# A rapid response 64-channel Photomultiplier tube camera for high-speed flow velocimetry

***Technical Design Note***

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**Abstract:** In this technical design note, the development of a rapid response photomultiplier tube (PMT) camera, leveraging field programmable gate arrays (FPGA) for high-speed flow velocimetry at up to 10 MHz is described. Technically relevant flows, for example, supersonic inlets and exhaust jets, have time scales on the order of microseconds, and their experimental study requires resolution of these timescales for fundamental insight. The inherent rapid response time attributes of a 64-channel photomultiplier array were coupled with two stage amplifiers on each anode, and were acquired using a FPGA-based system. Application of FPGA allows high data acquisition rates with many channels as well as on-the-fly preprocessing techniques. Results are presented for optical velocimetry in supersonic free jet flows demonstrating the value of the technique in the chosen application example for determining supersonic shear layer velocity correlation maps.

**Keywords:** Optical sensors, Photomultiplier, FPGA, High-speed flow, Velocimetry

## 1. Introduction

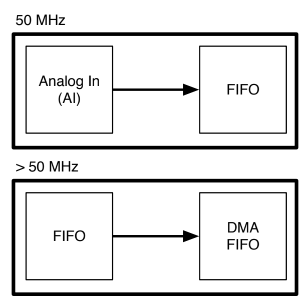
The need to better understand physically complex flows is a driving force in pushing the envelope of optical flow instrumentation innovation. Especially in high-speed flows, where the timescales of interest are on the order of microseconds, temporal requirements are of special interest and dictate sensor properties.

For many diagnostic applications, modern high speed cameras with frame rates up to 1 MHz have filled this need, and enabled time-resolved particle image velocimetry (TR-PIV)(Wernet 2007), high speed Schlieren photography, time-resolved Doppler global velocimetry (TR-DGV) (Thurow et al. 2005), as well as 3D flow visualization (Thurow et al. 2013). Limitations of these approaches arise at high Reynolds numbers, high speed flows, with large ranges of timescales and the frequent need to resolve weak signals requiring low detection thresholds. While photodiode arrays (Dahm et al. 1991, Fischer et al. 2009) have been used in the past for laser based flow instrumentation, PMT arrays with large sensor count (e.g. Hamamatsu H8500C as integrated herein) have only been used in the biomedical (Alva-Sánchez and Martínez-Dávalos 2009), nuclear physics (Pani et al. 2003) and astrophysics fields.

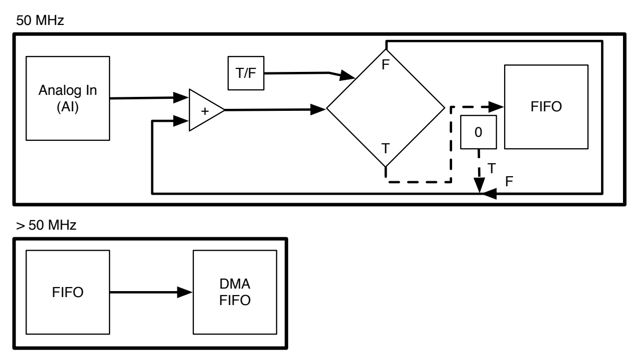
In this article, we survey the types of data acquisition systems currently in use in fluid dynamics instrumentation and discuss the advantages and applications for Field-Programmable Gate Arrays (FPGA) based systems in the evolution of laser based high-speed flow instrumentation. We present the integration of FPGA-based data acquisition into the development of a novel 64-anode PMT array camera system capable of recording flow field data at 10 millions samples per second (MS/s) over the course of several seconds. This camera is used for TR-DGV allowing data rates of 250 kHz and above for extended periods of time.

