CCD image sensor induced error in PIV applications

Mathieu Legrand1*, José Nogueira1, Alberth A. Vargas1, Rubén Ventas1, María del Carmen Rodríguez-Hidalgo2

1: Department of Thermal and Fluids Engineering, Universidad Carlos III, Madrid, Spain,
2: Departamento de Sistemas oceanográficos y navales, Universidad Politécnica de Madrid, Spain.
* correspondent author: mlegrand@ing.uc3m.es

Abstract The readout procedure of Coupled Charge Device (CCD) cameras is known to generate some image degradation in different scientific imaging fields, especially in astrophysics. In the particular field of Particle Image Velocimetry (PIV), widely extended in the scientific community, the readout procedure of the interline CCD sensor induces a bias in the registered position of particle images. Generally, there are differences on the position bias for the different images of a certain particle at each PIV frame. This leads to a substantial bias in the PIV velocity measurement (~ 0.1 pixels). Based on modern CCD technology and architecture, this work offers a description of the readout phenomenon and proposes a modeling for the CCD readout bias error magnitude. It predicts a velocity measurement bias when there is an illumination difference between two successive PIV exposures. The model matches the experiments performed with two 12 bit-depth interline CCD cameras (MegaPlus ES 4.0/E incorporating the Kodak KAI-4000M CCD sensor of 4 megapixels). For a certain camera, only two constant values are needed to characterize it and predict the error coming from the read-out procedure, in order to optimize acquisition setups. Simple procedures to obtain these values are described.

1. Introduction

During the past century, scientific imaging has proven its utility and capability in numerous fields. It covers the whole range from the largest observable objects in astronomy, down to the smallest ones in microscopy. It also assists critical domains of the modern society, such as medical imaging and environmental protection. Although photographic film technologies supposed an important scientific breakthrough and allowed for many studies, the recent developments of digital imaging enhance the capacities in a great extent. This is especially noticeable when dealing with image processing and storage. Among other applications, these improvements are a relevant benefit in most scientific research domains.

In particular, this evolution has allowed remarkable enhancement of Particle Image Velocimetry (PIV) as an image based, non-intrusive, and global velocimetry technique widely used in the field of fluid mechanics and thermal engineering. At its beginning, it was common to use pulsed illumination to record the particle image positions twice in a photographic film at different times, separated by a small time interval $\Delta t$. Besides relevant studies and results (Kompenhans 1986 and Lourenço 1986, Grant and Smith 1988, and Cho 1989, among others), the interrogation techniques, such as Young fringes analysis, were very delicate and time consuming (Grant, 1997). The quality of the experimental images could not be checked until developing the film, hours after the acquisition. An additional drawback of this analogue technique was that the photographic film was exposed twice, requiring specific devices to avoid directional ambiguity. Since the early 1990 decade (Willert and Gharib 1991), the use of Couple Charge Device (CCD) image sensors allowed for digital recording of particle position, greatly easing the image processing. This type of cameras also offers the possibility to acquire two different frames in a short time interval. The CCD cameras can operate in a double-frame mode, i.e. acquiring one different frame by exposure, thus solving the directional ambiguity problem.
The CCD image sensors have experimented great improvements since the early 80's. In the framework of Particle Image Velocimetry (PIV), the interline-transfer technology allowed to achieve very small inter-frame times, down to ~100 ns, enabling the measurement of fluid flows with a fast movement relative to the field of view.

Among the many lines of study in the use of CCD cameras in PIV, Nogueira et al. (2009) and Legrand et al. (2011) recently reported that the double-frame CCD cameras readout process present some relevant bias in the location of particles images, thus biasing the velocity measurement. Both works deal with the bias impact on the measurement error, and propose a way to evaluate its magnitude using a simple multiple Δt strategy, available for any usual PIV setup, when acquiring the images. Together with preliminary references from Raffel et al. (1998), the aforementioned studies attribute a displacement error to the CCD readout procedure, but generally there is a lack of information on the phenomenology of this bias error. Besides Nogueira et al. 2009 that reported some evidences of CCD illumination influence, no explicit dependency on internal or external variable is usually given. The present study is dedicated to exposing such dependencies in order to further characterize the CCD readout error, including the possible effect of temperature, Waczynski et al. (2001), and ambient humidity as suggested by Nogueira et. al 2009. This work also allows predicting when strategies such as the “multiple Δt” one may be appropriated to correct this kind of errors in the measurements, thus providing an additional tool to the researchers interested on designing a PIV acquisition protocol that optimizes the degree of accuracy of a PIV measurement.

2. Frame-transfer and Interline-transfer CCD image sensors

2.1. Sensor architecture: Frame transfer vs. interline-transfer.

Since its beginning, digital imaging and CCD sensors in particular, had experimented a large evolution and enhancement. Given the large variety of application fields, several different designs have emerged, depending on the particular requirements. As commented in the introduction, the implementation of PIV requires acquiring two single exposure frames in a short, or very short, interval of time Δt. For state-of-the-art CCDs, the minimum time to transfer (readout) all the pixels of a typical megapixel CCD sensor is about ~100 ms, far above the Δt needed in many application (typically in the order of few microseconds or even less than that). This requirement leaded to the development of cameras with two CCD arrays implanted in the acquisition chip.

