

# Modernization of the DLR L2F-System: A Comprehensive Hardware and Software Upgrade for Future Applications

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## ABSTRACT

Laser-2-Focus (L2F) also known as Laser Transit Velocimetry (LTV) is a non-intrusive optical measurement technique to determine flow velocities and turbulence intensities in demanding flow conditions with restricted optical access. Back in the early 1970s, first steps of development were made by Schodl (1974) at the Institute of Propulsion Technology of German Aerospace Center (DLR). Since then, L2F has been constantly enhanced by DLR in cooperation with commercial partners to expand its range of application, operability, and accuracy. Over time, L2F technology has been used for various applications in the field of turbomachinery by Hergt et al. (2019) and Wittrock et al. (2020), fundamental flow research by Ueki et al. (1997) and Burow et al. (2018), as well as in-flight flow anemometry by Curry (1983) and Beversdorff et al. (1997). The goal of these experimental investigations is to provide a comprehensive image of the flow conditions as well as comparative data for complex flow simulations and design studies. In particular, L2F has established in experimental turbomachinery research due to its low requirements on optical access size. Compressor and turbine test rigs featuring high technology readiness levels (TRL) are highly instrumented which impedes optical flow visualization with most optical diagnostic techniques. Other advantages of L2F are preventing a flow disturbance at the measuring point, measuring close to rotating components like rotors and enabling flow measurements at locations that are intricate or even impossible to measure with conventional probe measurement technology.

The increasing demand for reliable measurements from ever more complex environments requires miniaturized, robust and dependable measurement techniques. Therefore, the DLR's L2F system has been recently modernized and the previous laser system, light detectors and analog electronics were upgraded. New capabilities when implementing modern diode lasers, silicon photomultipliers (SiPMs), and FPGA-based signal processing electronics are elaborated. This modernized L2F system is much more flexible, manageable, and reliable compared to the former system architecture. Among others, the new electronics allow a L2F data evaluation routine that enables real post-processing of recorded L2F data sets, e.g. post-analyzing data depending on the foci permutation of interest or phase-sorting measurement data relative to a turbomachinery rotor trigger. Furthermore, the new FPGA-based electronics enable to capture scattered particle light from more than two laser light foci at the same time which allows a fundamental new data evaluation approach called Laser-3-Focus (L3F). The novel L3F concept includes filter routines that are expected to decrease noise originating from uncorrelated particle events in future applications.

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## 1. Introduction

In the early 1970s, Laser-2-Focus (L2F) was developed by Schodl (1974) at the Institute of Propulsion Technology of German Aerospace Center (DLR). A commercialization of L2F was established in cooperation with industry partners in the late 1970s that lasted for almost 20 years spreading various variants of L2F systems over the world. Since its first development by Schodl, L2F has been applied for many different research fields like in-flight laser anemometry by Curry (1983) and Beversdorff et al. (1997), spray diagnostic by Ueki et al. (2005), fundamental flow research by Ueki et al. (1997) and Burow et al. (2018), as well as turbomachinery research by Hergt et al. (2019) and Wittrock et al. (2020). After the commercialization ended, DLR pursued developing its L2F technology and Karpinski (2000) released a three-component L2F-Doppler system using Doppler Global velocimetry to determine the third velocity component along the observation direction. Today, L2F is mainly used in turbomachinery research, e.g. at DLR's Institute of Propulsion Technology. The institute runs several turbomachinery test facilities, e.g. a radial compressor rig, transonic cascade wind tunnel, turbine test facility or co/contra-rotating acoustic fan test rig, where L2F was applied in past and will support the development process of turbomachinery in future. In order to apply L2F at DLR's highly-instrumented test rigs, different L2F probe designs evolved over time to adapt the optical setup to severe measurement conditions.

Laser-optical anemometers are generally non-intrusive diagnostic techniques that capture flow velocities (and turbulence intensities) without disturbing the flow field itself like five-hole probes or hot-wire anemometry. L2F analyses Mie scattering of tracer particles that are either inherently part of the flow or artificially added. It is a stationary measurement technique that can only resolve time-averaged flow statistics, like mean velocities and turbulence intensities. Generally, L2F is a point measurement technique. Nonetheless, three-dimensional flow fields can be analyzed by traversing the measurement volume along all three spatial axes. In contrast to other widely-known and well-established laser-optical measurement techniques for flow field velocimetry like Particle Image Velocimetry or Laser Doppler Anemometry, L2F offers some features that are particularly advantageous for turbomachinery research. L2F is a back-scattering method, hence light scattered by the tracer particles is received by the same optics that are used to emit laser light to generate the measurement volume. This allows a compact optical setup and only requires one optical access for an implementation in a wind tunnel or turbomachinery rig. Additionally, due to its highly focused laser light beams, L2F features a high signal-to-noise ratio (SNR) which facilitates non-intrusive measurements in the vicinity of wind tunnel end walls, turbomachinery hubs and even moving rotor blades under rotational full speed.

The DLR's L2F system has been constantly enhanced depending on latest laser, detector or electronics technology on the market. Recently, modern diode lasers, silicon photomultipliers (SiPMs) and FPGA-based signal processing electronics were implemented in the existing architecture. These new components allow a novel way of performing and evaluating L2F measurements to which the

authors refer as Laser-3-Focus (L3F). The L3F approach provides more information of the underlying flow field, may reduce measurement time and increase SNR.

### 1.1. Working Principle of DLR's L2F System

The general L2F measurement principle can be compared with the concept of a light barrier. Two highly focused laser light beams are guided into a flow channel and span the L2F measurement plane. Tracer particles scatter laser light when passing the laser light foci. The tracer particle diameters are usually in the order of magnitude of the exciting laser light wavelength between 0.1 and 0.5  $\mu\text{m}$ . These small particles must feature a Stokes number  $St \ll 1$  to follow strong accelerations, as present in turbomachinery and transonic flow. The back-scattered light pulses are detected by the same optics as the laser light is sent into the flow channel. The spatial difference between the two laser light foci (beam separation) is well known and typically in the order of hundreds of micrometers. Thus, measuring the time difference between the light pulses  $\Delta t$  provides information about the time-of-flight (ToF) of the tracer particles along the measurement plane. From this the velocity of the particle can be deduced. As the tracer particles follow the flow precisely, the flow velocity is assumed to be equal to the particle velocity. A stepwise rotation of the measurement plane enables recording multiple data sets, each corresponding to a discrete angle position. A statistical analysis of the recorded time-of-flight data sets yields the statistical velocity distribution from which the time-averaged mean and standard deviation of flow velocity and angle can be derived.

