FLEET and PLIF velocimetry within a Mach 10 hypersonic air flow

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Femtosecond laser electronic excitation tagging (FLEET) and planar laser-induced fluorescence (PLIF) velocity measurements utilizing molecular tagging velocity (MTV) methods from three recent test campaigns conducted at the 31-in Mach 10 Air Tunnel at the NASA Langley Research Center are highlighted within. The FLEET measurements reported here include the first direct measurement of freestream velocity at this hypersonic wind tunnel facility. Measurement challenges were exasperated by the low gas density of the Mach 10 air freestream (~0.4\% of standard temperature and pressure conditions) and even lower gas densities within the hypersonic wake of a 70-degree sphere-cone model. In addition, the hypersonic freestream and very low speed velocities in the wake also tested the measurement dynamic range. To complement the FLEET measurements in the wake of the sphere-cone model, PLIF velocimetry using seeded nitric oxide was also performed. While NO-PLIF velocimetry has been performed at this facility several times by previous researchers, the use of a 1D diffractive optical element (DOE) for NO-PLIF velocimetry is reported here for the first time. The 1D DOE enabled the generation of up to 75 laser lines simultaneously and improved the spatial extent of the measurement three times compared to previous work. This enabled a wide velocity measurement plane of approximately 130 mm x 130 mm. The velocimetry methods demonstrated here are expected to improve wind tunnel characterization, provide critical data to validate CFD codes, and improve the design of flight vehicles for planetary entry.

I. Introduction

Velocity measurements in hypersonic wind tunnel facilities are highly desirable to characterize the flow conditions, to deliver test data to engineer better flight vehicles, and to provide validation data for computational fluid dynamics (CFD) simulations. Measurements within hypersonic flows (Mach numbers greater than 5) are particularly challenging to perform in a non-intrusive manner, as physical probes and particle-based measurement techniques often cannot be used within such facilities without disturbing the flow. Since hypersonic wind tunnel flows experience significant gas-dynamic expansion to accelerate these flows to high Mach numbers, low static densities within the freestream and wake also create challenging environments for density-based measurement techniques. On the other hand, molecular-based measurements such as planar laser-induced fluorescence (PLIF) and femtosecond laser electronic excitation tagging (FLEET), are well-suited for measurements within these flow fields [1]. The reader is also referred to recent articles by Miles et al. [2] and Jiang et al. [3] for an overview of measurement progress within hypersonic flows over the last several years.

In the present work, we apply the FLEET technique at 1 kHz repetition-rate to measure the freestream velocity of a Mach 10 hypersonic air flow and the wake velocity behind a blunt body. The reader is referred to a recent review of the FLEET measurement technique by Danehy et al. [4]. While the FLEET measurement technique has been used numerous times within high-speed nitrogen flows, there has only been limited use of the technique within high-speed air flows [5, 6, 7]. Challenges for the FLEET measurement technique within hypersonic air flows

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found in ground test facilities include low gas density and quenching of the FLEET signal by oxygen which reduces the peak signal intensity and shortens the lifetime of the FLEET signal.

Although recent efforts have been made to extend the spatial dimensionality of FLEET [8], only a single write line is generated for the FLEET measurements reported in this work. We instead perform multi-line molecular tagging velocimetry in the wake of the blunt body using the PLIF technique with seeded nitric oxide (NO) to measure the wake structure. NO-PLIF fluorescence tagging velocimetry, which was first reported by Danehy et al. [9], has been used within Mach 10 hypersonic boundary layers [10] and wakes [11]. In the present work, PLIF-based velocity measurements were performed in a 2D plane by using a 1D diffractive optical element (DOE) to split the ultraviolet (UV) laser beam into 75 beams, which were each focused near the wind tunnel centerline and behind the wake of the model. To the best of our knowledge, this is the first time a DOE optic has been used for gas phase molecular tagging velocimetry.

The wind tunnel model used in the present work is a 70-degree sphere-cone model that is representative of the LOFTID (Low-Earth Orbit Flight Test of an Inflatable Decelerator) flight vehicle. The LOFTID flight test was successfully performed on November 10, 2022, concurrently with wind tunnel testing. Although the FLEET and PLIF data from the wind tunnel test campaigns, which are highlighted in this wakeflow results section of this paper, were not available during flight test planning, the data are expected to be valuable to support post-flight reconstruction. The data are also expected to aid in the development of computational fluid dynamics codes, which will support the continued maturation of hypersonic inflatable aerodynamic decelerator (HIAD) technology for Earth re-entry and Martian entry, in addition to future missions towards planetary bodies further away in our solar system such as Titan.

II. Experimental Systems

The experimental systems for the FLEET and PLIF velocimetry measurements conducted at the NASA Langley 31-in Mach 10 Air Tunnel are described in this section. A brief overview of the blowdown wind tunnel is provided along with details of the single test condition used for the three different velocity measurements reported in this paper: freestream FLEET, wakeflow FLEET, and wakeflow PLIF. Detailed descriptions of the FLEET and PLIF measurement systems, as they were installed at the facility for these tests, are also provided. A brief description of the wind tunnel model used for the wakeflow FLEET and wakeflow PLIF velocity measurements is also provided.

