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Unseeded Velocimetry in Nitrogen for High-Pressure Cryogenic Wind Tunnels, Part 2: Picosecond-Laser Tagging

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Abstract

Picosecond laser electronic excitation tagging (PLEET) is implemented in a large-scale wind tunnel for the first time. High-speed, unseeded velocimetry is performed in the NASA Langley 0.3-m Transonic Cryogenic Tunnel; repetition rates up to 25 kHz are tested. Velocity measurements are assessed for accuracy and precision. Measurement errors vary in the range of 0.6–1.2%, while the instrument precision is found to lie between 1.2 m/s and 2 m/s and exhibits little variation over the full operating range of the facility. An examination of the signal intensity reveals little to no thermodynamic dependence, and the signal lifetimes exhibit an inverse dependence on both pressure and temperature. The PLEET signal is demonstrated to be largely unaffected by buoyancy despite the large temperature rise. The velocity dynamic range of the measurements is found to be a factor of at least 200 in these experiments with the capacity to measure much higher velocities as well. The spatial resolution of the velocity measurements is found to lie between 2 and 2.7 mm, and the maximum frequency response is 12.5 kHz with the ability to resolve up to 50 kHz with the current measurement system. Overall measurement uncertainties in the streamwise velocity are found to lie between 4% and 4.8% for high to low velocities, while the uncertainty in the transverse velocity is less than 6 m/s. The measurement uncertainties are found to be dominated by systematic errors in the calibration procedure, which could be improved in future experiments.

Keywords

velocimetry; transonic; picosecond laser

1. Introduction

In the first installment of this series of papers,[1] the femtosecond laser electronic excitation tagging (FLEET) velocimetry technique was examined for its use in high-pressure, cryogenic nitrogen environments. FLEET was found to perform admirably over all tested conditions, yielding typical overall accuracies within 1.7% and typical measurement

precisions in the range of 1–3 m/s. Both the previous study and the present one seek to examine the relatively new nitrogen-tagging techniques for use in high-pressure, cryogenic wind tunnels. These facilities, which include the National Transonic Facility (NTF) at NASA Langley Research Center and the European Transonic Windtunnel (ETW), are used regularly by commercial and research partners seeking to test vehicles at flight-accurate Reynolds numbers. Unit Reynolds numbers in excess of 4.2×10^8 1/m in gaseous N_2 have been reported in the literature.[2] Achieving these testing conditions requires the facilities to operate at high static pressures and cryogenic temperatures, which drive the flow density up and the viscosity down.[3,4,5] Operating at these extreme conditions, in addition to the rugged construction necessary to accommodate them, results in a wide range of negative consequences for the application of many diagnostic tools. For example, many physical probes such as pitot tubes and hotwires cannot survive the high dynamic pressures and thermal stresses imposed by the testing conditions. Consequently, there has been an ever-growing interest in the application of optical diagnostic techniques in these facilities due to their non-intrusive nature. However, facility operation and construction impose constraints on such applications. These limitations include minimal optical access, condensation and freezing of water vapor and oxygen on facility surfaces, beam-steering and optical distortion effects due to density fluctuations in and around the facilities, as well as tunnel contraction and vibration that lead to static and dynamic misalignment of optical systems.[4] Furthermore, the low-temperature, oxygen-free environments that typify the transonic cryogenic tunnel (TCT) facilities can impair the operation of techniques designed to work in less hostile environments such as pressure sensitive paint (PSP) [6], and Raman excitation and laser-induced electronic fluorescence (RELIEF) velocimetry.[7] As a result of these operational constraints, the scope of optical diagnostics that have been applied to TCT facilities historically has been limited in comparison to typical large-scale wind tunnels. Surface pressures and temperatures have been measured with modest success using cryogenic variants of temperature- and pressure-sensitive paints.[6,8,9] Density-sensitive diagnostics, such as schlieren, shadowgraph, and laser-scattering techniques have also found mixed results. The studies by Snow et al. document difficulties with density fluctuations within the NASA Langley 0.3-m TCT facility, which interfered with their attempts at performing the schlieren and shadowgraph techniques.[4,5] The work by Herring and Shirinzadeh demonstrated Rayleigh scattering-based measurements of off-body density in the same facility.[10,11] More recent work by Herring et al. indicated the potential for using Rayleigh scattering as an off-body density measurement in the NTF.[12] The application of optical velocimetry techniques have been sparser. At ETW, a particle image velocimetry (PIV) system was designed and implemented that allowed the measurement of velocity fields around various test articles.[13] In addition, a system utilizing condensing water vapor as the seeding medium was used to perform Doppler global velocimetry in the same facility. [14] At the NASA Langley TCT facilities, velocimetry has been historically limited to inferred measurements from physical probes. Operational protocols prohibit the seeding methods utilized at ETW for fear of contaminating the flow circuits. Two studies involving optical velocimetry techniques were completed at the NASA Langley TCT facilities, one utilizing laser Doppler velocimetry [15], and the other using laser transit anemometry.[16] While these techniques performed well, they relied on natural seed present in the facilities

resulting from an unknown source (potentially an oil leak somewhere in the flow circuit), and were applicable over only a limited range of the tunnel operating conditions.

The recent body of work from the authors has focused on developing unseeded optical velocimetry techniques for use in the NASA Langley TCT facilities and TCT facilities broadly. These studies have utilized the FLEET technique (first developed by Michael et al. [17]) to make reliable, multi-component velocity measurements in high-pressure, cryogenic environments, though their application has been limited to the NASA Langley 0.3-m TCT to date.[18] Information about the photo-physics of the FLEET excitation and emission can be found in both Refs. [17] and [19]. In addition to velocity measurements, this same technique was employed to make simultaneous measurements of off-body thermodynamic conditions in the same facility [20] and most recently used to measure the flowfield around a transonic airfoil.[21] However, one major limitation of the FLEET technique is the measurement repetition rate. For commercial systems, the laser repetition rate (and hence the maximum independent velocity sampling rate) is typically limited to only 1000 Hz (though custom research femtosecond laser systems can operate at up to 10 kHz at significantly reduced energy). Velocities have been measured at up to 200 kHz with a 1-kHz laser system, but the sequence of samples originated from the same laser pulse and were thus statistically correlated and were obtained at locations subsequently farther downstream.[18] For transonic and supersonic flows of interest, making time-resolved velocity measurements requires significantly higher sampling rates. To this end, a new technique known as picosecond laser electronic excitation tagging (PLEET), developed by Jiang et al. [22], is being advanced at NASA Langley Research Center for high-speed velocity measurements in TCT-type environments. The PLEET technique belongs to the same family of techniques as FLEET, which relies on a high-intensity, short-duration laser pulse to photo-dissociate nitrogen. By tracking the optical emission from the subsequent nitrogen recombination and relaxation, the gas velocity can be inferred. The PLEET effect is generated by utilizing a high-repetition-rate master-oscillator, powered-amplifier (MOPA) pulse-burst laser with a pulse duration on the order of picoseconds. Such laser systems have been used for making high-speed measurements such as PIV,[23] Rayleigh scattering,[24] and planar laser-induced fluorescence,[25] though often with pulse durations on the order of nanoseconds. This paper documents the first application of the PLEET technique (high-speed or otherwise) in a large-scale, ground-test facility, the NASA Langley 0.3-m TCT facility. The PLEET technique is first demonstrated over a wide range of velocities to test the dynamic range. A parametric study is performed to document the performance of the PLEET velocimetry over the full operational envelop of the 0.3-m TCT facility. The velocity measurement accuracy and precision are assessed. The thermodynamic dependences of the PLEET signal intensity are examined. Finally, the velocity dynamic range, spatial resolution, frequency response, and overall experimental uncertainty are detailed. Results reveal PLEET to be a powerful tool for making high-speed, unseeded velocity measurements over the full operational envelope of the 0.3-m TCT facility and high-pressure, cryogenic wind tunnels in general.