The so called frame-transfer technology consists in two identical rectangular CCD arrays, where one of them is protected from the incident light by a shield (generally a thin aluminum coating). With this arrangement (see Figure 1a), only one CCD array is able to collect light: the image array. When a first exposure is finished, all the photon generated charges in the elements (pixels) of this CCD array are simultaneously transferred to the second, light shielded, CCD: the storage array. Once the whole image has been transferred to the storage zone, taking ~10 to 100 µs depending on the design, a second exposure starts in the, now empty, image array. During the second exposure, the storage array is read out (~50 ms).

As the frame transfer operation is much faster than the readout, a shorter Δt between exposures is possible. For this architecture small time intervals for the first exposure and for Δt are possible, but the second exposure is limited by a much longer time than the first one (~50 ms vs. a few µs). This is so because the second frame has to wait, at the image array, until the first frame is read out from the storage array. When the readout of the first frame is finished, the image array of the second one is transferred to the storage array and then read out before a new double-frame acquisition is possible. The repetition rate of a single PIV measurement (i.e. a double-frame) is thus of the order of ~10 Hz (50 ms for each readout). In addition to the different exposure constrains between the first and second frames, if the illumination is continuous, the resulting performance may be compromised, because exposure integration is still occurring during the image transfer to the
storage array resulting in an image "smear" all along the CCD sensitive surface. Regarding cost, since twice the silicon area is required to implement this architecture, frame transfer CCDs have a significant higher cost than common full frame CCDs and take up more space.

Interline-transfer CCD (or interline CCD for short) were developed to avoid some of the shortcomings of the frame-transfer devices (Figure 1b) by locating the photo-detecting and storage elements closer than in the previous case. This is done by inserting photosensitive element lines in between lines of storage non-sensitive (light shielded) elements. These storage lines are also call vertical or parallel registers as they are used also in the readout procedure to drive the information towards the serial (horizontal) register. Since each photodiode is adjacent to one CCD storage unit, in this configuration the interline transfer is much faster than in frame transfer technology, reaching interframe times down to ~100 ns. This simple operation achieves the transfer of the entire exposed image into the adjoining storage sites.

The fast transfer, in conjunction with the now current higher pixel density formats, has extended the field of applications, including its common application to velocity measurement techniques like PIV. The major disadvantages of the interline CCD layout are a lower sensitivity per surface unit and a higher complexity, leading to higher unit costs. Among other reasons, the lower sensitivity occurs because at each pixel about half the area is needed for the interline storage array (fill factor $FF \sim 0.5$). This last issue requires the use of micro lenses mounted on top of the photodiodes forming vertical strips prisms. This configuration is useful to overcome the low fill factor $FF$ in the serial direction. But it produces a strong dependency on light incidence angle, giving quite different sensitivity between vertical (parallel), and horizontal (serial) direction.

Figure 2 presents the performances of the Kodak KAI4011 interline CCD provided with micro lenses. It shows the relative quantum efficiency (i.e. incoming light to charge conversion ratio) versus the light angle of incidence. A clear difference is observable between vertical and horizontal directions, due to the micro-lenses, photodiodes and CCD storage elements layout. In the vertical direction, almost all the incoming light is collected by the photodiode. On the contrary, the presence of the linear micro lens aligned in the vertical direction for light focusing on the photodiode (Figure 3) makes the quantum efficiency very dependent on incoming light incidence. This is an important issue when using image forming optics, since the image center would register more
illumination because of the higher quantum efficiency for its incidence angles. Meanwhile registered illumination would degrade along the horizontal direction rather quickly because of the more pronounced light incidence angles.

In the rest of the paper, the interline-CCD architecture is the one further analyzed and studied. Its short interframe time for a double-frame acquisition has made it the most frequent choice for PIV applications.

![Relative quantum efficiency vs. azimuthal angle (horizontal corresponds to the direction across interlines) of the Kodak KAI4011 4 megapixels interline CCD sensor.](Adapted from Kodak 2011)

### 2.2. Interline pixel architecture and readout procedure.

Figure 3 offers a simplified layout of a true “two phase buried channel” interline transfer CCD with a “pinned photodiode” pixel architecture. In this nomenclature, “pinned photodiode” means that the n-doped layer of the sensor is underneath a thin heavily p-doped layer that pins its potential (see the photodiode cross-sections in figure 3). This allows for a larger charge capacity and better blue response (details in Burkey et al. 1984). “Buried channel” indicates that the voltage gates (blue and orange in Fig. 3) of the vertical (parallel) register act over an n-doped buried channel instead of directly over the substrate (again the photodiode cross-sections in figure 3 show this detail). “Two phase” means that this register completes a charge shift after two timing clock steps following a procedure that is detailed further below in this subsection (Figure 4). This device (Janesick and Putman 2003, among others) is commonly used in high performance cameras oriented to PIV image acquisition. The layout of figure 3 shows the photo sensitive area (photodiode) where an incident photon produces an electron-hole pair in the \( p^+ - n \) junction by photo-electric effect. The generated electrons migrate away from the junction, towards the potential well in the n doped zone of the photodiode. Here the electrons are accumulated, or in other terms time-integrated, during the exposure time. The incident light is thus converted into electrical charges in a proportional way. If the illumination is too high or the exposure too long, the charge integration reaches the full well capacity, leading to saturation, which should be avoided. The Overflow Drain (OD) device, included to avoid spillage of saturated charges to neighbor CCD array elements, is also shown. A description of the key points in the readout procedure is given below.