A. Wind Tunnel Facility

All measurements reported in this paper were performed at the 31-in Mach 10 Air Tunnel located within the Langley Aerothermodynamics Laboratory (LAL) at the NASA Langley Research Center. An artist’s rendering of the wind tunnel facility is shown in Fig. 1. The wind tunnel is a blowdown hypersonic facility that features a 12.5 MW heater and a square test section with optical access on three sides. The facility has a typical freestream unit Reynolds number $Re_{\infty}/L$ range of approximately $1.8 \times 10^6 - 6.3 \times 10^6 \, \text{m}^{-1} \, (0.5 \times 10^6 - 1.8 \times 10^6 \, \text{ft}^{-1})$. Additional details on the facility can be found in Berger et al. [12].

Measurements reported in this paper were obtained at a single freestream condition corresponding to $Re_{\infty}/L = 1.8 \times 10^6 \, \text{m}^{-1}$ over three separate test campaigns. The calculated freestream velocity at this test condition was 1386 m/s according to computations based on the facility data acquisition system. Detailed stagnation and freestream parameters for this test condition are presented in Table 1. Run durations of 100 seconds were performed for the freestream measurements, which allowed for the translation of the laser system to several measurement locations within a single run, while providing a statistically significant time period (5 seconds) and data samples (5,000 independent measurements) per measurement location. Run durations were typically limited to 10 seconds for

<table>
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<th>Value</th>
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<td>$967 \pm 1 , [K]$</td>
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<tr>
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<tr>
<td>$u_{\infty}$</td>
<td>$1385 \pm 1 , [m/s]$</td>
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measurements with the model, due primarily to thermal concerns of the model hardware. This allowed for 10,000 independent measurements per location for the wakeflow FLEET and 100 independent measurements for the wakeflow PLIF. Run durations of 30 seconds were performed towards the end of the PLIF test campaign, with the longer runs not showing any additional negative effects on model hardware based on visual inspection.

B. FLEET System

The FLEET measurements of the tunnel freestream and model wake were performed with a 1 kHz femtosecond laser system (Spectra-Physics Solstice®). The laser system was located at the wind tunnel facility approximately 20 meters from the test section. Seven mirrors, coated to reflect ultrafast pulses centered at 800 nm, were used between the optical table housing the laser, which was located within an enclosed cart, and the lens system located at the tunnel test section. A CAD schematic of the FLEET set-up at the wind tunnel is shown in Fig. 2(a). Some self-focusing of the laser was observed over this long propagation distance; therefore, a telescope consisting of a -100 mm spherical lens and a +200 mm spherical lens was installed near the laser exit to ensure a nearly collimated laser beam at the test section, thereby minimizing the risk of damaging optics and tunnel windows. A second telescope consisting of a -75 mm spherical lens and a +200 mm spherical lens was installed near the test section to expand the laser beam diameter to approximately 45 mm before a 4-in diameter +500 mm spherical lens, located as close as 30 mm above the tunnel window, focused the femtosecond laser beam within the test section. The primary advantages of using the second telescope at the test section were to: 1) reduce the fluence of the laser as it passed through the approximately 54-mm-thick tunnel window to avoid damage, and 2) create a tighter focus within the test section, increasing the FLEET signal. The laser energy inside the test section was approximately 2 mJ per pulse.

Although freestream and wake measurements are reported at only a single spatial location in this paper, the FLEET optics were mounted on two different translation stages to allow the FLEET focus to be translated in two different directions. The final mirror and the lens system were located on a translation stage system that allowed the laser to be translated horizontally (in the +x direction) to probe several locations from the tunnel centerline and towards the side wall. Measurements were performed at discrete locations from the tunnel centerline to approximately

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Fig. 1. 3D schematic of the Langley Aerothermodynamics Laboratory (LAL) 31-in Mach 10 Tunnel, courtesy of Richard A. Wheless from the NASA Langley Research Center.
\( x = +180 \text{ mm} \) away from the centerline of the tunnel. In the current optical configuration, FLEET measurements were restricted to about 45\% of the distance from the centerline towards the wall because of the width of the top tunnel window. A second translation stage was paired with the focusing lens to allow the FLEET probe volume to be translated vertically (in the +y direction), which allowed measurements to be performed in the model wake at several different radial locations away from the model centerline.

The detection system used for the FLEET measurements consisted primarily of a 135 mm Canon® f/2 lens, a LaVision® S20 IRO, and a Phantom® TMX 7510. The camera lens was equipped with an ISSI® EF Lens Controller for remote focus adjustment, which allowed the camera focus to be remotely adjusted for the various probe locations during the 100 second freestream tunnel run. The TMX camera was operated in burst-mode at 875 kHz such that 10 images were obtained for every laser pulse, with the camera operating with 1280 by 64 pixels and with a pixel size of 18.5 microns. The spatial resolution of the FLEET camera was approximately 110 μm/pixel in the middle of the tunnel, with the camera system placed as close to the side window as practical to allow for increased spatial resolution. The camera timing was set-up such that the first image, which had charge built-up on the camera sensor due to the

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Fig. 2. 3D schematics of the wind tunnel facility with the measurement systems: (a) FLEET and (b) PLIF.
burst mode operation, was discarded and the second image was used as a dark noise background. Images 3-7 of the 10-image sequence correspond to different time delays for the freestream FLEET and images 3-9 of the 10-image sequence correspond to different time delays for the wakeflow FLEET. The acquisition of the initial FLEET image was set to approximately 250 ns after the laser pulse in order to eliminate any spurious laser scattering or Rayleigh scattering effects. This delay also was optimized such that the IRO could operate at very high gains corresponding to a gain of 82% on the IRO control for the freestream measurements and a gain of 88% on the IRO control for the wake measurements, without saturating the camera sensor. Such high gains necessitated eliminating all spurious light sources in the vicinity of the wind tunnel. The intensifier gates were varied from 70 to 600 ns during the acquisition burst, with longer gates occurring at later times to compensate for the decreasing signal intensity after the laser pulse. Only sequences of three images are discussed in this paper, corresponding to delays centered at: Δt = 0 μs for the initial image, Δt = 1.27 μs for the 1st delayed image, and Δt = 2.41 μs for the 2nd delayed image. A gate of 70 ns was used for the initial image and gates of 300 ns are used for the two delayed images. The longer gates for the two delayed images were used to compensate for the decaying FLEET signal.

