

Towards Simultaneous Multi-Parameter Measurements Using Burst-Mode Frequency-Scanning Planar Laser-Induced Fluorescence

Amanda M. Braun¹

NASA Postdoctoral Program at NASA Langley Research Center, Hampton, Virginia 23681 USA

Neil S. Rodrigues² and Paul M. Danehy³

NASA Langley Research Center, Hampton, Virginia 23681 USA

While planar laser-induced fluorescence (PLIF) can provide valuable flow visualization, there are many challenges in extracting quantitative measurements from the fluorescence intensity. To overcome the multi-parameter dependence of the signal intensity, frequency-scanning planar laser-induced fluorescence (FS-PLIF) provides the potential for 2D temperature, pressure, and velocity measurements by spectrally resolving the excitation spectrum of one or more fluorescence transitions to extract the Doppler shift, Doppler- and collisional-broadening of absorption lines, and the relative signal intensities of multiple transitions. This work aims to characterize a burst-mode FS-PLIF system consisting of a Spectral Energies, LLC burst-mode laser coupled with a Spectral Energies, LLC optical parametric oscillator using nitric oxide (NO) static pressure cell measurements. The effect of the OPO cavity on intensity fluctuations during frequency-scanning is investigated. A NO PLIF model is implemented to investigate the feasibility of property measurements using single- and two-NO-line scans.

I. Introduction

Quantitative, high-speed temperature, pressure, and velocity measurements are critical for the validation of computational/empirical models, which are used for the design and optimization of space and aeronautical vehicles. Laser-based diagnostic techniques can provide non-intrusive *in situ* measurements in the relevant flow fields of ground test facilities. However, most ground tests are performed in wind tunnels that contain only air or nitrogen within the freestream. Velocimetry techniques such as particle image velocimetry (PIV) or Doppler global velocimetry (DGV) require seeding the flow with particulates, which can reduce velocity accuracy due to particle lag across shocks and nonuniformity in the seeding [1]. Alternatively, planar laser-induced fluorescence (PLIF) techniques overcome this challenge by targeting either naturally occurring or seeded gas-phase fluorescence tracers. Nitric oxide (NO), which is typically excited with 226-nm laser light, has been successfully used as a flow tracer for visualization in a variety of hypersonic wake flows and boundary layers [2–4]. For velocity measurements, molecular tagging velocimetry (MTV) takes advantage of the fluorescence lifetime to track the spatial location of the fluorescence in time [5]. The NO MTV technique was more recently extended to kHz-rate velocity measurements using burst-mode lasers (BMLs) coupled with optical parametric oscillators (OPOs), similar to that used in the present work [6]. However, as fluorescence-based MTV measurements often relies on imaging of fluorescence excited by discrete laser lines or spots, the spatial resolution may be limited. Furthermore, this technique may not be viable in highly quenching environments.

¹ Postdoctoral Fellow, Advanced Measurements and Data Systems Branch, AIAA Member, amanda.braun@nasa.gov.

² Optical Physicist, Advanced Measurements and Data Systems Branch, AIAA Member.

³ Senior Technologist, Advanced Measurements and Data Systems Branch, AIAA Associate Fellow.

One challenge with making quantitative measurements based on NO PLIF signal, rather than tracking the fluorescence, is that the signal intensity depends on multiple flow parameters and is further complicated by collisional quenching effects and fluorescence lifetimes. Therefore, extracting quantitative flow property measurements from NO fluorescence intensity requires additional information. One strategy is to compare the fluorescence signal intensity at different incident laser wavelengths. For example, temperature measurements can be extracted using two-color PLIF, which uses two incident laser wavelengths tuned to different absorption peaks. Temperature is inferred based on the ratio of the PLIF signal intensities [7]. More recently, two-color PLIF has been extended to kHz-rate thermometry using BMLs to excite OH and formaldehyde [8, 9]. Alternatively, the potential for simultaneous, multi-parameter measurements has been explored by scanning the laser across one or multiple absorption lines to provide velocity information through detection of the Doppler shift and temperature/pressure information through sensitivity of Doppler- and collisional-broadening [10]. Initial implementations of frequency-scanning PLIF (FS-PLIF) were performed using continuous wave (cw) lasers by collecting PLIF images at discrete wavelength steps with effective multi-parameter measurement rates on the order of minutes, as reported by McDaniel *et al.* [10, 11]. Tunable pulsed lasers were used to make time-averaged 2D pressure, temperature, and velocity measurements in high-speed jet flows, though also limited to long data collection times [12, 13]. The discrete adjustment of the laser wavelength may be impractical in short-duration test facilities like expansion tunnels or Ludwig tubes, which typically have run durations on the order of milliseconds. Avoiding the necessity for discrete wavelength steps, continuous modulation of high-power cw lasers has also been demonstrated for 2D OH flame temperature measurements with an effective measurement time of 250 ms [14]. However, this approach may limit the achievable field-of-view due to low laser energies and still faces challenges for implementation in unsteady flows, particularly if the tracer mole fraction is affected by local flow oscillations, such as shear layers of unsteady jets or wakes.

More recently, frequency-scanning BML technology has been used to decrease the measurement time required for velocity measurements using DGV [15], as well as multi-parameter measurements using filtered Rayleigh scattering (FRS) [16]. For PLIF-based diagnostics utilizing BMLs and seeded OPOs to generate the required ultraviolet (UV) excitation wavelengths, both rapid modulation of the OPO seed [17] and rapid modulation of the BML seed [18] have been explored. However, several limitations were discussed in these studies. Previous work with rapid modulation of the OPO seed showed high amounts of pulse-to-pulse fluorescence intensity variation and OPO output bandwidth variation as the laser wavelength was scanned across an OH transition, which may present difficulties in extracting quantitative measurements [17]. Modulation of the BML seed was used to successfully scan across two NO transitions but was limited in achieving the multi-parameter measurement capability due to similar pulse-to-pulse intensity variation issues and significant uncertainty with the laser frequency across the scan due to a lack of individual wavelength measurements of the laser pulses [18].

With the addition of a high-speed wavemeter to measure individual pulse wavelengths, this work aims to build upon previous studies by using a Spectral Energies, LLC burst-mode optical parametric oscillator system. Utilizing NO gas cells with known conditions (temperature, pressure, and composition), the i) intra-burst intensity variations, ii) intra-scan OPO wavelength stability, and iii) accuracy of pressure estimations from the spectral fits are investigated to move towards high-fidelity multi-parameter NO PLIF measurements acquired within a period of 1 ms.

