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Correcting for color crosstalk and chromatic aberration in multicolor particle shadow velocimetry

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Abstract

Color crosstalk and chromatic aberration can bias estimates of fluid velocity measured by color particle shadow velocimetry (CPSV), using multicolor illumination and a color camera. This article describes corrections to remove these bias errors, and their evaluation. Color crosstalk removal is demonstrated with linear unmixing. It is also shown that chromatic aberrations may be removed using either scale calibration, or by processing an image illuminated by all colors simultaneously. CPSV measurements of a fully developed turbulent pipe flow of glycerin were conducted. Corrected velocity statistics from these measurements were compared to both single-color PSV and LDV measurements and showed excellent agreement to fourth-order, to well into the viscous sublayer. Recommendations for practical assessment and correction of color aberration and color crosstalk are discussed.

Keywords

particle shadow velocimetry; multicolor illumination; turbulent pipe flow; high-speed imaging

1. Introduction

This paper addresses treatment of errors that can arise when using multicolor illumination in particle shadow velocimetry (PSV) [1, 2]. Multicolor PSV (CPSV) is a flow diagnostic technique offering improved temporal resolution and dynamic range, at low cost. Particle shadow velocimetry is similar to particle image velocimetry (PIV) [3, 4] in that an illuminated 2D region of a seeded flow is imaged with a camera and velocity fields are estimated from displacement fields obtained from sequential particle shadow images. In PSV, the flow field is illuminated with pulsed LEDs rather than a laser, as in conventional PIV. A camera is placed on the optical axis of the LED lamp to image seed particle shadows. This technique can be used with single color illumination and a gray-scale camera. However, both dynamic range and temporal resolution can be increased with the use of multicolor LEDs and a color camera.

In standard PIV, a laser light sheet illuminates the flow; the depth of field is determined by the thickness of the light sheet. CPSV instead uses volumetric illumination and relies upon the camera's optics to set a narrow depth of focus. Micro-PIV, introduced by Santiago *et al* [5], also uses volumetric illumination to measure flow in microfluidic devices. Lasers [6], Hg-arc lamps [5] and LEDs [7, 8] have been used for illumination in micro-PIV and micro-PSV. A similar setup, miniature PIV, uses LED illumination and was investigated with back, forward, and side scattered light [9]. LED illumination has also been used for tomographic PIV [10] and to form a light sheet for traditional PIV [11].

Multiple laser colors and color cameras have been used to extend standard PIV as well. Gogenini *et al* presented a setup with a color camera and red and green lasers for illumination [12]. The red and green channels of the color camera recorded their corresponding laser pulses, separated by a small time delay. Brucker [13] used a similar setup to measure the out of plane velocity component using two color lasers and a color camera. Separate color channels of a camera have been used to take independent measurements to reduce the random error of velocity measurements [14]. Towers *et al* extracted separate velocity fields from a two-phase flow [15]. Here, fluorescent particles were used to seed one phase of the flow, with nonfluorescent particles in another. Funatanai *et al* used the blue channel of a color camera for standard PIV with red and green channels for two-color laser induced fluorescence thermometry [16].

Whereas single-color PSV uses a single color light source with a grayscale camera and results in datasets similar to standard DPIV, a combination of multicolor illumination and a color camera allows acquisition of multiple particle shadow images during a single exposure. When each particle shadow image is produced with a different color, color separation of the image results in a particle shadow field for each illumination color. Triggering different-colored illuminations at different instants during a single shutter opening results in more than one shadow image per particle, permitting improved temporal resolution. Velocity estimates can thus be made within a single frame over different time delays, introducing additional flexibility of dynamic range, especially for flows with large spatial gradients.

The laser is the most expensive component of a standard PIV system and requires specialized safety training. By using pulsed LEDs for illumination, CPSV improves simplicity and safety while reducing cost by an order of magnitude, or more. Currently, a high-speed laser costs roughly two orders of magnitude more than a specialized overdriven LED array lamp. Other costs, such as camera, computers, etc, are equivalent. Using an LED light source is not without challenges however. Higher magnification must be used with CPSV, compared to PIV, to isolate a narrow depth of field and to properly resolve particle shadows. As a result, to obtain large enough particle images for PIV displacement estimation, PSV must use either larger particles, or smaller fields of view, than conventional PIV [1, 2]. Meinhart *et al* [17] gives further discussion of the depth of field issues with volumetric illumination. Goss *et al* [1, 2] provides further details regarding particle sizes issues in PSV.

Multicolor illumination introduces other artifacts, specifically chromatic aberration and color crosstalk [2]. Chromatic aberrations arise because each illumination color propagates differently through the optical environment. This issue does not arise when using a single-wavelength illumination, such as a Nd : Yag laser, or a single color LED. Chromatic aberrations manifests in two forms: longitudinal and tangential. Longitudinal aberrations occur along the imaging axis and are caused by the lens' inability to focus all wavelengths to a single point. Goss *et al* [2] discuss how longitudinal aberrations affect multicolor PSV and its ability to isolate a measurement volume. Tangential chromatic aberrations occur across an image plane and result in a particle shadow image of a particle illuminated by one color to be displaced relative to the shadow of the same particle, simultaneously illuminated by a different color. A PIV displacement estimator cannot distinguish true physical particle displacements from these chromatic aberration-induced 'displacements', introducing a bias error in the displacement estimate.

