Response to reviewer 1

General comments

This study assesses four image based velocimetry techniques for measuring water velocity in shallow flows as would be observed in overland flows over paved surfaces during rainfall events. The problem is physically challenging, and the authors use a dedicated lab setup to assess these techniques with an eye to evaluating their potential for more difficult and varied conditions in the field. The work is derived from a larger project that has led to a number of significant publications over the last couple of years and is a direct extension of a 2019 paper that validated one of the approaches used (LSPIV). The validated approach is used as the reference condition for the current paper. The paper overall was well written and the methods appeared to be suitable for assessing the other velocimetry techniques.

Response:

We appreciate the reviewer for the time invested in reviewing our manuscript and for the positive evaluation of our work. We are grateful for the detailed review and believe that the constructive comments and suggestions will lead to a deeper and clearer analysis of the results presented in this article, contributing to significantly improve the quality of the manuscript. In this document, we present the responses to the reviewer comments indicating how we will address them in the revised version of the manuscript.

Despite the quality of the work, the authors in my opinion are too positive about the results. In looking at the results from my reviewer's perspective, it appears that the unseeded techniques are not suitable for measuring velocities in shallow flows. Even in relatively straight flows with low precipitation, there is an offset between the unseeded techniques and the LSPIV results that is not well explained. It is not clear to me how the magnitude of this offset could be predicted without controlled tests. As the precipitation intensity increases, the error in the unseeded techniques increases to the point where the results are no longer even correlated with the validated technique. In these conditions I would argue that the unseeded techniques are simply not suitable. Despite this, many of the statements in the discussion and conclusions are quite positive about the techniques. The optimism seems to be related to other studies or results that are not included in the current paper. Something needs to be adjusted, either by including those results (maybe cases without any precipitation at all?) or by drawing sharper lines about which techniques are reliable in different conditions.

Response:

Based on the comment of the reviewer, we have reread the manuscript and we agree that the discussion and conclusions appear too positive considering results presented for unseeded methods (BIV and SSIV). This may lead journal readers to confusion if a clear and contextualized interpretation of the results is not included. The positiveness showed is due to the great potential of unseeded techniques as a tool to obtain runoff velocity data from media sources commonly available in urban environments, such as surveillance cameras, traffic cameras, or even social media. From our point of view, this is a novel and powerful data source with a great potential to solve the current lack of surface runoff velocity data, which is key in the proper calibration of the increasingly more accurate 2D-1D dual urban drainage models that are currently being developed. The use of these data sources has been recently introduced in the field of urban drainage (Leitão et al. 2018, de Vitry et al. 2020). In addition, in contrast with the increasingly more common application of visualization techniques to rivers monitorization (Pearce et al. 2020, Tauro et al. 2016, Tauro et al. 2018), their use for urban runoff measurements is still limited to some initial applications on the analysis of the velocities in a stormwater storage facility (Zhu et al., 2019) and in simulated urban floods (Leitão et al. 2018), both without precipitation. Therefore, this is the first work where the influence of raindrop interference with the recorded images and their impact in the measurement of velocities is analyzed, and therefore is still much room for improvement in this novel implementation.

In this context, we consider as positive the results obtained from unseeded techniques for low rain intensities where the results correlate with LSPIV results, since two different techniques are being used. The different density and size of bubbles and artificial fluorescent particles explains the offset found for low rain intensities, since tracers are affected in different degrees by raindrop impacts and may be transported at different velocities. The gap obtained in this study between seeded and unseeded experiments may be thus interpreted as an indicator of the uncertainties that may appear when using visualization techniques in rainy conditions depending on the type of tracer. As commented by the reviewer, we think that the prediction of the magnitude of this offset is currently challenging, so further investigation on how rain impacts the transport of possible tracers appears as an interesting research line to reduce uncertainties in runoff velocity measurements. Finally, the different tracers analyzed also explain the different behavior of seeded and unseeded techniques when the rain intensity is increased. While raindrop impacts produce fast and random changes of position in bubbles, that are incremented with rain intensity, the higher density of fluorescent particles confers themselves inertia to avoid such sudden movements. We think that this great affection of raindrops in unseeded techniques, leading to erroneous results for high rain intensities, is an important result of the present work and we agree that this should have been clearer presented in the text.

