

Single-pixel PIV measurements of a differential-throttled aerospike nozzle jet in supersonic outer flow

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ABSTRACT

Aerospike nozzles are promising for future launch vehicles because they provide enhanced thrust performance by passive altitude adaptation. However, their complex flow behavior, especially under off-design and thrust-vectoring conditions, remains insufficiently understood due to limited experimental data. This paper presents PIV measurements of the mean flow field of a clustered, truncated linear aerospike nozzle at full differential throttling, in interaction with a supersonic outer flow. The study shows that single-pixel PIV can robustly resolve key features of the flow when image pre-processing and correlation function post-processing are systematically evaluated and selected carefully. The measurements reveal asymmetric shock structures and distinct recirculation regions behind the upper shroud and in the plug-base wake extending over the deactivated nozzle half. A consistent deflection of the jet core under full differential throttling is observed, indicating a steering potential, even though the quantitative effect on thrust vector control requires further analysis. The results provide new experimental evidence of how plume structure and nozzle–outer-flow interaction change under asymmetric aerospike nozzle operation. They demonstrate both the potential and the practical limitations of single-pixel PIV for resolving supersonic flows with sharp gradients and small-scale structures.

1. Introduction and research objectives

Space launchers and space planes have to deliver payloads efficiently while facing a wide range of ambient pressures during the ascent. Conventional bell nozzles, however, achieve optimal performance only at their design pressure ratio and suffer thrust losses and potential flow separation at off-design conditions. Aerospike (or plug) nozzles address these limitations by allowing the exhaust jet to expand against the ambient pressure, providing passive altitude adaptation and improved efficiency without moving parts (Arnold, 1954; Ruf and McConaughy, 1997; Cardenas et al., 2025). Aerospike nozzles are therefore of particular interest for future single-stage-to-orbit vehicles.

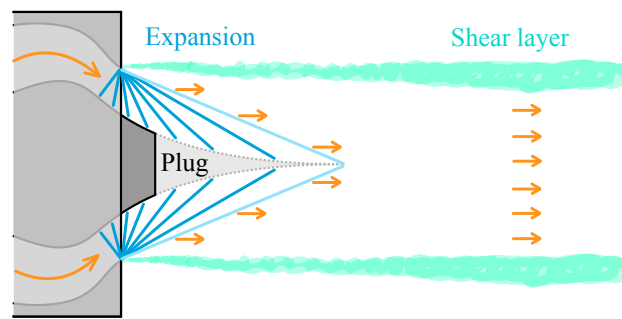


Figure 1. Schematic flow field of an aerospike nozzle jet at design conditions. The flow is shown for an ideal full-length contour.

The flow field of an aerospike nozzle jet at design conditions is drawn schematically in Fig. 1. Note that the flow is shown for a plug of full length (light gray). A truncated plug (dark gray) is a prominent adaptation for weight reduction and thermal management reasons. However, for simplicity, its effects on the flow field are omitted in this schematic. The flow inside the nozzle chamber reaches sonic speed where the cross section is narrowest, which is at the nozzle throats at the top and bottom half of the nozzle. From here, the flow starts to expand (blue), meaning it accelerates isentropically and turns outward, forming a free nozzle jet (orange). The flow expansion stops at the last expansion line/design characteristic (light blue), where the static pressures in the nozzle flow and ambient balance each other out. Under design operation, the plug contour perfectly guides the nozzle flow, and the velocity vectors align with the vehicle's flight direction for optimal thrust. Nozzle flow and ambient are separated by free shear layers (turquoise) that grow in the downstream direction.

Despite their theoretical advantages, aerospike nozzles remain underdeveloped due to limited experimental data and an insufficient understanding of their complex flow behavior. To advance their technical readiness, detailed flow field measurements and aerodynamic characterization are essential for optimizing design, ensuring stable and efficient operation throughout ascent, and validating numerical models. However, experimental velocity field data are scarce when it comes to aerospike nozzle research. Especially the combination of a nozzle flow with an outer flow replicating in-flight conditions is challenging to measure and to evaluate accurately. For this reason, particle image velocimetry (PIV) measurements within a controlled wind tunnel setting are performed in this study. An underexpanded cold air jet from a truncated linear aerospike nozzle is hereby combined with a supersonic outer flow around an aerodynamically shaped wind tunnel model, in which the nozzle is integrated. The nozzle flow operates under full differential throttling to simulate a thrust vector control scenario. Differential throttling is an interesting strategy, especially for clustered aerospike nozzles, since it avoids heavy and complex mechanical gimbals to generate a steering moment. Experimental studies of the resulting flow are important because these control concepts can introduce strong asymmetries in shocks, recirculation, and nozzle–outer-flow interaction. This can directly affect the steering capabilities and the assessment of thermal loads.

The flow field is seen to be rich in flow features like expansion and compression waves, shocks,

and high-speed shear layers. In addition, the truncated plug and the backward-facing step at the outer body's shrouds promote high vorticity regions with small recirculation areas. All those flow features are characterized by steep velocity gradients and can cause unsteady aeroacoustic phenomena such as jet screech. Therefore, an accurate characterization of shock locations, shear layer thickness, and growth is important. Moreover, the flow close to the plug surface and the main body base is important to measure in detail to estimate the thrust and drag of the vehicle. Ideally, the flow is resolved using 3D and time-resolved particle tracking velocimetry (PTV). However, the technique is not feasible for high-speed flows like supersonic jets. One of the main reasons is that the dynamics of the nozzle jet flow happen on time scales much shorter than measurable with available lasers and cameras. Also, in order to get three-dimensional flow field data, one would need to thicken the light sheet. This would make the scattered light from those particles difficult to detect, which are small and light enough to precisely follow the streamlines. With conventional 2D-PIV, a single velocity vector inside an interrogation window of size D spanning multiple pixels on the camera sensor is computed. This has the drawback that it acts as a spatial low-pass filter and under-predicts velocity gradients. Also note that experimental setups are usually not arbitrarily scalable to bigger sizes, which could compensate for spatial resolution issues. Therefore, a proper execution of the flow visualization techniques and selection of evaluation parameters becomes even more essential. The single-pixel ensemble correlation (SP) technique for PIV (Westerweel et al., 2004) is a promising approach to resolve the flow field with high spatial resolution, given the fact that a sufficient amount of particle image data is available. SP can generally be used for investigating turbulent flows (Scharnowski et al., 2012). However, in unsteady flow scenarios, when the correlation function is asymmetric and of more complex shape, the velocity estimation becomes more difficult (Kähler et al., 2006).

