Characterization Progress of an Absorption Laser Differential Interferometer

Joshua M. Weisberger, Brett F. Bathel, and Gregory C. Herring

NASA Langley Research Center

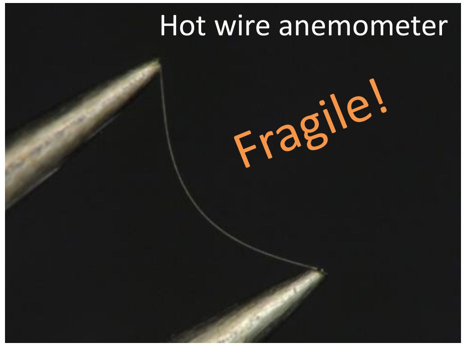
AIAA 2024 SciTech Forum

January 2024

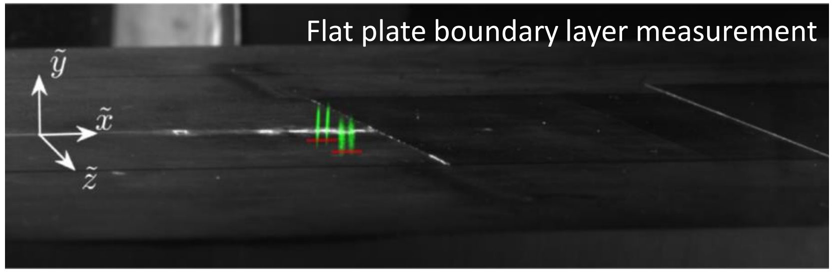
Motivation for Combined Absorption and LDI Measurements (A-LDI)

<u>Problem 1</u>:

- Interest in non-intrusive “optical hotwires” to make measurements of high frequency flow fluctuations
- Hypersonic wind tunnel freestream disturbances and boundary layer transition



Chou et al., AIAA-2021-0151



Weisberger et al., Applied Optics, 2020

<u>Problem 2</u>:

- Freestream flow properties (P, T, ρ, X) of wind tunnels derived from measured values elsewhere in facility

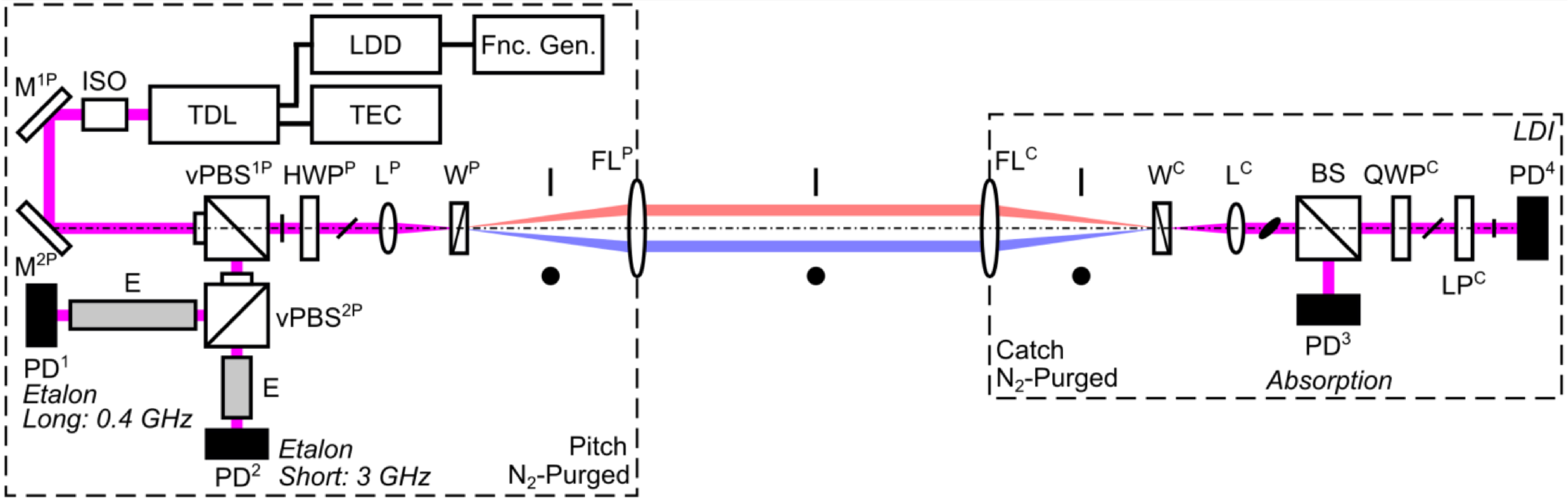
Real-Gas Flow Properties for NASA Langley Research Center Aerothermodynamic Facilities Complex Wind Tunnels

Brian R. Hollis

<u>Solution</u>: Simultaneous and colinear measurements of:

1. Flow fluctuations (small optical path length changes)
2. Flow gas properties (temperature, pressure, concentration)

Absorption Laser Differential Interferometer (A-LDI)

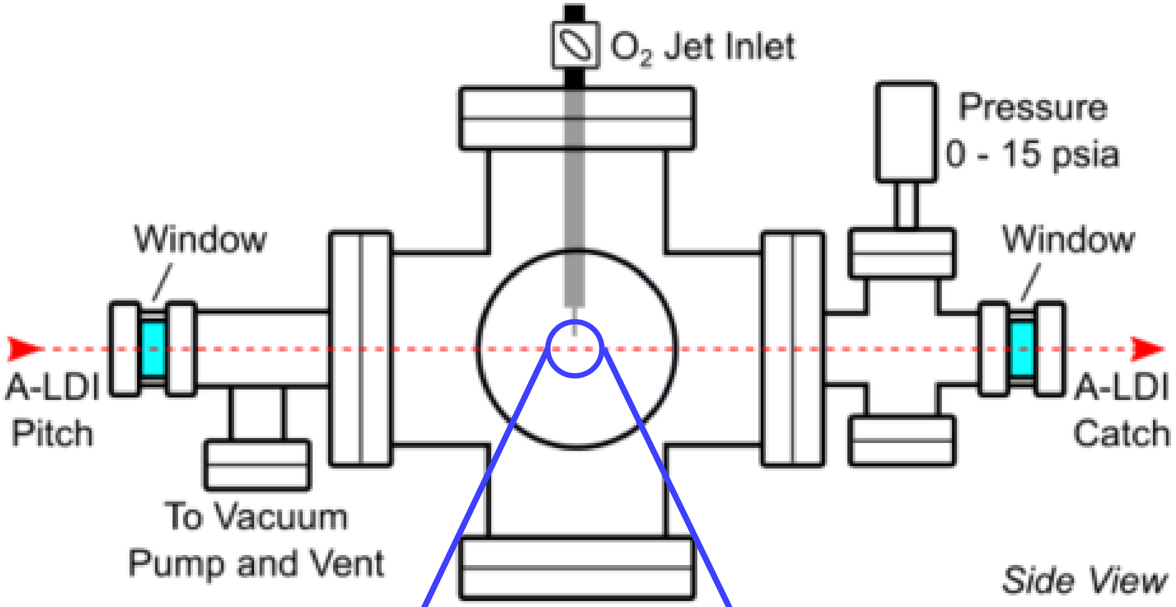


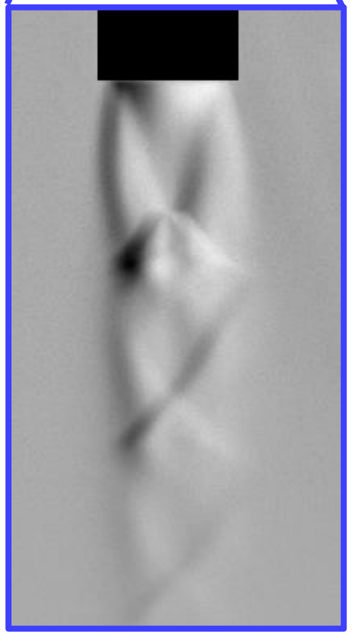
- LDI: Phase difference measurement between two beams (red, blue)
- Tunable diode laser (760 nm) probes O_2 absorption transitions
- Using direct absorption and wavelength modulation spectroscopy (DAS and WMS)
- All photodiodes acquire signal simultaneously (adjustable signal using $vPBS^{1P}$ and $vPBS^{2P}$)
- Pitch and catch sides of instrument purged with non-absorbing N_2 gas