2. Experimental Program

2.1. Test Facility

All experiments were conducted in the 0.3-m Transonic Cryogenic Tunnel (0.3-m TCT) located at NASA Langley Research Center in Hampton, VA. This facility is a fan-driven, closed-loop wind tunnel capable of operating with a number of different test gases including air, nitrogen (N_2), and sulfur hexafluoride (SF_6). [3] For these tests, only N_2 was used, which is required for the highest-Reynolds-number operation and the optimal performance of PLEET. The 0.3-m TCT can operate at total (stagnation) pressures ranging from 100 to 500 kPa and total temperatures from 100 to 325 K. Additionally, the facility operates stably at Mach 0.2 to 0.85, though there is some flexibility on both ends of this range for short durations. Test article blockage can prevent operation at the highest Mach numbers for some configurations and conditions.

The 0.3-m TCT test section has a double-shelled construction. The inner test section dimensions are 0.33 m $\times$ 0.33 m. The test section is surrounded by an outer plenum of nominally quiescent gas. The top and bottom walls of the facility were set to be slightly diverging during these tests to account for the growth of the boundary layers. Optical access for these experiments was afforded by two fused-silica windows: one large circular window penetrated the outer plenum, while a hexagonal, 'D'-shaped window allowed access to the inner test section. The general test section layout with window locations is shown in Fig. 1. In these tests, the streamwise coordinate of the tunnel was denoted the x-direction, while the vertical, top-wall-normal/transverse coordinate was assigned the y-direction.

2.2. Laser, Optical, and Data Acquisition Systems

The PLEET tests utilized an experimental pulse-burst laser system (Spectral Energies Quasimodo), which is a YAG-based, mixed diode/flashlamp-pumped system designed to generate 10-ms bursts of high-energy pulses with user-variable pulse durations. For these tests, the fundamental wavelength (1064 nm) was used to generate the PLEET effect. The laser oscillator ran at 25 kHz. Bursts of 250 pulses with approximate energy of 35 mJ/pulse and duration of 100 ps were used. It should be mentioned that the energy of the laser pulses varied throughout each burst, with the initial several pulses exhibiting lower pulse energies as the amplifier gain envelope ramped up. Approximately 15% of the laser pulses occurred before the pulse energy stabilized.

After emission from the laser, the beam was routed to the facility via a vertical optical periscope. The laser then went through a pair of actuated, lateral periscopes that adjusted where the receiving optics were positioned relative to the facility. This setup allowed the beam path to be dynamically adjusted to compensate for the contraction of the facility at low temperatures and thus allowed the laser beam path to stay aligned throughout testing. After passing through this system, the laser beam was transmitted through the outer facility window and into, first, an actuated horizontal periscope to adjust the streamwise position of the beam, and then a vertical periscope to bring the beam up to the height of the hexagonal window. The beam was then focused through a $f = +250$ mm spherical lens, coming to a focus at roughly the spanwise centerline of the tunnel. The measurement volume was

approximately 60 mm from the top wall of the facility. A diagram of this experimental setup is shown in Fig. 2.

The PLEET signal was recorded with a high-speed image intensifier (LaVision HS-IRO) lens-coupled to a high-speed CMOS camera (Photron SA-Z, 12-bit pixel depth). Imaging was done through a 135-mm, $f/2$ lens with a 14-mm-long macro ring yielding a magnification of approximately $130 \mu\text{m}/\text{px}$. The camera was externally triggered to acquire at 100 kHz, and the image intensifier used an 800-ns gate. The camera system and laser were synchronized such that the first camera exposure occurred $8.7 \mu\text{s}$ after the laser pulse (designated t_0), and three subsequent exposures, each delayed by $10 \mu\text{s}$, occurred before the next laser pulse. Unlike previous FLEET experiments,[1] this long delay was placed on the first exposure so that the UV emission from the first negative band of N_2^+ could be avoided. This UV emission is several orders of magnitude more intense in PLEET than FLEET but has a relatively short lifetime (approximately 500 ns).[22] The camera system imaged the PLEET signal in a quasi-boresight configuration, in which the imaging axis was nearly parallel to the direction of the laser beam propagation (offset by approximately 25°). This configuration can be seen in Fig. 2. The laser and camera view were through the same window.

The 0.3-m TCT facility was equipped with an extensive data acquisition system (DAS), which recorded relevant test conditions during the experiments. This system comprised an array of static and total pressure probes throughout the facility, as well as thermocouple probes and strain gauges. These data were read into a network of facility computer systems for processing as detailed in Ref. [18]. Velocities were calculated based on static and total pressure probes, a total temperature probe, and a real-gas equation of state (Beattie-Bridgeman equation) for computing the density of the gas. An additional correction factor was applied in these tests to account for the diverging walls of the facility. For each PLEET data run (typically lasting 10 ms), a data point from the facility system was collected for validation and verification of the velocimetry data in post-processing.

3. Analytical Methods

A sample sequence of the PLEET data is shown in Fig. 3, for a run at Mach 0.85, total pressure of 200 kPa, and total temperature of 275 K. This figure shows all images collected from two consecutive laser pulses. Much like the data seen in previous experiments using the FLEET technique in the boresight or quasi-boresight configurations, the signal has a nearly circular intensity pattern.[1,18,20] ²⁰However, the differing timing configuration, laser repetition rate, and the properties of the PLEET signal decay change the overall appearance of the images considerably. Most notably, the signals from previous laser pulses are visible within each image. The signal from six individual laser pulses is visible in each of the images of Fig. 3, with individual pulses originating as far as $200 \mu\text{s}$ before the present laser pulse. This section will discuss the methods that were utilized in the analysis of these data. A discussion of the centroid and displacement finding schemes, velocity calculations, signal intensity, and signal lifetime measurements are included.

