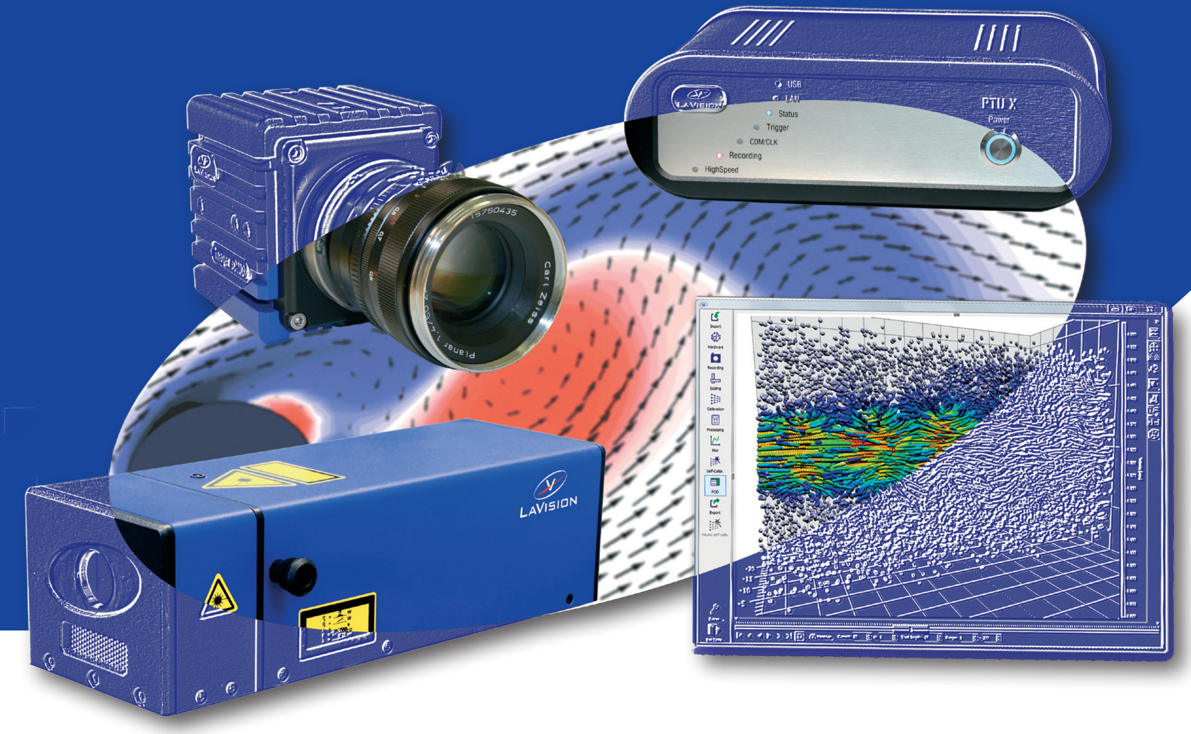
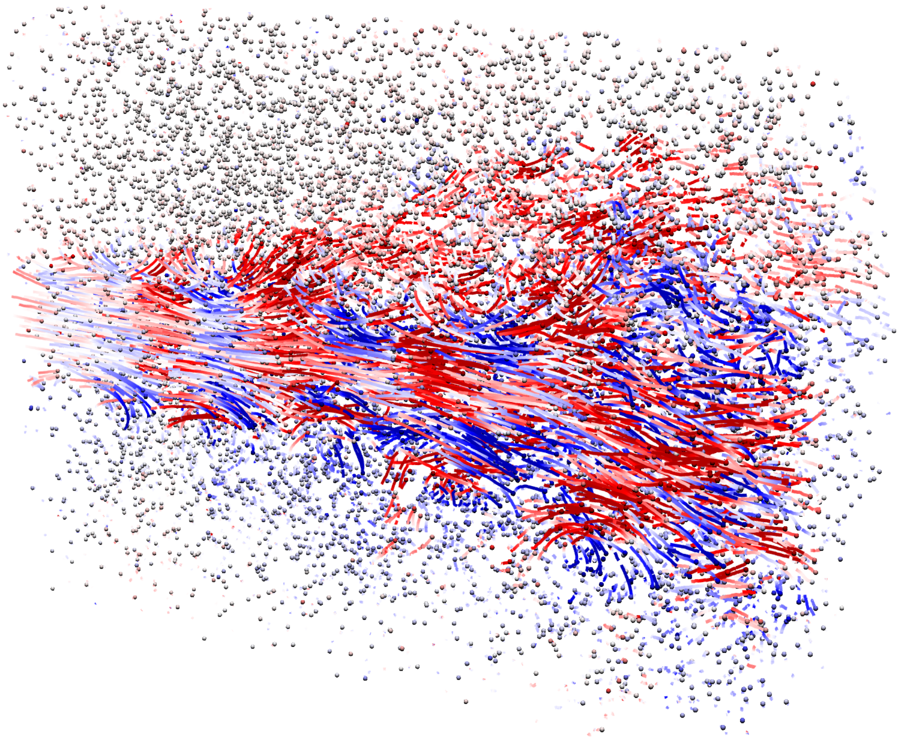


Product Manual

FlowMaster Shake-the-Box (4D PTV)

Item Number(s): 1105075



LaVision
FOCUS ON IMAGING

Product Manual for **DaVis 10.2**

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1 Safety Precautions

Before working with your **LaVision** system, we recommend to read the following safety precautions. Observing these instructions helps to avoid danger, to reduce repair costs and downtimes, and to increase the reliability and life of your **LaVision** system.

1.1 Laser Safety

If a laser[1] is integrated in your system, it is important that every person working with it has fully read and understood these safety precautions **and** the laser manual of the specific laser/LED.

Lasers included in **LaVision** systems may belong to Class 4 laser devices, which are capable of emitting levels of both visible and invisible radiation that can cause damage to the eyes and skin. It is absolutely necessary that protective eyewear with a sufficiently high optical density be worn at any time when operating the laser. The goggles must protect against all wavelengths that can be emitted, including harmonics. See your laser´s manual for further details.

Class 4 laser beams are by definition a safety and fire hazard. The use of controls, adjustments or performance of procedures other than those specified in the **LaVision** manual and the laser manual may result in hazardous radiation exposure.

AVOID EYE AND SKIN EXPOSURE TO DIRECT OR SCATTERED RADIATION. FOLLOW THE INSTRUCTIONS YOU CAN FIND IN THE CORRESPONDING LASER MANUAL FOR PROPER INSTALLATION AND SAFE OPERATION. USE PROTECTIVE EYEWEAR ALL THE TIME WHEN OPERATING THE LASER.

[1] In the following, ‘laser’ means any kind of laser, in particular Nd:YAG and dye lasers as well as Optical Parametric Oscillators at any wavelength and output energy. Also for high-power LEDs precautions should be taken.

Important instructions for safe laser handling:

- Before operating the laser, contact your laser safety officer.
- Read and understand the instruction manual of the particular type of laser. Take special care with respect to laser emission, high voltage and hazardous gases if in use.
- Declare a controlled access area for laser operation. Limit access to trained people. Never operate the laser in a room where laser light can escape through windows or doors. If possible, cover beam paths to avoid obstacles getting into the beam.
- Provide adequate and proper laser safety goggles to **all** persons present who may be exposed to laser light. The selection of the goggles depends on the energy and the wavelength of the laser beam as well as on the operation conditions. Check the laser´s manual for a detailed description.
- While working with lasers do not wear reflective jewelry like watches and rings, as these might cause accidental hazardous reflections.
- Avoid looking at the output beam, even diffuse reflections can be dangerous.
- Operate the laser at the lowest beam intensity possible.
- Avoid blocking the output beam or reflections with any part of the body. Use beam dumps to avoid reflections from the target.
- Wear clothes and gloves which cover arms and hands to avoid skin damage when handling in the optical path. Especially UV radiation can cause skin cancer.

1.2 Seizures Warning

WARNING: HEALTH HAZARD! STROBE LIGHTING CAN TRIGGER SEIZURES! Some people (about 1 in 4000) may have seizures or blackouts triggered by flashing lights or patterns. This may occur when viewing stroboscopic lights or objects illuminated by such devices, even if a seizure has never been previously experienced. Anyone who has had a seizure, loss of awareness, or other symptoms linked to an epileptic condition should consult a doctor before operating systems which include flashing lights, strobe lights, or a pulsed or modulated laser.

Stop operating the system immediately and consult a doctor if you have one of the following symptoms:

- convulsions, eye or muscle twitching, loss of awareness, altered vision, involuntary movements, disorientation.

To reduce the likelihood of a seizure when operating a system:

- Do not look directly at flashing light sources or on illuminated objects, e.g. into a strobe light or a flashing LED panel.
- Operate the system in a well-lit room.
- Take frequent breaks in normally illuminated areas.

1.3 Camera / Image Intensifier Safety

The camera integrated in your system is based on a CCD (Charge Coupled Device) or CMOS (Complementary Metal-Oxide Semiconductor) sensor with high resolution and high sensitivity. Optionally your system is equipped with a built-in or external image intensifier.

A LASER BEAM FOCUSED ON THE CHIP OR INTENSIFIER, EITHER DIRECTLY OR BY REFLECTION, CAN CAUSE PERMANENT DAMAGE TO THE CHIP OR INTENSIFIER. ANY LASER POWERFUL ENOUGH TO PRODUCE LOCALIZED HEATING AT THE SURFACE OF THE CHIP OR INTENSIFIER WILL CAUSE DAMAGE EVEN WHEN THE CAMERA OR INTENSIFIER POWER IS OFF. A CHIP OR INTENSIFIER DAMAGED BY LASER LIGHT IS NOT COVERED BY ITS WARRANTY.

Important instructions for safe camera handling:

- Fully read and understand the instruction manual of the specific type of camera.
- Put the protection cap on the camera lens whenever you do not take images, especially when the laser beam is adjusted. Switching off the camera / image intensifier does not protect the chip from damage by laser light.
- Use full resolution of the sensor and always read out the complete chip to have control of the intensity on all areas of the sensor.

- Make sure that no parts of the image are saturated, i.e. the intensity is below maximum gray level ($<$ 4095 counts for a 12-bit camera, $<$ 65535 counts for a 16 bit camera, ...).
- Start measurements with the lowest laser power and a small aperture of the camera lens.
- Increase laser power step by step and check the intensity on the corresponding image. Make sure that the sensor does not run into saturation.
- Bright parts in the experiment, like reflections on walls or big particles, will limit the maximum laser power. Modify the optical arrangement of your setup in order to remove bright reflections from the camera image.

2 Introduction

In this manual mainly the specific features of Shake-the-Box are illustrated. Therefore, this manual relies on several other **DaVis** manuals:

- **DaVis** (#1003001)
- **Programmable Timing Unit** (**PTU 9** #1004072) or (**PTU X** #1008606)
- **HighSpeed Manual** (#1007817)
- Additional manuals for specific **cameras** and **laser**
- **Volume Optics** (#1004048) or **Compact Volume Optics** (#1008439)
- **Laser Guiding Arm** (#1004089) (optional)

Please make sure to have these manuals at hand.

2.1 What actually is Shake-the-Box?

In short, Shake-the-Box is a special method to perform time resolved, three dimensional **particle tracking** (time resolved 3D-PTV or 4D-PTV). The name Shake-the-Box refers to an important step during the particle tracking procedure: predicted particle positions are optimized by 'shaking' the particles in 3D space. Please refer to Schanz et al.[1] for a full description of the method.

[1] Daniel Schanz, Sebastian Gesemann, Andreas Schröder, Shake-The-Box: Lagrangian particle tracking at high particle image densities, Exp Fluids (2016) 57:70

3 Sequence of Operation

To perform a Shake-the-Box experiment and analysis, several steps have to be performed in a certain order. Based on the experience with many experimental setups, **the following approach is highly recommended**:

1. setup cameras and illumination (3.2)
2. adjust area of interest (and Scheimpflug adapters if necessary) (3.3)
3. refocus on particles (3.4)
4. do perspective calibration (3.5)
5. record particle images (3.7)
6. do image preprocessing (4.1)
7. do volume self-calibration (4.2)
8. calculate optical transfer function (OTF) (3.10), (4.2)
9. calculate particle tracks using Shake-the-Box (3.11), (4.3)
10. calculate velocity or acceleration on a regular grid (4.4.1), (4.4.2)

The steps **1 to 5** in the sequence of operations need to be done **during** a Shake-the-Box **experiment**. The further analysis steps **6 to 10** do not require experimental equipment and can be done when the **experiment is finished**. Still, it is recommendable to do a first test processing on the first recordings to make sure that the optimal experimental settings are used.

The steps required during the experiment are covered in more detail in this chapter, whereas the remaining steps are only mentioned for completeness. Those are explained in detail in chapter 4.

3.1 Organization of recorded sequences in DaVis

Fig. 3.1 and Fig. 3.2 illustrate how **DaVis** represents recordings. These are two standard-cases using four cameras. In Fig. 3.1 1 is shown, how a single-frame, time-resolved recording is stored. Each camera records a single frame which is illuminated once, i.e. each image refers to a single instant in time. With four single-frame cameras, this means that each image consists of four frames, each for one camera. Fig. 3.1 2 shows how each image and frame can be selected with the frame and image slider shown below each recording in the display. The lower slider refers to the recorded image, here in total 9890 images had been recorded. The upper slider refers to the frame number *F* from 0 to 3 referring to the four cameras. This is the standard recording scheme for time-resolved Shake-the-Box, which is sensible if the flow features of interest are resolvable with the recording frequency, i.e. with the minimum frequency of cameras and light source.

Often, flows cannot be time-resolved. Here, double-frame recordings are the method of choice, where two frames are recorded with a short inter-frame time followed by a large time interval before the next double-frame image is recorded. Each frame is illuminated once by a light pulse. The two light pulses are separated by the time interval *dt*. The background light should be sufficiently weak or reduced by appropriate camera filters to make sure that the cameras only acquire the light of the two pulses scattered by the particles. This means, that the decisive time for resolving flow structures in this measurement is *dt*, not the interframe time nor the exposure time of the cameras. It has to be kept in mind that *dt* cannot be shorter than the interframe time. Therefore, **LaVision** offers dedicated PIV cameras with short interframe times for double-frame recording. For minimal *dt* also double-pulse In double-frame image, usually the exposure time of frame 2 is fixed and longer that the exposure time of frame 1. Therefore, the second frame is usually much more sensitive to background light. The temporal position and length of the light pulse defines the measurement.

Fig. 3.2 1 illustrates the image structure in **DaVis**. Four cameras with double-frame capability are used, i.e. each image consists of eight frames, whereas the order is: frame 0 and frame 1 is the double-frame image recorded by camera 1, frames 2 and 3 are recorded by camera 2, etc. This means frames 0, 2, 4, 6 are recorded at the same instant in time and also all odd frame numbers refer to the same recording time, respectively. Fig. 3.2 2 shows how images and frames can be selected in the **DaVis** display with the top slider referring to frames $F = 0...8$ and the bottom slider to the image number.

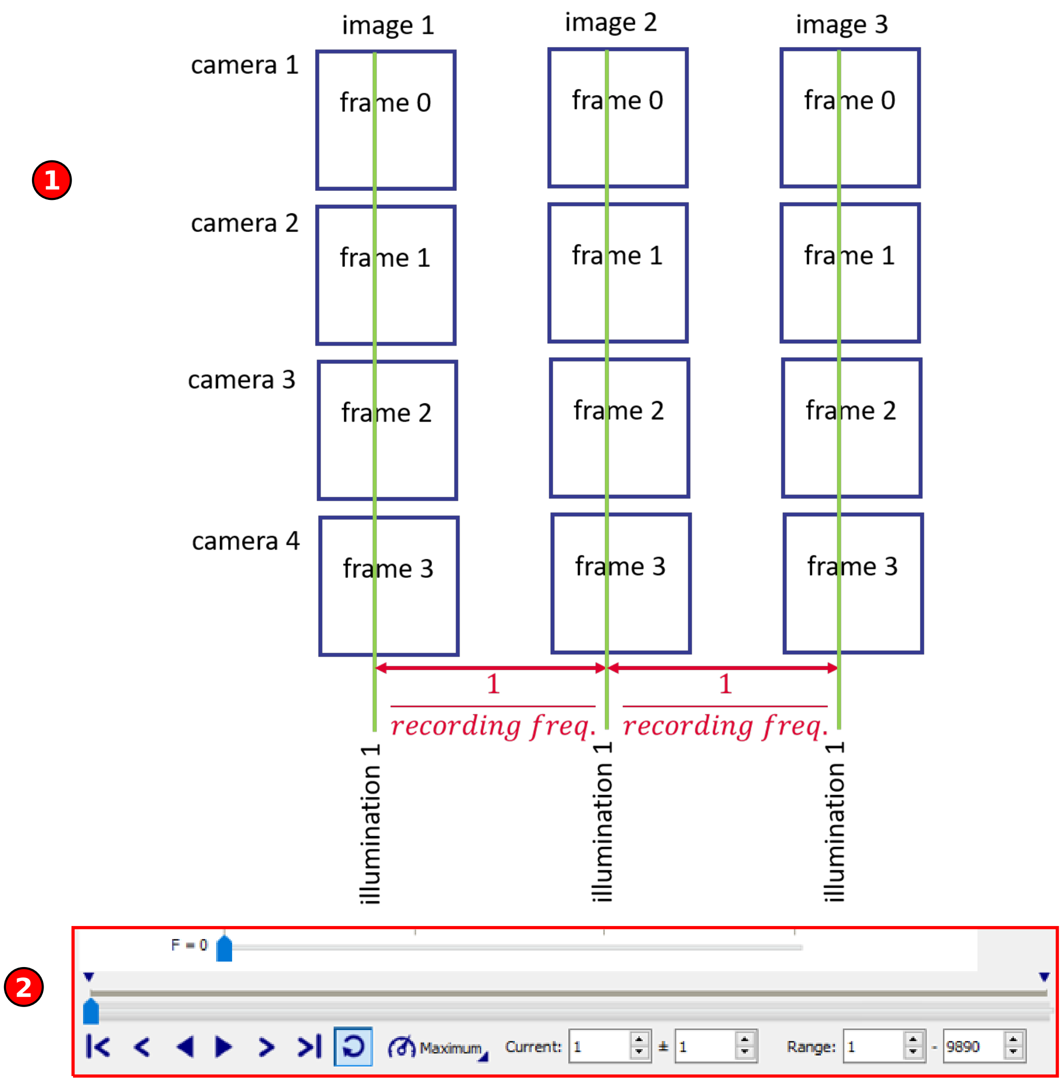


Figure 3.1: Representation of time-resolved recordings in DaVis with four single-frame cameras.

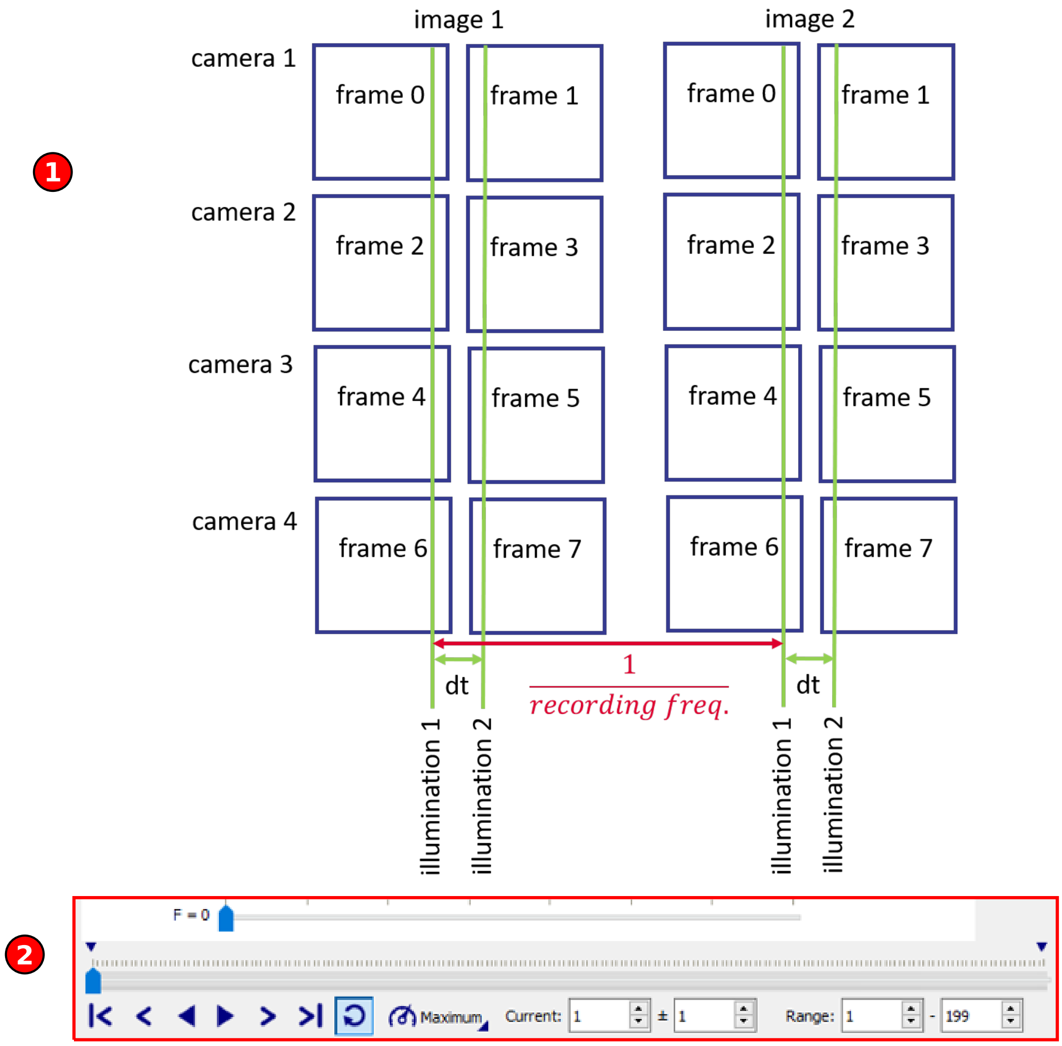


Figure 3.2: Representation of double-frame and double-pulse recordings in DaVis

For Shake-the-Box a third standard-option is available, referred to as four-pulse Shake-the-Box. Again, double-frame cameras are used, which means that the data representation in the **DaVis** display is the same as for 2-pulse Shake-the-Box shown above. Fig. 3.3 (1) illustrates the recording scheme. Each of the two frames is illuminated twice, whereas the times between the illuminations are defined as $Dt1$ (between illumination 1 and 2), $Dt2$ (between illumination 2 and 3) and $Dt4$ (between illumination 3 and 4).

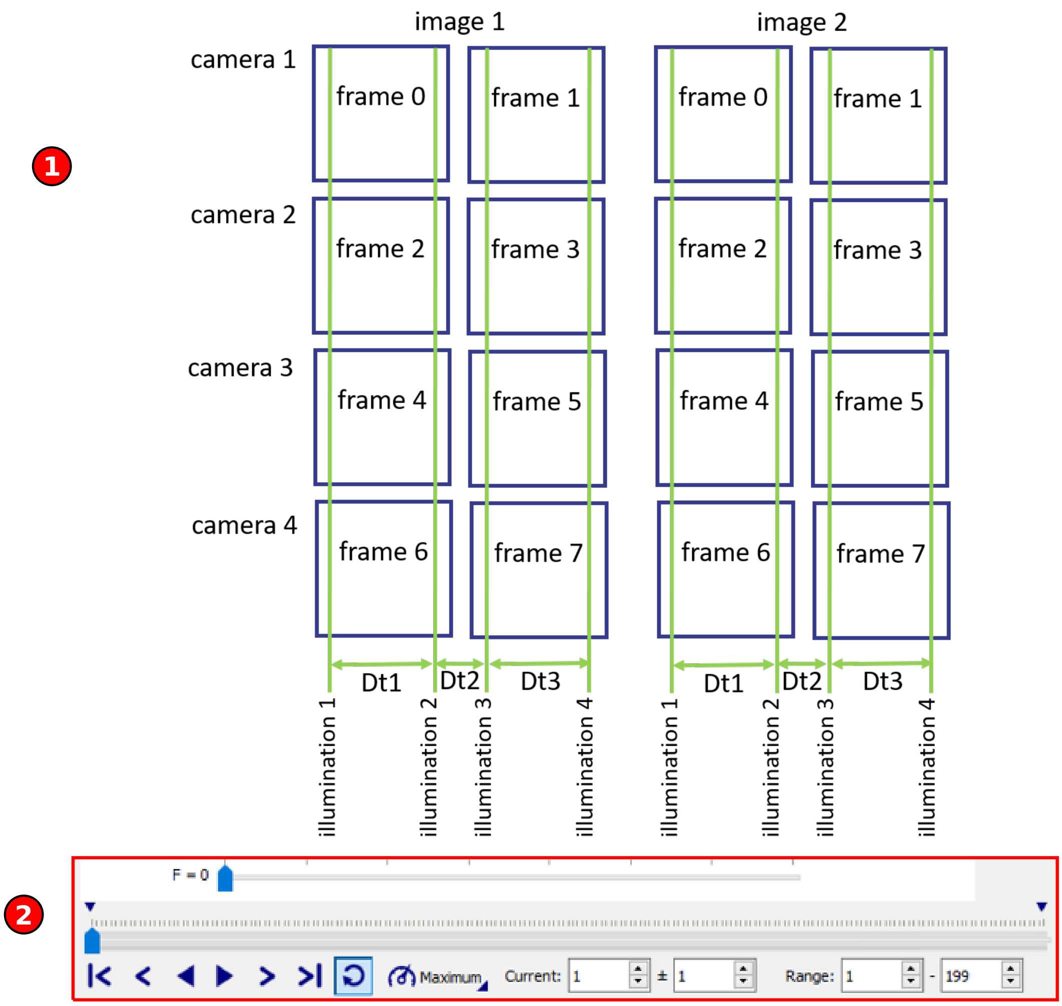


Figure 3.3: Representation of double-frame and four-pulse recordings in DaVis

3.2 Setup Cameras and Illumination

The hardware dialog and the recording dialog are documented in the DaVis main manual (# 1003001). Here, only a few specifics for Shake-the-Box recording are listed. For volumetric recording, at least three, usually four, cameras are used. The light source can either be a low speed laser, a high speed laser, a LED or a combination.

> **Note**: *Whether certain settings can be used with the system hardware has to be double-checked with the respective hardware documentation.*

3.2.1 Hardware Setup for Shake-the-Box

> **Note**: *Specific hardware settings, e.g. Q-switch timings, etc. must be observed closely and specified correctly in the hardware setup to avoid damage and for safety reasons.*

Different recording schemes can be configured:

- **Time-resolved recording:** With a single-frame or high-speed camera and a light source both with sufficiently high rates, time-resolved recording is possible (see Fig. 3.1).

- **Double-frame recording:** With one double-pulse laser and cameras with double-frame capability or high-speed cameras, double-frame recording with laser pulse A in frame 1 and laser pulse B in frame 2 can be performed (see Fig. 3.2), which is referred to as double-pulse Shake-the-Box or 2-pulse Shake-the-Box.

- **Quad-pulse recording:** With double-frame cameras and two double-pulse lasers, double-frame recording with 2 pulses in each frame (i.e. quad-pulse recording, also called 4-pulse recording), can be performed (see Fig. 3.3).

- **Other recording schemes** are possible, e.g. with multiple light sources illuminating at the same instant in time. These are special applications and not subject of this manual. How these can be set up is documented in the **DaVis** main manual (#1003001), the PTU manual and the high-speed manual.

A graphical representation of the actual hardware arrangement in use is shown in the display of the hardware setup window (Fig. 3.4 3):

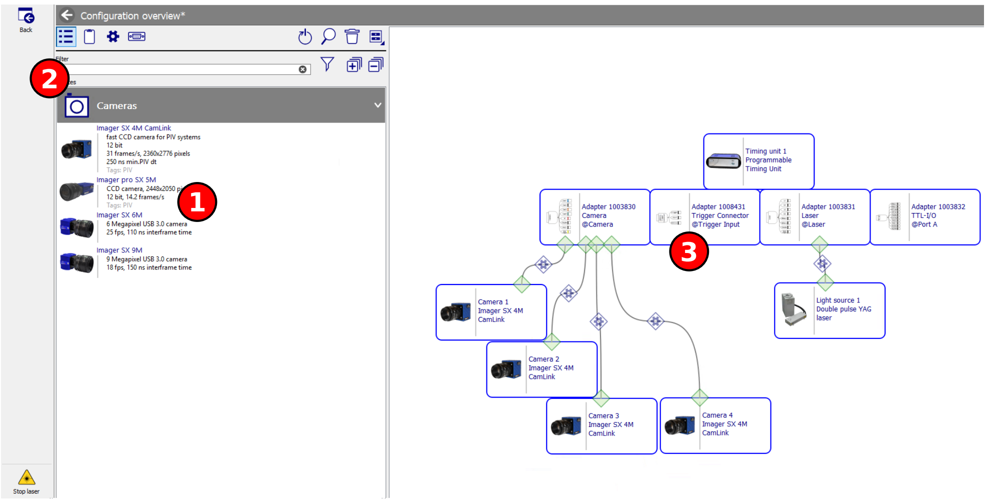


Figure 3.4: Overview of the hardware setup with a PTU X, four double-frame cameras, and a double-pulse laser.

This means, for each physically visible device of the total system, a device must be visible in the hardware arrangement. Wires connect the hardware to the respective adapter for the programmable timing unit (PTU), which should also be specified according to the adapters in use. Adding devices works by drag and drop from the list of devices shown on the left side in the Hardware Setup shown in Fig. 3.4 1 . The number of devices shown in the list can be reduced with the search function given by the text field on top of the list Fig. 3.4 2 .

Removing devices works by mouse over on these devices and clicking the red X-button (Fig. 3.5 1). For editing the device settings, the tooth wheel is clicked (Fig. 3.5 2), which opens the dialog for the settings of the respective device. The line configuration for a device is modified in the dialog which opens by clicking the tooth wheel displayed on the respective wire (Fig. 3.5 3).

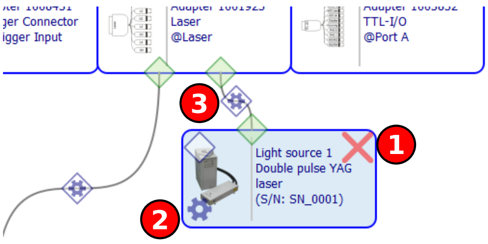


Figure 3.5: Mouse over to edit device settings or remove device.

Hardware setup for double-pulse recording in low-speed mode

A standard system allowing double-pulse recording with 4 double-frame cameras is shown in figure Fig. 3.4. A PTU X is included, four cameras and a double-pulse YAG laser. All are connected to the standard adapters. All hardware settings have to be set according to the respective hardware documentation. In this manual, only the PTU X device settings for the correct timing scheme in a standard Shake-the-Box system are lined out.

To ensure that the timings of camera exposures and laser pulses are correct, the device settings of the PTU X have to be checked. These are accessible by mouse-over over the PTU X and clicking the tooth wheel. The popup window for the device settings of the PTU X is shown in Fig. 3.6.

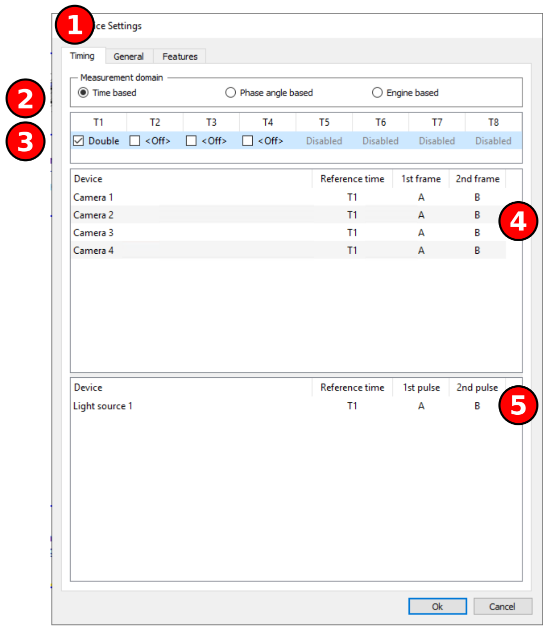


Figure 3.6: Standard Timing for the PTU X of Shake-the-Box system including four double-frame cameras recording the 1st pulse of a double pulse laser frame 1 of each camera and laser pulse 2 in frame 2 of each camera.

The timing card 1 is selected and a **Time-based** measurement domain is defined with the radio button 2 . Reference time **T1** is activated whereas all other checkboxes are unchecked. If not **Double** is displayed next to the checkbox, this has to be selected from the drop down menu showing up when clicking on this word (see Fig. 3.7). This specifies that a double-event is to be recorded, i.e. two instants in time, referenced as **A** and **B**, respectively, are defined in the timing scheme. In the upper subwindow the times for the cameras are listed 4 . They all refer to a common reference time, whereas the exposure time of frame 1 is defined such that it includes time instant A and the 2nd frame exposure time includes time instant B. Underneath the timing of the light sources are listed 5 . Here, only a single light source is listed as no more light sources had been included in the hardware setup. It shows that the 1st pulse emits at time instant A and the second pulse at time instant B. If any of the time settings is wrong, the settings can be modified by clicking on the respective letter.

In total, these settings define that laser pulse 1 emits at time A, which will be in the exposure time of frame 1 of all four cameras, and the second laser pulse emits at time instant B, which will be in the exposure time of frame 2 of all four cameras.

Note: *If the timings are set differently, this may lead to malfunction of the system including damage and safety risks, e.g. if two laser pulses are emitted at the same time instant.*

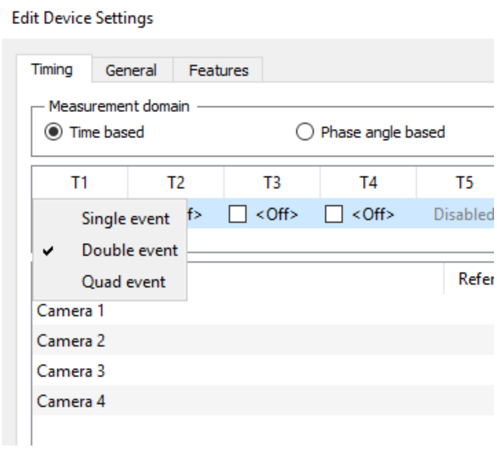


Figure 3.7: Drop down menu to specify the timing scheme.