Color crosstalk, on the other hand, arises from two effects. First, the color LEDs used for illumination do not produce pure color light, but rather a broad spectrum centered on the nominal LED color. Second, the filtered pixel array of the image sensor similarly responds to a broad spectrum. Thus illumination from, e.g. a nominally blue lamp, can be registered by red and green filtered pixels of the camera. As a result, it can appear as though a given particle is being illuminated by more than one color.

In this paper, the above bias effects in color Particle Shadow Velocimetry are investigated, and corrections are demonstrated. Color PSV measurements of a fully developed turbulent pipe flow are presented. Velocity estimates of this flow, obtained from the color PSV measurements, are compared to LDV [18, 19] measurements of the same flow to assess the effectiveness of the proposed corrections.

2. Artifacts arising in color PSV, and their treatment

Figure 1 shows a comparison between a PSV and PIV system, in terms of layout and components. Figure 1(a) shows a typical planar PIV setup, where the plane of measurement is illuminated by a light sheet, and the camera is positioned perpendicular to the light sheet to capture the light scattered from the seeding particles. In contrast, for CPSV, a color camera and multicolor LED lamp are placed on a single axis, on opposing sides of a flow field. While the camera is still perpendicular to the measurement plane, the camera now images a particle's shadow, rather than light scattered from it. A diffuser is often placed in front of the lamp to improve illumination uniformity. A high magnification, large aperture lens is used to isolate a narrow depth of field in the seeded flow [2]. Prior to measurement, the camera is focused on a target to fix a desired measurement location and to calibrate image magnification.

2.1. Color separation and interpolation

The color camera uses a Bayer mask, shown in figure 2(a), over the image sensor. This mask contains red, green, and blue filters, with each filter placed over a single pixel of the image sensor. The RGB filters used in color cameras motivates the use of RGB color flashes for illumination, though Goss *et al* [1] discusses reasons to use other LED colors.

In CPSV, each camera exposure is illuminated successively by each available lamp color, producing a multicolor image. To estimate displacement between illuminations, each RGB color image is then separated into three intensity maps using the knowledge of the camera's Bayer filter configuration, shown in figure 2(a). As shown in figure 2(b), the color-separated intensity maps are sparse, compared to the original image. The resulting holes are then filled using bilinear interpolation, resulting in three complete color-separated, interpolated intensity distributions, as shown in figure 2(c).

The final step in image pre-processing is to invert the intensity maps for each illumination color. This step enables processing the images of dark particle shadows on a light background, using standard DPIV software, developed for light particle images on a dark background. Inversion is accomplished by subtracting intensity maps from the average background. (The background is defined simply as the average of several intensity maps. For example, here the average background image is computed from 50 intensity maps.)

The color separation and interpolation process is illustrated in figure 3 for a small region of a CPSV image. Figure 3(a) shows the original color image, the result of three subsequent flashes of blue, green, and red LED lamps separated by small time-delays, as a particle moves from left to right. A checkered pattern corresponding to the Bayer array can be observed in the color image. Figure 3(b) shows color-separated, interpolated intensity maps for blue, green, and red illumination, respectively, from left to right. The intensity maps show the particle shadow image corresponding to their respective LED flashes. Note that interpolation has smoothed the checkerboard pattern so that particle images larger than a pixel are more readily identified. Figure 3(c) shows intensity-inverted images, now suitable for PIV software to estimate particle displacements.

Crosstalk can be observed in the green-illuminated intensity maps (figures 3(b) and (c)). To the left of the primary particle image, a 'ghost' particle is visible, co-located with the shadow in the blue-illuminated image. The ghost particle is due to crosstalk from the nominally blue illumination through the nominally green pixel filter. Note that while color cross-talk can be detected by inspection in this manner, color aberration is not as easily observed, except as described below.

The color separation and interpolation process affects CPSV spatial resolution, especially in terms of particle image size relative to pixel size. Gogenini *et al* addressed this issue in a PIV setup with color imaging and multicolor illumination [12]. They found that particle image sizes should be at least 2.5 pixels for green and 5 pixels for blue and red. Note the Bayer filter in figure 2 has twice as many green pixels as red or blue, effectively doubling its spatial resolution.

2.2. Color crosstalk correction

Correcting for color crosstalk can be accomplished by generating a crosstalk map for the color separated, interpolated intensity maps [1, 2]. In general, the intensity recorded by an individual color pixel is the superposition of the contributions of each colored lamp, weighted by a crosstalk coefficient [1, 2]. For example, the intensity R_p measured by a red-filtered pixel, illuminated by nominally red, green and blue lamps is given by:

$$R_P = c_{rr}R + c_{rg}G + c_{rb}B, \quad (1)$$

where R , G and B are the intensities of the red, green and blue light incident on the pixel, respectively, and c_{rr} , c_{rg} and c_{rb} are the crosstalk coefficients. The crosstalk subscript convention used here is as follows: the first letter indicates the color of the pixel of interest, and the second denotes the color of incident light. For example, crosstalk from the blue lamp into a red pixel is quantified by c_{rb} . The full crosstalk relations for an RGB system are given by:

$$\begin{bmatrix} R_P \\ G_P \\ B_P \end{bmatrix} = \begin{bmatrix} c_{rr} & c_{rg} & c_{rb} \\ c_{gr} & c_{gg} & c_{gb} \\ c_{br} & c_{bg} & c_{bb} \end{bmatrix} \begin{bmatrix} R \\ G \\ B \end{bmatrix}. \quad (2)$$

Note that a crosstalk coefficient map consists of these coefficients computed for each pixel, thus it characterizes any crosstalk gradients. It should be emphasized that, because velocity estimates are made using the color-separated, interpolated and inverted images, the crosstalk matrices are computed and used to correct images at that level of post-processing.

