

Appendix F: Tunable Diode Laser Absorption Spectroscopy Manual

Tunable Diode Laser Absorption Spectroscopy (TDLAS) was used in this study to obtain a high-bandwidth measurement of temperature. Since TDLAS is an optical technique, the bandwidth is only limited by the data acquisition system. Two water absorption features are probed, and the ratio of the absorbances is correlated to gas temperature. The method of operation, components, measurement procedure, and data processing related to the TDLAS-based measurement of gas temperature is described in this manual.

F.1. Method of Operation

The absorption of light at a given wavelength is a function of the concentration of the absorbing species, pressure, the linestrength, and the lineshape. The background of absorption spectroscopy is given in greater detail in Section 1.3.2. In summary, the linestrength is a much stronger function of temperature than the lineshape. Thus, the ratio of the absorption of two transitions is only a function of temperature.

As discussed in Section 3.1.1, the temperature dependence (lower-state energy) and the absorption from interfering species must be considered when selecting an absorption feature to probe. The current study sought water absorption features that exhibit a high dependence on temperature and negligible interference from other species. The features at 7444.37 cm^{-1} and 7185.59 cm^{-1} were chosen because they exhibit these characteristics.

Two lasers, one for each absorption feature, are directed across the flame. An effort is made to remain in the post-flame region to insure a relatively uniform temperature profile along the pathlength. The wavelength of the laser is adjusted in two ways. Adjustments to the mean operating condition are made through controlling the temperature of the diode casing through a Thermo-Electric Cooler (TEC). The temperature control allows the user to maintain the wavelength of the laser at the linecenter of the transition. To modulate the wavelength of the laser quickly, the

injection current to the diode laser is changed. The laser controller allows for an external voltage input for controlling the injection current. By modulating the injection current, typically with a sawtooth waveform, the wavelength of the laser can be scanned over an absorption feature. The dependency of the laser wavelength on case temperature and injection current is shown in Appendix B1.

Mean temperature, species concentration, and pressure measurements are made by modulating the injection current and recording the entire lineshape. For time-resolved measurements, the laser is maintained at the linecenter.

F.2. Experimental Setup

F.2.1. Experimental Hardware. The experimental setup for TDLAS includes the diode lasers, controllers, optics, and detectors as shown in Figure F.1. The semiconductor, distributed feedback, diode lasers, one at 1343 nm and one at 1392 nm, were obtained from Laser Components GmbH, Inc. They have a nominal power of 5 mW and can be tuned with respect to wavelength and power depending on case temperature and injection current. The lasers are mounted in diode mounts (ILX Lightwave LDM-4407) with thermo-electric coolers (TEC) to control the case temperature. A laser diode controller (ILX Lightwave LDC-3908, LDC-3916370 modules) is used to set temperature and injection current. The controller allows the injection current to be modulated via an external connection to a function generator. A laser diode beam is very diffuse, so off-axis paraboloidal reflectors (Melles-Griot) or aspheric lenses (New Focus 5723-H-C) are used to collimate the beam. The beam is directed across the flame, where a flat mirror reflects the beam back across the flame to the optical table. Another flat mirror (Newport 05D20ER.2-PF) directs the beam through a 2" focusing lens (Thorlabs LB1917-C) and onto a InGaAs photodiode detector (Thorlabs FGA10). The circuit diagram for the detector is shown in Appendix E. The circuit converts the current signal from the photodiode to a voltage signal and provides amplification. The bandwidth of the circuit is 10kHz.

The absorption of two transitions, and thus two lasers, is required for the temperature measurement. To insure accuracy, the beams must travel on approximately the same path. The beams are aligned to intersect in the measurement volume as seen in Figure F.2, so that the minimum distance occurred in the crucial path length. Care is taken to keep the total path length (from laser to detector) approximately equal for the two beams. The actual configurations for the laminar and turbulent combustors are shown in Figures F.3 and F.4, respectively.

