



# **Time Tagger User Manual**

***Release 2.22.6.0***

**Swabian Instruments**

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## GETTING STARTED

This chapter guides you from installing the Time Tagger software to making your first measurement.

Please refer to:

- *Installation Instructions* for installing the Time Tagger software on Windows or Linux.
- *Time Tagger Lab* for running your first measurement with the graphical user interface.
- *Programming Languages* for writing your first script in Python, C++, C#, LabVIEW, or MATLAB.
- *Hardware License Upgrades* for enabling purchased features on *Time Tagger Ultra/Time Tagger X*.
- *Usage Statistics Collection* for telemetry details and configuration options.

### 1.1 Installation Instructions

This section explains how to install the Time Tagger Software on Windows and Linux. Before installing and operating the Time Tagger, users are strongly advised to follow the guidelines for proper handling. For detailed information on operating conditions and limits, please refer to *Safety & Compliance*.

#### Time Tagger software download

<https://www.swabianinstruments.com/time-tagger/downloads/>

#### 1.1.1 Windows

Time Tagger software requires Windows 10 or higher (64 bit). Windows on Arm (ARM64) is currently not supported. Please use a Windows x64 (Intel/AMD) PC. For Windows 10, we provide full support only for those versions that are still actively supported by Microsoft. Older versions, while untested, might still work.

#### Installation

##### Windows installer

1. Download the installer from our [downloads site](#).
2. Run the installer and follow the instructions. This installs:
  - the USB drivers,
  - C++, Python, .NET, C#, LabVIEW, and MATLAB libraries,
  - the graphical user interface (GUI) *Time Tagger Lab*,
  - the examples,

- the offline documentation.
3. Connect your Time Tagger.
  4. We recommend connecting your computer to the internet once you run the Time Tagger software. This will make sure that the software can request the license needed to use the *Time Tagger Virtual* functionality to replay the recorded data, without having the Time Tagger connected. This functionality can always be used when a hardware time tagger is connected to the PC. If the PC cannot be brought online even once, but you need the license, please see the [related FAQ](#) on how to obtain an offline license.

The directory used to store the software license and application data can be customized; see [Application data directory](#).

Now you are ready to make a first measurement. You can either use:

- Graphical user interface: launch the *Time Tagger Lab*. Please refer to the [Time Tagger Lab](#) paragraph below.
- Programming languages: use the examples installed with the software (see your installation's `examples/<language>/` folder) to get familiar with the Time Tagger API. Please refer to [Programming Languages](#) section for further details.

### Python package

The Time Tagger Python package can also be installed from PyPI without using the full Windows installer. This installs the Python module only. To access a physical Time Tagger over USB, the Opal Kelly USB driver must also be available on the system.

1. Install the Python module for the Time Tagger in the Python environment you want to use:

```
pip install Swabian-TimeTagger
```

2. To communicate with a physical Time Tagger over USB, the Opal Kelly USB driver must be installed. If it is not already installed, please download and install the [Opal Kelly FrontPanelUSB driver](#) for Windows.

Afterward, connect the Time Tagger to the PC. If it was already connected during the installation, disconnect and reconnect it so that Windows re-enumerates the USB device.

3. In Device Manager, the device should appear under `FrontPanel` devices. If it appears under `Other devices` as an Opal Kelly XEM device, open the device properties and select `Driver -> Update Driver -> Search automatically for drivers`. After successful driver installation, the device should be listed under `FrontPanel` devices.
4. Connect to the Time Tagger:

```
from Swabian import TimeTagger

tagger = TimeTagger.createTimeTagger()
```

We recommend connecting your computer to the internet when creating the Time Tagger once. This allows the software to request the license needed to use the Time Tagger Virtual functionality to replay recorded data without having the Time Tagger connected. This functionality can always be used when a hardware Time Tagger is connected to the PC. If the PC cannot be brought online even once, but you need the license, please see the [related FAQ](#) on how to obtain an offline license.

### Time Tagger Lab

*Time Tagger Lab* is the GUI (Graphical User Interface) application for Windows operating systems. It is designed to perform standard measurements quickly and to get an interactive experience with your Time Tagger. For a step-by-step walkthrough, see the [Time Tagger Lab](#) section. Here, you can follow simple instructions to enable the Time Tagger's internal test signal and measure a *cross correlation* between two channels.

Launch the *Time Tagger Lab* application and select your device, switch to Detailed View, and enable the internal test signal on inputs 1 and 2 by checking the boxes on the very right column. You should see live count rates. Open Creator (F2), choose Bidirectional histogram - Correlation, set Reference = 1 and Click = 2, then add the measurement and press Play. A Gaussian peak should be displayed. You can zoom in using the controls on the plot. The detection jitter of a single channel is  $\frac{1}{\sqrt{2}}$  times the standard deviation of this two-channel measurement (the FWHM (Full-width at half-maximum) of the Gaussian peak is 2.35 times its standard deviation).

## 1.1.2 Linux

### Installation

#### deb/RPM package

1. Download and install the package for your Linux distribution from our [downloads site](#). The package installs the Python and C++ libraries including the examples and offline documentation.
2. Connect your Time Tagger.
3. We recommend connecting your computer to the internet once you run the Time Tagger software. This will make sure that the software can request the license needed to use the *Time Tagger Virtual* functionality to replay the recorded data, without having the Time Tagger connected. This functionality can always be used when a hardware time tagger is connected to the PC. If the PC cannot be brought online even once, but you need the license, please see the [related FAQ](#) on how to obtain an offline license.

The directory used to store the software license and application data can be customized; see [Application data directory](#).

Now you are ready to make a first measurement. You can use:

- Programming languages: use the examples installed with the software (see your installation's `examples/<language>/` folder) to get familiar with the Time Tagger API. Please refer to [Programming Languages](#) section for further details.

#### Python package

1. Install the Python module for the Time Tagger in your local environment (see [venv documentation](#)) using the command:

```
pip install Swabian-TimeTagger
```

2. Create a udev rule granting user access to Swabian Instruments devices (vendor ID 151f):

```
# Create /etc/udev/rules.d/60-swabian.rules with the correct permissions
echo 'SUBSYSTEM=="usb", ATTRS{idVendor}=="151f", MODE="0666"' | sudo tee /etc/udev/
rules.d/60-swabian.rules >/dev/null
```

This rule matches all USB devices with vendor ID 151f and sets their permissions to be readable/writable by any user on the system (MODE="0666").

#### Warning

MODE="0666" makes the device accessible to all local users. If you prefer a tighter policy, you can restrict access to a specific group (e.g. plugdev).

3. Reload udev rules so new devices plugged after this step are granted access:

```
sudo udevadm control --reload-rules
```

4. Connect your Time Tagger.
5. We recommend connecting your computer to the internet when creating the Time Tagger once. This allows the software to request the license needed to use the Time Tagger Virtual functionality to replay recorded data without having the Time Tagger connected. This functionality can always be used when a hardware Time Tagger is connected to the PC. If the PC cannot be brought online even once, but you need the license, please see the [related FAQ](#) on how to obtain an offline license.

Now you are ready to make a first measurement. Please refer to *Programming Languages* section for further details.

## Custom Python installation

- Install NumPy (e.g. `pip install numpy`), which is required for the Time Tagger libraries.
- The Python libraries are installed in your default Python search path: `/usr/lib/pythonX.Y/dist-packages/` or `/usr/lib64/pythonX.Y/site-packages/`.
- The examples can be found within the `/usr/share/timetagger/examples/python/` folder.

You can compile a Python module for custom Python installations in the following way:

The source of the Python wrapper `_TimeTagger.cxx` is provided in `/usr/lib64/pythonX.Y/site-packages/`. For building the wrapper, the GNU C++ compiler and the development headers of Python and numpy need to be installed. The resulting `_TimeTagger.so` and the high-level wrapper `TimeTagger.py` relay the Time Tagger C++ interface to Python.

```
PYTHON_FLAGS="-python3-config --includes --libs"
NUMPY_FLAGS="-I`python3 -c \"print(__import__('numpy').get_include())\"`"
TTFLAGS="-I/usr/include/timetagger -lTimeTagger"
CFLAGS="-std=c++17 -O2 -DNDEBUG -fPIC $PYTHON_FLAGS $NUMPY_FLAGS $TTFLAGS"

g++ -shared _TimeTagger.cxx $CFLAGS -o _TimeTagger.so
```

### 1.1.3 Application data directory

The Time Tagger software stores the local software license and other user-specific data in an application data directory. The default location depends on the operating system:

- **Windows:** `%APPDATA%\Swabian Instruments\Time Tagger` (typically `C:\Users\<username>\AppData\Roaming\Swabian Instruments\Time Tagger`)
- **Linux:** `~/.timetagger`

This directory is created automatically on first use and contains the following Time Tagger-related files:

- `License.txt`: the local software license for *Time Tagger Virtual*
- `LicenseRequest.txt`: a request file used during license acquisition
- `TelemetryDatabase.bin`, `TelemetrySettings.bin`: usage statistics data (see *Usage Statistics Collection*)

To use a custom directory, set the `TIMETAGGER_CONFIG_DIR` environment variable to the desired path before creating a Time Tagger instance or launching *Time Tagger Lab*. The directory is created automatically if it does not exist. This is useful in cases where the default application data location is unsuitable, for example on shared lab computers, in controlled deployment environments, or when running the Time Tagger library from a systemd service with a dedicated service user that has no writable home directory. In that case the service unit can set the variable explicitly:

**[Service]**`User=timetagger-service``Environment=TIMETAGGER_CONFIG_DIR=/var/lib/timetagger-service/appdata`**Warning**

Existing files are not migrated automatically when switching to a custom directory.

### 1.1.4 Offline installation

The TimeTagger software may require an internet connection to download necessary components and, as such, installation with network access is recommended. The following must be kept in mind when access to a network upon installation is limited.

#### License retrieval

If you require an hardware license upgrade, an internet connection is required to download the license used to enable the hardware channels. After the license has been retrieved, the TimeTagger and its software may be used offline on this computer from that point onward.

In some cases, it may not be possible for a computer to be connected to the internet under any circumstances. In this case, a license may be manually requested by contacting [support@swabianinstruments.com](mailto:support@swabianinstruments.com).

#### Windows installer

In addition to the above, the Windows TimeTagger installer may require an internet connection to download and authenticate necessary components of the software.

#### .NET Desktop Runtime

To use TimeTaggerLab, the .NET Desktop Runtime version 10 is required.

The installer will detect the runtime present on the computer and attempt to download the latest required version. If it is unable to do so, the installation will proceed but the TimeTaggerLab application will be blocked until a suitable run time is installed.

To manually install the .NET Desktop Runtime,

- download the installer from the official [Microsoft website](#) using a computer with network access,
- transfer the downloaded installer to the offline computer (e.g. via a USB pen-drive),
- install the software by following the instructions.

After successful installation, TimeTaggerLab should be ready to use.

#### Trusted certificate authorities

The TimeTagger software ships with signed USB drivers. To verify the authenticity of the signatures, [Windows validates the drivers' signature against a root trusted certificate authority \(CA\)](#). The trust lists are updated regularly so without internet access a computer cannot fetch updates to the certificate trust list. In this scenario, Windows will refuse to install USB drivers and the installation procedure will fail.

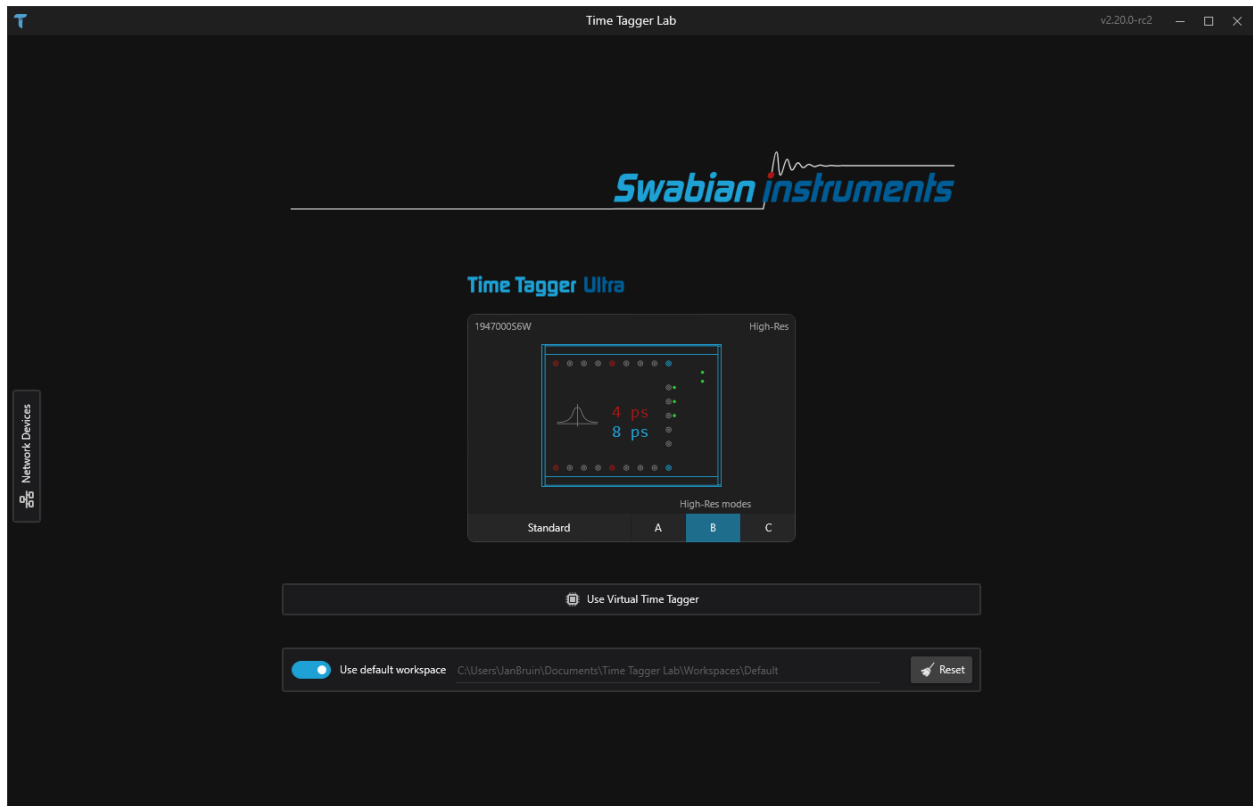
To update the trusted root certificates, you must either update your Windows installation over the network or contact your system administrator [to set up trusted root certificates updates manually on Windows](#).

## 1.2 Time Tagger Lab

*Time Tagger Lab* is the Windows GUI for Swabian Instruments' Time Tagger devices that you can use to run measurements with just a few clicks. Information on how to download and install the software and how to initiate a basic testing experiment can be found in the [Installation Instructions](#) section of the documentation. The purpose of this tutorial is to explore the capabilities of *Time Tagger Lab* in more detail and to cover the most common aspects of configuring and running measurements with it.

### 1.2.1 Selecting a device on the home screen

On the home screen of *Time Tagger Lab*, you will see all Time Tagger devices that are attached to your computer. Each device can be identified by its serial number, shown in the top left of the corresponding card. If your Time Tagger is not listed here, it may be because it is in use by another program or not yet powered up.



#### Note

*Time Tagger Ultra* and *Time Tagger X* have a “HighRes” option to achieve improved jitter that can be updated over-the-air. If you want to operate in these modes, you should select them here before clicking on the card. If you are interested in this option and your device has not been configured appropriately, please contact our team at [sales@swabianinstruments.com](mailto:sales@swabianinstruments.com).

For the *Time Tagger X* only, there is an additional option to select input impedance, see: [setInputImpedanceHigh\(\)](#).

If you have previously saved Time Tagger Network profiles, these will show up as separate cards after any USB-connected Time Taggers. The button **Network Devices** on the left of the screen opens a network browser to create network profiles. For a more detailed description of the Network client functionality, please refer to [Network client](#).

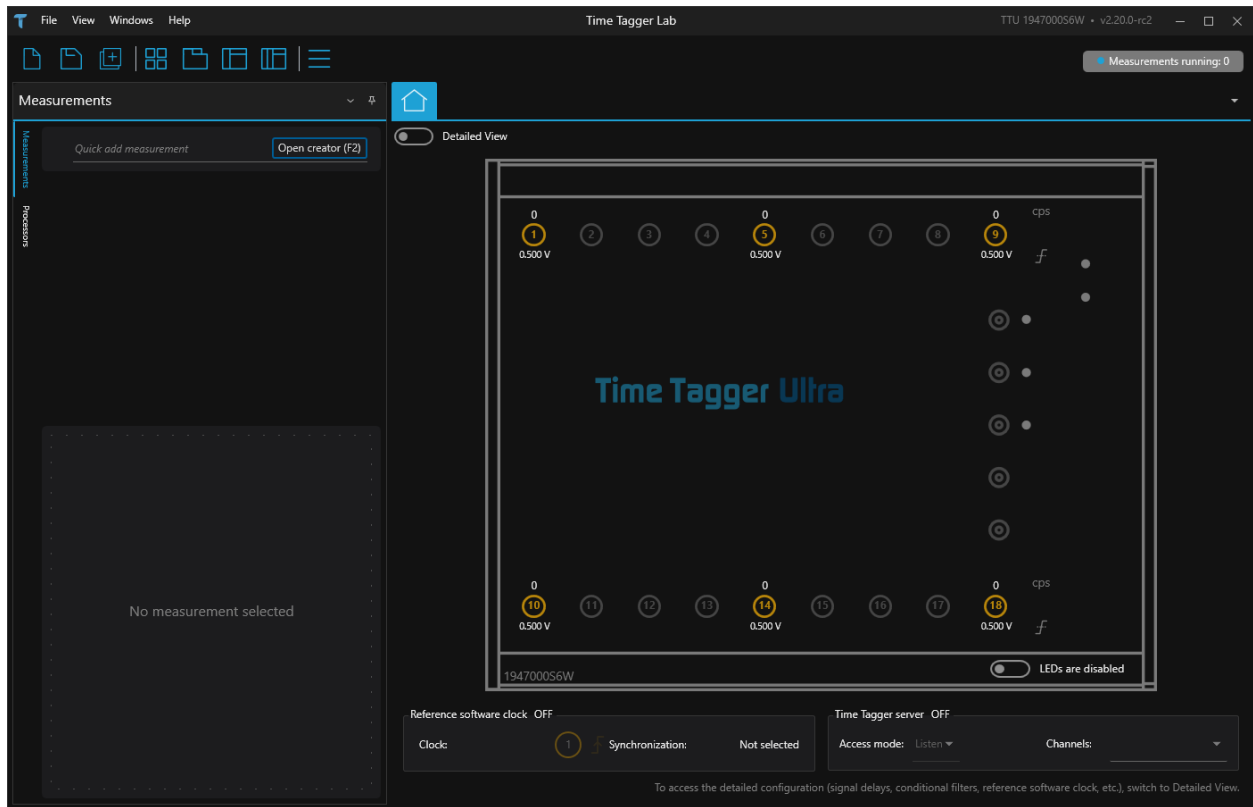
At the bottom of the screen, the workspace menu allows you to select the folder in which your configuration and settings will be stored, as well as an option to overwrite your previous workspace to default values.

The card named *Use Virtual Time Tagger* allows you to experiment with the functionality of *Time Tagger Lab* without a physical Time Tagger, using only simulated signals.

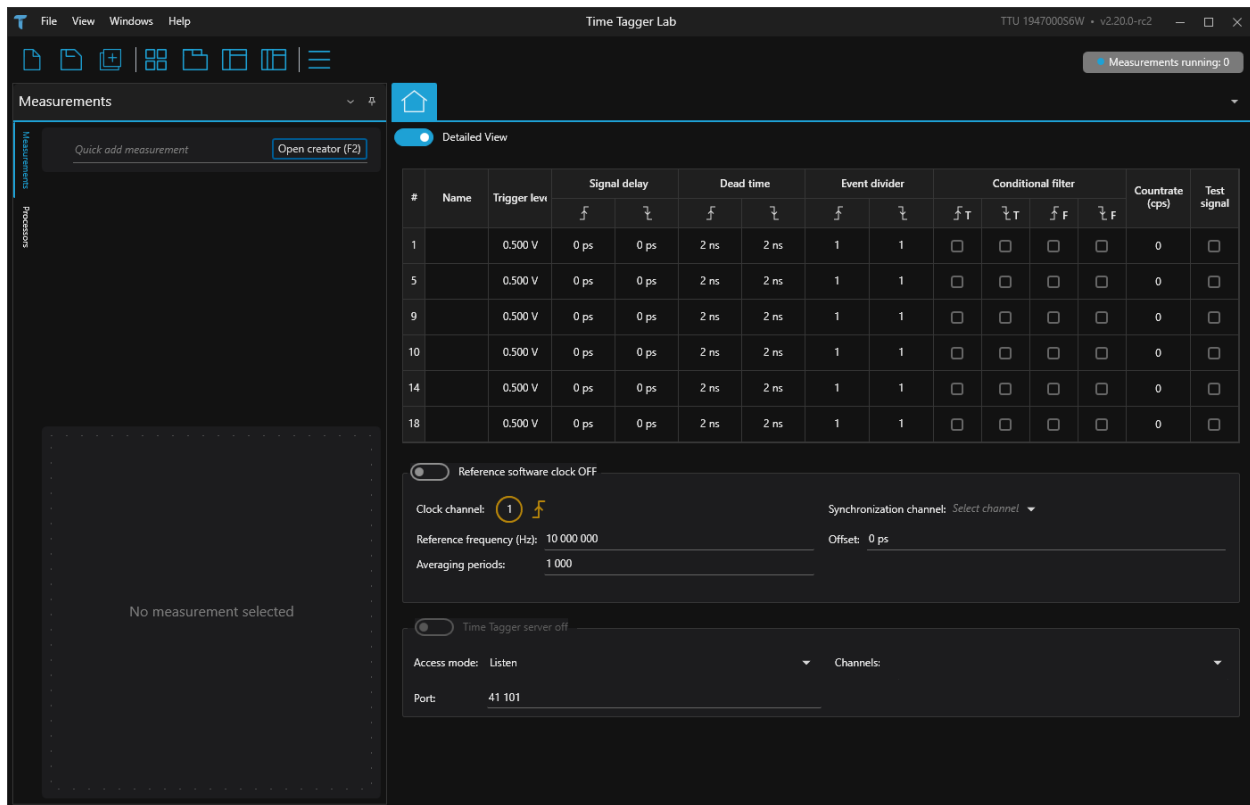
## 1.2.2 Configuring input channels

The first window that is shown is the device view. Here, you see a graphical representation of your Time Tagger with the available channels highlighted. The live count rate and trigger level are shown above and below each input, respectively. The trigger level can be adjusted with a slider that appears when hovering over the value. If you are using a *Synchronizer*, you can cycle through all synchronized Time Taggers using the arrow buttons to the right and left of the device.

Below the device view, you will see status indicators for the reference software clock and the time tagger server. To access detailed options for device settings, and to configure the reference clock and/or server, use the slider in the top left corner to switch to *Detailed View*.



In the detailed view, all channel configurations are listed in a table. Most parameters may be applied separately to rising and falling edges and all channels are treated fully independently of one another. Optionally, channels can be assigned a name to make them easier to identify later. When tuning the channel parameters (e.g. *Trigger level*, *Signal delay*, *Dead time*, *Event divider*, *Conditional filter*), it can be very useful to monitor their influence on the displayed live count rate. These values are shown in a separate column near the right hand side of the table, in counts per second (“cps”, rising edge events only).



## Trigger level

Adjusting the trigger level can help to maximize the signal to noise ratio of your measurement. You can adjust the trigger level in 1 mV increments, see: [setTriggerLevel\(\)](#). The available range of trigger levels depends on the specific Time Tagger model, as listed in the [Hardware](#) section. Often, the trigger level is set around half the maximum amplitude of the signal, as this is where the signal tends to be steepest. Please refer to our [knowledge base article on trigger levels](#) for more details.

## Signal delay

You can add an arbitrary delay to the signal with 1 ps resolution, see: [setInputDelay\(\)](#). The delay may be either positive or negative. This setting can be used to offset or align signals in time at different inputs, e.g. to correct for different cable lengths. For a more detailed discussion on the use of software and hardware delays, please refer to our [knowledge base article on delay compensation](#).

## Dead time

Because the dead time of the Time Tagger is often shorter than that of a detector, undesired signals (e.g. from afterpulsing) may sometimes be acquired as counts. To prevent this, one can modify the dead time to each channel individually, see: [setDeadtime\(\)](#). The default value is the minimum dead time for the Time Tagger device model.

## Event divider

When working with periodic signals with very high repetition rates (e.g. clocks or pulsed lasers), it may be necessary to reduce the rate of tags to prevent [Overflows](#). You can apply an event divider to the signal to divide down the rate of the signal by a factor of  $n$ , see: [setEventDivider\(\)](#).

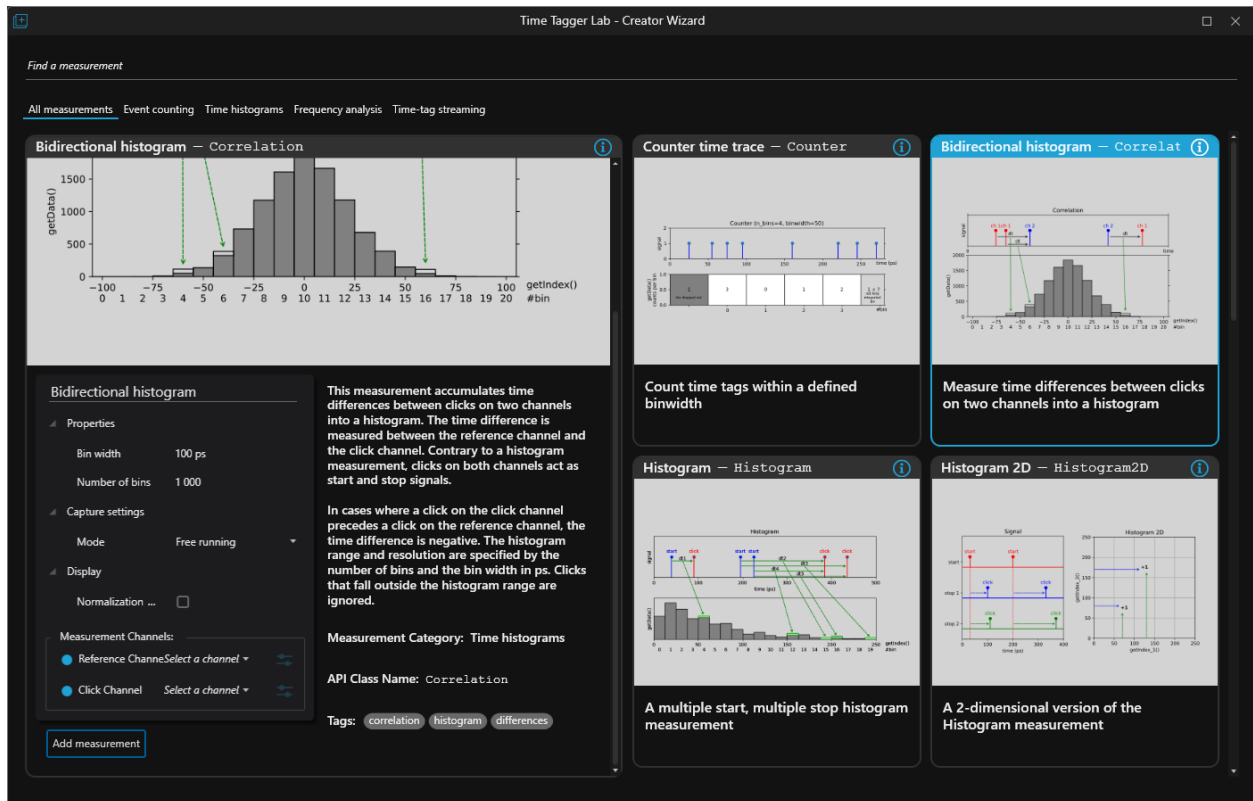


## Conditional filter

The conditional filter can be configured by selecting one or more *triggered* (T) and one or more *filtered* (F) channels, see: `setConditionalFilter()` as well as the in-depth guide [Conditional Filter](#).

### 1.2.3 Performing measurements

Measurements are listed on the left-hand panel of *Time Tagger Lab*. To start a new measurement, either type the name of that measurement in the *Quick add a measurement* box, or open the wizard with the button *Open Creator* or by pressing F2. The creator wizard lists all available measurements together with their descriptions and explanatory figures. For a more detailed description of all supported measurements, please refer to the [Measurement Classes](#) section of the documentation.



In the figure above, a *Bidirectional Histogram* measurement is selected within the creator wizard. This measurement is typically used for performing second order correlation / photon antibunching experiments. After adjusting the input parameters, the measurement can be added with the button *Add measurement*. If any parameter needs to be adjusted later, it can be done easily after the measurement has started and whilst it is running. If the input configuration is incomplete for a valid measurement, a warning will be displayed.

## The measurement view

Once a measurement is added, it will appear as an item in the measurements list and the corresponding chart will appear under a new tab in the main window. The main measurement controls *start*, *stop* and *restart* can be accessed in either location.

By default, measurement charts are organized as a horizontal list of tabs. However, you can freely rearrange them by right-clicking on a tab and choosing *float* or *New Horizontal / Vertical Document Group*. In particular on high-resolution monitors, this allows for displaying many measurements side-by-side with great flexibility.



## Measurements list

The measurements list on the top left shows all configured measurements. Their corresponding charts can be hidden or shown by clicking the 'eye' button. Right-clicking on a measurement opens a menu to clone or delete it.

## Chart view

The chart view on the right is a live display of the measurement data. Usually, it consists of two elements: a main chart above and an auxiliary chart below. Left of the main chart are the measurement controls, as well as zooming, panning, crosshair, data marker and logarithmic axis controls. Zooming is performed by clicking and dragging a box over the chart. Double-click on the chart to revert to automatic zoom limits. The measurement control for exporting data is described in more detail under [Saving measurement data](#).

Clicking on a legend checkbox toggles the visibility of that data series, and right-clicking the legend allows it to be moved to a different corner of the chart.

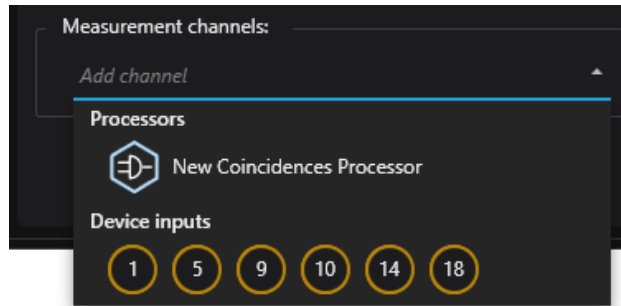
For most measurements, the auxiliary chart displays either the concurrent *Counter* or *FrequencyCounter* measurement of the measured input channels, which can be useful for monitoring purposes. Switch between these two measurements by clicking on the y-axis label of the auxiliary chart.

## Properties

*Time Tagger Lab* allows for on-the-fly changes to the inputs of your measurements in the corresponding properties box in the bottom-left corner of the screen. Changing *Display* properties only affects how the chart displays the data and does not interrupt the measurement. Changing other properties typically causes the measurement to restart, with the new settings in place. The *Capture settings* determine whether the measurement will run for a fixed amount of time (Single), repeatedly for a fixed time (Repeating) or indefinitely (Free running).

### 1.2.4 Processors and virtual channels

*Virtual Channels* have been partially implemented in *Time Tagger Lab* since software version 2.18.0. They are software-defined channels which behave like physical measurement channels, but are created by processors such as *Coincidences*, *Combinations*, *GatedChannel*, *Combiner* or *DelayedChannel*. Processors are created similarly to measurements, the main difference being that their output is not a chart but a (named) virtual channel which can be used as an input for measurements or other virtual channels. The icons used to represent physical channels are numbers within golden circles, whereas processors are represented by white hexagons around a stylized AND gate.



The tab for creating virtual channels is shown on the left-hand side of the screen and can be switched with the measurements tab. If it is convenient to show both the virtual channels and measurements side by side, the view can be switched with the layout buttons in the view menu. After a virtual channel is created, it will be listed under every Select/Add a channel control, alongside the physical input channels.

#### Processor tips and tricks

Processors can be a very powerful tool to analyze your data, but using them may involve complicated configuration interdependencies. To help prevent broken dependencies and other pitfalls, *Time Tagger Lab* restricts some of the choices you can make when creating and deleting processors. When editing the configuration of a processor, any measurements that use its virtual channels as inputs must be paused. In addition, the inputs to that processor may only include virtual channels belonging to previously created processors. When deleting processors or virtual channels, you will receive a warning listing all the dependent processors and measurements whose configuration will change due to the removal of the object.

When configuring multiple *Coincidences* channels with the same coincidence window, it is generally recommended to combine them in the same processor. The reason for this is that the computational performance is much higher than for many single-channel *Coincidences* processors.

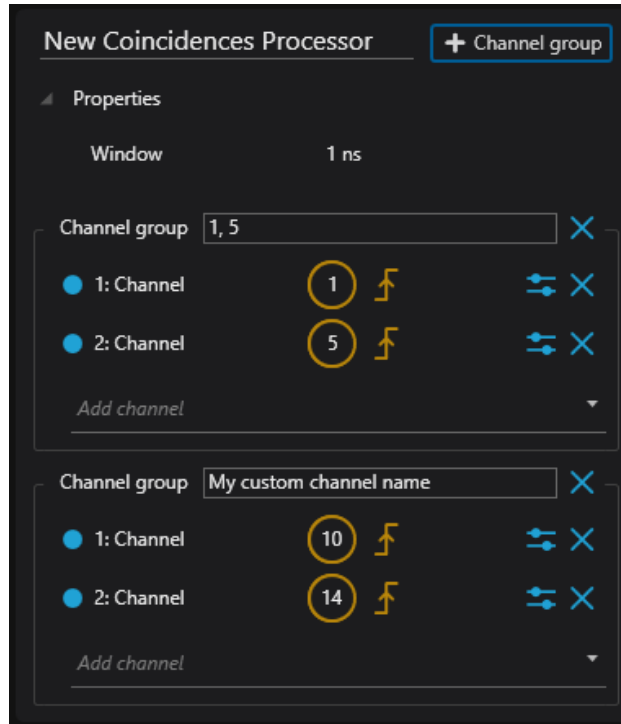
#### Virtual channel naming

All processors must have a unique name, and *Time Tagger Lab* assigns a default one which you may overwrite freely to make it more descriptive. For processors with only a single output, such as *DelayedChannel*, the virtual channel name matches the processor name. For processors with multiple possible outputs, such as *Coincidences* and *Combinations*, each virtual channel must have its own name. Again, *Time Tagger Lab* will assign default names which you are free to change. When selecting these virtual channels as inputs to a measurement or another processor, the channel name is selected from a drop-down menu.

### 1.2.5 Saving measurement data

These are the two ways of saving measurement data to file within *Time Tagger Lab* using the relevant chart control.

#### Note



If you want to save raw time tags to file from *Time Tagger Lab* use a *Time tag file writer* measurement instead, see also: *FileWriter*.

### Export data / trace data

**Export data / trace data** saves either the main or auxiliary chart data series as a tab-separated text file. The first line of the file contains descriptive header data.

### Export chart

**Save chart** as saves the main measurement chart as a PNG image.

## 1.2.6 Reference clock

The reference clock can be configured within the detailed device view. The reference clock provides a powerful software-defined tool to rescale the time base of the measured tags to an external clock. Select the input to be used for the clock channel, input the clock frequency and start and stop the reference clock using the toggle button. The 1PPS Synchronization channel input is an optional setting, which is typically needed for remote synchronization *Remote Synchronization of Time Taggers*.

## 1.2.7 Network server

From the detailed device view, a network server can be configured and enabled. For a detailed discussion of Time Tagger Network, see *The TimeTaggerNetwork class*. Select the appropriate server *AccessMode*: Listen, Control, or SynchronousControl. Start and stop the server using the toggle button.

Reference software clock OFF

Clock channel: 1

Reference frequency (Hz): 10 000 000

Averaging periods: 1 000

Synchronization channel: Select channel ▼

Offset: 0 ps

---

Time Tagger server off

Access mode: Listen ▼ Channels: ▼

Port: 41 101

## 1.2.8 Network client

Network client functionality has been a part of *Time Tagger Lab* since software version 2.20.0. Using this feature, you can use *Time Tagger Lab* to connect to a remote PC hosting a network server. The time tags are streamed from server to client in real time, and the look and feel of the client is very similar to connecting to a local Time Tagger by USB. The network server can be set up using either an instance of *Time Tagger Lab* or any of our supported programming languages, the only limitation is that it should be running in *AccessMode Control*.

Your maximum transfer rate may be lower over the network than over USB alone, depending on the speed and utilization of your network connection. Under ideal conditions, a 1 GBit connection may support up to around 25 MTags/s.

On the left-hand side of the home screen, the **Network Devices** button opens a side panel with an overview of all detected network devices.

☒ Time Tagger Ultra @laptop- office:41101

127.0.0.1 41101 Add

Profile name: My profile

Connect to 1 device

If the server you want to connect to is not automatically detected by the network browser, you can add the IP address manually to the list with the **Add** button. Connect to an available server by selecting the checkbox next to the corresponding Time Tagger and clicking on **Connect to 1 device**. Alternatively, you can create a merged Time Tagger Network object by selecting and connecting to multiple (synchronized) servers, please see *Remote Synchronization of Time Taggers* for more details.

Saving the workspace of a Time Tagger Network instance results in a Network Profile card appearing on the home

screen on next startup. This card contains all the settings associated with your session, in the same way that *Time Tagger Lab* saves your settings after connecting to USB devices. Network Profile cards can be renamed and deleted from the home screen.

### 1.2.9 Troubleshooting

*Time Tagger Lab* has several ways of displaying errors. Typically, these are not critical and a normal part of using the hardware. Understanding error messages helps to troubleshoot possible issues with your measurements.

#### Note

To reach out to Swabian Instruments user support, please contact us at [support@swabianinstruments.com](mailto:support@swabianinstruments.com)

### Overflows

A common error is *Overflows*, which occur when the tag rate is persistently above the hardware limits. For reference, the USB 2.0 interface of the *Time Tagger 20* is capable of 9 MTags/s, and the USB 3.0 interface of the *Time Tagger Ultra* and *Time Tagger X* can perform at 90 MTags/s. However, the actual rate you can achieve also depends on the CPU of the PC the Time Tagger is attached to. For a more detailed discussion of this topic, please refer to our [knowledge base article on rate limits](#).

When running Time Tagger Network, overflows may also occur due to saturation of the network bandwidth.

To avoid overflows, consider the use of *Event divider* or *Conditional filter* to reduce the streamed data rate.

### Log warning messages

*Time Tagger Lab* reports warning messages from the backend engine in the log viewer. Example messages would be a Time Tagger USB disconnection event, or a network client connecting to the local server. If the log viewer is not currently visible, you can open it with the menu item **Show Log Viewer** under **Windows**. Right-clicking anywhere within the log viewer gives the option to clear the log, or to suppress all existing alarms.

## 1.3 Programming Languages

In this section, we show how to interface the Time Tagger and perform measurements using the supported programming environments. The *Time Tagger* API is implemented in C++ and exposed to several higher-level languages via wrapper libraries (Python, MATLAB, LabVIEW, .NET). More details about the software interface are covered by the API documentation in the [Application Programming Interface](#) chapter.

Before you begin, ensure the Time Tagger software is installed; if not, see [Installation Instructions](#). Also make sure your Time Tagger device is connected to your computer and not in use by other applications (e.g., close *Time Tagger Lab*).

### 1.3.1 Python

1. Make sure a Python distribution is available. We provide full support for *actively supported Python versions* <<https://devguide.python.org/versions/>>\_. Older versions, while untested, might still work.
  - On **Unix/Linux** systems, a system-supported installation of Python should already be present.
  - On **Windows** systems, you can install Python by following [these instructions](#). We recommend the default installation (“Install Now”), as it includes all standard libraries and pip.
2. Make sure to install the required Python package (**NumPy**) as well as the recommended ones (**Matplotlib**, and **ipython**).

3. Open a command shell and navigate to the `.\examples\python\1-Quickstart` folder in your *Time Tagger* installation directory.
4. Start an ipython shell with plotting support by entering `ipython --pylab`.
5. Run the *hello\_world* script by entering `run hello_world`.

The *hello\_world* executes a simple yet useful measurement that demonstrates many essential features of the *Time Tagger* programming interface:

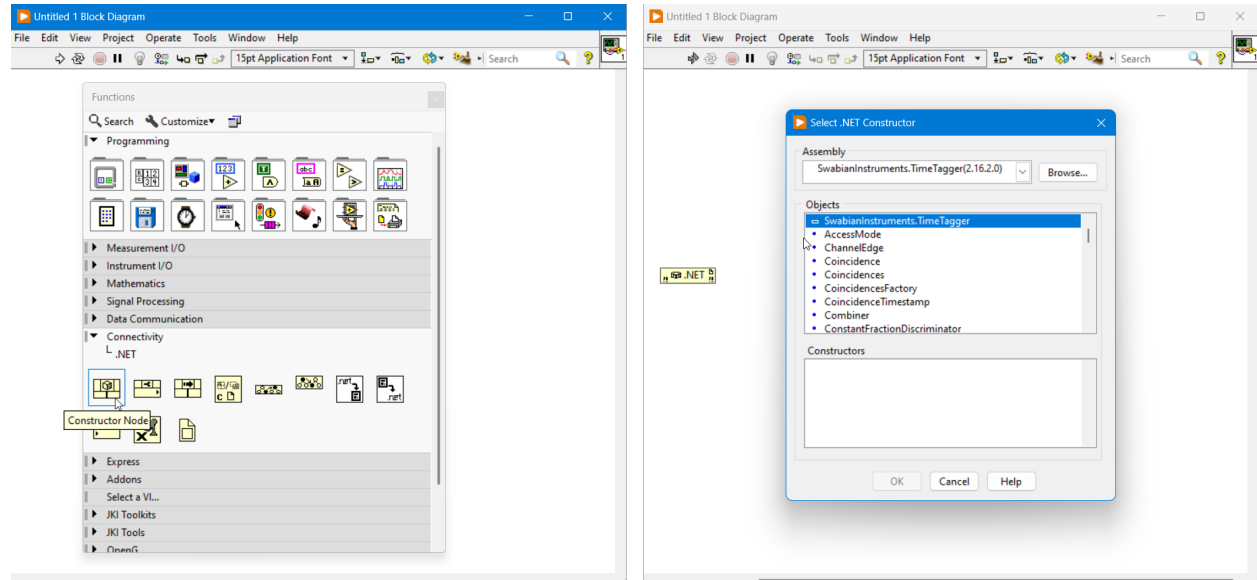
1. Connects your Time Tagger.
2. Starts the built-in test signal (~0.8 MHz square wave) and apply it to channels 1 and 2.
3. Controls the trigger level of your inputs - although it is not necessary here.
4. Initializes a standard measurement (*Correlation*) in order to find the delay of the test signal between channel 1 and 2.
5. Shows how to control the delay of different inputs programmatically.

You are encouraged to open and read the *hello\_world* file in an editor to understand what it does. With this basic knowledge, you can explore the other examples in the 1-Quickstart folder:

| No.                                                                                  | Topic                     | Classes & Methods                                                                                                     |
|--------------------------------------------------------------------------------------|---------------------------|-----------------------------------------------------------------------------------------------------------------------|
| <b>Basic software control</b> (folder <i>1-basic_software_control</i> )              |                           |                                                                                                                       |
| 1-A                                                                                  | Create a measurement      | <i>createTimeTagger()</i> , <i>Counter::getData()</i> , <i>Counter::getIndex()</i>                                    |
|                                                                                      | Count rate trace          | <i>Counter</i>                                                                                                        |
| 1-B                                                                                  | Start & stop measurements | <i>Countrate</i> , <i>start()</i> , <i>stop()</i> , <i>startFor()</i>                                                 |
| 1-C                                                                                  | Synchronize measurements  | <i>SynchronizedMeasurements</i>                                                                                       |
|                                                                                      | Use different histograms  | <i>Correlation</i> , <i>Histogram</i> , <i>StartStop</i> , <i>HistogramLogBins</i>                                    |
| 1-D                                                                                  | Virtual Channels          | <i>DelayedChannel</i> , <i>Coincidence</i> , <i>GatedChannel</i>                                                      |
| 1-E                                                                                  | Logging errors            | <i>setLogger()</i>                                                                                                    |
| 1-F                                                                                  | External reference clock  | <i>TimeTaggerSource::setReferenceClock()</i> , <i>FrequencyStability</i>                                              |
| <b>Controlling the hardware</b> (folder <i>2-controlling-the-hardware</i> )          |                           |                                                                                                                       |
| 2-A                                                                                  | Get hardware information  | <i>scanTimeTagger()</i> , <i>getSerial()</i> , <i>getModel()</i> , <i>getSensorData()</i> , <i>getConfiguration()</i> |
| 2-B                                                                                  | The input trigger level   | <i>setTriggerLevel()</i> , <i>getTriggerLevelRange()</i>                                                              |
| 2-C                                                                                  | Filter tags on hardware   | <i>setConditionalFilter()</i> , <i>setEventDivider()</i>                                                              |
| 2-D                                                                                  | Control input delays      | <i>setInputDelay()</i> , <i>Histogram2D</i>                                                                           |
| 2-E                                                                                  | Overflows                 | <i>getOverflows()</i> , <i>setTestSignalDivider()</i>                                                                 |
| 2-F                                                                                  | HighRes mode              | <i>createTimeTagger()</i> , <i>TimeDifferences</i>                                                                    |
| <b>Dump and re-analyze time-tags</b> (folder <i>3-dump-and-reanalyze-time-tags</i> ) |                           |                                                                                                                       |
| 3-A                                                                                  | Dump tags by FileWriter   | <i>FileWriter</i>                                                                                                     |
| 3-B                                                                                  | The Time Tagger Virtual   | <i>createTimeTaggerVirtual()</i> , <i>TimeTaggerVirtual</i>                                                           |
| <b>Working with raw time-tags</b> (folder <i>4-working-with-raw-time-tags</i> )      |                           |                                                                                                                       |
| 4-A                                                                                  | The FileReader            | <i>FileReader</i> , <i>TimeTagStreamBuffer</i>                                                                        |
| 4-B                                                                                  | Streaming raw time-tags   | <i>TimeTagStream</i>                                                                                                  |
| 4-C                                                                                  | Custom Measurements       | <i>CustomMeasurement</i>                                                                                              |

### 1.3.2 LabVIEW (via .NET)

In LabVIEW, you can access and program your Time Tagger through .NET interoperability.



A set of examples is provided in `.\examples\LabVIEW\` for LabVIEW 2014 and higher (32 and 64 bit).

### 1.3.3 MATLAB (wrapper for .NET)

Wrapper classes are also provided for MATLAB. The *Time Tagger* toolbox is automatically installed during the setup. If the *TimeTagger* is not available in your MATLAB environment try to reinstall the toolbox from `.\driver\Matlab\TimeTaggerMatlab.mltbx`.

The following changes in respect to the .NET library have been made:

- Static functions are available through the *TimeTagger* class.
- All classes except for *TimeTagger*, *TimeTaggerNetwork*, and *TimeTaggerVirtual* have a TT prefix (e.g. *TTCounterRate*) to prevent conflict with any variables/classes in your MATLAB environment.

Several examples demonstrating how to use the Time Tagger with MATLAB are provided in the `.\examples\Matlab\` folder. The 1-Quickstart directory has the same structure of the Python one (see Table above). These examples cover core topics such as basic measurements, hardware control, and postprocessing, providing a one-to-one correspondence between MATLAB and Python usage.

### 1.3.4 .NET

We provide a .NET class library (32, 64 bit and CIL) which can be used to access the TimeTagger from many high-level languages. Please consider the following notes:

- Namespace: `SwabianInstruments.TimeTagger`.
- The corresponding library `.\driver\xxx\SwabianInstruments.TimeTagger.dll` is registered in the Global Assembly Cache (GAC).
- Static functions (e.g. to create an instance of a *TimeTagger*) are accessible via `SwabianInstruments.TimeTagger.TT`.



### 1.3.5 C#

A sample Visual Studio C# project provided in the `.\examples\csharp\Quickstart` directory covers the basics of how to use the Time Tagger .NET API. An example of creating a custom measurement is also included.

Please copy the project folder to a directory within the user environment such that files can be written within the directory.

An example suite is provided in the `.\examples\csharp\ExampleSuite` directory. *ExampleSuite* is an interactive application that demonstrates various measurements that can be performed with the Time Tagger. Reference source code to setup and plot (with OxyPlot) each measurement is also provided within the application. Additionally, the application contains examples for creating and using *Virtual channels*, *Filtering* and *Accessing the raw time tags*.

#### Note

Running the Example Suite requires '.NET Core 3.1 Desktop Runtime (v3.1.10)'.

### 1.3.6 C++

The provided Visual Studio C++ project can be found in `.\examples\cpp\`. Using the C++ interface supports writing custom measurement classes with no overhead.

#### Note

- the C++ headers are stored in the `.\driver\include\` folder.
- the final assembly must link `.\driver\xYZ\TimeTagger.lib`.
- the library `.\driver\xYZ\TimeTagger.dll` is linked with the shared v142 or newer Visual Studio runtime (`/MD`).
- use `TimeTaggerD.lib` and `TimeTaggerD.dll` for the Visual Studio debug runtime (`/MDd`).
- use `libTimeTagger.dll` and `libTimeTagger.a` for the MinGW C++ ABI for the [MINGW32 and UCRT64 environment](#).

### Debug and Release Builds

The choice of build type can have a great effect on the code performance. In Visual Studio, the default compiler flags for Debug builds are `/MDd`, `/O0`, and `/Zi`. For Release builds these are `/MD`, `/O2`, and `/DNDEBUG`. It is crucial that you understand these flags and their implications on performance.

- **/O0 vs /O2**

This flag controls the general optimization level. `/O0` means no optimization, so every instruction is surrounded by `load_from_memory` and `store_to_memory`. This is a significant waste of CPU resources, but guarantees that every local variable can be inspected at all times. We suggest the use of the default optimization level `/O2` and to overwrite it only for required methods using pragmas (see the [MSVC optimize pragma](#)).

- **/MDd vs /MD**

This flag selects which (incompatible) runtime C++ ABI you want to use for the whole project. The debug runtime `/MDd` has additional fields and checks for e.g. better range checking. It is good practice to run your code with them at least once before each commit. As they are incompatible with each other, **all linked C++ libraries must use the same runtime**. This flag is the only difference between our debug `TimeTaggerD.dll` and non-debug `TimeTagger.dll` library. We suggest using `/MD` even for debug builds, otherwise the debug runtime will incur significant performance costs, including in the internals of the Time Tagger library.

- **/Zi**

This flag tells the compiler to generate a \*.pdb symbol file. This is used by the debugger to map e.g. the assembly to the C++ code and the stack to the local variable. As this has no performance overhead, we recommend using this flag for all internal builds.

- **/DNDEBUG**

The macro NDEBUG is the C way to disable assert(). Asserts are usually good at catching logic errors without much overhead.

The relevant choice is thus not whether to build using Debug or Release, but rather which set of flags to use. Please select each of them carefully based on your target.

## Code Sanitizers

We recommend the use of code sanitizers. Switching your Visual Studio compiler to CLANG allows you to use its undefined behavior, address, and thread sanitizers. Microsoft has also recently announced the MSVC compiler now ships with an address sanitizer, which finds out-of-bounds accesses, use-after-free and similar issues. Please consult the documentation for the [AddressSanitizer \(ASan\)](#) for [Windows with MSVC](#).

## 1.4 Hardware License Upgrades

The *Time Tagger Ultra* and *Time Tagger X* have a hardware license that can be upgraded to activate additional channels and features. To upgrade your license, please get in touch with [sales@swabianinstruments.com](mailto:sales@swabianinstruments.com). After purchasing a license upgrade, the new license becomes available within a few minutes. You can install your new license using *Time Tagger Lab* or via the Time Tagger API using the provided Python example.

Hardware license upgrades can be permanent or temporary. A permanent license has no expiration date, while a temporary license activates additional features until a set expiration date. The Time Tagger has two on-board license slots and can hold one license of each type at the same time.

The Time Tagger applies whichever stored license is currently valid and has the most recent issue date (the date the license was created, not flashed to the device). A temporary license is valid only until its expiration date. Once it expires, the Time Tagger falls back to the permanent license, if any.

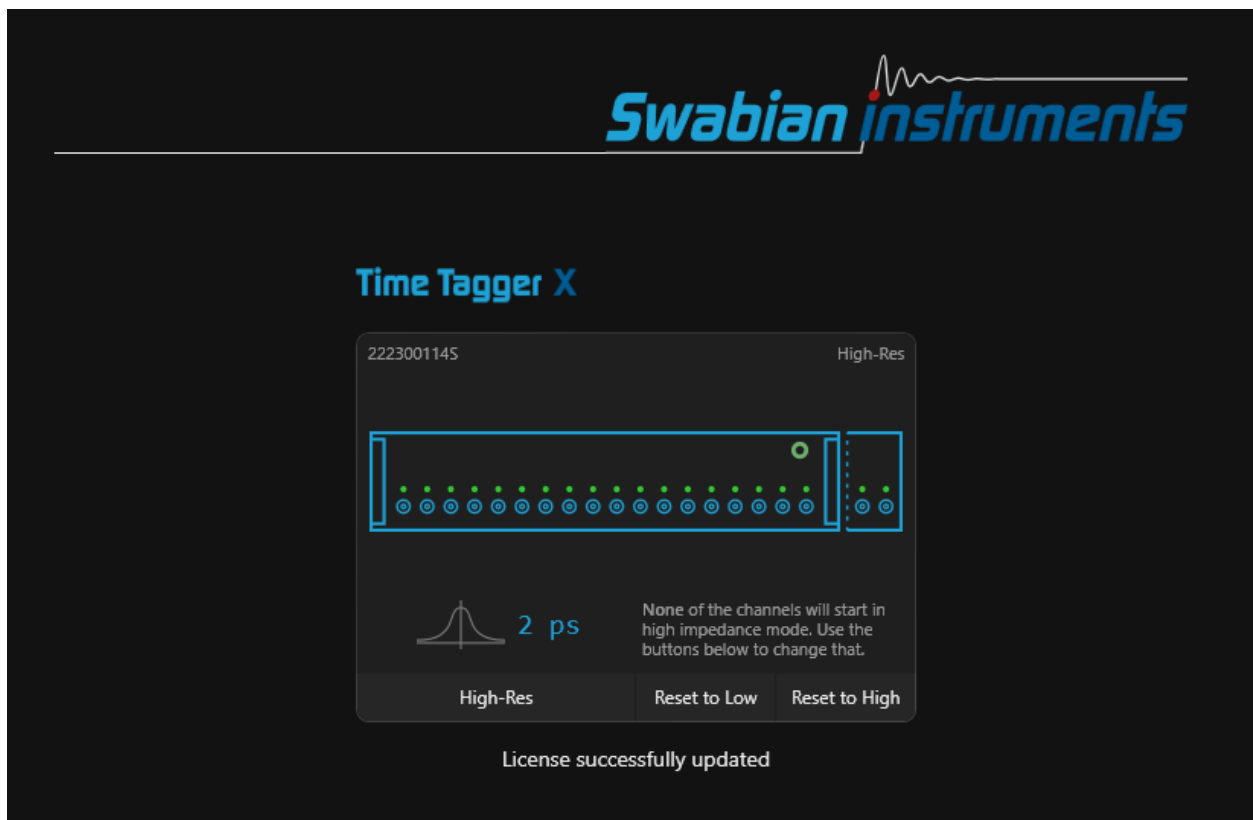
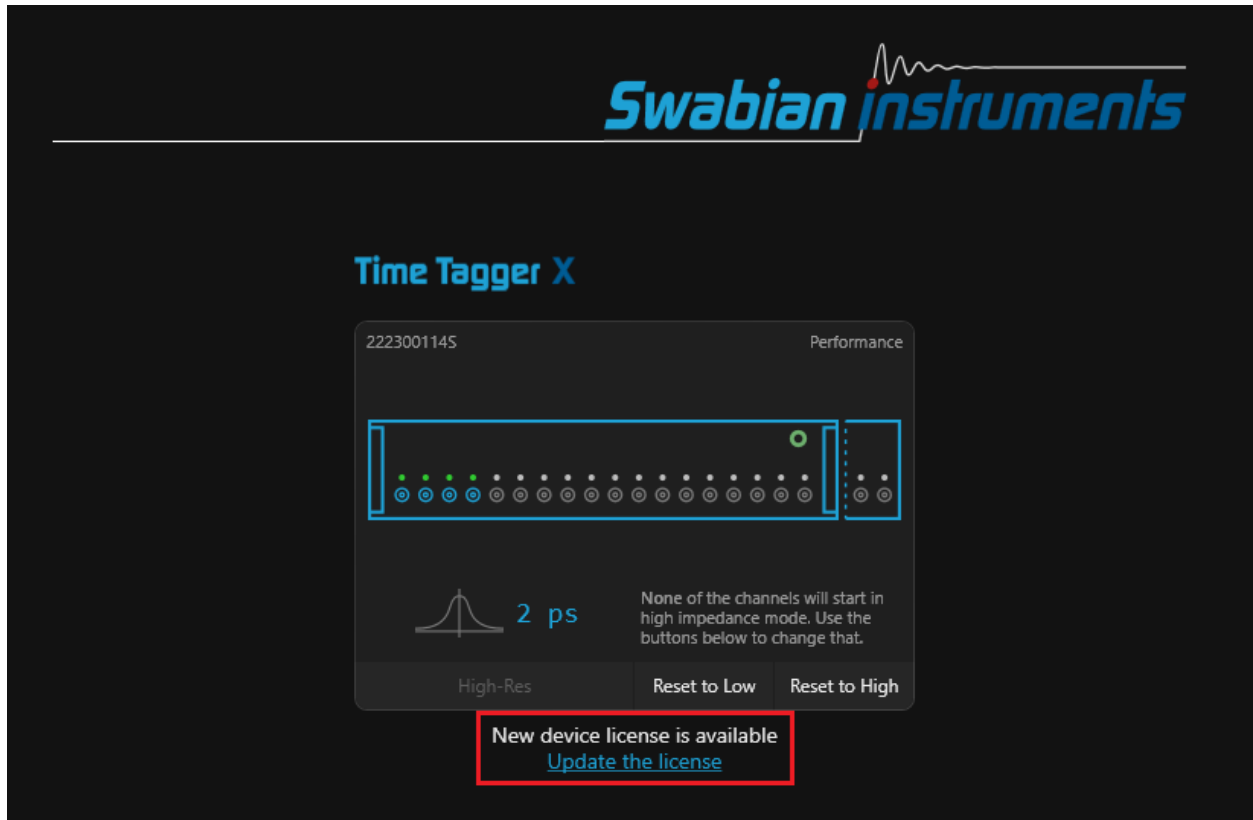
An active internet connection is needed once to fetch and apply a permanent license upgrade. A temporary license additionally requires a connection each time the Time Tagger is initialized, so that its expiration can be verified. If no connection is available, the temporary license is treated as not valid and the Time Tagger applies the permanent license, if any.

### 1.4.1 Time Tagger Lab

1. Connect the Time Tagger to your PC.
2. Start *Time Tagger Lab*.
3. If a new license is available, you will see the following:
4. Click on “Update the license”. The new license will be applied immediately and you will see:

#### Note

It is currently not possible to update the hardware licenses of Time Taggers that are connected to a [Synchronizer](#) using *Time Tagger Lab*. To perform a license update, power off the Synchronizer first by unplugging its power



supply. Then, the Time Taggers will be listed one-by-one and their licenses can be upgraded as described in the following section.

### 1.4.2 Python

A dedicated Python example `hardware_license_update.py` is included with the Time Tagger installation. The default path for the examples is `/usr/share/timetagger/examples/python/` and `C:\Program Files\Swabian Instruments\Time Tagger\examples\python\10-Hardware-License-Upgrades` for Linux and Windows, respectively.