The crosstalk coefficient matrix is found empirically by recording the intensity measured by each pixel when illuminated by a single color lamp. For example, equation (2) for only red illumination (i.e. $G = B = 0$) takes the form:

$$\begin{bmatrix} R_P \\ G_P \\ B_P \end{bmatrix} = \begin{bmatrix} c_{rr} & c_{rg} & c_{rb} \\ c_{gr} & c_{gg} & c_{gb} \\ c_{br} & c_{bg} & c_{bb} \end{bmatrix} \begin{bmatrix} R \\ 0 \\ 0 \end{bmatrix}, \quad (3)$$

which simplifies to

$$\begin{bmatrix} R_P \\ G_P \\ B_P \end{bmatrix} = \begin{bmatrix} c_{rr}R \\ c_{gr}R \\ c_{br}R \end{bmatrix} \quad (4)$$

leading to the following expression for the crosstalk coefficients:

$$\begin{bmatrix} R_P/R \\ G_P/R \\ B_P/R \end{bmatrix} = \begin{bmatrix} c_{rr} \\ c_{gr} \\ c_{br} \end{bmatrix}. \quad (5)$$

The total illumination intensity R is not known, so we define the coefficients relative to an unknown scale factor R , or arbitrary constraint R , e.g. $R = R_p + G_p + B_p$. The remaining coefficients are found similarly, for blue and for green illumination. The linear color unmixing approach shown here has also been used, for instance, in microscopy [20], and multicolor PIV [14]. In this article, we will show the effects of crosstalk on CPSV, i.e. the appearance of ‘ghost particles’, and demonstrate its removal in an example image.

2.3. Chromatic aberration correction

Tangential chromatic aberrations arise from the differences in how the various illumination wavelengths are refracted by the various materials along the optical path. This effect can result in a particle shadow image illuminated by different colors to appear at different locations on the image plane. An example of chromatic aberration is shown in figure 4, which shows shadows of dots printed on a glass target, imaged with a color camera, illuminated by both blue and red LEDs. The two images show an identical region of interest, for the color separated and interpolated intensity maps illuminated in one case by blue, and the other by red LED light. The effect of tangential chromatic aberration is easily observed in the relative vertical displacement of the dots between the two images. Tangential aberration does not affect PIV or single color PSV displacement estimates, because the optical path is the same for each illumination.

Axial chromatic aberration is also visible in figure 4, in the inability to bring the dots into focus simultaneously for both illumination colors. This effect can often be minimized during calibration, as long as the depth of field is not too narrow. When illuminating a calibration target, care should be taken to ensure that shadow images are equally in (or out of) focus for all illumination colors. This is possible if the depths of focus for the illumination colors overlap.

Two approaches to correcting for tangential chromatic aberration are treated here. The first is an image transformation akin to those commonly used in stereo PIV to correct for perspective distortions [21]. The second is to acquire images firing all illumination colors simultaneously, so that the only ‘displacement’ is due to chromatic aberration. The latter approach is hereafter referred to as the *zero-time delay*, or *ZTD* correction.

The transformation map approach is useful because it also serves as a calibration from image space to real space. In this process, a transformation function is generated from a target image consisting of a known geometry. A useful target for CPSV is a clear glass plate with a known grid of printed dots. The target is imaged under identical conditions to subsequent CPSV flow measurements. The transformation then maps the positions of dots illuminated by one color to their corresponding positions in intensity maps illuminated by another color. The particular transformation function that is used depends on the experimental setup. Image transformation functions can be generated using PIV analysis software such as Davis 8.0 (LaVision, Goettingen, Germany) or developed in-house.

A second approach to correcting chromatic aberration is to use a zero time delay vector subtraction [1]. In this process, color images of the flow are acquired, firing all illumination lamp colors simultaneously (i.e. with zero time delay). The color separated and interpolated

images corresponding to each pair of illumination colors are then processed with identical displacement engine settings that are used to process subsequent flow measurement data. The resulting vector fields are the error vectors due to tangential chromatic aberration. For robustness, an average vector field should be computed, either from an ensemble of many images, or by averaging over a single image along directions which the chromatic aberration does not change. Subtracting an average zero time delay vector field from flow measurement vector fields, as a post-processing step, thus removes the chromatic aberration bias. This approach, while simple to implement, does not, however, correct for optical distortions that may affect the different color separated and interpolated images similarly. For instance, an image distortion that affects blue and red images similarly is not incorporated into a zero time delay vector field, and is therefore not corrected.

It should be noted that as long as the optical path features producing chromatic aberration are essentially fixed in time, the chromatic aberration effect does not change from image to image. When estimating velocity statistics using central moments of the measured ensemble, the chromatic aberration error is the same for the instantaneous and mean velocity. As a result, chromatic aberration is expected to bias only mean velocity estimates.

