

1-D FLEET velocimetry in an overexpanded supersonic air jet

Léa Bernardot^{1,*}, Clément Pivard¹, Nelly Dorval¹, Renaud Jalain², Michael Scherman¹

1 : DPHY, ONERA, Université Paris Saclay, F-91123, Palaiseau, France

2 : DMPE, ONERA, Université Paris Saclay, F-91123, Palaiseau, France

* Correspondent author: lea.bernardot@onera.fr

Keywords: Laser diagnostics, unseeded velocimetry, FLEET, Supersonic Jets, Mach Disk

ABSTRACT

The study of non-adapted supersonic jets is essential for optimizing nozzle designs, reducing jet noise and improving the performances and durability of aerospace propulsion systems. Experimental data retrieved using non-intrusive optical diagnostics in representative test benches are necessary to optimize and validate the numerical models describing the complex physics of these jets and their associated shock structures. Femtosecond Laser Electronic Excitation Tagging (FLEET) is a molecular tagging velocimetry technique of increasing interest due to its straightforward implementation and its ability to operate without particle or gas seeding. This technique constitutes a relevant complement to traditional particle-based velocimetry for the investigation of high-speed flows, and for probing the steep velocity gradients occurring in the vicinity of shock structures in non-adapted supersonic jets. We report here a measurement campaign of FLEET velocimetry in a large-scale test facility called ADIJE at ONERA to characterize a round overexpanded supersonic jet of air. One-dimensional velocity measurements were performed at 15 axial positions along the jet centerline to map the mean axial velocity from the nozzle exit to two nozzle lip diameters downstream. To our knowledge, it was the first time that FLEET was applied to map out the velocity in an overexpanded jet with such a regular and extended spatial coverage. In particular, the explored area encompasses a strong normal shock also called "Mach disk" characterized by a sharp velocity gradient. The measured axial velocity drops from 1000 ± 50 m/s to 220 ± 30 m/s over one millimeter. The velocity mapping also provides insight into the jet topology in the vicinity of the shock. Additionally, a comparison was made with Particle Image Velocimetry (PIV) measurements and numerical results from Large Eddy Simulation (LES). The results obtained here with FLEET, which is a particle-free technique, constitute a valuable dataset for supersonic jets characterization and for improving and validating numerical models.

1. Introduction

The study of non-adapted supersonic jets is essential for optimizing nozzle designs, reducing jet noise and improving the performances and durability of aerospace propulsion systems. Such configuration occurs usually during the lift-off of a rocket, i.e. at sea-level, the nozzle operates in an overexpanded regime which is characterized by an ambient pressure exceeding the nozzle exit pressure. This pressure mismatch triggers the formation of complex shock structures

in the exhaust plume. While these structures do not directly alter the thrust efficiency, they govern the acoustic signature of the jet, drive mixing, and can act as a source of unsteady loads on nearby surfaces or airframe components (Simmons 2000). Therefore, a detailed understanding of these mechanisms is essential to ensure safe and efficient operation across the flight envelope (Frey *et al.* 1999).

Numerical simulation based on Reynolds-Averaged Navier-Stokes (RANS) or Large-Eddy Simulation (LES) are routinely employed to characterize the exhaust of high-speed propulsive nozzles (Kaushik *et al.* 2015, Martelli *et al.* 2020). However, in the case of overexpanded jets, these numerical models often face limitations regarding shock-turbulence interaction and flow separation prediction, necessitating further refinement (Martelli *et al.* 2025). The optimization and validation of the models, require a systematic comparison with experimental database. In particular, the velocity field is a key parameter to describe the aerodynamic properties of the flow.

Particle-based approaches such as Laser Doppler Velocimetry (LDV) and Particle Image Velocimetry (PIV) have become standard due to their ability to provide accurate measurements. However, the finite response time of the particles (also known as particle lag) may make it challenging to characterize the shock regions of supersonic jets where strong velocity gradients occur. To address this limitation, Molecular Tagging Velocimetry (MTV) can be employed to provide a direct measurement of the gas velocity (Huffman & Elliott 2009). Among the MTV techniques, Femtosecond Laser Electronic Excitation Tagging (FLEET) is a technique of increasing interest due to its straightforward implementation and its ability to operate without gas seeding (Michael *et al.* 2011).

When applied in air, FLEET relies on the non-resonant multiphoton excitation, ionization and dissociation of molecular nitrogen (N_2) by focused femtosecond laser pulses. The dissociated nitrogen atoms recombine into an excited state of N_2 and a long-lived optical emission is produced in the visible and near infrared domain as the molecules return to a lower energy state. This emission lasts for tens of microseconds and can be tracked using a gated-intensified camera. The local flow velocity is then determined by measuring the displacement of the laser-tagged molecules between successive images separated by a known time delay. Over the past fifteen years, FLEET has been successfully applied in various environments: in laboratory test flows (DeLuca *et al.* 2024), as well as large-scale facilities from subsonic to hypersonic flows (Dogariu *et al.* 2019, Reese *et al.* 2021). Several applications of FLEET in overexpanded supersonic jets were reported in the literature, though limited to small-scale laboratory setups. Among them Miles *et al.* (2013) and Zhang *et al.* (2020) presented velocity measurements at several locations in the jet and could reveal some features of the flow structure.

In the present work, we report an application of FLEET velocimetry in an overexpanded supersonic air jet in a large-scale test facility named ADIJE at ONERA. A mean velocity map was built from one-dimensional (1-D) velocity measurements performed at 15 axial positions along the jet axis, from the nozzle exit plane to several nozzle lip diameters (D) downstream. To our knowledge, it was the first time that FLEET was applied to map out the velocity in an overexpanded jet with such a regular and extended spatial coverage. In particular, the explored area encompasses a strong normal shock also called "Mach disk" characterized by a sharp velocity gradient. The velocity mapping provided insight into the jet topology in the vicinity of this shock. The analysis of these results was complemented by a comparison with PIV measurements and LES results.

