TEDIEL S.R.L.

Hardware Histogram

Histogramming the time differences of coincidence measurements allows for the analysis of the arrival time distribution of physical events captured by a detector. A **Time-to-Digital Converter** (TDC, or, commercially, Time Taggers) enables the high-precision measurement of the exact instant a detector (or reference) "clicks", i.e. generates a signal, facilitating the acquisition and transmission of this data, which is essential for various applications.

Unlike the direct transfer of all incoming **Timestamps** from the instrument—which would require storing large amount of data and offline processing to generate the desired histogram—the histogram computation is performed directly **on-board** by dedicated hardware logic. This enables the processing of a significantly higher number of events per unit of time without overloading the host computer, while also avoiding limitations imposed by the available data transfer bandwidth.

The characteristics of the hardware histogramming functionality of Tediel's **Felix** family of Time Taggers can be summarized in the following steps:

1. **Event Detection**: The TDC receives signals from one or more physical sources, such as single photon detectors or other sensing devices. If multiple sources are present in the experimental setup, they are generally connected to different inputs known as channels (Ch).
2. **Arrival Time Calculation**: The TDC measures the arrival time of each event on every channel with high timing precision. This process involves a series of operations that generate the Timestamp corresponding to when the electrical signal detected by the channel crosses a specific (user-definable) threshold. The Timestamp precision is in the order of tens of picoseconds rms.
3. **Time Difference Calculation**: Once the two channels of interest for coincidence analysis are selected, and after two events have been detected, and their respective arrival times calculated, the histogramming module computes the time difference between them. In this context, they are referred to as the Reference (Ref) and Measurement (Meas) channels. The applied operation is, thus:

$T_{Coincidence} = T_{Meas} - T_{Ref}$

Often, the reference channel is connected to a laser source; if operating at high frequency, it may be advantageous to use the dedicated Sync channel. In this example, the laser provides crucial timing information between the two events and can be used to study their temporal correlation.

4. **Histogram Generation**: The histogram is a graphical representation of the distribution of time differences between pairs of events obtained during an acquisition. It consists of a set of "bins" (time units) of arbitrary width, covering a Full Scale Range (FSR) of time, which is also of arbitrary dimension. If the calculated time difference falls within the selected FSR, it will correspond to a specific bin, whose count will be incremented by one.
5. **Results Visualization**: Results can be visualized graphically both during and after data acquisition. This provides a clear visual representation of the temporal distance distribution between events, allowing for the extraction of relevant information from the physical source; visualization is available in both linear and logarithmic scales (Y-axis). Furthermore, it is possible to generate text files (e.g., .csv) or screenshots (e.g., .png) of the acquisitions for convenient data processing and review.

The measurement and reference channels can be freely selected by the user from all available channels on the TDC.
Note: the **Sync** channel (or Channel 0) can only be used as a reference.

The number of hardware histogramming modules present in the device determines the total number of **Ref-Meas pairs** for which coincidences can be measured simultaneously online.