The photodiode is insulated from the next pixel by a heavily doped \( p^+ \) potential barrier to avoid the contamination of neighbor pixels. Figure 3 depicts this barrier in dark gray for easy identification. Adjacent to the photodiode, the CCD register, or storage area, is separated in two distinct areas VCCD-Φ1 and VCCD-Φ2 (where V indicates vertical layout of these elements in the CCD), connected to different voltage gates: V1 and V2, respectively. Narrow regions of weakly negatively doped \( n^- \) material lie between the parallel transfer electrode strips. These regions in the
buried channel are known as channel stops and are in charge to repel the electrons generated in the CCD, thus preventing electrons from wandering to another adjacent pixel on the CCD as Figure 4 details.

The photodiode and the VCCD-\(\Phi 2\) are connected together through a transfer gate which opens at the end of the first exposure in order to allow the extremely fast interframe charge transfer into the CCD register for storage. Cross sections through the photodiode and the CCD registers show the built-in light shield on top of the CCD register region. A simplified micro lens arrangement is also shown. Lenses cross section remains constant along the vertical direction, accounting for the directional quantum efficiency differences exposed in Figure 2. Thanks to their vertical design, VCCD-\(\Phi 1\) and VCCD-\(\Phi 2\) areas constitute the CCD vertical shift registers and allow the vertical readout of the image sensor.

**Figure 3:** True two phase buried channel interline CCD pixel architecture showing overflow drain (OD) and micro lens arrangement (Metal and Oxide layers are not shown for simplicity).

(Adapted from Kodak 2011)

Summarizing the working procedure of these CCDs, during the first exposure, the light gathered by each single pixel is integrated as electrical charges in the potential well of the photodiode. In a second step, the accumulated charges carriers at each pixel are simultaneously (all at once) transferred to the adjacent CCD register through a transfer gate at the VCCD-\(\Phi 2\) (see Figure 3). Then the readout of the whole CCD registers starts. This instant corresponds to internal clock time \(t_1\), as shown in Figure 4. At clock time \(t_2\), the vertical (parallel) shift clock triggers the transfer of all the charge from VCCD-\(\Phi 2\) to the next VCCD-\(\Phi 1\), applying the voltages shown in Figure 4 for V1 and V2. Next, at clock time \(t_3\), V1 and V2 are set again to the voltages indicated at time \(t_1\). This figure also unveils how the “channel stops” prevent charges from being trapped or left behind.
At this point, all horizontal pixel lines have been shifted one row downward, so that the lower line enters into the serial shift register (Figure 1b), responsible for horizontal readout. The horizontal clock shifts all the pixels of that line, one at a time, in an analogue way to the vertical shift procedure, for the whole line. This is done by sequentially applying voltage H1 and H2 to the CCD register gates (Figure 5). Horizontal clocking is not a “true two phase” one, but rather a “pseudo two phase” clocking (Kodak, 2008 and Theuwissen 1995) in order to enable the charge transfer in both direction. This is very useful for large chips, as separating the horizontal readout in two halves almost reduce the line timing to the half, enhancing CCD readout time performance.

Figure 5 illustrates the charge transfer and readout in the serial (horizontal) CCD register. As the charge packets are transported through this register, the last charge packet of the line is dumped on the output sense node where the electrons are converted to a voltage that is easier to work with for the rest of the electronics, in short: “off-chip”.

Conventional techniques usually employ a floating diffusion region for this output sense node. Floating diffusion consists in a gate-free node (i.e. no potential is imposed to it), thus it is separated to the last H1 gate by the output gate (OG) in order to avoid parasitic potentials. The output gate (OG) is a constant, low voltage gate generating a potential barrier meant to keep the charge packet waiting while the floating node is getting reset. At that time the reset gate (R) is positively biased to clamp the floating diffusion region to the reset drain potential (RD). Then the charge packet is transferred to the floating diffusion through the output gate. The change in potential between RD and the charge packet is sensed as a voltage through a high gain capacitance connected to the floating region. It is worth to notice that in the sensing process (charge to voltage conversion) the charge packet remains less than half the horizontal clock period, thus being the smallest transfer time in the whole chip. In addition, the distance between the last H1 gate and the floating diffusion is larger than the gate to gate distance (Figure 5 is not to scale).
Once the whole line has been read out through the floating diffusion node, via the on-chip amplifier, a new parallel shift occurs, thus repeating the whole process again, until the entire CCD array is read out.