We will thus revise the results and discussion chapters to clarify these points by, as suggested by the reviewer, drawing sharper lines between the performance of each methods, explaining deeply the offset obtained between seeded and unseeded techniques, and discussing the potential and possible challenges of visualization techniques to measure urban runoff velocities. Among other little modifications, the following sentence will be added in the Results and discussion and conclusions sections to clearly specify that unseeded methods are not working for high intensities:

“However, the velocity fields obtained for rain intensities of 50 and 80 mm h^{-1} showed that both the SSIV as well as the BIV techniques resulted in erroneous velocity distributions, being more affected the areas where greater velocities are developed”

“This also gives techniques that use bubbles as tracers an opportunity to measure velocities in extremely shallow flows where particles tend to be deposited. However, SSIV and BIV are more affected by the impact of raindrops leading to erroneous results for high rain intensities, especially for high velocity flows”

“Unseeded techniques are highly affected by raindrop impacts. First, the gap between seeded and unseeded techniques is reduced as the rain intensity is increased, so rain intensity would be considered to determine the velocity index for estimating depth-average velocities. Then, raindrop impacts also produce fast and random changes of position of the bubbles used as tracers, leading to erroneous velocities for high rain intensities. However, the ability of measuring extremely shallow flows where particles tend to be deposited, and their easy implementation without the need of adding artificial particles, make unseeded techniques worthy of future investigations as new source of runoff velocity data in urban catchments.”

The explanation of the offset between seeded and unseeded experiments will be completed in Section 3.2 and stated in conclusions as follows:

“All visualization techniques presented a similar velocity distribution for the lowest rain intensity (first row), although an offset of approximately 0.05 m s-1 was obtained for the unseeded techniques. This offset is produced because the different tracers used in seeded and unseeded experiments, which are affected in different degrees by raindrop impacts and may be transported at different velocities. Considering the novel application of these techniques in presence of rain, it can be deduced that all techniques obtained a good performance for 30 mm h^{-1} rainfall and that lower velocity indexes are required in the case of unseeded techniques to convert the results to depth-averaged velocities, as observed in previous references (Leitão et al., 2018; Martins et al., 2018; Naves et al., 2019a)”

“Both seeded and unseeded techniques provide suitable velocity distributions for lower rain intensities in case of unidirectional flows, observing an offset of approximately 0.05 m s-1 between them. This offset is a consequence of the different tracers used in seeded and unseeded experiments, which are affected in different degrees by raindrop impacts and may be transported at different velocities. Lower velocity indexes are thus required in the case of unseeded techniques to convert the results to depth-averaged velocities. In case of more complex flows, unseeded techniques are not able to adequately measure since bubbles have difficulties to follow the runoff generated.”

Questions and comments:

148 – Is the LSPIVb procedure significantly different than the LSPIV? In reading the methods I thought that the results might arrive at the same point as each requires a threshold, one applied to the difference, the other to the base images and then the

difference is then calculated. The results also show that they are nearly the same. The point of the LSPIVb analysis is not emphasized in the paper. What is the motivation for evaluating this technique? It is not really discussed in the results or appear in the conclusions to a significant extent. Does it 'better remove background and shadows. . .”? Should other people use it instead of the regular LSPIV?

Response:

This is an interesting comment of the reviewer. It is true that preprocessing of both LSPIV and LSPIVb depends on only one threshold, but the different purpose of these thresholds lead to different preprocessed images. First, the sliding background preprocess was applied in the LSPIV technique to remove all elements that remain fixed between two consecutive frames, including the road surface, other elements of the physical model, and immobile particles. The threshold used in this case corresponds a percentage of the grey value to consider that an element does not move since, although the pixel correspond to a immobile element, this value may slightly vary because of variations on water surface or raindrops interferences. In contrast, the binarization performed for LSPIVb technique seeks mainly to isolate the brightest pixels, which in this case will correspond with the fluorescence particles used as tracers. Then, we also remove deposited and immobile particles with the sliding background filter, but the binarization makes the previous margin of gray value used in LSPIV unnecessary.

Binarization is used in PIV studies (e.g. Zhou et al. 2013) to remove the remaining noise in raw PIV images, resulting in images where all the particles have the same intensity and thus have equal contribution to the correlation function. However, this preprocessing technique would lead to increase measurement uncertainty if the threshold value is not properly addressed (Raffel et al. 2018). The motivation of including binarization in seeded experiments (LSPIVb technique) was firstly consistency with the unseeded techniques found in the literature. While SSIV seeks to remove immobile features from frames through sliding background and analyze the movement of all other elements, BIV seeks to analyze only the movement of bubbles, which are identified as the brightest elements in the images, removing the rest of features from the images. When we applied these preprocessing procedures to seeded experiments images, we observed that the processed images were slightly different and the binarization (in LSPIVb technique) reduced the number of particles to analyze in the images. For example, this can be observed in the following figure (Figure R1), where the same frame obtained from seeded videos was preprocessed following the procedures for LSPIV and LSPIVb respectively.

