Tunable Diode Laser Absorption Spectroscopy (TDLAS) for Velocimetry and Water Concentration Measurements of Rocket Exhaust Plumes

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Abstract

Accurate species characteristic measurements are essential for evaluating rocket motor performance, yet traditional physical probes often introduce disturbances and uncertainties. This study investigates the feasibility of employing Tunable Diode Laser Absorption Spectroscopy (TDLAS) as a non-intrusive diagnostic tool to measure water velocity and concentration in rocket exhaust. By analyzing Doppler shifts in water absorption features using a near-infrared diode laser selected via HITRAN-guided spectral analysis, and utilizing a reference beam to mitigate background noise, the method facilitates precise velocimetry and concentration assessments through the application of Beer-Lambert's law. Preliminary tests with a cold gas thruster have successfully measured a wavelength shift corresponding to Doppler-induced velocity changes and determined varying water concentrations in a stationary medium, with further tests underway to validate the technique and quantify uncertainties. This work underscores TDLAS's potential for advanced diagnostics in high-temperature, high-velocity propulsion environments and its prospective application in both academic and commercial propulsion research.

Introduction

Background:

- Tunable Diode Laser Absorption Spectroscopy (TDLAS) is used across various industries for process control and precise gas detection and measurement. This method varies the wavelength in a tunable diode laser to measure absorbance phenomenon in the molecules desired to be measured, in a manner characterized by the Beer-Lambert's Law.
  - At a certain wavelength, the absorption of the molecule will cause a decrease in signal intensity that can be measured.
  - Properties like velocity, concentration, and can be derived using this method.
    - In our experiment, the target molecule is H_2O as it is a byproduct of combustion reactions.

$$\frac{\Delta\lambda}{\lambda_0} = \frac{u * \cos\theta}{c}$$

$\Delta\lambda$ = Change in wavelength from Doppler Shift
λ_0 = Ambient (no flow) wavelength
u = flow velocity
θ = Angle of laser into flow
c = speed of sound in Air = 3E8 m/s

Equation 1: Doppler Velocimetry Equation (1)

- HITRAN (High-Resolution Transmission Molecular Absorption Database) is a comprehensive database that provides spectroscopic parameters for molecules, used to model and simulate how light is absorbed and transmitted through gases. Using a reference water concentration in HITRAN, the area of absorption at our peak wavelength can be used to obtain our experimental concentration. The ratio of the absorption area from HITRAN and the area of absorption from our experiment will yield the concentration.

$$C_{exp} = C_{ratio} * C_{ref} \quad \Big| \quad C_{ratio} = \frac{\int Absorption\ Feature}{\int HITRAN\ Feature} \quad \Big| \quad C_{ref} = \frac{P_{vap}}{R * T}$$

Equation 2-4: Equations For Water Concentration

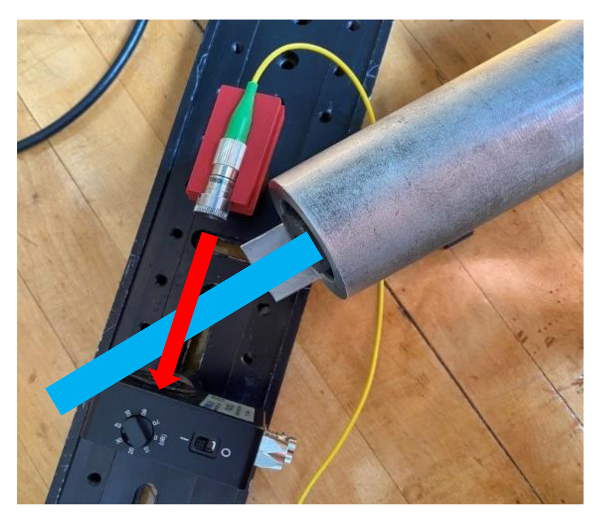
Research Objectives:

- Develop a non-intrusive rocket plume diagnostic.
- Record bulk plume velocity, temperature, and H_2O concentration.
- Prove TDLAS is viable as a diagnostic method for real-world test conditions.
- Validate wavelength shift measurement capability to within ±0.1 pm.