2.4. Summary of color corrections

Once the color-separated and interpolated images are in hand, the described above corrections above can be implemented. A color crosstalk correction should be made first, so that ‘ghost particle’ images are removed. The choice of chromatic aberration correction depends on two considerations: (1) whether the image is distorted, e.g. by perspective or wall curvature, (2) whether any distortion is as large as the displacements due to chromatic aberration. As shown below, empirical determination of the transformation map using a calibration target provides this information.

3. Glycerin tunnel experiment

An experiment was conducted to assess the effects of color crosstalk and chromatic aberration on CPSV, and to evaluate correction methods. CPSV measurements were taken in the ARL Penn State glycerin tunnel [22, 23]. The purpose of this experiment is to validate multicolor PSV measurements and evaluate the correction methods discussed in section 2. Of particular interest is comparison of the two proposed corrections for chromatic aberration. Velocity statistics up to fourth order are presented for multicolor PSV against LDV and single-color PSV measurements taken in the same facility [18, 19]. Multicolor PSV results are shown with and without the various correction methods applied.

3.1. Glycerin tunnel

CPSV experiments were conducted in the glycerin tunnel of the Applied Research Laboratory at the Pennsylvania State University (figure 5). The tunnel is a closed loop, low Reynolds number turbulent flow of ~99% glycerin (Reynolds number, based on pipe diameter and flow is approximately 8000). The flow is driven by a Gould centrifugal pump and 100HP Westinghouse electric motor. Tunnel flow conditions (glycerin density, glycerin viscosity, flow velocity, pressure drop, Reynolds number) are determined by the glycerin

temperature. Pump work raises the glycerin temperature and a heat exchanger is used for temperature control. In turn, the flow speed is controlled using the heat exchanger to alter glycerin viscosity. Further description of the facility can be found in Bakewell [22] and Chevrin [23].

The upper leg of the tunnel is composed of 6.6 m of 285 mm diameter stainless steel pipe, in sections, followed by a 1.1 m long test section. A 10 mm serrated ring at the entrance of the upper leg trips the boundary layers to ensure a turbulent flow. The measured pressure gradient indicates that the flow becomes fully developed roughly 9 pipe diameters upstream of the test section [19].

3.1.1. Flow condition monitoring—Twenty pressure taps lay at 30.5 cm increments along the length of the upper leg. An electric thermometer is placed at the end of the test section. Pressure and temperature is monitored during tunnel operation using an Agilent 34970A Data Acquisition system. Pressure gradient and temperature measurements provide estimates of flow properties and the friction velocity in the fully developed pipe flow.

Friction velocity was estimated from the measured axial wall pressure distribution in the pipe. In the fully developed region of the pipe flow, the pressure force driving the fluid is balanced by the frictional drag, resulting in the following expression for friction velocity:

$$u_* = \sqrt{2 \frac{\Delta p R}{\rho L}}, \quad (6)$$

where Δp is the pressure difference measured between two taps with axial separation L , ρ is the fluid density, and R the pipe diameter. Friction velocity uncertainty is 0.01 ms^{-1} , as detailed in [18, 19].

3.1.2. Optical diagnostics, test section, flow seeding—The tunnel test section, composed of clear acrylic, provides optical access to the flow, as shown in figure 6. The test section is 1.1 m long, has a cylindrical inner surface, and a square exterior cross-section. The inner diameter is 285 mm and has been polished to a $0.41 \text{ }\mu\text{m}$ RMS surface finish. A removable plug in the top of the test section provides access to the tunnel interior. The calibration target was attached to this plug and positioned along a pipe radius, and along the pipe axis.

The lens effect of the cylindrical inner surface of the test section is minimized by the square exterior and the close matching of acrylic and glycerin indices of refraction. Still, the index of refraction mismatch between the curved acrylic test section wall and the glycerin refracts incident light rays, giving rise to chromatic aberration bias displacement error in the wall normal direction that varies with position. Resolution of the wall-normal velocity by CPSV is thus challenging, due to the combination of chromatic aberration and the small magnitude of that velocity component, relative to the axial velocity.

Seeding for CPSV is provided by small air bubbles. The action of both the pump impeller and the turbulence in the flow produces bubbles $50 \text{ }\mu\text{m}$ in diameter. The bubbles have been

found to adequately follow the fluctuations of the turbulence in this flow [22], and were also used as seed particles in LDV measurements [18, 19].

3.2. Image acquisition

A Dimax camera (PCO, Kelheim, Germany) fitted with a 105 mm Nikon (Tokyo, Japan) lens and a single 14 mm extension ring was used for imaging. The depth of field was estimated to be less than 1.5 mm. The camera sensor is 2016×2016 pixels, with 12-bit dynamic range. Camware 2.19 (PCO, Kelheim, Germany) was used for camera control and image acquisition. All images were saved in a 16-bit TIFF format. A multicolor LED lamp manufactured by Innovative Scientific Solutions Inc. (Dayton, Ohio, USA) provided illumination. The lamp was placed on the opposing side of the flow as the camera. A TTL pulse from the camera indicating the beginning of an exposure was used to control a Berkeley Nucleonics (San Rafael, CA, USA) 555 pulse waveform generator. The waveform generator controlled the timing of the illumination pulses.

During calibration, the measurement region was fixed by focusing the camera on a clear NT57–981 Edmund Optics (Barrington, NJ, USA) glass calibration target with printed dots. The target dots are 0.25 mm in diameter with centers placed 0.50 mm apart, in a rectangular array. The dots on the glass target were used as control points for the image transformation process.