Within the present work, it is to experimentally resolve the flow of a clustered, truncated linear aerospike nozzle with differential throttling. The flow scenario is realized by deactivating the outflow from the bottom half of the nozzle. Whether this effectively deflects the nozzle plume during supersonic flight is investigated. The differences between interrogation window-based techniques and the single-pixel approach are highlighted. Using properly selected image pre-processing and correlation function treatment, the goal is to obtain a well-resolved mean velocity field of the given flow problem using the SP method.

2. Wind tunnel facility and nozzle model

Optical flow measurements were conducted in the Trisonic Wind tunnel Munich (TWM) at the University of the Bundeswehr Munich. The TWM is a blow-down facility capable of operating over a Mach number range from 0.3 to 3.0, thus covering subsonic, transonic, and supersonic flow regimes. The test section measures 300 mm in width and expands from 675 mm to 700 mm in height, compensating for boundary layer growth on the horizontal walls. Within the test section (see Fig. 2), an outer flow (purple) with Mach number Ma_∞ and total pressure $p_{0,\infty}$ reproduces

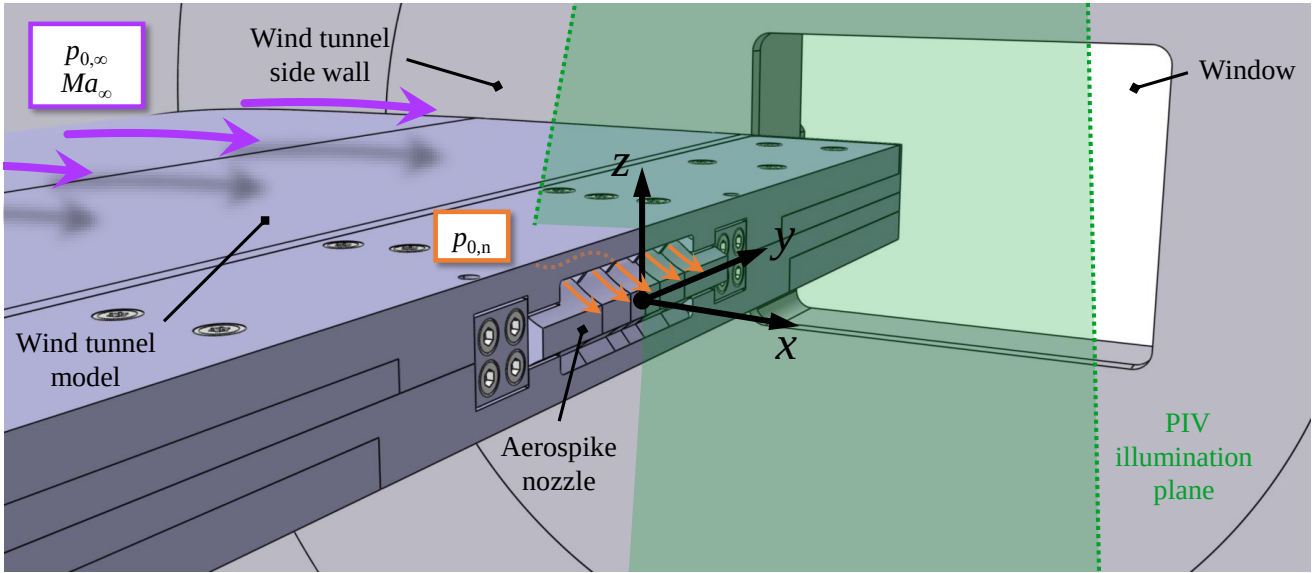


Figure 2. Schematic of the wind tunnel model positioned between the wind tunnel side walls. A clustered, truncated linear aerospike nozzle is integrated in the model.

the aerodynamic environment around a generic 2D space launcher wind tunnel model. The main body of the model itself is 25 mm high and 300 mm wide, fitting snugly between the test section's side walls. The main body contains a linear, truncated clustered aerospike nozzle at the trailing base area. The nozzle has a width of 50 mm and is centrally integrated in the wind tunnel model with respect to y and z . The plug contour of the nozzle is designed following a 2D method of characteristics, with a design Mach number of 2.5 and a design nozzle pressure ratio NPR of 17.1. The NPR is defined as the ratio between the total nozzle pressure within its settling chamber $p_{0,n}$ and the static pressure in the ambient freestream p_{∞} . The spike is significantly truncated to 24% of its theoretical full length. The spike length is defined with respect to x starting from the throat projected onto the x -axis. The nozzle is clustered, meaning that the top and bottom throats are subdivided into five equally spaced modules. Each module has a width of 9.15 mm and is separated from adjacent modules by a 1 mm wall. The configuration that will be investigated in this work is special in the sense that all bottom modules are deactivated, i.e., the outflow is blocked physically. This simulates the nozzle flow scenario for realizing thrust vector control via differential throttling. Any outflow from the nozzle is indicated in orange in Fig. 2. The nozzle is supplied individually through pressure lines feeding the model's settling chamber. This configuration enables independent control of $p_{0,n}$ relative to $p_{0,\infty}$. For further details on the model's main body geometry, refer to Bolgar et al. (2018) and Wißmann et al. (2025b). More details about the nozzle geometry are given in Wißmann et al. (2025a). For the measurement conducted here, $p_{0,n}$ was set to 8 bar, while the outer Mach number Ma_{∞} of the inflow was set to 2.0 with $p_{0,\infty} = 2.5$ bar. This results in a NPR of about 25 with $p_{\infty} \approx 0.32$ bar.

