

Dual-Tomographic Hybrid-PIV/PTV for extracting quantitative spatio-temporal structure of a turbulent jet

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ABSTRACT

Many flow studies of both practical and fundamental interest permit dimensional reduction through simplifying assumptions such as spatial symmetry or temporal averaging, enabling the use of accessible techniques like planar 2C–2D PIV and hotwire anemometry. However, accurate description of flows with complex three-dimensional geometry or significant temporal fluctuations demands more comprehensive kinematic measurements. This need has driven development of stereo-PIV (Buchner et al. (2012)), tomographic PIV (Soria (1996)), and holography (Sun et al. (2020)), which capture sufficient additional dimensions to infer the underlying multidimensional dynamics of such flows. However, acquiring data with temporal information encoded necessitates large reductions in spatial extent and/or resolution, greatly restricting the extraction of a flow’s full 3-D spatio-temporal dynamics. Here, a dual-tomographic PIV system is presented which bypasses these sacrifices by running two independent systems concurrently with a discrete time offset, encoding temporal dynamics at a resolution satisfying the Nyquist criterion up to $\mathcal{O}(10\text{ kHz})$ at high spatial resolution over a substantial physical domain. (Sikrora et al. (2022)) To validate the method, a simulation designed to match the characteristics of the real $M \approx 0.9$ jet experiment is carried out. Resolution and scaling is matched to the real PCO Panda 26 MPx DS cameras, which acquire 2-D image samples with a pixel size of approximately $10\text{ }\mu\text{m}$. This allows the reconstruction of full 3-D flow fields with ~ 100 billion voxels, spanning approximately 10 diameters downstream of the 5 mm jet exit. The dual-system configuration additionally de-correlates ghost particles between frames, mitigating the primary source of bias error in tomographic reconstructions. A computationally efficient hybrid PIV/PTV tracking scheme is proposed that initialises particle trajectories from the first two frames via full 3-D reconstruction and 3-D cross-correlation, then continues tracking in the image plane for frames 3 and 4, avoiding the most expensive processing stages entirely. To quantify algorithm performance, synthetic particle fields are generated by advecting particles through velocity fields from a high-resolution DNS of a Mach 0.6 turbulent round jet at $Re = 10,000$, with virtual cameras placed at experimentally equivalent positions. A parametric sweep over seeding density and search radius demonstrates robust track recovery up to 100k particles, with correct-to-incorrect track ratios remaining strongly favourable at this seeding level, establishing practical operating bounds for the experimental configuration.

1. Introduction and Methods

Turbulent shear flows are inherently three-dimensional spatial phenomena whose physical properties vary over time. These flows contain a variety of turbulent structures spanning many orders of length and time scales. The complete characterization of turbulent energy transfer and mixing requires capturing this full range, as large scales dominate momentum transport and entrainment while small scales control scalar mixing and dissipation. Many analyses of practical and fundamental interest reduce this dimensionality through simplifying assumptions, such as spatial symmetry or temporal averaging. This has the advantage of making them amenable to accessible experimental methods, such as planar 2C–2D particle image velocimetry (PIV) and hot-wire anemometry. However, in cases with complex 3D geometry or large temporal fluctuations about the mean, it is necessary to capture more of the 3C–3D flow’s kinematic variation.

This need has led to the development of many experimental methods, such as 3C–2D stereo PIV, which capture just enough of the additional information to infer the more complex multidimensional dynamics of the flow. Moving toward fully dimensioned experimental data almost always comes at the cost of resolution in at least one measurement dimension, forcing selection between micro-scale spatial resolution and macro-scale spatial domain coverage. This is further complicated with the consideration of temporal resolution, with extreme examples being high-resolution $\mathcal{O}(100 \text{ MPx})$ flow-field snapshots without any time component, or high-speed cameras that can acquire frames at $\mathcal{O}(100 \text{ kHz})$ but sacrifice an order of magnitude of spatial resolution in the process. These constraints are felt most acutely in fully resolved 3D spatial data, such as tomographic PIV, where the enormous scaling of spatial field sizes has historically made processing power a barrier to acquiring datasets of comparable sample size and flow scale to those usually obtained in planar PIV experiments.

However, parallel advances in PIV camera sensor technology and research-oriented supercomputing facilities mean that previously infeasible datasets can now be acquired and processed within reasonable experimental timelines, enabling analysis of a 5mm high-speed turbulent round jet at $M \approx 0.9$. PCO Panda 26 MPx DS cameras are used to acquire 3D flow-field reconstructions with a voxel size of approximately $10 \mu\text{m}$ and a total field size on the order of 100 billion voxels. This captures the full 3D flow field up to approximately 10 diameters downstream of the jet exit. The experimental arrangement is shown schematically in Figure 1.