Sub-Atmospheric Pressure-Controlled Test Cell

- No temperature control (ambient temperature)
- Lower pressures using vacuum pump
  - Roughly 0.01 atm to 1 atm (1.01 kPa to 101 kPa)
- Inside window-to-window path length fixed at 63.5 cm
- Gas jet inlet at test cell centerline
  - 100% O_2 or N_2 gas bottles
- Pressure gauge, 0 – 15 psia

→ Known T, P, L, X

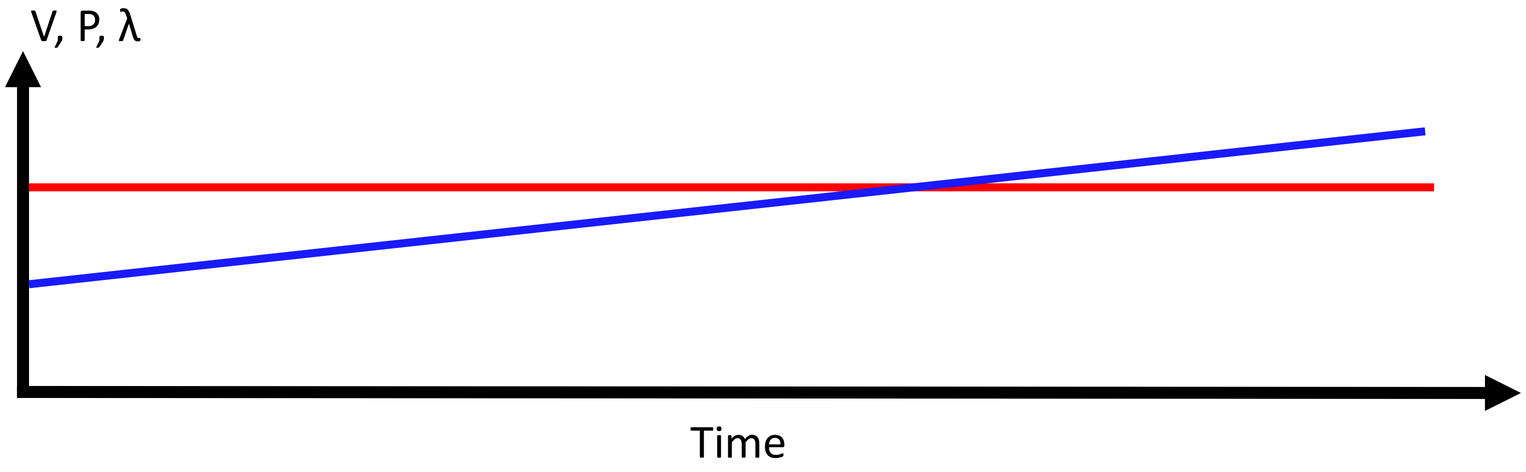




Schlieren image of 100% O_2 gas jet, image through side window

Laser Tuning Waveforms

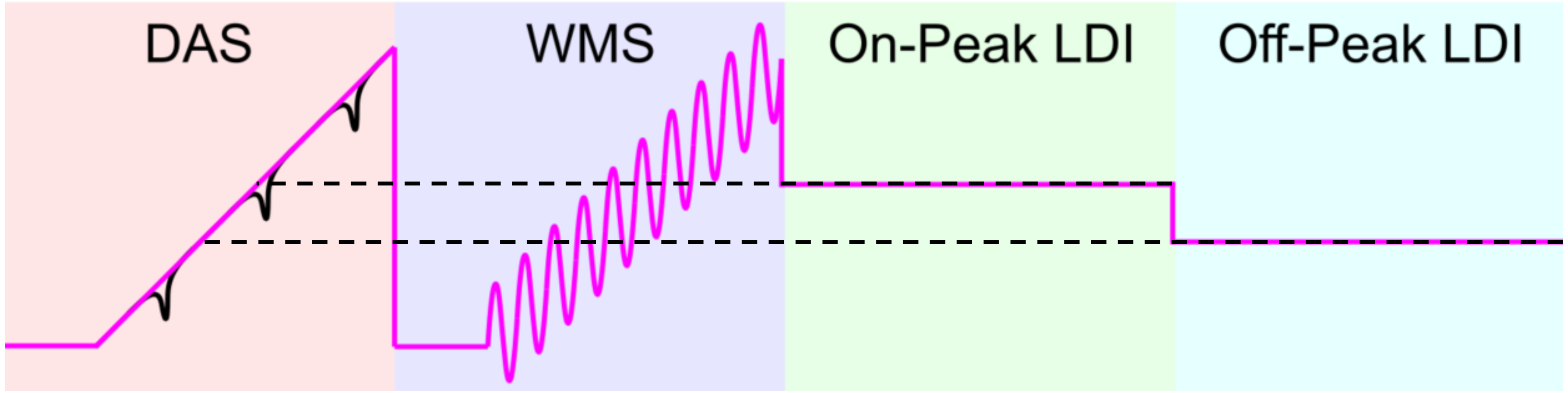
- Typical LDI/FLDI systems use a constant laser output power
  - Minimal absorption due to any gas species at these wavelengths (532 nm, 630 nm)
- Changing injection current changes output power and thus wavelength



- Absorption measurements using ramping injection current (red, blue)
  - Direct absorption spectroscopy (DAS): Easiest method, but lower SNR for weak absorption
  - Wavelength modulation spectroscopy (WMS): More difficult to implement, but lower detection limits, ideal for weak absorption of O_2 and small changes in flow properties
- Constant injection current absorption measurements can be ideal for simultaneous LDI measurements
  - Green: On-peak LDI places wavelength at the linecenter of an absorption feature
  - Cyan: Off-peak LDI places wavelength outside any absorption features (most like conventional LDI/FLDI measurements)

Laser Tuning Waveforms

- Typical LDI/FLDI systems use a constant laser output power
  - Minimal absorption due to any gas species at these wavelengths (532 nm, 630 nm)
- Changing injection current changes output power and thus wavelength

