Toward Simultaneous Velocity and Density Measurements Using FLEET and Laser Rayleigh Scattering

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Femtosecond laser electronic excitation tagging (FLEET) velocimetry and laser Rayleigh scattering are conducted concurrently and are evaluated for their suitability to measure velocity and density simultaneously in NASA Langley's 0.3-m Transonic Cryogenic Tunnel. FLEET velocimetry measurements are shown to be accurate to within 1.5 percent of the measured velocity throughout the facility testing envelope and exhibit a zero-velocity precision of 0.4 m/s. Rayleigh scattering density measurements indicate a characteristically linear dependence on flow density while having an accuracy within 5.4 percent of the measured density and a precision less than or equal to 6 percent. The preliminary assessment indicates that the joint technique would be advantageous for deployment in high-pressure, cryogenic test facilities.

1. Introduction

In the past few decades, laser diagnostics have pervaded most fields within the study of fluid mechanics, notably at the university level. However, many of the large-scale test facilities that are present at national and international research centers, most of which were not originally designed for such activities and are difficult to modify, often lag behind universities in this regard. One particular class of facility that has experienced this limitation is the high-pressure, cryogenic wind tunnels such as the National Transonic Facility (NTF) at NASA Langley Research Center (LaRC) in the USA and the European Transonic Windtunnel (ETW) in Germany. These facilities, developed to simulate very high Reynolds number transonic flows, are notoriously difficult to instrument due to their large scale, rugged construction, and a host of other issues related to operating at or near cryogenic conditions. Techniques that measure surface pressure,[1,2] temperature,[3,4] velocity,[5,6] and density[7,8,9] have been attempted in these types of facilities with varying degrees of success, and research into each of these areas is ongoing.

Of particular interest at NASA LaRC is the measurement of velocity within the two transonic cryogenic tunnels (TCTs) present on the center, the NTF and its pilot facility, the 0.3-m TCT. Historically, velocity measurements have been limited to probe-based measurements (e.g. Pitot probes and hot-wire anemometers). Techniques that utilize particles or droplets to function, such as particle image velocimetry (PIV)[5] and Doppler global velocimetry (DGV),[6] which have shown some success at the European wind tunnels, are currently prohibited in these facilities for fear of contaminating the flow circuits with particles or water/oil residues. Historical studies in the 0.3-m TCT, which utilized laser Doppler velocimetry[10] and laser transit anemometry,[11] were successful over a limited range of conditions but lacked repeatability. The current body of work by the authors investigates the use of the femtosecond laser electronic excitation tagging (FLEET)[12] velocimetry technique to bypass the issue of using particles within these facilities.[13,14,15] FLEET is a nonlinear optical process in which an ultrafast laser pulse is brought to an optical focus. The high intensity present within the focal volume induces a multi-photon absorption phenomenon, causing nitrogen molecules to ionize and dissociate. The luminescence resulting from the recombination of these atoms and molecules can be tracked spatially, allowing the flow velocity to be inferred. Since this technique requires only a single laser and camera system and operates on nitrogen, it is naturally well-suited to application in TCT facilities.

The current study examines extending the measurement capabilities of FLEET and the associated experimental setup to include multi-parameter measurements, notably the simultaneous measurement of density and velocity. In addition to the FLEET velocity measurements, the use of Rayleigh scattering from the same fs-laser pulse has been examined previously for use in a density measurement.[16] The simultaneous measurement of velocity and density would allow for the direct measurement of turbulent, compressible Reynolds stresses ($\langle \rho u_i' u_j' \rangle$) and other single-point statistics, generally. Consequently, such a measurement is exceedingly valuable to the experimental and computational research communities. The ability to make such a measurement in a challenging environment such as a high-pressure, cryogenic wind tunnel further underscores the value of such a technique. In this manuscript, the accuracy, precision, and spatial resolution of both FLEET velocimetry and laser Rayleigh scattering conducted in the 0.3-m TCT are evaluated independently.

2. Experimental Program

A. Test Facility

All experiments were conducted in the NASA Langley 0.3-m Transonic Cryogenic Tunnel (0.3-m TCT); a closed-loop, fan-driven wind tunnel capable of operating at Mach numbers ranging from 0.2 to 0.9. While able to operate on a number of test gases, all tests reported here were conducted in nitrogen (N_2). Operating total (stagnation) pressures ranged from 100 to 500 kPa, and the total temperature was varied from 100 K through 280 K.