II. Methodology

A. Experimental Setup

The experimental setup used to characterize the FS-PLIF system is shown in Fig. 1a. A custom Spectral Energies, LLC Quasimodo burst-mode laser, based on the master oscillator power amplifier (MOPA) architecture (see Ref. [19] for more details), was used in this work. Within the master oscillator, a continuous wave (cw) diode laser (Thorlabs; DBR1064-PN) was sliced into 10-ns pulses using fiber-coupled acousto-optic modulators (AOMs). Before pulse slicing, a function generator (FG) was used to modulate the laser diode wavelength by varying the current. This pulse train was then routed into the power amplifier stage consisting of multiple flashlamp-pumped Nd:YAG rods, where the pulses are amplified in “bursts” of a given duration, typically on the order of milliseconds.

After third harmonic generation (THG) of the fundamental 1064-nm beam, the remaining 532-nm laser beam was attenuated using polarizing beam splitters (PBS) and half wave plates (HWP), before being fiber-coupled into a high-speed wavemeter (HighFinesse; HF-WSF-600 VIS) capable of wavelength measurements at up to 24 kHz. The 355-nm laser beam was then routed into a Spectral Energies, LLC burst-mode OPO to generate the ~226 nm excitation wavelength typically used for NO PLIF. Within the OPO system, a beam splitter (BS) was used to split off approximately 70% of the 355-nm beam to be sent into the OPO cavity, with the remaining 30% of the 355 nm beam used for mixing in the sum frequency generation (SFG) crystal. A photodiode (PD1: Thorlabs; DET10A2) coupled with a 355 nm bandpass filter was used to monitor the 355-nm burst profile by detection of a weak back reflection.

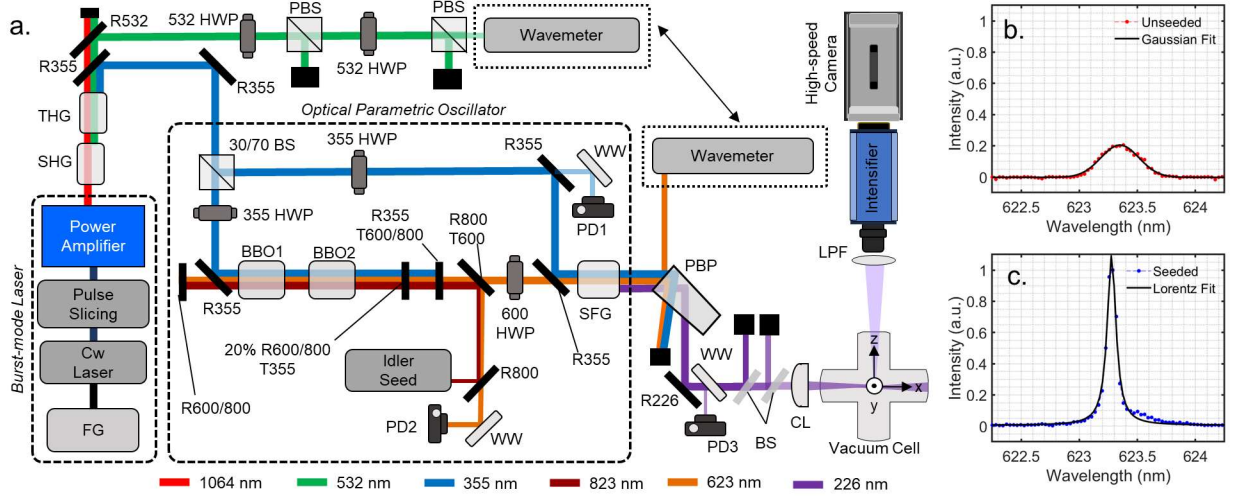


Figure 1: (a) Optical layout used to characterize the FS-BML and OPO used to generate the NO PLIF excitation wavelength. FG—function generator; SHG—second harmonic generation; THG—third harmonic generation; HWP—half wave plate; PBS—polarizing beam splitter; BS—beam splitter; WW—wedged window; PD—photodiode; R—reflect; T—transmit; SFG—sum frequency generation; PBP—Pellin-Broca prism; CL—cylindrical lens; LPF—longpass filter. (b) Unseeded spectral profile shown with a Gaussian fit and (c) seeded spectral profile with a Lorentz fit of the 623-nm signal beam generated acquired with a spectrometer.

The cavity consisted of two barium borate (BBO) crystals to generate the signal and idler beams at ~ 623 nm and ~ 823 nm, respectively. The OPO cavity was seeded with a narrowband cw laser at ~ 823 nm (Sacher Lasertechnik; Lion 830) which enabled the NO excitation lines to be resolved. The idler wavelength was fixed in this work and therefore can be monitored on a separate, low-speed wavemeter (HighFinesse; WS/6 UV). The signal beam spectral profile with and without seeding is shown in Fig. 1b and Fig. 1c, respectively, measured with a spectrometer (Ocean Optics; HR4000). Without seeding, the full width at half maximum (FWHM) of the signal beam was ~ 0.54 nm (~ 14 cm^{-1}) using a Gaussian lineshape as shown in Fig. 1b. With seeding, this linewidth becomes narrow near the seeded wavelength, fit to a Lorentzian FWHM of ~ 0.09 nm (~ 2.4 cm^{-1}) limited by the spectrometer resolution of 0.06 nm, as depicted in Fig. 1c. A small back reflection of the 623 nm beam was sampled using a wedged window (WW) and directed onto PD2, which was coupled with a 775 nm shortpass filter and iris to isolate the 623 nm light. The signal beam was then mixed with the remaining 30% of the 355 nm beam to produce the final 226 nm output. For this work, the 355 nm pump was kept at ~ 120 mJ/pulse total into the OPO which produced ~ 300 μJ /pulse at 226 nm.

A Pellin-Broca prism (PBP) was used to spectrally separate the nearly colinear 226, 355, and 623-nm output of the OPO. A 623-nm reflected beam from the PBP was fiber-coupled such that the signal beam could be monitored with the high-speed wavemeter in an alternative configuration. The 226-nm beam was then directed to the center of a vacuum cell. The OPO output was either focused with a +100 mm cylindrical lens (CL) or allowed to propagate without focusing. Two BSs were utilized to reduce the 226 nm per pulse energy to ~ 75 μJ /pulse before entering the vacuum cell. A third photodiode (PD3) detected a small portion of the 226-nm beam sampled using a WW. A high-speed camera (Photron; Fastcam SA-Z) coupled with an intensifier (LaVision; UV HS-IRO) and 105-mm UV camera lens was used to image the NO PLIF signal with ~ 230 nm longpass filter (LPF) to reject laser scattering. Two NO vacuum cells were utilized in this work: a sealed 0.13 atm/2% NO reference cell (Cell 1) and a variable pressure/concentration cell (Cell 2). The concentration of NO in Cell 1 may have been reduced by photodissociation that occurred in prior experiments since the observed absorption in the cell was much less than expected. Cell 2 was equipped with an inset window (also known by the manufacturer as a “re-entrant viewport”), a pressure transducer, and a photomultiplier tube (PMT: ET Enterprises; 9781B) installed on the top viewport.