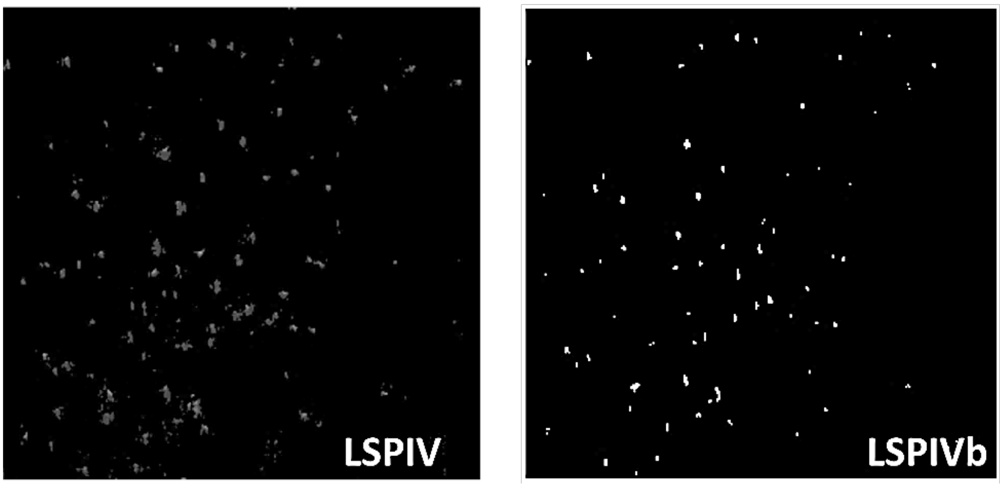

Figure R1. Preprocessed frame for LSPIV and LSPIVb imaging techniques.

In view of the differences between the images and the use of binarization in the literature, we decided to include LSPIVb technique to investigate the influence of binarization in the analysis of seeded experiments. As noted by the reviewer, the achieved results with both seeded techniques are very similar with slightly higher velocities obtained by techniques that use binarization. This similarity indicates that, except particles and bubbles, cameras did not record many other moving elements that disturb the results, so binarization does not include significant benefits in these experiments. Another interesting difference observed is that techniques including binarization resulted in noisier velocity results. This may be due to the fact that, if the binarization is applied, the sliding background filter may remove parts of tracers in motion that are overlapped in consecutive frames since no different grey values are considered, which also might explain the slightly higher velocities obtained. This indicates that binarization, which may be useful to isolate tracers if seeded experiments are performed with natural or regular artificial illumination, should be used with care in future applications and it is not recommended if the non-binarized images results in good correlations.

A detailed explanation of the motivation of evaluating LSPIVb and a more extended discussion about the similar results obtained using LSPIV and LSPIVb will be added to Methods and Results sections for a better comprehension of the achieved results. Specifically, the following text will be added to the methodology (Sections 2.2 and 2.2.1 respectively) to clarify the motivation of LSPIVb:

"Finally, a slight variation of the LSPIV methodology named LSPIVb was implemented to investigate the influence of binarization pre-process also in the analysis of seeded UV experiments. This strategy seeks to isolate the brightest pixels, which in this case correspond with the fluorescence particles, to ensure that other elements such as bubbles or water reflections are not interfering in the PIV analysis."

"This filter ensures that only the fluorescent particles are being considering in the PIV cross-correlation, preventing possible small interferences that bubbles or water reflections may produce despite the special illumination."

In addition, the similar results obtained by LSPIV and LSPIVb will be discussed in Results and discussion section as follows:

"Then, the velocity fields showed very similar results between LSPIV and LSPIVb and between SSIV and BIV with slightly higher velocities measured by methods using binarization pre-processing (LSPIVb and BIV). This similarity indicates that, except particles and bubbles, cameras did not record many other moving elements that disturb the results, so binarization does not includes significant benefits in these experiments. In addition, it has been observed that techniques that include binarization result in noisier velocity results (see velocity fields for 30 and 80 mm h-1 in the supplementary information). This may be due to the fact that, if the binarization is applied, the sliding background filter may remove parts of tracers in motion that are overlapped in consecutive frames since no different grey values are considered, which also might explain the slightly higher velocities obtained. Therefore, this filter should be used with care in future applications if it would be necessary to isolate tracers from other mobile elements."