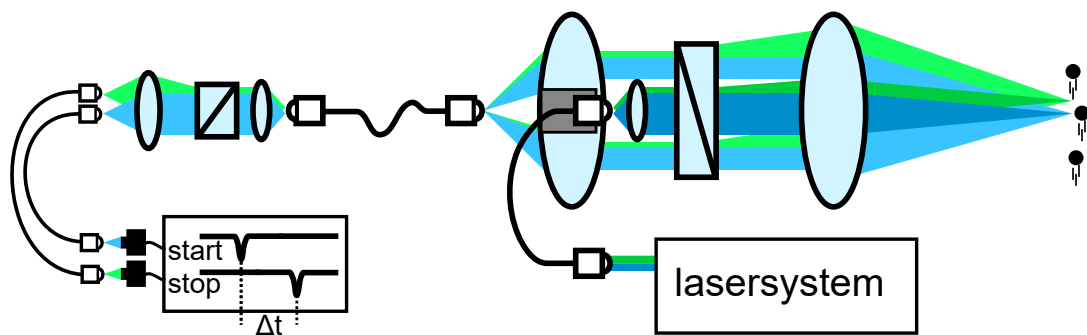


**Figure 1.** A schematic setup of a two-color-two-component L2F optimized for turbomachinery test bed applications. The optical setup is commonly partitioned into three units: laser system, front head, and detector unit connected via optical fibers. This facilitates the positioning of the remote-controlled L2F's front head setup in the restricted space close to a turbomachinery rig or flow channel while the detector unit is placed in the control room of the test facility.

A typical L2F setup optimized for turbomachinery test bed applications is depicted in Fig. 1. The optical setup is commonly partitioned into three units: laser system, front head and detector unit. This facilitates the experimental setup close to a turbomachinery rig or flow channel, since installation space is usually highly restricted. Only the L2F's front head is positioned next to the test bed

while the detector unit stays at the measuring station. The setup shown in Fig. 1 represents a two-color-two-component L2F setup. Two laser light beams with different wavelengths, illustrated in green and blue, are guided from the laser source through an optical fiber to the front head. Inside of the front head the light is spatially separated by an Amici prism and strikes the inner part of the front lens. The front lens focuses the laser light at two spatially separated focus points which represent the L2F measurement volume. The focus separation is determined by the deflection angle of the Amici prism that depends on the wavelength of the laser light and the focus length of the front lens. The back-scattered laser light that is generated by tracer particles striking the laser foci is collected by the outer area of the front lens. It is sent to the Amici prism which superimposes the received light. Another optical fiber guides the received laser light to the detector unit where it is spatially separated by another Amici prism again. Then, the two separated beams are respectively sent via an optical fiber to a highly sensitive light detector, e.g. a photomultiplier (PMT) or silicon photomultiplier (SiPM). The light detectors convert the short light pulses into electrical signals that can be processed and recorded, hereafter. A more detailed explanation of the measurement principle and the optical setup can be found in Schodl (1982) and Karpinski (2000).

The two-color-two-component L2F setup can be expanded to a multiple-color-two-component L2F that enables the adaption of the focus separation to the present turbulence intensity. Depending on the number of detector signals that can be simultaneously recorded by the electronics, the focus separation must be adapted either a priori. Measurements with a suitable focus separation allow to obtain more information of the fundamental flow, reduce measurement time and lower the systematic error of flow turbulence.

## 2. Modernization

The L2F system as described above can be separated in distinct operational subsystems. In this section the modernization of each subsystem is presented, successively. The overall aim of the modernization was the system's miniaturization, increase of robustness, reduction of the systematic measurement error and user-optimized handling.

### 2.1. Modern Laser System

Recent development in laser technology enables the replacement of the previously used Argon-Ion-laser-system which was capable of emitting light wavelengths of 476 nm, 488 nm, 496 nm, and 514 nm. Modern solid-state-laser-systems offer many improvements, e.g. compactness (water-cooling not necessary), larger maintenance intervals, and higher robustness against misalignment. The smaller setup space and power consumption makes them suitable for implementation in adverse conditions typical for turbomachinery component test rigs. Despite these obvious advan-

tages compact laser diodes may feature higher bandwidths and lower laser light power which has to be considered when selecting a new laser light source for a L2F system.

The new multi-wavelength laser system for the updated DLR-L2F system (as depicted in Fig. 2) includes distinct lasers that can be separately adjusted in power and modulated with frequencies in the realm of typical rotor blade frequencies. Three separate solid-state lasers manufactured by Oxxius operating at 488 nm (maximum power 200 mW), 505 nm (70 mW), 515 nm (150 mW), and a high-power CW fiber laser by AzurLight Systems at 532 nm (5 W) were implemented. The laser light beams are superimposed by dichroic mirrors before entering the fiber guiding the light to the L2F front head. The laser system can be fully remote controlled which allows an implementation in setups with high TRL where strict safety precautions are prescribed.

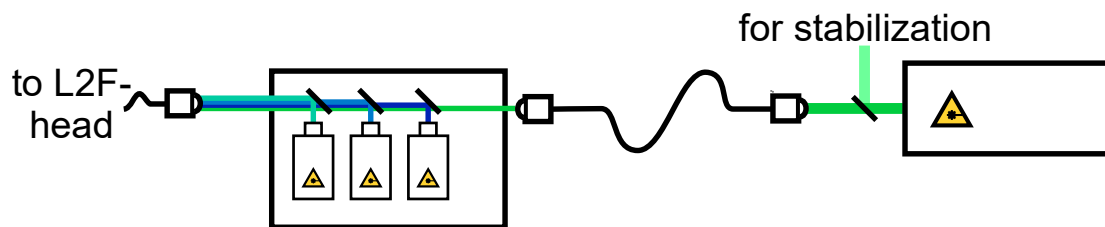


**Figure 2.** A schematic setup of the modern laser system. The three solid-state lasers by Oxxius and the high-power CW fiber laser by AzurLight Systems are superimposed by dichroic mirrors before guided through an optical fiber to the L2F front head. Part of the CW fiber laser light can be splitted from the main light path for stabilizing its frequency for combined L2F-Doppler-measurements.

As the 532 nm laser system can be frequency-stabilized it is suited for combined L2F-Doppler-measurements. Doppler measurements resolve the velocity component in the observation direction by analyzing the Doppler shift of the light scattered by the particles in the flow. Combining this measurement technique with two-component L2F measurements yields information of all three velocity components as demonstrated by Karpinski (2000) and Förster et al. (2002).