The example connects to the Time Tagger, retrieves the current license information with `getDeviceLicense()`, and fetches any available updates from the Swabian Instruments license server with `fetchDeviceLicenseUpdate()`. For each physical device in a possibly synchronized setup, it prints the current license and the new available configuration, distinguishing between permanent features and temporary features with their expiration date. The user is then prompted to confirm before the Time Tagger connection is released and the new license is flashed onto the device with `flashLicense()`.

## 1.5 Usage Statistics Collection

You can help us developing and improving the Time Tagger by enabling automated usage statistics collection. The usage statistics data collection is designed to help us better understand how the Time Tagger hardware and software are used. This data includes the performance indicators, configuration, the state of the Time Tagger, and API (Application Programming Interface) usage patterns.

The usage statistics data is pseudonymized<sup>1</sup> and cannot be linked to a specific user or specific hardware unit. On installation of the Time Tagger software, a random `user_id` will be created and added to the usage statistics reports. Users can review the contents of usage statistics data by using the `getUsageStatisticsReport()`. Also users can disable usage statistics data collection at any time via Time Tagger API as `setUsageStatisticsStatus(UsageStatisticsStatus.Disabled)`. It is possible to enable the usage statistics collection temporarily and without automatic uploading which may be helpful for debugging.

### 1.5.1 Contents of the usage statistics data

- Internal calibration data.
- Hardware sensor data obtainable with `getSensorData()` but with the serial number obscured.
- Time Tagger's configuration as returned by `getConfiguration()` but with the serial number obscured.
- All warning and error messages produced by the Time Tagger software. All identifying information like serial numbers is obscured.
- Average, minimal, and maximal aggregate data rate sent over USB in each usage session.
- Usage and configuration of the measurements and their performance indicators.
- Computer's processor name and capabilities, as well as the RAM size.

### 1.5.2 Ways of control

During software installation on Windows, you will be asked whether you want to join the Time Tagger improvement program. On Linux, usage statistics collection is disabled by default, and no explicit choice is requested during installation. You can enable, disable, or modify the usage statistics behavior at any later time using the programming interface (see below). Alternatively, on Windows, you can also change your decision by re-installing the Time Tagger software.

---

<sup>1</sup> Here “pseudonymized” means that the user retains privacy of their data and remain unidentified as long as their `user_id` (pseudonym) is not matched to their personal identity.

The following examples show how to perform key operations of enabling, disabling, and retrieving the usage statistics data. See also *Usage statistics functions*.

#### Get and set usage statistics collection status

```
# 0 - UsageStatisticsStatus.Disabled
# 1 - UsageStatisticsStatus.Collecting
# 2 - UsageStatisticsStatus.CollectingAndUploading
status = getUsageStatisticsStatus()

# Enable usage statistics collection without uploading
setUsageStatisticsStatus(UsageStatisticsStatus.Collecting)

# Enable usage statistics collection with uploading
setUsageStatisticsStatus(UsageStatisticsStatus.CollectingAndUploading)

# Disable usage statistics collection
setUsageStatisticsStatus(UsageStatisticsStatus.Disabled)
```

#### Get current usage statistics data

```
json_string = getUsageStatisticsReport()
```

### 1.5.3 Time Tagger Lab diagnostics

When *Time Tagger Lab* is used, it can automatically send application error reports and related diagnostics (later: “application error diagnostics”), as described in the EULA. Users can enable/disable sending application error diagnostics and sending Time Tagger usage statistics independently. By default sending application error diagnostics is enabled when sending usage data is enabled.



## HARDWARE

### 2.1 Operating conditions

Before installing and operating the Time Tagger, users are strongly advised to follow the guidelines for proper handling. For detailed information on the operating conditions of the Time Tagger, please consult the section *Safety & Compliance*.

### 2.2 Input channels

The Time Tagger has 8, 18, or 20 inputs (SMA-connectors) for *Time Tagger 20*, *Time Tagger Ultra*, or *Time Tagger X*, respectively. The electrical characteristics are tabulated below. Each input can detect both, rising and falling edges of an input pulse, and each input has two channels associated with it. Rising edges correspond to channel numbers 1 to 8, 18, or 20 for *Time Tagger 20*, *Time Tagger Ultra*, or *Time Tagger X*, respectively; and falling edges correspond to respective channel numbers -1 to -8, -18, or -20 for *Time Tagger 20*, *Time Tagger Ultra*, or *Time Tagger X*, respectively. Thereby, you can treat rising and falling edges in a fully equivalent fashion.

**Note**

Time Taggers delivered before mid-2018 were labeled using a legacy 0-based channel numbering scheme. The table below shows the legacy channel numbering scheme used by software versions up to v2.21.x. It is kept here as a reference for users interpreting older hardware labels or maintaining older code. Starting with v2.22.0, only the default 1-based scheme is supported, with rising edges numbered from 1 to  $N$  and falling edges from -1 to  $-N$ . Users upgrading to v2.22.0 or later should update their code accordingly.

|          | Time Tagger 20 / Ultra 8 |          | Time Tagger Ultra 18 |           |
|----------|--------------------------|----------|----------------------|-----------|
|          | rising                   | falling  | rising               | falling   |
| previous | 0 to 7                   | 8 to 15  | 0 to 17              | 18 to 35  |
| current  | 1 to 8                   | -1 to -8 | 1 to 18              | -1 to -18 |

## 2.2.1 Electrical characteristics

| Property                          | <i>Time Tagger 20</i> | <i>Time Tagger Ultra</i> | <i>Time Tagger X</i> |
|-----------------------------------|-----------------------|--------------------------|----------------------|
| Termination                       | 50 Ohm                | 50 Ohm                   | 50 Ohm / High-Z      |
| Input voltage range (recommended) | 0.0 to 3.0 V          | -3.0 to 3.0 V            | -1.5 to 1.5 V        |
| Maximum input (no damage)         | -0.3 to 5.0 V         | -5.0 to 5.0 V            | -3.0 to 3.0 V        |
| Trigger level range               | 0.0 to 2.5 V          | -2.5 to 2.5 V            | -1 to 1 V            |
| Minimum signal level              | 100 mV                | 100 mV                   | 100 mV               |
| Minimum pulse width               | 1.0 ns                | 0.5 ns                   | 350 ps               |

## 2.2.2 Configurable input termination - Time Tagger X only

The input termination of the *Time Tagger X* is configurable during runtime to either 50 Ohm or High-Z (see [`setInputImpedanceHigh\(\)`](#)). Usually 50 Ohm should be chosen to accomplish proper HF termination, but High-Z is useful in certain use cases with small amplitudes and weak output drivers.

**Caution**

When the *Time Tagger X* is unpowered or not configured (before [`createTimeTagger\(\)`](#) has been called), the input termination is High-Z. This is to protect the *Time Tagger's* input stage from potentially damaging operating conditions (e.g. signals into an unpowered input stage). Since software v2.17.0, the termination does not switch to 50 Ohm upon initialization anymore. However, the channel will switch to 50 Ohm by default as soon as it is registered. To prohibit this switching behavior, set the impedance explicitly to High-Z by [`setInputImpedanceHigh\(\)`](#) before the first usage of the respective input, e.g. in a measurement.

One of the following measures can be taken when connecting signal sources to the *Time Tagger X* which are sensitive to operation without termination:

- The signal source is only operated after the *Time Tagger X* is powered and configured properly. The *Time Tagger's* input termination is set to 50 Ohm.
- An external 50 Ohm termination is connected between SMA cable and the *Time Tagger's* input port. The *Time Tagger's* input termination is set to High-Z.
- An HF circulator or isolator is connected to the output of the signal source to prevent any potentially damaging reflections from getting into the output.



### 2.2.3 High Resolution Mode

The *Time Tagger Ultra Performance* and the *Time Tagger X* can operate in different High Resolution (HighRes) modes. An increased resolution is achieved by directing the signal from a single input to multiple time-to-digital converters (TDCs). Depending on the mode, 2, 4, or 8 TDCs are used per input. By averaging the results, a single timestamp with lower jitter is generated. On the other hand, this process reduces the number of usable signal inputs.

The tables show the usable inputs for the different modes. Channels available with the minimal four-channel license are shown without parenthesis. When additional channels are added, the priority will be given to the HighRes ones.

Table 1: Time Tagger Ultra Performance

| Mode     | HighRes channels             | Standard channels |
|----------|------------------------------|-------------------|
| Standard |                              | 1 - 4, (5 - 18)   |
| HighResA | 1, 3, 5, 7, (10, 12, 14, 16) | (9, 18)           |
| HighResB | 1, 5, 10, 14                 | (9, 18)           |
| HighResC | 5, 14                        | 9, 18             |

Table 2: Time Tagger X

| Mode     | HighRes channels  | Standard channels |
|----------|-------------------|-------------------|
| Standard |                   | 1 - 4, (5 - 20)   |
| HighResB | 1, 5, 9, 13, (17) |                   |

#### Note

As a result of the averaging process, the quality of the calculated timestamps is affected by relative changes in the internal delays of the contributing inputs. These delays are especially affected by the device's temperature. It is strongly recommended to let the device heat up for at least 10 s before starting a measurement. Constant average count rates (averaged over the timescale of hundreds of milliseconds) will provide the best results. If you need more information on this topic, please contact us via [support@swabianinstruments.com](mailto:support@swabianinstruments.com).

## 2.3 Data connection

The *Time Tagger 20* is powered via a USB connection. Therefore, you should ensure that the USB port is capable of providing the full specified current (500 mA). A USB  $\geq$  2.0 data connection is required for the performance specified here. Operating the device via a USB hub is strongly discouraged. The *Time Tagger 20* can stream about 9 MTags/s.

The *Time Tagger Ultra* and *Time Tagger X* has a USB 3.0 interface. This allows to stream up to 90 MTags/s to the PC. The actual number highly depends on the performance of the CPU the Time Tagger is connected to and the evaluation methods involved.

In addition, the *Time Tagger X* is equipped with both an SFP+ Port (10 GbE) and a QSFP+ port (40 GbE) which can be used for streaming up to 300 MTags/s or 1200 MTags/s respectively.

## 2.4 Calibration

The Time Tagger devices do not use a static, factory calibration. Each input channel is continuously self-calibrated from the most recent, naturally occurring events, assuming those events are not phase-locked or otherwise correlated to the instrument's time base. The self-calibration refreshes multiple times per second and tracks temperature-dependent delay variations in the FPGA delay lines. *Time Tagger 20* does not have a hardware CLK input enabled by design, so

the assumption above is always satisfied. For *Time Tagger Ultra* and *Time Tagger X*, which provide a hardware CLK input, ensure that the signals under investigation are not correlated to the active hardware reference. If you need to analyze signals locked to your external reference (e.g., monitor 1 PPS while using a 10 MHz locked clock), feed the reference into a regular input channel and enable the software PLL via `setReferenceClock()`. See the *In Depth Guide: Software-Defined Reference Clock* for details. For programmatic checks, `autoCalibration()` reports per-channel jitter.

## 2.5 LEDs

The Time Tagger devices have LEDs showing status information.

### 2.5.1 Time Tagger X

#### Front panel and power button

On its front panel, the *Time Tagger X* has an LED inside the power button and individual channel status LEDs:

Table 3: Power button LED

| Color  | Description                                   |
|--------|-----------------------------------------------|
| blue   | Device in standby, press button to turn it on |
| green  | Device running                                |
| orange | Device is getting ready                       |
| red    | An error occurred                             |

Table 4: Channel LEDs

| Color          | Description                                                                 |
|----------------|-----------------------------------------------------------------------------|
| dark           | Channel unavailable (according to your license)                             |
| blue           | Channel available but not used by a measurement                             |
| solid green    | Measurement running but no data within last 2 s                             |
| blinking green | Time tags are streamed to the PC.<br>Blinking frequency indicates data rate |
| solid orange   | Overflow                                                                    |
| solid red      | Error                                                                       |

#### Rear panel

Table 5: LED next to the *CLK IN* input

| Color       | Description                              |
|-------------|------------------------------------------|
| dark        | No clock signal                          |
| solid green | Valid reference or synchronization clock |
| solid red   | Invalid reference frequency              |
| solid blue  | Ext. clock valid, but not in use         |

Table 6: LED next to the *SYNC IN* input

| Color           | Description                         |
|-----------------|-------------------------------------|
| dark            | No synchronizer on <i>CLK</i> input |
| green or yellow | Valid signal at <i>SYNC IN</i>      |
| red             | Invalid signal at <i>SYNC IN</i>    |

Table 7: LED next to the *LOOP IN* input

| Color | Description                         |
|-------|-------------------------------------|
| dark  | No synchronizer on <i>CLK</i> input |
| green | Valid signal at <i>LOOP IN</i>      |
| red   | Invalid signal at <i>LOOP IN</i>    |

## 2.5.2 Time Tagger Ultra

The “Power” LED turns green when the power is supplied to the device.

Table 8: Status LED

| Color          | Description                                                                                                           |
|----------------|-----------------------------------------------------------------------------------------------------------------------|
| solid green    | Firmware loaded                                                                                                       |
| blinking green | Time tags are streaming                                                                                               |
| solid orange   | Overflows occurred.<br>LED turns orange for 0.3 s on overflow events.<br>Solid orange indicates continuous overflows. |
| solid red      | Device initialization failed<br>(check USB connection)                                                                |

Table 9: LED next to the *CLK* input

| Color                            | Description                                          |
|----------------------------------|------------------------------------------------------|
| dark                             | No clock signal                                      |
| solid green                      | Valid reference or synchronization clock             |
| solid red                        | Invalid reference frequency                          |
| solid blue                       | Ext. clock valid, but not in use                     |
| fast blinking red                | Calibration error on at least one channel            |
| blinking red (hardware <v1.5)    | Invalid signal at <i>SYNC IN</i> ( <i>AUX IN 1</i> ) |
| blinking yellow (hardware <v1.5) | Invalid signal at <i>LOOP IN</i> ( <i>AUX IN 2</i> ) |

Table 10: LED next to the *SYNC IN* input (hardware >=v1.5)

| Color | Description                         |
|-------|-------------------------------------|
| dark  | No synchronizer on <i>CLK</i> input |
| green | Valid signal at <i>SYNC IN</i>      |
| red   | Invalid signal at <i>SYNC IN</i>    |

Table 11: LED next to the *LOOP IN* input (hardware  $\geq$ v1.5)

| Color | Description                         |
|-------|-------------------------------------|
| dark  | No synchronizer on <i>CLK</i> input |
| green | Valid signal at <i>LOOP IN</i>      |
| red   | Invalid signal at <i>LOOP IN</i>    |

### 2.5.3 Time Tagger 20

The “Power” LED turns green when the power is supplied to the device.

Table 12: Status LED

| Color                 | Description                                                                                                          |
|-----------------------|----------------------------------------------------------------------------------------------------------------------|
| solid green           | Firmware loaded                                                                                                      |
| blinking green-orange | Time tags are streaming                                                                                              |
| red                   | Overflows occurred.<br>LED turns red for 0.1 s on every overflow event.<br>Solid red indicates continuous overflows. |
| solid blue            | Device initialization failed<br>(check USB connection)                                                               |

## 2.6 Test signal

The Time Tagger has a built-in test signal generator that generates a square wave with a frequency in the range 0.8 to 1.0 MHz. You can apply the test signal to any input channel instead of an external input. This is especially useful for testing, calibrating and setting up the Time Tagger initially. The *Time Tagger X* also provides the opportunity to put out two square wave signals with a variable frequency via the AUX Out ports on the back of the device.

## 2.7 Synthetic input delay

You can introduce an input delay for each channel independently. This is useful if the relative timing between two channels is important, e.g., to compensate for propagation delay in cables of unequal length. The input delay can be set individually for rising and for falling edges.

## 2.8 Synthetic dead time

You can introduce a synthetic dead time for each channel independently. This is useful when you want to suppress consecutive clicks that are closely separated, e.g., to suppress after-pulsing of avalanche photodiodes or as a simple way of data rate reduction. The dead time can be set individually for rising and for falling edges in each channel.

## 2.9 Event divider

You can introduce an event divider for each channel independently. This is useful to discard a given number of time tags before the next one is stored, e.g., to reduce the data transfer rate requirement at expense of the data accumulation efficiency. The event divider can be set individually for rising and for falling edges.

## 2.10 Conditional Filter

The Conditional Filter allows you to decrease the time tag rate without losing those time tags that are relevant to your application, for instance, where you have a high-frequency signal applied to at least one channel. Examples include fluorescence lifetime measurements or optical quantum information and cryptography, where you want to capture synchronization clicks from a high repetition rate excitation laser.

To reduce the data rate, you discard all synchronization clicks, except those that follow after one of your low rate detector clicks, thereby forming a reduced time tag stream. The software processes the reduced time tag stream in the exact same fashion as the full time tag stream.

This feature is enabled by the Conditional Filter. As all channels on your *Time Tagger* are fully equivalent, you can specify which channels are filtered and which channels are used as triggers that enable the transmission of a subsequent tag on the filtered channels.

### Note

In *Time Tagger 20*, the software-defined input delays, as set by the method `setInputDelay()`, do not apply to the Conditional Filter logic.

More details and explanations can be found in the *In Depth Guide: Conditional Filter*.

## 2.11 Bin equilibration

The discretization of electrical signals is never perfect. In time-to-digital conversion, this manifests as small differences (few ps) in the bin sizes inside the converter that even varies from chip to chip. This imperfection is inherent to any time-to-digital conversion hardware. It is usually not apparent to the user. However, when correlations between two channels are measured on short time scales, you might see this as a weak periodic ripple on top of your signal. We reduce the effect of this in the software at the cost of a decrease in the time resolution by  $\sqrt{2}$ . This feature is enabled by default. If your application requires time resolution down to the jitter limit, you can disable this feature.

## 2.12 Overflows

The *Time Tagger 20* is capable of continuous streaming of about 9 MTags/s. For the *Time Tagger Ultra* and *Time Tagger X*, continuous tags streamed can exceed 90 MTags/s, depending on the CPU of the PC the Time Tagger is attached to. Higher data rates for short times are buffered internally, so that no overflow occurs. If continuous higher data rates persist, the internal buffer gets completely filled. Therefore, some of the time tags are discarded and not transferred to the PC, resulting in data loss. The hardware allows you to check with `TimeTaggerSource::getOverflows()` whether an overflow condition has occurred. If no overflow is returned, you can be confident that every time tag is received.

### Note

When overflows occur, *Time Tagger* will still produce valid data blocks and discard the invalid tags in between. Your measurement data may still be valid, although your acquisition time will likely increase.

## 2.13 External Clock Input

**Note**

An alternative and more flexible way to apply an external clock signal is the use of `TimeTaggerSource::setReferenceClock()`. Since software v2.10, the software clock is recommended for applying an external clock.

**Time Tagger X and Time Tagger Ultra**

The external clock input can be used to synchronize different Time Tagger devices. The input clock frequency must be 10 or 500 MHz. The *CLK* input requires between 100 mVpp and 4 Vpp AC coupled into 50 Ohm, 500 mVpp is recommended. The lock status can be read off the LED color: If the *CLK* LED shines green, the *Time Tagger* is locked and uses the provided clock. If the LED is blue, a valid frequency is supplied, however, the Time Tagger is still configured to use the internal clocking source. In case of a wrong or unstable frequency, the LED will shine red. A 500 MHz *CLK* input without a Synchronizer will lead to red LEDs on *LOOP IN* and *SYNC IN*. Yet, the Time Tagger will still work normally and the LEDs can be ignored in this case.

External clock signal requirements:

The input clock signal must have a very low jitter to provide the specified performance of the *Time Tagger*. Please note that the timing specifications for the *Time Tagger Ultra* with respect to other devices on the same clock are only met from hardware version 2.3 and later.

**Caution**

In order to reach the specified input jitter for the Time Tagger with an external clock, the input signals must be uncorrelated to the external clock. This restriction does not exist for `setReferenceClock()`.

**Time Tagger 20**

The *Time Tagger 20* supports software clock feature only.

## 2.14 Synchronization signals

**Time Tagger X and Time Tagger Ultra**

Up to 8 *Time Tagger Ultra* and/or *Time Tagger X* units can be synchronized in such a way that they behave like a unified Time Tagger. This requires additional hardware, the Swabian Synchronizer. The Synchronizer uses the additional hardware connections: *SYNC IN*, *LOOP IN*, *LOOP OUT* and *FDBK OUT* (see *Synchronizer*).

**Warning**

On *Time Tagger Ultra* units sold before September 2020, the synchronization signals use the ports labeled *AUX IN 1*, *AUX IN 2*, *AUX OUT 1*, *AUX OUT 2*. A mapping of the signal names is included in the Synchronizer documentation (see *Synchronizer*). If you own one of these units and would like to have a sticker to update your labels, please reach out to Swabian Instruments [support](#).

**Time Tagger 20**

Synchronization of multiple *Time Tagger 20* devices is not possible.

## 2.15 FPGA link

### *Time Tagger X*

The Ethernet based FPGA link can be used for connecting customer's FPGA designs directly to the *Time Tagger X*. The connection is provided through either SFP+ or QSFP+ connector on the back panel of the *Time Tagger X*. Either one of them can be active and shall be used for connection of customer's design using either a Direct Attach Cable (DAC) or optical fiber transceiver. More details and explanations can be found in the [In Depth Guide: FPGA link](#).

### *Time Tagger Ultra and Time Tagger 20*

*Time Tagger Ultra* and *Time Tagger 20* have no support for FPGA link.

## 2.16 General purpose IO (GPIO)

### *Time Tagger Ultra*

Starting from the Time Tagger v2.6.6, the general purpose inputs and outputs on *Time Tagger Ultra* are used for synchronization signals. New *Time Tagger Ultra* devices will have updated labeling of these IO ports. See, [Synchronizer](#)

### *Time Tagger 20*

The *Time Tagger 20* is equipped with four general purpose IO ports that interface directly with the system's FPGA. These are reserved for future implementations.

## 2.17 19-inch rack mount

### *Time Tagger X*

The *Time Tagger X* can either be installed in a 19-inch rack, requiring two height units, or operated as a tabletop instrument.

### *Time Tagger Ultra*

Swabian Instruments offers an extra housing to make the tabletop *Time Tagger Ultra* mountable in a 19-inch rack.

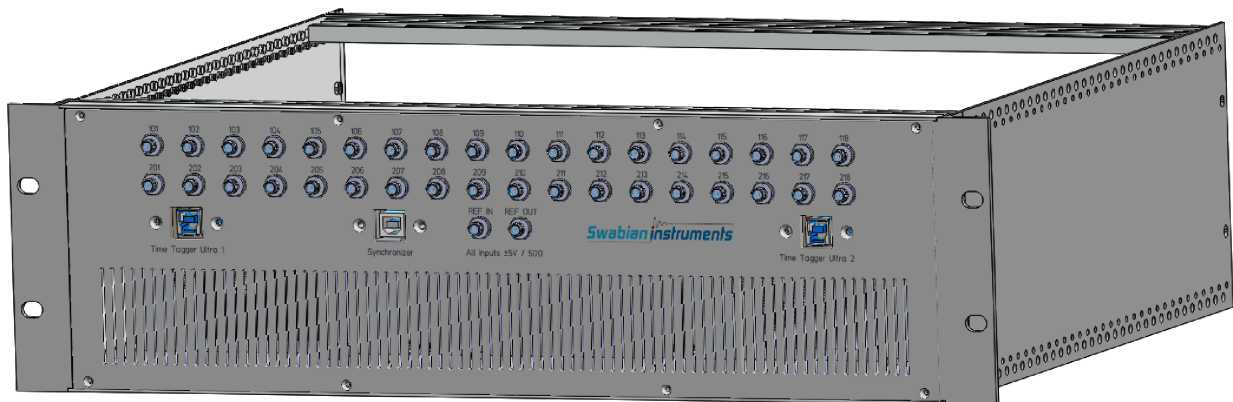


Fig. 1: Rack mount for up to two *Time Tagger Ultra* and one Synchronizer

Table 13: Specifications of the *Time Tagger Ultra* rack mount

| Parameter              | Value                                                                                                        |
|------------------------|--------------------------------------------------------------------------------------------------------------|
| Channels               | Up to 18 with one <i>Time Tagger Ultra</i> installed<br>Up to 36 with two <i>Time Tagger Ultra</i> installed |
| Height units           | 3                                                                                                            |
| Depth                  | 37 cm                                                                                                        |
| Weight without devices | 3.5 kg                                                                                                       |

Please get in touch with [sales@swabianinstruments.com](mailto:sales@swabianinstruments.com) for additional information.

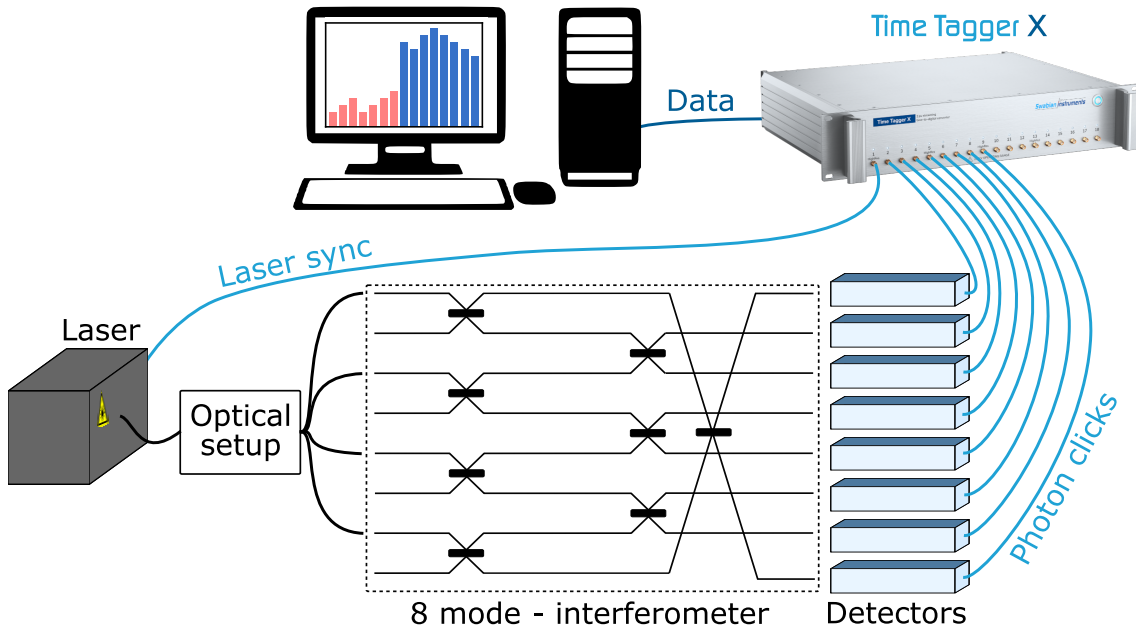
### ***Time Tagger 20***

Swabian Instruments doesn't provide an option to mount the *Time Tagger 20* in a 19-inch rack.



### 3.1 Measuring Coincidences

Quantum interference lies at the heart of photon-based technologies, such as photonic quantum computing, quantum metrology, and quantum networks. One of the key requirements for high-fidelity operations in these technologies is the indistinguishability of photons, a key property of quantum states. The level of indistinguishability between two photons is typically determined by measuring the Hong–Ou–Mandel (HOM) interference visibility: if the photons are identical and enter separately a balanced beam splitter, they will always exit the beam splitter together in the same output mode. If a detector is set up on each of the outputs, then the photons cannot be separately detected by the two detectors simultaneously. Thus, coincidence measurements enable the detection and analysis of correlated events, notably the simultaneous detection of entangled photons. When more than two photons are involved in a multiphoton quantum interference experiment, the interference capability extends beyond the pairwise distinguishability, and generalizations of the HOM effect to the many-particle case have been recently proposed. One method to quantify the  $n$ -photon indistinguishability relies on a cyclic multiport interferometer with  $N = 2n$  optical modes, composed of  $2n$  beam splitters placed along two cascaded layers. The quantum interference pattern, resulting from the injection of  $n$  indistinguishable photons into the  $2n$  ports-interferometer and obtained through a multiphoton coincidence detection, is a direct measurement of the  $n$ -photon indistinguishability.



This tutorial shows how to set up a measurement to count coincidence events between groups of input channels. In our example, we count fourth-order coincidences between four photons injected into an integrated eight-mode cyclic interferometer.

### 3.1.1 Time Tagger configuration

To perform our coincidence-counting experiment, we first connect the Time Tagger and select the channels used.

```
tagger = createTimeTagger()
input_channels = tagger.getChannelList(ChannelEdge.Rising)[:8]
```

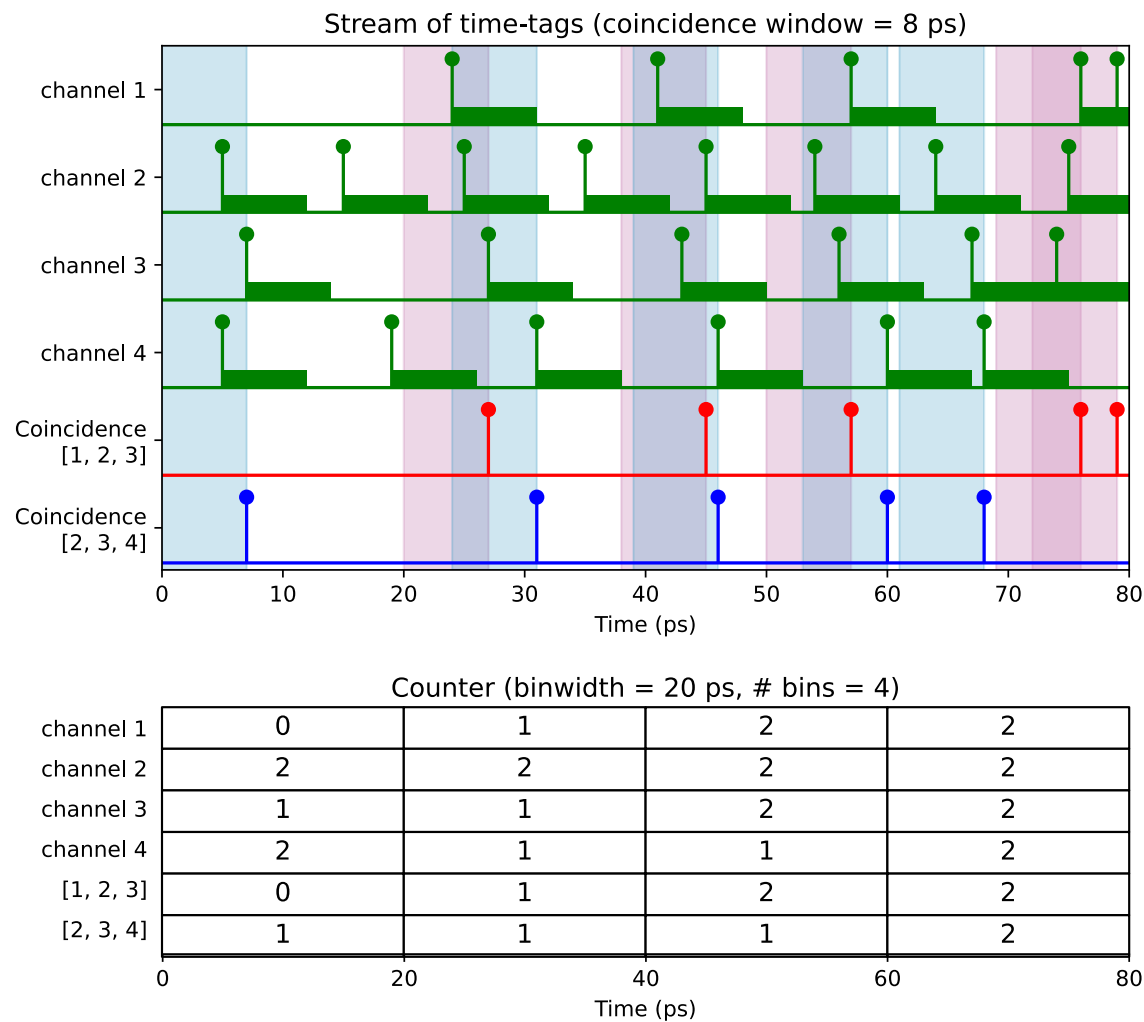
The Time Tagger hardware allows you to specify a trigger level voltage for each input channel. The default trigger level is 0.5 V. In our example, we set the trigger level to 0.3 V for all the channels.

```
for ch in input_channels:
    tagger.setTriggerLevel(ch, 0.3)
```

### 3.1.2 Coincidence-counting

Our protocol for counting coincidence events is schematically illustrated in the figure below. For clear visualization, the diagram considers coincidences for two groups of three channels among four input channels used. First, we define a time window as the largest time difference between events on the input channels to be considered as a coincidence (size of rectangular shaded colored areas). Next, we generate new streams of tags, which correspond to coincidence events occurring for each group of input channels (Coincidence [1, 2, 3] and Coincidence [2, 3, 4]). Finally, we count the events on each channel (bottom panel).

Our method can be implemented by creating the virtual channel *Coincidences*, which detects coincidence clicks on multiple channel groups within the given coincidenceWindow. In this regard, it is good to remember that this is a



software-defined channel; therefore, it receives time-tags from the physical input channels and generates a new data stream in the PC. The Time Tagger does not detect coincidences onboard the hardware.

In our example, we consider fourth-order coincidence events from eight input channels.

```
ORDER = 4
groups = list(itertools.combinations(input_channels, ORDER))

coincidences_vchannels = Coincidences(tagger, groups, coincidenceWindow=100)
```

Finally, the physical input channels and the *Coincidences* virtual channel are fed into the *Counter* measurement class.

```
#Generate a list including input and virtual channels
channels = [*input_channels, *coincidences_vchannels.getChannels()]

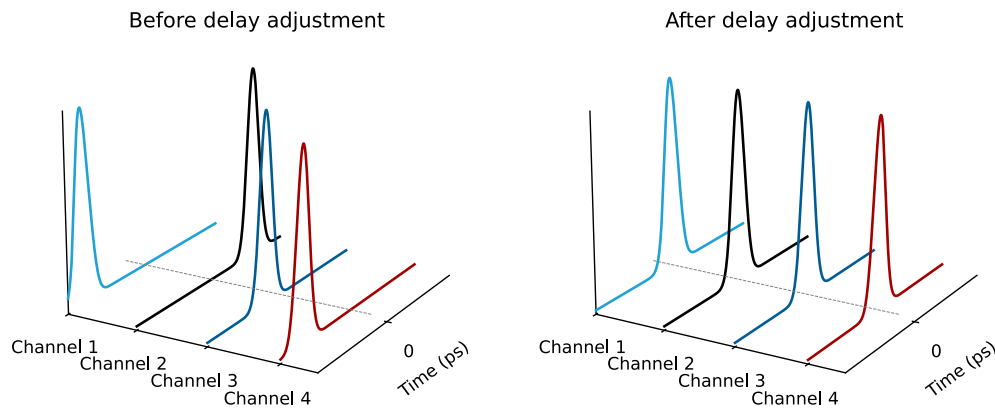
counting = Counter(tagger, channels, 1e10, 300)

measurementDuration = 10e12 # 10 s
counting.startFor(measurementDuration)
counting.waitUntilFinished()

index = counting.getIndex()
counts = counting.getData()
```

### 3.1.3 Delay adjustment for coincidence detection

When detecting coincidence events, it is essential to have signals aligned in time. Delays between channels inevitably arise from experimental conditions, such as different optical paths or cable lengths, and inherent delays in the detectors. Such delays can be compensated in the Time Tagger by providing a proper input delay.



If the signals are sufficiently correlated, the best way to quantify the time misalignment between the channels is to perform multiple *Correlation* measurements. The peak of the *Correlation* curve between two channels is centered at the relative delay. This value is employed a posteriori to compensate the time misalignment between the two channels.

In our example, we keep the first channel as a reference and alternatively measure the *Correlation* between it and all the others. Finally, we align all the signals in time, using `setInputDelay()` method.

```
# Set input delays to 0, otherwise the compensation result will be incorrect.
for ch in input_channels:
    tagger.setInputDelay(ch, 0)

# Create SynchronizedMeasurements to operate on the same time tags.
sm = SynchronizedMeasurements(tagger)

#Create Correlation measurements
corr_list = list()
for ch in input_channels[1:]:
    corr_list.append(
        Correlation(sm.getTagger(), input_channels[0], ch, binwidth=1, n_bins=5000)
    )

# Start measurements and accumulate data for 1 second
sm.startFor(int(1e12), clear=True)
sm.waitUntilFinished()

# Determine delays
delays = list()
for corr in corr_list:
    hist_t = corr.getIndex()
    hist_c = corr.getData()
    #Identify the delay as the center of the histogram through a weighted average
    dt = np.sum(hist_t * hist_c) / np.sum(hist_c)
    delays.append(int(dt))

print("Delays:", delays)

# Compensate the delays to align the signals
for ch, dt in zip(input_channels[1:], delays):
    tagger.setInputDelay(ch, dt)
```

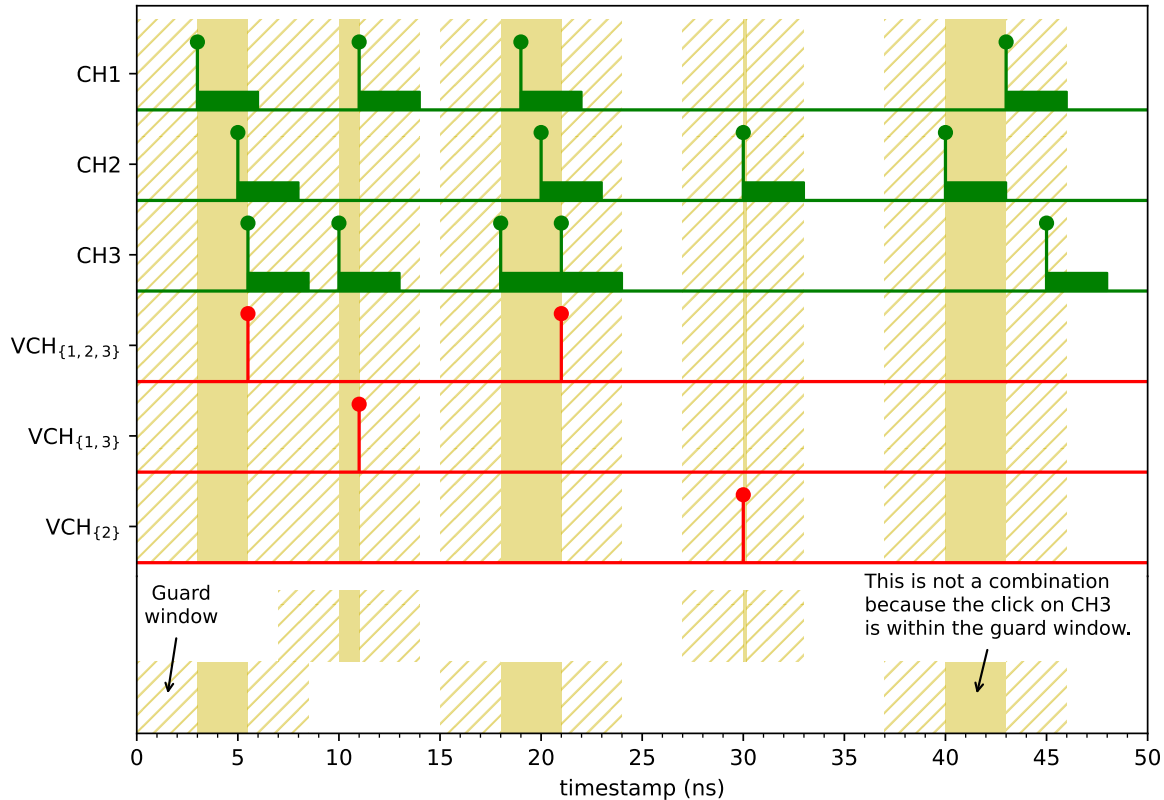
You can check that the delays are properly compensated by repeating the *Correlation* measurements and verifying that the histograms are centered at zero.

### 3.1.4 Exclusive coincidences using Combinations virtual channel

The indistinguishability of the input photons in a quantum interferometry experiment results in a large number of forbidden output configurations, among the possible many-particle states. This can be viewed as the generalization of the original two-photon HOM effect extended to the case of multiple ports and photons. In this regard, it turns out to be beneficial to consider coincidence measurements with specific restrictions. For instance, excluding certain coincidences based on the occurrence of events happening right before or after them can be important e.g., to eliminate the effect of background noise, hence for refining quantum state tomography or interference studies.

The best approach to achieve this goal is to employ the virtual channel *Combinations*. It detects coincidence clicks on all possible  $(2^N - 1)$  channel subgroups from a given number ( $N$ ) of channels, when no additional events occur within two guard windows, one preceding the first event starting the coincidence, the other following the last event concluding the coincidence. We report below a representative sketch of *Combinations* virtual channel given three input channels.

It should be noted that the combination of events on channels 1, 2, 3 results in the generation of a timestamp exclusively on the virtual channel  $VCH_{\{1,2,3\}}$  and not on  $VCH_{\{1,3\}}$  or  $VCH_{\{2\}}$ . This distinction, however, does not apply to the virtual



channel *Coincidence*s, as the coincidences between channels 1, 2, and 3 constitute a subset of coincidences between 1 and 3. Contextualizing this to the quantum interferometry experiment with four input photons and eight output ports, coincidences of order higher than four, made possible only by dark counts, are discarded on the fourth-order combinations. This is true if all eight channels are input to the *Combinations* virtual channel.

In the following minimal example, we demonstrate how to obtain the virtual channel numbers for fourth-order combinations, that can be input to the *Counter* measurement class. The goal of the example is to ensure that each combination includes at least one number from each of the sets {1, 2}, {3, 6}, {4, 5}, and {7, 8}.

```
# Create the Combinations virtual channel
combinations_vchannels = Combinations(tagger, input_channels, window_size=100)

#Define sets of inclusion
set1 = {1, 2}
set2 = {3, 6}
set3 = {4, 5}
set4 = {7, 8}

# Filter combinations of four channels groups based on conditions
filtered_combinations = [list(comb) for comb in groups
    if any(num in set1 for num in comb)
    and any(num in set2 for num in comb)
    and any(num in set3 for num in comb)
    and any(num in set4 for num in comb)]

# Create a list with the virtual channels monitoring the combinations
```

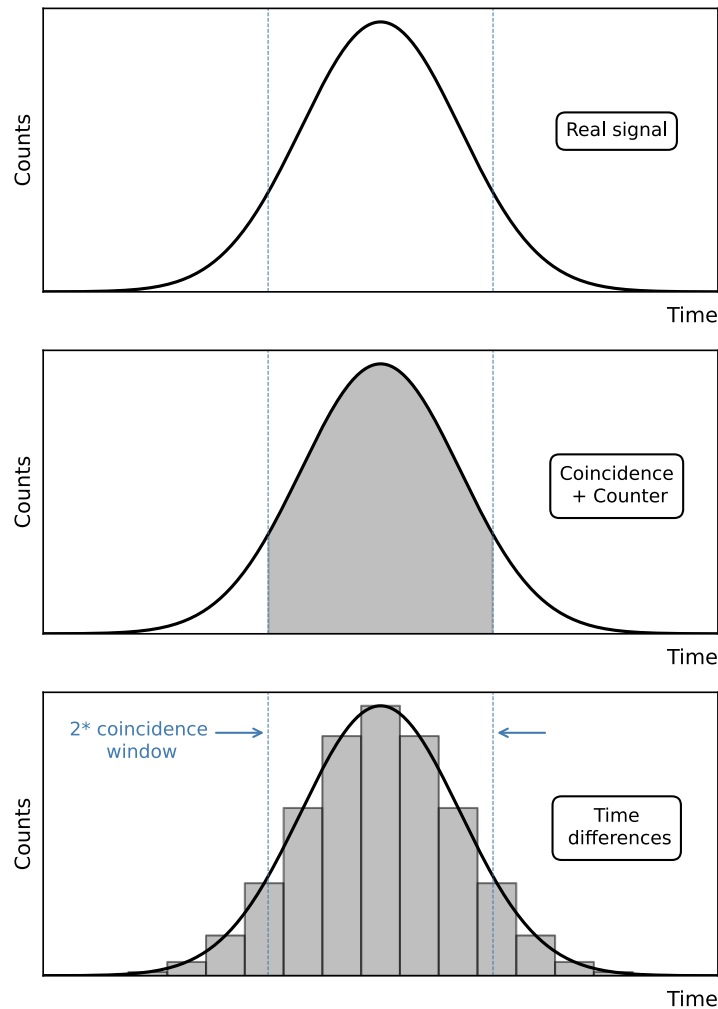
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```
virtualchannelsnumber = []
for group in filtered_combinations:
    virtualchannelsnumber.append(combinations_vchannels.getChannel(group))
```

### 3.1.5 Coincidence-counting vs Correlation Measurement

Let us now restrict the discussion to two channels. In this case, coincidence-counting can also be directly related to the *Correlation* measurement class. *Correlation* accumulates a histogram of time differences between the two channels, where clicks on both channels are considered as start and stop events (multiple start, multiple stop). As a result, the histogram contains both positive and negative time differences. On the other hand, the “*Coincidence + Counter*” approach does not discriminate the order of the clicks. A coincidence event is generated whenever the two time tags are separated by at most *coincidenceWindow*, regardless of which click arrived first. For two channels, a coincidence window of  $W$  corresponds to the range from  $-W$  to  $+W$  in the correlation histogram, so the total accepted width is  $2W$ . To obtain matching coincidence counts from *Correlation*, sum all histogram bins covering this interval. For exact agreement, choose the *Correlation* bin width such that the boundaries at  $-W$  and  $+W$  coincide with bin edges, as illustrated in the figure below.

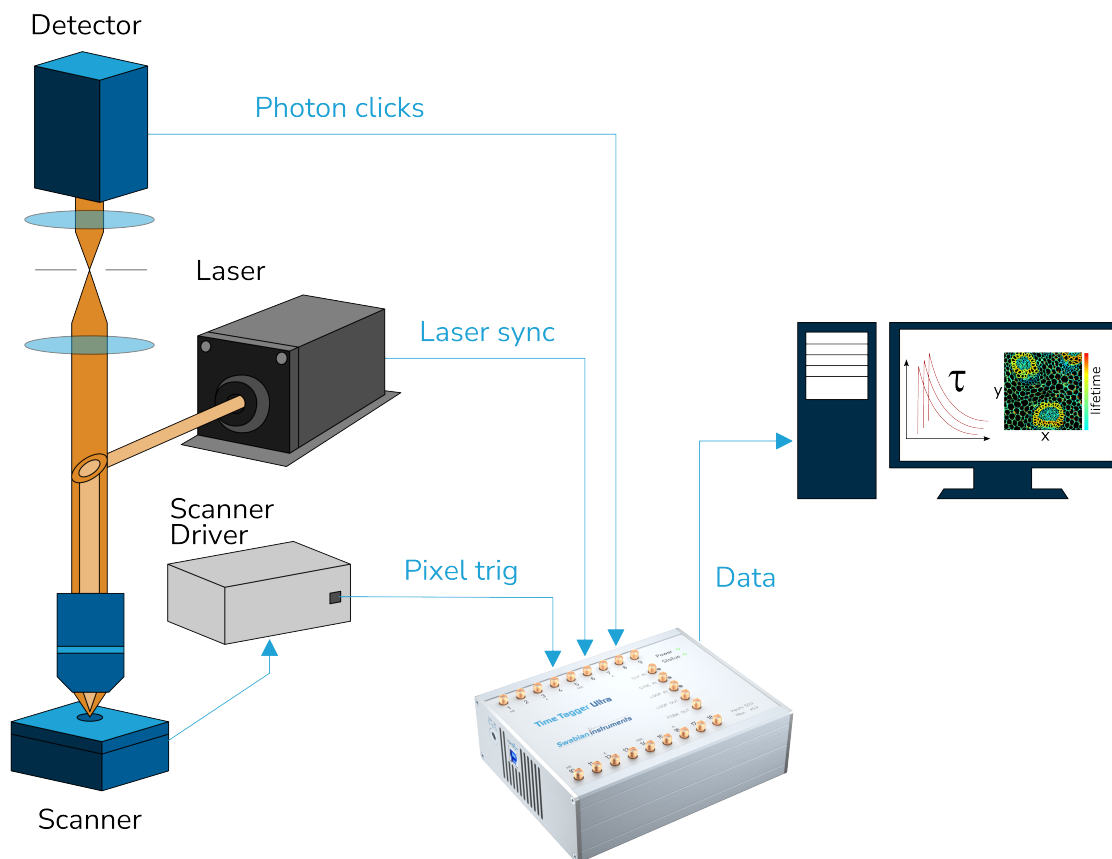


## 3.2 Confocal Fluorescence Microscope

This tutorial guides you through setting up a data acquisition for a typical confocal microscope controlled with Swabian Instruments' Time Tagger. In this tutorial, we will use Time Tagger's programming interface to define the data acquisition part of a scanning microscope. We will make no specific assumption of how the position scanning system is implemented except that it has to provide suitable signals detailed in the text.

The basic principle of confocal microscopy is that the light, collected from a sample, is spatially filtered by a confocal aperture, and only photons from a single spot of a sample can reach the detector. Compared to conventional microscopy, confocal microscopy offers several advantages, such as increased image contrast and better depth resolution, because the pinhole eliminates all out-of-focus photons, including stray light.

The following drawing shows a typical confocal fluorescence microscope setup.

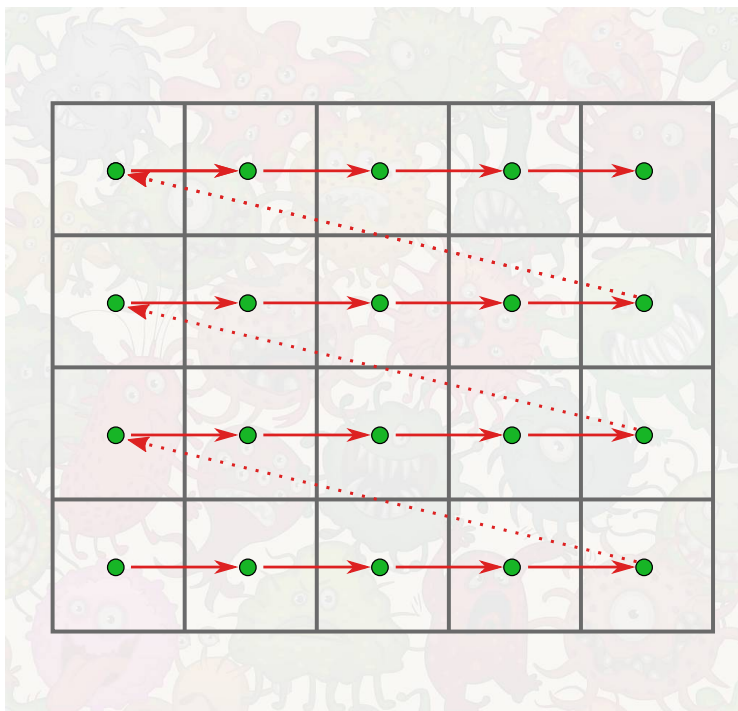


In this setup, the objective focuses the excitation light from the laser at the fluorescent sample and, at the same time, collects the resulting emission. The emission photons pass through the confocal aperture and arrive at the single-photon detector (SPD). For every detected photon, the SPD produces a voltage pulse at its output, namely a photon pulse.

### Image from a raster scan

In the confocal microscopy, the detection area is a small diffraction-limited spot. Therefore, to record an image, one has to scan the sample surface point-by-point and record the detector signal at every location. The majority of scanning microscopes employ a raster scan path that visits every point on sample step-by-step and line-by-line. The figure below visualizes the travel path in a typical raster scan.





In the figure above, the scan starts from the bottom-left corner and proceeds horizontally in steps. At each scan position, the scanner has to wait for arbitrary integration time to allow sufficient photon collection. This process stops when the scanner reaches the top-right point.

Along the scan path, the positioner generates a pulse for every new sample position. In the following text, we will call this signal a pixel pulse.

To measure a confocal fluorescence image, the arrival times of the following three signals must be recorded: photon pulses, laser pulses, and pixel pulses.

### 3.2.1 Time Tagger configuration

The Time Tagger library includes several measurement classes designed for confocal microscopy.

We will start by defining channel numbers and store them in variables for convenience.

```
PIXEL_START_CH = 1 # Rising edge on input 1
PIXEL_END_CH = -1 # Falling edge on input 1
LASER_CH = 2
SPD_CH = 3
```

Now let's connect to the Time Tagger.

```
tt = createTimeTagger()
```

The Time Tagger hardware allows you to specify a trigger level voltage for each input channel. This trigger level, always applies for both, rising and falling edges of an input pulse. Whenever the signal level crosses this trigger level, the Time Tagger detects this as an event and stores the timestamp. It is convenient to set the trigger level to half a signal amplitude. For example, if your laser sync output provides pulses of 0.2 V-amplitude, we set the trigger level to 0.1 V on this channel. The default trigger level is 0.5 V.

```
tt.setTriggerLevel(PIXEL_START_CH, 0.5)
tt.setTriggerLevel(LASER_CH, 0.1)
```

The Time Tagger allows for delay compensation at each channel. Such delays are inevitably present in every measurement setup due to different cable lengths or inherent delays in the detectors and laser sync signals. It is worth noting that a typical coaxial cable has a signal propagation delay of about 5 ns/m.

Let's suppose that we have to delay the laser pulse by 6.3 ns, if we want to align it close to the arrival time of the fluorescence photon pulse. Using the Time Tagger's API, this will look like:

```
tt.setInputDelay(LASER_CH, 6300) # Delay is always specified in picoseconds
tt.setInputDelay(SPD_CH, 0)      # Default value is: 0
```

Now we are finished with setting up the Time Tagger hardware and are ready to proceed with defining the measurements.

### 3.2.2 Intensity scanning microscope

In this section, we start from an easy example of only counting the number of photons per pixel and spend some time on understanding how to use the pixel trigger signal. The Time Tagger library contains the generic [CountBetweenMarkers](#) measurement that has all the necessary functionality to implement the data acquisition for a scanning microscope.

For the [CountBetweenMarkers](#) measurement, you have to specify on which channels the photon and the pixel pulses arrive. Also, we have to specify the total number of points in the scan, which is the number of pixels in the final image. Furthermore, we assume that the pixel pulse edges indicate when to start, and when to stop counting photons and the pulse duration defines the integration time. If your scanning system generates pixel pulses of a different format, take a look at the section [Alternative pixel trigger formats](#).

As a first step, we create a measurement object with all the necessary parameters provided.

```
nx_pix = 300
ny_pix = 200
n_pixels = nx_pix * ny_pix

cbm = CountBetweenMarkers(tt, SPD_CH, PIXEL_START_CH, PIXEL_END_CH, n_pixels)
```

The measurement is now prepared and waiting for the signals to arrive. The next step is to send a command to the piezo-positioner to start scanning and producing the pixel pulses for each location.

```
scanner.scan(
    x0=0, dx=1e-5, nx=nx_pix,
    y0=0, dy=1e-5, ny=ny_pix,
)
```

#### Note

The code above introduces a *scanner* object which is not part of the Time Tagger library. It is an example of a hypothetical programming interface for a piezo-scanner. Here, we also assume that this call is non-blocking, and the script can continue immediately after starting the scan.

After we started the scanner, the Time Tagger receives the pixel pulses, counts the events at each pixel, and stores the count in its internal buffer. One can read the buffer content periodically without disturbing the acquisition, even before the measurement is completed. Therefore, you can see the intermediate results and visualize the scan progress.

The resulting data from the *CountBetweenMarkers* measurement is a vector. We have to reorganize the elements of this vector according to the scan path if we want to display it as an image. For the raster scan, this reorganization can be done by a simple reshaping of the vector into a 2D array.

The following code gives you an example of how you can visualize the scan process.

```
while scanner.isScanning():
    counts = cbm.getData()
    img = np.reshape(counts, nx_pix, ny_pix)
    plt.imshow(img)
    plt.pause(0.5)
```

### 3.2.3 Fluorescence Lifetime Microscope

In the section *Intensity scanning microscope*, we completely discarded the time of arrival for photon and laser pulses. The Time Tagger allows you to record a fluorescence decay histogram for every pixel of the confocal image by taking into account the time difference between the arrival of the photon and laser pulses. This task can be achieved using different *Measurement Classes* from the Time Tagger library. In this subsection, we will instead use the easy-to-handle *Flim* measurement.

The *Flim* measurement calculates the time differences between laser and photon pulses and accumulates them in a histogram for every pixel. The measurement class constructor requires timing and imaging parameters, as shown in the following code snippet.

```
nx_pix = 300 # Number of pixels along x-axis
ny_pix = 200 # Number of pixels along y-axis
n_pixels = nx_pix * ny_pix # number of histograms
n_bins = 2000 # number of bins in a histogram
binwidth = 50 # in picoseconds

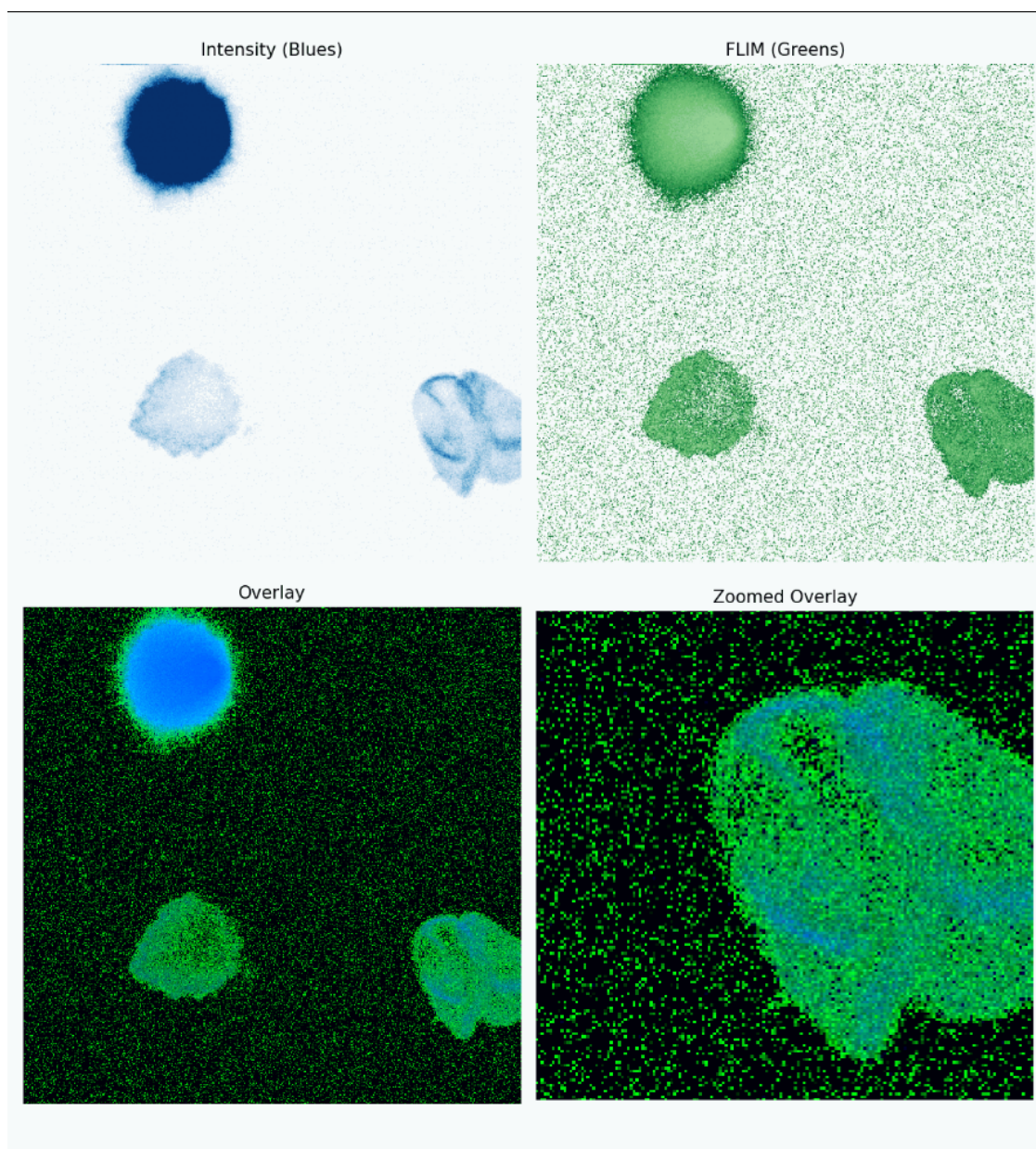
flim = Flim(tt,
    start_channel=LASER_CH,
    click_channel=SPD_CH,
    pixel_begin_channel=PIXEL_START_CH,
    n_pixels=n_pixels,
    n_bins=n_bins,
    binwidth=binwidth
)
```

Now we start the scanner and either wait until the scan is completed or we can read the current data in real time and display it during the scan.