Hardware setup for four-pulse recording in low speed mode

A standard system allowing four-pulse recording with 4 double-frame cameras is shown in Fig. 3.8. A PTU X is included, four cameras and two double-pulse YAG laser. To be able to connect two lasers, the standard laser adapter 1003831 has to be replaced by the adapter 1001923 Fig. 3.8 1 .

All hardware settings have to be set according to the respective hardware documentation. In this manual, only the PTU X device settings for the correct timing scheme in a standard 4-pulse Shake-the-Box system are lined out.

To ensure that the timings of cameras exposures and laser pulses are correct, the device settings of the PTU X have to be checked. These are accessible by mouse-over over the PTU X and clicking the tooth wheel. The popup window for the device settings of the PTU X is shown in Fig. 3.9. The timing card 1 is selected and a **Time-based** measurement domain is defined with the radio button 2 . Reference time **T1** is activated whereas all other checkboxes are unchecked. If not **Quad** is displayed next to the checkbox, this has to be selected from the drop down menu showing up when clicking on this word (see Fig. 3.10). This specifies that a quad-event is to be recorded, i.e. four instants in time, referenced as **A**, **B**, **C**, and **D** respectively, are defined in the timing scheme. In the upper subwindow the times for the cameras are listed 4 . They all refer to a common reference time, whereas the exposure time of frame 1 is defined such that it includes time instants A and B labeled as $A + B$ and the 2nd frame exposure time includes time instants C and D ($C + D$). Underneath the timing of the light sources are listed. Here, two light sources are listed as these are included in the hardware setup. It shows that the 1st pulse of laser 1 emits at time instant A and the second pulse at time instant D. For the second light source, the first pulse emits at time instant B and the second pulse at time instant C. If the settings in the device settings card have to be changed, this can be done by clicking on the respective line and column.

In total, these settings define that laser 1 pulse 1 emits at time A, which will be in the exposure time of frame 1 of all four cameras. Then, laser 2 emits pulse 1 also in the recording time of frame 1 (time instant B). Exposure of frame 1 ends. Then, exposure time of frame 2 of all four cameras starts and records pulse 2 of laser 2 (C) and pulse 2 of laser 1 (D).

Note: *If the timings are set differently, this may lead to malfunction of the system including damage and safety risks, e.g. if two laser pulses are emitted at the same time instant.*

Time-resolved Shake-the-Box recording in low-speed mode

A possible setup for time-resolved recording, i.e. with a single illumination in the single frame of a camera (see Fig. 3.1), there are two most common options for Shake-the-Box recording. Either a single-pulse light source, e.g. the high-power LED-Flashlight 300 combined with four single-frame cameras is used or a double-pulse laser is used in the way that the two pulses of the laser emit alternating such that all emitted pulses have a constant

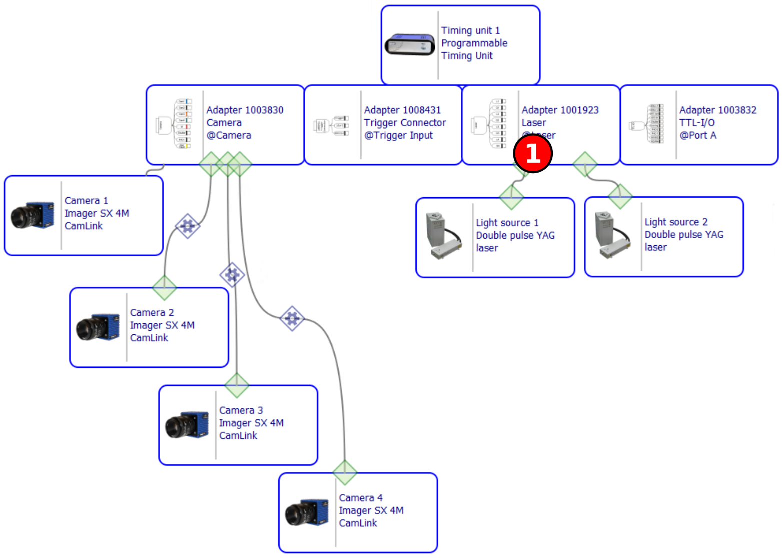


Figure 3.8: Hardware setup for 4-pulse Shake-the-Box system including four double-frame cameras recording two laser pulses in frame 1 of each camera and two laser pulses in frame 2 of each camera.

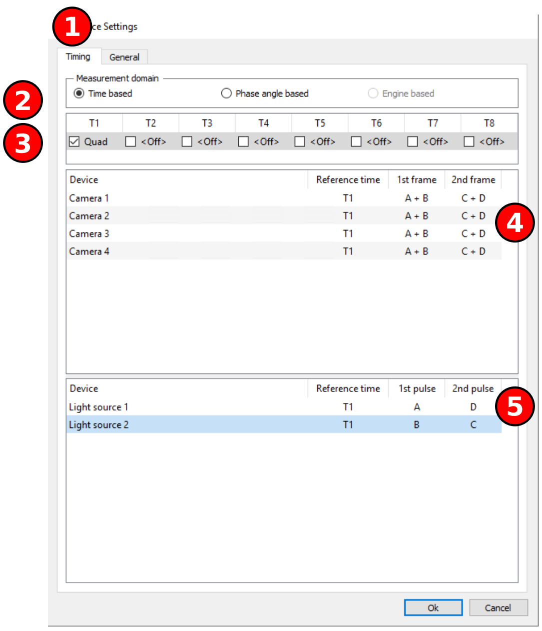


Figure 3.9: Standard Timing for the PTU X of Shake-the-Box system including four double-frame cameras recording the 1st pulses of two double pulse laser frame 1 of each camera and the second pulses of the same two lasers in frame 2 of each camera in the order: Light source 1, pulse 1 (time instant A) - light source 2, pulse 1 (time instant B) - light source 2, pulse 2 (time instant C) - light source 1, pulse 2 (time instant D).

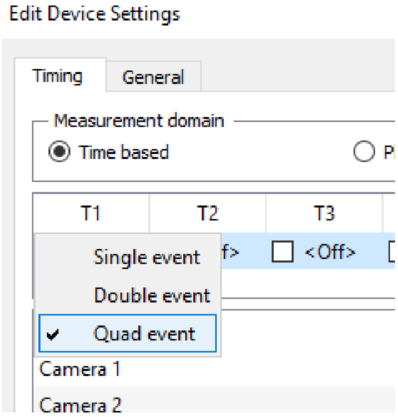


Figure 3.10: Drop down menu to specify the timing scheme.

time interval to each other, wheres the four single-frame cameras record one of these pulses in each image. This is illustrated in Fig. 3.11. Everything can be connected with the standard adapters 1003830 and 1003831 to the programmable timing unit PTU X.

Time-resolved recording with a double-pulse laser

The timing-scheme is visualized in Fig. 3.11. Usually, a double-pulse laser has a comparatively low repetition rate between the two first pulses of the two double-pulses, e.g. 15 Hz. The short inter-pulse time *dt* between the two pulses of a double-pulse laser cannot be reached between the two starts of a double-pulse sequence. Still, a 15 Hz double-pulse laser can be used for time-resolved recording at a rate of up to 30 Hz by organizing the timing structure such the two pulses alternate at a constant time interval. For this purpose, the hardware setup is organized as shown in Fig. 3.12. In addition to the four single-frame cameras, a double-pulse laser is included AND the Laser multiplexer. This is not an additional physical device but a software feature enabling this trigger option.

The timing scheme for the TTL signals sent by the PTU have to be set as shown in Fig. 3.13. In the device settings in single-event mode, the light source only shows a single pulse now emitted at time instant A, as shown in Fig. 3.13. This is emitted in the recording time of the first and only frame of the single-frame cameras. No second pulse shows up. The difference is later visible in the recording dialog, where the maximum recording frequency for single-frame is now twice as high as without the multiplexer (if the cameras do not define a lower maximum of the recording frequency).

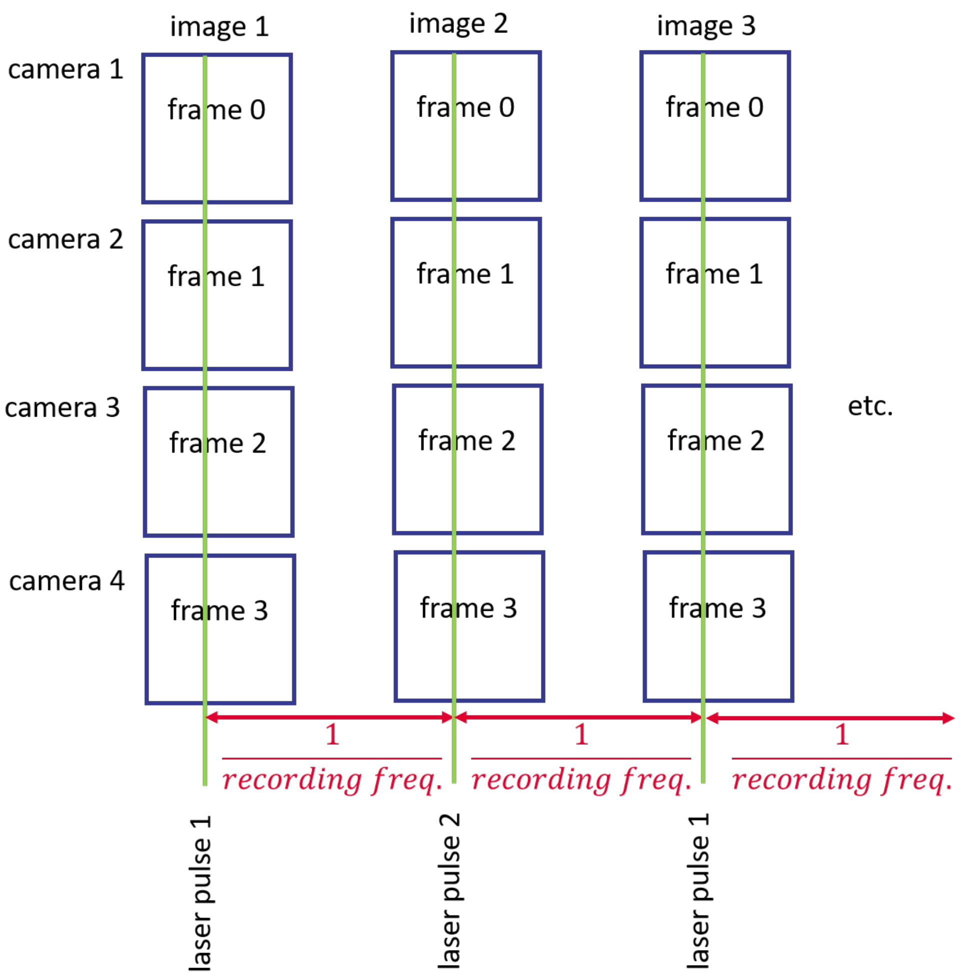


Figure 3.11: Timing scheme for time-resolved recording with a double-pulse laser with alternating pulses firing at a constant time interval.

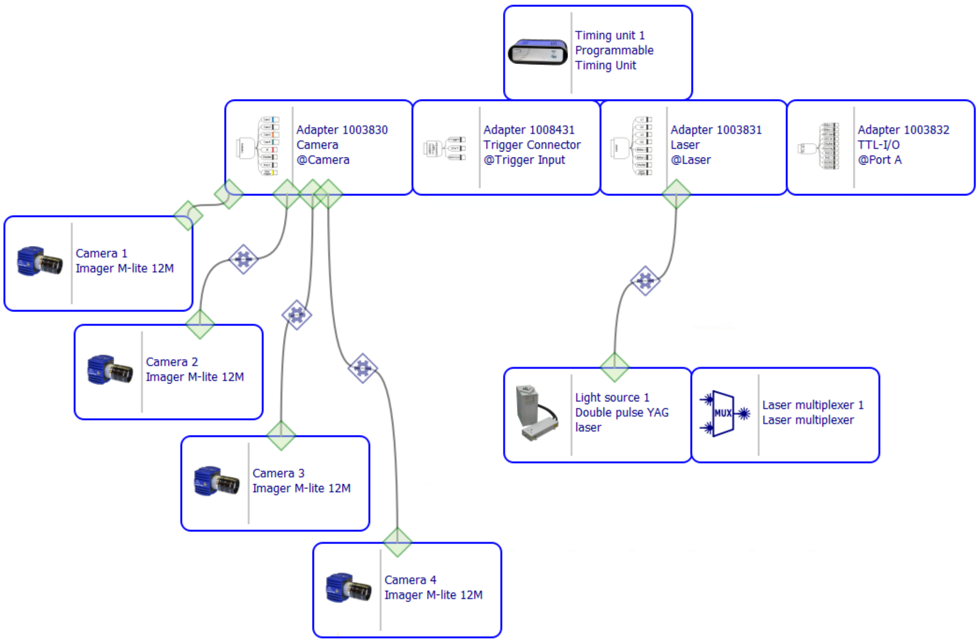


Figure 3.12: Hardware setup for time-resolved recording with single-frame cameras and a double-frame laser.

Note: *The device settings of the laser must NOT be changed for this recording mode, i.e. if the* ***Max. frequency [Hz]*** *in the Device Settings of the laser is 15 Hz for double-pulse mode, this settings MUST BE THE SAME for use with the multiplexer. The doubled frequency range shows up only in the recording dialog. Changing these settings might cause malfunction of the system, damage, and safety risks.*

Time-resolved recording with a single-pulse light source

In many cases a single-pulse light source like the high-power LED-Flashlight 300 can be used for time-resolved recording. Fig. 3.14 shows a possible setup with PTU X, four single-frame cameras and the LED-Flashlight 300.

The LED-Flashlight 300 can be used either in double-pulse or in single-pulse mode. This has to be specified in the device settings. More details on the LED and how to connect the trigger lines are given in the LED manual (#1011475). Here, it is assumed that the mode should be selectable in DaVis (not only directly at the LED) and that the selected mode is the bright Pulsed Overdrive Mode. The settings have to be as shown in Fig. 3.15. The PTU X timing is set as given in Fig. 3.16 activating reference time T1 only, defining a single event and setting 1st frame of all light sources to time instant A, and the first pulse of the light source to time A.

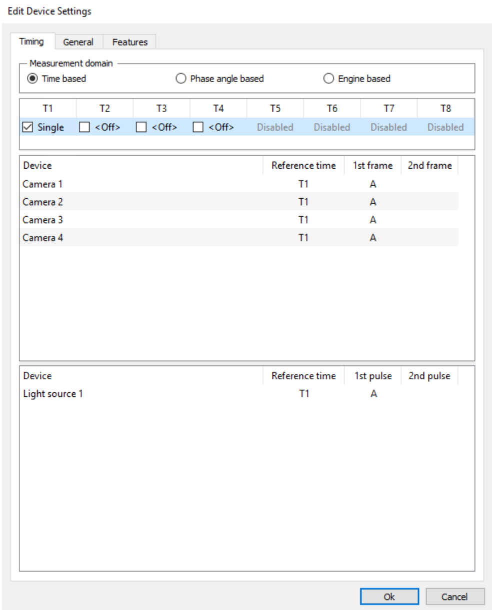


Figure 3.13: Timing in the device settings of the PTU X for time-resolved recoring with single-frame cameras and a double-pulse laser with multiplexer.

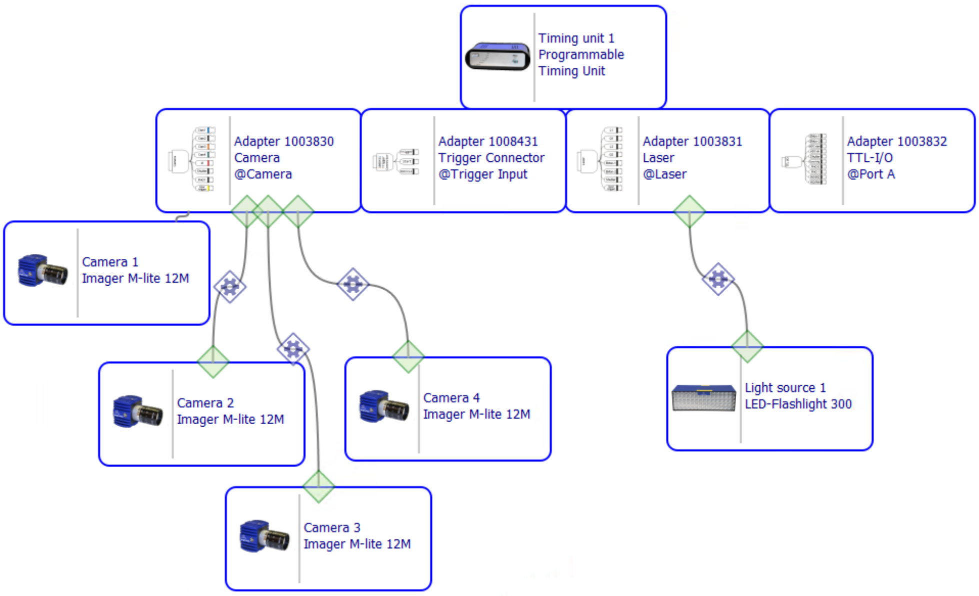


Figure 3.14: Hardware setup for time-resolved recording with single-frame cameras and the LED-Flashlight 300.

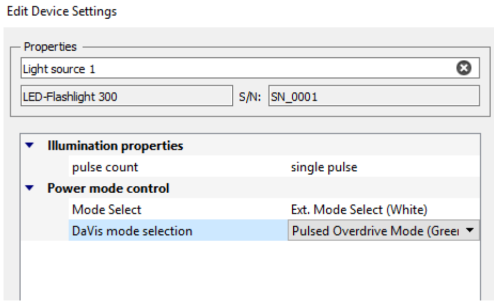


Figure 3.15: Hardware device setting for the LED-Flashlight 300 in pulsed overdrive mode selectable via DaVis and single pulse.

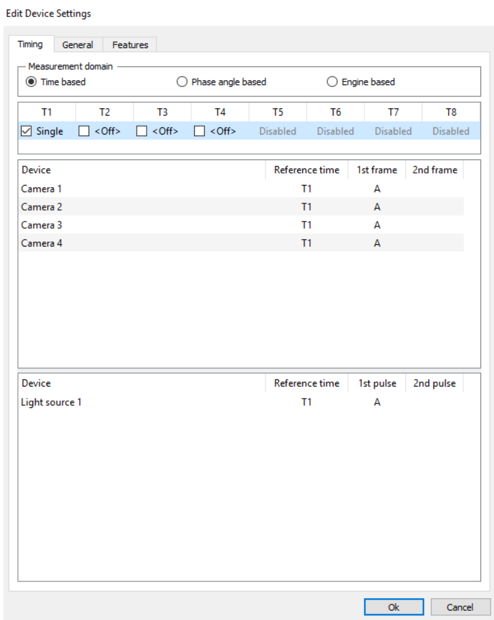


Figure 3.16: PTU X Timing settings for four single-frame cameras and LED-Flashlight 300 used in single-pulse mode.

> **Note**: *Make sure that all timings and device settings are set correctly. Other settings might cause system damage and safety risks, e.g. by two light pulses firing unexpectedly and/or simultaneously.*

3.2.2 The Recording Dialog

Having set up the hardware correctly, images can be recorded. From the **DaVis** main menu, the Recording dialog can be accessed with the recording button in the **DaVis** main window. Here, only a few main features are lined out. More details on the recording dialog can be found in the **DaVis** main manual (#1003001)

The overview of Device and Timing Settings in the Recording Setup are shown in Fig. 3.17. Here, the sections are subdivided into

1. Setting whether the light source is switched on.

2. Selecting of the activated pulses. For a single-pulse light source, only pulse A, referring to the 1st pulse, is shown here. For double-pulse light sources, e.g. double-pulse lasers, also Pulse B can be defined here, which is the 2nd laser pulse. In the special case of using a laser multiplexer for alternating image illumination with a double-frame laser, only Pulse A is shown here, which refers to both pulses of the laser. For the LED-Flashlight 300, the pulse length can be set. For lasers, the pulse energy is modified in %.

3. Main settings for all cameras are listed here, which means whether the camera is activated, which exposure time is present and which frame mode (single or double) is selected.

4. In timing section, all further timings can be modified, taking the settings in the Hardware Setup into account. This means for instance, if the cameras cannot record at a rate beyond 100 Hz according to the hardware setup, the image rate cannot exceed this rate.

5. On the very right an icon can be found, which opens a window showing the current timing plot of the TTL signals sent to the hardware of the system. This can be very helpful to understand the currently set timing. It should be kept in mind that light sources and cameras will only show up in this dialog, if activated. Each trigger event is represented by a rectangle, whereas camera exposure times are represented in blue and all activated light sources show a green peak,

when one of the light sources emits. For an LED this peak can also be a rectangle reflecting the pulse length of the LED. For double-pulse lasers, the Q-switch trigger determines when the laser pulse is emitted.

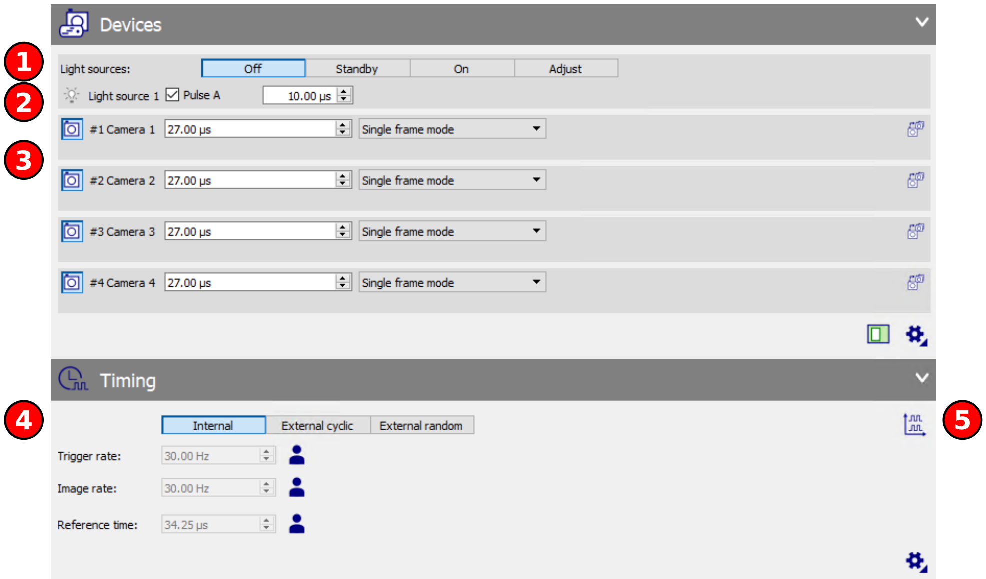


Figure 3.17: Device and Timing settings for time-resolved recording with single-frame cameras and a single-pulse light source.

Time-resolved recording with single-frame cameras and a single-pulse light source

For a time-resolved recording with single-frame cameras and a single-pulse light source, the respective options in the recording dialog are shown in Fig. 3.17. All cameras offer only a single-frame option. For the LED-Flashlight 300 as the light source, the total light energy illuminating the camera frame is defined by the pulse length. The timing plot shown in Fig. 3.18 shows that the light source illuminates from reference time 34.25 µs (red dashed line) for 10 µs (green), which is recorded in the exposure time of all four cameras (blue). The trigger pulses of the four cameras (black lines) are automatically send with respect to reference time T1 (red line) such that the exposure times start at T1.

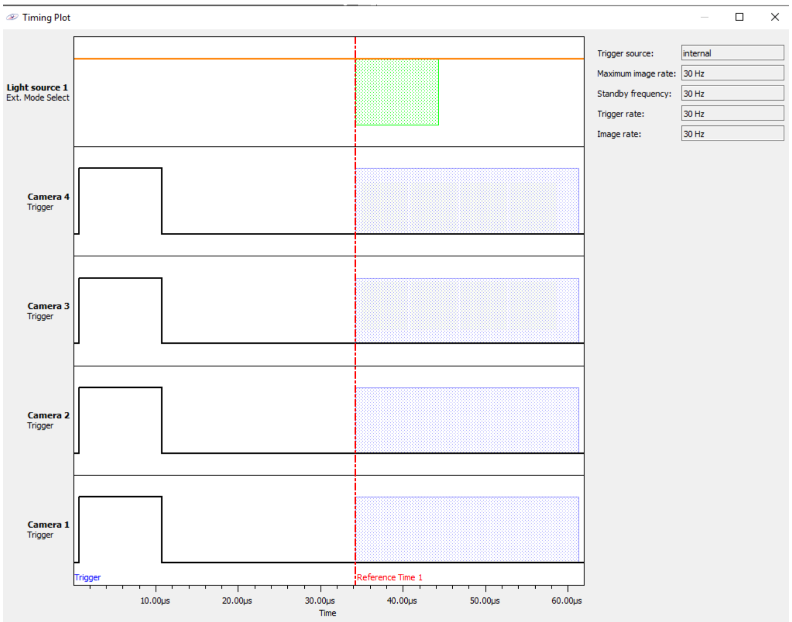


Figure 3.18: Timing Plot for time-resolved recording with single-frame cameras and a LED-Flashlight 300.

Time-resolved recording with single-frame cameras and a double-pulse light source set up with a laser multiplexer

Section 3.2.1 explains how the hardware has to be set up for time-resolved recording with a double-pulse laser firing its two pulses in an alternating fashion. Assuming a double-pulse laser with a Max. frequency [Hz] of 15 (set in the Device Settings of the laser in the Hardware Setup with respect to the specifications in the laser hardware manual), this enables time-resolved recording at a rate of 30 Hz. The recording setup looks as shown in Fig. 3.19.

In contrast to a recording with the LED-Flashlight 300, the laser light source allows for a specification of the pulse energy in % (Fig. 3.19 1). Due to the laser multiplexer, only a single pulse **Pulse A** is shown here, which refers to the pulse energy of both pulses of the laser. The timing scheme now shows a trigger rate of 30 Hz, which is twice the Max. frequency of the laser when used in double-pulse mode (Fig. 3.19 2). The timing diagram is shown in Fig. 3.20. Here, it is clear that two Q-Switches (determining when the laser emits) and two Flash lamps (time difference between Flash lamp and Q-switch trigger determines how much energy is in the resulting laser light pulse) are present in the single light source. Reference time T1 corresponding to the time of the light pulse emission is marked by a red

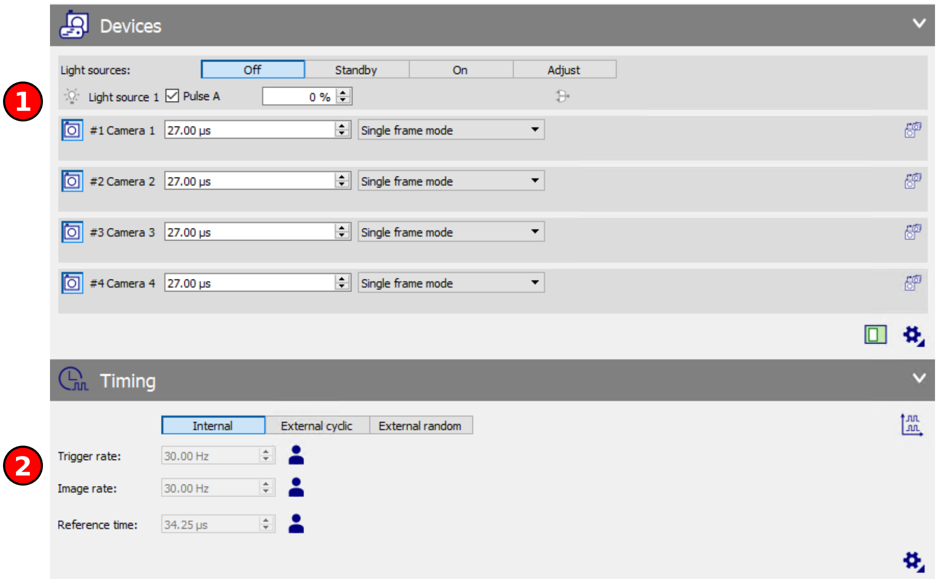


Figure 3.19: Device and Timing settings for time-resolved recording with single-frame cameras and a single-pulse light source.

line. Only a single cicle of the recording is shown. Therefore, at the first glance, the timing diagram seems to indicate that two pulses are emitted simultaneously. A closer look reveals that they both refer to the same light source. This means, the two pulses alternate, i.e. in cicle 1, only flash lamp 1 and q-switch 1 are triggered and illuminate the four camera frames during the simultaneous camera exposure times, whereas in cicle 2 flash lamp 2 and q-switch 2 are triggerd to and illuminate the four camera frames during the simultaneous camera exposure times and so forth.

Double-frame recording with double-frame cameras and a double-pulse light source

The scheme for double-frame recording with four cameras and a double-pulse laser is shown in Fig. 3.2. Section 3.2.1 in the subsection **Low Speed** shows the hardware setup in Fig. 3.4 and Fig. 3.6. Having set up all hardware accordingly, two laser pulses are emitted in double-pulse mode, selectable in the Recording dialog as shown in Fig. 3.21 1 . The pulse energies can be defined separately. For the cameras, the double-frame mode must be selected. Single-frame mode is accessible as this is useful for the recording of calibration images. In the double-frame and double-pulse Shake-the-Box recording, all cameras are set to double-frame mode and the two pulses are activated at a reasonable output energy.

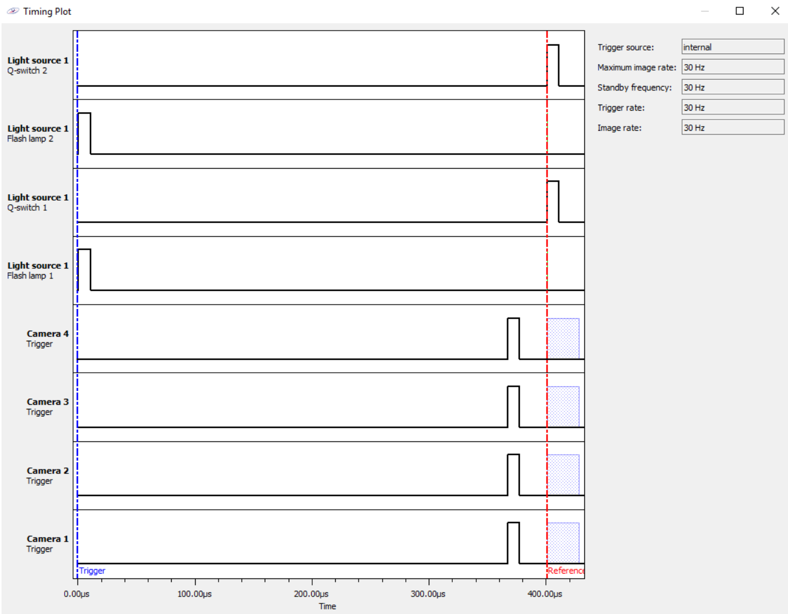


Figure 3.20: Timing Plot for time-resolved recording with single-frame cameras and a double-pulse light source.

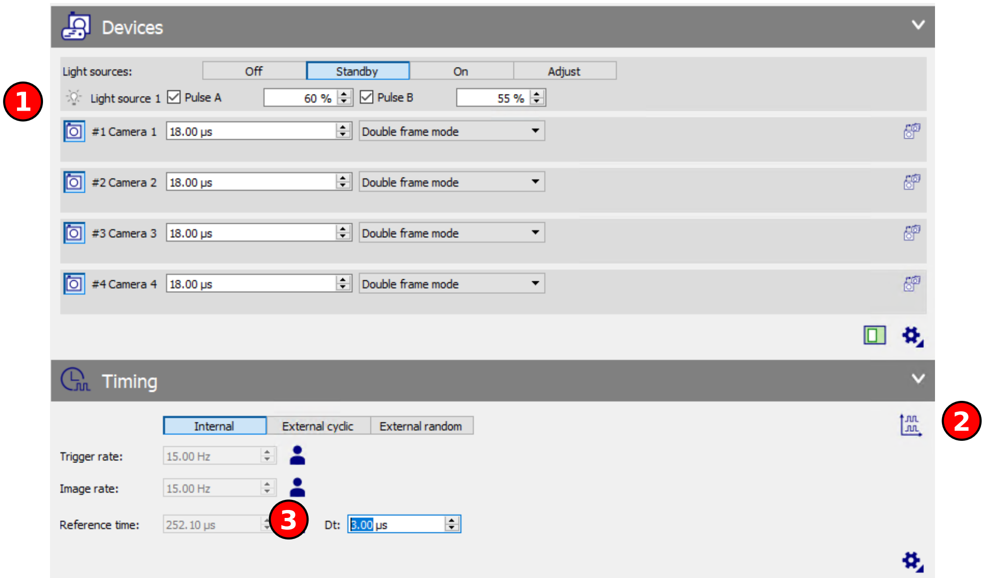


Figure 3.21: Device and Timing settings for time-resolved recording with single-frame cameras and a single-pulse light source.

The timing plot can again be accessed (see Fig. 3.21 2) showing the diagram displayed in Fig. 3.22. Laser pulse 1 emits at reference time T1 and is therefore not visible as green pulse at it is covered by the red line marking the reference time. Laser 2 emits after light pulse 1 at a pulse separation time specified in the recording dialog as *Dt* (see Fig. 3.21 3). With respect to the reference time T1 **DaVis** defines the exposure times of the cameras such that pulse 1 illuminates frame 1 close to the end of the exposure time and pulse 2 illuminates frame 2. For a larger Dt value, the red line (marking the time instant of pulse 1 and reference time T1) appear earlier in the first camera exposure time, whereas pulse 2 within the exposure time of frame 2 is shifted to a later time.

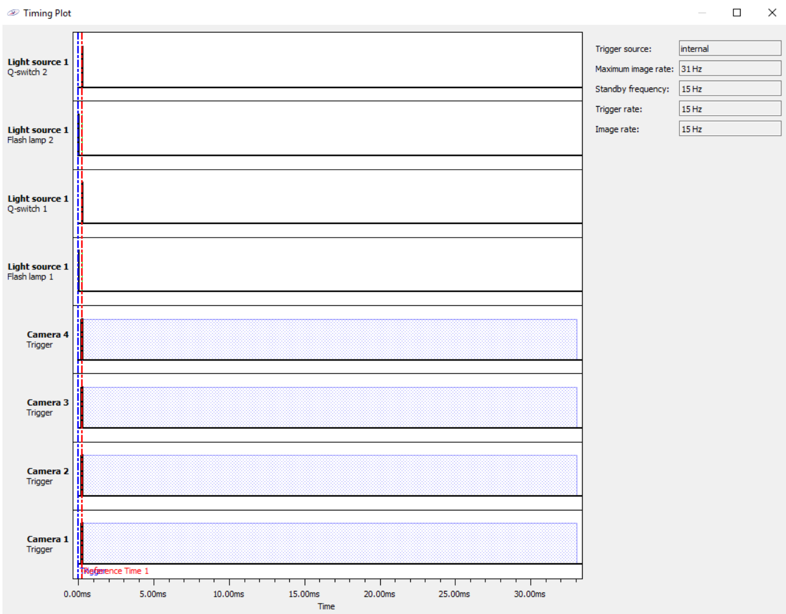


Figure 3.22: Timing Plot for double-frame recording with double-frame cameras and a double-pulse light source.