Two overlapping NO transitions previously used in Ref. [18] were targeted for this work: the $R_1(5.5) + Q_{21}(5.5)$ line pair near 44224 cm^{-1} and the $Q_1(11.5) + P_{21}(11.5)$ line pair near 44222 cm^{-1} . A triangle waveform was used to scan the frequency of the BML laser diode seed (and not the OPO seed) across these transitions. The BML was operated at 100 kHz with a 1 ms burst duration, yielding ~ 100 laser pulses. The high-speed wavemeter was operated to record measurements at 20 kHz, thereby giving a wavelength measurement of every 5th laser pulse. Example burst profiles and corresponding pulse wavelength measurements converted to OPO output wavenumber, are shown in Fig. 2 for fixed-wavelength, 500 Hz single-line scan, 2000 Hz single-line scan, and 500 Hz two-line scan.

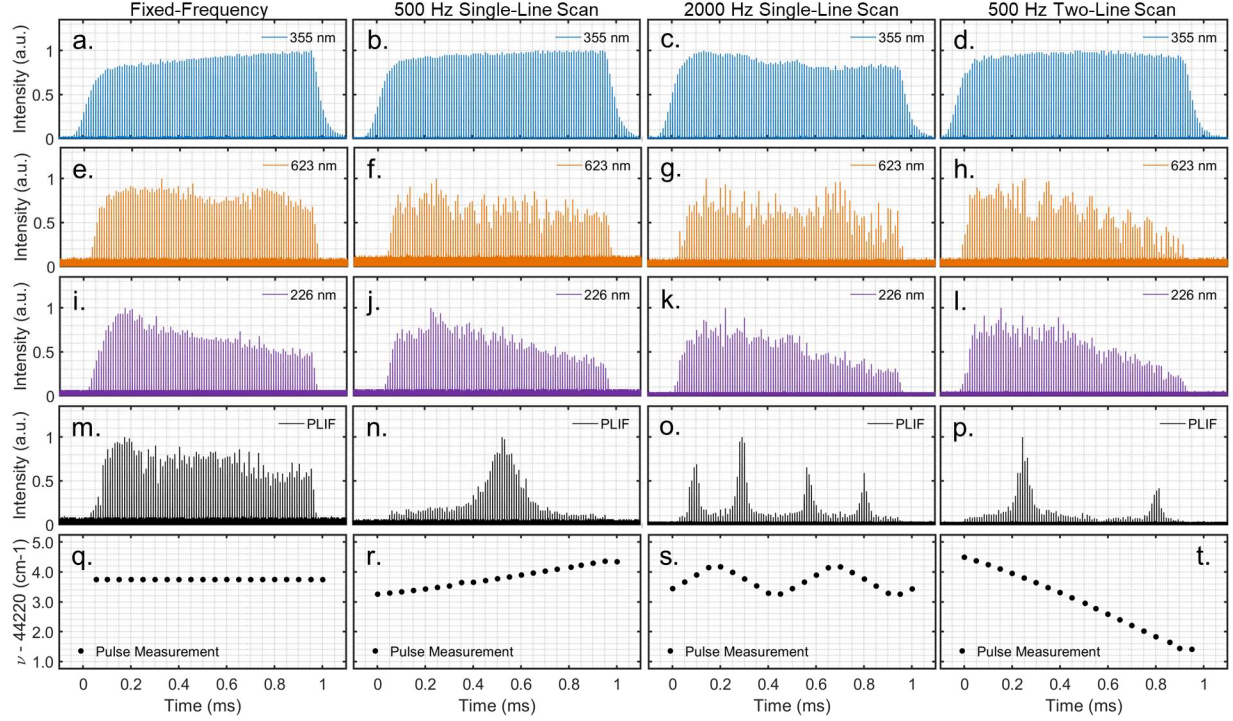


Figure 2: Burst profiles of the (a-d) 355 nm, (e-h) 623 nm, (i-l) 226 nm sampled laser beams along with (m-p) fluorescence signal measured using the photomultiplier tube in Cell 1 at 0.10 atm/0.5% NO and (q-t) corresponding 532 nm pulse measurements converted to OPO wavenumber. The laser operating conditions are noted above each column.

The 355-nm profile remains nearly unchanged throughout the burst, although there are some pulse-to-pulse energy fluctuations during the 2000 Hz scan (Fig. 2c). The 623-nm and 226-nm burst profiles show pulse-to-pulse fluctuations during frequency-scanning which will be investigated (Fig. 2f-h and Fig. 2j-l).

B. Data Processing

For each burst, the mean of 50 images acquired with the laser off was subtracted from the laser-on camera images. The pixel intensities were normalized by 4096: the maximum number of counts for the 12-bit camera. Next, using the wavemeter exposure signal and the camera intensifier gate signal, each camera frame and wavemeter measurement was matched to the corresponding laser pulse from the recorded burst profiles. The pulses in-between the wavemeter measurement at 20 kHz were approximated through linear interpolation. Depending on which laser beam the wavemeter was measuring (ν_{SHG} or ν_{SIG}) either Equation (1) or (2) was used to calculate the OPO output frequency ν_{OUT} after SFG:

$$\nu_{OUT} = 3\nu_{SHG} - \nu_{IDLER} \quad (1)$$

$$\nu_{OUT} = 2\nu_{SIG} + \nu_{IDLER}. \quad (2)$$

According to the manufacturer, the idler seed wavelength measurements from the low-speed wavemeter had an absolute accuracy of 700 MHz (~ 0.023 cm⁻¹), while both the 532 and 623 nm pulse measurements from the high-speed wavemeter had an absolute accuracy of 600 MHz (~ 0.020 cm⁻¹).