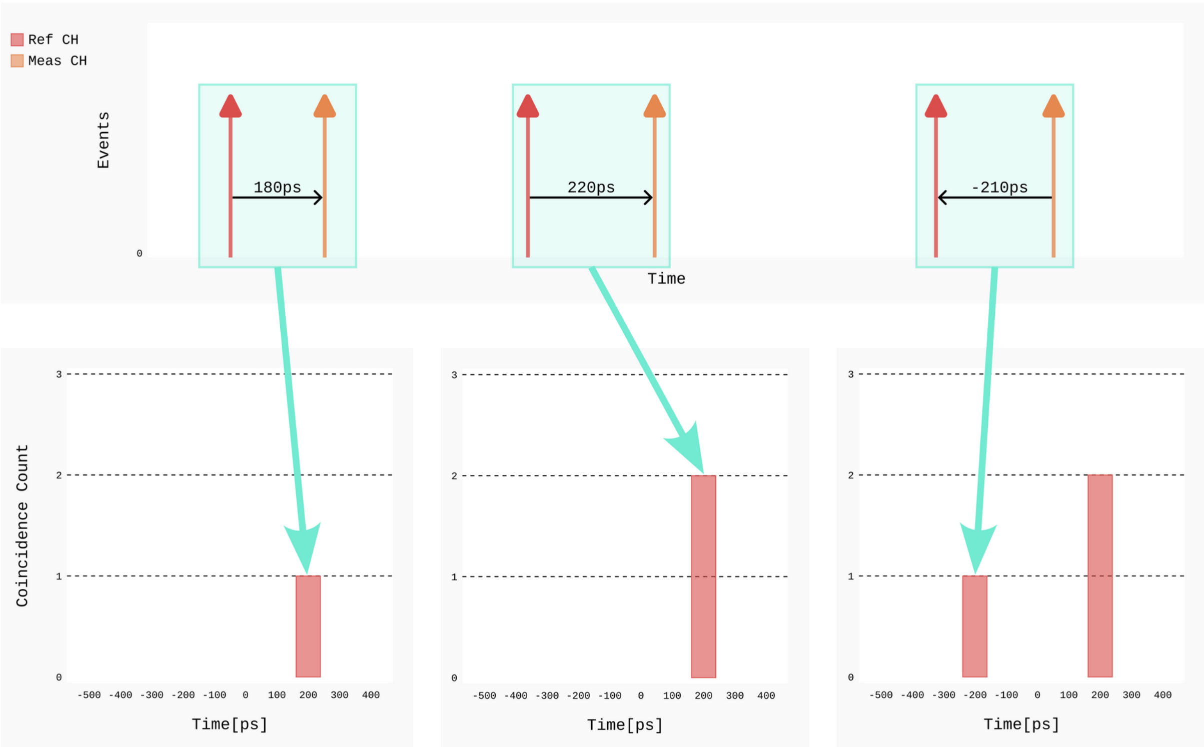


Figure 1: Example of the histogram building process: for each coincidence, the corresponding bin is incremented.

Boundaries

The histogram records coincidence events only if the calculated time difference falls within a specific range, known as the **Full Scale Range (FSR)**. This FSR can be defined by the user through the **Left Bound** and **Right Bound** parameters. These bounds can also be negative, thereby allowing the system to histogram events where the measurement event occurred prior to the reference event.
Note: The condition **Right Bound > Left Bound** must always be satisfied.

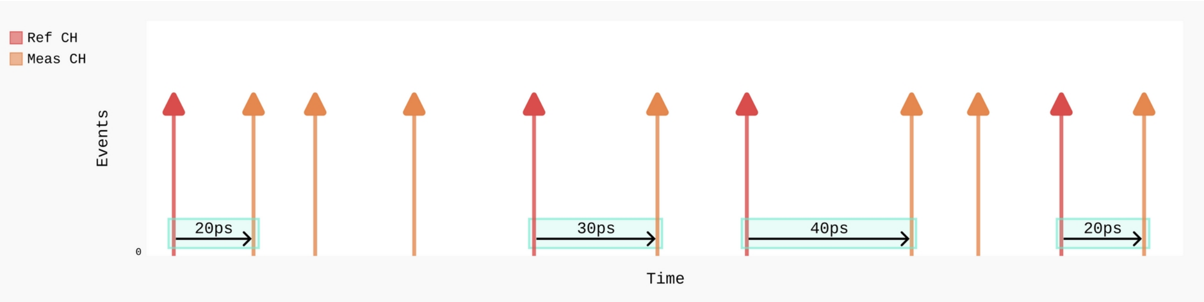
The width of the histogram bins can also be selected by the user via the **Bin Width** parameter; however, the maximum number of bins available in each hardware histogram module is fixed by the firmware and cannot be altered. This imposes constraints on the minimum allowable Bin Width, based on the chosen **Left Bound** and **Right Bound** parameters: $BW_{min} = \frac{(RB - LB)}{N_{MAXBIN}}$

Single Hit vs Multi-Hit

Depending on the acquisition requirements, the user can choose between **Single Hit** or **Multi-Hit** modes.