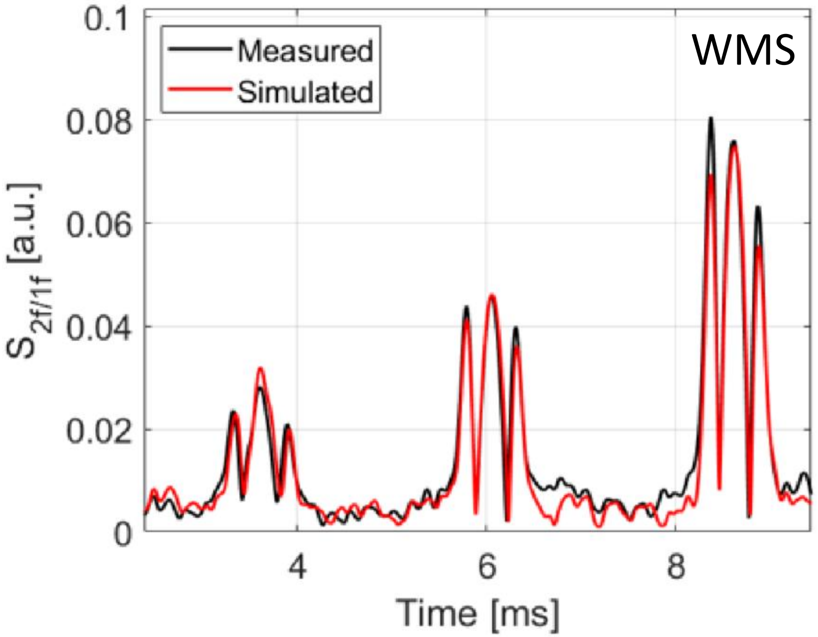


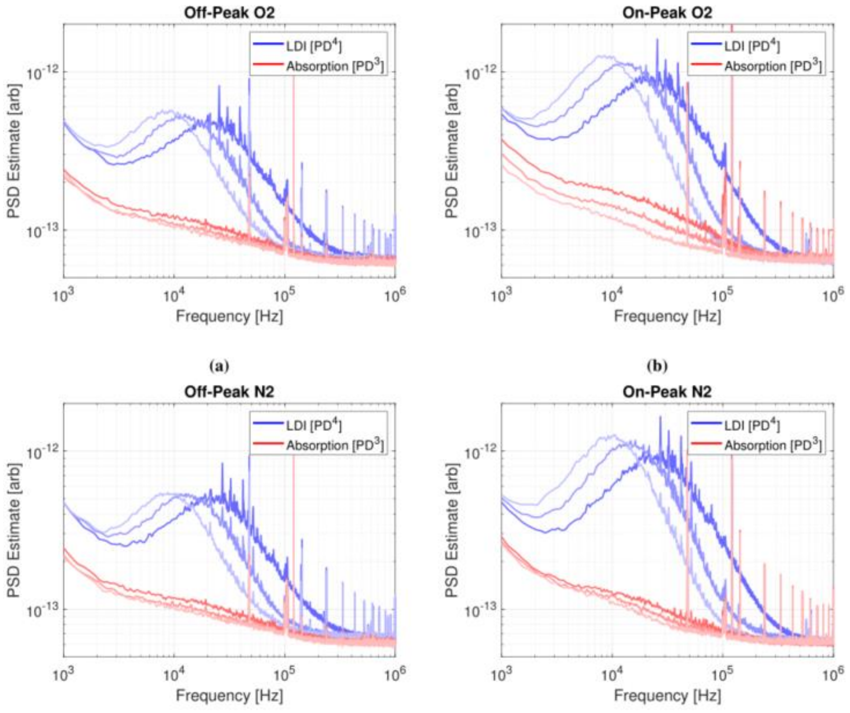
- Absorption measurements using ramping injection current (red, blue)
  - Direct absorption spectroscopy (DAS): Easiest method, but lower SNR for weak absorption
  - Wavelength modulation spectroscopy (WMS): More difficult to implement, but lower detection limits, ideal for weak absorption of O_2 and small changes in flow properties
- Constant injection current absorption measurements can be ideal for simultaneous LDI measurements
  - Green: On-peak LDI places wavelength at the linecenter of an absorption feature
  - Cyan: Off-peak LDI places wavelength outside any absorption features (most like conventional LDI/FLDI measurements)

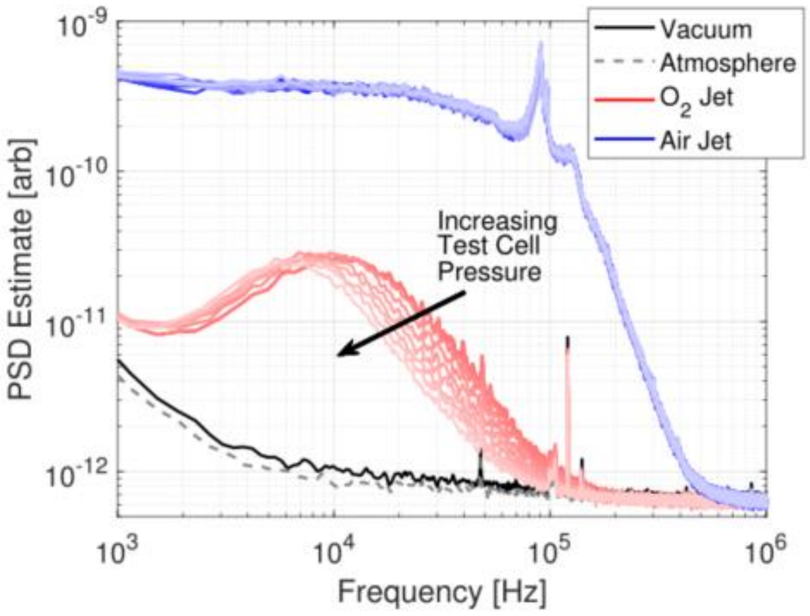
Previous Progress Overview

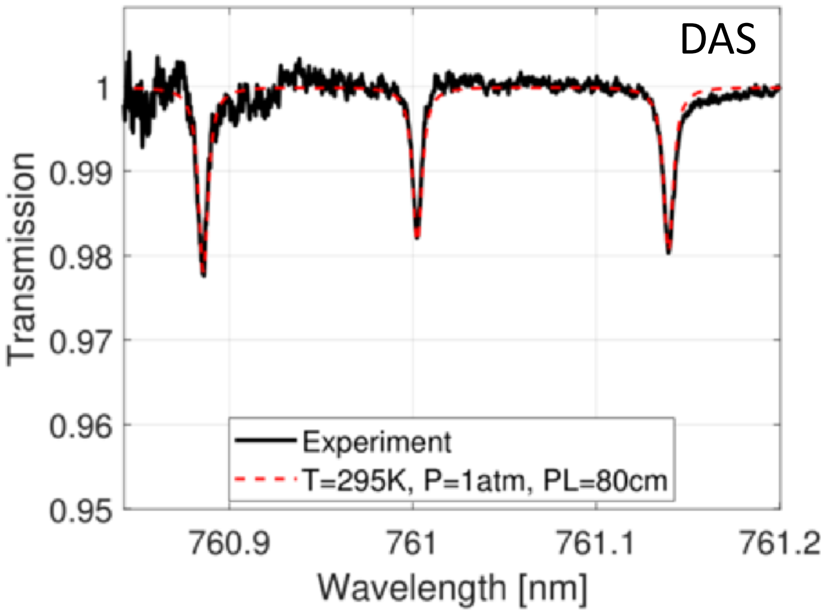
Weisberger, Herring, Bathel, and Chou, "*Absorption Laser Differential Interferometry for Simultaneous Colinear Flow Property and Fluctuation Measurements*," 2023 AIAA Aviation Forum, 2023-4369.

1. Validated the DAS and WMS aspects of the absorption measurement
2. LDI measurement sensitive to flow fluctuations
3. Simultaneous absorption and LDI measurements at same sampling rate