After acquisition, the raw images are processed using the MLOS–SMART reconstruction algorithm, given in Eq. (1), Atkinson & Soria (2009). To increase the effective depth of field by allowing unfocused particles, an optical transfer function (OTF) corrected weighting function, given in Eq. (2), is used. (Schanz et al. (2013)) The OTF is estimated during an initial volume self-calibration (VSC) performed on each system.

$$I_j^{c+1} = I_j^c \cdot \prod_{i=1}^{N_p} \left[\left(\frac{P_i}{\sum_m W_{im} I_m^c} \right)^{a W_{ij}} \right]^{1/N_a} \quad (1)$$

$$W_{ij} = W(x, y) = \rho \cdot \exp \left(-\frac{1}{2} \begin{pmatrix} x \\ y \end{pmatrix}^T \begin{pmatrix} a & b \\ b & c \end{pmatrix} \begin{pmatrix} x \\ y \end{pmatrix} \right) \quad (2)$$

The reconstruction is enabled by processing on a large-scale parallel research supercomputer which, in single-node operation, runs a parallelised in-house code with up to 3 TB of simultaneous memory usage. This permits processing with approximately 6 billion initial nonzero voxels in each field, similar to sparsity ratios reported in past tomographic PIV experiments Scarano (2013). With conservative cubic window sizes of 128^3 voxels and a 50% window overlap, this corresponds to a grid spacing of approximately 0.67 mm^3 and $\sim 400,000$ vectors per field.

Consistent with the earlier discussion on data dimensionality, the method provides enough resolution and scale to capture a broad range of instantaneous 3D spatial structures of high Reynolds number turbulent shear flows. However, we still lack the final element required to extract the true spatio-temporal dynamics that drive such systems, namely time. To avoid the sacrifices in image resolution and laser pulse energy necessitated by fully time-resolved acquisition, we propose a dual tomographic PIV system that builds on previously established planar studies. (Chaugule et al. (2023), Sikrora et al. (2022)) An orthogonally polarised Innolas SpitLight DPS EVO IV laser produces sets of four pulses at $3 \mu\text{s}$ intervals and a repetition rate of 1 Hz; these are split into two pairs via polarising optics and imaged by each system. The acquired data thus consist of an ensemble of pairwise time-resolved 3D vector fields in which the temporal dynamics of the flow are encoded at a resolution that satisfies the Nyquist criterion up to $\mathcal{O}(10 \text{ kHz})$.

One of tomographic PIV's main challenges is the faithful reconstruction of the imaged 3D particle fields. While planar 2C–2D MCCDPIV methods approximate the vector fields directly through cross-correlation of two single exposed images of the seeding particles, tomography adds a layer of abstraction: approximating the true, unseen 3D particle field from a set of 2D projections recorded by each camera. Inverting this highly underconstrained system—for example, using SMART or ART—introduces errors that can bias the velocity measurement. (Atkinson & Soria (2009)) This is especially critical for the dual system proposed here, since the temporal dynamics are contained in frame-to-frame fluctuations in local velocity. The mitigation of such issues would enable more faithful measurements with higher vector densities and inclusion of finer turbulent scales in the data.

Ghost particles play a significant role in these errors and can severely limit the depth of field and the achievable seeding density, leading many tomographic reconstructions to take the shape of a “fat sheet” rather than a more cubic domain. In standard single-system high-spatial resolution tomographic PIV, differentiating true particles from ghost particles is challenging because ghosts

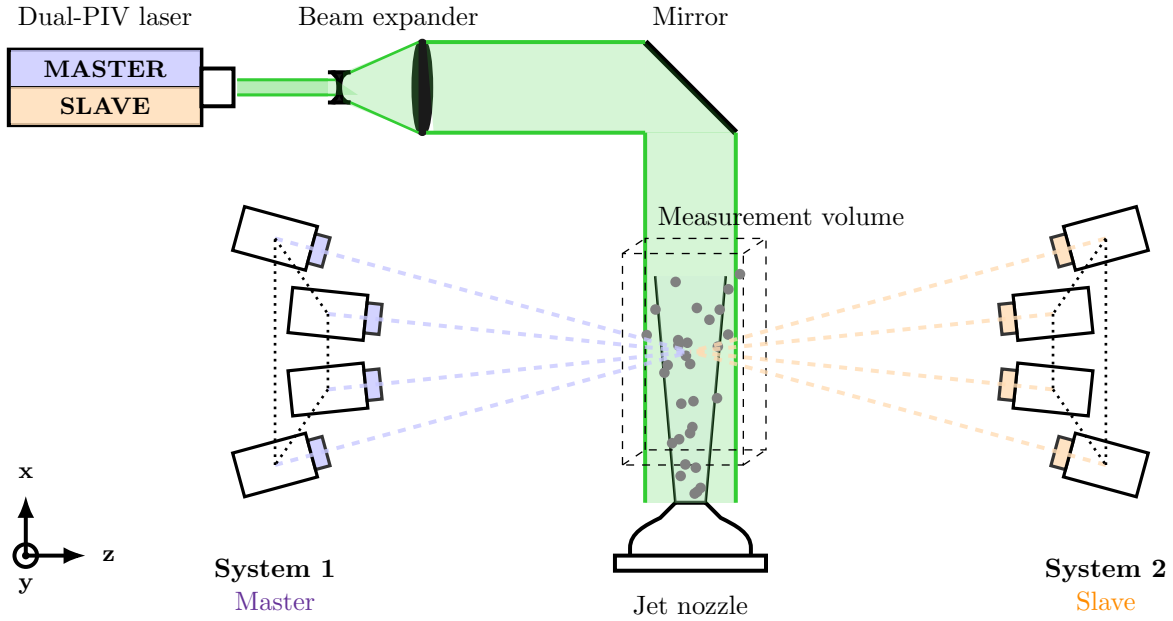


Figure 1. Diagram of experimental configuration

tend to follow the mean flow path between frames and therefore correlate as if they were truly present.

