

CRONO

a Single-Photon Timing Camera

User Manual

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2 INTRODUCTION

CRONO is a specialized single-photon timing camera engineered to deliver cutting-edge performance in single-photon imaging applications. This technical manual provides a comprehensive understanding of CRONO camera, its specifications, and capabilities.

2.1 CRONO MAIN FEATURES

CRONO is a single photon counting and timing camera based on a high-performance imaging array of independent smart pixels. Each pixel comprises a single-photon avalanche diode (SPAD) detector, a dedicated Active Quenching Circuit (AQC), an 8-bit counter, a Time to Digital Converter (TDC) with 312.5 ps bin width and column/row readout electronics. This on-chip integrated device provides single-photon sensitivity, high electronic noise immunity, and high readout speed. Currently two imaging arrays are available: a 2-D imager of 64 pixels arranged in 8 rows by 8 columns, and a linear array of 128 pixels. The CRONO is shown in Figure 1.

CRONO is a “*frame-based*” camera, which means it is an imaging device that measures light inside individual frames, or still images, taken in sequence at regular intervals. This is the opposite behavior of “*Event-based*” cameras where each pixel operates independently and asynchronously, reporting events as they occur, and staying silent otherwise.

When configured in counting mode, each pixel of CRONO will count how many photons were detected inside a frame. Frames are acquired in global shutter mode, with low interframe dead-times. When configured in timing mode, each pixel of the CRONO will detect and measure one single photon arrival time per frame, with a timing precision of about 440 ps (Full Width at Half Maximum), a bin-width of 312.5 ps and a full-scale range of 1.28 μ s. Frame durations are user selectable and can be as short as 780 ns at full pixel resolution in both modes. In these conditions, CRONO will operate with an outstanding frame rate of 1.28 Mframes per second, acquiring up to about 164 Mtime-tags/s in timing mode, and up to about 2.5 Gphoton/s in counting mode.

A common gate signal can be applied to each pixel of the entire array to simultaneously turn ON or OFF the SPADs when desired. Whenever the Gate signal is high, all SPADs are active and ready to detect events. On the other hand, when the Gate signal is low all SPADs are deactivated.



Figure 1. The CRONO camera.

This behavior is useful whenever a section in time of the impinging light signal needs to be rejected, e.g. the residual light from an exciting laser pulse in FLIM measurements. The gate signal can either be provided to the camera through a coaxial input or be internally generated, thanks to an integrated signal generator with 1 ns resolution.

CRONO is capable of synchronizing with external instrumentation. The start of each frame can be either synchronized to CRONO internal clock or to an external signal, and CRONO is also capable of generating an arbitrary signal with 1 ns resolution to drive an external laser. Configurable coaxial outputs can also be used to forward internally generated synchronization and utility signals to external equipment, like the actual internal frame start and gate signals.

CRONO pixels feature high photon-detection efficiency (PDE) in the visible and near-UV spectral region, and low dark-counting rates, even at room temperature. The optional integrated micro-lens-array (MLA) ensures a fill factor of 75% for beam divergence up to 24° full-angle. The imager is easily integrated into common optical setups thanks to a Thorlabs® SM1 thread and a C-mount mechanical adapter. A Super-Speed USB 3.0 type-C computer interface ensures a fast PC connection.

2.2 THE SPAD DETECTOR

A SPAD is a p-n junction which, ideally, has no current flowing through it when it is reverse-biased well above its breakdown voltage. Under this operating condition, the absorption of even a single photon generates an electron-hole pair, which is accelerated by the high electric field across the junction. The energy of the charge carriers is eventually large enough to trigger a macroscopic avalanche current of few milliamperes through the device, which, indeed, precisely signals the photon absorption. The SPAD biasing electronics, namely the Active Quenching Circuit (AQC), is integrated on the same Silicon chip. The AQC senses the avalanche current, quenches it and resets the diode to its initial quiescent state above breakdown. The avalanche is quenched by decreasing the voltage across the SPAD junction below breakdown for an adjustable time (hold-off), that ranges from few tens to few hundreds of nanoseconds. The SPAD bias voltage is then restored to its initial state, and thus the diode is ready to detect the next photon. The total time that is required to restore the SPAD to the initial state, following an avalanche triggering, is named dead-time. During the dead-time, no photons can be detected. The AQC provides, additionally, a voltage pulse to an associated counter and a TDC, which are also integrated in each pixel together with the AQC.

The measurement of light signals by a SPAD has several advantages concerning the signal to noise ratio. No analogue measurement of voltage or current is needed since the detector acts like a digital Geiger counter. It follows that no electronic noise is added by analogue to digital converters or amplifiers while measuring the signal. Additionally, the detector is less sensitive to the electromagnetic interference, or the electrical noise generated by external equipment, differently from charge coupled devices.

The primary noise sources for SPADs are:

1. *Dark counts.* This noise source comprises all the physical processes that can start an avalanche across the SPAD junction, but which are not caused by the absorption of a photon. The typical source of dark counts is the thermal carrier generation process. Dark counts are the dominant noise source for the SPADs of CRONO.

2. *Afterpulsing*. Any avalanche triggering can statistically trigger an additional avalanche within few microseconds inside the detector (after-pulse). This spurious event is caused by carriers that were trapped during the avalanches, and are eventually released, with a statistically varying delay. If a carrier is released after the dead-time has elapsed, it is accelerated by the electric field across the junction and can trigger another avalanche, exactly like photo-generated electron-hole pairs. Since the release of trapped carriers is governed by an exponential probability distribution starting from the quenching of the avalanche, the longer the dead-time, the lower the number of carriers released when the SPAD is ON and thus, the lower the afterpulsing. CRONO camera at normal operating conditions has an a low afterpulsing of about 1-2%.
3. *Optical Crosstalk*. In a triggered pixel of the array, during the flow of the avalanche current, secondary photons are emitted by hot carriers. These can propagate through the Silicon chip and trigger the other SPADs of the array, with a higher probability, the closer they are to the one that initially fired. Optical crosstalk probability is very low among the pixels of CRONO being equal to about 10^{-5} ; this is due to the large distance between the pixels of the array. Its contribution to the total noise is therefore negligible. This holds true in case of arrays without a microlens array (MLA). Whenever an MLA is mounted on top of a SPAD array, additional optical paths are introduced for the secondary photons thus increasing the Optical Crosstalk to about 0.5%

Since it is not possible to distinguish SPAD avalanches by the actual event (noise generation or photon absorption) that triggered them, in this document any avalanche will be simply referred to as “event”.

2.2.1 Further readings

1. M. Ghioni, A. Gulinatti, I. Rech, F. Zappa, S. Cova, “Progress in Silicon Single-Photon Avalanche Diodes”, *IEEE Journal of Selected Topics in Quantum Electronics*, **2007**, 13, 852-862.

3 PART LIST

The following is a list of parts included with the CRONO camera series:

1. Safety instructions (Hardcopy and USB stick);
2. User's Manual and Datasheet (USB stick);
3. Test Report (Hardcopy)
4. CRONO PC software and libraries (USB stick)
5. One wall mount power supply with various local plug adaptors.
6. One CRONO camera (shown in Figure 1).
7. A cable adapter from the camera multi-coaxial connector to standard SMA connectors.
8. One USB-C to USB-A cable.

Before operating any of the above listed parts, it is mandatory to thoroughly read this user manual to understand how to safely and properly use them. Additionally, if you are missing any hardware or have questions about the hardware you have received, please contact Micro Photon Devices Srl.

4 CRONO HARDWARE CHARACTERISTICS

4.1 ELECTRICAL CONNECTIONS

CRONO has power and USB connections on one side, and a multi-coaxial connector for various control input-output signals on the other side, as shown in Figure 2. A cable adapter from the multi-coaxial connector to standard SMA connectors, as shown in Figure 3, is also provided with the camera. A description of the inputs and the outputs can be found in Table 1. The Electrical specifications of the inputs and outputs are reported in Table 2.

CRONO is not equipped with a power switch, therefore for powering it ON simply connect first the provided power supply to the Product and then the power supply to the electrical socket. To power off the module simply disconnect the power supply from the electrical socket.



To avoid fire or shock hazard, observe all the ratings below. The ⚠ symbol is placed on CRONO enclosure next to the relevant terminals. Do not apply a potential to any terminal, including the common terminal, that exceeds the maximum rating of the terminal.

For supplying the CRONO camera use only the provided power supply.

USB-C connector must only be used to connect the CRONO camera to a PC compliant with the USB standard for data transfer. USB-C connector is not intended for providing power to the camera nor to power any other device.

For using the multi coaxial I/O employ only the provided SMA adapter. The maximum allowed voltage between any pair of SMA shields is 0 V. The maximum allowed voltage between any SMA shields, the USB-C shield and the enclosure is 0 V. The maximum voltage between the signal pin of any SMA and SMA shields is 5 Vrms.

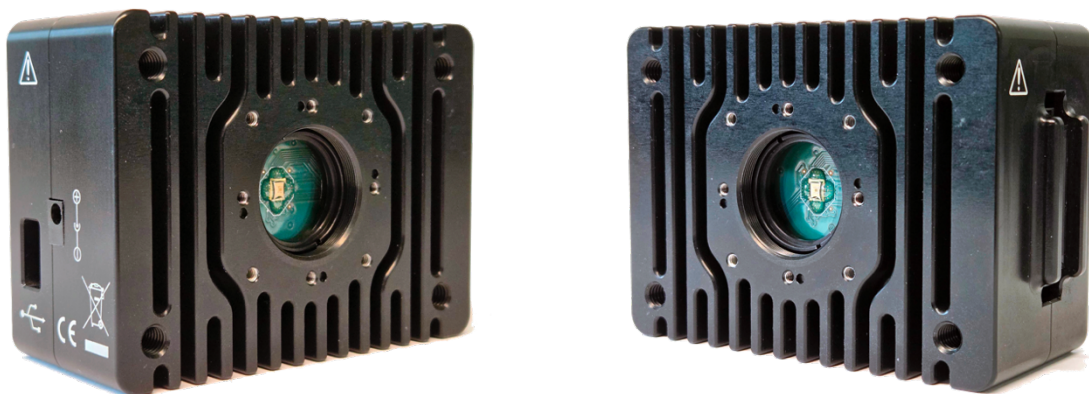


Figure 2. Camera side-views: hardware connections, USB and power supply on the left, multi-coaxial connector on the right.

Table 1. CRONO Inputs and Outputs description.

USB	Super-speed USB 3.0 type C connector. It is recommended to use USB cables shorter than 2 m.
+12VDC	Jack for connecting the provided +12 V power supply.
IN1 EXTERNAL START	Coaxial input. The input has a fixed DC impedance of 50 Ohm and is used for externally generated Frame Start signals. It is equipped with an input comparator that has a software-programmable threshold ranging from +2.5V to -2.0V. Additionally, an internal pre-scaler may optionally divide the frequency of comparator's output by an arbitrary factor up to 1000; in case of aperiodic input signals, the divider acts as a pulse skipper where, given n the dividing factor, $(n-1)$ input pulses are skipped after each valid input. See Table 2 for complete electrical specifications and paragraph 5.1.4 for more info on this input.
IN2 EXTERNAL GATE AUX BIT A	Coaxial input. The input has a fixed DC impedance of 50 Ohm, and it is equipped with an input comparator, that has a software-programmable threshold ranging from +2.5V to -2.0V. It is used for externally generated Gate signals or as the Auxiliary Bit A, when the camera is configured in <i>time tagging</i> mode. See Table 2 for complete electrical specifications and paragraphs 5.1.2 and 5.2.1 for more info on this input.
IN3 EXTERNAL TRIG AUX BIT B	Coaxial input. The input has a fixed DC impedance of 50 Ohm and accepts 3.3V LVCMOS logic levels (5V tolerant). It is used for an externally generated trigger or as the Auxiliary Bit B, when the camera is configured in <i>time tagging</i> mode. See Table 2 for complete electrical specifications and paragraph 5.1.6 for more info on this input.
OUT1	Coaxial output. It requires 50 Ohm DC terminated transmission lines. Electric pulses of 3.3V LVCMOS are generated at this output. By default, it outputs the internally generated Laser Sync signal, but it can be configured for other signals. See Table 2 for complete electrical specifications and paragraph 6.6 for more info on this output.
OUT2	Coaxial output. It requires 50 Ohm DC terminated transmission lines. Electric pulses of 3.3V LVCMOS are generated at this output. By default, it outputs a copy of the Frame Start signal as received by the SPAD array, but it can be configured for other signals. See Table 2 for complete electrical specifications and paragraph 6.6 for more info on this output.
OUT3	Coaxial output. It requires 50 Ohm DC terminated transmission lines. Electric pulses of 3.3V LVCMOS are generated at this output. By default, it outputs a copy of the Gate signal as received by the SPAD array, but it can be configured for other signals. See Table 2 for complete electrical specifications and paragraph 6.6 for more info on this output.