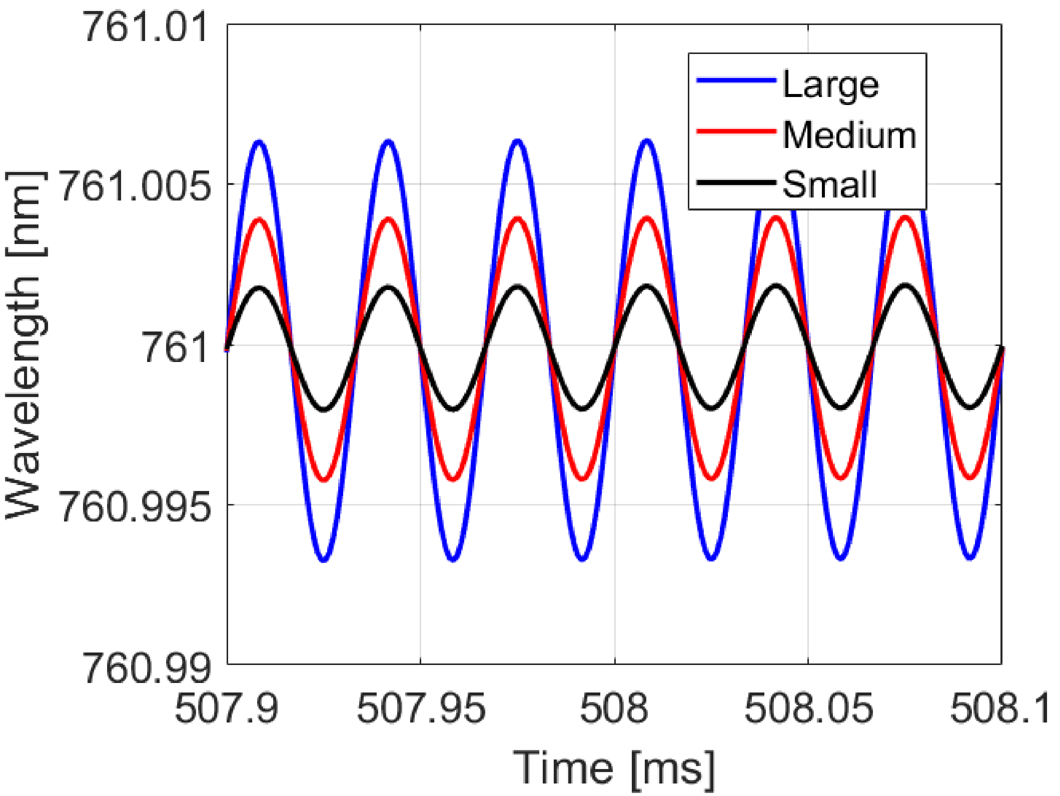


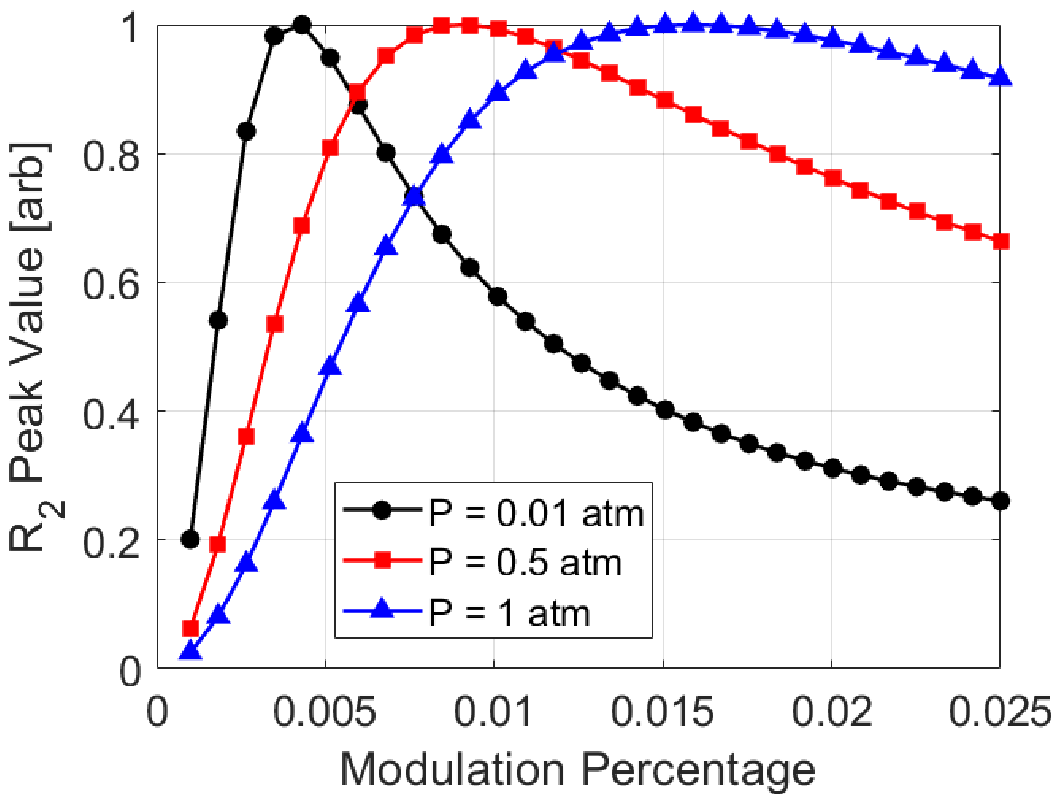






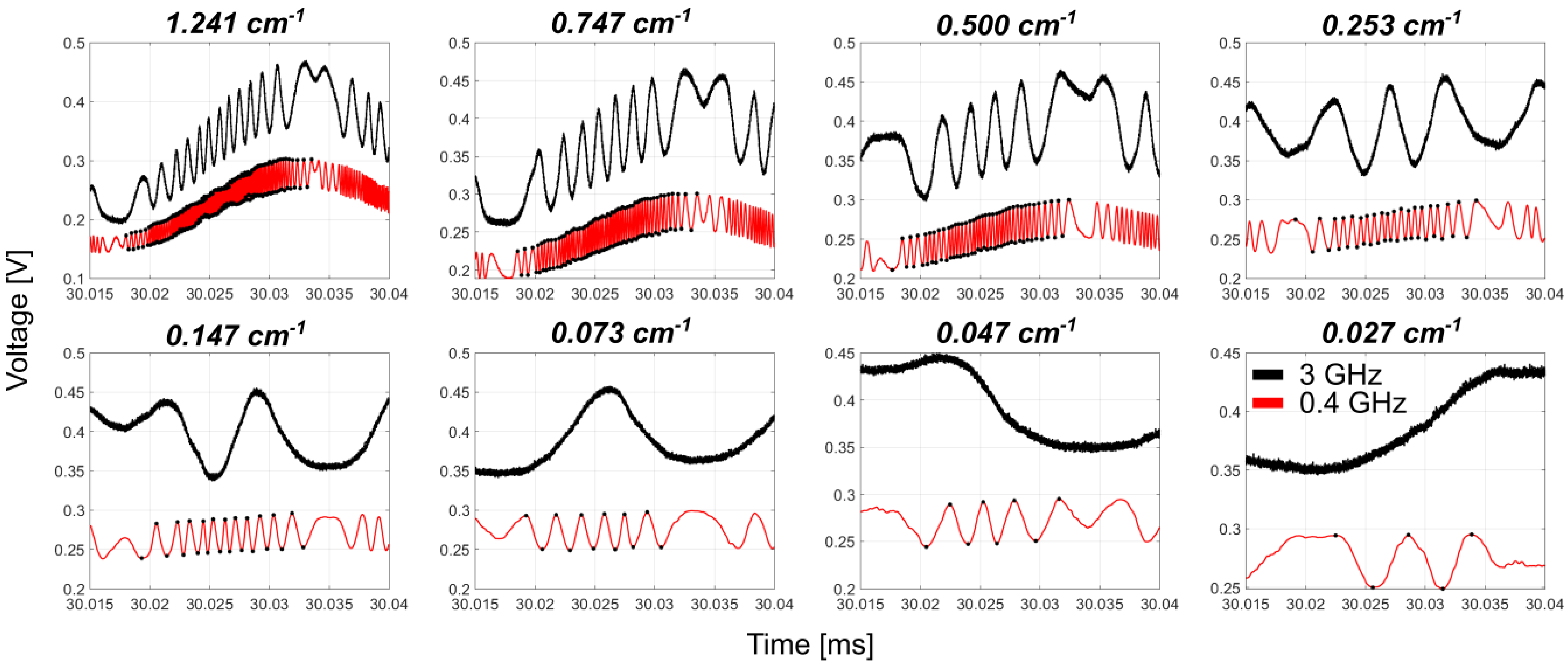
1) Verify that the longer 0.4 GHz etalon is suitable for lower pressure WMS measurements