## 2. High-speed high-bandwidth data acquisition

A variety of commercial data acquisition systems (DAQs) are used in current experimental fluid mechanics applications, including Ethernet based modular and non modular DAQ units, USB based DAQ units, PCIexpress (PCIe) based DAQ cards, and other specialized modular DAQ based on proprietary platforms. While some Ethernet- and USB-based systems offer a large choice of multichannel systems (1-32 channels/board), most systems suffer from interface-related low data rates (up to 2 MS/s) and high latencies (Starkloff and Bisking 2007; Ullrich 2007). PCIe DAQ cards usually do not offer as many channels but enable unique applications requiring extremely high data acquisition rates as high as 2 GS/s, e.g. the DAQ used for single point Laser-Doppler Velocimetry (Brooks et al. 2014; Lowe et al. 2014) in supersonic flow. Chassis systems like the PXI and PXIe systems are a special case as they integrate the PCI/PCIe technology into a modular data acquisition/test system platform (Clark et al. 2002; Starkloff and Bisking 2007; Nosbusch 2012). While most systems offer FPGA capabilities, current PXIe chassis systems allow the application of multiple FPGA units with ADC modules capable of up to 32 analog input channels (per module) at speeds of 50 MS/s in addition to high-speed synchronization and trigger capabilities. Thus, current PXIe systems can fulfill the technology requirements for high-speed flow instrumentation.




a. Streaming




b. Inline-addition

**Figure 1:** Examples of FPGA-Adapter Module Integration (executed on FPGA hardware)

## 3. FPGA integration for high-speed data acquisition

FPGAs are logic structures similar to gated arrays with the additional advantage of being reconfigurable for user-specific purposes. While FPGAs perform slower than traditional (fixed) masked arrays by a factor of 3 and have a 10 times lower packing density, their flexible programming makes them optimal for “rapid product development and prototyping” (Trimberger 1992). Translated to instrument development application, this means new capabilities in managing and preprocessing high throughput data and data volume in high-speed (>2 MS/s per channel) measurement applications.

Previously FPGAs have found application in real-time particle image velocimetry (PIV) (Yu et al. 2006). Direct processing of a limited amount of camera information using FPGA capability allows for reducing data streams to manageable levels enabling flow control feedback mechanism. Scaling of FPGA-based data acquisition systems for TR-DGV has been demonstrated previously (Ecker et al. 2014a). Herein further development of a new multi PMT sensor unit for high-speed flow application is described and demonstrated for an example application.

FPGAs can be reconfigured for user-specific purposes. Before the FPGA code can be run, the FPGA code must be compiled for the specific FPGA unit, which results in a configuration file that specifies how the FPGA unit uses its resources to operate as directed. Once compilation is performed, different codes can be uploaded to the FPGA unit's static memory, allowing rapid reconfiguration of the device logic for different applications.

Depending on application, FPGA programming strategies may vary between two extremes: (1) data streaming (no data processing) and (2) complete processing of the data via FPGA with only fully reduced data being output. The process of data streaming via the FPGA is depicted in a pseudo flow diagram in figure 1a. While the loop containing the interface to the ADC must run at the prescribed adapter module clock rate, other loops on the FPGA hardware may run on derived clocks. Each loop is executed at its defined clock speed. First-In First-Out (FIFO) data streams can be used as buffers to transport information across clock domains, storing data in the FPGA's block RAM and slice memory. Additionally, commercial FPGA software wrappers offer the option to use Direct Memory Access (DMA) FIFO's to stream data directly into the controller's system memory. The code running on the host side can then access these data and process them or write them to disk. Some FPGA units have on board memory, which can be used to buffer data streams. Because current PXIe FPGA cards are based on first generation PCIe their bandwidth is limited to 1 GB/s (4x slot); direct streaming of more than 1 GB/s is not possible (eg. 10 channels at 50 MS/s) without onboard buffering to avoid data stream overflows.