```
while scanner.isScanning():
    counts = flim.getCurrentFrame()
    img3D = counts.reshape((xDim, yDim, bins))

    # User defined function that estimates fluorescence lifetime for every pixel
    flimg = get_lifetime(img3D)

    plt.imshow(flimg)
    plt.pause(0.5)
```



**Note**

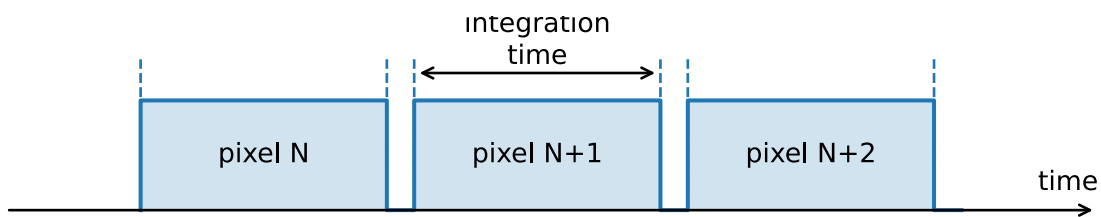
The animation above runs with reduced replay speed to clearly visualize the scanning of the image.

Besides the live (*current*) frame, the *Flim* measurement class also provides *ready* and *summed* frames. These frames can be accessed via the corresponding methods: *Flim::getCurrentFrameIntensity()*, *Flim::getReadyFrameIntensity()*, and *Flim::getSummedFramesIntensity()*, respectively. The intensity is directly normalized with the integration time of the pixels. For more information, please see the documentation of the *Flim* class.

### 3.2.4 Alternative pixel trigger formats

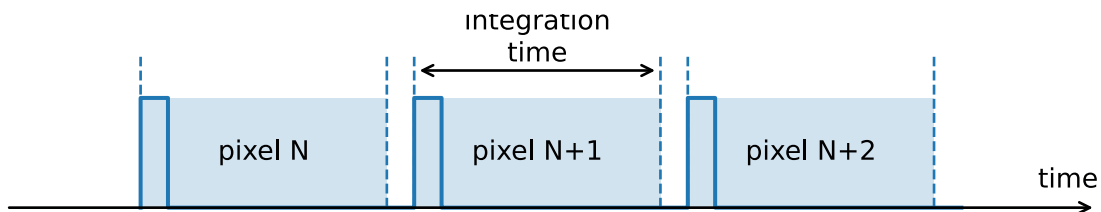
What if a piezo-scanner provides a different trigger signal compared to considered in the previous sections? In this section, we look into a few common types of trigger signals and how to adapt our data acquisition to make them work.

#### Pixel pulse width defines the integration time



The case when the pulse width defines the integration time has been considered in the previous subsections.

#### Pixel pulse indicates the pixel start



When a pixel pulse has a duration different from the desired integration time, we must define the integration time manually. One way would be to record all events until the next pixel pulse and rely on a strictly fixed pixel pulse period. Alternatively, we can create a well-defined time window after each pixel pulse, so the measurement system becomes insensitive to the variation of the pixel pulse period.

One can define the time window using the *DelayedChannel* which provides a delayed copy of the leading edge for the pixel pulse.

```
integr_time = int(1e10) # Integration time of 10 ms in picoseconds
delayed_vch = DelayedChannel(tt, PIXEL_START_CH, integr_time)
PIXEL_END_CH = delayed_vch.getChannel()

flim = Flim(tt,
    start_channel=LASER_CH,
```

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```

click_channel=SPD_CH,
pixel_begin_channel=PIXEL_START_CH,
pixel_end_channel=PIXEL_END_CH,
n_pixels=n_pixels,
n_bins=n_bins,
binwidth=binwidth
)

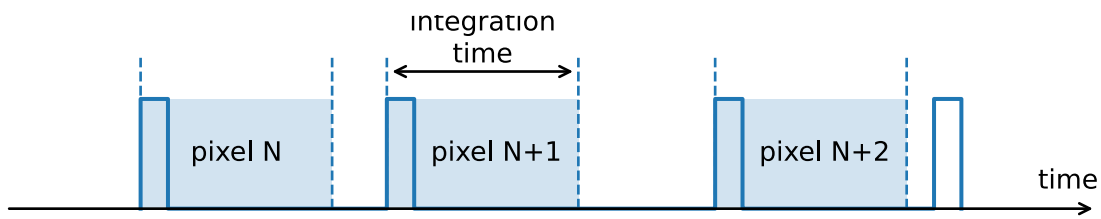
```

The approach with using *DelayedChannels* allows for a constant integration time per pixel even if the pixel pulses do not occur at a fixed period. For instance, in a raster scan, more time is required to move to the beginning of the next line (fly-back time) compared to the pixel time.

### Warning

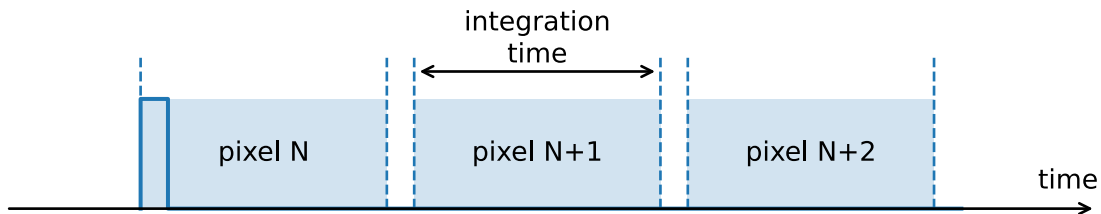
You have to make sure that pixel pulses do not appear before the end of the integration time for the previous pixel.

### FLIM with non-periodic pixel trigger



In some cases, a scanner generates the pixel pulses with no strictly defined period. However, most scanning measurements require constant integration time for every pixel. In this case, we can still use the exact same logic as described above.

### Line pulse but no pixel pulses



When a scanning system only has the line-start signal and does not provide the pixel pulses, we have to define time intervals for each pixel by other means. The pixel markers can be easily generated with *EventGenerator* virtual channel which generates events at times relative to the trigger event. Furthermore, the *EventGenerator* allows you to generate not only pixel markers that are equally spaced but also pixels that are spaced non-uniformly or have time varying integration times. For instance, you will find the *EventGenerator* particularly powerful, if you work with resonant galvo-scanners and need to correct integration time and pixel spacing according to the speed profile of your scanner. The example below shows how to apply *EventGenerator* for generation of pixel markers.



```

nx_pix = 300          # Number of pixels along x-axis
ny_pix = 200          # Number of pixels/lines along y-axis
integr_time = int(3e9) # Integration time of 3 ms in picoseconds
line_duration = 1e12  # Duration of the line scan in picoseconds
binwidth = 50         # in picoseconds
n_bins = 2000         # number of bins in a histogram
n_pixels = nx_pix * ny_pix # number of histograms

LINE_START_CH = 3

# Pixels are equally spaced in time (constant speed)
pixel_start_times = numpy.linspace(0, line_duration, nx_pix, dtype='int64')
# Pixel integration time is constant
pixel_stop_times = pixel_start_times + integr_time

# Create EventGenerator channels
pixel_start_vch = EventGenerator(tt, LINE_START_CH, pixel_start_times.tolist())
pixel_stop_vch = EventGenerator(tt, LINE_START_CH, pixel_stop_times.tolist())

PIXEL_START_CH = pixel_start_vch.getChannel()
PIXEL_END_CH = pixel_stop_vch.getChannel()

flim = Flim(tt,
    start_channel=LASER_CH,
    click_channel=SPD_CH,
    pixel_begin_channel=PIXEL_START_CH,
    pixel_end_channel=PIXEL_END_CH,
    n_pixels=n_pixels,
    n_bins=n_bins,
    binwidth=binwidth
)

```

The FLIM measurement class also allows to trigger new frames with a hardware signal, if your scanner is able to provide a signal before starting a new frame. This can be useful if your scanner needs some time to come back to the starting position of the image.

```

FRAME_BEGIN_CH = 4

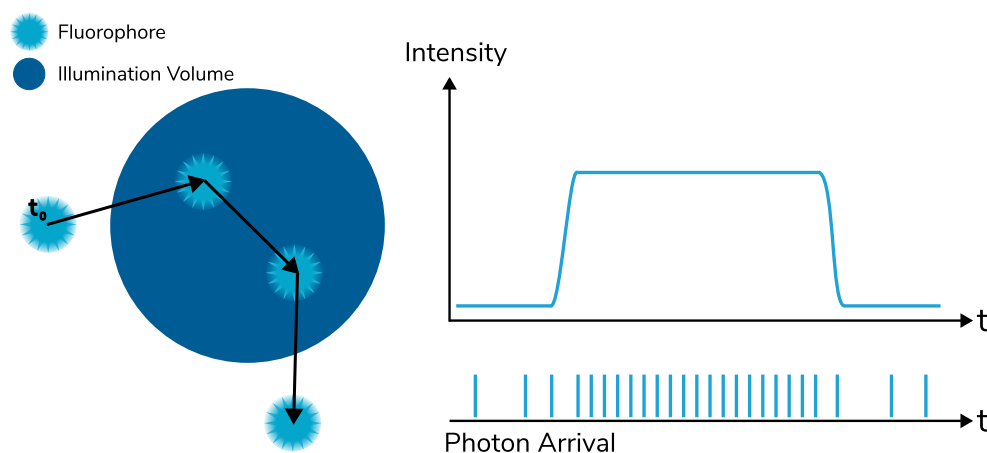
flim = Flim(tt,
    start_channel=LASER_CH,
    click_channel=SPD_CH,
    pixel_begin_channel=PIXEL_START_CH,
    pixel_end_channel=PIXEL_END_CH,
    frame_begin_channel=FRAME_BEGIN_CH,
    n_pixels=n_pixels,
    n_bins=n_bins,
    binwidth=binwidth
)

```

Additionally, we also provide the possibility of averaging multiple frames, as well as stopping acquisition after a pre-defined number of frames. Python examples are provided in the *examples* folder of the TimeTagger software package.

### 3.3 Fluorescence Correlation Spectroscopy

Fluorescence correlation spectroscopy (FCS) is a technique that analyzes fluorescence fluctuations at the single-molecule level to infer fluorophore concentration, diffusion, and kinetic parameters underlying the signal. A laser excites a small number of fluorophores within a tiny observation volume. As molecules diffuse in and out, the intensity fluctuates primarily due to Brownian motion and, in some cases, photophysical processes such as triplet blinking. In the single-photon regime, the detector produces individual photon events, and the Time Tagger precisely time-stamps their arrival times. Using these timestamps, the Time Tagger software and API enable computation of the correlation function  $G(\tau)$ , from which particle number, diffusion coefficients, and reaction or conformational rates can be estimated.



This tutorial shows how to perform FCS and advanced variants like fluorescence cross-correlation spectroscopy (FCCS), pulsed interleaved excitation (PIE), and raster image correlation spectroscopy (RICS), with the Swabian Instruments Time Tagger for data acquisition and live analysis. After a brief recap, the tutorial shows how to configure channels and triggers, align delays, acquire single-photon timestamps, and compute the correlation function  $G(\tau)$  (auto-/cross-correlation) using multiple- $\tau$  binning.

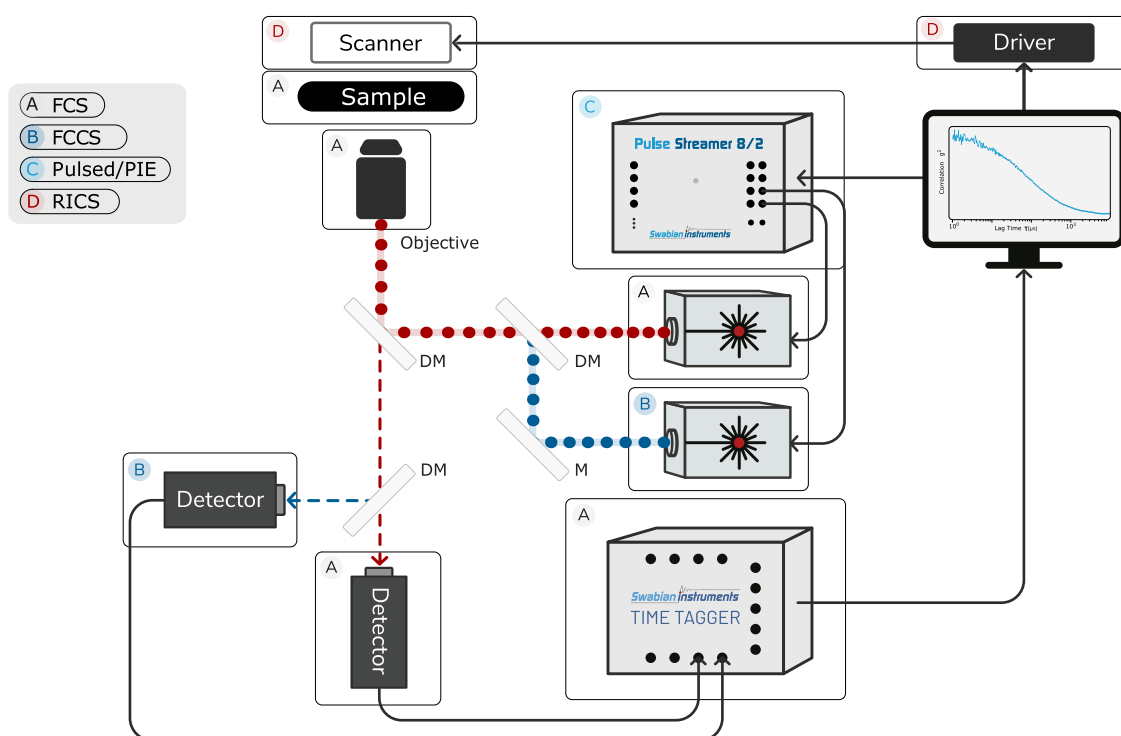
The tutorial covers:

- **FCS:** set up a single-detector, continuous-wave (CW) workflow, run autocorrelation on the detector channel, monitor  $G(\tau)$ , and visualize traces.
- **FCCS:** acquire dual-color streams on two detectors/lasers, compute cross-correlation, and visualize traces for downstream interaction analysis.
- **PIE:** drive interleaved excitation pulses (via [Pulse Streamer](#)), define time-gating windows, and suppress spectral cross-talk while retaining lifetime information.
- **RICS:** integrate a scanning stage, map timestamps to pixels/lines, and compute spatially resolved correlation maps.



### 3.3.1 Microscope Setup

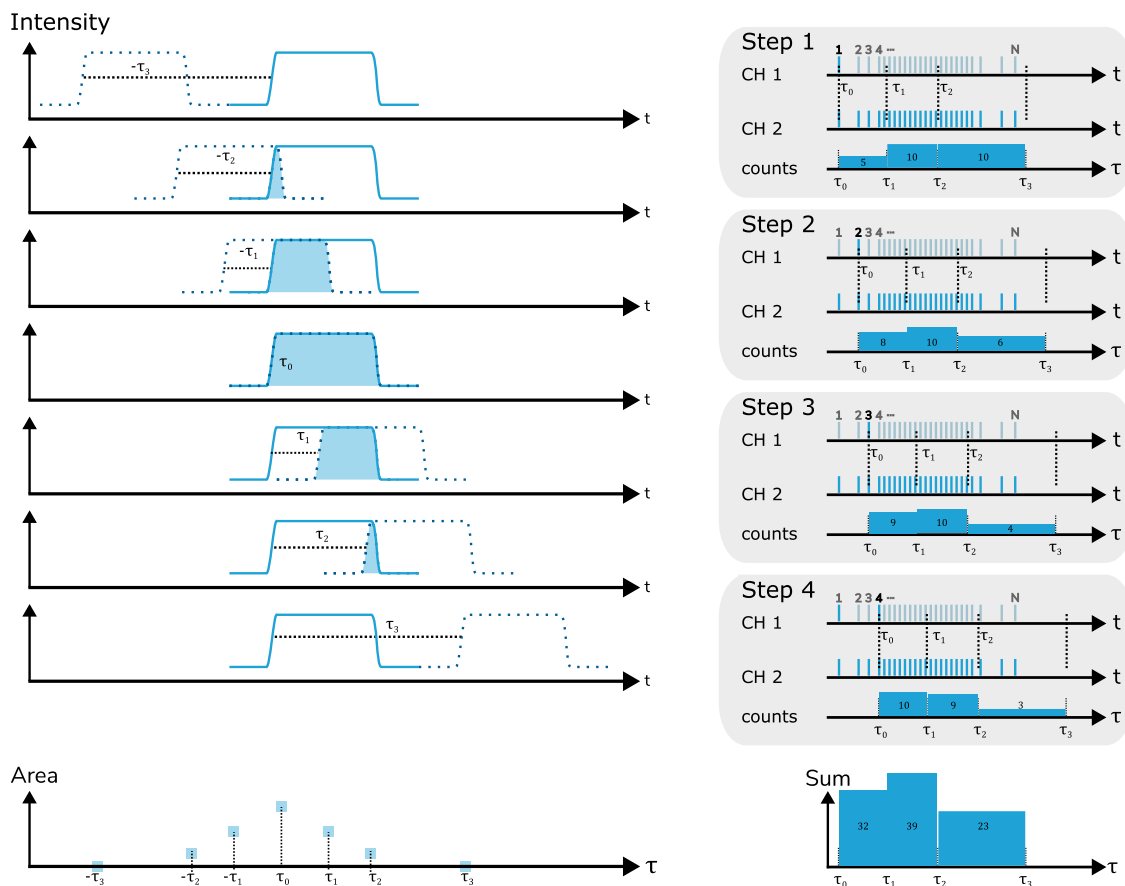
FCS can be performed on microscope setups such as confocal or two-photon excitation, which create small, well defined observation volumes (typically in the order of  $1 \mu m^3$ ) to capture low fluorophore numbers (0.1-100). The observation volume is typically modeled as a 3D Gaussian ellipsoid. The simplest setup contains one laser, one single-photon detector, the optical elements and the Time Tagger for data acquisition, as well as the fluorescent sample (A). The system can be expanded to include multiple lasers and detectors (B), a [Pulse Streamer](#) as the laser driver for pulsed measurements, including PIE (C), and a scanning stage for RICS (D).



### 3.3.2 Single Photon Correlation

In FCS, relevant dynamics, such as particle diffusion and reaction kinetics, span timescales from microseconds to seconds. Building a correlation function from time-stamped single-photon data, therefore, requires an algorithm that is both memory-wise and computationally efficient across several lag times decades.

A naive approach, using a [Histogram](#) with uniform time bins, becomes impractical when trying to cover a broad range of lag times  $\tau$  while preserving high temporal resolution. This is where the multiple-tau approach comes in. Instead of using equally spaced bins, this algorithm uses logarithmic binning: the bin width increases with  $\tau$ , allowing coverage of large timescales without excessive memory or CPU usage.

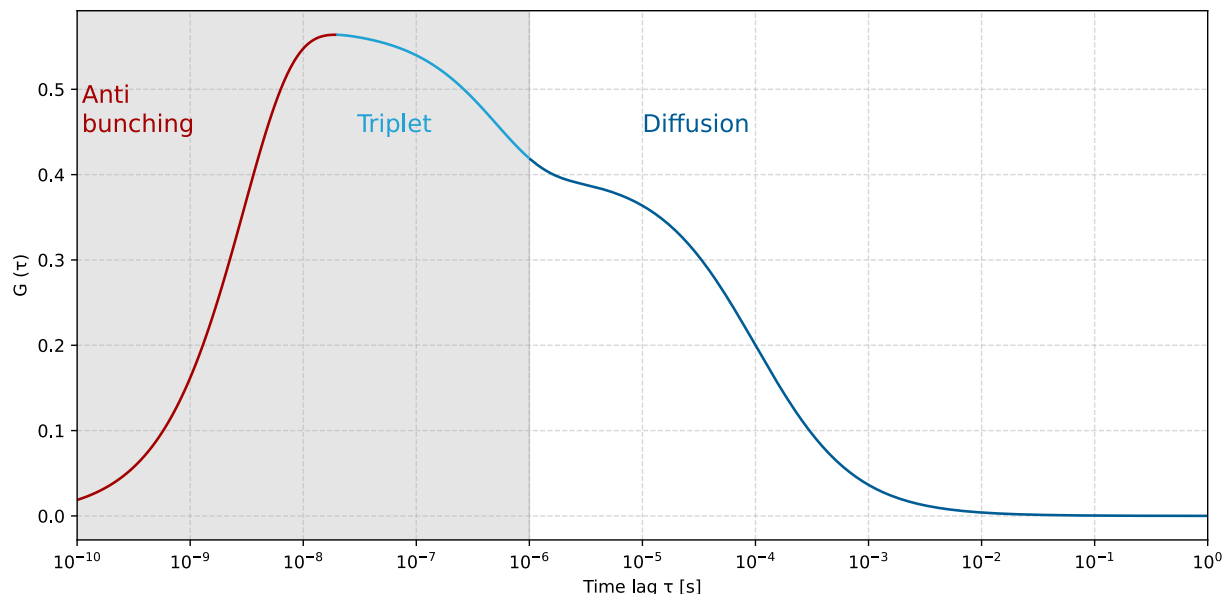


The sketch above illustrates a typical autocorrelation (CH 1 = CH 2) algorithm. On the left is the intensity-trace view, where the signal is shifted by  $\tau$  and multiplied by itself. On the right is the event-based (single-photon) view.

In the event-based autocorrelation, each photon arrival time serves as a reference (starting with 1 in step 1 out of  $N$ ). From this reference point, the lag times  $\tau_0, \tau_1, \tau_2, \dots$  are discretized according to the logarithmic binning. For each lag interval, the number of photons is counted and stored in the corresponding bin. By accumulating data from all  $N$  reference points (Step 1, Step 2,  $\dots$ , Step  $N$ ) and normalizing for bin width and the number of available photon pairs (not shown) at each  $\tau$ , one obtains the final autocorrelation curve. For a detailed description of the algorithm, please refer to the publication [T. Laurence, S. Fore, and T. Huser, Opt. Lett. 31, 829-831 \(2006\)](#).

The correlation curve  $G(\tau) = g^{(2)}(\tau) - 1$  shows three characteristic regions. Region I and II capture antibunching and triplet state dynamics at very short time scales and are commonly omitted in FCS plots (gray region). Region III reflects the diffusion of fluorophores through the observation volume and is the region of interest for further FCS analyses. The data from this region is typically fitted with a model that corresponds to the experimental expectation (3D/2D/anomalous diffusion, triplet correction, etc.). The model then reveals the sample's parameters. In practice, the overall curve shape and the value of  $G(\tau)$  at short- $\tau$  (e.g.,  $\mu s$ ) are informative about diffusion and particle number.

All regions can be computed simultaneously using the Time Tagger library, as will be shown next.



### 3.3.3 Time Tagger configuration

The Time Tagger library provides several measurement classes designed for microscopy. We start by defining channel assignments and then add the necessary configuration.

```
DETECTOR_1_CH = 1 # Rising edge on input 1
DETECTOR_2_CH = 2 # Optional: FCCS
LASER_CH = 3      # Optional: Lifetime
```

Connect to the Time Tagger:

```
from Swabian import TimeTagger
tt = TimeTagger.createTimeTagger()
```

The Time Tagger hardware allows you to specify an individual trigger level voltage for each input channel. This trigger level applies to both rising and falling edges of an input pulse. Whenever the signal crosses this threshold, the Time Tagger registers an event and stores its timestamp. It is often convenient to set the trigger level to half the signal amplitude. For example, if your laser sync output provides pulses of 0.2 V amplitude, set the trigger level to 0.1 V on this channel. The default trigger level is 0.5 V.

```
tt.setTriggerLevel(DETECTOR_1_CH, 0.5)
tt.setTriggerLevel(DETECTOR_2_CH, 0.4)
tt.setTriggerLevel(LASER_CH, 0.1)
```

The basic hardware setup is complete; next we define the measurements.

### 3.3.4 Continuous Wave Laser

Building the autocorrelation function with the multiple- $\tau$  approach is straightforward in the API. First, define your experiment parameters and create the *HistogramLogBins* measurement.

```
exp_start = -7 # 100 nanoseconds
exp_stop = 0   # 1 second
```

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```
n_bins = 150
hist_log_bins = TimeTagger.HistogramLogBins(tagger=tt,
                                             click_channel=DETECTOR_1_CH,
                                             start_channel= DETECTOR_1_CH,
                                             exp_start=exp_start,
                                             exp_stop=exp_stop,
                                             n_bins=n_bins)
```

By default, the measurement starts immediately after creation, begins acquiring time tags and computing the autocorrelation on channel DETECTOR\_1\_CH. Acquisition can be controlled via the *common methods* shared by all measurement classes. To run the measurement for a fixed duration, use *startFor()*:

```
DURATION = 60e12 # one minute
hist_log_bins.startFor(capture_duration=DURATION)
```

While the measurement is running, you can poll *isRunning()* and update a live plot of  $G(\tau)$ :

```
import matplotlib.pyplot as plt

while hist_log_bins.isRunning():
    g2 = hist_log_bins.getDataObject().getG2()
    tau = hist_log_bins.getBinEdges() # shape: (n_bins+1)
    plt.plot(tau[1:], g2)
    plt.pause(0.1)
```

You can fit the measured  $G(\tau)$  on the fly with a model suited to your sample and optical parameters.

### 3.3.5 Fluorescence Cross-Correlation Spectroscopy

When studying molecular interactions between two or more molecules, fluorescence cross-correlation spectroscopy (FCCS) becomes a powerful extension of FCS. In practice, it is useful to acquire the two autocorrelations alongside the cross trace: they provide per-channel quality checks and a reference when interpreting the cross-correlation. With the Time Tagger API, create three *HistogramLogBins* measurements: autocorrelation on detector 1 (*start\_channel* = *click\_channel* = DETECTOR\_1\_CH), autocorrelation on detector 2 (*start\_channel* = *click\_channel* = DETECTOR\_2\_CH), and the FCCS cross-correlation (e.g., *start\_channel* = DETECTOR\_2\_CH, *click\_channel* = DETECTOR\_1\_CH). Start them together with the *SynchronizedMeasurements* helper class so they share the same acquisition window and can be directly compared.

```
sm = TimeTagger.SynchronizedMeasurements(tt)
sync_proxy = sm.getTagger()

hist_log_bins_11 = TimeTagger.HistogramLogBins(tagger=sync_proxy,
                                             click_channel=DETECTOR_1_CH,
                                             start_channel= DETECTOR_1_CH,
                                             exp_start=exp_start,
                                             exp_stop=exp_stop,
                                             n_bins=n_bins)

hist_log_bins_22 = TimeTagger.HistogramLogBins(tagger=sync_proxy,
                                             click_channel=DETECTOR_2_CH,
                                             start_channel= DETECTOR_2_CH,
                                             exp_start=exp_start,
                                             exp_stop=exp_stop,
```

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```

n_bins=n_bins)

hist_log_bins_12 = TimeTagger.HistogramLogBins(tagger=sync_proxy,
                                                click_channel=DETECTOR_1_CH,
                                                start_channel= DETECTOR_2_CH,
                                                exp_start=exp_start,
                                                exp_stop=exp_stop,
                                                n_bins=n_bins)

sm.startFor(DURATION)
sm.waitUntilFinished()

```

CW excitation can photo-bleach fluorophores or drive triplet-state saturation, both of which degrade signal quality. Background from scattered light also reduces the signal-to-noise ratio (SNR). Pulsed excitation helps mitigate these effects and enables timing-based strategies (e.g., lifetime, gating, PIE).

### 3.3.6 Pulsed Laser

Pulsed lasers offer several important advantages for FCS. The first one is that well-defined laser pulses provide access to fluorescence lifetime information of the sample. More details on this topic can be found in the [FLIM application page](#) or in the *Confocal Fluorescence Microscope* tutorial.

A second advantage is control over excitation timing: the pulse sequence can be configured to minimize bleaching and to allow recovery of fluorophores from non-radiative triplet states. To achieve this, the pulse period is typically chosen longer than the characteristic relaxation times, which in practice corresponds to repetition rates of about 80-100 MHz (12.5-10 ns) or lower. The pulse duration is adjusted so that, on average, approximately one emission event per pulse is expected. In this regime, the detected click rate is usually about 1% of the laser repetition rate, (e.g., 1 MHz on the detector for a 100 MHz laser). Under such conditions, the laser trigger generates roughly 80-100 MTags/s, while each detector records 0.8-1 MTags/s; the overall stream can meet or exceed the sustained transfer limit from the Time Tagger to the PC (90 MTags/s).

To reduce the bandwidth without losing physical information, the *Conditional Filter* can be used. With this hardware setting enabled, the Time Tagger transmits only the next tag on a high-rate channel after a tag on a low-rate channel. For pulsed excitation, it is useful to delay the laser channel by one laser period so that the photon-originating laser event is forwarded. This can be achieved with the *setDelayHardware()* feature. After applying the Conditional Filter, the laser can be “pushed back” in software with *setDelaySoftware()*. See the in-depth guide *Conditional Filter* for details.

```

laser_frequency = 100e6 # 100 MHz
laser_period = 1/laser_frequency * 1e12 # picoseconds

tt.setDelayHardware(LASER_CH, int(laser_period)) # Delay is specified in picoseconds
tt.setDelayHardware(DETECTOR_1_CH, 0) # Default value is 0

tt.setConditionalFilter(trigger=[DETECTOR_1_CH], filtered=[LASER_CH])
tt.setDelaySoftware(LASER_CH, -int(laser_period))

```

This approach extends to multiple lasers and detectors.

#### Note

If fixed delays exist between laser and detector (e.g., cable length or device latency), compensate them first with per-channel hardware delays via *setDelayHardware()*.

On pulsed-laser setups, autocorrelation often benefits from aligning bin edges to integer multiples of the laser period. This is supported by *HistogramCustomBins* and not by *HistogramLogBins*. In the following example, we run these two measurements in parallel by using *SynchronizedMeasurements* and compare the results. The only difference between the two analyses is the time binning: the custom bin edges are aligned precisely to integer multiples of the laser period, while *HistogramLogBins* uses a purely logarithmic grid.

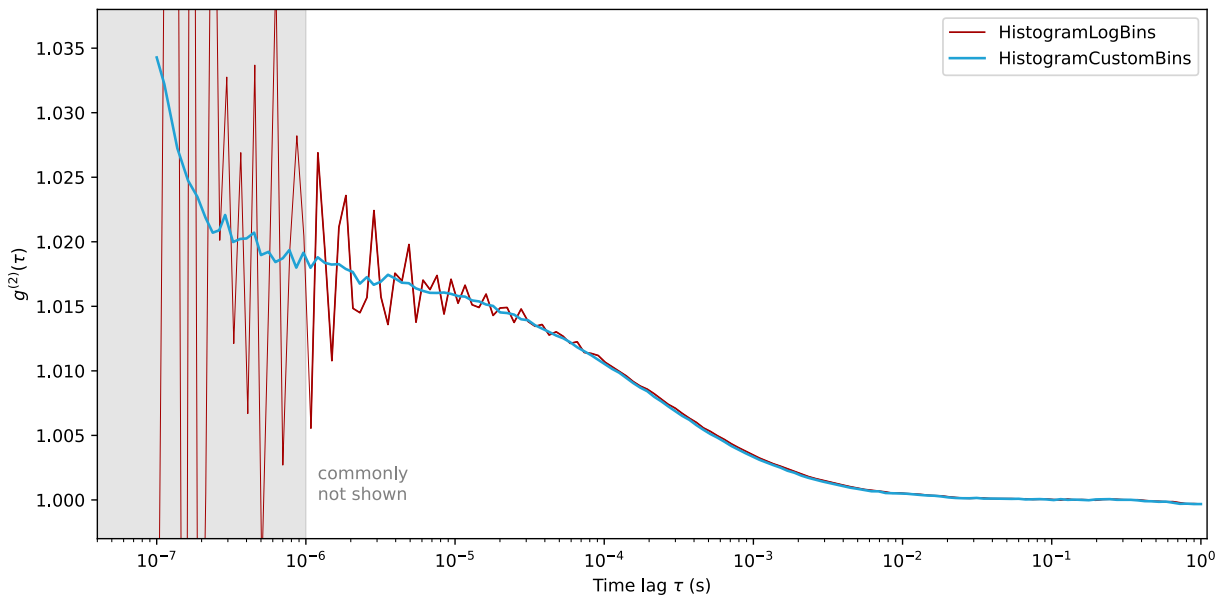
```
hist_log_bins = TimeTagger.HistogramLogBins(sync_proxy, DETECTOR_1_CH, DETECTOR_1_CH,
                                           exp_start, exp_stop, n_bins)

# Example of custom bin edges starting from logarithmic grid (picosecond units)
log_bin_edges = np.logspace(exp_start, exp_stop, num=n_bins + 1, base=10.0, dtype=np.
    ↪float64) * 1e12

custom_bin_edges = np.round(log_bin_edges / laser_period) * laser_period
custom_bin_edges = np.unique(custom_bin_edges) # remove duplicates

hist_cust_bins = TimeTagger.HistogramCustomBins(tagger=sync_proxy,
                                                click_channel=DETECTOR_1_CH,
                                                start_channel=DETECTOR_1_CH,
                                                binedges=custom_bin_edges)
```

The effect of aligning bin edges to the laser period is most evident at short lag times. When a purely logarithmic grid is slightly misaligned with the laser pulse train, especially below 10 microseconds, *HistogramLogBins* can produce a spiky correlation trace. By contrast, *HistogramCustomBins* uses period-aligned edges, yielding a smoother correlation curve at short timescales.



As a reminder, for extended runs, the laser stability can affect the analysis. A practical mitigation is to lock the Time Tagger to the laser via *setReferenceClock()*, keeping detector timestamps phase-aligned to the pulse train. When operated with the Reference Clock, the system also supports the Conditional Filter functionality, as discussed in the in-depth guide *Software-Defined Reference Clock*.

### 3.3.7 Spectral Overlap and Pulsed Interleaved Excitation

FCCS with two or more lasers and detectors can be set up as described in the section *Fluorescence Cross-Correlation Spectroscopy*. Additionally, you can measure fluorescence lifetime on the same time tags stream in parallel. This can be achieved by using the *SynchronizedMeasurements* class together with the *Histogram* measurement.

```
lifetime_binwidth = 100 # ps
n_bins = 250

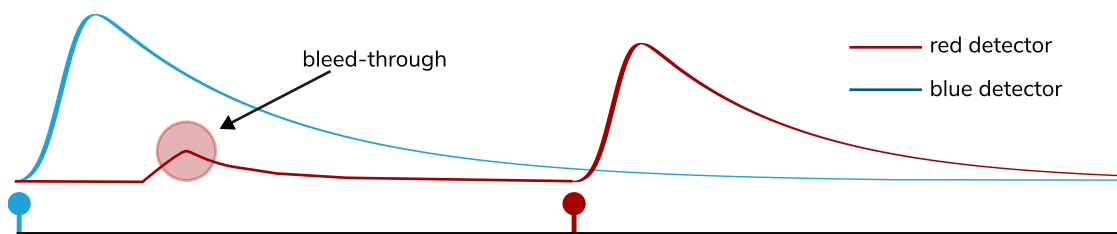
hist_cust_bins = TimeTagger.HistogramCustomBins(tagger=sync_proxy,
                                                click_channel=DETECTOR_1_CH,
                                                start_channel=DETECTOR_2_CH,
                                                binedges=custom_bin_edges)

hist_1 = TimeTagger.Histogram(tagger=sync_proxy,
                              click_channel=DETECTOR_1_CH,
                              start_channel=LASER_CH,
                              binwidth=lifetime_binwidth,
                              n_bins=n_bins)

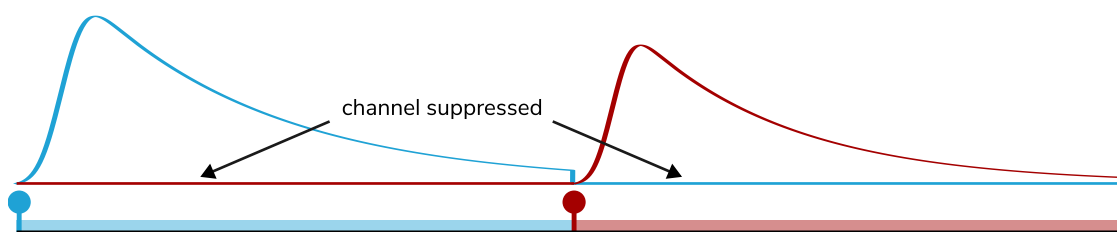
hist_2 = TimeTagger.Histogram(tagger=sync_proxy,
                              click_channel=DETECTOR_2_CH,
                              start_channel=LASER_CH,
                              binwidth=lifetime_binwidth,
                              n_bins=n_bins)
```

Dual-color FCCS setups may introduce spectral cross-talk between fluorophores. This can be identified by exciting one laser at a time and inspecting the intensity trace or the lifetime histogram of both detectors. In Step 1 of the sketch below, the blue laser excites both the blue and the red fluorophore (bleed-through). In the next step, the red laser excites the red fluorophore in the red detector channel as expected.

## Step 1 - Interleave laser pulses



## Step 2 - Gate detector clicks



A practical way to suppress spectral overlap is pulsed interleaved excitation (PIE). PIE is typically performed in two steps:

1. Interleave the lasers in time: laser 1 is triggered, a defined delay (often comparable to the fluorescence lifetime) elapses, and laser 2 is triggered. This temporal separation allows each detected photon to be associated with its excitation laser.
2. Gate the detector channels: short time windows are applied so that each detector accepts photons only in the interval that follows its own laser pulse. For example, the red detector channel is open immediately after the red laser pulse; the blue detector channel is open immediately after the blue laser pulse. This gating ensures that each detected photon is attributed to the correct excitation source.

An example implementation, using the [Pulse Streamer](#) to drive the lasers and the Time Tagger to define the gates in software, is shown below. The laser period and pulse duration are experiment-dependent. Detector channels are gated with [DelayedChannel](#) (to define the stop edge) and [GatedChannel](#).

```
from pulsestreamer import PulseStreamer
ps = PulseStreamer('pulsestreamer')

LASER_blue = 1
LASER_red = 2
DET_blue = 3
DET_red = 4
... # configure trigger levels, hardware delays, conditional filters

pulse_pattern_blue = [(2, 1), (24, 0)] # 2 ns HIGH, 24 ns LOW
pulse_pattern_red = [(13, 0), (2, 1), (11, 0)] # 13 ns low (pulse period), 2 ns HIGH, 11 ns LOW
```

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```

seq = ps.createSequence()
seq.setDigital(0, pulse_pattern_blue) # connect PS channel 0 to blue laser
seq.setDigital(1, pulse_pattern_red) # connect PS channel 1 to red laser
ps.stream(seq) # start the pulse stream

# define gates using delayed channels
pulse_period = 13_000 # ps
blueStop = TimeTagger.DelayedChannel(tt, LASER_blue, pulse_period)
redStop = TimeTagger.DelayedChannel(tt, LASER_red, pulse_period)

blueGate = TimeTagger.GatedChannel(tt, [DET_blue], LASER_blue, blueStop.getChannel())
redGate = TimeTagger.GatedChannel(tt, [DET_red], LASER_red, redStop.getChannel())

red_channel = redGate.getChannel()
blue_channel = blueGate.getChannel()
... # use red_channel and blue_channel for FCS, FCCS, lifetime analysis, etc.
    # instead of the original DET_blue and DET_red channels

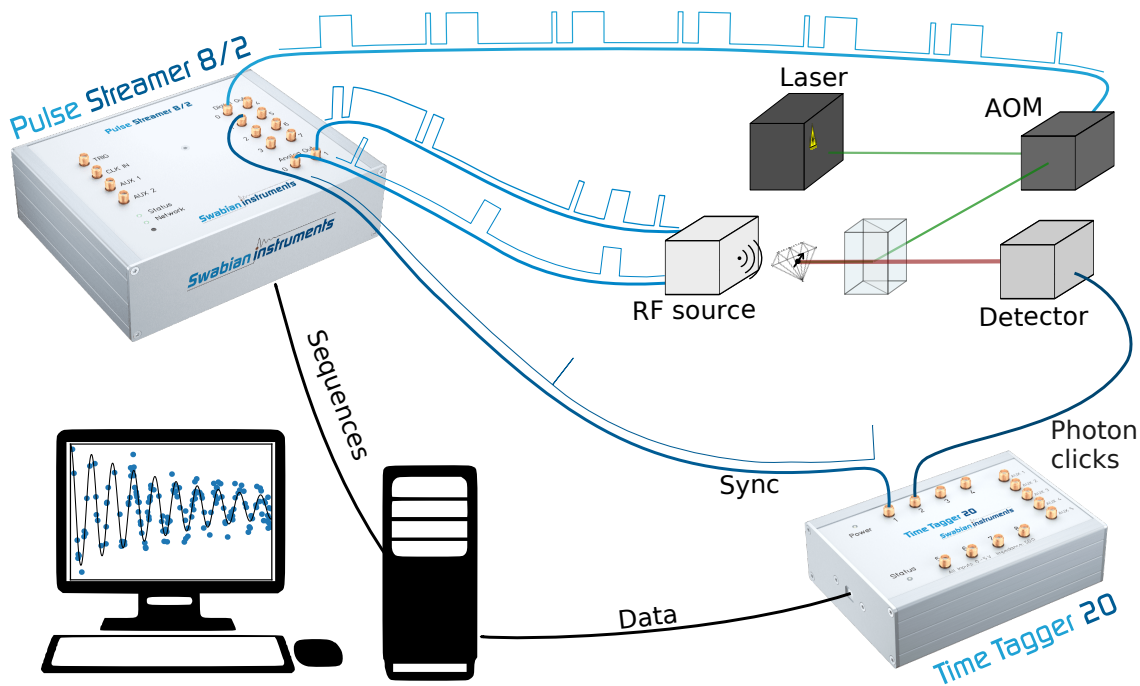
```

PIE separates the blue and red fluorescence signals with minimal spectral cross-talk, producing per-excitation FCS/FCCS traces. Gating operates in real time, so acquisition and analysis remain live. The same approach can be combined with scanning to obtain spatially resolved FCS maps across multiple pixels.

## 3.4 Optically Detected Magnetic Resonance

Optically detected magnetic resonance (ODMR) is a spectroscopic technique used to study electron spins in materials. It involves applying sequences of optical and microwave pulses to manipulate and probe the spin states of electrons. By analyzing the response of the material's photoluminescence to these pulses, valuable information about the spin properties and dynamics can be obtained. This technique is particularly useful for studying spin-based quantum technologies and materials such as diamond NV centers, as also shown in this [application note](#).

This tutorial shows how to set up a pulsed ODMR experiment using our Time Taggers and Pulse Streamer. Pulsed ODMR offers distinct advantages over continuous mode, including enhanced contrast and reduced sensitivity to laser power fluctuations. Leveraging Time Taggers provides precise timing control for accurate data acquisition and analysis, making it ideal for probing fast spin dynamics with high resolution.



### 3.4.1 Creation of optical and microwave pulse patterns

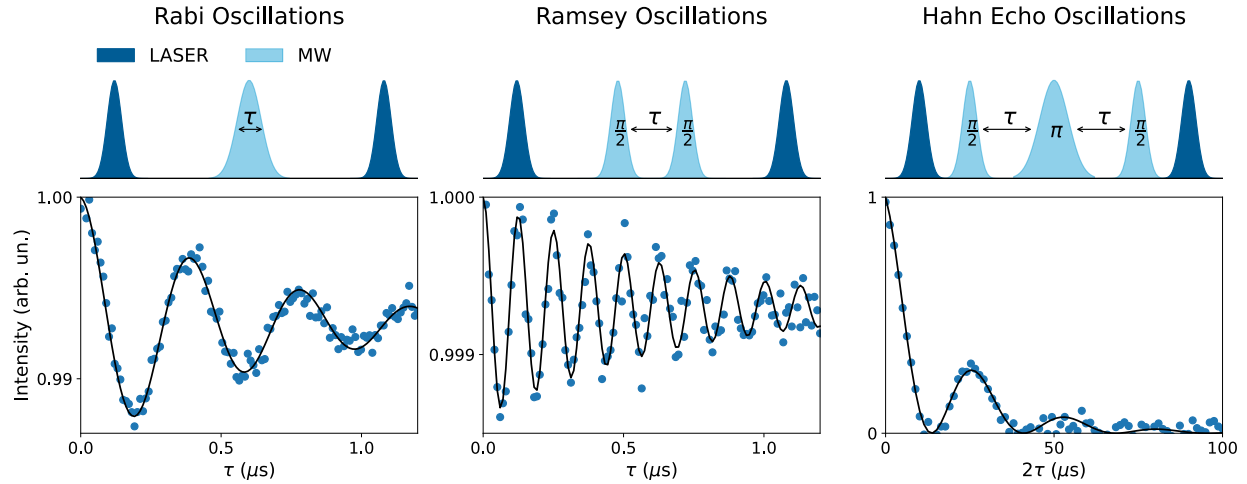
In this tutorial we consider a spin-1 system. In most sequences, an initial optical pulse serves to initialize the system, e.g., preparing it in state  $|m_s = 0\rangle$ . Following this initialization, a series of microwave (MW) pulses and free evolution periods manipulate the spin state. Finally, a second optical pulse interrogates the spin state projection along the  $(|m_s = 0\rangle, |m_s = +1\rangle)$  basis, often via optical emission or absorption intensity, while also resetting the system for subsequent measurements. Various pulse sequences are commonly employed for different measurements:

1. **Rabi Oscillation Sequence:** In this sequence, a single MW pulse of variable duration is applied, causing the spin to oscillate between the  $|m_s = 0\rangle$  and  $|m_s = +1\rangle$  states. The amplitude of the Rabi oscillations provides information about the energy splitting between the two states. From this measurement the duration of  $\pi$ - and  $\pi/2$ -pulses can be inferred as half and quarter periods of the oscillations, respectively.
2. **Ramsey Sequence:** This sequence involves two  $\pi/2$  MW pulses separated by a variable delay. The delay time determines the phase relationship between the two pulses, affecting the interference pattern observed in the spin state. Analysis of the Ramsey fringes allows for precise measurement of the spin coherence time  $T_2^*$ .
3. **Hahn Echo Sequence:** In this sequence, a  $\pi/2$ -pulse is followed by a delay time and then a  $\pi$ -pulse. The second pulse flips the spin state, and the delay allows for dephasing to occur. The echo signal observed after the  $\pi/2$ -pulse provides information about the spin dephasing time  $T_2$ .

To create any of these sequences, we make use of the Sequence class of our Pulse Streamer 8/2. This class allows to independently set pulse patterns on each channel. A pulse pattern is represented by a tuple in the form (duration, level). The duration is always specified in nanoseconds and the level is either 0 or 1 for digital output.

First of all, we connect to the Pulse Streamer.

```
# Change the following line to use your specific Pulse Streamer IP address
ip_hostname='169.254.8.2'
pulser = PulseStreamer(ip_hostname)
```



Next, we declare the channels names, and all the relevant parameters for creating a sequence to measure Rabi Oscillations and quantifying the duration of a  $\pi$ -pulse. To achieve this, we need to create the following patterns:

1. A pattern to drive the laser, enabling it to emit optical pulses for system initialization and readout.
2. A pattern to drive a high isolation microwave switch for gating the microwave pulses.
3. A pattern for synchronization purposes.
4. A pattern to measure the incoming photons during the readout pulse for time-gated analysis.

```
# Channel names
OPTICAL_CH = 0
MW_CH = 1
SYNC_CH = 2
GATE_CH = 3
# Digital levels
HIGH=1
LOW=0

# Change the values according to your experiment
PERIOD = 8000 # period of each pattern
INIT_PULSE_DUR = 2000 # width of initialization optical pulses
READOUT_PULSE_DUR = 300 # width of readout optical pulses
PAUSE = 1000 # time between a readout and next initialization pulse
```

We define then a set of values over which the MW pulse duration ( $\tau$ ) is swept, to ultimately build the desired pulse patterns.

```
tau = np.arange(100, 2000, 100)

# For each selected MW pulse width, the experiment is repeated multiple times
N_LOOPS = 1000

# Optical pattern
optical_patt = [(INIT_PULSE_DUR, HIGH), (PERIOD-INIT_PULSE_DUR-READOUT_PULSE_DUR-PAUSE, LOW),
                (READOUT_PULSE_DUR, HIGH), (PAUSE, LOW)]*N_LOOPS*len(tau)
```

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```

# MW pattern
# Initialize the MW pulse pattern
mw_patt = []
for ti in tau:
    mw_patt.extend([(INIT_PULSE_DUR, LOW), (ti, HIGH), (PERIOD-INIT_PULSE_DUR-ti,
    LOW)]*N_LOOPS)

# Pulse pattern that marks a new value of a MW pulse duration
sync_patt = [(10, HIGH), (PERIOD*N_LOOPS-10, LOW)]*len(tau)
# Add last sync pulse to the pattern to mark the end of the acquisition
sync_patt.extend([(10, HIGH)])

# Pattern for gating detector clicks
gate_patt = [(PERIOD-READOUT_PULSE_DUR-PAUSE, LOW), (READOUT_PULSE_DUR,HIGH),
              (PAUSE, LOW)]*N_LOOPS*len(tau)

# Set channels using class Sequence
seq = Sequence()
seq.setDigital(OPTICAL_CH, optical_patt)
seq.setDigital(MW_CH, mw_patt)
seq.setDigital(SYNC_CH, sync_patt)
seq.setDigital(GATE_CH, gate_patt)

# Display your sequence
seq.plot()

```

### 3.4.2 Signal generation and detection

To perform ODMR measurements, we connect the Time Tagger and declare the channels used. Here, we can also adjust the hardware settings for each channel.

```

tagger = createTimeTagger()
GATE = 1
SYNC = 2
DETECTOR = 3

```

Then, we need to filter the incoming detector clicks revealed by the Time Tagger according to the generated gate pattern. This can be done at the software level by employing the virtual channel [GatedChannel](#). The rising and falling edges of the gate signal are used to open and close each time gate, respectively.

```

gated_detector_vch = GatedChannel(tagger, DETECTOR, GATE, -GATE)
# Get the channel number that will be used in the CBM measurement
gated_detector = gated_detector_vch.getChannel()

```

Next, we set up a [CountBetweenMarkers](#) measurement to count the filtered events on a detector channel between sync events, that herald the change of the MW pulse width. The counts are accumulated in an array whose number of bins is equal to the number of  $\tau$  values.

```

cbm = CountBetweenMarkers(tagger, gated_detector, SYNC, CHANNEL_UNUSED, len(tau))
cbm.start()
tagger.sync()

```

Now that the measurement is set up, the sequence can be run by the Pulse Streamer and the events counted by the Time Tagger. We run the sequence once

```
N_RUNS = 1
final = OutputState.ZERO()
pulser.stream(seq, N_RUNS, final)
```

and we collect the data

```
ready = False

# Periodically get data until the CountBetweenMarkers completes the acquisition
while ready is False:
    time.sleep(.2)
    # Check if the measurement is ready
    ready = cbm.ready()
    counts = cbm.getData()
    # You may add progress visualization code here
```

### 3.4.3 Sweeping modes

There are different ways to acquire and accumulate data in these pulsed ODMR experiments. We report here two protocols to collect events to visualize Ramsey oscillations.

In the first method, the interpulse delay  $\tau$  is swept and the data are collected in a single acquisition step after executing the whole sequence. The example code is analogous to the one of the previous paragraph, except for the construction of the Ramsey sequence.

```
DUR_PI = 200 # Change value according to the outcome of Rabi measurement
tau = np.arange(100, 1500, 100) # Interpulse time delay

mw_patt = []
for ti in tau:
    mw_patt.extend([(INIT_PULSE_DUR, LOW), (DUR_PI/2, HIGH), (ti, LOW),
                    (DUR_PI/2, HIGH), (PERIOD-ti-DUR_PI-INIT_PULSE_DUR, LOW)]*N_LOOPS)
```

In the second approach, we repeat the sequence for the same interpulse delay multiple times, as usual, and accumulate the data before changing the interpulse delay.

```
#The optical, the sync and gate patterns do not depend on the interpulse delay
optical_patt = [(INIT_PULSE_DUR, HIGH), (PERIOD-INIT_PULSE_DUR-READOUT_PULSE_DUR-PAUSE, LOW),
                (READOUT_PULSE_DUR, HIGH), (PAUSE, LOW)]*N_LOOPS
sync_patt = [(10, HIGH), (PERIOD*N_LOOPS-10, LOW)]
sync_patt.extend([(10, HIGH)])
gate_patt = [(PERIOD-READOUT_PULSE_DUR-PAUSE, LOW), (READOUT_PULSE_DUR,HIGH), (PAUSE, LOW)]*N_LOOPS

seq = Sequence()
seq.setDigital(OPTICAL_CH, optical_patt)
seq.setDigital(SYNC_CH, sync_patt)
seq.setDigital(GATE_CH, gate_patt)
```

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```

counts = []

# For each interpulse delay, events on the detector channel
# between two sync marker events are accumulated
cbm = CountBetweenMarkers(tagger, gated_detector, SYNC, CHANNEL_UNUSED, 1)
tagger.sync()

mw_patt = []
for ti in tau:
    mw_patt = [ (INIT_PULSE_DUR, LOW), (DUR_PI/2, HIGH), (ti, LOW),
                (DUR_PI/2, HIGH), (PERIOD-ti-DUR_PI-INIT_PULSE_DUR, LOW)]*N_LOOPS

    seq.setDigital(MW_CH, mw_patt)

    cbm.start()

    # Run the sequence
    pulser.stream(seq, N_RUNS, final)

    ready = False

    # Get data every while
    while ready is False:
        time.sleep(.2)
        ready = cbm.ready()
        data = cbm.getData()

    # Store the total counts for each interpulse delay into an array
    counts.append(data)

```

### 3.4.4 ODMR contrast

Quantifying the ODMR contrast, defined as the differential photoluminescence signal between measurements with and without applying microwave radiation, is crucial for several reasons. It serves as a direct indicator of the efficiency of spin manipulation and the sensitivity of the measurement setup. High contrast values typically correspond to better signal-to-noise ratios, enabling more precise determination of resonance frequencies and spin relaxation times.

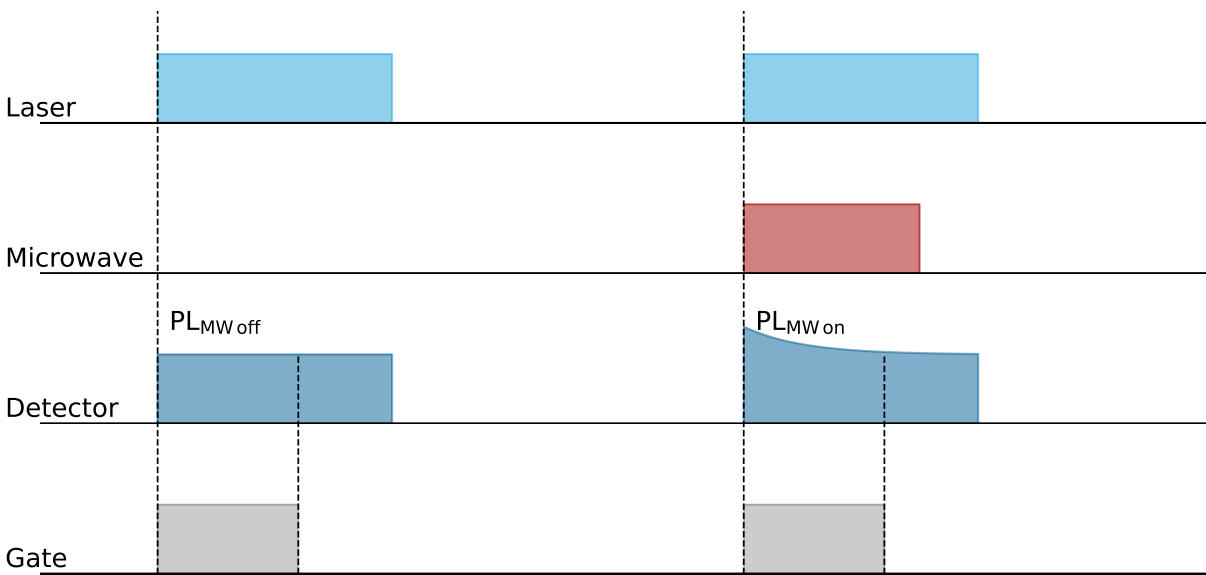
The schematics of this measurement is reported in the figure below. This trivial sequence is repeated for each different microwave frequency selected, to obtain in the end an ODMR spectrum.

For the data acquisitions, there are two possible implementations:

1. **A single CountBetweenMarkers measurement:** the rising and falling edges of the gate are used as *begin\_channel* and *end\_channel*, respectively, and  $2N$  as *n\_values*, where  $N$  is the number of frequencies to measure. In the output array, one gets, for each frequency, the counts while the MW is off in the even bins (0,2,4,6,...) and the counts while the MW is on in the odd bins (1,3,5,7,...).

```
cbm = CountBetweenMarkers(tagger, DETECTOR, GATE, -GATE, 2N)
```

2. **Two different CountBetweenMarkers measurements:** one collects counts when the MW frequency is on and one when the MW frequency is off. In this case MW indicator pulses are needed as markers. For the first *CountBetweenMarkers* the rising and the falling edges of the MW indicator pulse are used as *begin\_channel* and *end\_channel*, respectively. On the contrary, for the second measurement the falling edge of the MW indicator pulse is used as *begin\_channel* and the rising edge as *end\_channel*. The gate signal should be used to filter the detector clicks



at the software level using the the virtual channel [GatedChannel1](#), as described in the previous paragraph. This ensures the same acquisition time, for each frequency, when the microwave is on and when it is off.