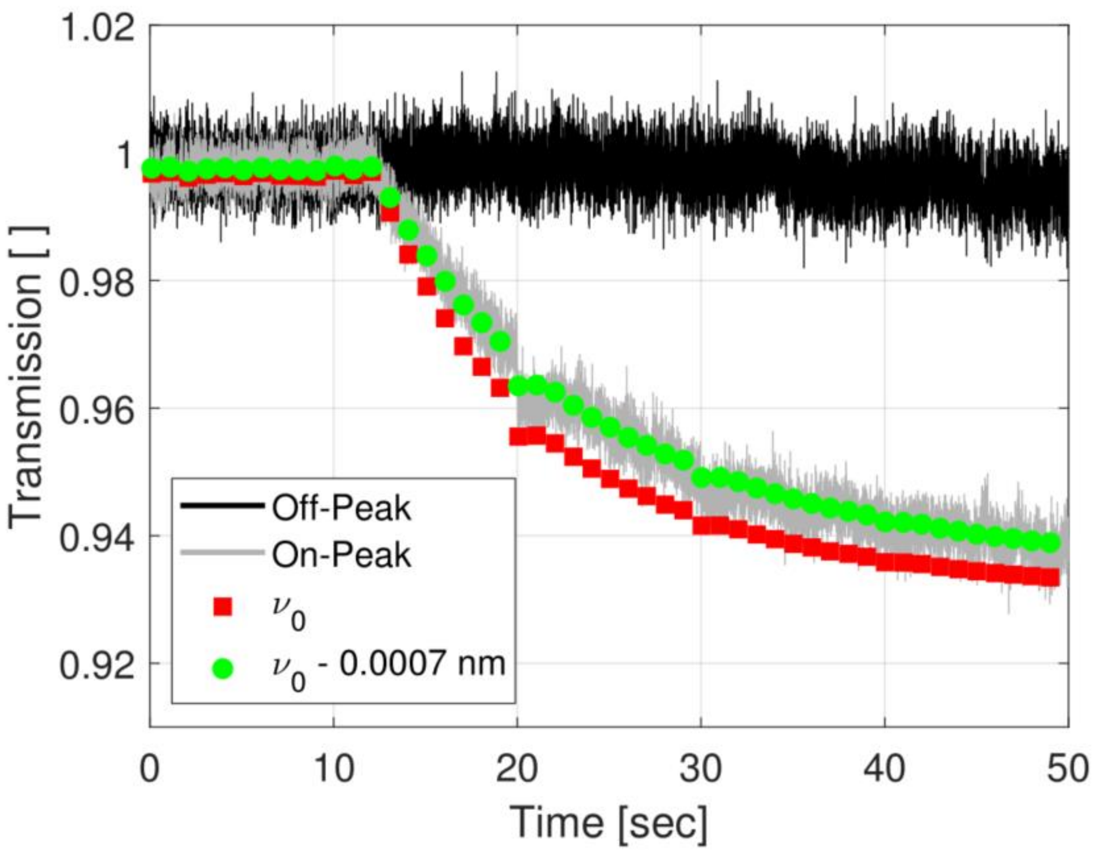
- Larger pressure, larger modulation depth (amplitude of fast modulation)
- Smaller pressure, smaller modulation depth

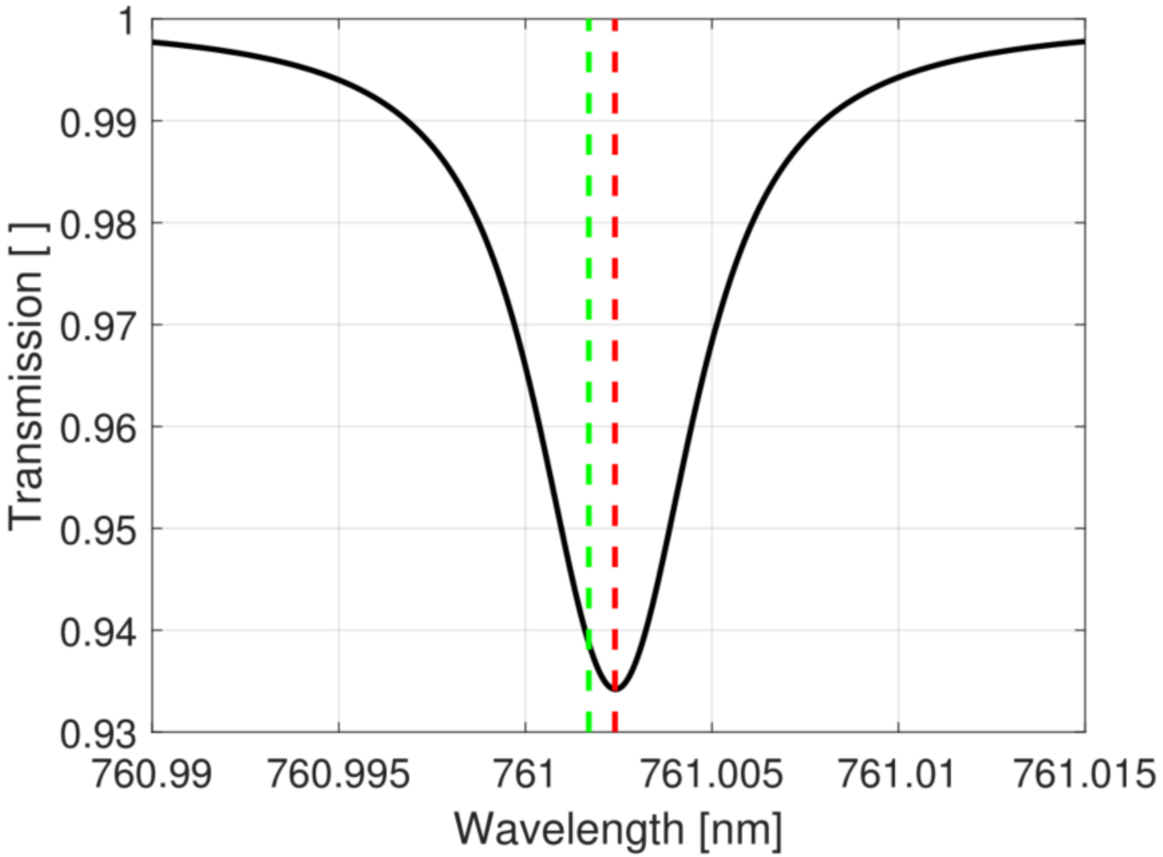
Goal 1) Etalon Comparison: 3 GHz vs. 0.4 GHz



- Higher modulation depths characteristic of broader absorption features
  - Sufficient fringe peaks using 3 GHz etalon until 0.5 cm^{-1}
- Lower modulation depths for lower pressure measurements
  - 3 GHz etalon does not have enough fringe peaks for fitting
  - 0.4 GHz etalon sufficient down to 0.027 cm^{-1}

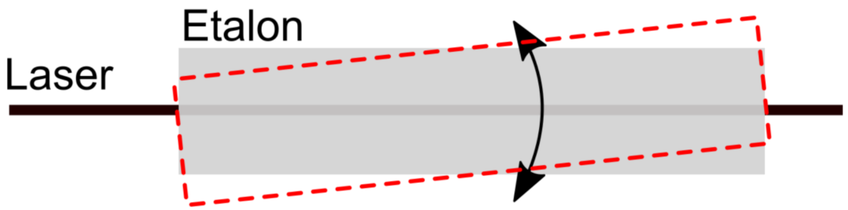
2) Test the concept of fixed-wavelength direct absorption using an etalon as a relative wavemeter