To explore the feasibility of determining parameters from the FS-PLIF system, the NO PLIF signal intensity, $S(A, C, \delta\nu, P, T, U, \nu)$, at laser frequency ν was modeled using Equation (3):

$$S(A, C, \delta\nu, P, T, U, \nu) = A \int L(\sigma_L, \nu + \delta\nu) F(P, T, U, \nu) d\nu + C, \quad (3)$$

where A is the amplitude, C is the background, $\delta\nu$ is any laser wavelength offset due to the uncertainty in the pulse wavelength measurements, P is the pressure, T is the temperature, and U is the velocity. The term $L(\sigma_L, \nu + \delta\nu)$ was

accounting for the incident laser spectral profile, which was modeled as a Gaussian with FWHM, σ_L , of 0.015 cm^{-1} . The NO excitation fluorescence spectrum, $F(P, T, U, \nu)$, was calculated using Equation (4):

$$B(P, T, U, \nu) = \sum_{J''} F_B(T, J'') B_{12} G_v(\delta\nu_D, \Delta\nu_D, \delta\nu_C, \Delta\nu_C), \quad (4)$$

where the absorption coefficients B_{12} and line positions for NO were taken from LIFBASE [20] while any quenching effects were neglected. The Boltzmann fraction $F_B(T, J'')$ is calculated using Equation (5) [21]:

$$F_B(T, J'') = \frac{hcB_V}{k_B T} (2J'' + 1) \exp \left[-B_V hc \frac{J''(J'' + 1)}{k_B T} \right], \quad (5)$$

where J'' is the rotational quantum number, h is Planck's constant, c is the speed of light, k_B is the Boltzmann constant, B_V is the effective rotational constant with value of 169.5701 m^{-1} [22]. The Voigt profile $G_v(\Delta\nu_D, \delta\nu_D, \Delta\nu_C, \delta\nu_C)$ is calculated using the algorithm by McLean et al. [23]. The Doppler shift is given by $\delta\nu_D = \nu U/c$ and the Doppler-broadening was calculated as $\Delta\nu_D = [7.16 \times 10^{-7}](\nu)\sqrt{T/m_{NO}}$ where m_{NO} is the molecular weight of NO [21]. The collisional shift, $\delta\nu_C$, and collisional-broadening, $\Delta\nu_C$, were found using empirical fits from di Rosa [13] given by $\delta\nu_C = -0.18 (P [\text{atm}])(295/T)^{0.5}$ and $\Delta\nu_C = 0.585 (P [\text{atm}])(295/T)^{0.75}$, considering only collisions with N_2 . Approximately 88% of the residuals between the NO LIF profile described here and the NO LIF profile generated with LIFBASE [20] was less than 15%, and all < 4% of the maximum value, with a maximum deviation of 25% for the vacuum cell conditions used in this work. For the work reported in this paper, the temperature was fixed at 300 K (approximately room temperature) and the velocity was fixed at 0 m/s, leaving only pressure as the unknown.

A nonlinear least squares fitting routine was developed to solve for two parameters using Equations (3-5): the laser wavelength offset, $\delta\nu$, and the pressure, P . First, Equations (3-5) were solved for A, C , and $\delta\nu$ with P set to the known cell pressure. Second, the value of $\delta\nu$ was added to the experimental wavelength values as a correction and Equation (3-5) were solved again for A, C , and P . An example of this fitting process for the pixel at location P1 in Fig. 3a is shown in Fig. 3b-c using Cell 1. In the first step, depicted in Fig. 3b, the laser wavelength offset was found to be 0.001 cm^{-1} . In the second step, shown in Fig. 3c, the pressure was found to be 0.14 atm when the laser wavelength correction was used. The pressure estimation from two additional pixels (P2 and P3) are shown in Fig. 3d-e which were estimated to be 0.14 atm and 0.13 atm, respectively. Similarly, Fig. 4 demonstrates the fitting process applied to a single NO line scan using Cell 2 at 0.10 atm at three pixels showing the effect of saturation and absorption on the pressure estimate. The NO concentration in Cell 2 was uncertain due to limitations in dilution of NO in nitrogen which is likely the cause of the significant absorption effects seen in Fig. 4a. Saturation effects are believed to have been introduced due to focusing of the cylindrical lens. Measurements in Cell 2 were limited to the region close to the re-entrant window, near P1, to avoid introducing complicated saturation and absorption effects, as the focus on the current paper is on characterizing the laser system. As seen in Figs. 3 and 4, the residuals in the fits show artifacts of pulse-to-pulse variations in the fluorescence spectra, which will be investigated in the following section.

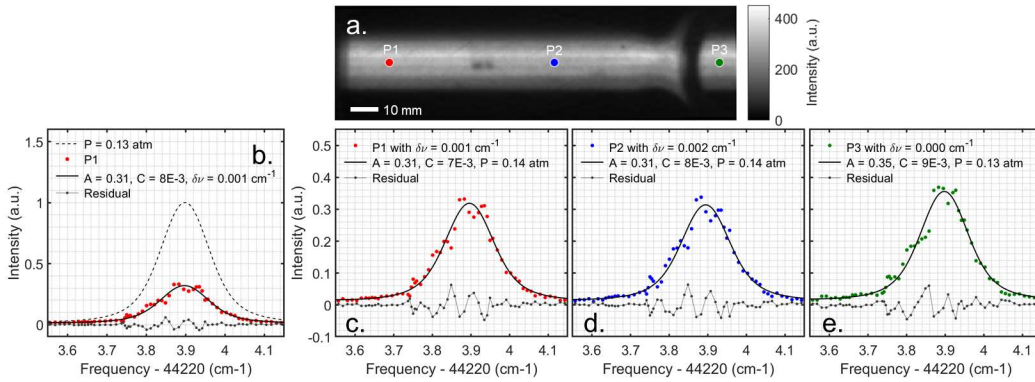


Figure 3: (a) Mean NO PLIF intensity in Cell 1 during a scan across a single NO absorption line with three pixels indicated (P1-P3). (b) Experimental NO PLIF intensity at pixel P1 compared to the modeled NO PLIF intensity. Pixel intensity and best fit for pressure after wavelength correction for (c) P1, (d) P2, and (e) P3.

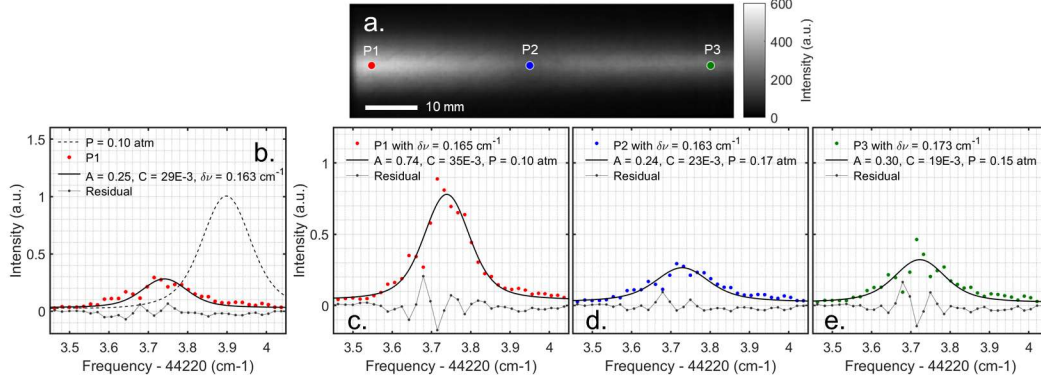


Figure 4: (a) Mean NO PLIF intensity in Cell 2 operated at 0.10 atm/0.5% NO during a scan across a single NO absorption line with three pixels indicated (P1-P3). (b) Experimental NO PLIF intensity at pixel P1 compared to the modeled NO PLIF intensity. Pixel intensity and best fit for pressure after wavelength correction for (c) P1, (d) P2, and (e) P3.