3.1. Centroid Determination

The centroid of the PLEET signal in each frame was determined through the use of a surface-fitting algorithm. Unlike previous FLEET data, the intensity distributions were not markedly eccentric. Thus, a bi-directional normal distribution was fit to the raw data:

$$I_j(x, y) = I_{0,j} \exp \left[-\left(\frac{x - x_{0,j}}{\sigma_{x,j}} \right)^2 - \left(\frac{y - y_{0,j}}{\sigma_{y,j}} \right)^2 \right], \quad (1)$$

where, $x_{0,j}$ and $y_{0,j}$ are the centroid coordinates in px, $\sigma_{x,j}$ and $\sigma_{y,j}$ are the width parameters for the x - and y -directions, respectively, and $I_{0,j}$ is the peak intensity within the distribution. The subscript j refers to the particular frame of data being evaluated in a given burst, where $j = 1$ refers to the first frame ($j \in [1, 24]$). Each of these parameters was fit to a frame of data using a least-squares fitting routine. For each fit, the standard R^2 parameter and the signal-to-residual ratio (SRR), peak intensity divided by the RMS value of the residual signal after subtracting the surface fit from the original image, were calculated. To accept a particular fit, the R^2 parameter was held to a threshold of 0.7 while the SRR was held to a threshold of 50; with the former being a much more stringent criterion than the latter. This threshold placed a lower limit on the allowable spatial precision of the fitting routine of 0.1 px. A total of 24 frames of data were analyzed for each laser pulse, allowing a time series of centroid positions to be constructed. The remaining parameters were used in the calculation of the signal intensity and lifetime. Approximately 15% of the data were rejected due to low signal counts, mostly ($> 90\%$) occurring at the start of each burst of data before the laser gain envelope had ramped up entirely. Data rejection rates conditional upon the first frame of data in a burst being valid varied from set to set and were affected primarily by the signal lifetime and velocity.

3.2 Velocity Estimation

Velocities were estimated by modeling the x - and y -trajectories as linear functions of time. This model equation can be expressed as:

$$s_{i,j}(t) = u_{i,1 \rightarrow j} t + s_{i,j,0}, \quad (2)$$

where i refers to the directional index and j again refers to the frame of data. The subscript $1 \rightarrow j$ indicates that for each direction i , the model equation was fit (using a least-squares fitting routine) to the centroid positions of all frames 1 through j . The velocity extracted from this fitting routine is expressed as $u_{i,1 \rightarrow j}$, while the current and initial positions are written as $s_{i,j}$ and $s_{i,j,0}$, respectively. At least three valid frames of data were required in each burst to perform this fitting, and all frames 1 through j needed to be valid. For each fit, the R^2 value was calculated for both directions of fit, and the rejection threshold was set to 0.95. Both directions needed valid fits in order to accept the velocity calculation. These selection criteria served to ensure the model equation was valid. If only two frames of data were available due to a short signal lifetime or after being rejected by the previous method, the velocity was instead calculated on a point- to-point basis as:

$$u_i = \frac{\Delta s_{i, 1 \rightarrow 2}}{\Delta t}, \quad (3)$$

where the subscript $1 \rightarrow 2$ indicates that the calculation was performed over the first two frames only, and the parameter Δt is the interframe delay imposed by the camera framing rate, $10 \mu\text{s}$ in these experiments. The rejection rate of data from velocity evaluation was 0.5%, while the overall data rejection rate was still $\sim 15\%$.

For each dataset, basic statistics including the mean and standard deviation of the velocities were calculated. These metrics were calculated in two ways. The first calculation was performed on the basis of maximum number of frames; each individual velocity calculation could include up to the entirety of 24 frames, and irrespective of the number, all valid samples were included in the calculations. The second method calculated these statistics for a progressively greater number of frames, which meant that fewer samples were included as the number of required frames increased. While mean velocities did not vary significantly from these two methods, the standard deviation often did. This distinction was used to allow more accurate comparisons of the statistics while evaluating the measurement precision.

3.3 Signal Lifetime

The peak signal intensities extracted through the surface fitting algorithm (denoted $I_{0,j}$ above) were used to generate a time series of intensity for each burst of data. These data were then fit with a tri-exponential function; both single- and bi-exponential functions failed to capture the long-term behavior of the data. This function was of the form:

$$I(t) = \frac{I_0}{n_1 + n_2 + n_3} \left[n_1 \exp\left(-\frac{t}{\tau_{f,1}}\right) + n_2 \exp\left(-\frac{t}{\tau_{f,2}}\right) + n_3 \exp\left(-\frac{t}{\tau_{f,3}}\right) \right], \quad (4)$$

where the three τ_f terms represent the three characteristic fall times while the corresponding n terms represent their relative magnitudes. It was noted in the previous study on FLEET [1] that directly evaluating the signal lifetimes in this manner proved troublesome when trying to assess thermodynamic dependences due to the excessive sensitivity to noise and the large number of correlations that can be constructed. To approach this analysis in similar fashion, two empirical lifetimes were extracted from the data, corresponding to the time it took for the signal to fall to $1/e$ of its original value (τ_1) and $1/e^2$ of its original value (τ_2). These data were extracted from the tri-exponential model equation (Eq. 4) after being fit to the experimental data. The original fit parameters I_0 , $\tau_{f,k}$, and n_k were used in the assessment of the signal intensities, as will be described in the next section. For each data set, both the mean and standard deviation of these lifetimes were calculated and used in the assessments that follow.

3.4 Signal Intensity

Two relevant signal intensities were extracted from the fitted data. The first of these was the peak initial intensity, which comes from the exponential fitting procedure described in Section III.C and is denoted I_0 . The second signal intensity that was extracted from the data

is the total or integrated intensity, and will be denoted I_t . The total intensity is defined as the total emission of light over the lifetime of the signal and can be expressed as:

$$I_t = I_0 \frac{n_1 \tau_{f,1} + n_2 \tau_{f,2} + n_3 \tau_{f,3}}{n_1 + n_2 + n_3}, \quad (5)$$

where I_0 , n , and τ_f represent the same parameters as in Eq. 4. Equation 5 is the result of integrating Eq. 4 from $t = 0$ to $t = \infty$. The total intensity is thus a combined parameter that represents not only the absolute signal intensity, but the lifetime of the signal as well, both of which affect the precision of the velocity measurement. Both the mean and standard deviations of these two intensities were evaluated for each data set.