The facility is constructed with a double-shelled design; the central test section (or test cell) is surrounded by a pressurized plenum of nominally quiescent gas. This construction allowed the presence of either adjustable or slotted walls in the test section. The test section has cross-section dimensions of approximately 0.33 m × 0.33 m. The test section was set to have slightly diverging walls to account for boundary layer growth over most conditions. Optical access to the facility was afforded by two fused-silica windows penetrating the plenum and test section. A large, circular window penetrated the outer plenum wall, while a 'D'-shaped hexagonal window (henceforth referred to as the D-window) was situated in the wall of the inner test section to allow optical access to the inner test cell.

B. Laser System

Both density and velocity measurements utilized a pulsed, regeneratively-amplified Ti:sapphire laser (Spectra-Physics Solstice) with a center wavelength of 800 nm, bandwidth of 20 nm, and a repetition rate of 1 kHz. Data sets were collected with pulse energies around 1 mJ at the laser source, although between 30 to 50 percent of this energy was attenuated through the beam path. The laser system was situated on a platform roughly 3 m above the test section; the beam was brought down to the level of the facility with a pair of periscopic mirrors. To allow for adjustment during facility contraction (a common occurrence when operating at cryogenic conditions), the beam was first routed through a pair of horizontal periscopes that could be translated to keep the beam in alignment. The beam was then transmitted into the plenum of the facility, elevated to the height of the D-window, and passed through a f = +250 mm spherical lens before entering the test section. The laser beam path at the facility level is detailed in Fig. 1.

C. Data Acquisition Systems

Imaging of the FLEET signal was done using a high-speed image intensifier (LaVision HS-IRO) lens-coupled to a high-speed CMOS camera (Photron Mini AX-200). A 135-mm, $f/2$ objective lens and a bandpass filter (400 nm to 775 nm passband) were used on the camera. This camera system was operated in a triggered burst mode in which 1000 bursts of 25 images were acquired each second, with the acquisition rate within each burst being 200 kHz. This timing configuration allowed the FLEET signal generated by each laser pulse to be imaged multiple times to track its motion in a Lagrangian frame of reference. The FLEET signal was viewed from a quasi-boresight perspective, in which the imaging line-of-sight was nearly parallel to the direction of laser propagation (horizontally offset by

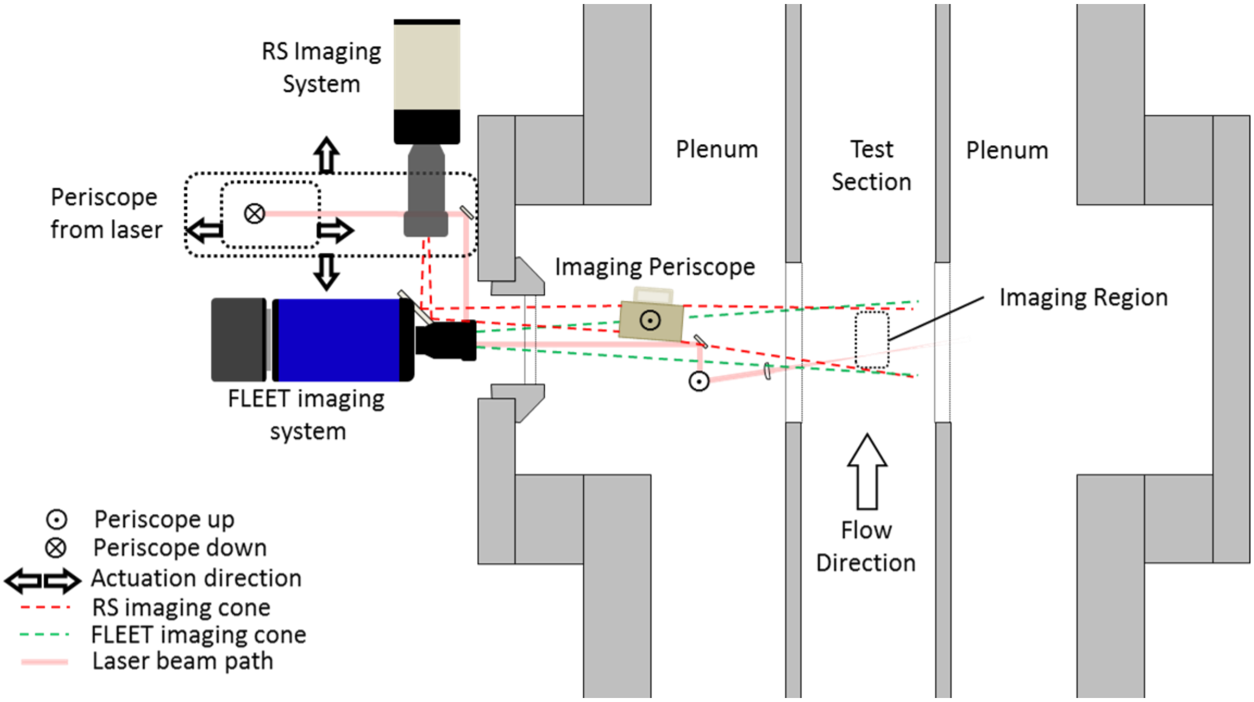

Figure 1. Top view of the laser and optical systems in and around the 0.3-m TCT facility.

approximately 30 degrees). The FLEET imaging system was aligned to be perpendicular to the principal flow direction.

