3D3C-coherent structure measurements in a free turbulent jet

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Abstract The near-field of a free turbulent air jet at Reynolds number 65000 was investigated by means of tomographic particle image velocimetry (TPIV). The averaged three-dimensional and three-component (3D3C) velocity fields were characterized according to standard jet quantities, such as centerline decay rate and jet-broadening rate amongst others. These values were in agreement with the few investigations [GRI06, GAN02] that have been performed in the non–fully developed turbulence regime of the flow. The main focus was laid on the investigation of coherent structures (CS³) that were analyzed by means of statistics. The CS³ were separated and extracted by constrained ensemble correlation (EC) that leads the 3D3C similarity field around an event that was chosen as a marker of a distinct CS. Although it does not yield a velocity field around that event, it is possible to make conclusions about the velocity field. Therefore it is similar to a technique called linear stochastic estimation [ADR94]. Especially flow structures around streaks were the main issue of the research. Their average local structure and the frequency of appearance could be derived with this analysis technique, which yielded similar results as shown in Matsuda et al. [MAT05] and Horii et al. [HOR04] but without the use of Taylor’s frozen turbulence [TAY38]. Compared to reconstructed volumetric velocity fields [HOR04] the present paper shows better results in terms of obedience to incompressibility of the velocity field by at least one order of magnitude at a much higher Reynolds number. Regarding the investigation of spatial structures, a discrepancy between the alignment of streaks and their surrounding vortical structures was measured and appears to be a self-similar property of turbulent jets.

1. Introduction

The study of coherent structures (CS³) in turbulent flows is essential for the understanding of turbulence mechanisms that alter significantly the global behavior of many flows. The recently developed tomographic particle image velocimetry [ELS05] allows the capturing of instantaneous three-dimensional and three-component (3D3C) velocity fields. This technique provides the possibility to obtain a vast number of velocity estimates within a volume of a given flow. Compared to other decent 3D3C measurement techniques [TRO08], tomographic PIV yields a fairly dense instantaneous velocity field that can be characterized by flow quantities that require all three velocity components (e.g. Reynolds stresses) or their derivatives (e.g. continuity, dissipation, etc.), and that are usually not entirely accessible by other measurement techniques. Another significant issue is that it measures an instantaneous flow field, because recent investigations show a serious deficiency in the validity of Taylor’s frozen turbulence [SCH09, MOI09]. The free turbulent jet flow is one of the easiest turbulent shear flows and consequently it was investigated for a long period of time and there exist a multitude of publications about its turbulent characteristics. The classical publications about jets, such as Wygnanski et al. [WYG69] and Hussein et al. [HUS94] worked basically with a small number of probes and were very limited in the determination of spatial correlations. Additionally most of them laid the focus on the fully–developed regime ($x > 20D$). Very few publications deal with the near-field of jets like Liebmann et al. [LIE92] and Ganapathisubramani et al. [GAN02], who used PIV and stereographic PIV to draw conclusions about the vortex formation. These techniques have the deficiency of measuring
the flow field in just one plane. As a consequence complex spatial dependencies cannot be resolved. More recent works [HOR04, MAT05, GAN08] try to reconstruct the third dimension of the flow by relying on Taylor’s frozen turbulence, hence transforming time sampled 2D3C data into 3D3C data. Still, the validity of this transformation is doubtful [MOI09, SCH09], especially at high Reynolds numbers. This paper presents a new approach using tomographic PIV to measure the instantaneous velocity near-field of a jet without any additional assumptions about the flow. Therefore it can be used as a cross validation tool of the widely used Taylor’s hypotheses.

2. Experimental Setup and Measurement Procedure

2.1 Setup

The experiment has been performed at the German Aerospace Center (DLR) in Göttingen, Germany. The schematic and a photograph of the experimental setup are shown in Figure 1 and Figure 2, respectively. A round nozzle with a diameter $D = 15$ mm was mounted onto a rigid support made out of Linos’ X95 structural rails. This support was also used to fix four Imager Pro X 4M cameras in such a way that they built a squared pyramid with the investigation area in the upper apex. The cameras had Zeiss lenses with a focal length of 135 mm and additional Scheimpflug adapters. These adapters were used to align the focal plane of each camera to the investigation volume for a sharp projection of the all particles in the volume. The investigation area had a size of $5 \times 5 \times 2$ cm$^3$ and was illuminated by two Nd:YAG dual-cavity laser systems with a beam power of 200 mJ per cavity. Two laser systems were used to augment the light intensity within the measurement volume. This was necessary since the laser beam had to be expanded to illuminate the whole volume, which of course decreases the energy density.