Finally, an additional point will be added to conclusions:

"The similarity found between LSPIV and LSPIVb and between SSIV and BIV indicates that binarization preprocessing has not significant benefits in these experiments since cameras did not record moving elements that significantly disturb the results. In addition, it has been found that this procedure lead to noisier results, so binarization should be used with care in future applications if it would be necessary to isolate tracers from other mobile elements."

Minor issues:

16 - complex sentence. should split into one about the natural tracers and the second about the raindrop impacts.

Response:

The sentence will be split and slightly modified to simplify the text:

"First, the use of naturally-generated bubbles and water shadows and glares as tracers allows the unseeded techniques (SSIV and BIV) to measure extremely shallow flows. However, these techniques are more affected by raindrop impacts, which even lead to erroneous velocities in the case of high rain intensities."

47 – sentence starting with 'For instance' is not clear to me. Should be rewritten in a more direct style.

Response:

The sentence will be rewritten in a more direct style as follows:

> *"Zhu et al. (2019) achieved errors below 14% using this technique in a full-scale stormwater detention basin, although in some bordering points these could rise up to 44%."*

61 – sentence starting with 'That study' is too complex. Should be split into two ideas.

Response:

The sentence will be rewritten for a better understanding:

> *"The presence of raindrops in the experiments can generate disturbances in the water surface and also interfere in the visualization of images, so that study used UV illumination and fluorescent particles as artificial tracers to satisfactorily address these issues."*

87 and 106 – is Naves et al 2019b an archive? Data availability should be clarified.

Response:

Yes, the reference is from a dataset published by the authors in the open access repository Zenodo. This includes videos, images and related information to replicate our study or produce new results. This will be specified within the text as follows:

> *"The freely available experimental dataset (Naves et al. 2019b) described in Naves et al. (2020b) was used in this study for the assessment of different imaging velocimetry techniques.*
>
> *"Examples of these images obtained from UV seeded and LED unseeded experiments, which are openly available for others to use in the dataset published by the authors (Naves et al., 2019b), are included in Fig. 2."*

101 - Best to say what was done step by step. e.g. Videos were recorded at 4K resolution and 25Hz. 1500 frames (eq. to 60 s) were extracted from the longer recording for analysis.

Response:

As recommended, the sentences will be rewritten to clarify the methodology:

> *"During the experiments, videos were recorded at 4K resolution and 25 Hz. 1500 frames of steady flow (equivalent to 60 s) were then extracted from the longer recording and processed for analysis. To do this, frames were scaled and ortho-rectified using the known 2D coordinates of 28 and 24 reference surface points for each camera. Finally, the reference points placed in the intersection between the recorded areas of each camera were used to crop and join the images, resulting in raw images where 1 pixel corresponds to 1 mm in real-world coordinates."*

120 – so all particles are assumed to be moving? Is this realistic? Is there a velocity threshold?

Response:

Some of the particles used as tracers may settle on the road surface due to the extreme low depths developed in some areas of the road surface and to the rugosity of the concrete surface. While the rest of particles follow the runoff generated, these particles appear immobile in the images recorded. This can lead to erroneous velocity results when the PIV cross-correlation is performed, because the null velocity of these particles can reduce the mean velocity of the particles of a determined interrogation area. The sliding background preprocess avoids this issue removing the immobile particles and focusing the analysis on the particles that are being transported by the flow. In addition, this procedure does not produce any velocity threshold in the results since only the particles that remain immobile between two consecutive frames are removed from the analysis, as can be also checked in the previous work published by the authors (Naves et al. 2019a). However, as stated within the text, the seeded techniques are not able to measure velocities in areas with extreme shallow flows (Area 2) because the artificial particles cannot be transported, and unseeded techniques appear as suitable tools to be further explorer for these conditions.

The sentence will be rewritten to clearly explain the removal of immobile particles:

> *"That methodology requires pre-processing of images through a sliding background (SLB), which eliminates the background of the images and particles that remain immobile between frames. These particles, which are deposited due to the extreme low depths developed and the rugosity of the concrete surface, should be removed to avoid that the null velocities resulted from them condition the PIV analysis."*

156 – restatement of the aim/objective. Not necessary in the methods.