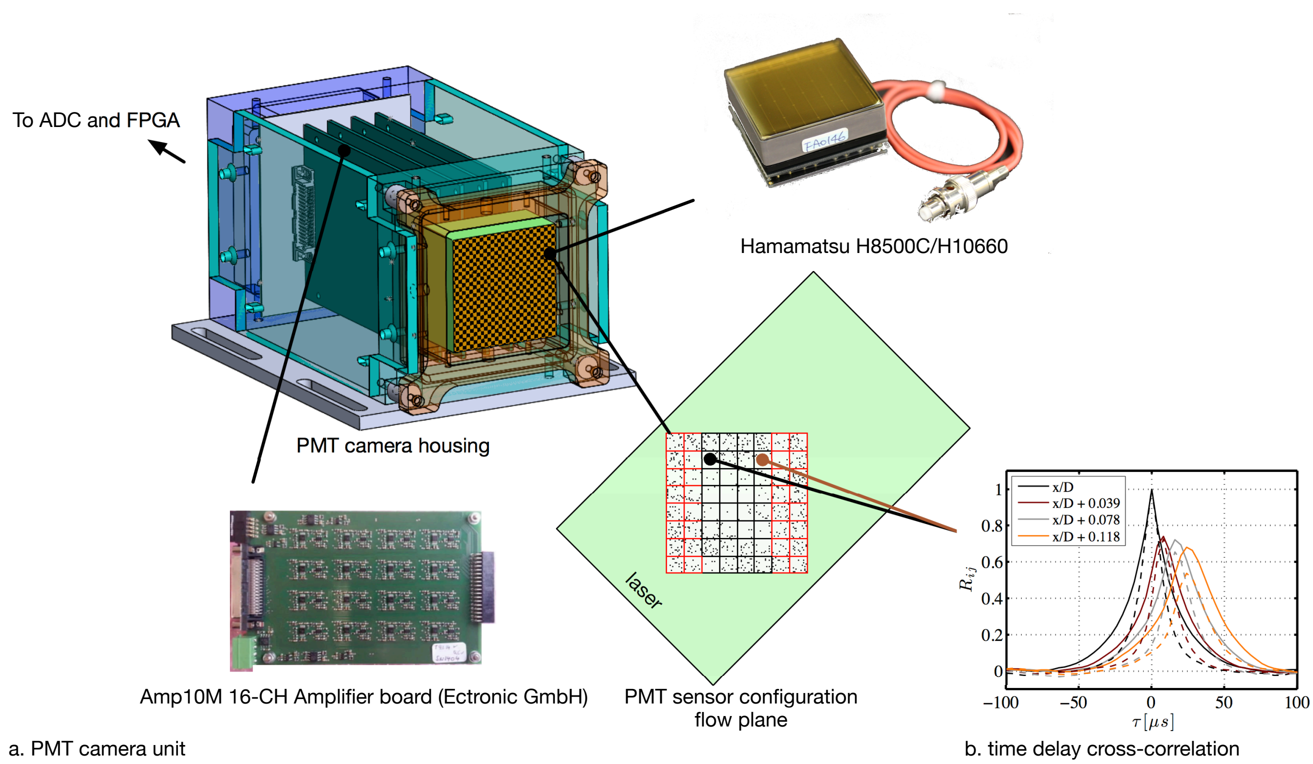



**Figure 2:** Spatially resolving PMT camera

Figure 1b illustrates inline addition of a set number of samples as a method of data preprocessing and bandwidth reduction. An event trigger is used to gate a true/false loop, either writing the number to the FIFO buffer or returning its value to the next time cycle.

This is an effective approach to reduce the data stream to levels that can be handled by the system's bandwidth. In the simplest variant, this method can be used to integrate a select amount of samples to increase the measurement signal-to-noise ratio (SNR). In a more applied case, the loop could be controlled by an event, e.g. the voltage peak on the output of a photomultiplier tube (PMT) induced by photons scattered from particles passing through a laser beam. The integrated value would then simply be a representative measure for the intensity of the elastic Mie scattering. Fast Fourier transform (FFT) based processing techniques like used for Laser Doppler Velocimetry could benefit from inline FFT processing, which would allow on-the-fly velocity data at high data rates.

**4. PMT-camera**

For the purpose of time and spatially resolved DGV for high speed flow application a PMT camera based on the 64 channel flat panel type Hamamatsu H8500C and H10966 series PMT has been developed. TR-DGV is a velocimetry technique capable of directly sensing the velocity induced Doppler shift. Velocity sensitivity is enabled by using a molecular gas filter, which functions as a transfer function from frequency to intensity. The classic implementation utilizes the ratio between the filtered and unfiltered light to determine the Doppler shift. The examples presented in this report are based on but not limited to the application of this classic reference technique for time resolved velocimetry (Ecker et al. 2014b). A model of the camera unit with photographs of the amplifier boards (4) and the PMT unit are shown in figure 2a. The PMT configuration imaged onto the flow plane via a camera lens allows correlating all channels at any given time, extracting instantaneous and statistical information on the flow physics. Figure 2b shows an example of the time delay cross-correlation across 4 PMTs in a supersonic shear layer.