To improve ghost-particle identification and removal, we employ an iterative method that exploits the additional snapshots in the dual-tomographic PIV set-up. In each frame, a particle field is initialised based on an OTF-corrected MLOS-SMART reconstruction. Processing with a sparse clustering algorithm identifies particle centroids in the domain; these include both real and ghost particles, which are initially indistinguishable.

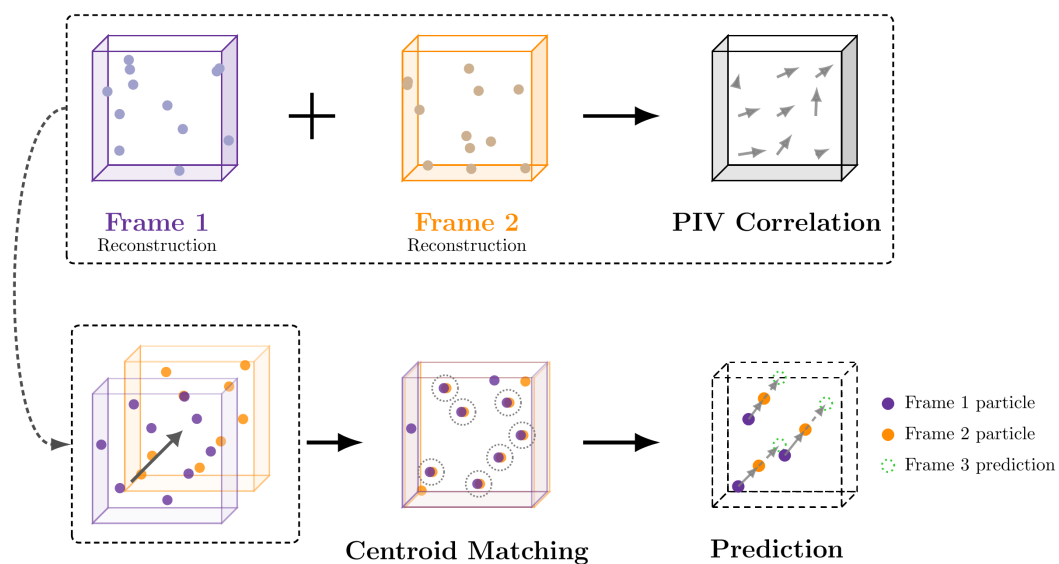
However, unlike regular single-tomographic PIV data, the exact perspectives differ between frames from system 1 and system 2, so the instantaneous distribution of ghost particles is distinct in the two systems. As in single-tomographic PIV, the flow field is estimated via the correlation of each sequential frame pair, denoted V_1 , V_2 and V_3 for frames (1,2), (2,3) and (3,4), respectively. Although the discrete time offset between systems makes direct correction of ghost particles impossible, the velocity field at each time step can be used as a mapping function to the most likely position of an identified particle at the next time step. This enables pairing particles with their most probable counterparts at each successive time step in a hybrid PIV-PTV manner, similar to Sun et al. (2025). Because ghost particles are not expected to match on a particle-to-particle basis between the two tomographic systems, true particles can be identified as those with kinematically reasonable pathways that persist throughout all frames. In order to avoid the full costs involved

with reconstruction and PIV correlation across all 4 frames, an image-plane based tracking method is instead utilised for frames 3 and 4 after initialising frames 1 and 2 as per the method just discussed. This process is shown graphically in figure 2.