III. Results and Discussion

A. Intra-scan Cavity Stability

In this section, the effect of scanning the pump frequency on the OPO output is investigated. From the voltage signals recorded on PD1-3, the peak pulse intensities of the mixing wavelengths (355 and 623 nm) and the OPO output (226 nm) were recorded across the mostly steady portion of the burst for 10 independent bursts. The coefficient of variation (CV) was calculated by dividing the standard deviation of the pulse intensities by the mean pulse intensity. This process was repeated for the three waveforms applied to the seed: 0 mV corresponding to fixed frequency operation, 60 mV 500 Hz triangle wave corresponding to a single NO line scan, and 200 mV 500 Hz triangle wave corresponding to a two-NO-line scan. The 623-nm pulse wavelength was monitored on the high-speed wavemeter as an indication that the OPO was seeded during the burst.

The results are shown in Fig. 5a-c for the 355 nm pump, 623 nm signal, and 226 nm laser beams. In Fig. 5a, the 355 nm beam showed pulse intensity variations of <5% of the mean for all conditions, although the intensity variation was increased when using the 200-mV scan. This may be due to the change in the BML seed laser power or the fundamental wavelength being modulated across the Nd:YAG gain bandwidth. For the signal beam, shown in Fig. 5b, the pulse intensity variations are <15% of the mean without any scanning voltage applied. However, the levels of variation increase to near 17% and 22% for 60 mV and 200 mV waveforms, respectively. The 226 nm output, shown in Fig. 5c, shows pulse intensity variation of ~8% with the 0 mV waveform. The variation which increases to ~12% of the mean pulse intensity for the 60-mV waveform and ~15% of the mean pulse intensity for the 200-mV waveform.

The increase in intensity variations was theorized to be due to scanning over cavity modes as suggested by Miller et al. [17] The FSR of the cavity was calculated as $FSR_{OPO} = c \{2[(L_{CAVITY} - L_{BBO})n_{AI} + L_{BBO}n_{BBO}]\}^{-1}$ where c is the speed of light. The cavity length, L_{CAVITY} , was ~125 mm, the total crystal length, L_{BBO} , was ~24 mm, and the index of refraction of the BBO crystals, n_{BBO} , was taken to be 1.67 giving a cavity FSR of ~1.05 GHz.

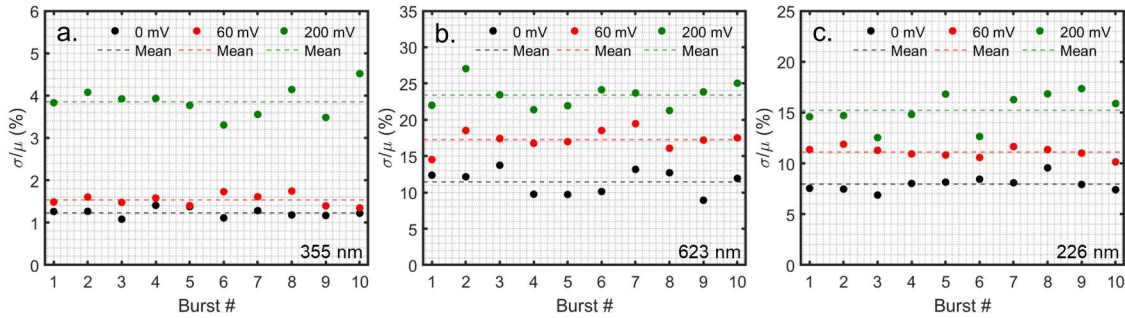


Figure 5: Coefficient of variation (σ/μ) in percentage of 10 independent bursts collected with 0 mV, 60 mV, and 200 mV triangle waveforms applied to the BML seed for the (a) 355 nm, (b) 623 nm, and (c) 226 nm pulse intensities across a 1-ms burst.

A representative 623 nm burst profile acquired while the BML seed was scanned with a 60 mV/500 Hz waveform is shown in Fig. 6a. From the 623 nm pulse wavelength measurements, shown in Fig. 6b, the pulse intensities from this burst were fit to a theoretical etalon profile. The best-fit free-spectral range (FSR) was ~ 1.0 GHz as shown in Fig. 6c which is within 8% of the calculated value. However, attempts at reducing the finesse of the cavity through slight misalignment of the 623/823 nm reflector did not show systematic reduction of this interference pattern.

This intensity pattern also appeared in the NO PLIF intensity, to varying degrees. Efforts were made to correct this using the 226-nm burst profile. The 226-nm pulse intensities were normalized by the mean value then the NO PLIF signal was divided by the corresponding normalized pulse intensity value. The results for three single-line scans in Fig. 7a-b and three two-line scans are shown in Fig. 7d-f in Cell 1 for a single camera pixel with simultaneous PMT voltage signals, both normalized to the maximum value. The intensity variation is reduced using this correction although not completely removed in the single-line scans. At room temperature of 300 K, the two NO absorption line peaks should have similar peak intensity based on simulations with LIFBASE. However, Fig. 7d-e show higher intensity on the camera pixel for the absorption line near 44224 cm^{-1} before and after correction. These results indicate that there may be other mechanisms causing these intensity variations, such as variations in the laser bandwidth as observed by Miller et al. [17], which may require further investigation.

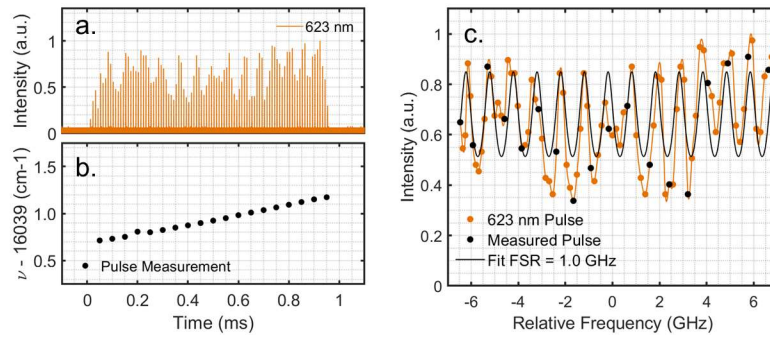


Figure 6: (a) Raw 623 nm burst profile collected while scanning the BML seed with (b) corresponding pulse wavelength measurements. (c) Pulse intensities across the burst compared with an etalon model.