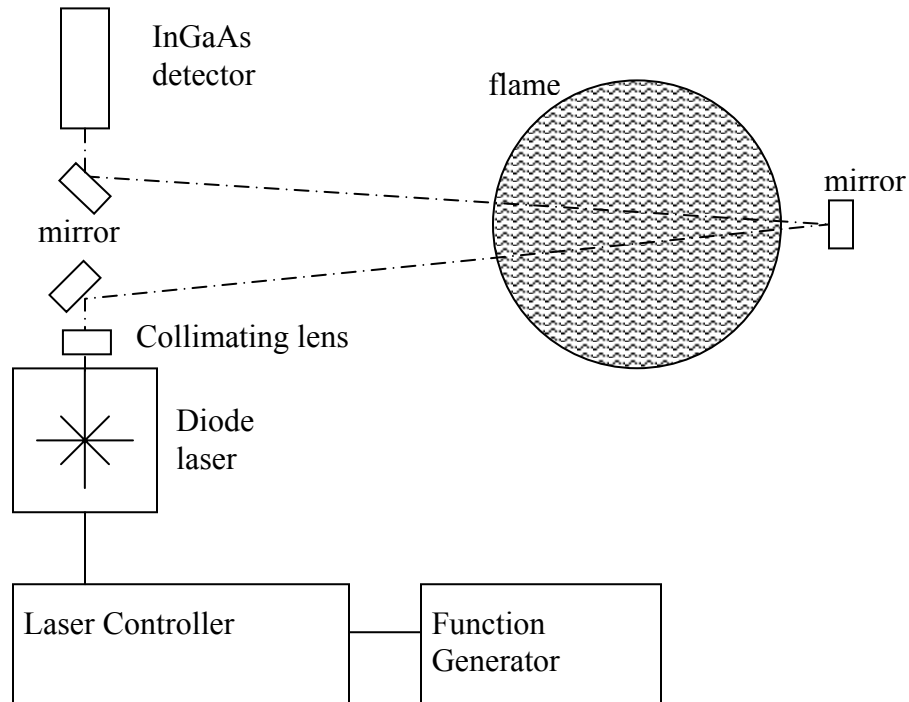


Figure F.1. Diode-Laser Experimental Setup. The beams (only one shown) pass through the flame twice to increase signal to noise ratio.

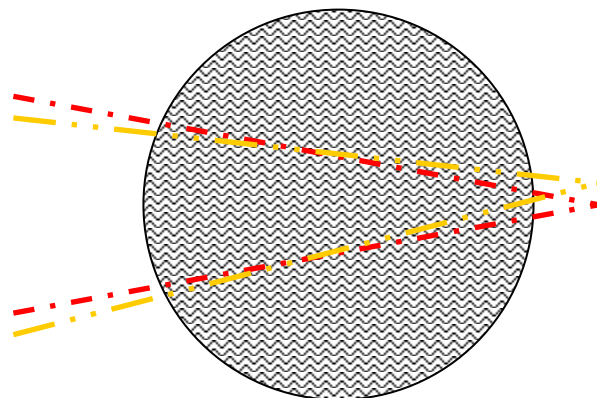


Figure F.2. Beam Paths. The beams are on approximately the same path.