Table 2. Electrical Characteristics of the CRONO measured at room temperature (25°C)

Symbol	Parameter	Signal	Min	Typ	Max	Unit
V _{IH}	Input logic-high voltage (+5V tolerant)	EXT_TRIG	+2.4		+3.3	V
V _{IL}	Input logic-low voltage	EXT_TRIG	0		+0.8	V
V _{IN}	Input voltage (-4V to +5V tolerant)	EXT_START, EXT_GATE	-2.0		+3.0	V
V _{TH}	Adjustable input threshold	EXT_START, EXT_GATE	-2.0		+2.5	V
t _{ir}	Input rise time (10%-90%)	IN1, 2, 3			3	ns
t _{if}	Input fall time (10%-90%)	IN1, 2, 3			3	ns
t _{pulse,TRIG}	EXT_TRIG pulse duration	EXT_TRIG	10			ns
f _{TRIG}	EXT_TRIG frequency	EXT_TRIG			50	MHz
t _{pulse,START}	EXT_START pulse duration	EXT_START	2			ns
f _{START}	EXT_START Frequency	EXT_START			80	MHz
t _{ON,GATE}	EXT_GATE ON duration	EXT_GATE	5			ns
t _{OFF,GATE}	EXT_GATE OFF duration	EXT_GATE	12			ns
V _{OH}	Output logic-high voltage (on 50Ω)	OUT 1, 2, 3		+2.7		V
V _{OL}	Output logic-low voltage (on 50Ω)	OUT 1, 2, 3		0		V
t _{or}	Output rise time	OUT 1, 2, 3		1		ns
t _{of}	Output fall time	OUT 1, 2, 3		1		ns
-	Interframe deadtime timing mode (depending on holdoff)	-	55		165	ns
-	Interframe deadtime counting mode			55		ns
-	SPAD deadtime	-	40		150	ns
-	Camera Internal memory	-		1024		MiB
-	Number of bits in counting mode	-		8		
-	Number of bits in timing mode	-		12		
-	TDC bin size	-		312.5		ps
-	Total time jitter in timing mode (FWHM)	-		440		ps
-	TDC range	-		1280		ns
-	TDC DNL	-		3		%
-	Readout Time	-	780			ns
-	Internal Gate Generator time resolution	-		1		ns
-	Laser Sync Generator time resolution	OUT1		1		ns
-	EXT_START pulse to gate ON delay	EXT_START		5		ns

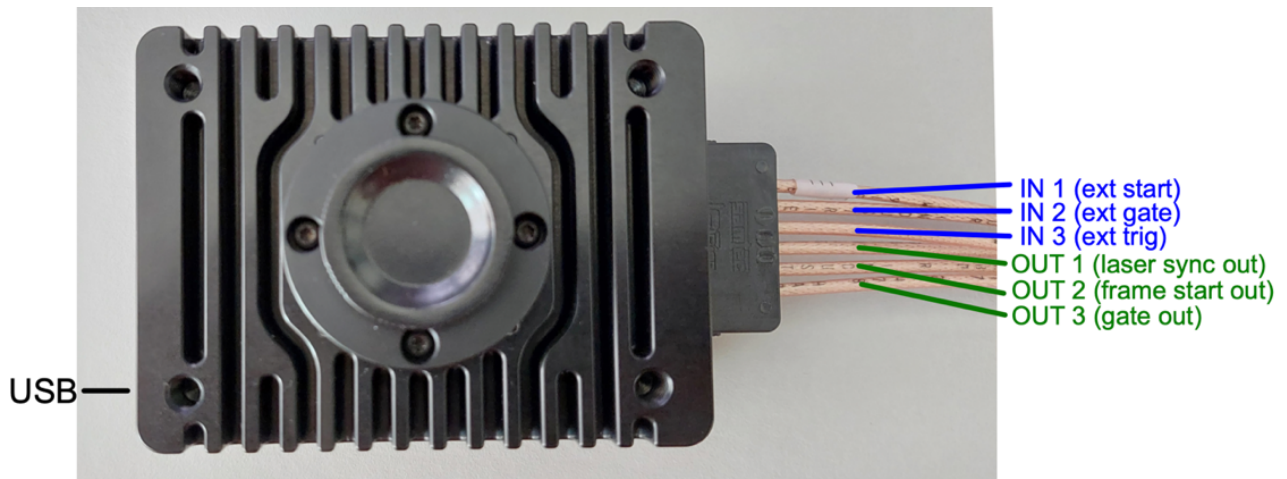


Figure 3. CRONO Camera with the cable adapter and the SMA output description.

4.2 CAMERA MECHANICAL DIMENSIONS

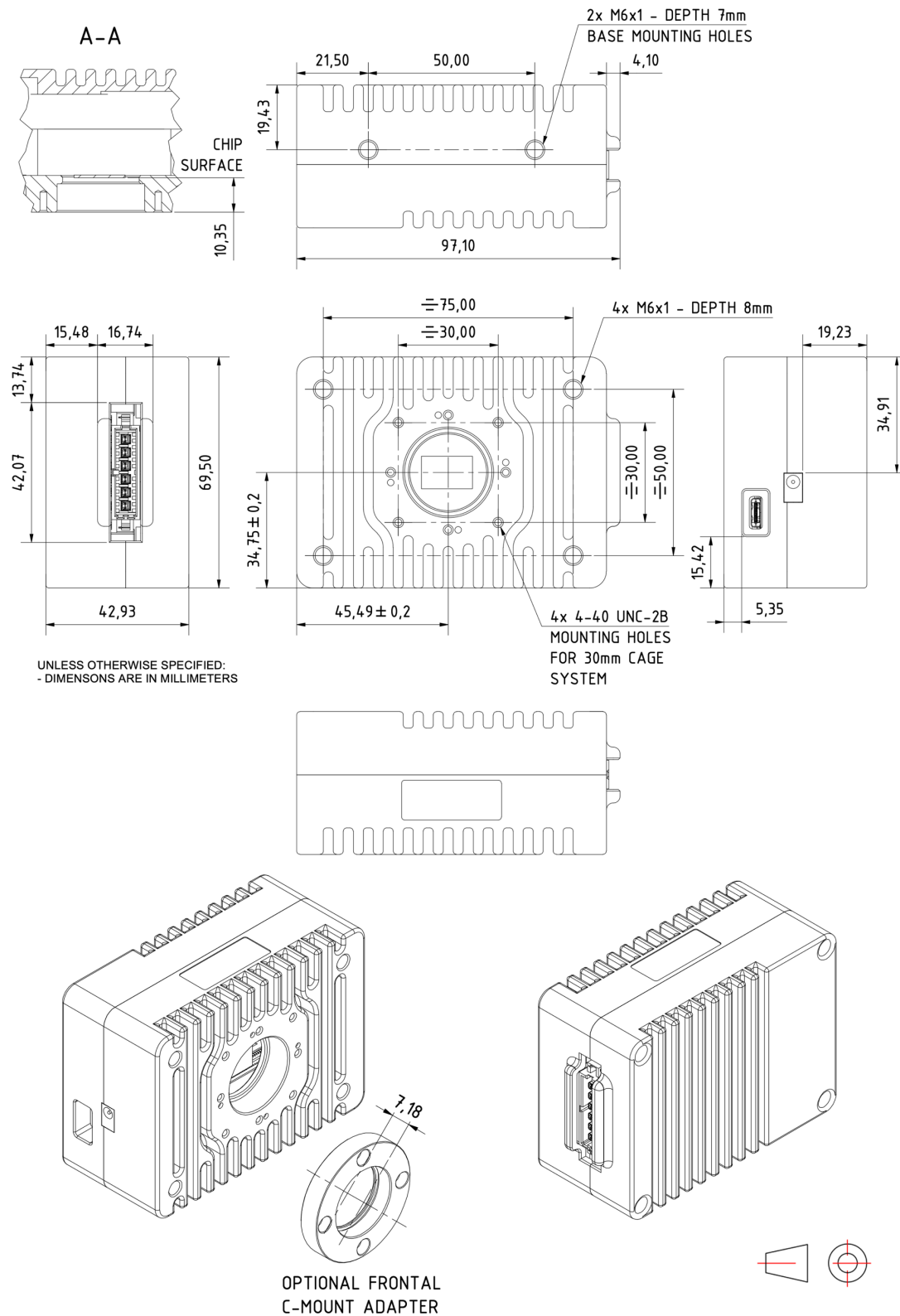


Figure 4. CRONO mechanical dimensions. All dimensions in mm. Camera's weight is 720 g.

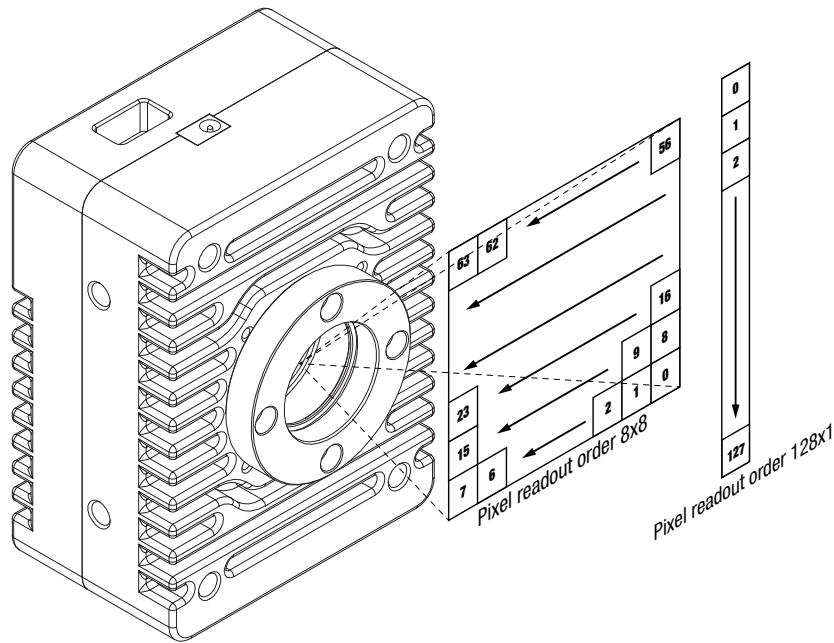


Figure 5. CRONO imager orientation and readout order with reference to the camera mechanical enclosure.