## 2.2. (Silicon) Photomultipliers

Low intensity light pulses originating from tracer particles scattering laser light when passing the laser foci in the L2F measurement volume were detected and converted into electric signals by photo-multiplier-tubes (PMTs) so far. These vacuum phototubes offer very high gain in combination with low noise which makes them a great fit for low light level detection. However, the operation of PMTs requires high-voltage power supply and comparably big installation space. Furthermore, PMTs are sensible to overexposure, e.g. caused by laser light reflected from moving parts in turbomachines or reflections on static flow channel end walls. This necessitates either shuttering the laser light when the L2F laser foci approach high reflective surfaces or rapidly reducing the PMTs' operating voltage to prevent them from irreversible damage. The PMT model

implemented in the former L2F signal chain is the 9813B by ET Enterprises electron tubes with an outer diameter of 52.3 mm and length of 170 mm. During regular L2F measurement these detectors were operated at a maximum voltage of 1500 V resulting in a maximum gain of  $6 \times 10^6$  according to the data sheet provided by its manufacturer. Nevertheless, these detectors have a significant higher gain reserve up to  $140 \times 10^6$  when running at a their certificated maximum operating voltage of 3000 V.

A newer generation of low light level detectors, so called silicon photomultipliers (SiPMs), were tested and evaluated in an extensive lab study to replace the established PMTs for L2F applications. These semiconductor detectors are available in different sizes that vary in active area as well as spectral range, and feature a maximum gain in the required order of magnitude. They typically consist of hundreds of pixel-like single-photon avalanche diodes (SPADs), operate at low voltages, and are resistant to magnetic fields and overexposure. General disadvantages of SiPMs are lower reserve in gain and higher dark count rate that intensifies with increasing sensor temperature. Cooling the detector by the use of e.g. thermoelectric heat pumps such as Peltier elements can lower the dark count rate significantly. On top of that, SiPMs show optical crosstalk and afterpulsing behaviour due to their design architecture. These effects contribute to the overall noise level and must be considered when selecting a SiPM model for a particular application.

In order to replace the previously used PMTs the L2F system's signal requirements must be fulfilled to implement new detectors in the existing signal chain. The constant fraction discriminators (CFD) that process the amplified detector signals (see Fig. 6) only except negative linear pulses of -5 mV to -5 V at 50 ohm with a minimum width of 1 ns. Certainly, the spectral range of the light detectors has to fit the system's laser light wavelength range of 488 nm to 532 nm and should show a peak sensitivity in the vicinity of the laser wavelength domain.

Three SiPM models by Broadcom were found that fulfill these requirements. Their specifications are summarized in table 1. The detectors mainly differ in their number of SPADs and active area, respectively. The maximum gain of all three models is  $9 \times 10^6$  for a maximum over voltage of 16 V. The maximum operating voltage is 48.5 V (or rather 50 V) which eliminates the necessity of a high-voltage power supply as needed for PMTs. Therefore, initial lab tests could be done with a standard lab power supply. The detectors all feature a spectral range of 250 nm to 900 nm with a peak sensitivity of 420 nm. Broadcom provides the NUV-MT Evaluation Kit (AFBR-S4E001) as an evaluation platform for different SiPM models of the AFBR-S4NxxPyy4M SiPM family. The evaluation kit includes the three SiPM models in table 1, an amplifier PCB and a DC readout PCB. The amplifier PCB includes a two-staged amplifier and is designed for single-photon and multiple-photon detection whereas the DC readout PCB is optimized for maximum dynamic range readouts. The amplifier PCB is powered by an external power supply delivering  $\pm 2.5$  V to  $\pm 8.5$  V and has two SMA outputs. It includes a high voltage filter to minimize voltage fluctuations of the SiPM operating voltage. The first output signal is generated by applying only the first amplification stage and then passing the signal through a buffer with unity gain. The polarity of this signal 1

is negative and optimized to maintain the signal shape. Broadcom states this output as the energy output since the integration of these signals provides the delivered charge that is proportional to the amount of detected photons. The second output uses both amplifier stages while the second stage includes a Pole-Zero filtering network. This filter changes the signal shape and is designed to reduce the fluctuations due to dark counts. The resulting signal has a positive polarisation. Broadcom states this output as the timing output since it is optimized for timing resolution performance. The DC readout PCB does not include any amplifier stages and does not need any external power supply. Only a low-pass filter is implemented to minimize voltage ripples from the SiPM voltage source. According to Broadcom it is designed to observe SiPM signals without potential restrictions that come with amplifier circuits, for instance an influence on signal amplitude or bandwidth.

| SiPM models           |                    | AFBR-S4N22P014M     | AFBR-S4N44P014M | AFBR-S4N66P014M |
|-----------------------|--------------------|---------------------|-----------------|-----------------|
| Number of SPADs       | [-]                | 2464                | 8334            | 22428           |
| Active area           | [mm <sup>2</sup> ] | 2 × 2               | 3.72 × 3.62     | 6 × 6           |
| Spectral range        | [nm]               | 250 – 900           | "               | "               |
| Peak sensitivity      | [nm]               | 420                 | "               | "               |
| Maximum gain          | [-]                | 9 × 10 <sup>6</sup> | "               | "               |
| Breakdown voltage     | [V]                | 32.5                | "               | "               |
| Maximum over voltage* | [V]                | 16                  | "               | "               |

**Table 1.** Specifications of the tested SiPM models AFBR-S4NxxP014M by Broadcom. The detectors mainly differ in number of SPADs and active area, respectively. The maximum over voltage\* is specified with 16 V, nevertheless the manufacturer assured a safe operation up to 17.5 V resulting in an operating voltage of 50 V.

The SiPM tests were performed by analyzing real particle signals applying L2F on a free jet. The new detectors were illuminated by the back-scattered particle light leaving the optical fiber that guides the color-separated light in the detector unit to the respective detector as depicted in Fig. 1. During initial tests the detectors' noise level exceeded the particle signals due to ambient light impacting on the detectors active area. Hence, for all test cases described below the detector test setup was placed in a housing to shield from all other light sources than the particle back-scattered light.

First, the medium sized SiPM AFBR-S4N44P014M was tested in combination with the DC read-out board applying an over voltage of 11.5 V. The oscilloscope showed extremely low signal rates which prevent feasible L2F measurements since the measurement time depends on the accumulation of a sufficient number of correlated signal pairs to perform the statistical analysis of the ToFs. The reason might be that most of the non-amplified signals do not pass the oscilloscope's trigger level which was set above the dark noise level. Besides, the DC readout board output signal has a positive polarity which does not match the CFD's input signal requirements.

Second, the two outputs of the amplifier PCB were tested with the AFBR-S4N44P014M and at the same operating conditions as the DC readout board.