2.3. Readout smearing.

When transferring electrical charges through the serial or parallel registers, it is essential that the whole of the charge packet moves to the next electrode; otherwise the image integrity would be lost. Unfortunately, the charge transfer is not perfect, and some charges may leak out of the potential wells by diffusion (among other complex phenomena out of the scope of this study), generating some smearing of the image acquired by the CCD. For PIV applications, the images usually consist in a dark background with bright dots corresponding to particle scattering. Smearing of these images along a privileged orientation generates undesirable error in the location of the particles. Departure from perfect charge transfer efficiency (\(\text{CTE}\)), due to small traps in the silicon structure, may generate the mentioned smearing. The traps extract a small amount of charge and release it at a later time, thus transferring the charge into the following charge packet. Thus, the charge transfer efficiency (\(\text{CTE}\)) is dependent on clock frequency. It is generally 99.9999 \% (charge transfer inefficiency is \(\text{CTI} = 1 - \text{CTE} \sim 10^{-6}\)) for vertical shift registers, but somewhat less for horizontal shifts (\(\text{CTI} \sim 10^{-5}\)) because of the necessary higher operating rate (a whole line has to be read out until the next vertical shift can occur, thus limiting the whole process speed). Finally, \(\text{CTI}\) at the floating diffusion node is suspected to be the largest one, since charge packets are driven here for the smallest amount of time in all the readout circuit.

Smearing that can be explained by \(\text{CTI}\) has been found in PIV images in the past, its tendency to deform particle images generates biases on the particle image location as large as 0.2 pixels (Nogueira et al. 2009). Fortunately, for PIV applications, both the first and second exposures are smeared in the same direction reducing the error induced on velocity measurements. However charge transfer efficiency is not identical for the first and for the second image capture readout, leading to a residual differential bias in the digitally registered particle displacement. This bias has already been observed and its magnitude evaluated for particular cases by Nogueira et al. (2009) and Legrand et al. (2010 and 2011).

There are other error sources within the readout process that have been studied in this work. The study indicates that they do not have a predominant role in contemporary PIV errors. Nevertheless, they are briefly commented below. The first one is related to the fact that some interline architectures using photodiodes could suffer from image lag as a consequence of a non perfect charge transfer from the photodiode to the CCD storage area, i.e. some charges keep trapped in the photodiode. This could yield ghost images in the second exposure. Fortunately this last issue is almost inappreciable in most recent CCDs, offering image lags of the order of 10 e⁻ in respect to
full well capacity (typically 40,000 e\(^{-}\)). Unlike photographic film, the CCD device can saturate when over exposed. The charges (e\(^{-}\)) are generated in proportion to the collected light, i.e. exposure time. If the potential well of the photodiode does not have the capacity to hold the charge created by the photoelectric effect, it will "bloom" or spill into the adjacent active areas corrupting the image information. Almost all recent interline transfer CCDs incorporate anti-blooming devices in order to alleviate this problem. It generally consists on Vertical and/or Horizontal Overflow Drain devices respectively. As an example, an overflow drain (OD for short) is depicted in figure 3. It is separated from the photodiode potential well by a potential barrier. The capacity of the OD well is larger than the photodiode one. The barrier between photodiode and OD is designed to a level that it is lower than the barriers between pixels, so that when the collected charge exceeds this level it spills vertically through the silicon and is swept away through the n substrate. Although these devices allow for anti-blooming and thus contamination of other pixels, it does not prevent saturation to occur, which would obviously bias the PIV correlation (Lecuona, 2004). In any case, over-exposure and saturation should be avoided.

Even below the saturation exposure (e.g. 60 %), some light leakage to the adjacent vertical CCD register can occur while the array is being read out. This leakage can be produced by different mechanisms: direct incident light on the CCD register, refraction by concave lenses redirecting light on the CCD register instead of the photodiode, and waveguide effect of multiple reflections and refractions through the lens and silicon layers (Teranishi et al. 1987). However, these effects are largely eliminated in conventional interline devices (typically bellow 0.01 % as commented in Janesick and Putman (2003)).

3. Displacement bias in PIV applications.

Although different mechanisms are involved in image smearing artifact, (i.e. CTI, image lag, blooming and light leakage), the major effect is attributed in this paper to the CTI, especially at the floating diffusion node. This hypothesis relays on the observation that the amount of smearing does not depend on the location of the particle image within the CCD. As a consequence, the CTI at intermediate transfers does not seem to be relevant compared with the one at this node. Upon this assumption, the authors elaborate a simple model to predict the amount of smear produced during image frame readout.

Other scenarios may be present in special conditions. For space mission cameras where CCDs are more exposed to radiation, as reported by Whitmore et al. (1999) and Waczynski et al. (2001), energetic particles such as the ones coming from cosmic rays can generate additional electron traps in the silicon structure. This increases the CTI at intermediate transfers. Also, other sources of smearing like CCD image binning, that has been reported to strongly bias particle centroids position (e.g. Kholnmatov et al. 2010), are left out of the scope of this work.

3.1. Readout error modeling.

Charge transfer efficiency CTE is generally defined as the amount of transferred charges \( I \) in a single register shift in respect to the accumulated charges \( I_0 \) before the shift. CTI is then the complementary part, simply defined as \( CTI = 1 - CTE \). Waczynski et al. (2001) reported that CTI was sensitive to the integrated charge packet \( I_0 \). Based on the results from that work, CTI has been modeled as shown in Eq. (1a).

\[
CTI = 1 - \frac{I}{I_0} = L \cdot I_0^{-\alpha} \quad (1a)
\]
\[
CTI = (I_{ref}/I_0)^\alpha \quad (1b)
\]
Where $L$ is a charge loss coefficient and $a$ corresponds to a positive value. To make emphasis on the physical meaning of this equation, this paper uses the normalization given in Eq. 1b rather than the nomenclature of Eq. 1a. Clearly, $I_{ref} = L^{1/a}$. 