Single Hit

In standard histogram operation, at most one time difference (coincidence) is recorded for each reference event within the **FSR**. If multiple events occur for a single reference, only the first one will be histogrammed.



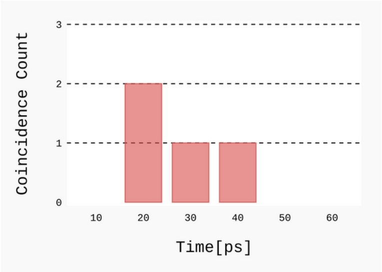
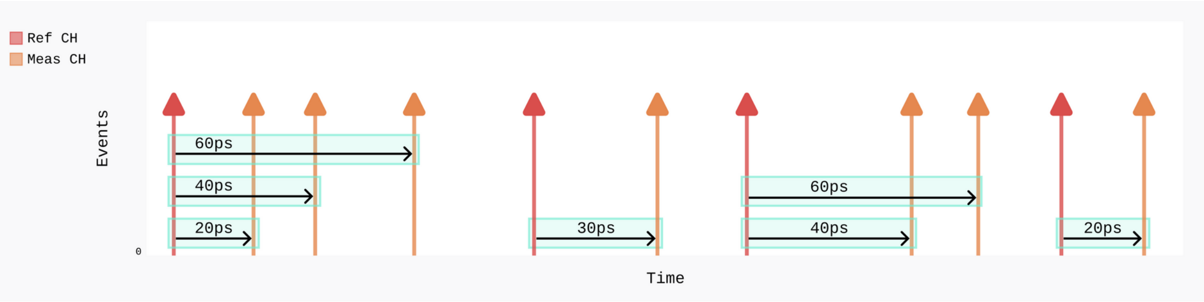


Figure 2: Single Hit Histogram construction: the incoming Meas events following the first one are ignored and do not generate coincidences.

Multi-Hit

By enabling **Multi-Hit** mode, it is also possible to calculate and histogram more than one time difference (coincidence) for each reference event. This applies in cases where multiple measurement events occur within the **FSR** for the same reference event.



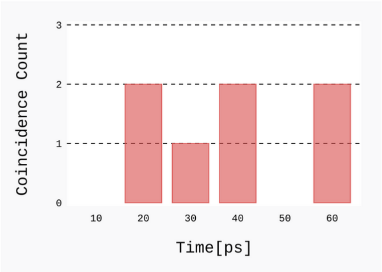


Figure 3: Multi Hit Histogram construction: the incoming Meas events following the first one, which also fall inside the FSR, are also considered and contribute to generate further coincidences.

Acquisition Modes

There are two distinct acquisition modes for the histogram:

- **Single Continuous Integration**
- **Multiple Separate Integrations**

Single Continuous Integration

In this mode (referred to as **Accumulate** in the software), the same histogram continuously integrates coincidences until the process is manually stopped by the user. This is useful for long-term recording of a physical process to achieve a specific statistical confidence level.