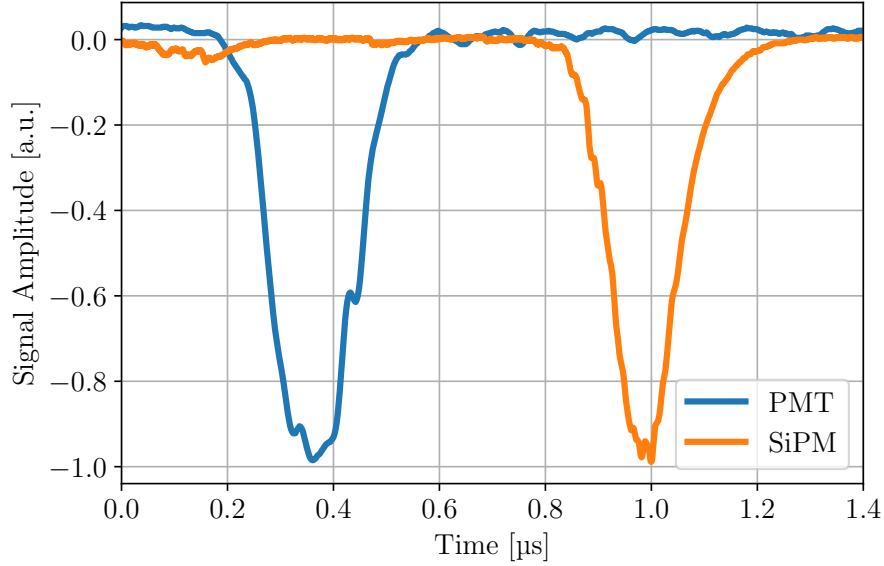


**Figure 3.** Comparison of the signal shape of typical PMT and SiPM signals produced by L2F particle events. The PMT signal was processed and powered by the old L2F Polytec electronics. The SiPM signal was processed by the Broadcom amplifier PCB while using the energy output 1 and powered by a standard lab power supply. The signals shapes resemble each other.

A comparison showed that energy output 1 fulfills the demands of the L2F system quite satisfactory. Even though it is not optimized for timing purposes its bandwidth is still high enough for the L2F application. Further, it delivers high signal rates in combination with the favored negative signal polarity. Timing output 2 showed comparable signal rates and overall noise level but a positive polarity. As output 1 is already fast enough the higher bandwidth of output 2 has no benefit for our L2F application. Since output 1 is optimized to maintain the signal shape its signal and the former PMT signal strongly resemble each other in amplitude and shape. A comparison of typical PMT and SiPM signals captured under the same conditions is shown in Fig. 3. The similarity is clearly visible.

Third, the performance of the three different SiPM models were investigated by analyzing the amplifier PCB output 1. The signal rate was recorded by an in-house developed ratemeter based on a Raspberry Pi Pico and time-averaged over 120 s. For every sensor size the distance between the SiPM's position relative to the ferrule of the optical fiber was set to match the FWHM of the circular light spot  $d$  on the sensor with the edge length  $a$  of the respective sensor  $d \approx a$ . The goal was to illuminate the chip fairly well to lower dark counts on non-exposed SPADs without light being cut off at the rim of the active area. The time-averaged signal rate for different over voltages for the three detectors is plotted in Fig. 4.

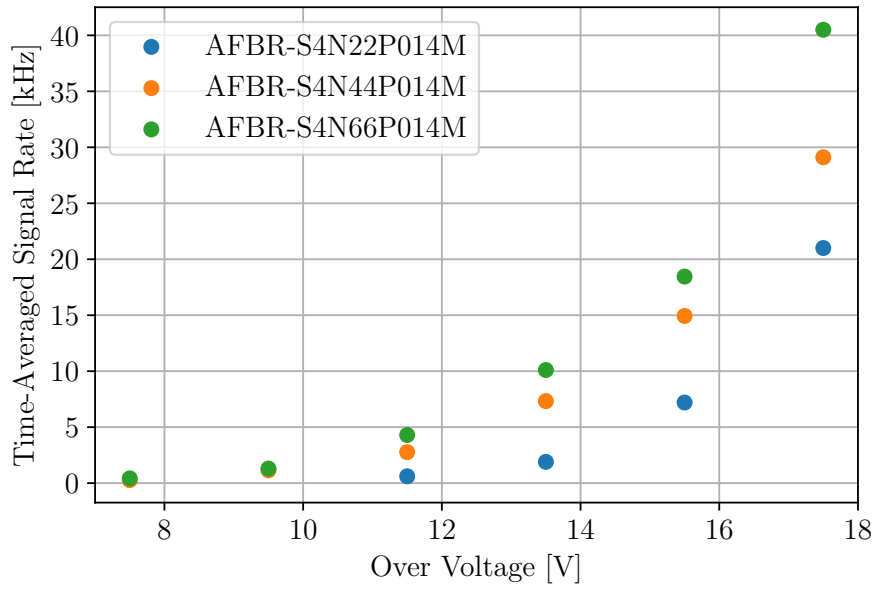


**Figure 4.** Time-averaged data rates measured for different over voltages of the three SiPM models capturing L2F particle signals from a free jet. The data was recorded by an in-house developed ratemeter and time-averaged over 120 s.

The figure shows that AFBR-S4N66P014M captures the highest signal rate which is more evident for higher over voltage. The better performance of AFBR-S4N66P014M can be explained by its higher number of SPADs. In general SPADs cannot differentiate between single or multiple photon events. As soon as they are triggered by an event an avalanche of charge carriers is started. During this off-state the detector cannot detect any other photons impacting on the SPAD. Only after the diode is reset by its quenching resistor the detector can detect another photon event. Thus, the higher the number of illuminated SPADs on a SiPM, the more photons can be converted into signal. Therefore the number of SPADs is a trade off between the dynamic range needed for a strong signal and the increasing noise level due to dark counts produced by the individual SPADs.

Fourth, the SiPM model AFBR-S4N66P014M was considered for further investigations due to its better performance regarding the data rate to shorten L2F measurement time. The optimal position of the AFBR-S4N66P014M relative to the optical fiber's ferule was experimentally investigated. The SiPM setup was mounted inside of a non-rotating zoom housing to linearly adapt the relative distance between the ferule and the sensor while shielding the sensor from ambient light. Finding an optimum distance is crucial to lower the overall noise level since it determines how many SPADs are exposed to the particle light. Signal rates averaged over 20 s were captured by the ratemeter for different relative positions. In Fig. 5 three data sets are shown for different over voltages. The data sets are normalized to their respective maximum for each over voltage. The figure shows that the distance set according to the formula  $d \approx a$  is not optimal. In fact, the optimum distance seems to be reached when the FWHM of the particle light spot is equal to the

diagonal width of the sensor  $d \approx \sqrt{2}a$ . Consequently, it is beneficial to illuminate the entire active area of the chip and ditching some light where the light spot does not overlap the chip's active area. Slight deviations of several tenth of a millimeter from this optimum position neither effect the signal rate nor the SNR, significantly. A small deviation of angle of ferule relative to the sensor surface did not show a significant influence on the signal rate. Therefore the setup is robust to small misalignment. The effect of cooling the SiPMs was not investigated so far as the low noise levels at ambient temperature does not justify the additional technical effort and resulting costs at this moment.