Due to the long exposure time of the second frame of double-frame cameras with a minimum interframe time of usually less than 1 µs, the second frame exposure is that long that the timing scheme of the laser pulses is hardly visible. With the mouse wheel, the user can zoom into the timing plot (into the region around the red line marking pulse 1 and the reference time T1). Then, the timing becomes visible as shown in Fig. 3.23. The position of the plot in the window can be changed by pressing the left mouse key and dragging the plot.

The short gap between the two camera exposures (white gap between the two blue rectangles) refers to the interframe time. The distance between

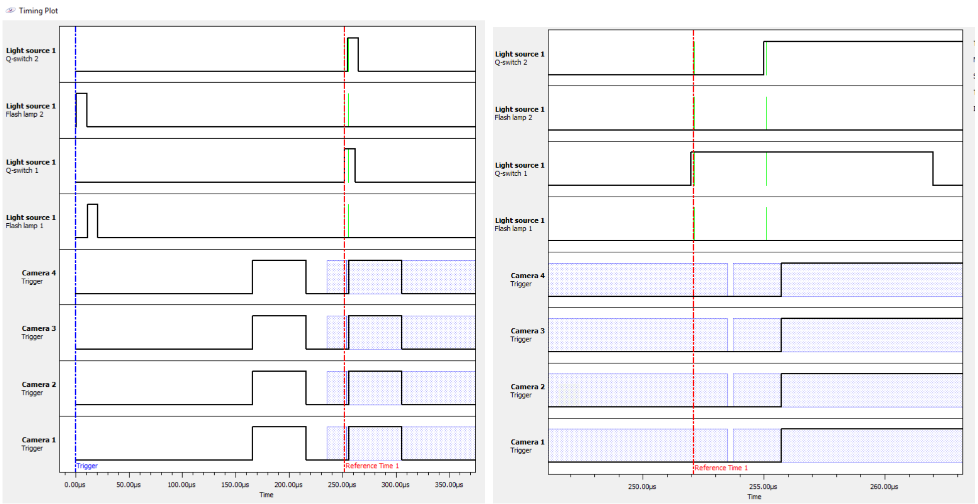


Figure 3.23: Timing Plot for double-frame recording with double-frame cameras and a double-pulse light source, zoomed in (left), greatly zoomed in (right).

the red line and the green pulse is the time difference between the two laser pulses (here: 3 µs). In the expanded diagram it is clear that the first pulse illuminates frame 1 whereas the second pulse illuminates frame 2.

4-pulse Shake-the-Box Recording

The scheme for double-frame recording with four cameras and two double-pulse lasers for 4-pulse Shake-the-Box is shown in Fig. 3.3. Section 3.2.1 in the subsection **Low Speed** shows the hardware setup in Fig. 3.8 and Fig. 3.9. Having set up all hardware accordingly, two lasers emit each two pulses in double-pulse mode, which is selectable in the recording dialog as shown in Fig. 3.24 1 . The pulse energies can be defined separately. For the cameras, the double-frame mode must be recorded. Single-frame mode is accessible as this is useful for the recording of calibration images. In the double-frame and four-pulse Shake-the-Box recording, all cameras are set to double frame mode and the four pulses are activated at a reasonable output energy.

In the device settings two light sources appear. Being two double-pulse lasers, laser 1 and laser 2 emit two pulses each, referred to as Pulse A and Pulse B. The timing scheme defined in the PTU X device settings in the hardware setup defines in which order these light pulses are emitted.

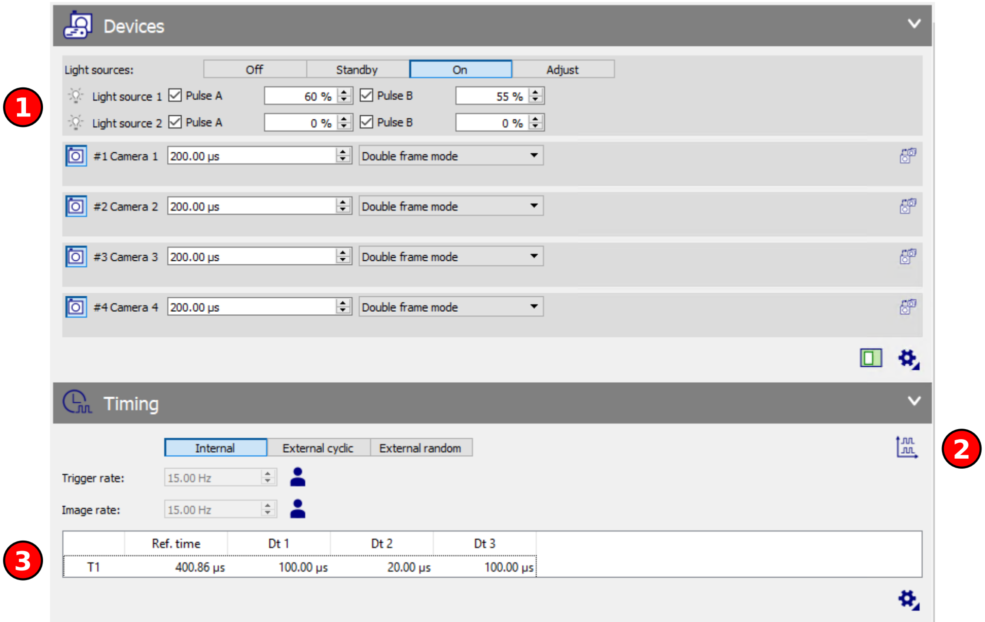


Figure 3.24: Device and Timing settings for double-pulse recording with double-frame cameras and a two double-pulse lasers.

Note: *The temporal order of the light pulses is defined in the hardware setup! It is NOT reflected in the arrangement of the devices menu in the Recording Dialog! Also the physical connections of the TTL-signal trigger connectors have to be checked and can change the output order of the light pulses.*

For the hardware setup and timings defined above (see Fig. 3.8) and shown in Fig. 3.26, the order of the light pulses is given by:

laser 1 pulse 1 $\Leftarrow$ time between the pulses *Dt1* $\Rightarrow$ laser 2 pulse 1 $\Leftarrow$ time between the pulses *Dt2* $\Rightarrow$ laser 2 pulse 2 $\Leftarrow$ time between the pulses *Dt3* $\Rightarrow$ laser 1 pulse 2.

Fig. 3.25 illustrates this recording scheme.

Note: *This makes clear that the time instants A, B, C, D known from the Timings of the PTU Device Settings in the Hardware Setup Dialog do not necessarily correspond to the laser pulse labels A and B in the Recording Dialog!*

The timing plot can again be accessed (see Fig. 3.24 2). The timing diagram can be enlarged, as explained above. A laser is emits, when the Q-switch trigger is sent (reflected by the rectangle function in the shown TTL-signal plot. This make clear that Light Source 1 opens the first Q-switch

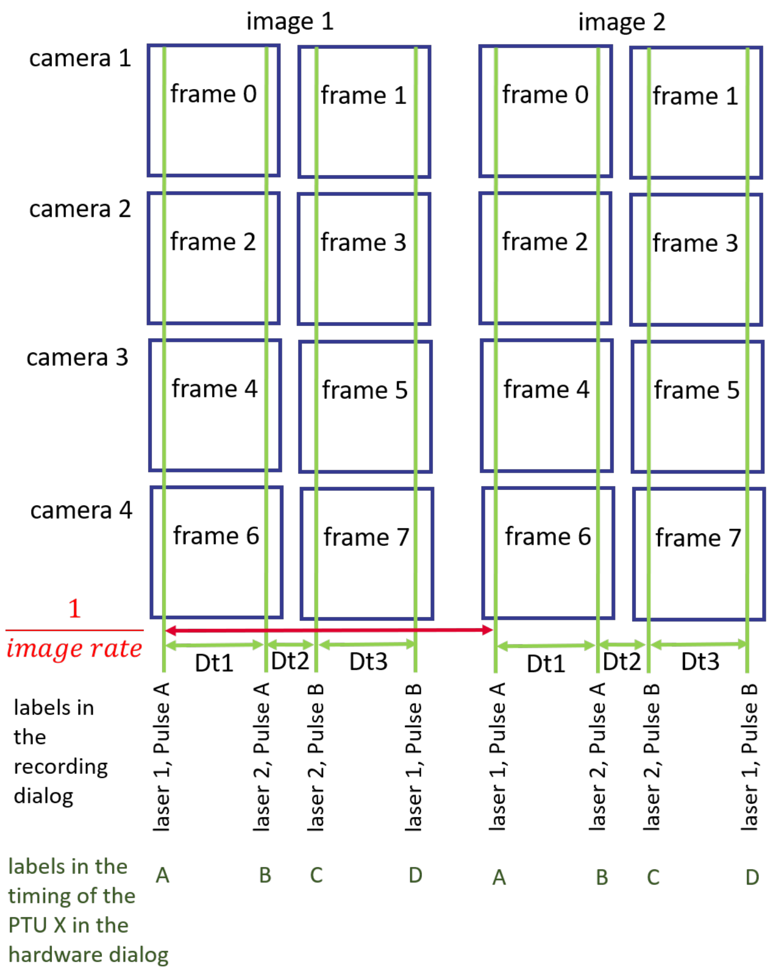


Figure 3.25: Visualzation of the 4-pulse pulse and camera frame timings if the PTU timings are set in the Hardware setup as defined in Fig. 3.26 and the trigger lines are connected accordingly.

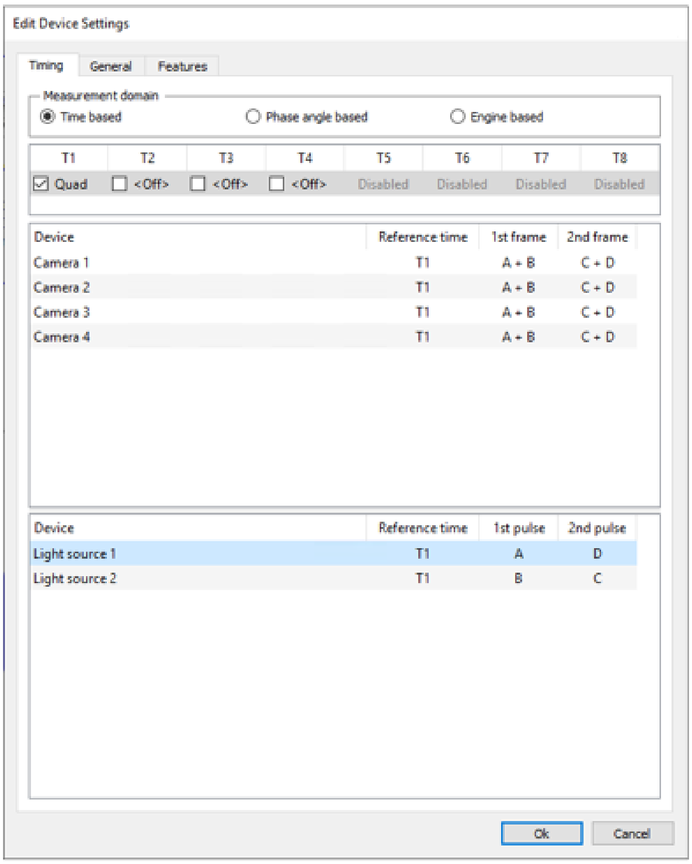


Figure 3.26: PTU X timings set in the Hardware Setup Dialog for four-pulse recording.

during the exposure time of frame 1. Dt1=100 µs later, laser 2 emits its first pulse (Light source 2, Q-switch 1). This time corresponds to the reference time T1, which is represented by the red line $T1 \approx 400\mu s$. Approximately 12 µs later, the exposure time of frame 1 ends and the exposure time of frame 2 starts after the interframe time. Dt2=20 µs after the second emitted laser pulse, i.e. after light pulse 1 of laser 2, laser 2 emits its second pulse (shown by the rect-function in the TTL-signal in Light Source 2, Q-switch 2. Finally, after another Dt3=100 µs time interval, laser 1 emits its second pulse (shown as rect in the TTL-signal of Light source 1, Q-switch 2).

The exposure time of frame 1 can be modified in the camera device settings of the recording dialog. This must be adapted to the required pulse delay Dt1 between the first two pulses. Fig. 3.24 3 shows the list of the three Dt timings Dt1, Dt2 and Dt3 which are the pulse separation times between the four pulses.

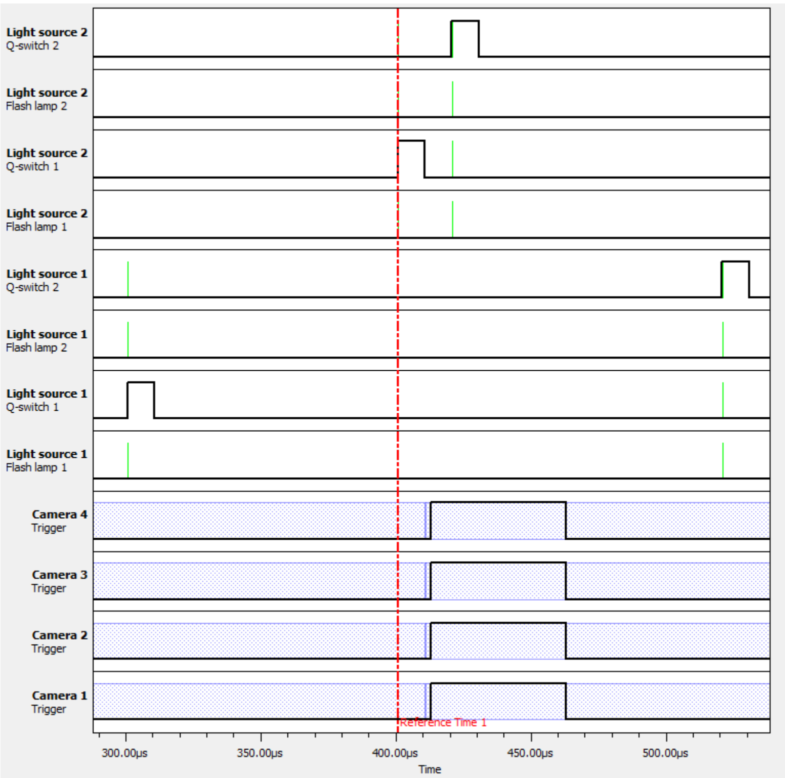


Figure 3.27: Timing Plot for double-frame recording with double-frame cameras and two double-pulse lasers for 4-pulse Shake-the-Box (zoomed for better visibility).

3.2.3 Required optical components

The following optical components are required to do a Shake-the-Box experiment:

- **Cameras:** 2 to 6 (or even up to 8) cameras. **Shake-the-Box** only works for time resolved recordings, where the maximum particle shift between two images should be about 10 pixel. So the recording rate of the cameras need to be high enough to allow such a time resolved recording. Depending on the flow speed and the area of interest, 10 Hz can be time resolved (e.g. slow flow and large field of view). In other circumstances (e.g. high speed flow or small field of view) 10 kHz or more may be required to gather time resolved recordings. This question needs to be considered carefully when planning a Shake-the-Box system.

- **Camera mounts:** Camera mounting is very important for volumetric flow measurements, much more important than for planar PIV. As the volumetric techniques require very accurate camera calibration (spatial accuracy better than 0.1 pixel), the camera mounts need to be very stiff to maintain such a calibration accuracy over the measurement period (e.g. when temperature changes or vibrations occur). Volume self-calibration can recover from some amount of positional camera drift, but the smaller that kind of drift can be kept, the better. The principle of volume self-calibration and the software settings are described in section 4.2.1. Volume self-calibration is faster, easier and more reliable when the drift is minimized by a stable and stiff camera mount. High quality gear heads proofed to be very useful in this situation, as they allow both, easy adjustment and stiff mounting. The specified payload of the gear heads needs to fit to the camera weight: e.g. heavy high repetition rate cameras need the heavy duty class of gear heads, whereas lightweight cameras will work well with standard gear heads.

- **Light source:** Corresponding to the desired repetition rate of the camera recordings, the light source needs to be capable to deliver light pulses at the desired repetition rate. Among laser light sources, dual pulse lasers allow more flexibility as they may be used to gain higher energy at a lower rate or double the rate at lower energy. Also continuous wave may be sufficient. Nowadays, in water applications and in air flows seeded with LaVision's helium-filled soap bubbles, LED illumination can also be sufficient.

- **Lens:** Just as in planar PIV, the focal length of the lens needs to fit to the desired area of interest and the required working distance. As Shake-the-Box measurements are done in a volume, as opposed to planar measurements in a very thin sheet, the objective needs to be set to larger f-stop values to get the complete volume in focus.
- **Scheimpflug adapters** are useful if the volume is thin or at least not too thick. When the ratio between depth and width of the AOI approaches 1, Scheimpflug adapters are not needed anymore.
- **Laser guiding arm:** An optional laser guiding arm is often a very convenient way to deliver the laser light to the required measurement location. It is also a very safe way to guide the laser light. The setup is much quicker, easier, more flexible and safer compared to (open) multi mirror setups.
- **Seeding particles:** As the light budget is often limited for volumetric measurement, choosing the seeding carefully can be crucial for the success of Shake-the-Box measurements.

  In air there are only a few choices: oil droplets, DEHS, titan dioxide, water droplets, disco fogger, and the recent alternative Helium filled soap bubbles (HFSB). Among these particles HSFB is the only tracer with a size significantly bigger than (1 µm). Small particles follow the flow very accurately, but they scatter very little light. For this reason, volumetric measurements using these small seeding particles are restricted to small measurement volumes. For large scale measurements in air Helium filled soap bubbles have been developed. Due to their size, they allow for a more economic usage of the illuminating light, while the Helium filling makes them light enough for air flow measurements.

  In water or other liquids, there is more flexibility to select from a wider range of particle sizes that fit to the measurement task. Glass hollow spheres, often used in planar PIV, are not recommended for multi camera volumetric measurements. Hollow glass spheres show a Mie scattering characteristic with a very inhomogeneous intensity that strongly depends on the scattering angle. This results in inhomogeneities of the scattered intensity viewed from different directions. So the chance is high, that always one or more cameras have to be positioned in such an angle that they record a very unfavorable part of the complex Mie scattering curve. Polyamid (polystyrene, polyethylene) particles (especially white ones) have a much more homogeneous scattering characteristic and have been found to work well for volumetric flow measurements. They are available in a broad range of sizes (10 µm to 100 µm and even larger) so that an appropriate size can be selected for a given experiment.

Seeding Density: The requirements for the seeding density are a bit stronger than for stereo PIV. There should be about one to three particles in a 4×4 pixel area. Over the whole volume, the seeding should be as homogeneous as possible. The volume should not be opaque in any parts of the images. Ideally there should be no more than one particle projected to each camera pixel.

- **Volume illumination optics:** In combination with a laser a special optics is needed to create a volume illumination from a laser beam. **LaVision** offers three different optics suitable for different experimental situations: two kinds of volume optics for thick volumes and a sheet optics that can be used to illuminate thin volumes. For a volumetric illumination, the volume optics creates a collimated illumination in a volume with an aspect ratio (height/thickness) of 1 to 3.2 and a cross section of up to 50 mm$\times$ 50 mm or 50 mm$\times$ 100 mm. It is highly recommended to add an adjustable mechanical aperture between the volume optics and the measurement volume. Such an aperture cuts a rectangular cross section out of the Gaussian shaped volumetric beam. This helps to define sharp borders within the measurement domain and to restrict the required focal depth to the required minimum. Four magnetic plates can be arranged on the aperture (as shown below) to ensure an optimal illumination. With the sheet optics, a thin measurement volume can be illuminated. This illumination is not collimated. For more details for volumetric illumination, please refer to the volume optics and the divergent sheet optics manuals.

Volume optics (part number 1108676).

Divergent sheet optics (part number 1108405).

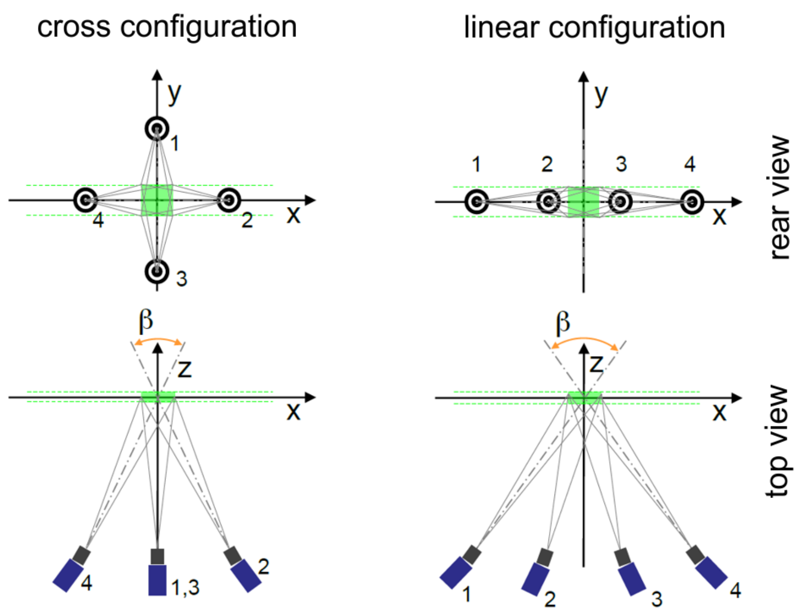
Rectangular aperture.

- **Calibration plate** Since Shake-the-Box depends strongly on an accurate calibration, **LaVision** recommends the newest calibration plates (types 058-5, 106-10, 204-15 or 309-15). Hand-made calibration targets may lead to poor results. For calibration plates 058-5, 106-10, 204-15 and 309-15, most times only a single view of the plate is necessary for the calibration.

3.2.4 Camera setup

The camera setup is very flexible for volumetric flow measurements. The setup can be adapted to experimental preconditions (like direction of optical access windows) or to characteristics of the seeding (e.g. put all cameras in forward scattering for oil droplet seeding). Also, if using a 3D calibration target with markers on both sides of the calibration plate, cameras can be mounted on both sides of the plate. So there are many options for the general camera setup, that can be adapted to the requirements of the experiment.

However, some important constraints should be kept in mind: The cameras should be placed in a way, such that each camera gets a very different viewing angle into the measurement volume. Especially, it is not optimal to put two cameras opposing each other, as they will see the measurement volume roughly with the same viewing angle. Also the stereo base, which is related to the angle between the cameras providing the largest difference in viewing angle) should be as broad as possible. An overall aperture of 60 to 90 degree would be optimal to get a high accuracy in all space dimensions, especially in the out of plane dimension: If the camera angle is very small, the precision of the out of plane component (z-component) will be significantly lower than for the in plane components (x and y).



Two common setups have been used a lot in the last years: one is the **cross** configuration the other is the **linear** configuration. Both have their strengths and weaknesses: The cross configuration is optimal in providing different viewing directions into the measurement volume. However, it is mechanically more challenging to assemble the cameras in the cross configuration. Especially, it is a little harder to set up Scheimpflug adapters with correct Scheimpflug axes. The linear setup on the other hand does only provide viewing directions on a common plane. In practice, this is compensated by a much simpler mechanical setup and easy to setup Scheimpflug adapters. Both configurations yield excellent results when designed and implemented carefully.

3.3 Adjust Area of Interest and Scheimpflug

This section describes the second step in the sequence of operations listed at the beginning of chapter 3.

1. Place the calibration target in the center of the measurement volume.
2. Enter the recording dialog and use 'Grab' to get a live image from the cameras.
3. Camera 1 must look at the front side of the calibration plate. The front side is where the type of the plate is printed, e.g. 106-10 or 204-15.
4. Adjust the area of interest, focus and Scheimpflug angle for all cameras carefully using the calibration target and a small f-stop (e.g. 1.8 or 2.4). All cameras must see the same area of interest and must have a similar magnification.

3.4 Refocus on Particles

This section describes the third step in the sequence of operations listed at the beginning of chapter 3.

- Remove the calibration target.
- Setup the volume illumination.
- Seed the volume with particles.
- While using 'Grab' images with the laser turned on adjust the lens aperture and focus for all cameras, such that all particles are clear and sharp.

3.5 Perspective Calibration

This section describes the fourth step in the sequence of operations listed at the beginning of chapter 3. From now on, do not touch the cameras or the camera cables any more.

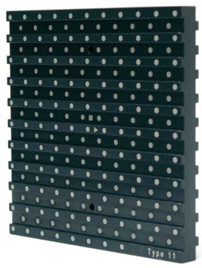
3.6 Camera calibration

For Shake-the-Box, a camera volume calibration is needed. A volume calibration is a camera calibration in which not only the mapping of a single *xy* world plane to the CCD chip is calibrated but also the *z* dependence of the mapping from a world point to the camera chip.

LaVision offers multiple calibration plates tailored to different demands. The selected calibration plate is placed at one or multiple positions in the measurement volume to record several views of the calibration plate.

The calibration of the measurement volume can be done in three different ways:

1. single view,
2. coplanar equidistant views,
3. independent views.



Which method to use depends on the experimental conditions and the available devices. Before the calibration methods are discussed, a few terms are explained that will be used in the following:

- **2D calibration plates** have crosses or dots on a single plane.
- **3D calibration plates** have two planes with calibration marks separated by the plane distance *dz*. Such a plate is shown above.
- The **polynomial fit** uses a 3rd order polynomial to model the perspective and optical image distortion for the mapping from a world plane to the CCD camera sensor. A volume mapping is achieved by the interpolation between multiple world plane calibrations. The world planes have to be coplanar and equidistant.

- The **pinhole fit** is a computer model for the mapping of world points to the camera sensor. In this model, the camera positions as well as internal camera parameters like focal length and radial lens distortion are estimated. **Volume Self-Calibration** automatically transfers a pinhole calibration to polynomial calibration.

3.6.1 Single view

- **2D calibration plate:** This calibration is the worst case and should only be used if no other calibration is possible. A single view of a 2D calibration plate can only be used in combination with a **pinhole fit**. No camera should look perpendicularly onto the 2D plate, because then the pinhole fit cannot estimate the correct focal length and plate distance. Please consider using a 3D calibration plate or a translation unit and record multiple views.
- **3D calibration plate:** This calibration is acceptable if the plane separation dz is not too small compared to the depth of the measurement volume. Both, pinhole fit and polynomial fit can be used in this case. For polynomial fit, the depth of the measurement volume should not exceed about ten times dz.

3.6.2 Coplanar, equidistant views

For coplanar, equidistant type of calibration, the calibration plate must be fixed to a translation unit that can move the calibration plate in equidistant steps along the z direction.

The calibration plate has to be adjusted exactly perpendicularly to the z direction on the translation unit. Any inaccuracy in the adjustment will result in a greater fitting error (in case of a pinhole fit) or will result in a non-Cartesian volume calibration (in case of the polynomial fit). The latter means that the computed vectors are located on a slightly skewed coordinate system.

The z range of the views should cover the complete measurement volume. If, for example, the reconstruction has to be done from -10 mm to 10 mm, then the first view of the calibration should be recorded at $z = -10$ mm and the last view at $z = 10$ mm.

Both, polynomial fit and pinhole fit can be used for this calibration method.

The **pinhole fit** will be recommended if the measurement is in air without optical distortions or if the optical distortions at media boundaries are minimized by placing the cameras perpendicularly to planar media boundaries, e.g. by applying prisms with matched refractive indices in front of each camera. An advantage of the pinhole fit is that changes of the calibration during the self-calibration procedure (see below) are interpretable and predictable.

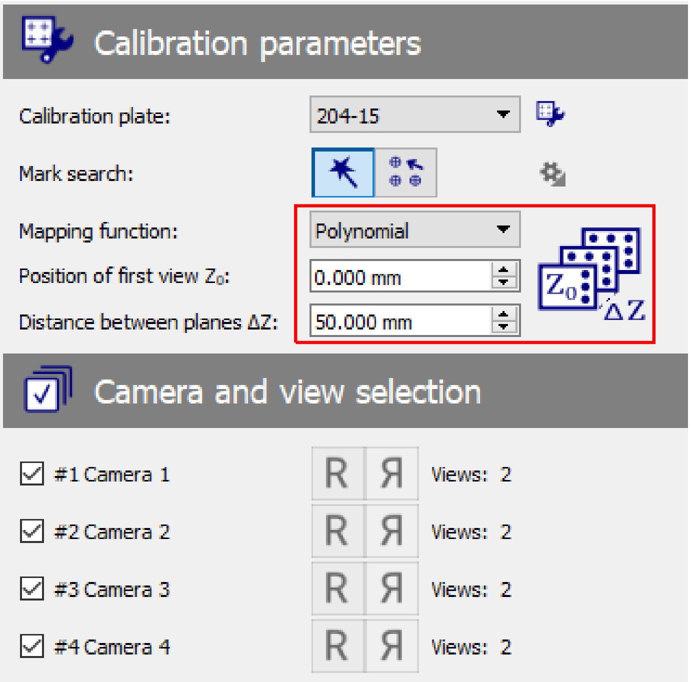
The **polynomial fit** is recommended for all experiments in which optical distortions at media boundaries occur.

The **number of views** depends on the optical distortions of the setup. If there are no distortions, e.g. for measurements in air, 2 views will be enough. For stronger distortions, e.g. for measurements in a cylinder, five to ten views should be used (in this case a polynomial fit is advisable).

2D plates and 3D plates can be used. For a polynomial fit, only the first plane of a 3D plane is used for calibration.

To prevent the coordinate system from being tilted in comparison to the desired orientation, e.g. tangential to the main flow direction, the calibration plate can be positioned with the help of a laser light sheet. A light sheet can, for example, be generated with the help of an respective aperture positioned between the volume optics and the measurement volume. The **laser light sheet** should be centered at $z = 0$ and the positions of the calibration plate should be placed symmetrically to both sides of the sheet. It is recommended to use an odd number of views on the calibration plate, such that the central view is at $z = 0$. So, to place the light sheet in the center of the calibration volume, and place the calibration plate in such a way that its front is tangential to the sheet. An exception from this rule is a setup where some cameras look at the backside of the calibration plate. In this case adjust the middle of the calibration plate to the laser light sheet for the central view.

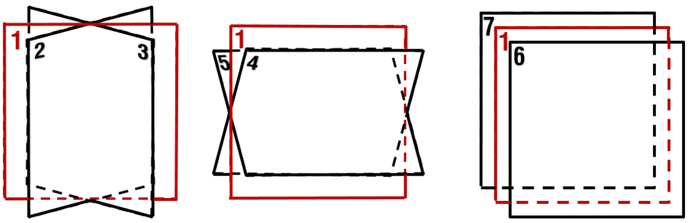
In the example below, the first view of the calibration plate is at $z = -0$ mm, the second view is in a distance of 50 mm to the first view. The z axis points towards the cameras, i.e. it is defined automatically by the calibration such that the resulting coordinate system is right-handed.



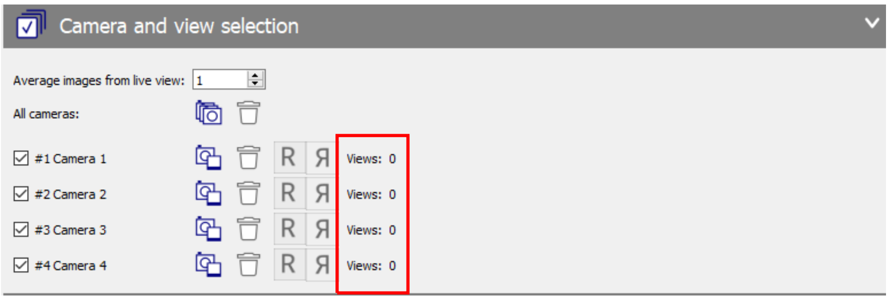
3.6.3 Independent views

Independent views are recordings of the calibration plate, for which the calibration plate is moved forth or back or is tilted vertically or horizontally relative to the first view. This type of calibration can only be used together with a **pinhole fit**. This calibration should only be used if the measurement is in air without optical distortions or if the optical distortions at media boundaries are minimized by placing the cameras perpendicularly to planar media boundaries.

The number of views for this calibration should be five to seven. The first view defines the plane $z = 0$ of the calibration volume. The 5 to 7 views could be positioned as shown below. In reference to position 1 at z=0 possible additional positions of the calibration plate are sketched below.



The advantage of this calibration type is, that it adds more information to the pinhole approximation compared to the single view calibration and that no translation unit is required. The plate can be fixed at various arbitrary positions. For each position, a recording is acquired and automatically, the number or views are counted.

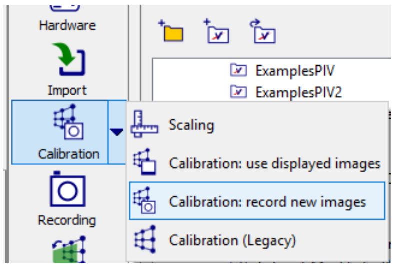


More details about the background on perspective calibration can be found in chapter 5.

