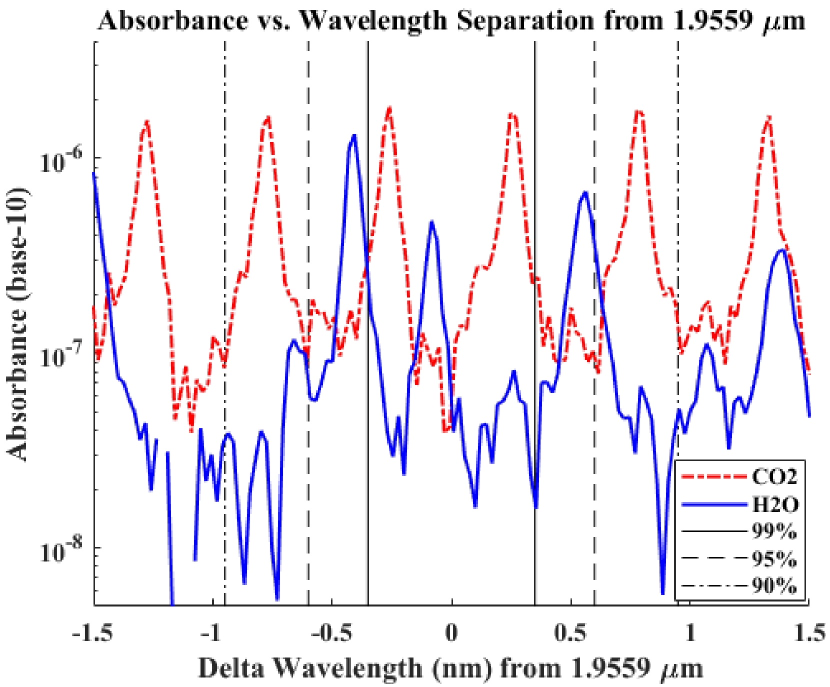
- Plots are of methane at the three highest densities of peaks: 1.645, 2.370, 3.241 µm

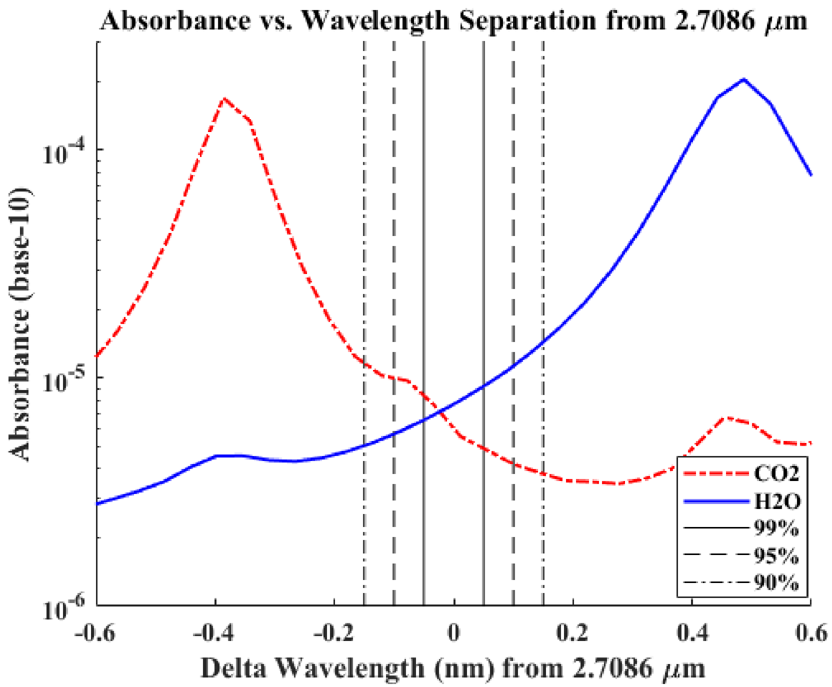






Example Application: CO2 and H20





Project Reporting

- Dissertation: Practical Design Guidelines for Fugitive Gas Detection from Unmanned Aerial Vehicles. Published by CU Boulder.
- "Analysis of the impact of wavelength separation on reflectivity error for differential absorption lidar using the ASTER spectral library," J. Appl. Remote Sens. **11**(3), 036008 (2017), doi: 10.1117/1.JRS.11.036008

Final Thoughts

- Expectation of "throw a ground-based instrument on a UAV" overlooks true difficulty.
  - Mass, power, reflectivity, beam diameter, etc…
  - Cost inversion with the instrument 10x the UAV
- Not talked about, but consider…
  - Quantum Cascade Lasers
  - Fiber lasers
  - Systems on a chip

THANK YOU!