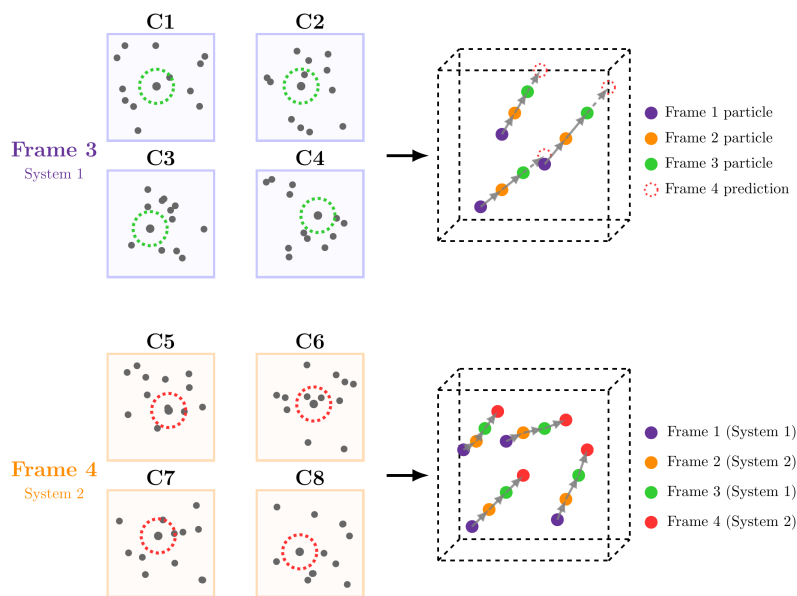
To better understand and predict how key experimental parameters influence the viability of particle identification and ghost removal, simulations which approximate the experimental conditions are undertaken. With a voxel domain of identical scale and virtual cameras at equivalent spatial coordinates, particles are spawned throughout the domain with a 2D Gaussian spread centred on the jet axis. By applying a simplified analytical advection function to the particles, they are stepped forward in time via an Euler update scheme to obtain particle distributions at four time steps. The particle tracking scheme may then be carried out just as it would be on experimental samples, but with the benefit of knowing which particles are the ground-truth trajectories. This permits a parametric study of factors such as measurement noise, particle-stepping errors, seeding density and search radius on the refinement of the fields, as well as a baseline validation of the scheme's functionality. Parameters of the actual experiment may then be optimised based on this synthetic study for the real particle reconstructions.

2. Synthetic particle field generation

In order to carry out a simulation of the experimental configuration the first step is to replicate the particle distributions that are generated via seeding in the true flow. An in-house high-fidelity multi-block DNS parallel code (ECNSS) that has been tested and validated in previous studies (Stegeman, Perez, et al. (2016), Stegeman, Soria, & Ooi (2016), Karami, Edgington-Mitchell, & Soria (2018), Karami, Stegeman, et al. (2018), Karami et al. (2020), Karami & Soria (2018)) is used to solve the compressible Navier-Stokes equations for a Mach 0.6 turbulent jet. Karami et al. (2019) gives details on the numerical method and visualisations of the flow are shown in figure 3. The jet has Reynolds Number 10,000 and is simulated to 30 diameters downstream of the exit, with sufficient spanwise range to capture the entire jet. Particles were spawned at random points inside the cartesian subdomain spanning 1-11D downstream of the jet exit in x, 9 diameters across the jet in y and 3 diameters across the jet in z. The depth in z was selected such that there is one diameter of span either side of the jet's initial core width in all directions and full 3-D structures are captured until approximately 6D downstream. A controlled number of particles are randomly spawned within this subdomain at the first timestep of the simulation, then allowed to advect downstream via a simple Euler update scheme. Since the simulation has a very fine timescale, 16 timesteps are used to generate the tracks, from which a skip fraction can be used to change the mean displacement between frames. A skip fraction of 4 was chosen, such that the largest particle displacement between frames is approximately 50 voxels in the jet core, which matches the values used in the experiment. An example of the input ground truth tracks for the 100k particle case is given in figure 4.



(a) Initialisation stage for the image plane particle tracking



(b) In-frame tracking stage for the last two frames

Figure 2. Processing pipeline for the hybrid Tomo-PIV/PTV algorithm

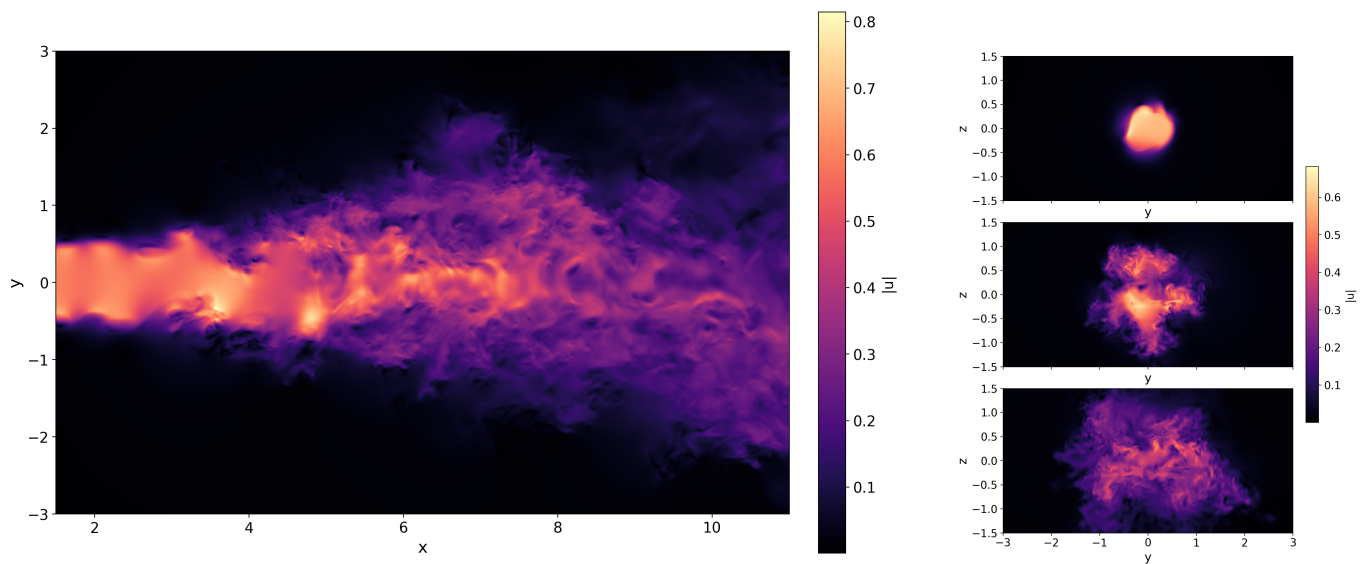


Figure 3. Left: X-Y centreline U magnitude from the simulated base flow. Left: Y-Z slices at $x=2,5$ and 8 of U magnitude from the simulated base flow.