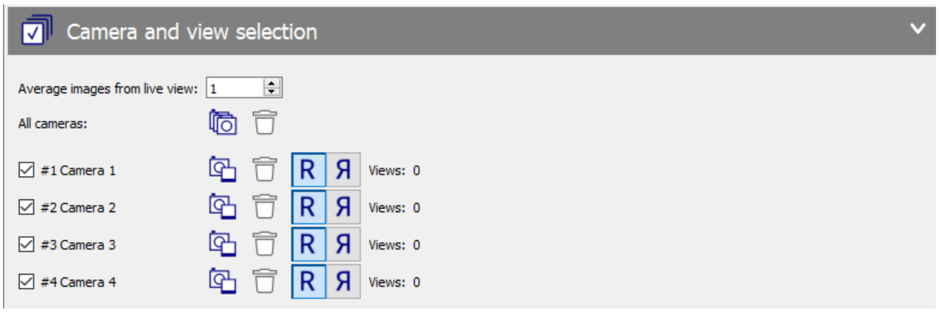
3.6.4 Calibration dialog

- From now on, do not touch the cameras or the camera cables anymore. Do not put or remove filters or camera caps. Avoid vibration or shocks to the camera frame.
- Place the calibration target in the center of the measurement volume and align carefully. The calibration target defines the orientation of the coordinate system.
- As shown below, please make sure that you select the correct number of cameras with a joint coordinate system in the calibration dialog.
- For a 2D (single plane) calibration target, you need to move the target in equidistant steps in the out of plane direction (3-5 steps, depending on optical distortions and volume thickness).
- For all cameras select single frame recording with a long exposure time (e.g. 100 ms) to record the calibration target.
- Use additional illumination for the target if the contrast is too poor.
- Follow the steps of the calibration dialog.
- Use the polynomial or pinhole calibration model.
- For details on the software for the calibration procedure please refer to the calibration chapter of the **DaVis 10** manual (#1003001). There the calibration is described for one or two cameras. There are also situations in which a multi-step procedure with the calibration dialog

"Calibration (Legacy) are required. For a Shake-the-Box project, a calibration either with displayed previously recorded calibration images in a multi-set or with new images "Calibration: record new images" is required. To start a new calibration, click the calibration button in the left toolbar and select "Calibration: record new images":



For Shake-the-Box experiments with more than 2 cameras, the process is identical to the one with one or two cameras. Make sure that all cameras which need to be calibrated for your Shake-the-Box experiment are activated in the camera view selection.

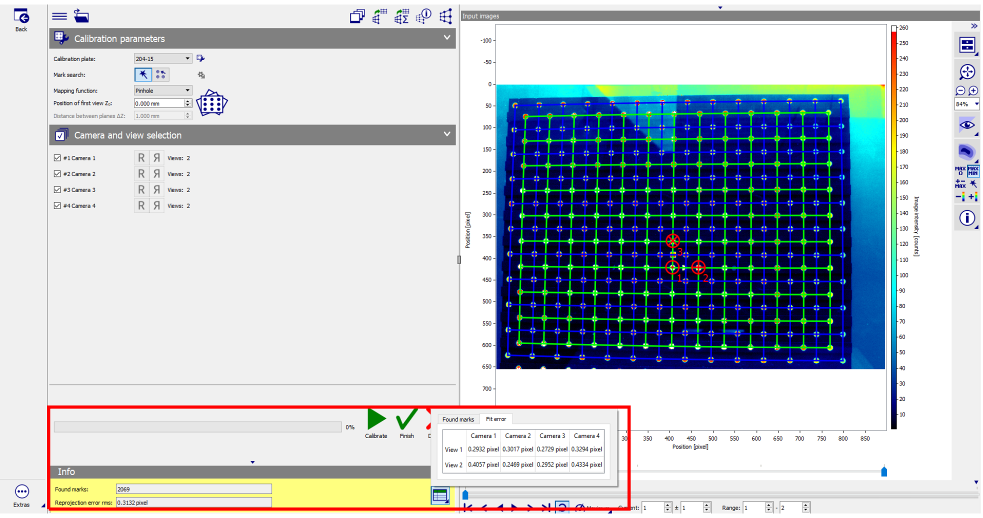


A good calibration is very important for Shake-the-Box. So the **average deviation to marks** should be about **0.1 to 0.5 pixel**. This is normally achieved with the new **LaVision** calibration plates (types 106-10, 204-15, 309-15 or 058-5) and the coplanar polynomial calibration. If it is impossible to obtain a calibration of such a high quality, even calibrations can be used with 1 to 2 pixel errors, if the consecutive volume self-calibration is successful, i.e. reduces the calibration error to less than 0.1 pixel.

3.7 Record particle images

This section describes the fifth step in the sequence of operations listed at the beginning of section 3.

Seeding conditions for particle image recording:



- Optimal seeding density for final analysis is achieved if there are particles all over the illuminated volume, and you can still see the some background between particles in the camera images. In the special case of **four-pulse Shake-the-Box** recording, the seeding density must be lower (at least a factor of 2) than for all recordings illuminating each frame once to meet this condition.

- If you can only see bright particles and no more background in between, then the particle density is too high. For 4-pulse Shake-the-Box, this condition has to be met in the 4-pulse illumination mode, not only for a single illumination per frame.

Defining pulse separation time dt:

- Adjust the time separation dt between first and second exposure such that the particles move about 7-10 pixel at maximum. For 4-pulse Shake-the-Box, this is the time separation Dt2 between the 2nd pulse illuminating frame 1 and the 3rd pulse illuminating frame 2. Double exposure of a particle in the nearly same position must be avoided, i.e. the minimum pulse separations $Dt1$ and $Dt3$ of the pulses illuminating the same frame has a lower limit determined by the slowest recorded region in the flow field. This lower limit does not apply to $Dt2$ at pulse 2 and pulse 3 illuminate separate camera frames. Therefore, it should always be assured that $Dt2 \geq Dt1$ and $Dt2 \geq Dt3$. Usually $Dt2$ is by a factor 2 to 4 larger than $Dt3$ $Dt1$, while $Dt1 = Dt3$. How much the first and last pulse separation can be larger that between the central pulses depends on the flow field and on the seeding density. The more regular the flow field and the larger the seeding density, the better the particles can be tracked even with a larger pulse separation.

Reduced seeding density for volume Self-calibration

- First, recordings for volume self-calibration should be done. Though, it may be possible to perform a volume self-calibration at the high ideal seeding density if the disparities are not too large, it is recommendable to record images at lower seeding density for volume self-calibration.
  - Therefore, reduce the seeding density in the flow to about one fifth
  - OR, if this is not possible, reduce the illuminated volume thickness to about one fifth using the mechanical aperture. Make sure that recordings with illuminated particles all over the volumes are obtained, i.e. the aperture has to be moved along the depth direction. Volume Self-calibration can only be performed where particles are recorded.

  Then, record approximately 100 particle images with low particle density for volume self-calibration purposes. After the recordings for volume self-calibration
  - Increase seeding density again
  - OR restore full volume illumination.
- In the special case of **four-pulse Shake-the-Box** recording, it is recommendable to record separate images for the volume self-calibration which use only a single laser pulse per frame. This excludes effects on the optical transfer function and on the volume self-calibration by overlapping particle images due to a double-exposure of the two frames. If the particle seeding density is optimized for four-pulse Shake-the-Box, illuminating with only one pulse per frame will reduce the effective particle seeding density in the image by a factor of 2. This means that, having found the optimal seeding for 4-pulse Shake-the-Box, by simply reducing the number of illuminations, a good particle seeding density is recorded for Volume Self-calibration.

Record particle images

- Second, with the optimal, higher, seeding density evaluated above, record as many particle images or series of particle image-recordings as you need for the final analysis.

3.8 Image preprocessing

Image preprocessing is the sixth step in the sequence of operations in the list at the beginning of chapter 3. Most raw camera images are preprocessed before further analysis, for instance to reduce background noise, e.g. due to reflections in the setup.

For more information on image preprocessing see section 4.1 in the 'Software reference' chapter.

3.9 Volume Self-calibration

Volume self-calibration is the seventh step in the sequence of operations listed at the beginning of chapter 3.

- The purpose of Volume self-calibration is to remove any residual calibration disparities using recorded particle images
- Volume self-calibration requires two steps: 1st: calculation of the disparity vector map and 2nd: correction of the calibration (mapping function)
- These two steps can be repeated again and again, until the remaining disparity is below 0.1 voxel in all sub volumes.

The principle of volume self-calibration and the software settings are described in section 4.2.1.

3.10 Calculate optical transfer function

This section describes the eights step in the sequence of operations listed at the beginning of chapter 3.

- The optical transfer function (OTF) is **required** for Shake-the-Box

- It allows to precisely **reconstruct virtual camera images** from 3D particle positions
- Reconstructed camera images are used to **optimize** 3D particle **positions** and **intensity**
- The OTF is calculated after volume self-calibration
- First, **average particle patterns** are calculated, using the same operation as in volume self-calibration in the Volume Self-Calibration dialog. This has to be done before leaving the dialog. Then, the OTF is stored in the Properties section of the project.

3.11 Calculate particle tracks

This section describes the ninth step in the sequence of operations (3).

- Particle tracks are calculated using preprocessed particle images
- The operation **’Shake-the-Box’** from the group **’3D-PTV processing’** is used in the processing dialog. For double-frame and double-pulse (not 4-pulse) data, also a predictor-based method is available **’Shake-the-Box double-frame with predictor’**.

More details are given in section 4.3.

4 Software reference

4.1 Image pre-processing

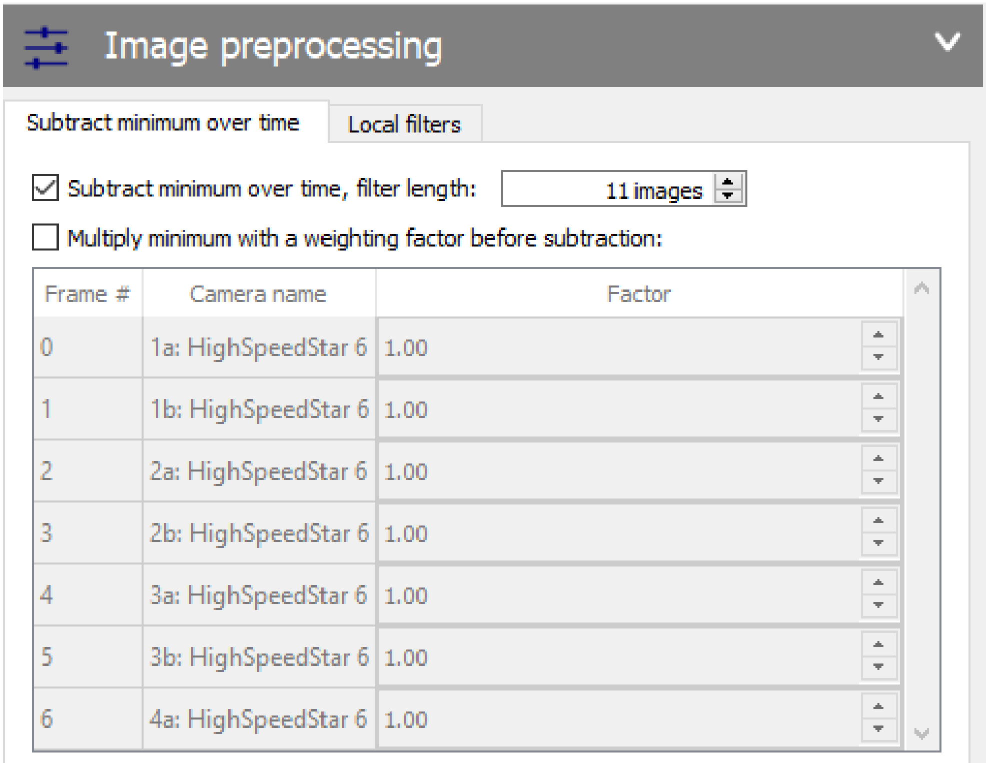
This section describes the sixth step in the sequence of operations listed at the beginning of section 3. Use the processing operation 'image preprocessing' from the '3D PTV processing' group to do the image preprocessing on all recorded particle images

Image preprocessing is often a necessary step before the Shake-the-Box calculation and the volume self-calibrationwith the calculation of the optical transfer function.

The purpose of image preprocessing is to remove the camera background and the camera noise and, in this way, to achieve nicely shaped particle images with zero background. Additionally, a 'geometric mask' can be used to remove noise or reflections in- or outside the desired illuminated part.

In the batch processing group **'Filter'** the batch operation **'Image preprocessing'** exists, that allows a combination of several image preprocessing steps in a single operation.

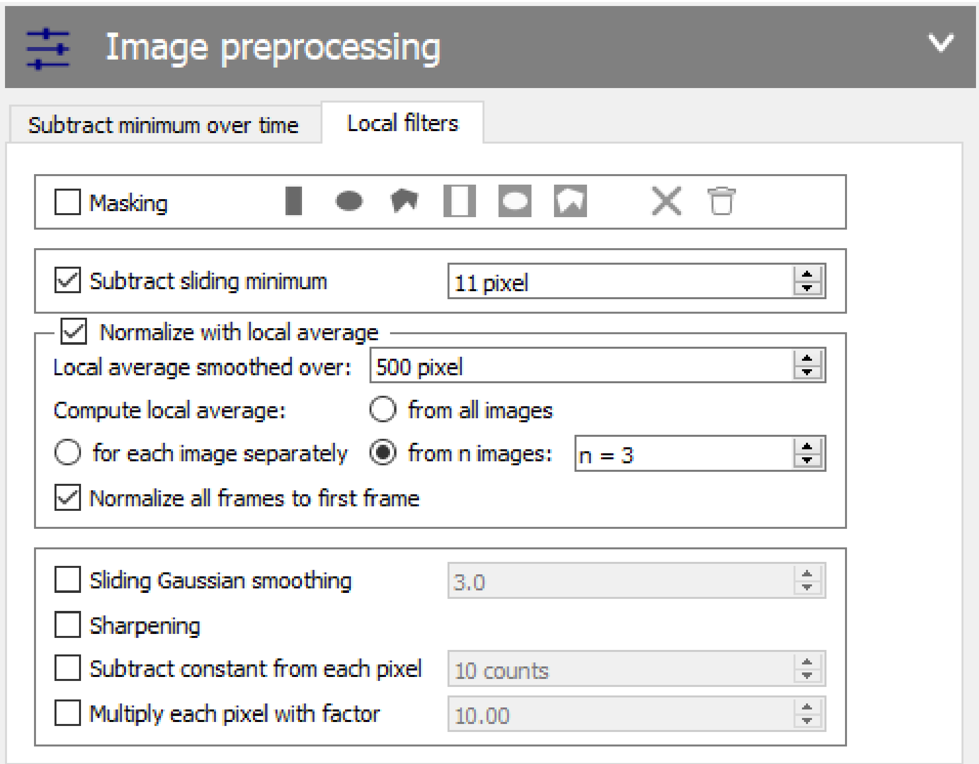
It is very important to use the same preprocessing and type of images (same seeding, same camera adjustment etc.) for the calculation of the optical transfer function and for the Shake-the-Box calculation. Otherwise, the optical transfer function will not fit to the images. The following figure displays **recommended settings** that can be used with typical recordings of particle images:



The individual preprocessing steps are separated into two parameter cards. The first card is called Subtract minimum over time and contains the following options:

- **Subtract minimum over time:** This option enables the subtraction of the minimum image intensity found within all images in the range of the specified filter length. The preprocessing is performed for each pixel separately. The filter length is always an uneven number of images and is at least three. The maximum filter length needs to be smaller or equal to the number of images in the source set.

- **Multiply minimum with a weighting factor before subtraction:** When activating this option, the sliding minimum calculated before will be multiplied with the specified weighting factor to reduce the background noise even more. The weighting factor can be adjusted for each frame (camera) individually.



Within the second parameter card, all available spatial/local filter operations are accessible. The individual preprocessing operations are calculated in sequence from top to bottom. The steps are the following:

The individual preprocessing steps are calculated in sequence from top to bottom. The steps are the following:

- **Masking:** Here, a geometric mask can be defined for each frame separately. In order to do so, select the desired mask and draw the shape directly into the Source display, then switch to the next frame and draw the mask accordingly. An arbitrary number of masks can be combined. By clicking on the red cross symbol, the selected mask is erased and by clicking on the bin, all masks are deleted. For more information on mask creation, see chapter 'masking functions' in the **DaVis Software Manual #1003001**. The use of a geometric mask is recommended to mask out areas with very weak or no laser light illumination and to get rid of reflections or other image artifacts that are no particle images.

- **Subtract sliding minimum:** this spatial pre-processing filter is used to remove the image background by subtracting the local minimum from each pixel. The size of the local region (in pixel) can be adjusted by the parameter. The smaller the particles are, the smaller can be the region: use a region of 5×5 pixel for small particles. Use 11×11 pixel for bigger particles. This filter does not use temporal information, so it is no minimum over time.

- **Normalize with local average:** Use this filter to equalize the particle intensity on a larger scale (typical 500 pixel) . This can be used to normalize for inhomogeneous laser illumination, intensity differences due to changes in the scattering angles (mainly in air) and intensity differences between the first and the second laser pulse.

  The parameter **Local average smoothed over** determines the size of the local normalization filter. 100 pixel is a good start value for many images. For small images (e.g. from high speed cameras) or smaller structures you may lower the filter length (e.g. to 50 pixel). For large images (e.g. from cameras with 11 Mpixel or more) or large structures you may increase the length (e.g. to 1000 – 2000 pixel).

  Compute local average ... has two different modes: **from sum of all images** and **for each image separately**. The first mode should be used for low seeding densities to get a better local average intensity by using the sum of all images. The second mode can be used for higher seeding densities and is faster than the first mode.

  Normalize all frames to first frame normalizes the average intensity for all cameras and exposures to the first cameras and first exposure. This option should be used in general. After applying this filter, the average intensity from all cameras and all exposures will be the same. This makes sure, e.g. that the threshold for particle detection that is used for
  method will work equally well for all cameras.

- **Gaussian smoothing:** For low seeding density or noisy images, one can apply a Gaussian smoothing filter to improve the particle images. This filter increases the particle size. Hence, particle overlap will become stronger, especially for higher seeding densities. Overlapping particles are more difficult for the Shake-the-Box algorithm. For low seeding concentrations this is not a problem.

- **Sharpening:** The sharpening filter can be used after Gaussian smoothing to reduce the effective particle size again. This filter is more useful for Tomographic PIV than for Shake-the-Box. Using Gaussian smoothing and sharpening together results in a good noise reduction without spreading the particles too much or without increasing the ghost energy for Tomographic PIV.

- **Subtract constant from each pixel:** This filter should be used, if there is still a noisy background in between particles after the previous image pre-processing steps. To get a low number of ghost particles, it is helpful to lower the background noise to zero counts.
- **Multiply each pixel with factor:** The intensity of the particles may be low after image pre-processing. Images are stored in 16 bit format by default, allowing intensities from 0 to 65000 counts. To make use of this dynamic range, it is useful to multiply the image with a factor, such that the strongest particles have about 10000 to 60000 counts.

4.2 Volume self-calibration and optical transfer function (OTF): work flow

This section gives an overview about the processing steps that are required to perform volume self-calibration and to calculate the optical transfer function (OTF). Both steps need to be done before particle tracks are calculated with Shake-the-Box.

It is strongly recommended to do a volume self-calibration before further evaluating Shake-the-Box recordings.

The figure following summarizes the processing steps.

1. **Perspective calibration:** Before doing any volume self-calibration or OTF processing, the perspective calibration based on calibration target images needs to be done. See section 3.5 for more information on the perspective calibration.

2. **Optional Image pre-processing:** Image pre-processing is optional. Depending on the image quality. Image pre-processing is used to enhance the particle image quality and to remove background noise or artifacts. If image pre-processing is used, it is very important to use the **same image pre-processing to calculate the optical transfer function and to do Shake-the-Box!** See section 4.1 for more information on image pre-processing.

3. **Volume self-calibration step 1: compute disparity vectors** Volume self-calibration seeks to eliminate any remaining calibration inaccuracy. Particle images or pre-processed particle images are used to do volume self-calibration. Volume self-calibration is an iterative process that repeats the steps 3, 4 and 5 until the remaining calibration inaccuracies fall below some threshold or the calibration does not improve any longer. More information on the first step of volume self-calibration is given in the sections 4.1, 4.2.1 and 5.

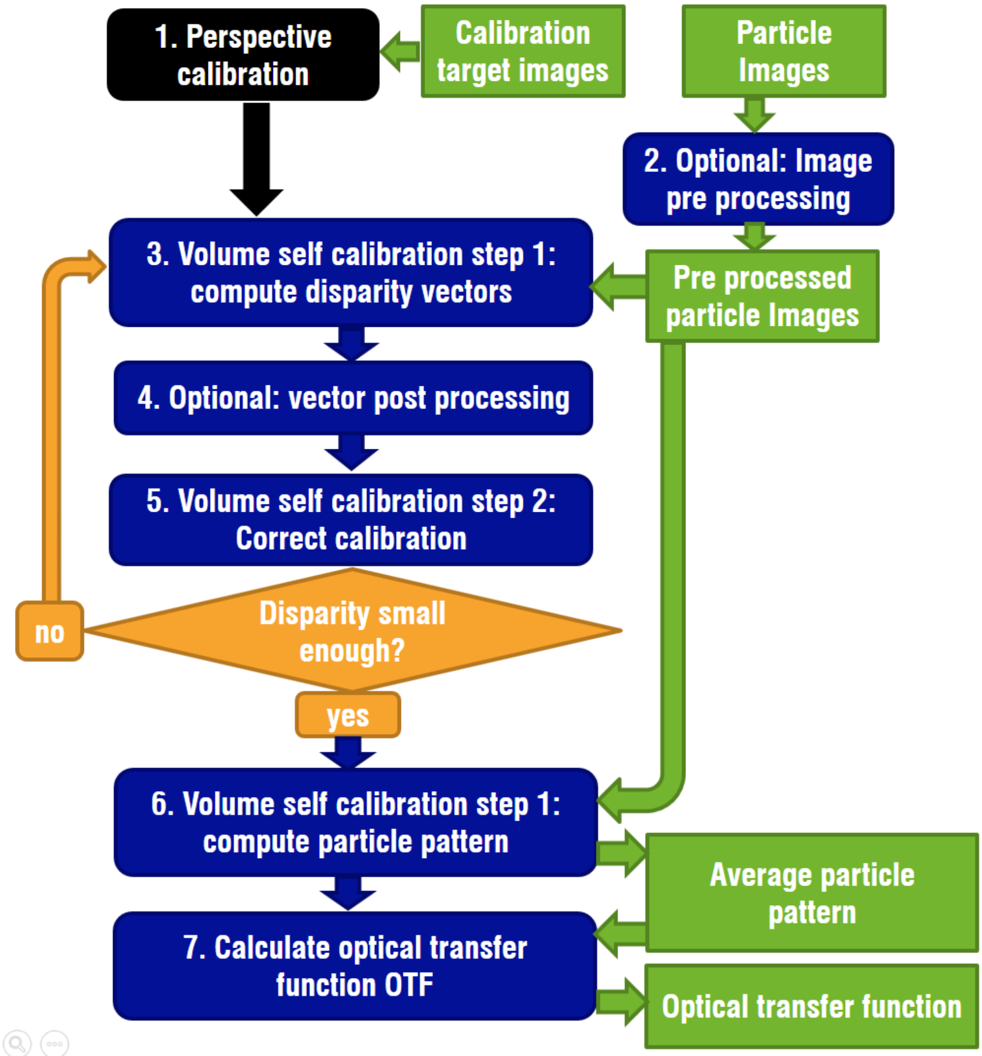
4. **Optional: vector post-processing** The result from the first volume self-calibration step is a disparity vector field. Optional vector post-processing can be used to eliminate spurious disparity vectors and to smoothen the disparity field.

5. **Volume self-calibration step 2: Correct calibration** The second step of volume self-calibration is the correction of the current calibration or mapping functions using the calculated disparity vectors. A

new calibration is generated and stored in the project settings. As mentioned above, the steps 3, 4 and 5 are repeated until the remaining calibration inaccuracies fall below some threshold. More details on the second step of volume self-calibration are given in sections 4.2.1 and 5.

6. **Volume self-calibration step 1: compute particle pattern** After the convergence of the calibration disparity correction, the first step of volume self-calibration is used again but for a different purpose. This time the aim is to calculate the average particle pattern that is produced on each camera for a certain subvolume. Later, these patterns are used to fit the optical transfer function. More information is given in section 4.2.1 and 4.2.2.

7. **Calculate optical transfer function OTF** Using the average particle pattern calculated in the last step, the final processing step is to calculate the optical transfer function from these patterns. An elliptical Gaussian model is fitted for each subvolume and each camera to represent the OTF. More information is given in section 4.2.2.



4.2.1 Volume self-calibration

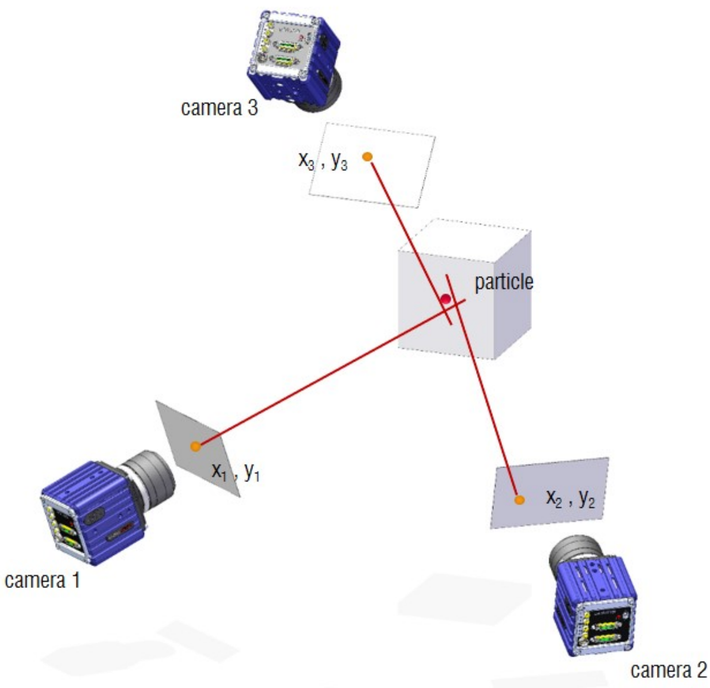
Volume self-calibration is implemented as a two step procedure: First the disparity vectors are calculated, then the perspective calibration is corrected using the disparity vectors. Vector post processing can optionally be applied between step 1 and step 2 to get rid of outliers or to smooth the disparity vectors.

The processing operation for step 1 is also used to calculate the particle patterns which are required to calculate the optical transfer function for Shake-the-Box.

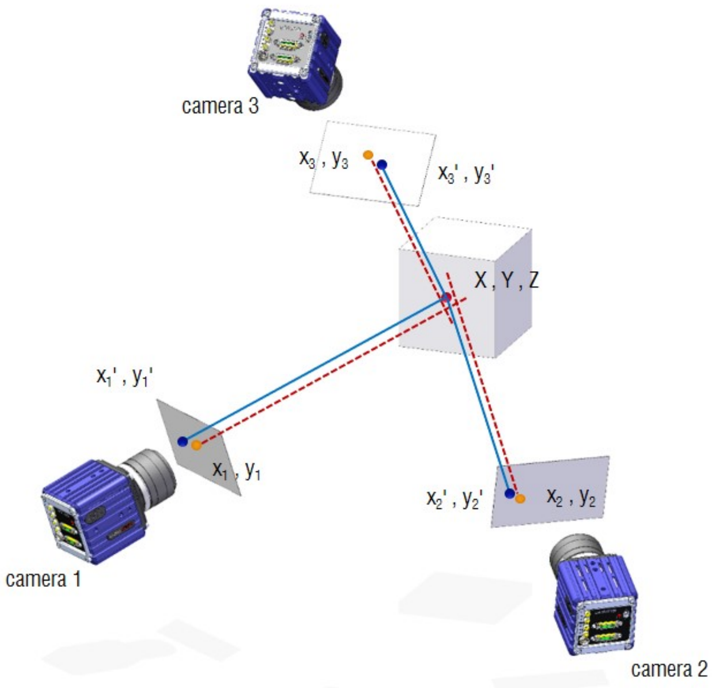
Compute disparity vectors

What are disparity vectors?

Disparity vectors indicate errors in the perspective calibration or mapping function, respectively. The concept of disparity vectors is based on the following idea: From the volumetric calibration (based on images from a 3D calibration target or multiple views of a 2D target) the **lines-of-sight** for each pixel are known: Each pixel is collecting light only from particles that are located along its line-of-sight. Consider a single particle observed by three cameras. Let the positions of this particle on the camera sensors be $(x_1, y_1), (x_2, y_2), (x_3, y_3)$. For a perfect perspective calibration, without any calibration errors, the lines-of-sight from all cameras would intersect exactly in a single point in 3D space, the true particle position (X, Y, Z).



There will always be some amount of error in a real world calibration. The result is, that the lines-of-sight from different cameras do not intersect in a single point. This is shown in the figure above. The figure reflects exactly the situation that occurs in an experiment: we can only measure the sensor positions $(x_1, y_1), (x_2, y_2), (x_3, y_3)$ of a particle, but we do not know the true particle position (X, Y, Z) in 3D space. For a perfect calibration where all lines-of-sight intersect in a single point, the real world position would just be the unique intersection point that can be calculated using the calibrated mapping functions. In the case of calibration errors, like in the figure above, we need to **estimate** a 'best guess' for the 3D position (X, Y, Z): we select a point (X, Y, Z) that is somehow closest to the lines-of-sight from all cameras. This problem is known as the triangulation problem in particle tracking velocimetry (3D-PTV).



Once we decided on a 'best guess' 3D world position (X, Y, Z) for the particle, we can use the mapping functions from the perspective calibration to **project this position back** on each camera sensor as shown in the figure above. The back projected positions are labeled (x'_1, y'_1), (x'_2, y'_2) and (x'_3, y'_3).

Now, we can define the **disparity vectors** for each camera $\vec{d_1}$, $\vec{d_2}$ and $\vec{d_3}$ as vectors pointing from the particle positions on the sensor to the respective back projected positions:

$$\vec{d_i}(X, Y, Z) = \begin{pmatrix} x_i \\ y_i \end{pmatrix} - \begin{pmatrix} x'_i \\ y'_i \end{pmatrix}, \; i = \{1, 2, ..., N_{cameras}\} \tag{4.1}$$

Clustering of disparity vectors: Disparity Map

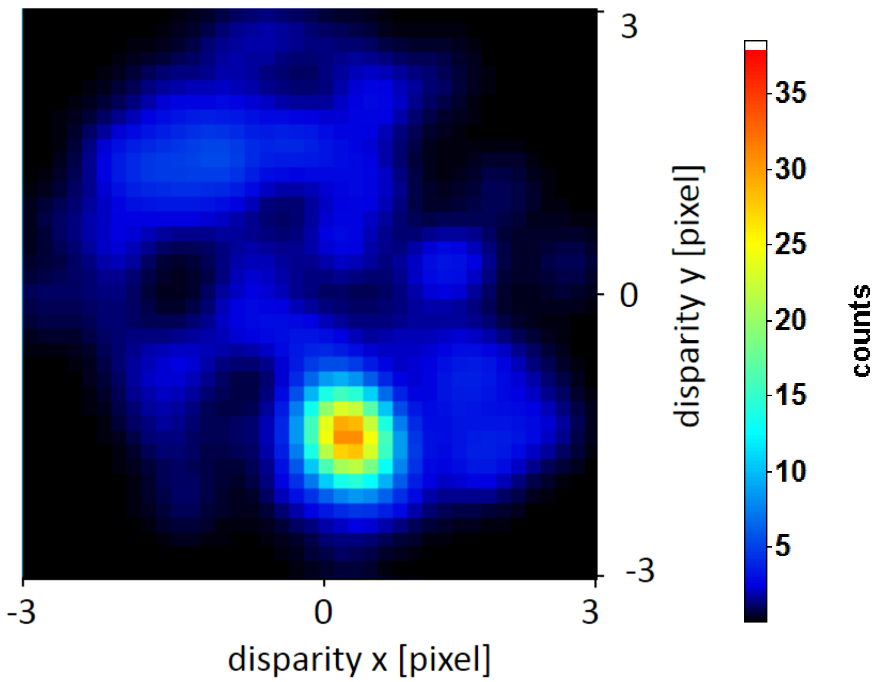
Using the definition for disparity vectors from equation 4.1, a disparity vector can be calculated for **each individual particle** that is recorded in the camera images. As the goal of volume self-calibration is the correction of the mapping functions, it makes sense to divide the measurement volume into a number of discrete **subvolumes** N_x x N_y x N_z and to combine the disparity information of all particles within a specific subvolume. Since the 'best guess' 3D world position is known for each particle from triangulation, the assignment of each particle to a certain subvolume is easily achieved.

The task is now to calculate **an average disparity vector** for each subvolume **from all particles** that are located in this subvolume. It was found that **simple averaging** of all disparity vectors **did not work well** due to **outliers** that often lead to strong bias errors in the average. A more robust clustering algorithm is applied, which determines the most likely disparity value or the mode value. To this end, a 2D probability density function (PDF) with 40×40 bins is created. 40×40 bins have been found to be a good compromise between spatial resolution and accuracy. The size of each bin is explained below.

The **range** that is used for the disparity vector **PDF** is based on the following idea: For the 3D particle detection algorithm that is applied here, a **maximal allowed triangulation error** ϵ_T has to be specified. As a consequence, the disparity vectors, calculated by the re-projection of the best guess positions, cannot be larger than the maximal allowed triangulation error ϵ_T in any case. So it makes sense to restrict the range of the disparity vector PDF by $\pm\epsilon_T$. So if e.g. the maximal allowed triangulation error ϵ_T of **three pixel** is applied, then the range of the disparity vector PDF will be from **-3 pixel to 3 pixel** in the x- and y-direction. As the number of bins for the PDF is fixed to 40×40 here, each bin will represent disparity vectors from an area of $2 \cdot 3/40$ pixel in this example or 0.15×0.15 pixel.

Usually, a PDF is generated by assigning each relevant value to a single bin. Here, that would mean, the (x,y) value of the disparity vector of each individual particle in the respective sub volume is assigned to one bin resulting in the two dimensional PDF of all particles in the sub volume. The most likely value in this PDF could be identified as the total disparity within this sub-volume. However, it has turned out that the sub-pixel accuracy of the location of the total disparity in each sub-volume can be estimated more precisely if not only a single bin for each particle disparity vector is added to the histogram. Instead, a 2D Gaussian blob of height 1 and width of one-tenth of the maximal allowed triangulation error ϵ_T such that the bin of each particle disparity vector adds up to the adjacent bin as well. Here, the definition of the Gaussian blob width was again found to be a good compromise between spatial resolution and accuracy.