The laser Rayleigh scattering (RS) was imaged using an electron-multiplying CCD camera (Princeton Instruments PhotonMAX 512). The images were acquired with an exposure time of 10 μs, and the exposure was temporally adjusted such that the laser pulse fell near the falling edge of the exposure. This strategy was employed to reduce the amount of resonant FLEET signal and background fluorescence that were acquired in each image. The RS camera was equipped with a 185-mm, $f/2.8$ lens and a bandpass filter (center wavelength 800 nm, bandwidth 25 nm) to remove light that was not at the laser wavelength. The RS imaging was conducted through a series of horizontal and vertical periscopes; the camera was situated anti-parallel to the principal flow direction. The periscopes turned the imaging line-of-sight first, perpendicular to the flow outside of the facility plenum, second, vertical within the plenum, and finally, nearly perpendicular to the flow before the D-window, which served as the final imaging perspective. Due to the slight oblique angle at which the imaging was done, the lens f-stop was reduced to $f/5.6$ to increase the depth-of-field and maintain focus in the images. The orientation of both camera systems and the imaging lines of sight are shown schematically in Fig. 1. The RS camera acquired images at approximately 30 Hz. All equipment was synchronized by a series of pulse generators (LabSmith LC880 and Berkeley Nucleonics BNC 575-4), which were synced to the master trigger signal from the laser.

In addition to the imaging systems, the 0.3-m TCT facility has an extensive data acquisition system (DAS), consisting of an array of wall pressure taps, thermocouples, pitot probes, and pressure transducers to measure relevant properties of the flow. These probes were situated throughout the test section walls and within the plenum. Data from this equipment was read into facility computer systems for processing. In post-processing, additional parameters such as the velocity, density, and Reynolds number were inferred from the pressure and temperature measurements using an equation of state (Beattie-Bridgeman equation[17]) and the thermodynamic properties of nitrogen.[18] A facility data point was collected during each FLEET/RS data acquisition run to measure the corresponding facility conditions.

3. Results and Discussion

A. FLEET Velocimetry

A sample burst of FLEET data is shown in Fig. 2a along with the corresponding measured trajectory (Fig. 2b). The FLEET signal forms a short line roughly 2 mm in length. However, due to the boresight imaging perspective, the signal appears as an oblong spot in the images. Unlike PIV and many other velocimetry techniques such as laser Doppler velocimetry (LDV) and hot-wire anemometers, FLEET is a Lagrangian measurement technique. The initial signal that is generated by the laser pulse is sequentially imaged (four individual images are overlain in Fig. 2a) to measure the signal’s trajectory as it advects with the flow. By performing linear regression between three or more points within such a trajectory, the velocity of the FLEET signal (and consequently, the flow) can be inferred. This methodology provides a superior measurement precision in comparison to using a two-point measurement since the linear fit is less susceptible to imaging and numerical noise present in the constitutive images.

Velocities obtained from the FLEET data were compared to those measured by the facility DAS, which utilized pressure and temperature measurements to infer the freestream velocity. A comparison between these measurements is presented in Fig. 3a, which shows the individual percent error encountered throughout the facility testing envelope. Velocities ranged from 45 m/s up to 260 m/s. Relatively low error is observed throughout much of the experimental envelope; the peak error was found to be around 3.5 percent of the measured velocity, which occurred near the liquid-vapor saturation point. At such conditions, a fog is often present within the test section due to either