4.3 CAMERA OPTICAL PROPERTIES AND MICROLENS ARRAY CHARACTERISTICS

CRONO camera is based on an array of 8x8 or 128x1 SPAD sensors, as shown in Figure 5. The SPAD pixels have a round active area of 30 μm diameter and 75 μm pitch. Seen from another perspective, the CRONO camera can be thought as based on an imager composed by an array of 8x8 or 128x1 square pixels, each one having the side of 75 μm , side by side and with no gaps in-between, but where only a portion of the pixel is actually active: a round area of 30 μm diameter in the centre (i.e. the SPAD sensor active area).

Therefore, we can define two different Photon Detection Efficiencies (PDE):

1. A SPAD-PDE as the PDE of the active area of the SPAD sensor (shown in Figure 6)
2. An Imager-PDE as the PDE of the square pixel with 75 μm side.

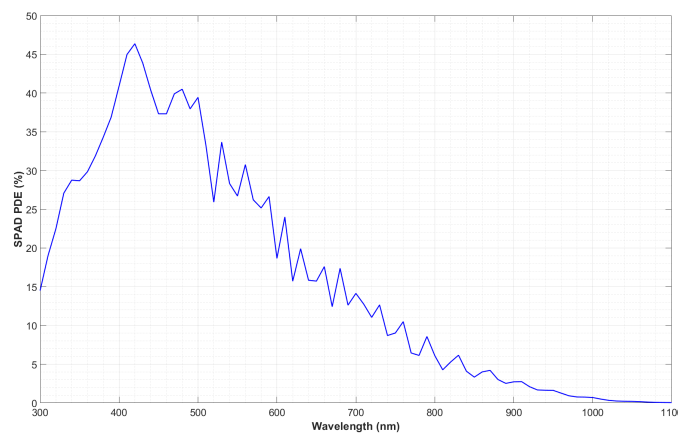


Figure 6. SPAD-PDE, i.e. the PDE of the active area of the SPAD sensor.

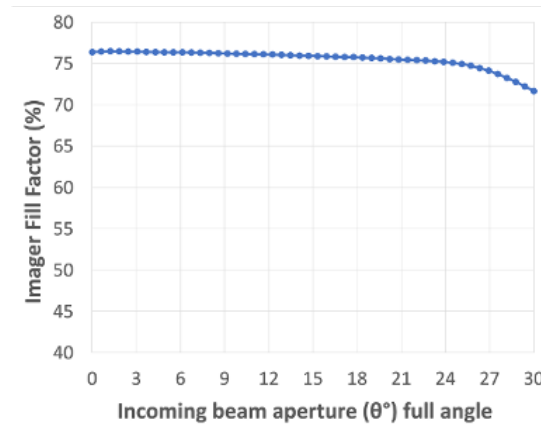


Figure 7. Imager fill factor, defined as the ratio between the pixel area and the SPAD sensor area.

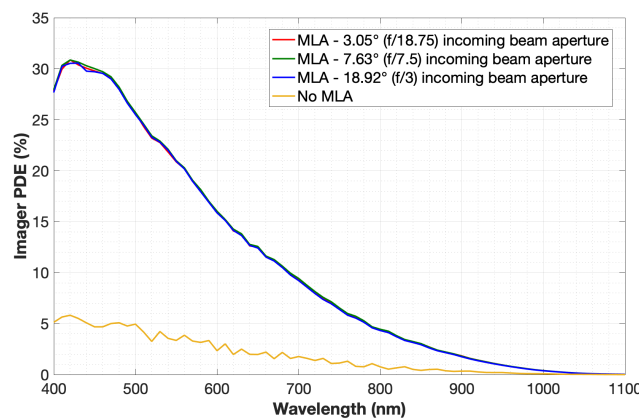


Figure 8. CRONO measured ImagerPDE: without MLA and for three incoming beam apertures when with MLA.

The Imager-PDE can be calculated multiplying the SPAD-PDE by the imager fill factor, defined as the ratio between the equivalent sensing area and the square pixel area. In case of an imager without a microlens array (MLA), the fill factor (also called native fill factor in this case) is a pure geometrical calculation and, for the CRONO, equals to 12.56 %. In case of an imager with a MLA, the fill factor can be calculated by multiplying the native fill factor by the MLA Concentration Factor (CF), defined as the ratio between the collected light with lenses and the collected light without lenses. The CF actual value will depend slightly on the incoming beam wavelength and greatly on its aperture. Figure 7 shows the calculated imager fill factor for a CRONO camera having a SPAD array with MLA, as a function of the incoming beam aperture (full angle). Data in Figure 7 has been obtained averaging over three different wavelengths (400 nm, 600 nm and 800 nm). Figure 8 shows a measured Imager-PDE for a CRONO with no MLA as well as the Imager-PDE of a CRONO with MLA, at three incoming beam apertures. It is worth nothing the smoothing effect of the MLA on the PDE ringing.

Camera full specifications

For the full list of CRONO specifications please refer to the CRONO datasheet. This can be found in the provided USB key or can be downloaded from the MPD website inside the CRONO product page (recommended procedure for always obtaining the latest version).

4.4 MAXIMUM INPUT POWER, A GUIDELINE

Since the CRONO is an array of single-photon counters, when detectors are ON the incoming power per pixel should be “low”. In other, and more specific words, to avoid permanent damage to a single pixel in the medium/long-term period, the single SPAD’s count rate (CR) should be kept below saturation, i.e. up to a few Mc/s at maximum.

The power impinging onto a single detector can be calculated as follows:

$$P = \frac{hc}{\lambda} \times \frac{CR}{\eta}$$

where η is the SPAD photon detection efficiency (PDE) at the specific wavelength (λ), h is the Plank constant and c is the speed of light in vacuum. Exact values of the PDE can be also extrapolated from the curve shown in Figure 7. By inserting the numbers in the formula, powers values ranging from a few tens of pW, at 400 nm, to a few nW, at $\lambda = 1 \mu\text{m}$ are obtained. Supposing to have an array with MLA and to spread the light over the entire array, the maximum input power can be increased by a factor of 64 or 128, depending on the actual CRONO version.

Nevertheless, it is safe to expose the CRONO to direct sunlight (or to light with the same power of about hundreds of nW per pixel) for very short periods. Leaving the array exposed on these conditions for tens of minutes/hours will lead to pixel(s) damage in form of increased Dark Count Rate (DCR) and/or afterpulsing probability.

When the detector is OFF it is instead safe to expose it to direct sunlight or illuminate it with a brighter laser. In this case, precise numbers on the maximum acceptable values before damaging the detectors are currently not known, even in scientific literature. However, the damage here is caused by thermal issues, so unless very high-power densities are used (like for example W/mm^2), the detectors should be safe. By following these guidelines, the CRONO will not have any limited lifespan or failures.

4.5 CAMERA SYSTEM REQUIREMENTS

- SuperSpeed USB 3.0, type-C interface.
- Host computer (minimum requirements)
 - 2 GHz processor and 4 GB of RAM
 - SSD recommended for full speed continuous acquisition.
- Supported operating systems
 - CronoView
 - Microsoft Windows 10,11 (64-bit version)
 - SDK
 - Microsoft Windows 10,11 (64-bit version)
 - Linux Ubuntu 22.01 LTS 64 bit, or compatible distributions (different distributions should work but were not tested).

5 CRONO OPERATION

CRONO camera features two mutually exclusive modes of operation: a frame-based photon timing mode and a frame-based photon counting one. They share the same acquisition and readout scheme, the main difference being the information that is retrieved from the acquired photons. In this paragraph, first a description of the common acquisition features is provided, then a specific explanation of the two operation modes is given.

5.1 GENERAL ACQUISITION FEATURES

5.1.1 Frame-Based acquisition

In CRONO's jargon, a *frame* is the time window during which the SPADs are activated, exposed to photons and their avalanche signals are processed (i.e. counted or timed by their respective in pixel electronics). A CRONO data *acquisition* consists of a sequence of frames. *Frame* duration, numbers of frames in an *acquisition*, *frames* frequency and synchronization, starting or ending time of the *acquisition* are all parameters that can be set by the user using the provided control software or SDK, or electrical inputs. Please refer to chapter "Configuring CRONO" for further details regarding acquisition control.

Frame duration is controlled by the *Frame-Start* signal which can be either internally or externally generated. At each rising edge of the *Frame-Start* signal a new *frame* is initiated. CRONO employs a *global shutter* readout scheme, which means that each *frame* starts and ends at the same time for all pixels. It also employs a double-buffering scheme, meaning that when a *Frame-Start* rising edge arrives, data currently in each pixel are first transferred in readout registers (for being readout during the following *frame*), and then data registers are reset and made ready for a new *frame*. In this way the non-active time between adjacent frames is very small (few tens of ns). With the entire imager active, the Maximum frame-rate for a CRONO is 1.28 MHz, i.e. a frame duration of 780 ns. Higher rates are possible only by reducing the number of active pixels. The maximum framerate is determined by the readout time of the imager, which is equal to:

1. $10 \text{ ns} \times N_{\text{pixel}} + 140 \text{ ns}$ for CRONO 8x8
2. $5 \text{ ns} \times N_{\text{pixel}} + 140 \text{ ns}$ for CRONO 128x1.

5.1.2 SPAD gating

CRONO includes the capability to activate SPAD detectors during precise time windows through a common gate signal. When Gate is OFF, SPADs are biased below breakdown and cannot detect any photon, nor generate dark-counts. The gate signal can be internally generated or externally provided to the *IN2* input. Internal gate generator can be programmed to perform any pattern inside the *frame* time, with a nominal 1 ns step, T_{ON} of at least 5 steps and T_{OFF} of at least 12 steps. When *Frame-Start* is internal (see paragraph below), the actual step may be larger, depending on the chosen internal *Frame-Start* frequency. The actual value is returned by the software. External gate signal can assume any pattern with T_{ON} of at least 5 ns and T_{OFF} of at least 12 ns. In both cases, the actual gate applied to the SPADs is masked to keep detectors OFF during the transition between *frames*, to avoid incorrect data recording, and also every time

the TDC full scale range is reached. Therefore, the gate actually applied to the SPADs (actual gate) depends on this internal masking, which in turn depends on the operation mode and hold-off time. The actual applied gate can be monitored using one of the coaxial outputs (*OUT3* by default).

5.1.3 Internal generation of Frame-Start

The internally generated *Frame-Start* signal is always periodic, and its frequency is programmable via the CRONO Software from 20 kHz to the maximum rate imposed by the readout time needed for the configured number of active pixels. When using the internal *Frame-Start* it is possible to use the internal generation of the gate signal, or the external gate signal from the *IN2* input. When using the internally generated *Frame-Start*, it is also possible to use an external trigger to synchronize the acquisitions. See paragraph 5.1.6 below for more details.