Goal 2) Etalon Angling – Impact on Free Spectral Range

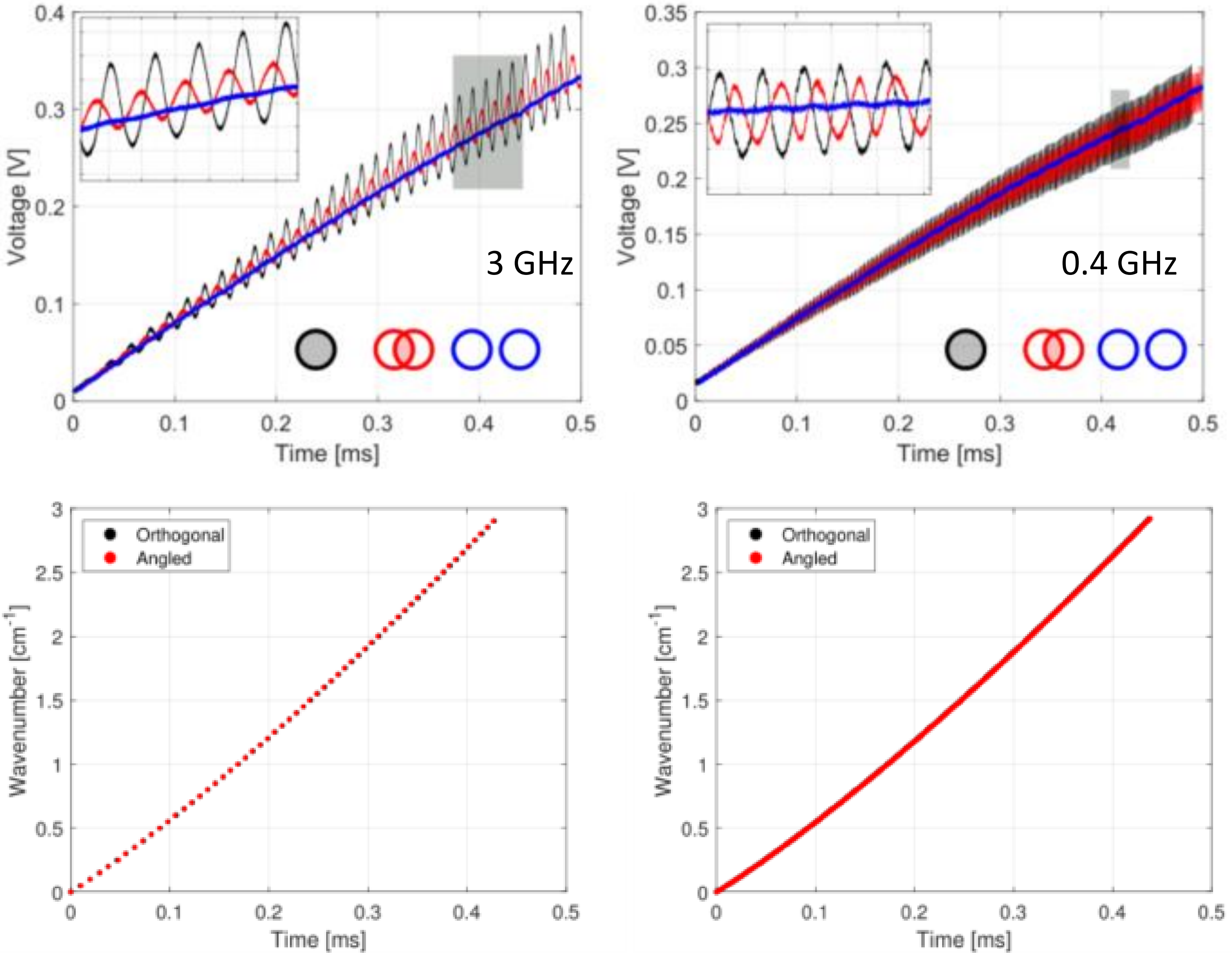
- Does angling of etalon relative to laser beam affect the free spectral range?



- Top plots:
  - Single DAS ramp data for 3 GHz and 0.4 GHz etalons for three etalon rotations

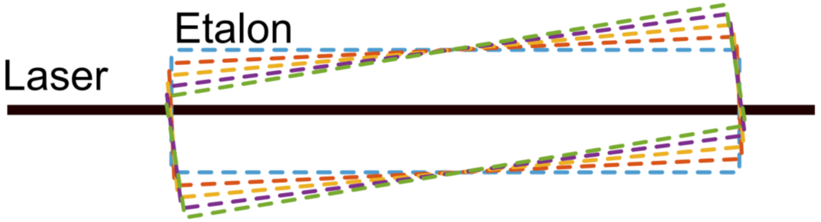
- Each fit peak wavenumber incremented by FSR of etalon

- Bottom plots:
  - Angled and orthogonal *v-t* calibration curves the same
  - No appreciable effect of angling etalon on FSR



Goal 2) Etalon Angling – Impact on Fringe Position

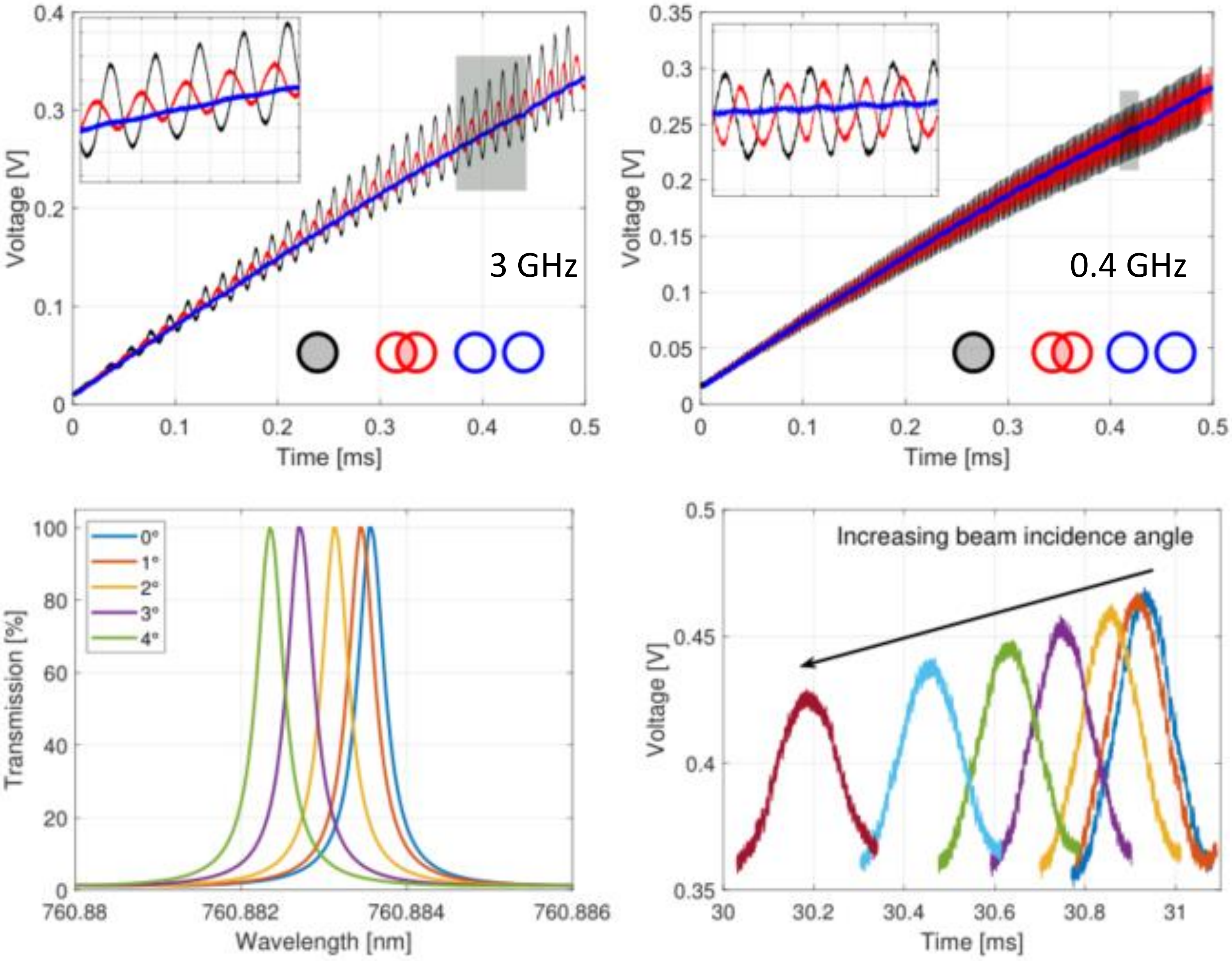
- Can angling the etalon be used to shift the fringe peak in wavelength?