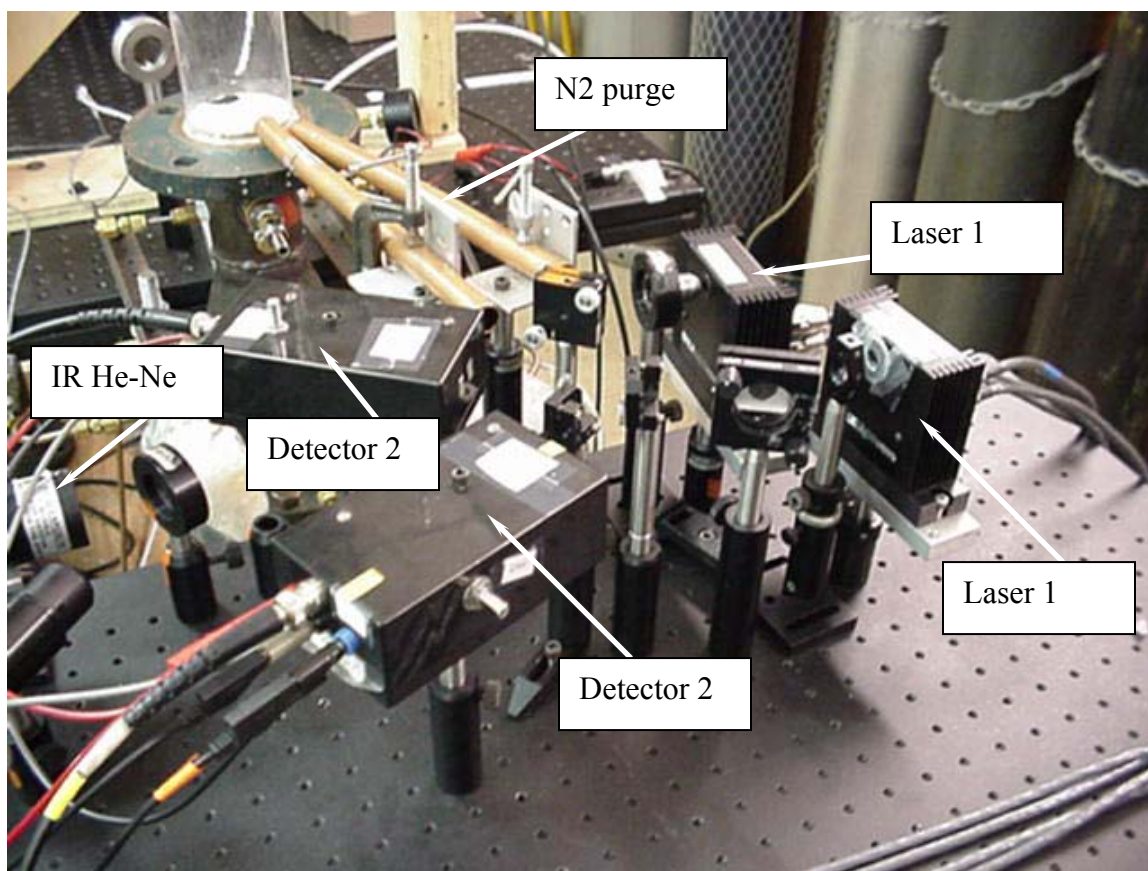


Figure F.3. Laminar Burner Setup. The lasers and detectors were kept on the same optical bench: 1-1343nm, 2-1392nm.