5.1.4 External generation of Frame-Start

The externally generated *Frame-Start* signal can be provided by an external source via the *IN1* input of the camera. External start generation is useful when dealing with pulsed laser systems that cannot be externally triggered but do provide a synchronization signal. An external *Frame-Start* signal may also be desired whenever the data acquisition needs to be performed with complex temporal patterns not necessarily periodic, as the internal generated one. The external *Frame-Start* signal is: optionally frequency divided by the camera; sampled with 1 ns resolution; then fed to pixels registers to record data. When using external *Frame-Start*, the internal gate pattern generation is not available. Instead, the internal gate is set fixed to the “SPADs ON” level, while, of course, proper masking of regions across *frame* boundaries is still applied (see paragraph 5.1.2). External gating is instead possible, with the same masking applied. The external *Frame-Start* signal can be periodic or aperiodic and, for proper generation of the internal masking signal, the user must inform the camera software of its minimum expected period, *after* optional frequency division. Of course, in case of periodic signals the minimum expected period is simply *the* signal period. The minimum expected period must, of course, be longer than the camera readout time, given the selected number of pixels. This value will be used to program an internal signal generator, so that the proper gate masking can be applied, thus effectively defining the frame time. For example, let’s suppose that an external *Frame-Start* frequency of 1MHz is defined and that the internal gate (fixed to SPADs-ON level) is selected. At the first pulse of the external *Frame-Start* signal, the *frame* is started, and the actual gate is set to ON. After 1 μ s, minus the mask time, the actual gate is set to OFF, effectively ending the frame integration. At 1 μ s a new external *Frame-Start* pulse arrives and marks the start of a new *frame*. It should be noted that the actual gate will not return to ON until a new external *Frame-Start* pulse is received. In case of aperiodic external *Frame-Start*, with minimum expected period of 1 μ s (i.e. expected *Frame-Start* period programmed by the user in the CRONO), the effective integration time for each *frame* will always be 1 μ s minus the mask time, even in case the following *Frame-Start* pulse arrives much later respect to the previous one (e.g. 1 ms). It should also be noted that any external *Frame-Start* pulse arriving during the (programmed) expected *frame* time will be ignored. When using external *Frame-Start*, external triggering is not available, since each *frame* is already aligned to the external *Frame-Start* signal.

5.1.5 Laser Sync Output Signal

CRONO optionally provides an output synchronization signal for pulsed photon sources. The dedicated *Laser Sync Output* signal at coaxial output *OUT1* is synchronous with the *Frame-Start* signal and features a fully programmable pattern generator with 1 ns nominal resolution, like the internal gate signal. When using an externally provided *Frame-start*, a 1 ns jitter is expected due to the sampling of the external signal.

5.1.6 External Trigger Signal

Normally data acquisitions begin right after a start command is sent from the PC to the camera. In some cases, it is desirable to delay the frames sequence, or to segment it in bursts, by waiting for an external triggering signal following the software start command. This can be achieved by providing an *External Trigger* signal to the dedicated coaxial input port *IN3* while enabling external triggering via software and using internally generated *Frame-Start*.

During an active acquisition, positive edges of the *External Trigger* signal fire a burst of regularly spaced frames. Bursts of a single frame are allowed. A *Busy* signal is generated when a *frame burst* is being generated, and optionally provided via any of the coaxial outputs. As depicted in Figure 9, positive edges of the *External Trigger* signal occurring while *Busy* is asserted are ignored.

The *frame rate* in a burst is equal to the programmed internal *Frame-Start* frequency and the number of frames is equal to the set *External Trigger Burst Frames* parameter. If a single indefinitely long burst is desired, the *External Trigger Burst Frames* parameter must be set to 0 (see Figure 9, lower side).

External Triggering cannot be used in conjunction with an external *Frame-Start* signal. The *External Trigger* signal is simply ignored when the camera is configured to accept an external *Frame-Start*.

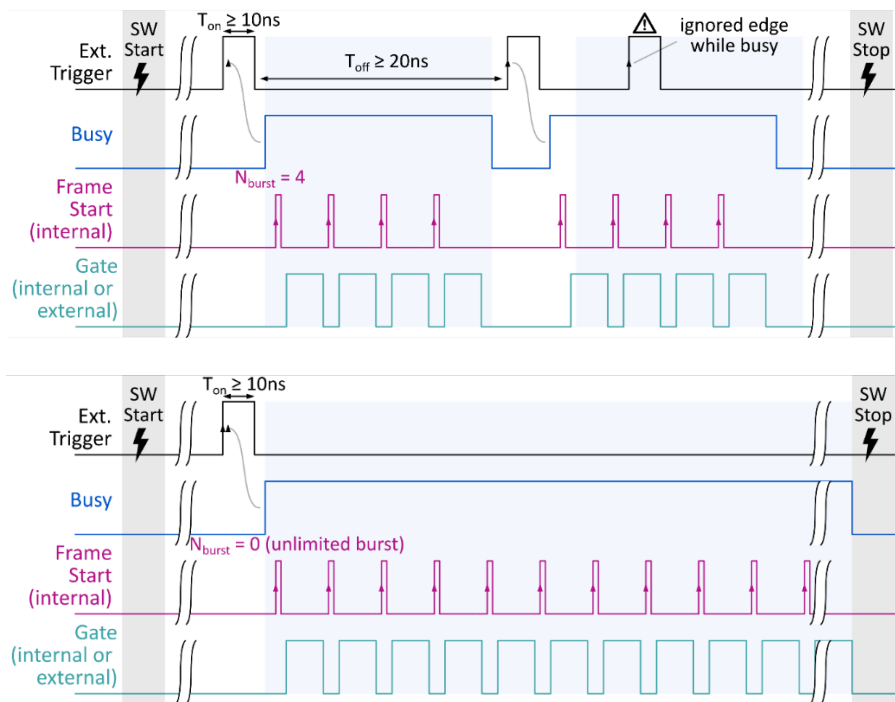


Figure 9. Signals involved during triggered acquisition, with a finite burst length (upper side), and an unlimited triggered acquisition (bottom side).

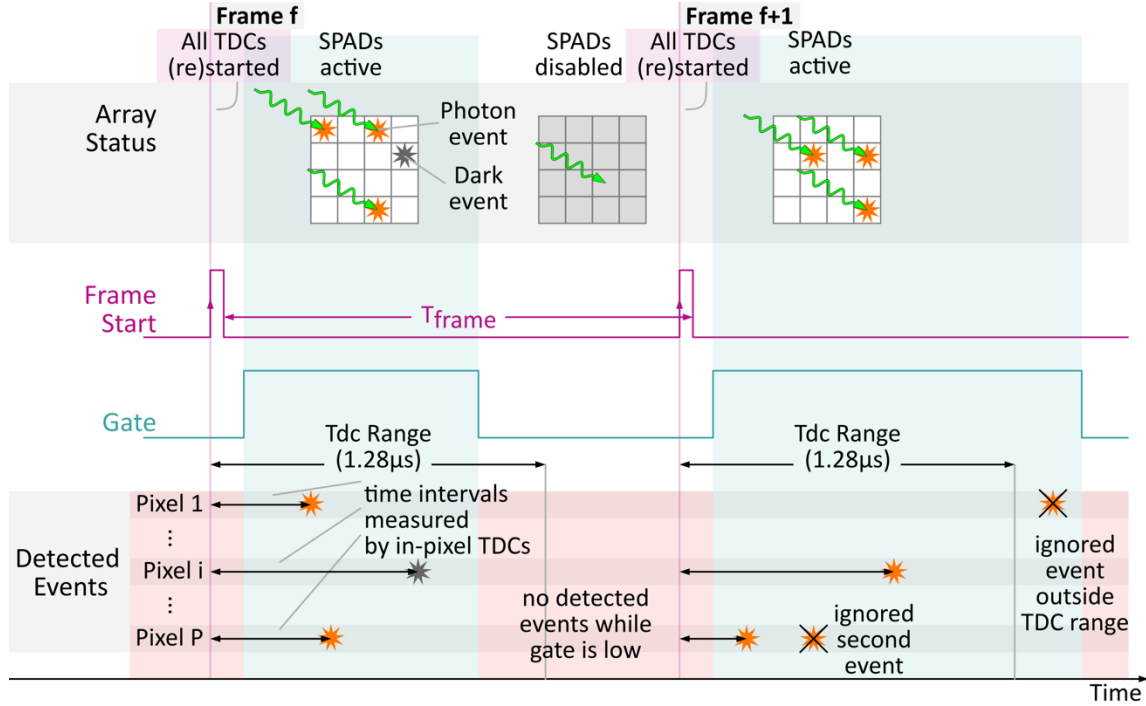


Figure 10. Timing mode operation.

5.2 FRAME-BASED SINGLE PHOTON TIMING MODE

When set in frame-based single-photon *timing* mode, CRONO can detect and measure one single photon arrival time (or more in general one *event time*) per pixel and per frame. Since the intrinsic time resolution of the employed SPAD is much better than TDC's one, the latter sets the ultimate timing precision of about 440 ps FWHM (Full Width at Half Maximum).

In *timing* mode, the *Frame-Start* signal, either internally or externally generated, in addition to the already described role in defining *frames* boundaries, is also applied to the *TDC* as the *Start* signal from which time within a frame is measured. The *Stop* signal is instead provided by each SPADs.

Let's now understand how a *timing* acquisition works with the help of Figure 10. The first *frame* starts with the first rising edge of the *Frame-Start* signal which globally resets and *starts* all the TDCs within the imager, in addition to resetting all the readout registers. Each TDC will then measure the elapsed time between the common *Start* and the detection of an *event* by the associated SPAD, which marks the TDC *Stop*. The maximum measurable time, given by the TDC range, has a duration of 1.28 μ s. TDCs are based on a flash architecture, which can sample a 200 MHz reference clock 16 times per period (i.e. once every 312.5 ps). For each conversion two samples are taken, one for the *Start* and one for the *Stop* (*fine* codes). The number of elapsed clock cycles between *Start* and *Stop* are also recorded (*coarse* code). Combining the *coarse* code with the difference between the *Stop* and *Start* *fine* code gives the conversion result: the output of each TDC is simply the progressive number of the time bins of 312.5 ps in which the event occurred inside the 12-bit TDC range. If no event is detected during the TDC range, the overflow condition is detected, and no code is produced. In addition to that, due to TDC internal architecture, *Start* or *Stop* events that happen too close to the rising or falling edges of the TDC's internal reference clock may be incorrectly handled.

This conversion occurrence is therefore detected and filtered by the camera, and the reserved 0xFFFF code is produced, meaning that an event was detected but not correctly timed.

Following the start of all the TDCs, SPADs can be turned ON by using the common Gate signal which can be either internally generated or externally provided via the *IN2* input. For proper operations, SPADs must be kept off during TDC latching and reset at the end of this frame. For this reason, any applied gate is internally masked around the frame boundary region. The actual applied gate depends on the correct masking time, which in turn depends on the operation mode and hold-off time. The actual applied gate can be monitored using one of coaxial outputs (*OUT3* by default). It should be noted that the actual window for successful event detection *and* timing is limited by the full-scale range of the in-pixel TDC AND the actual gate ON window: if the actual open gate extends beyond the end of the TDC range, any event detected after the end of the TDC range is discarded; if a SPAD is turned OFF before the end of the TDC range, no event detection, and thus TDC conversion, will be possible following the gate closing.

The arrival of the second Frame Start rising edge will mark the end of the first frame and the start of the second one, and so on until the end of the acquisition. At each new frame the CRONO sensor array will automatically perform detection and timing for all pixels while simultaneously transmitting the data of the previous frame to the internal CRONO data processing and buffering hardware.

5.2.1 Auxiliary inputs Sampling

CRONO has the capability to time-tag with low resolution auxiliary inputs A and B at either rising or falling edges, which can be selected via software, at the coaxial inputs *IN1* and *IN2*. This provides additional synchronization and event tracking for various applications. Signal edges that occur within a *frame* are associated to a *Super Coarse Time* corresponding to the progressive number of the containing *frame*. Refer to paragraph 7.4 for further details about time tagging codes.

5.2.2 Timing Data Format

As better explained in paragraph 7.4, four data formats are available for acquisition performed in timing mode: *Raw*, *Frames*, *Histogram*, *Time-tags*.

Raw format is an optimized data format for single photon cameras. The data provided by the internal CRONO hardware is not processed and is provided as-is. It is meant to be later retrieved and converted to another usable format.

Frames format provides a set of numeric matrixes, each containing the TDC conversion code for each pixel during a *frame* within the *acquisition*, including overflows and to-be-filtered events. This format contains all event data organized in a convenient way, but will produce the largest possible dataset, since also useless data points are included.