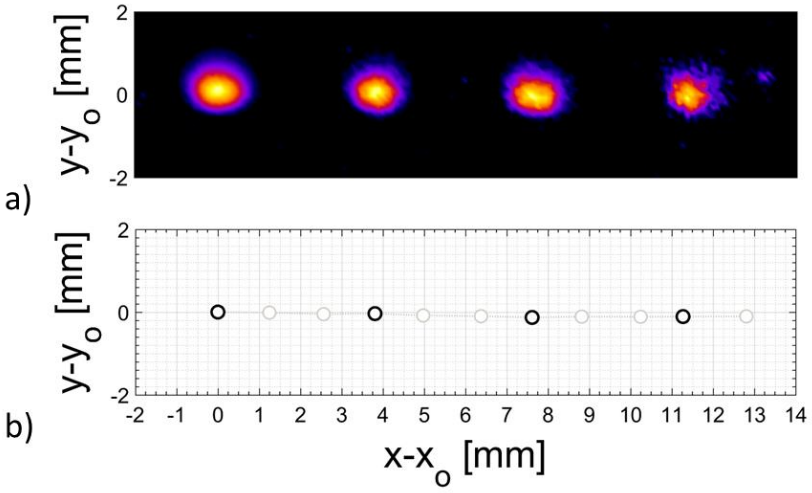

Figure 2. Sample burst of FLEET data and measured trajectory. a) Overlain FLEET images (only every third image shown for clarity) and b) measured trajectory. Grayed-out points in b) correspond to omitted images. Flow conditions for the figure are Mach 0.75, P = 0.85 kPa, and T = 247 K.

unevaporated liquid nitrogen (LN_2) droplets or secondary condensation, which interferes with the focusing of the fs-laser beam and the formation of the FLEET signal. Nonetheless, the measurements were reasonably accurate even at these conditions, indicating a degree of robustness to the measurement technique. Overall, the mean percent error throughout the entire operational envelope was found to be 1.5 percent, while the RMS percent error was found to be 1.7 percent over the same domain of conditions, with individual data set errors typically holding a positive bias.

The measurement precision was evaluated by taking the sample standard deviation of all measured velocities in a given data set. Invoking this method presumes that all velocity fluctuations are the result of instrumental imprecisions, but obviously include other contributions (such as freestream turbulence fluctuations). To anchor these measurements, a run taken in quiescent N_2 was analyzed and assessed for its precision, which was found to be 0.4 m/s based on one standard deviation. This value represents approximately 0.8 percent of the lowest velocity tested and 0.15 percent of the highest velocity. The results of the velocity precision assessments during the actual testing can be found in Fig. 3b. In these measurements, the measurement precisions were (predictably) all greater than the zero-velocity reference, ranging from roughly the zero-velocity value at most conditions up to nearly 20 m/s at conditions near the liquid-vapor saturation point, which were adversely affected for the same reasons the accuracy was diminished in these same circumstances. These points excluded, the velocity precision was found to be less than 5 percent throughout the domain of conditions tested, with over half of all conditions tested exhibiting precisions less than one percent of the measured velocities. The three trends mentioned previously were likely due to an

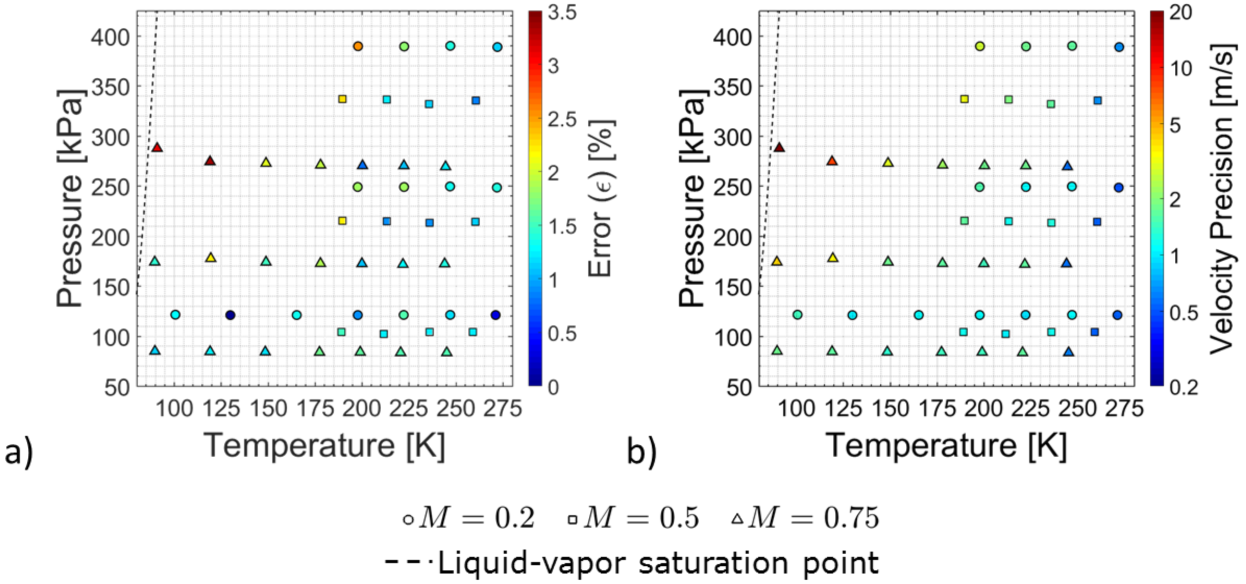

Figure 3. FLEET accuracy and precision as functions of the tunnel operating conditions. a) Velocity accuracy and b) velocity measurement precision (shown with a logarithmic color scale).