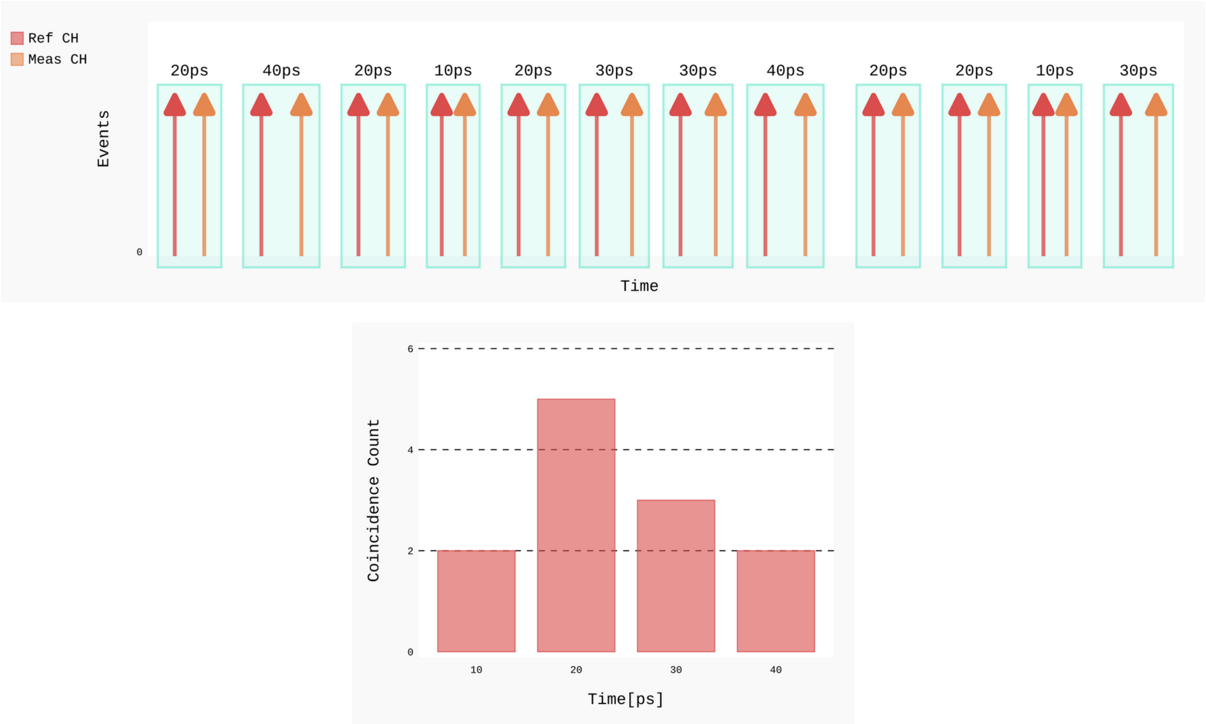


Figure 4: Continuous Integration example

Multiple Separate Integrations

This mode is designed for acquiring event histograms where the integration time must be well-defined and relatively short. This allows for the observation of the temporal evolution of the phenomena of interest or the acquisition of data from different coordinates if they change between integrations (e.g., **LiDAR, or Diffuse Optics** applications).