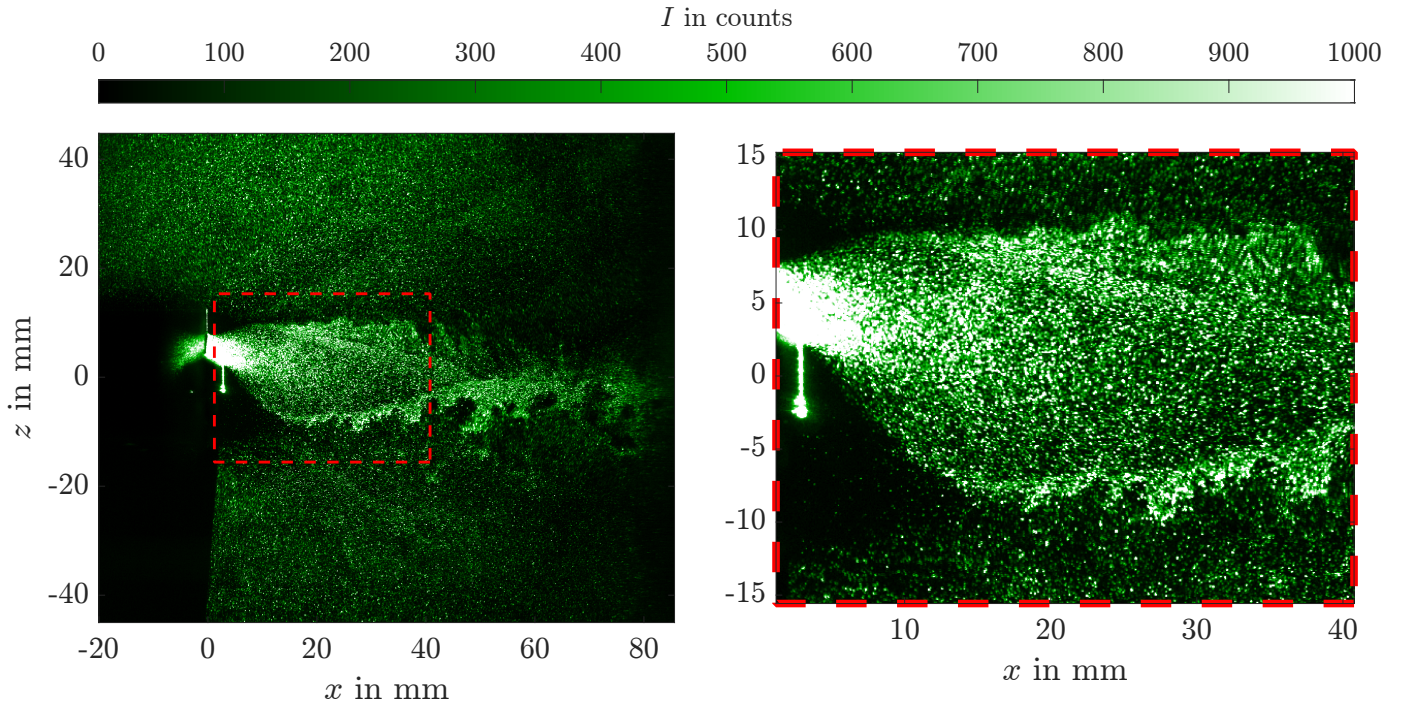


Figure 3. Raw particle image in an overview (left) and close-up representation (right). The red box indicates the region in which velocity fields are calculated.

3. Measurement setup and particle image recording

Two-dimensional, two-component (2D2C) PIV measurements with 5 kHz sampling rate were carried out in the xz -plane. The illumination plane is indicated in green in Fig. 2. A double-pulse Nd:YAG laser (DM150-532-DH, Photonics Industries International Inc.) was used to form the light sheet. The light sheet entered the test section from the top (along the z -axis), resulting in shaded areas below the bottom sides of the model. The flow was seeded with Di-Ethyl-Hexyl-Sebacat (DEHS) tracer particles of mean diameter below $1\ \mu\text{m}$ (Raffel et al., 2018), exhibiting a response time of approximately $2\ \mu\text{s}$ (Ragni et al., 2011). Seeding for the outer flow was introduced upstream of the settling chamber, while a separate system supplied particles to the nozzle flow. Particle images were recorded using a high-speed camera (Phantom v2640, Vision Research Inc.). The field of view (FOV) covered $2048\ \text{px} \times 1272\ \text{px}$, with a spatial scaling of $14.18\ \text{px/mm}$. The laser pulse separation time was set to $1.5\ \mu\text{s}$, yielding mean particle image displacements of maximum 15 px in the jet core. A total of 10^4 double-frame images were captured. An exemplary particle image snapshot is shown in Fig. 3. On the left, the entire captured FOV is shown, alongside the region in which velocity fields are computed (red). This region is $560\ \text{px} \times 440\ \text{px}$ in width and height, respectively, and is shown in an enlarged representation on the right-hand side. The raw image demonstrates the local differences in seeding density, which is a result of the experiment's and flow's complexity. The nozzle flow close to the throats tends to be strongly seeded. At the same time, particles big enough to scatter significant light towards the camera sensor suffer from a high moment of inertia. Therefore, regions with high vorticity and steep velocity gradients, such

as the main body shroud wake and plug base wake, are poorly seeded. The independent seeding supplies for the nozzle and outer flow additionally cause seeding density differences between the flows, as can be seen in Fig. 3 as well.

4. SP-PIV evaluation scheme

To obtain the average velocity field, the SP-PIV method is utilized, which determines the ensemble average particle image shift with spatial resolution up to the camera sensor's pixel size. Note that the true resolution of the velocity field's information density using PIV is limited by the tracer particle image size and can theoretically not be better than 1.84 px, as shown by Kähler et al. (2012). The concept behind SP-PIV is that the method computes the cross-correlation for each pixel, while the intensity of one pixel over time in the first frame is compared to the intensity of surrounding pixels of the corresponding particle image in the second frame. Averaging the correlation functions before peak detection increases the signal-to-noise ratio and yields a statistically converged displacement field. To enhance the correlation signal, symmetric double correlation (Avallone et al., 2015) is included in the evaluation. The correlation function C for an image pair A and B reads as

$$C(X, Z, s_X, s_Z) = \sum_n \left(A'_n(X, Z) \cdot B'_n(X + s_X, Z + s_Z) \right) / \left(\sigma_A(X, Z) \cdot \sigma_B(X + s_X, Z + s_Z) \right), \quad (1)$$

where X and Z are the discrete spatial coordinates in the image plane, which are related to x and z via the magnification and pixel size of the imaging setup. s_X and s_Z are the coordinates in the correlation plane. n denotes the image-pair index, i.e., it runs over all image pairs in the ensemble. A' and σ_A represent the fluctuations and standard deviation of A . Final velocity vectors at each pixel are based on the average correlation plane within a square, Gaussian weighted $3 \text{ px} \times 3 \text{ px}$ window, i.e., averaged with respect to its closest neighbors.