increase in the genuine freestream fluctuations, corresponding to increasing Reynolds numbers at higher velocities, lower temperatures, and higher pressures.

The assessments of accuracy and precision compare favorably with similar techniques in the literature. The historical studies utilizing LDV in this facility found velocity error to be less than 1 percent typically, while the reported velocity standard deviations were below 1 percent.[10] The present studies find the same order of accuracy and slightly lesser precision, but they were conducted over a broader range of conditions and highly repeatable. Other related molecular tagging velocimetry (MTV) techniques differ considerably in their reported measurement accuracy and precision. Velocity measurements by Sijtsema *et al.* utilizing the APART technique found accuracies ranging from 5 to 13 percent depending on the flow being used to characterize.[19] Lempert *et al.* assessed the velocity accuracy of acetone MTV measurements applied to supersonic microjets and found it to be approximately 3.5 percent.[20] 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 percent, while the RMS error was between 0.8 and 1.2 percent.[21] These same studies reported velocity precisions as low as 0.08 m/s, or approximately 1.2 percent of the flow velocity. Finally, studies by Bathel et al., which utilized NO MTV to study various hypersonic flows reported measurement uncertainties of approximately 3 percent, or 30 m/s.

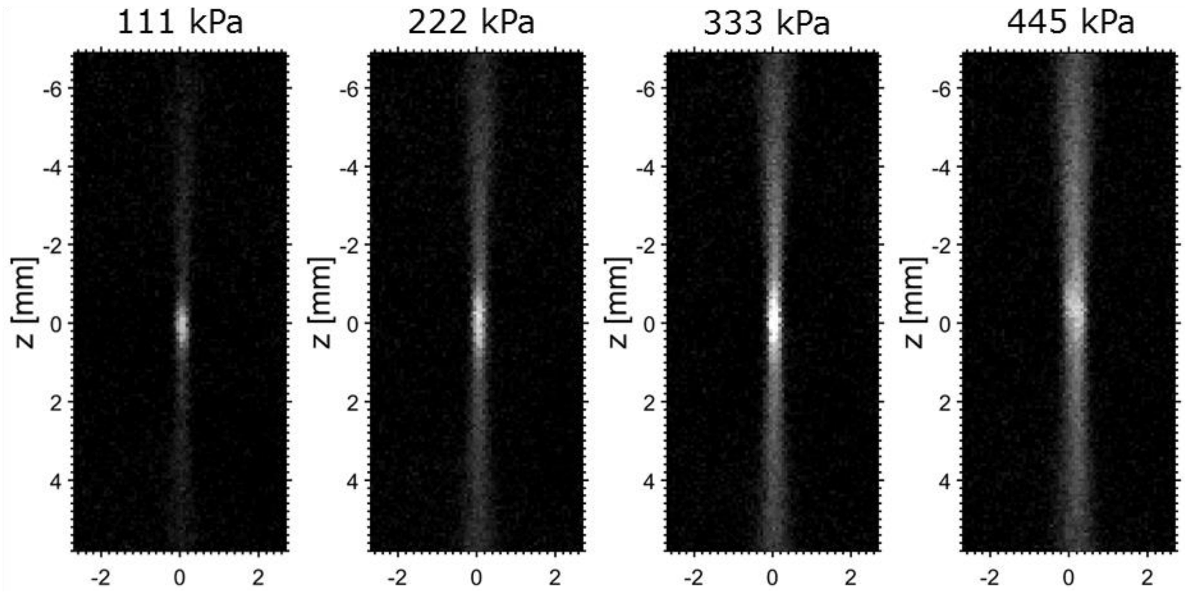

Figure 4. Sample instantaneous Rayleigh scattering images taken at four different pressures. Mach 0.4 and T = 228 K for all conditions.

In the context of these related measurements, the velocity measurements performed using FLEET in the 0.3-m TCT facility are of comparable quality or exceed the performance observed in other studies.