Camera shutter and illumination timings were selected to ensure particle displacements suitable for displacement estimation across the velocity gradient in the wall-normal direction. Figure 7 shows a schematic of the timing of the lamp and camera. A sequence of 8000 images was recorded at 1 kHz with an exposure length of $960 \mu\text{s}$. Images were saved in pairs, denoted frame A and frame B, with illumination pulses straddling the pairs of images, as depicted in figure 7. Illumination timing is shown in table 1 relative to the opening of the shutter for a frame A of an image pair. All illumination pulses were $5 \mu\text{s}$ in duration. The flow tracers were approximately 8 pixels in diameter, on average, and displaced roughly 1.4 pixels in the bulk flow region during the illumination pulse. During zero-time delay measurements, all lamp colors were illuminated simultaneously within an exposure. A sequence of 200 images was recorded for ZTD measurements.

3.3. Displacement estimation

3.3.1. Pre-processing—The raw color images were color separated into intensity maps using the Bayer filter configuration of the camera. Holes in the color-separated intensity maps were filled using bilinear interpolation. Intensity maps of particle shadows were inverted by subtracting from an average background, and compressed to 8-bit TIFF format.

A set of images were corrected for color crosstalk and chromatic aberration prior to displacement estimation. Both the transformation map and the zero-time delay corrections for chromatic aberration were determined by imaging a transparent calibration glass target, described above. Davis 8.0 was used for image transformation, de-warping the images using a third-order polynomial fit generated from the calibration target images. Separate

transformation functions were generated for blue and red images, which mapped these images to a common coordinate system.

3.3.2. Velocity estimation processing—Davis 8.0 (LaVision, Goettingen, Germany) used a standard FFT based cross correlation algorithm to estimate particle shadow displacements. A 64×64 pixel interrogation region, with a 4 : 1 elliptical weighting, was used for the initial pass. The second and third passes used a 32×32 pixel window, with a 2 : 1 elliptical weighting, to improve resolution of the wall-normal velocity gradient. All passes used an interrogation region overlap of 50%. After each correlation pass, vector filtering was conducted. A vector was removed by a median filter if a least one of its components was greater than 3 standard deviations from the median component of neighboring vectors. Holes were then filled using nearest neighbor interpolation. ZTD images were processed identically to measurement vectors. The ensemble average of the ZTD vectors was then used for the post-processing subtraction to correct for chromatic aberration.

Vector statistics were computed from the velocity field ensembles, as well as by spatially averaging the vector fields in the streamwise direction. The first and last two columns of vectors in the field were not included in these streamwise averages, due to the likelihood of particle entry or exit during image pair acquisition. Processing yielded 4000 blue–blue velocity fields and 8000 blue–red velocity fields.

3.4. Uncertainty analysis

CPSV uncertainty analysis was conducted following the technique of Petrie *et al* [24], which uses synthetic images derived from the acquired images. This approach was developed to holistically incorporate such effects as illumination, particle size, pixel resolution, to PIV measurement uncertainty, in a practical manner. A CPSV measurement image was shifted a specified distance (in general, a non-integer number of pixels) using image processing to generate a second with a known, uniform displacement. The shifting process uses bilinear interpolation to perform a non-integer image shift. The original and its synthetically shifted image were analyzed by the displacement engine (LaVision DaVis 8.0). Displacement error was defined as the difference between the displacement field estimate and that imposed in the image shift. The statistics of this difference are used to estimate both the bias and random uncertainty of the mean displacement. Uncertainty estimation for statistics of order 2 or higher are estimated for contributions from random uncertainty only, using expressions developed by Benedict and Gould [25].

4. Results

4.1. Cases studied

PSV and CPSV measurements were conducted in the ARL Penn State glycerin tunnel, for a field of view covering the near-wall region ($0 < y^+ < 100$). Physical dimensions of the useful measurement FOV were $11 \text{ mm} \times 42 \text{ mm}$. Working fluid temperature was 37.8°C , with resulting density $\rho = 1250 \text{ kg m}^{-3}$, and kinematic viscosity $\nu = 220 \times 10^{-6} \text{ m}^2\text{s}^{-1}$. The measured axial pressure distribution yielded a friction velocity of $u_* = 0.42 \text{ m s}^{-1}$. For the LDV measurements of the same flow, in the same facility [19], the friction velocity was 0.40

m s^{-1} . Vector fields estimated from the PSV and CPSV measurements had a spatial resolution of 0.64 wall units.

4.2. Illumination and image quality

In the glycerin working fluid, illumination quality varied considerably with color. In particular, the green LEDs used were not able to produce a satisfactorily diffuse and intense illumination over the whole field of view. The combination of RGB LED illumination and camera RGB image sensor filters used in this study results in appreciable crosstalk from blue into green, but little between blue and red. In principle, there is also crosstalk from green into blue, but there was not enough green light to contaminate the readings of the blue pixels. Crosstalk correction results, then, focus on a single demonstration example. In addition, color aberration correction studies are limited to blue and red illumination.

