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Sciacchitano, Andrea; Discetti, Stefano

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## Editorial

# Special issue on uncertainty quantification in particle image velocimetry and Lagrangian particle tracking

Andrea Sciacchitano<sup>1,\*</sup>   
and Stefano Discetti<sup>2</sup> 

<sup>1</sup> Faculty of Aerospace Engineering,  
TU Delft, Delft, The Netherlands

<sup>2</sup> Aerospace Engineering Research  
Group, Universidad Carlos III de  
Madrid, Leganés, Spain  
E-mail: [A.Sciacchitano@tudelft.nl](mailto:A.Sciacchitano@tudelft.nl)

The determination of a confidence interval is a key requirement for any measurement. In particle image velocimetry (PIV), the quantification of the measurement uncertainty strengthens the suitability of the technique for the discovery of new physics of fluid flows, as well as for the validation of numerical simulations by computational fluid dynamics.

The present special issue on uncertainty quantification (UQ) in PIV and Lagrangian particle tracking (LPT) follows the successful one published in 2015 [1], which focused on the *a-posteriori* UQ of instantaneous two-component PIV measurements. Since then, the PIV technique has greatly advanced, further extending its range of applicability from micrometric scales to metre-scale three-dimensional flow measurements. In this special issue, the uncertainty associated with different aspects of the PIV and LPT techniques is addressed, including seeding particles, system calibration and imaging, the evaluation of derived flow properties, and novel processing algorithms based on neural networks.

Bias errors in PIV statistics caused by the temporal and spatial inhomogeneity of seeding particles (intermittent particle seeding or conditional particle sampling) as well as by the particle lag are investigated by Martins *et al* [2]. By making use of a synthetic PIV experiment based on large eddy simulations, the authors show that particle lag and intermittent seeding yield bias errors on the local average velocities. The errors are even larger for derived flow quantities, such as Reynolds stresses, turbulent fluxes and velocity gradients.

Paolillo and Astarita [3] analyse the contribution to the measurement uncertainty of different calibration models applied to optical systems that include refractive surfaces, i.e. interfaces separating two media with different refractive indexes. Models based on physical laws (refractive camera model, relying on the pinhole camera model and on a ray-tracing procedure) as well as analytical models (based on polynomials, multi-plane polynomials and rational functions) are comparatively assessed. The results show that the refractive camera model outperforms the analytical models, and that the latter require high-order polynomials to minimise the calibration errors.

Qureshi *et al* [4] investigate the measurement errors of PIV and PTV in presence of particle image streaks, often caused by the relatively long exposure times in supersonic or hypersonic flows or bio-medical applications. The results based on the analysis of synthetic and experimental images show that the PTV

\* Author to whom any correspondence should be addressed.



algorithm performs well only for short streaks, whereas larger streaks yield a significant reduction of the particle match reliability and an increase of the RMS displacement error. In contrast, the PIV algorithm exhibits higher robustness and is able to handle long-exposure particle streaks, with little sensitivity to the particle image diameter and intensity.

Two of the works of this special issue deal with peak locking, arguably the most reported error in PIV measurements. Nogueira *et al* [5] further develop their recently proposed multi- $\Delta t$  strategy for the correction of peak-locking errors in statistical ensembles, namely the local velocity average and the fluctuations root-mean-square. In particular, the authors address the problem of the calibration of the error model coefficients based on real experimental data. The application of their error correction strategy to a jet flow results in a reduction of the peak locking errors by 30% for the average velocity, and by factor 2.5 for the fluctuations root-mean-square. Similarly, Adatrao *et al* [6] investigate the systematic UQ and peak locking error correction of velocity statistics (time average and Reynolds stress) via a multi- $\Delta t$  approach. In the proposed approach, image recordings are acquired with multiple time separations, and a least-square regression is performed to achieve more accurate flow statistics and an estimate of the confidence interval.

Rajendran *et al* [7] introduce a method to estimate the sensitivity and reliability of *a-posteriori* PIV-UQ approaches. The method, named meta-uncertainty, is based on the perturbation of the recorded particle images, and the quantification of the uncertainty from both original and perturbed images. The authors also propose to apply the meta-uncertainty as a weighting metric to combine the uncertainty estimates from different PIV-UQ algorithms, showing improved performance of the combined UQ scheme compared to the individual ones.

Recent advances in the application of machine-learning methods to PIV image processing are posing new research questions on the corresponding UQ, as well as paving the way to new strategies embedding UQ in the processing. Barnkob *et al* [8] present an assessment of the uncertainty of particle image model functions, normalized cross-correlation and neural networks for defocusing particle tracking. The authors explore different levels of astigmatism, noise and particle image overlap. Their results show that particle image model functions perform best for low levels of noise and particle images overlap, while cross-correlation is more robust in presence of large noise and particle image density. Neural networks show worse performances, although the authors remark the margin of improvement of deep-learning methods. Morrell *et al* [9] introduce Bayesian convolutional neural networks (BCNNs) as a technique to process PIV images and simultaneously quantify the uncertainty. The method is based on learning distributions of the weights of the CNN using variational Bayes. The authors investigate BCNNs with input based on image interrogation regions, cross-correlation maps, and a combination of both, obtaining the best results when the input is only based on cross-correlation maps.

Uncertainty on derived flow properties data is another flourishing research line in UQ from PIV. In this special issue four contributions are ascribed to this category.

A grid-free least-square method for pressure evaluation from scattered LPT data is assessed by Brobov *et al* [10]. The least-squares method can be used for reconstruction on irregular or regular grids and aims to minimization of random noise. The authors assess the accuracy of the method with synthetic images based on DNS of the flow over a hemisphere mounted on a surface, focusing on the effect of the particle image densities up to 0.02 particles per pixel and different image noise level.

Castellanos *et al* [11] developed a framework to estimate *a-priori* the uncertainty of boundary-layer parameters from ensemble particle tracking

velocimetry (EPTV). The tool mimics systematic errors due to finite spatial resolution and random errors due to convergence using analytical composite-profile formulations or simulations at matched conditions when available. The statistical dispersion of the estimated parameters from a set of simulated profiles is then used to infer the uncertainty range of the EPTV measurement.

The contribution by Faiella *et al* [12] is focused on the error propagation in pressure fields computed from velocimetry measurements. The authors demonstrate an analogy between the error propagation in pressure field calculations from velocity data with buckling theory of elastic bodies. The analogy is then exploited to analyze the effects of spatial frequency and location of the error on the error propagation from velocimetry data and pressure fields.

Spoelstra *et al* [13] examined the uncertainty of the drag measurement for the case of a cyclist riding through the measurement domain, in a configuration for aerodynamic drag measurement referred as Ring of Fire (RoF). The authors found that the procedure to detect the edge of the momentum deficit region has a relevant influence on the uncertainty of the measured drag. The effect of spatial resolution is shown to be less significant, provided that the interrogation window size lays within 5%–25% of the characteristic length scale of the object transiting in the RoF.

We sincerely hope that the readers of Measurement Science and Technology will find this special issue useful to support the quantification of the uncertainty of future PIV and LPT measurements.

### Data availability statement

No new data were created or analysed in this study.

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### ORCID iDs

Andrea Sciacchitano  <https://orcid.org/0000-0003-4627-3787>

Stefano Discetti  <https://orcid.org/0000-0001-9025-1505>

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