180 – again repetition of aim, but shouldn't be necessary.

183 – novelty should be addressed in intro with aim and objectives.

193 – more repetition of the aim

195 – I think that the reference technique statement should also be used as a scoping statement at the end of the introduction with the aim/objectives. Mixing it in here reduces the clarity of what is being done and what the starting point for the new contribution is.

Response:

We agree with the reviewer. The final statement of the introduction section will be completed to include clearer the aim, the novelties, and the starting point of the new contribution. This content will be removed from the rest of the manuscript where, as noted by the reviewer, it is not necessary.

> *"Therefore, experimental videos of the overland flow generated by three different rain intensities, under laboratory-controlled conditions and recorded with and without artificial particles, are used in this study to comparatively assess the performance of different seeded and unseeded imaging velocimetry techniques under rainy conditions. First, the sensitivity of the velocity results to the analysis parameters is investigated in order to test the robustness of each method. Then, the resulting velocity*

fields are compared to analyze the feasibility of using each visualization technique in different characteristic flows developed in urban catchments, and to investigate the influence of rain intensity in velocity measurements as novel contribution. The LSPIV method, already validated in Naves et al. (2019a), is used as the reference technique in this analysis. Finally, the feasibility of these imaging techniques to measure runoff velocities in real field applications is discussed."

166 – Description of correlation matrix calculation is too brief. Need to help readers who may want to apply this technique themselves. Is this following what was done for other publications?

Response:

The correlation matrix was computed using the Discrete Fourier transform (DFT) in the frequency domain, which is calculated using a fast Fourier transform (FFT). This is a common procedure to estimate particle displacement that is detailed in the bibliography of reference about PIV (Raffel et al., 2007; Adrian et al., 2011). The PIVLab software has this procedure implemented (Thieckle and Stamihus, 2014), where multi-pass window and deformation algorithm were used to improve the signal to noise ratio. The window size at the second pass achieves a higher spatial resolution. The searching area (SA) matches with the IA and 50% of overlapping was selected in all cases in the present work. The following text and references will be included in the text to complete the information about the correlation matrix calculation:

"Common procedures to estimate this particle displacement, and thus flow velocity, has been applied in the present work (Raffel et al., 2007; Adrian et al., 2011). The discrete Fourier transform (DFT), calculated using a fast Fourier transform (FFT), was used to compute the correlation matrix in the frequency domain. Moreover, two passes of a multi-pass window deformation algorithm were used in the present work, having the window size at the second pass to achieve a higher spatial resolution. The searching area (SA) matches with the IA and 50% of overlapping was selected in all cases in the present work. These procedures are included in most of the conventional PIV algorithms such as PIVLab (Thieckle and Stamihus 2014), or OpenPIV (Taylor et al. 2010)."

174 – not clear what you mean by 'which were investigated as an optimum'.

Response:

These values were selected after some preliminary tests where the good performance detecting spurious vectors was checked. The sentence will be modified:

"After preliminary tests testing the performance detecting spurious vectors in the PIV results, the values of the two parameters of this filter were set to ε = 0.15 and threshold = 3. "

226 – 'This was to approach the conditions of worse devices . . .' is not clear.

Response:

The sentence will be rewritten as follows:

> *"This simulates the FAR of worse installed devices that may serve as media source to measure urban runoff velocities in field applications, such as traffic or surveillance cameras following the ideas stated in Leitão et al. (2018)."*

279 – what type of flow specifically is in the area? The shallowness? Should be clarified.

Response:

Yes, it corresponds with the lowest depths analyzed. This will be clarified:

> *"The very low depths developed in this area also increases the variability of the mean velocities depending on the pair of frames analyzed."*

284 – should note that there is a degradation of quality with FAR, as expected.

Response:

We agree that it is a useful remark and it will be included.

> *"Finally, an expected degradation was noted when FAR is reduced, but within assumable ranges that make it possible to consider cameras with lower FAR as media source for field applications."*

317 - change phrasing. The current sentence uses a double negative. I think you mean that the unseeded technique is not able to measure the highest velocities, but i'm not sure.