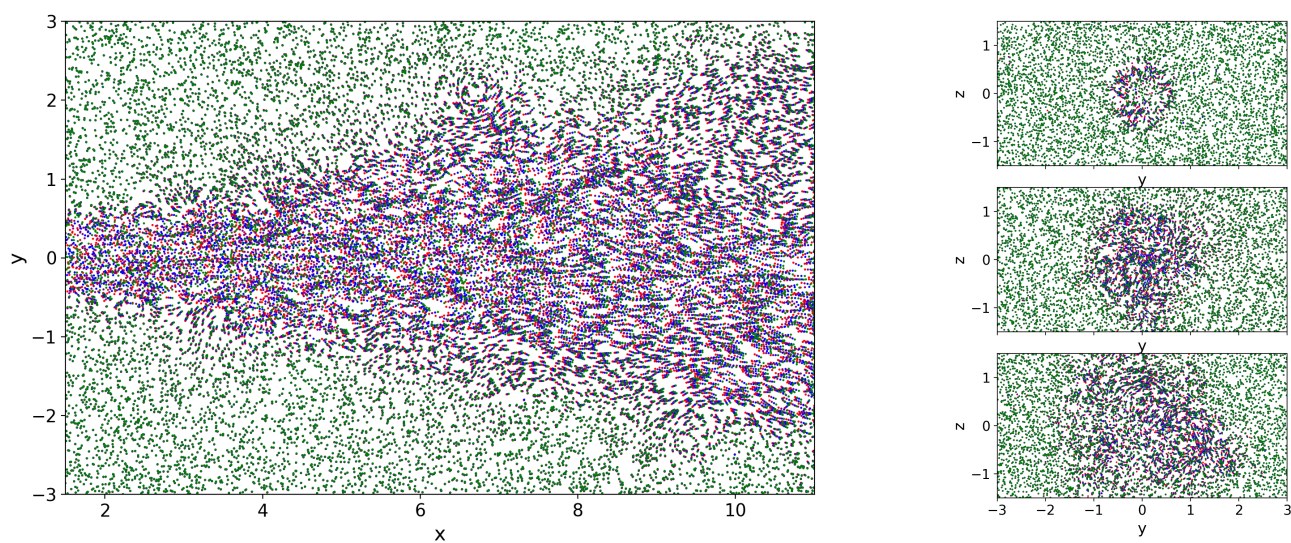


Figure 4. Left: Particle tracks in the centre 150 Z voxel slice for the 100k particle case. Left: Particle tracks in 150 X voxel slices centered at $x=2,5$ and 8 for the 100k particle case.

3. Sample processing

3.0.1. Particle track initialisation

As shown in figure 2, sample processing begins with reconstructing 3-D fields from the first two frames and correlating them via 3C-3d multigrid/multipass cross-correlation digital PIV (MCCD-PIV) (Sun et al. (2025)), with an example shown in figure 5. Reconstructions are performed with 20 SMART iterations and then clustered in 3-D space to yield centroids. The raw 3-D voxel fields are then cross-correlated (key parameters given in table 1), with the advantage that the two-system configuration de-correlates ghost particles between frames. As such, PIV vector estimates will avoid being biased toward the mean of the flow by ghosts as is common in tomographic PIV experiments, but will still suffer from increased noise in the frames.

Table 1. Key PIV parameters used in the density/noise sweep

Parameter	Value
Window size (i, j, k) [vox]	92, 48, 48
Vector spacing (i, j, k) [vox]	48, 24, 24
Initial window shift [vox]	32, 0, 0
Interrogation volume [vox]	[0:5000, 1000:4000, 1750:3250]