2. Materials and methods

A. Test facility and characteristics of the supersonic jet

The measurements were conducted in the ADIJE facility at ONERA. It consists of an instrumented pipe connected to a de Laval nozzle whose throat and exit diameter are 19.4 mm and 40 mm respectively. The nozzle is supplied with a continuous flow of pre-heated air at a mass flow rate of approximately 1 kg/s. The resulting overexpanded jet exhausts into atmospheric pressure air with a Mach number around 3. Previous characterization of the jet by shadowgraphy highlighted several shock cells with the first one exhibiting a Mach disk as depicted on Figure 1. Two sets of inlet temperature and pressure were explored (see Tab. 1). The first one corresponds to the nominal operating conditions of the facility. The second set of conditions is easier to achieve and produces a supersonic jet that was readily characterized by several optical diagnostics including PIV (Jalain *et al.* 2026). In both cases, a temperature and pressure ramp up of 30 minutes was necessary to reach a 45 minutes stable supersonic jet. Once the target operating conditions were reached, the measured parameters such as inlet pressure, inlet temperature and mass flow rate remained very stable (see Tab. 1) throughout the entire test run, leading to a stationary jet. To obtain these parameters, the flow is characterized through a calibrated throat equipped with thermocouple and pressure sensors, upstream from ADIJE nozzle. From this equipment, the total pressure and temperature are measured, and the mass flowrate is computed.

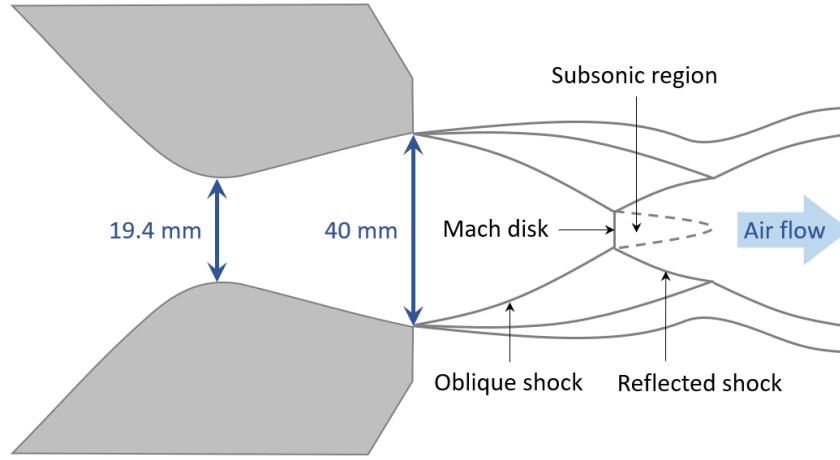


Figure 1. Schematic of the nozzle geometry and the exhaust plume structure represented by the density discontinuity lines in the first shock-cell. The Mach disk is depicted, as well as the subsonic region located downstream.

Table 1. Operating conditions of the supersonic nozzle. The indicated values correspond to the average plus or minus the standard deviation measured over the course of the whole test run.

Test run	Total inlet temperature (K)	Total inlet pressure (bar)	Mass flow rate (kg/s)
# 1	806 ± 6	25.3 ± 0.3	1.03 ± 0.01
# 2	684 ± 3	21.2 ± 0.6	0.95 ± 0.03

The open-air exhaust configuration generated extreme acoustic levels within the test chamber, preventing physical operator access for realignment or system modifications during the rig operation. Furthermore, the test could not be interrupted once initiated, as extended pressure and temperature ramp-up periods were required to achieve stable inlet conditions. Consequently, all systems and data acquisitions were controlled remotely.

B. FLEET setup and data acquisition

A 1030 nm Yb:KGW femtosecond laser (Pharos PH2, Light Conversion) was employed for the FLEET measurements. The laser system is capable of delivering 200-fs duration pulses with an energy of 2 mJ at a repetition rate tunable from 1 Hz to 10 kHz continuously. The experimental setup configuration in the facility room is schematized in Figure 2. For stability, the laser system was set up in an adjacent room of the test facility and placed on a concrete slab. The laser beam was directed to the facility room through the wall and aligned vertically perpendicular to the flow using a tenfold of high-reflectivity mirrors. The laser was focused at the centerline of the jet with a 200 mm focal length plano-convex lens. The laser energy measured in before the focusing lens

was 1.67 ± 0.01 mJ. An 8 mm-long emission line of tagged nitrogen molecules was produced, long enough to cover the full radial width of the Mach disk.

Two motorized translation stages were used to translate both the laser and the camera along the jet axis from 0 to 120 mm downstream the nozzle exit plane to measure the velocity profile at 15 distinct axial positions. A spatial step of 1 mm was selected in the vicinity of the Mach disk, where a steep velocity gradient occurs. A coarser step of 5 to 10 mm was applied upstream and downstream of the shock region. The motorized translation stages have a precision and repeatability of a few μm (Newport MTN300PP). A displacement of the nozzle in the jet direction axis (x-axis) of 2.9 ± 0.1 cm (test run #1) and 2.2 ± 0.1 cm (test run #2) was measured during the temperature ramp-up period and then remained stable (± 0.1 cm) once the targeted conditions were reached. To determine the laser position in the x-direction, the laser was translated upstream of the jet until the beam intersected the nozzle lip during the jet stationary regime to determine the zero-reference position. For y- and z-directions, the measurement location was first roughly estimated during the alignment process using the cold, non-expanded nozzle as a reference. The simple geometry, combined with the confirmation by LES and previous measurement allow to consider the jet as axisymmetric. This property was exploited to determine the measurement position in the y-direction *a posteriori*. Consequently, only the position in the z-direction remained uncertain. It is also worth noting that the thermal expansion of the nozzle in the y and z-directions was not monitored and could thus add to this uncertainty.