```
MW_IND = 4

# Create a SynchronizedMeasurements instance that allows you to process the same tags
synchronized = SynchronizedMeasurements(tagger)
sync_tagger_proxy = synchronized.getTagger()

# Accumulate counts when the MW is on
cbm_mw_on = CountBetweenMarkers(sync_tagger_proxy, gated_detector, MW_IND, -MW_IND, N)

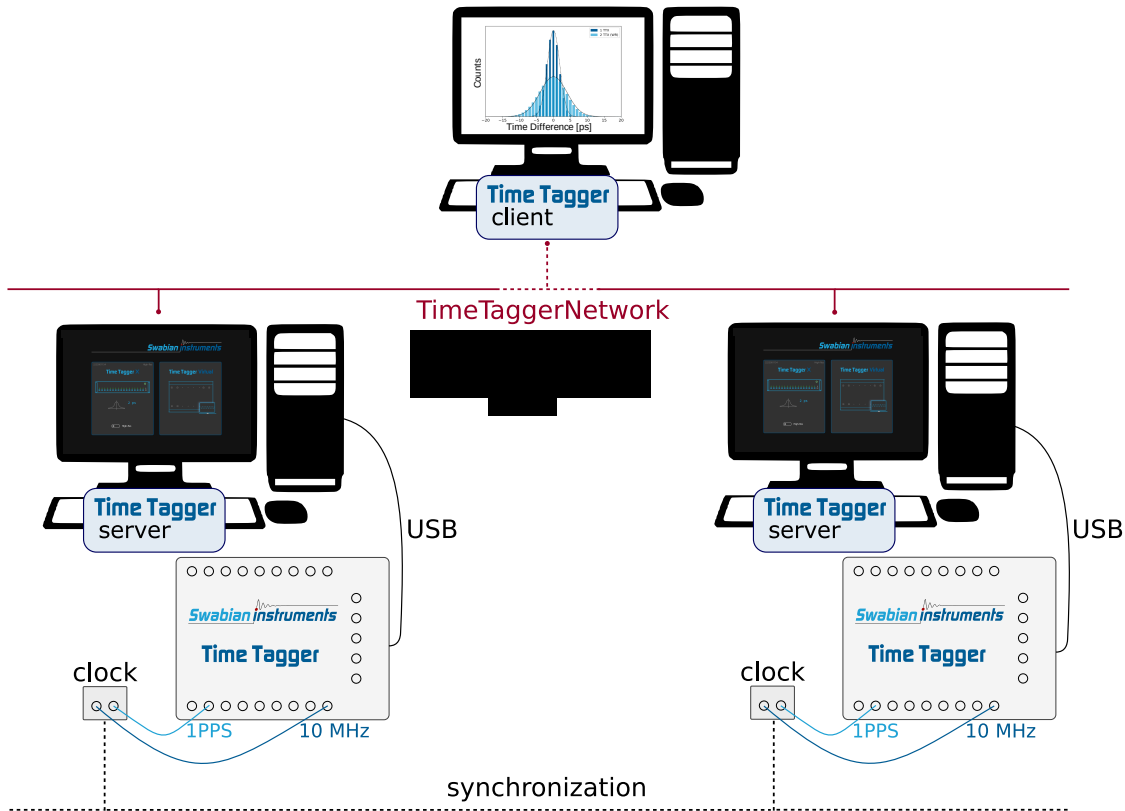
# Accumulate counts when the MW is off
cbm_mw_off = CountBetweenMarkers(sync_tagger_proxy, gated_detector, -MW_IND, MW_IND, N)
```

### 3.5 Remote Synchronization of Time Taggers

In high-precision applications such as distributed time monitoring, telecommunications, quantum communication, and quantum key distribution, synchronizing time-tagging devices across remote locations is crucial. When Time Taggers operate independently, their clocks run free, and even small differences in their frequencies accumulate over time, creating significant timing discrepancies across multi-device setups.

To overcome this challenge, a synchronization-agnostic and versatile approach is employed. This method supports any synchronization technology that provides a frequency reference signal (e.g., 10 MHz) and a 1PPS (Pulse Per Second) timing signal, as shown in the figure below. For example, the [White Rabbit](#) is a widely adopted technology that enables picosecond-level synchronization precision with sub-nanosecond accuracy across remote setups, as detailed in this [application note](#). The synchronization process relies on the two timing signals combined with software-based solutions, including functionalities such as the ReferenceClock, to unify the time bases of the distributed Time Taggers. Users must ensure that their hardware infrastructure supports the required synchronization signals to enable this functionality. Moreover, when using the ReferenceClock with *Time Tagger 20*, an inherent timing error of approximately 200 ps needs to be considered. More details can be found in the [setReferenceClock\(\)](#) documentation and the related in-depth guide (*Software-Defined Reference Clock*).

This tutorial demonstrates how to achieve remote synchronized operation of Time Taggers. It provides a step-by-step guide to synchronizing multiple Time Taggers across distributed locations, unifying their time bases, and merging time tag streams from remote network nodes for real-time processing using the *TimeTaggerNetwork* functionality, which supports simultaneous connections to multiple servers from version 2.18 onward.



### 3.5.1 Establishing a common time base across distributed locations

A critical step in synchronizing Time Taggers across remote locations is establishing a unified time base. Within our approach, this is achieved by associating the 1PPS signal fed into the Time Tagger, which is generated at each location with an external clock locked to a Grand Master (GM), with the Coordinated Universal Time (UTC) provided by the host PC. To ensure accurate synchronization, the PC clocks at all locations must remain aligned to UTC with a time shift of less than 0.5 seconds. Synchronizing the PC clock is therefore essential because it allows the system to associate the 1PPS signal at each location with the correct UTC second, ensuring that all timing data is unified under a common temporal framework.

The PC clock alignment to UTC can be achieved using reliable synchronization protocols such as Network Time Protocol (NTP) or Precision Time Protocol (PTP). Standard operating system synchronization tools (e.g., Windows Time Service, Linux's *ntpd* or *chrony*) configured to synchronize with either publicly available or internal time servers, are sufficient to maintain synchronization shift below 0.5 seconds. For enhanced robustness, ease of use, or advanced configuration options, dedicated synchronization software solutions such as the [Meinberg NTP](#) software package are recommended.



### 3.5.2 Starting a Time Tagger Server at each location

Once the PC clocks at all locations are aligned to UTC, the next step is to configure each Time Tagger to operate within a unified time base. By default, timestamps generated by a Time Tagger are relative to when the device was initialized in software. This means that if multiple Time Taggers start at different times, identical physical events occurring simultaneously at different locations receive different timestamps.

To synchronize the Time Taggers, enabling measurements across time tag streams generated at remote locations, the ReferenceClock must be activated. This ensures that all Time Taggers apply a UTC-based offset to their time base, allowing simultaneous events at remote locations to receive identical timestamps, regardless of when each Time Tagger was started. The ReferenceClock achieves this by locking the internal clock to an external distributed frequency reference (e.g., 10 MHz) and using the 1PPS signal to establish absolute time alignment. To guarantee that the 1PPS edge is associated with the correct UTC second, the *synchronization\_offset* argument in the `setReferenceClock()` function can be specified to compensate any constant phase offset between the computer's system time and the PPS signal. Initially, the *synchronization\_offset* parameter can be set to 0, allowing the Time Tagger to determine the required offset and prompt the user with a warning if the system time is badly aligned to the 1PPS signal. In such a case, the lock is released and the `setReferenceClock()` function must then be called again by the user with the reported offset (in ps) to establish and maintain a stable lock.

To set up each Time Tagger, a connection to the device is first established in software. Hardware settings such as trigger levels and dead time should be configured according to the specific measurement requirements. Then, the ReferenceClock is enabled, aligning the internal time base with the external synchronization signals. Finally, a server is started on the host PC, making the Time Tagger accessible over the network for real-time data collection.

```
from Swabian import TimeTagger

# Connect to the Time Tagger via USB
tagger = TimeTagger.createTimeTagger()

# Declare the channel names and corresponding physical connections
frequency_channel = 1
PPS_channel = 2

# Define the hardware settings here, such as trigger level or dead time.

# Enable the ReferenceClock
tagger.setReferenceClock(clock_channel=frequency_channel,
                        clock_frequency=10e6,
                        time_constant=1e-4,
                        synchronization_channel=PPS_channel,
                        synchronization_offset=0,
                        wait_until_locked=True)

# Start the Server.
# TimeTagger.AccessMode sets the access rights for clients.
# Port defines the network port to be used
tagger.startServer(access_mode=TimeTagger.AccessMode.Control, port=41101)
```

**Warning**

Activating the ReferenceClock shifts and rescales the internal time base of the Time Tagger. As a result, all ongoing measurements on every channel will be affected. Data recorded after activating the ReferenceClock will no longer be comparable with data acquired beforehand from the same Time Tagger instance.

### 3.5.3 Connecting to multiple Time Tagger Servers over the network

Once the Time Tagger servers are running at different locations, a client PC can connect to them to retrieve and process synchronized measurement data. The connection process relies on network communication, where the client searches for available Time Tagger servers and establishes a link to them.

To automatically discover servers on the local network, the function `scanTimeTaggerServers()` is used. This function sends multicast UDP messages to detect active Time Tagger servers and retrieve their IP addresses. However, its effectiveness depends on the network configuration. Since multicast messages typically remain within the same local subnet, their ability to reach servers across different subnets depends on whether the network routers forward multicast packets. If the function does not detect any servers, it is likely that multicast routing is either not enabled or unreliable in the network. In cases where `scanTimeTaggerServers()` fails to find a server, the user needs to know the IP addresses and network ports of the servers to connect to, when calling `createTimeTaggerNetwork()` on the client PC.

```
# Use the scanTimeTaggerServers() function to search for Time Tagger servers in the
↪ local network
servers = TimeTagger.scanTimeTaggerServers()
print("{} servers found.".format(len(servers)))
print(servers)

# Create a TimeTaggerNetwork instance and connect to the desired servers
server_addresses = ["192.168.1.100:41101", "192.168.1.101:41101"] # Replace with the
↪ IPs of the servers to connect to
ttn = TimeTagger.createTimeTaggerNetwork(server_addresses)
```

**Warning**

When a `TimeTaggerNetwork` object is created and connected to multiple servers, the time tag streams from different locations are merged into a unified data stream for measurements. This merging process relies on a sorting algorithm and requires that all incoming time tag streams have similar timestamps, meaning the Time Taggers must be properly synchronized. If the time bases are not aligned, stream merging fails.

### 3.5.4 Accessing individual servers

When using a `TimeTaggerNetwork` object to connect to multiple Time Tagger servers, it is possible to access and control each individual server separately. This is particularly useful when extracting detailed device-specific information that is not channel-dependent, such as checking overflow states using methods like `getOverflows()`.

The `getServers()` method of the `TimeTaggerNetwork` class returns a list of `TimeTaggerServer` objects, each representing one of the connected servers. These server objects act as proxies, providing access to all relevant control functions available in `TimeTaggerBase` and `TimeTaggerHardware`, as long as the servers were created with `AccessMode::Control` privileges. Unlike the `TimeTaggerNetwork` object, a `TimeTaggerServer` object cannot be used to perform measurements directly. Namely, it is not possible to pass the `TimeTaggerServer` object on to any measurement creator.

For example, to retrieve overflow information from a specific server:

```
# Retrieve the list of connected Time Tagger servers
servers = ttn.getServers()

# Access a specific server
server_A = servers[0]

# Retrieve overflow information from the server
overflows = server_A.getOverflows()
```

It is also possible to adjust hardware settings using either the *TimeTaggerServer* object or the globally mapped channels via the *TimeTaggerNetwork* object. Both approaches yield the same result:

```
# Adjust dead time via the server object
server_A.setDeadtime(1, 1000)

# Equivalent operation using TimeTaggerNetwork global channel mapping
ttn.setDeadtime(1001, 1000)
```

With the current Software, using *TimeTaggerServer* objects for configuration is primarily a convenience, as they serve as proxies for direct interaction with specific servers. However, *TimeTaggerServer* provides four specific functions that are not available in *TimeTaggerNetwork*: *getAddress()*, *getAccessMode()*, *getClientChannel()*, *getReferenceClockState()*.

### 3.5.5 Verification of the synchronization technology using a single Time Tagger

To evaluate the precision of the synchronization technology, a single Time Tagger can be used before considering a multi-device setup. The proposed verification consists of enabling the ReferenceClock on one external reference, typically the master if there is a hierarchy, and using a second external reference as an input to the *FrequencyStability* measurement class. This allows direct analysis of the synchronization precision using built-in measurement tools.

The measurement provides stability metrics such as Allan Deviation (ADEV), Modified Allan Deviation (MDEV), and Time Deviation (TDEV), which quantify timing fluctuations over different timescales. These results characterize the synchronization performance and provide a reference before working with multiple Time Taggers.

The first external reference is connected to an input channel and used to enable the ReferenceClock. Since all analyses are performed on the same hardware, there is no need for a PPS signal for time synchronization. The second and additional external references are fed into other input channels and analyzed using the *FrequencyStability* measurement. The measurement runs over a range of averaging times to extract stability metrics.

```
import numpy as np
import time

# Define synchronization channels
ch_master = 1
ch_slave = 2

# Enable the ReferenceClock using the first external reference
tt.setReferenceClock(clock_channel=ch_master, clock_frequency=10e6)

# Define measurement steps (logarithmically spaced averaging times)
steps = np.unique(np.logspace(0, 7, 100, dtype=np.int64))

# Initialize Frequency Stability measurement on the second reference
fs = TT.FrequencyStability(tt, ch_slave, steps, average=1)
```

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```
# Allow the measurement to collect data
time.sleep(100) # Adjust as needed

# Retrieve frequency stability results
obj = fs.getDataObject()
tau = obj.getTau()
ADEV = obj.getADEV()
TDEV = obj.getTDEV()
MDEV = obj.getMDEV()
```

### 3.5.6 Measuring synchronization precision across multiple Time Taggers

Before starting experiments where Time Taggers are deployed in remote locations, it is useful to verify the synchronization precision while the units are still physically close to each other. This ensures that the synchronization setup is working correctly before the Time Taggers are separated.

The verification follows the method described in Swabian Instruments' [application note](#) on remote synchronization. A common test signal is split using a power splitter or any other method that guarantees that identical copies of the signal are fed into both Time Taggers. The signal is then connected to an input channel of each device. The [Correlation](#) measurement class is used to analyze the arrival times of events recorded by both Time Taggers, providing a direct measure of synchronization precision.

The measurement is performed using the *TimeTaggerNetwork* in a dual-server setup, as discussed in the previous sections.

```
import matplotlib.pyplot as plt

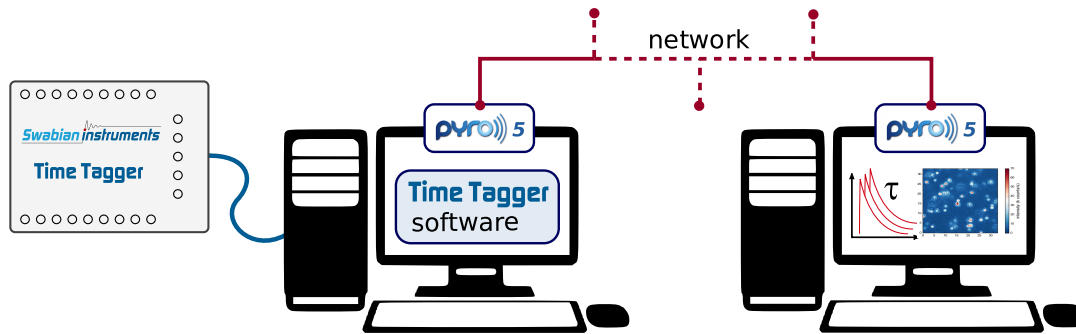
# Define the correlation measurement between input channels on both Time Taggers
# We assume the test signal is fed into the third input of each Time Tagger
corr = TimeTagger.Correlation(ttn, 1003, 2003, binwidth=1, n_bins=1000)

# Start the measurement and run it for a given time
corr.startFor(10e12)
corr.waitUntilFinished()

# Retrieve the correlation data
index = corr.getIndex()
counts = corr.getData()

# Plot the correlation result
plt.plot(index, counts)
plt.xlabel("Time Difference (ps)")
plt.ylabel("Counts")
plt.title("Correlation of Synchronized Time Taggers")
plt.grid()
plt.show()
```

## 3.6 Remote Time Tagger with Python



The **Time Tagger** is a great instrument for data acquisition whenever you detect, count, or analyze single photons. You can quickly set up a time correlation measurement, coincidence analysis, and much more. However, at some point in your project, you may want to control your experiment remotely. One option is to use remote desktop software like VNC, TeamViewer, Windows Remote Desktop, etc. What if you want to control your remote experiment programmatically? Are you using multiple computers and want to collect data from many of them at the same time? The solution for this is a remote control interface. Luckily, this task is very common and many software libraries cover the challenge of dealing with network sockets and messaging protocols.

In the following, we want to demonstrate two ways of connecting to a Time Tagger over a network: *Network Time Tagger* and *Pyro5*.

By using *Network Time Tagger*, a remote computer has direct access to the Time Tag stream and can perform measurements locally, as if the Time Tagger was directly connected over USB. *Network Time Tagger* is an ideal solution for sharing a Time Tagger between different computers. Moreover, it is the only way to connect to multiple Server Time Taggers with a single software object, enabling the processing of Time Tag streams from different servers on-the-fly. On the other hand, *Pyro* can be used to access a Time Tagger remotely. From a remote computer, *Pyro* can start measurements on the computer connected to the time tagger and return the results.

### 3.6.1 Sharing a Time Tagger with Network Time Tagger

From Time Tagger software version 2.10 onward, Time Tagger supports remote operation ‘out-of-the-box’ with *Network Time Tagger*. *Network Time Tagger* implements a server on a computer connected to a Time Tagger and sends the Time Tag stream directly to the clients. Clients can then connect to the server and run arbitrary measurements independently on their own computers as if they are directly connected to the hardware device.

The server can be set up with the Time Tagger Graphical User Interface (Time Tagger Lab) or the Time Tagger API through `TimeTagger::startServer()`. When setting up the server, the host can decide on the level of access for the clients. With `AccessMode::Control`, the clients have full access to data from all channels and can change the settings of the Time Tagger. With `AccessMode::Listen`, the host can decide to only share data from specific channels.

Clients can connect to the server using the Time Tagger API with `createTimeTaggerNetwork()`. Once connected, measurements can be performed directly on the client side. Function calls are identical to the ones used to control a Time Tagger locally. Therefore, programs written with the Time Tagger API can be easily adapted to run on a remote computer.

#### Note

*Network Time Tagger* can also be used to access a Time Tagger with different programming languages at the same time, both locally or on a remote computer. With `createTimeTaggerNetwork()`, it is for example possible to run simultaneous measurements with MATLAB and Python.

Below is a minimal working example for setting up a Network Time Tagger server and client with Python 3.6.

Listing 1: Starting a Network Time Tagger server

```
from Swabian import TimeTagger

tagger = TimeTagger.createTimeTagger()
#connect to the Time Tagger via USB

tagger.startServer(access_mode = TimeTagger.AccessMode.Control, port=41101)
# Start the Server. TimeTagger.AccessMode sets the access rights for clients. Port_
↪ defines the network port to be used
# The server keeps running until the command tagger.stopServer() is called or until the_
↪ program is terminated
```

Listing 2: Connecting to a Network Time Tagger server

```
from Swabian import TimeTagger

tagger = TimeTagger.createTimeTaggerNetwork('ip:port')
# Connect to the Time Tagger server. 'ip' is the IP address of the server and 'port' is the_
↪ port defined by the server. The default port is 41101

correlation = TimeTagger.Correlation(tagger=tagger, channel_1=1, channel_2=2, binwidth=1,
    ↪ n_bins=1000)
# tagger can be used to perform measurements as if the client was connected to the_
↪ TimeTagger via USB. In this case, the client starts a correlation measurement.
# After a measurement is finished, the client can disconnect with TimeTagger.
↪ freeTimeTagger(tagger)
```

### 3.6.2 Remote control of a Time Tagger with Pyro

Pyro5 is a Python library that allows operation of a Time Tagger from a remote computer. It is able to send API commands to the remote Time Tagger and to obtain their return values. In the following, we describe how to use Pyro5 and achieve seamless access to the *Time Tagger's API* remotely.

Listing 3: Teaser code

```
import matplotlib.pyplot as plt
from Pyro5.api import Proxy

TimeTagger = Proxy("PYRO:TimeTagger@server:23000")
tagger = TimeTagger.createTimeTagger()

hist = TimeTagger.Correlation(tagger, 1, 2, binwidth=5, n_bins=2000)
hist.startFor(int(10e12), clear=True)

x = hist.getIndex()
while hist.isRunning():
    plt.pause(0.1)
    y = hist.getData()
    plt.plot(x, y)
```

### 3.6.3 Remote procedure call

Remote procedure call (RPC) is a technology that allows interaction with remote programs by calling their procedures and receiving the responses. This involves a real code execution on one computer (server), while the client computer has only a substitute object (proxy) that mimics the real object running on the server. The proxy object knows how to send requests and data to the server and the server knows how to interpret these requests and how to execute the real code.

In the case of Pyro5, the proxy object and server code are provided by the library and we only need to tell Pyro5 what we want to become available remotely.

### 3.6.4 Initial setup

You will need to have a Python 3.6 or newer installed on your computer. We recommend using Anaconda distribution.

Install the [Time Tagger software](#) if you have not done it yet. The description below assumes that you have the Time Tagger hardware and are familiar with the [Time Tagger API](#).

The last missing part, the Pyro5 package, you can install from [PyPi](#) as

```
pip install Pyro5
```

### 3.6.5 Minimal example

Here we start from the simplest functional example and demonstrate working remote communication. The example consists of two parts: the server and the client code. You will need to run those in two separate command windows.

#### Server code

We need to create an adapter class with methods that we want to access remotely and decorate it with `Pyro5.api.expose()`. The following code is very simple. Later, we will extend it to expose more of the Time Tagger's functionality.

```
import Pyro5.api
from Swabian import TimeTagger as TT

@Pyro5.api.expose
```

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```

class TimeTaggerRPC:
    """Adapter for the Time Tagger Library"""

    def scanTimeTagger(self):
        """This method will become available remotely."""
        return TT.scanTimeTagger()

if __name__ == '__main__':
    # Start server and expose the TimeTaggerRPC class
    with Pyro5.api.Daemon(host='localhost', port=23000) as daemon:
        # Register class with Pyro
        uri = daemon.register(TimeTaggerRPC, 'TimeTagger')
        # Print the URI of the published object
        print(uri)
        # Start the server event loop
        daemon.requestLoop()

```

### Client code

On the client side, we need to know the unique identifier of the exposed object, which was printed when you started the server. In Pyro5, every object is identified by a special string (URI) that contains the object identity string and the server address. As you can see in the code below, we do not use the Time Tagger software directly but rather communicate to the server that has it.

```

import Pyro5.api

# Connect to the TimeTaggerRPC object on the server
# This line is all we need to establish remote communication
TimeTagger = Pyro5.api.Proxy("PYRO:TimeTagger@localhost:23000")

# Now, we can call methods that will be executed on the server.
# Lets check what Time Taggers are available at the server
timetaggers = TimeTagger.scanTimeTagger()
print(timetaggers)

>> ['17400000ABC', '17500000ABC']

```

Congratulations! Now you have a very simple but functional communication to your remote Time Tagger software.

### 3.6.6 Creating the Time Tagger

By now, our code can communicate over a network and can only report the serial numbers of the connected Time Taggers. In this section, we will expand the server code and make it more useful. The next most important feature of the server is to expose the `createTimeTagger()` method to tell the server to initialize the Time Tagger hardware.

You may be tempted to extend the `TimeTaggerRPC` class as follows:

```

@Pyro5.api.expose
class TimeTaggerRPC:
    """Adapter for the Time Tagger Library"""

    def scanTimeTagger(self):

```

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```

        """Return the serial numbers of the available Time Taggers."""
        return TT.scanTimeTagger()

    def createTimeTagger(self):
        """Create the Time Tagger."""
        return TT.createTimeTagger() # This will fail! :(

```

To our great disappointment, the `createTimeTagger()` method will fail when you try to access it from the client. The reason is in how the RPC communication works. The data and the program code have a certain format in which it is stored in the computer's memory, and this memory cannot be easily or safely accessed from a remote computer. The RPC communication overcomes this problem using data serialization, i.e., converting the data into a generalized format suitable for sending over a network and understandable by a client system.

The *Pyro5*, more specifically the *serpent* serializer it employs by default, knows how to serialize the standard Python data types like a list of strings returned by `scanTimeTagger()`. However, it has no idea how to interpret the *TimeTagger* object returned by the `createTimeTagger()`. Moreover, instead of sending the *TimeTagger* object to the client, we want to send a proxy object which allows the client to talk to the *TimeTagger* object on the server.

For the *TimeTagger*, we define an adapter class. Then we modify the `TimeTaggerRPC.createTimeTagger` to create an instance of the adapter class, register it with Pyro, and return it. Pyro will automatically take care of creating a proxy object for the client.

```

@Pyro5.api.expose
class TimeTagger:
    """Adapter for the Time Tagger object"""

    def __init__(self, args, kwargs):
        self._obj = TT.createTimeTagger(*args, **kwargs)

    def setTestSignal(self, *args):
        return self._obj.setTestSignal(*args)

    def getSerial(self):
        return self._obj.getSerial()

    # ... Other methods of the TT.TimeTagger class are omitted here.

@Pyro5.api.expose
class TimeTaggerRPC:
    """Adapter for the Time Tagger Library"""

    def scanTimeTagger(self):
        """Return the serial numbers of the available Time Taggers."""
        return TT.scanTimeTagger()

    def createTimeTagger(self, *args, **kwargs):
        """Create the Time Tagger."""
        tagger = TimeTagger(args, kwargs)
        self._pyroDaemon.register(tagger)
        return tagger
        # Pyro will automatically create and send a proxy object
        # to the client.

```

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```

def freeTimeTagger(self, tagger_proxy):
    """Free Time Tagger. """
    # Client only has a proxy object.
    objectId = tagger_proxy._pyroUri.object
    # Get adapter object from the server.
    tagger = self._pyroDaemon.objectsById.get(objectId)
    self._pyroDaemon.unregister(tagger)
    return TT.freeTimeTagger(tagger._obj)

```

### 3.6.7 Measurements and virtual channels

By now, we can list available Time Tagger devices and create TimeTagger objects. The remaining part is to implement access to the measurements and virtual channels. We will use the same approach as with the TimeTagger class and create adapter classes for them.

```

@Pyro5.api.expose
class Correlation:
    """Adapter class for Correlation measurement."""

    def __init__(self, tagger, args, kwargs):
        self._obj = TT.Correlation(tagger._obj, *args, **kwargs)

    def start(self):
        return self._obj.start()

    def startFor(self, capture_duration, clear):
        return self._obj.startFor(capture_duration, clear=clear)

    def stop(self):
        return self._obj.stop()

    def clear(self):
        return self._obj.clear()

    def isRunning(self):
        return self._obj.isRunning()

    def getIndex(self):
        return self._obj.getIndex().tolist()

    def getData(self):
        return self._obj.getData().tolist()

@Pyro5.api.expose
class DelayedChannel():
    """Adapter class for DelayedChannel."""

    def __init__(self, tagger, args, kwargs):
        self._obj = TT.DelayedChannel(tagger._obj, *args, **kwargs)

```

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```

def getChannel(self):
    return self._obj.getChannel()

@Pyro5.api.expose
class TimeTaggerRPC:
    """Adapter class for the Time Tagger Library"""

    # Earlier code omitted (...)

    def Correlation(self, tagger_proxy, *args, **kwargs):
        """Create Correlation measurement."""
        objectId = tagger_proxy._pyroUri.object
        tagger = self._pyroDaemon.objectsById.get(objectId)
        pyro_obj = Correlation(tagger, args, kwargs)
        self._pyroDaemon.register(pyro_obj)
        return pyro_obj

    def DelayedChannel(self, tagger_proxy, *args, **kwargs):
        """Create DelayedChannel."""
        objectId = tagger_proxy._pyroUri.object
        tagger = self._pyroDaemon.objectsById.get(objectId)
        pyro_obj = DelayedChannel(tagger, args, kwargs)
        self._pyroDaemon.register(pyro_obj)
        return pyro_obj

```

**Note**

The methods `Correlation::getIndex()` and `Correlation::getData()` return `numpy.ndarray` arrays. Pyro5 does not know how to serialize `numpy.ndarray`, therefore for simplicity of the example, we convert them to the Python lists.

More efficient approach would be to register custom serializer functions for `numpy.ndarray` on both, server and client sides, see [Customizing serialization](#) section of the Pyro5 documentation.

### 3.6.8 Working example

Download the complete source files

- `simple_server.py`
- `simple_example.py`

Start the server in a terminal window:

```
> python simple_server.py
```

Now open a second terminal window and run the example:

```
> python simple_example.py
```

Let us take a look at the source code of the example (shown below). You may recognize that it is practically the same as using the Time Tagger package directly. The only difference is that the im-

port statement `import TimeTagger` is replaced by the proxy object creation `TimeTagger = Pyro5.api.Proxy("PYRO:TimeTagger@localhost:23000")`.

Listing 4: simple\_example.py

```
import numpy as np
import matplotlib.pyplot as plt
import Pyro5.api

TimeTagger = Pyro5.api.Proxy("PYRO:TimeTagger@localhost:23000")

# Create Time Tagger
tagger = TimeTagger.createTimeTagger()
tagger.setTestSignal(1, True)
tagger.setTestSignal(2, True)

print('Time Tagger serial:', tagger.getSerial())

hist = TimeTagger.Correlation(tagger, 1, 2, binwidth=2, n_bins=2000)
hist.startFor(int(10e12), clear=True)

fig, ax = plt.subplots()
# The time vector is fixed. No need to read it on every iteration.
x = np.array(hist.getIndex())
line, = ax.plot(x, x * 0)
ax.set_xlabel('Time (ps)')
ax.set_ylabel('Counts')
ax.set_title('Correlation histogram via Pyro-RPC')
while hist.isRunning():
    y = hist.getData()
    line.set_ydata(y)
    ax.set_ylim(np.min(y), np.max(y))
    plt.pause(0.1)

# Cleanup
TimeTagger.freeTimeTagger(tagger)
del hist
del tagger
del TimeTagger
```

#### See also

The Time Tagger software installer includes more complete examples of the RPC server that includes more measurements, virtual channels and implements custom serialization of `numpy.ndarray` types. You can usually find the example files in the `C:\Program Files\Swabian Instruments\Time Tagger\examples\python\7-Remote-TimeTagger-with-Pyro5`.

### 3.6.9 What is next?

One can follow the ideas presented in this tutorial and implement a fully featured Python package. You can find an experimental version of such package at [PyPi](#). Instead of manually wrapping every class and function of the Time Tagger API, the package employs metaprogramming and automatically generates adapter classes.

Let us know if you have any questions about RPC interface for the Time Tagger.

You can expand on the ideas presented in this tutorial, and implement remote control for your complete experiment.



## SOFTWARE OVERVIEW

At the heart of the *Time Tagger* software is a multi-threaded processing engine that receives the time tag stream and feeds it to all running measurements. The measurements and the virtual channels are parallel processing units that analyze the time tag stream each in their own way. For example, a *Countrate* measurement analyzes all time tags from one or more specific channels and calculates the average number of tags received per second. A *Correlation* measurement computes the cross-correlation between two channels, typically by sorting the time tags in histograms, and so on. Such a powerful architecture enables you to perform any conceivable digital time-domain measurement in real time. You have several choices on how to use this architecture.

### 4.1 Graphical user interface

The easiest way of using the *Time Tagger* is the graphical user interface *Time Tagger Lab*, available on Windows only. It allows you to interact with the hardware, create measurements, get live plots, and save and load the acquired data. Refer to the *Time Tagger Lab* section to get started.

### 4.2 Precompiled libraries and high-level language bindings

The Time Tagger library provides a comprehensive set of ready-to-use measurement classes, covering event counting (e.g. *Countrate*), time-difference histograms (e.g. *Correlation*), phase and frequency analyses (e.g. *FrequencyStability*), time-tag streaming (e.g. *FileWriter*). These measurements cover the most common applications of our devices. The library ships as precompiled binaries with bindings for Python, MATLAB, LabVIEW, and .NET, so you can start a complex measurement from the language of your choice with a few lines of code. Refer to *Getting Started* and *Application Programming Interface* for further details.

### 4.3 C++ API

The underlying software architecture is provided by a C++ API that implements two classes: one class that represents the Time Tagger and one class that represents a base measurement. On top of that, the C++ API also provides all predefined measurements that are made available by the high-level language bindings. To use this API, you have to write and compile a C++ program.





## APPLICATION PROGRAMMING INTERFACE

The Time Tagger API provides methods to control the hardware and to create *measurements* that are hooked onto the time tag stream. It is written in C++ and we also provide wrapper classes for several common higher-level languages (Python, MATLAB, LabVIEW, .NET). Maintaining this transparent equivalence between different languages simplifies documentation and allows you to choose the most suitable language for your experiment. The API includes a set of standard *measurements* that cover common tasks relevant to photon counting and time-resolved event measurements. These classes will most likely cover your needs and, of course, the API provides you a possibility to implement your own custom measurements. Custom measurements can be created in one of the following ways:

- Subclassing the *IteratorBase* or *CustomMeasurement* class (best performance, but only available in the C++, C# and Python API - see example in the installation folder)
- Using the *TimeTagStream* measurement and processing the raw time tag stream.
- Offline processing when you store time-tags into a file using *FileWriter* and then read the resulting file to perform desired analysis of the time-tags. This also enables to keep a record of the complete chronology of the events in your experiment.

### 5.1 Examples

Often the fastest way to get an impression on the API is through examples. Several examples for multiple programming languages are available in the Time Tagger installation folder.

#### 5.1.1 Measuring cross-correlation

The code below shows a simple yet operational example of how to perform a cross-correlation measurement with the Time Tagger API. In fact, such simple code is already sufficient to perform real-world experiments in a lab.

```
# Create an instance of the TimeTagger
tagger = createTimeTagger()

# Adjust trigger level on channel 2 to 0.25 V
tagger.setTriggerLevel(2, 0.25)

# Add time delay of 123 picoseconds on the channel 3
tagger.setInputDelay(3, 123)

# Create Correlation measurement for events in channels 2 and 3
corr = Correlation(tagger, 2, 3, binwidth=10, n_bins=1000)

# Run Correlation for 1 second to accumulate the data
corr.startFor(int(1e12), clear=True)
```

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```
corr.waitForFinished()

# Read the correlation data
data = corr.getData()
```

### 5.1.2 Using virtual channels

Time Tagger API implements on-the-fly time-tag processing through *virtual channels*. The following example shows how time-tags from two different real channels can be combined into one virtual channel.

```
tagger = createTimeTagger()

# Enable internal generator to channels 1 and 2. Frequency ~800 kHz.
tagger.setTestSignal([1,2], True)

# Create virtual channel that combines time-tags from real inputs 1 and 2
vc = Combiner(tagger, [1, 2])

# Create countrate measurement at channels 1, 2 and the "combiner" channel
rate = Countrate(tagger, [1, 2, vc.getChannel()])

# Run Countrate for 1 second and print the result for all three channels
rate.startFor(int(1e12), clear=True)
rate.waitForFinished()
print(rate.getData())

>> [ 800008.81  800008.81 1600017.62]
```

From the results, we see that the combined event rate is a sum of the event rates at both input channels, as expected.

### 5.1.3 Using multiple Time Taggers

You can use multiple Time Taggers on one computer simultaneously. In this case, you usually want to associate your instance of the *TimeTagger* class to the Time Tagger device. This is done by specifying the serial number of the device, an optional parameter, to the factory function *createTimeTagger()*.

```
tagger_1 = createTimeTagger("123456789ABC")
tagger_2 = createTimeTagger("123456789XYZ")
```

The serial number of a physical Time Tagger is a string of digits and letters (every Time Tagger has a unique hardware serial number). It is printed on the label at the bottom of the Time Tagger hardware. In addition, the *scanTimeTagger()* method shows the serial numbers of the connected but not instantiated Time Taggers. It is also possible to read the serial number for a connected device using *getSerial()* method.

You can find more examples supplied with the TimeTagger software. Please see the `examples\<language>` subfolder of your *Time Tagger* installation. Usually, the installation folder is `C:\Program Files\Swabian Instruments\Time Tagger`.

### 5.1.4 Using Time Tagger remotely

Using Network Time Tagger you can stream the time-tags to a remote computer(s) and process them independently. You can easily work with your Time Tagger device over the network as if your remote computer is connected directly to the hardware. This example shows how you can start the server, connect a client to it and perform a simple countrate measurement.

You can start the server by calling `startServer()` on an existing *TimeTagger* object.

```
# Connected to the hardware as usual
tagger = createTimeTagger()

# Start the server with full remote control enabled
tagger.startServer(AccessMode.Control)

# Keep this process running
input('Press ENTER to exit the server process...')

# Stop the server if user pressed ENTER key
tagger.stopServer()

# Disconnect from the hardware
freeTimeTagger(tagger)
```

For simplicity of the example we assume that the server is running as a separate process on the same computer. Therefore, we run the client code on the same computer and use `localhost` as a server address. You can also adjust the server address and try the client code on another PC.

```
# Server address, we assume it runs on the same computer
address = 'localhost'

# Connect to the server
ttn = createTimeTaggerNetwork(address)

# Enable test signal on the remote hardware
ttn.setTestSignal(1, True)
ttn.setTestSignal(2, True)

# Create `Countrate` measurement and run it for a fixed duration
cr = Countrate(ttn, [1,2,3])
cr.startFor(1e12)
cr.waitUntilFinished()

# Print the resulting data
print(cr.getData())

# Close the connection to the server
freeTimeTagger(ttn)
```

## 5.2 The TimeTagger Library

The Time Tagger Library contains classes for hardware access and data processing. This section covers the units and terminology definitions as well as describes constants and functions defined at the library level.

### 5.2.1 Units of measurement

#### `timestamp_t`

Time is measured and specified in picoseconds. Time-tags indicate time since device start-up, which is represented by a 64-bit integer number. Note that this implies that the time variable will roll over once approximately

every 107 days. This will most likely not be relevant to you unless you plan to run your software continuously over several months, and you are taking data at the instance when the rollover is happening.

Analog voltage levels are specified in volts.

## 5.2.2 Channel numbers

### `channel_t`

You can use the Time Tagger to detect both rising and falling edges. Throughout the software API, the rising edges are represented by positive channel numbers starting from 1 and the falling edges are represented by negative channel numbers. Virtual channels will automatically obtain numbers higher than the positive channel numbers.

## 5.2.3 Unused channels

There might be the need to leave a parameter undefined when calling a class constructor. Depending on the programming language you are using, you pass an undefined channel via the static constant `CHANNEL_UNUSED`, which can be found in the TT class for .NET and in the TimeTagger class in MATLAB.

## 5.2.4 Constants

constexpr `channel_t` **CHANNEL\_UNUSED**

Can be used instead of a channel number when no specific channel is assumed. In MATLAB, use `TimeTagger.CHANNEL_UNUSED`.

## 5.2.5 Enumerations

enum class **AccessMode**

Controls how the Time Tagger server delivers the data-blocks to the connected clients, and if the clients are allowed to change the hardware settings.

*Values:*

enumerator **Listen**

Clients cannot change settings on the Time Tagger and only subscribe to the exposed channels. The data-blocks are delivered asynchronously to every client.

enumerator **SynchronousListen**

The same as `AccessMode::Listen` but the data is delivered synchronously to every client.

### **Warning**

This mode is not recommended for general use. The server will attempt to deliver a data-block to every connected client before sending the next data-block. Therefore, the data transmission will always be limited by the slowest client. If any of the clients cannot handle the data rate fast enough compared to the data-rate produced by the Time Tagger hardware, all connected clients will be affected and the Time Tagger hardware buffer may overflow. This can happen due to the network speed limit or insufficient CPU speed on any of the connected clients.

enumerator **Control**

Clients have control over all settings on the Time Tagger. The data-blocks are delivered asynchronously to every client.

enumerator **SynchronousControl**

The same as [AccessMode::Control](#) but the data is delivered synchronously to every client.

**Warning**

This mode is not recommended for general use. The server will attempt to deliver a data-block to every connected client before sending the next data-block. Therefore, the data transmission will always be limited by the slowest client. If any of the clients cannot handle the data rate fast enough compared to the data-rate produced by the Time Tagger hardware, all connected clients will be affected and the Time Tagger hardware buffer may overflow. This can happen due to the network speed limit or insufficient CPU speed on any of the connected clients.

enum class **ChannelEdge** : int

Selects the channels that [TimeTaggerHardware::getChannelList\(\)](#) returns.

*Values:*

enumerator **All**

Rising and falling edges of channels with HighRes and Standard resolution.

enumerator **Rising**

Rising edges of channels with HighRes and Standard resolution.

enumerator **Falling**

Falling edges of channels with HighRes and Standard resolution.

enumerator **HighResAll**

Rising and falling of channels edges with HighRes resolution.

enumerator **HighResRising**

Rising edges of channels with HighRes resolution.

enumerator **HighResFalling**

Falling edges of channels with HighRes resolution.

enumerator **StandardAll**

Rising and falling edges of channels with Standard resolution.

enumerator **StandardRising**

Rising edges of channels with Standard resolution.

enumerator **StandardFalling**

Falling edges of channels with Standard resolution.

enum class **CoincidenceTimestamp**

Defines what timestamp to use for a coincidence event in *Coincidence* / *Coincidences*.

*Values:*

enumerator **Last**

Use the last time-tag to define the timestamp of the coincidence.

enumerator **Average**

Calculate the average timestamp of all time-tags in the coincidence and use it as the timestamp of the coincidence.

enumerator **First**

Use the first time-tag to define the timestamp of the coincidence.

enumerator **ListedFirst**

Use the timestamp of the channel at the first position of the list when *Coincidence* or a group of *Coincidences* is instantiated.

enum class **FpgaLinkInterface**

Determines which Ethernet Port on the *Time Tagger X* should be used in *TimeTagger::enableFpgaLink()*.

*Values:*

enumerator **SFPP\_10GE**

Use the SFP+ Port on the *Time Tagger X* for FPGA link output.

enumerator **QSFP\_40GE**

Use the QSFP+ Port on the *Time Tagger X* for FPGA link output.

enum class **GatedChannelInitial**

The initial state of a *GatedChannels*.

*Values:*

enumerator **Closed**

The gate is closed initially.

enumerator **Open**

The gate is open initially.

enum class **Resolution**

Defines the resolution mode of the Time Tagger on connection using *createTimeTagger()*. Details on the available inputs are listed in the *hardware overview* .

*Values:*

**enumerator Standard**

Use one time-to-digital conversion per channel. All physical inputs can be used.

**enumerator HighResA**

Use two time-to-digital conversions per channel. The resolution is increased by a factor of  $\simeq \sqrt{2}$  compared to the Standard mode, but only a reduced number of certain inputs can be used. Some inputs may remain in Standard mode depending on your license.

**enumerator HighResB**

Use four time-to-digital conversions per channel. The resolution is increased by a factor of  $\simeq 2$  compared to the Standard mode, but only a reduced number of certain inputs can be used. Some inputs may remain in Standard mode depending on your license.

**enumerator HighResC**

Use eight time-to-digital conversions per channel. The resolution is increased by a factor of  $\simeq \sqrt{8}$  compared to the Standard mode, but only a reduced number of certain inputs can be used. Some inputs may remain in Standard mode depending on your license.

**enum class Tag : Type**

Specifies the type of a time tag.

*Values:*

**enumerator TimeTag**

Indicates a standard event corresponding to a detected signal edge.

**enumerator Error**

Indicates a hardware or communication-related error condition (e.g., plugging an external clock source, invalidating the global time base).

**enumerator OverflowBegin**

Marks the beginning of an interval with incomplete data because of too high data rates.

**enumerator OverflowEnd**

Marks the point where the internal overflow condition ended, resuming normal event tagging.

**enumerator MissedEvents**

A virtual event indicating the number of lost events per channel within an overflow interval. This event might be sent repeatedly if the number of lost events is large.

**enum class UsageStatisticsStatus**

*Values:*

**enumerator Disabled**

Usage statistics collection and upload is disabled.

enumerator **Collecting**

Enable usage statistics collection local but without automatic uploading. This option might be useful to collect usage statistics for debugging purpose.

enumerator **CollectingAndUploading**

Enable usage statistics collection and automatic upload

enum class **TestSignalSource**

Defines which source of the Time Tagger on-device test signal should be used by `setTestSignal()`.

*Values:*

enumerator **Digital**

Injects the signal digitally within the FPGA.

The signal is multiplexed on-chip immediately before the TDC. This mode bypasses the analog input stage (comparators, etc.) and offers the highest signal integrity.

**Note**

This is the default setting.

enumerator **Analog**

Injects the signal via hardware relays at the analog input stage.

The signal is routed through the physical input path, allowing for verification of the comparator and other front-end electronic components.

The minimum supported frequency is 100 kHz.

**Note**

Only supported on *Time Tagger X* PCB revision v1.3 or later.

## 5.2.6 Functions

*TimeTagger* **createTimeTagger**(str serial = "", *Resolution* resolution = *Resolution::Standard*)

Establishes the connection to a first available Time Tagger device and creates a *TimeTagger* object. Optionally, the connection to a specific device can be achieved by specifying the device serial number.

If the HighRes mode is available, it can be selected from *Resolution*. Details on the available inputs are listed in the [hardware overview](#).

In MATLAB, this function is accessed as `TimeTagger.createTimeTagger`.

**Parameters**

- **serial** – Serial number string of the device or empty string.
- **resolution** – Select the resolution of the Time Tagger. The default is *Resolution::Standard*.



**Throws**

`RuntimeError` – if no Time Tagger devices are available or if the serial number is not correct.

**Returns**

A Time Tagger object

*TimeTaggerVirtual* **createTimeTaggerVirtual**(str filename = "", *timestamp\_t* begin = 0, *timestamp\_t* duration = -1)

Creates a *TimeTaggerVirtual* object. Virtual Time Tagger uses files generated by the *FileWriter* as data source instead of the Time Tagger hardware. This allows you to use all Time Tagger library measurements for offline processing of the dumped time tag stream. For example, you can repeat the analysis of your experiment with different parameters, like different binwidths etc.

The file parameter can specify a header file or single specific file as shown in the following example.

```
# Assume we have following the files in the current directory:
# filename.ttbin
# filename.1.ttbin
# filename.2.ttbin

# Replay all files named "filename.NN.ttbin" sequentially
replay_source.appendFile('filename.ttbin')

# Replay a single file "filename.1.ttbin"
replay_source.appendFile('filename.1.ttbin')
```

In MATLAB, this function is accessed as `TimeTagger.createTimeTaggerVirtual`.

**Parameters**

- **filename** – File name of the initial file. This file defines the available external channels. Default is an empty string which creates a simulated Time Tagger with 18 channels.
- **begin** – Time offset from the beginning of the file in ps to start the replay at. Default is 0.
- **duration** – Duration in picoseconds to be read from the file. *duration=-1* will replay everything. Default is -1.

**Returns**

Time Tagger Virtual object

*TimeTaggerNetwork* **createTimeTaggerNetwork**(str[] addresses)

Creates a new *TimeTaggerNetwork* object. During creation, the object tries to open a connection to the specified Time Tagger servers that have been created by *TimeTagger::startServer()*. This makes the remote time-tag stream locally available.

When more than one server is specified, the channel number of the n-th server is offset by  $n * 1000$ , e.g., channel 3 of the second server will become 2003. Moreover, the different servers must be synchronized to an external clock. If the connection fails, the method will throw an exception.

In MATLAB, this function is accessed as `TimeTagger.createTimeTaggerNetwork`.

**Parameters**

**addresses** – IP addresses, or hostnames, of the servers. Use hostname:port for each server.

**Throws**

- `RuntimeError` – if the connection to the server cannot be made.
- `RuntimeError` – if the address string has an invalid format.
- `RuntimeError` – if attempting to connect to multiple non-synchronized servers.

**Returns**

Time Tagger Network object

str **extractDeviceLicense**(str license)

Converts the hardware device license from binary format to JSON.

**Parameters**

**license** – The binary license, encoded as a hexadecimal string.

**Returns**

a JSON string containing the current device license.

void **flashLicense**(str serial, str license)

Flashes the hardware device license to the Time Tagger identified by the serial number provided.

**Note**

The Time Tagger must not be instantiated while updating the license.

**Parameters**

- **serial** – The serial of the device to flash the license to.
- **license** – The binary license, encoded as a hexadecimal string.

str **getTimeTaggerServerInfo**(str address = "localhost:41101")

Returns Time Tagger configuration, exposed channels, hardware channels and virtual channels as a JSON formatted string.

**Parameters**

**address** – IP address, hostname or domain-name of the server, where the Time Tagger server is running. The port number is optional and can be specified if server listens on a port other than default 41101.

**Throws**

- **RuntimeError** – if the connection to the server cannot be made.
- **ValueError** – if the address string has an invalid format.

**Returns**

Information about server, available channels and exposed channels.

void **freeTimeTagger**(*TimeTaggerBase* tagger)

Releases all Time Tagger resources and terminates the active connection.

**Parameters**

**tagger** – Time Tagger Base object to disconnect

str[] **scanTimeTagger**(bool include\_model\_name = false)

Returns a list of the serial numbers of the connected but not instantiated Time Taggers. It may return serials blocked by other processes or already disconnected some milliseconds later.

In MATLAB this function is accessible as `TimeTagger.scanTimeTagger()`.

**Parameters**

**include\_model\_name** – If True, the method returns also the model for each device, as “serial,model” (default: False).

**Returns**

List of serial numbers

str[] **scanTimeTaggerServers()**

Scans the network for available Time Tagger servers.

**Note**

The server discovery algorithm uses multicast UDP messages sent to the address 239.255.255.83:41102. This method is expected to work well in most situations, however there is a possibility when it could fail. The servers may not be discoverable if the system firewall rejects multicast traffic or blocks access to UDP port 41102. Additionally, multicast traffic is typically not forwarded to other IP networks by routers.

**Returns**

A list of addresses of the Time Tagger servers that are available in the network.

logger\_callback **setLogger**(logger\_callback callback)

Registers a callback function, e.g. for customized error handling. Please see the examples in the installation folder on how to use it. Callback function shall have the following signature *callback(level, message)*. By default, the log messages are printed into the console.

Python example:

```
def logger_func(level, message):
    print(level, message)
setLogger(logger_func)
```

MATLAB example:

```
function logger_func(level, message)
    fprintf('%d : %s\n', level, message)
end
TimeTagger.setLogger(@logger_func)
```

void **mergeStreamFiles**(str output\_filename, str[] input\_filenames, int[] channel\_offsets, *timestamp\_t*[] time\_offsets, bool overlap\_only)

This function merges a list of time tag stream files into one file. The merged stream file can be loaded into the *TimeTaggerVirtual* for processing. The file merging combines streams into one with the possibility of specifying a constant time offset for each input stream file. Additionally, it is possible to specify channel number offset if the input stream files were recorded from the same channel numbers, for instance, using two Time Tagger devices. The parameters *input\_filenames*, *channel\_offsets*, and *time\_offsets* shall be of equal length.

This function handles the \*.ttbin files the same way as the *TimeTaggerVirtual::replay()*.

See also: *FileWriter* , *FileReader* , and *The TimeTaggerVirtual class* .

**Note**

When merging multiple stream files recorded at different times or from different devices, you have to be aware of possible time base differences. This function does not rescale the data into a common time base as this would require additional information and external synchronization signal. If you want to improve the synchronicity of the time base between two devices, please send the reference clock signal to any of the available inputs of each Time Tagger and set up the *TimeTaggerBase::setReferenceClock()*.

**Parameters**

- **output\_filename** – Filename where to store the merge result \*.ttbin.
- **input\_filenames** – List of dump files that will be merged.
- **channel\_offsets** – Channel number offset for each \*.ttbin file. Useful when input files have the same channel numbers.
- **time\_offsets** – Time offset for each \*.ttbin file in picoseconds.
- **overlap\_only** – If True, then merge only the regions where the time is overlapping.

str **getVersion()**

Get the version of the Time Tagger software installed.

**Returns**

Version of the Time Tagger software.

**Usage statistics data collection**

See also the section *Usage Statistics Collection*.

void **setUsageStatisticsStatus**(*UsageStatisticsStatus* new\_status, bool persistent\_config = true)

This function allows a user to override the system-wide default setting on collection and submission of the usage statistics data. This function operates within the scope of a current OS user. The system-wide default setting is given during the installation of the Time Tagger software. Please run the installer again to allow collection and uploading or to disable the usage statistics.

**Parameters**

- **new\_status** – New status of the usage statistics data collection.
- **persistent\_config** – If true, the setting is saved and persists across future process executions for the current OS user (default: true).

*UsageStatisticsStatus* **getUsageStatisticsStatus()**

Get the current status of the usage statistics for the current user. The status is described by the *UsageStatisticsStatus*.

**Returns**

Current status of the usage statistics for the current user.

str **getUsageStatisticsReport()**

This function returns the current state of the usage statistics report as a JSON formatted string. If there is no report data available or it was submitted just now, the output is a message: *Info: No report data available yet*. If you had given your consent earlier and then revoked it, this function will still return earlier accumulated report data.

**Returns**

Usage statistics data encoded as JSON string.

**5.2.7 Helper classes**

class **ChannelGate**

## Public Functions

**ChannelGate**(*channel\_t* gate\_open\_channel, *channel\_t* gate\_close\_channel, *GatedChannelInitial* initial = *GatedChannelInitial::Open*)

This object defines an evaluation gate that is passed to a measurement class. The time-tag stream itself is not modified but sections of the stream can be excluded from the evaluation. In contrast to time-tag stream based gating (see *GatedChannel*), this concept allows the measurement class to calculate the correct data normalization.

### Parameters

- **gate\_open\_channel** – Number of the channel that opens the evaluation gate.
- **gate\_close\_channel** – Number of the channel that closes the evaluation gate.
- **initial** – Initial state of the evaluation gate.

## 5.3 TimeTagger Classes

The Time Tagger classes represent the different time-tag sources for your measurements and analysis. These objects are created by factory functions in the *Time Tagger library*:

### Time Tagger

The *TimeTagger* represents a hardware device and allows access to hardware settings. To connect to a hardware Time Tagger and to get a *TimeTagger* object, use *createTimeTagger()*.

### Virtual Time Tagger

The *TimeTaggerVirtual* allows replaying files created with the *FileWriter*. To create a *TimeTaggerVirtual* object, use *createTimeTaggerVirtual()*.

### Network Time Tagger

The *TimeTaggerNetwork* allows the (remote) access to a Time Tagger made available via *startServer()*. The *TimeTaggerNetwork* object is created with *createTimeTaggerNetwork()* which also establishes a client connection to the server.

All these objects share a common interface defined by the *TimeTaggerBase* and *TimeTaggerSource* classes. In addition, hardware-specific methods, for use with *TimeTagger* and *TimeTaggerNetwork* objects, are defined in the *TimeTaggerHardware* class.

### 5.3.1 General Time Tagger features

#### class **TimeTaggerSource**

This class defines methods used to configure a source of time tags, being either a *TimeTaggerBase* object, or a TimeTagger-like object such as a *TimeTaggerServer*. All Time Tagger classes implement these methods by subclassing *TimeTaggerBase* which itself subclasses *TimeTaggerSource*.

Subclassed by *TimeTaggerBase*, *TimeTaggerServer*

## Public Functions

void **setInputDelay**(*channel\_t* channel, *timestamp\_t* delay)

Convenience method that calls *setDelaySoftware()* if you use a *Time Tagger 20* or if the delay is beyond the supported range defined by *getDelayHardwareRange()*, otherwise *setDelayHardware()* is called.

### Parameters

- **channel** – Channel number.
- **delay** – Delay time in picoseconds.

*timestamp\_t* **getInputDelay**(*channel\_t* channel)

Convenience method that returns the sum of *getDelaySoftware()* and *getDelayHardware()*.

**Parameters**

**channel** – Channel number.

**Returns**

Delay time in picoseconds.

void **setDelayHardware**(*channel\_t* channel, *timestamp\_t* delay)

Sets an artificial delay per *channel*. The delay can be positive or negative. This delay is applied onboard the Time Tagger directly after the time-to-digital conversion, so it also affects the *Conditional Filter*. The maximum/minimum value allowed can be retrieved using *getDelayHardwareRange()*. If you exceed the maximum hardware delay range, please use *setDelaySoftware()* instead.

**Note**

Method is not available for the *Time Tagger 20*.

**Parameters**

- **channel** – Channel number.
- **delay** – Delay time in picoseconds.

*timestamp\_t* **getDelayHardware**(*channel\_t* channel)

Returns the value of the delay applied onboard the Time Tagger in picoseconds for the specified *channel*.

**Note**

Method is not available for the *Time Tagger 20*.

**Parameters**

**channel** – Channel number.

**Returns**

Delay time in picoseconds.

*timestamp\_t*[] **getDelayHardwareRange**(*channel\_t* channel)

Returns a vector containing the minimum and the maximum allowable values for the hardware input delay for the specified channel:

| Device                   | Hardware delay range               |
|--------------------------|------------------------------------|
| <i>Time Tagger 20</i>    | not available                      |
| <i>Time Tagger Ultra</i> | $\pm 2000000$ ( $\pm 2.0$ $\mu$ s) |
| <i>Time Tagger X</i>     | $\pm 2500000$ ( $\pm 2.5$ $\mu$ s) |

**Parameters**

**channel** – Channel number.

**Returns**

Minimum and maximum hardware input delay in picoseconds.

void **setDelaySoftware**(*channel\_t* channel, *timestamp\_t* delay)

Sets an artificial delay per *channel*. The delay can be positive or negative. This delay is applied on the computer, so it does not affect onboard processes such as the Conditional Filter.

#### Note

This method has the best performance when less than 100 events arrive within the time of the largest delay set. For example, if the rate over all channels used is 10 MTags/s, the signal can be delayed efficiently up to 10  $\mu$ s. For larger delays, please consider using *DelayedChannels* instead.

#### Parameters

- **channel** – Channel number.
- **delay** – Delay time in picoseconds.

*timestamp\_t* **getDelaySoftware**(*channel\_t* channel)

Returns the value of the delay applied on the computer in picoseconds for the specified *channel*.

#### Parameters

- **channel** – Channel number.

#### Returns

Delay time in picoseconds.

*timestamp\_t* **setDeadtime**(*channel\_t* channel, *timestamp\_t* deadtime)

Sets the dead time of a channel in picoseconds. The minimum dead time is defined by the internal clock period, which is 6 ns for the *Time Tagger 20*, 2 ns for the *Time Tagger Ultra*, and 1.333 ns for the *Time Tagger X*. For the *Time Tagger 20*, the requested dead time will be rounded to the nearest multiple of the 6 ns clock cycle. The other models allow for arbitrary dead times greater than the respective minimum dead time.

As the dead time passed as an input might be altered to the rounded value, the rounded value will be returned. The maximum dead time is 393  $\mu$ s for the *Time Tagger 20*, 2147  $\mu$ s for the *Time Tagger Ultra*, and 716  $\mu$ s for the *Time Tagger X*. Larger dead times will result in an exception.

#### Note

The specified dead time is 2.1 ns for *Time Tagger Ultra* and 1.5 ns for *Time Tagger X*. With the default setting of the hardware dead time filter, an event arriving between the default hardware dead time and the specified dead time after the last event of that channel might be dropped (e.g., an event arriving between 2 ns and 2.1 ns after the last event on that channel for *Time Tagger Ultra*).

#### Parameters

- **channel** – Channel number.
- **deadtime** – Dead time value in picoseconds.

#### Returns

Resulting dead time in picoseconds, that might be rounded to the nearest valid value (minimum dead time or multiple of the clock period).

*timestamp\_t* **getDeadtime**(*channel\_t* channel)

Returns the dead time value for the specified *channel*.

**Parameters****channel** – Channel number.**Returns**

Dead time value in picoseconds.

*timestamp\_t*[] **getDeadtimeRange**(*channel\_t* channel)

Returns a vector containing the minimum and the maximum allowable values for the dead time for the specified channel.

**Parameters****channel** – Channel number.**Returns**

Minimum and maximum dead time values in picoseconds.

void **setConditionalFilter**(*channel\_t*[] trigger, *channel\_t*[] filtered)Activates or deactivates the conditional filter. Time tags on the filtered channels are discarded unless they were preceded by a time tag on one of the trigger channels, which reduces the data rate. More details can be found in the *In-Depth Guide: Conditional Filter*.**Parameters**

- **trigger** – List of channel numbers
- **filtered** – List of channel numbers

void **clearConditionalFilter**()Deactivates the event filter. Equivalent to `setConditionalFilter([], [])`.*channel\_t*[] **getConditionalFilterTrigger**()

Returns the collection of trigger channels for the conditional filter.

**Returns**

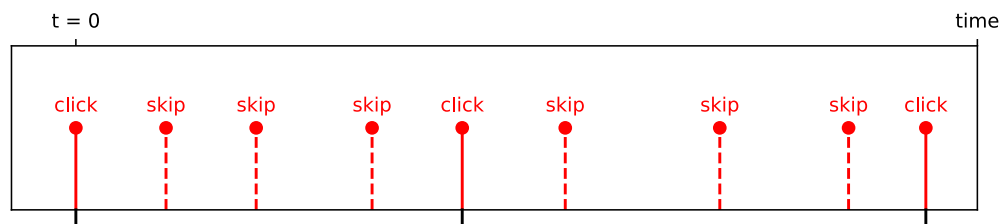
List of channel numbers.

*channel\_t*[] **getConditionalFilterFiltered**()

Returns the collection of channels to which the conditional filter is currently applied.

**Returns**

List of channel numbers.

void **setEventDivider**(*channel\_t* channel, int divider)

Applies an event divider filter with the specified factor to a channel, which reduces the data rate. Only every n-th event from the input stream passes through the filter, as shown in the image. The divider is a 16 bit integer, so the maximum value is 65535.

Note that if the conditional filter is also active, the conditional filter is applied first.

Also note that the event divider is not supported on the *TimeTaggerVirtual*.**Parameters**

- **channel** – Physical channel number.



- **divider** – Divider factor, min. 1 and max. 65535.

int **getEventDivider**(*channel\_t* channel)

Gets the event divider filter factor for the given *channel*.

See `setEventDivider` for further details.

**Parameters**

**channel** – Physical channel number.

**Returns**

Divider factor value.

int **getOverflows**()

Returns the number of overflows (missing blocks of time tags due to limited USB data rate) that occurred since start-up or last call to `clearOverflows()`.

**Returns**

Number of overflows.

int **getOverflowsAndClear**()

Returns the number of overflows that occurred since start-up and sets them to zero (see, `clearOverflows()`).

**Returns**

Number of overflows.

void **clearOverflows**()

Sets the overflow counter to zero.

void **setReferenceClock**(*channel\_t* clock\_channel, float clock\_frequency = 10e6, float time\_constant = 1e-3, *channel\_t* synchronization\_channel = `CHANNEL_UNUSED`, *timestamp\_t* synchronization\_offset = 0, bool wait\_until\_locked = true)

Defines in software one of the input channels as the base clock for all channels. This feature sets up a software phase-locked loop (PLL) and rescales all incoming time-tags according to the time base provided by the *clock\_channel*. This clock frequency alignment is called “syntonization”.

The Reference Clock is able to handle signals decimated by `setEventDivider()` and it is possible to recover the dismissed tags in software. The new time base is characterized by “ideal clock tags” separated by exactly the defined `clock_period = 1E12/clock_frequency`. For measurements, you can use both, rescaled and ideal clock tags. The injection of ideal clock tags can be controlled by `setConditionalFilter()`, by default all tags are injected.

While the PLL is enabled but not locked, the time base of the instrument is invalid. In this case, the time-tag stream changes to the overflow mode. This means that after a call to `setReferenceClock()`, you will typically find overflows because the PLL starts from an unlocked state.

Beyond the clock syntonization, the Reference Clock can also take a *synchronization\_channel* to align the absolute time base of the Time Tagger to an external time base. Currently, the synchronization channel expects one pulse per second (1PPS) that is aligned precisely to a UTC second. The corresponding UTC second is retrieved from the computer’s system clock which requires the use of a time standard via PTP. The synchronization feature is important for merging time-tag streams in the *TimeTaggerNetwork*.

**Warning**

For the *Time Tagger 20*, a phase error of 200 ps needs to be considered when using the reference clock.

**Parameters**

- **clock\_channel** – The physical channel that is used as reference clock input.
- **clock\_frequency** – The frequency of the reference clock. The value should not deviate from the real frequency by more than a few percent. If the event divider is active on this channel, you still provide the original input frequency. Default: 10E6, for 10 MHz.
- **time\_constant** – The time period to average over in seconds. The suppression of discretization noise is improved by a higher *time\_constant*. If the value is too large, however, this will result in increased phase jitter due to the drift of the internal clock or the applied software clock signal. Default: 1E-3, for 1 ms.
- **synchronization\_channel** – The physical channel that provides a 1PPS signal representing a UTC second.
- **synchronization\_offset** – Sets a manual offset to the computer's system time in ps. This is necessary if the system time is badly aligned to the 1PPS signal of the synchronization system. As this might change from start-up to start-up, it is recommended to synchronize both, the synchronization system and the computer's system time, to UTC. Default is 0.
- **wait\_until\_locked** – Blocks the execution until the software clock is locked. Throws an exception on locking errors. All locking log messages are filtered while this call is executed. Default: True

void **disableReferenceClock()**

Disable the software-defined reference clock.

*ReferenceClockState* **getReferenceClockState()**

Provides an object representing the current state of the software-defined reference clock. This includes the configuration parameters as well as dynamic values generated based on the incoming signal.

class **TimeTaggerBase** : public virtual *TimeTaggerSource*

The *TimeTaggerBase* class defines methods and functionality present in all Time Tagger objects. Every *measurement* and *virtual channel* instance requires a reference to a *TimeTaggerBase* object to associate with.

Subclassed by *TimeTagger*, *TimeTaggerNetwork*, *TimeTaggerVirtual*

## Public Functions

void **setSoftwareClock**(*channel\_t* input\_channel, float input\_frequency = 10e6, float averaging\_periods = 1000, bool wait\_until\_locked = true)

Defines in software one of the input channels as the base clock for all channels. This feature sets up a software phase-locked loop (PLL) and rescales all incoming time-tags according to the software clock defined. The PLL provides a new time base with “ideal clock tags” separated by exactly the defined *clock\_period*. For measurements, you can use both, rescaled and ideal clock tags.

While the PLL is not locked, the time base of the instrument is invalid. In this case, the time-tag stream changes to the overflow mode. This means that after every call to *setSoftwareClock()*, you will find overflows because the PLL starts from an unlocked state.

### Warning

It is often useful to apply this feature in combination with *setEventDivider()* on the *input\_channel*. The values of *input\_frequency* and *averaging\_periods* correspond to the transferred time-tags, not to the physical frequency. Changing the *divider* independently after setting up the software clock may

lead to a failure of the locking process. Do not add *input\_channel* to the list of *filtered* channels in *setConditionalFilter()*.

### Warning

For the *Time Tagger 20*, a phase error of 200 ps needs to be considered when using the software clock.

### Parameters

- **input\_channel** – The physical channel that is used as software clock input.
- **input\_frequency** – The frequency of the software clock after application of *setEventDivider()* (e.g. a 10 MHz clock signal with *divider* = 20 has *input\_frequency* = 500 000). The value should not deviate from the real frequency by more than a few percent. Default: 10E6, for 10 MHz.
- **averaging\_periods** – The number of cycles to average over. The suppression of discretization noise is improved by a higher *averaging\_periods*. If the value is too large, however, this will result in increased phase jitter due to the drift of the internal clock or the applied software clock signal. Default: 1000.
- **wait\_until\_locked** – Blocks the execution until the software clock is locked. Throws an exception on locking errors. All locking log messages are filtered while this call is executed. Default: True.

void **disableSoftwareClock()**

Disable the software clock.

*Deprecated:*

use *disableReferenceClock*

*SoftwareClockState* **getSoftwareClockState()**

Provides an object representing the current software clock state. This includes the configuration parameters as well as dynamic values generated based on the incoming signal.

*Deprecated:*

use *getReferenceClock*

### Returns

An object that contains the current state of the software clock.

int **getFence**(bool alloc\_fence = true)

Generate a new fence object, which validates the current configuration and the current time. This fence is uploaded to the earliest pipeline stage of the Time Tagger. Waiting on this fence ensures that all hardware settings, such as trigger levels, channel registrations, etc., have propagated to the FPGA and are physically active. Synchronizes the Time Tagger internal memory so that all tags arriving after the *waitForFence()* call were actually produced after the *getFence()* call. The *waitForFence()* function waits until all tags, which are present at the time of the function call within the internal memory of the Time Tagger, are processed. This call might block to limit the number of active fences.

### Parameters

**alloc\_fence** – Optional. If False, a reference to the most recently created fence will be returned instead. Default: True.

**Returns**

The allocated fence.

bool **waitForFence**(int fence, int timeout = -1)

Wait for a fence in the data stream. See [getFence\(\)](#) for more details.

**Parameters**

- **fence** – Fence object, which shall be waited on.
- **timeout** – Optional. Timeout in milliseconds. Negative means no timeout, zero returns immediately. Default: -1.

**Returns**

True if the fence has passed, false on timeout.

bool **sync**(int timeout = -1)

Ensures that all hardware settings, such as trigger levels, channel registrations, etc., have propagated to the FPGA and are physically active. Synchronizes the Time Tagger internal memory, so that all tags arriving after a sync call were actually produced after the sync call. The sync function waits until all tags, which are present at the time of the function call within the internal memory of the Time Tagger, are processed. It is equivalent to [waitForFence\(\)](#).

The operation of this method on the [TimeTaggerNetwork](#) depends on the server access mode. If the [TimeTaggerNetwork](#) is connected to the Time Tagger server started in [AccessMode::Control](#) or [AccessMode::SynchronousControl](#), the synchronization will be done all way through the server and the hardware. If the Time Tagger server started in [AccessMode::Listen](#) or [AccessMode::SynchronousListen](#), the client will be able to synchronize only with the server but will not synchronize with the Time Tagger Hardware. However, if a USB synchronization fence was created by the server side, the clients will also see it.

See also:

- [getFence\(\)](#), [waitForFence\(\)](#), [TimeTagger::startServer\(\)](#), [AccessMode](#)
- [Synchronization of the Time Tagger pipeline](#)

**Parameters**

**timeout** – Optional. Timeout in milliseconds. Negative means no timeout, zero returns immediately. Default: -1.

**Returns**

True if the synchronization was successful, false on timeout.

[channel\\_t](#) **getInvertedChannel**([channel\\_t](#) channel)

Returns the channel number for the inverted edge of the channel passed in via the channel parameter. In case the given channel has no inverted channel, CHANNEL\_UNUSED is returned.

**Parameters**

**channel** – Channel number.

**Returns**

The inverted channel number.

bool **isUnusedChannel**([channel\\_t](#) channel)

Returns true if the passed channel number is CHANNEL\_UNUSED.

**Parameters**

**channel** – Channel number.

**Returns**

True/False.

str **getConfiguration()**

Returns a JSON formatted string (dict in Python) containing complete information on the Time Tagger settings. It also includes descriptions of measurements and virtual channels created on this Time Tagger instance.

**Returns**

Time Tagger settings and currently existing measurements.

**xtra methods****Note**

The following **xtra** methods are mainly for development purposes and may be discontinued in future software versions without further notice.

void **xtra\_setAutoStart**(bool auto\_start)

Configures if the new measurements and virtual channels start automatically upon creation. This is true by default for all measurements and virtual channels in all TimeTaggers, but disabled by default for the *SynchronizedMeasurements::getTagger()* proxy objects.

**Warning**

Disabling the auto start of new measurements and virtual channels is not recommended for most of the use cases and requires the user to start all the defined measurements and virtual channels in the correct order manually, with explicit calls to *IteratorBase::start()* or *IteratorBase::startFor()*,

**Parameters**

**auto\_start** – Select whether the auto start of new measurements and virtual channel is enable.

bool **xtra\_getAutoStart()**

Returns whether the auto start of new measurements and virtual channels is enabled.

**Returns**

The current auto start state of new measurements and virtual channel.

### 5.3.2 Time Tagger

class **TimeTaggerHardware**

This class provides the basic methods for configuring *TimeTagger* hardware, directly via USB or over the network.

Subclassed by *TimeTagger*, *TimeTaggerNetwork*, *TimeTaggerServer*

## Public Functions

void **setTriggerLevel**(*channel\_t* channel, float voltage)

Set the trigger level of an input channel in Volts.

### Parameters

- **channel** – Physical channel number
- **voltage** – Trigger level in Volts

float **getTriggerLevel**(*channel\_t* channel)

Returns trigger level for the specified physical channel number.

### Parameters

**channel** – Physical channel number

### Returns

The applied trigger voltage level in Volts, which might differ from the input parameter due to the DAC discretization.

*timestamp\_t* **getHardwareDelayCompensation**(*channel\_t* channel)

Returns the currently applied hardware delay compensation for the given *channel*, in picoseconds.

This is the built-in calibration value used to compensate fixed, channel-dependent input delays. The returned value reflects the current state of hardware delay compensation. If hardware delay compensation has been disabled using *setHardwareDelayCompensationActive()*, this function returns 0.

The value returned by this function does not include additional delays configured with *TimeTaggerSource::setDelayHardware* or *TimeTaggerSource::setDelaySoftware*.

### Parameters

**channel** – Physical channel number.

### Returns

Hardware delay compensation in picoseconds.

void **setHardwareDelayCompensationActive**(bool use\_compensation)

Enables or disables hardware delay compensation globally. When enabled, fixed channel-dependent input delays are compensated. This setting affects all channels.

The hardware delay compensation is active by default at the start up of the Time Tagger. Use *getHardwareDelayCompensation()* to query the effective compensation for a specific channel.

### Parameters

**use\_compensation** – If true, enables hardware delay compensation; if false, disables it.

void **setInputImpedanceHigh**(*channel\_t* channel, bool high\_impedance)

Sets the input impedance to High-Z for the specified *channel*. Before *createTimeTagger*, after *TimeTagger::reset()*, and after *freeTimeTagger*, If not set explicitly to High-Z by *setInputImpedanceHigh*, the input will switch to 50 Ohm by default as soon as the input is used.

```
# Upon initialization, all inputs are in the High-Z state:
tagger = TimeTagger.createTimeTagger()

# If you want to keep a channel in High-Z, set it right after initialization:
tagger.setInputImpedanceHigh(1, True)

# The Time Tagger will now stay in High-Z on channel 1, channel 2 will switch_
```

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```
↪ to 50 Ohm:
cr = TimeTagger.CountRate(tagger, [1, 2])
```

**Note**

Method is only available for the *Time Tagger X*.

**Parameters**

- **channel** – Physical channel number.
- **high\_impedance** – True/False.

bool **getInputImpedanceHigh**(*channel\_t* channel)

Returns whether the input impedance is set to high-Z for the specified *channel*.

**Note**

Method is only available for the *Time Tagger X*.

**Parameters**

**channel** – Physical channel number.

**Returns**

State of high input impedance.

void **setInputHysteresis**(*channel\_t* channel, int value)

Sets the input hysteresis value for the specified *channel*. Oscillations of the measured signal within the hysteresis range around the trigger value are ignored and therefore do not trigger new events. Supported values are 1 mV, 20 mV, 70 mV. Default input hysteresis value is 20 mV.

**Note**

Method is only available for the *Time Tagger X*.

**Parameters**

- **channel** – Physical channel number.
- **value** – Hysteresis voltage value in mV (1, 20, 70).

int **getInputHysteresis**(*channel\_t* channel)

Returns the voltage value in mV of the input hysteresis for the specified *channel*.

**Note**

Method is only available for the *Time Tagger X*.

**Parameters**

**channel** – Physical channel number.

**Returns**

Hysteresis voltage value in mV.

void **setNormalization**(*channel\_t*[] channels, bool state)

Enables or disables Gaussian normalization of the detection jitter. Enabled by default.

**Parameters**

- **channels** – List of physical channel numbers.
- **state** – True/False.

bool **getNormalization**(*channel\_t* channel)

Returns whether the Gaussian normalization of the detection jitter is enabled for the specified channel.

**Parameters**

**channel** – The physical channel to query

**Returns**

True/False

str **getSerial**()

Returns the hardware serial number.

**Returns**

Serial number string.

str **getModel**()

Returns the model name as string.

**Returns**

Model name as string

str **getPcbVersion**()

Returns Time Tagger PCB (Printed circuit board) version.

**Returns**

PCB version.

float[] **getDACRange**()

Return a vector containing the minimum and the maximum DAC (Digital-to-Analog Converter) voltage range for the trigger level.

*Deprecated:*

Since version 2.18. Please use [\*getTriggerLevelRange\(\)\*](#) instead.

**Returns**

Minimum and maximum voltage, in volts.

float[] **getTriggerLevelRange**(*channel\_t* channel)

Return a vector containing the minimum and the maximum voltage range for the trigger level of a given channel.

**Parameters**

**channel** – Physical channel number.

**Returns**

Minimum and maximum voltage for the given *channel*, in volts.



*channel\_t*[] **getChannelList**(*ChannelEdge* type = *ChannelEdge::All*)

Returns a list of channels corresponding to the given *type*.

**Parameters**

**type** – Limits the returned channels to the specified channel edge type.

**Returns**

List of channel numbers.

void **setHardwareBufferSize**(int size)

Sets the maximum buffer size within the Time Tagger. The default value is 64 MTags, but can be changed within the range of 32 kTags to 512 MTags. Please note that this buffer can only be filled with a total data rate of up to 500 MTags/s. See also, *Synchronization of the Time Tagger pipeline*.

**Note**

*Time Tagger 20* uses by default the whole buffer of 8 MTags, which can be filled with a total data rate of up to 40 MTags/s.

**Parameters**

**size** – Buffer size, must be a positive number.

int **getHardwareBufferSize**()

Returns the maximum buffer size within the Time Tagger.

**Returns**

Maximum hardware buffer size.

*timestamp\_t* **getPsPerClock**()

Returns the duration of a clock cycle in picoseconds. This is the inverse of the internal clock frequency.

**Returns**

The clock period in picoseconds.

void **setStreamBlockSize**(int max\_events, int max\_latency)

This option controls the latency and the block size of the data stream. Depending on which of the two parameters is exceeded first, the block stream size is adjusted accordingly.

**Note**

The block size will be reduced even further when no new tag arrives within roughly 1-2  $\mu$ s.

**Parameters**

- **max\_events** – Maximum number of events within one block (4096 - 32M), default: 1M events
- **max\_latency** – Maximum latency in milliseconds for constant input rates (1 to 10000), default: 20 ms.

int **getStreamBlockSizeEvents**()

Returns the block size of the data stream. See *setStreamBlockSize()* for further details.

**Returns**

The maximum number of events within one block.

int **getStreamBlockSizeLatency**()

Returns the latency of the data stream. See [setStreamBlockSize\(\)](#) for further details.

**Returns**

The maximum latency in milliseconds.

void **setTestSignal**(*channel\_t*[] channel, bool enabled)

Connects or disconnects the channels with the on-device uncorrelated signal generator.

**Note**

When used on a *TimeTaggerVirtual* object, this method activates a Gaussian signal generator with a 9 ps RMS jitter, on the specified *channel*. *This functionality is primarily for development use and is not intended for general application.*

**Parameters**

- **channel** – List of physical channel numbers.
- **enabled** – True/False

bool **getTestSignal**(*channel\_t* channel)

Returns true if the internal test signal is activated on the specified *channel*.

**Parameters**

**channel** – Physical channel number.

**Returns**

True/False.

void **setTestSignalDivider**(int divider)

Change the frequency of the on-device test signal.

- For the *Time Tagger Ultra* and *Time Tagger X*, the base frequency is 403.2 MHz and the default divider 504 corresponds to ~800 kCounts/s.
- For the *Time Tagger 20*, the base frequency is 62.5 MHz and the default divider 74 corresponds to ~850 kCounts/s.

**Parameters**

**divider** – Frequency divisor factor.

int **getTestSignalDivider**()

Returns the value of test signal division factor.

**Returns**

The frequency divisor factor.

str **getDeviceLicense**()

Returns a JSON formatted string (dict in Python) containing license information of the Time Tagger device, for instance, model, edition, and available channels.

**Returns**

License information.

str **getSensorData()**

Prints a JSON formatted string (dict in Python) containing all available sensor data for the given board. The *Time Tagger 20* has no onboard sensors.

**Returns**

Sensor data.

void **disableLEDs**(bool disabled)

Disables all channel LEDs and back LEDs.

**Note**

This feature currently lacks support for disabling the power LED on the *Time Tagger X*.

**Parameters**

**disabled** – True/False.

void **setLED**(int bitmask)

Manually change the state of the Time Tagger LEDs. The power LED of the *Time Tagger 20* cannot be programmed by software.

Example:

```
# Turn off all LEDs
tagger.setLED(0x01FF0000)

# Restore normal LEDs operation
tagger.setLED(0)
```

- 0 -> LED off
- 1 -> LED on

**illumination bits**

- 0-2: status, rgb - all Time Tagger models
- 3-5: power, rgb - *Time Tagger Ultra* only
- 6-8: clock, rgb - *Time Tagger Ultra* only
- 0 -> normal LED behavior, not overwritten by setLED
- 1 -> LED state is overwritten by the corresponding bit of 0-8

**mask bits**

- 16-18: status, rgb - all Time Tagger models
- 19-21: power, rgb - *Time Tagger Ultra* only
- 22-24: clock, rgb - *Time Tagger Ultra* only

**Parameters**

**bitmask** – LED bitmask.

void **setSoundFrequency**(int freq\_hz)

Set the Time Tagger's internal buzzer to a frequency in Hz.

**Parameters**

**freq\_hz** – The sound frequency in Hz, use 0 to switch the buzzer off.

void **setTimeTaggerNetworkStreamCompression**(bool active)

Enables/disables the compression of TimeTags before they are streamed from the server to the clients.

**Note**

Activation can be helpful for slow network environments ( $\leq 100$  MBit/s) if the bandwidth is the limiting factor. For instance, the amount of streamed data of periodic signals is reduced by about a factor of 2. The compression, on the other hand, leads to increased CPU utilization and is not advantageous for fast networks ( $\geq 1$  GBit/s).

**Parameters**

**active** – Flag defining whether the compression is enabled (default: False).

void **setInternalClockTrim**(float frequency\_offset\_ppm)

Configures a small frequency offset for the internal clock.

**Note**

This method is available for *Time Tagger X* only, starting from hardware revision 1.4.

**Parameters**

**frequency\_offset\_ppm** – The relative offset in ppm, supported is a range of up to  $\pm 50$  ppm.

float **getInternalClockTrim**()

Queries the configured small frequency offset for the internal clock.

**Returns**

the configured small frequency offset in parts per million.

class **TimeTagger** : public virtual *TimeTaggerBase*, public virtual *TimeTaggerHardware*

This class provides access to the hardware and exposes methods to control hardware settings, such as trigger levels or even filters. Behind the scenes, it opens the USB connection, initializes the device and receives and manages the time-tag-stream.

## Public Functions

void **reset**()

Reset the Time Tagger to the start-up state.

float[] **autoCalibration**()

Runs an auto-calibration of the Time Tagger hardware using the built-in test signal.

This function is primarily intended as a diagnostic helper. The returned array contains two values per physical channel, corresponding to the rising and falling edges. The order matches *getChannelList()*.

The returned values are given in picoseconds and describe the discretization-related timing uncertainty from the calibration data with dithering disabled.

#### Note

In High-Resolution mode, the returned values are not meaningful.

#### Returns

List of calibration values in picoseconds.

int[,] **getDistributionCount()**

Returns the calibration data represented in counts.

#### Returns

Calibration data in counts.

float[,] **getDistributionPSecs()**

Returns the calibration data represented in picoseconds.

#### Returns

Calibration data in picoseconds.

void **enableFpgaLink**(*channel\_t*[] channels, str destination\_mac, *FpgaLinkInterface* link\_interface = *FpgaLinkInterface::SFPP\_10GE*, bool exclusive = false)

Enable the FPGA link of the *Time Tagger X*.

#### Parameters

- **channels** – List of channels, which shall be streamed over the FPGA link.
- **destination\_mac** – Destination MAC, use an empty string for the broadcast address of “FF:FF:FF:FF:FF:FF”.
- **link\_interface** – Selects which interface shall be used, default is *FpgaLinkInterface::SFPP\_10GE*.
- **exclusive** – Determines if time tags should exclusively be transmitted over Ethernet, increasing Ethernet performance and avoiding USB issues, default is mixed USB and ethernet.

void **disableFpgaLink()**

Disable the FPGA link of the *Time Tagger X*.

void **startServer**(*AccessMode* access\_mode, *channel\_t*[] channels = *channel\_t*[], int port = 41101)

Start a Time Tagger server that can be accessed via *TimeTaggerNetwork*. The server access mode controls if the clients are allowed to change the hardware parameters. See also: *AccessMode*.

#### Throws

*RuntimeError* – If server is already running.

#### Parameters

- **access\_mode** – *AccessMode* in which the server should run. Either control or listen.
- **channels** – Channels to be streamed. Used only when access\_mode=*AccessMode.Listen* or access\_mode=*AccessMode.SynchronousListen*.
- **port** – Port at which this Time Tagger server will be listening on.

void **stopServer()**

Stops the Time Tagger server if currently running, otherwise does nothing.

bool **isServerRunning()**

Checks if the server is still running.

**Returns**

True is server is running and False otherwise.

void **setServerAddress**(str ip\_address)

By default a Time Tagger in server mode will bind to IP address 0.0.0.0, exposing the server via all IPv4 addresses of the local machine. This may be undesirable in the presence of multiple network hardware within the same machine. To prevent exposure to multiple networks, the binding IP address may be configured to refer to specific network hardware.

**Parameters**

**ip\_address** – The IP address, or hostname.

str **getServerAddress()**

Gets the IP address, or hostname, to which the Time Tagger server shall bind.

**Returns**

The IP address, or hostname.

str[] **getConnectedClients()**

Returns the IP addresses and port numbers of the clients currently connected to the Time Tagger server.

**Returns**

A list of IP addresses and port numbers, as strings.

### Device independent xtra methods

#### Note

The following **xtra** methods are mainly for development purposes and may be discontinued in future software versions without further notice. The **xtra** setter methods in this first section are only available for the *Time Tagger Ultra* and the *Time Tagger X*.

void **xtra\_setAvgRisingFalling**(*channel\_t* channel, bool enable)

Configures if the rising and falling events shall be averaged.

This is implemented on the device before any filter like event divider and it does not require to transfer both events.

They need to be manually delayed to be within a window of +-500 ps of error, else events might get lost. This method has no side effects on the channel *getInvertedChannel()*, you can still fetch the original events there. However if both are configured to return the averaged result, the timestamps will be identical.

**Parameters**

- **channel** – The channel, on which the average value shall be returned.
- **enable** – Select whether the averaging feature is enabled.

bool **xtra\_getAvgRisingFalling**(*channel\_t* channel)

Return the state of the averaging of rising and falling edges.

**Parameters**

**channel** – The channel for which the averaging state is returned.

**Returns**

The current enable state.

void **xtra\_setHighPrioChannel**(*channel\_t* channel, bool enable)

Sets the priority state of a channel. This setting is applied on the hardware before USB transfer.

If a buffer overflow occurs, channels with high-priority state will interrupt the overflow mode and be transmitted as standard time-tags (*Tag::Type::TimeTag*). Timing information of low-priority channels is dismissed in overflow mode and only the number of counts is transmitted (*Tag::Type::MissedEvents*). A typical application of the high-priority channels is *CountBetweenMarkers* with high-priority markers. In this case, the overflow range will be ideally sliced by the markers.

**Warning**

Interrupting the overflow mode may break the protection mechanism the overflow mode provides. This may lead to irreversible loss of events, not only loss of their timing information. High priority should only be assigned to low-count-rate channels, e.g. pixel triggers or similar control events.

**Parameters**

- **channel** – The channel on which the high-priority state shall be enabled.
- **enable** – Select whether high priority is enabled.

bool **xtra\_getHighPrioChannel**(*channel\_t* channel)

Get the priority state of a channel.

**Parameters**

**channel** – The channel for which the priority state is returned.

**Returns**

The current enable state of the high-priority feature on this channel.

**TTX-only xtra methods****Note**

The following xtra methods are mainly for development purposes and may be discontinued in future software versions without further notice. The xtra setter methods in this second section are only available for the *Time Tagger X*.

void **xtra\_setAuxOut**(int channel, bool enabled)

Enables/Disables the Aux Out signal for the specified Aux *channel*.

**Parameters**

- **channel** – Aux channel number.
- **enabled** – True/False.

bool **xtra\_getAuxOut**(int channel)

Returns whether the Aux Out signal is enabled for the specified Aux *channel*.

**Parameters**

**channel** – Aux channel number.

**Returns**

State of the Aux Out signal.

void **xtra\_setAuxOutSignal**(int channel, float frequency)

Sets the signal shape, i.e., duty cycle and frequency, of the Aux out signal for the specified Aux *channel*.

**Parameters**

- **channel** – Aux channel number.
- **frequency** – Frequency of the Aux Out base signal frequency.

float **xtra\_getAuxOutSignalFrequency**(int channel)

Returns the divider for the frequency of the Aux Out signal generator or the specified Aux *channel*.

**Parameters**

**channel** – Aux channel number.

**Returns**

Frequency of the frequency of the Aux Out signal generator.

float **xtra\_measureTriggerLevel**(*channel\_t* channel)

Measures and returns the applied voltage threshold of the specified *channel*.

**Parameters**

**channel** – Channel number.

**Returns**

Applied voltage threshold of a channel

void **xtra\_setClockSource**(int source)

Specifies the different clock sources:

- 0 - internal clock
- 1 - external clock 10 Mhz
- 2 - external clock 500 MHz.

**Parameters**

**source** – Number of the clock source. Allowed values: 0, 1, 2.

int **xtra\_getClockSource**()

Returns the used clock source:

- -1: auto selecting of below options
- 0: internal clock
- 1: external 10 MHz
- 2: external 500 MHz.

**Returns**

Number of the clock source.



void **xtra\_setClockAutoSelect**(bool enabled)

Enables/Disables the auto clocking function.

**Parameters**

**enabled** – True/False.

bool **xtra\_getClockAutoSelect**()

Returns whether the auto clocking function is enabled.

**Returns**

State of auto clocking.

void **xtra\_setClockOut**(bool enabled)

Activates/Deactivates the 10 MHz clock output.

**Parameters**

**enabled** – True/False.

void **xtra\_enableStreamInterfaceUDP**(str pc\_ip, str pc\_mac, str tagger\_ip, int MTU = 9000)

Reconfigure the time tag stream to use the SFP+/UDP interface instead of USB.

**Note**

At the current stage of development, only the time tag data stream is routed over SFP+. All device configuration and control communication still requires an active USB connection.

**Note**

The SFP+ port does not implement ARP, so the MAC address of the receiving host must be provided explicitly.

**Note**

The Time Tagger sends UDP packets from port 8764; the receiving host must listen on port 8765.

**Parameters**

- **pc\_ip** – The IPv4 address of the receiving host on the same network, in dotted-decimal notation (e.g. “192.168.3.10”).
- **pc\_mac** – MAC address of the receiving host, in colon- separated hexadecimal notation (e.g. “01:23:45:67:89:AB”).
- **tagger\_ip** – The IPv4 address for the Time Tagger’s SFP+ interface, in dotted-decimal notation.
- **MTU** – Maximum Transmission Unit (MTU) of the receiving network interface, in bytes. The accepted range is [512, 9500] (default: 9000).

void **xtra\_disableStreamInterfaceUDP**()

Disable the SFP+/UDP time tag stream and revert to USB delivery.

The stream is terminated immediately and all subsequent time tags are transferred over USB.

## Public Functions

void **setTestSignalSource**(*TestSignalSource* source)

Sets the source of the Time Tagger on-device test signal.

### Note

The default source is *TestSignalSource::Digital*.

### Note

This method is only available for the *Time Tagger X* (PCB v1.3+).

### Parameters

**source** – The desired source of the test signal generator.

*TestSignalSource* **getTestSignalSource**()

Retrieves the currently configured test signal source.

### Returns

The current source of the Time Tagger on-device test signal.

str[] **fetchDeviceLicenseUpdate**()

Checks for new hardware device licenses and retrieves them if available. If a new license is found, use `extractDeviceLicense()` to parse it and `flashLicense()` to apply it to the device.

### Returns

An array of raw licenses in hex string format, or an empty array if no newer license is found on the server.

## 5.3.3 The TimeTaggerVirtual class

class **TimeTaggerVirtual** : public virtual *TimeTaggerBase*

The *TimeTaggerVirtual* allows replaying earlier stored time-tag dump files created by the *FileWriter*. Using the virtual Time Tagger, you can repeat your experiment data analysis with different parameters or even perform different measurements.

Here is a minimal code snippet showing how to replay your data setting one measurement:

```
# Initialize the TimeTaggerVirtual by passing the name of the file to the
↳ constructor.
virtual_tagger = TimeTagger.createTimeTaggerVirtual("filename.ttbin")

# Define all the virtual channels and measurements by passing the TimeTaggerVirtual
↳ object
# to the tagger argument.
countrate = TimeTagger.Countrate(tagger=virtual_tagger, channels=[1,2])

# Start the replay of the data using the method run()
virtual_tagger.run()

# Wait until all time tags, or the selected chunk of it, are analyzed
```

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```
virtual_tagger.waitForFinished()
```

```
# Retrieve the data
```

```
data = countrate.getData()
```

#### Note

The virtual Time Tagger requires a free software license, which is automatically acquired from the Swabian Instruments license server when `createTimeTagger` or `createTimeTaggerVirtual` is called while a Time Tagger is attached. Once received, the license is permanently stored on this PC and the Virtual Time Tagger will work without Time Tagger hardware attached.

## Public Functions

```
int[] run(float speed = -1.0)
```

Start the replay at given speed factor. A value of *speed*=1.0 will replay at a real-time rate. All *speed* values < 0.0 will replay the data as fast as possible but stops at the end of all data. If no file for replay is queued, *speed* < 0.0 is replaced by *speed* = 1.0 for simulations. This automatic speed selection is also the default value. Extreme slow replay speed between 0.0 and 0.1 is not supported.

#### Parameters

**speed** – Replay speed factor.

#### Returns

IDs of the queued files.

```
int replay(str file, timestamp_t begin = 0, timestamp_t duration = -1, bool queue = true)
```

*Deprecated:*

Since version 2.18. Please use `createTimeTaggerVirtual` and `run()/appendFile()` instead.

Replay a dump file specified by its path *file* or add it to the replay queue. If the flag *queue* is false, the current queue will be discarded and file will be replayed immediately. The *file* parameter can specify a header file or single specific file as shown in the following example.

See also: `FileWriter`, `FileReader`, and `mergeStreamFiles()`.

#### Warning

Replaying data in small chunks is not recommended for long recordings. Each `replay()` call reads the file from the beginning up to the specified *begin*, even though only the data between *begin* and *begin* + *duration* is processed. This leads to significant overhead for chunks with higher *begin* values. Replaying the whole file at once is more efficient.

#### Parameters

- **file** – The file to be replayed.
- **begin** – Duration in picoseconds to skip at the beginning of the file. A negative time will generate a pause in the replay.
- **duration** – Duration in picoseconds to be read from the file. *duration*=-1 will replay everything. (default: -1)
- **queue** – flag if this file shall be queued. (default: *True*)

**Returns**

ID of the queued file.

void **stop()**

This method stops the current file and clears the replay queue.

int **appendFile**(str filename, *timestamp\_t* begin = 0, *timestamp\_t* duration = -1, bool clear = false)

Add a new file to the queue of files to be replayed. If the file includes channels that are not present in the initial file passed to createTimeTaggerVirtual, these channels will be ignored during replay and are not accessible by measurements.

**Parameters**

- **filename** – The name of the file to be replayed.
- **begin** – Duration in picoseconds to skip at the beginning of the file. A negative time will generate a pause in the replay.
- **duration** – Duration in picoseconds to be read from the file. *duration=-1* will replay everything. (default: -1)
- **clear** – If *True*, the current queue is cleared and the given file starts a new queue. (default: *False*, i.e. append to existing queue)

**Returns**

ID of the queued file.

bool **waitForCompletion**(int ID = 0, int timeout = -1)

*Deprecated:*

Since version 2.18. Use Please *waitUntilFinished()* instead.

Blocks the current thread until the replay is completed.

bool **waitUntilFinished**(int ID = 0, int timeout = -1)

Blocks the current thread until the replay is completed.

This method blocks the current execution and waits until the given file has finished its replay. If no ID is provided, it waits until all queued files are replayed.

This function does not block on a zero timeout. Negative timeouts are interpreted as infinite timeouts.

**Warning**

Calling *waitUntilFinished()* on a paused timebase, such as before calling *run()*, will block the current thread indefinitely.

**Parameters**

- **ID** – Selects which file to wait for. (default: 0)
- **timeout** – Timeout in milliseconds.

**Returns**

True if the file is complete, false on timeout.

void **setReplaySpeed**(float speed)

*Deprecated:*

Since version 2.18. Please use `run()` instead.

Configures the speed factor for the virtual tagger. A value of `speed=1.0` will replay at a real-time rate. All `speed` values  $< 0.0$  will replay the data as fast as possible but stops at the end of all data. This is the default value. Extreme slow replay speed between 0.0 and 0.1 is not supported.

#### Parameters

**speed** – Replay speed factor.

float **getReplaySpeed()**

Returns the current speed factor. Please see also `setReplaySpeed()` for more details.

#### Returns

The replay speed factor

`channel_t[]` **getChannelList()**

Returns all channels available within the input file.

#### Returns

List of channel numbers.

### 5.3.4 The TimeTaggerNetwork class

The *Network Time Tagger* enables sending the time-tag stream to other applications and even remote computers for independent processing. You can use it with any Time Tagger hardware device by starting the time-tag stream server with `startServer()`. Once the server is running, the clients can connect to it by calling `createTimeTaggerNetwork()` and specifying the server address. Starting with version 2.18, a *TimeTaggerNetwork* client can connect to multiple servers and merge their time tag streams, provided the servers are synchronized (e.g. using the White Rabbit protocol). Once the servers are running, the clients can connect to them by calling `createTimeTaggerNetwork()` and specifying the servers addresses. A client can be any computer that can access the servers over the network or another process on the same computer. Servers and clients can run on different operating systems or use different programming languages.

#### Note on Performance

The Network Time Tagger server sends a time-tag stream in a compressed format requiring about 4 bytes per time tag. Every client receives the data only from the channels required by the client. The maximum achievable data rate will depend on multiple factors, like server and client CPU performance, operating system, network adapter used, and network bandwidth, as well as the whole network infrastructure.

In a 1 Gbps Ethernet network, it is possible to achieve about 26 MTags/second of the total outgoing data rate from the server. Note that this bandwidth is shared among all clients connected. Likewise, a 10 Gbps Ethernet network allows reaching higher data rates while having more clients. In our tests, we reached up to 40 MTags/s per client.

When you run the server and the client on the same computer, the speed of the network adapters installed on your system becomes irrelevant. In this case, the operating system sends the data directly from the server to the client.

class **TimeTaggerNetwork** : public virtual *TimeTaggerBase*, public virtual *TimeTaggerHardware*

The *TimeTaggerNetwork* represents a client-side of the Network Time Tagger and provides access to the Time Tagger server. A server can be created on any physical Time Tagger by calling `TimeTagger::startServer`. The *TimeTaggerNetwork* object is created by calling `createTimeTaggerNetwork`.

**Note**

Although the *TimeTaggerNetwork* formally inherits from *TimeTaggerBase*, almost all methods of the hardware *TimeTagger* are available on the client (except for *TimeTagger::startServer()* and *TimeTagger::stopServer()*). These redundant methods are not listed in this section. A call to a method that exists on *TimeTagger* will be forwarded to the server. When using the *TimeTaggerNetwork* with multiple servers, these forwarded method calls are always directed to the first connected server. An exception is *TimeTaggerHardware::getChannelList()*, which is handled on the client and returns all channels available across all connected servers. To extract information or interact with a specific server, use *getServer()* to access a *TimeTaggerServer* object. Some methods on *TimeTaggerNetwork* offer similar functionality to those on the hardware *TimeTagger*, but are implemented on the client side and can be recognized by the suffix *Client*. If the server is running in *AccessMode::Listen* or *AccessMode::SynchronousListen* and a method call forwarded to the server would cause setting changes on the server-side, the call will raise an exception on the client. This scheme of forwarding may lead to unexpected behavior: If the server is started in *AccessMode::Listen* or *AccessMode::SynchronousListen* with a restricted set of *channels* and you call *TimeTaggerHardware::getChannelList()* on the client side, not all channels returned by this method can be accessed. You can request the list of accessible channels from the server with *getTimeTaggerServerInfo*.

**Public Functions**

bool **isConnected()**

Check if the Network Time Tagger is currently connected to a server.

**Returns**

True/False.

void **setDelayClient**(*channel\_t* channel, *timestamp\_t* time)

Sets an artificial software delay per channel on the client side. To specify it on the server side, see *setDelaySoftware()* or *setDelayHardware()*. The latter is not available for the *Time Tagger 20*. This delay will be applied only on this object and will not affect the server settings or delays at any other clients connected to the same Time Tagger server.

**Parameters**

- **channel** – The channel number.
- **time** – Delay time in picoseconds.

*timestamp\_t* **getDelayClient**(*channel\_t* channel)

Returns the value of the delay applied on the client-side in picoseconds for the specified channel.

**Parameters**

**channel** – Channel number.

**Returns**

Input delay in picoseconds.

int **getOverflowsClient()**

If the server is not able to send all the time-tags to the client, e.g. due to limited network bandwidth, the time-tag stream switches to the overflow mode. This means that the client might experience additional overflow events that are not originating from the hardware. This counter counts all missing blocks of time tags occurred in all the hardware devices and on the network since the client connection or last call to *clearOverflowsClient()* or *getOverflowsAndClearClient()*.

**Returns**

The value of the client-side overflow counter.

int **getOverflowsAndClearClient()**

The same as *getOverflowsClient()* but also clears the client-side counter. See *getOverflowsClient()* for more information on client-side overflows.

void **clearOverflowsClient()**

Clears the overflow counter on the client-side. A call to *getOverflows()* will return the information as it is available on the server. See *getOverflowsClient()* for more information on client-side overflows.

*TimeTaggerServer* **getServer**(str ip\_address)

**Parameters**

**ip\_address** – the IP address, or hostname, of the desired *TimeTagger* server.

**Throws**

ValueError – if *ip\_address* does not match an address used in the call to *createTimeTaggerNetwork*.

**Returns**

a *TimeTaggerServer* object, for configuration and control purposes.

*TimeTaggerServer*[] **getServers()**

**Returns**

a list of pointers to all *TimeTaggerServer* objects making up the *TimeTaggerNetwork* client.

The *TimeTaggerServer* class contains all relevant control methods present in *TimeTaggerBase* and *TimeTaggerHardware*.

*TimeTaggerServer* objects allow control of a TimeTagger in server mode, provided has been created with *AccessMode::Control* privileges. However, unlike *TimeTaggerBase*, *TimeTaggerServer* cannot be used to perform measurements.

class **TimeTaggerServer** : public virtual *TimeTaggerHardware*, public virtual *TimeTaggerSource*

Control and configure individual *TimeTagger* servers via a *TimeTaggerNetwork* object.

**Public Functions**

str **getAddress()**

**Returns**

the IP address, or hostname, of the server object.

*AccessMode* **getAccessMode()**

**Returns**

the AccessMode of the underlying *TimeTagger* server.

*channel\_t* **getClientChannel**(*channel\_t* server\_channel)

**Returns**

the channel number on the *TimeTaggerNetwork* object corresponding to *server\_channel*.

### 5.3.5 Additional classes

struct **ReferenceClockState**

## Configuration State

### *timestamp\_t* **clock\_period**

The rounded clock period matching the input frequency set in *TimeTaggerSource::setReferenceClock()*.

### *channel\_t* **clock\_channel**

The input channel of the periodic clock signal set in *TimeTaggerSource::setReferenceClock()*.

### *channel\_t* **synchronization\_channel**

The 1 pulse per second channel representing the (UTC) second *TimeTaggerSource::setReferenceClock()*.

### *channel\_t* **ideal\_clock\_channel**

A virtual channel number to receive the ideal clock tags. During a locking period, these tags are separated by *clock\_period* by definition. To receive the rescaled measured clock tags, use *clock\_channel*.

### float **averaging\_periods**

The averaging periods set in *TimeTaggerBase::setReferenceClock()*.

### *timestamp\_t* **synchronization\_offset**

The manual offset to the computer's system time in ps. This is necessary if the system time is badly aligned to the 1PPS signal of the synchronization system.

### bool **enabled**

Indicates whether the reference clock is active or not.

### int **event\_divider**

The event divider of the *clock\_channel*.

## Runtime Information

Beyond the configuration state, the object provides current runtime information of the software clock:

### bool **is\_locked**

Indicates whether the PLL of the software clock was able to lock to the input signal.

### bool **is\_synchronized**

Indicates whether the absolute timebase is aligned to the *synchronization\_channel*.

### int **error\_counter**

Amount of locking errors since the last *TimeTaggerBase::setReferenceClock()* call.

### *timestamp\_t* **last\_ideal\_clock\_event**

Timestamp of the last ideal clock event in picoseconds.



float **period\_error**

Current deviation of the measured clock period from the ideal period given by *clock\_period*.

float **phase\_error\_estimation**

Current root of the squared differences of *clock\_input* timestamps and ideal clock timestamps. This value includes the discretization noise of the *clock\_input* channel.

struct **SoftwareClockState**

The `SoftwareClockState` object contains the current configuration state:

### Configuration State

*timestamp\_t* **clock\_period**

The rounded clock period matching the input frequency set in `TimeTaggerBase::setSoftwareClock()`.

*channel\_t* **input\_channel**

The input channel of the software clock set in `TimeTaggerBase::setSoftwareClock()`.

*channel\_t* **ideal\_clock\_channel**

A virtual channel number to receive the ideal clock tags. During a locking period, these tags are separated by *clock\_period* by definition. To receive the rescaled measured clock tags, use *clock\_channel*.

float **averaging\_periods**

The averaging periods set in `TimeTaggerBase::setSoftwareClock()`.

bool **enabled**

Indicates whether the software clock is active or not.

### Runtime Information

Beyond the configuration state, the object provides current runtime information of the software clock:

bool **is\_locked**

Indicates whether the PLL of the software clock was able to lock to the input signal.

int **error\_counter**

Amount of locking errors since the last `TimeTaggerBase::setSoftwareClock()` call.

*timestamp\_t* **last\_ideal\_clock\_event**

Timestamp of the last ideal clock event in picoseconds.

float **period\_error**

Current deviation of the measured clock period from the ideal period given by *clock\_period*.

float **phase\_error\_estimation**

Current root of the squared differences of *clock\_input* timestamps and ideal clock timestamps. This value includes the discretization noise of the *clock\_input* channel.

## 5.4 Virtual Channels

Virtual channels are software-defined channels as compared to the real input channels. Virtual channels can be understood as a stream flow processing units. They have an input through which they receive time-tags from a real or another virtual channel and output to which they send processed time-tags.

Virtual channels are used as input channels to the measurement classes the same way as real channels. Since the virtual channels are created during run-time, the corresponding channel number(s) are assigned dynamically and can be retrieved using `getChannel()` or `getChannels()` methods of virtual channel object.

### 5.4.1 Available virtual channels

#### Note

In MATLAB, the Virtual Channel names have common prefix TT\*. For example: Combiner is named as TTCombiner. This prevents possible name collisions with existing MATLAB or user functions.

#### *Coincidence*

Detects coincidence clicks on two or more channels within a given time window.

#### *Coincidences*

Detects coincidence clicks on multiple channel groups within a given time window.

#### *Combinations*

Detects coincidence clicks on all possible combinations of given channels within a given time window, preceded and followed by two guard windows of the same width without any events on these channels.

#### *Combiner*

Merges events from multiple channels into a single channel.

#### *ConstantFractionDiscriminator*

Detects rising and falling edges of an input signal and returns the average time.

#### *DelayedChannels*

Creates delayed replicas input channels.

#### *EventGenerator*

Generates a signal pattern for each trigger event.

#### *FrequencyMultiplier*

Multiplies the frequency of a periodic signal on a channel.

#### *GatedChannels*

Passes input signals only while the gate is open, defined by start and stop trigger channels.

#### *TriggerOnCountrate*

Generates an event when the count rate of a given channel crosses given threshold value.

### 5.4.2 Common methods

`VirtualChannel.getChannel()`

`VirtualChannel.getChannels()`

Returns the channel number(s) corresponding to the virtual channel(s). Use this channel number the very same way as the channel number of physical channel, for example, as an input to a measurement class or another virtual channel.

**Important**

Virtual channels operate on the time tags that arrive at their input. These time tags can be from rising or falling edges of the physical signal. However, the virtual channels themselves do not support such a concept as an inverted channel.

**getConfiguration()**

Returns configuration data of the virtual channel object. The configuration includes the name, values of the current parameters and the channel numbers. Information returned by this method is also provided with [getConfiguration\(\)](#).

**Returns**

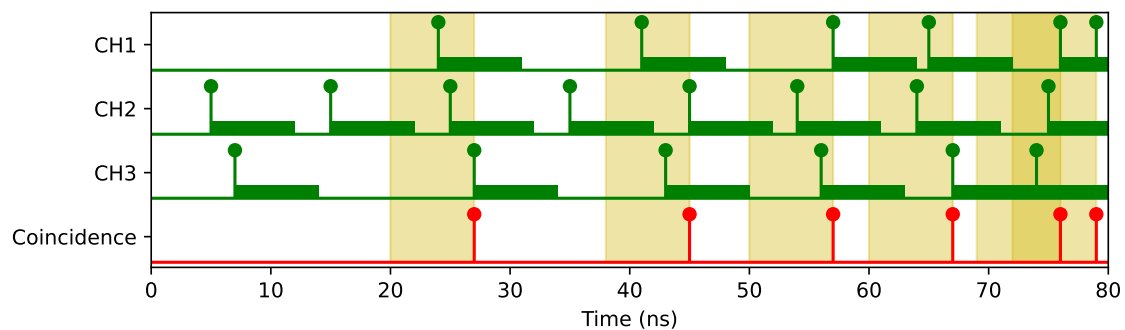
Configuration data of the virtual channel object.

**Return type**

dict

### 5.4.3 Coincidence

class **Coincidence** : public *Coincidences*



Detects coincidence clicks on two or more channels within a given window. Every time a coincidence is detected on the input channels (AND logic), *Coincidence* emits a tag on the virtual channel. The timestamp assigned to the coincidence on the virtual channel can be set using the parameter *timestamp*. By default, the timestamp from the last event received to complete the coincidence is used.

*See all common methods*

**Public Functions**

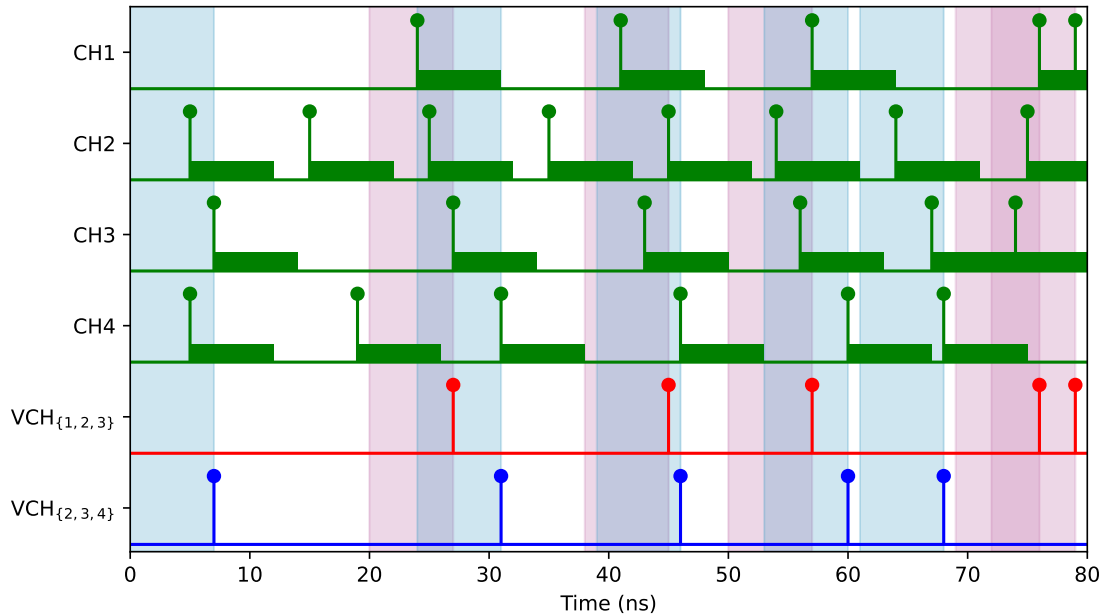
**Coincidence**(*TimeTaggerBase* tagger, *channel\_t*[] channels, *timestamp\_t* coincidenceWindow = 1000, *CoincidenceTimestamp* timestamp = *CoincidenceTimestamp::Last*)

**Parameters**

- **tagger** – Time Tagger object instance.
- **channels** – List of channels on which coincidence will be detected in the virtual channel.
- **coincidenceWindow** – Maximum time between all events for a coincidence in picoseconds (default: 1000).
- **timestamp** – Type of timestamp for the virtual channel (default: Last).

### 5.4.4 Coincidences

class **Coincidences** : public *IteratorBase*



Detects coincidence clicks on multiple channel groups within a given window. If several different coincidences are required with the same window size, *Coincidences* provides better performance compared to multiple virtual *Coincidence* channels. One object of the *Coincidence* class is limited to 64 unique channels in the list of channel groups (*coincidenceGroups*).

Example code:

```
from Swabian.TimeTagger import Coincidence, Coincidences, CoincidenceTimestamp, \
    createTimeTagger
tagger = createTimeTagger()

coinc = Coincidences(tagger, [[1,2], [2,3,5]], coincidenceWindow=10000, \
    timestamp=CoincidenceTimestamp.ListedFirst)
coinc_chans = coinc.getChannels()
coinc1_ch = coinc_chans[0] # double coincidence in channels [1,2] with timestamp \
    of channel 1
coinc2_ch = coinc_chans[1] # triple coincidence in channels [2,3,5] with timestamp \
    of channel 2