4. Results

The results from these studies are broadly divided into five sections. First, the accuracy of the velocity measurements is discussed as a function of the tunnel operating conditions (velocity and thermodynamic conditions). The measurement precision is examined over these same operating parameters. Third, the thermodynamic dependencies of the PLEET signal intensity and lifetime are evaluated. A brief assessment of the effects of buoyancy on the measured velocity and trajectory follows. Finally, a discussion of other measurement parameters such as the spatial resolution, measurement dynamic range, frequency response, and overall experimental uncertainty complete this section.

4.1. PLEET Velocity Measurement Accuracy

Assessment of the velocity measurement accuracy was performed by comparing the PLEET-measured velocities to the velocities calculated by the facility DAS. Unlike previous tests in the facility, an additional correction factor was applied to the facility velocity measurements to account for the diverging walls of the test facility. A comparison of data taken at numerous pressures over a wide range of Mach numbers (0.2 to 0.85) and elevated temperatures is shown in Figure 4. Qualitatively, the PLEET velocity measurements align well with those measured by the facility DAS; perfect agreement is indicated by the dashed line. To quantitatively assess the deviation, two quantities shall be defined here. The first is the standard error, which represents the mean of all measurement errors:

$$\varepsilon = \frac{\sum_{k=1}^n |u_{PLEET,k} - u_{DAS,k}|}{\sum_{k=1}^n u_{DAS,k}}. \quad (6)$$

The second quantity is the RMS error:

$$\varepsilon_{RMS} = \frac{\sqrt{\frac{1}{n} \sum_{k=1}^n (u_{PLEET,k} - u_{DAS,k})^2}}{\frac{1}{n} \sum_{k=1}^n u_{DAS,k}}, \quad (7)$$

which represents an aggregate error across all measurement points. Both of these quantities can be expressed as a percentage by multiplying the result of the calculations by 100. For the

elevated temperature case depicted in Fig. 4, the mean error was found to be 0.6%, while the RMS error was found to be 0.8%.

To assess the performance of PLEET velocimetry at cryogenic temperatures, a similar assessment was carried out over a limited range of Mach numbers, specifically Mach 0.4 and 0.8, and a much broader range of thermodynamic conditions. This comparison is shown in Figs. 5a and 5b. Figure 5a, which details a similar comparison to that shown in Fig. 4, again indicates a strong quantitative agreement between the PLEET-measured velocities and those calculated by the facility DAS. The standard and RMS errors were found to be 1.0% and 1.2%, respectively. Thus, the measurement error was again found to be an improvement over similar FLEET measurements at these same test conditions.[18] Moreover, these data were collected on separate days, indicating stability in the measurement system exceeding that of the FLEET measurements (though this is result of the mechanics of the experimental setup rather than the physics of the PLEET technique itself).

Referring to Fig. 5b, further investigation of these velocity data indicates that the overall performance of the technique was largely uniform over the operational envelope of the facility. Specifically, it is observed that the velocity measurement error, though it did vary from set to set, did not show any particular trend with respect to either the operating temperature or pressure of the 0.3-m TCT facility. Individual errors ranged from 0.1% to fewer than 2%. This independence is again an improvement over the previous FLEET measurements, which indicated decreasing accuracy with lower temperature and higher pressures. This change can be attributed to modifications made to the optical setup that allowed for remote translation of the external optics to accommodate for the contraction and general motion of the test section during operation. Thus, decreasing accuracy due to misalignment was controlled during this testing campaign. More discussion of the thermodynamic behavior of PLEET will be given in the context of the PLEET signal intensity and lifetime measurements in Section 4.3.

The previous velocity measurements made by Gartrell et al. in the 0.3-m TCT facility utilizing LDV (discussed in Section I) found their velocity error to be typically less than 1%. [15] Additionally, the previous measurements utilizing the FLEET technique found the accuracy to be 0.5–1.5%. [1,18] The PLEET velocimetry technique performs as well as these historical benchmarks with the advantage of being able to measure at 10 s of kHz and being applicable over the entire operational envelope of the facility without sacrificing the quality of the measurements. Accuracy figures for molecular tagging velocimetry are not widely reported since it is difficult to obtain a consistent and well-characterized reference measurement. Those assessments that are reported in the literature vary broadly. Velocity measurements by Sijtsema et al. utilizing the APART (air photolysis and recombination tracking) technique found accuracies ranging in 5–13% depending on the flow being used to characterize.[26] Lempert et al. assessed the velocity accuracy of acetone MTV measurements applied to supersonic microjets and found it to be approximately 3.5%. [27] Recent studies by André et al. compared hydroxyl MTV measurements in a low-speed jet to PIV measurements at the same flow conditions and found that the observed mean velocity error was within 2%, while the RMS error was within 0.8–1.2%. [28] In comparison, the

PLEET measurements are found to be of equal or superior accuracy with the advantages of being both unseeded and high-speed.

4.2 PLEET Velocity Measurement Precision

The velocity measurement precision was defined in this analysis as the standard deviation of all velocities measured via PLEET for each dataset. This method does not discriminate between velocity fluctuations resulting from precision errors and those resulting from genuine fluctuations in the flow. The velocity precision taken across a wide range of Mach numbers and pressures is shown in Fig. 6. Figure 6a shows the magnitude of the velocity precision, while Fig. 6b shows the same data as a percent of the mean velocity. The zero-velocity precision, indicated by the dashed line in both figures, was estimated as the mean of the fluctuating velocity in the y -component over all datasets, which nominally had a zero velocity. This approximation was performed in lieu of a true wind-off measurement because the high repetition rate of the measurement technique combined with the long lifetime of the signal made it impossible to discern the signal from individual shots at such conditions. A lower laser repetition rate could have been used (i.e., single pulses), but acquiring a statistically significant number of measurements would have been very time consuming. It should also be stated for clarity that only four data points were included in the individual velocity calculations. Four data points were used in order to ensure that a fair comparison was made between all datasets. At the lowest velocities measured in these tests, PLEET spots from consecutive bursts began overlapping each other (discussed in Section 4.5.1). This occurrence limited the number of points that could be clearly distinguished at these velocities. As datasets taken at higher velocities did not suffer from this problem, it would have been possible to include many more data points in the velocity calculations. Thus, the trajectories were limited to only four points to keep the representation of the measurement precision consistent across all data sets.