- Bottom left:
  - Etalon manufacturer simulations for various laser incidence angles
  - Decrease in wavelength with increasing angle

- Bottom right:
  - Experimental data for seven etalon angles
  - Decrease in time (wavelength) with increasing angles matches simulations

- Can finely adjust position of etalon fringe peaks via tilt-tuning

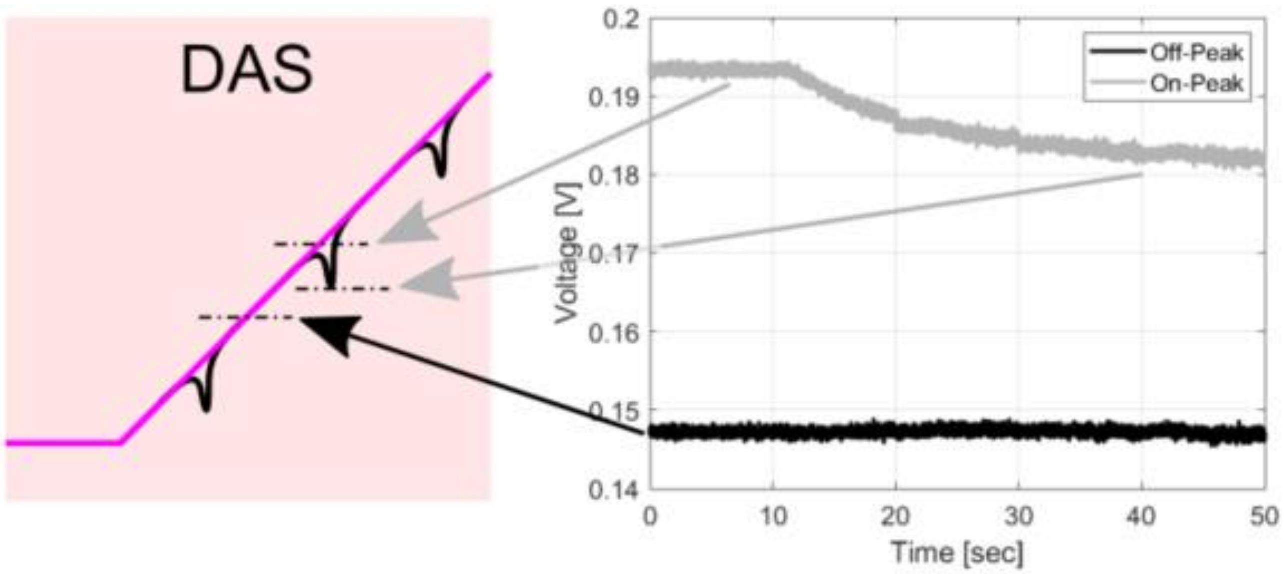


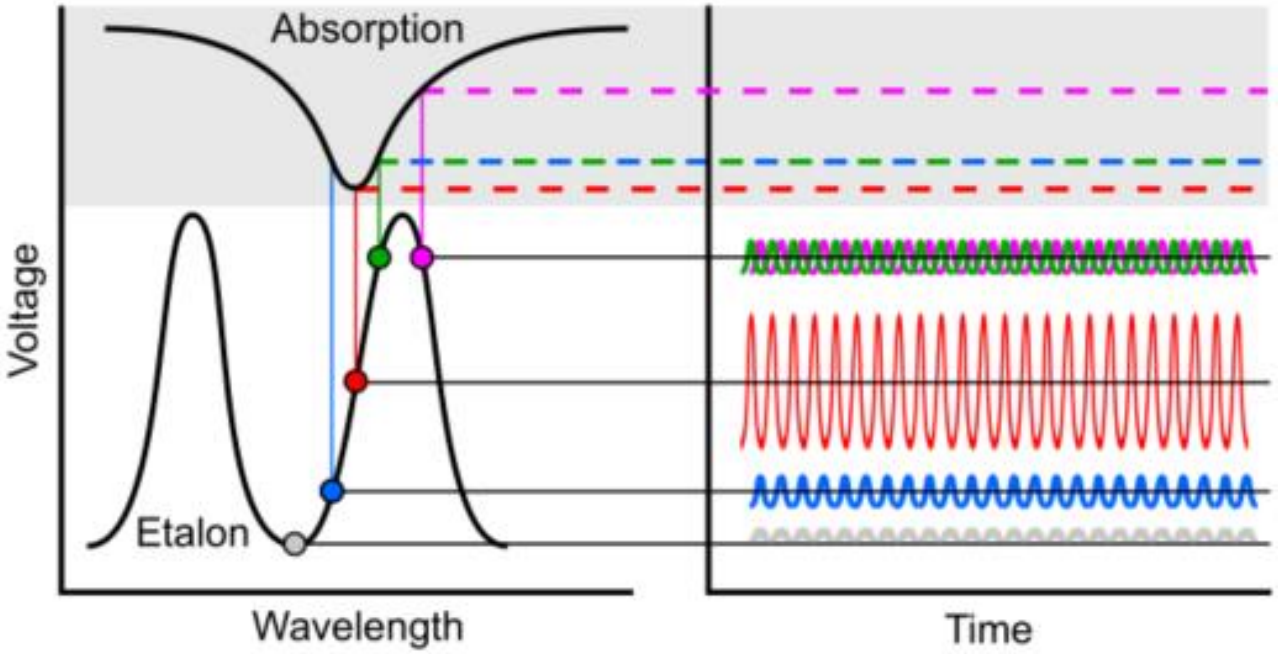
Goal 2) Fixed-Wavelength Absorption // Concept

- Top figure
  - Off-peak: no change with increasing O_2 concentration
  - On-peak: increase in absorption with O_2 concentration

- Bottom schematic:
  - Five fixed laser wavelengths (● ● ● ● ●)
  - Photodiode time series of wavelength-fluctuating signal shown at right
  - Middle of etalon fringe peak gives highest sensitivity to change in wavelength
  - Left side of fringe: wavelength increase -> etalon signal increase
  - Right side of fringe: wavelength increase -> etalon signal decrease

- Monitoring absorption and etalon data channels gives precise wavelength at every data point
  - Only true if wavelength shift stays on one side of fringe





Goal 2) Fixed-Wavelength Absorption // Etalon Fringe Positioning

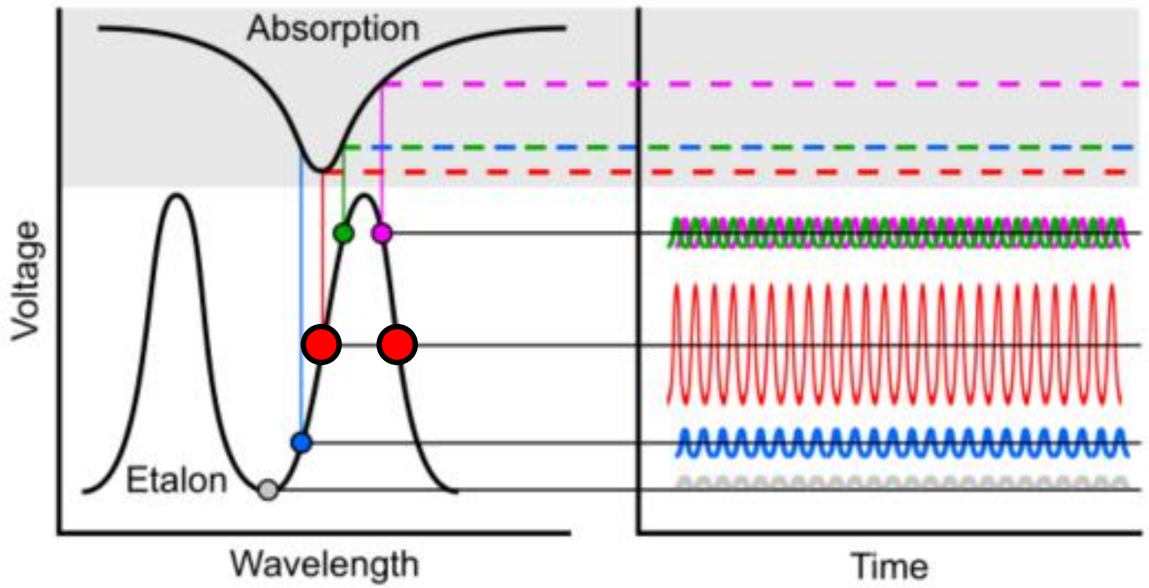
- Want to place linecenter of absorption feature at middle of etalon fringe peak (●)
  - Place on either side of fringe