B. Rayleigh Scattering

Sample instantaneous laser Rayleigh scattering images are presented in Fig. 4. In these images, the laser beam enters (converging) from the top, passes through the optical focus, and diverges as it exits the imaging field of view. These images have been cropped, rotated, and were subjected to a numerical background subtraction routine. The bright section near the center of each image is residual FLEET signal and light from other non-linear optical processes resulting from the fs-laser excitation that was nearly resonant with the laser wavelength, allowing it to pass through the filter. The quality of the instantaneous images was of great concern to the authors. A previous attempt at using laser Rayleigh scattering from an ultrafast laser source found insufficient signal with instantaneous images over most of the testing matrix and required four-shot accumulations to provide sufficient signal for analysis.[14] The use of an EMCCD sensor in these studies as compared to an sCMOS camera provided a significant increase in the signals (due both to gain and higher quantum efficiency) with comparable read noise. As a result, the instantaneous images were of sufficient quality to allow assessment of the density using the single-shot Rayleigh scattering images. In the analysis of the data, the Rayleigh scattering signal was summed across the width of, and

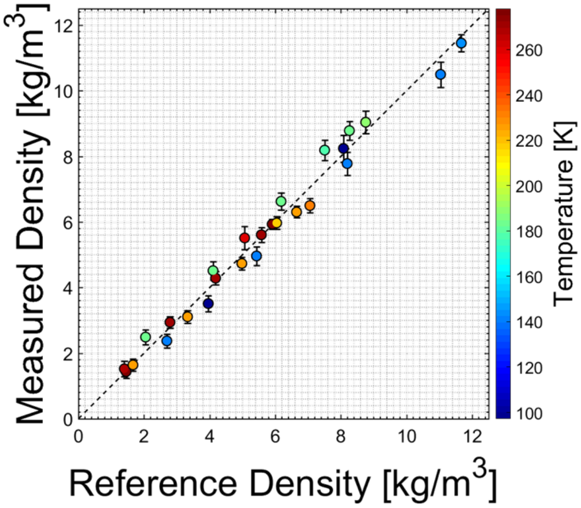

Figure 5. Comparison of density measured through Rayleigh scattering with the facility data acquisition system. Dashed line indicates perfect agreement, and uncertainty bars represent the 95 percent (2σ) bounds.

along the laser beam up to, but not including, the focus: the central region at the laser's focus containing the residual FLEET signal was specifically omitted from consideration in this analysis.

Figure 5 shows a comparison of the density measured through Rayleigh scattering to that measured by the facility DAS. The uncertainty bars in Fig. 5 correspond to the 95% (2σ) confidence level. To assess the measurement accuracy, the experimental data was fit with a linear function (RS signal vs density), and the signals predicted at each density were then compared to the observed signal at these same densities. This procedure is similar to the type of calibration that would be applied to *in situ* data. Using this methodology, the mean error was found to be 5.4 percent (with symmetric positive and negative biasing as is expected with this methodology), while the RMS error was found to be 6.4 percent. The measurement precision was taken to be the standard deviation of the observed signals in each data set. At the 95 percent confidence level, the precision was found to be approximately 6 percent, with a lower percent precision observed at higher densities due to the signals increasing over both the fixed read noise and the shot noise, which only grows as the square root of the signal intensity. This measurement precision is a significant improvement over the previous attempts at performing Rayleigh scattering in the same facility[14] likely owing to the higher signal to noise ratio as described previously. It should also be noted that no correction was made for shot-to-shot laser intensity variations, which account for $O(1\%)$ of the fluctuations. Thus it is possible to further reduce the observed fluctuations.

Assessing these measurements in a broader context is difficult due to the unusual temperature and pressure conditions in which the measurements were made. Inferred density measurements in similar conditions made by Woodmansee et al. using high-resolution N_2 coherent anti-Stokes Raman spectroscopy (CARS) in a lab-scale underexpanded jet showed a few percent error (not stated overtly) when comparing their measurements to a theoretical distribution, and precisions ranging from 4 to 10 percent.[22] Density measurements made via nitric oxide laser-induced fluorescence by Gross et al. operated with a measurement uncertainty of 2 percent in a moderate pressure, low temperature flow (Mach 2 turbulent boundary layer).[23] Filtered Rayleigh scattering (FRS) experiments of Forkey et al.[24] showed total measurement uncertainties of approximately 5 percent in measuring gaseous densities. Additionally, absolute molecular density measurements made by Balla and Everhart in a low-temperature Mach 10 flow yielded precisions between 32 and 6 percent, with the larger imprecision occurring at the lowest densities.[25] Ultimately, though the conditions under which the measurements were made were not identical, similar or superior accuracies and precisions were observed with these density measurements compared with using other optical diagnostics.