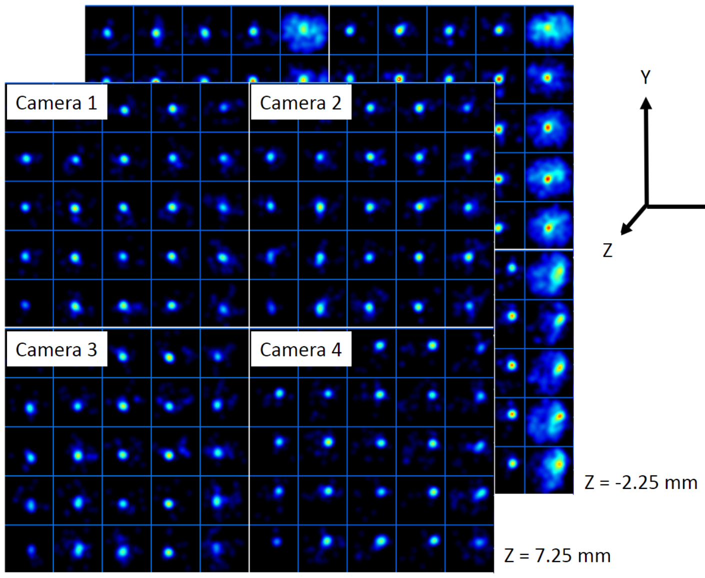
This special PDF, made up by summing Gaussian blobs from disparity vectors of all particles within a subvolume, is called **disparity map** in the following.



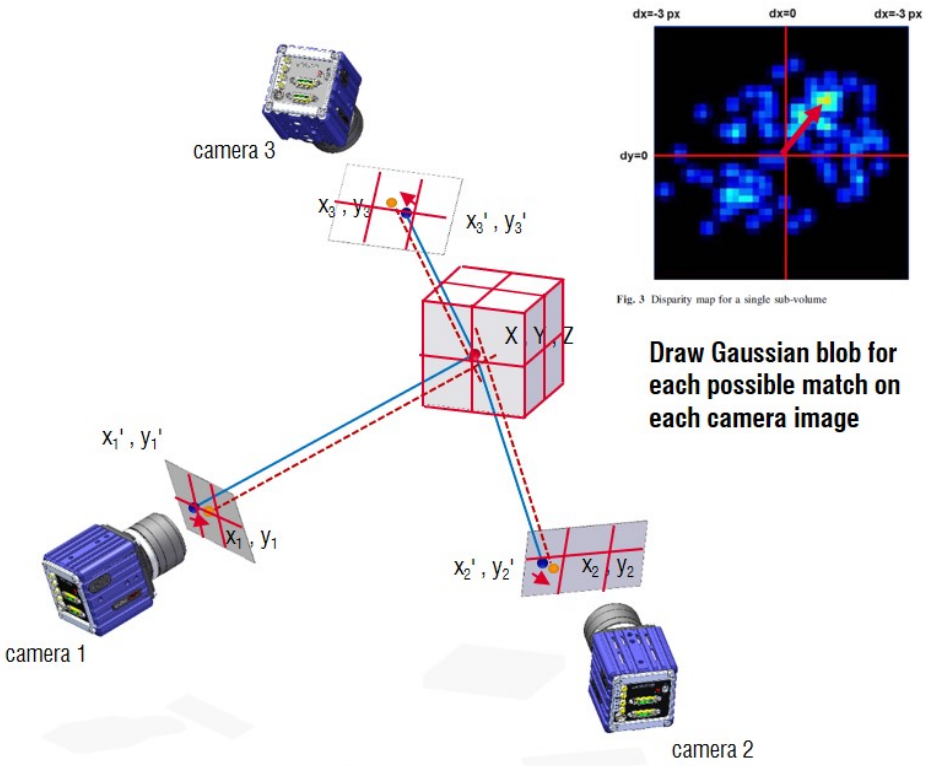
An example of a disparity map, made up by Gaussian blobs from several particles and a maximal allowed triangulation error ϵ_T of 3 pixel is shown in the figure above. Note that the peak (red) does not represent the blob of a single particle. It is made up by **the sum of many particles**. As the intensity of the peak is about 35 counts, this peak is made up by the sum of at least 35 particles at that disparity map location.

Also note the presence of a background of Gaussian blobs in the disparity map that are far off the peak location (dark blue regions). These **outliers**, as mentioned above, prohibit the application of simple averaging. The reason for these outliers will be discussed later in more detail.

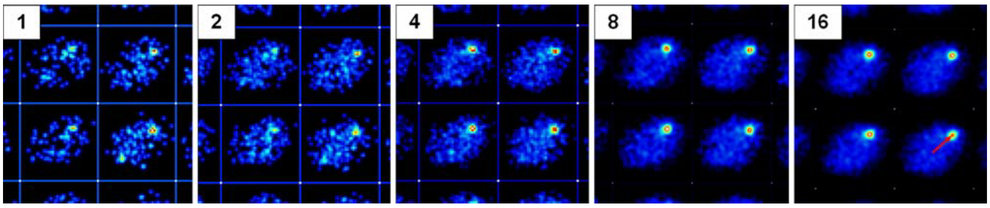
Partitioning of the measurement domain



As the disparity may not be constant all over the measurement domain, the measurement volume is divided in several subvolumes. Disparity maps are generated for each subvolume and each camera. In the example above, the measurement volume has been divided in 5 × 5 × 2 **subvolumes** for each of the **four cameras** in use.



Using multiple images

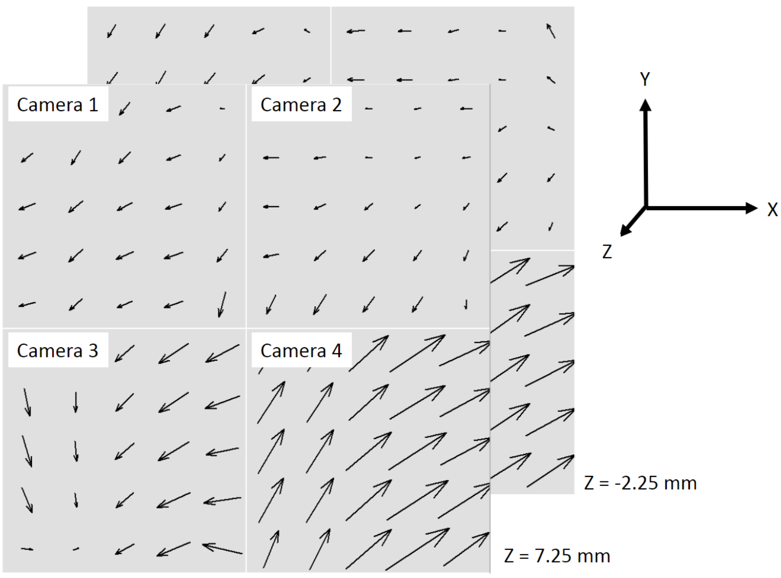


Assuming that the disparity is constant during the recording of a series of particle images, the information from many time steps can be used to increase the effective number of particles that contribute to the disparity maps. This increases the signal-to-noise ratio. In the figure above, disparity maps are shown that have been calculated from a single image (left), from two images, from four images, from eight images and finally from sixteen images (right). Note how it is difficult to find the true peaks from only one image (left) and how the true disparity peak becomes clearer and the signal-to-noise ratio increases when using more and more images.

Typically, **at least 50 to 100 images are used for volume self-calibration**. In special cases more images can be used (1000 or more). If analysis time is not critical, simply all images from a recording should be used. It will always be advantageous to use more images.

Disparity vectors

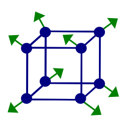
Disparity vectors are calculated from the disparity maps.

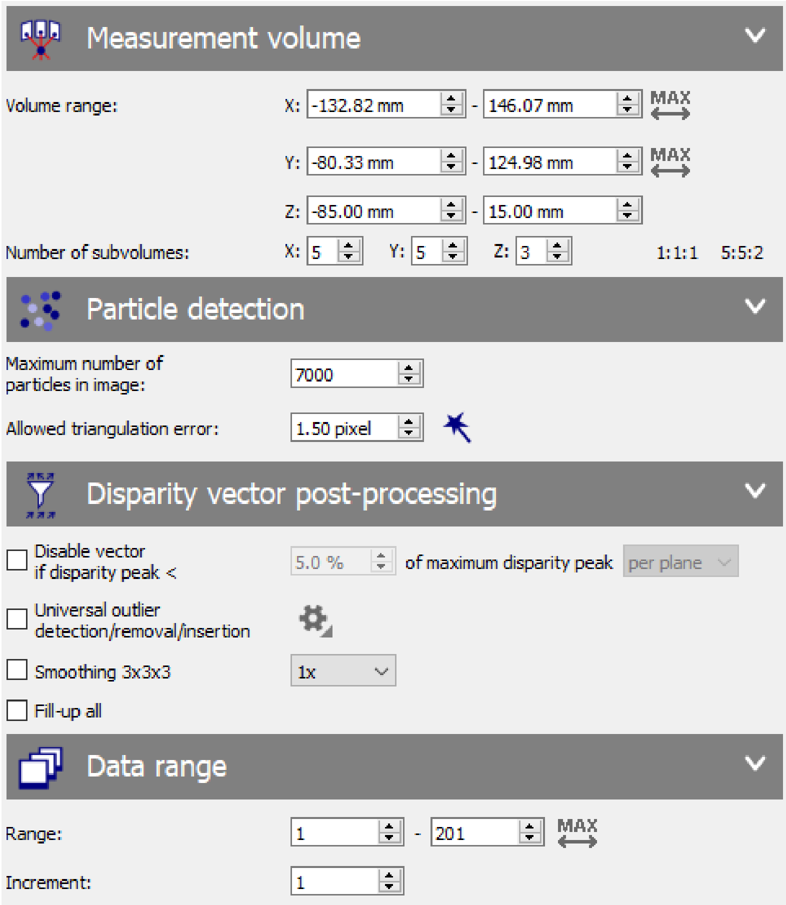


The offset of the peak from the center position in each disparity map describes the most likely disparity for a given subvolume. The peak position is determined with sub-pixel precision for all disparity maps. The disparity is then visualized by fields of 2D vectors. Corresponding to the number of disparity maps in the example above, there are **5 x 5 x 2 disparity vectors** for each of the **four cameras**. Note how the disparity pattern is different for different cameras. On the other hand the disparity pattern changes only slightly for different z-positions of the same camera. The disparity vectors often show a systematic pattern for each camera. Random disparity vectors are often a result of noisy or non-converged disparity maps. In this case the number of images used for processing should be increased. Individual outliers in the disparity field can be replaced using 3D vector post processing.

Software settings

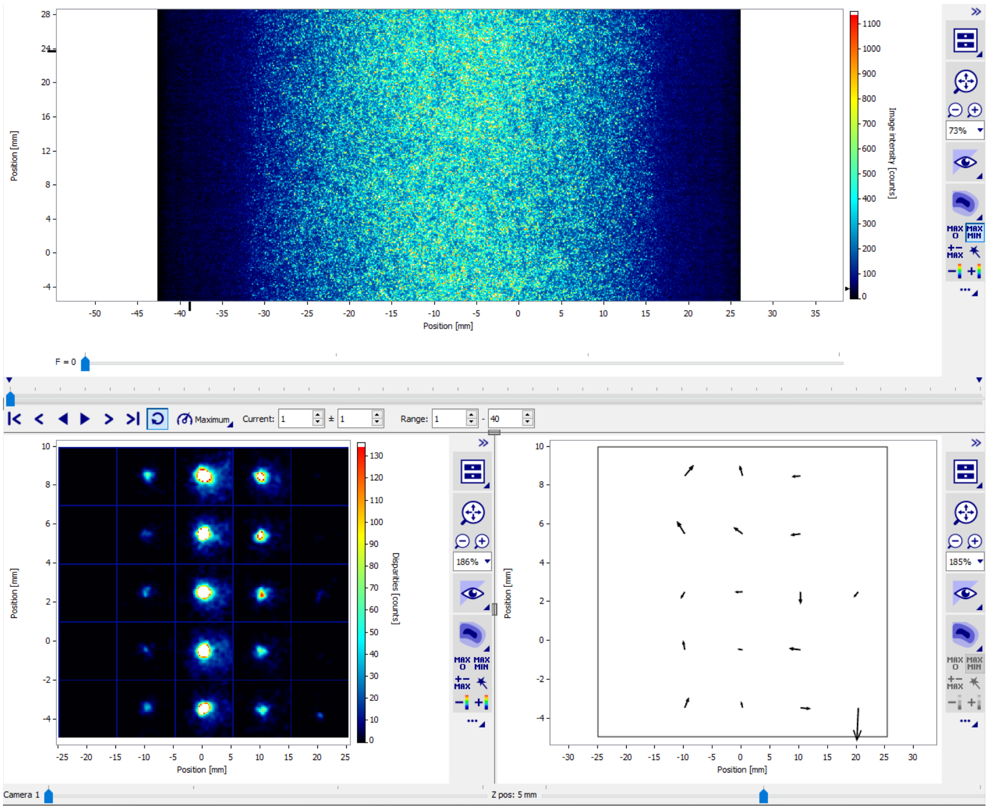
To perform volume self-calibration, select the raw or pre-processed **particle images as the source** for the processing and enter the **volume self-calibration dialog** with the button displayed in the margin.



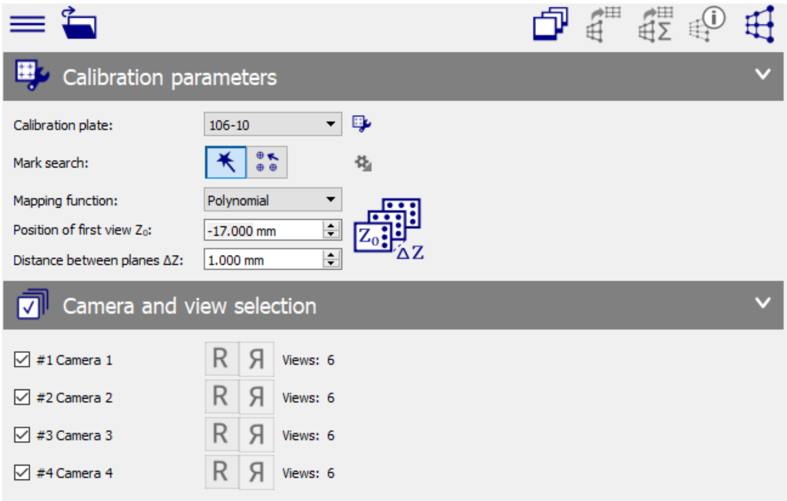


The volume self-calibration dialog will show up with the parameters listed on the left side. The settings for **Measurement volume**, **Particle detection**, and **Data range** can be expanded and collapsed.

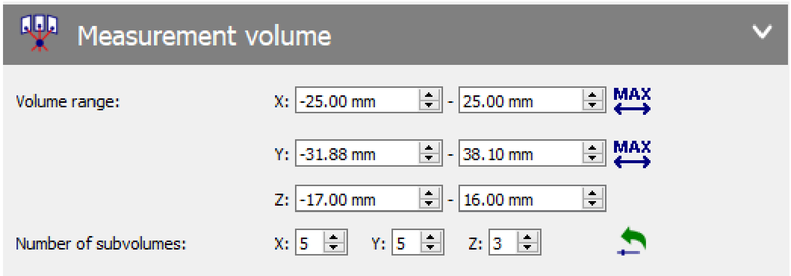
In the **Measurement volume** subdialog, the measurement volume is defined in physical space in mm scale. Using the **’max’** buttons for ’volume x-range’ or ’volume y-range’ will set the volume corresponding to the size of the corrected images (which is determined during the perspective calibration dialog). This is often a reasonable choice, if the illuminated part covers the complete recorded images.



If, however, the illuminated part covers only a fraction of the recorded images, then it is useful to reduce the volume to the actually illuminated part. If the volume, specified in this dialog, contains parts that are not illuminated, the corresponding disparity maps will show only very weak peaks or no peaks at all. This situation should be avoided because for such disparity maps the resulting disparity vectors are not reliable. In the figure above, the laser illumination does not cover the complete image in the horizontal direction, there are dark bars at the left and at the right of the images. Correspondingly, the disparity maps at the left and at the right show no peaks. The **'volume x-range' needs to be reduced** in this example to get peaks in all disparity maps.



The setting of the z range in the peak triangulation dialog has to correspond to these settings defined before, as shown below.



Please keep in mind that for a perspective calibration with a single view of a 3D calibration plate, the calibration plate should be positioned in the center of the measurement volume.

3D disparity map parameters

Also **number of sub-volumes** is specified in the **Measurement Volume** sub dialog for the x, y and z-direction. The volume specified in the other sub dialog is evenly divided in as many subvolumes as specified here, e.g. $5 \times 5 \times 3$ subvolumes in the figure above. A disparity map and a disparity vector is calculated for each subvolume separately. The subvolumes do not overlap. A new 3rd order polynomial mapping function is fitted using the disparity information from each subvolume. A polynomial is fitted for each subvolume in the z-direction. As a polynomial fit of order 3 needs some minimum number of data points for the fit to be stable (e.g. not oscillating between data points), the minimum number of subvolumes is restricted to 5×5 in the x- and y-direction. Also, usually, it is not necessary to use a much bigger number of subvolumes in the x- and y-direction. The number of subvolumes in the z-direction needs to be at least two in order to get a line of sight calibration or volume calibration. The number of subvolumes in z also depends on the thickness of the measurement volume: If the volume is thin, two sub volumes will be enough, if the volume is thicker, more subvolumes can be used. Usually 2 to 3 subvolumes in z are enough to get converging volume self-calibration results.

To reset the default value, a default button is present at the right side, which sets the values to $5 \times 5 \times 2$ again.

In the **Particle detection** parameter subdialog, the **Maximum number of particles** is specified. According to this number, the brightest particles from each camera image will be detected. This number is applied to each individual time step in a recording series and also to each frame in a double frame image. If there are fewer particles in the image than specified by this number, all detectable particles will be used. Depending on the camera sensor size and the particle concentration, this number may vary from about 1000 to 200000 or even more (for large sensors and high seeding concentrations).

During multiple iterations of volume self-calibration, it is often useful to start with a small number (e.g. 1000 particles) to capture initial large disparities. Using a small number in the beginning, limits the number of ghost particles that could otherwise be overwhelming if large triangulation errors (see below) result from capturing large initial large disparities.

In later refining iterations, the number of 2D particles can be increased and the triangulation error will be decreased.

The number of actually detected particles is shown at the bottom in a yellow box.

Specifying a **huge number** for the 'Maximum Number of particles' (like 1000000 in the example above) will effectively show all 2D particles or all 2D peaks available in each camera frame (however, counting two overlapping particle with a single peak as only one particle). Depending on the data quality and the image pre-processing, this number may include only 'real' particles (for perfect image quality) or more or less false particles that result from random peaks of some noisy background. So one should not blindly trust this number as being all real particles. Still, it will give an idea about the absolute maximum number of particles that can be expected.

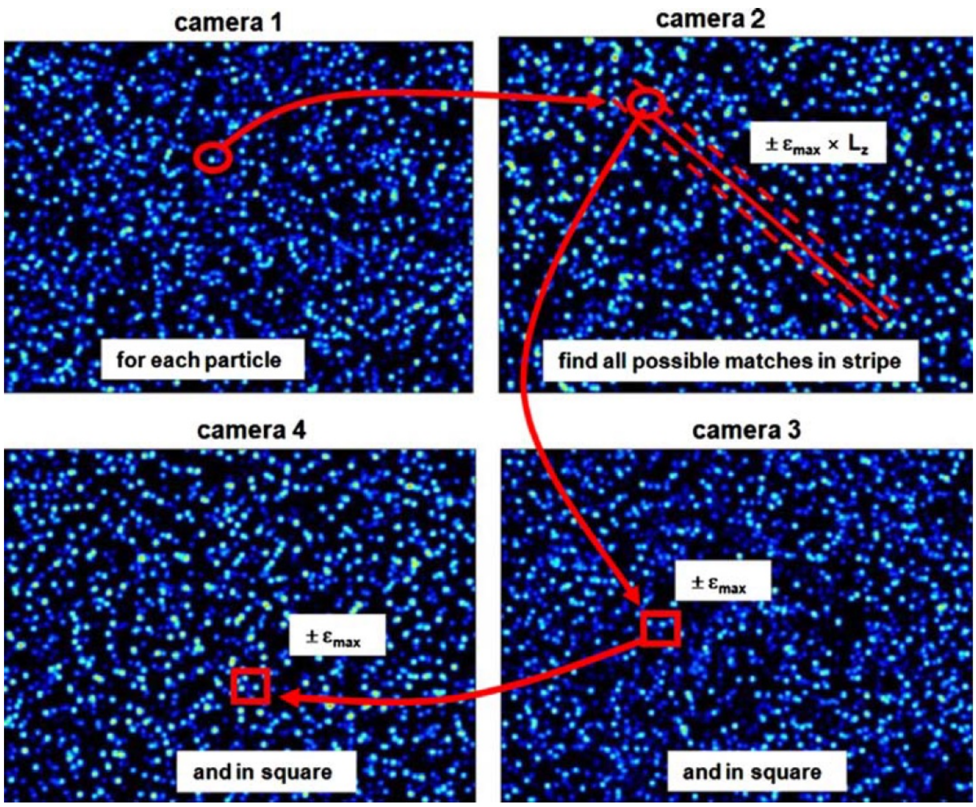
'Allowed triangulation error' parameter: As described above, volume self-calibration is based on position detection of individual particles in 3D space from multiple camera images, which is called 'triangulation'. As we seek to correct an unknown amount of calibration disparity, we need to take into account, that the lines-of-sight of a single particle from the different cameras will usually not intersect in a single point in space. The lines-of-sight from all cameras may come close in the vicinity of the true 3D position of the particle, but they will not intersect in a single point. There will be some deviation of the lines-of-sight. This deviation is quantified by the **average length of the disparity vectors** for each particle, called the **triangulation error** (equation 4.1). The **'allowed triangulation error'** (ε_{max}) parameter determines the amount of deviations of the lines-of-sight that should be tolerated by the triangulation procedure: only particles with a triangulation error **below or equal to** the 'allowed triangulation error' are **used to build up the disparity maps**. Particles with a triangulation error **above** the 'allowed triangulation error' are **rejected**.

On the right side of the Allowed triangulation error box, a magic wand is displayed. This button allows for an automatic detection of the allowed triangulation error parameter. Using this auto button can help to get a reasonable starting value for the triangulation error: When 'auto' is pressed, the triangulation error is first set to 0.5 pixel. The triangulation procedure is run and the number of detected 3D particles is determined. Then the allowed triangulation error is increased in steps of 0.5 pixel unless at least as many 3D particles have been detected as 2D particles have been specified as the 'peak detection 2D' parameter: 'Maximum number of particles'. The simple idea is, that there should be one 3D particle for every 2D particle in the images. Using the 'auto' button should give a good starting value for the further processing. When the 'auto' procedure is finished, the disparity maps should be calculated from all available input images (or at least using a sufficiently large number of input images).

If this procedure leads to a large triangulation error (bigger than 5 pixel) and one does not get convincing peaks in the disparity map, one can lower 'maximum number of particles' in the 'peak detection 2D' parameters.

Detect matching particles

The 'allowed triangulation error' ε_{max} plays a second important role for the detection of matching particles in the different camera images. Up to now, it was assumed that the positions of a specific particle in each camera image are already known. Considering images with a large number of particles, like in the following figure, the problem to be discussed now is **how to find matching particles in all camera images** representing the same particle in 3D space. For the naked eye it is nearly impossible to detect the position of the same particle in different camera images. All particles look very similar and a particle cannot be detected reliably by its shape or intensity. However, from the perspective volume calibration, the line-of-sight for each pixel is known, which helps with the identification of individual particles:



Starting with the position of a **single particle in camera 1** (the particle within the red circle in the top left), and knowing the line-of-sight for each pixel, a beam can be projected through 3D space. Observed by camera 2, this beam will form a **straight line on the sensor in camera 2**. This line is called the epipolar line (red, solid line top right). In principle the length of the line-of-sight of a particle is endless, so that the epipolar line should cross the image in camera 2 from one border to the other. In practice however, only a finite volume is illuminated, so that only a finite part of the line-of-sight needs to be investigated further: As the minimal and maximal z-position of the illuminated volume is known (or can roughly be estimated), the search for a matching particle can be restricted to a certain length L_z. The endpoints of the of the projected line correspond to the points in 3D space where the line-of-sight of the particle from camera 1 enters and leaves the illuminated volume. The actual length L_z of this line is determined by the observation angle between camera 1 and 2 and the depth of the illuminated volume: the bigger the angle or the thicker the illuminated depth, the longer the line.

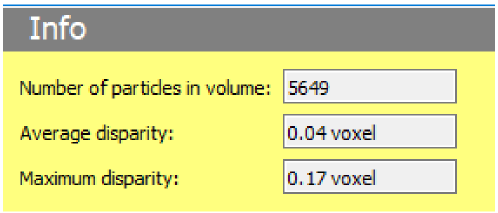
Using this epipolar geometry, the search for matching particles between cameras 1 and 2 can be restricted to the vicinity of this finite part of the epipolar line in camera 2. Due to an unknown amount of remaining calibration disparities, the matching particle **cannot be expected to be located exactly on top of this line**. This would only be the case for a perfect calibration without any errors. A certain amount of deviation from this line needs to be tolerated. This tolerance corresponds directly to the expected amount of the remaining calibration inaccuracies: If a large deviation is expected, a bigger deviation from the line needs to be tolerated. If small deviations can be assumed, the search for a matching particle can be restricted to an area closer to this line. So instead of looking for matches only on a line, an area needs to be considered that has a size corresponding to $2 \times \varepsilon_{max} \times L_z$. This area is located between the dashed lines in the top right of the figure above. All particles in this area are **possible matches** for the single particle that has been selected from camera 1.

To detect 3D particle locations, all possible matches between the particle from camera 1 and all particles inside the epipolar stripe from camera 2 are investigated further: Each particle position within the stripe is used to do a triangulation to get a hypothetic 3D position for that combination. If the 3D particle position is correct, then there need to be also matching particle positions in cameras 3 and 4 (or all other cameras if there are more than 4). The central position of this AOI is calculated by mapping the hypothetic 3D position to cameras 3 and 4 (using the known line of sight calibrations). Around this central position a square section with the size of $(2 \times \varepsilon_{max})^2$ is investigated to find also possible matching particles there (see figure above, bottom left and bottom right).

Depending on the particle density and the allowed triangulation error ε_{max} there may be only a single, a few or a large number of combinations of all the particles located in the investigated regions for cameras 2, 3 and 4. As there is no further knowledge about individual particles available, here simply all possible combinations are used to finally do a triangulation using all cameras and to detect the back projection error, and plot it in the disparity map.

How large should the allowed triangulation error be? As the remaining calibration deviation is usually unknown, a chicken-and-egg situation occurs here. The only way to solve this problem is to start with some initial guess and to optimize the settings by trial and error, inspecting the resulting disparity maps carefully for the presence of consistent peaks in all sub volumes for all cameras.

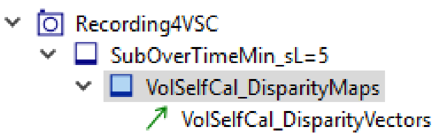
After the calculation of the disparity vector field and the optional vector post processing, the calibration can be modified to account for the detected disparities. The resulting quality of the calibration is displayed in the yellow Info box in the bottom left corner.



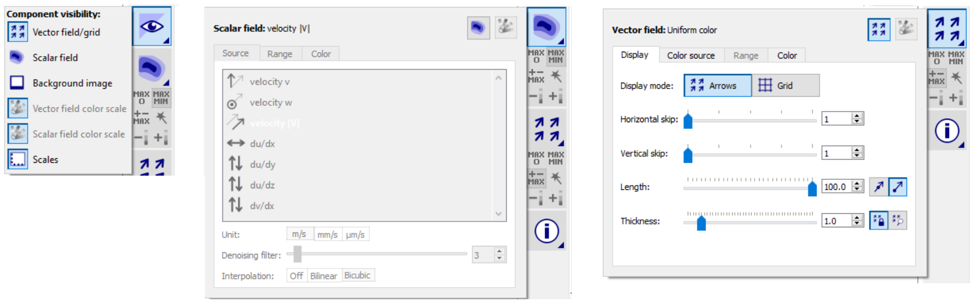
The calculated volume self-calibration correction can be accepted with the **Accept** button.

If necessary, the resulting calibration can be further refined with the Refine button. With this setting, the calibration is refined with the current settings.

The steps of the volume self-calibration can be checked also after the calibration. In the tree view of the recording used for the volume self-calibration, the disparity maps and the disparity vectors are listed.

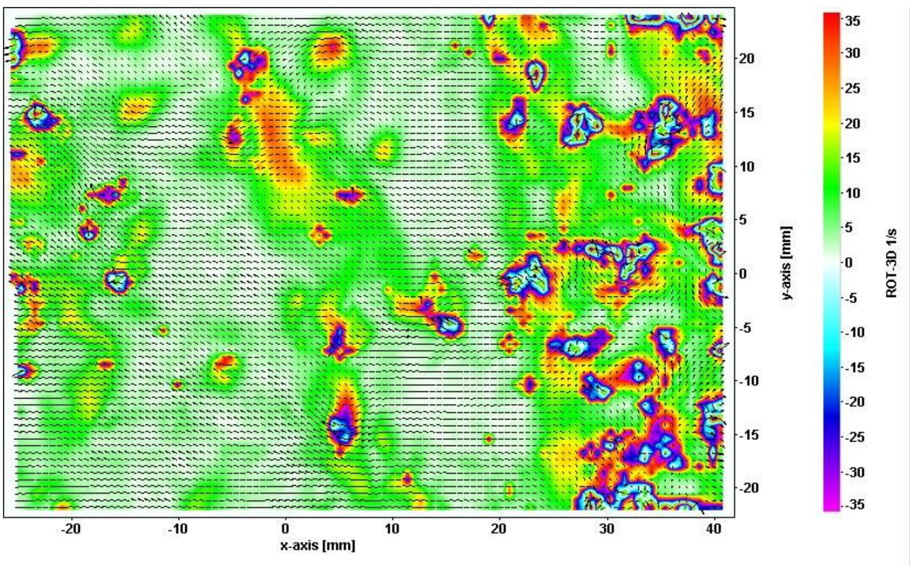


As **VolSelfCal_DisparityMaps** the disparity maps are listed for all refinement steps and under **VoldSelfCal_DisparityVectors** the information in the respective disparity vectors is stored. Here, the usually required settings to visualize these very short vectors are

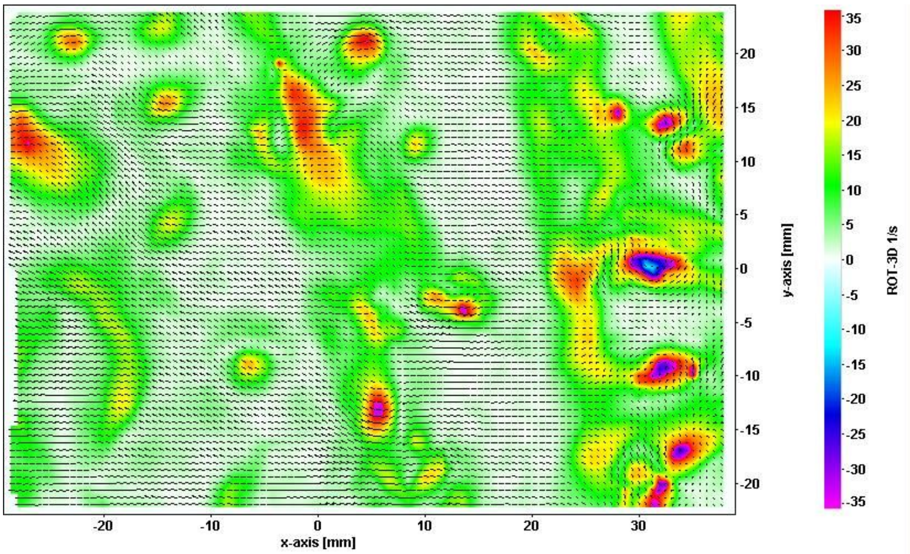


Comparison with and without volume self-calibration

The improvement in vector quality is often dramatic, especially if the calibration errors are about 2 pixel in some areas. Here is again the Karman street in water flowing to the left behind a cylinder positioned just outside the right of the image (z-position about in the middle of the volume):



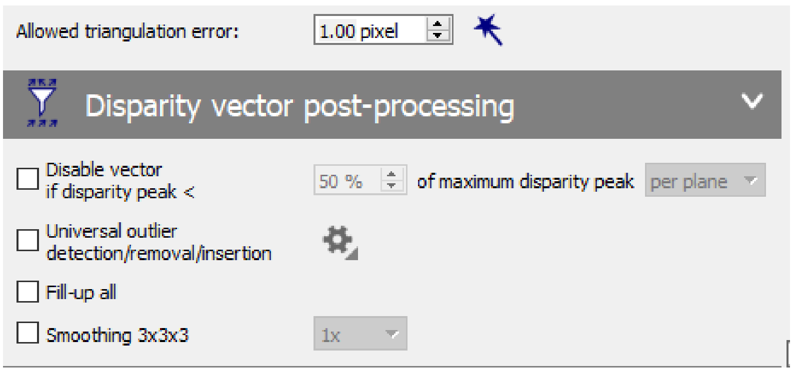
Above: no volume self-calibration, no vector post-processing, color = V_z



With volume self-calibration, no vector post-processing, color = V_z

4.2.2 Calculate optical transfer function

The optical transfer function (OTF) can be calculated as soon as the correction performed by the volume self-calibration has been accepted at least once. It has to be done for the final step of the volume self-calibration. Hence, after the acception of all refinements of the calibration required. Then, the allowed triagulation error is set to 1 to make sure that very well-fitting particles are used for the calculation of the OTF, and all vector post-processings are disabled. All other settings remain as before.

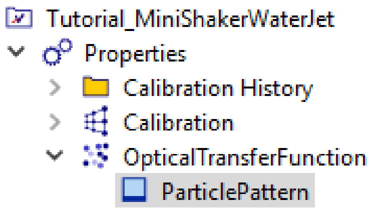


When these settings are ensured, the button **OTF** is pressed.

After the processing, a result 'OpticalTransferFunction' is created. In the result, the fitted Gaussian ellipses are plotted. **Remember the location** of this result, as the location needs to be specified for the Shake-the-Box processing as a processing parameter.

The volume self-calibration dialog is left with the **Finish** button.

Then, the OTF is automatically stored in the Properties folder of the current project and every Shake-the-Box calculation performed on data in this project with automatically use this OTF.

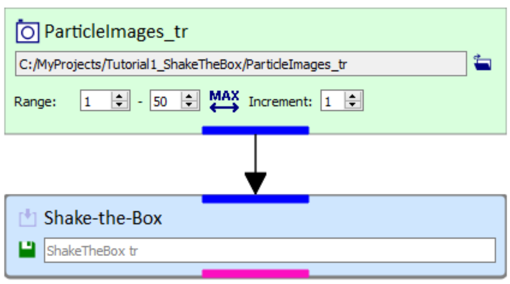


If the entry OTF is selected, the mean particle pattern will show up in the result window on the right side. When the lowest slider is moved to the right position, the OTF will be displayed.