C. PLIF System

The NO-PLIF molecular tagging velocimetry (MTV) measurements were performed using a 10 Hz Spectra-Physics® Pro-230 Nd:YAG laser that was used to pump a Sirah® Cobra Stretch dye laser with a frequency conversion unit (FCU). The second harmonic of the 10-ns pulsed YAG laser at a 532 nm wavelength was used to pump the dye laser to generate a 622 nm wavelength, which was sum-frequency mixed with the third harmonic of the YAG laser at 355-nm wavelength to generate approximately 4 mJ per pulse of UV tunable light near 226 nm wavelength. Further details on the PLIF system can be found in Rodrigues et al. [13]. The laser systems were located within an enclosed cart, with a propagation distance of approximately 13 meters between the optical table and the optics at the test section. A CAD schematic of the PLIF set-up at the wind tunnel is shown in Fig. 2(b). The laser wavelength was tuned to the Q-branch band-head of NO near 226.26 nm and was directed to the test section using five mirrors that were coated to reflect 226-nm light.

To perform MTV, a commercial 1D diffractive optical element (DOE) was used to split the collimated 226 nm beam near the test section into 75 collimated but diverging beams of nearly equal laser energy. A +1000 mm spherical lens (with a clear aperture of approximately 14 cm) was used to collimate the diverging angles of these beams, while simultaneously focusing each individual beam at the centerline of the tunnel. Compared to previous work at the facility such as the one reported by Bathel et al. [10] using a micro lens array, the use of the 1D DOE allowed for up to three times as many write lines to be generated (75 vs. 25) and the individual beams were focused to narrower lines at the test section. Narrower lines help increase the fluorescence signal intensity and also make tracking displacement of the lines more precise. The laser lines were carefully aligned to cross through the centerline of the wind tunnel model and the +1000 mm spherical lens was placed such that the focal point of the laser line was near the model centerline.

Fluorescence from the laser beams appeared as parallel lines by the PLIF camera, which was located on the side window of the tunnel. The PLIF camera system consisted of an intensified Andor® iStar front-illuminated scientific CMOS (sCMOS) camera. The camera sensor featured an 18-mm diameter WE-AGT photocathode with ultra-fast gating and used the P46 phosphor. The size of the round photocathode relative to the size of the rectangular sensor resulted in signal not being acquired for the pixels near the corners of the sensor. The sCMOS sensor incorporated 2560 by 2160 pixels with a 6.5-micron pixel size, but 2x1 binning of the sensor in the direction of laser propagation was performed during data acquisition to reduce the memory load during image acquisition. The 2x1 binning resulted in 2560x1080 pixels with an effective pixel size of 6.5 x 13 micron. The camera was operated at 20 Hz and configured to provide two intensifier gates centered approximately Δt = 0.59 μs apart. An intensifier gate of 20 ns was used for the initial image and a gate of 200 ns was used for the delayed image. The acquisition of the initial image was set to approximately 20 ns after the laser pulse in order to eliminate any spurious laser scattering and to remove the uncertainty associated with laser jitter. The longer gate used in the second exposure compensated for the reduced fluorescence resulting from the exponentially decaying signal. The camera was operated with a 45-mm Cerco® f/1.8 UV camera lens and a long-wavelength-pass filter with an edge near 230 nm, which blocked the laser wavelength near 226 and fluorescence from the (0, 0) band, but transmitted fluorescence from the (0, 1) through (0, 5) bands. The camera system was placed relative to the side window such that the field-of-view was large enough to view the entire vertical wake. The images were binned in a 1x2 pixel binning prior to performing an image dewarping, such that the image prior to dewarping corresponds to 1280x1080 pixels, with a spatial resolution corresponding to approximately 149 μm/pixel.
D. Wind Tunnel Model

The wind tunnel model used for this work was a 70-degree sphere-cone based on the LOFTID (Low Earth Orbit Flight Test of an Inflatable Decelerator) flight vehicle [14]. The model featured a metal forebody, with an outer diameter of 127 mm (5"), and a stereolithography (SLA) manufactured plastic aft body. A schematic of the wind tunnel model is shown in Fig. 3. A smooth concave aft body design with a cylindrical payload was used for this test entry and a blade sting was used to hold the model away from its centerline within the wind tunnel, thereby not

Fig. 3. 3D CAD schematics of the 70-degree sphere-cone model used for the present work: (a) side view and (b) back view. The model forebody and payload shown in (a) are geometrically representative of the LOFTID flight vehicle. The smooth aft body features 130 small holes for seeding the flow with nitric oxide, shown in (b), with the location of the PLIF velocimetry on the model centerline indicated by the purple line.