5. Image pre-processing

Spatial and temporal light intensity variations are to be mitigated, especially for ensemble correlation PIV methods. This is because bright particle images contribute more to the average correlation peak formation compared to darker ones (see Eq. 1). Hence, flow features in regions of low light scattering tend to be under-represented. In addition, exceptionally bright intensity outliers should be avoided since they would heavily bias the ensemble correlation. To compensate for that, a possible first intensity normalization method is to clip the captured light intensity on the raw images to a value $I_{\max}$, i.e., any light intensity $I > I_{\max}$ is set to $I_{\max}$. $I_{\max}$ is typically chosen based on the intensity of poorly illuminated but meaningful particle images in dark areas. In addition, the sliding minimum image intensity is subtracted. This filter is hereafter referred to as the intensity-clipping-filter (IC-filter). A second method to consider is combining a sliding minimum and maximum filter

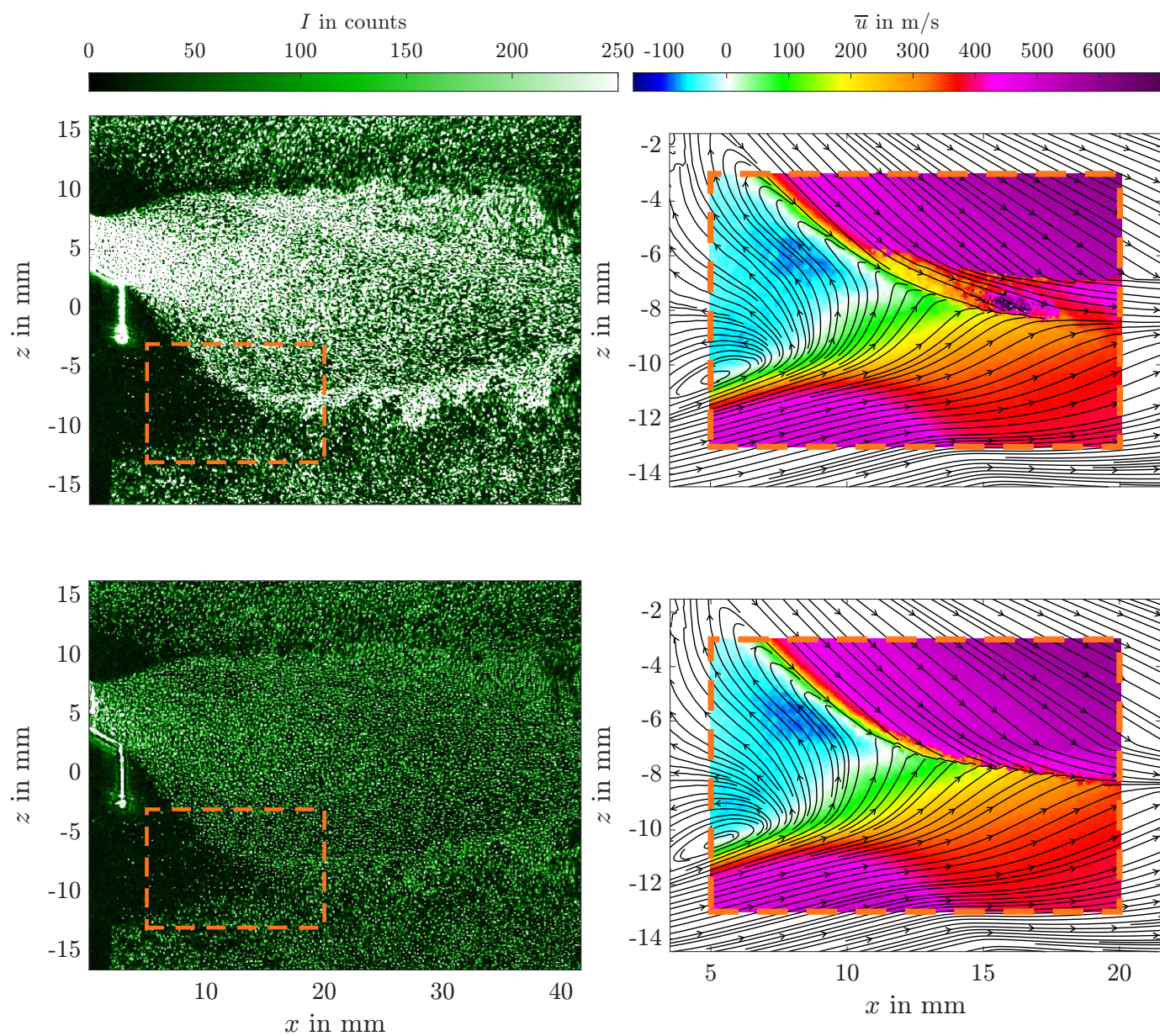


Figure 4. Preprocessed PIV images utilizing a filter subtracting the sliding minimum with intensity clipping (top row), and a min-max-filter with noise suppression (bottom row).

for intensity normalization. This min-max-filter (MM-filter) spatially searches for local minimum and maximum intensities within a small window of a certain kernel size. Other intensity values are then scaled based on the minimum/maximum found, which enhances the particle image contrast and homogenizes the image intensity. Choosing an appropriate filter kernel size is especially important in unevenly illuminated flow fields. While with a too large kernel the filter behaves more like global normalization without fixing local illumination issues, a too small kernel can distort particle intensities and shapes locally, and amplify noise in darker regions of lower seeding concentration. To mitigate the noise amplification, a threshold intensity value is defined (typically the same $I_{\max}$ as above). If within the filter region, the global maximum intensity is below that threshold, the min-max filter is replaced by just subtracting the minimum intensity. The snapshot from Fig. 3, but after applying either image pre-processing method, is shown in Fig. 4 (left). For both the IC-filter (top row) and the MM-filter (bottom row), a kernel size of $5 \text{ px} \times 5 \text{ px}$ was chosen. $I_{\max}$ for the intensity clipping and for the MM-filter thresholding was chosen to be 250 counts. The processed images highlight that the MM-filter performs better in terms of intensity normalization, reducing the impact of different seeding densities of the nozzle and outer flow.