C. Regarding simultaneous measurements

The data in these tests, though collected concurrently, were not time-correlated. Consequently, using the data to assess joint statistics in velocity and density is not possible currently. Nonetheless, the individual assessments of these techniques provide insight into the advantages and shortcoming of such a simultaneous measurement if and when it is conducted. This section will specifically focus on the accuracy, precision, spatial resolution, and temporal resolution of such a measurement and how it pertains to the components of the joint technique.

There are several primary advantages to this experimental scheme. The techniques are both experimentally simple to implement; a single laser and camera are required for both of these techniques (one camera per measurement), and they both operate off the same laser pulse. This simplicity is paramount for the implementation in challenging experimental environments like the one discussed in this paper, where the experimental conditions include large-amplitude vibrations and shifting optical paths. Alternative MTV techniques often require multiple overlapping laser beams to excite and probe the flow; maintaining optical alignment under these experimental conditions would be very difficult. The second main advantage is that the two measurements, though originating from the same pulse, are independent techniques. The experimental independence is advantageous because it means the two techniques are unlikely to suffer from the same experimental biases, implying a possibility of correcting any observed biases. Moreover, in constructing joint statistics, it is unlikely that a measurement bias in one technique or the other will be further amplified in the multiplication or convolution process. Finally, the velocity measurements provided by FLEET are two-component as presented in these studies, but can be measure three-velocity components as well with stereoscopic imaging.[26] As a result, multiple components of the turbulent fluxes and stresses can be directly measured much like the velocity components with a multi-wire hotwire anemometer, but without any assumptions made regarding the density. Combined with the experimental simplicity, this joint technique has the potential to provide a wealth of information with a lesser degree of difficulty than related techniques.

Despite the potential advantages of this joint technique, the limitations observed in the individual component measurements will affect the simultaneous measurement adversely. The measurement accuracies presented here (1.5 percent for velocity and 5.4 percent for density), were comparable or exceeded those of similar and related techniques found in the literature. However, the larger errors and symmetric biasing observed in the density measurements indicate a greater likelihood of a biased compressible Reynolds stress measurement, since it is unlikely that such a bias could be detected and subsequently corrected. Ultimately these factors would be pooled into an uncertainty for the joint measurement, and the determination of sufficiency would lie with the researcher in need of the data. Much the same could be said of the measurement precision, where similarly favorable comparisons with the literature were found. However, the measurement precision has a more pronounced effect on the quality of the joint measurement because it directly affects the sensitivity of the technique. The observed precisions pose a limitation to the levels of fluctuations that can be observed in the experiment. For instance, freestream fluctuations in velocity are typically below 1 percent, and the homogeneity in the density is likely of the same order. As a consequence, it is unlikely that an accurate assessment of freestream turbulent fluctuations or Reynolds stresses could be clearly resolved with the current experimental apparatus. In addition to the contributions from the velocity precision (which are relatively small, but of the same order as the freestream fluctuations), the fluctuations in density would artificially increase the observed Reynolds stress. This does not imply that the technique is without merit, simply that it is suitable for measurements in more chaotic environments where turbulent fluctuations in the velocity and thermodynamic properties are larger. For instance, a common flow in TCT-type facilities is the wake of an airfoil or bluff body. The FLEET measurement system described in this paper was used to assess such a wake in a previous study.[15] Turbulent fluctuations in such environments are substantially greater in magnitude, and as a result, the instrument precisions in both components of the joint measurement comprise a small portion of the observed fluctuations. In such an environment, the joint FLEET/RS measurement would be more than satisfactory for measuring turbulent quantities of interest. As stated previously, the precision of the RS measurements could be further enhanced by making corrections for the shot-to-shot laser energy fluctuations, which were not done in these studies. This could further extend the range of applicability of the joint technique, though it is still unlikely it would be sufficient for an analysis of freestream conditions due to the small magnitudes involved.

The spatial resolution is another concern for the joint measurement as it is currently constructed. The velocity measurements have a minimum spatial resolution corresponding to the length of the trajectory considered in evaluating the velocity, and it takes on a minimum value of the FLEET spot size (approximately 2 mm). Additionally, boresight imaging causes a line-of-sight integration effect, meaning that the entire length of the line is compressed into a single spot. This effect broadens the span-wise spatial resolution to the length of the line, or approximately 2 mm. Thus, for the velocity measurements, the minimum spatial resolution is a 2 mm × 2 mm × 2 mm volume. Further to this, the density measurement extracted from the Rayleigh scattering is nonlocal since the measurement specifically excluded the region where the FLEET signal is concentrated (as described in Section 3.B). The implication of the nonlocality is that the minimum effective spatial resolution of the joint measurement (as currently constructed) is 2 mm × 2 mm in the streamwise and transverse directions, and up to 6 mm in the span-wise direction. Obviously the needs of the experiment dictate whether this is sufficient, but these measurements exceed the resolution afforded by most hotwires.