An additional mirror was inserted into the setup to reflect back the laser beam in itself, giving the beam the possibility to pass the measurement volume twice. This brings two advantages: a) light that was not scattered by particles during the first passage could be scattered in the second passing, and b) the illumination became symmetric so that the tracer particles had a similar light scattering intensity for all cameras. The seeding particles were Di-2-Ethylhexyl-Sebacat (DEHS) droplets that are common tracer particles in airflows and have an average diameter of $1 \to 2 \mu m$. Due to the small particle size, inertial forces acting on the particles were negligible so that the droplets are supposed to follow the flow dynamics. The seeding was introduced into a pressurized chamber where they mixed homogeneously with air and subsequently ejected horizontally into the laboratory by the nozzle. LaVision’s software DaVis 7.4 controlled a Programmable Timing Unit (PTU9) that synchronized the imaging process with the illumination. The very same software was used to reconstruct the volumes by means of tomographic PIV [ELS05] and to calculate the three-dimensional motion field using cross-correlation.

<table>
<thead>
<tr>
<th>Setup properties</th>
<th>Measurement parameter</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nozzle diameter</td>
<td>0.015 m</td>
</tr>
<tr>
<td>Investigation area</td>
<td>0.05 x 0.05 x 0.02 m$^3$</td>
</tr>
<tr>
<td>Cameras</td>
<td>4 Megapixels</td>
</tr>
<tr>
<td>Laser beam intensity</td>
<td>2 x 200 mJ / pulse</td>
</tr>
<tr>
<td>Seeding Particles</td>
<td>DEHS</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Exit velocity</th>
<th>Mach 0.2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reynolds Number</td>
<td>65000</td>
</tr>
<tr>
<td>Sampling frequency</td>
<td>4 Hz</td>
</tr>
<tr>
<td>Number of samples</td>
<td>750</td>
</tr>
<tr>
<td>Separation time</td>
<td>15 $\mu$s</td>
</tr>
</tbody>
</table>

2.2 Measurement procedure and velocity field estimation

The measurement was performed with an exit velocity of about Mach 0.2 ($U_0 = 65.43$ m/s), which leads to Reynolds number $Re = 65000$. Hence the jet flow was in the turbulent regime and turbulence behavior was occurring. The velocity field was measured 750 times at a frame rate of 4 Hz at five adjacent positions, covering a streamwise range of 0.2 to 15.6 diameters from the nozzle exit. The jet was permanently running while carrying out the measurement and the seeding
was set in such a way that the images were covered with 50% particles. The separation time between consecutive images was adjusted so that the maximal particle displacement was about 10 pixels, which provided a sufficient dynamic range to capture large and small velocities. The large f-stop of \( f_n = 16 \) expanded the depth of focus, which allowed getting sharp particle images throughout the volume.

After a volumetric calibration procedure \([\text{WIE08}]\) the intensity distribution within the volume could be reconstructed from the set of four instantaneous projections by means of the \textit{multiplicative algebraic reconstruction technique} (MART) \([\text{HER76}, \text{ELS05}]\). The voxel-to-pixel-ratio was set close to one, so that the computational reconstruction domain could be discretized into \( 1205 \times 1205 \times 483 \) voxels with a volume of \((41\mu m)^3\) each. All pairs of consecutive intensity volumes were used to retrieve the velocity field by a 3D multigrid cross-correlation approach. The final correlation window size was \( 64 \times 64 \times 64 \) voxels with an overlap of 75%, leading to a total number of \( 75 \times 75 \times 29 \) vectors with a vector spacing of 0.04D. The actual spatial resolution is 0.09D and is capable to measure flow dynamics starting from a wavelength of 0.17D \([\text{NOG05}]\).

### 2.3 Computational Effort

The computational cost of the volume reconstruction was enormous since more than 700 million voxels had to be handled at the same time. Using float-values the storage of the intensity variable needed about 2.7 Gbytes of memory. The time consumption for the reconstruction (3 iterations of MART) of one set of four images and the correlation of the consecutive volumes was about 180 and 120 CPU minutes, respectively. The evaluation of all images took about 2 month on four computing clusters with a total number of 24 cores.