Eq. (1) shows that more illumination (larger value of $l_0$) implies a smaller charge transfer inefficiency. The results of Waczyński et al. (2001) show that $a \sim 2/3$ for the tested interline-transfer CCDs. This reference also tested deteriorated CCDs irradiated by high energy proton beams (simulating space mission camera irradiation) at several irradiation levels. The parameter $a$ remained almost constant ($a \sim 0.65 \pm 15\%$), whereas $L$ was growing for more deteriorated CCDs. Eq. (1) also indicates that CTI would be different for the first and second exposure images if the collected light $l_0$ were different.

As CTI is expected to be larger at the floating diffusion gate, charge transfer process is simulated at that point. It is assumed that the trapped charges at floating diffusion are left behind to form part of the next pixel readout. CTI terms are neglected, leading to Eq. (2) for the charge $i(i)$ sensed for pixel $i$. It depends on the accumulated charge $l_0(i)$ at this pixel location, and on the released charges coming from the previously readout pixel $(i - 1)$.

$$I(i) = l_0(i) \cdot (1 - CTI(i)) + l_0(i - 1) \cdot CTI(i - 1)$$ (2)

In PIV applications, the CCD camera operates in a double frame mode, registering seeding particle image positions at two different times, separated by an interval $\Delta t$. With this information, the displacement of particle clusters is estimated by local cross-correlations (Raffel et al. 1998) between both frames. If $l_0$ were the same for the particle image at both first and second frame exposure, the images would be smeared the same amount and the effect of this read out process deficiency on the measured displacement would be minimized (except for a small sub-pixel interpolation error due to the correlation peak shape, but this can be assimilated to a peak locking error (Nogueira et al. 2001 and 2009, and Legrand et al. 2011)).

Unfortunately, in PIV applications, light sources are difficult to operate with exactly the same amount of light each shot. In general two short laser light pulses (separated by $\Delta t$) are needed to achieve enough illumination for both exposures, since seeding particles use to be very small and their scattering is weak in respect to incident light. In order to achieve two pulses in the very brief $\Delta t$ time interval, two laser heads are typically required. Besides the difficulty of tuning both lasers to emit the same amount of energy, the Gaussian profiles of the two laser beams are not identical and may generate some local illumination differences across the region under study. In addition, displacement of particles within the Gaussian profile between both exposures would generate illumination differences even in a perfectly laser sheet tuned PIV experiment (Nobach and Bodenschutz 2009 and Nobach 2011). Thus the relative illumination difference $\Delta l_0/l_0$ seems to be a key parameter to take into account when studying the displacement bias errors.

To evaluate the effect of this source of error on a PIV measurement, 1-D Gaussian particle images of $d_p = 2.2 \text{ e}^{-2}$ diameter are used as a first approximation. A CCD fill factor $FF = 1$ is considered for simplicity. The first exposure particle image has a maximum intensity $l_{max,1} = l_{max} + \Delta l_{max}/2$, while the second one has $l_{max,2} = l_{max} - \Delta l_{max}/2$. The illumination difference is thus defined as $\Delta l_{max} = l_{max,1} - l_{max,2}$, whereas $l_{max}$ is the average maximum particle intensity $l_{max} = (l_{max,1} + l_{max,2})/2$. As first particle image location relative to the entire pixel plays an important role in PIV errors (Legrand et al. 2011), particle images have been located from -0.5 to +0.5 pixels respect to the pixel center. In addition, real PIV images generally present a non-zero background, mostly accounting for background illumination/laser reflections and dark current effect. To reproduce this issue, a background level $l_{background} = 10$ counts has been added to all the pixels of the generated particle images. Then, the generated 1-D particle images are artificially
smeared following Eq. (2), and this is performed for both exposures. Finally, the smeared particle images are cross-correlated, using a 3-points Gaussian sub-pixel peak fitting algorithm to find the correlation maximum and from this the estimated displacement is calculated. The process is repeated for 51 different first particle image locations in the CCD (ranging from -0.5 to +0.5 pixel), and then the average is computed. Then the difference between this value and the real displacement is obtained giving the error estimation. These calculations have been performed for different particle displacement ranging from 0 to 1 pixel. The results include the error coming from this modeling of the read-out error coupled with the unavoidable peak-locking phenomenon emerging from the chosen peak fitting function and the lack of resolution of the CCD sensor to describe small particle (Nogueira et al. 2009 Legrand et al. 2011). In order to tell apart the contribution corresponding to the CCD read-out error, the mentioned calculations were compared with those obtained from the same procedure but excluding the simulation of the readout error, described in Eq. 2. The results indicate that the bias error coming from the CCD read-out for a particle displacement of 0 pixels is a good reference for any other displacement. The magnitude of this error, namely the displacement bias error, \( B \), is shown in Figure 6 for the mentioned displacement of 0 pixels. For the rest of possibilities tested (i.e. displacements ranging from 0 to 1 pixel), the curves in figure 6a may displace \( \pm 0.01 \) pixels up or down, but the slope practically does not change.

Figure 6a depicts the results of this error evaluation for different image illumination intensities \( I_{\text{max}}/I_{\text{ref}} \) and for different relative illumination differences \( \Delta I_{\text{max}}/I_{\text{max}} \) between the two exposures. For a constant \( I_{\text{max}}/I_{\text{ref}} \), the displacement bias \( B \) is almost proportional to the relative illumination difference \( \Delta I_{\text{max}}/I_{\text{max}} \).