4.3 Calculate particle tracks with Shake-the-Box

Before entering this step, **calibration, volume self-calibration and OTF calculation** need to be finished already, see 4.2 for details.

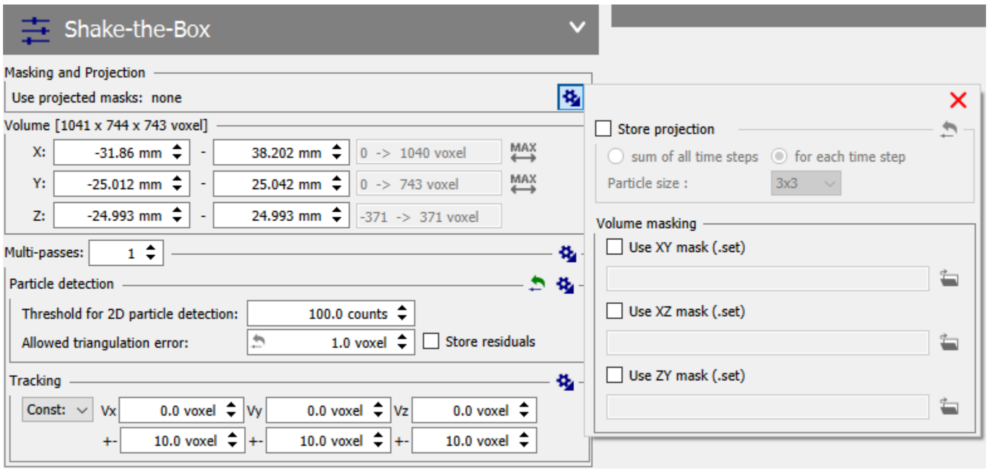
Select the particle images or the preprocessed particle images as source set. If image preprocessing is used, make sure that the same preprocessing has been applied for this source set as had been applied for the processing the source set for the calculation of the optical transfer function. Any preprocessing which alters the shape of the particle images in comparison to the preprocessing used for calculating the OTF is likely to worsen the result of a Shake-the-Box calculation. Preprocessings which do not affect the shape of the particle images, e.g. different maskings, can be used in addition to the particle image preprocessing used for the calculation of the optical transfer function.



Select the operation **'Shake the Box'** from the **'PTV-3D processing'** group. Automatically, the operation identifies from the input data set whether a time-resolved computation (tr) or a double-frame (2-pulse or 4-pulse) processing is to be performed. This is directly visible in the default storage name, i.e. ShakeTheBox tr for time-resolved data and ShakeTheBox 2-pulse or 4-pulse for data recorded as double-frames.

General parameter settings for Shake-the-Box:

- **Masking and Projection:** When enabling **Store projection**, the reconstructed particles will be used to create synthetic projection images of the reconstructed volume. These images can be created for each time step individually or as the sum of all particles of all time steps, resulting in only one volume projection. The particles will be projected as Gaussian intensity blobs with the size of them defined by the parameter **Particle size**.



With the **Volume masking** option, you can specify mask planes for the different spatial directions; XY, XZ and ZY. As the masks specified here are planar masks, they will be extended over the volume by applying the mask to each voxel plane: e.g. the XY mask will be applied to all Z-planes in the 3D voxel space.

Use the Select Set button **FOLDER ICON**, to select a **DaVis** set that contains an image with a mask. The image size has to be the same size (in pixel) as the corresponding plane in the specified direction: So for a reconstructed volume of e.g. 1000 x 500 x 250 voxel (X,Y,Z) the corresponding mask images need to have the sizes: 1000 x 500 pixel for the XY mask, 1000 x 250 pixel for the XZ mask and 250 x 500 pixel for the ZY mask. For double frame images and for time resolved images only the first time step of the masked image is used for the volume mask!

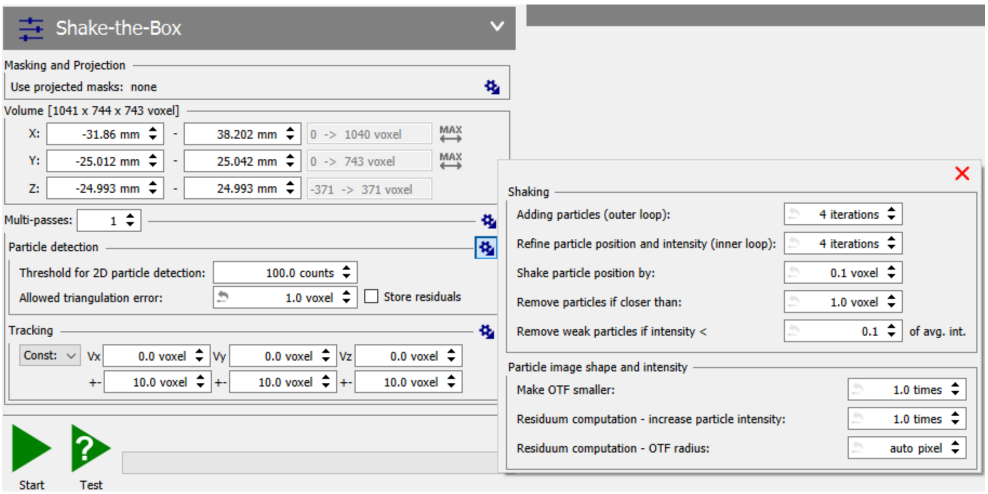
- **Volume settings - X, Y, Z:** specifies the maximum volume where particles may be detected. Using the 'max ' buttons for X and Y sets the volume to the corrected image size. After volume self-calibration the corrected image size (the buttons are deactivated if the corrected image size is specified already) is the same as the volume specified for volume self-calibration. The X and Y range of the volume can be adjusted to sizes bigger than 'max' if needed. The Z range has be known from the experiment. In doubt, the volume should be set bigger. Later the volume may be reduced again (for faster analysis) based on the visual inspection of the 3D results.

- **Threshold for 2D particle detection:** this value determines the intensity of peaks from the particle images that should be considered as particle images. Depending on the image pre-processing, the particle images may still contain some amount of noisy background. This threshold should be set to be higher than any potential noise peak to only detect true particle images.

- **Allowed triangulation error:** This parameter specifies the maximum triangulation error that is tolerated to accept particle matches from different cameras. See 4.2.1 for a detailed discussion on how this parameter effects 3D particle triangulation. Here, only well matching particles should be detected, so that very often an 'Allowed triangulation error' of 1.0 voxel is sufficient to detect matching particles. In some situation this value needs to be increased to 1.5 voxel or even 2.0 voxel to detect all particles. Using a value that is too large here can result in the detection of far too many 3D particles and prohibit a stable convergence of Shake-the-Box to the true 3D particle number. In doubt, it is best to start with a small number and increase slightly while monitoring the number of identified tracks. Usually, there is an optimum value. Below and above this value fewer tracks are detected. To judge the convergence several time steps must be analyzed. Depending on the seeding density 30 to 100 time steps may be required to achieve convergence. The 'statistics histogram' can be used to monitor the number of tracked particles.

- **Store Residuals** If this checkbox is checked, the residual images after the iterative particle reconstruction[1] will be stored. This allows for a more detailed assessment of the selected Shake-the-Box parameters. On the other hand, it does increase computation time and the required storage space.

Iterative Particle Reconstruction parameter settings for Shake-the-Box:



- **Shaking**
  - **Adding particle (outer loop):** Shake-the-Box is an iterative process with an outer loop (add particle loop) and an inner loop (refine iterations, see below). In the outer loop new particles are added using remaining particles from the residuum. The more outer loops, the higher is the possibility to detect even the last particle from the residuum. On the other hand more loops can increase the processing time significantly.
    Default: 4
  - **Refine particle position and intensity (inner loop):** In the inner 'refine' loop, the particle position ('shaking')and the intensity is updated in each inner iteration and weak or close particles are removed. The more iterations, the higher the possible precision but also the higher the computation time.
    Default: 4
  - **Shake particle position by:** This parameter defines the amount of spatial distance that is used to 'shake' the particle around to

[1] Details on iterative particle reconstruction can be found in Wieneke "Iterative reconstruction of volumetric particle distribution, Meas. Sci. Technol. (2012) **24** 024008.

find the optimal position (which minimizes the residuum). The smaller this value, the higher the final accuracy, however a smaller value may require overall more iterations. Good results have been found for values between 0.05 voxel to 0.2 voxel.
Default: 0.1 voxel

- **Remove particles if closer than:** If a 3D particle is detected very close to an already existing particle, it is likely, that the new particle results from triangulation of some left-over intensity peaks in the residuum of the other particle. Such double detections should be avoided. To do so, all particle are removed, that are too close to another particle.
  Default: 1 voxel

- **Remove weak particles if intensity $<$:** The intensity of predicted and triangulated particles is adapted in each iteration. A particle is removed if its intensity falls below the threshold specified by this parameter. The threshold is relative to the average intensity of all particles in a given time step.
  Default: 0.1

• **Particle image shape and intensity**

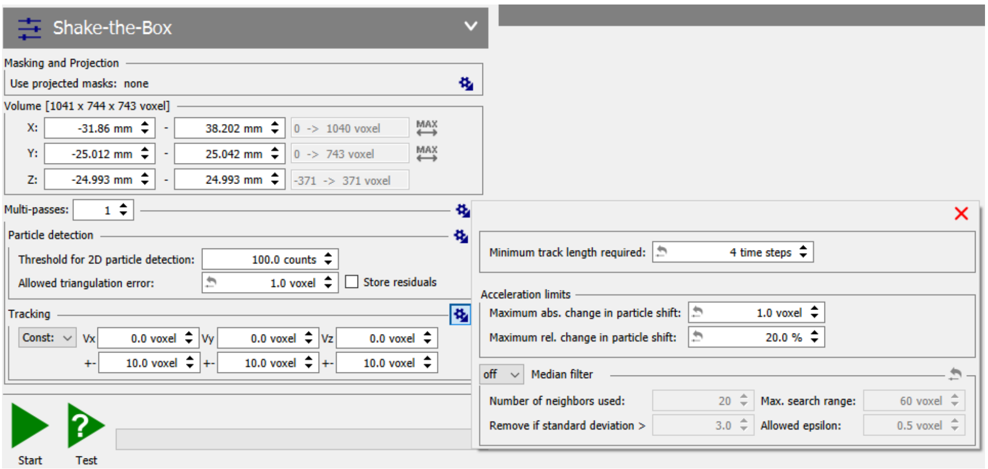
- **Make OTF smaller ... times** allows to apply a global scaling factor to broaden the OTF or make it smaller. A value greater than 1 means smaller OTF, a value smaller than 1 means broader OTF. Usually only values bigger than 1 needs to be used to make the OTF smaller and thinner. Often the OTF size is overestimated by the OTF calculation procedure. The values that have been found to be useful are 1.0 (synthetic data) to 2.0. Usually, a larger factor is used for small particles.
  Default: 1.0. Use 1.0-1.3 (small particles, 1-3 pixel), 1.0-1.2 (bigger particles, 4 pixel or bigger)

- **Residuum computation: increase particle intensity ... times** Before starting a new triangulation iteration, a residuum is calculated that uses this factor to enhance the particle intensity. The idea is to make sure, that for all cameras no (positive) intensity is left at a particle position. It has been found, that it is better to subtract a little too much than to subtract too little. If too little is subtracted, there will often be some remaining intensity at a particle location (due to noise) that will be recognize as a new

particle during triangulation. This situation should be avoided. Typical values are 1.0 to 2.0.
Default: 1.0

- **Residuum computation - OTF radius:** This parameter specifies the radius that is used to calculate the residuum for a single particle. E.g. for a radius of 2, the area that is used to calculate a residuum for a single particle will be restricted to 5 x 5 pixel. This radius needs to be as large or larger than the maximal actual particle radius found in the recorded images. On the other hand, the smaller this value, the faster the computation. The auto options determines this value from by analyzing the OTF function.
Default: auto

Tracking parameter settings for **Shake-the-Box time-resolved**:



- **Velocity limits**
  - **Vx, Vy, Vz:** average or mean pre shift: If the flow has a non zero mean component, the expected shift can be entered here. This often allows lower search limits for the following '+-' settings. The values can be entered in **voxel** or in **m/s**.
  - **+-:** This is the dynamic range of the expected flow or particle shift. It has to be large enough to capture all existing particle shifts in the flow. However, if the setting is too high, processing may take much longer and false tracks may be detected.

    So e.g. with settings like Vx = 5 voxel +- 7 voxel, the shift in x that can be detected is in the range from -2 voxel to 12 voxel. If unexpectedly, in some parts of the measurement volume, tracks are missing, the reason could be, that the range for the velocity limits has been set to small or the offset 5 voxel is wrong.

- **Minimum track length required:** Tracks will only be accepted if they have at least the length specified here. The adjustable range is from 4 to 10 time steps. A smaller number results in more tracks, a higher number ensures longer tracks with sometimes less noise, especially for the acceleration.

- **Acceleration limits**

  - **Maximum abs. change in particle shift:** To enforce the temporal matching of true matching particles and to exclude unlikely tracks, the allowed acceleration can be limited by this and the following parameter. This parameter specifies the maximum change of the shift from one time step to the next in voxel. This is an absolute value that is required to take e.g. some random position inaccuracy for static or very slow moving particles into account.
    Default: 1 voxel

  - **Maximum rel. change in particle shift:** This is the corresponding parameter for a threshold of relative velocity change. The idea is that particles that move a longer distance between two time steps may also exhibit a larger amount of change in the direction or magnitude of the shift from one time step to the other.
    Default: 20 %

- **Median filter:** A median filter is used to remove spurious tracks that do not fit to the neighboring tracks. In this way, wrong tracks or ghost tracks can be removed. The filter can be applied iteratively: The settings can range from 'off' (no median filter applied) up to '10x' (median filter is applied 10 times). It depends on particle density, image quality and the smoothness of the flow how many times this filter needs to be applied iteratively. Often this filter can be switched off, especially for time-resolved data. If switched on, typical iteration numbers are 3 to 10. The best way to find good parameter settings is to set some values, then do a processing for 20 to 30 time steps and then to inspect carefully the 3D track display to look for spurious tracks. The median filter is using the nearest neighbors of a particle in question to determine the deviation of the neighboring velocity values from the median of all neighbors. Then the deviation of the velocity of the particle in question is compared to the deviation of the neighbors. If the deviation exceeds the deviation of the neighbors by some factor, the particle is removed. Four parameters control the behavior of the median filter:

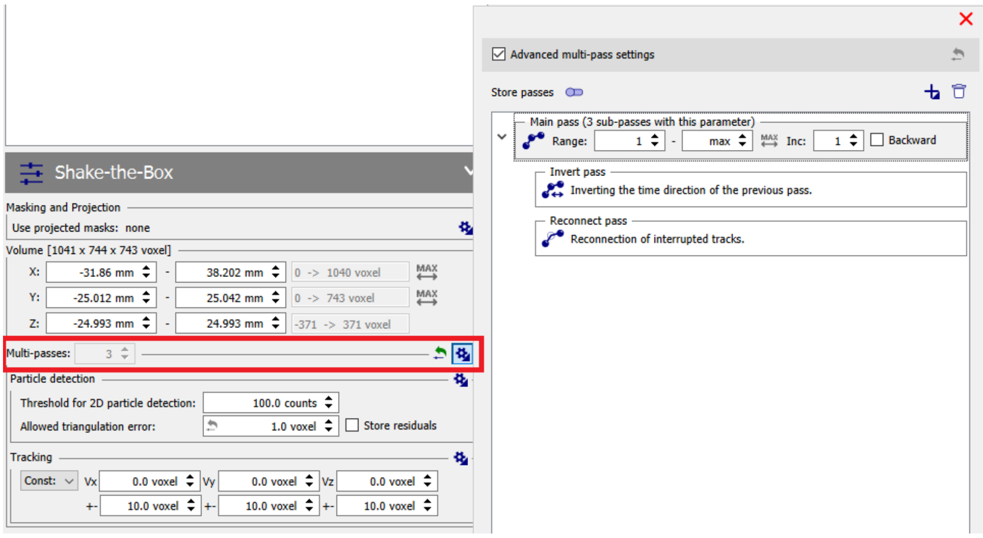
- **Number of neighbors used:** Determines the number of nearest neighbors that are used to calculate the deviation from the median. Typical values are 10 to 20. For higher particle concentrations a higher number can be used.

- **Max. search range:** determines the maximum search range for neighbor particles. Depending on the seeding concentration a smaller or bigger range may be necessary to find enough neighbors. Use a small value for dense seeding (20 voxel) and a large value (about 100 voxel) for sparse seeding. No matter how large this range is, the search will stop if as many neighbors as **Number of neighbors used** (see above) particles have been found.

- **Remove if standard deviation** $>$ The particle in question is removed, if its deviation of velocity from the median of the neighbors is bigger than the value of this parameter times the standard deviation of the neighboring velocities from the median. Typical values are 3 to 5. For dense seeding particles (high seeding concentration) or smooth local flow, the value can be smaller; for sparse seeding particles (low seeding density) or irregular (turbulent) local flow, the value needs to be bigger to not remove true and valid tracks.

- **Allowed epsilon:** In smooth flow regions, the deviation of the velocities from the median can become very small. True tracks may therefore be removed, because the deviation resulting from measurement noise is above the specified deviation criterion. To take the measurement noise into account, this epsilon value can be specified: Tracks are not removed, until their deviation from the median is not at least above this epsilon. Typical values are 0.5 to 1.0 voxel.

Multi-pass parameter settings for Shake-the-Box:

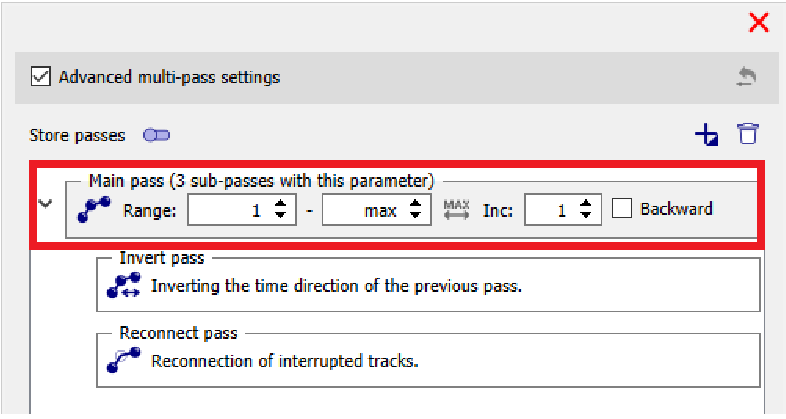


- **Multi-passes:** Increases or decreases the number of calculated passes within the Shake-the-Box calculation. Per default, the Multi-passes are set to 1 and therefore, a standard Shake-the-Box processing is conducted. When increasing the pass number, pre-defined multi-pass recipies will be created and a Multi-pass Shake-the-Box will be conducted. When opening the advanced parameter settings card, the suggested multi-pass scheme can be seen.

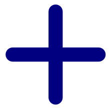
- **Advanced multi-pass settings:** Checking this option will enable the advanced multi-pass settings and the pre-defined multi-pass schemes can be edited. **Note:** When the checkbox is deactivated again, the multi-pass scheme will be redefined according to the latest used default settings of **DaVis**.

- **Store passes:** Per default, only the final Shake-the-Box pass will be stored. By activating this slider button, all sub-passes will be saved as well. In the project tree, they will be located as individual sub sets of the final Shake-the-Box result set.

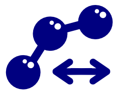
- **Main pass:** The Main pass represents the parameter configurations on the main parameter card. It is always the first pass in the list and cannot be deleted. If necessary, the image set range and increment can be adjusted, here. Furthermore, by checking the box **Backward**, Shake-the-Box starts from the end of the image set and processes the images in a backward sense. **Note:** The Shake-the-Box result set will always be saved in forward direction, independently of the forward/backward direction of the passes.



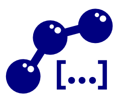
- **Add a new pass:** New passes can be added by pressing the + button. A list will open, from which the desired pass type can be selected. New passes can also be added by right-clicking on another pass. Except of a special **Custom pass**, all available pass types will inherit the Shake-the-Box parameters from the above lying **Main pass** or the special **Custom pass** (noticeable by the indented position of these sub-passes). Following passes can be selected:



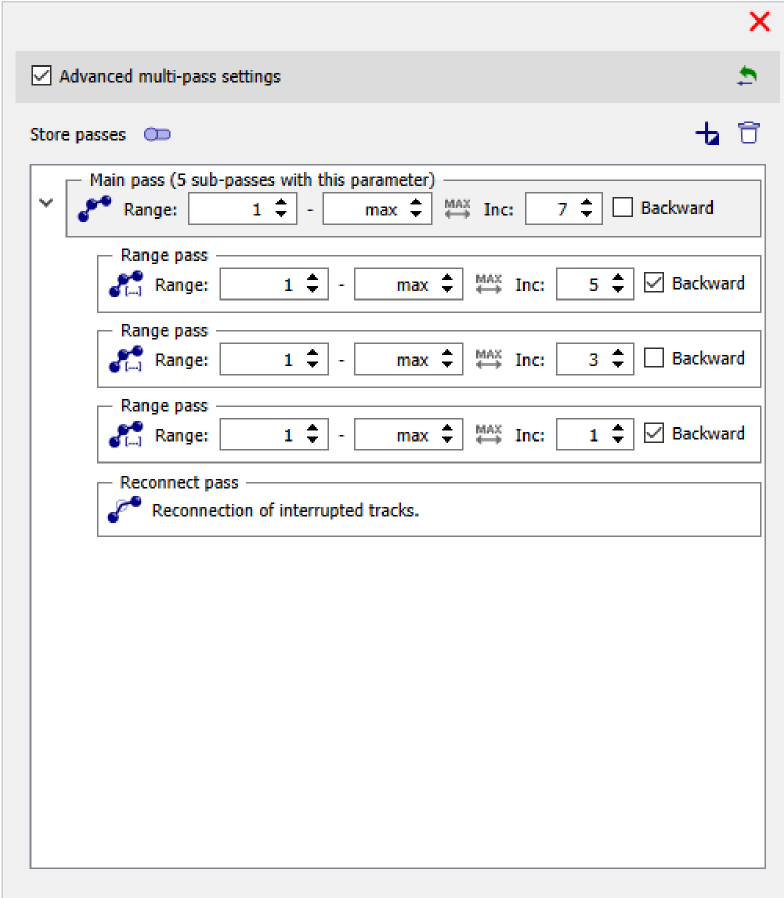
  - **Invert pass:** This pass inverts the direction (in a temporal sense) of the previous pass while keeping the rest of the parameters unchanged. Therefore, if the previous pass is selected as a backward pass, the **Invert pass** will now be processed in forward direction and vice versa. It is recommended to perform at least one forward and backward pass during the Shake-the-Box processing in order to get converged results even at the beginning of the recording sequence.

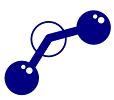


  - **Range pass:** With this pass, the processed image range as well as the processed image increment can be separately specified. This pass can be used to enable a Variable-Timestep Shake-the-Box (VT-STB)[2] approach (see exemplary Multi-pass scheme below). For this, the image range is kept at maximum and only the increment is decreased with each following pass. By doing so, slow particle tracks will be reconstructed in the first passes. And with every following pass, faster particle tracks are allowed to occur.

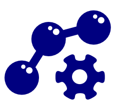


[2] D. Schanz, M. Novara and A. Schröder (2020): Variable-Timestep Shake-The-Box (VT-STB) for flows with high dynamic range. 3rd Workshop and 1st Challenge on Data Assimilation & CFD Processing for PIV and Lagrangian Particle Tracking, 19.-20.11. 2020, Online





- **Reconnect pass:** During the processing of this pass, the triangulation of new particles is deactivated. Therefore, the focus of this pass is to try to reconnect interrupted trajectory segments. Since no new particles are detected, the previous passes should already lead to a well reconstructed flow field. It is recommended to always use this pass as the last pass of each multi-pass scheme, as it can noticeably increase the average track length. This pass is always processed in forward direction and has no further adjustable parameters

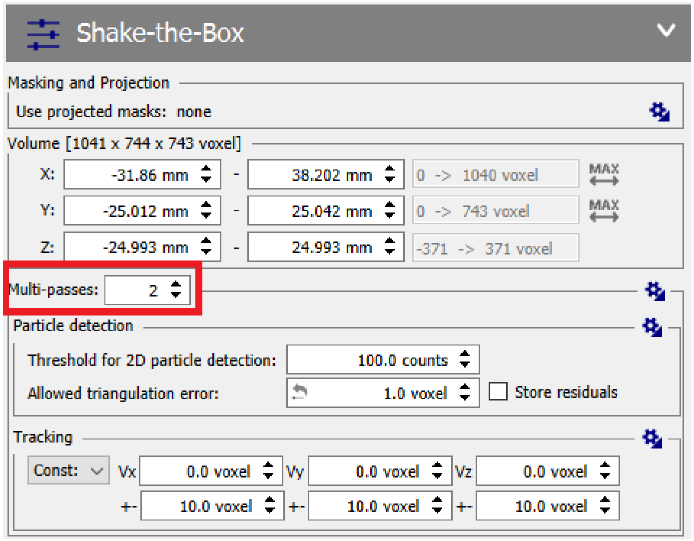


- **Custom pass:** With the help of the custom pass, a complete new set of Shake-the-Box parameters can be defined. As this pass type gives a lot of freedom in the parameter choice it is only recommended for very advanced users. But by enabling a custom set of parameters for each individual custom pass, the Shake-the-Box processing can be individually tuned for very complex and transient flow fields.

- **Delete selected pass:** Pressing this button will remove the selected pass from the multi-pass scheme. If no pass is selected, the last pass will be deleted. Passes can also be deleted by right-clicking on a pass and by selecting the according entry. Please note, that the Main pass cannot be deleted and will always be the first entry of the list.

Additional parameters for Shake-the-Box 2-pulse:

- **General**



  - **Multi-passes/ Number of iterations:** This parameter defines how often IPR, i.e. iterative particle reconstruction[3], is executed and a consecutive tracking is performed. For each iteration, IPR is performed according to the parameters specified in the card “Iterative Particle Reconstuction” including outer and inner loop. The idea is sketched in Fig. 4.1 for the assumption *Number of iterations*=2; *Adding particles (outer loop)*=4; *Refine particle position and intensity (inner loop)*=4:

    First, the camera images are used for adding particles to the set of suspected particle positions by triangulation (outer loop). Then, the inner loop, the actual shaking, is performed four times. Having computed the residual images by subtracting the particle images of detected particles from the camera images, the residual images are used for a renewed computation of additional suspected particle positions in 3D space (outer loop). Having

[3]Details on iterative particle reconstruction can be found in Wieneke “Iterative reconstruction of volumetric particle distribution, Meas. Sci. Technol. (2012)**24** 024008.

done this for the number of iterations specified in *Adding particles (outer loop)* (here 4), the particles are tracked, i.e. matched in the two frames of the camera image. If a median filter is activated, this is applied to the resulting tracks. For the particles with partners which are not deleted by the median filter, the algorithm enters directly the inner loop of the Shake-the-Box algorithm to again shake these particles to the best matching position and subtract their images from the camera images. From the resulting residuals, again particles are added by triangulation. This means, the adding of particles in the outer loop is done only 3 times for a specified parameter *Adding particles (outer loop)*=4 after the first iteration of *Number of iterations*. This process of repeated particle tracking, filtering and shaking, computing residuals etc. is done as often as specified by the parameter *Multi-passes* or *Number of iterations* in the advanced settings.

In contrast to a time-resolved Shake-the-Box processing, not all Multi-pass pass types are available, since these depend on the information obtained in the temporal domain. Only the **Custom pass** can be used, here, which enables a fine-tuning of the Shake-the-Box operation, if necessary.

- **Tracking**
  - **Reference vector field:** By changing the drop-down item from Const: to File: or Set: it will be possible to load 3D grid based data as a reference for the STB tracking. This can be fortunate in situations when the rough or average direction of a particle field is known, e.g. from a temporal average of a recording series with a short dt allowing for a shift of 10 px at maximum and now a recordings with a longer dt shall be evaluated. Then the reference vector field can be useful to allow for particle pairings even for large shifts between the two pulses. If a reference vector field is loaded, the offset values for the velocity components Vx, Vy and Vz will be deactivated. The user only needs to specify around which search radius of the position calculated from the reference vector field, the particle has to be searched for.

Parameters for 4-pulse Shake-the-Box

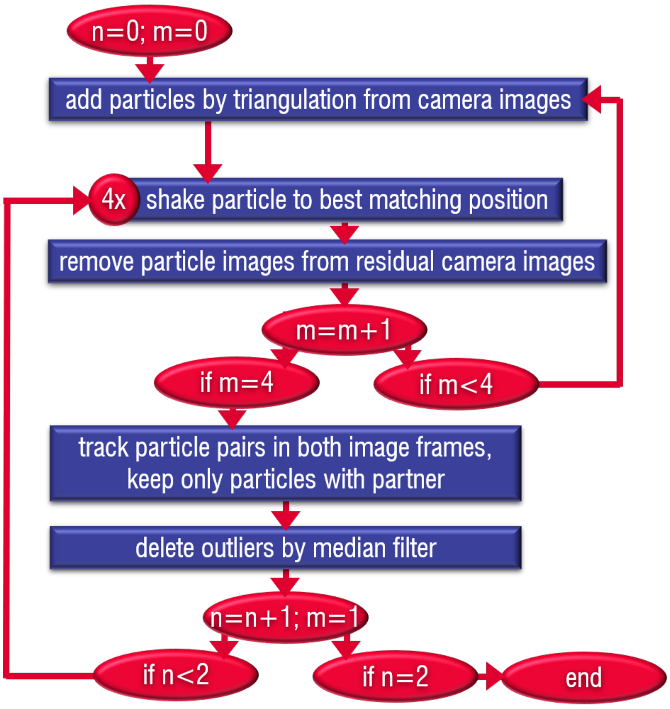
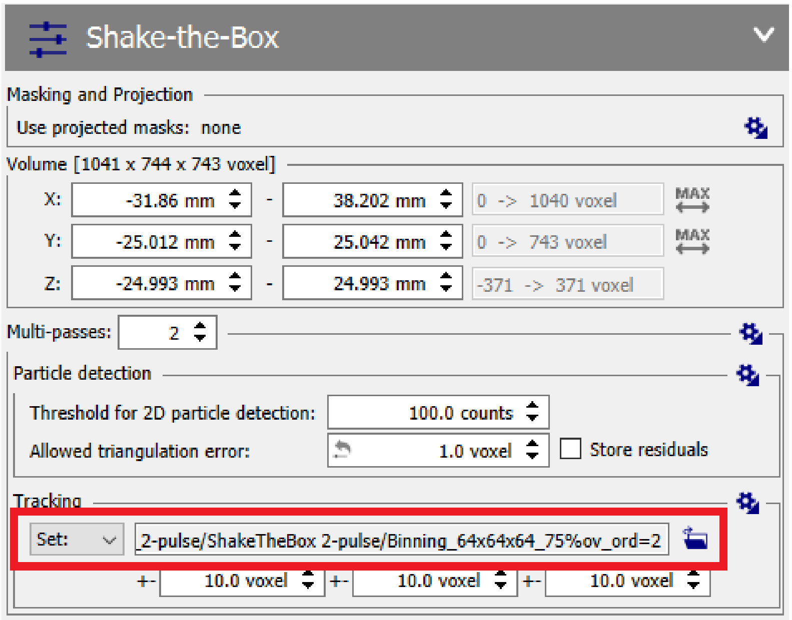


Figure 4.1: Sketch showing the main steps of a double-pulse Shake-the-Box calculation for standard parameters for IPR ans with *Number of iterations* 2.



The parameter cards for 4-pulse Shake-the-Box are identical to the parameters for 2-pulse Shake-the-Box. From the attributed in the recorded images, **DaVis** automatically detects whether a double-frame recording was performed in 2-pulse or in 4-pulse mode. The velocity limits specified in the tracking parameter card refer to the shortest pulse separation time $Dt2$ between the second and the third light pulse.

The only difference between the evaluation of a 4-pulse in comparison to a 2-pulse Shake-the-Box recording is the tracking step, which can be seen when comparing sketch in Fig. 4.1 for 2-pulse Shake-the-Box and the sketch in Fig. 4.2 for 4-pulse Shake-the-Box. The tracking scheme of 4-pulse Shake-the-Box is visualized in Fig. 4.3. All four instant in time are combined to a single track. First, all particles detected by triangulation and consecutive shaking are combined to a 2-pulse track which meet the velocity limits specified in the parameter card Tracking. Second, the relation between the short pulse sepation time $Dt2$ and the longer pulse separation times $Dt1$ and $Dt3$ are used combined with the 2-pulse tracks to find the approximate positions of the particle at the time instant of pulse 1 and and the time instant of pulse 4.