### 3. Results

#### 3.1 Instantaneous Velocity Fields

In terms of the validation of the instantaneous flow fields, a first survey by eye was performed to assure a sufficiently good calibration to yield physically reasonable results (Figure 3). Another mean of validation is based on the fact that air at a speed of 65 m/s is nearly incompressible, which means that \( \text{div}(\vec{u}) \) should be zero. This validation method is just viable because all three velocity components are accessible including their spatial gradients. Figure 4 shows a color contour plot where the color indicates the degree of divergence in one slice through an instantaneous

![Figure 1: Scheme of the experimental setup](image)

![Figure 2: Photograph of the measurement setup](image)
volume. The average non-dimensional divergence (normalization by $D$ and $U_0$) is smaller than its RMS, which is around $2.6 \cdot 10^{-3}$. This appears to be quite good since other investigations [HOR04] deal with RMS values above 5% at a much lower Reynolds number. This underlines the advantage of having the instantaneous velocity field measured and not reconstructed ones using the Taylor’s *frozen turbulence*, which is highly questionable in non–fully developed turbulent flow.

![Instantaneous turbulent velocity field](image1)

![Normalized turbulent divergence](image2)

### 3.2 Statistical Analysis

Since we want to apply statistics to get information about the flow, we want to examine the continuous joint probability density function (PDF) $\rho(u(\bar{x},t))$ that holds the probability to get a certain velocity vector $\bar{u}$ at a specific position $\bar{x}$ and time $t$. Essential property of $\rho$ is that its integral over the whole range $\bar{x}$ and $t$ and all possible states of $\bar{u}$ equals one.

$$\int d\bar{u} \int d\bar{x} \int dt \rho(\bar{u}(\bar{x},t)) = 1$$

Since we have sampled $\rho$ temporally $t_1,...,t_T$ and spatially $x_{i,j,k}$, we can approximate $\rho$ with a discrete function $P$ with the same integral behavior

$$\sum_{i=1}^N \sum_{j=1}^T \int d\bar{u} P(\bar{u}(x_i,t_j)) = 1$$

For convenience the discrete measurement position $\bar{x}$ within a volume is indexed with a single index $x_i$. The separation time between two adjacent instantaneous measurements $\bar{u}(x_i,t_j), \bar{u}(x_i,t_{j+1})$ exceeds the spatiotemporal correlation length. Therefore we assume statistically independent measurements in time. This means that any temporal normalized correlation between two different time steps is zero.

$$\text{corr}[\bar{u}(x_i,t_j), \bar{u}(x_i,t_{j+1})] = \delta_{ij} \quad \forall \ell, \ell'$$

Furthermore this means that the joint PDF does not depend on the parameter time. This assumption can be reinforced by looking at the detachment frequency of ring vortices at the nozzle, which are spatial separated by about one nozzle diameter. The CS$^3$ convect about 500$D$ within two measurements for the slowest average centerline velocity of $U = 2000D/s$, which exceeds the length of the measurement volume ($3D$) by several orders. Therefore it is highly probable that the measurement data can be assumed statistically independent in terms of its temporal dependency.

This allows determining the time-average flow field $\bar{u}(x_i)$ by calculating its temporal expectation value at every point within the volume.

$$\bar{u}(x_i) = \frac{1}{T} \sum_{t=1}^T \int d\bar{u} [\bar{u}(x_i,t) \cdot P(\bar{u}(x_i,t)) ]$$
The time-averaged flow field and its profiles are shown in Figure 5 and Fig 6, respectively. Furthermore this data was used to retrieve common non-dimensional parameters that characterize a jet flow. The most important quantities are listed in the following table.

<table>
<thead>
<tr>
<th>Quantity</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Exit velocity</td>
<td>( U_0 = 65.47(3) \text{ m/s} )</td>
</tr>
<tr>
<td>Spreading rate</td>
<td>( \eta_{1/2} = 0.091(1) )</td>
</tr>
<tr>
<td>Decay of the centerline velocity</td>
<td>( B = 7.21(1) )</td>
</tr>
<tr>
<td>Length of the potential core</td>
<td>( x_p / D = 5.61(3) )</td>
</tr>
<tr>
<td>Virtual origin</td>
<td>( x_0 / D = -1.60(2) )</td>
</tr>
</tbody>
</table>

It has to be pointed out that even though 750 measurements were taken, the temporal average converged just up to an average residual of \( O(10^{-6}) \), which is insufficient for smooth appearances of second order properties in areas where the turbulent flow dominates. The average RMS residual is \( O(10^{-3}) \). Since the flow has a rotational symmetry, this deficiency can be diminished by additionally averaging in the spatial domain.