Fig. 4. (a) Instantaneous and (b) average NO-PLIF images, with signal intensity shown in a logarithmic scale, of the hypersonic wake created by the 70-degree sphere-cone model at the \( Re_{\infty}/L = 1.78 \times 10^6 \text{ m}^{-1} \) condition. The location of the wakeflow FLEET measurement described in this paper is indicated by the red \( x \) in (b).
noticeably affecting the flow at the model centerline. FLEET wakeflow measurements were performed at several spanwise ($r$) locations in the model wake at a single streamwise location of $z = 12$ mm. For the NO-PLIF wakeflow measurements, an internal gas pathway design allowed nitric oxide gas at a volumetric flowrate of 1 SLM to be seeded into the wake through 130 small holes located on the aft body. The small (0.56 mm diameter) holes were located in a pattern designed to promote uniform seeding. The NO flowrate was varied from 0.05 SLM to 1 SLM during shakedown testing, with the NO flow not appearing to affect the wakeflow based on PLIF flow visualization. Figure 4 shows an instantaneous and average 2D PLIF image at the model centerline for the wind tunnel conditions shown in Table 1. Flow visualization data were acquired during the same test entry as the PLIF velocimetry data by replacing the 1D DOE with a negative cylindrical lens to form a 2D laser sheet. Results from the PLIF flow visualization, and the quantitative metrics that are extracted from the flow visualization images, such as the radial extent of the wake, are not discussed within the current paper.

III. Results and Discussion

A. Freestream FLEET

Cropped, time-averaged and instantaneous images of the freestream FLEET measurements at the centerline of the wind tunnel are shown in Fig. 5. The initial images are shown in Fig. 5(a) and images at two different delays corresponding to $\Delta t = 1.27 \mu s$ and $\Delta t = 2.41 \mu s$ are shown in Fig. 5(b) and (c), respectively. The average images

![Fig. 5](image)

Fig. 5. Average and instantaneous freestream FLEET images at the wind tunnel centerline: (a) initial image centered at $t = 0 \mu s$, (b) 1st delay image centered at $t = 1.27 \mu s$, (c) and 2nd delay image centered at $t = 2.41 \mu s$. The aspect ratio of the image is 1:1.
shown on the left column of Fig. 5 consist of 5000 laser shots and possess a high signal-to-noise ratio (SNR). The instantaneous FLEET images on the right column show lower SNR for both the initial image and the delayed image at Δt = 1.27 μs, with further reduced SNR for the delayed image at Δt = 2.41 μs. When considering the very low gas densities of the Mach 10 freestream at this condition, approximately 0.005 kg/m³ or 0.4% of standard temperature and pressure (STP) conditions, the relatively distinct FLEET spot of the single-shot data enables freestream FLEET measurements. In addition, the clear displacement of the FLEET signal between the initial image and the two delayed images illustrate their feasibility for a velocity measurement. It is noted that the instantaneous FLEET signal appears to become more spatially diffuse with time. The spread in the signal within (b) and (c) may be partially attributed to the wider gates of 300 ns, as the expected image blurring is less than 4 pixels for (b) and (c), compared to less than one pixel for the gate of 70 ns for (a). However, it is also possible that the very low gas densities of the freestream results in relatively rapid diffusion of the FLEET signal.

Given that the spanwise component of velocity is negligible for freestream velocity measurements, the cropped, time-averaged and single-shot FLEET images were processed with a full-vertical-bin to improve the precision of the location of the centroid of the FLEET signal in the streamwise direction. This resulted in a vertical spatial resolution of approximately 2 mm for the freestream velocity measurements. The FLEET signal intensity vs. streamwise displacement (Δx) are shown in Fig. 6 for the images presented in Fig. 5. Three distinct peaks can clearly be observed for both the time-averaged and single-shot data in Fig. 6. Also shown in Fig. 6 are the fits used to calculate the centroids, with the position of the centroids themselves indicated by vertical dashed lines. An iterative procedure was used for the fitting routine such that a Gaussian curve was first used for the pseudo-Voigt fit. The pseudo-Voigt fit equation was a weighted sum of the Gaussian and Lorentzian equations and generally resulted in better fits near the wings compared to the simple Gaussian.

While the acquisition of an initial and delayed image for molecular tagging velocimetry can provide a velocity measurement based on a single Δz and Δt, four different methods to calculate velocity are available using the initial image and the two delayed images. Velocity measurements using the initial image and the first delayed image at Δt = 1.27 μs are noted in this paper with a "2→1" subscript, whereas velocity measurements using the first delayed image (Δt = 1.27 μs) and the second delayed image (Δt = 2.41 μs) are noted with a "3→2" subscript and velocity measurements using the initial image (Δt = 0 μs) and second delayed image (Δt = 2.41 μs) are noted with the "3→1" subscript. A fourth method of using a linear fit with all three shot data is noted with the "FIT" subscript. Time-averaged and instantaneous velocity measurements using all four methods are presented in Fig. 7, for the images shown in Fig. 5 and the fits shown the Fig. 6. Agreement within 1% is observed for the freestream velocity when comparing the four methods for the time-averaged data. The experimental uncertainty of velocity was calculated in quadrature for the "2→1", "3→2", and "3→1" methods based on the calculated 95% confidence of the fits, estimated timing uncertainty (<< 1%), and estimated magnification uncertainty (1%). A different approach was taken for the calculated uncertainty of the "FIT" method, as this is reported as the calculated 95% confidence of only the linear fit. A much lower uncertainty of a mere 2 m/s is reported for the time-averaged measurement using the "FIT" method, compared to similar values of 15 - 18 m/s for the other three methods.