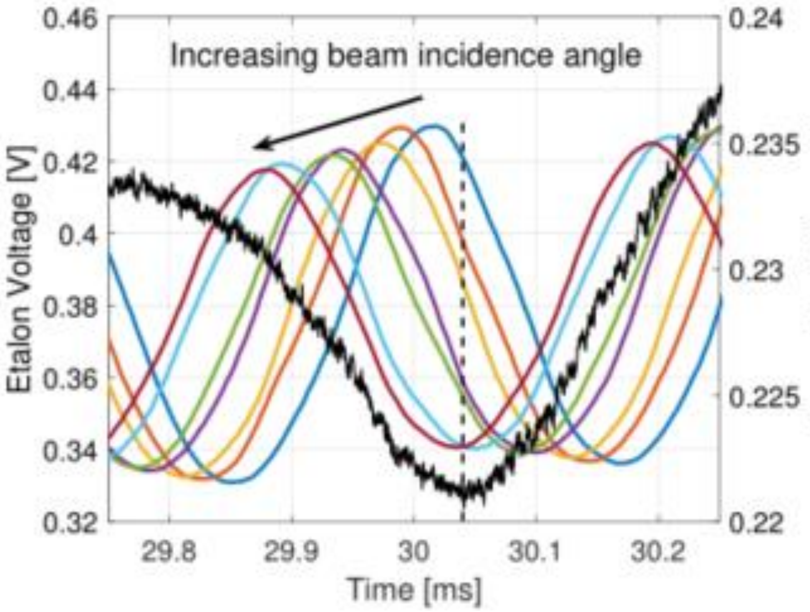
- Use tilt-tuning of etalon to adjust etalon fringe position in real-time
  - Black: O_2 absorption feature
  - Colors: Various etalon angles relative to laser beam

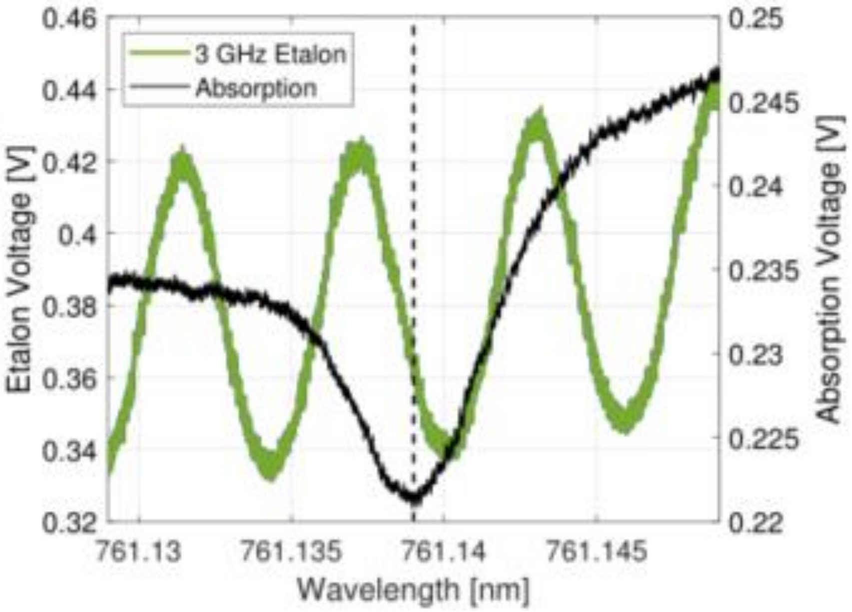
- Bottom right:
  - Final etalon fringe position relative to absorption feature linecenter

- Need only a single calibration data set before running

- Usable wavelength range limited to half fringe width

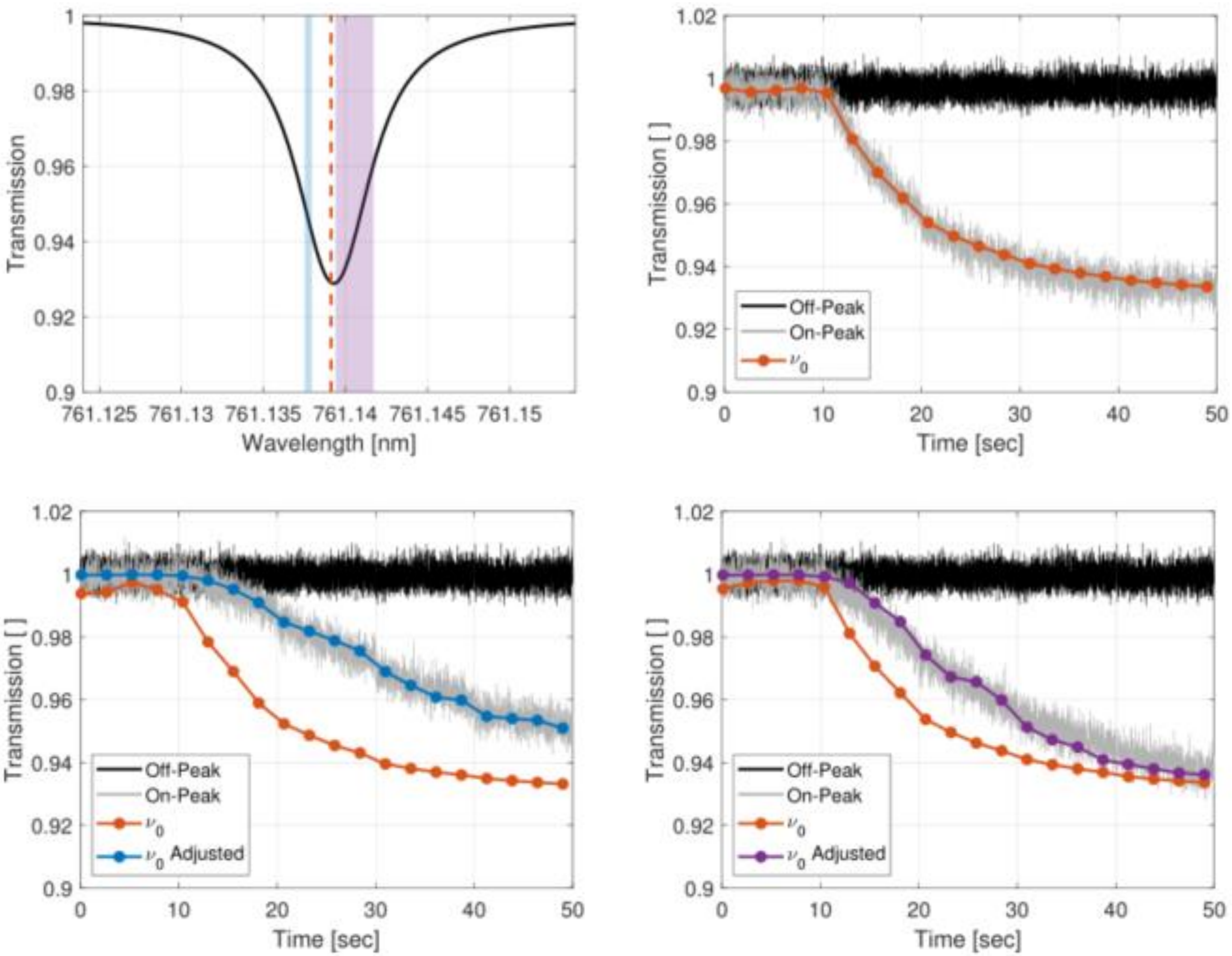






Goal 2) Fixed-Wavelength Absorption // Results

- Data taken at three wavelengths (gray)
  - Lower wavelength from linecenter
  - Absorption linecenter
  - High wavelength from linecenter
- Absorption and etalon data monitored
- Simulations of absorption from known test cell properties (*P*, *T*, *X*, *L*)
- Absorption at feature linecenter matches well
- Shorter- and longer-wavelength absorption simulations match data when laser wavelength drift from etalon accounted for



Conclusions

- Longer etalon (0.4 GHz) has sufficiently short free spectral range to be useful for expected freestream pressures in testing facilities

- Fixed-wavelength DAS a viable option to obtain absorption and LDI at same sampling rate
  - Etalon can be used as a real-time relative wavemeter
  - Angling etalon relative to laser provides fringe adjustment for optimum positioning relative to absorption feature

- Truly simultaneous, colinear absorption and LDI measurements are feasible, and provide measurements of different physical quantities
  - <u>LDI</u> : Optical path length changes resulting in a measure of flow fluctuations
  - <u>Absorption</u>: Changes in O_2 absorption, and insensitive to optical path length changes due to index of refraction

Supported by NASA Transformational Tools and Technologies (TTT) and Hypersonic Technologies Project (HTP)