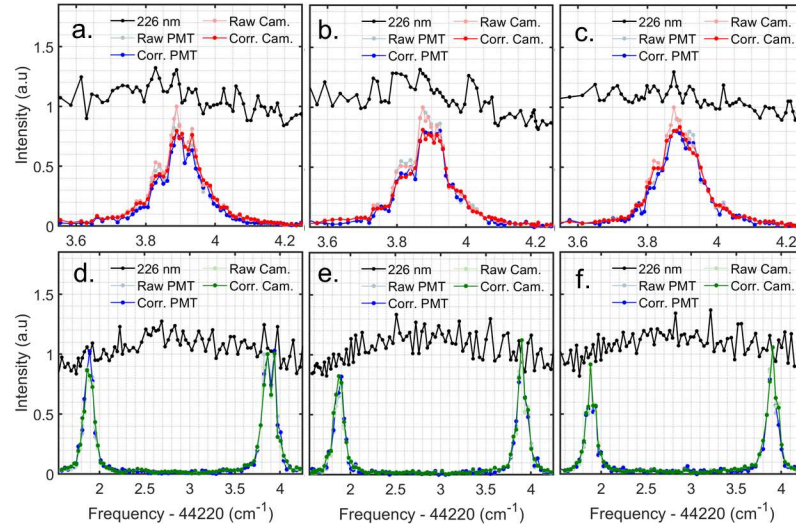


Figure 7: Raw NO PLIF signal at a single pixel (Cam) and from the PMT compared to corrected signals using the 226-nm pulse peak intensities for three (a-c) single line scans and (d-f) two-line scans.

B. Fluorescence Excitation Scans

In this section, the feasibility of pressure and velocity measurements using the FS NO PLIF system was investigated. Two configurations for the laser scan were tested: i) scans across the $R_1(5.5) + Q_{21}(5.5)$ line pair and ii) scans across both the $R_1(5.5) + Q_{21}(5.5)$ line pair and the $Q_1(11.5) + P_{21}(11.5)$ line pair. For 10 bursts, a 10×10 -pixel

region of the image near P1 in Fig. 3a was averaged and then fit for pressure, with the temperature and velocity fixed. The results from the images acquired using single-line scans in Cell 1 are shown in Fig. 8a-j. The mean absolute offset was 0.006 cm^{-1} with a standard deviation of 0.0055 cm^{-1} . The mean pressure was estimated to be 0.125 atm with a standard deviation of 0.011 atm which is within 5% of the nominal cell pressure of $\sim 0.13 \text{ atm}$. Evidence of the fluorescence intensity change due to the cavity can be observed around 44223.9 cm^{-1} and around 44224.05 cm^{-1} . Similarly, the results for the two-line scans in Cell 1 are shown in Fig. 9a-j where the mean pressure was estimated as 0.118 atm (with a standard deviation of 0.013 atm) which is $\sim 10\%$ lower than the nominal cell pressure. The variation observed in the absorption line peak intensity would greatly affect any temperature measurements using two-line thermometry. Careful correction of this intensity fluctuation would be necessary to make accurate temperature measurements using the two-line scans.

To investigate intra-burst variability, the wavelength offset and pressure in the same 10×10 -pixel region was fit on a pixel-by-pixel basis for each burst. The mean and standard deviation of the results are shown for the single and two-line scans in Fig. 10a-b. For both the single and two-line scans, the pressure measurements fell within 20% of the nominal value of 0.13 atm . The wavelength offset was $\sim 0.01 \text{ cm}^{-1}$ for the single line scans and $\sim 0.06 \text{ cm}^{-1}$ for the two-line scans. For a velocity measurement using the Doppler shift, this would correspond to an error of $\sim 70 \text{ m/s}$ and $\sim 400 \text{ m/s}$, respectively. Therefore, a robust measurement of any wavelength offset would be crucial for performing Doppler velocimetry with this technique.

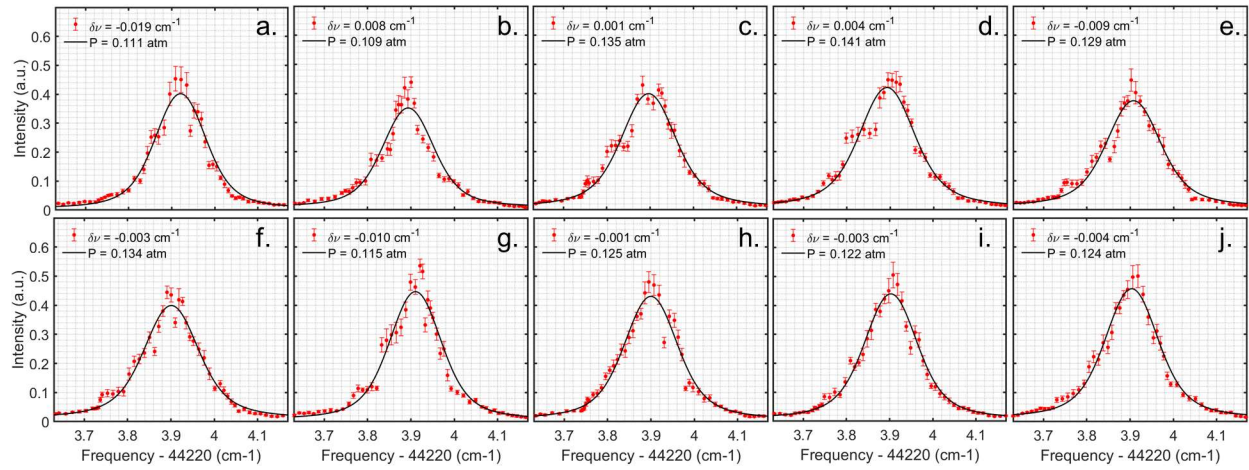


Figure 8: (a-j) Wavelength offset and pressure estimations of the mean of a 10×10 -pixel region of NO PLIF signal in Cell 1 from a single-line frequency scan.