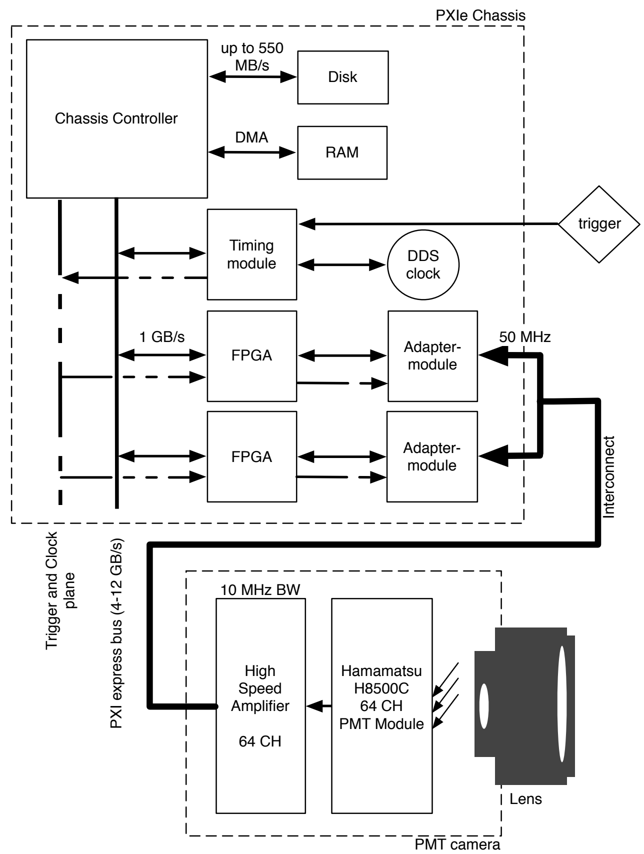



**Figure 3:** FPGA based PMT camera system

As multichannel high speed amplifiers for PMTs are not commercially available, a 16 channel amplifier board (Amp10M) that is directly interfaced with the PMT panel as well as the FPGA adapter module, was designed and custom built by Ectronic GmbH, Karlsruhe, Germany. This amplifier unit allows amplifying single particle signals on all 64 channels at a bandwidth of 10 MHz (at -3 dB). Each channel of the amplifier unit employs an AC-coupled two stage amplification with 200 Ohms input and 100 Ohms output impedance (50 Ohms differential), with an amplification of 100, resulting in maximum output voltages between $\pm 1$ V. The board uses an AD8132 differential output driver to enable long (5 m) interconnect distances between amplifier and adapter module.

Figure 3 shows the signal flow integration of both amplifier and PMT unit into the FPGA system. The 64-channel PMT is directly interfaced with the 16-channel high-speed amplifier boards (housed in a custom aluminum case). This camera unit is directly connected to the ADC unit on the 32-channel NI 5752 adapter module via a very-high-density cable interconnect (VHDCI) cable. The adapter module is attached to a NI PXIe-7965R card, which is powered by a Virtex-5 SX95T FPGA chip.

With the current FPGA and PXIe implementation this setup allows a steady 2 GB/s data transfer rate per 64-channel camera system. In order to decrease the system's data rate to a manageable amount, the FPGA unit employs inline addition processing as presented in figure 1b. Inline addition of the samples allows reducing the data rate to 1GB/s per slot while boosting signal to noise ratio (SNR). The sampling clock rates of the two adapter modules containing the ADC are synchronized by using a direct digital synthesizer (DDS) clock generated by a NI PXIe-6674T timing module and relayed via a timing bus line. Synchronization of data acquisition is achieved via a global trigger on a different high-speed line network (device to device skew < 500 ps) on the same bus (Ullrich 2007). All data are streamed to the controller memory via DMA and then written to disk. The recording timespan is limited only by the available controller memory enabling long duration flow observations.