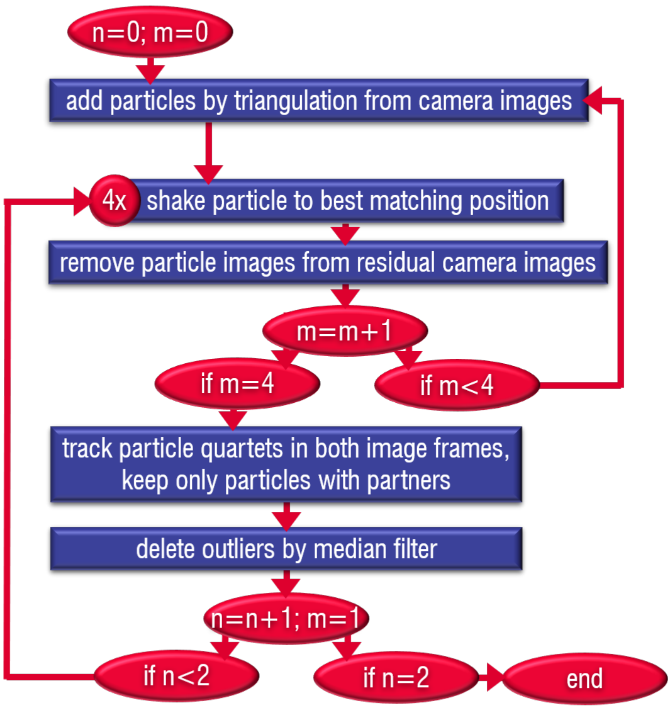


Figure 4.2: Sketch showing the main steps of a double-pulse Shake-the-Box calculation for standard parameters for IPR ans with *Number of iterations (IPR + tracking)* 2 for 4-pulse Shake-the-Box

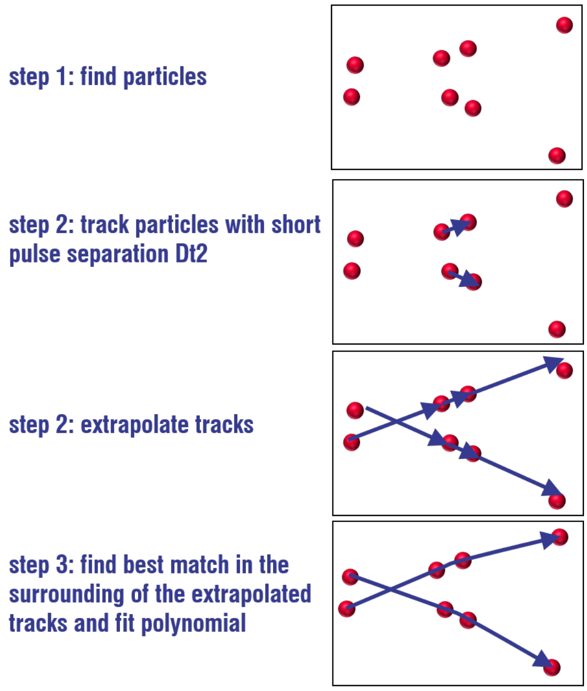
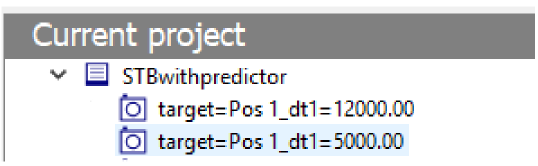


Figure 4.3: Sketch visualizing the tracking scheme of 4-pulse Shake-the-Box

Additional parameters for Shake-the-Box with predictor

A combined evaluation of two recordings with different dts can also be done in one batch operation: Shake-the-Box double-frame with predictor. For using this operation, a multi-set is required which contains two sets of recordings, one recording with a short dt dt_{short}, which is used for the calculation of a temporal average grid-based vector field and one set with a longer dt up to typically $dt_{short} \leq dt_{long} \leq 6 \cdot dt_{short}$. Whether the set with the long or with the short dt is recorded first is not important for the operation. It is essential that the two sets which should be used for a Shake-the-Box double-frame with predictor operation are arranged consecutively in one multi-set. How multi-sets with different parameters are recorded is documented in the DaVis main manual #1003001.



The multiset is selected as input for the processing dialog. On the left side the range of the cycles is specified, which is 2 for processing of a multiset containing 2 sets.

The image range displays the full range of the longer set. If, for example a multiset with 2 different dts has been recorded and the multiset for the predictor calculation, i.e. with the shorter dt contains 200 double-frame images, whereas the second set with the longer dt contains 1000 double-frame images, the maximum of 1000 will be displayed here. The difference between the lengths of the multisets is visible on the left side of the processing dialog where the input is shown. With the slider at the bottom, the set in the multiset is selected. The top slider shows the image in the respective set. The total number of images will therefore change from 200 to 1000 for a multi-set containing 2 sets, one with 200, and one with 1000 images. The processing direction for the set is “Over images - cycle after cycle”.

The velocity limits in the parameter card “Tracking” refer to the velocity and acceleration limits for the longer dt. The limits will be downscaled by DaVis for the short-dt recording. Therefore, the particle shift and acceleration limits must be defined for dt_{long}.

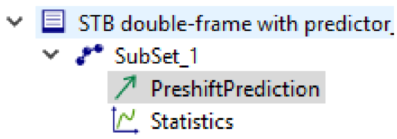
The new parameter card “Convert to grid for predictor” affects the predictor only. Having calculated Shake-the-Box tracks from the recordings with a short dt, e.g. from 200 images, the resulting tracks are binned and time-averaged analogously to the operation “convert to grid” in the group “Convert to grid”. The polynomial fit order for velocity and acceleration is the “spatial polynomial order” and the filter length is set to 11.

“Start processing” will therefore automatically calculate Shake-the-Box with predictor by

1. calculating Shake-the-Box tracks for the set with the shorter dt value dt_{short} with velocity and acceleration limits downscaled from the settings set in the dialog to the short dt.
2. if activated: apply a median filter to the resulting Shake-the-Box tracks
3. convert the Shake-the-Box double-frame tracks to a regular 3D grid as defined in the parameters “Convert to grid for predictor”.
4. use the resulting 3D grid data as reference vector field for the double-frame Shake-the-Box evaluation of the second data set with $dt_l ong$, now using velocity and acceleration limits in specified in the parameter card “Tracking”.

The result is one Shake-the-Box particle track field of track lengths 2.

The result of the Shake-the-Box multi-set is not displayed within the dialog. It is displayed in the DaVis project tree view with the default name “STB double-frame with predictor”. The result set contains the resulting Shake-the-Box tracks, which is a particle set, the result of the prediction of the particle shift labeled “PreshiftPrediction”, which is a 3D vector grid, and the Statistics of the calculation, which shows how many particles have been triangulated for each image, i.e. the average of the triangulated particles in the two frames of one image, and the number of tracks retrieved from each time step.



In contrast to the operation “Shake the Box” the operation “Shake the Box double-frame with predictor” displays an additional result referred to as “PreshiftPrediction” in the tree view. This data contains the grid data used as predictor in the Shake-the-Box double-frame caculation with long dt. The other items in the tree view are explained below in the section Shake-the-Box Results. The operation convert-to-grid is explained in section 4.4.

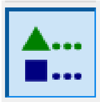
All steps of a Shake-the-Box double-frame with predictor calculation can likewise be performed by applying the operations

1. Shake-the-Box with double-frame input data with a short dt; if desired: with a median filter
2. convert the Shake-the-Box double-frame tracks with the operation “convert to grid” in the group “convert to grid”
3. use the resulting 3D grid data as reference vector field for the double-frame Shake-the-Box evaluation of the second input data set with dt_long, now using velocity and acceleration limits in the parameter card “Tracking” which are longer than for the set with a short dt, respectively.

Shake-the-Box Results

A Shake-the-Box will give particle tracks. Either with a track length of 2 for double-frame data or with a track length of at least “Minimun track length required” specified in the parameter card Tracking for time-resolved Shake-the-Box.

Furthermore, a result called "**Statistics**" is displayed in the tree view. With the button



the labels for the data can be displayed.

All data is displayed as value over image number.

For time-resolved data:

- the **red** line shows the number of active tracks, i.e. the number of continued tracks from the previous time step.
- the **green** line shows the number of triangulated particles in the current time step (real particles and ghost particles).
- the **blue** line shows the number of new tracks versus in the current time step.

For double-frame data:

- the **green** line shows the number of tracks detected from the current double-frame image.
- the **red** line shows the average number of triangulated particles in the current time step (real particles and ghost particles) of the two frames in one image.

For data resulting from the operation Shake-the-Box double-frame with predictor, the additional object "**PreshiftPrediction**" appears in the tree view, which contains the grid-based data resulting from the short-dt recording used for the prediction of the particle shift in the long-dt measurement. Details on the operation are explained above.

Particle field stitching

In the group '3D-PTV processing" the operation "Particle field stitching" can be performed on multi-sets, which contain multiple Shake-the-Box results in different positions. This is only applicable for data recorded with robotic support including the respective calibration, which is covered in the respective manual #1012075 DaVis and Robot Control.

4.4 Convert to Grid

4.4.1 Binning

With the processing operation **'Binning'** from the **'Convert to grid'** group, **velocity or acceleration from Shake-the-Box track data is converted to a regular grid**. The conversion can deliver a vector field for each time step or an average field over the range of selected time steps. The user specifies a **subvolume size** or bin size in voxel and an **overlap** in % (similar to interrogation volumes in tomographic PIV). A subvolume size of e.g. 48 voxel with 75% overlap will result in a velocity or acceleration field that has a **vector spacing** or **grid** of 12 voxel: a vector is calculated for every 12 voxel in the x- y- and z-direction. For the binning, all tracks in the vicinity of a grid point are used to calculated the velocity or acceleration at this point. The contribution of a track to this grid point is weighted by the distance of the track from the grid point, using a Gaussian weighting function. The width of the Gaussian weighting function is chosen, so that it has the same *effective* size, or the same spatial filtering effect, as a cube with the user specified subvolume size.

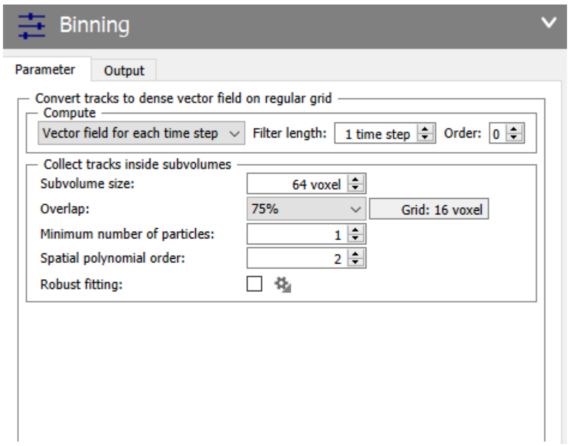
Before the binning, velocity or acceleration have to be calculated for each particle using the particle track data. The way how velocity or acceleration are calculated is determined by the recording mode of the particle images:

- **2-pulse (double pulse) recording:** velocity is calculated using the **finite difference** between the particle positions from the two time steps. Acceleration can not be calculated here.
- **4-pulse recording** (each particle is recorded twice in each of the double frame images)**:** velocity or acceleration are calculated from a **polynomial fit** of order two for the particle position from the four time steps. If the particle shift is so small, that the two images of a particles can not be separated in a single frame, then the velocity is calculated by a finite difference and the acceleration is set to zero.
- **time resolved recording:** velocity or acceleration are calculated from a **polynomial fit** of user specified length (in time steps) and order.

Once velocity or acceleration are known for each particle, velocity or acceleration for a grid point are calculated using **polynomial regression** for all particles in the vicinity of the grid point (applying the Gaussian weighting mentioned above). The order of the polynomial can be selected by the user in the range from zero to two. The **order of zero** corresponds to binning with a **Gaussian weighted average**.

Parameter for all recording types

Two sections in the upper part of the **'Parameter'** dialog are common to all types of recordings, a third section is only available for time resolved data (see below):



In the **'Compute'** section of the dialog, the user decides to either calculate a **'Vector field for each time step'** or a single **'Average vector field'** for all time steps in the selected processing range. If the option **'Vector field for each time step'** is selected, it is also possible to incorporate the **sliding binning** method by increasing the **'Filter length'** above 1. By doing so, the neighboring timesteps are included during the vector calculation in order to enhance the temporal consistency of the flow field. The **'Order'** of the filter can be selected and defines the order of the polynomial that is fitted in the time dimension:

- **Order = 0:** Gaussian weighted average, only the mean value is determined. The result is smooth but maxima may be damped.
- **Order = 1:** The offset and the linear gradients are fitted.
- **Order = 2:** Offset, linear gradients and curvature are fitted. Maxima are preserved but the result may be more noisy.

Binning size, overlap and regression parameter are specified in the section **'Collect tracks inside subvolume'** of the 'Parameter' dialog. The **'Subvolume size'** determines the size of bins in voxel (e.g. 64 voxel refers to a volume of 64 x 64 x 64 voxel). Tracks inside this volume contribute to the grid point in the center of a subvolume. The specified size is the *effective size*. Internally, the software uses a volume that is twice as big and applies a Gaussian weighting based on the track distance from the subvolume center.

The **'Overlap'** determines the vector spacing on the grid and is entered in percent (similar to PIV). The corresponding **'Grid'** spacing is calculated and displayed whenever the overlap or subvolume size are changed. Note that changing the overlap may change the subvolume size as only integer grid spacing is possible!

A vector in the result will only be present (valid) if at least the selected **'Number of particles'** are located inside the subvolume of a grid point. The smallest possible setting is one, so that a vector will be calculated if at least a single particle is present within a given subvolume. Using larger numbers here will result in a better average, but this may also result in holes inside the vector volume if the particle density is too low or the subvolume size is too small.

The **'Spatial polynomial order'** defines the order of the polynomial that is fitted to the local particle tracks for each grid point:

- **Order = 0:** Gaussian weighted average, only the mean value is determined. The result is smooth but maxima may be damped.
- **Order = 1:** The offset and the linear gradients are fitted.
- **Order = 2:** Offset, linear gradients and curvature are fitted. Maxima are preserved but the result may be more noisy.

Robust fitting allows to reduce the influence of outliers in the resulting vector field by applying an "Iterative Reweighted Least Squares" method. The implemented loss function (Cauchy-Lorentz) calculates a weight for every particle velocity. Based on the residual r to the performed fit the weight w will be adjusted iteratively. Since the weighting function is not scale invariant, the residuals are normalized with the scaled median absolute deviation (MAD), which is a robust estimator for the standard deviation, and with a tuning constant t. Based on the scaled residual r, the weights w are calculated as:

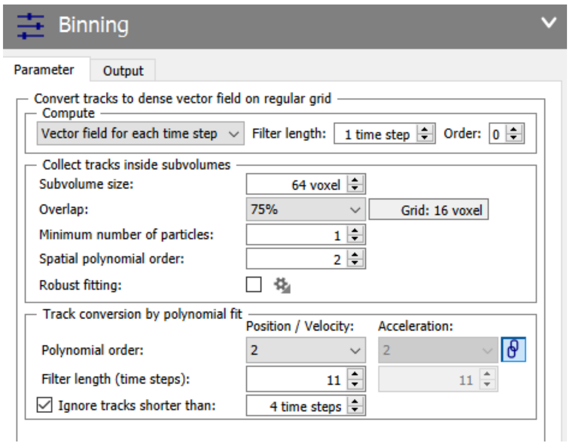
$$w = 1/(1 + r^2) \text{ with } t = 2.385$$

Advanced settings for the robust fitting weight function are adjustable by clicking on the gear wheel next to the check box. The advanced settings are:

- **Maximum number of iterations:** Defines the maximum number of iterations within the "Iterative Reweighted Least Squares" method. This value may be increased, if the source vector field includes a large amount of outlier vectors.
- **Epsilon:** If the magnitude of a vector in pixel units (the average for single average method) does not change more than Epsilon from one iteration to the next, the "Iterative Reweighted Least Squares" method stops, even before the maximum number of iterations is reached.
- **Scale factor for tuning constant:** The tuning constant t can be rescaled to change the influence of outliers. As t is set (min. 0.25) to lower values, the influence of outliers decreases. With a higher value for t (max. 5), outliers are weighted heavier and contribute stronger to the final vector.

Parameter for time resolved recordings

For time results, the **Parameter** dialog contains the additional group **'Track conversion by polynomial fit'**:



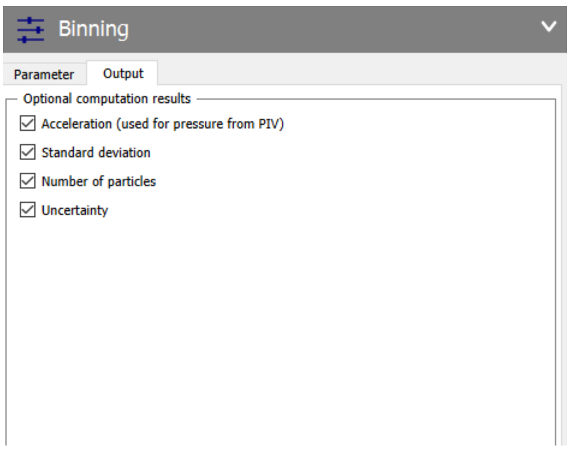
The **'Polynomial order'** and the **'Filter length (time steps)'** are specified for the **'Position / Velocity'** and the **'Acceleration'** either separately or linked together (when the **'chain'** button is active). The **default** choice is to **link** values and to use the **order of two**, which allows the calculation of velocity (first derivative) and acceleration (second derivative). The optimal filter length depends on the flow, the particle shift and the image quality. The dialog allows to enter values in the range of 'order + 1' to 1023. Typical value are in the range of 5 to 21. There are some rules that can help to choose a proper filter length:

- smaller shift - longer filter length: if the particle shift is small, more time steps can be used to filter noise while still not damping the motion and avoiding truncation error.
- if the images are noisy and the image quality is not optimal, a larger filter length can lead to more reliable velocity and acceleration data, although some smoothing of the real particle track can occur.
- small flow structures - smaller filter length, large flow structures bigger filter length: if the flow structures are small and the filter length is too large, then the filtered curve may not represent the actual motion of the particle anymore due to truncation error. If, on the other hand, the flow structures are large, a bigger filter length can filter noise very effectively while maintaining the true flow structures.

Furthermore, by activating the option **'Ingore tracks shorter than:'** trajectories with a smaller number of tracked time steps than defined in the spin-box are completely ignored during the binning operation. Very short tracks are most likely wrongly connected particles/ ghost tracks. These would just contribute to a higher noise level in the final result and often it can be advantageous to ignore these tracks.

Output selection

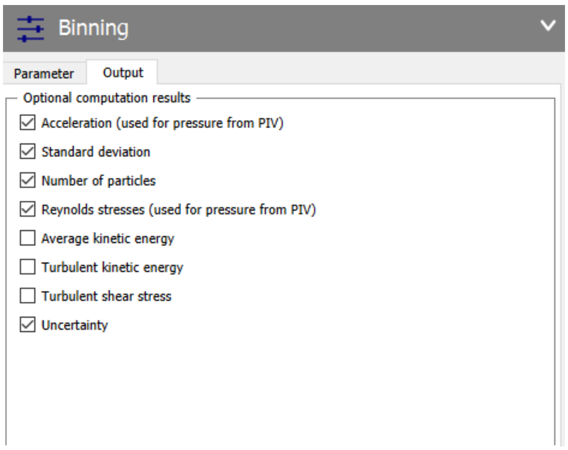
Velocity is always written to the output vector field of the binning operation. Additional data output can be configured in the 'Output' dialog. The options are different for instantaneous or average results. For **instantaneous** fields, the following options are available:



- **Acceleration:** The acceleration vector id calculated for each grid point from the curvature of the particle track. Acceleration data is stored as a **second vector frame** in the result. This option is not available for 2-pulse recordings.
- **Standard deviations:** The standard deviation of the data from all contributing tracks to the current grid point is stored as scalar components. They can be displayed (as vector background) or extracted.
- **Number of particles:** The number of particles that contribute to the data of each grid point is stored.
- **Uncertainty:** The uncertainty of the averaged velocity $U_{\overline{V}}$. It is calculated from the standard deviation σ of all velocity vectors within the bin and the number of contributing particles/samples N:

$$U_{\overline{V}} = \frac{\sigma}{\sqrt{N}}$$

For **average vector fields**, additional options are:



- **Reynolds stress:** The Reynolds stress terms are calculated and stored as scalar fields. They are used, if present, from the **Pressure from PIV** operation to calculate the average pressure field.

$$R_{ij} = \overline{V_i' V_j'} = \frac{1}{N-1} \sum_{n=1}^{N} (V_{i,n} - \overline{V_i})(V_{j,n} - \overline{V_j}) \text{ for } i, j = \text{x,y,z}$$

- **Average kinetic energy:** The scalar field of the average kinetic energy distribution is calculated

$$AKE = \frac{1}{2} |\overline{V}|^2$$

- **Turbulent kinetic energy:** The scalar field of the turbulent kinetic energy is calculated

$$TKE = \frac{1}{2}(R_{xx} + R_{yy} + R_{zz}) \text{ for 3-component vectors}$$

$$TKE = \frac{3}{4}(R_{xx} + R_{yy}) \text{ for 2-component vectors}$$

In the planar case it is assumed that for the turbulent kinetic energy the invisible third component $\mathbf{V_z}$ contains a similar contribution as the values calculated for $\mathbf{V_x}$ and $\mathbf{V_y}$ as the distribution of turbulence is isotropic. So the formula is corrected for this and leads to a value that is 50% higher.

- **Turbulent shear stress:** The turbulent shear stress is calculated when selecting this option and stored as a scalar field

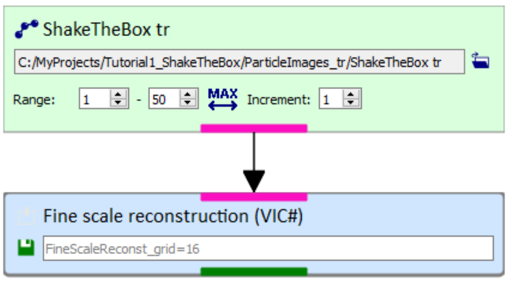
$$TSS = \frac{1}{2} \cdot (\lambda_{max} - \lambda_{min})$$

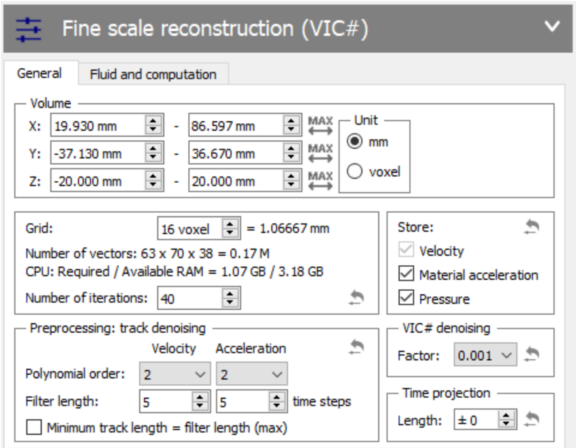
, where λ_{max} and λ_{min} are the maximum and minimum Eigenvalue of the Reynolds stress tensor. For the 2D case this can be analytically written as

$$TSS = \sqrt{\frac{1}{4}(R_{yy} - R_{xx})^2 + R_{xy}^2}\ .$$

4.4.2 Fine scale reconstruction (VIC#)

With the processing operation **'Fine scale reconstruction (VIC#)'** from the **'convert to grid'** group, **velocity or acceleration from Shake-the-Box track data is converted to a regular grid**. Fine scale reconstruction is more sophisticated than binning (4.4.1) and allows the reconstruction of fine details of the flow structure. This is achieved using the information from particle motion AND the physical laws of fluids to assimilate the flow field in between particles tracks. In this way up to a hundred times more velocity vectors than particles can reliably be reconstructed, leading to unsurpassed spatial resolution of the results.





General parameters

- **Volume (X,Y,Z)**: specify the volume to be used for the reconstruction. The volume can be specified in 'mm' or 'voxel'. Using the 'max' button for a certain dimension (X,Y or Z) will set the reconstruction size in this direction to the size of the particle track input data (which had been specified during particle track calculation). So, in case of doubt, use the 'max' buttons for all directions. If, however, only a smaller sub-volume is of interest, reducing the volume can save considerable computation time.

- **Grid:** Specifies the grid spacing between vectors in the result in voxel units. Entered values are also converted and displayed in 'mm'. Also, the 'Number of vectors' in the different directions and the overall number (here 0.15M = 150000) is displayed. This is an important number: **The number of vectors should in general not be bigger than 64 times the number of tracked particles!**

- **Number of iterations:** Fine scale reconstruction is an iterative method. Usually, the more iterations are used, the better are the results, but the higher is the computation time. 40 iterations is a compromise between computing time and quality. If the best quality should be achieved 100 iterations or more can be useful. Also, more iterations are needed if the number of result vectors is large.

- **Store:** determine the properties that are stored in the result.

  – **Velocity:** is always stored in the output, it is just shown for completeness here.

- **Material acceleration:** store acceleration as a second frame in the result.
- **Pressure:** store pressure as a scalar field. This option is only available when a pressure license is available.

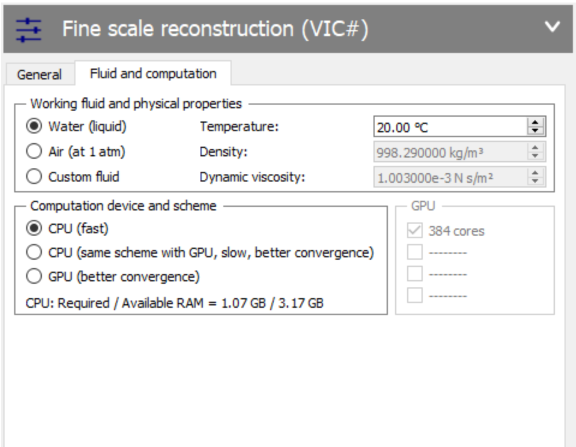
- **Preprocessing: track denoising:** Velocity and acceleration are calculated from particle tracks using a polynomial fit with selectable order and length (length is the number of time steps used for the fit). The polynomial fit acts like a denoising filter. The lower the order and the bigger the length, the better is the noise suppression. The polynomial filter also acts like a low pass filter which will damp higher frequencies. Default settings are order 2 and length of 5 time steps, both for velocity and acceleration. Usually, the same values are used for velocity and acceleration, but there is the freedom to experiment with different values. E.g. if the resulting acceleration is too noisy, one might increase the filter length.
  - **Polynomial order:** range 1 to 3. Order of 1 corresponds to linear fitting.
  - **Filter length:** Number of time steps used for polynomial fitting. If a track is shorter than the filter length, then the available time steps are used as length.
  - **Minimum track length = filter length (max):** When this option is selected, only tracks are used that are at least as long as the specified filter length. Shorter tracks are ignored. If the filter length is different for velocity and acceleration, the maximum is used as threshold. Sometimes, short tracks show more noise and can worsen the result, this can be avoided using this option.
- **VIC# denoising Factor:** emphasizes correction of velocity field based on pressure field. Noisy vortical structures smaller than pressure structures will be smoothed. On the other hand, if the small vortical structure is real and strong, the pressure field can suffer from aliasing effects. Please set this value regarding flow characteristics:
  - **0:** if there are strong small vortical structures, e.g. thin shear layer.
  - **0.001:** if no information of flow is available.
  - **1.0:** if all vortical structures are sufficiently large.

- $>$**1.0:** if the flow field is noisy, denoising is thus required.

- **Time projection:** The time projection method enables the solver to sample more information from neighboring time-steps. If velocity vectors change small, e.g. lesser than half of grid size for Length = ± 1 , it can be assumed that particle trajectories follows the first-order Taylor expansion, e.g., $u(t + dt) = u(t) + du/dt(t)$. The time projection method collects such projected information, and thus improves the dynamic range under the certain flow condition. Please note that the [Length] parameter must satisfy following condition to avoid malfunction:

$$\text{Length} \leq 0.5 \cdot h/u_{\max} \tag{4.2}$$

where h is the grid size and $u_{\max}$ is the maximum magnitude of velocity.



Fluid and computation

- **Working fluid and physical properties:** In order to obtain physically correct results the properties of the working fluid must be defined. For water and air (at 1 atm) the density and the dynamic viscosity are automatically defined by providing the fluid's temperature. If these values do not match the experiment or if another fluid is used, a Custom fluid can be defined, for which all properties can be defined separately.

- **Computation device and scheme:** Three different computation schemes are implemented for the VIC# algorithm. Dependent on your hardware and your licenses you may choose between:

- CPU (fast): Fast CPU implementation of the VIC# algorithm, may not convergence as well as the other schemes. Still slower as GPU computation.
- CPU (same scheme as GPU, slow, better convergence): Equivalent implementation as the GPU computation scheme with better convergence but longer calculation times
- GPU (better convergence): Provides the quickest computation speed by utilizing an optimized GPU computation with good convergence behavior, GPU for PIV package is required

The required memory for the computation is shown alongside the available RAM capacity of the system. It is generally recommended to use the GPU computation scheme. But if the reconstruction problem gets too large and exceeds the accesible memory of the GPU, one of the two CPU schemes may be selected. If more then one GPU is recognized by the system, the corresponding number of check boxes will be enabled on the right site of the parameter card with their respective number of cores. By activating the desired check box, the computation will run on the selected graphics card. Please note, the CUDA SDK (at least version 11.0) should be installed. Even though the corresponding library (CUDA SDK V11.0) is already included in DaVis, it is strongly recommended that users install the latest CUDA SDK and GPU drivers on their PC for optimal performance, as well.

Background

In the following, the mathematical background of **Fine scale reconstruction** is described. The knowledge of this background is not necessary to use the operation, it may help, however, to better understand the underlying principles.

Fine scale reconstruction is based on VIC# (Vortex in Cell "Sharp")[4], which in turn is an optimized successor of VIC+ (Vortex in Cell Plus)[5]. The basic idea is to reconstruct velocity, acceleration and pressure from particle tracks on a very dense grid. The reconstructed data should fit to the track

[4]Jeon YJ, Schneiders JFG, Müller M, Michaelis D, Wieneke B. "4D flow field reconstruction from particle tracks by VIC+ with additional constraints and multigrid approximation", Proceedings of the 18th International Symposium on Flow Visualization, Zurich, Switzerland June 26-29, 2018

[5]Schneiders JFG and Scarano F. "Dense velocity reconstruction from tomographic PTV with material derivatives", Experiments in Fluids, Vol. 57, No.9, pp.139, 2016

data in the vicinity of a track, and should globally obey the laws of fluid dynamics at the same time. The procedure of fitting measured data using a physical model is also called **data assimilation**. As physical laws are used to fill the gaps between particle tracks, the spatial resolution achievable with VIC# is way higher than the resolution from simple binning.

Fine scale reconstruction derives velocity $\mathbf{u}$, acceleration $\mathbf{a}$ and pressure data p on a dense grid from particle track data by an optimization method: It calculates flow field variables by minimizing a certain cost function J that includes several terms from two different groups:

1. terms related to the measured particle tracks (4.3, 4.9)
2. terms related to the laws of fluid dynamics and vector calculus (4.6 - 4.10)

The first group is made up by two terms: A term that takes the measured particle velocity $\mathbf{u}_{PTV}$ into account:

$$J_{\mathbf{u}} = \sum_n \left\| \mathbf{u}_n - \mathbf{u}_{PTV,n} \right\|^2 \tag{4.3}$$

and another term that takes the measured acceleration of the particles $\mathbf{a}_{PTV}$ into account:

$$J_{\mathbf{a}} = \sum_n \left\| \mathbf{a}_n - \mathbf{a}_{PTV,n} \right\|^2 \tag{4.4}$$

where $\mathbf{a}$ is the particle acceleration or material derivative

$$\mathbf{a} = \frac{D\,\mathbf{u}}{Dt} \tag{4.5}$$

and the sum runs over all particles n of a given time step. For the optimization problem, $J_{\mathbf{u}}$ and $J_{\mathbf{a}}$ make sure that the final solution will fit to the actual velocity and acceleration of the particle tracks that have been measured with Shake-the-Box .

Note that **Fine scale reconstruction** is done for each time step separately. Here, a time step can be a single time step from time resolved data, or a single result from 2-pulse or 4-pulse Shake-the-Box . For time resolved data and 4-pulse data, $\mathbf{u}$ and $\mathbf{a}$ are calculated by fitting polynomials to the track data. For 2-pulse data, only $\mathbf{u}$ is available from the finite difference of the positions from two points in time, so that the cost function $J_{\mathbf{a}}$ (4.9) is neglected.

To calculate the differences $\mathbf{u}_n - \mathbf{u}_{PTV,n}$ and $\mathbf{a}_n - \mathbf{a}_{PTV,n}$ in the cost functions $J_{\mathbf{u}}$ and $J_{\mathbf{a}}$, $\mathbf{u}$ and $\mathbf{a}$ need to be known at the particle positions, which, in general, do not coincide with the grid positions. Therefore **u** and **a** are interpolated using tricubic interpolation.

The following terms, related to the laws of fluid dynamics and vector calculus, are added to the cost function, to assure additional constraints:

Divergence free vorticity:

$$\bar{J}_{\omega} = \sum_{\mathbf{\Omega}} \|\nabla \cdot \omega\|^2 \tag{4.6}$$

Incompressible fluid resulting in divergence free velocity:

$$\bar{J}_{\mathbf{u}} = \sum_{\mathbf{\Omega}} \|\nabla \cdot \mathbf{u}\|^2 \tag{4.7}$$

Divergence free partial derivative of velocity:

$$\bar{J}_{\partial \mathbf{u}/\partial t} = \sum_{\mathbf{\Omega}} \left\| \nabla \cdot \frac{\partial \mathbf{u}}{\partial t} \right\|^2 \tag{4.8}$$

Material acceleration is rotation free:

$$\bar{J}_{\mathbf{a}} = \sum_{\mathbf{\Omega}} \|\nabla \times \mathbf{a}\|^2 \tag{4.9}$$

Navier Stokes equation assuming incompressible and inviscid flows, also used to refine pressure calculation:

$$\bar{J}_{p} = \sum_{\mathbf{\Omega}} \left\| \frac{1}{\rho} \nabla p + \mathbf{a} \right\|^2 \tag{4.10}$$

In the above equations, the summation is over the entire volume of grid points $\mathbf{\Omega}$.

All the terms are added to get the final cost function J:

$$\boxed{J = J_{\mathbf{u}} + \alpha^2 J_{\mathbf{a}} + \gamma \left(h^2 \bar{J}_{\omega} + \bar{J}_{\mathbf{u}} + \alpha^2 \left(\bar{J}_{\partial \mathbf{u}/\partial t} + \bar{J}_{\mathbf{a}} + \bar{J}_{p} \right) \right)}, \tag{4.11}$$

where h is the grid spacing:

$$h := \text{ grid spacing}, \tag{4.12}$$

the weighting coefficient α is the ratio between the standard deviation of velocity $\sigma_{\mathbf{u},\mathrm{PTV}}$ and the standard deviation of the acceleration $\sigma_{\mathbf{a},\mathrm{PTV}}$, calculated directly from the particle tracks:

$$\alpha = \frac{\sigma_{\mathbf{u},\mathrm{PTV}}}{\sigma_{\mathbf{a},\mathrm{PTV}}}, \tag{4.13}$$

and the weighting coefficient γ takes the ratio from the number of tracks and the number of grid points into account:

$$\gamma = 8h^2 \, \frac{\text{number of particle tracks}}{\text{number of grid points}}. \tag{4.14}$$

4.5 Track post processing

4.5.1 Particle projections

Calculates reprojected, synthetic images from the three viewing directions XY, XZ and YZ from the particle data present in the Shake-the-Box results set. The calculated images are stored in a new subfolder called **'Projection'**. The particles are modeled as perfect Gaussian blobs.