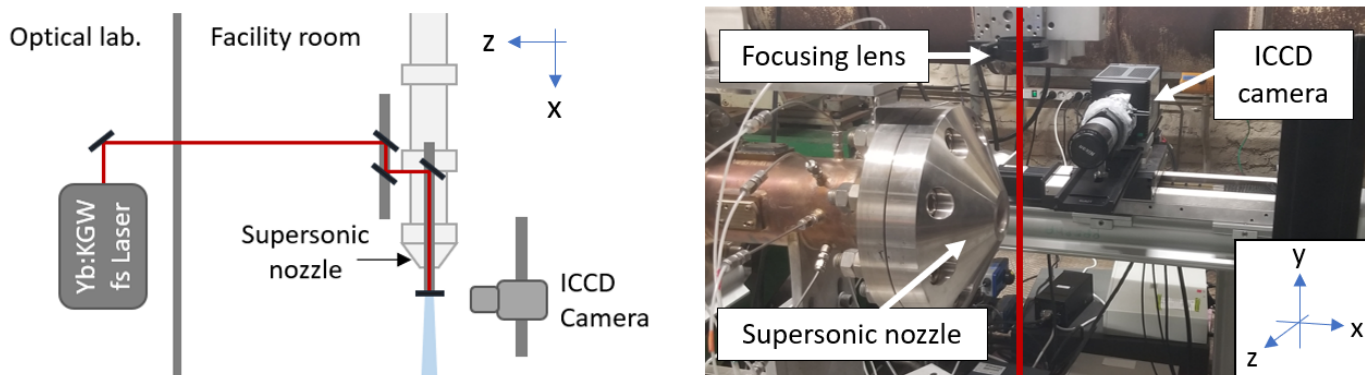


Figure 2. Schematic and photograph of the FLEET experimental setup in the facility room.

The FLEET emission line was imaged with a gated intensified CCD camera (PI-MAX4 1024 EMB, Gen III Hbf, Teledyne Princeton Instruments) positioned orthogonally to both the laser and flow direction (see Fig. 2). A visible 200 mm-focal lens with an f/4 aperture and a set of spacers (total extent of 68 mm) were used to achieve a field of view of $14 \text{ mm} \times 14 \text{ mm}$. The camera was operated in full-frame with 1024×1024 pixels, leading to a resolution of $13.5 \mu\text{m}$ per pixel. A timing diagram of the images acquisition process is shown on Figure 3. Two sets of images were acquired

at each measurement positions (see Tab. 2) with a frame rate of 4 Hz (limited by the maximum frame rate of the camera). The first set was acquired at zero time-delay relative to the laser pulse arrival time, which is denoted as t_0 . The emission line imaged at t_0 served as the reference for the displacement measurement. The second set of images was acquired at a time delay Δt relative to t_0 to image the advected emission line. The intensifier gate width was set to 100 ns at t_0 and 200 ns at $t_0 + \Delta t$. On-chip accumulation over hundreds of laser shots was performed to achieve a sufficient signal-to-noise ratio (SNR) at $t_0 + \Delta t$. Depending on the location within the jet, the SNR was between 20 and 100 in the brightest area of the emission line.

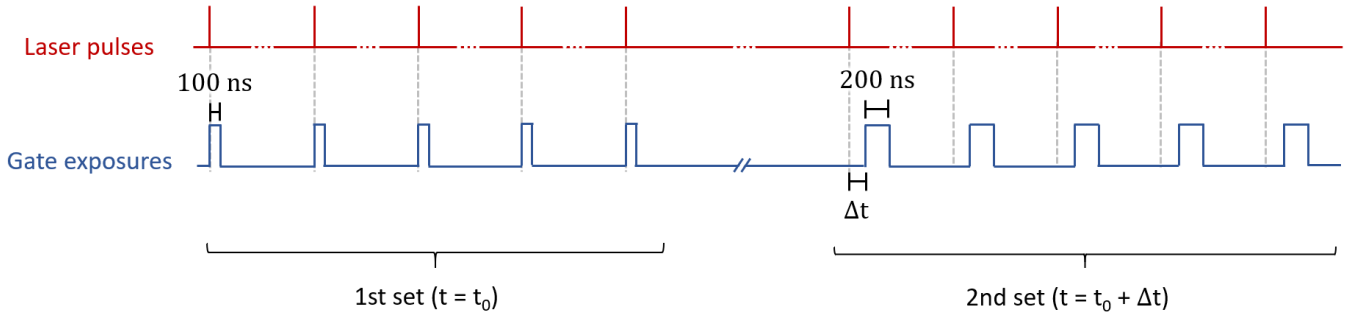


Figure 3. Time diagram of FLEET images acquisition.

The value of the time delay Δt is an important parameter to consider that influences both the spatial resolution and the precision of the velocity measurement. Due to the lack of knowledge of the intermediate evolution between the two acquired images, the velocity is averaged over the spatial extent of the emission line displacement. As Δt decreases, the displacement is reduced and finer velocity gradients or flow structures can be resolved. On the contrary, the measurement precision decreases since the relative uncertainties on the line displacement (limited by the precision on the center-line determination) and on the time delay Δt (limited by a 12-ns laser/camera temporal jitter) both increase. The Δt value also impacts the signal-to-noise ratio as the molecular emission intensity decays exponentially with time. The spatial resolution can be estimated as the product of the local velocity v and time delay Δt . During test run #1, the objective was to investigate the flow topology in the vicinity of the Mach disk. Hence, a short time delay of 200 ns was chosen to ensure a good spatial resolution. On the other hand, test run #2 aimed to retrieve precise velocity measurements to be compared to PIV and LES results. In this case, Δt was set to 900 ns to increase the measurement precision while keeping a spatial resolution of ~ 1 mm or less (see Tab. 3), corresponding to the finest step between two successive measurement locations.