The streamwise velocity fields for both pre-processing strategies are determined within the square cutout highlighted in orange in Fig. 4 (left). The results are shown in Fig. 4 (right). Both velocity fields are overall quite similar. However, within the cutout region, non-physical artifacts appear in the case of the IC-filter. These are supposed to be a result of the inhomogeneous particle image intensities, leaving a stronger bias towards the faster nozzle flow coming from the top (positive y). Since the MM-filter is seen to perform better in terms of intensity normalization, it is decided to go with this pre-processing method for the final velocity field calculations.

6. Evaluation of the velocity field results

The entire velocity fields within the FOV are computed using the MM-filter for image pre-processing. Interrogation window-based PIV velocity fields are additionally computed to highlight the spatial resolution benefit of the SP approach. Conventional snapshot PIV evaluation was applied, computing instantaneous velocity fields with interrogation windows of $D = 32 \text{ px}$ and 16 px size. The instantaneous fields are post-processed with a universal outlier detection scheme (Westerweel and Scarano, 2005), before average fields are computed by averaging the instantaneous velocity fields over time. The mean streamwise velocity $\bar{u}$ is shown in Fig. 5 (top row). An additional field is computed using the average correlation method (ACM) introduced by Meinhart et al. (2000) with $D = 16 \text{ px}$ (see Fig. 5 bottom left). In any case, a 50% window overlap with Gaussian-weighted circular interrogation windows is chosen. Here, streamlines highlight the local flow direction representative of all plots.* The computed velocity field using the SP method is shown in the bottom right.

*Streamlines may appear to originate or terminate within the measurement domain. This, however, should be interpreted as artifacts from the plotting method rather than physical features due to 3D flow mechanics.

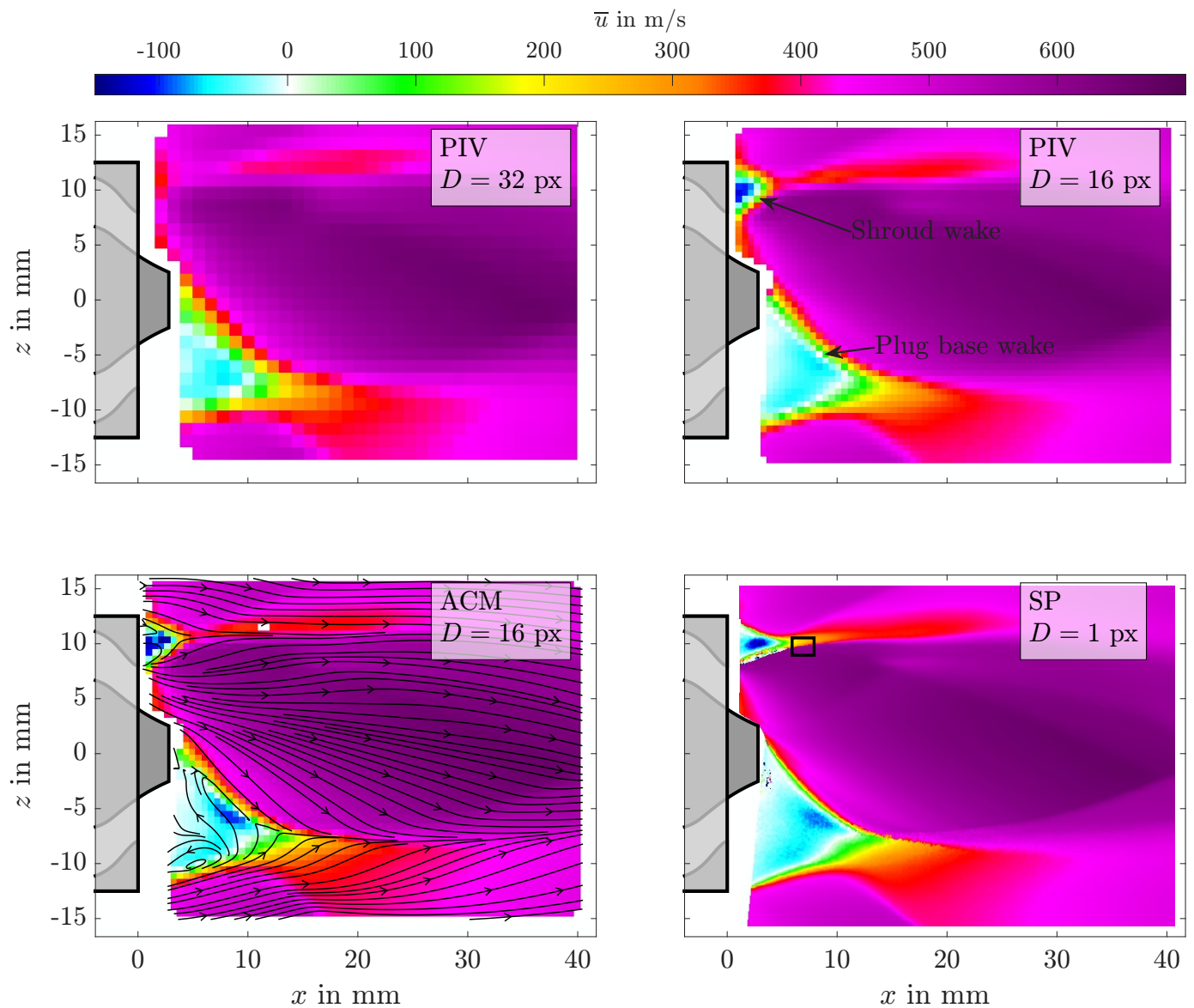


Figure 5. Average streamwise velocity computed for the supersonic nozzle flow in combination with supersonic outer flow. Conventional PIV velocity vector averaging is performed in the top plots for two different interrogation window sizes D . The plot in the bottom left shows the velocity field following the average correlation method. The bottom right plot shows the velocity field computed using the SP-PIV method.