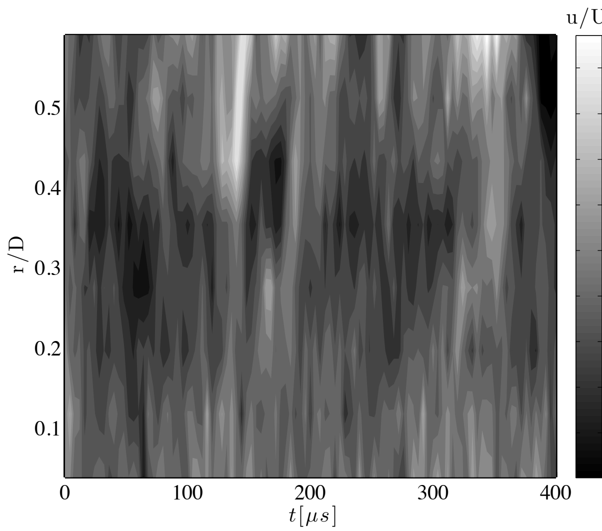
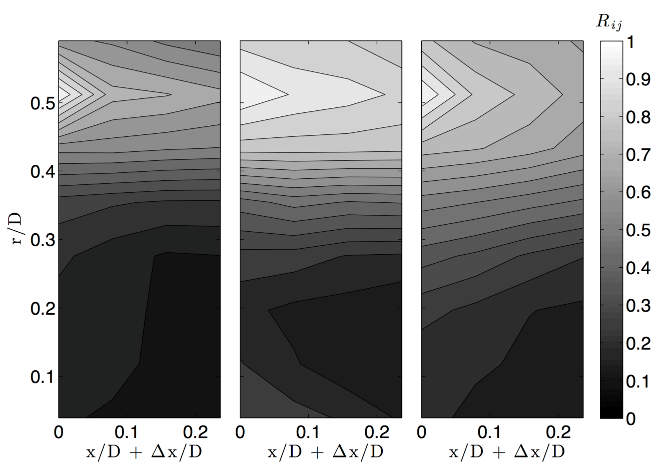



**Figure 4:** Velocity fluctuation time series in a hot supersonic jet (M=1.65, TTR=1.6, x/D=6)

## 5. Results

Figure 4 shows an application of the PMT camera in a TR-DGV system in a supersonic hot jet (Mach number, M = 1.65; total temperature ratio, TTR = 1.6; nozzle diameter, D = 1.5 in). The figure shows the velocity fluctuation time series on 8 PMTs perpendicular to the streamwise velocity component just downstream of the potential core, revealing strong intermittent velocity fluctuations. All data from the PMT camera were acquired by a NI PXIe DAQ system using 50 MS/s, consolidated into a 10 MHz signal via on-board processing and down sampled to 250 kHz in post processing.




**x/D=6** **x/D=8** **x/D=10**

**Figure 5:** 2nd order peak correlation map on the shear layer of a supersonic hot jet (M=1.65, TTR=1.6) using 32 pixels of the PMT camera. Reference at $\Delta x/D = 0$ and r/D = 0.52

Figure 5 shows results from a study conducted by Ecker et al. (Ecker et al. 2014b) in the same jet. Using 32 points on the camera system, velocity information was used to generate 2nd and 4th order correlations, peak correlation maps, convective velocities as well as integral time scales – leveraging the statistical advantage of the long duration recording capability of the PMT/FPGA system.

**6. Conclusions**

In this article we briefly discussed commonly available data acquisition systems for flow instrumentation and give a comparison with regards to bandwidth and sampling rate to FPGA based systems. The working principles of FPGA are summarized and examples on how inline processing can be integrated in a system are given. With the current availability of hardware and software tools, FPGA units give an attractive capability for rapid development of the-state-of-the-art instrumentation.

The integration of a commercial FPGA system with custom high-speed amplifiers and 64-channel PMT arrays into a rapid response 64-channel PMT camera for optical time (up to 10 MHz) and spatially resolved flow velocimetry is described. The applicability of this new camera technique is demonstrated on the example of a TR-DGV system applied to a supersonic, heated jet flow. Based on those experiences, we believe FPGA units to be extremely useful for rapid development of highly complex data acquisition systems, due the flexibility to adapt to quickly changing requirements in high-speed flow velocimetry it provides.

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