Table 2. Image acquisition parameters.

Test run	Image set	Time delay (Δt)	Gate width	Camera gain	On-chip accumulation	Number of images
# 1	1st	0 ns	100 ns	5 %	1	20
	2nd	200 ns	200 ns	100 %	200	50
# 2	1st	0 ns	100 ns	5 %	1	20
	2nd	900 ns	200 ns	100 %	300	50

Table 3. Estimated spatial resolution as a function of the local velocity v and time delay Δt .

v	Δt	
	200 ns	900 ns
200 m/s	40 μm	180 μm
500 m/s	110 μm	495 μm
1100 m/s	220 μm	990 μm

C. Data processing

Prior to the test runs, the imaging system was spatially calibrated using a calibration grid placed in the plane of the laser beam. The scale factor used to convert pixels into a physical length was found to be 74 pixels per millimeters (i.e. 13.5 $\mu\text{m}/\text{pixel}$). The velocity determination procedure is presented in Figure 4. For each measurement position, two series of images representing the emission line at t_0 and $t_0 + \Delta t$ were recorded and averaged. A median filter with a 5-pixel window size was then applied to both images to smooth out the noise without erasing the fine structures. To facilitate the fitting procedure, a region of interest (ROI) containing the FLEET signal was defined. For each row of pixels within the ROI, the intensity profile was fitted with a Gaussian curve to determine the center-line position with a sub-pixel resolution at both t_0 and $t_0 + \Delta t$. A 1-D velocity profile was then obtained by measuring the displacement of the tagged molecules for each row of pixels along the line. The rows where the SNR was smaller than 4 were discarded.

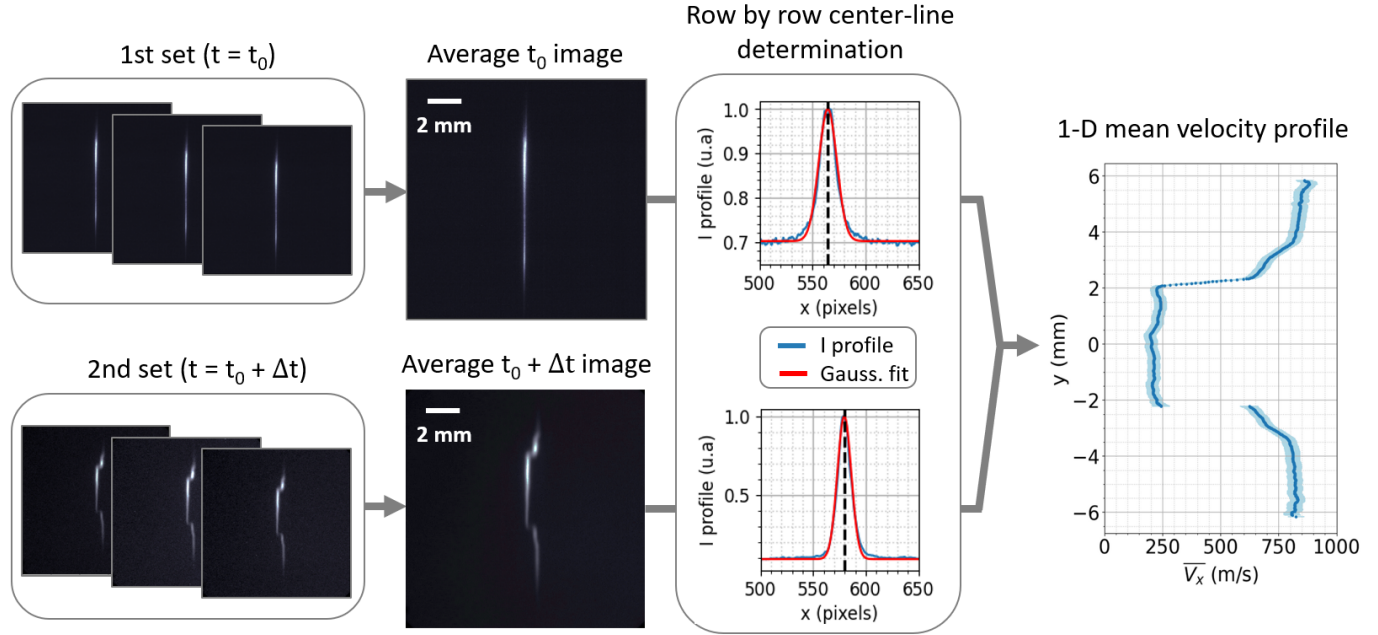


Figure 4. FLEET images processing.

Notably, this procedure assumes that the molecules are advected in the x-direction only (i.e. parallel to the jet axis) and is thus only sensitive to the x-velocity component and neglects any contribution from the radial components.

In high-speed flows, velocity measurements obtained from MTV techniques can be subject to motion blur effects. "Motion blur" refers to the apparent spatial broadening of the emission line due to the motion of the tagged species during camera exposure. When motion blur occurs, the apparent center-line position is shifted in the downstream direction. Therefore, the distance traveled by the molecules is overestimated, subsequently leading to an overestimation of the flow velocity. A common correction method consists in using an effective time delay Δt_{eff} computed from the time between the center of the exposure gates instead of the time between the start of each exposures. However, this gate-centered method ignores any signal lifetime effects and might over-correct the velocity if the signal intensity decays during the exposure gate. On Figure 5 is displayed a FLEET signal decay curve measured during test run #2 in the post-shock region at the axial position $x = 51$ mm. The emission intensity at the center of the line was measured at five time delays. A dual-exponential fit (DeLuca *et al.* 2014) was then applied to determine the decay parameters A , τ_A , B , and τ_B (eq. 1) reported in Table 4.

$$I(t) = A \exp\left(-\frac{t}{\tau_A}\right) + B \exp\left(-\frac{t}{\tau_B}\right) \quad (1)$$