The velocity precision magnitude shown in Fig. 6a indicates the fluctuating velocity to be fairly consistent at 1.5 m/s between Mach 0.2 and 0.55. These values are slightly greater in magnitude than the estimated zero-velocity precision, which has a magnitude of 1.2 m/s. At greater Mach numbers, the precision begins to trend upward, reaching a peak value of 2.58 m/s. Figure 6b indicates that these trends represent, first, a steady decline in the percent precision followed by a slight uptick above Mach 0.6. Previous FLEET measurements in the same facility indicated similar trends.[1] At lower mean velocities, the fluctuating velocity tracks well with the zero-velocity precision, indicated by the near-constant fluctuating velocity magnitude. This indicates that the quantity being measured is largely the result of the instrument precision rather than true fluctuations in the flow. Only when the natural velocity fluctuations in the flow begin exceeding the noise of the instrument precision does the trend change, which again occurs between Mach 0.55 and 0.6.

Further assessment of the measurement precision was performed at reduced temperatures and a limited range of Mach numbers as previously done for measurement accuracy. These data are detailed in Fig. 7, showing the velocity precision magnitude as functions of the operating temperature and pressure. Very similar magnitudes are observed to the elevated-temperature assessment in Fig. 6; the velocity precision magnitudes ranged from 1 m/s up to

2.4 m/s. For the data acquired at Mach 0.4, the majority of data sets exhibited precisions ranging from 1 to 2 m/s, which are nearly identical to the measurements taken at elevated temperatures. Most of the data sets that exhibited high velocity fluctuation magnitudes were taken at Mach 0.8, which might be due to the increase in natural velocity fluctuations indicated in Fig. 6. The precision, much like the measurement error, seems largely independent of the operating conditions in the facility; no clear trends are apparent in the data. It can be concluded from these observations and the previous information regarding the accuracy of the technique that performance of PLEET is essentially uniform throughout the operation envelope of this type of facility. The thermodynamic dependences of the PLEET technique will be further examined in Section 4.3.

4.3 Thermodynamic Dependences of PLEET Signal

This section will briefly examine the thermodynamic dependences of the PLEET signal. This analysis will include firstly, the PLEET signal intensity and, secondly, the PLEET signal lifetime.

4.3.1. PLEET Signal Intensity.—The thermodynamic dependences of the peak PLEET signal intensity are detailed in Fig. 8; the uncertainties shown represent the 1 σ bounds. The pressure dependence shown in Fig. 8a does not indicate any distinct trend. A slight positive correlation exists between the pressure and signal intensity, but it is not conclusive and falls within the uncertainty of the data. This lack of trend is repeated in both the temperature and density dependences shown in Figs. 8b and 8c. The observed behavior deviates significantly from the trends observed from FLEET signal at similar conditions. Notably, it was demonstrated that there was a strong linear dependence on density to the FLEET signal. [1,20] While this is discouraging from a diagnostic perspective, there are three main differences which exist between these sets of measurements that could readily explain the disparate behaviors. First, the peak PLEET intensity data were collected 8.7 μ s after the laser pulse, in comparison to only 70 ns after for the FLEET measurements. Second, the FLEET measurements utilized a bandpass filter to remove the contributions of both the laser bandwidth and the majority of emission from the first negative and second positive bands of N₂. These near-ultraviolet components greatly contaminated the PLEET signal, appearing several orders of magnitude more intense than the first positive emission captured with the FLEET technique. In addition to necessitating the temporal shift in the collection of the PLEET signal, which has been shown to significantly change the thermodynamic response of the closely related FLEET technique, it is not known how the UV components of FLEET respond over these conditions either. Finally, it is suspected that the shot-to-shot and burst-to-burst variations in the laser pulse energy have a strong influence on the observed behavior of the peak signal intensity. Unfortunately, no data regarding the PLEET signal intensity currently exists that is either spectrally resolved or at the necessary test conditions to fully understand why the behaviors differ so substantially, though the two cited reasons likely account for some of the discrepancy.

The total signal intensity as functions of the thermodynamic conditions is shown in Fig. 9. The total signal intensity, which represents the amount of signal emitted for the entirety of the PLEET lifetime, serves as the numerical equivalent of holding a very long exposure with

the camera on stationary PLEET signal. The pressure dependence shown in Fig. 9a indicates a negative correlation between the pressure and total signal intensity, although there is significant vertical spread in the signal. It will be shown in Section 4.3.2 that this trend is predominantly the effect of the behavior of the signal lifetime. The temperature dependence (Fig. 9b) shows a null trend, with no significant variation occurring across the range of temperatures tested. Finally, the density dependence in Fig. 9c indicates a subtle negative trend in the signal, mirroring the pressure response observed in Fig. 9a. Again, the response observed appears to be very application-specific, as it was with the peak intensity. Since the observed trends are extrapolated back to the time of the laser pulse and forward to notional infinity in constructing this signal, it is difficult to gauge how accurately the measurements represent the photo-physics of the PLEET technique. Further investigation with more closely controlled gating and spectral filtering would be required to ascertain the true behavior of this signal. However, the relatively consistent behavior across the thermodynamic conditions is actually beneficial from the standpoint of velocimetry. As noted in Sections 4.1 and 4.2 previously, both the velocity accuracy and precision were found to be consistent across the entire facility operational envelope, which is in large part because these intensity parameters are able to remain largely independent of the thermodynamic conditions.

4.3.2 PLEET Signal Lifetime.—Characterization of the PLEET signal lifetime is crucial for predicting the performance of the PLEET technique for given experimental conditions. The signal lifetime of the closely-related FLEET technique has been shown to have a strong correlation with the velocity measurement precision and also has shown some promise at being indicative of thermodynamic conditions.[20] The initial studies of PLEET indicated significantly longer lifetimes than the FLEET technique, although the mechanism for this disparity is not understood at present.[22] The data taken in these tests confirm these observations. The first PLEET lifetimes ($1/e$) are shown as functions of the thermodynamic conditions in Fig. 10. A clear inverse dependence is apparent when compared with pressure (Fig. 10a). The observed lifetimes vary from approximately $40\ \mu\text{s}$ at the lowest-pressure conditions to as low as $8\ \mu\text{s}$ at the highest pressures. Additionally, the color-coding with temperature suggests that higher temperatures correspond to shorter lifetimes. Indeed, replotting the data as a function of temperature (Fig. 10b) suggests the same trend, with lower temperatures yielding longer lifetimes (in addition to lower pressures). The density dependence is correspondingly unclear in Fig. 10c.