Comparing the single-shot velocities shows an agreement within 1% between the four methods, while the calculated uncertainties for all four methods range from 15 m/s to 19 m/s. This implies that the linear fit may not necessarily be the best method to process the single-shot data. While three data points are better than two, using three data points may increase the likelihood of significant Poisson noise appearing in the single-shot image due to the image intensifier operating at very high gain. Single-shot velocity measurements were calculated using all four methods for N = 5000 laser shots and Table 2 shows some of the key metrics for comparison of the different methods: arithmetic mean (μ) of velocity u, two times the standard deviation (2σ) of u, a 2σ/√N precision metric, and the μ of the calculated velocity uncertainty U(u). Such 2σ results are reported here because they are associated with 95%

<table>
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<th>Method</th>
<th>μ of u</th>
<th>2σ of u</th>
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Table 2. Comparison of mean velocity of u and velocity uncertainty U(u) based on four different methods for freestream velocity measurements, computed using a sample size of 5000 instantaneous data points.
Fig. 6. Freestream FLEET signal intensity vs. streamwise position $z$ at the tunnel centerline based on full vertical binning of the FLEET signal for three time delays: (a) time-averaged data, (b) instantaneous data. Also shown are pseudo-Voigt fits, with the calculated centroids illustrated as vertical dashed lines.
Fig. 7. Freestream displacement ($\Delta z$) vs. time ($\Delta t$) for three different time delays for: (a) time-averaged data, (b) representative instantaneous data. Also shown are the time-averaged velocity $\bar{u}$ and instantaneous velocity $u$ based on four different methods.

Fig. 8. Freestream velocity $u$ vs. time using the 3→1 method for data processing. Five seconds of wind tunnel data are shown in (a). A sub-set of the data is shown in (b) for 0.1 seconds of the recorded data. The measured $u_{\text{RMS}}/u_{\text{MEAN}} \approx 1.7\%$ for this test condition.
confidence intervals. While all four methods performed similarly, the “3→1” method (highlighted in Table 2) appears to perform the best in terms of the mean of the velocity uncertainty. This can be attributed to the larger displacement from the “3→1” method compared to the “2→1” and “3→2” methods, while using only two, instead of three, data points and thereby reducing the possibility of Poisson noise confounding the FLEET signal. All 5000 single-shot velocity measurements using the “3→1” method are shown in Fig. 8(a), with a sample of the data from  \( t = 2\) s to  \( t = 2.1\) s shown in (b). The mean velocity of 1389 m/s agrees within 0.2% of the velocity calculated using the wind tunnel facility data acquisition system. Furthermore, the root-mean-square (RMS) of velocity normalized to the mean was determined to be  \( u_{\text{RMS}}/u_{\text{MEAN}} = 1.9\%\). Based on the mean of the calculated velocity uncertainty of 1.2% using this method, we believe that the  \( u_{\text{RMS}}/u_{\text{MEAN}} = 1.9\%\) reflects a value of freestream fluctuation that is not simply limited by the instrument precision; in other words, we believe this value contains real fluctuations from the facility. Further improvements in the fitting procedure and a more precise estimate of the magnification uncertainty are expected to reduce the calculated uncertainty of velocity. Ongoing efforts to determine the  \( u_{\text{RMS}}/u_{\text{MEAN}}\) at nearly stagnant (or zero-velocity) conditions for a range of gas densities will also be useful to quantify the precision of the instrument, which may better inform determination of the actual freestream velocity fluctuations. In future publications, we plan to report  \( u_{\text{RMS}}/u_{\text{MEAN}}\) at other freestream Re/L conditions of 3.6\( \times \)10\(^6\) m\(^{-1}\) and 5.4\( \times \)10\(^6\) m\(^{-1}\), which may possess larger fluctuations based on their greater Reynolds numbers.

**B. Wakeflow FLEET**

FLEET measurements within the wake of the 70-deg. sphere-cone model are reported at the model centerline \( r = 0\) and approximately 12 mm downstream of the model payload (\( z = 12\) mm). This measurement location corresponds to a very low-speed region of the hypersonic wake and was believed to possess reverse flow towards the payload based on computational fluid dynamics simulations of similar model geometries. It presents a unique velocity measurement challenge as the magnitude of velocity at this location is believed to be significantly lower than the freestream velocity. The gas density at this location is also believed to be much lower than the freestream gas density, due to the higher temperature (approximately 10 times the freestream temperature) and lower pressure (approximately half the freestream pressure).

Cropped time-averaged and instantaneous images of the wakeflow FLEET measurements are shown in Fig. 9. Time-averaged and instantaneous images are shown in (a) and (b), respectively, for the initial image at  \( \Delta t = 0\) \( \mu\)s, the first delayed image at  \( \Delta t = 1.27\) \( \mu\)s, and the second delayed image at  \( \Delta t = 2.41\) \( \mu\)s. The average images shown in Fig. 9(a) consist of 10,000 laser shots and has a smooth appearance. The instantaneous FLEET images in Fig. 9(b) show relatively good SNR for the initial image, lower SNR for the 1\(^{st}\) delayed image at  \( \Delta t = 1.27\) \( \mu\)s, and even lower SNR for the 2\(^{nd}\) delayed image. The very low gas densities at this measurement location are believed to also encourage rapid diffusion of the FLEET signal: the width of the FLEET signal appears to become wider with increased delay despite an expected negligible impact of motion blur. Unlike the clear displacement seen for the freestream FLEET signal between the initial image and the two delayed images, the much lower velocity flow in this wake region does not indicate a clear displacement in even the average wakeflow FLEET image. Nonetheless, full vertical bins provided enough averaging to obtain single-shot velocities. This method is believed to be valid for this spatial location because the spanwise component of velocity is believed to be negligible here. Furthermore, the reduced vertical spatial resolution of approximately 2 mm is believed to be much smaller than the spatial scales of the relatively large-scale structures of the flow based on the PLIF flow visualization images such as the one shown in Fig. 4. The spanwise gradient of the streamwise velocity (\( \Delta u/\Delta r \)) is also believed to be negligible for this region, based on the PLIF molecular tagging velocimetry measurements reported in the following section.