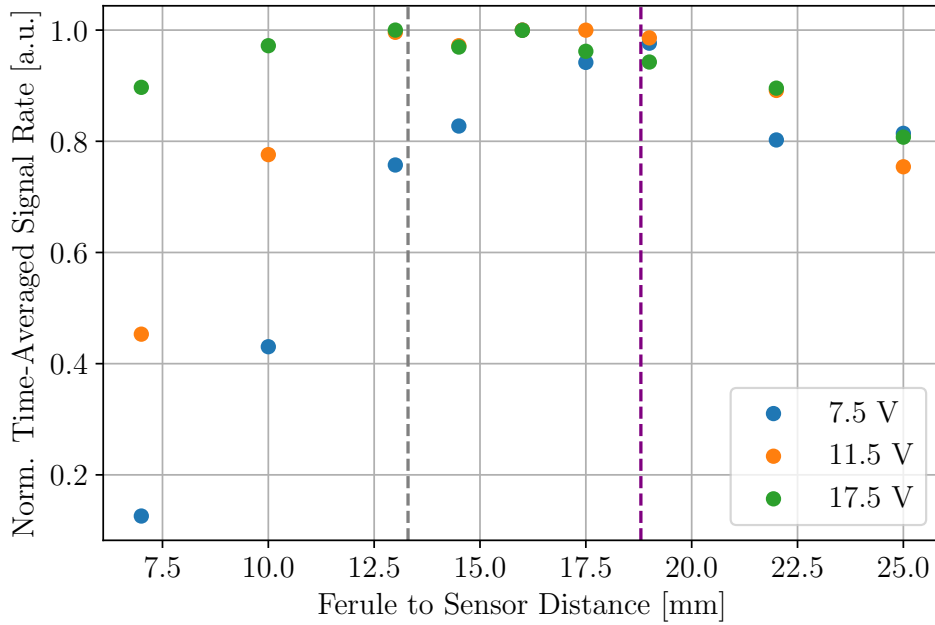


**Figure 5.** Time-averaged data rates for different relative distances between the optical fiber ferule illuminating the AFBR-S4N66P014M and its sensor surface. The measurements were performed at three different over voltages and time-averaged over 20 s, respectively. The data sets are normalized to their respective maximum for each over voltage. Moreover, the initial estimate for the optimal distance according to  $d \approx a$  is marked in grey and the experimentally obtained optimum distance  $d \approx \sqrt{2}a$  in purple.

A remote controllable power supply for each SiPM is needed to operate them in a turbomachinery test bed environment since it is important to adjust the over voltage depending on the signal rate and noise level. Thus, a more robust and sophisticated power supply (N8031N) by CAEN was implemented in the L2F architecture. In order to shield the SiPMs from ambient light, the four detectors are housed inside of enclosed tubes, respectively.

### 2.3. Measurement and Control Electronics

The electronic signal chain can be depicted from Fig. 6. It consists of four SiPMs by Broadcom respectively connected to a Broadcom amplifier PCB, a constant fraction discriminator (CFD) by

Fast ComTec GmbH for each SiPM and one compact (2-unit-NIM) FPGA-based time-to-digital converter (TDC) by Surface Concept. Each combination of SiPM, amplifier and CFD processes the light pulses from one of the four laser light foci, respectively.

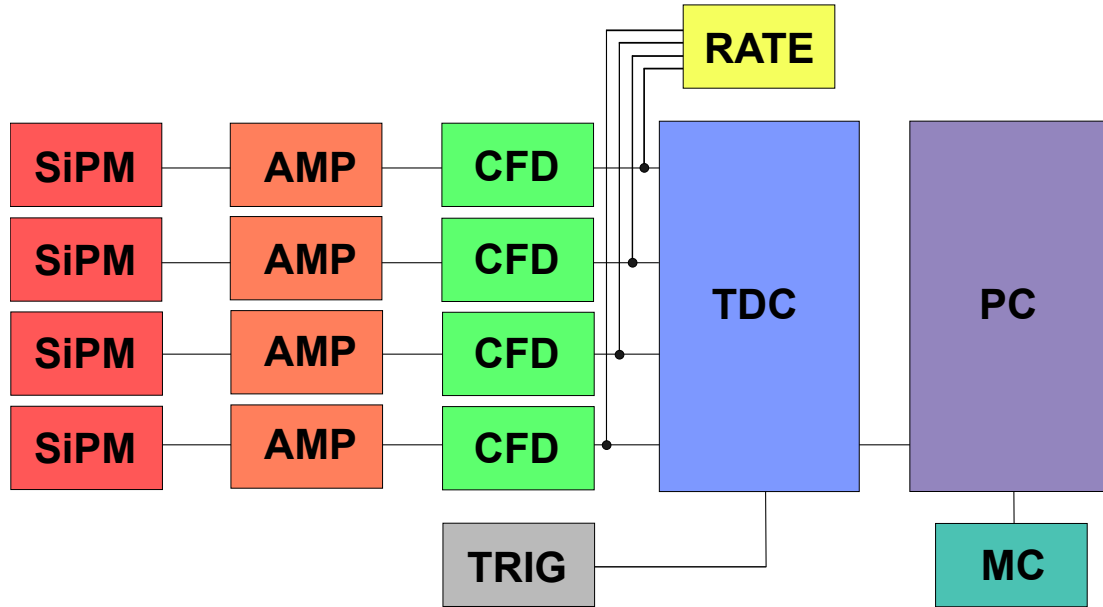


**Figure 6.** Schematic scheme of the new electronic signal chain that consists of the following subcomponents: silicon-photomultiplier (SiPM), amplifier PCB (AMP), constant fraction discriminator (CFD), time-to-digital converter (TDC), trigger signal source (TRIG), ratemeter (RATE), step motor controller (MC), personal computer (PC).