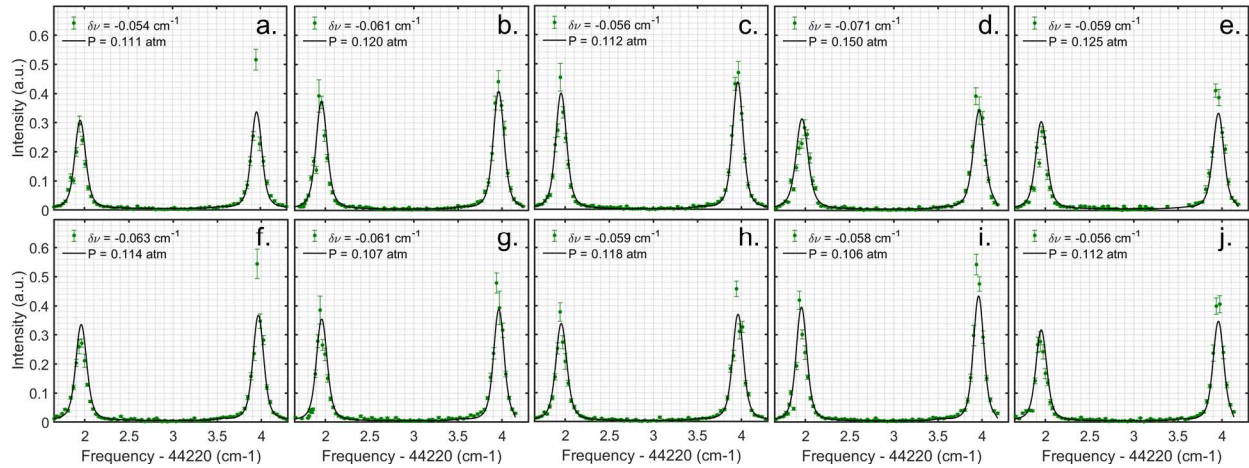


Figure 9: (a-j) Wavelength offset and pressure measurements of the mean of a 10×10 -pixel region of NO PLIF signal in Cell 1 from a two-line frequency scan.

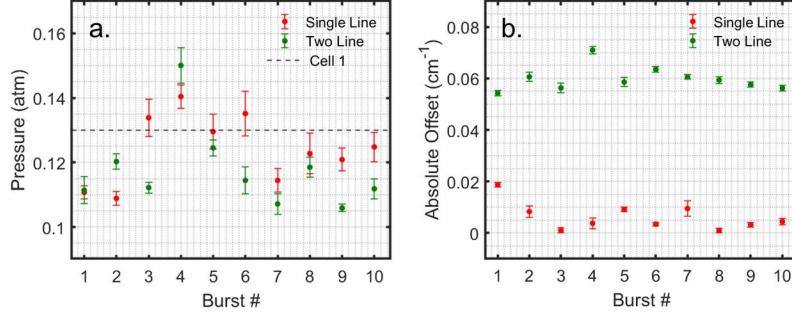


Figure 10: Mean and standard deviation of (a) pressure compared to the known value and (b) absolute wavelength offset estimated in each pixel within a 10×10 -pixel region of Cell 1.

Calibration can be used to remove these wavelength offsets, for example by comparing with measurements made in a separate reference cell or with a more accurate wavemeter. Eliminating this systematic error would allow velocity to be measured with an uncertainty dominated by the random error in the measurement of the shift, calculated using one standard deviation across all 100 pixels and all 10 bursts to be 0.0053 cm^{-1} and 0.0047 cm^{-1} for the single and two-line scans, respectively. This corresponds to a velocity measurement error of $\sim 36 \text{ m/s}$ which may be acceptable in many hypersonic facilities where velocities can range from 100s to 1000s of m/s.

Finally, Fig. 11a-c show the results of fitting a 10×10 -pixel region near the entry window in Cell 2, depicted in Fig. 1a, which was operated at cell pressures of 0.01 atm, 0.10 atm, and 0.30 atm. At the lowest pressure, Fig. 11a, the profile is narrow (dominated by Doppler broadening) while the profile broadens as the pressure is subsequently increased in Fig. 11b and Fig. 11c. The fitted pressures show agreement with the gauge-measured pressures at the two higher pressures and agree within 20% for the lower pressures where the collisional broadening is smaller and harder to measure.

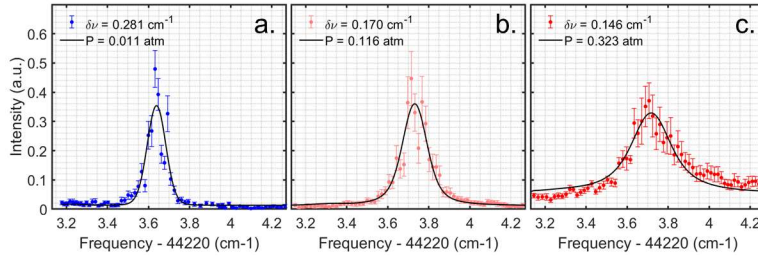


Figure 11: Wavelength offset and pressure estimation of the mean of a 10×10 -pixel region of NO PLIF signal in Cell 2 from a single-line frequency scan with the cell operating at (a) 0.01 atm, (b) 0.10 atm, and (c) 0.30 atm.

IV. Conclusions and Future Work

In this paper, characterization of frequency-scanning a BML to pump an OPO for frequency-scanning NO PLIF is presented and discussed. Building upon prior work with FRS, the implementation of a high-speed wavemeter allowed for direct pulse wavelength measurement of both the 532 nm beam, which was used to infer the 355-nm pump laser wavelength, and the 623 nm signal beam. Utilizing multiple photodiodes, the burst profiles of the pump, signal, and output laser beams were monitored to investigate the intensity variation while frequency-scanning the BML seed. The pulse intensity variations of the 226-nm OPO output were found to increase as the pump laser wavelength was scanned across a larger frequency range, possibly due to scanning the wavelength across the cavity modes of the OPO. Further work towards mitigating this effect is necessary.

Using this system, single and two-line NO PLIF intensity profiles as a function of laser frequency are depicted in vacuum cells of known pressure. A simple NO-PLIF model was developed and implemented to fit the experimental results for pressure. Across 10 independent bursts, pressure measurements from both the single and two-line scans agreed with the known pressure to within 25%. However, implementation of proper pulse-to-pulse fluorescence intensity correction would be necessary to perform two-line thermometry using the two-line scans.

Acknowledgments

A.M. Braun was supported by an appointment to the NASA Postdoctoral Program at the NASA Langley Research Center, administered by Oak Ridge Associated Universities under contract with NASA. The authors acknowledge the support of the NASA Space Technology Mission Directorate (STMD) Game Changing Development (GCD) project *Entry Systems Modeling*. The NASA Aeronautics Research Mission Directorate (ARMD) Transformative Aeronautics Concepts Program (TACP) project *Transformational Tools and Technologies* (TTT) provided support for the initial laser purchase and earlier phases of frequency scanning burst-mode laser research at NASA Langley. The authors acknowledge Christopher Crabtree from Spectral Energies, LLC for setting up the burst-mode laser at the NASA Langley Research Center as well as Paul Hsu and Naibo Jiang from Spectral Energies, LLC for setting up the optical parametric oscillator at NASA Langley Research Center.