3.4 Turbulent quantities connected to spatial gradients

The significant feature of TPIV is that it can resolve spatially distributed instantaneous velocity estimates and their gradients, which makes it an excellent tool to investigate turbulent flows. Many quantities depend on all spatial gradients of the velocity components that could not be assessed instantaneously with former measurement techniques. Tomographic PIV fixes this limitation and allows the direct determination of properties such as continuity, dissipation rate, turbulence production and Kolmogorov length without simplifying the calculation with any additional physical model, e.g. local turbulent isotropy.

According to [HIN59] the dissipation rate \( \varepsilon \) is defined as temporal average of products of spatial fluctuation gradients (Einstein notation)

\[
\varepsilon = \nu \left( \frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i} \right) \frac{\partial u_j}{\partial x_i}
\]

Most commonly simplifications are made to assess the dissipation by comparing the magnitudes of the derivatives. Usually derivatives are neglected or expressed in terms of the spatial gradient of the
main component in streamwise direction $\varepsilon_{iso} \approx 15\nu(\partial \bar{u}/\partial x)^2$ [ROT72]. Sometimes this gradient is further approximated by other quantities (e.g. Taylor length) that can be measured more accurately [ANT80, FRI71]. In this experiment the dissipation rate and the turbulence production rate was calculated for every instant and then averaged over time. The result was normalized by the jet width $b$ and the average centerline velocity $U_c$ and is shown in Figure 7. It illustrates that the dissipation happens in the inner part of the jet with a nearly homogeneous rate. The dissipation rate was also calculated using the isotropic approximation. A comparison of both verifies the isotropic assumption to estimate the dissipation for large distance from the nozzle. Figure 8 shows the planewise averaged ratio of the dissipation rate $\varepsilon$ to the isotropic dissipation rate $\varepsilon_{iso}$ including the standard deviation as error bars. This graph states that this approximation holds quite well if the main objective is to measure the average dissipation far away from the nozzle with a sufficiently large number of measurement data ($\varepsilon/\varepsilon_{iso} \rightarrow 1$). In terms of small distances, the anisotropic behavior is dominating the average fluctuations and therefore the isotropic assumption fails. This graph can be used to estimate the error made by using this approximation or even to conclude corrections.

![Normalized turbulent dissipation rate](image1)

![Averaged dissipation ratio](image2)

### 3.4 Coherent Structures

Of primary interest was the qualitative and quantitative characterization of CS² in the jet flow. The vast number of spatial sampling estimates within each instantaneous measurement volume was used to make up for the lack of too few time samples. This allowed the probing the joint PDF up to second order properties that still provided meaningful results. The joint PDF can be described by its average $\bar{u}(x_i)$ and its covariance matrix $(\Sigma)_i = \text{corr}[\bar{u}(x_i), \bar{u}(x_j)]$. Since this matrix is too large to be handled computationally ($>2 \cdot 10^{10}$ entries × velocity discretization), some simplifications have to be made. Instead of looking at the joint PDF and its spatial inter–relationship between the velocities, we simplify the problem by picking out a smaller subset of measurement positions. The first non-trivial set contains two positions that is feasible in terms of computation and still provides new insight into the dynamics.

$$\tilde{\rho}(\bar{u}(x_i), \bar{u}(x_j)) \quad \forall i \neq j$$

For this model the covariance matrix has the size $2 \times 2$ and holds the velocity variances of each position at the diagonal elements and the cross-correlations of both positions at the off-diagonal elements. The off-diagonal elements contain the relationship between velocity components at both positions. This analysis technique is commonly known as two-point-correlation and widely used for measurements with multiple input signals (e.g. multiple probes). Tomographic PIV offers an
enormous number of simultaneous measurements that can be analyzed in terms of its pair-wise relation. Still, the amount of all correlation pairs outnumbers the acceptable problem size (>26 billion correlations). Most of the time it is not necessary to calculate all correlations because of symmetries. Therefore it is reasonable to set special positions \( x_o \) and correlate their velocity components \( \tilde{u}(x_o) \) with the entire velocity field. In the following this particular velocity vector is called “event” \( \mathbf{e}(x_o) \). The average similarity of such an event to the entire velocity field can be estimated by ensemble correlation averaging [MEI00].

\[
\bar{R}(x_o) = \frac{1}{T} \sum_{t=1}^{T} \text{corr}[\mathbf{e}(x_o,t), \tilde{u}(x,t)]
\]