Response:

Yes, we wanted to explain why unseeded techniques are not able to measure velocity when rain intensity and flow velocities are high. The text will be rewritten as follows:

> "Then, the problems of unseeded techniques (SSIV and BIV) measuring velocities with high rain intensity are not produced because of a lack of tracers since, as can be observed in the videos provided in Naves et al. (2019b), the number of bubbles in that area increases with the rain intensity. These are caused by the erratic trajectory of the bubbles observed in the unseeded videos for high rain intensities due to the impact of raindrops on the water surface."

322 – 'non-artificial' is again kind of a double negative. Just say what it is - the natural bubbles.

Response:

Thanks for the remark, 'non-artificial bubbles' will be substituted by 'natural bubbles'.

445 – do you mean that the problem is not trivial?

Response:

We referred to the difficulties of applying the seeded experiments methodology in real urban catchments during rain events, especially seeding particles. The sentence will be rewritten to avoid confusion:

> *"However, the ability of measuring extremely shallow flows where particles tend to be deposited, and their easy implementation without the need of adding artificial particles, make unseeded techniques worthy of future investigations as new source of runoff velocity data in urban catchments."*

24 – replace 'Specifically' with 'However'?

117 – 'estimate' is better than 'obtain' for this sentence.

117 – 'from the analysis of the images presented in the previous point' is not necessary.

224 – suggest 'typical of' rather than 'in consonance with'

261 – Acronym not introduced until next page (FAR)

325 – suggest 'prevents' rather than 'avoids'.

325 – 'from' obtaining

414 – should be Figure 10

Response:

Thanks again for the detailed review, we agree with the comments and these mistakes will be corrected in the revised version of the manuscript.

References:

Adrian, L., Adrian, R. J., and Westerweel, J.: Particle image velocimetry (No. 30), Cambridge University Press, 2011.

Leitão, J. P., Peña-Haro, S., Lüthi, B., Scheidegger, A., & de Vitry, M. M. (2018). Urban overland runoff velocity measurement with consumer-grade surveillance cameras and surface structure image velocimetry. Journal of Hydrology, 565, 791-804.

de Vitry, M. M., & Leitão, J. P. (2020). The potential of proxy water level measurements for calibrating urban pluvial flood models. Water Research, 115669.

Zhu, X., and Lipeme Kouyi, G.: An analysis of LSPIV-based surface velocity measurement techniques for stormwater detention basin management. Water Resour. Res., 55(2), 888-903, https://doi.org/10.1029/2018WR023813, 2019.

Pearce, S., Ljubičić, R., Peña-Haro, S., Perks, M., Tauro, F., Pizarro, A., ... & Paulus, G. (2020). An evaluation of image velocimetry techniques under low flow conditions and high seeding densities using Unmanned Aerial Systems. Remote Sensing, 12(2), 232. https://doi.org/10.3390/rs12020232

Raffel, M., Willert, C.E., Wereley, S.T., and Kompenhans, J.: Particle Image Velocimetry. Springer Berlin Heidelberg. 2007.

Raffel, M., Willert, C. E., Scarano, F., Kähler, C. J., Wereley, S. T., & Kompenhans, J. (2018). Particle image velocimetry: a practical guide. Springer.

Tauro, F., Petroselli, A., Porfiri, M., Giandomenico, L., Bernardi, G., Mele, F., ... & Grimaldi, S. (2016). A novel permanent gauge-cam station for surface-flow observations on the Tiber River. Geoscientific Instrumentation, Methods and Data Systems, 5(1), 241-251. https://doi.org/10.5194/gi-5-241-2016

Tauro, F., Petroselli, A., & Grimaldi, S. (2018). Optical sensing for stream flow observations: A review. Journal of Agricultural Engineering, 49(4), 199-206. https://doi.org/10.4081/jae.2018.836

Zhou, X., Doup, B., & Sun, X. (2013). Measurements of liquid-phase turbulence in gas–liquid two-phase flows using particle image velocimetry. Measurement Science and Technology, 24(12), 125303. https://doi.org/10.1088/0957-0233/24/12/125303

Thielicke, W., and Stamhuis, E.: PIVlab–towards user-friendly, affordable and accurate digital particle image velocimetry in Matlab, J. Open Res. Softw., 2(1), http://doi.org/10.5334/jors.bl, 2014.

Taylor, Z.J., Gurka, R., Kopp, G.A., and Liberzon, A. 2010. Long-duration timeresolved PIV to study unsteady aerodynamics. IEEE Transactions on Instrumentation and Measurement, 59(12): 3262–3269. doi:10.1109/TIM.2010.2047149.