Histogram format organizes data in a set of per-pixel histograms. For each pixel, event data are accumulated in histograms constructed using *N_Integration* consecutive frames, where *N_Integration* is a parameter configurable by the user, smaller than the total number of *frames* in the *acquisition*. For instance, if the *acquisition* is 1000 *frames* long, and *N_Integration* is set to 10, each histogram will be constructed using data from 10 consecutive *frames*, and a total of $100 \times N_{\text{pixel}}$ histograms will be generated. Histogram format will not retain all information available in the original data, but instead present them in

an aggregated form. It's a compact format useful when only the distribution of event, and not their exact sequence, is needed.

Time-tags format presents data as a stream of useful *events* (overflows and filtered events are not reported), not organized in frames. For each event a time-tag is produced, which, in addition to the conversion code from the TDC (*Micro Time*), contains also the number of the pixel to which it corresponds, and the progressive number of the frame in which the event occurred (*Super Coarse Time*). In this way it is possible to record and arrange in time all the events detected by the camera. It is also possible to time-tag aux events occurring at coaxial inputs IN1 and IN2 (only with *Super Coarse Time*). *Time-tags* format preserves all information available in the original data, and it's particularly useful when the event rate is low, being more compact than *Frames* format, although more complex to manage. Instead, when the event rate is high, with many valid conversions in each frame, the *Frame* format could be more suitable, due to the reduced processing overhead.

5.3 FRAME-BASED SINGLE PHOTON COUNTING MODE

CRONO features a photon *counting* mode in which, as the name suggests, pixels count the number of detected events occurring within a *frame*. Gate signal plays the same role as in timing mode: SPADs can only fire while the actual Gate is ON. Each pixel can count up to 255 events per *frame*, any additional event will cause the 8-bit counters to roll-over yielding to incorrect counts. The user must be aware of this limitation and care must be taken to avoid excessive events within a *frame*, especially when dealing with low frame rates and long gates, since no warning is given by the camera in case of counters' overflow.

5.3.1 Counting Data Format

As better explained in paragraph 7.4, two data formats are available for acquisition performed in counting mode: *Raw* and *Frames* format.

Raw format is an optimized data format for single photon cameras. The data provided by the internal CRONO hardware is not processed and is provided as-is. It is meant to be later retrieved and converted to another usable format.

Frames format provides a set of numeric matrixes, each containing the number of events counted by each pixel during a *frame* within the *acquisition*. When using *Frames* data format, it is possible to apply *frame accumulation* to the output data. In this case, the numeric matrix will contain the counts per pixels accumulated over $N_Integration$ frames, with $N_Integration$ lower than the total number of *frames* in the *acquisition*. For instance, if the *acquisition* is 1000 *frames* long, and $N_Integration$ is set to 10, each numeric matrix will contain the accumulated counts per pixel over 10 *frames*, and a total of 100 matrixes will be provided. The use of *frame accumulation* is a convenient way to extend *frame* duration in *counting* mode beyond the hardware limit of 50 μ s, thus reducing data amount when extremely high frame rates are not needed. It should be noted that, since SPADs do not have readout noise, *frame accumulation* is a noiseless process.

6 CONFIGURING CRONO

CRONO is a versatile camera for Single-Photon acquisition. For this reason, several configuration parameters are available. Many of them need to be set before starting the acquisition, to capture data in line with the specific requirements of the measurement setup in use. The following sections will provide detailed information on the configuration process. It's worth noting that the configuration can be accomplished through both the *CronoView* desktop application and the *CRONO Software Development Kit (SDK)*. Users seeking in-depth information about available configuration library functions should consult the SDK manual.

6.1 OPERATION MODE AND OUTPUT DATA FORMAT SELECTION

CRONO operation mode (i.e. counting or timing mode) and output data format must be chosen before choosing any other CRONO setting. When using the SDK, Operation mode can be set via *pixelMode* parameter of the *CRONO_ConfigAcquisition()* function. In addition, the desired decoded output data formats must be enabled by asserting one or more of the boolean parameters of *CRONO_ConfigAcquisition()*. Available decoded formats are *Frames*, *Time-Tags*, *Histogram*, *Live*. Refer to chapter 7.4 for further details about CRONO output data formats and to the SDK manual for information about proper activation of formats.

6.2 NUMBER OF ACTIVE PIXELS

In the default setup, all Pixels within the CRONO sensor are active and contribute to the overall data generation (64 for 8x8 sensors, or 128 for 128x1 sensors). In some cases, it is desirable to enable only a fraction of the pixels. This can be accomplished by adjusting the number of active pixels through software setting. The set of active pixels is always contiguous and always starts with the first pixels. As an example, if the number of active pixels is set to 4 only pixels with index 0, 1, 2, and 3 will be enabled (refer to Figure 5 for pixel numbering convention). Reducing the number of active pixels has two effects. The more obvious is that data throughput of the camera for a given framerate is reduced. The second one is that, since the readout time is reduced, a higher frame rate is attainable. In fact, the readout time is equal to $10\text{ ns} \times N_{\text{pixel}} + 140\text{ ns}$ for CRONO 8x8 and $5\text{ ns} \times N_{\text{pixel}} + 140\text{ ns}$ for CRONO 128x1.

6.3 SPAD DEAD TIME

All SPADs share a global signal that sets the SPAD Dead Time. The user can select the desired dead time via the CRONO software, allowed values range from 40 ns to 150 ns. By default, the dead time is set to the minimum possible value equal to 40 ns.

6.4 FRAME-START CONFIGURATION

Depending on the nature of the measurement setup, user can select internally or externally generated *frame-start* signal.

When using the internally generated *frame-start* signal, the user must configure the *frame-start Frequency*. In the SDK, this can be achieved by setting the *frameRate* parameter via the *CRONO_ConfigFrameStartInternal()* function.

When working with an external *frame-start*, the user must select an appropriate value for the corresponding parameters:

Frame Rate	Expected maximum rate of the external <i>frame-start</i> signal. Proper choice of this parameter allows the CRONO internal hardware to correctly configure the internal control signals. See paragraph 5.1.4 for more details.
Input threshold	Threshold voltage for the <i>IN1/EXTERNAL START</i> input port. Allowed values range from -2.0V to +2.5V.
Triggering Edge	Parameter that selects which edges of the external signal cause a new <i>frame</i> to begin. When set to <i>RISING</i> , frames do start at a rising edge of the external signal. When set to <i>FALLING</i> , frames start on a falling edge.
Division Factor	This parameter is the division factor of the external <i>frame-start</i> signal pre-scaler. Useful when dealing with external synchronization signals with a frequency higher than the maximum CRONO frame rate, e.g. pulsed lasers with an 80 MHz repetition rate. Set this parameter to 1 when no division is needed (pre-scaler is bypassed).

6.5 SPAD GATE CONFIGURATION

SPAD Gate signal can be generated either internally or externally.

When employing the internally generated Gate signal, the user can configure an arbitrary on-off temporal pattern with a nominal step resolution of 1ns. When *Frame-Start* is internal, the actual step may be larger, depending on the chosen internal *Frame-Start* frequency. The actual value is returned by the software. The total pattern length is limited to the frame time or the TDC full-scale, whichever is shorter. A gate mask may be applied by the camera software, see paragraph 5.1.2.

Alternatively, if an external Gate signal is provided, one must set the *IN2/EXTERNAL GATE* input port threshold voltage. Allowed values range from -2.0V to +2.5V. If desired, the external signal can be inverted before being fed to the CRONO sensor via the internal logic.

6.6 OUTPUT SIGNALS SELECTION

All three SMA outputs can be programmed to output different signals for synchronization and monitoring purposes. The following table describes the available output signals for each SMA output port.

OUT	Output Signal	Description
1	LASER SYNC OUT	Laser synchronization signal. Synchronous with internally generated Frame Start signal.
2	FRAME START	Forwarded copy of the Frame Start signal as received by the CRONO Sensor.
3	GATE	Forwarded copy of the actual Gate signal as received by the CRONO Sensor.
Any	10 MHz REF	10 MHz reference signal. Generated in the same clock domain of the internally generated Frame Start, Gate and Laser sync out signals.
Any	BUSY	Busy CRONO signal. This signal is asserted while CRONO is busy generating the signals of a frame or a burst of frames. Trigger-in and external Frame-Start edges are ignored while Busy is asserted.
Any	EXTERNAL START	Copy of the external start signal, as received by IN1 port after division (if enabled).
Any	TRIGGER IN	Copy of the trigger in signal.
Any	AUX IN A SAMPLE	Copy of the sampled Auxiliary input A according to the current sampling mode. Only changes state at the beginning of a frame.
Any	AUX IN B SAMPLE	Copy of the sampled Auxiliary input B according to the current sampling mode. Only changes state at the beginning of a frame.

6.7 AUXILIARY INPUTS SAMPLING MODE SELECTION

CRONO has the capability to time-tag auxiliary inputs A and B at either rising or falling edges, which can be selected via software. This provides additional synchronization and event tracking for various applications. Signal edges that occur within a frame are associated with a *Super Coarse Time* corresponding to the progressive number of the containing frame. The resulting 64-bit tagging code has an all-zero TDC conversion and a special pixel index equal to 1024 and 2048 for input A and B respectively. Refer to section 7.4 for further details about time tagging codes.

6.8 LIVE-ONLY MODE ACQUISITIONS

The special Live-Only acquisition mode allows the user to test the behavior of CRONO, including input and output control signals and detected event rates on pixels, in a measurement setup. It is especially useful when used inside *CronoView* GUI application, to get a real time view of acquired data.

A subset of CRONO Settings can be changed on-the fly during an active acquisition in Live-Only Mode. These include SPAD dead-time, internal/external gate selection, gate output pattern, Laser Sync Out

pattern, Output signal selection on all output SMA ports and Auxiliary inputs sampling mode. It's not possible to live change the number of active pixels, the operation mode, and the *frame-start* parameters.

When controlling CRONO via the *CronoView* GUI application, the Live-Only is enabled using the dedicated Live button. Alternatively, when programming via the CRONO SDK library, the Live-Only mode is enabled by calling *CRONO_ConfigAcquisition()* function with the parameter *liveEnable* set to true but all other data format parameters set to false. Please refer to the SDK manual for further details.

7 ACQUIRING DATA

7.1 STARTING AND STOPPING ACQUISITIONS

After configuration, data acquisitions can be started at any time via the SDK `CRONO_StartAcquisition()` function or the corresponding command in the *CronoView* GUI application. When calling the function or through the GUI command one must assign a proper value to the following two parameters:

- *Acquisition Maximum Frames*: this specifies the total number of frames to be acquired within the acquisition. When the number of acquired frames reaches this value, CRONO stops acquiring additional frames even if a valid Frame Start Signal is still being generated and sent to the Pixel array. This parameter must be set to 0 if an indefinitely long (continuous) acquisition is desired.
- *Integration Period Frames (N_{int})*: this determines both the histograms and counts integration period expressed in frames.

When the desired amount of data has been acquired, `CRONO_StopAcquisition()` SDK function or its GUI counterpart must be called. The stop command must always be invoked to properly finalize an acquisition even when the *Acquisition Maximum Frames* number has been already reached. The acquisition can be stopped *forcibly* or *gracefully*. When *forced stop* is selected, the ongoing acquisition halts immediately even if the predefined frame count is not reached; un-decoded and unsaved data still in the buffers are discarded. This may result in trunked frame at the end of saved files. When *graceful stop* is selected and the *Acquisition Maximum Frames* is set to a non-zero value, the function waits until the acquisition reaches the desired number of frames. Finally, when *graceful stop* is selected during a continuous acquisition (*Acquisition Maximum Frames* set to zero) download is stopped immediately, but data still in the buffers are entirely decoded and properly saved. This may require some additional time depending on the current acquisition status.