It can be chosen, whether the **'sum of all time steps'** shall be created (resulting in a single image for every projected direction) or whether a single set of projections **'for each time step'** shall be calculated and saved.

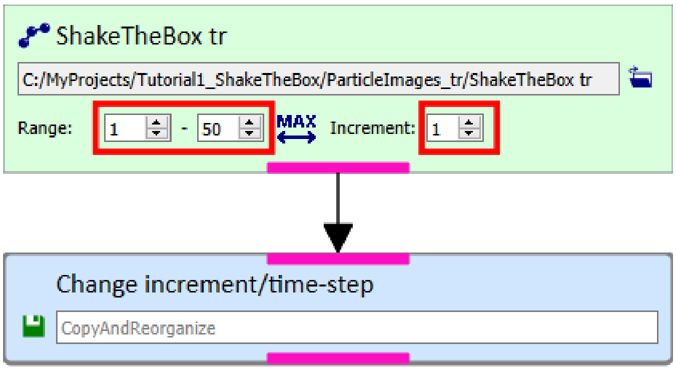
The size of the projected particles in pixel can be set by the parameter **'Particle size'**.

4.5.2 Change increment/ time-step

Copy tracks of the input set from the specified range with an increment $\geq$ 1. For time-resolved data, the result consists of at least 3 time steps.

This operation can be used to reduce the set size if you have performed, for example, an over-sampled measurement and just need down-sampled data for your further data analysis.

The parameters for this operation can be adjusted in the range and increment settings of the input set in the operation list.



4.5.3 Rotate and shift

This operation can be used to shift (translate) and/or rotate all particles from the input set along and/or about each of the three main axis X, Y and Z. The rotation is specified in degrees and can be set in a range between -180° and 180°. Shifts are specified in mm and can either be positive or negative.

4.5.4 Crop or extend field of view

If the whole bounding box of the input set or just single axis directions shall be cropped or extended, this operation can be used. By activating/deactivating the checkboxes, the axis along which to crop or to extend can be specified. The **'max'** button sets the values of the spin boxes to the current size of the boundary box.

4.5.5 Particle track stitching

Within this operation, sets of tracks (organized in a joint multi-set) are stichted/merged to a single result set. For a system with robot control, where a sub-set usually represents a separate sub-volume at a different position in the global flow field, the result set contains the track data from all the multiple sub-volumes and therefore creating a single large volume.

Note: This operation is working properly only for multi-sets originating from a robotic STB scanning work flow. If you want to merge track data from non-robotic measurements please use the Merge particle tracks operation.

4.5.6 Merge particle tracks

Merge particle tracks allows the user to combine the input set with several other sets. For example, this can be necessary, when working with phase-locked measurements. For this, two options are available: **'Merge particle tracks'** and **'Append particle tracks'**.

'Merge particle tracks' takes all considered sets and overlays the results. Therefore, all particles in the first, second, third, ... time step of all sets will be gathered in the first, second, third, ... time step of the resulting set. This option can be used with differently sized sets but the result set will always be the size of the longest input set.

'Append particle tracks' adds the time steps of the specified sets to the end of the input set in the order of appearance as displayed in the selection list. The size of the result set will be the sum of the sizes of all combined sets.

New sets can be added by pressing the **'+'** button. In order to delete a set from the operation, the set must be selected and the bin button must be pressed.

4.5.7 Spatial median filter

Delete tracks that do not fit to the neighborhood. The filter method within this operation is identical to the median filter already described in Sec. 4.3 . This operation can be used after a successful Shake-the-Box analysis to remove still remaining erroneous tracks.

4.5.8 Minimum track length filter

Removes tracks shorter than a given length, whereas the length is defined as the number of tracked time steps.

4.5.9 Range filter

Delete tracks or parts of tracks that do not fulfil the specified velocity and/or acceleration conditions.

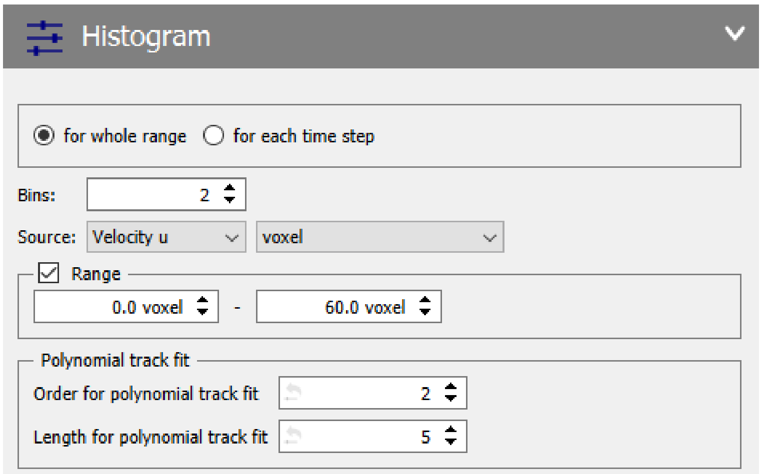
4.5.10 Repair filter

This operation tries to connect segmented tracks, based on the defined velocity and acceleration limits. The **'Velocity limits'** can be defined for each coordinate separately and supports the definition of velocity in **'m/s'** or in unscaled **'voxel'** units. For a further refinement of the repairing step, the **'Acceleration limits'** are considered as well. Here, the user can define the **'Maximum absolute change in particle shift'** of a particle between succeeding time steps with the unscaled **'voxel'** unit and the **'Maximum relative change in particle shift'** in **'%'**.

The reconnection/repairing is done by an interpolation of the missing particle in the gap between two trajectory segments. Interrupted trajectories can occur in difficult seeding situations, where a high probability of overlapping particles exists or when particles are hardly brighter then the noise floor. This operation can provide longer trajectories, especially for PTV processings, whereas due to the advanced tracking approach of STB, the operation may only result in a few repair tracks. Since the operation needs temporal information to reconnect the trajectories, it is only applicable for time-resolved recordings.

4.5.11 Histogram

Calculates a histogram of a selected properties from all reconstructed particles in the selected source set. It is possible to create a single histogram from the data of the whole measurement by selecting the option **'for whole range'** or to create an individual histogram for each time step/ snapshot of the whole measurement by selecting **'for each time step'**.



The default number of bins defined by **'Bins'** is set to 10 but can be freely chosen between 2-9999. The choice of available **'Source'** track properties depends on the data set. By specifying either an unscaled unit (**'pixel'** or **'voxel'**) or a scaled unit (**'m'**,**'m/s'**,...) the scaling of the result histogram can be defined, accordingly.

When activating the check box **'Range'** the minimum and maximum limit of the histogram can be defined manually, elsewise these are calculated automatically. Particles, which fall below or above the specified limits, will be placed in the first or last bin, respectively.

In order to calculate any velocity or acceleration values, two additional **'Polynomioal track fit'** parameters must be defined, namely the **'Order for polynomial track fit'** (between 1 and 3) and the **'Length for polynomial track fit'**.

4.5.12 Acceleration analysis

This operation calculates the instantaneous acceleration values of all particles in the source set and plots the results in a scatter plot. This plot can be used to investigate the occurring accelerations in the data set and can support the definition of suitable acceleration limits within the Shake-the-Box operation.

By right-clicking on either the X or Y axis, the plotted variables can be chosen from the following selection:

- Relative change of particle shift
- Acceleration
- Velocity

All of these values will be displayed with their unscaled units in order to match the parameter definition within the Shake-the-Box operation. For a more physical analysis use the other provided tools such as the **Histogram** operation.

4.6 Export

4.6.1 Tecplot export

With the **'Tecplot export'** operation, the Shake-the-Box result data can be exported in other file formats. Available options are:

- .dat file
- .plt file (Tecplot specific file format)
- .szplt file (Tecplot specific file format)

Whereat the '.dat'-file option procduces plain ASCII text files, the options '.plt' and '.szplt' create binary files in a Tecplot-readable format. For more information on the Tecplot specific file formats, please refer to `https:\\www.tecplot.com`.

Further operation options consider the file naming, the inclusion of uncertainty information and the required parameters for the polynomial fitting as needed for time-resolved and four-pulse recordings.

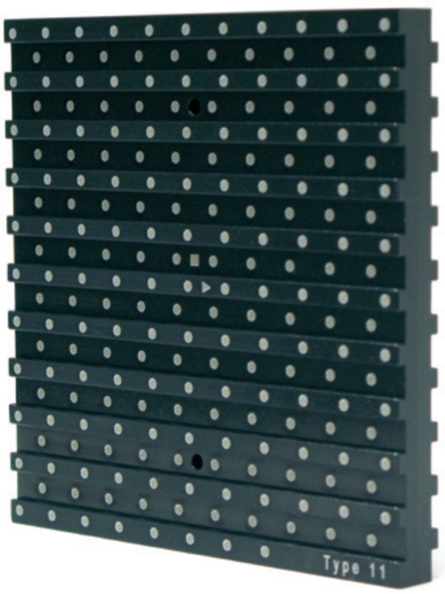
When selecting the export **'In project'**, the export files will be automatically saved in a new sub-folder of the current source set. By toggling the button **'Filename'**, another path and folder name can be specified.

For time-resolved and four-pulse measurements, the additional checkbox **'Include uncertainties'** can be activated. As a result, not only the particle coordinates, velocities and accelerations will be exported but also their corresponding uncertainty values [6].

In order to deduce the velocity information from the discrete particle coordinates, a sliding polynomial fitting approach is utilized. For this, the polynomial order and the filter length can be set with the parameters **'Order for polynomial track fit'** and **'Length for polynomial track fit'**, respectively.

[6]Details on DaVis' Shake-the-Box uncertainty quantification approach can be found in Janke and Michaelis "Uncertainty Quantification for PTV / LPT data and Adaptive Track Filtering", 14th International Symposium on Particle Image Velocimetry - ISPIV 2021, August 1-5, 2021, `https://doi.org/10.18409/ispiv.v1i1.125`.

5 Background on Perspective Calibration



The term **perspective calibration** is used here to describe the general process of relating pixel positions of the camera sensor to real world positions in the measurement space. This calibration process is required to calculate real world positions and velocities in **physical units** like mm and m/s in the laboratory coordinate system **from pixel locations** on the camera sensor.

How a calibration is done in **DaVis** is explained in section 3.6. Here, more practical considerations on specific issues and some details on the theoretical background are given. Especially, for experimenters already used to calibration for planar PIV measurements, this section illustrates the differences to calibration for volumetric data.

5.1 Purpose

The purpose of the perspective calibration in the specific context of **volumetric** flow measurement techniques, like Tomographic PIV, Shake-the-Box or 3D-PTV, is slightly different from the purpose of perspective calibration for planar measurement (2D-PIV, Stereo-PIV, 2D-PTV).

The main focus of the **perspective calibration for 2D-PIV** is to obtain a mapping function that simply maps the real world positions to positions on a single camera sensor. The real world positions are defined in the user specific laboratory coordinate system. For 2D-PIV, the **mapping functions** $M_{x,i}, M_{y,i}$ are only needed to correct the perspective image distortion that results from lens distortions or a non-perpendicular camera angle:

$$
\begin{aligned}
x_i &= M_{x,i}(x, y) \\
y_i &= M_{y,i}(x, y)
\end{aligned}
\tag{5.1}
$$

where x_i and y_i are the pixel coordinates of the i^{th} camera and x, y are the real world coordinates in the plane at $z = 0$. The knowledge of these mapping functions allows for the calculation of **undistorted** or **corrected images** in real world coordinates x, y.

For **Stereo-PIV** (2D3C), the situation is already more complex because not only the mapping functions themselves are needed, but also their **spatial derivatives** in the measurement plane, i.e. at $z = 0$. The derivatives are required to solve the normal equation:

$$
\begin{aligned}
u_i(x_i, y_i) = & \quad \frac{\partial M_{x,i}(x,y)}{\partial x}\, u(x,y) \\
& + \quad \frac{\partial M_{x,i}(x,y)}{\partial y}\, v(x,y) \\
& + \quad \frac{\partial M_{x,i}(x,y)}{\partial z}\, w(x,y) \\
v_i(x_i, y_i) = & \quad \frac{\partial M_{y,i}(x,y)}{\partial x}\, u(x,y) \\
& + \quad \frac{\partial M_{y,i}(x,y)}{\partial y}\, v(x,y) \\
& + \quad \frac{\partial M_{y,i}(x,y)}{\partial z}\, w(x,y)
\end{aligned}
\tag{5.2}
$$

for the three unknown velocity components u, v, w given the calculated in-plane velocity components in the distorted images u_i, v_i for each camera. Note that in equation 5.2 the number of cameras can be equal or greater than 2 to solve for u, v, w. This allows Stereo-PIV with more than two cameras and results in smaller velocity errors.

In both cases, 2D-PIV and Stereo-PIV, the mapping functions $M_{x,i}, M_{y,i}$ and their derivatives only need to be known at $z = 0$.

On the other hand, for **volumetric velocity measurements**, the mapping functions must be determined not only for $z = 0$ but for x, y, z in the complete measurement volume:

$$\begin{aligned} x_i &= M_{x,i}(x, y, z) \\ y_i &= M_{y,i}(x, y, z). \end{aligned} \tag{5.3}$$

For the volumetric techniques, the concept of image correction does not apply anymore: Image correction can only be applied if the illuminated tracer particles are located on a single plane in space. Since the tracer particles are distributed over a whole range of z-positions, there is no way of retrieving corrected real world positions by a simple planar image correction of the camera images. More advanced techniques are required to obtain 3D world positions of the tracer particles from multiple camera images. These techniques include tomographic reconstruction and 3D particle triangulation. Both techniques require a perspective calibration that can be described better by the idea of a **line-of-sight calibration**: For each pixel of a given camera, or more precisely for each location on the camera sensor, we need to know exactly the line-of-sight, which describes the exact path through the 3D-space along which a specific pixel collects light.

Mathematically, the line of sight (LOS) for a location (x_i, y_i) on the sensor of camera i is the set of all 3D points (x, y, z) such that $x_i = M_{x,i}(x, y, z)$ and $y_i = M_{y,i}(x, y, z)$:

$$\mathrm{LOS}(x_i, y_i) = \{(x, y, z) \mid x_i = M_{x,i}(x, y, z) \ \wedge \ y_i = M_{y,i}(x, y, z)\} \tag{5.4}$$

In the most simple cases, e.g. measurement in free air without any glass walls or other optical media in the light path, the line of sight for all pixels will simply be a straight line. In more complex situations, like measurements in fluids, where multiple changes of the refraction indices occur, the line of sight may deviate significantly from a straight line due to light refraction at the interfaces of the different media. Luckily, in most experimental measurement situations, the refraction index is constant within the measurement volume itself, so that the line of sight of each pixel is at least **a straight line inside the measurement volume**. Important exceptions are measurements in flames or measurement in complex structures that are not perfectly index-of-refraction matched. These situations are discussed in more detail in the volume self-calibration section.

5.2 Errors

No matter how hard we try, there will always be some error in the perspective calibration. There are several different types of errors involved in the perspective calibration, and it may be very helpful to understand how different errors affect different measurement techniques.

In general, **volumetric techniques like tomographic PIV and Shake-the-Box require a perspective calibration that is much more accurate** compared to the planar techniques (2D-PIV and Stereo-PIV), especially when the objective is to measure at high tracer particle concentrations. Whereas in planar PIV calibration errors of several pixel will still lead to acceptable results, this is very different for tomographic PIV, 3D-PTV and Shake-the-Box where the maximum calibration **error should be below 0.1 pixel**. In fact, new working principles and new analysis techniques had to be adopted and developed, over a learning period of many years, to come up with a **reliable procedure** to assure such small calibration errors for successful tomographic PIV and Shake-the-Box experiments. The following three points summarize the most important factors of a reliable calibration procedure for volumetric flow measurements at high tracer particle concentrations:

1. **Stiff camera mounting:** the cameras should be mounted as stiffly as possible. It is often useful to mount all cameras on a common frame. This frame should not be attached to any source of vibrations or mechanical shocks. It is most important that the cameras do not move **relative to each other**. The construction of such a camera frame should be realized carefully. The setup should be stiff, while still allowing for an easy adjustment of the area of interest, which seem to be very contradictory tasks. However, there are high quality gear heads available that allow both, a stiff and adjustable setup. The gear heads are usually rated for a specific payload capacity. Especially for heavy high-repetition-rate cameras, heavy duty gear heads with a high payload capacity are required.

2. **Unmodified lens settings:** Camera calibration and tracer particle recordings need to be done with the same and unmodified lens set-

tings. In planar PIV, there might be the temptation to modify the lens settings between camera calibration and the recording of tracer particle images. These modifications include removal of filters for calibration (to gather more light), changing the aperture or refocusing on particles after the calibration.

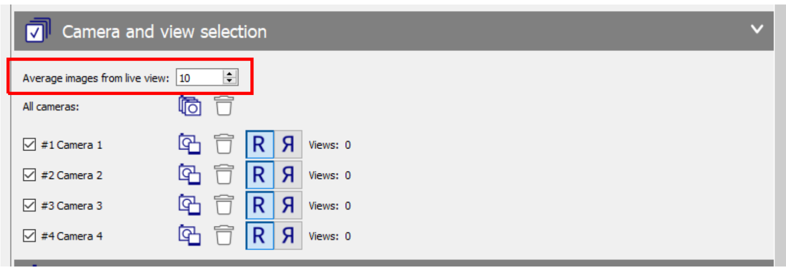
All these modification have been found to be fatal for tomographic PIV, 3D-PTV and Shake-the-Box experiments and should entirely be avoided. Therefore, the usual procedure should be in the following order:

- Adjust the area of interest using the calibration target.
- Refocus and adjust the aperture using tracer particle images.
- do the perspective calibration.
- Do particle image recordings.
- Optional: do a safety calibration with the calibration target again after the particle image recordings.

Modifications of the camera or lens settings also includes **influences that often occur unnoticed**: slight changes in camera orientation due to temperature changes, vibrations, shocks, forces that act on camera cables and so on. All these influences can invalidate the perspective calibration. Hence actions should be taken to avoid such changes: **keep temperature constant if possible, avoid vibrations and shocks, do not touch the cameras or lenses between calibration and recording, use strain-relief for cables**, and so on.

Often bandpass filters for the laser light are added to the camera lenses to reduce disturbing background illumination. The problem with **camera filters** and the perspective calibration is, that the cameras gather only a small portion of the ambient (white) light when the filters are in place. Therefore, sometimes the filters have been removed for calibration in planar PIV experiments. It should be clear now, that we cannot do this for tomographic PIV and Shake-the-Box experiments. To get enough light for the calibration without removing the filters, the **exposure time of the cameras should be increased** largely (e.g. up to seconds if the camera allows). For high-repetition-rate cameras this may require to operate the camera at the lowest possible rate for calibration (see that you may have to do an 'intensity correction' every time after changing the repetition rate). Another way to gather enough light is the usage of a **strong spotlight** for calibration. Here, it is sometimes not possible to find a single spotlight position so that all cameras show a nice image of the calibration target: some cameras may show a nice image, whereas other cameras suffer from strong reflections or poor contrast. In such cases, each camera can record the calibration target separately so that the position of the spotlight can be optimized for one camera after the other.

In all cases, recording a series of e.g. ten or a hundred images and calculating the average can help additionally to increase the signal to noise ratio of the calibration images. Such an averaging option is available in the **DaVis** calibration dialog in "Calibration: record new images". Alternatively, previously recorded images can be used and



a batch processing can be applied to average multiple images prior to accessing the dialog via "Calibration: use displayed images".

3. **Apply Volume Self-Calibration:** Volume self-calibration is a technique to detect and correct calibration errors in tomographic PIV, 3D-PTV and Shake-the-Box experiments. Starting from a calibration-target based calibration, volume self-calibration makes use of the recorded particle images themselves to detect and correct calibration errors. A very important aspect of self-calibration is that a calibration which has been done at one point in time e.g. prior to the recording of particle images, may become inaccurate at another point in time. The reason for this is that the camera mounts and the optics are never 100 % stiff. Hence, the camera orientation or the magnification or the focal plane will change a tiny bit over time. However, over time already these tiny changes can result in calibration inaccuracies in the order of several pixels. These inaccuracies need to be detected and corrected to achieve the required calibration accuracy of better than 0.1 pixel.

The basic principle for the detection and correction is as follows: If the position of a certain tracer particle is known in each camera image, then the volume calibration, or line-of-sight calibration allows the projection of the lines of sight of this particle through the 3D measurement space 5.4. For a perfect calibration without any errors, the lines of sight from all cameras would intersect in a single point in space, the true 3D position of the tracer particle. In a real experiment, the lines of sight will **not intersect** in a single point but will deviate from each other. These *deviations* of the lines of sights can be used to detect and correct systematic errors in the calibration.

The exact definition of the *deviations* of the lines of sight of the same particle from different cameras is not trivial, especially if more than two cameras are involved. One possible definition of such deviations is related to the problem of detecting the *best* 3D position given a number of 2D positions on the camera sensors and a calibration. It is known as the triangulation problem. A well suited approach for the triangulation problem is to minimize the *back-projection error*. Given a set of 2D positions (of a single tracer particle) (x_i, y_i) for all cameras $i, i = 1, \ldots, N_c$, the calibrated mapping functions $M_{x,i}(x,y,z), M_{y,i}(x,y,z)$ and an arbitrary point in 3D space (x,y,z), the back projection error e_{bp} is:

$$e_{bp}(x,y,z) = \sqrt{\frac{1}{N_c}\sum_i [x_i - M_{x,i}(x,y,z)]^2 \; + \; [y_i - M_{y,i}(x,y,z)]^2} \tag{5.5}$$

The triangulated position (x_T, y_T, z_T), or the best-guess position, is the point in 3D space that minimizes the back projection error:

$$(x_T, y_T, z_T) = \underset{(x,y,z)}{\arg\min} \;\; e_{bp}(x,y,z) \tag{5.6}$$

For a perfect calibration without any errors, the lines-of-sight of a single tracer particle would intersect in a single point such that $e_{bp}(x_T, y_T, z_T) = 0$.

In a real experiment with a real calibration, the minimal back projection error will be larger than zero due to remaining calibration errors and errors in the detection of 2D particle positions on the sensor. In fact, the different contributions to the sum in the definition of the back projection error 5.5 provide very detailed and valuable information about systematic calibration errors, that are used to alter the mapping functions in a way to minimize systematic (non random) parts of the back projection errors. A detailed explanation of the volume self-calibration and how it is applied can be found in section 4.2 of this manual.

Considering the three points mentioned above carefully: In the past, stiff camera mounts, unaltered lens settings, application of volume self-calibration, has already lead to many successful volumetric flow measurements in a broad range of applications and should be helpful for more successful applications to come.

6 Support

If you have a technical problem or a question regarding hardware or software which is not adequately addressed in the documentation, please contact your local representative or **LaVision** service directly.

You can contact service at **LaVision** GmbH by:

e-mail:	**service@lavision.de**
phone:	**+49 551 9004 229**

Alternatively, you may submit your problem using the **Support Request Form** in the **Support** section of the **LaVision** website `www.lavision.com`.

In order to speed up your request, please include the following information:

- The order number of your system (see section 6.1).
- The number of the used dongle (see section 6.1).
- A short description of the problem.
- The **LaVision** service file (see section 6.2).
- Some logfiles if you have a reproducible software problem (see section 6.3).
- Information on the Windows operating system and service pack used on the corresponding computer.

6.1 Order and Dongle Number

To be able to find information on the delivered hardware components and customer details in the **LaVision** database, your order number is required. This number can be found in the toolbar menu **Extras – About** or on the original **DaVis** installation medium (see Fig. 6.1).

In the **About DaVis** dialog you find the dongle number and order number information. The **Version ID** is the build number of the **DaVis** version, shown on top of the dialog.

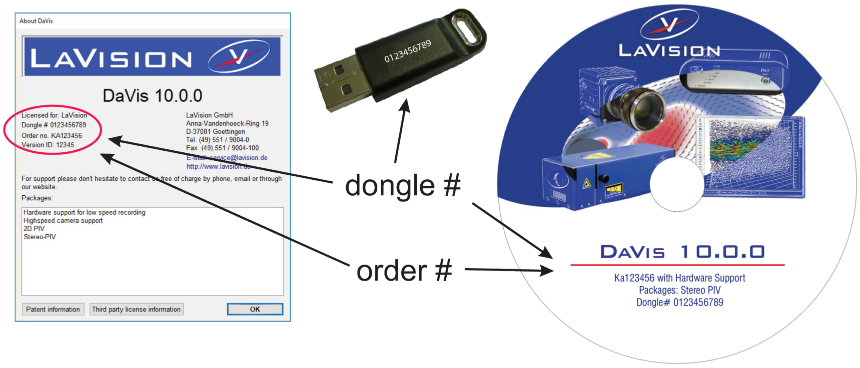


Figure 6.1: Dongle and order no. in **Extras - About** and on the installation DVD.

The dongle number is required to exclude possible license problems. This number is printed on the hardware key as well. The dongle number and the order number can also be found on the original **DaVis** install medium.

Please include the order number and/or the dongle number in your service requests.

6.2 LaVision Service File

In order to be able to reproduce a software problem, it could be essential to know the exact hardware setup and software parameters in **DaVis**. All currently used parameters and all error messages that have been shown since the last **DaVis** start can be extracted using the toolbar menu **Extras – Service – Create service file for LaVision support**.

After you have selected this menu, the system will write all values for the relevant variables into a `LSFX` file. This file will also contain the current settings of the hardware setup, acquisition setup and processing operation lists. The procedure will take some seconds!

The `LSFX` file will be written automatically to a folder selected by the user and the Windows explorer opens at the end with this folder. The name of the file contains the order number and dongle number that is extracted from your software (`#ordernumber_donglenumber.lsfx`). Send the `LSFX` file as attachment to your email together with the description of your problem to `service@lavision.de`.

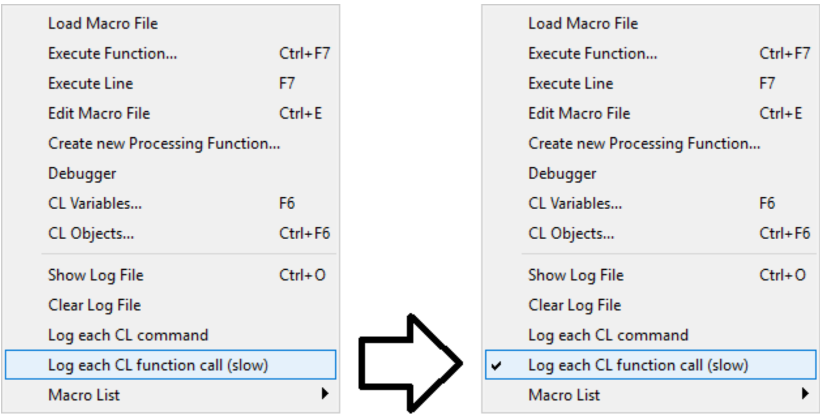
6.3 Log File

During startup of **DaVis**, some log files are generated in the **DaVis** subdirectory `Users/<name>/log` (until version 10.2.0) or in **DaVis** subdirectory `ProgramData/log` (since version 10.2.1). The standard log files are separated for certain areas of the software and get corresponding names for easier access by service. The log files from the Command Language are named like `LOG_<date>_<time>.txt` with date and time of the **DaVis** startup, e.g., `LOG_170615_150343.txt`. **DaVis** holds the last ten CL log files and removes older ones automatically.

If you have a reproducible software problem in **DaVis**, please send the complete log folder together with your email. These files contain all functions you have called and all error messages that have been displayed after you activated the log. Please proceed as follows:

1. Start **DaVis** and use the toolbar menu **Extras – Macro – Clear Log file**.

2. Enable the **Log each CL function call (slow)** entry in the menu. This feature is active if you see a flag at the left side of the entry. Every time you click on this entry, its status is changed.



3. Try to reproduce your problem, e.g., until an error message is displayed.

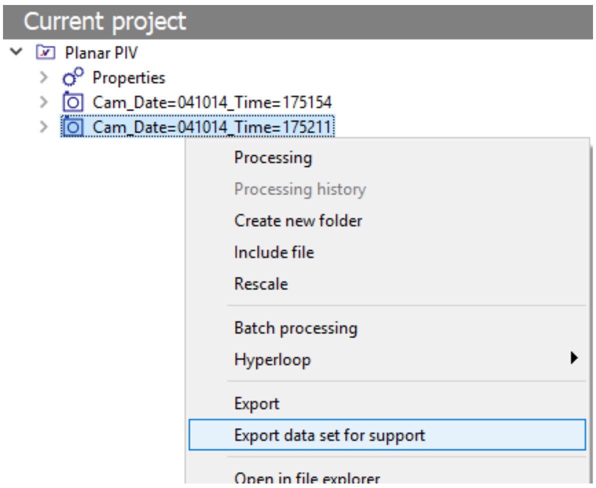
4. A log file has been generated in the **DaVis** main directory. Send this text file attached to your email.

5. Disable mode **Log each CL function call (slow)**. This function is deactivated if you do not see a flag next to the entry.

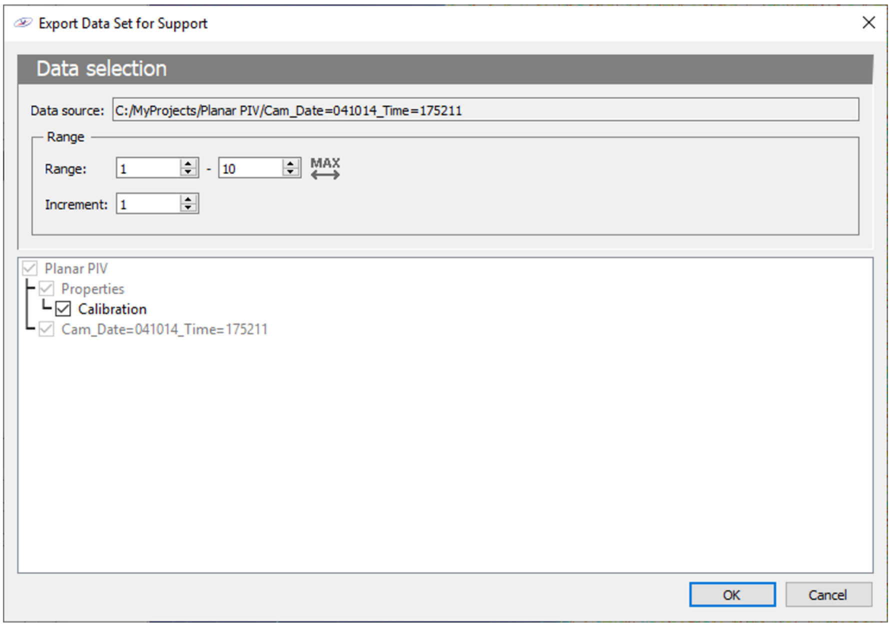
6.4 Export Data Set for Support

Some problems can only be reproduced using images or data that contain particular information or artifacts. For error analysis, it can be necessary to provide exemplary data that need to be extracted from the corresponding project.

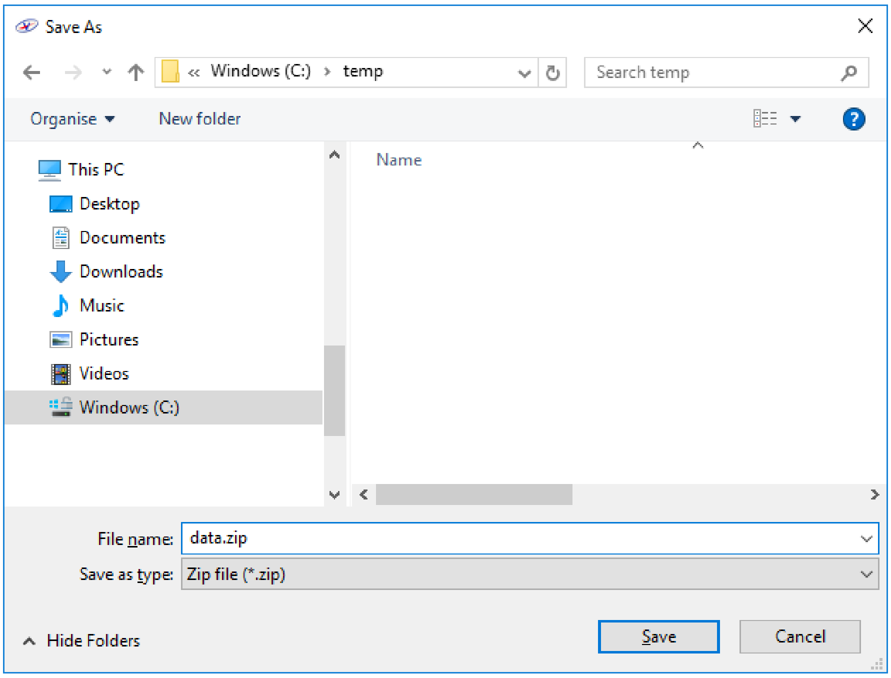
Depending on the project type, the number of cameras used, and the error, it can be necessary to provide the corresponding calibration (spatial, temperature, etc.) and derivative data as well. A convenient way to extract the data from the project is the **Export data set for support** option, which you can select by right-clicking on the corresponding data set in the tree view of the **Project manager**.



In the **Export data set for support** dialog, specify the range of data which you would like to extract from the data source by entering the range (i.e., first and last image). If a calibration is available in the project, this will be added by default. You have the option to deselect this part if it is not relevant.



After clicking the **OK** button, you need to specify location and file name for the `zip` file that contains the selected data.



DaVis will ask to open the containing folder or to send an email to `service@lavision.de`.

Note: Files with a size of more than 20 MB should not be sent by email. **LaVision** can provide a link for uploading data via file drop. Please contact `service@lavision.de` for details.

6.5 Shipment of Defective Items

If any item needs to be returned to **LaVision** GmbH for service or repair, please contact the **LaVision** service to obtain a **RMA** (Return Material Authorization) number together with an RMA form. This will list all items with SN and a short description of the problem. Place the RMA form in the box with the item(s) being returned. Return the authorized item(s) according to the shipping instructions.

Shipping instructions:

- Be sure to obtain an RMA number and RMA form.
- Add the signed RMA form to the shipping documents.
- Ship only the items that are authorized.
- Use the original boxes to avoid damages during transportation.
- **Remove cooling water from the laser!**
- **Use antistatic bags for computer boards!**
- Ship returned items to:

  LaVision GmbH
  Anna-Vandenhoeck-Ring 19

  37081 Göttingen

  GERMANY

Note: Shipments received by **LaVision** without an RMA number may be refused.

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FOCUS ON IMAGING

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