The low light pulses are detected and converted into electric signals by the SiPMs. These electric signals are processed by the amplifier PCB. As the amplitudes of the particle signals depend on various factors, such as particle diameter and position at which the particles pass the foci, using a leading-edge discrimination would cause a time jitter. Therefore, the CFD is implemented to generate a trigger signal depending on a pre-defined constant fraction of the signal amplitude which minimizes the time jitter. The CFD converts the electrical L2F signals into low voltage signals featuring sharp-rising edges that can be processed by the TDC. The TDC records time-stamps of these pulses with an internal measurement rate of 40 MHz and a digital time resolution of 82.3 ps. The eight signal inputs simultaneously capture the signals from the detectors and allow to record rotor triggers or other relevant signals on the remaining signal inputs as well. The TDC records a time stamp for every registered pulse and its time resolution is at least more than ten times higher than the old analog electronics. In contrast, the old electronics processed pulses from only two detectors, a priori allocated as start and stop channel, and passed them to a time-to-analog converter (TAC) that could only process their temporal distance. Then, this analog ToF data was fed into a multichannel analyzer (MCA) to digitize the analog ToFs by sorting them into one of 256 channels with a previously set maximum ToF. Now, the information of the actual time stamps

is saved for a post processing analysis. This data can be correlated to parallel recorded test bed trigger data, e.g. rotor or blade trigger of a turbomachine in order to phase-sort the measurement data. In addition, the new electronics feature a compact design, a python application programming interface and is remote-controllable.

The modernization of the electronics includes a new step motor control electronics to drive the 5-phase step motor by Berger Lahr implemented in the L2F's front head and synchronize it with the modernized system. The motor rotates the Amici prism inside of the front head to perform L2F measurements at different angular positions to resolve the flow angle. The electronics are based on an Arduino MEGA 2560 micro-controller that reads the hardware limit switches and the photoelectric barrier that serves as a zero-reference mark. It further addresses L298N motor drivers which power the five coils of the step motor in a sequence rotating the motor step wise. The communication between the L2F control software and the micro-controller is provided by serial interface. The step motor control electronics is designed in an Eurocard format, a standardized printed circuit board format.

## 2.4. System Control Software

The L2F system's control software was entirely modernized to handle the interconnection of the new electrical devices. A new Graphical User Interface (GUI) was developed in Python to facilitate device management and improving L2F data acquisition. The main functions of the GUI are the following: handling the TDC communication to start and stop data acquisition as well as saving TDC measurement data, controlling the step motor to enable ToF measurements at different angle positions, quasi-real-time data evaluation for live plotting, and processing user inputs to adapt data acquisition settings. The structure of the command and data connections between the system's subcomponents is shown in Fig. 7.

The TDC communication and data handling is provided by the scTDC SDK, a software development kit for C and C++ written by the device's manufacturer Surface Concept GmbH. The software package includes the Python interface scTDC Python SDK that allows access to the library functions to initialize, deinitialize the device, start measurements and receive data. The device configuration can be adapted by editing a configuration text file which allows to change parameters like enabled or disabled channels, extended measurement mode, time reference channels, enable external triggering, etc. The GUI allows the user to change the configuration file settings at the software's frontend and prevents editing the configuration text file manually. The TDC data acquisition is stopped by either selecting a maximum measurement time or maximum start events at an allocated start channel. The TDC measurement data is accessed via an customized data callback function of the scTDC Python SDK. This function allows to buffer TDC measurement data packages in a queue to save or process them, consecutively. The TDC measurement data consists of a two column array that holds information about channel and time stamp for each event cap-

tured at a TDC's enabled channel. The data is saved in a text file, for each measurement and step motor angle position, respectively.

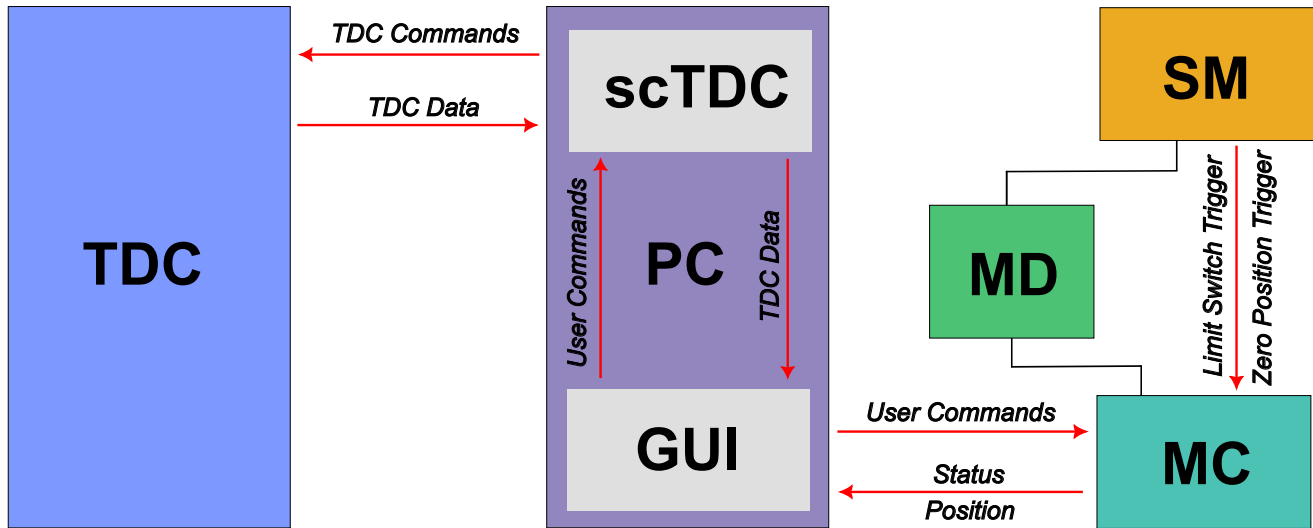


**Figure 7.** A schematic flow chart of the command and data connection between the electronic subcomponents. The graphical user interface (GUI) handles user commands to control the time-to-digital converter (TDC) via the software development kit (scTDC). Furthermore, the GUI communicates with the step motor controller (MC) based on a micro-controller that sends position drive commands to the motor drivers (MD) that power the coils of the step motor (SM). The SM sends limit switch and zero position triggers to the MC that calculates the step motor angle position and transmit it to the GUI.

Moreover, the GUI controls the step motor position and rotation direction. It sends position drive commands to the step motor controller as well as checks position arrival commands that are sent from the micro-controller to the computer after each step motor movement.