The spatial resolution enhancement of the velocity field by reducing the interrogation window size becomes apparent in the plots. Major differences in the determined flow field are hereby observed in the wake region of the main body's shroud ($x \approx 3 \dots 5$ mm, $y \approx 10$ mm). Only for $D \leq 16$ px the flow in that region shows its recirculating nature, whereas for $D = 32$ px that region is improperly resolved. This shows that too coarse interrogation windows are not suited for such a flow problem. The coexistence of small-scale, low flow velocity regions on the one hand, and high velocity regions on the other hand, makes a proper choice of D difficult. If D is too large, details in the flow might be smeared out. In addition, velocity gradients in fast and thin shear layers tend to be under-predicted when D is too coarse. However, if D becomes smaller, approaching single-pixel precision, more details within the wake and shear layers downstream of the shroud and base are resolved. Thus, the SP-PIV method is the preferred choice for the present flow problem.

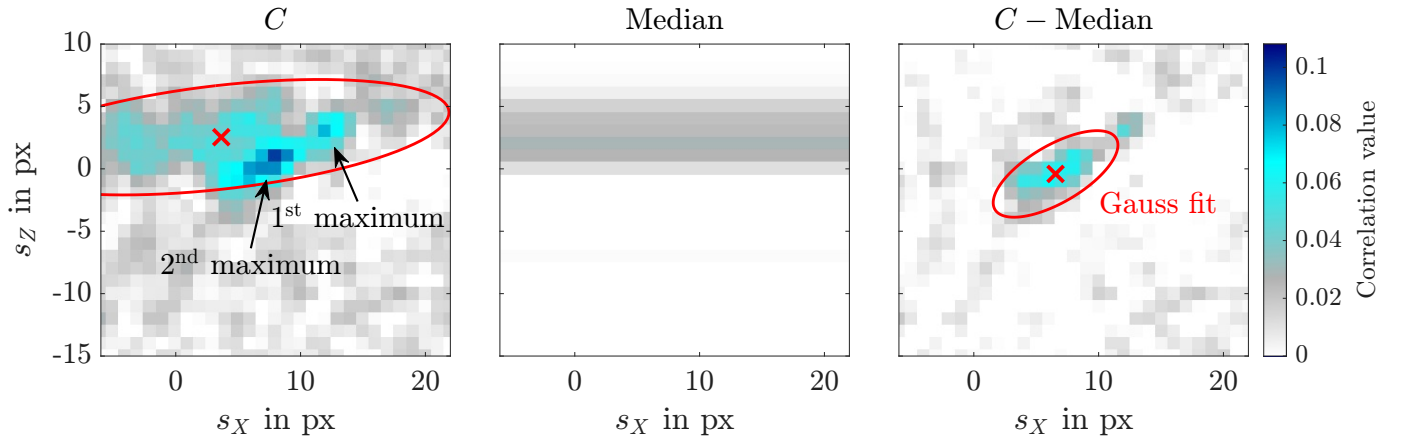


Figure 6. Exemplary correlation functions computed using the SP method at a pixel located within the black rectangle in Fig. 5 (bottom right). The correlation function is shown on the left, while the one-dimensional spatial median is shown in the center. The correlation function subtracted by the median is shown in the right plot. The 2D Gaussian fit result is shown as red ellipses. The shape represents the 2σ confidence level, while the cross marks the center.

It is observed that the SP method can produce exceptionally steep velocity gradients, especially at the inner shear layer of the shroud wake just downstream of the upper nozzle lip. To better understand the details of the average vector field from the SP method, an exemplary correlation function from within the shear layer region (see black rectangle in the bottom right of Fig. 5) is shown in Fig. 6 (left). The correlation value is color-coded for the pixel displacements in streamwise (s_X) and vertical (s_Z) direction. For sub-pixel accuracy, the velocity field information is gathered through a 2D Gaussian fit function (red ellipse). The plotted ellipse represents the 2σ confidence levels. The cross marks the center position from which u and w are obtained. The signal correlation peak is observed to be elongated with two local maxima. While the first one corresponds to the faster jet flow with a stronger upward z component, the second one belongs to the slower and more turbulent shear layer flow in the shroud wake. The reason behind both maxima being represented in this correlation function is supposed to be the thin and unstable shear layer, which is assumed to exhibit a slight periodic meandering. In certain image frames, the pixel captures the flow within the shroud wake region, whereas in other time instances, it captures the nozzle jet. The probability of staying at those turning points is higher in such periodic motions, which causes the two maxima

to stand out. Another observation is an almost horizontal and one-dimensional background pattern/stripe. The pattern is a result of the different seeding densities of the nozzle flow and shroud wake, creating a strong illumination offset (see Fig. 4). This represents a source of uncertainty during peak fitting: The maximum correlation value of the smeared peak is lower than for a narrow peak, representing a single steady velocity component. This reduces the signal-to-noise ratio with respect to the background pattern. Another problem can arise due to the two maxima. When the single Gauss fit is not able to represent the two maxima adequately, this can create scenarios where the fit favors one maximum over the other at a certain location, while for an adjacent pixel, the fit favors and snaps onto the other maximum. The consequence would be a biased ensemble statistic and unnaturally sharp transitions, leading to over-represented gradients in the averaged velocity field. This would motivate the use of multi-Gaussian models for correlation functions with more than one physically meaningful maximum to reduce spurious discontinuities while preserving flow features.