Methods

The TDLAS method was used to analyze the absorption of laser light by water gas molecules as the laser wavelength was scanned across an absorption feature. As depicted in Figure 2, wavelength scanning was achieved using a function generator. Specifically, a sawtooth waveform was generated as input to the laser controller to be superimposed over the laser injection current. As the injection current to the diode laser changed, the wavelength output of the laser also changed. The peak absorption wavelength generated by the diode laser was 1387.52 nm, a value found through HITRAN simulations where a distinguishable absorption dip can be seen.

The reference scan ranged from 1387.475 nm to 1387.617 nm which were input values set to encapsulate the target wavelength. Experiments were conducted with the beam path at +30 degrees relative to the exhaust outlet (blue shift configuration) with the photodetector placed downstream. Blowdown data was collected as the thruster ran. The absorption features in the experimental data were then analyzed and compared to the reference data to record wavelength shifts and infer the velocity of the exhaust gas.



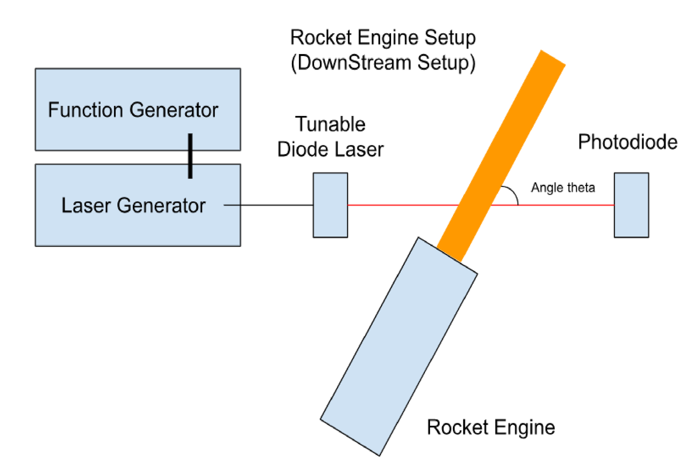
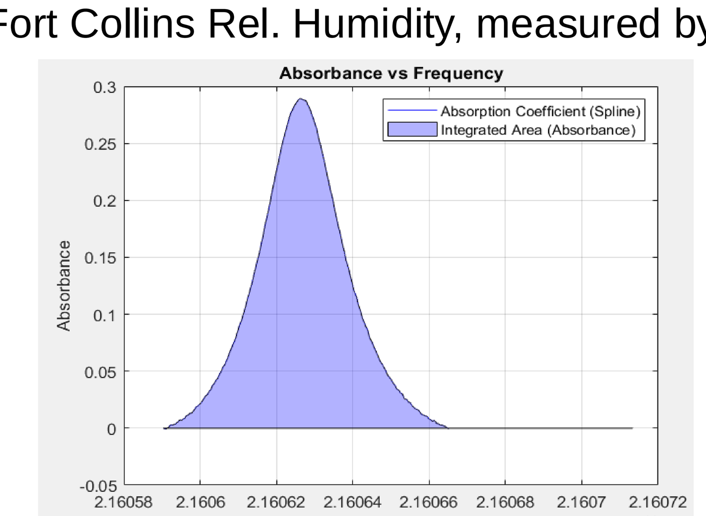