The FLEET signal intensity vs. streamwise displacement (\( \Delta z \)) after full-vertical-binning is shown in Fig. 10(a) for the average images presented in Fig. 9(a). Three distinct peaks can clearly be observed for the time-averaged data shown, with the pseudo-Voigt fits and resulting calculated centroids (show as vertical lines) indicating a reverse flow (i.e. \( \Delta z < 0 \)). The four different methods to determine velocity that were described earlier in the section for freestream velocity measurements were also applied for the time-averaged wakeflow FLEET data. The time-averaged velocity measurements are shown in Fig. 11(b), along with the \( \Delta z \) vs. \( \Delta t \). Agreement within 4% of the measured velocity is observed for the wakeflow velocity when comparing the four methods for the time-averaged data. Similar to the freestream FLEET measurements, the lowest calculated uncertainty (\( \pm 2\) m/s) was calculated using the “FIT” method. While similar values of uncertainties of 12 m/s and 13 m/s were calculated for the “2→1” and “3→2” methods, respectively, a lower uncertainty was calculated for the “3→1” method, which can be attributed primarily to the larger displacement. Although the initial image and both time delays were used for calculating velocity of the time-average images, based on Fig. 9(b) it is clear that the instantaneous image at  \( \Delta t = 2.41\) \( \mu\)s shows worse SNR than the images at  \( \Delta t = 0\) \( \mu\)s and  \( \Delta t = 1.27\) \( \mu\)s. This was typical for the entire data set of 10,000 laser shots and the “2→1” method was determined to be the best approach for processing single-shot velocity at this test condition. The instantaneous
Fig. 9. (a) Average and (b) instantaneous wake flow FLEET images near the model centerline and approximately 12 mm downstream of the payload: (a) initial image centered at $t = 0 \mu s$, (b) 1$^{st}$ delayed image centered at $t = 1.27 \mu s$, (c) and 2$^{nd}$ delayed image centered at $t = 2.41 \mu s$.

Fig. 10. (a) Wakeflow FLEET signal intensity vs. streamwise position $z$ near the model centerline and approximately 12 mm downstream of the payload based on full vertical binning of the time-averaged FLEET signal for three different time delays. (b) Displacement ($\Delta z$) vs. time ($\Delta t$) for three different time delays using the time-averaged data. Also shown in (a) are the pseudo-Voigt fits, with the centroid illustrated as vertical dashed lines. Also show in (b) is the time-averaged velocity $\bar{u}$ based on four different methods.
wakeflow FLEET signal intensity vs. streamwise position for two subsequent laser shots are shown in Fig. 11, along with the pseudo-Voigt fits and the calculated centroid position. Fig 11(a), which corresponds to the instantaneous image in Fig. 9(b), shows a slight positive ($\Delta z > 0$) displacement, whereas Fig. 11(b), acquired on the next laser pulse shows a negative ($\Delta z < 0$) displacement. While a slight reverse flow of approximately -60 m/s for the time-averaged measurements seem to agree with our intuition of this flowfield, the flow is also unsteady for this Reynolds number condition based on the instantaneous PLIF images and therefore velocities that oscillate between positive (away from the payload) and negative (towards the payload) appear to be reasonable at this location.

Figure 12(a) shows a time-series of the streamwise velocity for the entire ten seconds of the wind tunnel run (10,000) laser shots. The majority of the data appears to be within the -200 m/s < $u$ < 0 m/s range and indeed the corresponding histogram in Fig. 12(b) shows peaks for bins centered at -100 m/s, -50 m/s, and 0 m/s (using a bin size of 50 m/s). The mean value for velocity $u$ is -62 m/s and the calculated RMS of velocity is 105 m/s based on the current data processing method. The RMS value may be negatively influenced by outlier data points in the velocity time series. The histogram of the velocity uncertainty is shown in Fig. 12(c), with the majority of the measurement single-shot uncertainty in the 40 – 60 m/s range. A map of the velocity uncertainty vs. velocity is shown in Fig. 12(d).