![Figure 6: Readout displacement bias as a function of relative difference illumination between two exposures, for gaussian profile particles (\( FF = 1 \)) and for different maximum intensities \( I_{\text{max}} \). \( I_{\text{ref}} = 18.7 \) (L = 5) ; \( a = 0.55 \) a: Case for real displacement = 0 and particle diameter 2.2 pixels. b: For different particle image diameter \( d_p \) (ranging from 1.2 to 4.4 pixels).](image)

In Figure 6a, the average slope of the curves depends on the maximum normalized collected light \( I_{\text{max}}/I_{\text{ref}} \), being proportional to \( (I_{\text{ref}}^{1/2}/I_{\text{max}}^{3/2}) \). A third parameter to take into account is the particle image diameter \( d_p \). Expanding the previous evaluation to particle diameters from 1.2 to 4.4 pixels, reveals that the bias is proportional to \( d_p^{-4/5} \). These results can be combined to obtain the adimensional plot of Figure 6b and the expression proposed in Eq. (3).

\[
\frac{B}{\text{pix}} \sim C \cdot \left(\frac{\Delta I_{\text{max}}}{I_{\text{max}}}\right) \cdot \left(\frac{I_{\text{ref}}}{I_{\text{max}}}\right)^{1/2} \cdot \left(\frac{d_p}{\text{pix}}\right)^{-4/5}
\]  

(3)
In this expression, “pix” indicates the pixel side length. The results from Figure 6 allow for a displacement bias prediction in PIV measurements, but the constants $I_{\text{ref}}$ and $C$ have to be fitted for each particular PIV camera in order to obtain reliable predictions. This is the objective of the next subsection.

3.2. Displacement bias in real PIV CCD cameras.

In order to validate the previous error modeling and expression (3), an experimental test procedure that uses real images has been designed. The camera used for this validation is the “MegaPlus” model ES 4.0/E of 4 megapixels, 12 bit dynamic range, incorporating the Kodak KAI-4000M CCD sensor, provided with micro lenses. The general architecture and clock timing corresponds to the description in Section 2. In addition, the parallel shift is divided in two halves of 2048×1024 pixels: the top region performs upward vertical shifts of 1024 rows, and the bottom half does it downwards. Serial shifts at both ends of the vertical shift registers are also divided in two parts in order to diminish the readout time and thus enhance the frame rate. This is performed using the pseudo two-phase timing, already commented in Section 2. A sketch of the general KAI-4000M layout is shown in Figure 7. Such a readout arrangement results in four on-chip amplifiers and the resulting four video outputs, one for each quadrant Q (numbered in Figure 7).

![Figure 7: Kodak KAI-4000M image sensor layout.](Reproduced from Kodak KAI-4000M performance specifications from Kodak 1999)

In addition to the relative illumination difference between two exposures, the experimental procedure includes the evaluation of temperature and ambient humidity possible effects. These could be relevant variables as reported by Waczynski et al. 2001 and suggested by Nogueira et al. 2009, and sometimes harsh experimental environments determine the working conditions of the cameras in industrial wind tunnels or open facilities.

In general the CCD temperature may be different from the ambient one. CCD chips are cooled by Peltier cells in order to enhance their sensitivity (quantum efficiency) and reduce thermal noise (dark current). However, most of these Peltier cells are operating against ambient temperature, without thermal control, achieving basically an almost constant temperature drop $\Delta T$ respect to the ambient. This is the case of the tested camera.

The experimental setup is described in Figure 8. An environmental chamber, controlled by a PC, maintains a constant temperature (within $\pm 1$ °C) and relative humidity (within $\pm 5$ %). The PIV
camera is located inside this chamber, and it is synchronized with the PIV laser operation thanks to another PC. The environmental chamber viewing window enables the camera to acquire images of the illuminated seeding particles \(d_p = 10 \mu m\) suspended in quiescent water. With the experimental setup magnification and diffraction limited spot, the diameter of the particle image has been estimated to be \(d_{pi} \sim 16 \mu m\), corresponding to \(\sim 2.2\) pixels.

Figure 8: Experimental setup.

The time interval between the two laser pulses \(\Delta t\) is set to assure that the particle displacements to measure are smaller than \(\sim 10^{-3}\) pixel. This way, any displacement bias \(B\) larger than this value will be detected by the PIV cross-correlation.

The PIV measurements have been repeated for two MegaPlus CCD cameras, for different temperatures \(\{5, 10, 15, 20, 25\} \degree C\), different relative humidities \(\{40, 60, 80\} \%\), and different laser energies \(\{50, 70, 90\} \%\) of maximum nominal shot energy \(380\) mJ at 532 nm). For each measurement condition, a series of 200 image couples were acquired in order to achieve reliable average statistics. Once the images were acquired, the maximum intensities for each image couple \(I_{!}I_{!}\) and \(I_{!}I_{!}\) were computed. The displacement field (bias \(B\)) was computed through PIV cross-correlation, using \(64 \times 64\) pixels\(^2\) interrogation windows, with 50\% overlap. The ensemble average vector field displacement was finally calculated for each PIV grid location \((64 \times 64)\) for each 200 image couples series.