The Lagrangian nature of the velocity measurement limits the degree to which the spatial resolution of the velocity measurement could be improved. It is possible to improve the RS measurement, however. Specifically, overcoming the nonlocality of the measurement would reduce the spatial resolution to that of the velocity limit. As described above, the limitation stems from the residual light originating in the focal volume of the optical path, which interferes with the Rayleigh scattering signal. Eliminating this residual FLEET signal could potentially be accomplished in several ways. One possibility is to utilize a different wavelength for excitation, such as the second harmonic (400 nm) or a line resonant with transition in nitrogen as is done with the STARFLEET technique (around 202 nm).[27] By utilizing a shorter wavelength, the scattering signal could be moved to a less contaminated spectral region, and would also have the advantage of a larger RS cross-section, though at reduced energy. Another possibility is to use an alternative optical filtering strategy. For example, a narrower bandpass filter would remove more of the residual FLEET signal (and part of the scattering signal), but may work favorably to remove the excess signal near the focus. Alternatively, a pair of optical filters could be used (one broad and one narrow), and the relative angles between the two filters could be adjusted to optimize the passband to reduce the residual FLEET signal as much as possible. Finally, utilizing an intensified camera with a proper temporal gate could be advantageous in reducing the residual signal as well. In the current experiment, the laser pulse fell within 1 μs of the end of the EMCCD's exposure. However, a significant portion of the FLEET signal is generated within the first few hundred nanoseconds. Thus, if proper temporal gating could be achieved, much the observed FLEET signal could be avoided. A combination of any of these strategies would likely lead to an improvement in the spatial resolution of the RS measurements, and thus the joint measurement as well.

The temporal resolution of the joint measurement is the final topic for consideration in this section. The temporal resolution is currently limited by the RS measurement, which was limited to a frame rate of 30 Hz. This rate could have been improved by a factor of 2 by decreasing the region of interest on the sensor. The velocity measurements were obtained at 1000 Hz (for independent samples), but would have to be reduced to the RS measurements framing rate for a simultaneous measurement. Consequently, the measurements obtained with this system would not be time-resolved in the context of most flows of interest. Despite this limitation, the measurement system is well-suited to acquiring ensemble-averaged statistics. It is possible that the temporal resolution of the joint measurement could be improved by utilizing a high-speed camera and intensifier system, much like the strategy used for imaging the FLEET. This change would allow the RS measurements to be conducted at up to 1000 Hz, which may be sufficient for some flows. However, such a change would likely lead to a significant increase in imaging noise, which would further worsen the precision of the RS density measurement. Whether the tradeoff would be advisable depends on the requirements of the experiments. It could also be possible to achieve higher data acquisition rates by utilizing a pulse-burst laser system, which has been used to achieve similar velocity measurements to FLEET at up to 100 kHz with the PLEET technique.[28] However, the PLEET technique would likely produce an even greater spectral contamination than FLEET, meaning the spatial resolution might worsen, and most camera sensors are far less sensitive to the near infrared (NIR) wavelength at which the technique is typically conducted (1064 nm). Ultimately, there are tradeoffs involved with all of these strategies, and the requirements of the experiment will need to be known to dictate the best course of action.

4. Conclusions

This paper explored the possibility of combining FLEET velocimetry and laser Rayleigh scattering to make simultaneous measurements of velocity and density in high-pressure, cryogenic environments. This combination of techniques would allow a direct measurement of turbulent, compressible Reynolds stresses as well as other joint, single-point statistics. The experiments, which were conducted in NASA Langley's 0.3-m Transonic Cryogenic Tunnel, found the FLEET velocimetry measurements to have an accuracy of 1.5 percent and measurement precisions less than 1 percent in the majority of data sets. The RS measurements, which were conducted concurrently, were found to be of sufficient quality to make instantaneous measurements with the data. The inferred density measurement error was found to be 5.4 percent, while the precision was found to be around 6 percent. The potential for simultaneous measurement and resulting spatial and temporal resolutions was discussed. In particular the current detection strategy could be used if several mm spatial resolution is acceptable while modifications to the detection system could be implemented to achieve finer spatial resolution.

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