The fit result (red ellipse) in the left plot is strongly affected by the illumination bias and correlation background pattern, and wrongly predicts the average velocity. This demonstrates that erroneous displacement peak selection can happen when the primary correlation peak is superimposed by a secondary peak/pattern. The secondary signal, on the one hand, may be of fluid-mechanical origin, for example, in flows with alternating velocity components. In such cases, the correlation function legitimately contains two maxima that represent competing particle image displacements. On the other hand, a secondary maximum or a broad, quasi-one-dimensional background may arise from measurement artifacts rather than flow physics. A typical example would be an irregular illumination of the PIV plane caused by laser light reflections or refraction at interfaces. Another reason for irregular illumination can be inhomogeneous seeding density, arising from density gradients in the flow, or due to different seeding sources. These effects can introduce intensity offsets or structured backgrounds that impact the correlation function and distort the Gaussian peak fitting. Image pre-processing, as discussed earlier, can deal with some of these effects, but eliminating them entirely is not possible. In such cases of non-physical correlation artifacts, treating the correlation functions before Gaussian fitting and peak detection can filter out spurious backgrounds and reduce the influence of the illumination offset. Background suppression, such as spatial median subtraction, is found to improve the stability of the peak fit locally. The median of the correlation value is hereby computed one-dimensionally along each row and column of the correlation value, subsequently. The determined median is shown in Fig. 6 (center). The correlation function after median subtraction is shown in the plot on the right-hand side. The Gauss fit result on the processed correlation function is shown again as a red ellipse, demonstrating that the bias towards the one-dimensional background pattern is successfully removed. It has to be noted that the median subtraction can not always stabilize the peak fitting. For instance, if the unwanted artifacts in the correlation function are of similar dominance/intensity as the true signal peak, the median subtraction strongly affects the flow-related correlation values. This is observed in the wake flow close to the plug base wall. The issue arises from a combination of a lack of particle image data contributing to a significant signal peak and a strong background

illumination from laser light reflections close to the plug surface.

A key challenge remains, which is that for any strategy, it is hard to distinguish between secondary peaks that include physical information and those that are unwanted artifacts. On the one hand, aggressive filtering risks removing multi-peak structures associated with real flow dynamics. Also, filtering influences the shape of the correlation function, and therefore, of the Gaussian fit. Since the shape can be used to estimate Reynolds stresses, these correlation function treatments have to be used with caution when higher-order statistics are extracted from the correlation function. On the other hand, insufficient filtering might leave biases that negatively influence the peak fitting and displacement peak estimation. This motivates future research on algorithms that combine correlation function filtering with additional plausibility criteria, such as spatial continuity constraints.

7. Flow field analysis

Up to this point, the focus has been on optimizing the PIV processing to obtain an ensemble-averaged velocity field with high spatial resolution. In this final section, the aerodynamic questions introduced earlier are addressed: What are the key flow features of a linear aerospike nozzle under full differential throttling, and does differential throttling produce a measurable jet deflection under supersonic outer flow conditions? The final SP-PIV results are shown in Fig. 7, presenting the mean streamwise (top) and vertical (bottom) velocity components, u and w , respectively. Streamlines indicate the local flow direction.

The flow exiting the top nozzle half accelerates downstream, starting from the throat lip ($x = 0$ mm, $y = 8$ mm) by means of an isentropic Prandtl-Meyer (PM) expansion. The horizontal velocity component u accelerates locally up to 660 m/s within the jet core further downstream. When the supersonic outer flow reaches the main body's shroud ($x = 0$ mm, $y = \pm 12.5$ mm), it experiences a PM expansion as well. The outer flow turns inwards after expansion and creates a reduced static pressure seen by the nozzle jet. This increases the effective NPR and creates a nozzle jet underexpansion. The streamlines indicate that this causes the nozzle flow to turn towards positive z just downstream of the throat. While the main outflow close to the nozzle throat has vertical components of about $w \approx -200$ m/s due to the inward inclination of the nozzle, the underexpansion leads to vertical velocities of about $w \approx 250$ m/s. A small recirculation region with backflow speeds exceeding -100 m/s and a thin shear layer further downstream emerge, separating the nozzle and outer stream. Both the nozzle and the outer flow are realigned to the horizontal inflow direction by means of oblique shock waves named inner and outer realignment shocks (see Fig. 7 bottom). When the nozzle flow passes the plug shrouds, another PM expansion causes strong negative w velocities of up to -470 m/s. Slightly downstream, the flow is realigned via an oblique shock referred to as the trailing shock. The deactivated nozzle flow from the bottom half ($y < 0$ mm) for differential throttling allows this strong expansion with supersonic w magnitudes. The deactivated bottom half also causes the outer flow on the bottom half to expand at reduced back-pressure conditions.