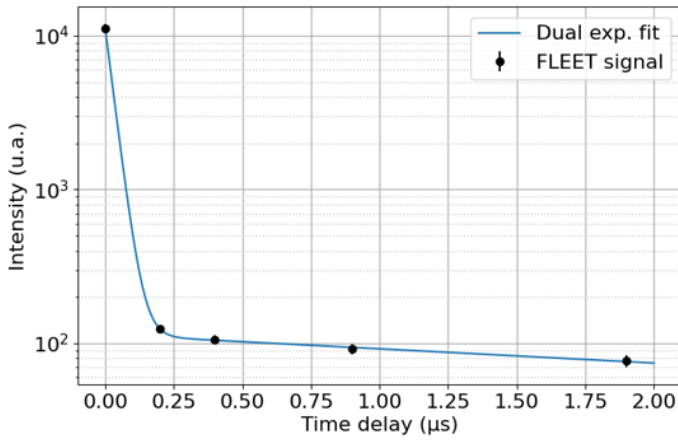


Figure 5. Signal intensity decay measured in the post-shock region of the jet.

Table 4. Signal decay parameters determined from dual-exponential fit.

A	τ_A (ns)	B	τ_B (ns)
$11\,090 \pm 10$	30 ± 2	114 ± 8	4700 ± 1300

When $\Delta t = 900$ ns (i.e. for test run #2) the decay rate is governed by the slow component with a time constant in the microseconds scale (see Fig. 5 and Tab. 4). In this case, the gate-centered method would be a valid approach as the signal intensity remains nearly constant during the 200-ns camera exposure. However, when $\Delta t = 200$ ns (i.e. for test run #1) the influence of the fast component with a 30-ns time constant becomes non-negligible rendering the gate-centered method no longer appropriate. Consequently, the methodology recently proposed by Mark Gragston (2025) was employed in this work to correct this bias. Briefly, Gragston's algorithm takes as input the experimental parameters (camera resolution, inter-frame delay, exposure time) and the signal decay parameters (see Tab. 4). For a given range of velocities, it numerically simulates the appearance of the emission line as imaged by the camera, both with and without blur. By comparing the two cases, a mapping is computed allowing to go from blur-affected velocity to actual velocity as shown on Figure 6. A linear fit is then performed to retrieve the correction parameters to be applied to the FLEET data such that:

$$v_{corrected} = m \times v_{measured} + b \quad (2)$$

Table 5 displays the correction factors m obtained from Gragston's method and from the gate-centered method. In the latter case, it corresponds to the ratio between the effective and actual time delays $\Delta t_{eff} / \Delta t$. As expected, both correction methods yield the same result for $\Delta t = 900$ ns (test run #2). However, for $\Delta t = 200$ ns (test run #1), using the gate-centered method would result in an 16% over-correction of the velocity.

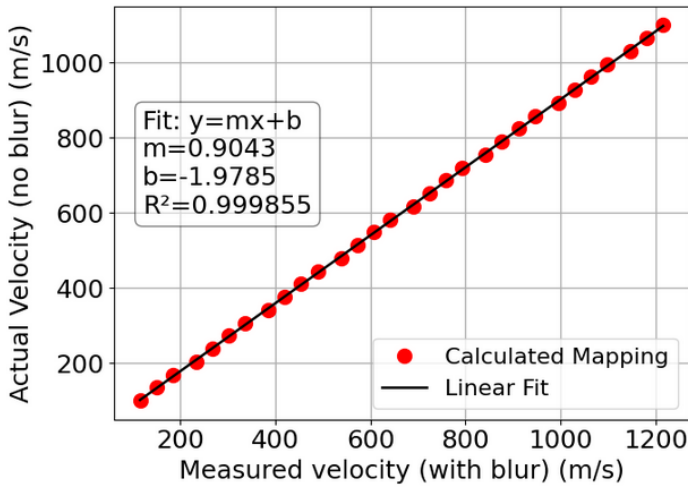


Figure 6. Example of Gragston's correction mapping calculated for the range of velocities encountered in the supersonic jet.

Table 5. Motion blur correction factors for each test run. All input parameters were the same except for the time delay Δt which was 200 ns for test run #1 and 900 ns for #2 (Tab. 2).

Test run	Gragston's correction m	Gate-centered correction
#1	0.83 ± 0.02	0.67 ± 0.05
#2	0.90 ± 0.02	0.90 ± 0.02

Varying the input signal decay parameters from Table 4 within their uncertainty bounds results in a $\pm 2\%$ variation of the output correction factor m ; this value is therefore retained as the uncertainty on the motion blur correction (see Tab. 5). For simplicity, the same signal decay parameters were used to correct the velocity profiles at all measurement locations. However, it is known that the FLEET signal intensity and lifetime depend on the local nitrogen density (Burns *et al.* 2018, Peters *et al.* 2021). Because the density varies greatly across the shock cell, the decay curve on Figure 5 may not be representative of the signal behavior at every location in the supersonic jet. As a consequence, the uncertainty associated with motion blur correction could actually be greater than 2%.