The correlation of a scalar field with a vector field is done for each component separately, thus yielding a three-dimensional similarity estimate of this event. The previously mentioned low number of time samples prohibits getting smooth results. That’s why additional averaging in space was done. The assumption is that points that are close by, most probably obey the same distribution function. The term “close by” has to be defined properly in such a way so that this assumption remains valid. This is the case if the Euclidean distance between two points is much smaller than the Taylor length \( \lambda_T \).

\[
p(\tilde{u}(x_o)) = p(\tilde{u}(x_j)) \land \|x_j - x\|_2 \ll \lambda_T
\]

This length scale can be used to define a local neighborhood \( \mathcal{N}(x_o) \) and thus the spatial averaging domain. By just including the left and the right position in each dimension gives a total of \( 3^3 \) positions that are averaged additionally to the time average (\( \lambda_T \approx 0.2D \)). Special symmetries in the flow might allow the averaging over entire spatial dimensions (e.g. boundary layer [SCH09]).

\[
\bar{R}(x_o) = \frac{1}{T} \sum_{t=1}^{T} \sum_{x \in \mathcal{N}(x_o)} \text{corr}[\mathbf{e}(x,t), \tilde{u}(x + (x - x_o),t)]
\]

The ensemble correlation was applied to estimate the local structure of velocity fluctuations around the position \( x_o = (13.88,0,0) \) with a \( 3 \times 3 \times 3 \) neighborhood. The result of the autocorrelation of each velocity component is shown in Figure 9. The axes show the local displacement \( \Delta x \) and \( \Delta y \) from \( x_o \), which is in local coordinates \((0,0)\). Apparently, these three plots look quite different. The autocorrelation of \( \tilde{\mathbf{u}} \) is elongated in streamwise direction, while \( \tilde{\mathbf{v}} \) extends mainly in spanwise direction. Those preferences can be connected to streaks that have a preferred orientation along the axis or away from it. The correlation \( \tilde{\mathbf{v}} \) appears slightly more difficult to be interpreted. Obviously there is an asymmetry, which indicates that the turbulent flow is rather correlated into the past \( (\Delta x < 0) \) than into the future \( (\Delta x > 0) \). It depicts the average CS that occurs at this position, which is a leftover structure from ring vortices that degenerated and fell apart. This process is shown in Figure 10, where the initial ring vortex (a) is deformed by random fluctuations (b), which generated additional forces that lead to a breakdown of the original structure [HUS86].
The bow-like structure in \( \overline{ww} \) (Figure 9) can be identified with a part of the decomposed vortex ring shown in Figure 10c. The other complement structure at this point, which appears quite rarely, is drawn in light gray, due to the time argument that was pointed out previously. More apparent is this structure in Figure 11 that depicts the correlation of two components of the vorticity \( \overline{\omega_y \omega_x} \). Here, the shape is essentially the same but there is additional information about the rotational sense. It states that the vorticity has a different sign depending on the side of the event. This agrees quite well with the standard hairpin model [NIC01, ADR07]. The average CS is a fragment of a previously broken vortex ring, that forms hairpin–like structures [HUS86]. With EC technique it is possible to estimate the size as well as the local structure of the average CS by a set of correlation scalar fields \( \overline{(e(x_o)u_i(x))} \), \( i = 1,2,3 \).}

\[ \overline{\rho R(x)} = \overline{\rho R(x|c)} + \overline{\rho R(x|\neg c)} \]

### 3.5 Constrained ensemble correlation

The previously shown results characterized the average CS that appears at a distinct position. Most often this is a superposition of several different CSs that cannot be distinguished anymore. This can be avoided in the first place by a decomposition of the velocity field to extract information about individual CSs. Assuming the average flow structure around a high-speed streak is to be investigated, an adequate constraint like \( u > 0 \) can be included to achieve a separation. In general all kinds of constraints \( c \) can be included to decompose the similarity field: e.g. positive vorticity, small \( \lambda_2 \) or even multiple constraints. A similar approach to estimate the most likely velocity field is called linear stochastic estimation, which was already proposed by Adrian [ADR94]. Since it is a decomposition, its combination sums up the unconstrained ensemble correlation.