As part of further data processing, we plan to condition the mean and RMS of velocity based on the quality of the fitted data, in order to examine the influence of the outlier data points.
Fig. 12. Wakeflow FLEET measurements using the “2→1” method of data processing: (a) instantaneous velocity vs. time, (b) velocity histogram, (c) velocity uncertainty histogram, and (d) velocity uncertainty vs. velocity.
C. Wakeflow PLIF Velocimetry

The time-averaged initial NO-PLIF MTV image illustrating the laser lines generated by the DOE is shown in Fig. 13. One hundred single-shot images were used to generate this time-averaged image, which shows 66 individual write lines out of the 75 total laser lines generated by the DOE. The 9 laser lines not seen in this image are present in the region near the model forebody and shoulder. These lines do not induce fluorescence at the 0° angle-of-attack configuration due to NO not being present at these locations. Positioning these lines slightly upstream of the wake, however, allowed measurements at the near-wake to be performed for the -5° angle-of-attack configuration, which was also tested during the campaign, without having to realign the laser lines. The camera timing was configured such that the initial image was acquired approximately 20 ns after the laser pulse, with the time delay between the first and second image centered at Δt = 0.59 μs. The relatively high levels of PLIF signal near the shoulder of the model can be attributed to the nonuniform NO concentration in the wake and are more evident in the linear scale image in Fig. 13 compared to the log-scale images in Fig. 4. Also evident in Fig. 13 is the stronger laser line several inches downstream of the payload, which coincides with the zero-order laser line generated from the DOE. This stronger laser line can largely be attributed to the wings of the laser beam overfilling the DOE, which are then focused at the wind tunnel due to the +1000 mm spherical lens. During wind tunnel runs towards the later portion of the test campaign, this effect was eliminated by using an aperture upstream of the DOE optic to clip the wings of the laser beam. While the thicker lines near the model shoulder and at the zero-order line induce some challenges for the MTV data processing, another challenge is that the laser lines are slightly angled by <0.5° relative to the camera rather than being translated vertically at 90°. While a correction for the angle is not performed for the current work, future efforts will more closely assess the need for this correction based on the relative angle between the laser lines and the model, which is aligned nearly parallel to the freestream flow (<0.1° offset) using a laser level.

The initial and delayed PLIF MTV images were further binned by 8 pixels in the vertical direction and a peak detection algorithm was used to segment each of the MTV lines. This operation was performed for each radial position after pixel binning due to the slight angle in the direction of laser propagation. Similar to the FLEET measurements, a pseudo-Voigt fit was also used to determine the centroid locations of the initial and delayed images on for each line and at each spanwise location. Figure 14(a) shows data for initial and delayed locations of a single laser line, located approximately 17 mm from the model payload. The laser angle is greatly exaggerated in this figure due to the scaling of the axes. The uncertainties in the streamwise location U(z) for the initial and delayed data, which were calculated based on the 95% confidence interval of the fit, are also shown in Fig. 14(a) as horizontal bars. Since the initial data should ideally represent a line in the absence of noise, a linear fit was used to determine the initial location of the line. This linear fit is shown as a black line in Fig. 14(a) and was used along with the delayed location to determine the

Fig. 13. NO-PLIF molecular tagging velocimetry initial image showing the laser lines generated by the DOE. The laser lines were positioned slightly upstream of the model such that 66 individual write lines (out of 75 total laser lines) are visible within the wake at the 0° angle-of-attack configuration.
Fig. 14. (a) Radial position $r$ vs. streamwise location $z$ and (b) spanwise position $r$ vs. displacement $\Delta z$ based on a single laser line located approximately 12 mm from the payload. Also shown in (a) is the linear fit for the initial ($t = 0$ $\mu$s) streamwise position, used to define the initial location for the $\Delta z$ measurement. The laser angle is greatly exaggerated in (a) due to the axes scaling.
displacement $\Delta z$ at each spanwise position. The displacement for this line is shown in Fig. 14(b), with the uncertainty in displacement represented as horizontal bars. The uncertainty in displacement $U(\Delta z)$ was calculated in quadrature based on the 95% confidence interval of the linear fit used to determine the initial location and the 95% confidence interval for the centroid of the fitted delayed data. Relatively small displacements within 0.2 mm were observed between $-50 \text{ mm} < r < 50 \text{ mm}$, implying a relatively large region of very low but negative streamwise velocity in the central wake. As mentioned in the previous section, this further justifies the use of the full-vertical-bin of the cropped wakeflow FLEET images near the centerline of the wake.

Fig. 15 shows the time-averaged streamwise velocity and the streamwise velocity uncertainty, superimposed on the wind tunnel model, for all 66 lines simultaneously created in the wake. The 2D velocity map shows the large positive streamwise velocity in the shear-layer that approaches 1000 m/s, a stagnation (zero velocity, indicated

![Fig. 15. Time-averaged streamwise velocity obtained by NO-PLIF molecular tagging velocimetry: (a) streamwise velocity $\bar{u}$, (b) uncertainty in streamwise velocity $U(\bar{u})$.](image-url)
by the black line) region within the wake, and reverse flow velocity near -200 m/s in the downstream wake near the model centerline. A calculated velocity uncertainty within 50 m/s was generally observed for most of the wake, with larger values of uncertainty near the shear layer. Similar to the FLEET measurements, the PLIF streamwise velocity uncertainty was calculated in quadrature by considering the estimated uncertainties due to displacement, timing (<< 1%), and magnification (1%).