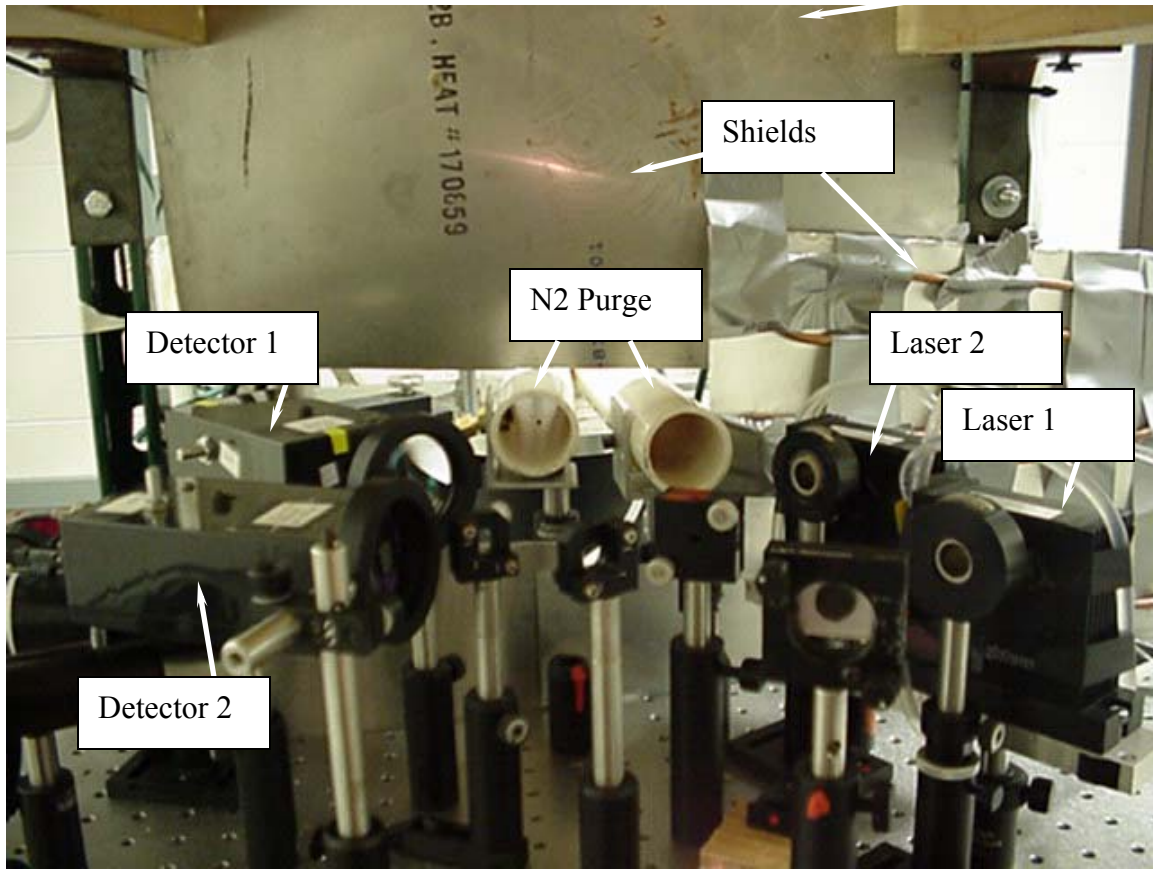


Figure F.4. Turbulent Burner Setup. Water-cooling and shields protect the optics from the flame.

F.2.2. Care of Diode Lasers. Diode lasers are extremely sensitive to static electricity and surges in voltage. There are several concerns that must be kept in mind when dealing with diode lasers:

1. Never handle the diode laser with a tool (including fingers) that are not grounded. Static electricity may cause the diode laser to fail.
2. Take care never to drive the diode laser at voltages and currents beyond its capacity. The diode laser controller should be configured to restrict voltage, current, and case temperature.
3. Be sure to connect all equipment to a common ground to protect against ground loops.

4. Always configure the diode laser mounts to keep the diode voltage floating. Grounding the diode laser to earth ground will increase susceptibility to line power fluctuations and surges.

F.2.3. Alignment of Optics. There is no substitute for practice in learning to align optics. However, a few suggestions might be helpful.

When aligning an optical setup for the first time, or if the optics have become badly out of alignment, place a visible He-Ne laser in place of the detector. Align the optics so that the visible laser shines directly on the head of the IR laser. Then, turn the IR laser on and adjust the IR laser so that the beam follows the same path as the visible laser.

In my experience, it is best to always work the laser to the detector when aligning optics. For the TDLAS setup,

1. Align the aspheric lens to achieve a well – collimated and symmetric beam.
2. Align the nearest mirror to direct the beam across the flame.
3. Adjust the mirror on the opposite side of the flame to direct the beam back across the flame.
4. Adjust the far mirror to direct the beam onto the detector.
5. Once the lasers are aligned on the correct path, small adjustments can be made to maximize the detector output.
6. The detector gain can then be adjusted to the desired output voltage.

The detector signal may begin to oscillate due to etalon effects (reflections) in the optical path. If this occurs, make small adjustments to the optical path until the oscillations are no longer observed.

F.3. Measurement Procedure

F.3.1. Theoretical Lineshapes. Theoretical lineshapes are calculated to identify attractive transitions and to determine physical parameters. The HITRAN database

contains spectroscopic parameters for many important molecules. The HITEMP database includes parameters for high-temperature transitions. Many of the parameters are theoretical, although some have been experimentally verified. Using these parameters, theoretical lineshapes can be computed to compare with measured lineshapes. Also, the theoretical properties are used to calculate the temperature dependence of transitions (see Section 3.1.1). The Matlab program “spectra.m” calculates theoretical lineshapes based on the parameters in HITRAN and HITEMP.

F.3.1. Lineshape Data. When a high-bandwidth measurement is not required, the wavelength of the laser is scanned over the entire absorption feature. The temperature and injection current is set through the laser controller to maintain the laser at the linecenter. A function generator is used to send a sawtooth waveform to the external modulation connection on the laser controller. Observing the lineshape on an oscilloscope, the case temperature and mean current can be adjusted to position the linecenter of the transition at the center of the waveform. The amplitude of the sawtooth wave should be adjusted so that at least 30% of the waveform is outside of the transition. For the setup at the VACCG, analog output channel 0 was connected to the modulation input on the diode laser controller. The Labview program “funken.vi” was used to create a 50 Hz sawtooth waveform with amplitude of 0.2 Volts. Diode lasers can be modulated at up to 10 kHz. However, your data acquisition system must be able to record at least three times the modulation frequency. The Labview program “diagnostic_main.vi” was used to record the lineshape data. The data was processed by the Matlab program “v_scan.m”. This program fit baselines to the data to solve for the reference intensity (see Appendix B2) and plotted the resulting lineshape. The program also calculates the peak absorbance which is used in the temperature calculation.

By fitting theoretical lineshapes, using the data from the HITRAN database, to the measured lineshapes, species concentration, pressure, and broadening coefficients can be determined. The program “tst_voigtfit.m” was used to fit theoretical lineshapes to measured lineshapes.