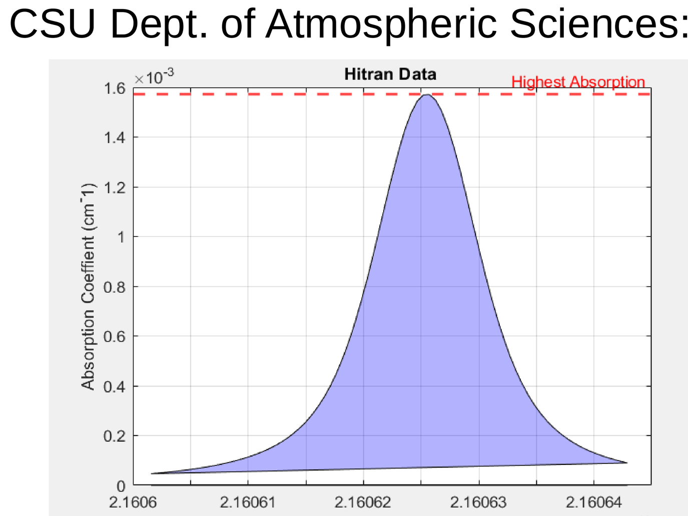
Figure 1 (left) shows the angled cold gas thruster nozzle aligned with the experimental setup. The blue arrow indicates the path that the water gas molecules followed during the experiment; the red arrow shows the path the laser light travels. Figure 2 (right) is a schematic diagram of the planned instrument setup with the rocket engine.

Results & Analysis

Water Concentration Measurements

Fort Collins Rel. Humidity, measured by CSU Dept. of Atmospheric Sciences:13.4% at 16:00 (Time of Testing).





- TDLAS system yielded 13.57% humidity reading through 5 tests.
- This yields an accuracy of ±0.3% for water concentration measurements.
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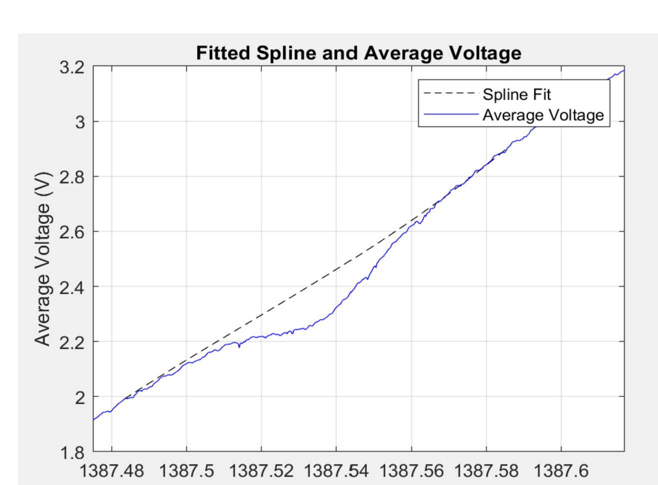
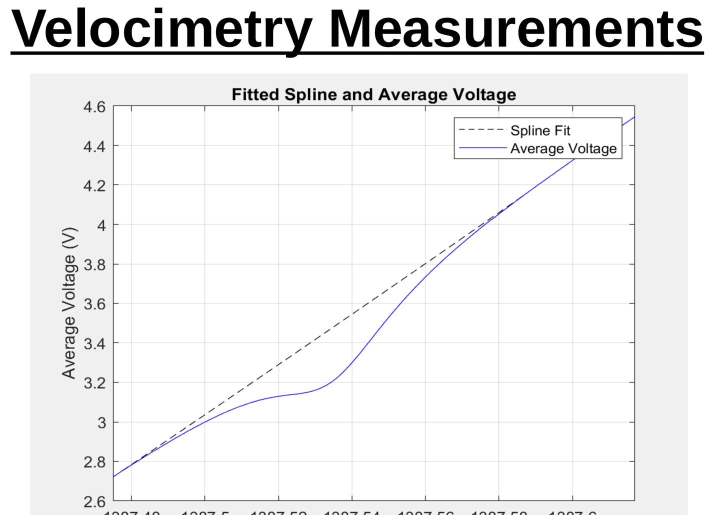
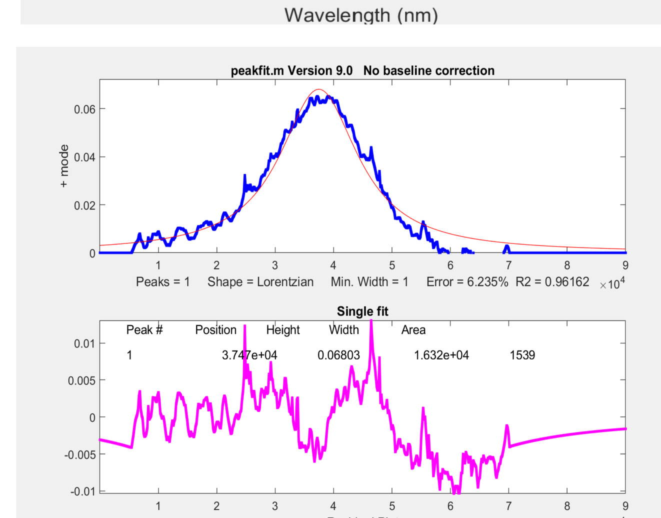
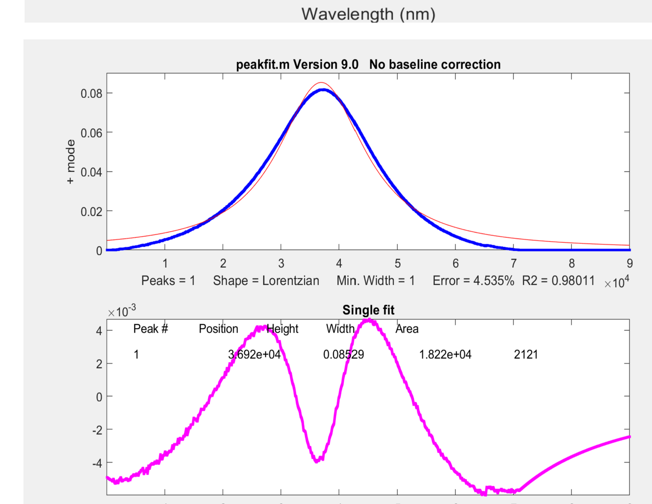
Velocimetry Measurements