4.3. Example of color crosstalk correction

As noted above, significant crosstalk in the setup used here was limited to blue into green. Figure 3 shows an example. Figure 8 shows a demonstration of crosstalk correction, applied to the green-illuminated intensity map shown in figure 3. Crosstalk from the blue flash into the green intensity map appears as a ‘ghost particle’ due to crosstalk from blue illumination into the green pixels. As shown in the figure 8(b) image, the proposed crosstalk correction effectively removes the ghost particle. The rather obvious point should be raised that the best way to avoid crosstalk is to ensure the spectra of the illumination colors and the image sensor filters do not overlap.

4.4. Relative effects of chromatic aberration and image distortion

As shown in figure 4, the printed dots on the calibration target appear in different locations for different illumination colors due to chromatic aberration. In this section, the relative magnitudes of chromatic aberration and the image distortion are compared. Intensity maps of the calibration target, described in section 3.2, illuminated with either blue or red light, were used. The centers of the printed dots were identified for the resulting blue and red intensity maps. The centers of the printed dots were identified by binarizing the image with a threshold intensity value and then computing the centroids of the printed dot shadows.

Figure 9(a) shows a sketch of the dot images for two intensity maps, each illuminated by a different color. A single, vertical line of calibration target marker dots, in the center of the image and in the wall-normal direction illustrate how the assessment was made. The differences in wall-normal spacing of successive control points on a single intensity map (e.g. blue) are denoted δ_d . Differences in wall-normal spacing of control points between blue and red intensity maps are denoted δ_{ca} . These measures can be used to assess the relative magnitudes of chromatic aberration and distortion using a plot of both δ_d and δ_{ca} versus control point location y . Image distortion is indicated by the strength of the variation of δ_d with y —if the curve is flat, there is no distortion. Chromatic aberration is indicated by the difference in the δ_d and δ_{ca} curves, at any given y .

Figure 9(b) shows profiles of δ_d from a blue-illuminated intensity map, and δ_{ca} between blue- and red-illuminated intensity maps, as a function of wall-normal position. The profile

of d does not vary strongly with y , indicating that the blue intensity map is not substantially distorted in the wall normal direction. The profile of c_a is offset from the d profile. In addition, this offset varies with wall-normal position. Chromatic aberration also varies with wall-normal position, shown by the non-zero slope of the c_a profile. These results strongly suggest that chromatic aberration errors bias the particle displacement results much more strongly than image distortion, in the optical setup reported here. It is recommended that this manner of assessment be performed using image calibration data, in order to guide the choice of bias corrections.

4.5. Assessment of chromatic aberration corrections to velocity

4.5.1. Mean velocity vector fields—Ensemble averaged velocity vector fields from the glycerin tunnel experiment are shown in figure 10. The tunnel wall is at the top of the images, and flow is from left to right. The vector fields were computed from intraframe blue–red cross correlation. In figure 10(a) chromatic aberration bias error in the wall normal velocity component is especially evident, given that the mean flow near the wall is essentially parallel. Figure 10(b) shows the vector field after application of the zero-time-delay correction, in which the bias error in the wall normal velocity component is substantially reduced. The effectiveness of the correction is not as evident near the wall, in the center of the image, where some relative attenuation of illumination was observed, resulting in reduced particle image contrast.

4.5.2. Velocity statistics profiles—Profiles of velocity statistics obtained from CPSV measurements are now shown, to assess the effectiveness of chromatic aberration corrections. Figure 11 shows profiles of the mean streamwise and wallnormal velocity components for $y^+ < 100$. Five velocity estimates are shown in the plots: (1) those obtained by intraframe correlation, illuminated by blue and red LEDs (denoted ‘blue–red’), uncorrected for chromatic aberration, (2) those obtained by intraframe correlation, illuminated by blue and red LEDs corrected for chromatic aberration correction using a zero-time-delay (ZTD) approach (denoted ‘blue–red with ZTD’), (3) those obtained by intraframe correlation, illuminated by blue and red LEDs corrected for chromatic aberration using a distortion map (denoted ‘blue–red with image transformation correction’), (4) those from frame-straddled blue LED illumination (denoted ‘blue–blue’), and (5) LDV measurements of velocity in the same facility [18, 19]. For clarity, uncertainty bars are shown at only three locations: $y^+ = 3.5, 10.6, 36.0$, for the ‘blue–red’ velocity estimates.

Figure 11(a) shows mean axial velocity, $\langle U^+ \rangle$, measured by CPSV, PSV, and LDV. All corrected CPSV estimates result in mean axial velocity that is within uncertainty of both LDV and PSV. Note that chromatic aberration has at most a weak impact on streamwise displacement, so the agreement of all the results is not surprising. The mean wall-normal component, $\langle V^+ \rangle$, is shown in figure 11(b) and is a better indicator, in this flow geometry, of the behavior of chromatic aberration and the effectiveness of its correction. Both the single color PSV (‘blue–blue’) and LDV measurements, unaffected by chromatic aberration, show an essentially zero $\langle V^+ \rangle$. The uncorrected two-color CPSV (‘blue–red’) profiles indicate a spurious wall-normal velocity, due to chromatic aberration. The zero time delay and image transformation methods both reduced the effects of chromatic aberration in the wall normal

component substantially, though the former appears to be more effective than the latter. Subsequent plots of higher-order velocity statistics show all these cases, with the exception of ZTD-corrected velocity. Zero-time-delay vector subtraction results are only shown for mean results, because the subtraction does not affect higher order statistics.