In these tests, temperature and relative humidity effects are negligible when compared with the effect of \(\Delta I_{max}/I_{max}\), and \(I_{max}/I_{ref}\). Variations due to temperature and humidity are smaller than \(\sim 0.015\) pixels, so their effect has been neglected in the rest of the paper. Nevertheless, it is worth to mention that at 5 \degree C, the camera has shown many operation problems, in particular when operating at high relative humidity. These data points are not shown in Figure 9, as PIV correlation only yielded spurious vector calculations due to the high level of image deterioration.

Figure 9 shows the results obtained for the first camera at each PIV grid location of the first CCD quadrant (Q1 in Figure 7) for the 36 valid series of 200 image couples. As data present some dispersion, a moving average filter (64 points) has been included in the plot to highlight the linear data tendency. In particular, Figure 9a shows the result of the model discussed in Section 3.1 for horizontal (serial) shift, with \(I_{ref} = 18.7\) (i.e. a charge loss factor \(L = 5\)), and an exponent \(a = 0.55\). An excellent agreement between modeling and experimental results can be appreciated, validating the model described in subsection 3.1. Figure 9b shows the displacement bias, but this time in the vertical (parallel) direction. As commented in the previous Section, it is much smaller than the serial one (by a factor \(\sim 30\)).
Figure 9: Measured displacement bias $B$ for each PIV grid location in quadrant Q1. The rms value of the dispersion around the moving average is $\sim 0.015$ pixels for image a and $\sim 0.01$ for image b.

Figure 10 depicts the results of the horizontal (serial) displacement bias for both cameras. Here, each quadrant data have been averaged in order to present a single point for each measurement condition. The results are coherent with the one presented in the previous figure, but they unveil the behavior of each one of the four quadrants for each tested camera. Quadrants Q1 and Q4 exhibit similar positive displacement biases, which is coherent with the fact their serial shifts are in the same direction. In opposition, quadrants Q2 and Q3 show similar negative displacement biases, in opposite direction to Q1 and Q4, in agreement with the general layout of the CCD sensor readout presented in Figure 7.

Figure 10: Average measured displacement bias per quadrant for both MegaPlus cameras $\Delta I_{\text{max}}$ and $I_{\text{max}}$ both in grey levels for 12 bit cameras.
The magnitude of the bias is very similar for both camera 1 and camera 2, as well as for left or right quadrants. Typical values of $\Delta I_{\text{max}} \cdot I_{\text{max}}^{-1.5} \approx 0.02$, yield horizontal displacement bias errors $B$ of the order of $\sim 0.05$ pixels, which are not negligible for PIV applications.

For different camera models, the readout bias may be different but, with similar architecture, would follow the same principles, thus allowing for calibrating cameras error. In particular, once the procedure in this section has validated Eq. (3) and it has been established that temperature and humidity effects are secondary, the values of the parameters $I_{\text{ref}}$ and “a” can be easily assessed for a particular camera model. To do this, the $\Delta t$ can be reduced so that the real displacements are negligible, a double frame acquisition can provide the average value of $B$ for the camera (if it has a single readout structure) or for each quadrant (if it is a multi-quadrant one). For this acquisition, an average $\Delta I_{\text{max}}$ and $I_{\text{max}}$ can be obtained by checking the grey levels at the center of the particles (local maxima) at each frame. A few of this kind of acquisitions changing laser power between first and second images can be implemented in Eq. (3) to provide the researcher with the values of $I_{\text{ref}}$ and “a” for the cameras. This knowledge allows for an improved design of the experimental PIV acquisition procedure: i.e. if a multiple $\Delta t$ strategy is proposed for bias correction in this particular application (Legrand et al. 2011), the amount of error corresponding to the CCD readout can be established “a priori”.

In addition, this camera calibration is relevant as far as it allows to establish the values of $\Delta I_{\text{max}}$ and $I_{\text{max}}$ for which the readout error bias is acceptable in a particular application.

Increasing the detail of the assessment in respect to the average readout values given in Figure 10, Figure 11 presents the average measured characteristics at each PIV grid node along the whole view under test, for a series of 200 images ($T = 20^\circ$C, relative humidity 60%, laser intensity: 70% of maximum 400mJ). This figure depicts the spatial variation of the local $I_{\text{max}}$ (figure 11a), the local $\Delta I_{\text{max}}/I_{\text{max}}$ (figure 11b), the local bias $B$ (figure 11c), and the local difference between the prediction from Eq. (3) and the real bias, $B$, across the CCD chip for a certain PIV setup.

The $I_{\text{max}}$ light intensity variations across the CCD chip in Figure 11a correspond to a laser sheet light that is coming from right to left. Across the horizontal direction, the effect of the combination of the light extinction by the seeding particles and the divergence of the laser sheet is clearly appreciable. Along the vertical direction, the Gaussian shape intensity profiles of the laser sheets are noticeable. Although it is somehow irregular the difference between illumination pulses in Figure 11b is coherent with two Gaussian profiles overlapping but with non coincident axes, indicating a slight misalignment of the laser beams centers, magnified by the cylindrical lens that generate the laser sheets. Even though both laser heads are tuned to emit the same amount of energy, the mentioned misalignment generates differences on the local relative illumination in the region of interest for the two different acquisition times separated by $\Delta t$.