References

- [1] W. D. Urban and M. G. Mungal, "Planar velocity measurements in compressible mixing layers," *J. Fluid Mech.*, vol. 431, pp. 189–222, Mar. 2001, doi: 10.1017/S0022112000003177.
- [2] P. Danehy, P. Palma, A. Houwing, and T. McIntyre, "Comparison of theoretical laser-induced fluorescence images with measurements performed in a hypersonic shock tunnel," in *Advanced Measurement and Ground Testing Conference*, American Institute of Aeronautics and Astronautics, 1996. doi: 10.2514/6.1996-2236.
- [3] N. Jiang *et al.*, "Megahertz-Rate Imaging of Hypersonic Boundary-Layer Instabilities in a Mach 10 Shock Tunnel," *AIAA J.*, vol. 61, no. 2, pp. 534–542, 2023, doi: 10.2514/1.J061880.
- [4] N. S. Rodrigues *et al.*, "Application of PLIF to Investigate the Hypersonic Wake of a LOFTID-Relevant Model at Mach 10," NASA/TM-20240000817, Apr. 2024.
- [5] P. M. Danehy, S. O'Byrne, A. Frank, P. Houwing, J. S. Fox, and D. R. Smith, "Flow-Tagging Velocimetry for Hypersonic Flows Using Fluorescence of Nitric Oxide," *AIAA J.*, vol. 41, no. 2, pp. 263–271, 2003, doi: 10.2514/2.1939.
- [6] N. S. Rodrigues, N. Jiang, P. Hsu, S. Roy, and P. M. Danehy, "Multiline molecular tagging velocimetry of nitric oxide at 100 kHz using an injection-seeded burst-mode OPO," *Appl. Opt.*, vol. 63, no. 5, pp. 1247–1257, Feb. 2024, doi: 10.1364/AO.507732.
- [7] J. M. Seitzman and R. K. Hanson, "Two-line planar fluorescence for temporally resolved temperature imaging in a reacting supersonic flow over a body," *Appl. Phys. B*, vol. 57, no. 6, pp. 385–391, Dec. 1993, doi: 10.1007/BF00357380.
- [8] P. S. Hsu, N. Jiang, J. J. Felver, D. K. Lauriola, P. M. Danehy, and S. Roy, "10 kHz two-color OH PLIF thermometry using a single burst-mode OPO," *Opt. Lett.*, vol. 46, no. 10, pp. 2308–2311, May 2021, doi: 10.1364/OL.423062.
- [9] X. Liu, Y. Wang, Z. Wang, and F. Qi, "Single camera 20 kHz two-color formaldehyde PLIF thermometry using a dual-wavelength-switching burst mode laser," *Opt. Lett.*, vol. 46, no. 20, pp. 5149–5152, Oct. 2021, doi: 10.1364/OL.439735.
- [10] J. C. McDaniel, B. Hiller, and R. K. Hanson, "Simultaneous multiple-point velocity measurements using laser-induced iodine fluorescence," *Opt. Lett.*, vol. 8, no. 1, pp. 51–53, Jan. 1983, doi: 10.1364/OL.8.000051.
- [11] J. M. Donohue and J. C. McDaniel, "Computer-controlled multiparameter flowfield measurements using planar laser-induced iodine fluorescence," *AIAA J.*, vol. 34, no. 8, pp. 1604–1611, Aug. 1996, doi: 10.2514/3.13278.
- [12] S. V. Naik, W. D. Kulatilaka, K. K. Venkatesan, and R. P. Lucht, "Pressure, Temperature and Velocity Measurements in Underexpanded Free Jets using Laser-Induced Fluorescence Imaging," *AIAA J.*, vol. 47, no. 4, pp. 839–849, Apr. 2009, doi: 10.2514/1.37343.
- [13] M. D. di Rosa, "High-Resolution Line Shape Spectroscopy of Transitions in the Gamma Bands of Nitric Oxide," Ph.D. Dissertation, Stanford University, 1996.
- [14] S. Wang and R. K. Hanson, "Quantitative 2-D OH thermometry using spectrally resolved planar laser-induced fluorescence," *Opt. Lett.*, vol. 44, no. 3, pp. 578–581, Feb. 2019, doi: 10.1364/OL.44.000578.
- [15] R. A. Burns, T. W. Fahringer, and P. M. Danehy, "Velocity measurements across an oblique shock using pulse-burst cross-correlation DGV," in *AIAA Scitech 2021 Forum*, American Institute of Aeronautics and Astronautics, 2021. doi: 10.2514/6.2021-0120.
- [16] A. M. Braun *et al.*, "Demonstration of Frequency-Scanning Burst-Mode Filtered Rayleigh Scattering for Multi-Parameter Gas-Phase Measurements," in *AIAA Scitech 2024 Forum*, American Institute of Aeronautics and Astronautics, 2024. doi: 10.2514/6.2024-1095.

- [17] J. D. Miller, M. Slipchenko, T. R. Meyer, N. Jiang, W. R. Lempert, and J. R. Gord, “Ultrahigh-frame-rate OH fluorescence imaging in turbulent flames using a burst-mode optical parametric oscillator,” *Opt. Lett.*, vol. 34, no. 9, pp. 1309–1311, May 2009, doi: 10.1364/OL.34.001309.
- [18] N. S. Rodrigues, P. M. Danehy, N. Jiang, P. Hsu, J. Leicht, and S. Roy, “100 kHz High-Spectral-Resolution NO-PLIF Measurements for Compressible Flows,” in *AIAA SCITECH 2023 Forum*, American Institute of Aeronautics and Astronautics. doi: 10.2514/6.2023-0405.
- [19] J. Felver, M. N. Slipchenko, E. L. Braun, T. R. Meyer, and S. Roy, “High-energy laser pulses for extended duration megahertz-rate flow diagnostics,” *Opt. Lett.*, vol. 45, no. 16, pp. 4583–4586, Aug. 2020, doi: 10.1364/OL.400831.
- [20] J. Luque and D. R. Crosley, “LIFBASE: Database and Spectral Simulation Program (Version 1.5),” *SRI Int. Rep. MP 99-009*, 1999.
- [21] A. C. Eckbreth, *Laser Diagnostics for Combustion Temperature and Species*, CRC Press, 1996.
- [22] T. G. Drozda, C. R. Ground, W. T. Knapp, and P. M. Danehy, “Simple, Fast Nitric Oxide Planar Laser-Induced Fluorescence Model for Computational Fluid Dynamics Applications,” *AIAA J.*, vol. 61, no. 4, pp. 1759–1771, Apr. 2023, doi: 10.2514/1.J062264.
- [23] A. B. McLean, C. E. J. Mitchell, and D. M. Swanston, “Implementation of an efficient analytical approximation to the Voigt function for photoemission lineshape analysis,” *J. Electron Spectrosc. Relat. Phenom.*, vol. 69, no. 2, pp. 125–132, Sep. 1994, doi: 10.1016/0368-2048(94)02189-7.