Figure 12 shows second-order velocity statistics. In figure 12(a), shows u^+ , the streamwise velocity standard deviation in wall units. Here, the blue–red CPSV and LDV are within uncertainty bands between $y^+ = 4$ and $y^+ = 30$. Below $y^+ = 4$ the blue–red CPSV profiles show a large increase in RMS, likely due to near-wall noise, due to reduced particle shadow contrast. Blue–blue CPSV and LDV profiles are within uncertainty between $y^+ = 9$ and $y^+ = 30$. The single color PSV (blue–blue) profiles also show a high near wall RMS, further indicating that the observed velocity RMS increase near the wall is due to illumination and image contrast issues. Velocity covariance (Reynolds stress), in wall units, is shown in figure 12(c). This quantity tapered off rapidly toward zero for $y^+ < 6$, indicating an increasing lack of correlation between the two components as the wall is approached. This occurs in regions where both velocity component standard deviations (u^+ and v^+) are high, again suggesting uncorrelated noise affects measurement in the near wall region. As noted above, in this region, illumination and particle image contrast were lowest. Finally, the larger departures of the single-color illumination (blue–blue) from the LDV results, compared to the multicolor illumination (blue–red) are likely due to the high correlation of illumination noise between the images illuminated by the same color, compared to the multicolor illumination, where the illumination noise is likely uncorrelated [14].

Figure 13 show profiles of velocity skewness. For stream- wise velocity skewness, CPSV and LDV profiles are within the CPSV uncertainty above $y^+ = 8$. Discrepancies are found below $y^+ = 8$, again likely due to near wall noise in the images. The filtering required to remove spurious vectors reduced the skewness of the U component of the velocity probability distribution. The V skewness profiles show fluctuations at $y^+ < 10$ for all CPSV measurements. The blue–blue profile fluctuates about zero below $y^+ = 1$ and both blue–red datasets fluctuate below $y^+ = 5$. LDV and all CPSV measurements are within uncertainty above $y^+ = 11$. Flatness profiles are shown in figure 14. In the streamwise component, all measurements are contained within the CPSV uncertainty. Discrepancies are shown between each CPSV dataset below $y^+ = 4$. CPSV profiles for flatness of the wall normal component If the velocity and LDV are within uncertainty above $y^+ = 30$. This is again likely due to the filtering of the noisy vectors resulting from lowered illumination near the wall.

5. Discussion

For multicolor PSV, two corrections for chromatic aberration were presented. The first correction, the zero-time delay (ZTD) approach, was estimated by processing pairs of color-separated images taken with a time delay of zero between illumination flashes. This provides a correction vector field, which is later subtracted from velocity measurements taken in the same field of view, and processed using the same displacement engine settings. The second method was a distortion map, generated from illuminating a calibration target. This map was used to effectively de-warp the color-separated, interpolated images prior to processing by the displacement engine.

The zero time delay correction was found to better correct for chromatic aberration in the setup tested. In that setup, the wall-normal velocity was most affected by chromatic aberration because of the transverse curvature of the flow passage. These results suggest that the zero-time-delay subtraction appears to be the more useful chromatic aberration correction, at least for the geometry studied. The simplicity of the ZTD method also makes it a more attractive method. Image transformation requires accurate identification of object points on an image to produce the mapping function. Small, random errors in locating these points can introduce errors in the transformation mapping, resulting in bias errors in displacement estimates. The zero time delay correction is thus in a sense more robust, as long as errors due to image distortion are smaller than those due to chromatic aberration, as was the case here. Additional uncertainty due to ZTD correction is on the order of the PSV measurement for single-color illumination.

The results reported here also strongly indicate that higherorder velocity statistics can be measured with reasonable accuracy using PSV, as long as any bias errors due to multicolor illumination are corrected for in the mean velocity field.

The principle impact of color crosstalk is the appearance of spurious ‘ghost’ images, which are the result of particle shadows illuminated by one color appearing due to overlap between illumination and Bayer filter spectra. In principle, occurrence of this error can be reduced by careful selection of illumination sources and image sensor color filters to minimize spectral overlap, but this is not always possible. In fact, in the experimental setup described herein, there was little overlap between green and red, or red and blue. Furthermore, the green illumination was greatly attenuated by the glycerin working fluid, so that crosstalk between blue and green was limited to blue crossing into green. A demonstrative crosstalk correction map was obtained by acquiring color images illuminated by a single color, then comparing the intensity of all the color separated and interpolated images. Solving the system of crosstalk equations was shown, in a demonstration, to effectively remove a ‘ghost’ image.

Single color PSV (blue–blue dataset) velocity statistics, to fourth order, compared favorably to LDV measurements of the same flow [18], except near the tunnel wall, where illumination issues resulted in reduced PSV image contrast. Single color PSV does not suffer from color crosstalk or chromatic aberration and therefore no additional corrections were required.

It should be emphasized that these findings may be limited to the particular case studied here. As such, it is recommended that the relative magnitudes of each error source be evaluated using images of a known target, as demonstrated in section 4.4, to identify which corrections are best. These evaluations are performed as part of the image calibration process.

6. Summary

This article describes the assessment and treatment of two issues which may arise in using multicolor illumination for Particle Shadow Velocimetry, namely, color crosstalk and chromatic aberration. These effects are shown to introduce errors in displacement estimates of particle-seeded flows. Corrections for these errors were presented and implemented for

data acquired in a fully developed turbulent pipe flow, using a color camera with a standard Bayer filter and a red, green, and blue LED illumination.