Figure 11c shows that the horizontal displacement bias may strongly vary across each quadrant, revealing a bias magnitude that can be locally much higher than the average given in Figure 10. Left quadrants (Q2 and Q3) and right quadrants (Q1 and Q4) are easily distinguishable with their opposite horizontal bias, as commented in the previous paragraphs. Finally, the difference between the predictions coming from Eq. (3) and the real bias, $B$, plotted in Figure 11d, shows that this magnitude can be small enough to use the predictions for measurement corrections.
Figure 3: Local characteristics of a 200 images series.
(a) Local $I_{\text{max}}$ [grey levels]; (b) Local $\Delta I_{\text{max}}/I_{\text{max}}$ [-]; (c) $B$ [pixels];
(d) Local difference between the prediction from Eq. (3) and the real value of $B$ [pixels].

Results from figures 9 to 11 indicate that $\Delta I_{\text{max}}$ can generate significant error coming from the readout procedure. It follows that laser illumination quality is of crucial importance for PIV applications. State-of-the-art lasers do not guarantee a perfect matching between the beam profiles coming from both laser heads and this makes almost unavoidable to have local laser illumination differences in a PIV experiment. Even if this problem is overcome, it is impossible to generate perfect top-hat profiles for the laser sheet. In consequence, the movement of the particles within the laser sheet also generates illumination differences as commented in subsection 3.1. In conclusion, readout displacement bias should virtually occur in any PIV application.

In addition to that, the second CCD exposure is usually much longer than the first one, and may receive more stray background light than the first one. The associated illumination differences would generate bias errors in the read-out procedure. The conclusion leads to highlight the importance of avoiding spurious sources of light and the use of interferometric filters as means to reduce measurement errors.

Nogueira et al. (2009) as well as Legrand et al. (2011) already discussed the feasibility of a multiple $\Delta t$ strategy designed to evaluate the bias error, including the possibility of correcting it under certain circumstances. However, the present work is shedding light on the physical phenomenon of particle image smearing, and predicts the magnitude and whether or not some readout displacement bias would be present in the measurements.

PIV cameras are expensive devices and a particular laboratory does not usually have many different models, this study focuses on the characterization of two cameras of the same model, but it
indicates the procedure for other PIV researchers to perform the same kind of characterization for different PIV CCD cameras among the many types available. Results from different laboratories and different cameras would constitute relevant information in the future, allowing for a better design of the PIV acquisition procedure.

4. Conclusions

Previous studies on PIV applications have shown that state of the art CCD cameras induce a bias in the measured velocity. This work studies the architecture and the readout procedure of this kind of cameras, widely used in PIV with the aim at explaining the source of this bias. A predictive model based on considering that the charge transfer inefficiencies during the readout are especially relevant at the floating diffusion gate, which converts the accumulated charges into a voltage. This model is coherent with the bias errors observed in PIV measurements, related to smear of the particle images along the serial charge transfer direction. The expression obtained for the bias error, $B$, is:

$$ B_{\text{pix}} \sim C \cdot \left( \frac{\Delta I_{\text{max}}}{I_{\text{max}}} \right) \cdot \left( \frac{I_{\text{ref}}}{I_{\text{max}}} \right)^{1/2} \cdot \left( \frac{d_p}{\text{pix}} \right)^{-4/5} $$

This expression indicates that only two camera parameters ($I_{\text{ref}}$ and $a$) are needed to evaluate the bias produced by illumination differences between two PIV frames.

The expression has been validated for two 12 bit-depth interline CCD cameras (Kodak KAI-4000M CCD sensor, 4 megapixels provided with micro lenses). Simple procedures to obtain the mentioned camera parameters are indicated providing a characterization of these cameras in respect to this error in which $I_{\text{ref}} = 18.7; a = 0.55$.

Tests indicate that the influence of the humidity and temperature of the working environment of the cameras on the error (smaller than $\sim 0.015$ pixels) is secondary in respect to the effect of the illumination differences. For common values of this parameters ($\Delta I_{\text{max}} / I_{\text{max}} \sim 0.2$), the displacement bias has been shown to be significant with this camera model (in the order of $\sim 0.05$ pixels).

As illumination differences between two laser pulses are almost unavoidable in a contemporary PIV application, the CCD readout displacement bias will occur in almost any experiment. Results from different laboratories and different cameras, providing further validation and the values of $I_{\text{ref}}$ and $a$ for each model, would constitute relevant information, allowing to optimize the design of the PIV acquisition procedure for a certain set-up.

Acknowledgements

This work has been partially funded by the Spanish Research Agency grant ENE2006-13617 “TERMOPIV: Combustión y transferencia de calor analizadas con PIV avanzado”; the regional grant CCG08-UC3M/ENE-4432 “PIVEROT: Mejora en la medida PIV de campos fluidos de quemadores LSB por reducción de errores producidos por efectos termopsicrométricos en los sensores CCD”; and the Madrid Community grant CCG10-UC3M/ENE-5126 “ES-COMB: Estructuras coherentes en quemadores de combustión limpia”.

We would like also to express a special acknowledgement to the laboratory technicians Mr. Manuel Santos and Mr. Carlos Cobos, for their help in the experimental setup elaboration.
References