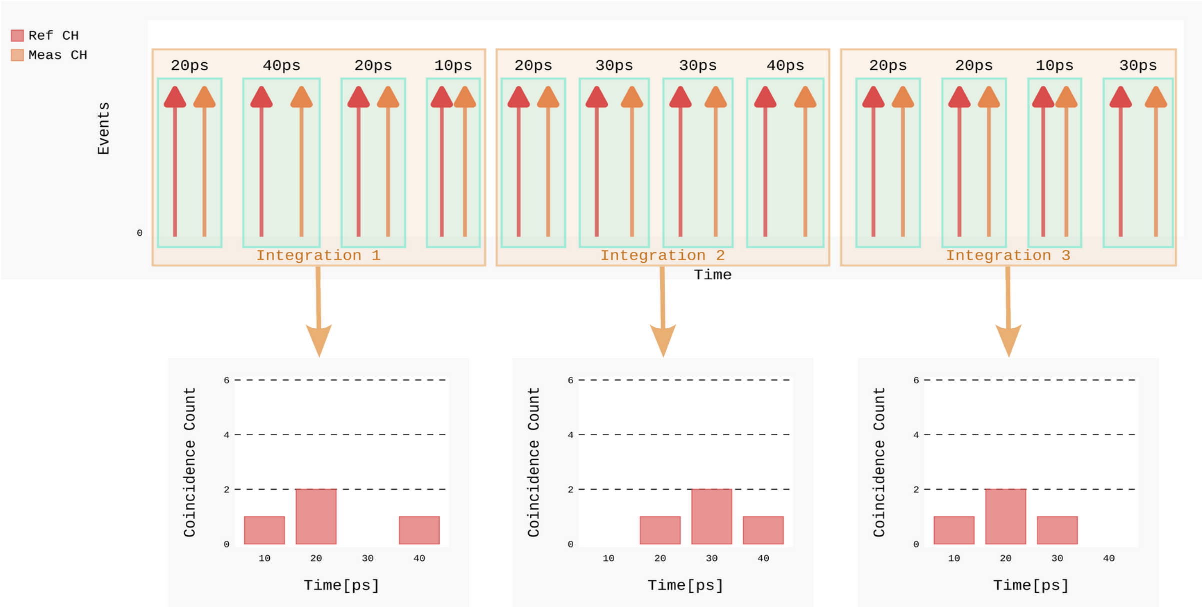


Figure 5: Example of Multiple Separate Integrations

There are three adjustable parameters to define the histogram acquisition: the **total acquisition duration**, and the **start** and **stop** times for each histogram integration.

Acquisition Duration

The acquisition duration can be determined in three different ways:

- **Continuous:** The user manually starts and stops the acquisition process.
- **Time Interval:** The user defines the total acquisition duration in terms of time.
- **Repetition:** The user specifies the total number of integrations to be acquired.

Start Acquisition

The start of each integration for a group of histograms can be triggered in two ways:

- **Via an internal timing parameter** called **Integration Time** (expressed in seconds). A new integration start signal is generated at every **Integration Time**; the previous integration, if active, is concluded and transmitted to the PC.

- **Via an external signal** connected to the **Trigger Channel**, which commands the generation of a new integration start. The Trigger Channel can be chosen from one of the available device channels.

The **Integration Time** parameter has a resolution of **1.2288 µs**.

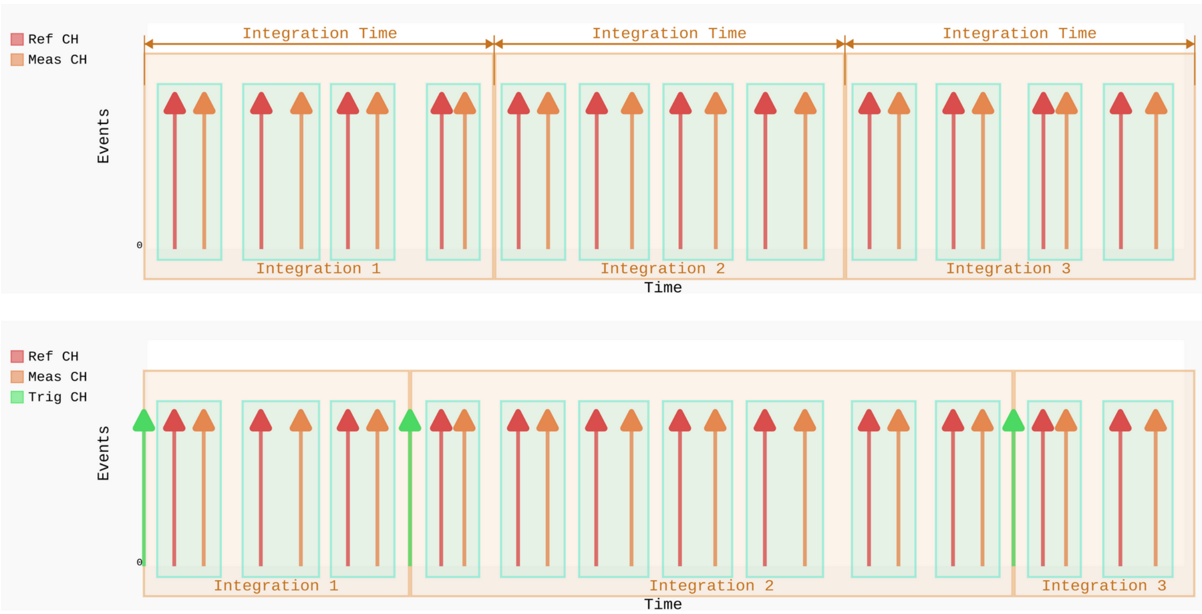


Figure 6: Start mechanism example: above, using the Integration Time, below using the Trigger Channel.