F.3.2. Direct Absorption Data. When a high-bandwidth measurement is needed, the diode lasers are maintained at the linecenter. For each set of direct absorption data, lineshape data is recorded at steady state to calculate the reference intensity. An alternate method is to break off part of the laser beam to send to a second detector. Using direct absorption, the bandwidth of the measurement is only limited by the data acquisition hardware.

F.3.3. Flame Dynamics Measurement Procedure. A procedure was developed to obtain accurate dynamics measurements of gas temperature.

1. Align Optics: The diode laser optics must be aligned to insure accurate absorption data. First, the parabolic mirror or aspheric lens must be adjusted to collimate the beams. The aspheric lenses used in this study provided a reasonably collimated beam with a diameter of approximately 3-5 mm. Once adequate collimation is achieved, the beams are directed along the paths shown in Figure 3.5. Working from laser to detector, the mirrors are adjusted to center the beam on the detectors. Often when first placing optical components, a visible He-Ne laser was placed at the place of the detector. In this manner, adjusting the visible beam from the He-Ne and the beam from the diode laser to follow the same path aligned the beams. Care must be taken to keep the beam path parallel (at the same axial coordinate with respect to the burner) along the path length. The detector gain is then adjusted to an output voltage of 2-4 Vdc. Optical noise may infiltrate the detector signal as a result of etalon effects (reflections of the various optical components feeding back to the detector). This noise source can be remedied by making small adjustments to the beam path.

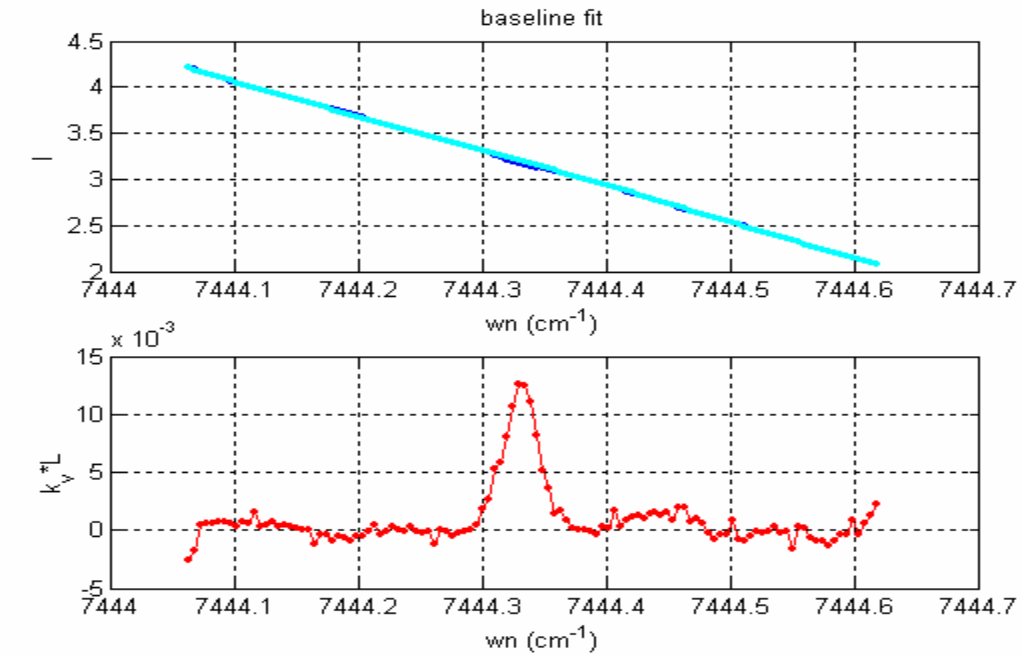
2. Ambient Air Absorption: The absorption from ambient air (humidity) must be measured to correct the flame absorption measurements. Although the majority of the path length outside of the measurement volume is purged with nitrogen, significant absorption from ambient air is still present. With the nitrogen purge on and dry air flowing through the measurement volume, a wavelength-scanning technique (see Appendix B2) is used to measure the absorption resulting from humidity in the ambient air.