Color crosstalk was not found to affect the results presented here, though a color crosstalk correction technique was demonstrated. Further assessment of the effect of color crosstalk on PSV displacement estimation is required. It was also found that, between chromatic aberration and image distortion, the former provided the dominant contribution to bias error. As a result, the simply implemented zero-time delay correction worked quite well, as shown by comparison of corrected velocity statistics measured by CPSV to those measured by laser-Doppler velocimetry. Finally, it was demonstrated that chromatic aberration effects primarily the mean velocity, and that higher-order velocity statistics can be estimated from CSPV measurement if the bias is removed from the mean velocity field.

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Figure 1. Schematic comparing arrangement of particle image velocimetry (PIV) and particle shadow velocimetry (PSV) systems. (a) PIV system, (b) PSV system.

Figure 2.

Schematic showing color image separation and interpolation. (a) Original color image pixel distribution by color, for Bayer filter array placed over a color camera image sensor, (b) color separated images, showing 'blank' pixels, (c) color-separated, interpolated images, where color-separated images are filled by interpolating from existing intensity data.

Figure 3.

Demonstration of image pre-processing of original color images to intensity maps for each color illumination. (a) Original color image of single particle moving from left to right, illuminated successively by blue, green, and red illumination. Note checkerboard pattern due to Bayer filter distribution. (b) Color separated, interpolated images for each illumination color, (c) inverted color-separated, interpolated images. Note ghost image in green-illuminated intensity map, due to crosstalk from blue illumination.

Figure 4.

Illustration of chromatic aberration. Color-separated, interpolated intensity maps developed from a color image of a calibration target, illuminated by different colors: (a) blue-illuminated image, (b) red-illuminated image. Calibration target is transparent plate with 0.25 mm diameter printed dots. Tangential chromatic aberrations evident from the relative vertical locations of the dots. Axial aberration causes the difference in focus of the dots.

Figure 5.

Schematic of the glycerin tunnel facility (not to scale). Measurements conducted in transparent acrylic test section (see figure 6). Flow in upper leg reaches fully developed condition approximately 1.7 m upstream of acrylic test section. Working fluid temperature is controlled using a heat exchanger (not shown). Because working fluid viscosity is a strong function of temperature, the heat exchanger is used to control flow speed.

Figure 6.

Test section schematic, showing dimensions and location of measurement field of view (FOV). (a) Side view, (b) end view. Nominal measurement FOV dimensions were 11 mm (streamwise) $\times$ 42 mm (radial).

Figure 7.

A schematic of the timing used in the glycerin tunnel experiment. Times shown in table 1 are given relative to the opening of the camera shutter for a frame A.

Figure 8.

Demonstration of crosstalk correction of green-illuminated image containing ghost particle from blue illumination (shown in figure 3(c)) crosstalk through the green Bayer filter. (a) Green-illuminated image, prior to crosstalk correction, containing ghost particle. (b) Ghost particle removed from green-illuminated image, after crosstalk correction.

Figure 9.

Relative impact of image distortion and chromatic aberration. (a) Schematic of a calibration target dots, where the gray and white dots indicate shadows illuminated by different-colored light. The two sets of dots appear offset from one another due to chromatic aberration. The difference in vertical location within a single color image (denoted Δ_d) is a measure of image distortion. The difference between dot positions between the separate color illuminations (denoted Δ_{ca}) is a measure of chromatic aberration. (b) Results corresponding to part (a), the difference in wall-normal position of the control points from a calibration image —: Δ_d , $\cdots$: Δ_{ca} .

Figure 10.

Comparison of mean velocity vector fields obtained from CPSV in the near wall region of the glycerin tunnel, showing effect of chromatic aberration correction. Vector fields obtained from intra-image correlation between blue and red illuminations. Orientation of the vector field matches the field of view sketch in figure 6. (a) Uncorrected vector field. Note visible component of wall-normal fluid motion. (b) Vector field after application of zero-time-delay correction—note diminishment of wall-normal component.

Figure 11.

Ensemble averaged velocity profiles. $\circ$: blue-blue; $\square$: blue-red; $\triangle$: blue-red with zero time delay Subtraction; $\times$: blue-red with image transformation. —: LDV [18]. (a) Streamwise mean velocity, $\langle U^+ \rangle$, (b) wall-normal mean velocity, $\langle V^+ \rangle$.

Figure 12.

Second-order velocity statistics profiles for fully developed pipe flow. $\diamond$: blue–blue; $\square$: blue–red; $\times$: blue–red with image transformation. —: LDV [18]. (a) streamwise velocity standard deviation in wall units, (b) wall-normal standard deviation, in wall units, (c) Reynolds stress (covariance of streamwise and wall-normal velocities), in wall units.

Figure 13. Skewness of streamwise (a) and wall normal (b) components of velocity. $\diamond$: blue–blue; $\square$: blue–red; $\times$: blue–red with image transformation. —: LDV from Fontaine [18].

Figure 14. Flatness of streamwise (a) and wall normal (b) components of velocity. $\diamond$: blue-blue; $\square$: blue-red; $\times$: blue-red with image transformation. —: LDV from Fontaine [18].

Table 1.

Illumination timing used in glycerin tunnel experiment, given relative to first opening of camera shutter.

Frame	Flash	Time (μs)
A	Blue	830
	Red	950
B	Blue	1010
	Red	1130