- The measured shift in wavelength from our reference test to our blowdown test was 0.00087 nm
- A peak fitting program was used to smooth out the noise in the data to measure the shift.
- The angle of incidence from this test was 30° with the laser aiming downstream of the laser
- The laser was 4 cm downstream of the exit of the nozzle
- With the change in wavelength measure the velocity measurement is 217.205 m/s

Conclusions

Velocity Measurement:

The measured velocity from the cold gas thruster using our system was 217.205 m/s. This was the bulk velocity downstream of the nozzle. Our laser system measured the velocity 4 cm away from the exit of the nozzle. An uncertainty in our measurement is the reference data and the blowdown data were taken at two separate times. This is because the team only had one photodetector. Slight variations in running the laser in two separate tests give the measurement some uncertainty. Future work will allow for the reference and test to record simultaneously.

The cold gas thruster used in the experiment is in Colorado State University's Thermo-Fluid Sciences Lab and is used for classroom experiments. The efficiency of the CD nozzle is unknown meaning the theorical values for the exit velocity are calculated using ideal states. The exit velocity of the nozzle was calculated to be 619.0519 m/s using isentropic compressible flow equations for dry air (2). The actual system with humid air would lead to a slightly lower velocity but the water concentration in the chamber is unknown. The laser was set up further downstream of the plume which is why the measured velocity is lower than the exit velocity. The test on the cold gas thruster is to validate that our system can measure meniscal changes in the wavelength to measure velocity.

Water Concentration:

Future Work

Future testing will involve applying the TDLAS system to a rocket exhaust plume generated by combustion. This will allow an investigation of the diagnostic technique in a more representative high-temperature and high-velocity flow environment.

Another area of future interest is performing temperature measurements of the rocket exhaust plume using TDLAS. Scans collected at a larger path length should allow for more resolvable absorption lines suitable for thermometry analysis. This can have important implications for fully characterizing the rocket motor performance.

References and Acknowledgements

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(2) John David Anderson, Modern compressible flow with historical perspective. Boston [U.A.] Mcgraw-Hill [20]10, 2003.

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