3. Flame Absorption: After the flame has reached steady-state, the lasers must be realigned to adjust for beam-steering effects of the flame (density gradients deflect the beam the same way water bends light). Then, a wavelength-scanning technique is used to measure the mean absorption from the flame. The data is also used to solve for the reference intensity of the dynamic data. For the dynamic (time-resolved) data, a direct absorption method is used, i.e. the lasers are maintained at the linecenters of the transitions that they are probing. The desired frequency resolution (1 kHz) and the speed of the data acquisition system (8 channels at 3 kHz) prohibited using a wavelength-scanning technique for the dynamic data. For the turbulent data, mean absorption data was collected at each modulation frequency using the wavelength-scanning technique. Due to the steady nature of the laminar flame, mean absorption data was only recorded at the beginning and end of each test.

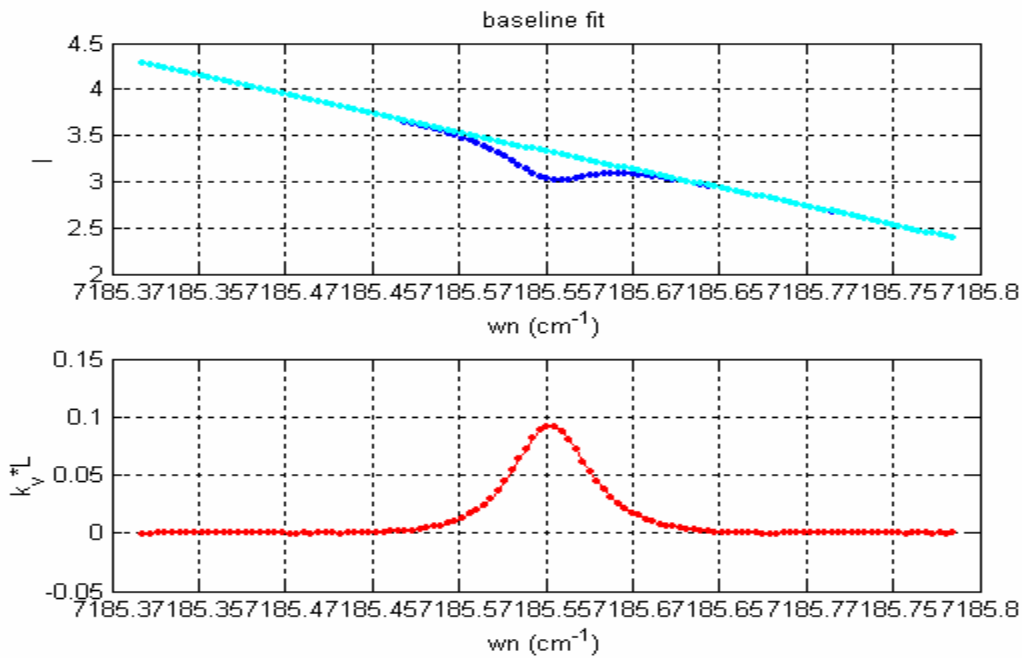
4. Data Post-Processing: The mean data from the wavelength-scanning technique and the direct absorption data are used to obtain a high-bandwidth measurement of gas temperature. First, the wavelength-scanning data is used to find the reference intensities and steady-state gas temperature as detailed in Appendix B2. To obtain accurate temperature data, the absorption data is corrected with respect to the ambient air as shown in equation F.1.

$$K_{flame} = K_{total} - K_{air} \quad (F.1)$$

where K_{flame} is the absorption used in the temperature calculation, total refers to the uncorrected data, and air refers to the absorption due to the ambient air. Figure F.5 shows typical absorption lineshapes in the ambient air. Figure F.6 shows typical absorption lineshapes of the flame that have not yet been corrected.



(a)



(b)

Figure F.5. Absorption Lineshapes in Ambient Air. The absorption of water in ambient air must be accounted for to obtain accurate temperatures (a) 7444.37 cm^{-1} (b) 7185.59 cm^{-1} .