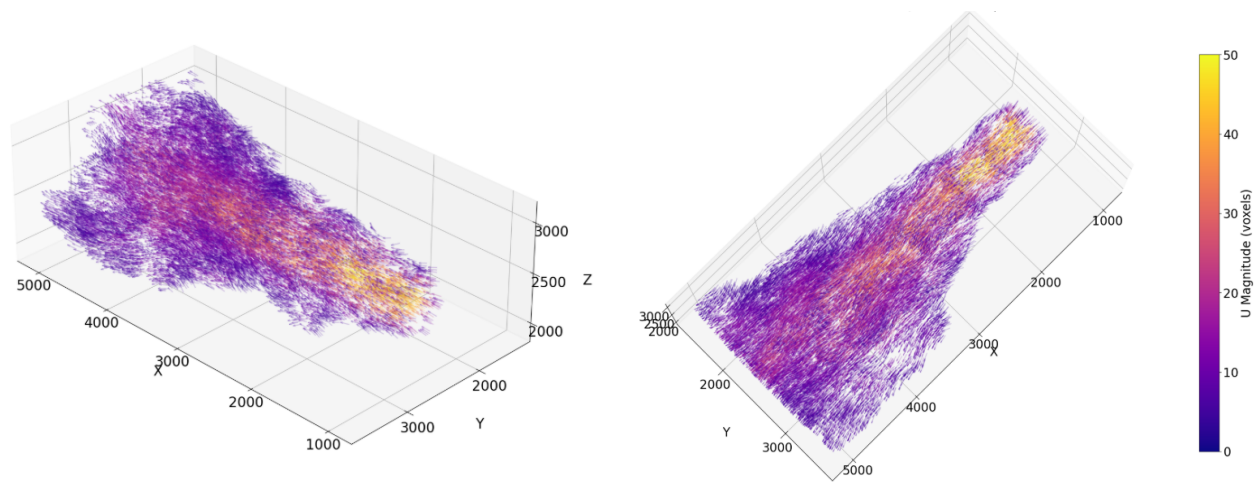


Figure 5. Two views of the PIV vector field for the 100,000 particle case, shown with a vector magnitude threshold of 5 to separate the flow from the background

3.0.2. Particle Tracking in the Image Planes

To avoid the intensive processing involved with 3-D reconstruction in frames 3 and 4, image-plane based searching is used in a manner similar to particle tracking velocimetry (PTV). (Sun et al. (2025)) However, unlike regular planar PTV, the particle is tracked simultaneously in all four camera frames at shared voxel space (x,y,z) points and tracked in 3-D via mappings. As part of the initial calibration of the camera systems, Soloff polynomials (Soloff et al. (1997)) of the form given in equations 3 and 4 are generated.

$$\begin{aligned} u = & a_0 + a_1x + a_2y + a_3x^2 + a_4xy + a_5y^2 + a_6x^3 + a_7x^2y \\ & + a_8xy^2 + a_9y^3 + a_{10}z + a_{11}xz + a_{12}yz + a_{13}x^2z \\ & + a_{14}xyz + a_{15}y^2z + a_{16}z^2 + a_{17}xz^2 + a_{18}yz^2 \end{aligned} \quad (3)$$

$$\begin{aligned} v = & b_0 + b_1x + b_2y + b_3x^2 + b_4xy + b_5y^2 + b_6x^3 + b_7x^2y \\ & + b_8xy^2 + b_9y^3 + b_{10}z + b_{11}xz + b_{12}yz + b_{13}x^2z \\ & + b_{14}xyz + b_{15}y^2z + b_{16}z^2 + b_{17}xz^2 + b_{18}yz^2 \end{aligned} \quad (4)$$

where:

- (x, y, z) are voxel-space coordinates
- (u, v) are image pixel coordinates
- $a_0, \dots, a_{18}$ and $b_0, \dots, b_{18}$ are the Soloff calibration coefficients

Since this mapping has already been determined, given that a particle has a predicted position it can be mapped back into camera space at that particular location. If the particle was truly at that location, all cameras would register a high intensity simultaneously. As such, in a method known as Shake-The-Box particle tracking (Schanz et al. (2016)), one can calculate the product of each camera's intensity within a spatial region centered on the predicted particle position. This 3-D kernel of intensity products can then be evaluated for a maxima, which is then taken to be that particle's most likely updated position. Bilinear sub-pixel interpolation enables sub-pixel accuracy in the determination of the peak location, in addition to half-voxel sized grid spacing.

This method has the distinct advantage of not requiring the entire 3-D domain to be reconstructed during tracking, as well as avoiding PIV vector field calculation, thus avoiding the most computationally expensive stages of the processing. However, a premise of this method's functionality is

particles having a pre-existing trajectory estimate. As such, particles must still first be initialised in the domain through the reconstruction of frames 1 and 2. A first-pass PIV estimate, combined with sparse cluster identification to convert the voxel field into discretised point representations of particles, enables initial pairs to be identified via a hybrid PIV/PTV approach as shown in figure 3. For frames 3 and 4, the image plane tracking proceeds using the PIV driven estimate of where the centroids in frame 2 would most likely be found. If there are no viable peaks within the predicted region, that centroid candidate is removed. To maximise recovered particles within the limited frames, the algorithm is run with two forms of recursive candidate finding. Firstly, at the start of the scheme any centroids which did not successfully find a match in 3-D via the PIV advancement are attempted again using an interpolated displacement estimate from nearby successful matches. Secondly, once an entire pass has completed, the 4 frame trajectories are fed back into the algorithm as the flow initialisation instead of the PIV, allowing smaller scale variations to be used in centroid matching and identify matches missed by the initial PIV.