Stop Acquisition

The termination (**stop**) of a histogram integration can be executed based on two different factors, both of which are active simultaneously:

- **Arrival of a new "Start" signal:** The current window is automatically closed, and a new one is initiated.
- **Gating Mode:** The current window is automatically closed upon reaching the **Gate Length**, a parameter that specifies the maximum integration length of the window.

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Once the Gate Length is reached following a start signal, integration is halted until a new "**Start**" occurs.

The minimum **Gate Length** value is **100 µs**, with a setting resolution (**LSB**) of **1.2288 µs**.

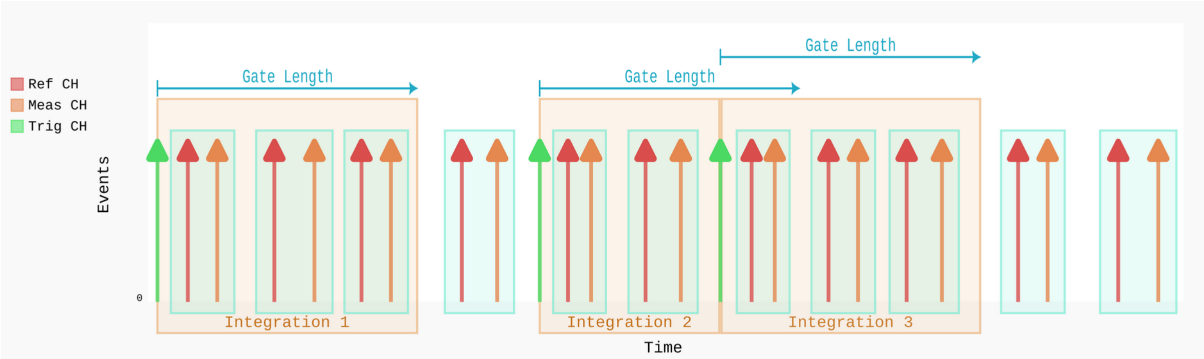

Figure 7: Stop mechanism example: the first and third windows are closed based on Gate Length parameter; the second one is closed due to the arrival of a new "Start".

Glossary

- **Accumulate:** Histogram accumulation mode, typically used for long acquisition durations.
- **Bin:** The basic accumulation unit of a histogram, representing a specific value interval.
- **Bin Width:** The width, expressed in time, of a single histogram bin. User-configurable.
- **Bounds:** The **Left** and **Right** limits of the histogram, which define the **Full Scale Range (FSR)**.
- **Channel:** Each physical input of the TDC device (e.g., **Sync**, **Ch0**, **Ch1**).
- **Coincidence:** A **Meas-Ref** time difference whose value falls within the **FSR**.
- **Event:** An above-threshold electrical signal captured by the TDC.

- **Gate Length:** A fixed acquisition duration starting from the beginning of an integration.
- **Gating:** An acquisition mode used to specify specific fractions of the **Integration Time** to be acquired.
- **Histogram Module:** Silicon-implemented logic that calculates the histogram of time differences between events from the **Measure** and **Reference** channels.
- **Integration Time:** The duration of a single integration period.
- **Measure:** The TDC channel whose timestamp is used as the **minuend** in the time difference calculation.
- **Multi-Hit:** A histogramming mode that allows for multiple coincidences per **Reference** event.
- **Reference:** The TDC channel whose timestamp is used as the **subtrahend** in the time difference calculation.
- **Repetition:** The total number of integrations to be acquired.
- **Single Histogram Integration:** Histogramming in accumulation mode.
- **Single Hit:** A histogramming mode that records, at most, one coincidence per **Reference** event.
- **Sync:** A TDC channel (**Channel 0**) optimized for high-frequency periodic signals (e.g., lasers). **Note:** In a histogram, it can only be utilized as a **Reference** channel.
- **TDC: Time-to-Digital Converter**, also known as a **Time Tagger**, **Coincidence Electronics**, or **Time-Correlated Single Photon Counting (TCSPC)** device.
- **Time Interval:** The total duration of the acquisition.
- **Timestamp:** A digital word representing the absolute time of an event, referenced to the device power-on.
- **Trigger Channel:** A dedicated channel for an external trigger signal used to initiate a new integration.