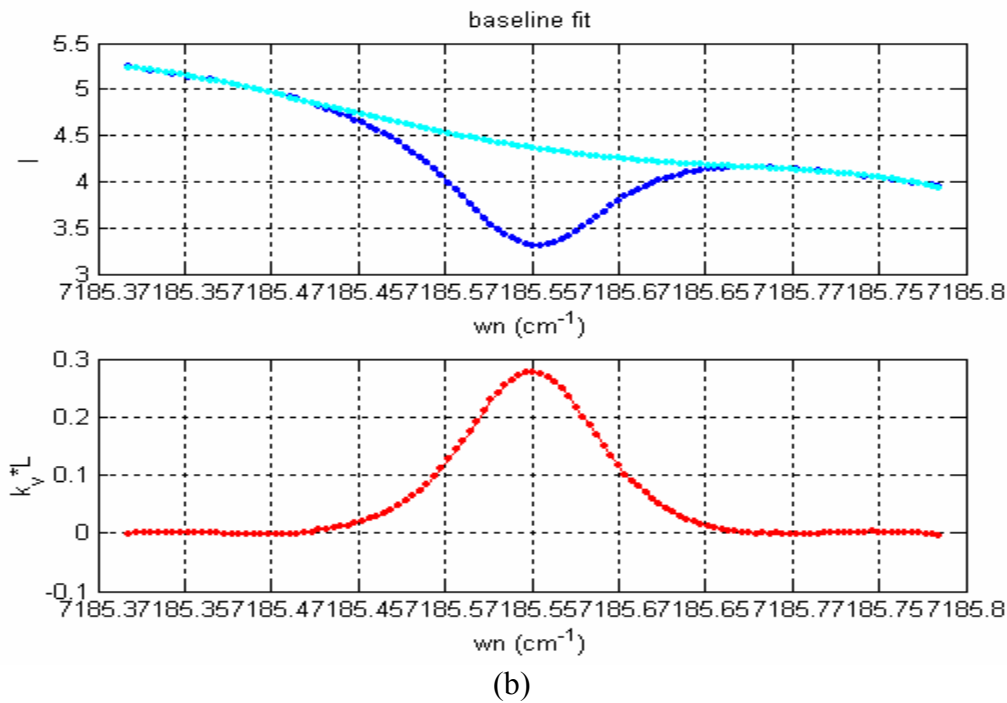
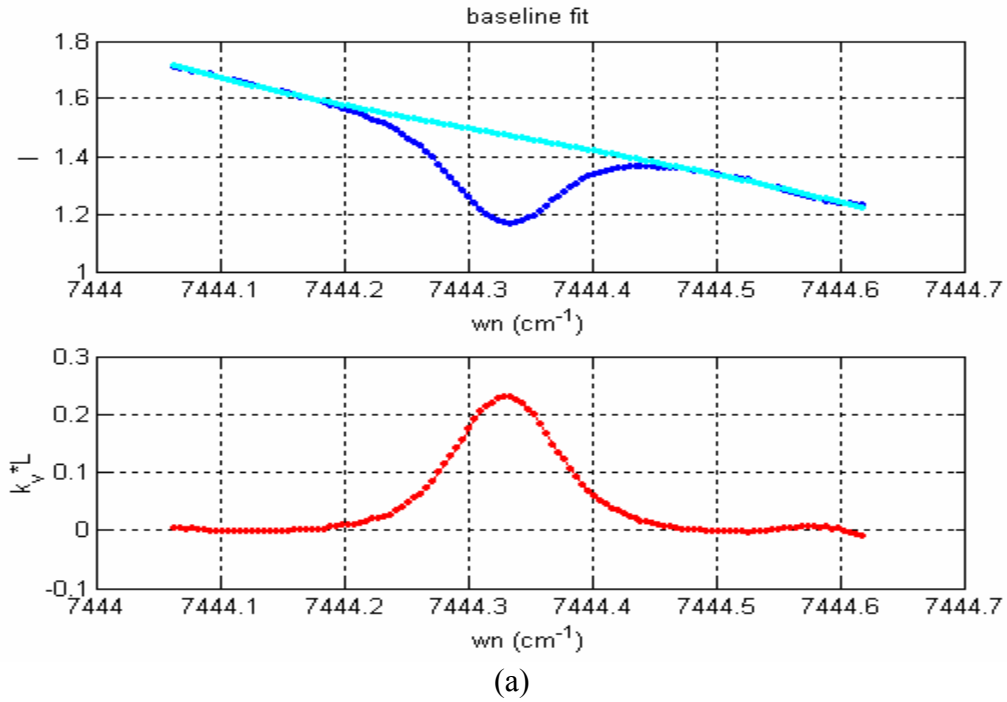


Figure F.6. Absorption Lineshapes with Flame. The water absorption in the presence of the flame is much greater than the background absorption.