The second PLEET lifetimes ($1/e^2$) are plotted in Fig. 11. Roughly the same trends are observed as those with the first lifetime. An inverse dependence on pressure is observed in Fig. 11a, while Fig. 11b again indicates a negative correlation with temperature. The second lifetimes appear slightly greater than twice that of the first lifetimes, which is suggestive of the multi-exponential behavior of the PLEET signal. Second lifetimes ranged from $20\ \mu\text{s}$ at the highest pressures/highest temperatures to nearly $100\ \mu\text{s}$ at the low end of conditions. It is important to note that these lifetimes, both the first and second, are notably longer than that of the FLEET data taken at nearly identical conditions. The longest second lifetimes observed peaked near $70\ \mu\text{s}$ in those studies.[1] Visually, the signal did appear to persist much longer in the PLEET images, with signal visible for a few hundred μs (refer to Fig. 3). With FLEET, observing signals beyond $60\ \mu\text{s}$ was rare. Again, the exact mechanism

responsible for the longer signal lifetimes is unclear. From an operational standpoint, it is possible that the prolonged appearance of the PLEET signal in comparison to previous FLEET tests was a consequence of delaying the initial exposure. Since the image intensifier was adjusted to maximize the signal in the first visible frame, maximizing it at a point in the signal lifetime long after the first rapid component of the emission-decay occurs could make the signal seem to linger. Another possibility is that the PLEET excitation opens an additional kinetic pathway through which to generate dissociated N atoms. Both FLEET and STARFLEET rely, in part, on the direct photo-dissociation of N₂ for this operation. It is through the (rate-limiting) recombination of such atoms that the excited nitrogen B-state leading the first positive emission typifying FLEET is populated. However, PLEET differs from these techniques in that a larger portion of the excitation energy likely contributes to the direct photoionization of N₂, resulting from the longer laser pulse duration. It is possible that the larger population of N₂⁺ allows the dissociative recombination pathway

($N_2^+ + e^- \rightarrow N + N + 2.07 \text{ eV}$) to provide a larger contribution to the overall pool of N atoms, extending the lifetime of the observed signal. More work seeking to model the overall chemical kinetics of the PLEET and FLEET excitation will help to explain these behaviors, but lies beyond the scope of this paper.

4.4 PLEET Tracking Reliability and Buoyancy

An additional concern arises when using PLEET in comparison to FLEET in that it appears to deposit more energy into the flow. Although early rotational spectra seem to indicate a similar temperature rise to the FLEET technique,[22] this same method seemed to underestimate the temperature rise predicted by Rayleigh scattering by nearly a factor of 2. [19] Until similar measurements are made for the PLEET technique, it is unclear how much of a temperature rise is present. Regardless of the actual magnitude of the temperature perturbation, it raises questions about the tracking reliability of the PLEET spot (and, likewise, that of FLEET and even STARFLEET). Specifically, two related effects are brought into question: the velocity tracking reliability and the trajectory tracking reliability. The distinction between these two effects has to do with the use of the PLEET signal. The velocity tracking reliability is a question of instantaneous adherence to the local flow behavior; whether the PLEET spot or line takes on the velocity of the flow between recorded images frames. In addition to the excitation process locally altering the behavior of the flow being studied, flow structures such as shockwaves, contact surfaces, and rapid expansions could cause velocity lag effects similar to that experienced by particles or droplets in high-speed flows. If an analogous relaxation time were to be constructed for such density perturbations, it is likely that it would have implications for the frequency response of the technique as well. Trajectory tracking is instead a long-term behavior, and requires that the PLEET spot adhere to the behavior of the flow for a given period of observation. This utilization of the signal has requirements that are more stringent on the tracking reliability of the PLEET spot, since it requires adherence to the surrounding flow physics for a prolonged period of time. Such adherence has implications to the use of PLEET for both pathline assessment around aerodynamic bodies and linearity testing in the characterization of test facilities.

While a full simulation of the excitation and convection of the PLEET spot is beyond the scope of this paper, the effects of buoyancy as a unit problem can be bounded by some simple analytical tools. In this analysis, which will seek to place bounds on the effects of buoyancy at conditions relevant to high pressure, cryogenic tunnels, two parameters will be defined to examine the velocity and trajectory tracking reliability. Regarding velocity tracking, the heating due to excitation will induce a velocity opposite the direction of gravity. This buoyant velocity (u_y) can be defined as:

$$\Delta u_y = \left(\frac{\rho_f}{\rho_{PLEET}} - 1 \right) g \Delta t, \quad (8)$$

where g is the local acceleration due to gravity (9.81 m/s^2), ρ_f and ρ_{PLEET} are the fluid and PLEET-spot densities, respectively, and t is the time of observation. This equation arises from a simple force balance between buoyancy and gravity acting on the PLEET spot. For these analyses, the density of the PLEET spot was assumed to be uniform and was defined from the ideal gas law as:

$$\rho_{PLEET} = \frac{P_f}{R(T_f + \Delta T)}, \quad (9)$$

where R is the specific gas constant for nitrogen (roughly 297 J/(kg-K)), and T is the temperature rise due to excitation. This definition assumes that the gas behaves as a thermally perfect gas and that the excitation process is isobaric with respect to the surrounding fluid. It is also assumed that the temperature differential remains indefinitely, though it will dissipate with time in reality. The second parameter, which is concerned with the trajectory tracking reliability, is the buoyant displacement:

$$\Delta y = \frac{1}{2} \left(\frac{\rho_f}{\rho_{PLEET}} - 1 \right) g \Delta t^2, \quad (10)$$

which models the displacement as the result of a kinematic acceleration due to buoyancy. The results of these analyses are summarized in Fig. 12. In this assessment, it was assumed that the time frame of observation was similar to these tests at $250 \mu\text{s}$. Figure 12a shows the estimated buoyant velocity at the end of this observation window for temperature perturbations ranging from 10 K (consistent with STARFLEET) up to 1000 K (consistent with PLEET). As is apparent, larger temperature perturbations result in larger buoyant velocities. For this particular operational envelope, the density varies by over a factor of ten throughout, resulting in a large variation in this velocity parameter. An absolute peak velocity of only 0.04 m/s was found in this analysis. While not a favorable observation, this velocity change is significantly smaller than the velocity measurement precision (1.2 m/s approximately). Consequently, regardless of the magnitude of the temperature perturbation, the effect on the measured velocity is not of sufficient magnitude over the observation time period to be discernable. However, it should be noted that if streamlines exhibited curvature, this buoyant velocity would result in a slight deviation in the mean velocities.

The buoyant displacement shown in Fig. 12b exhibits similar trends to that of the buoyant velocity. Larger displacements correspond to both higher flow densities and larger temperature perturbations. A peak displacement of less than 5 μm is estimated from this analysis, which is below the limit of the precision of both the surface fitting algorithm (about 13 μm) and the velocity measurement precision as discussed with the buoyant velocity. For completeness, the overall angle of the flow was examined for different velocities as well assuming the maximum possible buoyant velocity, as shown in Fig. 13. The maximum observed deflection angle, occurring at the lowest velocities is found to lie below 0.05° . These figures decrease substantially as the bulk velocity of the flow is increased. These basic analyses, though the physics entailed are exaggerated to make the scenario as extreme as possible, indicate that there is little concern over the tracking reliability due to buoyancy effects alone, at least for straight streamlines. While these results are encouraging, this analysis still does not address some of the larger issues regarding tracking reliability, namely the effects of step changes in direction, velocity, or the frequency response. Recent work by New-Tolley *et al.*, which utilized numerical simulations to examine femtosecond-laser perturbations in laminar shear flows, found a distinct lack of tracking reliability in regions of high shear.[29] Thus, a significant amount of work is needed, both experimental and computational, to better understand the effects of the density perturbations on the measurement of rapidly varying flows.