7.2 RETRIEVING DATA

Once started, the acquisition of data from the camera is continuous, and the internal 1GB camera memory is used as a buffer. To avoid any data loss, the PC must download data as fast as possible, so that the camera buffer does not get full. If this event occurs, new data are lost, and the acquisition is aborted. CRONO software employs several processes in background and additional software buffers, in order to download, decode and, if requested, save data at the maximum speed, minimizing the risk to fill up the camera buffer. However, due to the very high rate at which data can be generated, and depending also on the type of acquisition, decoding and saving-format selected, this is not always possible. Users should then adjust accordingly the acquisition settings or measurement setup. Raw data rate is reduced by reducing the framerate, the number of active pixels and the number of detected events. Processing and saving time is reduced by deselecting decoding formats, and saving only raw data, to be then processed offline.

The *CronoView* GUI application is a convenient and intuitive tool to acquire data, convert and save it directly to disk. It does not, however, enable users to perform real-time data analysis. This capability, essential in some cases to avoid storing large datasets on disk, is instead offered by the CRONO SDK. The

SDK library internally buffers data in the host PC's RAM, allowing users to initiate and terminate acquisitions, retrieve data, and perform real-time analysis, all within a single execution thread. This streamlined workflow enhances the camera's usability for a wide range of applications. Different SDK functions are used to access data in the different available formats, *Frames*, *Time-Tags*, *Histogram*. These functions can be called during an active acquisition and enable users to perform real-time data processing according to their own algorithms. Please refer to the SDK documentation and code examples for further details.

7.2.1 Live data extraction

During a running acquisition, it is possible to extract from the data stream individual frames or histograms at a low rate. This is useful to have live feedback on the acquisition, while still acquiring data at full speed. In counting mode, the extracted frame reports the sum of the counts per pixel in *Integration Period Frames* as defined when acquisition was started. In timing mode, the extracted frame reports for each pixel how many frames of the N_{int} *Frames* had a valid TDC conversion. In addition, for each pixel also a histogram of the TDC conversion values, over N_{int} *Frames*, is available. Live data can be retrieved using the SDK function `CRONO_GetLiveData()`, or viewed graphically in the GUI.

7.3 ACQUISITION STATUS CHECKING

CRONO features a status monitoring mechanism, which provides users with real-time inspection into ongoing and completed data acquisitions. This feature allows users to keep a close eye on the progress of frame acquisition and data buffering. Users have access to status parameters such as the number of acquired frames and RAM usage on the camera itself and the connected host PC. It is also possible to know if a running acquisition is still on-going, or if it has reached the required number of frames. The SDK function `CRONO_GetAcquisitionStatus()` provides such information and can be called at any time during an acquisition.

7.4 ACQUISITION DATA FORMATS

For each acquired frame, the CRONO sensor provides a numeric array containing the timing or counting data of each pixel. In timing mode, pixels that do not detect any event in a given frame and thus cause a TDC overflow do output an all-zeros code, while others that do detect one or more events will emit a code proportional to the time of arrival of the first event relative to the frame start. The CRONO hardware will then pack this data, so that only meaningful values are transmitted to the host PC via the USB 3.0 interface, i.e. TDC overflow events, very common in photon-starved application, are not transmitted. The resulting optimized stream is called CRONO *Raw* format, and it can be saved on the host PC as is, for offline user processing. In addition to that, the CRONO software offers few additional unpacked formats: for timing acquisition *Time Tagging*, *Histograms*, *Frames* formats, for counting acquisition only *Frames* format. All these formats are described in the following paragraphs.

7.4.1 Time-Tags Format (Timing Mode Only)

In *Time-Tags* format, each detected and timed event from any frames and any CRONO pixel gets *tagged* with a 64-bit code. Such code contains data about both the temporal and spatial nature of the event. Bit fields in the 64-bit word are reported in the following table.

Field Name	Field Bits	Description
Super Coarse Time	63...32	Zero-based index of the Frame Start Pulse that triggered the frame in which the event occurred. Coincides with the (zero-based) frame index inside an acquisition when using the internally generated Frame Start Signal. Does not necessarily coincide with the frame index when provided externally since some external Frame Start pulses may not fire a frame while the sensor is busy. Always starts from zero at each new acquisition.
Reserved Bits	31...24	Bits Reserved for future use. Equal to all-zeros for all event tags.
TDC Conversion	23...12	Time interval from the positive edge of the frame start signal to the detected event as measured by the TDC. Valid values range from 1 up to 4094 included. The TDC LSB is equal to 312.5 picoseconds, corresponding to a full-scale range of 1280 ns. Code 4095 is reserved in raw data for incorrectly timed event, and thus it does not ever appear in Time-Tags format. When the event refers to an Auxiliary input, this field is always 0, since only Super Coarse Time is available for Aux inputs.
Pixel Index	11...0	Zero-based Index of the Pixel in which the event occurred. Only this field provides spatial information about the event. Possible normal values: 0 to 63 for 8x8 pixels sensors, 0 to 127 for 128x1 pixels sensors. Special values: a pixel index equal to 1024 indicates an event occurring on the auxiliary input A and a pixel index equal to 2048 indicates an event occurring on auxiliary input B.

Time tagging codes are sorted in ascending *Super Coarse Time* and ascending *Pixel Index* (with the exception of auxiliary input events that always precede Pixel events inside a frame). Tags are not sorted in TDC Conversion order. This sorting is directly inherited by the internal readout hardware: frames are read sequentially in time and for each frame auxiliary Input events are read followed by pixel events in ascending pixel index order (from 0 to 63 or 127).

For a single acquisition the final time tagging data set size in bytes is given by:

$\text{Length_timetags} = (\text{number of SPAD events} + \text{external events}) * (8 \text{ bytes per time tag})$

The value of *Super Coarse Time* can be used to effectively extend the TDC range. For instance, when acquiring frames at a constant rate with an internally generated frame start signal, *Super Coarse Time*

coincides with the progressive index of frames. This information, combined with the nominal frame rate allows to calculate the *absolute* time of detected events.

A practical example: acquisition is started with a constant frame rate of 1.25 MHz (period = 800ns) using internal generation. An event is detected at

- *Super Coarse Time* = 4 (fifth frame in the acquisition)
- *TDC conversion value* = 1062 (i.e. 331.875 ns)

The combined time of the event is $4 \times 800 \text{ ns} + 331.875 \text{ ns} = 3531.875 \text{ ns}$.

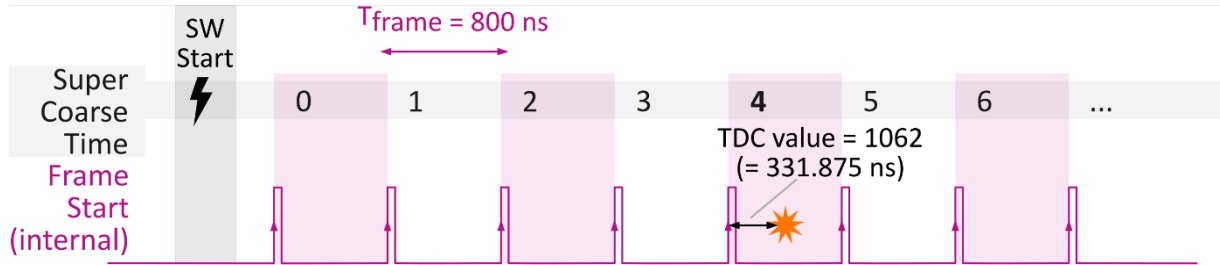


Figure 11. Time range extension using Super Coarse Time in time-tags format.

7.4.2 Histograms Format (Timing Mode Only)

The *Histograms* format provides a histogram of the TDC codes for every pixel and every N_{int} frames. This number of frames is referred to as the *Integration Period Frames* parameter in both CRONO SDK and CronoView GUI application. A contiguous 1-D array of 32-bit unsigned integers contains the histogram counts for all P active pixels and all TDC values. Figure 12 illustrates the layout and order of Histograms data values.

For an acquisition of N_f frames, a *Integration Period Frames* parameter value of N_{int} and P active pixels the final data set size in bytes is given by:

$$\text{Length_histograms} = 4096 * \text{floor}(N_f / N_{int}) * P * (4 \text{ bytes per histogram bin})$$

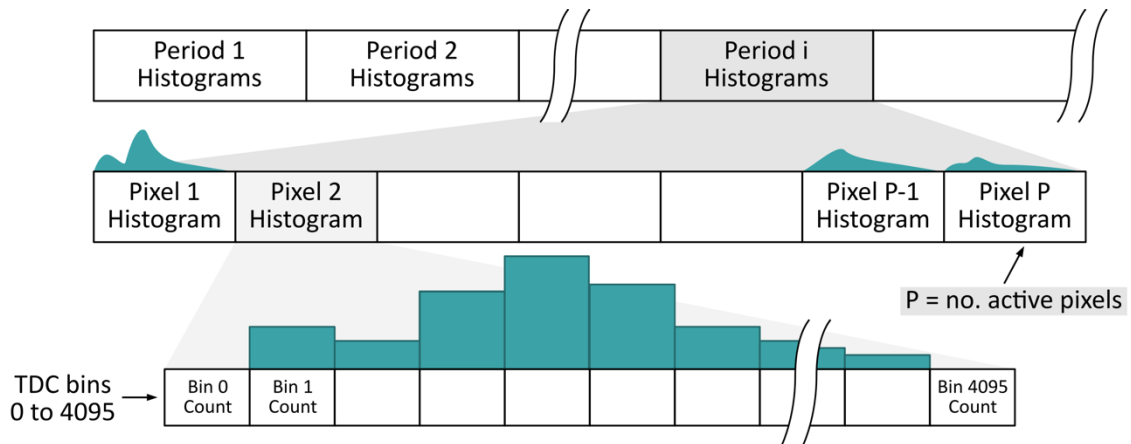


Figure 12. Data order in Histograms format.

The Histograms format is meant to provide aggregated information over many frames. Any information regarding the frames in which each single events occur is lost. Information regarding external input events

is not included as well. TDC conversion code 0 is reserved in raw data for overflow, and TDC conversion code 4095 is reserved in raw data for incorrectly timed event. They are not used in *Histogram* format, so the corresponding bins are always empty.

7.4.3 Frames Format

In Frames format, data is delivered as a 1-D array of 32-bit unsigned integers. As shown in Figure 13, data concatenation preserves the chronological order of frames and the order of pixels.

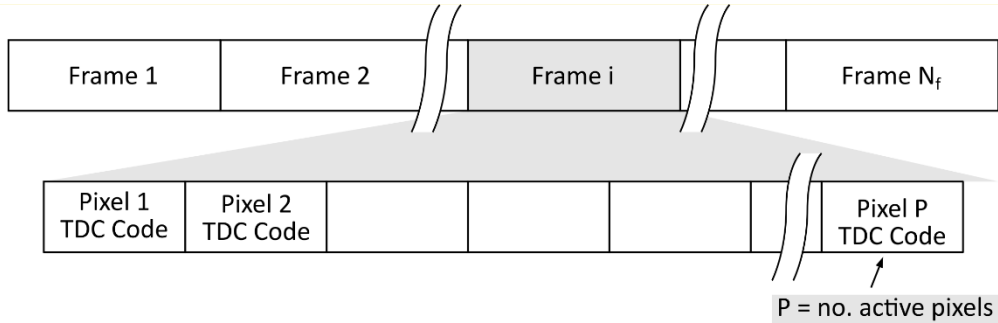


Figure 13. Data order in Frames format.