The GUI provides three main measurement modes: single measurement mode (SMM), angle traverse measurement mode (TMM) and continuous measurement mode (CMM). The SMM allows a TDC measurement depending on the predefined maximum measurement time or start events at a single step motor position. However, the TMM represents the actual L2F measurement since this mode provides a sequence of TMMs at predefined step motor positions. These are allocated by choosing the number of angle positions, their relative angular distance and the central angle position. The CMM serves as a live plot option to evaluate present flow conditions and noise level at different step motor positions. The receiving data packages from the TDC are stored in a ring buffer which length can be adjusted by the user. The data inside that ring buffer is frequently evaluated and plotted in a histogram to visualize and investigate the current flow situation. In general, the ring buffer allows an endless measurement and the step motor position can be changed during its operation. By adjusting the length of the ring buffer, the responsiveness of the live plot to velocity changes in the mean flow is adjusted. The CMM facilitates finding the angle position with the highest number of correlated events, which is commonly used as a first guess of the center angle

for the TMM. During the continuous measurement mode the TDC data is not saved in a text file.

Another feature of the GUI is the selection of the foci pair of interest for live plotting. Not only ToF data but also velocity data can be plotted which is calculated from buffered ToFs by considering the focus separation of the selected foci pair. In addition, the program provides an emergency stop button that interrupts the step motor movement and TDC data acquisition immediately when hit.

## 2.5. L2F Data Evaluation Routines

In addition, a new evaluation software package is under development. In the different routines the ToF data is analyzed depending on the foci permutation of interest and phase-sorted relative to a recorded (turbomachinery rotor) trigger. The data of each step motor angle position within an angle traverse is loaded and the following operations are performed to filter the data and calculate ToFs:

First the signals stemming from periodical trigger (e.g. rotor or blade triggers) are analysed to check for regularity. If strong fluctuations in the trigger period are found the affected data sequences can be excluded from further evaluation. Then, the detected light pulses are checked for correlated pulse pairs, i.e. the pulse pairs stemming from the same particle passing both laser foci. The particle velocity is calculated based on the ToF between the light signal pairs and the well-known distance of the selected laser foci. Further, a time stamp for every correlated pulse pair is saved with the data set.

After filtering and performing the velocity calculation from the ToF measurements of the tracer particles, a histogram is generated for each step motor angle position. Each of these 2D-plot histograms represents the time-averaged velocity distribution of the tracer particles at its respective measurement angle. A 3D-plot histogram can be generated by stacking the velocity data of all step motor angle positions. This plot represents the overall time-averaged velocity and angle distribution. The mean and standard deviation of these quantities is determined by fitting a model function e.g. Gaussian function to the data.

Moreover, the time stamps of the correlated pulse pairs can be used for any kind of phase-sorted evaluation in relation to a recorded periodical trigger signal, e.g. phase averaged velocity or angle distributions. This is a significant improvement compared to the old system where phase-resolved data sorting had to be chosen before the measurement.

## 3. L3F

The L2F method as described in section 1.1 involves an a priori selection of a pair of laser foci. At any time only light scattered by particles passing these particular laser foci is detected and

processed for evaluation of the temporal distance  $\Delta t$ . If two pulses are registered on the dedicated detectors with a certain  $\Delta t$ , it is not possible to differentiate whether this event was caused by a single particle passing both foci one after another (correlated event) or two independent particles causing this series of pulses (uncorrelated event). These two cases are schematically shown in Fig. 8.

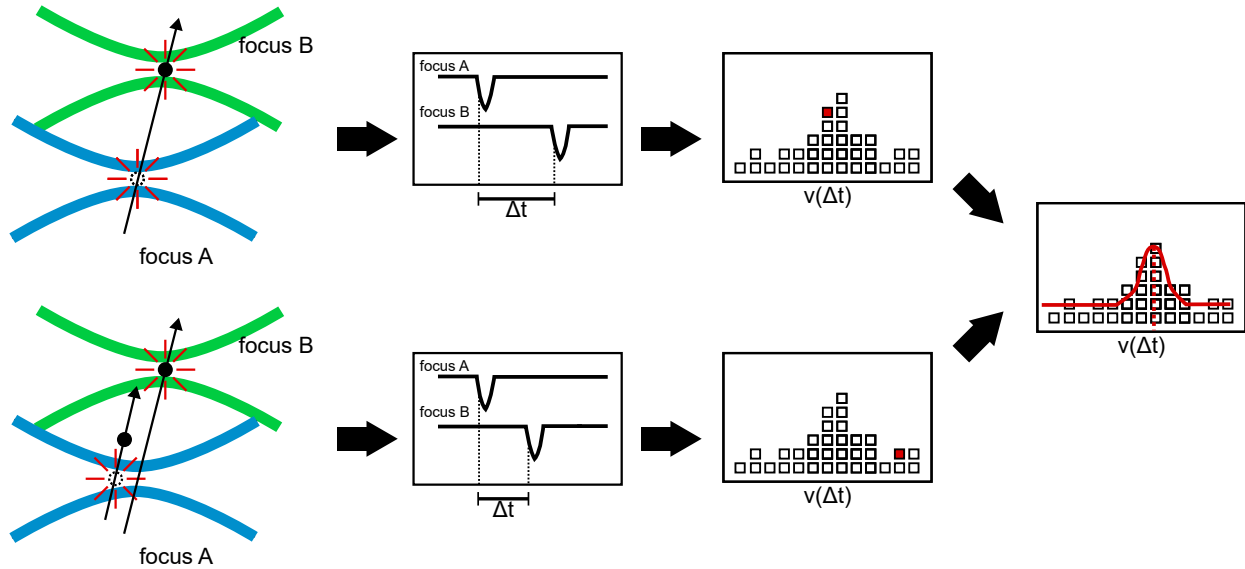


**Figure 8.** Comparison between a correlated event in which both scattered light pulses are generated by the same particle (top) and an uncorrelated event caused by the passage of two independent particles through the laser foci (bottom). Both events are included in the statistical analysis.

The statistical analysis shows that the uncorrelated events/signal pairs are randomly distributed, as both pulses are independent of each other. On the other hand, the  $\Delta t$  of the correlated events accumulate at a characteristic time interval which reflects the real ToF (respectively velocity) distribution of the particles. The fundamental flaw of a purely statistical discrimination of uncorrelated measurements results in the following disadvantage for measurements in turbulent flows: Large amounts of data must be recorded as statements regarding the velocity can only be made if a statistical accumulation of the measurements is formed over the background of noise.