E. Uncertainties determination

Firstly, the spatial scale factor s used to convert pixels into a physical length was determined with a precision of 0.2%, limited by the width of the calibration-grid lines on the camera image. Secondly, a temporal jitter of 12 ns was measured between the laser pulse and the gate exposure and was taken as the uncertainty δt on the time delay Δt . This value represents the upper bound for δt as the use of on-chip accumulation and image averaging helped to mitigate the jitter effect. Thirdly, the Gaussian fitting procedure described in section 2.C returns an error δx_1 for the center-line determination at t_0 and δx_2 for the center-line determination at $t_0 + \Delta t$. Both δx_1 and δx_2 usually represent one pixel or less. The total error δx on the center-line displacement Δx is then computed as $\delta x = \sqrt{\delta x_1^2 + \delta x_2^2}$. Fourthly, an uncertainty of 2 % is tied to the correction of motion blur effects as detailed in the previous section. Assuming that all the sources of uncertainty are

independent, the total uncertainty δv for the velocity v is given by the standard error propagation rule:

$$\delta v = \frac{\Delta x}{\Delta t} \times s \times m \times \sqrt{\left(\frac{\delta m}{m}\right)^2 + \left(\frac{\delta s}{s}\right)^2 + \left(\frac{\delta x}{\Delta x}\right)^2 + \left(\frac{\delta t}{\Delta t}\right)^2} \quad (3)$$

Where s and m denote the spatial scale factor and the motion blur correction factor respectively. Finally, because the images of the initial and displaced emission line were acquired in two separate sets, a potential velocity bias of ± 15 -25 m/s was estimated from the systematic offsets observed between adjacent velocity profiles in regions where the velocity gradients are supposedly minimal. It is attributed to fluctuations in the laser tagging position between t_0 and $t_0 + \Delta t$ even though on-chip accumulation and image averaging mitigated this effect. Table 6 summarizes the estimated sources of uncertainties of both test run. Overall for test run #1, the measurement uncertainties were between 50 m/s and 100 m/s for the lowest and highest velocities respectively. For test run #2, they ranged from 30 to 35 m/s. The precision increase is attributed to the longer time delay employed in the second configuration.

Table 6. Uncertainty budget for FLEET velocity measurements. The indicated values are upper bounds. (*) Total uncertainty for the lowest vs (**) highest measured velocities.

Test run	$\delta s/s$	$\delta m/m$	δt	δx	Offset bias	Total
#1	0.2 %	2 %	12 ns	1 pixel	25 m/s	50*-100** m/s
#2					15 m/s	30*-35** m/s

3. Results and discussion

A. FLEET mean velocity mapping

1-D velocity profiles measured at all the axial positions were concatenated to produce a 2-D mapping of the mean velocity as shown on Figure 7 from the nozzle exit plane to respectively three (test run #1) and two nozzle lip diameters (test run #2). A linear interpolation was performed between the consecutive measurement locations indicated by vertical dotted lines. The white patches correspond to regions of insufficient SNR. Within the investigated region, a large dynamic range of mean axial velocity was measured with values spanning from 200 m/s to 1100 m/s. The resulting velocity map reveals a sustained supersonic area extending from the nozzle exit to the Mach disk, followed by a post-shock low-velocity region fully apparent. For test run #1, the Mach disk location is revealed by the steep velocity drop from 1050 ± 100 m/s to 230 ± 50 m/s, between axial positions $x = 57$ mm and $x = 58$ mm (see Fig. 7a and 7b). During the second test run, the nozzle was operated with lower inlet temperature and pressure (see Tab. 1) to match the conditions

of the PIV campaign (Jalain *et al.* 2026). Under these conditions, the Mach disk was observed to be located further upstream on the jet axis, between $x = 48$ mm and $x = 49$ mm with the velocity dropping from 1000 ± 35 m/s to 220 ± 30 m/s (see Fig. 7c). This region was scanned twice, with both scans agreeing on the shock location within 1 mm (see Fig. 8). This consistency reflects the robustness of FLEET measurements. The incident and reflected oblique shocks are also clearly visible on the maps from small velocity changes in the supersonic regions upstream and downstream of the Mach disk.

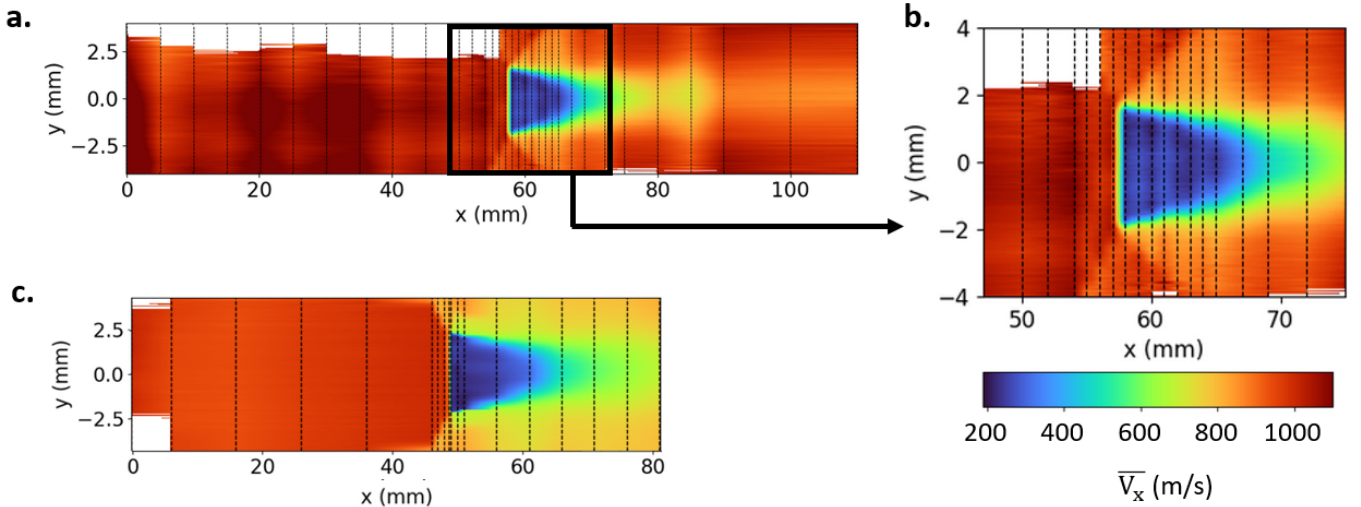


Figure 7. **a.** Spatial distribution of mean axial velocities ($\overline{V_x}$) measured during test run #1. **b.** Magnification of **a.** in the Mach disk region. **c.** Spatial distribution of mean axial velocities ($\overline{V_x}$) measured during test run #2. The y-axis is stretched relative to the x-axis for better visibility.