4. Parametric sweep

To investigate the sensitivity of the algorithm to various key experimental parameters while avoiding having an excessively large sweep, the key variables analysed were number of particles and tracking search radius. In addition to these experimental settings, the impact of multi-pass centroid initialisation and multi-pass 4-frame tracking were included to determine their ability to improve particle recovery. A key difficulty is dealing with the contradiction that a smaller search radius is less likely to match with a ghost particle while a larger search radius is more likely to find particles with acceleration and curvature. To this end, analysis was also done using a subset of ground truth particles with a mean frame-to-frame displacement of at least 20 voxels. This allows the sweeps to identify potential conditions under which the algorithm's performance for the bulk of particles may diverge from its performance on the smaller but dynamically important subset of particles in the high flow regions of the jet. Overall recovery rates for the cases can be seen in figure 7, with good results up to 100k particles. The high displacement subset continues to improve its detection rate across all radii, while after the 14 radius case the bulk of detections have plateaued.

The portion of seeded particles successfully recovered peaked at the 50k particle case for all radii, as shown in figure 7. Below this, the sparsity of the 10k particle field meant that PIV initialisation was poorer and thus recovery lower. For the higher seeding cases, a high percentage of true particles were still initialised as centroids, but did not get selected due to excessive numbers of nearby ghost particles. This is shown clearly in the almost total saturation of incorrect particle tracks seen for the 200k case, with performance becoming poorer as search radius increases. Figure 8 shows the ratio of correctly identified ground truth particles to incorrect tracks for the 50k, 100k and 200k particle count cases. The magnitude of this ratio shows a strong sensitivity of the proportion of good tracks to particle count. At 50k, there are hundreds of good tracks for each incorrect one,

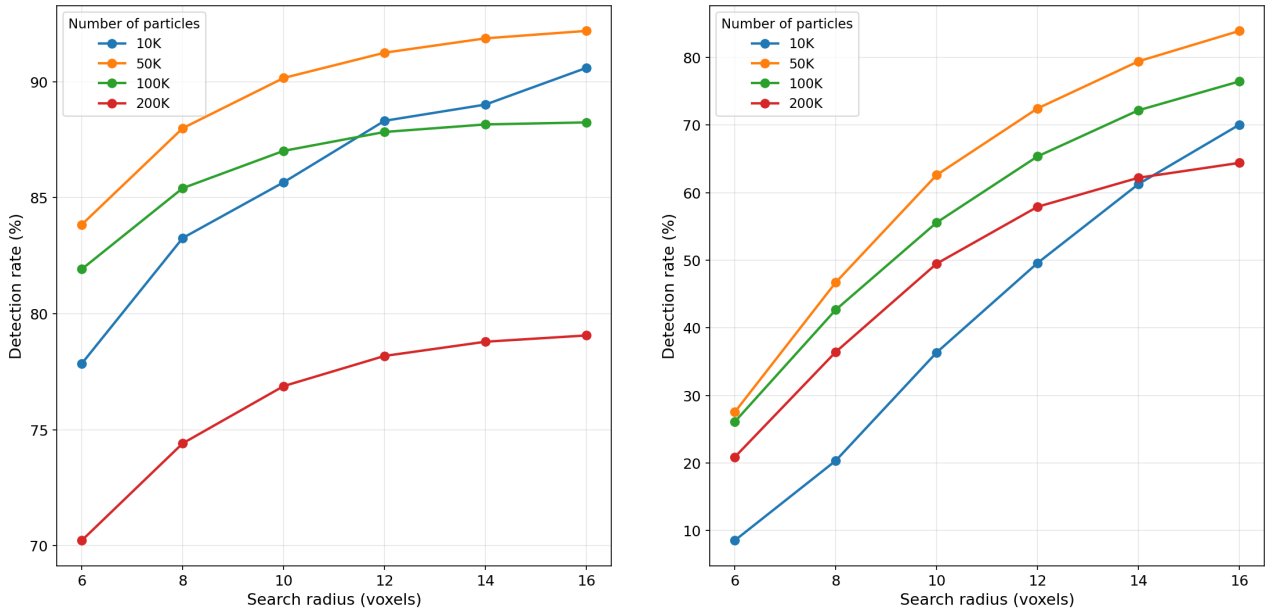


Figure 6. Left: % ground truth particles recovered for different search radii. (r) **Right:** % high-displacement ground truth particles recovered for different search radii. (r)

while for 200k false tracks dominate. For most radii at the 100k level there is still a strong dominance of correct tracks. Across all levels, high displacement tracks yielded in the samples had a lower proportion of real tracks.

5. Conclusions

A dual-tomographic hybrid PIV/PTV system with an accompanying processing algorithm has been presented for extracting quantitative spatio-temporal structure from high Reynolds number turbulent shear flows. The system is capable of overcoming traditional resolution trade-offs inherent to standard tomographic PIV, encoding temporal dynamics at up to $\mathcal{O}(10 \text{ kHz})$ without sacrificing spatial resolution or domain size. The dual-system configuration additionally de-correlates ghost particles between frames, minimising a primary source of bias error in tomographic reconstructions. A computationally efficient tracking scheme is proposed that avoids full 3-D reconstruction in the final two frames by performing image-plane tracking after particle initialisation from PIV-driven trajectory estimates. Performance across a range of seeding densities and search radii has been quantified using synthetic particle fields generated from a high-resolution DNS of a Mach 0.6 turbulent round jet. Results demonstrate robust track recovery up to 100k particles, with correct-to-incorrect track ratios across both low and high speed particles remaining strongly favourable at this seeding level.