4.5 Other Measurement Parameters

4.5.1 Velocity Dynamic Range.—Streamwise velocities ranging from 65 m/s up to nearly 270 m/s were resolved in these studies without any change in experimental parameters. In addition, low velocities of similar magnitude to the measurement precision (1.2 m/s) were resolved in the transverse direction. At face value, it could be concluded that the velocity dynamic range was around 200 and that there was ample headroom to resolve velocities 10 or more times that experienced in these tests. While not as broad as the measurements made with FLEET, which found a minimum dynamic range of 650,[1] PLEET also varies slightly from FLEET in its ability to assess a wide range of velocities due to the long lifetime of the signal. As demonstrated in Fig. 3, the signal from previous excitations persists for several laser pulses. Unfortunately, this imposes some limitations regarding the ability of the PLEET signal to resolve a range of velocities without changing numerous parameters of the measurement system. The spacing between subsequent shots can be expressed as:

$$\Delta s = u_f \frac{f_{camera}}{f_{laser}} \Delta t = \frac{u_f}{f_{laser}}, \quad (11)$$

where u_f is the total velocity of the flow, f_{camera} is the acquisition rate of the imaging system, f_{laser} is the repetition rate of the pulse-burst laser system, and Δt is the interframe delay of the camera. If the requirement is that subsequent spots do not overlap, the diameter of the spots must also be considered in this assessment. Phrased differently, a given spot size and velocity set a limit on the maximum repetition rate of the laser system. Consider a 2-mm-diameter spot, for example. For the laser parameters used in these studies, namely a

repetition rate of 25 kHz, this places a limitation on the lowest velocity of 50 m/s. The signal lifetime also factors into this assessment to some extent; since the signal is initially orders of magnitude more intense than it would be at the time of the next laser pulse, it is likely that 'fresh' signal could be easily discerned from older signal, relaxing this limitation to some extent.

There is thus not a fundamental limitation on the range of velocities that could be resolved with the overall PLEET system, but a limitation exists on what could be resolved with a single set of experimental parameters. For instance, if a measurement were being conducted in which the PLEET spot was to be spatially translated to generate a profile and the laser settings were fixed, there would be a limit imposed on what velocities in the flow could be resolved without changing experimental parameters. If the measured velocities within that profile varied from 500 m/s to 50 m/s with a 2-mm spot size, the system would not experience any limitation. If on the other hand, a much wider range of velocities were encountered (for example, negative, stagnant, and high positive velocities, as would be present in many separated flow scenarios), PLEET might be limited in its ability to resolve the full range of velocities without consecutive spots overlapping in certain regions. Thus, an *a priori* assessment of the range of velocities would be necessary to ensure that the laser repetition rate and frame rate of the camera were optimized to ensure the broadest dynamic range possible.

4.5.2 Measurement Spatial Resolution.—The spatial resolution of the PLEET measurements is influenced by a number of factors including the PLEET spot size, flow velocity, and the inter-frame delay of the imaging system. The PLEET spot size imposes a limitation on the scale of flow features that can be resolved. Specifically, the surface fitting/centroid finding scheme treats the entirety of the PLEET spot as a single fluid element. Not all flow features acting on scales smaller than this diameter can thus be resolved. While the spot size varies from set to set, the initial PLEET spot size is nearly uniform at 2 mm.

The second limitation stems from the advection of the PLEET spot. Specifically, the motion of the PLEET spot between frames results in a minimum length scale that can be resolved. The minimum length scale can be expressed as $\Delta s = u_f \Delta t$, where u_f is the flow velocity and

Δt is the interframe delay. For these studies, which tested velocities ranging from 65 m/s to 270 m/s, this distance ranged from 650 μm to 2.7 mm. An additional limitation is placed on the spatial resolution by the desired velocity measurement precision. That is, increasing the measurement precision can be achieved by considering additional data points in each velocity calculation. In so doing, the effective spatial resolution is adjusted according to the length of the trajectory considered. There is thus a tradeoff between measurement precision and spatial resolution. In summary, the spatial resolution is limited to 2–2.7 mm at a minimum for the lowest to highest velocities, respectively, but may increase depending on the demands of the experiment.

4.5.3 Frequency Response.—The primary advantage of the PLEET system over a comparable FLEET system is the ability to make high-repetition-rate velocity measurements. The experimental parameters used in these experiments utilized a laser

repetition rate of 25 kHz, allowing the resolution of 12.5 kHz flow oscillations at maximum. The pulse-burst laser system can output sufficient pulse energies to generate PLEET at up to 100 kHz, allowing flow oscillations of up to 50 kHz to be resolved. While this is in general accurate, one possible limitation to consider concerning the PLEET velocity measurements again concerns the long lifetime of the PLEET signal (discussed in Section 4.5.1 above regarding the velocity dynamic range). Due to the long lifetime of the PLEET signal, using an excessive repetition rate at low velocities can lead to the overlapping of consecutive spots, which can make resolving velocities accurately impossible if the effect is too severe. As an example, if a flow of interest had a mean velocity of 200 m/s and the PLEET spot size were 2 mm as in these studies, a 100-kHz repetition rate could be used without suffering from overlap in the imaging. However, if the flow were only 10 m/s, this repetition rate would prove too high to make velocity measurements without contamination from previous PLEET signal. Thus, the flow being considered has an effect on the maximum-attainable frequency response of the measurement system.