Across the whole explored area, the velocity profiles exhibit systematic offsets that vary from one profile to another with a magnitude of respectively 50 m/s and 30 m/s for test runs #1 and #2. As this is observed even in regions where the velocity gradients are supposedly minimal, we believe that these variations are non-physical and arise from the offset bias related to the two-step acquisition method discussed in section 2.

B. Comparison with PIV and LES

Figure 8 shows a comparison of the mean axial velocity along the jet axis ($y = 0$ mm) measured by FLEET and PIV, and calculated via LES. The PIV data are the result of an average over 450 instantaneous fields. As the PIV standard deviation is a combination of real velocity fluctuations and measurement uncertainty, error bars are difficult to obtain. Here, the standard deviation is used as conservative estimate of the PIV uncertainty to enable comparison with the FLEET data.

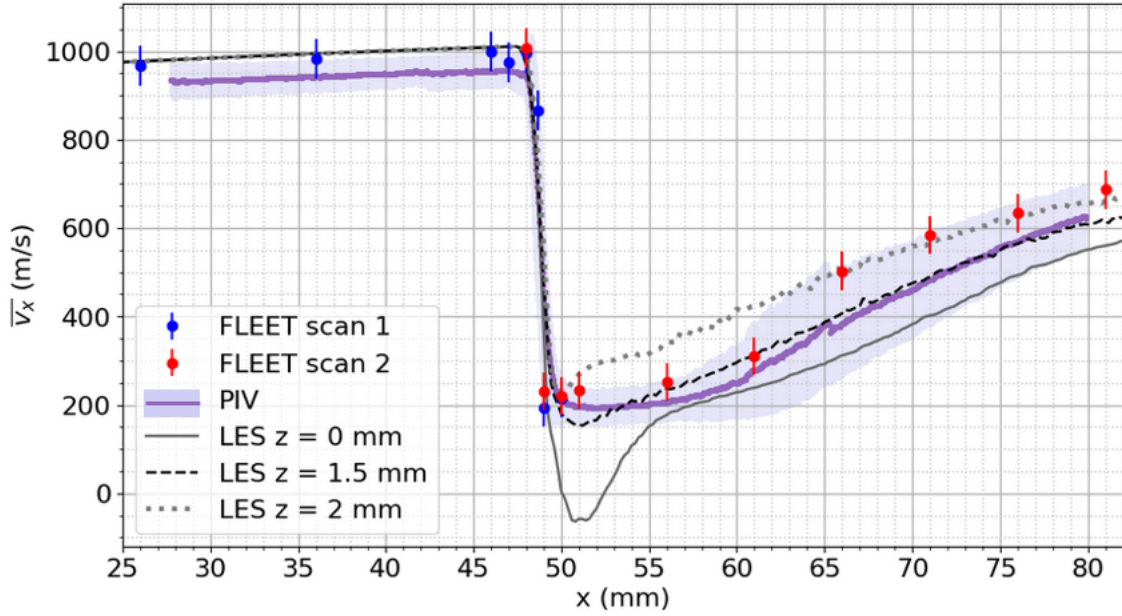


Figure 8. Comparison of the mean axial velocity along the jet axis ($y = 0$ mm) measured by FLEET and PIV and calculated via LES for test run #2 condition. PIV measurements and LES calculations were adapted from Jalain *et al.* 2026.

FLEET and PIV measurements are in good agreement within 5% although some discrepancies can be noticed. For $x > 65$ mm, FLEET measurements exceed both PIV and LES (at $z = 0$ mm) by 100 m/s, matching the upper bound of the PIV standard deviation. A significant misalignment in the z direction is unlikely as the sharp velocity drop at the Mach disk matches the PIV and LES data. However, a slight angle between the FLEET translation axis and the jet axis may exist. This is consistent with the observed higher velocity value for $x > 65$ mm and with the LES simulation results in the plane $z = 2$ mm. Also, it is worth mentioning that since a dilatation of the ADIJE structure was observed in the x -direction, dilatation in the y and z -directions might also occur leading to a slight jet axis direction shift that was not corrected nor monitored during the test.

Regarding the Mach disk location along the x -axis, FLEET and PIV are in good agreement within 1 mm. A statistical analysis of instantaneous PIV fields revealed axial oscillation of the Mach disk position around 47.75 mm with a peak-to-peak amplitude of approximately 1.5 mm (Jalain *et al.* 2026). This could not be captured by FLEET measurements owing to the use of on-chip accumulation and images averaging.

LES results are consistent with FLEET and PIV measurements except downstream of the shock where a major discrepancy lies. LES predicts a near-zero or slightly negative velocity revealing a recirculation zone, whereas both FLEET and PIV measure at least 200 m/s. Both experimental techniques resolve the steep velocity gradient across the shock with a sharpness comparable to that of LES, suggesting that: (1) particle lag effects should be minimal for PIV under

the present conditions, and (2) FLEET and PIV measurement planes are close to the jet axis (at $z = 0$ mm) and not significantly offset in the vicinity of the Mach disk. However, experimental data do align with the LES profile calculated at $z = 1.5$ mm, indicating that a slight offset of the measurement plane is plausible. Nonetheless, the existence of a negative velocity or recirculation region downstream of a Mach disk in supersonic jets remains a matter of ongoing research as no experimental evidence has been reported to this day (Kudryavtsev *et al.* 2024). Plus, the confidence in the LES results in this region is limited due to their high sensitivity to modelling choices such as inlet boundary conditions, numerical dissipation, and turbulence closure. Therefore, the mismatch between measured and calculated velocities downstream of the shock could also be attributed to a LES numerical artefact. Overall, the knowledge of the measurement location within the jet is critical for assessing the reliability of our experimental data. The location in the z -direction is the most challenging to determine and therefore constitutes a source of uncertainty.