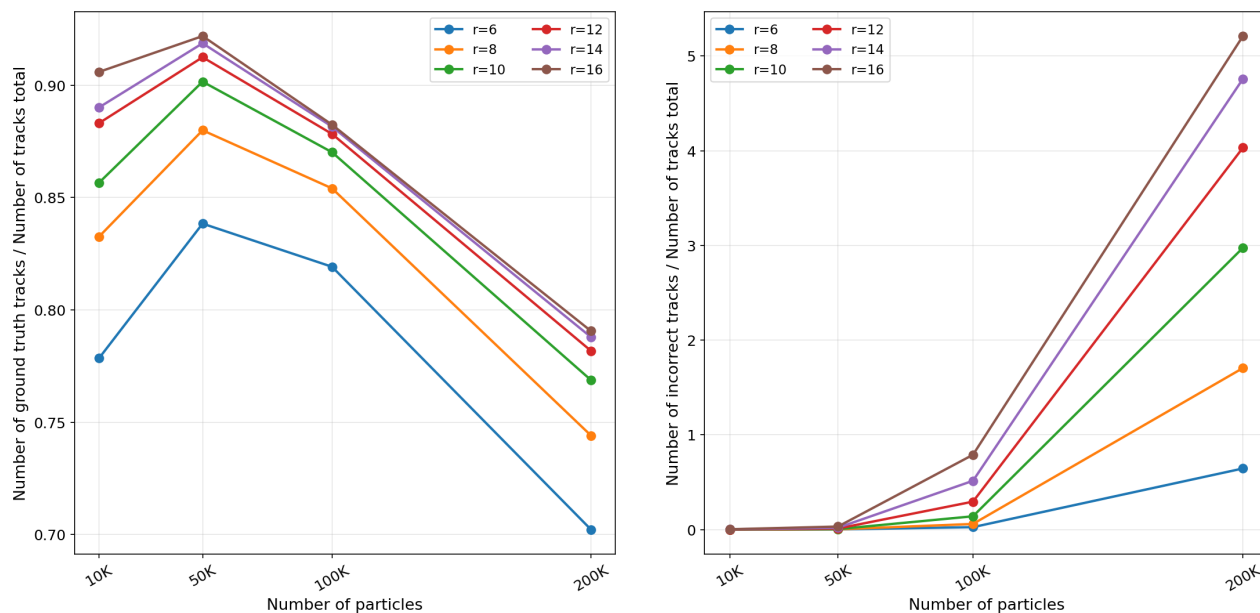


Figure 7. Left: Recovered ground truth particles normalised by particle count for different search radii. (r) **Right:** Incorrectly identified tracks normalised by particle count for different search radii. (r)

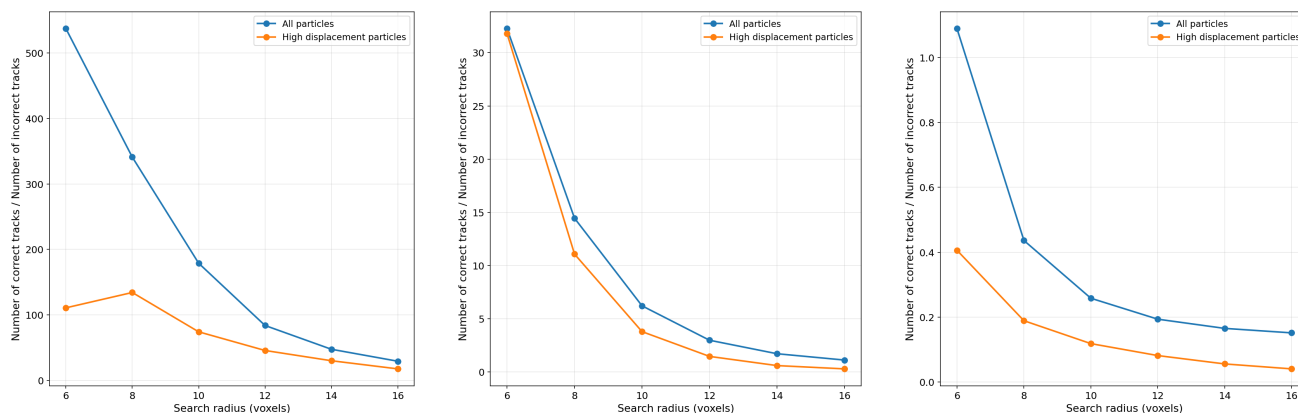


Figure 8. Left to right: Ratio of recovered ground truth particles to incorrect tracks for the 50k, 100k and 200k particle cases for the full particle and high-displacement particle sets

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Nomenclature

d	Jet exit diameter [m]
M	Mach number [-]
Re_d	Reynolds number based on jet diameter [-]

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