In timing mode, the entire array is composed by concatenating TDC values of each pixel. When a TDC overflows an all-zeroes code is used. When an event is detected but incorrectly timed, a 4095 decimal code is used. For an acquisition of N_f frames and P active pixels the final data set size in bytes is given by:

$$\text{Length_frames_timing} = N_f * P * (4 \text{ bytes per value})$$

In counting mode, the entire array is composed by concatenating counts of each pixel accumulated over N_{int} frames. For an acquisition of N_f frames and P active pixels the final data set size in bytes is given by:

$$\text{Length_frames_counting} = N_f / N_{int} * P * (4 \text{ bytes per value})$$

The final length of data does not depend on the number of detected events. As a consequence this format is the least efficient in terms of disk storage space, especially in timing mode since in photon-starved application typically frames are mostly populated by all-zeros *no event* codes. Any information regarding external input events is not included in the *Frames* format.

7.4.4 Raw Format

CRONO raw format is an optimized data format for single photon cameras. The data provided by the CRONO camera is not processed and is provided as-is. This data format enables acquisitions at the highest frame and event rates without being limited by the processing capabilities of the host CPU (though the maximum data transfer is still limited by the USB 3.0 interface), since no real-time conversion is required. Data saved in this format retains the full information of all events including auxiliary input tagging and is meant to be later retrieved and converted to another usable format. Both the CRONO View GUI application and the CRONO SDK provide the functionality to convert *raw* data to *Time Tagging*, *Histograms* or *Frames* formats. Please refer to the SDK reference manual and high-level language examples for further details.

Data is organized in acquisition **Frames**, but, to reduce data volume, values from pixels that did not get triggered during a frame are not transferred.

As shown in Figure 14, each **Frame** is composed by 4 sections, organized in 32bit words.

- A **Header**, including a special 24bit delimiter, 2 bits for aux inputs sampling, and 6 bits for the size of the **Selection Matrix**, as number of 32 bit words, which depends on the number of pixel in use.
- A 32-bit **Macro Time Stamp**, with the progressive number of the frame.
- A **Selection Matrix** where each bit corresponds to a pixel, with a 1 for a triggered pixel and a 0 for a not triggered pixel.
- A variable size **Pack** containing data of pixels that effectively produced data during the frame. The size of the **Pack** section is given by the number of bits per conversion (that depends on the acquisition mode) multiplied by the number of 1s in the **Selection Matrix**. In counting mode, each item of the pack corresponds to the counted events within the frame. Pixels that counted 0 are not transmitted. In timing mode, each item of the pack corresponds to the TDC conversion value. Pixels that did not get triggered during TDC range are not transmitted, while value 4095 is reserved for incorrectly timed events.

Transfer from camera to PC usually occurs in **Blocks** of $1024 \times 1024 \times 32 \text{ bit} = 4 \text{ MiB}$ to maximize data throughput. Since the size of a **Frame** is variable, the number of **Frames** in a **Block** is also variable, and the remaining space is padded with the word 0xFFFFFFFF.

HEADER	31-8: Magic 0xCFC0DE	7-6: Aux inputs state	5-0: Number of Matrix rows
TIMESTAMP	Progressive number of frames		
MATRIX	Selection Matrix. The number of rows of this section is indicated in bits 5-0 of header 128x1 $\Rightarrow$ up to 4 rows, depending on the number of pixels in use 8x8 $\Rightarrow$ up to 2 rows, depending on the number of pixels in use		
PACK	Actual data. Number of rows is $\text{ConvSize} \times \text{ValidPop} / 32$, where: - ValidPop is the number of 1s in MATRIX - ConvSize is 8 in counting mode or 12 in timing mode		

Figure 14. Individual Frame structure in RAW format.

7.5 FILE FORMATS

Each data format corresponds to a different file type that is possible to create using the SDK (for raw format) or the CronoView software (for processed formats).

All file formats share the same basic structure.

The file starts with a 64bit binary signature **0x4d5044ff05000000**.

After the signature, a variable size textual header is added. The header is composed by several LF terminated lines, divided in sections. The first section starts with the line ***__SETTINGS__*** and contains all the acquisition settings, one setting per line, each line ending with “;”. For instance, the active pixel setting is reported as “*activePixels* = 128; ”. The second section starts with the line ***__DEVICE_INFO__*** and reports device type and FW and SDK versions. The third section starts with the line ***__ACQUISITION_INFO__*** and reports time and data of acquisition, the type of the file and some additional information specific to the type of the file. Finally, the line ***__DATA__*** marks the start of measurement data section, which follows in binary format according to the data type description given in paragraph 7.4.

8 CRONOVIEW GUI

The CRONO camera comes equipped with the CronoView acquisition and control application designed for the Microsoft Windows operating system. This graphical user interface (GUI) offers direct access to all camera functions and serves as a tool for real-time data display. It can also be used to replay raw data and convert them in one of the decoded data formats. However, for more extensive and flexible camera control, it is advisable to use the Software Development Kit (SDK) libraries.

8.1 INSTALLATION

Start the installation process by double-clicking the installer executable and follow the step-by-step installation instructions. Please note that device driver from OpalKelly, provided on the CRONO USB-Key, must be installed before connecting the camera to the PC.

8.2 MENU COMMANDS

8.2.1 File

- Open Device: open a connected device through the device selection window.
- Open Raw File: open a raw data file and use *CronoView* as a format converter.
- Close Device/Raw File: close the open device/raw file.
- Set acquisition folder: set the folder to be used for acquisition.
- Save configuration: save *CronoView* configuration to a xml file.
- Open configuration: load *CronoView* configuration from a xml file.
- Export SDK configuration file: export CRONO configuration to a CRONO SDK configuration file.
- Import SDK Configuration file: import CRONO configuration from a CRONO SDK configuration file.

8.2.2 Tools

- Reset settings to defaults: reset all *CronoView* settings to default values.

8.2.3 View

- Signal Configuration window: show the Signal Configuration window.
- Diagnostic Window: show the Diagnostic window.

8.2.4 Help

- About CronoView: show infos about *CronoView* and SDK version.

8.3 MAIN WINDOW

The *CronoView* main window (Figure 15) gives access to the main SPAD settings and acquisition parameters. It also visualizes the live timing and counting data and other real-time status information. The window is divided in six sections: *Status*, *Pixel/SPAD settings*, *Acquisition*, *SPAD Array View*, *Event Count Rates* and *TDC Histograms*. A brief description of each is given in the following subsections.

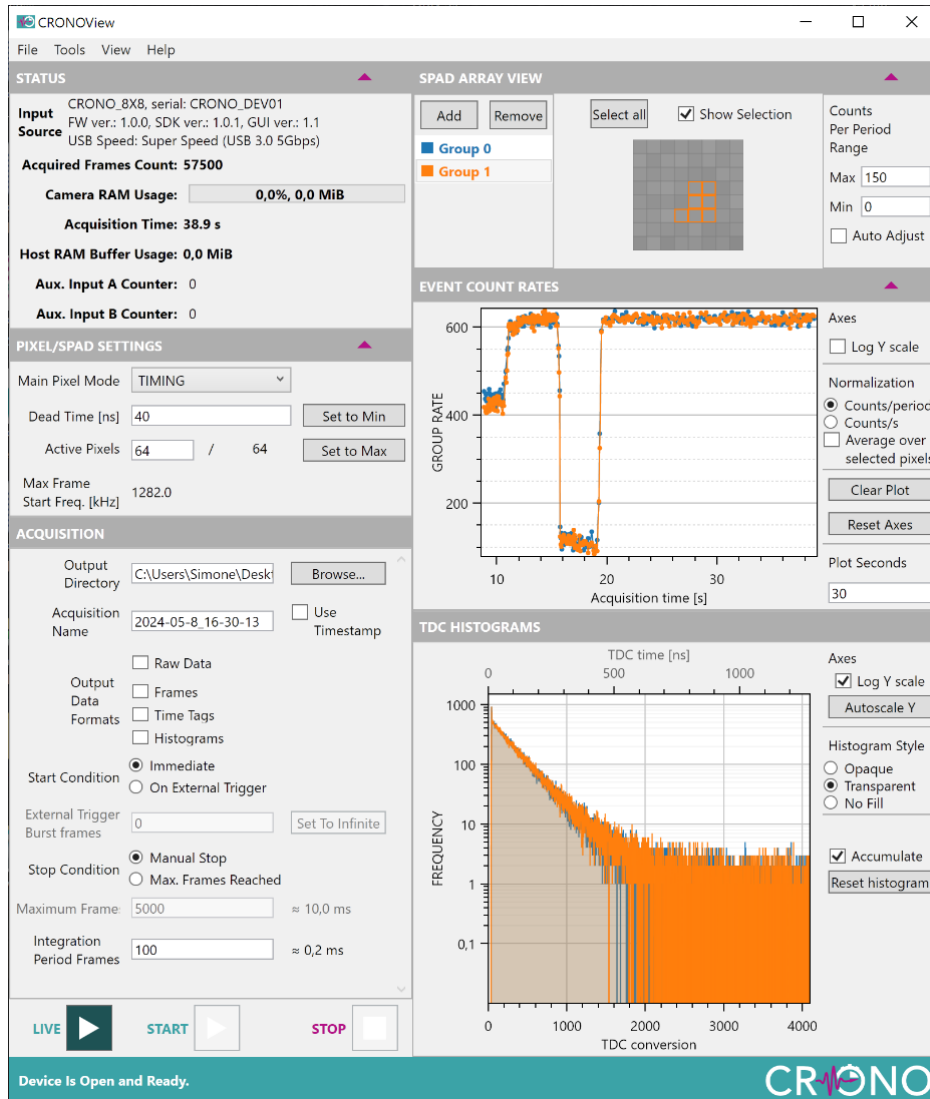


Figure 15. CronoView main window.

8.3.1 Status section

The status section shows information about the Input Source, whether a physical device or an opened raw file, and many counters to monitor the acquisition in progress or that simply show their value at the end of an acquisition. These are:

- **Acquired Frames Count:** the number of acquired frames since acquisition start.
- **Camera RAM Usage:** the current usage of in-camera RAM.
- **Acquisition time:** elapsed acquisition time i.e. time since acquisition start.
- **Host RAM Usage:** the usage of host PC RAM.
- **Aux. Input A Counter:** number of detected edges for auxiliary Input A since acquisition start.
- **Aux. Input B Counter:** number of detected edges for auxiliary Input B since acquisition start.

All displayed fields automatically update during an ongoing acquisition and retain the displayed value until a new acquisition is started.

8.3.2 Pixel/SPAD Settings section

This section allows to configure the following pixel-related parameters:

- **Main Pixel Mode:** the mode of operation of all Pixels. It can be either Counting or Timing.
- **Dead Time:** set dead time of all the in-pixel SPADs expressed in nanoseconds.
- **Active Pixels:** number of active pixels on the sensor. For any given valid number, the set of active pixels is always contiguous and always starts with the first pixels. As an example, if the number of active pixels is set to 4 only pixels with index 0, 1, 2, and 3 will be enabled.

At the bottom of the Pixel/SPAD section the **Maximum Frame Start Frequency** is displayed. The value is automatically updated in accordance with the set number of active pixels.