The streamwise distributions of the time-averaged velocity for three different spanwise locations are shown in Fig. 16(a) and the spanwise distributions for four different streamwise locations are shown in Fig. 16(b). The streamwise distribution in (a) shows a velocity near -200 m/s near the model centerline at a streamwise location z near 70 mm. For spanwise locations of r = 27.5 mm and r = 50.7 mm, the streamwise velocities increase significantly as the shear layer of the wake is reached. Figure 16(b) clearly illustrates the radial extent of the wake for four different streamwise positions corresponding to z = 17 mm, z = 49 mm, z = 80 mm, and z = 112 mm. The radial extent of the wake is apparent from the velocity profiles based on the relatively high velocities at the shear layer. Also evident in Fig. 16(b) are the negative velocities near the r = 0 location, particularly at z = 80 mm. As mentioned previously, the wakeflow FLEET measurements presented in the previous section was obtained at a location corresponding to the model centerline and 12 mm downstream of the payload (r = 0 cm, z = 12 mm). The average PLIF measurement at this location was -50 (±65) m/s, which agrees within 10 m/s or 17% of the FLEET measurement at -60 (±2) m/s.

![Graphs showing velocity profiles](image)

**Fig. 16.** Velocity profiles of the time-averaged streamwise velocity ($\bar{u}$) obtained by NO-PLIF molecular tagging velocimetry: (a) streamwise distribution of $\bar{u}$, (b) spanwise distribution of $\bar{u}$. 
IV. Summary and Conclusions

In the present work, we summarize recent efforts in a Mach 10 hypersonic air flow facility using the FLEET and PLIF velocity measurement techniques. The velocity measurements described here focus on a single wind tunnel condition corresponding to $Re/L = 1.8 \times 10^6 \text{ m}^{-1} (0.54 \times 10^6 \text{ ft}^{-1})$, which is the lowest Reynolds number operating conditions typically used in this facility. FLEET measurements in the wind tunnel freestream and within the wake of a blunt-body model were performed for the first time at this facility. The measurements at the centerline show a measured velocity very close to the expected velocity of 1386 m/s based on the tunnel data acquisition system, with the mean velocity agreeing to approximately 0.2%. The $u_{\text{RMS}}/u_{\text{MEAN}}$ was determined to be 1.7% for this wind tunnel conditions and we believe that this likely includes a contribution from the true velocity fluctuations in the freestream and an estimated measurement precision of 1.2%. These velocity measurements of the freestream are the first reported direct measurements of velocity at the facility to the best of our knowledge. As part of on-going efforts, measurements that have already been acquired at the various spatial locations closer to the wind tunnel wall will be analyzed to generate a velocity profile of the freestream that shows the structure in terms of its core flow and growing boundary layer. Our intention is to report velocity profiles and velocity fluctuations for the three most commonly used Reynolds number conditions of this wind tunnel as part of future publications.

The wakeflow FLEET measurements and the wakeflow PLIF measurements represent quantitative measurements of the wake for a 70-degree sphere-cone model. The wakeflow FLEET measurements near the model centerline and at a streamwise distance approximately 12 mm from the payload show a range of velocities, primarily with the -150 m/s to 50 m/s range. The unsteady flow features revealed through the PLIF flow visualization performed during a preceding test entry corroborate with the relatively large range of velocities observed at this location based on the instantaneous FLEET data. Although not reported in this paper, wakeflow FLEET measurements were obtained for several spanwise locations of the model during this test entry for all three primary Reynolds numbers of the facility. Our intention is to describe the FLEET velocity measurements based on the different wake locations and report comparisons between the three Reynolds numbers in future publications. These future publications will also take advantage of the spatial extent of the PLIF velocity measurements, which provides coverage of the entire near wake over a region of approximately 130 mm by 130 mm. While the current time-averaged PLIF velocity measurements can be compared with steady CFD codes, on-going efforts to process the single-shot PLIF data will also be useful for comparisons with unsteady CFD codes. Comparisons between the FLEET and PLIF wake velocity measurements are also on-going, with the initial comparison showing an agreement within 10% for the two measurement techniques. Comparison of the two velocity techniques will be useful since they have different strengths: FLEET having the benefit of a 1 kHz repetition-rate but limited to a single short line at these wind tunnel conditions, and PLIF having the benefit of a greater spatial extent but being limited to a repetition-rate of 10 Hz. A third approach of utilizing emerging burst-mode laser technology as part of future efforts would also provide velocity data in the 20-200 kHz repetition-rate range for comparisons with unsteady CFD codes.

Acknowledgments

The authors acknowledge the support of the NASA Space Technology Mission Directorate (STMD) Game Changing Development (GCD) program Entry Systems Modeling and the Technology Demonstration Missions (TMD) program LOFTID. The authors also acknowledge the support of the NASA Aeronautics Research Mission Directorate (ARMD) Aerosciences Evaluation and Test Capabilities (AETC) Test Technology (TT) project for support of the FLEET measurements. The authors thank C. Mark Cagle from the NASA Langley Aeronautics Systems Engineering Branch for design of the wind tunnel model and W. Holt Ripley from the NASA Langley Advanced Measurements and Data Systems Branch for assistance with measurement set-up at the wind tunnel. The authors also thank the entire staff at the LAL 31-in Mach 10 Air Tunnel for their efforts during the wind tunnel test entry, especially facility safety head Lianne Kuster and facility coordinator Anthony Robbins. N.S. Rodrigues also thanks Dr. Ross A. Burns and Dr. Jonathan E. Retter from the NASA Langley Advanced Measurements and Data Systems Branch, affiliated with the National Institute of Aerospace during the test planning phase of this work, for helpful discussions regarding the FLEET set-up and Dr. Timothy Fahringer for assistance with the spatial calibration of the PLIF images. Specific vendor and manufacturer names are explicitly mentioned only to accurately describe the test hardware. The use of vendor and manufacturer names does not imply an endorsement by the U.S. Government, nor does it imply that the specified equipment is the best available.
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