4. Conclusion

We report here an application of FLEET velocimetry in a large scale overexpanded supersonic air jet in the ADIJE test facility at ONERA. Two velocity maps were built for two conditions from the one-dimensional velocity measurements performed at several axial positions along the jet axis, ranging from the nozzle exit to several nozzle lip diameters. Mean velocities were retrieved over a large dynamic range with values spanning from 200 m/s to 1100 m/s. The position of the Mach disk was determined in both operating conditions from the characteristic steep velocity gradient followed by a low-velocity pocket. The incident and reflected oblique shocks were also revealed by the velocity mapping. These results highlight the ability of FLEET to investigate complex shock structures without any flow seeding. A comparison was made with PIV measurements and LES simulations. FLEET and PIV show a good agreement within their respective uncertainty bounds and are qualitatively consistent with LES simulations. However, a major discrepancy between experimental and numerical results is observed downstream of the Mach disk, where LES predicts a recirculation region that was not observed experimentally. The results obtained here with FLEET further expand the experimental database on supersonic overexpanded jets and constitute a valuable dataset to support the improvement and validation of numerical models.

Acknowledgments

The authors would like to thank the entire staff operating the ADIJE facility at ONERA, as well as Philippe Nicolas for his technical assistance during the installation of the FLEET setup in

the facility room. Additional thanks are given to Christophe Brossard, Rosa Santagata, Adrien Langenais and Aurélien Houard for their helpful scientific input and discussions.

References

- Burns, R. A., Peters, C. J., & Danehy, P. M. (2018). Unseeded velocimetry in nitrogen for high-pressure, cryogenic wind tunnels: part I. Femtosecond-laser tagging. *Measurement Science and Technology*, 29(11), 115302
- DeLuca, N. J., Miles, R. B., Kulatilaka, W. D., Jiang, N., & Gord, J. R. (2014). Femtosecond laser electronic excitation tagging (FLEET) fundamental pulse energy and spectral response. In *30th AIAA Aerodynamic Measurement Technology and Ground Testing Conference* (p. 2227).
- DeLuca, N. J., Miles, R. B., Jiang, N., Kulatilaka, W. D., Patnaik, A. K., & Gord, J. R. (2017). FLEET velocimetry for combustion and flow diagnostics. *Applied Optics*, 56(31), 8632-8638.
- Dogariu, L. E., Dogariu, A., Miles, R. B., Smith, M. S., & Marineau, E. C. (2019). Femtosecond laser electronic excitation tagging velocimetry in a large-scale hypersonic facility. *AIAA journal*, 57(11), 4725-4737.
- Frey, M., & Hagemann, G. (1999, June). Flow separation and side-loads in rocket nozzles. In *35th Joint Propulsion Conference and Exhibit* (p. 2815).
- Gragston, M. (2025). Computational analysis of motion blur correction for molecular tagging velocimetry. *AIAA Journal*, 63(9), 3689-3699.
- Huffman, R., & Elliott, G. (2009). An experimental investigation of accurate particle tracking in supersonic, rarefied, axisymmetric jets. In *47th AIAA Aerospace Sciences Meeting including The New Horizons Forum and Aerospace Exposition* (p. 1265).
- Jalain, R., Petit, S., Blaisot, B., Lupoglazoff, N., & Langenais, A. (2026) High-resolution velocity field in the first Mach disk region of an overexpanded supersonic jet. In *22nd International Symposium on Applications of Laser and Imaging Techniques to Fluid Mechanics, Lisbon, Portugal*.
- Kaushik, M., Kumar, R., & Humrutha, G. (2015). Review of computational fluid dynamics studies on jets. *American Journal of Fluid Dynamics*, 5(3A), 1-11.
- Kudryavtsev, A. N., Kashkovsky, A. V., & Shershnev, A. A. (2024). Formation of a reverse flow behind the Mach disk at various Reynolds numbers. *Thermophysics and Aeromechanics*, 31(5), 957-961.
- Martelli, E., Saccoccio, L., Ciottoli, P. P., Tinney, C. E., Baars, W. J., & Bernardini, M. (2020). Flow dynamics and wall-pressure signatures in a high-Reynolds-number overexpanded nozzle with free shock separation. *Journal of Fluid Mechanics*, 895, A29.

- Martelli, E., Jaunet, V., Della Posta, G., & Bernardini, M. (2025). Experimental and Numerical Analysis of the Intermittency in a Nozzle Overexpanded-Flow. *arXiv preprint arXiv:2512.12317*.
- Michael, J. B., Edwards, M. R., Dogariu, A., & Miles, R. B. (2011). Femtosecond laser electronic excitation tagging for quantitative velocity imaging in air. *Applied optics*, 50(26), 5158-5162.
- Miles, R. (2013). Femtosecond laser electronic excitation tagging (FLEET) for imaging flow structure in unseeded hot or cold air or nitrogen. In *51st AIAA Aerospace Sciences Meeting including The New Horizons Forum and Aerospace Exposition* (p. 340).
- Peters, C. J., Burns, R. A., Miles, R. B., & Danehy, P. M. (2021). Effect of low temperatures and pressures on signal, lifetime, accuracy and precision of femtosecond laser tagging velocimetry. *Measurement Science and Technology*, 32(3), 035202
- Reese, D. T., Thompson, R. J., Burns, R. A., & Danehy, P. M. (2021). Application of femtosecond-laser tagging for unseeded velocimetry in a large-scale transonic cryogenic wind tunnel. *Experiments in Fluids*, 62(5), 99.
- Simmons, F. (2000). Rocket exhaust plume phenomenology. American Institute of Aeronautics and Astronautics, Inc.
- Zhang, Y., Marshall, G., Beresh, S. J., Richardson, D., & Casper, K. M. (2020). Multi-line FLEET by imaging periodic masks. *Optics letters*, 45(14), 3949-3952