4.5.4 Measurement Uncertainty.—Though the measurement accuracy and precision have been clearly defined and assessed in these experiments, few situations exist in which a well-characterized reference measurement is available for comparison. For example, any test conducted in the flowfield around a model that was not previously assessed (as is often the case) would lack such a reference. Thus, it is useful to assess what the measurement uncertainties would be for experiments such as these were the reference not available. A detailed uncertainty analysis on a similar measurement system has been carried out by the authors in Ref. [21]. The uncertainties in question during these experiments were identical, so the results from those studies will be summarized briefly here. The primary sources of uncertainty that contribute to the velocity measurements are the magnification of the imaging system, rotation of the imaging system with respect to the primary axes of the tunnel, the precision of the surface fitting/centroid finding algorithm, and the linear fitting routine used to extract velocities. The magnification uncertainties result from the large depth-of-field of the imaging system used in conjunction with the boresight-imaging configuration in these studies. As a result of the large depth-of-field, the signal looks in focus on the camera system whether or not it lies within the plane at which calibration data were taken. This uncertainty is the most substantial of the set, resulting in a 3–4% uncertainty in all measured velocities. Note also that if it were possible to view the signal orthogonally (for instance, imaging through the sidewall of the tunnel while bringing the laser beam in through the top wall), this uncertainty would be greatly reduced in magnitude provided the position of the laser beam could be maintained. The uncertainties resulting from camera system rotation differ depending on the axis of rotation. For rotations about the x - or y -axis, uncertainties result primarily from out-of-plane (z -) velocities. Since the flow is essentially unidirectional in these studies, the maximum uncertainty in the streamwise velocity from rotations about the y -axis are around 0.5 m/s, while those in the transverse velocity resulting from rotations about the x -axis are less than 0.1 m/s. Rotations about the z -axis (imaging axis) yield additional uncertainties of up to 1 m/s and 6 m/s for the streamwise and transverse velocities, respectively. The analytical uncertainties resulting from the data processing procedures take on values very similar to those found in Ref. [21], with the uncertainty in both primary velocity components of less than 0.7 m/s. Assessing the

overall uncertainty in the system, it is found that the streamwise velocity has a total uncertainty not exceeding 4–4.8% for high to low velocities, respectively, while the total uncertainty in the transverse velocity component is approximately 6 m/s, owing primarily to the potential rotation about the z-axis and the large disparity between the streamwise and transverse velocities. These tests had the advantage of a reference velocity for comparison, showing that the overall measurement uncertainties were significantly greater than the measurement errors found during the experiments. However, such uncertainties would need to be accounted for if the flow did not have a reference measurement for comparison.

The single-shot uncertainty values that were estimated compare favorably with other MTV and optical velocity measurements. Measurements by Bathel et al. in a large-scale hypersonic facility found single-shot velocity uncertainties to be as low as 2.7% when using NO molecular-tagging velocimetry, though higher values were typical.[30] Uncertainties estimated for laser-induced thermal acoustics performed by Hart et al. varied within 1–4%. [31] Iodine tagging velocimetry in a Mach 10 wake flow by Balla conservatively estimated measurement uncertainties to be around 10%.[32] From this brief comparison, the composite uncertainties from these PLEET studies fall in line with other comparable measurements that have been made in large-scale facilities without the additional experimental complications of seeding gases and multi-laser optical setups and with the significant advantage of a high measurement repetition rate.

5. Conclusions

These studies examined the utility of the PLEET technique for use in large-scale wind-tunnel facilities, most notably, the high-pressure, cryogenic wind tunnels. The experiments that were conducted consisted of high-repetition-rate velocity measurements conducted in the 0.3-m Transonic Cryogenic Tunnel at NASA Langley Research Center. Comparison of the measured velocities with those of the facility data-acquisition system indicated measurement errors of 0.6–1.2% across multiple days, indicative not only of the quality of the velocity measurements but also the stability of the instrument itself. Assessment of the measurement precision found a zero-velocity precision of 1.2 m/s. Wind-on precision indicated relatively uniform precision of approximately 1.5 m/s from Mach 0.2 to Mach 0.6, while above this Mach number the fluctuating velocity began increasing considerably, suggesting true fluctuations in the flow velocity. Both the measurement precision and the measurement accuracy were found to be relatively insensitive to the tunnel operating conditions. Through the analysis of the signal intensity, a weak positive correlation with mostly scatter was found. The signal lifetimes exhibited an inverse dependence on both temperature and pressure. Assessment of the effects of buoyancy found no significant influence on the measured velocities or trajectories. The velocity dynamic range could only conclusively be measured to be around 200 in these studies, though there was ample headroom to increase the maximum velocity by over an order of magnitude. Due to the prolonged lifetime of the PLEET signal, a limitation (resulting from the overlap of consecutive PLEET signals) is imposed on the velocity dynamic range if the experimental parameters are fixed. The spatial resolution of the PLEET measurements was found to lie between 2 and 2.7 mm for single pulses, though a lesser (larger magnitude) resolution might be needed to ensure a certain degree of velocity precision. The frequency response of the

PLEET system was found to be consistent with the maximum repetition rate of the laser, though the long lifetime of the signal and the possibility of velocity lag due to the density perturbation could create practical limitations below the operational limits of the pulse-burst laser system. Finally, an assessment of the overall measurement uncertainties found the streamwise velocity to have uncertainties of 4–4.8% for high to low velocities, while the transverse velocity was subject to uncertainties up to 6 m/s. These have demonstrated that PLEET is a viable technique for use in large-scale, TCT-type facilities, exhibiting nearly uniform experimental quality over the entire operational envelope.

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Figure 1.
Perspective view of 0.3-m TCT test section.

Figure 2.
Diagram of optical setup used in PLEET experiments.

Figure 3.

Sample time-series of PLEET data detailing spatial and temporal progression of signal. Data were collected at Mach 0.85, $P_t = 200$ kPa, and $T_t = 275$ K.

Figure 4.
Measured velocity (PLEET) versus reference velocity (DAS) at elevated temperatures.
Diagonal line indicates perfect agreement.

Figure 5.

PLEET velocity accuracy throughout the 0.3-m TCT operational envelope. a) Measured velocity versus corrected facility DAS velocity and b) measurement error as a function of the operating pressure, temperature, and Mach number.

Figure 6.

PLEET velocity precision as a function of Mach number. a) velocity precision magnitude and b) percent precision. Dashed lines indicated the zero-velocity precision.

Figure 7.
Observed PLEET velocity precision magnitude throughout the 0.3-m TCT operational envelope.

Figure 8.

Peak PLEET signal intensity as a function of thermodynamic conditions. a) pressure, b) temperature, and c) density.

Figure 9.
Total PLEET signal intensity as a function of thermodynamic conditions. a) Pressure, b) temperature, and c) density.

Figure 10.

First PLEET lifetime as function of thermodynamic conditions. a) Pressure, b) temperature, and c) density.

Figure 11.

Second PLEET lifetime as function of thermodynamic conditions. a) Pressure, b) temperature, and c) density.

Figure 12.

Effects of buoyancy on velocity and trajectory of PLEET signal as functions of tunnel operating temperature and pressure. a) maximum buoyant velocity and b) maximum buoyant displacement.

Figure 13.
Maximum deflection angle caused by buoyancy for different flow velocities.

Figure A1.

Control volume constructed to derive quasi-1D flow equations with friction. The depicted area change is exaggerated for clarity.

Figure A2.

Calculated velocity correction as a function of inlet velocity and Reynolds number.