The new problem is to define constraints, which uniquely define just the type of CS that has to be investigated. The more constraints are included, the better is the separation of this structure but on the other hand less data applies to it. Of course, it is a trade–off between matching a distinct CS and the quality of the average result that has to be considered. Consequently, the constraint was set quite loosely to \( c = \{u > 0\} \), to obtain a deeper insight into high-speed streaks and their surrounding flow depending on the position of the streak. The constrained EC estimates the average similarity with respect to an event. Because the applied
constraint demands a positive sign at the event position, the EC gives also information about the average direction of the surrounding flow. Therefore the similarity field can be interpreted as a velocity field, whose vectors have the magnitude of the similarity measure. If the event position and the velocity vector position get more and more apart they become uncorrelated, which is reflected in the strong decay of the magnitude of $\tilde{R}$. For further studies the constrained EC was normalized vectorwise to diminish the distortion effects of the similarity measure. The assumption is that all turbulent fluctuations have a similar average magnitude and the direction of the vectors remains unchanged. This yields a vector field that can be analyzed by common measures, such as $\lambda_2$ [JEO95]. It was indicated previously that high-speed streaks are accompanied by surrounding vortices. These have a distinct orientation depending on the location $x_0$ of the streak. The Figure 12 shows the iso-surface of the swirl-measure $\lambda_2$ around a high-speed streak, which is indicated by the arrow. The middle graph was calculated on the centerline of the jet, while the other two graphs were calculated at shifted positions to either the left or the right side by half a diameter ($y = \pm 1/2D$). All three plots show a small area in the center with no vortical structures but ring–like vortices around them. It has to be pointed out that the structure is still a superposition of multiple CSs, which means that it is unlikely to have a full ring vortex. Instead there are just lower and upper parts that average to a closed ring vortex. Similar results were presented by Matsuda et al. [MAT05], who used Taylor’s frozen turbulence to derive 3D flow fields from time sampled 2D measurements.

![Figure 12: Vortical structures (\(\lambda_2\)-contour) around high-speed streaks (arrows) at different positions from the jet axis](image)

$y/D = \{-1/2, 0, 1/2\}$

Apparently, the streaks as well as the “ring” vortex orientation have a dependency on the radial distance from the jet axis. The alignment of the streaks was determined by the angle $\theta$ between the jet axis and the event vector and is shown in Figure 13. This was done for three different distances from the nozzle. After applying the self–similar coordinate transformation these orientational dependencies match each other, which indicates that this is a general characteristic of turbulent jet flows. The plot in Figure 14 shows a comparison of the streak orientation (solid line) and the normal of the vortex plan. Again the vortical structures appear to obey to a general self–similar rule. The direct comparison to the streak and the vortical structure orientation shows that
they differ up to 20°. This indicates that the vortical structures tilt stronger away from the jet axis to lower velocities than the streak itself. At the same time the distance between diametral vortical structures is elongated in radial direction. These two facts accompany the breakdown of $CS^5$, where ring vortices get distorted by random fluctuations and generate bumps that have a different convection velocity. This causes the vortex ring to deform even more until it breaks apart [DAZ06].

![Figure 13: Orientation of the streak according to the jet axis](image1)

![Figure 14: Orientation of the vortical structures around a jet](image2)

4. Conclusions

Since the upcoming of tomographic PIV, it has become an indispensible tool for the investigation of turbulent structures and verification of turbulent models. Although it cannot achieve a spatial resolution comparable to stereographic PIV, its advantage is the particular property to gain instantaneous 3D3C velocity data without additional assumptions. The lower magnitude of the flow field divergence can be seen as an indicator that TPIV describes more accurately 3D flows than reconstructions of time-resolved 2D3C PIV measurements. This becomes even more important if $CS^5$ have a large correlation lengths but bad aspect ratios like for boundary layers [SCH09]. With respect to jet flows this becomes an issue in the near-field of the nozzle. There, general assumptions (like isotropy) are invalid and give erroneous results that could be compared to the values calculated without those assumptions. The results can be used to improve numerical models to describe also non–fully developed flow regimes by including empirically measured dependencies of anisotropic behavior.

The constrained ensemble correlation analysis is a powerful tool to extract special flow behavior that can be examined afterwards. Furthermore the possibility to use Fast Fourier Transforms to calculate the constrained EC makes it fairly efficient in terms of computational time. The results achieved by constrained EC fit the general knowledge about $CS^5$ in jets and provided furthermore the possibility of new volumetric analysis methods in 3D. Those methods are capable to capture whole structures and with a sufficiently large number of samples can lead to highly converged averages using multiple constraints.

The major drawback is that it provides a similarity field and not directly the velocity field. A natural starting point to fix this disadvantage would be to use maximum likelihood methods that give the most probable turbulent velocity estimate with respect to a given event. This will be of great interest for future investigations of turbulent dynamics.
References