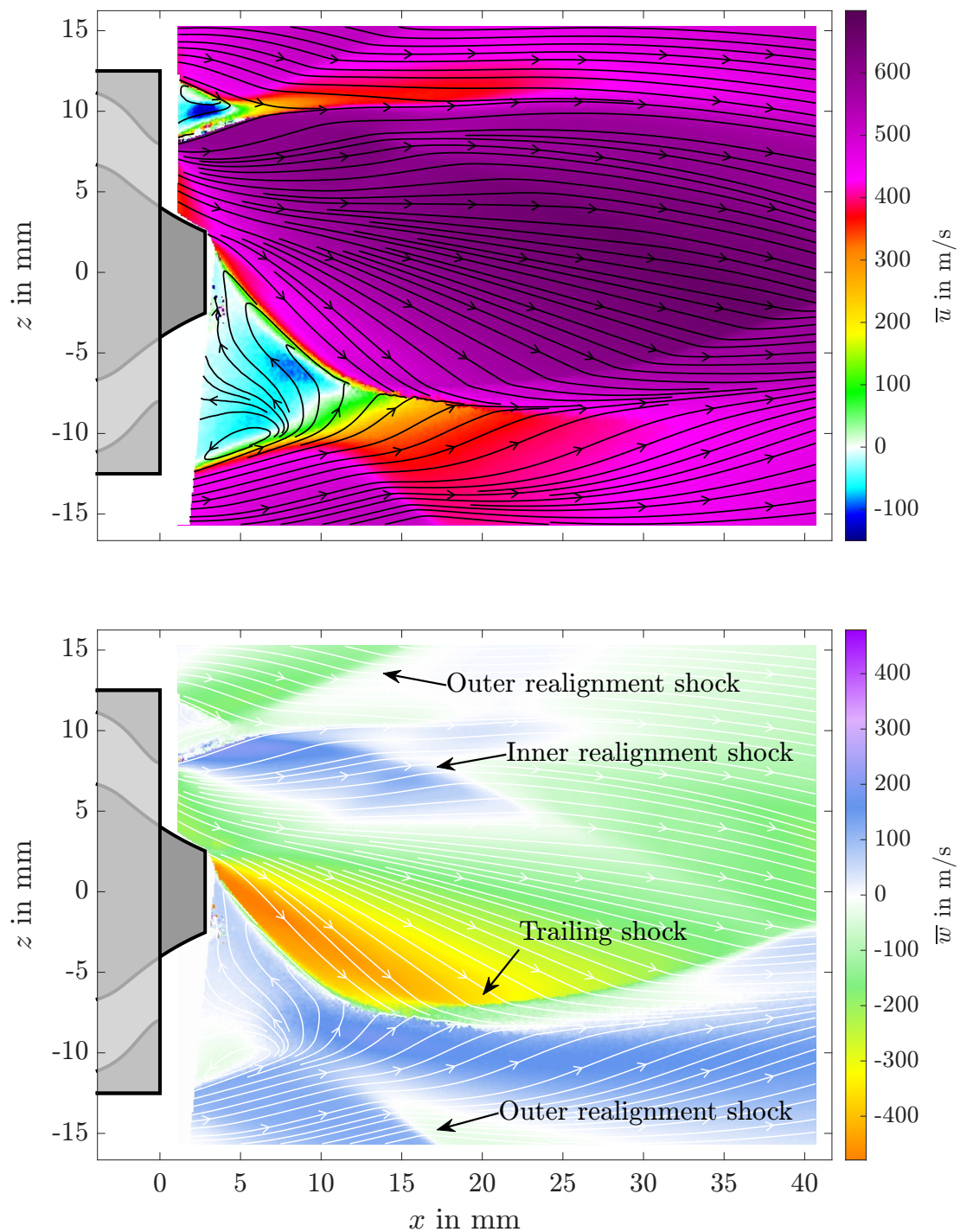


Figure 7. Average streamwise (top) and vertical (bottom) velocity field computed with the SP-PIV method. Minmax-filtering was applied for image pre-processing. The correlation functions were processed with a median subtraction filter.

As a consequence, the bottom outer realignment shock emerges further downstream, meaning asymmetric outer flow shock locations and strengths comparing the top and bottom halves of the planar symmetric wind tunnel model. Another consequence is the plug base wake extending across the deactivated nozzle half. The wake region features backflow of up to -100 m/s locally. From the streamlines, it becomes evident that the plug base wake is mostly fed by the outer flow. This is assumed to be due to the compression in the form of the outer realignment shock, across which the static pressure increases drastically. This causes the flow downstream of the shock to curl towards the lower-pressure base wake. In practice, the nozzle flow consists of a hot exhaust gas and can impose substantial thermal loads on the nozzle components. Recirculation regions near the nozzle base can further increase these loads by trapping hot gas close to the surfaces and convectively heating the base (Venkatapathy et al., 1995). Therefore, identifying and characterizing these recirculation zones is of high importance. For a complete characterization, however, single-plane PIV is often insufficient when the recirculation regions exhibit strong three-dimensional flow structures.

8. Summary and conclusions

Using single-pixel PIV, the mean flow field of a linear aerospike nozzle at full differential throttling in interaction with a supersonic outer flow was measured in a controlled wind-tunnel environment. To obtain the most accurate ensemble-averaged velocity field, this work evaluated image pre-processing and ensemble-correlation post-processing in detail before performing the flow-field analysis. The main conclusions are summarized in two parts: (i) practical considerations for applying SP-PIV to supersonic, high-gradient flows, and (ii) key observations from the measured aerospike nozzle flow field.

- (i) Since SP-PIV is an ensemble-correlation technique, the contribution of individual particle images to the final velocity probability distribution is weighted by their image intensity. When particle brightness varies strongly, this can bias the result of the correlation, and therefore should be reduced. During the experimental procedure, this can be achieved by minimizing reflections, improving illumination uniformity, and ensuring homogeneous seeding density, especially when multiple seeding systems are used. In supersonic base flows, strong gradients and vorticity can create dark regions because large (bright) particles do not follow the streamlines into these regions. These effects cannot be fully controlled experimentally and require careful PIV data processing. Local min-max type filters for image pre-processing effectively normalize the particle image brightness, but also may amplify noise in dark regions. Increased noise reduces the correlation signal-to-noise ratio. While regular background illumination patterns can often be reduced by background subtraction methods applied to related correlation functions, low signal-to-noise makes these steps more sensitive and can promote spurious peaks and non-physical vectors. Overall, pre-processing must be chosen to stabilize the correlation. However, locally distorting the particle image information that

defines the displacement peak is a common spillover effect that should be considered when gathering Reynolds stress information from the correlation peak fit. For the present supersonic nozzle flow, min-max filtering and correlation function treatment by means of spatial median subtraction was found to produce the best velocity field results.

- (ii) The results provide insight into the main features of the present aerospike flow field under full differential throttling. Mean recirculation regions were identified in the wake of the upper shroud of the main body and in the plug-base wake, which also extends over the lower, deactivated nozzle half. The flow exhibits asymmetric shock structures. The jet core's deflection is consistent, but with competing expansion processes: an outward expansion near the nozzle throat and an inward expansion associated with the truncated plug base shroud. Quantifying the impact of this deflection on the vertical momentum component and thrust vector control capability requires more elaborate thrust or momentum-flux evaluations, which will be the target for future work.

Towards higher spatial resolution PIV, the amount of aerodynamic information that can be extracted from a mean flow field increases, which makes SP-PIV a powerful tool for flows with sharp gradients and small-scale structures. At the same time, supersonic measurements introduce specific limitations related to particle image quality and intensity variations. This study shows that measures taken to improve the stability of the evaluated velocity field can locally modify the outcome and may shift the subsequent fluid-mechanics interpretation. Therefore, the advantage of looking in more detail into flow features comes with the responsibility to validate the flow field results. A closer look at the results of the ensemble correlation and peak fitting is a necessary evaluation step in order to avoid fluid mechanics interpretations on velocity fields that contain non-physical results.

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