8.3.3 Acquisition section

The Acquisition section allows users to access the core acquisition controls and settings. Three buttons allow to *Start* a full acquisition, to start a *Live-Only* acquisition, or to *Stop* both. The section offers the following user-configurable parameters:

- **Output Directory:** directory in which the acquisition data files are saved.
- **Acquisition Name:** name of the current acquisition. If the *Use Timestamp* checkbox is ticked, the name is automatically set to the current timestamp (date and time) whenever an acquisition is started. The name is used as a prefix for all file names corresponding to the enabled output data formats.
- **Output data Formats:** up four different output data formats can be enabled simultaneously. Each active data format will result in the creation of the corresponding data file. Refer to paragraph 7.4 for further details about the available data formats. At least one format must be selected to enable the *Start* button. If a *Live-Only* acquisition instead is desired, there is no need to select any format, and these field are ignored.
- **Start Condition:** condition for triggering the beginning of a new acquisition. If *Immediate* is selected, the acquisition starts right after the *Start* button is pressed. If *On External Trigger* is selected, once the *Start* button is pressed the acquisition will start only on an external trigger pulse.
- **External Trigger Burst Frames:** number of frames for each burst triggered by each external trigger pulse. If set to zero a single undefinedly long burst is triggered on the first trigger pulse occurring after the *Start* button has been pressed.
- **Stop Condition:** selects which event will stop an ongoing acquisition. If *Manual Stop* is selected, the acquisition stops when the *Stop* button is pressed. If the *Maximum Frames Reached* option is selected, the acquisition ceases upon reaching a number of frames equal to *Maximum Frames*.
- **Maximum Frames:** maximum number of frames in an acquisition. If the Stop condition is set at *Maximum Frames Reached*, an acquisition automatically stops when the acquired frame count reaches this the value of *Maximum Frames*. This value is ignored if the stop condition is set on Manual Stop allowing the user to acquire an unlimited number of frames.
- **Integration Period Frames:** number of consecutive frames that will be used to compute the accumulated image, calculate the event rate and build the histogram.

8.3.4 Spad Array View section

This section shows the entire CRONO sensor by representing each pixel as a square. The squares are shaded with a grayscale color linearly related to the counts over **Integration Period Frames** for the corresponding pixel. In counting mode, counts are the effective counts per pixel. In timing mode, a single count per frame is added if the TDC has registered a valid conversion during the frame.

On the right side one can input the range of counts to be visualizes by setting the minimum and maximum count values. The visualized pixel grayscale g value is then:

$$(\text{pixel grayscale}) = \frac{(\text{pixel counts}) - (\text{minimum value})}{(\text{maximum value}) - (\text{minimum value})}$$

If the pixel count value exceeds the set maximum, the pixel will be colored in red. Likewise, the pixel will be colored in blue if the count gets below the set minimum. It is possible to enable the auto adjustment of the range levels, which will then occur on every image update.

On the left side of the SPAD Array View section one can select, add or remove a *pixel group*. Pixel groups are sets of pixels for which a TDC histogram and a time series in the event count rates plot is created. A single pixel can be added in the currently selected pixel group by simply clicking over it. Multiple pixels can be selected/deselected holding *Ctrl* key on the keyboard while clicking. If a pixel belongs to the currently selected pixel group, its square contour will show the color associated to the group.

8.3.5 Event Count Rates section

This section displays the time series of the count rates for each active pixel group. During an active acquisition, the live data is automatically updated every *Integration Period Frames*. At each update, a new point in the event counts rates plots is added for each active pixel group. By default the plot keeps track of all count rates values within a 30 second time window. The width of the time window can be changed in the *Plot Seconds* box. Displayed values can be the actual total counts per *Integration Period*, the normalized total count rate per second, or the corresponding averages over the selected pixels. The plot can be zoomed-in by dragging a rectangle with the right button of the mouse, and then moved around dragging with the left button. A double right click will reset the zoom.

This time series plot is useful to keep an eye on the changes of the pixel count rates. This proves especially useful when aligning the CRONO camera relative to light sources and optics in a measurement setup.

8.3.6 TDC Histograms

With each live data update, a new TDC conversion code histogram is displayed in the TDC Histogram section. The TDC histogram is displayed with two time-scales: the bottom time scale expresses times in terms of TDC codes (1 bin = 312.5 picoseconds) while the top timescale expresses times in nanoseconds. It is possible to keep histograms accumulating by ticking the *Accumulate* checkbox. In this case the histogram can be reset clicking the *Reset* button. The histogram can be zoomed-in by dragging a rectangle with the right button of the mouse, and then moved around dragging with the left button. A double right click will reset the zoom.

Please note that any information regarding the Super coarse time is not displayed in the TDC histogram.

8.4 SIGNALS CONFIGURATION WINDOW

The Signals Configuration Window enables users to customize essential control input signals for the CRONO sensor. Additionally, this window allows users to configure troubleshooting and utility output signals that are directed to the three coaxial ports, and to enable and configure Aux input sampling.

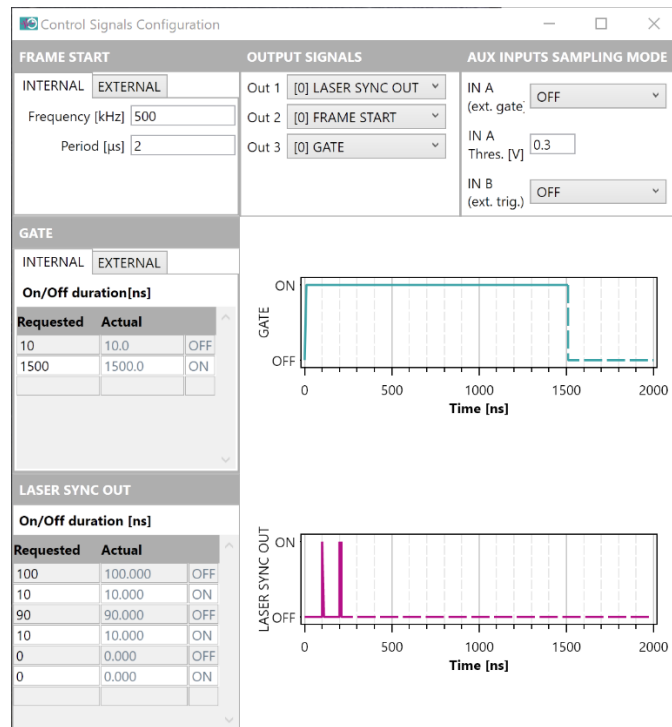


Figure 16. CronoView signal configuration window.

8.4.1 Frame Start section

This section allows to choose between internally or externally generated *Frame-Start* signal. The desired source is selected simply by activating the corresponding tab.

If an internally generated *Frame-Start* signal is desired, the frame frequency or period must be specified. For an externally generated *Frame-Start* signal, one must specify the input comparator threshold, the triggering edge (rising or falling), the division factor and the expected external start minimum period. This last parameter must be the minimum expected time between two consecutive pulses of the *divided* external frame start signal. As an example: if the external signal is a 80 MHz square wave from a laser and the division factor is set to 80, the minimum time between two rising edges of the divided signal is 1.0 microsecond.

8.4.2 Gate section

This section allows to switch between internally and externally generated gate signals. The selection is done by activating the corresponding tab.

When the internally generated gate signal is selected together with internal *Frame-Start* signal, the user can input an arbitrary pattern with a nominal resolution of 1 ns. The pattern is represented by alternating

ON and OFF time periods expressed in nanoseconds. Since the actual resolution depends on the chosen *Frame-Start* frequency, the actual value for each section is reported. Once an internal gate signal pattern is given or modified, at the right of this section an automatically refreshing plot displays the temporal behavior of the given pattern.

When the internally generated gate signal is selected together with external *Frame-Start* signal, the gate is always ON and cannot be configured.

When the externally generated gate signal is selected, it is possible to specify the input comparator threshold and the triggering edge (rising or falling).

8.4.3 Laser Sync Out section

This section allows to input an arbitrary pattern for the Laser sync out signal. The pattern is similar to the one for the internally generated gate signal described above.

8.4.4 Output Signals section

This section allows to select which internally generated signal is to be forwarded to the three output coaxial ports. By default Output 1 forwards the Laser Sync Out signal, Output 2 forwards the a copy of the frame start signal (as received by the sensor) and output 3 forwards a copy of the gate signal (as received by the sensor).

8.4.5 Auxiliary inputs sampling mode section

This section is used to configure the sampling mode of the two auxiliary inputs (off, rising edge, falling edge, both edges). For Aux A it is also possible to set the input threshold, Aux B has fixed LVCMOS levels.

8.5 DIAGNOSTIC WINDOW

The diagnostic window can be used to monitor the internal camera temperature, and several voltages and currents. It can be useful to help remote debugging by MPD support in case of operation issues. It also reports the current frequency for the three coaxial inputs.

THERMAL		VOLTAGES	
T Power U19	25.1 °C	V12	11.84 V
T Carrier U3	21.2 °C	V3.3	3.28 V
T Sensor	24.3 °C	VspadH	29.98 V
		Vspad5	5.11 V
		Vspad3.3	3.36 V
CURRENTS		INPUT SIGNALS	
I12	329.13 mA	Ext Start Frequency	0.00 kHz
IspadH	0.43 mA	Ext Gate Frequency	0.00 kHz
Ispad5	0.04 mA	Ext Trig Frequency	0.00 kHz
Ispad3.3	0.00 mA		

Figure 17. CronoView diagnostic window.

9 APPENDIX I: DESCRIPTION OF CRONO CHARACTERIZATION FILES

Crono cameras are fully characterized before shipping by MPD. Some of the characterization files are shared with customers and included in the provided USB key. This document describes how to read and understand them.

9.1 DARK COUNTING RATE CUMULATIVE DISTRIBUTION - CRONO_SNxx_BG_CUMDISTR.PNG

This file shows the cumulative distribution of the dark counts over all the pixels of the imager. The distribution is obtained ordering in ascending order the dark counting rate of all the pixels and normalizing the x axis to 100%. It must be read as follows: given a desired maximum dark counting rate, represented on the y axis, the percentage of pixels below that value is given by the corresponding x value.

9.2 DARK COUNTING RATE MAP – CRONO_SNxx_DCRMAP.FRAMES.DAT

This file shows a map of the dark counts over all the pixels of the imager when measured with a dead-time of 40 ns and over 10 s, as a single frame in *Frames* format. The DRC in counts per seconds (cps) for each pixel is thus the value reported in the file, divided by 10.

9.3 DETECTION EFFICIENCY MAP AND AVERAGE

Given the very good reproducibility and consistency of the Crono photon detection efficiency (PDE) among fabricated samples, Micro Photon Devices Srl is not measuring it on all fabricated devices, but only on randomly selected samples. To check if this data is available and to request it, customers can write to support@micro-photon-devices.com. Such data, if available, will be sent to customers.

In case of Crono camera without micro lens array, the SPAD-PDE will be provided through 2 files:

1. Crono_SNxx_PDE.txt. This file contains the Crono detection efficiency averaged over all the pixels of the array as a function of the wavelength. SNxx refers to the serial number of the camera.
2. Crono_SNxx_PDEmap.PDE.dat. This file contains the map of the detection efficiency over all the SPAD pixels of the array. SNxx refers to the serial number of the camera.

In case of Crono camera with micro lens array, the ImagerPDE will be provided through 4 files:

1. Crono_SNxx_ImagerPDE.txt. This file contains the Crono ImagerPDE averaged over all the pixels of the array as a function of the wavelength and F#. SNxx refers to the serial number of the camera. Since the SPAD active area PDE depends on the wavelength and the microlens CE depends on the wavelength AND on the incoming beam F-number, we provide the ImagerPDE as a function of wavelength at different impinging light beam F-Numbers.
2. 3 ImagerPDE map files named Crono_SNxx_ImagerPDEmap_F#yyy.PDE.dat, where SNxx is the serial number of the camera and F#yyy is the F-number of the light impinging the detector.

Note that *.PDE.dat* files are frames-type files (see paragraph 7.5) composed by 61 frames, each corresponding to a different wavelength, starting from 400 nm and ending at 1000 nm in 10 nm steps. For

each pixel, the value reported corresponds to the measured PDE percentage multiplied by 100, i.e., a value of 3856 corresponds to a PDE of 38.56%.

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