The direct absorption data suffers low-frequency modulation due to beam steering and flow discontinuities. These effects are countered by applying a 2000th order Finite Impulse Response (FIR) digital bandpass filter to the data at the excitation frequency

(frequency at which the flame was acoustically forced). The filter is applied so as not to affect the phase of the signal, as seen in Figure F.7. The mean is then added back to the filtered signal. The resulting signal is taken as the intensity I . The reference intensity, I_0 , is solved for using the lineshape data through equation F.2

$$I_0 = \frac{\bar{I}}{\exp(-(K_{tot,o} + K_{air}))} \quad (F.2)$$

where \bar{I} is the mean intensity, $K_{tot,o}$ is the uncorrected absorption from the wavelength-scanning measurement, and K_{air} is the absorption from the ambient water. For the laminar data, the same reference intensity is used throughout the data set. In the turbulent case, the reference intensity was solved for at each excitation frequency. The temperature is computed at each time step by plugging the ratio of the absorbances of the two transitions, R , into equation 3.1. A spectrum analysis is then calculated on the resulting time trace data to obtain power spectral densities and frequency response functions. All post-processing is completed using Matlab ®.

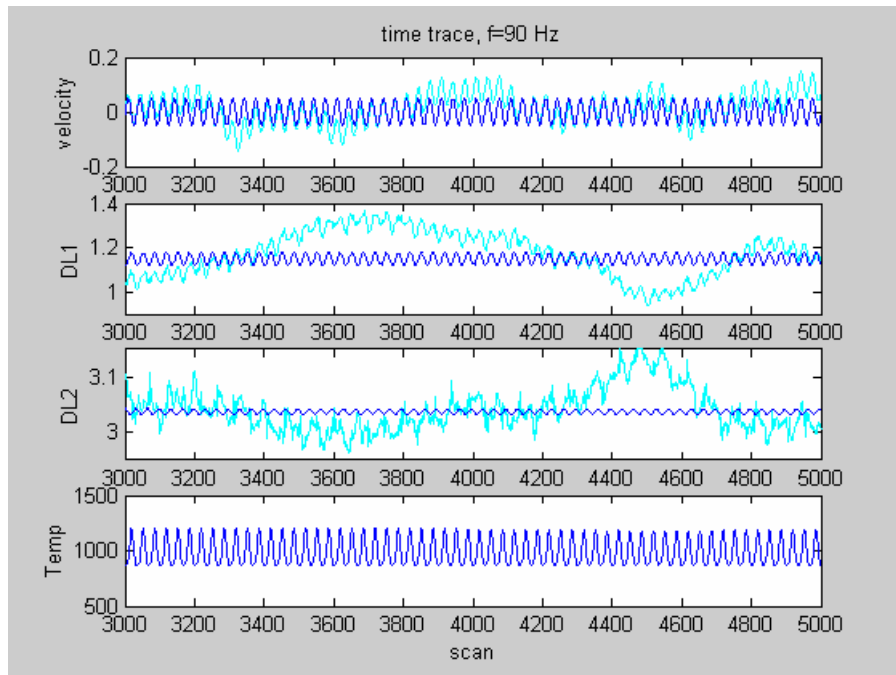


Figure F.7. Digital filter. The digital filter does not affect the phase of the data

F. 4. List of Software.

Labview

diagnostic_main.vi: displays and records analog input voltages

flame_dynamics.vi: provides all data acquisition (lineshape data, direct absorption data, modulation of the diodes, and speaker voltages) to obtain frequency response data on the laminar burner.

flame_dynamics_turb_r1.vi: provides all data acquisition for obtaining frequency response data on the turbulent combustor

funge.vi: allows the user to control analog outputs to modulate the diode lasers or force the loudspeaker

Matlab

biread_data.m: reads the binary data from channels 0 to 7 from flame_dynamics.vi and flame_dynamics_turb_r1.vi into Matlab

biread_diode.m: reads the binary files containing lineshape data into Matlab

biread_params.m: reads the binary file from flame_dynamics.vi and flame_dynamics_turb_r1.vi containing excitation levels, excitation frequencies, and data acquisition scan rate

frf.m: performs all data processing for frequency response data and saves the final result

frf_plot.m: front panel for frf.m for the laminar data, allows user to choose case to compute and which data to plot

frf_plot_turb_r1.m: front panel for frf.m for the turbulent data

frf_results.m: plots processed data for the laminar burner

frf_results_turb.m: plots processed data for the turbulent combustor

tranfit.m: optimizes an initial guess of a dynamic model to match frequency response data

model_compare.m: compares dynamic model parameters – laminar

model_compare_turb.m: compares dynamic model parameters - turbulent