The only way to better suppress uncorrelated events is to collect more information about the trajectory of the particles and to evaluate this in the analysis. An extended measurement method was devised for this purpose called Laser-3-Focus (L3F) as now three laser foci  $A, B, C$  are used. It was implemented using the modernized electronics as previously reported. Here, the scattered light signal from more than two foci is detected and analyzed. The expansion of the system from two to three foci already results in significant enhanced information about the movement of the particles along their trajectory with a manageable amount of additional technical effort. In our system the time stamp for every pulse is recorded. This makes it possible to assess whether a single event (which now consists of a triplet of pulses) is a correlated event, generated by a single particle, or

an uncorrelated event, generated by two or three independent particles. Accordingly, the velocities  $v_{ij}$  (with  $i, j \in [A, B, C]$ ) must be calculated from the flight times  $\Delta t_{ij}$  between the different pairs of foci using the focus distances  $d_{ij}$ . If a single particle generates all three pulses within a triplet and the velocity of the particles in the microscopic measurement volume is approximately constant, the measured velocity between the pairs of foci should also be constant (within the limits of the measurement accuracy).

$$v_{AB} = \frac{d_{AB}}{\Delta t_{AB}} \stackrel{?}{\approx} v_{BC} = \frac{d_{BC}}{\Delta t_{BC}} \stackrel{?}{\approx} v_{AC} = \frac{d_{AC}}{\Delta t_{AC}} \quad (1)$$

This condition is not fulfilled for uncorrelated events. In comparison to the L2F method two additional filters for uncorrelated events are established in the L3F routine:

1. The L3F method only analyses events formed by triplet of pulses.
2. For each pulse triplet the consistency of the calculated velocity is checked according to formula 1.

The L3F data evaluation routine shows that uncorrelated events can be discriminated on a single event basis and thus the background in the velocity distribution is reduced. This is shown schematically in Fig. 9.

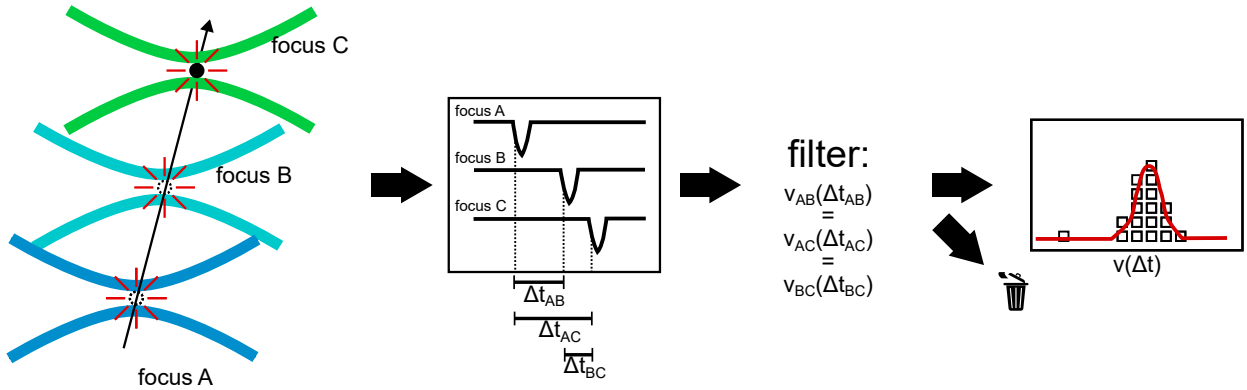


**Figure 9.** The passage of a particle through three foci generates three scattered light pulses. This allows to calculate the ToF between the foci. If all pulses were generated by the same particle, the analysis should result in the same velocity and the event is part of the velocity distribution. If this is not the case, the event can be discarded.

#### 4. Conclusion

This paper presents the recent modernization steps of the DLR's L2F system with the objective to miniaturize the system, increase its robustness, simplify its operation, as well as lower the systematic measurement error. A new multi-wavelength laser system based on solid-state and fiber

laser technology was implemented to keep the ability to adapt the focus separation depending on the turbulence intensity. Moreover, new SiPM light detectors were tested to replace the old PMTs featuring similar signal pulse shape but higher robustness and easier handling. Different sensor models were analyzed and the one featuring the highest active area of 6x6 mm fulfills the requirements best for the L2F application. Besides, a new system control software was developed for data acquisition, live plotting and user-friendly device handling. The old electronics were replaced by FPGA-based electronics which allow for novel L2F data evaluation routines that enable selecting the focus separation after data acquisition in post processing. The new components were tested in a lab environment measuring flow velocities of a free jet flow and meet or even exceed the performance of the old system.

The ability to record light pulses originating from all foci in parallel allows for a fundamental new measurement approach called L3F. The L3F concept was presented as a further development of the established L2F method. This novel approach enables new filter routines that are expected to lower noise from uncorrelated events in future applications.

## 5. Outlook

The modernized L2F system will be used in an upcoming measurement campaign at DLR's co/ contra-rotating acoustic fan test rig to perform measurements of flow velocities in the vicinity of a spinning fan rotor to prove its applicability at turbomachinery rigs. In addition, the new L3F data evaluation approach will be further developed and validated in lab scale experiments to show its potential benefits. A first L3F data analysis attempt already showed a dramatic reduction of the noise level caused by uncorrelated events. Further advantages and limitations of L3F will be figured out in real flow measurements, e.g. in a wind tunnel or compressor cascade rig. In near future, the modernized L2F system will be upgraded to resolve the third velocity component, for instance by adding a subsystem to analyze the Doppler shift of the scattered light in observation direction.

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## Nomenclature

|          |                                             |       |
|----------|---------------------------------------------|-------|
| $v$      | Velocity                                    | [m/s] |
| $v_{ij}$ | Particle velocity between focus $i$ and $j$ | [m/s] |

|                 |                                                          |     |
|-----------------|----------------------------------------------------------|-----|
| $d_{ij}$        | Focus separation between focus $i$ and $j$               | [m] |
| $t$             | Time                                                     | [s] |
| $\Delta t_{ij}$ | Particle event time difference between focus $i$ and $j$ | [s] |
| $ToF$           | Time of Flight                                           | [s] |

## List of Abbreviations

|      |                                 |
|------|---------------------------------|
| AMP  | Amplifier PCB                   |
| CFD  | Constant Fraction Discriminator |
| CMM  | Continuous Measurement Mode     |
| DLR  | German Aerospace Center         |
| GUI  | Graphical User Interface        |
| L2F  | Laser-2-Focus                   |
| L3F  | Laser-3-Focus                   |
| LTV  | Laser Transit Velocimetry       |
| MC   | Step Motor Controller           |
| MCA  | Multichannel Analyzer           |
| PMT  | Photomultiplier                 |
| RATE | Ratemeter                       |
| SiPM | Silicon Photomultiplier         |
| SMM  | Single Measurement Mode         |
| SNR  | Signal-to-Noise Ratio           |
| SPAD | Single-Photon Avalanche Diode   |
| TAC  | Time-to-Analog Converter        |
| TDC  | Time-to-Digital Converter       |
| TMM  | Angle Traverse Measurement Mode |
| TRIG | Trigger Signal Source           |
| TRL  | Technical Readiness Level       |

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