# or equivalent but less performant
coinc1 = Coincidence(tagger, [1,2], coincidenceWindow=10000, \
    timestamp=CoincidenceTimestamp.ListedFirst)
coinc2 = Coincidence(tagger, [2,3,5], coincidenceWindow=10000, \
    timestamp=CoincidenceTimestamp.ListedFirst)
coinc1_ch = coinc1.getChannel() # double coincidence in channels [1,2] with \
    timestamp of channel 1
coinc2_ch = coinc2.getChannel() # triple coincidence in channels [2,3,5] with \
    timestamp of channel 2
```

See all common methods

#### Note

Only C++ and python support jagged arrays (array of arrays, like `uint[][]`) which are required to combine several coincidence groups and pass them to the constructor of the *Coincidences* class. Hence, the API differs for Matlab, which requires a cell array of 1D vectors to be passed to the constructor (see Matlab examples provided with the installer). For LabVIEW, a *CoincidencesFactory*-Class is available to create a *Coincidences* object, which is also shown in the LabVIEW examples provided with the installer).

Subclassed by *Coincidence*

### Public Functions

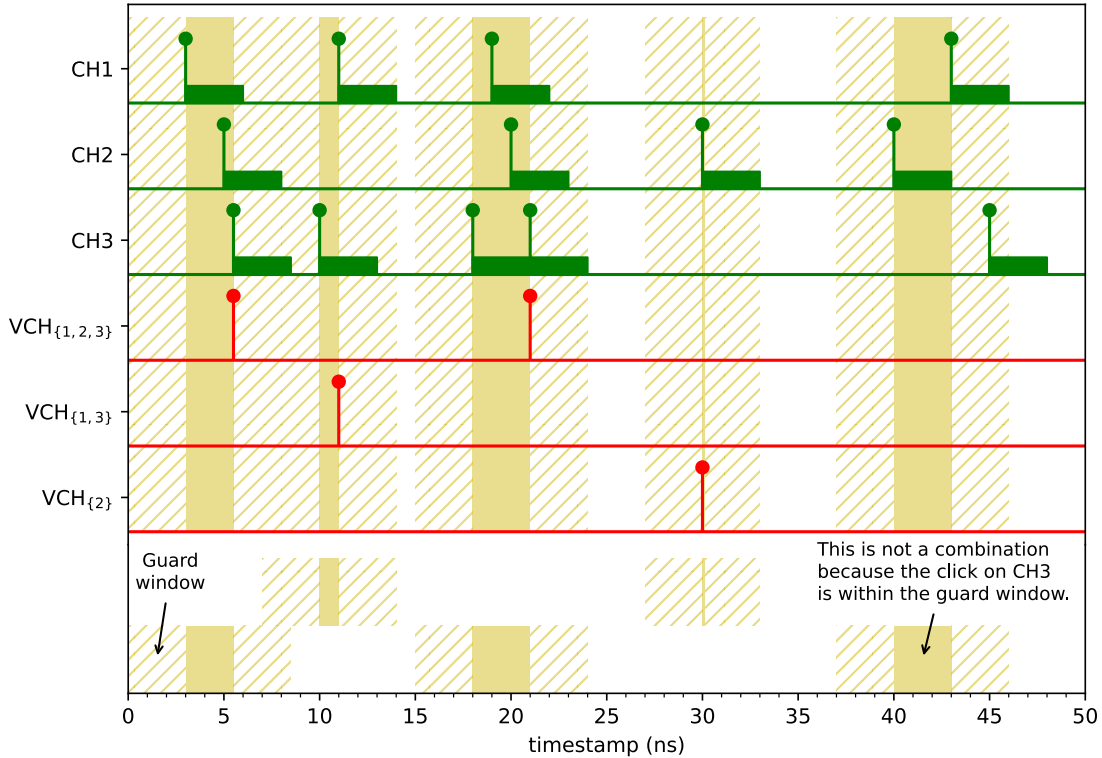
**Coincidences**(*TimeTaggerBase* tagger, *channel\_t*[][] coincidenceGroups, *timestamp\_t* coincidenceWindow, *CoincidenceTimestamp* timestamp = *CoincidenceTimestamp::Last*)

#### Parameters

- **tagger** – Time Tagger object instance.
- **coincidenceGroups** – List of channel groups on which coincidence will be detected in the virtual channel.
- **coincidenceWindow** – Maximum time between all events for a coincidence in picoseconds.
- **timestamp** – Type of timestamp for the virtual channel (default: Last).

### 5.4.5 Combinations

class **Combinations** : public *IteratorBase*



A combination is a group of clicks on a set of channels within a given time window. This time window is surrounded by two guard windows of the same width. These guard windows do not contain any events on the channels being monitored.

The heralding guard window precedes the first click in the combination. The following guard window starts at the time of the last event within the combination window. If there is a click on one of the monitored channels within the guard windows, no combination event is generated. A new combination window then starts with the next click after an empty guard window.

Every time a combination is detected on the monitored channels, *Combinations* emits a tag on the corresponding virtual channel. The timestamp on this virtual channel is the time of the last event included in the combination. Given  $N$  input channels to be monitored, there will be  $2^N - 1$  possible combinations, each having a corresponding virtual channel number.

In addition,  $N$  extra virtual channels called *SumChannels* are created. This class emits a click on the  $n$ -th of these channels on each  $n$ -fold combination, regardless of the channels that contributed to the combination. For instance, this is useful for pseudo-photon-number-resolution with detector arrays.

*See all common methods*

#### Note

Multiple events on the same channel within one time window are counted as one.

### Public Functions

**Combinations**(*TimeTaggerBase* tagger, *channel\_t*[] channels, *timestamp\_t* window\_size)

#### Parameters

- **tagger** – Time Tagger object instance.

- **channels** – List of channels on which the combinations will be detected.
- **window\_size** – Maximum time between all events to make a combination, minimum time without any event detected before and after the combination window, expressed in picoseconds.

*channel\_t* **getChannel**(*channel\_t*[] input\_channels)

Returns the virtual channel number corresponding to the combination formed by the given set of input channels.

#### Warning

The *Combinations* class enables the virtual channel corresponding to a specific combination of input channels only after an explicit call to *getChannel()*, *getChannels()* or *getChannelByMask()*. This is essential to manage computational demands, as the number of possible combinations increases exponentially with the number of input channels.

#### Parameters

**input\_channels** – List of channels forming the combination monitored by the returned virtual channel.

#### Returns

Virtual channel number monitoring the combination.

*channel\_t*[] **getChannels**(*channel\_t*[][] list\_of\_input\_channel\_sets)

Returns a list of virtual channel numbers corresponding to the combinations formed by the given list of sets of input channels.

#### Warning

This method can quickly increase the computational demands of the *Combinations* class, as all returned virtual channels are automatically enabled.

#### Parameters

**list\_of\_input\_channel\_sets** – List of sets of channels forming the combinations monitored by the returned virtual channels.

#### Returns

List of virtual channel numbers monitoring the set of combinations.

*channel\_t* **getChannelByMask**(int input\_mask)

Returns the virtual channel number corresponding to the combination formed by the given set of input channels encoded as mask.

#### Warning

The *Combinations* class enables the virtual channel corresponding to a specific combination of input channels only after an explicit call to *getChannel()*, *getChannels()* or *getChannelByMask()*. This is essential to manage computational demands, as the number of possible combinations increases exponentially with the number of input channels.

**Parameters**

**input\_mask** – Bitmask of channels forming the combination monitored by the returned virtual channel.

**Returns**

Virtual channel number monitoring the combination.

`channel_t[]` **getCombination**(`channel_t` virtual\_channel)

Returns the set of input channels forming a combination event on the given virtual channel *virtual\_channel*.

**Parameters**

**virtual\_channel** – Virtual channel storing the clicks from the combination formed by the returned channels.

**Returns**

List of channels forming the combination monitored by the input virtual channel.

`channel_t` **getSumChannel**(int n\_channels)

Returns the virtual channel number on which an event is generated when any combination of exactly *n\_channels* clicks is detected within the *window\_size*.

**Parameters**

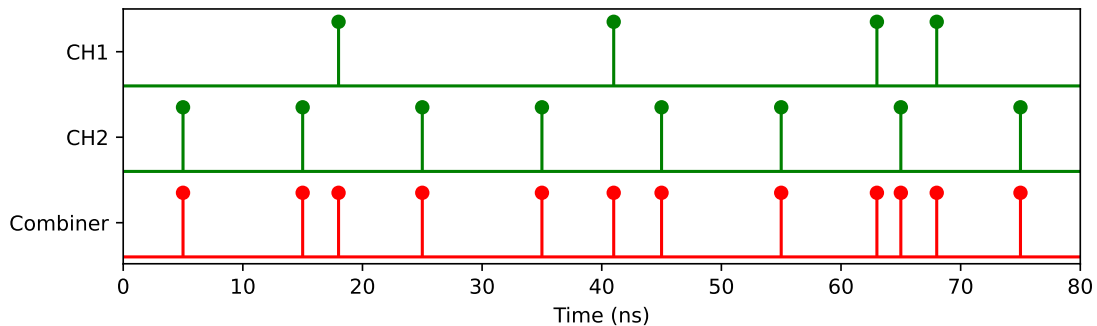
**n\_channels** – Length of the combinations monitored by the returned virtual channel.

**Returns**

Virtual channel number monitoring all combinations of *n\_channel* clicks.

## 5.4.6 Combiner

class **Combiner** : public *IteratorBase*



Merges two or more channels into one. Every time an event is detected on any of the input channels (OR logic), *Combiner* emits a tag on the corresponding virtual channel.

*See all common methods*

**Public Functions**

**Combiner**(*TimeTaggerBase* tagger, `channel_t[]` channels)

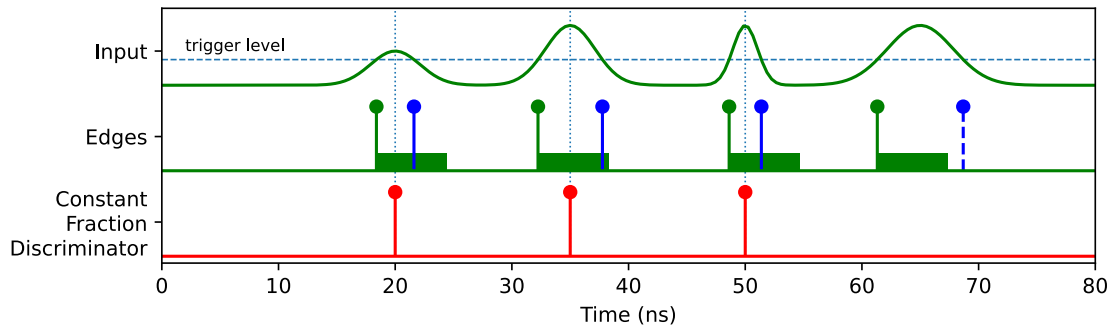
**Parameters**

- **tagger** – Time Tagger object instance.
- **channels** – List of channels to be combined into a single virtual channel.



### 5.4.7 ConstantFractionDiscriminator

class **ConstantFractionDiscriminator** : public *IteratorBase*



Constant Fraction Discriminator (CFD) detects rising and falling edges of an input pulse and returns the average time of both edges. This is useful in situations when precise timing of the pulse position is desired for the pulses of varying durations and amplitudes.

For example, the figure above shows four input pulses separated by 15 nanoseconds. The first two pulses have equal widths but different amplitudes, the middle two pulses have equal amplitude but different durations, and the last pulse has a duration longer than the *search\_window* and is therefore skipped. For such input signal, if we measure the time of the rising edges only, we get an error in the pulse positions, while with CFD this error is eliminated for symmetric pulses.

*See all common methods*

#### Note

The virtual CFD requires the time tags of the **rising** and **falling** edge. This leads to:

- The transferred data of the input channel is twice the regular input rate.
- When you shift the signal, e.g., via `TimeTaggerBase::setInputDelay()`, you have to shift both edges.
- When you use the conditional filter, apply the trigger from both channels.

In addition, you may encounter data rate limitations due the computational complexity of this virtual channel. Consider using `TimeTagger::extra_setAvgRisingFalling()` for similar functionality when the variation between pulse durations is small. There, the computations are performed on the Time Tagger hardware instead of on your PC, and only half the data rate needs to be transferred for the same result.

#### Public Functions

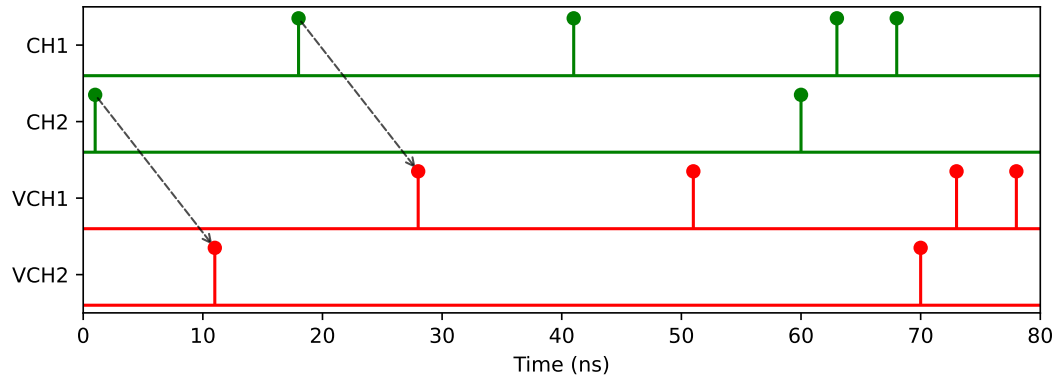
**ConstantFractionDiscriminator**(*TimeTaggerBase* tagger, *channel\_t*[] channels, *timestamp\_t* search\_window)

#### Parameters

- **tagger** – Time Tagger object instance.
- **channels** – List of channels on which to perform the CFD. Specify rising edges only; corresponding falling edges will be registered automatically.
- **search\_window** – Maximum pulse duration, in picoseconds, for detection.

## 5.4.8 DelayedChannels

class **DelayedChannels** : public *IteratorBase*



Clones multiple input channels, which can be delayed by a time specified with the *delay* parameter in the constructor or the `DelayedChannels::setDelay()` method. A negative delay will delay all other events.

*See all common methods*

### Note

If you want to set a global delay for one or more input channels, `TimeTaggerBase::setInputDelay()` is recommended as long as the delays are small, which means that not more than 100 events on all channels should arrive within the maximum delay set.

Subclassed by *DelayedChannel*

### Public Functions

**DelayedChannels**(*TimeTaggerBase* tagger, *channel\_t*[] input\_channels, *timestamp\_t* delay)

#### Parameters

- **tagger** – Time Tagger object instance.
- **input\_channels** – Channels to be delayed.
- **delay** – Time by which the inputs are delayed, expressed in picoseconds.

void **setDelay**(*timestamp\_t* delay)

Allows modifying the delay time.

### Warning

Calling this method with a reduced delay time may result in a partial loss of the internally buffered time tags.

#### Parameters

- **delay** – Delay time in picoseconds.

class **DelayedChannel** : public *DelayedChannels*

Single channel wrapper of *DelayedChannels*. If several different delayed channels are required with the same delay, *DelayedChannels* provides better performance compared to multiple *DelayedChannel* virtual channels.

*See all common methods*

### Public Functions

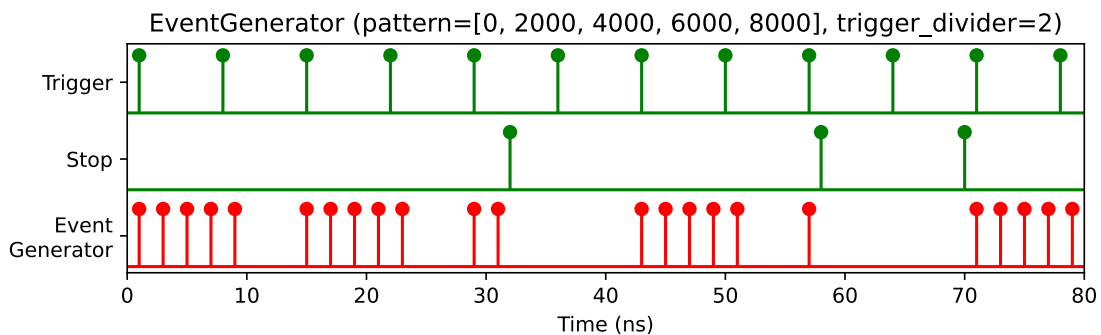
**DelayedChannel**(*TimeTaggerBase* tagger, *channel\_t* input\_channel, *timestamp\_t* delay)

#### Parameters

- **tagger** – Time Tagger object instance.
- **input\_channel** – Channel to be delayed.
- **delay** – Time by which the input is delayed, expressed in picoseconds.

## 5.4.9 EventGenerator

class **EventGenerator** : public *IteratorBase*



Emits an arbitrary pattern of timestamps for every trigger event. The number of trigger events can be reduced by *trigger\_divider*. The start of a new pattern does not abort the execution of unfinished patterns, so patterns may overlap. The execution of all running patterns can be aborted by a click of the *stop\_channel*, i.e. overlapping patterns can be avoided by setting the *stop\_channel* to the *trigger\_channel*.

*See all common methods*

### Public Functions

**EventGenerator**(*TimeTaggerBase* tagger, *channel\_t* trigger\_channel, *timestamp\_t*[] pattern, int trigger\_divider = 1, int divider\_offset = 0, *channel\_t* stop\_channel = *CHANNEL\_UNUSED*)

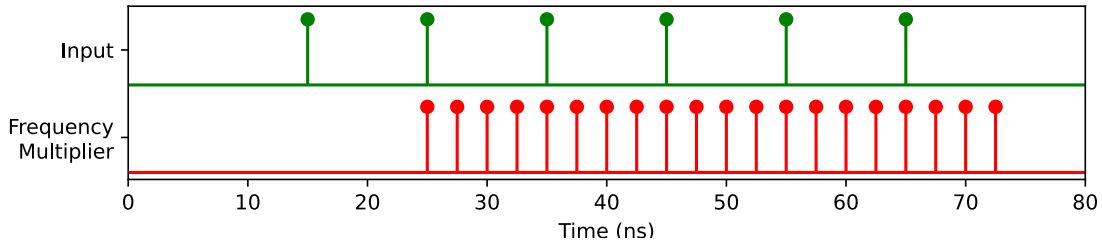
#### Parameters

- **tagger** – Time Tagger object instance.
- **trigger\_channel** – Channel number of the trigger signal.
- **pattern** – List of relative timestamps defining the pattern executed upon a trigger event.
- **trigger\_divider** – Factor by which the number of trigger events is reduced (default: 1).
- **divider\_offset** – If *trigger\_divider* > 1, the *divider\_offset* the number of trigger clicks to be ignored before emitting the first pattern (default: 0).

- **stop\_channel** – Channel number of the stop channel.

### 5.4.10 FrequencyMultiplier

class **FrequencyMultiplier** : public *IteratorBase*



The *FrequencyMultiplier* inserts copies of the original input events from the *input\_channel* and adds additional events to match the upscaling factor. The algorithm used assumes a constant frequency and calculates out of the last two incoming events the intermediate time stamps to match the frequency given by the *multiplier* parameter.

The *FrequencyMultiplier* can be used to restore the actual frequency applied to an *input\_channel* which was reduces via the *EventDivider* to lower the effective data rate.

See all common methods

#### Warning

Very high output frequencies create a high CPU load, eventually leading to *overflows*.

#### Public Functions

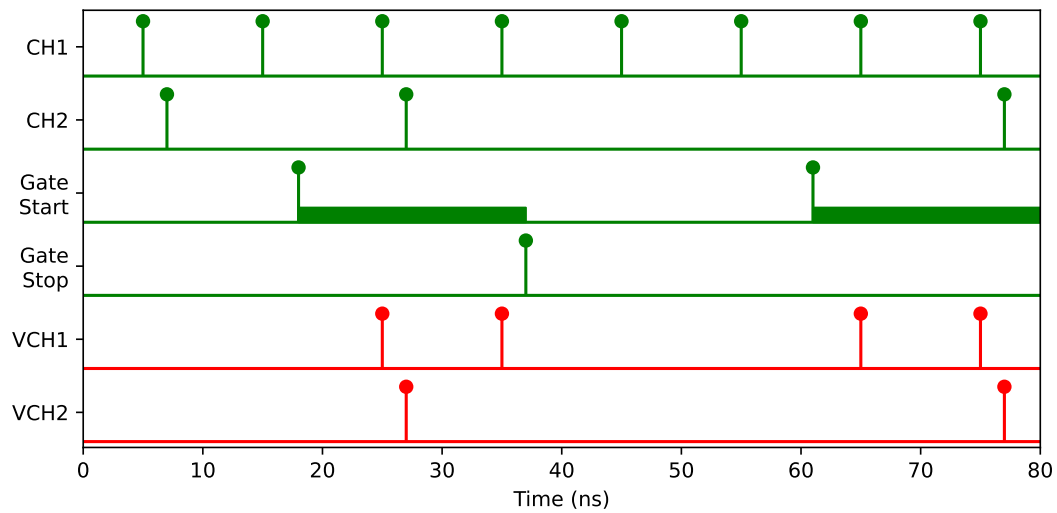
**FrequencyMultiplier**(*TimeTaggerBase* tagger, *channel\_t* input\_channel, int multiplier)

##### Parameters

- **tagger** – Time Tagger object instance.
- **input\_channel** – Channel on which the upscaling of the frequency is based on.
- **multiplier** – Frequency upscaling factor.

### 5.4.11 GatedChannels

class **GatedChannels** : public *IteratorBase*



Transmits the signals from *input\_channels* to new virtual channels while the gate is open. The gate is opened by an event on *gate\_start\_channel* and closed by an event on *gate\_stop\_channel*.

*See all common methods*

This behavior applies to all software versions starting from 2.10.8.

#### Note

If one of the channels in *input\_channels* is identical to *gate\_start\_channel* or *gate\_stop\_channel*, the internal execution order of the transmission decision and the gate operation (opening or closing) becomes important. For each tag on such an input channel, the transmission decision is made based on the previous gate state. After that decision for the tag itself, the same tag may toggle the gate state.

- **If one of the channels in *input\_channels* is identical to *gate\_stop\_channel*:** If the gate is open before a tag on that specific channel arrives, the tag passes and closes the gate afterward. Subsequent tags are blocked until an event on *gate\_start\_channel* opens the gate again. For that specific input channel, this means that once the gate is open, the next tag on that channel will pass and then close the gate. This is analogous to the behavior of the Conditional Filter, with *gate\_start\_channel* acting as the trigger and that specific input channel acting as the filtered channel.
- **If one of the channels in *input\_channels* is identical to *gate\_start\_channel*:** If the gate is closed before the tag on that specific channel arrives, the tag is blocked but opens the gate afterward. Subsequent tags then pass until an event on *gate\_stop\_channel* closes the gate again. For that specific input channel, this means that after a closing event, the next tag on that channel is blocked and reopens the gate.

Subclassed by *GatedChannel*

## Public Functions

**GatedChannels**(*TimeTaggerBase* tagger, *channel\_t*[] input\_channels, *channel\_t* gate\_start\_channel, *channel\_t* gate\_stop\_channel, *GatedChannelInitial* initial = *GatedChannelInitial::Closed*)

### Note

Note that *gate\_stop\_channel* == *gate\_start\_channel* will result in an exception.

### Parameters

- **tagger** – Time Tagger object instance.
- **input\_channels** – Channels to be gated.
- **gate\_start\_channel** – Channel on which a signal detected opens the gate and enables the transmission of the *input\_channels*.
- **gate\_stop\_channel** – Channel on which a detected signal closes the gate and disables transmission of the *input\_channels*.
- **initial** – Initial gate state. If an overflow occurs, the gate is reset to this state as well (default: *GatedChannelInitial::Closed*).

class **GatedChannel** : public *GatedChannels*

Single channel wrapper of *GatedChannels*.

## Public Functions

**GatedChannel**(*TimeTaggerBase* tagger, *channel\_t* input\_channel, *channel\_t* gate\_start\_channel, *channel\_t* gate\_stop\_channel, *GatedChannelInitial* initial = *GatedChannelInitial::Closed*)

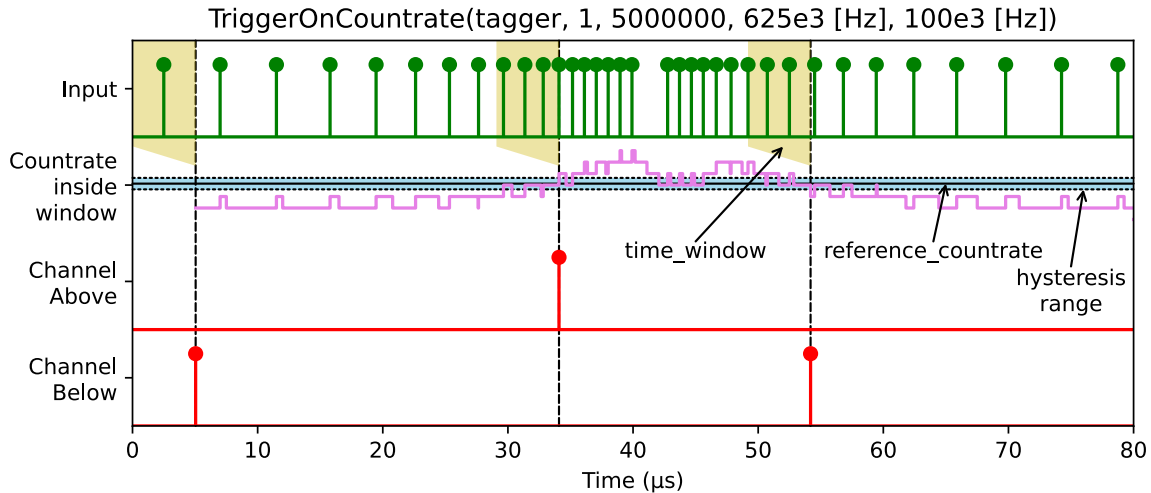
### Note

Note that *gate\_stop\_channel* == *gate\_start\_channel* will result in an exception.

### Parameters

- **tagger** – Time Tagger object instance.
- **input\_channel** – Channel to be gated.
- **gate\_start\_channel** – Channel on which a signal detected opens the gate and enables the transmission of the *input\_channel*.
- **gate\_stop\_channel** – Channel on which a detected signal closes the gate and disables transmission of the *input\_channel*.
- **initial** – Initial gate state. If an overflow occurs, the gate is reset to this state as well (default: *GatedChannelInitial::Closed*).

### 5.4.12 TriggerOnCountrate



class **TriggerOnCountrate** : public *IteratorBase*

Measures the count rate inside a rolling time window and emits tags when a defined *reference\_countrate* is crossed. A *TriggerOnCountrate* object provides two virtual channels: the *above* and the *below* channels. The *above* channel is triggered when the count rate exceeds the threshold (transition from *below* to *above*). The *below* channel is triggered when the count rate falls below the threshold (transition from *above* to *below*).

To avoid the emission of multiple trigger tags in the transition area, the *hysteresis* count rate modifies the threshold with respect to the transition direction: An event in the *above* channel will be triggered when the channel is in the *below* state and rises to  $\text{reference\_countrate} + \text{hysteresis}$  or above. Vice versa, the *below* channel fires when the channel is in the *above* state and falls to the limit of  $\text{reference\_countrate} - \text{hysteresis}$  or below.

The time tags are always injected at the end of the integration window. You can use the *DelayedChannel* to adjust the temporal position of the trigger tags with respect to the integration time window.

The very first tag of the virtual channel will be emitted a *time\_window* after the instantiation of the object and will reflect the current state, so either *above* or *below*.

*See all common methods*

#### Public Functions

**TriggerOnCountrate**(*TimeTaggerBase* tagger, *channel\_t* input\_channel, float reference\_countrate, float hysteresis, *timestamp\_t* time\_window)

#### Parameters

- **tagger** – Time Tagger object instance.
- **input\_channel** – Channel number of the channel whose count rate will control the trigger channels.
- **reference\_countrate** – The reference count rate in Hz that separates the *above* range from the *below* range.
- **hysteresis** – The threshold count rate in Hz for transitioning to the *above* threshold state is  $\text{countrate} \geq \text{reference\_countrate} + \text{hysteresis}$ , whereas it is  $\text{countrate} \leq \text{reference\_countrate} - \text{hysteresis}$  for the *below* state.

\<= reference\_countrate - hysteresis for transitioning to the *below* threshold state. The hysteresis avoids the emission of multiple trigger tags upon a single transition.

- **time\_window** – Rolling time window size in picoseconds. The count rate is analyzed within this time window and compared to the threshold count rate.

*channel\_t* **getChannelAbove()**

Get the channel number of the *above* channel.

*channel\_t* **getChannelBelow()**

Get the channel number of the *below* channel.

*channel\_t*[] **getChannels()**

Get both virtual channel numbers: [*getChannelAbove()*, *getChannelBelow()*].

float **getCurrentCountRate()**

Get the current count rate averaged within the *time\_window*.

bool **injectCurrentState()**

Emits a time tag into the respective channel according to the current state. This is useful if you start a new measurement that requires the information. The function returns whether it was possible to inject the event. The injection is not possible if the Time Tagger is in overflow mode or the time window has not passed yet. The function call is non-blocking.

bool **isAbove()**

Returns whether the Virtual Channel is currently in the *above* state.

bool **isBelow()**

Returns whether the Virtual Channel is currently in the *below* state.

## 5.5 Measurement Classes

The Time Tagger library includes several classes that implement various measurements. All measurements are derived from a base class called *IteratorBase* that is described further down. As the name suggests, it uses the *iterator* programming concept.

All measurements provide a set of methods to start and stop the execution and to access the accumulated data. In a typical application, the following steps are performed (see *example*):

1. Create an instance of a measurement
2. Wait for some time
3. Retrieve the data accumulated by the measurement by calling a *.getData()* method.

### Note

In MATLAB, the Measurement names have common prefix TT\*. For example: *Correlation* is named as *TTCorrelation*. This prevents possible name collisions with existing MATLAB or user functions.

The available measurements are grouped by the following categories: *Event counting*, *Time histograms*, *Fluorescence-lifetime imaging (FLIM)*, *Phase & frequency analyses*, *Time-tag-streaming*, and *Helper classes*.

All the existing classes are listed alphabetically below:

### *Correlation*

Computes auto- and cross-correlations between channels.



***CorrelationPairs***

Computes auto- and cross-correlations between all pairs of a list of channels.

***Counter***

Counts events on one or more channels using fixed-width bins and a circular buffer output.

***Countrate***

Measures the average event rate on one or more channels.

***CustomMeasurement***

Implements a custom measurement by processing the raw time-tag stream with minimal overhead.

***Dump***

Deprecated - please use *FileWriter* instead. Writes raw time-tags to file in an uncompressed binary format.

***FileReader***

Reads time-tags from a compressed file written by the *FileWriter* measurement.

***FileWriter***

Writes time-tags into a file with a lossless compression. It replaces the *Dump* class.

***Flim***

Measures time histograms for fluorescence lifetime imaging.

***FrequencyCounter***

Measures frequency and phase evolution of periodic signals at periodic sampling intervals.

***FrequencyStability***

Analyzes the frequency stability of periodic signals at different time scales.

***GatedCounter***

Counts events on one or more channels within gates defined by one or two marker channels.

***Histogram***

Accumulates a histogram of time differences between two channels.

***Histogram2D***

Accumulates a 2D histogram of correlated time differences.

***HistogramCustomBins***

Accumulates a histogram of time differences using custom binning.

***HistogramLogBins***

Accumulates a histogram of time differences using logarithmic binning.

***HistogramND***

Accumulates an N-dimensional histogram of time differences.

***IteratorBase***

Provides a base class for implementing custom measurements.

***PhaseNoise***

Analyzes the phase stability of a periodic signal in the frequency domain.

***PulsePerSecondMonitor***

Monitors the timing and stability of 1 pulse-per-second (PPS) signals.

***Sampler***

Samples the digital state of channels triggered by another channel.

***Scope***

Detects signal edges for visualization, similar to a ultrafast logic analyzer.

### *StartStop*

Accumulates a histogram of start-stop time differences between two channels.

### *SynchronizedMeasurements*

Synchronizes multiple measurement instances for parallel acquisition and control.

### *TimeDifferences*

Accumulates histograms of time differences between two channels, optionally swept using one or two trigger channels.

### *TimeDifferencesND*

Accumulates multi-dimensional histograms of asynchronous time differences.

### *TimeTagStream*

Provides low-level access to the raw time-tag stream for custom processing. See [Raw Time-Tag-Stream access](#) to get on overview about the possibilities for the raw time-tag-stream access.

## 5.5.1 Common methods

### class **IteratorBase**

#### void **clear()**

Discards accumulated measurement data, initializes the data buffer with zero values, and resets the state to the initial state.

#### void **start()**

Starts or continues data acquisition. This method is implicitly called when a measurement object is created.

#### void **startFor**(*timestamp\_t* capture\_duration, bool clear = true)

Starts or continues the data acquisition for the given duration (in ps). After the *duration* time, the method [stop\(\)](#) is called and [isRunning\(\)](#) will return False. Whether the accumulated data is cleared at the beginning of [startFor\(\)](#) is controlled with the second parameter *clear*, which is True by default.

#### Parameters

- **capture\_duration** – Acquisition duration in picoseconds.
- **clear** – Resets the accumulated data at the beginning (default: True).

#### void **stop()**

After calling this method, the measurement will stop processing incoming tags. Use [start\(\)](#) or [startFor\(\)](#) to continue or restart the measurement.

#### void **abort()**

Immediately aborts the measurement, discarding accumulated measurement data, and resets the state to the initial state.

#### Warning

After calling [abort\(\)](#), the last block of data might become irreversibly corrupted. Please always use [stop\(\)](#) to end a measurement.

#### bool **isRunning()**

Returns True if the measurement is collecting the data. This method will return False if the measurement was stopped manually by calling [stop\(\)](#) or automatically after calling [startFor\(\)](#) and the *duration* has passed.

**Note**

All measurements start accumulating data immediately after their creation.

**Returns**

True if the measurement is still running.

bool **waitUntilFinished**(int timeout = -1)

Blocks the execution until the measurement has finished. Can be used with [startFor\(\)](#). This is roughly equivalent to a polling loop with [sleep\(\)](#).

```
measurement.waitUntilFinished(timeout=-1)
# is roughly equivalent to
while measurement.isRunning():
    sleep(0.01)
```

**Parameters**

**timeout** – Timeout in milliseconds. Negative value means no timeout, zero returns immediately.

**Returns**

True if the measurement has finished, False on timeout.

*timestamp\_t* **getCaptureDuration**()

Total capture duration since the measurement creation or last call to [clear\(\)](#).

**Returns**

Capture duration in ps.

str **getConfiguration**()

Returns configuration data of the measurement object. The configuration includes the measurement name, and the values of the current parameters. Information returned by this method is also provided with [TimeTaggerBase::getConfiguration\(\)](#).

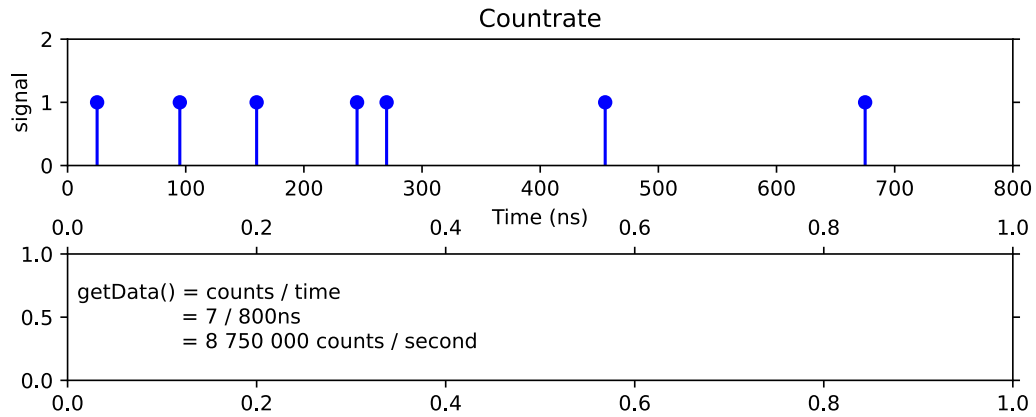
**Returns**

Configuration data of the measurement object.

## 5.5.2 Event counting

### Countrate

class **Countrate** : public *IteratorBase*



Measures the average count rate on one or more channels. Specifically, it determines the counts per second on the specified channels starting from the very first tag arriving after the instantiation or last call to `clear()` of the measurement. The `Countrate` works correctly even when the USB transfer rate or backend processing capabilities are exceeded.

*See all common methods*

### Public Functions

**Countrate**(*TimeTaggerBase* tagger, *channel\_t*[] channels)

#### Parameters

- **tagger** – Time tagger object instance.
- **channels** – Channels for which the average count rate is measured.

float[] **getData**()

#### Returns

Average count rate in counts per second.

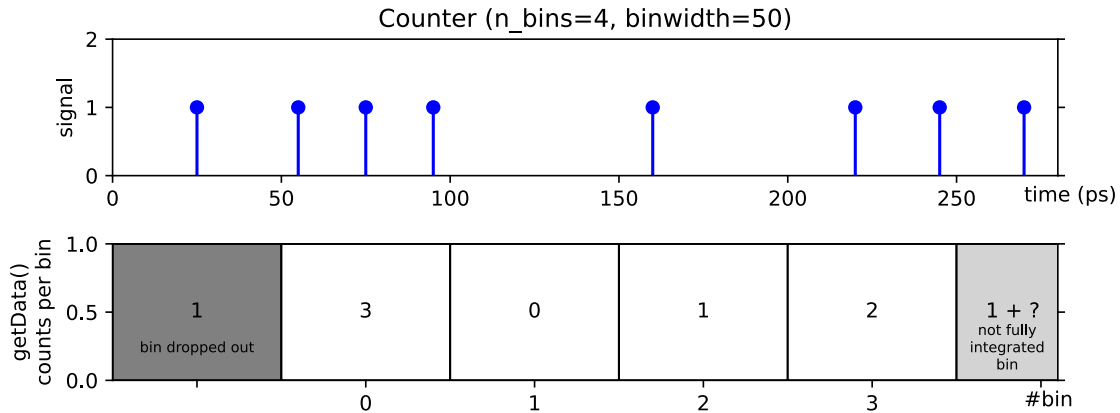
int[] **getCountsTotal**()

#### Returns

The total number of events since the instantiation of this object.

### Counter

class **Counter** : public *IteratorBase*



Time trace of the count rate on one or more channels. Specifically, this measurement repeatedly counts tags within a time interval *binwidth* and stores the results in a two-dimensional array of size *number of channels* by *n\_values*. The incoming data is first accumulated in a not-accessible bin. When the integration time of this bin has passed, the accumulated data is added to the internal buffer, which can be accessed via the *getData...* methods. Data stored in the internal circular buffer is overwritten when *n\_values* are exceeded. You can prevent this by automatically stopping the measurement in time as follows `counter.startFor(duration=binwidth*n_values)`.

*See all common methods*

## Public Functions

**Counter**(*TimeTaggerBase* tagger, *channel\_t*[] channels, *timestamp\_t* binwidth = 1000000000, int n\_values = 1)

### Parameters

- **tagger** – Time tagger object.
- **channels** – Channels used for counting tags.
- **binwidth** – Bin width in ps (default: 1e9).
- **n\_values** – Number of bins (default: 1).

int[,] **getData**(bool rolling = true)

Returns an array of accumulated counter bins for each channel. The optional parameter *rolling*, controls if the not integrated bins are padded before or after the integrated bins.

When *rolling*=True, the most recent data is stored in the last bin of the array and every new completed bin shifts all other bins right-to-left. When continuously plotted, this creates an effect of rolling trace plot. For instance, it is useful for continuous monitoring of countrate changes over time.

When *rolling*=False, the most recent data is stored in the next bin after previous such that the array is filled up left-to-right. When array becomes full and the *Counter* is still running, the array index will be reset to zero and the array will be filled again overwriting previous values. This operation is sometimes called “sweep plotting”.

### Parameters

**rolling** – Controls how the counter array is filled (default: True).

### Returns

An array of size *number of channels* by *n\_values* containing the counts in each fully integrated bin.

*timestamp\_t*[] **getIndex()**

Returns the relative time of the bins in ps. The first entry of the returned vector is always 0.

**Returns**

A vector of size *n\_values* containing the time bins in ps.

float[,] **getDataNormalized**(bool rolling = true)

Does the same as [getData\(\)](#) but returns the count rate in Hz as a float. Not integrated bins and bins in overflow mode are marked as *NaN*.

**Parameters**

**rolling** – Controls how the counter array is filled (default: True).

**Returns**

An array of size *number of channels* by *n\_values* containing the count rate in Hz as a float in each fully integrated bin.

int[] **getDataTotalCounts()**

Returns total number of events per channel since the last call to [clear\(\)](#), excluding the currently integrating bin. This method works correctly even when the USB transfer rate or backend processing capabilities are exceeded.

**Returns**

Number of events per channel.

*CounterData* **getDataObject**(bool remove = false)

Returns *CounterData* object containing a snapshot of the data accumulated in the *Counter* at the time this method is called.

**Parameters**

**remove** – Controls if the returned data shall be removed from the internal buffer (default: False).

**Returns**

A *CounterData* object providing access to a snapshot data.

class **CounterData**

Objects of this class are created and returned by [Counter::getDataObject\(\)](#), and contain a snapshot of the data accumulated by the *Counter* measurement.

**Public Functions**

*timestamp\_t*[] **getIndex()**

Returns the relative time of the bins in ps. The first entry of the returned vector is always 0 for [size\(\)](#) > 0.

**Returns**

A vector of size [size\(\)](#) containing the relative time bins in ps.

int[,] **getData()**

**Returns**

An array of size *number of channels* by [size\(\)](#) containing only fully integrated bins.

float[,] **getDataNormalized()**

Does the same as [getData\(\)](#) but returns the count rate in Hz. Bins in overflow mode are marked as *NaN*.

**Returns**

An array of size *number of channels* by [size\(\)](#) containing the count rate in Hz as a float only for fully integrated bins.

float[,] **getFrequency**(*timestamp\_t* time\_scale = 1000000000000)

Returns the counts normalized to the specified time scale. Bins in overflow mode are marked as *NaN*.

**Parameters**

**time\_scale** – Scales the return value to this time interval. Default is 1 s, so the return value is in Hz. For negative values, the time scale is set to *binwidth*.

**Returns**

An array of size *number of channels* by *size()* containing the counts normalized to the specified time scale.

int[] **getDataTotalCounts**()

Returns the total number of events per channel since the last call to *IteratorBase::clear()*, excluding the counts of the internal bin where data is currently integrated into. This method works correctly even when the USB transfer rate or backend processing capabilities are exceeded.

**Returns**

Number of events per channel.

*timestamp\_t*[] **getTime**()

This is similar to *getIndex()* but it returns the absolute timestamps of the bins. For subsequent calls to *Counter::getDataObject*, these arrays can be concatenated to obtain a full index array.

**Returns**

A vector of size *size()* containing the time corresponding to the return value of *getData()* in ps.

int[] **getOverflowMask**()

Array of values for each bin that indicate if an overflow occurred during accumulation of the respective bin.

**Returns**

An array of size *size()* containing overflow mask.

## Public Members

int **size**

Number of returned bins.

int **dropped\_bins**

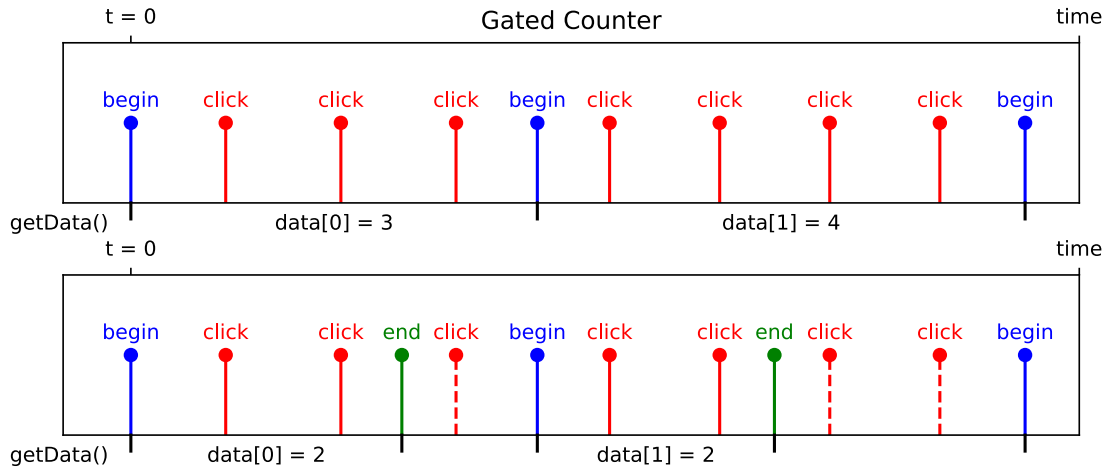
Number of bins which have been dropped because *n\_values* of the *Counter* measurement has been exceeded.

bool **overflow**

Status flag for whether any of the returned bins have been in overflow mode.

## GatedCounter

class **GatedCounter** : public *IteratorBase*



Counts events on a list of channels within the time indicated by “start” and “stop” signals. The bin edges between which counts are accumulated are determined by one or more hardware triggers. Specifically, the measurement records data into an array of shape *number of channels* by *n\_values* (initially filled with zeros). It waits for tags on the *begin\_channel*. When a tag is detected on the *begin\_channel*, it starts counting tags on all *click\_channels*. When the next tag is detected on the *begin\_channel*, it stores the current counter values (one per click channel) as the next column in the data array, resets the counter to zero and starts accumulating counts again. If an *end\_channel* is specified, the measurement stores the current counter values and resets the counters when a tag is detected on the *end\_channel* rather than the *begin\_channel*. You can use this, e.g., to accumulate counts within a gate by using rising edges on one channel as the *begin\_channel* and falling edges on the same channel as the *end\_channel*. The accumulation time for each value can be accessed via [getBinWidths\(\)](#). The measurement stops when all entries in the data array are filled.

*See all common methods*

## Public Functions

**GatedCounter**(*TimeTaggerBase* tagger, *channel\_t*[] click\_channels, *channel\_t* begin\_channel, *channel\_t* end\_channel = *CHANNEL\_UNUSED*, int n\_values = 1000)

### Parameters

- **tagger** – Time tagger object.
- **click\_channels** – Channels on which clicks are received, gated by *begin\_channel* and *end\_channel*.
- **begin\_channel** – Channel that triggers the beginning of counting and stepping to the next value.
- **end\_channel** – Channel that triggers the end of counting (optional, default: *CHANNEL\_UNUSED*)
- **n\_values** – Number of values stored (data buffer size) (default: 1000)

int[,] **getData()**

### Returns

Array of size *number of channels* by *n\_values* containing the acquired counter values.

*timestamp\_t*[] **getIndex()**

### Returns

Vector of size *n\_values* containing the time in ps of each start click in respect to the very first start click.



*timestamp\_t*[] **getBinWidths()**

**Returns**

Vector of size *n\_values* containing the time differences of ‘start -> (next start or stop)’ for the acquired counter values.

bool **ready()**

**Returns**

True when the entire array is filled.

class **CountBetweenMarkers** : public *IteratorBase*

Same as *GatedCounter*, but for a single *click\_channel* only.

*Deprecated:*

Since version 2.22. Please use the multi-channel class *GatedCounter* instead.

## Public Functions

**CountBetweenMarkers**(*TimeTaggerBase* tagger, *channel\_t* click\_channel, *channel\_t* begin\_channel, *channel\_t* end\_channel = *CHANNEL\_UNUSED*, int n\_values = 1000)

**Parameters**

- **tagger** – Time tagger object.
- **click\_channel** – Channel on which clicks are received, gated by *begin\_channel* and *end\_channel*.
- **begin\_channel** – Channel that triggers the beginning of counting and stepping to the next value.
- **end\_channel** – Channel that triggers the end of counting (optional, default: *CHANNEL\_UNUSED*)
- **n\_values** – Number of values stored (data buffer size) (default: 1000)

int[] **getData()**

**Returns**

Array of size *n\_values* containing the acquired counter values.

*timestamp\_t*[] **getIndex()**

**Returns**

Vector of size *n\_values* containing the time in ps of each start click in respect to the very first start click.

*timestamp\_t*[] **getBinWidths()**

**Returns**

Vector of size *n\_values* containing the time differences of ‘start -> (next start or stop)’ for the acquired counter values.

bool **ready()**

**Returns**

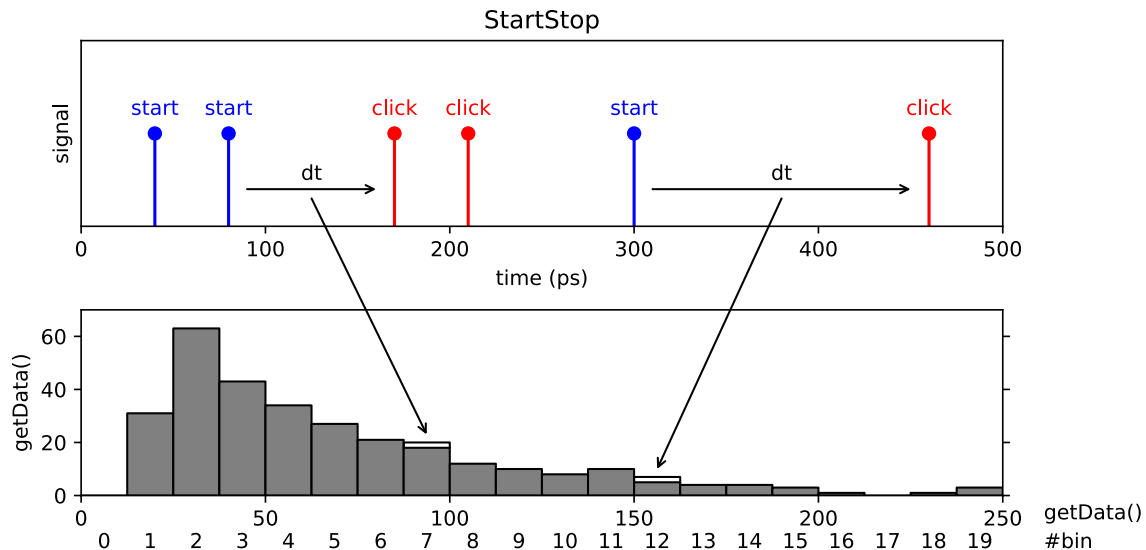
True when the entire array is filled.

### 5.5.3 Time histograms

This section describes various measurements that calculate time differences between events and accumulate the results into a histogram.

#### StartStop

class **StartStop** : public *IteratorBase*



A simple start-stop measurement. This class performs a start-stop measurement between two channels and stores the time differences in a histogram. The histogram resolution is specified beforehand (*binwidth*) but the histogram range is unlimited. It is adapted to the largest time difference that was detected. Thus all pairs of subsequent clicks are registered. Only non-empty bins are recorded.

*See all common methods*

#### Public Functions

**StartStop**(*TimeTaggerBase* tagger, *channel\_t* click\_channel, *channel\_t* start\_channel = CHANNEL\_UNUSED, *timestamp\_t* binwidth = 1000)

##### Parameters

- **tagger** – Time tagger object instance.
- **click\_channel** – Channel on which stop clicks are received.
- **start\_channel** – Channel on which start clicks are received (default: CHANNEL\_UNUSED).
- **binwidth** – Bin width in ps (default: 1000).

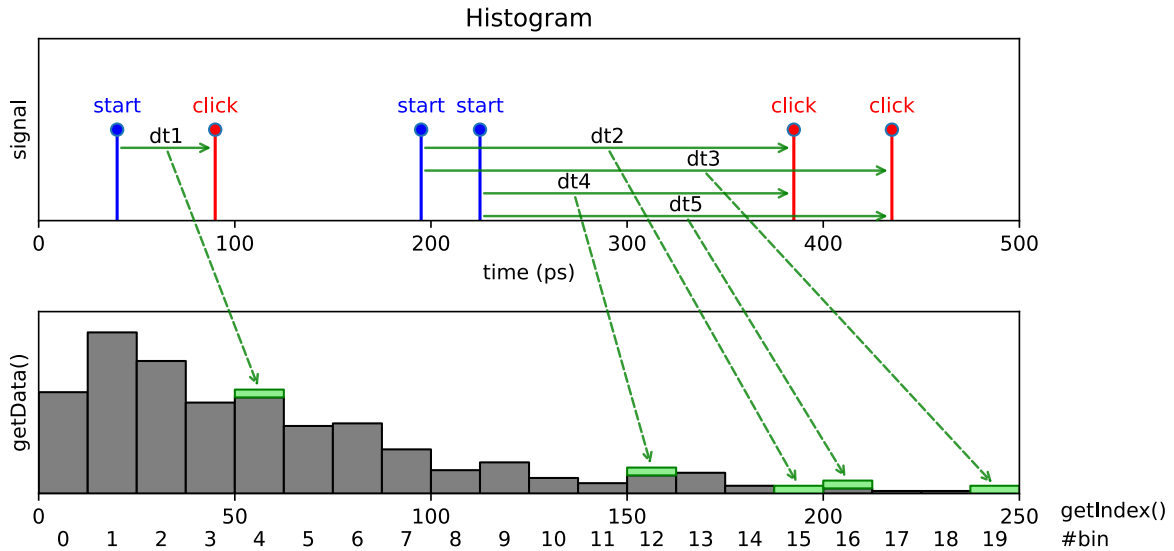
*timestamp\_t* [,] **getdata**()

##### Returns

An array of tuples (array of shape Nx2) containing the times (in ps) and counts of each bin. Only non-empty bins are returned.

## Histogram

class **Histogram** : public *IteratorBase*



Accumulate time differences into a histogram. This is a simple multiple start, multiple stop measurement. This is a special case of the more general *TimeDifferences* measurement. Specifically, the measurement waits for clicks on the *start\_channel*, and for each start click, it measures the time difference between the start clicks and all subsequent clicks on the *click\_channel* and stores them in a histogram. The histogram range and resolution are specified by the number of bins and the bin width specified in ps. Clicks that fall outside the histogram range are ignored. Data accumulation is performed independently for all start clicks. This type of measurement is frequently referred to as a ‘multiple start, multiple stop’ measurement and corresponds to a full auto- or cross-correlation measurement.

*See all common methods*

### Public Functions

**Histogram**(*TimeTaggerBase* tagger, *channel\_t* click\_channel, *channel\_t* start\_channel = *CHANNEL\_UNUSED*, *timestamp\_t* binwidth = 1000, int n\_bins = 1000)

#### Parameters

- **tagger** – Time tagger object instance.
- **click\_channel** – Channel on which clicks are received.
- **start\_channel** – Channel on which start clicks are received (default: *CHANNEL\_UNUSED*).
- **binwidth** – Bin width in ps (default: 1000).
- **n\_bins** – The number of bins in the histogram (default: 1000).

int[] **getData()**

#### Returns

A one-dimensional array of size *n\_bins* containing the histogram.

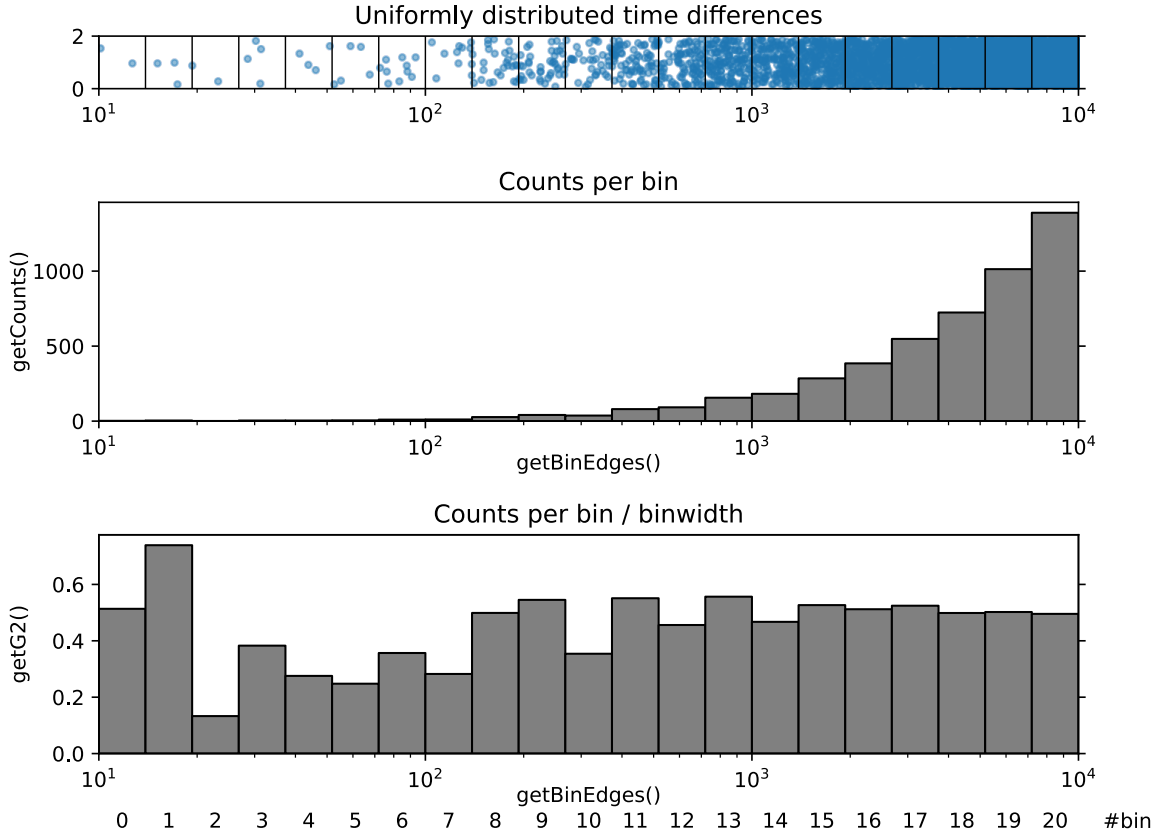
`timestamp_t[] getIndex()`

#### Returns

A vector of size `n_bins` containing the time bins in ps.

## HistogramLogBins

class **HistogramLogBins** : public *IteratorBase*



The *HistogramLogBins* measurement is similar to *Histogram* but the bin edges are spaced logarithmically. As the bins do not have a homogeneous binwidth, a proper normalization is required to interpret the raw data.

For excluding time ranges from the histogram evaluation while maintaining a proper normalization, *HistogramLogBins* optionally takes two gating arguments of type *ChannelGate*. This can, e.g., be used to pause the acquisition during erroneous ranges that have to be identified by virtual channels. The same mechanism automatically applies to overflow ranges.

The acquired histogram  $H(t)$  is normalized by

$$\tilde{H}(\tau) = I(\tau) \cdot C_{\text{click}} \cdot C_{\text{start}},$$

with an estimation of counts  $I(\tau)$  and the click and start channel count rates,  $C_{\text{click}} = N_{\text{click}}/t_{\text{click}}$  and  $C_{\text{start}} = N_{\text{start}}/t_{\text{start}}$ , respectively. Typically, this will be used to calculate

$$g^{(2)}(\tau) = \frac{H(\tau)}{\tilde{H}(\tau)}.$$

For  $t \gg 10^{\text{exp\_stop}}$  s and without interruptions,  $I(\tau)/t$  will approach the binwidth of the respective bin. During the early acquisition and in case of interruptions,  $I(\tau)$  can be significantly smaller, which compensates for counts that are excluded from  $H(\tau)$ .

*See all common methods*

Subclassed by *HistogramCustomBins*

## Public Functions

**HistogramLogBins**(*TimeTaggerBase* tagger, *channel\_t* click\_channel, *channel\_t* start\_channel, float exp\_start, float exp\_stop, int n\_bins, *ChannelGate* click\_gate = None, *ChannelGate* start\_gate = None)

### Parameters

- **tagger** – Time tagger object instance.
- **click\_channel** – Channel on which clicks are received.
- **start\_channel** – Channel on which start clicks are received.
- **exp\_start** – Exponent  $10^{\text{exp\_start}}$  in seconds where the very first bin begins.
- **exp\_stop** – Exponent  $10^{\text{exp\_stop}}$  in seconds where the very last bin ends.
- **n\_bins** – The number of bins in the histogram.
- **click\_gate** – Optional evaluation gate for the *click\_channel*.
- **start\_gate** – Optional evaluation gate for the *start\_channel*.

*HistogramLogBinsData* **getDataObject()**

### Returns

A data object containing raw and normalization data.

*timestamp\_t[]* **getBinEdges()**

### Returns

A vector of size  $n\_bins+1$  containing the bin edges in picoseconds.

*int[]* **getData()**

*Deprecated:*

Since version 2.17.0. Please use *getDataObject()* and *HistogramLogBinsData::getCounts()* instead.

### Returns

A one-dimensional array of size  $n\_bins$  containing the histogram.

*float[]* **getDataNormalizedCountsPerPs()**

*Deprecated:*

Since version 2.17.0.

### Returns

The counts normalized by the binwidth of each bin.

*float[]* **getDataNormalizedG2()**

*Deprecated:*

Since version 2.17.0. Please use `getDataObject()` and `HistogramLogBinsData::getG2()` instead.

**Returns**

The counts normalized by the binwidth of each bin and the average count rate.

class **HistogramLogBinsData**

Contains the histogram counts  $H(\tau)$  and the corresponding normalization function  $\tilde{H}(\tau)$ .

**Public Functions**

float[] **getG2()**

**Returns**

A one-dimensional array of size  $n\_bins$  containing the normalized histogram  $H(\tau)/\tilde{H}(\tau)$ .

int[] **getCounts()**

**Returns**

A one-dimensional array of size  $n\_bins$  containing the raw histogram  $H(\tau)$ .

float[] **getG2Normalization()**

**Returns**

A one-dimensional array of size  $n\_bins$  containing the normalization  $\tilde{H}(\tau)$ .

**Public Members**

*timestamp\_t* **accumulation\_time\_start**

Effective accumulation time of the *start\_channel* in picosecond.

This is the total time during which the *start\_channel* was open for evaluation, i.e., not excluded by *start\_gate*. This is the time base used for the *start\_channel* countrate in the normalization.

*timestamp\_t* **accumulation\_time\_click**

Effective accumulation time of the *click\_channel* in picosecond.

This is the total time during which the *click\_channel* was open for evaluation, i.e., not excluded by *click\_gate*. This is the time base used for the *click\_channel* countrate in the normalization.

*timestamp\_t* **capture\_duration**

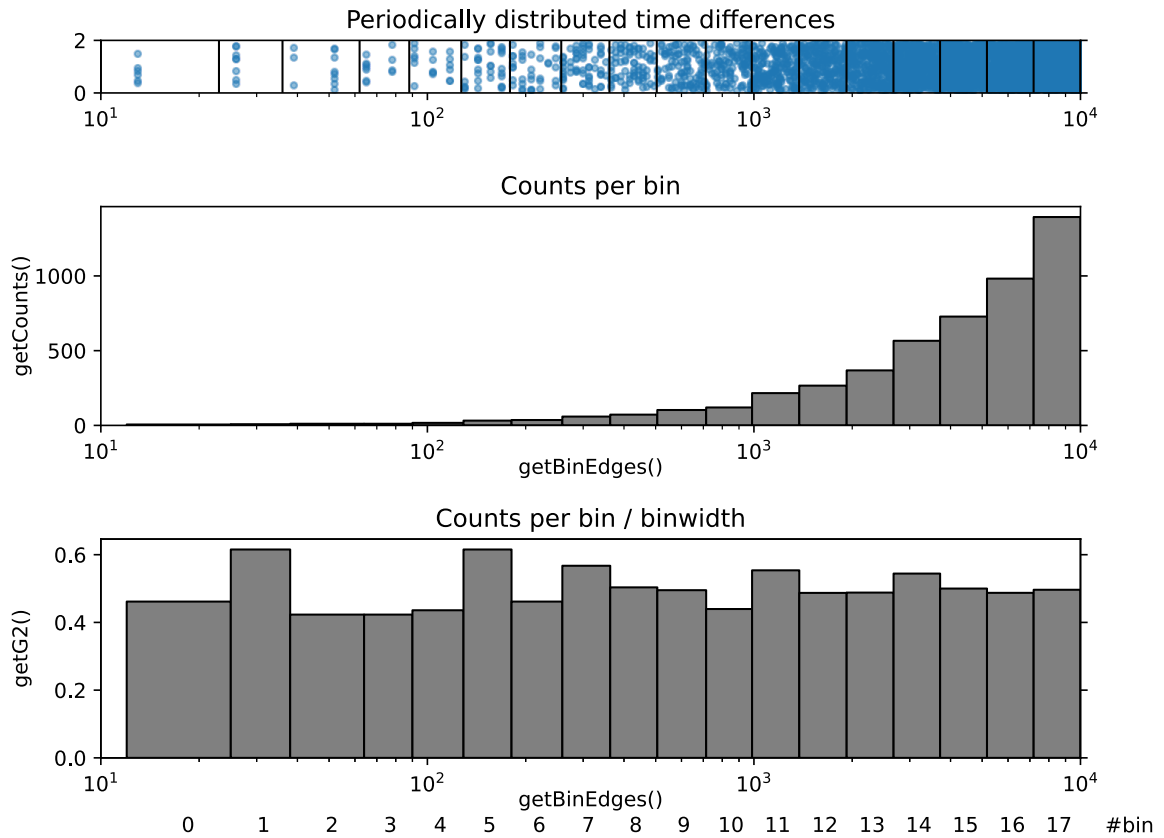
Total capture duration in picoseconds since the measurement creation or last call to `IteratorBase::clear()` (equivalent to `IteratorBase::getCaptureDuration()`).

**Note**

Unlike *accumulation\_time\_start* / *accumulation\_time\_click*, *capture\_duration* is not reduced by channel gates. It represents the overall acquisition time base.

## HistogramCustomBins

class **HistogramCustomBins** : public *HistogramLogBins*



*HistogramCustomBins* is an alternative to *HistogramLogBins* that supports explicitly defined bin edges. Like *HistogramLogBins*, it is optimized for applications with very large bins. Compared to *Histogram*, its performance is much better when the average bin width is much larger than the average period of the input events, and much worse otherwise.

The primary use case for *HistogramCustomBins* is the analysis of data over extremely large correlation windows with manually defined bin edges, for example in correlation spectroscopy with pulsed laser excitation; see the *Fluorescence Correlation Spectroscopy tutorial* for details.

The measurement data can be retrieved in the same way as for *HistogramLogBins*, using the *HistogramLogBinsData* object. For more information, see *HistogramLogBins*.

**Note**

This measurement and *HistogramLogBins* have a time complexity of  $(\text{start\_rate} + \text{click\_rate}) * n\_bins$ . So it is good to keep the amount of bins small, usually down to just a few hundred bins.

**Public Functions**

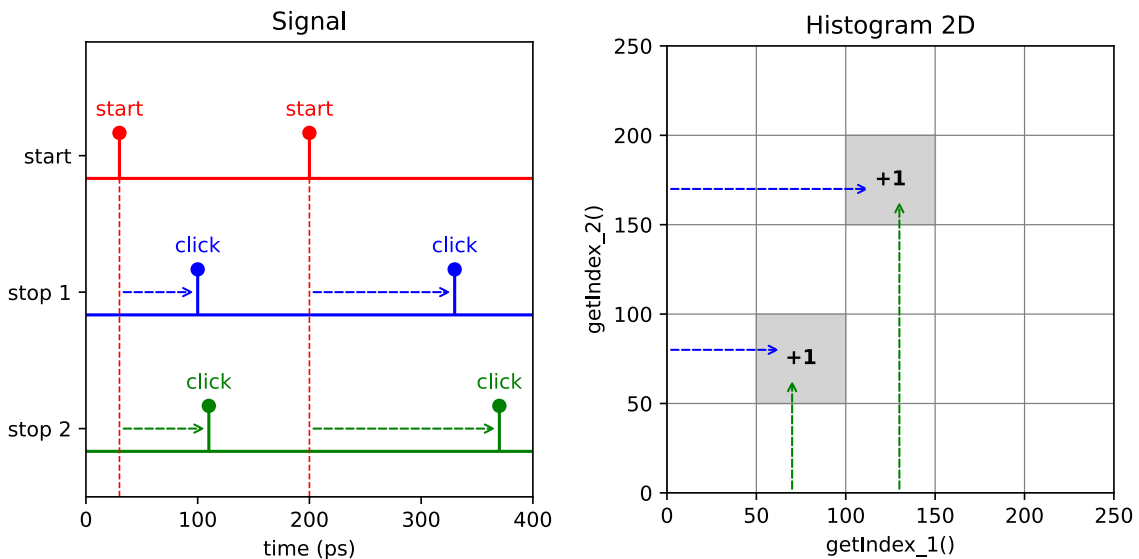
**HistogramCustomBins**(*TimeTaggerBase* tagger, *channel\_t* click\_channel, *channel\_t* start\_channel, *timestamp\_t*[] binedges, *ChannelGate* click\_gate = None, *ChannelGate* start\_gate = None)

**Parameters**

- **tagger** – Time tagger object instance.
- **click\_channel** – Channel on which clicks are received.
- **start\_channel** – Channel on which start clicks are received.
- **binedges** – The timestamps of the edges of the bins.
- **click\_gate** – Optional evaluation gate for the *click\_channel*.
- **start\_gate** – Optional evaluation gate for the *start\_channel*.

**Histogram2D**

class **Histogram2D** : public *IteratorBase*



This measurement is a 2-dimensional version of the *Histogram* measurement. The measurement accumulates two-dimensional histogram where stop signals from two separate channels define the bin coordinate. For instance, this kind of measurement is similar to that of typical 2D NMR spectroscopy. The data within the histogram is acquired via a single-start, single-stop analysis for each axis. The first stop click of each axis is taken after the start click to evaluate the histogram counts.

*See all common methods*



## Public Functions

**Histogram2D**(*TimeTaggerBase* tagger, *channel\_t* start\_channel, *channel\_t* stop\_channel\_1, *channel\_t* stop\_channel\_2, *timestamp\_t* binwidth\_1, *timestamp\_t* binwidth\_2, int n\_bins\_1, int n\_bins\_2)

### Parameters

- **tagger** – Time tagger object
- **start\_channel** – Channel on which start clicks are received
- **stop\_channel\_1** – Channel on which stop clicks for the time axis 1 are received
- **stop\_channel\_2** – Channel on which stop clicks for the time axis 2 are received
- **binwidth\_1** – Bin width in ps for the time axis 1
- **binwidth\_2** – Bin width in ps for the time axis 2
- **n\_bins\_1** – The number of bins along the time axis 1
- **n\_bins\_2** – The number of bins along the time axis 2

int[,] **getData**()

### Returns

A two-dimensional array of size *n\_bins\_1* by *n\_bins\_2* containing the 2D histogram.

*timestamp\_t*[:,] **getIndex**()

Returns a 3D array containing two coordinate matrices (*meshgrid*) for time bins in ps for the time axes 1 and 2. For details on *meshgrid* please take a look at the respective documentation either for [Matlab](#) or [Python NumPy](#).

### Returns

A three-dimensional array of size *n\_bins\_1* x *n\_bins\_2* x 2.

*timestamp\_t*[] **getIndex\_1**()

### Returns

A vector of size *n\_bins\_1* containing the bin locations in ps for the time axis 1.

*timestamp\_t*[] **getIndex\_2**()

### Returns

A vector of size *n\_bins\_2* containing the bin locations in ps for the time axis 2.

## HistogramND

class **HistogramND** : public *IteratorBase*

This measurement is the generalization of [Histogram2D](#) to an arbitrary number of dimensions. The data within the histogram is acquired via a single-start, single-stop analysis for each axis. The first stop click of each axis is taken after the start click to evaluate the histogram counts.

[HistogramND](#) can be used as a 1D [Histogram](#) with single-start single-stop behavior.

*See all common methods*

## Public Functions

**HistogramND**(*TimeTaggerBase* tagger, *channel\_t* start\_channel, *channel\_t*[] stop\_channels, *timestamp\_t*[] binwidths, int[] n\_bins)

#### Parameters

- **tagger** – Time tagger object.
- **start\_channel** – Channel on which start clicks are received.
- **stop\_channels** – Channel list on which stop clicks are received defining the time axes.
- **binwidths** – Bin width in ps for the corresponding time axis.
- **n\_bins** – The number of bins along the corresponding time axis.

int[] **getData**()

Returns a one-dimensional array of the size of the product of *n\_bins* containing the histogram data. The array order is in row-major. For example, with *stop\_channels*=[ch1, ch2] and *n\_bins*=[2, 2], the 1D array would represent 2D bin indices in the order [(0,0), (0,1), (1,0), (1,1)], with (index of ch1, index of ch2). Please reshape the 1D array to get the N-dimensional array. The following code demonstrates how to reshape the returned 1D array into multidimensional array using NumPy:

```
channels = [2, 3, 4, 5]
n_bins = [5, 3, 4, 6]
binwidths = [100, 100, 100, 50]
histogram_nd = HistogramND(tagger, 1, channels, binwidths, n_bins)
sleep(1) # Wait to accumulate the data
data = histogram_nd.getData()
multidim_array = numpy.reshape(data, n_bins)
```

#### Returns

Flattened array of histogram bins.

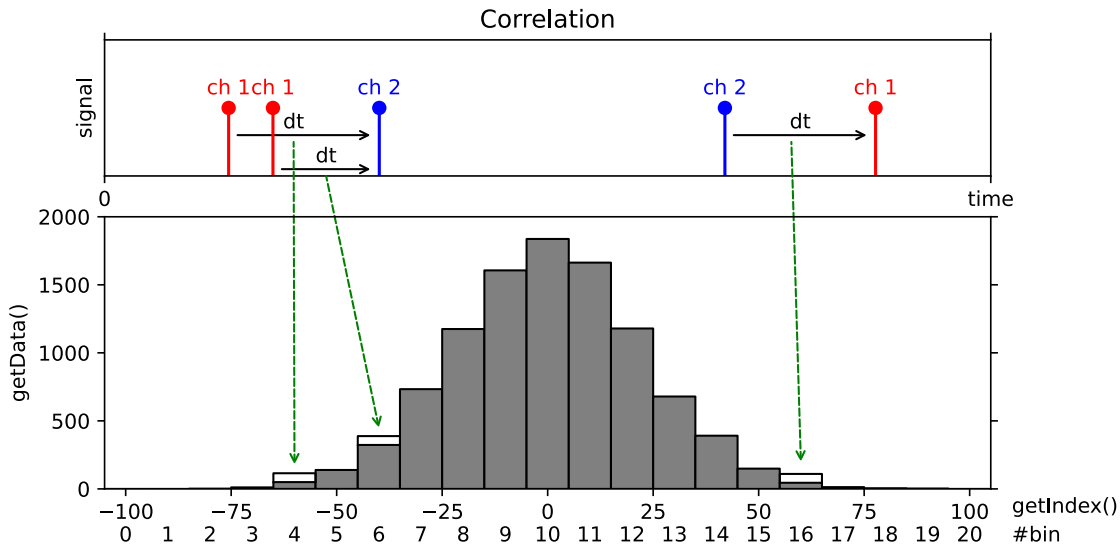
*timestamp\_t*[] **getIndex**(int dim = 0)

#### Returns

A vector of size *n\_bins*[dim] containing the bin locations in ps for the corresponding time axis.

## Correlation

class **Correlation** : public *IteratorBase*



Accumulates time differences between clicks on two channels into a histogram, where all clicks are considered both as “start” and “stop” clicks and both positive and negative time differences are calculated.

*See all common methods*

#### Note

To perform multiple cross-correlations between any pairs within a set of channels, [CorrelationPairs](#) might offer a better performance.

### Public Functions

**Correlation**(*TimeTaggerBase* tagger, *channel\_t* channel\_1, *channel\_t* channel\_2 = *CHANNEL\_UNUSED*, *timestamp\_t* binwidth = 1000, int n\_bins = 1000)

#### Parameters

- **tagger** – Time tagger object.
- **channel\_1** – Channel on which (stop) clicks are received.
- **channel\_2** – Channel on which reference clicks (start) are received (when left empty or set to *CHANNEL\_UNUSED* -> an auto-correlation measurement is performed, which is the same as setting **channel\_1** = **channel\_2**) (default: *CHANNEL\_UNUSED*).
- **binwidth** – Bin width in ps (default: 1000).
- **n\_bins** – The number of bins in the resulting histogram (default: 1000).

int[] **getData()**

#### Returns

A one-dimensional array of size *n\_bins* containing the histogram.

float[] **getDataNormalized()**

Return the data normalized as:

$$g^{(2)}(\tau) = \frac{\Delta t}{\text{binwidth}(\tau) \cdot N_1 \cdot N_2} \cdot \text{histogram}(\tau),$$

where  $\Delta t$  is the capture duration,  $N_1$  and  $N_2$  are number of events in each channel.

**Warning**

This normalization assumes that the histogram span is much smaller than the measurement duration. For large delay ranges, reduced overlap at large absolute delays is not taken into account. In such cases, use `HistogramLogBins` or `HistogramCustomBins` and `HistogramLogBinsData::getG2Normalization()`.

**Returns**

Data normalized by the binwidth and the average count rate.

`timestamp_t[]` **getIndex()**

**Returns**

A vector of size `n_bins` containing the time bins in ps.

**CorrelationPairs**

class **CorrelationPairs** : public *IteratorBase*

Accumulates time differences between clicks on any pair of channels into a histogram, where all clicks are considered both as “start” and “stop” clicks and both positive and negative time differences are calculated.

*See all common methods*

**Public Functions**

**CorrelationPairs**(*TimeTaggerBase* tagger, `channel_t[]` channels, `timestamp_t` binwidth = 1000, int n\_bins = 1000)

**Parameters**

- **tagger** – Time tagger object.
- **channels** – List of channels on which reference (start) events and (stop) clicks are received.
- **binwidth** – Bin width in ps (default: 1000).
- **n\_bins** – The number of bins in the resulting histogram per pair of channels (default: 1000).

*CorrelationPairsData* **getDataObject()**

Returns a *CorrelationPairsData* object containing a snapshot of the data accumulated in the *CorrelationPairs* at the time this method is called.

**Returns**

An object providing access to a snapshot data.

`timestamp_t[]` **getIndex()**

**Returns**

A vector of size `n_bins` containing the time bins in ps.

class **CorrelationPairsData**

## Public Functions

`int[,.] getCounts(bool exclude_self_coincidences = true)`

### Parameters

**exclude\_self\_coincidences** – Controls if autocorrelation histograms ( $i == j$ ) exclude same-event pairs (a timestamp correlated with itself), removing the  $\delta$ -like spike at  $\tau = 0$  (default: True).

### Returns

A three-dimensional array of size  $n\_channels \times n\_channels \times n\_bins$  containing the histogram, where  $n\_channels$  is the total number of channels:

- The first index selects the **start channel**.
- The second index selects the **stop channel**.
- The third index runs over the histogram bins.

`float[,.] getG2(bool exclude_self_coincidences = true)`

Return the data normalized as:

$$g^{(2)}(\tau) = \frac{\Delta t}{\text{binwidth}(\tau) \cdot N_1 \cdot N_2} \cdot \text{histogram}(\tau),$$

where  $\Delta t$  is the capture duration,  $N_1$  and  $N_2$  are number of events in each channel.

### Warning

This normalization assumes that the histogram span is much smaller than the measurement duration. For large delay ranges, the reduced overlap at large absolute delays is not taken into account.

### Parameters

**exclude\_self\_coincidences** – Controls if autocorrelation histograms ( $i == j$ ) exclude same-event pairs (a timestamp correlated with itself), removing the  $\delta$ -like spike at  $\tau = 0$  (default: True).

### Returns

A three-dimensional array of size  $n\_channels \times n\_channels \times n\_bins$  containing the data normalized by the *binwidth* and the average count rate, where  $n\_channels$  is the total number of channels:

- The first index selects the **start channel**.
- The second index selects the **stop channel**.
- The third index runs over the histogram bins.

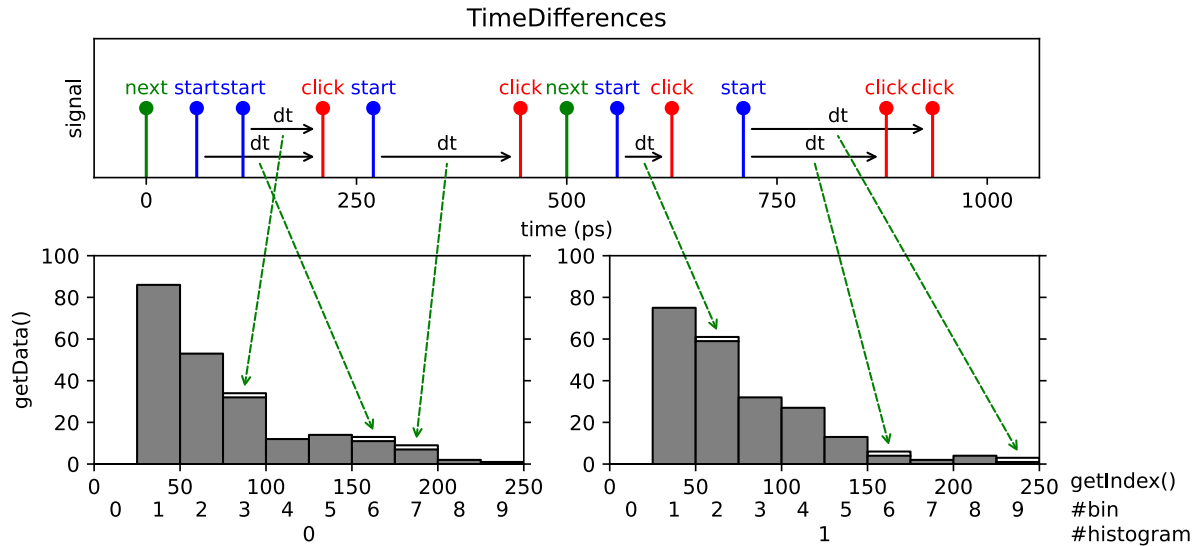
`timestamp_t[] getIndex()`

### Returns

A vector of size  $n\_bins$  containing the time bins in ps.

## TimeDifferences

class **TimeDifferences** : public *IteratorBase*



A one-dimensional array of time-difference histograms with the option to include up to two additional channels that control how to step through the indices of the histogram array. This is a very powerful and generic measurement. You can use it to record consecutive cross-correlation, lifetime measurements, fluorescence lifetime imaging and many more measurements based on pulsed excitation. Specifically, the measurement waits for a tag on the *start\_channel*, then measures the time difference between the start tag and all subsequent tags on the *click\_channel* and stores them in a histogram. If no *start\_channel* is specified, the *click\_channel* is used as *start\_channel* corresponding to an auto-correlation measurement. The histogram has a number *n\_bins* of bins of bin width *binwidth*. Clicks that fall outside the histogram range are discarded. Data accumulation is performed independently for all start tags. This type of measurement is frequently referred to as ‘multiple start, multiple stop’ measurement and corresponds to a full auto- or cross-correlation measurement.

The time-difference data can be accumulated into a single histogram or into multiple subsequent histograms. In this way, you can record a sequence of time-difference histograms. To switch from one histogram to the next one you have to specify a channel that provide switch markers (*next\_channel* parameter). Also you need to specify the number of histograms with the parameter *n\_histograms*. After each tag on the *next\_channel*, the histogram index is incremented by one and reset to zero after reaching the last valid index. The measurement starts with the first tag on the *next\_channel*.

You can also provide a synchronization marker that resets the histogram index by specifying a *sync\_channel*. The measurement starts when a tag on the *sync\_channel* arrives with a subsequent tag on *next\_channel*. When a rollover occurs, the accumulation is stopped until the next sync and subsequent next signal. A sync signal before a rollover will stop the accumulation, reset the histogram index and a subsequent signal on the *next\_channel* starts the accumulation again.

Typically, you will run the measurement indefinitely until stopped by the user. However, it is also possible to specify the maximum number of rollovers of the histogram index. In this case, the measurement stops when the number of rollovers has reached the specified value.

*See all common methods*

## Public Functions

**TimeDifferences**(*TimeTaggerBase* tagger, *channel\_t* click\_channel, *channel\_t* start\_channel = *CHANNEL\_UNUSED*, *channel\_t* next\_channel = *CHANNEL\_UNUSED*, *channel\_t* sync\_channel = *CHANNEL\_UNUSED*, *timestamp\_t* binwidth = 1000, int n\_bins = 1000, int n\_histograms = 1)

**Note**

A rollover occurs on a *next\_channel* event while the histogram index is already in the last histogram. If *sync\_channel* is defined, the measurement will pause at a rollover until a *sync\_channel* event occurs and continues at the next *next\_channel* event. With undefined *sync\_channel*, the measurement will continue without interruption at histogram index 0.

**Parameters**

- **tagger** – Time tagger object instance.
- **click\_channel** – Channel on which stop clicks are received.
- **start\_channel** – Channel that sets start times relative to which clicks on the click channel are measured.
- **next\_channel** – Channel that increments the histogram index.
- **sync\_channel** – Channel that resets the histogram index to zero.
- **binwidth** – Binwidth in picoseconds.
- **n\_bins** – Number of bins in each histogram.
- **n\_histograms** – Number of histograms.

int[,] **getData()**

**Returns**

A two-dimensional array of size *n\_histograms* by *n\_bins* containing the histograms in row-major format.

*timestamp\_t*[] **getIndex()**

**Returns**

A vector of size *n\_bins* containing the time bins in ps.

void **setMaxCounts**(int max\_counts)

*Deprecated:*

Please use [setMaxRollovers\(\)](#) instead. Sets the number of rollovers at which the measurement stops integrating. To integrate infinitely, set the value to 0, which is the default value.

**Parameters**

**max\_counts** – Maximum number of sync/next clicks.

void **setMaxRollovers**(int max\_rollovers)

Sets the number of rollovers at which the measurement stops. To integrate infinitely, set the value to 0, which is the default value.

**Parameters**

**max\_rollovers** – Maximum number of rollovers (histogram index resets).

int **getHistogramIndex()**

**Returns**

The index of the currently processed histogram or the waiting state. Possible return values are:

- -2: Waiting for an event on *sync\_channel* (only if *sync\_channel* is defined)
- -1: Waiting for an event on *next\_channel* (only if *sync\_channel* is defined)
- 0 ... (*n\_histograms* - 1): Index of the currently processed histogram.

int **getCounts()**

**Returns**

The number of rollovers (histogram index resets).

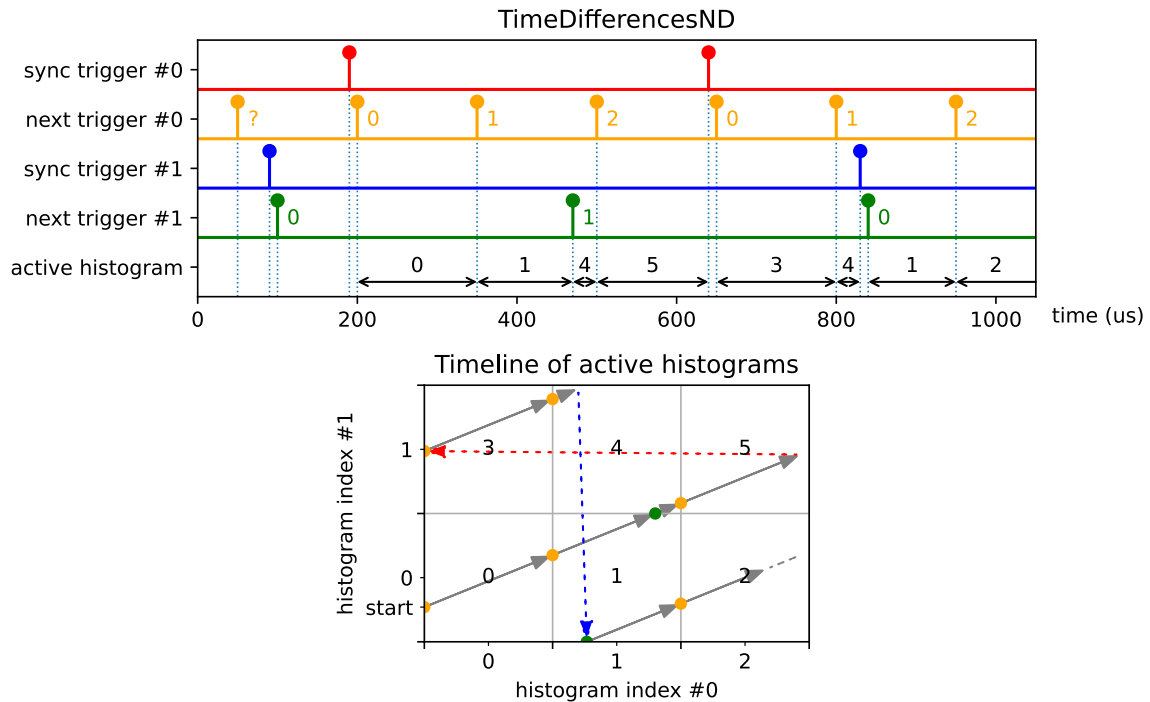
bool **ready()**

**Returns**

True when the required number of rollovers set by [setMaxCounts\(\)](#) has been reached.

## TimeDifferencesND

class **TimeDifferencesND** : public *IteratorBase*



This is an implementation of the [TimeDifferences](#) measurement class that extends histogram indexing into multiple dimensions. Please read the documentation of [TimeDifferences](#) first.

It captures many multiple start - multiple stop histograms, but with many asynchronous *next\_channel* triggers. After each tag on each *next\_channel*, the histogram index of the associated dimension is incremented by one and reset to zero after reaching the last valid index. The elements of the parameter *n\_histograms* specify the number of histograms per dimension. The accumulation starts when *next\_channel* has been triggered on all dimensions.

You should provide a synchronization trigger by specifying a *sync\_channel* per dimension. It will stop the accumulation when an associated histogram index rollover occurs. A sync event will also stop the accumulation and reset the histogram index of the associated dimension. A subsequent event on the corresponding *next\_channel* will start the accumulation again. The synchronization is done asynchronously, so an event on the *next\_channel* increments the histogram index even if the accumulation is stopped. The accumulation will start when a tag on the *sync\_channel* arrives with a subsequent tag on *next\_channel* for all dimensions.



Please use `TimeTaggerBase::setInputDelay()` to adjust the latency of all channels. In general, the order of the provided triggers including maximum jitter should be:

old start trigger -> all sync triggers -> all next triggers -> new start trigger.

*See all common methods*

## Public Functions

**TimeDifferencesND**(*TimeTaggerBase* tagger, *channel\_t* click\_channel, *channel\_t* start\_channel, *channel\_t*[] next\_channels, *channel\_t*[] sync\_channels, int[] n\_histograms, *timestamp\_t* binwidth, int n\_bins)

### Parameters

- **tagger** – Time tagger object instance.
- **click\_channel** – Channel on which stop clicks are received.
- **start\_channel** – Channel that sets start times relative to which clicks on the click channel are measured.
- **next\_channels** – Vector of channels that increments the histogram index.
- **sync\_channels** – Vector of channels that resets the histogram index to zero.
- **n\_histograms** – Vector of numbers of histograms per dimension.
- **binwidth** – Width of one histogram bin in ps.
- **n\_bins** – Number of bins in each histogram.

int[,] **getData()**

### Returns

A two-dimensional array of size  $M$  by  $n\_bins$  containing the histograms in row-major format, where  $M$  is the total number of histograms, calculated as the product of all elements in  $n\_histograms$ . The histograms are indexed according to the multidimensional shape defined by  $n\_histograms$ , with each row representing a unique combination of histogram trigger indices. The ordering of histograms in the output is based on the standard left-to-right index mapping (`std::layout_left`), with the leftmost index in  $n\_histograms$  changing most frequently when counting through the histograms. The position of each histogram is computed as a linear offset using strides that increase from left to right.

*timestamp\_t*[] **getIndex()**

### Returns

A vector of size  $n\_bins$  containing the time bins in ps.

void **setMaxRollovers**(int[] max\_rollovers)

Sets the maximum number of rollovers per direction at which the measurement stops. It stops after the first maximum is met. To integrate infinitely, set the value to 0, which is the default value.

### Parameters

**max\_rollovers** – Maximum number of rollovers (histogram index resets).

int[] **getHistogramIndex()**

### Returns

The indices of the currently processed histogram or the waiting state. Possible return values are:

- -2: Waiting for an event on *sync\_channel* (only if *sync\_channel* is defined)

- -1: Waiting for an event on *next\_channel* (only if *sync\_channel* is defined)
- 0 ... (*n\_histograms* - 1): Index of the currently processed histogram.

int[] **getRollovers()**

**Returns**

The number of rollovers (histogram index resets).

## 5.5.4 Fluorescence-lifetime imaging (FLIM)

This section describes the FLIM related measurements classes of the Time Tagger API.

### FlimAbstract

class **FlimAbstract** : public *IteratorBase*

This is an interface class for FLIM measurements that defines common methods.

Subclassed by *Flim*, *FlimBase*

#### Public Functions

bool **isAcquiring()**

Tells if the class is still acquiring data. It can only reach the false state if *stop\_after\_outputframe* > 0.

This method is different from *isRunning()* and indicates if the specified number of frames is acquired. After acquisition completed, it can't be started again.

**Returns**

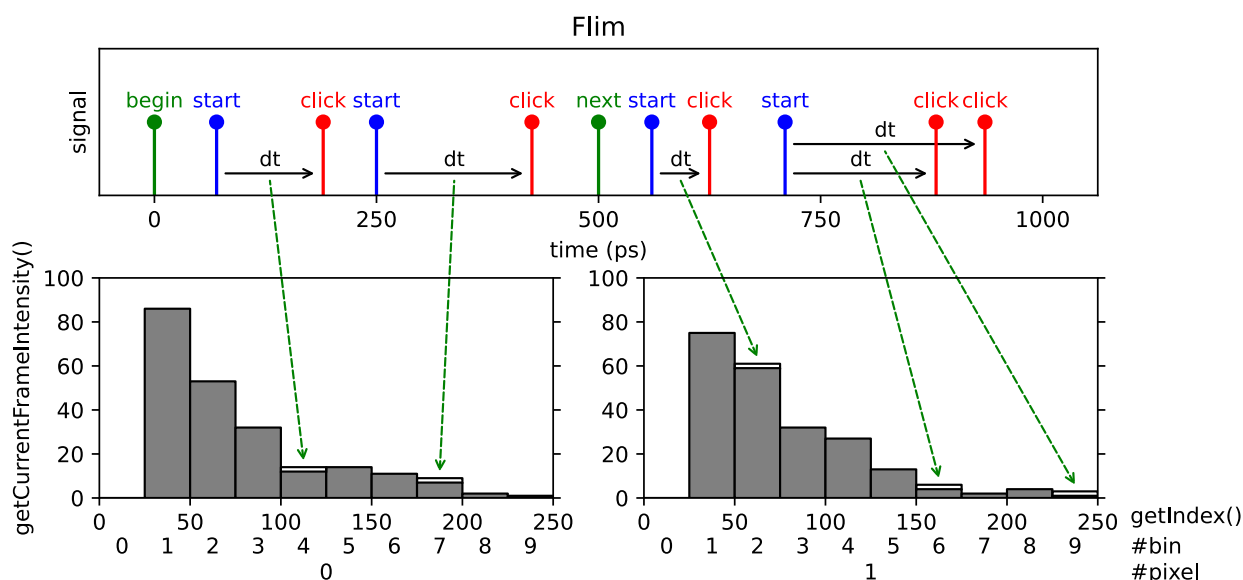
True/False.

### Flim

Changed in version 2.7.2.

**Note**

The Flim (beta) implementation is not final yet. It has a very advanced functionality, but details are subject to change. Please give us feedback ([support@swabianinstruments.com](mailto:support@swabianinstruments.com)) when you encounter issues or when you have ideas for additional functionality.



Fluorescence-lifetime imaging microscopy (FLIM) is an imaging technique for producing an image based on the differences in the exponential decay rate of the fluorescence from a sample.

Fluorescence lifetimes can be determined in the time domain by using a pulsed source. When a population of fluorophores is excited by an ultrashort or delta-peak pulse of light, the time-resolved fluorescence will decay exponentially.

This measurement implements a line scan in a FLIM (Fluorescence-lifetime imaging microscopy) image that consists of a sequence of pixels. This could either represent a single line of the image, or - if the image is represented as a single meandering line - this could represent the entire image.

We provide two different classes that support FLIM measurements: *Flim* and *FlimBase*. *Flim* provides a versatile high-level API. *FlimBase* instead provides the essential functionality with no overhead to perform Flim measurements. *FlimBase* is based on a callback approach.

Please visit the Python example folder for a reference implementation.

**Note**

Up to version 2.7.0, the *Flim* implementation was very limited and has been fully rewritten in version 2.7.2. You can use the following 1 to 1 replacement to get the old *Flim* behavior:

```
# FLIM before version 2.7.0:
Flim(tagger, click_channel=1, start_channel=2, next_channel=3,
     binwidth=100, n_bins=1000, n_pixels=320*240)

# FLIM 2.7.0 replacement using TimeDifferences
TimeDifferences(tagger, click_channel=1, start_channel=2,
               next_channel=3, sync_channel=CHANNEL_UNUSED,
               binwidth=100, n_bins=1000, n_histograms=320*240)
```

class **Flim** : public *FlimAbstract*

High-Level class for implementing FLIM measurements. The *Flim* class includes buffering of images and several analysis methods.

This class supports expansion of functionality with custom FLIM frame processing by overriding virtual/abstract *frameReady()* callback. If you need custom implementation with minimal overhead and highest performance, consider overriding *FlimBase* class instead.

The data query methods are organized into a few groups.

The methods *getCurrentFrame...()* relate to the active frame which is currently being acquired.

The methods *getReadyFrame...()* relate to the last completely acquired frame.

The methods *getSummedFrames...()* operate to all frames which have been acquired so far. Optional parameter *only\_ready\_frames* selects if the current incomplete frame shall be included or excluded from calculation.

The methods *get...Ex* instead of an array return a *FlimFrameInfo* object containing frame data with additional information collected at the same time instance.

*See all common methods*

#### Warning

When overriding this class, you must set *pre\_initialize=False* and then call *initialize()* at the end of your custom constructor code. Otherwise, you may experience unstable or erratic behavior of your program, as the callback *frameReady()* may be called before construction of the subclass completed.

## Public Functions

**Flim**(*TimeTaggerBase* tagger, *channel\_t* start\_channel, *channel\_t* click\_channel, *channel\_t* pixel\_begin\_channel, int n\_pixels, int n\_bins, *timestamp\_t* binwidth, *channel\_t* pixel\_end\_channel = *CHANNEL\_UNUSED*, *channel\_t* frame\_begin\_channel = *CHANNEL\_UNUSED*, int finish\_after\_outputframe = 0, int n\_frame\_average = 1, bool pre\_initialize = true)

### Parameters

- **tagger** – Time tagger object instance.
- **start\_channel** – Channel on which start clicks are received for the time differences histogramming.
- **click\_channel** – Channel on which clicks are received for the time differences histogramming.
- **pixel\_begin\_channel** – Start marker of a pixel (histogram).
- **n\_pixels** – Number of pixels (histograms) of one frame.
- **n\_bins** – Number of histogram bins for each pixel.
- **binwidth** – Bin size in picoseconds.
- **pixel\_end\_channel** – End marker of a pixel - incoming clicks on the *click\_channel* will be ignored afterwards (optional, default: *CHANNEL\_UNUSED*).

- **frame\_begin\_channel** – Start the frame, or reset the pixel index (optional, default: `CHANNEL_UNUSED`).
- **finish\_after\_outputframe** – Sets the number of frames stored within the measurement class. After reaching the number, the measurement will stop. If the number is 0, one frame is stored and the measurement runs continuously (optional, default: 0).
- **n\_frame\_average** – Average multiple input frames into one output frame (default: 1).
- **pre\_initialize** – Initializes the measurement on constructing (optional, default: True). On subclassing, you must set this parameter to False, and then call `initialize()` at the end of your custom constructor method.

`int[,]` **getCurrentFrame()**

**Returns**

The histograms for all pixels of the currently active frame, 2D array with dimensions [n\_bins, n\_pixels].

*FlimFrameInfo* **getCurrentFrameEx()**

**Returns**

The currently active frame data with additional information collected at the same instance of time.

`float[]` **getCurrentFrameIntensity()**

**Returns**

The intensities of all pixels of the currently active frame. The pixel intensity is defined by the number of counts acquired within the pixel divided by the respective integration time.

`int` **getFramesAcquired()**

**Returns**

The number of frames that have been completed so far, since the creation or last clear of the object.

*timestamp\_t[]* **getIndex()**

**Returns**

A vector of size n\_bins containing the time bins in ps.

`int[,]` **getReadyFrame(int index = -1)**

**Parameters**

**index** – Index of the frame to be obtained. If -1, the last frame which has been completed is returned. (optional, default: -1).

**Returns**

The histograms for all pixels according to the frame index given. If *index* is -1, it will return the last frame, which has been completed. When *stop\_after\_outputframe* is 0, the index value must be -1. If *index* >= *stop\_after\_outputframe*, it will throw an error. 2D array with dimensions [n\_bins, n\_pixels]

*FlimFrameInfo* **getReadyFrameEx(int index = -1)**

**Parameters**

**index** – Index of the frame to be obtained. If -1, the last frame which has been completed is returned. (optional, default: -1).

**Returns**

The frame according to the index given. If *index* is -1, it will return the latest completed frame. When *stop\_after\_outputframe* is 0, index must be -1. If *index* >= *stop\_after\_outputframe*, it will throw an error.

float[] **getReadyFrameIntensity**(int index = -1)

**Parameters**

**index** – Index of the frame to be obtained. If -1, the last frame which has been completed is returned. (optional, default: -1).

**Returns**

The intensities according to the frame index given. If *index* is -1, it will return the intensity of the last frame, which has been completed. When *stop\_after\_outputframe* is 0, the index value must be -1. If *index* >= *stop\_after\_outputframe*, it will throw an error. The pixel intensity is defined by the number of counts acquired within the pixel divided by the respective integration time.

int[,] **getSummedFrames**(bool only\_ready\_frames = true, bool clear\_summed = false)

**Parameters**

- **only\_ready\_frames** – If true, only the finished frames are added. On false, the currently active frame is aggregated. (optional, default: True).
- **clear\_summed** – If True, the summed frames memory will be cleared. (optional, default: False).

**Returns**

The histograms for all pixels. The counts within the histograms are integrated since the start or the last clear of the measurement.

*FlimFrameInfo* **getSummedFramesEx**(bool only\_ready\_frames = true, bool clear\_summed = false)

**Parameters**

- **only\_ready\_frames** – If true, only the finished frames are added. On false, the currently active frame is aggregated. (optional, default: True).
- **clear\_summed** – If True, the summed frames memory will be cleared. (optional, default: False).

**Returns**

A sum of all acquired frames with additional information collected at the same instance of time.

float[] **getSummedFramesIntensity**(bool only\_ready\_frames = true, bool clear\_summed = false)

**Parameters**

- **only\_ready\_frames** – If true, only the finished frames are added. On false, the currently active frame is aggregated. (optional, default: True).
- **clear\_summed** – If True, the summed frames memory will be cleared. (optional, default: False).

**Returns**

The intensities of all pixels summed over all acquired frames. The pixel intensity is the number of counts within the pixel divided by the integration time.

void **initialize()**

This function initialized the *Flim* object and starts execution. It does nothing if constructor parameter `pre_initialize==True`.

### Protected Functions

virtual void **frameReady**(int frame\_number, int[] data, *timestamp\_t*[] pixel\_begin\_times, *timestamp\_t*[] pixel\_end\_times, *timestamp\_t* frame\_begin\_time, *timestamp\_t* frame\_end\_time)

The method is called automatically by the Time Tagger engine for each completely acquired frame. In its parameters, it provides FLIM frame data and related information. You have to override this method with your own implementation.

#### Warning

The code of override must be fast, as it is executed in context of Time Tagger processing thread and blocks the processing pipeline. Slow override code may lead to the buffer overflows.

#### Parameters

- **frame\_number** – Current frame number.
- **data** – 1D array containing the raw histogram data, with the data of pixel *i* and time bin *j* at index  $i * n\_bins + j$ .
- **pixel\_begin\_times** – Start time for each pixel.
- **pixel\_end\_times** – End time for each pixel.
- **frame\_begin\_time** – Start time of the frame.
- **frame\_end\_time** – End time of the frame.

### FlimFrameInfo

class **FlimFrameInfo**

This is a simple class that contains FLIM frame data and provides convenience accessor methods.

#### Note

Objects of this class are returned by the methods of the [FLIM] classes. Normally user will not construct *FlimFrameInfo* objects themselves.

### Public Functions

int **getFrameNumber()**

#### Returns

The frame number, starting from 0 for the very first frame acquired. If the index is -1, it is an invalid frame which is returned on error.

bool **isValid()**

#### Returns

A boolean which tells if this frame is valid or not. Invalid frames are possible on errors, such as requesting the last completed frame when no frame has been completed so far.

int **getPixelPosition()**

**Returns**

A value which tells how many pixels were processed for this frame.

int[,] **getHistograms()**

**Returns**

All histograms of the frame, 2D array with dimensions [n\_bins, n\_pixels].

float[] **getIntensities()**

**Returns**

The summed counts of each histogram divided by the integration time.

int[] **getSummedCounts()**

The summed counts of each histogram.

*timestamp\_t*[] **getPixelBegins()**

An array of the start timestamps of each pixel.

*timestamp\_t*[] **getPixelEnds()**

An array of the end timestamps of each pixel.

## Public Members

int **pixels**

Number of pixels in the frame.

int **bins**

Number of bins of each histogram.

int **frame\_number**

Current frame number.

int **pixel\_position**

Current pixel position.

## FlimBase

The *FlimBase* provides only the most essential functionality for FLIM tasks. The benefit from the reduced functionality is that it is very memory and CPU efficient. The class provides the *FlimBase.frameReady* callback, which must be used to analyze the data.

class **FlimBase** : public *FlimAbstract*

This is a minimal class that acquires a FLIM frame and calls virtual/abstract *frameReady()* callback method with the frame data as parameters. This class is intended for custom implementations of fast FLIM frame processing with minimal overhead. You can reach frame acquisition rates suitable for realtime video observation.

If you need custom FLIM frame processing implementation while retaining functionality present in the *Flim* class, consider subclassing *Flim* instead.

*See all common methods*



**Warning**

When overriding this class, you must set `pre_initialize=False` and then call `initialize()` at the end of your custom constructor code. Otherwise, you may experience unstable or erratic behavior of your program, as the callback `frameReady()` may be called before construction of the subclass completed.

**Public Functions**

**FlimBase**(*TimeTaggerBase* tagger, *channel\_t* start\_channel, *channel\_t* click\_channel, *channel\_t* pixel\_begin\_channel, int n\_pixels, int n\_bins, *timestamp\_t* binwidth, *channel\_t* pixel\_end\_channel = *CHANNEL\_UNUSED*, *channel\_t* frame\_begin\_channel = *CHANNEL\_UNUSED*, int finish\_after\_outputframe = 0, int n\_frame\_average = 1, bool pre\_initialize = true)

**Parameters**

- **tagger** – Time tagger object instance.
- **start\_channel** – Channel on which start clicks are received for the time differences histogramming.
- **click\_channel** – Channel on which clicks are received for the time differences histogramming.
- **pixel\_begin\_channel** – Start marker of a pixel (histogram).
- **n\_pixels** – Number of pixels (histograms) of one frame.
- **n\_bins** – Number of histogram bins for each pixel.
- **binwidth** – Bin size in picoseconds.
- **pixel\_end\_channel** – End marker of a pixel - incoming clicks on the *click\_channel* will be ignored afterwards (optional, default: *CHANNEL\_UNUSED*).
- **frame\_begin\_channel** – Start the frame, or reset the pixel index (optional, default: *CHANNEL\_UNUSED*).
- **finish\_after\_outputframe** – Sets the number of frames stored within the measurement class. After reaching the number, the measurement will stop. If the number is 0, one frame is stored and the measurement runs continuously (optional, default: 0).
- **n\_frame\_average** – Average multiple input frames into one output frame (default: 1).
- **pre\_initialize** – Initializes the measurement on constructing (optional, default: True). On subclassing, you must set this parameter to False, and then call `initialize()` at the end of your custom constructor method.

void **initialize()**

This function initialized the *Flim* object and starts execution. It does nothing if constructor parameter `pre_initialize==True`.

**Protected Functions**

virtual void **frameReady**(int frame\_number, int[] data, *timestamp\_t*[] pixel\_begin\_times, *timestamp\_t*[] pixel\_end\_times, *timestamp\_t* frame\_begin\_time, *timestamp\_t* frame\_end\_time)

The method is called automatically by the Time Tagger engine for each completely acquired frame. In its parameters, it provides FLIM frame data and related information. You have to override this method with your own implementation.

**Warning**

The code of override must be fast, as it is executed in context of Time Tagger processing thread and blocks the processing pipeline. Slow override code may lead to the buffer overflows.

**Parameters**

- **frame\_number** – Current frame number.
- **data** – 1D array containing the raw histogram data, with the data of pixel *i* and time bin *j* at index  $i * n\_bins + j$ .
- **pixel\_begin\_times** – Start time for each pixel.
- **pixel\_end\_times** – End time for each pixel.
- **frame\_begin\_time** – Start time of the frame.
- **frame\_end\_time** – End time of the frame.

### 5.5.5 Phase & frequency analyses

This section describes measurements that expect periodic signals, e.g., oscillator outputs.

#### FrequencyCounter

class **FrequencyCounter** : public *IteratorBase*

This measurement calculates the frequency and the phase of a periodic signal at evenly spaced sampling times. If the *ReferenceClock* is active, the sampling times will automatically align with the *ReferenceClockState::ideal\_clock\_channel*. For details on using an external reference via the *ReferenceClock* see the *In Depth Guide: Software-Defined Reference Clock*.

Multiple channels can be analyzed in parallel to compare the phase evolution in time. Around every sampling time, the time tags within an adjustable *fitting\_window* are used to fit the phase.

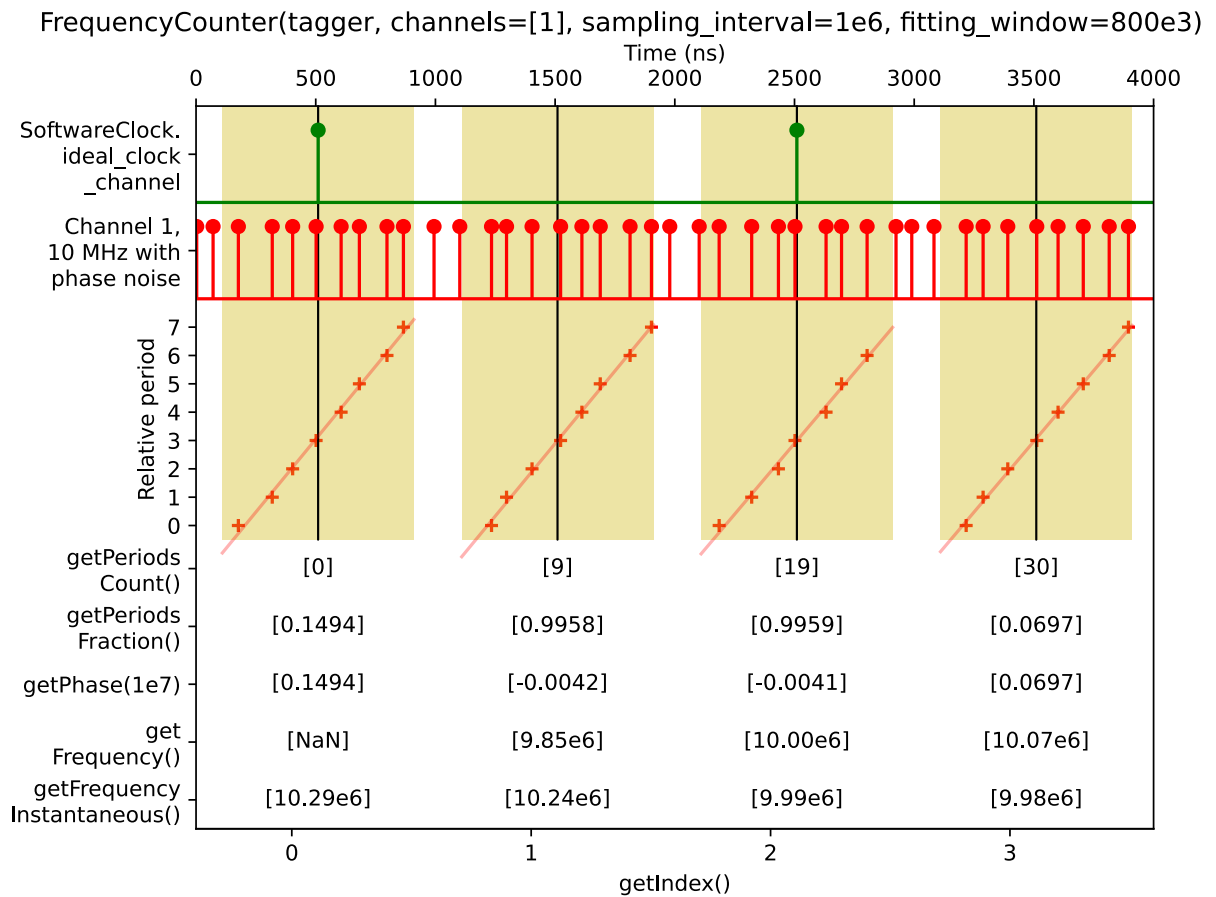
*See all common methods*

#### Public Functions

**FrequencyCounter**(*TimeTaggerBase* tagger, *channel\_t*[] channels, *timestamp\_t* sampling\_interval, *timestamp\_t* fitting\_window, int n\_values = 0)

**Parameters**

- **tagger** – Time Tagger object instance.
- **channels** – List of channels to analyze.
- **sampling\_interval** – The sampling interval in picoseconds. If the *ReferenceClock* is active, it is recommended to set this value to an integer multiple of the *ReferenceClockState::clock\_period*.
- **fitting\_window** – Time tags within this range around a sampling point are fitted for phase calculation.
- **n\_values** – Maximum number of sampling points to store.



*FrequencyCounterData* **getDataObject**(int event\_divider = 1, bool remove = false, bool channels\_last\_dim = false)

Returns a *FrequencyCounterData* object containing a snapshot of the data accumulated in the *FrequencyCounter* at the time this method is called. The *event\_divider* argument can be used to scale the results according to the current setting of *TimeTagger::setEventDivider()*. The *remove* argument allows you to control whether the data should be removed from the internal buffer or not.

#### Parameters

- **event\_divider** – Compensate for the *EventDivider* (default: 1).
- **remove** – Control if data is removed from the internal buffer (default: True).
- **channels\_last\_dim** – Determines the memory layout of the output data (default: False).
  - If true, data is stored with channels as the last dimension (row-major order for channels).
  - If false, data is stored with channels as the first dimension (column-major order for channels).

#### Returns

An object providing access to a snapshot data.

class **FrequencyCounterData**

#### Public Functions

*timestamp\_t*[] **getIndex()**

Index of the samples. The reference sample would have index 0, counting starts with 1 at the first sampling point.

#### Returns

The index of the samples.

*timestamp\_t*[] **getTime()**

Array of timestamps of the sampling points.

#### Returns

The timestamps of the sampling points.

*timestamp\_t*[,] **getPeriodsCount()**

The integer part of the phase, i.e. full periods of the oscillation.

#### Returns

Full cycles per channel and sampling point.

float[,] **getPeriodsFraction()**

The fraction of the current period at the sampling time.

#### Warning

Be careful with adding *getPeriodsCount()* and *getPeriodsFraction()* as the required precision can overflow a 64bit double precision within minutes. In doubt, please use *getPhase()* with the expected frequency instead.

#### Returns

A fractional value in range [0, 1) per channel and sampling point.

float[,] **getPhase**(float reference\_frequency = 0)

The relative phase with respect to a numerical reference signal, typically at the expected frequency. The returned phase is dimensionless and expressed in cycles, i.e. a value of 1.0 corresponds to one full period. The reference signal starts at phase 0 at index 0, so the return value of this method is identical to that of [getPeriodsFraction\(\)](#) for index 0.

#### Parameters

**reference\_frequency** – The reference frequency in Hz to subtract (default: 0.0 Hz).

#### Returns

Relative phase values per channel and sampling point.

float[,] **getFrequency**(*timestamp\_t* time\_scale = 1000000000000)

The average frequency between two consecutive sampling points. It is derived from the change in accumulated phase between consecutive sampling points. At index 0, there is no previous phase value to compare with, so the method returns an undefined value *NaN*.

#### Parameters

**time\_scale** – Scales the return value to this time interval. Default is 1 s, so the return value is in Hz. For negative values, the time scale is set to *sampling\_interval*.

#### Returns

A frequency value per channel and sampling point.

float[,] **getFrequencyInstantaneous**()

The instantaneous frequency obtained from the current fitting window. This value corresponds to the slope of the linear fit and therefore represents the local frequency at the sampling point.

#### Returns

An instantaneous frequency value per channel and sampling point.

int[,] **getOverflowMask**()

If an overflow range overlaps with a fitting window, the values are invalid. This mask array indicates invalid elements and can be used to filter the results of the other getters.

#### Returns

1 indicates that the sampling point was affected by an overflow range, 0 indicates valid data.

## Public Members

int **size**

Number of sampling points represented by the object.

*timestamp\_t* **overflow\_samples**

Number of sampling points affected by an overflow range since the start of the measurement.

bool **align\_to\_reference**

Indicates if the sampling grid has been aligned to the *ReferenceClock*.

*timestamp\_t* **sampling\_interval**

The sampling interval in picoseconds.

*timestamp\_t* **sample\_offset**

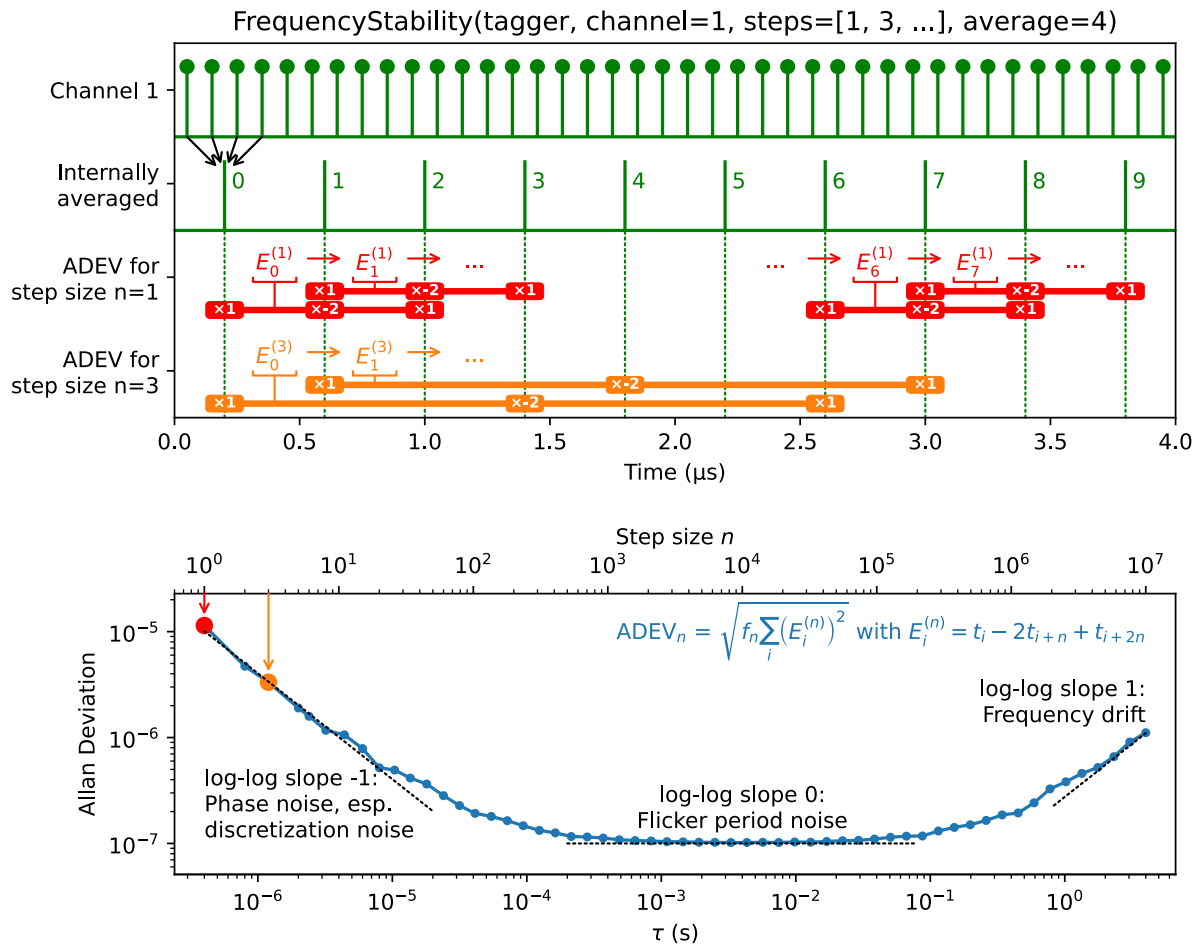
Index offset of the first sampling point in the object.

bool **channels\_last\_dim**

The memory layout of the output data:

- If True, the data is stored with channels as the last dimension (row-major order for channels).
- If False, the data is stored with channels as the first dimension (column-major order for channels).

## FrequencyStability



class **FrequencyStability** : public *IteratorBase*

Frequency Stability Analysis is used to characterize periodic signals and to identify sources of deviations from the perfect periodicity. It can be employed to evaluate the frequency stability of oscillators, for example. When the Time Tagger's internal clock stability falls short of requirements, locking to a stable external reference is recommended. This can be achieved by calling `TimeTaggerSource::setReferenceClock()`. See the *In Depth Guide: Software-Defined Reference Clock* for details.

A set of established metrics provides insights into the oscillator characteristics on different time scales. The most prominent metric is the Allan Deviation (ADEV). *FrequencyStability* class executes the calculation of often used metrics in parallel and conforms to the IEEE 1139 standard. For more information, we recommend the *Handbook of Frequency Stability Analysis*.

The calculated deviations are the root-mean-square  $\sqrt{f_n \sum_i (E_i^{(n)})^2}$  of a specific set of error samples  $E^{(n)}$

with a normalization factor  $f_n$ . The step size  $n$  together with the oscillator period  $T$  defines the time span  $\tau_n = nT$  that is investigated by the sample. The error samples  $E^{(n)}$  are calculated from the phase samples  $t$  that are generated by the [FrequencyStability](#) class by averaging over the timestamps of a configurable number of time-tags. To investigate the averaged phase samples directly, a trace of configurable length is stored to display the current evolution of frequency and phase errors.

Each of the available deviations has its specific sample  $E^{(n)}$ . For example, the Allan Deviation investigates the second derivative of the phase  $t$  using the sample  $E_i^{(n)} = t_i - 2t_{i+n} + t_{i+2n}$ . The full formula of the Allan deviation for a set of  $N$  averaged timestamps is

$$\text{ADEV}(\tau_n) = \sqrt{\frac{1}{2(N-2n)\tau_n^2} \sum_{i=1}^{N-2n} (t_i - 2t_{i+n} + t_{i+2n})^2}.$$

The deviations can be displayed in the Allan domain or in the time domain. For the time domain, the Allan domain data is multiplied by a factor proportional to  $\tau$ . This means that in a log-log plot, all slopes of the time domain curves are increased by +1 compared to the Allan ones. The factor  $\sqrt{3}$  for  $|\text{ADEV}|/|\text{MDEV}|$  and  $\sqrt{10/3}$  for  $|\text{HDEV}|$ , respectively, is used so that the scaled deviations of a white phase noise distortion correspond to the standard deviation of the averaged timestamps  $t$ . In some cases, there are different established names for the representations. The [FrequencyStability](#) class provides numerous metrics for both domains:

| Allan domain                    | Time domain                                                          |
|---------------------------------|----------------------------------------------------------------------|
|                                 | Standard Deviation (STDD)                                            |
| Allan Deviation (ADEV)          | $\text{ADEV}_{\text{Scaled}} = \frac{\tau}{\sqrt{3}} \text{ADEV}$    |
| Modified Allan Deviation (MDEV) | $\text{Time Deviation TDEV} = \frac{\tau}{\sqrt{3}} \text{MDEV}$     |
| Hadamard Deviation (HDEV)       | $\text{HDEV}_{\text{Scaled}} = \frac{\tau}{\sqrt{10/3}} \text{HDEV}$ |

*See all common methods*

## Public Functions

**FrequencyStability**(*TimeTaggerBase* tagger, *channel\_t* channel, int[] steps, *timestamp\_t* average = 1000, int trace\_len = 1000)

### Note

Use *average* and [TimeTagger::setEventDivider\(\)](#) with care: The event divider can be used to save USB bandwidth. If possible, transfer more data via USB and use *average* to improve your results.

### Parameters

- **tagger** – Time tagger object.
- **channel** – The input channel number.
- **steps** – The step sizes to consider in the calculation. The length of the list determines the maximum number of data points. Because the oscillator frequency is unknown, it is not possible to define  $\tau$  directly.
- **average** – The number of time-tags to average internally. This downsampling allows for a reduction of noise and memory requirements (default: 1000).
- **trace\_len** – Number of data points in the phase and frequency error traces, calculated from averaged data. The trace always contains the latest data (default: 1000).

*FrequencyStabilityData* **getDataObject()**

**Returns**

An object that allows access to the current metrics.

class **FrequencyStabilityData**

**Public Functions**

float[] **getTau()**

The  $\tau$  axis for all deviations. This is the product of the *steps* parameter of the *FrequencyStability* measurement and the measured average period of the signal.

**Returns**

The  $\tau$  values.

float[] **getADEV()**

The overlapping Allan deviation, the most common analysis framework. In a log-log plot, the slope allows one to identify the type of noise:

- -1: white or flicker phase noise like discretization or analog noisy delay
- -0.5: white period noise
- 0: flicker period noise like electric noisy oscillator
- 0.5: integrated white period noise (random walk period)
- 1: frequency drift, e.g., induced thermally.

**Sample**

$$E_i^{(n)} = t_i - 2t_{i+n} + t_{i+2n}.$$

**Domain**

Allan domain.

**Returns**

The overlapping Allan Deviation.

float[] **getMDEV()**

Modified overlapping Allan deviation. It averages the second derivate before calculating the RMS. This splits the slope of white and flicker phase noise:

- -1.5: white phase noise, like discretization
- -1.0: flicker phase noise, like an electric noisy delay.

The metric is more commonly used in the time domain, see *getTDEV()*:

**Sample**

$$E_i^{(n)} = \frac{1}{n} \sum_{j=0}^{n-1} (t_{i+j} - 2t_{i+j+n} + t_{i+j+2n}).$$



**Domain**

Allan domain.

**Returns**

The overlapping MDEV.

float[] **getHDEV()**

The overlapping Hadamard deviation uses the third derivate of the phase. This cancels the effect of a constant phase drift and converges for more divergent noise sources at higher slopes:

- 1: integrated flicker period noise (flicker walk period)
- 1.5: double integrated white period noise (random run period).

It is scaled to match the ADEV for white period noise.

**Sample**

$$E_i^{(n)} = t_i - 3t_{i+n} + 3t_{i+2n} - t_{i+3n}.$$

**Domain**

Allan domain.

**Returns**

The overlapping HDEV.

float[] **getSTDD()**

Standard deviation of the periods.

**Warning**

The standard deviation is not recommended as a measure of frequency stability because it is non-convergent for some types of noise commonly found in frequency sources, most noticeable the frequency drift.

**Sample**

$$E_i^{(n)} = t_i - t_{i+n} - \text{mean}_k(t_k - t_{k+n}).$$

**Domain**

Time domain.

**Returns**

The standard deviation.

float[] **getADEVScaled()**

**Domain**

Time domain.

**Returns**

The scaled version of the overlapping Allan Deviation, equivalent to `getADEV() * getTau()` /  $\sqrt{3}$ .

**float[] getTDEV()**

The Time Deviation (TDEV) is the common representation of the Modified overlapping Allan deviation `getMDEV()`. Taking the log-log slope +1 and the splitting of the slope of white and flicker phase noise into account, it allows an easy identification of the two contributions:

- -0.5: white phase noise, like discretization
- 0: flicker phase noise, like an electric noisy delay.

**Domain**

Time domain.

**Returns**

The overlapping Time Deviation, equivalent to `getMDEV() * getTau()` /  $\sqrt{3}$ .

**float[] getHDEVscaled()****Warning**

While HDEV is scaled to match ADEV for white period noise, this function is scaled to match the TDEV for white phase noise. The difference of period vs phase matching is roughly 5% and easy to overlook.

**Domain**

Time domain.

**Returns**

The scaled version of the overlapping Hadamard Deviation, equivalent to `getHDEV() * getTau()` /  $\sqrt{10/3}$ .

**float[] getTraceIndex()**

The time axis for `getTracePhase()` and `getTraceFrequency()`.

**Returns**

The time index in seconds of the phase and frequency error trace.

**float[] getTracePhase()**

Provides the time offset of the averaged timestamps from a linear fit over the last `trace_len` averaged timestamps.

**Returns**

A trace of the last `trace_len` phase samples in seconds.

**float[] getTraceFrequency()**

Provides the relative frequency offset from the average frequency during the last `trace_len + 1` averaged timestamps.

**Returns**

A trace of the last *trace\_len* normalized frequency error data points in pp1.

float[] **getTraceFrequencyAbsolute**(float input\_frequency = 0.0)

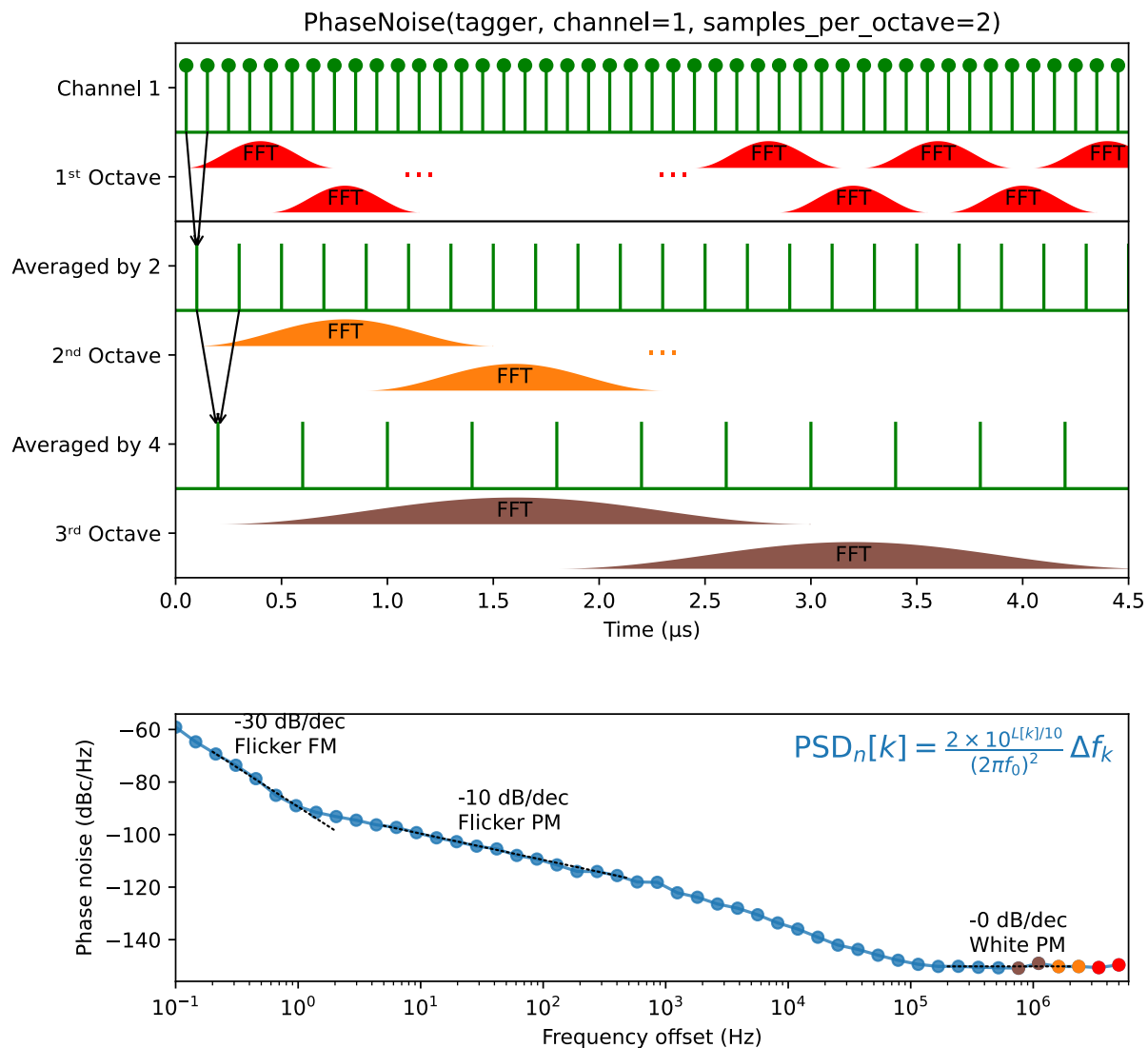
Provides the absolute frequency offset from a given *input\_frequency* during the last *trace\_len* + 1 averaged timestamps.

**Parameters**

**input\_frequency** – Nominal frequency of the periodic signal (default: 0 Hz).

**Returns**

A trace of the last *trace\_len* frequency data points in Hz.

**PhaseNoise**

class **PhaseNoise** : public *IteratorBase*

This measurement provides a phase noise estimator with spectral samples distributed quasi-logarithmically

over frequency offset. When the Time Tagger's internal clock stability falls short of requirements, locking to a stable external reference is recommended. This can be achieved by calling `TimeTaggerSource::setReferenceClock()`. See the *In Depth Guide: Software-Defined Reference Clock* for details.

Welch's method is employed to estimate the power spectral density (PSD) from the time tag stream:

- The time tag stream is divided into overlapping sequences of  $NFFT = 4 * \text{samples\_per\_octave}$  samples.
- The linear regression is applied to each sequence to remove constant phase and frequency offsets, yielding demodulated phase samples.
- A Hann window is applied to each sequence to suppress spectral leakage and mitigate edge effects in the Fast Fourier Transform (FFT). These windowing operations are visualized in the sketch as the colored envelope curves (red, orange, brown) spanning overlapping time tags sequences.
- The squared magnitude of each FFT result is computed and averaged over time to reduce variance.
- Sequences are processed with 50% overlap to improve spectral stability and compensate for the window's reduced sensitivity at the edges.

Welch's method provides a spectrum with linearly spaced spectral samples. To achieve a quasi-logarithmic distribution, only the upper half of each FFT output is retained. The lower-frequency half is reconstructed by recursively averaging adjacent timestamp pairs and reapplying Welch's method at each level of decimation, as shown in the sketch. This recursive refinement yields `samples_per_octave` spectral samples per octave.

*See all common methods*

## Public Functions

**PhaseNoise**(*TimeTaggerBase* tagger, *channel\_t* channel, int samples\_per\_octave = 32)

### Parameters

- **tagger** – Time Tagger object instance.
- **channel** – The channel to analyze.
- **samples\_per\_octave** – The number of phase noise samples per octave (default: 32). For optimal FFT performance, this should be set to a power of two.

*PhaseNoiseData* **getDataObject()**

Returns a *PhaseNoiseData* object containing a snapshot of the data accumulated in the *PhaseNoise* at the time this method is called.

### Returns

An object providing access to a snapshot data.

class **PhaseNoiseData**

## Public Functions

float[] **getPhaseNoise()**

Array of phase noise measurement results.

### Returns

The phase noise measurement results in dBc/Hz.

float **getIntegratedJitter**(float lower\_bound = 12000.0, float upper\_bound = -1.0)

Integrates the phase noise and calculate the estimated RMS jitter.

**Note**

The integration starting from 0 Hz will diverge for any noise source with a spectral power density law starting from  $1/f$ . This includes Flicker phase noise, any frequency noise and any frequency drifts.

**Parameters**

- **lower\_bound** – The lower frequency offset boundary for the integration in Hz (default:  $12e3$ ).
- **upper\_bound** – The upper frequency offset boundary for the integration in Hz (default:  $-1$ ). Negative values are interpreted as the Nyquist frequency.

**Returns**

The integrated phase noise as estimated RMS jitter in seconds.

float[] **getOffset()**

Array of frequency offsets for all spectral samples.

**Returns**

The frequency offset for each spectral sample in Hz.

int[] **getAveragedSequences()**

Array of the number of averaged sequences for all spectral samples.

**Returns**

The number of averaged sequences for each spectral samples.

float **getFrequency()**

Average carrier frequency of the *PhaseNoise* measurement.

**Returns**

The average carrier frequency in Hz.

**PulsePerSecondMonitor**

class **PulsePerSecondMonitor** : public *IteratorBase*

This measurement allows the user to monitor the synchronicity of different sources of 1 pulse per second (PPS) signals with respect to a reference source. For each signal from the reference PPS source, comparative offsets are calculated for the other signal channels. Upon processing, a UTC timestamp from the system time is associated with each reference pulse.

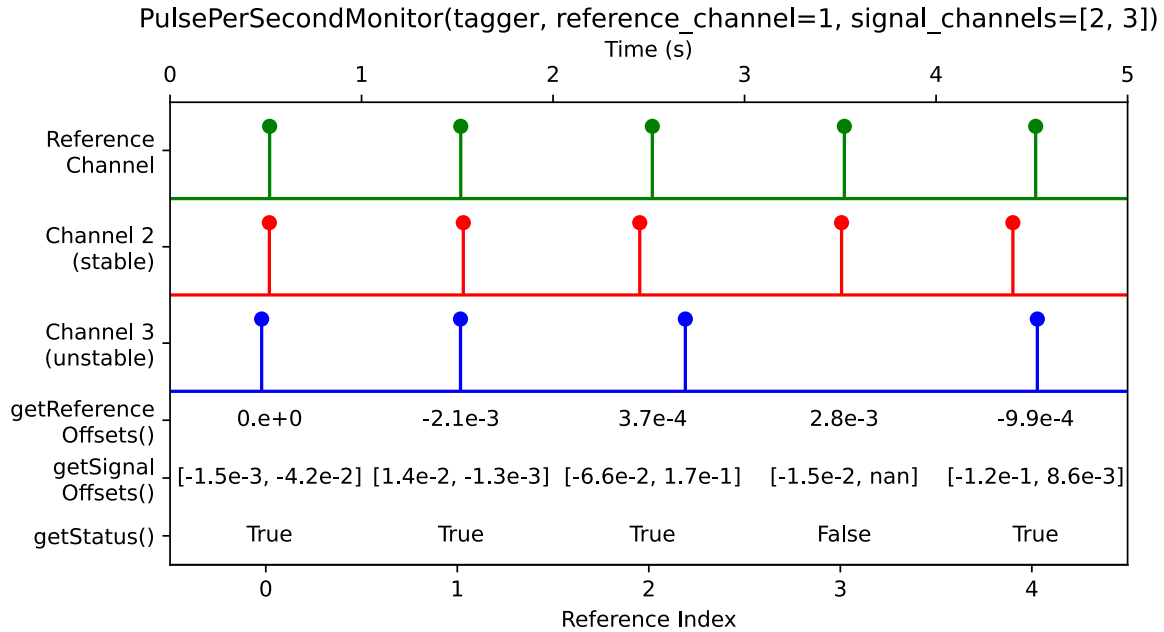
The monitoring starts on the first signal from the reference source and will run uninterrupted until the measurement is stopped. If a signal from a channel is not detected within one and a half periods, its respective offset will not be calculated but the measurement will continue nonetheless.

By specifying an output file name, the monitoring data can be continuously written to a comma-separated value file (.csv).

*See all common methods*

**Note**

If you need to monitor reference drift over many PPS epochs, using *PulsePerSecondData::getReferenceOffsets()*, or you need traceability to a lab standard, it is advisable to feed a stable external reference (e.g., 10 MHz) into a regular input of the Time Tagger and



enable the *ReferenceClock* via `TimeTaggerSource::setReferenceClock()`. See the *In Depth Guide: Software-Defined Reference Clock* for details. On the other hand, the internal clock is sufficient to monitor time offsets of multiple PPS channels relative to one reference PPS, provided the edges refer to the same nominal second.

## Public Functions

**PulsePerSecondMonitor**(*TimeTaggerBase* tagger, *channel\_t* reference\_channel, *channel\_t*[] signal\_channels, str filename = "", *timestamp\_t* period = 1E12)

### Parameters

- **tagger** – Time Tagger object instance.
- **reference\_channel** – The channel number corresponding to the PPS reference source.
- **signal\_channels** – A list of channel numbers with PPS signals to be compared to the reference.
- **filename** – The name of the .csv file to store measurement data. By default, no data is written to file (default: "").
- **period** – The assumed period of the reference source, typically one second, in picoseconds (default: 1e12).

*PulsePerSecondData* **getDataObject**(bool remove = false)

Returns a *PulsePerSecondData* object containing a snapshot of the data accumulated in the *PulsePerSecondMonitor* at the time this method is called. To remove the data from the internal memory after each call, set *remove* to *True*.

### Parameters

- **remove** – Controls if the returned data shall be removed from the internal buffer.

### Returns

An object providing access to a snapshot data.

class **PulsePerSecondData**

### Public Functions

int[] **getIndices()**

The indices of each reference pulse in the *PulsePerSecondData* object. The first reference pulse will have index 0, each subsequent pulse from the reference source increments the index by one. In case of overflows in the reference channel, this index will be incremented by the number of missed pulses.

#### Returns

A list of indices for each pulse from the reference source.

float[] **getReferenceOffsets()**

A list of offsets of each reference pulse with respect to its predecessor, with the period subtracted. For a perfect PPS source, this offset would always be zero. The offset of the first pulse is always defined to be zero. If a reference signal is missing, its offset is defined to be *NaN*.

#### Returns

A list of the offsets of each reference with respect to the previous.

float[,] **getSignalOffsets()**

For each reference contained in the *PulsePerSecondData* object a list of offsets for each signal channel is given, in the channel order given by *signal\_channels*. If any signal is missing, its offset is defined to be *NaN*.

#### Returns

A list of lists of offsets for each *signal\_channel* for given reference pulses.

float[] **getUtcSeconds()**

The number of elapsed seconds from the beginning of the Unix epoch (1st of January 1970) to the time at which each reference pulse is processed, as a floating point number.

#### Returns

A list of the number of seconds since the Unix epoch to the time of processing, for each reference pulse.

str[] **getUtcDates()**

The UTC timestamps for the system time at which each reference pulse is processed, as a string with ISO 8601 formatting (YYYY-MM-DD hh:mm:ss.ssssss).

#### Returns

A list of the UTC timestamp at processing time, for each reference pulse.

bool[] **getStatus()**

A list of booleans values describing whether all signals, including from the reference source, were detected. *True* corresponds to a complete collection of signals, *False* otherwise.

#### Returns

A list of bools describing the signal integrity for each reference pulse.

### Public Members

int **size**

Number of reference pulses contained in the *PulsePerSecondData* object.

### 5.5.6 Time-tag streaming

Measurement classes described in this section provide direct access to the time tag stream with minimal or no pre-processing.

#### Time tag format

The time tag contain essential information about the detected event and have the following format:

| Size   | Type                  | Description                     |
|--------|-----------------------|---------------------------------|
| 8 bit  | enum <i>Tag::Type</i> | overflow type                   |
| 8 bit  | –                     | reserved                        |
| 16 bit | uint16                | number of missed events         |
| 32 bit | int32                 | channel number                  |
| 64 bit | int64                 | time in ps from device start-up |

#### TimeTagStream

class **TimeTagStream** : public *IteratorBase*

Allows user to access a copy of the time tag stream. It allocates a memory buffer of the size *max\_tags* which is filled with the incoming time tags that arrive from the specified channels. User shall call *getData()* method periodically to obtain the current buffer containing timetags collected. This action will return the current buffer object and create another empty buffer to be filled until the next call to *getData()*.

*See all common methods*

#### Public Functions

**TimeTagStream**(*TimeTaggerBase* tagger, int n\_max\_events, *channel\_t*[] channels)

##### Parameters

- **tagger** – Time tagger object instance.
- **n\_max\_events** – Buffer size for storing time tags.
- **channels** – List of channels to be captured.

*TimeTagStreamBuffer* **getData()**

Returns a *TimeTagStreamBuffer* object and clears the internal buffer of the *TimeTagStream* measurement. Clearing the internal buffer on each call to *getData()* guarantees that consecutive calls to this method will return every time-tag only once. Data loss may occur if *getData()* is not called frequently enough with respect to *n\_max\_events*.

##### Returns

Buffer object containing timetags collected.

int **getCounts()**

##### Returns

The number of stored tags since the last call to *getData()*.

class **TimeTagStreamBuffer**



## Public Functions

*timestamp\_t*[] **getTimestamps()**

Returns an array of timestamps.

### Returns

*Event* timestamps in picoseconds for all chosen channels.

*channel\_t*[] **getChannels()**

Returns an array of channel numbers for every timestamp.

### Returns

Channel number for each detected event.

int[] **getOverflows()**

*Deprecated:*

Since version 2.5. Please use *getEventTypes()* instead.

int[] **getEventTypes()**

Returns an array of event type for every timestamp. See, *Time tag format* . The method returns plain integers, but you can use *Tag : Type* to compare the values.

### Returns

*Event* type value for each detected event.

int[] **getMissedEvents()**

Returns an array of missed event counts during an stream overflow situation.

### Returns

Missed events value for each detected event.

## Public Members

int **size**

Number of events stored in the buffer. If the size equals the maximum size of the buffer set in *TimeTagStream* via *n\_max\_events*, events have likely been discarded.

bool **hasOverflows**

Returns True if a stream overflow was detected in any of the tags received. Note: this is independent of an overflow of the internal buffer of *TimeTagStream*.

*timestamp\_t* **tStart**

Return the data-stream time position when the *TimeTagStream* or *FileWriter* started data acquisition.

*timestamp\_t* **tGetData**

Return the data-stream time position of the call to *TimeTagStream::getData()* method that created this object.

## FileWriter

class **FileWriter** : public *IteratorBase*

Writes the time-tag-stream into a file in a structured binary format with a lossless compression. The estimated file size requirements are 2-4 Bytes per time tag, not including the container the data is stored in. The continuous background data rate for the container can be modified via *TimeTagger::setStreamBlockSize()*. Data is

processed in blocks and each block header has a size of 160 Bytes. The default processing latency is 20 ms, which means that a block is written every 20 ms resulting in a background data rate of 8 kB/s. By increasing the processing latency via `TimeTagger::setStreamBlockSize(max_events=524288, max_latency=1000)` to 1 s, the resulting data rate for the container is reduced to one 160 B/s. The files created with `FileWriter` measurement can be read using `FileReader` or loaded into the Virtual Time Tagger.

The `FileWriter` is able to split the data into multiple files seamlessly when the file size reaches a maximal size. For the file splitting to work properly, the filename specified by the user will be extended with a suffix containing sequential counter, so the filenames will look like in the following example:

```
fw = FileWriter(tagger, 'filename.ttbin', [1,2,3]) # Store tags from channels 1,2,3
# When splitting occurs the files with following names will be created
#   filename.ttbin      # the sequence header file with no data blocks
#   filename.1.ttbin    # the first file with data block
#   filename.2.ttbin
#   filename.3.ttbin
#   ...
```

In addition, the `FileWriter` will query and store the configuration of the Time Tagger in the same format as returned by the `TimeTaggerBase::getConfiguration()` method. The configuration is always written into every file.

See also: `FileReader` , *The TimeTaggerVirtual class* , and `mergeStreamFiles`.

*See all common methods*

#### Note

You can use the `Dump` for dumping into a simple uncompressed binary format. However, you will not be able to use this file with Virtual Time Tagger or `FileReader`.

## Public Functions

**FileWriter**(*TimeTaggerBase* tagger, str filename, *channel\_t*[] channels)

Class constructor. As with all other measurements, the data recording starts immediately after the class instantiation unless you initialize the `FileWriter` with a `SynchronizedMeasurements`.

#### Note

Compared to the `Dump` measurement, the `FileWriter` requires explicit specification of the channels. If you want to store timetags from all input channels, you can query the list of all input channels with `TimeTagger::getChannelList()`.

#### Parameters

- **tagger** – The time tagger object.
- **filename** – Name of the output file.
- **channels** – List of real or virtual channels.

void **split**(str new\_filename = "")

Close the current file and create a new one. If the *new\_filename* is provided, the data writing will continue into the file with the new filename and the sequence counter will be reset to zero.

You can force the file splitting when you call this method without parameter or when the *new\_filename* is an empty string.

**Parameters**

**new\_filename** – Filename of the new file. If empty, the old one will be used (default: empty).

void **setMaxFileSize**(int max\_file\_size)

Set the maximum file size on disk. When this size is exceeded a new file will be automatically created to continue recording.

The actual file size might be larger by one block.

**Parameters**

**max\_file\_size** – Maximum file size in bytes (default: ~1 GByte).

int **getMaxFileSize**()

**Returns**

The maximal file size in bytes. See also [setMaxFileSize\(\)](#).

int **getTotalEvents**()

**Returns**

The total number of events written into the file(s).

int **getTotalSize**()

**Returns**

The total number of bytes written into the file(s).

void **setMarker**(str marker)

Writes a comment into the file. While reading the file using the [FileReader](#), the last marker can be extracted.

**Parameters**

**marker** – An arbitrary marker string to write at the current location in the file.

## FileReader

class **FileReader**

This class allows you to read data files store with [FileReader](#). The [FileReader](#) reads a data block of the specified size into a [TimeTagStreamBuffer](#) object and returns this object. The returned data object is exactly the same as returned by the [TimeTagStream](#) measurement and allows you to create a custom data processing algorithms that will work both, for reading from a file and for the on-the-fly processing.

The [FileReader](#) will automatically recognize if the files were split and read them too one by one.

Example:

```
# Lets assume we have following files created with the FileWriter
# measurement.ttbin      # sequence header file with no data blocks
# measurement.1.ttbin    # the first file with data blocks
# measurement.2.ttbin
# measurement.3.ttbin
# measurement.4.ttbin
```

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```
# another_meas.ttbin
# another_meas.1.ttbin

# Read all files in the sequence 'measurement'
fr = FileReader("measurement.ttbin")

# Read only the first data file
fr = FileReader("measurement.1.ttbin")

# Read only the first two files
fr = FileReader(["measurement.1.ttbin", "measurement.2.ttbin"])

# Read the sequence 'measurement' and then the sequence 'another_meas'
fr = FileReader(["measurement.ttbin", "another_meas.ttbin"])
```

See also: *FileWriter* , *The TimeTaggerVirtual class* , and *mergeStreamFiles*.

## Public Functions

**FileReader**(str[] filenames)

This is the class constructor. The *FileReader* automatically continues to read files that were split by the *FileWriter*.

### Parameters

**filenames** – Filename(s) of the files to read.

*TimeTagStreamBuffer* **getData**(int n\_events)

Reads the next *n\_events* and returns the buffer object with the specified number of timetags. The *FileReader* stores the current location in the data file and guarantees that every timetag is returned once. If less than *n\_elements* are returned, the reader has reached the end of the last file in the file-list *filenames*. To check if more data is available for reading, it is more convenient to use *hasData()*.

### Parameters

**n\_events** – Number of timetags to read from the file.

### Returns

A buffer of size *n\_events*.

bool **hasData()**

### Returns

True if more data is available for reading, False if all data has been read from all the files specified in the class constructor.

str **getConfiguration()**

### Returns

A JSON formatted string (dict in Python) that contains the Time Tagger configuration at the time of file creation.

*channel\_t*[] **getChannelList()**

### Returns

All channels available within the input file.

str **getLastMarker()**

**Returns**

The last processed marker from the file (see also `FileWriter::setMarker()`).

**Dump**

class **Dump** : public *IteratorBase*

Writes the timetag stream into a file in a simple uncompressed binary format that store timetags as 128bit records, see *Time tag format*.

*See all common methods*

**Warning**

The files created with this class are not readable by *TimeTaggerVirtual* and *FileReader*. For storing time tag data intended for re-reading or postprocessing, use the *FileWriter* measurement class instead.

**Public Functions**

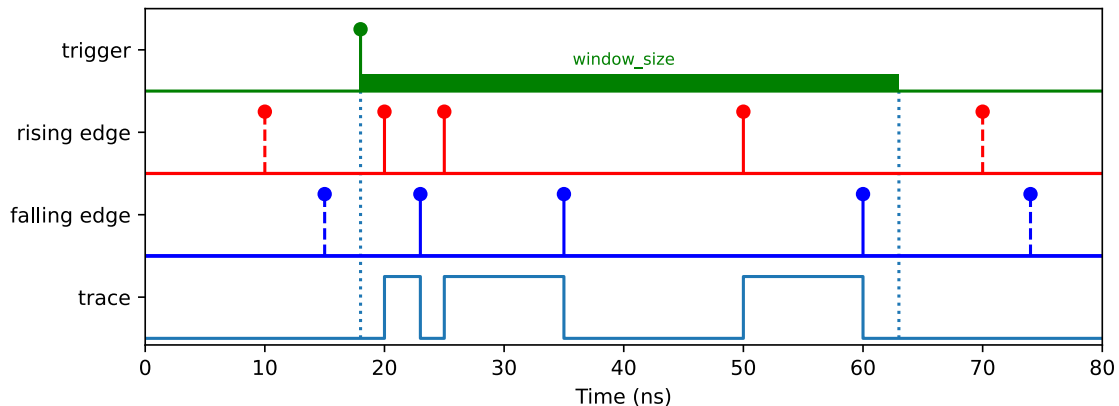
**Dump**(*TimeTaggerBase* tagger, str filename, int max\_tags, *channel\_t*[] channels = *channel\_t*[])

**Parameters**

- **tagger** – Time Tagger object instance.
- **filename** – Name of the output file.
- **max\_tags** – Stop after this number of tags has been dumped. Negative values will dump forever.
- **channels** – List of channels which are dumped to the file (when empty or not passed all active channels are dumped).

**Scope**

class **Scope** : public *IteratorBase*



The *Scope* class allows to visualize time tags for rising and falling edges in a time trace diagram similarly to an ultrafast logic analyzer. The trace recording is synchronized to a trigger signal which can be any physical or virtual channel. However, only physical channels can be specified to the *event\_channels* parameter. Additionally,

one has to specify the time *window\_size* which is the timetrace duration to be recorded, the number of traces to be recorded and the maximum number of events to be detected. If `n_traces < 1` then retriggering will occur infinitely, which is similar to the “normal” mode of an oscilloscope.

*See all common methods*

#### Note

*Scope* class implicitly enables the detection of positive and negative edges for every physical channel specified in *event\_channels*. This accordingly doubles the data rate requirement per input.

### Public Functions

**Scope**(*TimeTaggerBase* tagger, *channel\_t*[] event\_channels, *channel\_t* trigger\_channel, *timestamp\_t* window\_size = 1000000000, int n\_traces = 1, int n\_max\_events = 1000)

#### Parameters

- **tagger** – The time tagger object instance.
- **event\_channels** – List of channels.
- **trigger\_channel** – Channel number of the trigger signal.
- **window\_size** – Time window in picoseconds (default: 1 ms).
- **n\_traces** – Number of trigger events to be detected (default: 1).
- **n\_max\_events** – Max number of events to be detected (default: 1000).

*Event*[][] **getData()**

Returns a tuple of the size equal to the number of *event\_channels* multiplied by *n\_traces*, where each element is a tuple of *Event*.

#### Returns

*Event* list for each trace.

bool **ready()**

#### Returns

Returns whether the acquisition is complete which means that all traces (*n\_traces*) are acquired.

int **triggered()**

#### Returns

Returns number of trigger events have been captured so far.

*timestamp\_t* **getWindowSize()**

#### Returns

Returns the *windows\_size* parameter.

struct **Event**

Pair of the timestamp and the new state returned by *Scope::getData()*.

## Public Members

*timestamp\_t* **time**

Timestamp in ps.

*State* **state**

Input state.

enum **State**

Current input state. Can be unknown because no edge has been detected on the given channel after initialization or an overflow.

*Values:*

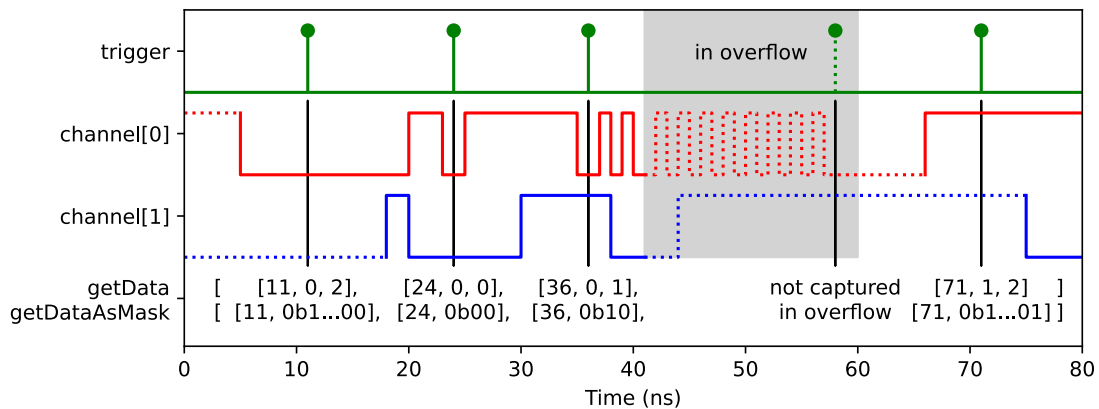
enumerator **UNKNOWN**

enumerator **HIGH**

enumerator **LOW**

## Sampler

class **Sampler** : public *IteratorBase*



The *Sampler* class allows sampling the state of a set of channels via a trigger channel.

For every event on the trigger input, the current state (low: 0, high: 1, unknown: 2) will be written to an internal buffer. Fetching the data of the internal buffer will clear its internal buffer, so every event will be returned only once.

Time Tagger detects pulse edges and therefore a channel will be in the unknown state until an edge detection event was received on that channel from the start of the measurement or after an overflow. The internal processing assumes that no event could be received within the channel's deadtime otherwise invalid data will be reported until the next event on this input channel.

*See all common methods*

**Note**

The maximum number of channels is limited to 63 for one *Sampler* instance.

**Public Functions**

**Sampler**(*TimeTaggerBase* tagger, *channel\_t* trigger, *channel\_t*[] channels, int max\_triggers)

**Parameters**

- **tagger** – The time tagger object instance.
- **trigger** – Channel number of the trigger signal.
- **channels** – List of channels to be sampled.
- **max\_triggers** – The number of triggers and their respective sampled data, which is stored within the measurement class.

*timestamp\_t*[:,] **getData()**

Returns and removes the stored data as a 2D array ( $n\_triggers \times (n\_channels + 1)$ ):

```
[timestamp of first trigger, state of channel 0, state of channel 1, ...],
[timestamp of second trigger, state of channel 0, state of channel 1, ...],
...
```

Where the state means:

```
0 -- low
1 -- high
2 -- undefined (after overflow)
```

**Returns**

Sampled data

*timestamp\_t*[:,] **getDataAsMask()**

Returns and removes the stored data as a 2D array ( $n\_triggers \times 2$ ):

```
[timestamp of first trigger, (state of channel 0) << 0 | (state of channel 1) <
↪ < 1 | ... | any_undefined << 63],
[timestamp of second trigger, (state of channel 0) << 0 | (state of channel 1) <
↪ < 1 | ... | any_undefined << 63],
...
```

Where state means:

```
0 -- low or undefined (after overflow)
1 -- high
```

If the highest bit (data[63]) is marked, one of the channels has been in an undefined state.

**Returns**

Sampled data.



## 5.5.7 Helper classes

### CustomMeasurement

**class** CustomMeasurement(*tagger*)

Python and C# wrapper for [CustomMeasurementBase](#).

#### Parameters

**tagger** ([TimeTaggerBase](#)) – Time Tagger object instance.

**process**(*incoming\_tags*, *begin\_time*, *end\_time*)

Override this method to implement the measurement logic. The method is called whenever a new chunk of time tags is available.

#### Parameters

- **incoming\_tags** – Chunk of incoming time tags for this call.
- **begin\_time** (*int*) – Begin timestamp of the processed chunk.
- **end\_time** (*int*) – End timestamp of the processed chunk.

This method is executed on the Time Tagger backend thread and is the performance-critical part of a custom measurement. The *incoming\_tags* buffer is only valid during the current call and may be overwritten by the next one. If you need to store tags, create a copy. In Python, it is usually advisable to use [numpy.array\(\)](#) and vectorized NumPy operations, or compiled code such as [Numba](#) if explicit iteration over the tags is required.

#### Note

In Python, the *incoming\_tags* are a [structured Numpy array](#). You can access single tags as well as arrays of tag entries directly:

```
first_tag = incoming_tags[0]
all_timestamps = incoming_tags['time']
```

#### mutex

Context manager object (see [Context Manager Types](#)) that locks the mutex when used and automatically unlocks it when the code block exits. For example, it is intended for use with Python's “with” keyword as

```
class MyMeasurement(CustomMeasurement):
```

```
    def getData(self):
        # Acquire a lock for this instance to guarantee that
        # self.data is not modified in other parallel threads.
        # This ensures to return a consistent data.
        with self.mutex:
            return self.data.copy()
```

#### Note

You can find an example of how to use the CustomMeasurement in the installation folder. Further custom measurement examples are available in the [Time-Tagger-Custom-Measurements](#) repository.

class **CustomMeasurementBase** : public *IteratorBase*

Base class for implementing custom measurements in C++, C#, and Python.

This helper class provides low-overhead access to the raw time tag stream and can be used to implement custom measurement logic in wrapper languages.

Typical usage:

- derive a custom measurement class,
- register all channels that should be forwarded to the measurement,
- call *finalize\_init()* once construction is complete,
- implement the processing callback.

The processing callback is executed on the Time Tagger backend thread. Therefore, it should return quickly and avoid unnecessary overhead.

*See all common methods*

### Public Functions

void **register\_channel**(*channel\_t* channel)

Registers a channel whose tags should be forwarded to this measurement.

#### Parameters

**channel** – Channel number to register.

void **unregister\_channel**(*channel\_t* channel)

Unregisters a previously registered channel.

#### Parameters

**channel** – Channel number to unregister.

void **finalize\_init**()

Finalizes the initialization of the measurement.

Call this after all required channels have been registered and the custom measurement object has been fully constructed.

bool **is\_running**()

Returns whether the measurement is currently running.

#### Returns

true if the measurement is running, otherwise false.

### Public Static Functions

static void **stop\_all\_custom\_measurements**()

Stops all currently running custom measurements.

This can be used during shutdown of the target language runtime to avoid races with still active custom measurement callbacks.

### SynchronizedMeasurements

## class **SynchronizedMeasurements**

The *SynchronizedMeasurements* class allows for synchronizing multiple measurement classes in a way that ensures all these measurements to start, stop simultaneously and operate on exactly the same time tags. You can pass a Time Tagger proxy-object returned by *getTagger()* to every measurement you create. This will simultaneously disable their autostart and register for synchronization.

### Public Functions

**SynchronizedMeasurements**(*TimeTaggerBase* tagger)

#### Parameters

**tagger** – The time tagger object instance.

*TimeTaggerBase* **getTagger()**

Returns a proxy tagger object which can be passed to the constructor of a measurement class to register the measurements at initialization to the synchronized measurement object. Those measurements will not start automatically.

#### Note

The proxy tagger object returned by *getTagger()* is not identical with the *TimeTagger* object created by *createTimeTagger()*. You can create synchronized measurements with the proxy object the following way:

```
tagger = TimeTagger.createTimeTagger()
syncMeas = TimeTagger.SynchronizedMeasurements(tagger)
taggerSync = syncMeas.getTagger()
counter = TimeTagger.Counter(taggerSync, [1, 2])
countrate = TimeTagger.Countrate(taggerSync, [3, 4])
```

Passing *tagger* as a constructor parameter would lead to the not synchronized behavior.

void **start()**

Calls *IteratorBase::start()* for every registered measurement in a synchronized way.

void **startFor**(*timestamp\_t* capture\_duration, bool clear = true)

Calls *IteratorBase::startFor()* for every registered measurement in a synchronized way.

#### Parameters

- **capture\_duration** – Acquisition duration in picoseconds.
- **clear** – Resets the accumulated data at the beginning (default: True).

void **stop()**

Calls *IteratorBase::stop()* for every registered measurement in a synchronized way.

void **clear()**

Calls *IteratorBase::clear()* for every registered measurement in a synchronized way.

bool **waitUntilFinished**(int timeout = -1)

Equivalent to *IteratorBase::waitUntilFinished()* for synchronized measurements.

#### Parameters

**timeout** – Timeout in milliseconds. Negative value means no timeout, zero returns immediately.

**Returns**

True if the synchronized measurements have finished, False on timeout.

bool **isRunning()**

Calls *IteratorBase::isRunning()* for every registered measurement and returns true if any measurement is running.

void **registerMeasurement**(*IteratorBase* measurement)

Registers the *measurement* object into a pool of the synchronized measurements.

**Note**

Registration of the measurement classes with this method does not synchronize them. In order to start/stop/clear these measurements synchronously, call these functions on the *SynchronizedMeasurements* object after registering the measurement objects, which should be synchronized.

**Parameters**

**measurement** – Any measurement (*IteratorBase*) object.

void **unregisterMeasurement**(*IteratorBase* measurement)

Unregisters the *measurement* object out of the pool of the synchronized measurements.

**Note**

This method does nothing if the provided measurement is not currently registered.

**Parameters**

**measurement** – Any measurement (*IteratorBase*) object.

## IN DEPTH GUIDES

This section contains articles that provide in depth details on the Time Tagger hardware and software.

## 6.1 Software-Defined Reference Clock

### 6.1.1 Overview of synchronization concepts

Like many other instruments, the Time Tagger can be locked to an external clock. Unlike conventional implementations, however, it supports two different synchronization concepts.

#### Traditional hardware reference clock

Among the inputs of the Time Tagger, you will find one labeled CLK or CLK IN. This input can be used to provide an external frequency reference. If the device's hardware PLL (Phase-locked loop) accepts the applied frequency, the Time Tagger switches to the external reference which takes over the clock role from the internal oscillator. As a result, the FPGA (Field-programmable gate array) of the Time Tagger that performs the TDC (Time-to-digital conversion) is driven directly by the external clock. However, this concept has three major drawbacks:

1. The CLK IN accepts only specific frequencies within a narrow tolerance range. For example, a *Time Tagger Ultra* or *Time Tagger X* accepts only 10 MHz or 500 MHz; a frequency of 9.5 MHz would already be rejected. As a result, it is often not possible to lock the Time Tagger directly to a laser system, even though using the laser as the master clock of an experiment may be desirable.
2. For signals that are strongly correlated with the external reference, the self-calibration of the Time Tagger does no longer operate correctly. This self-calibration relies on the assumption that incoming events are randomly distributed with respect to the TDC. This condition is always fulfilled when the internal oscillator is used, but it may be violated when the FPGA clock is defined by an external reference.
3. The loop filter is fixed in hardware. Therefore, the cutoff frequency between the external clock and the built-in reference cannot be configured. For drifting references, a high cutoff frequency allows faster tracking, whereas for very stable references, a low cutoff frequency provides better suppression of white noise.

There are still use cases that make use of the hardware clock (see [Synchronizer](#)).

#### Software-defined reference clock

The alternative and recommended concept is the software-defined reference clock. It has been introduced in software version 2.10 under the label *Software Clock* and has been extended in version 2.18 to the *Reference Clock*. In contrast to the traditional hardware synchronization, the TDC is always performed with respect to the internal oscillator of the Time Tagger. The external reference is applied to one of the standard signal inputs. This means, on the hardware level, it is handled like any other signal. On the software level, however, it is evaluated immediately by a software PLL. Based on the new time base provided by the PLL, the entire time-tag stream is rescaled. This means that the behavior of all virtual channel and measurement objects will feel to the user just like the external clock has been applied to the instrument itself.

### 6.1.2 Setting up the software-defined reference clock

After connecting a clock signal to one of the inputs of the Time Tagger, you can declare the respective input as the system clock by the `setReferenceClock()` method:

```
from Swabian import TimeTagger
tagger = TimeTagger.createTimeTagger()
tagger.setEventDivider(channel=1,
                      divider=2)
tagger.setReferenceClock(clock_channel=1,          # channel number
                        clock_frequency=10E6,      # frequency in Hz
                        time_constant=1E-3,         # time constant in seconds
                        wait_until_locked=True)

# This command would be ignored because channel #1 is restricted by the Reference Clock.
# The user receives a warning.
tagger.setEventDivider(channel=1
                      divider=100)
```

In this example, a 10 MHz clock is connected to channel #1. One important aspect is that the `clock_frequency` takes the actual frequency of the physical signal at the input. While the *Reference Clock* is active, an *Event Divider* cannot be set by `setEventDivider()`. This means that the *Reference Clock* is aware of the original frequency before division and is able to inject events at the place of dismissed events.

The locking behavior of the *Reference Clock* depends strongly on the `time_constant` parameter. It determines the time until the clock settles upon frequency changes. A small `time_constant` allows the frequency to be tracked more quickly, but with less averaging. On the other hand, larger values improve averaging, but the lock may be lost if the frequency changes too rapidly. In addition, stronger averaging increases the influence of phase noise on the measurement. The optimal value depends on the characteristics of the reference. If the *Reference Clock* loses the lock, the Time Tagger will switch to the overflow mode and timing information is lost.

The following figure illustrates the effect of the *Reference Clock* for two signals with an average frequency of 10 MHz. For clarity, the frequency fluctuations and measurement jitter are exaggerated. In practice, the *Reference Clock* would not be able to lock to signals of such poor quality.

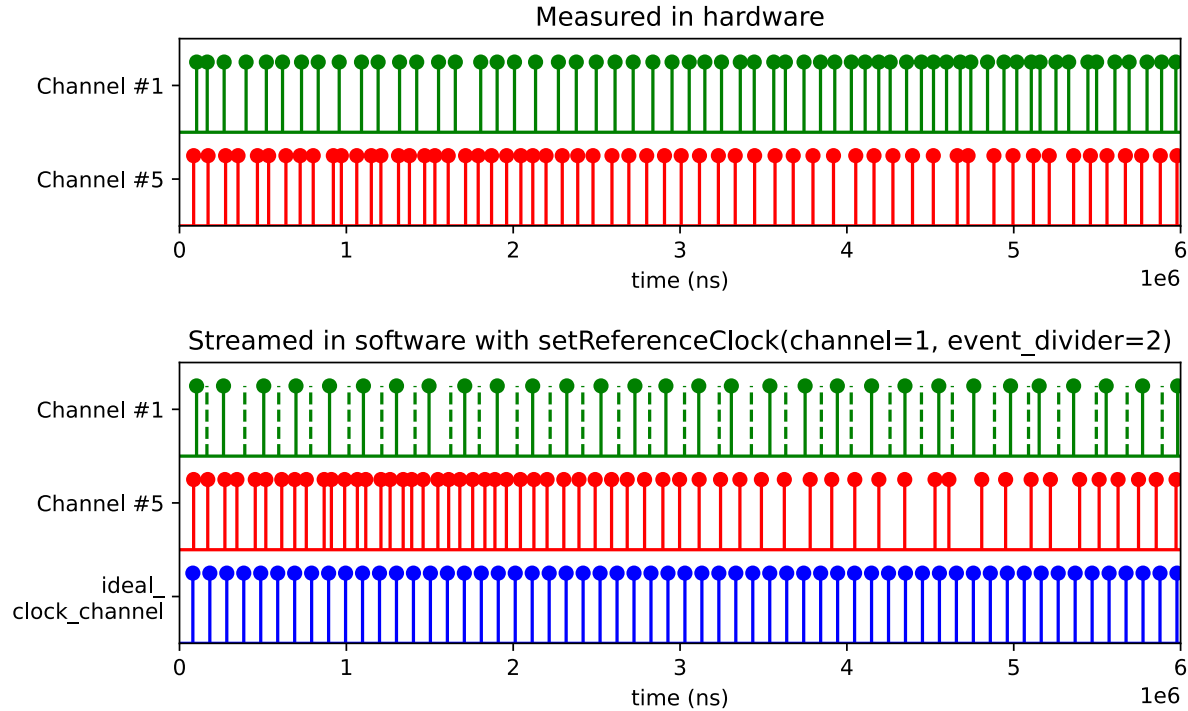
In the upper panel, the input signal on channel #1 oscillates more slowly in the first half, resulting in larger separations between events, and more quickly in the second half, resulting in smaller separations. For the signal on channel #5, the behavior is reversed. In addition, both signals include measurement jitter, which causes the spacing between neighboring events to vary randomly.

The middle panel shows the effect of declaring channel #1 as the *Reference Clock*. Compared to the upper panel, the signal on channel #1 now appears much more uniform, while the frequency variation on channel #5 becomes more pronounced. This is because the *Reference Clock*, and therefore the software-defined time base, follows the frequency changes of channel #1. Note that the original measurement jitter is still present on both channels.

The bottom panel shows the `ReferenceClockState::ideal_clock_channel`. While the *Reference Clock* computes the adjusted time base, it can also determine the expected timestamps of all events, including those that were filtered out, and, therefore, not transmitted. These “ideal” time tags are separated by numerically exact intervals. Since `ReferenceClockState::ideal_clock_channel` is based on channel #1, it largely removes the effect of measurement jitter and can therefore serve as an improved replacement signal.

### 6.1.3 Technical limitations

Before setting up the *Reference Clock*, you should consider a few limitations. In particular, it is important to understand which signals can be used as clock signals and what accuracy can theoretically be achieved.



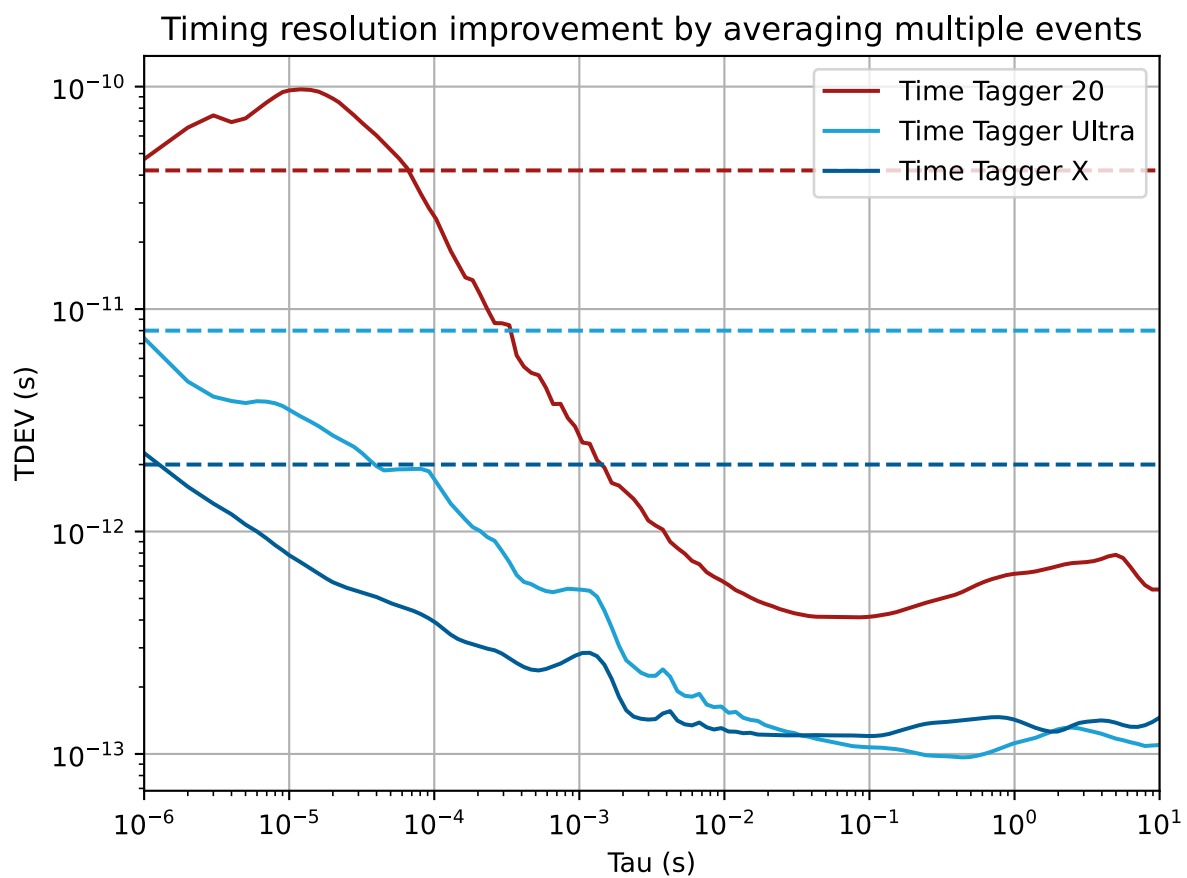
### Input signal limitations

In comparison to a traditional hardware clock, which on a *Time Tagger Ultra* and *Time Tagger X* only accepts 10 MHz or 500 MHz, the software-defined *Reference Clock* is much more flexible and can operate with arbitrary input frequencies. For *Time Tagger Ultra* and *Time Tagger X*, we recommend using reference clock frequencies between 100 kHz and 475 MHz or 700 MHz, respectively. Tracking and evaluating periodic signals requires a sufficient internal oscillator, which the *Time Tagger 20* is lacking, unfortunately. For this reason, the *Time Tagger 20* will not achieve the performance discussed in this article. When configuring the *Reference Clock* on a *Time Tagger 20*, a warning is displayed indicating that the resulting phase error may be large. Whether this is acceptable depends on the experiment, but we will not consider the *Time Tagger 20* further in this guide.

### Resolution limitations

The figure above shows the TDEV (Time deviation) of a 1 MHz signal on two inputs. It can be interpreted as the resolution limit for the various Time Tagger models using the *Reference Clock*. The TDEV is a metric that can be measured using the *FrequencyStability* measurement class. It estimates the timing error of signal events separated by a given  $\tau$  while taking into account averaging over all available data points. The measurement is performed using a power splitter to route the 1 MHz signal to two inputs, #1 and #5. Although the split signal is phase-locked at all times, the measurement jitter on the two inputs is independent. The relevant question is therefore how strongly the individual measurement error can be reduced by averaging.

In this experiment, channel #1 is used as the *clock\_channel* in *setReferenceClock()*, while channel #5 is analyzed with *FrequencyStability*. On the left, the  $\tau$  axis starts at 1  $\mu$ s, corresponding to the 1 MHz signal. The data point at 1  $\mu$ s represents the shortest possible interval between consecutive events and therefore does not allow for averaging. Accordingly, the curves start at the specified timing resolution of the respective model. At larger timescales, averaging over more events improves the timing resolution. The TDEV settles between 100 and 200 femtoseconds for both, the *Time Tagger Ultra* and the *Time Tagger X*. This means, that for both models, there is a more or less common non-white noise floor. While white noise can be eliminated at a rate of  $\frac{1}{\sqrt{n}}$  by averaging over  $n$  events, this is not the case, e.g., for  $\frac{1}{f}$ -noise.





## 6.1.4 Advanced features

### Emulating the Conditional Filter

In most cases it is neither necessary nor desirable to transmit the full clock signal to the PC. For periodic signals such as a clock, the straightforward way to reduce the data rate is to use the *EventDivider*. For a typical 10 MHz clock, an event divider of 100 can easily be applied without reducing performance.

Consider a fluorescence lifetime experiment: A femtosecond-laser, which can be regarded as a clock, excites a sample and, from time to time, a photon is emitted a few nanoseconds later. In this case, one of the signals is aperiodic, and the traditional filtering solution would be the *ConditionalFilter*: Each photon allows exactly one laser event to pass to the PC. This results in pairs of events, typically one photon event and one laser event. Their time differences can be easily evaluated by measurements such as *Histogram*.

However, this approach has two drawbacks in comparison to the *EventDivider* approach:

1. You have to use 50% of the available bandwidth for laser events, instead of reducing the bandwidth by a factor of 100 with the *EventDivider*.
2. You cannot benefit from the improved temporal resolution of the *ReferenceClock* on the periodic channel, because the transmitted signal is no longer periodic.

For this scenario, the *ReferenceClock* includes a feature that emulates the behavior of the *ConditionalFilter* while internally using the *EventDivider*. The following code shows how to set up this emulation:

```
tagger.setEventDivider(channel=1,
                      divider=100)
reference_clock_state = tagger.getReferenceClockState()
tagger.setConditionalFilter(trigger=[2],
                           filtered=[reference_clock_state.ideal_clock_channel])
tagger.setReferenceClock(clock_channel=1,
                        clock_frequency=80E6)
```

As you can see, the emulator is configured in the same way as *ConditionalFilter*, using *setConditionalFilter()*. It works as a modification of the way events are injected in the *ReferenceClockState::ideal\_clock\_channel*. The dismissed events are recreated during the rescaling process and immediately filtered by trigger events. The effect is shown in the following sketch:

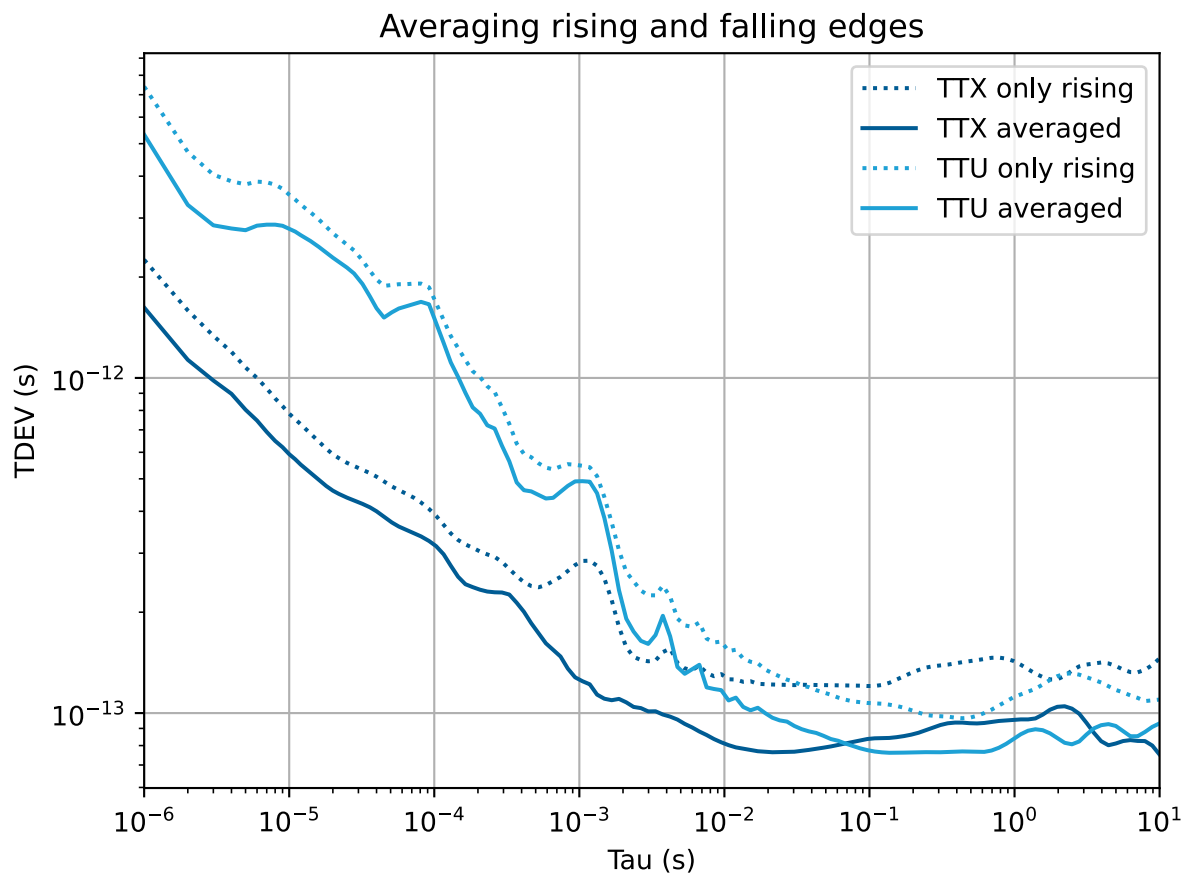
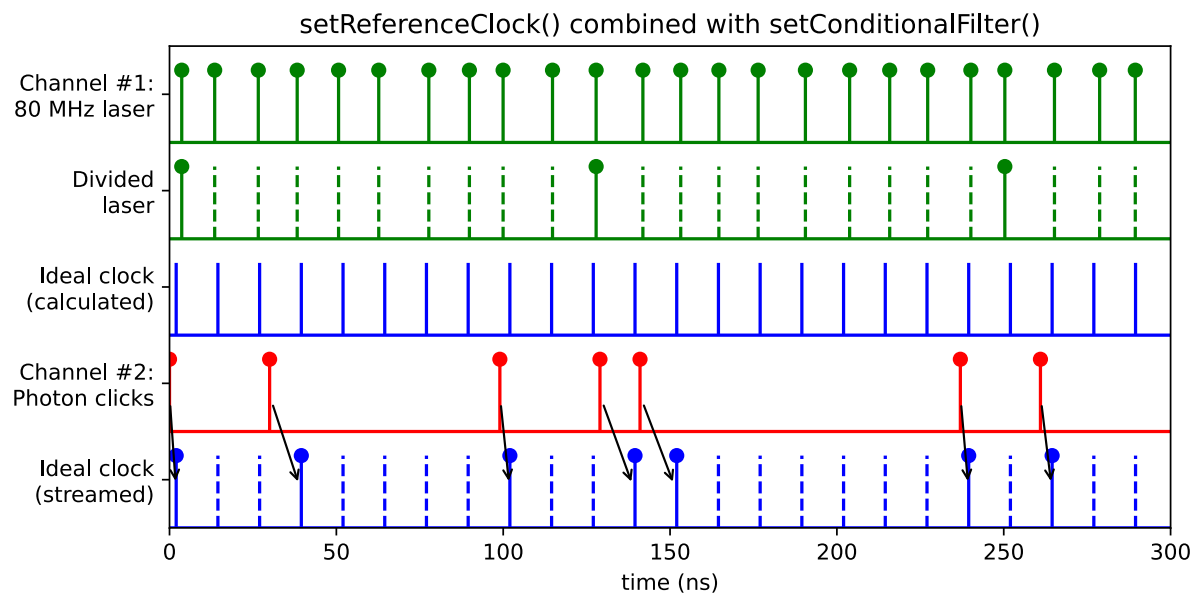
Note that the jitter of the measured laser events is widely eliminated in the ideal clock and that comparatively few events need to be transferred.

### Averaging of rising and falling edges

On the *Time Tagger Ultra* and *Time Tagger X*, there is an experimental feature that typically allows to improve the noise characteristics of periodic signals: By using the *TimeTagger::xtra\_setAvgRisingFalling()* method, you can configure the Time Tagger such that it transmits the average of a close-by rising and falling edge. This eliminates anti-correlated noise. Low-frequency noise (e.g. flicker  $1/f^*$ ) on the analog input voltage shifts the trigger level transitions in the opposite direction on rising and falling edges (for similar rise vs fall times). For the white noise part (which is per definition uncorrelated), it yields  $\sqrt{2}$ . It is not yet fully clear which effects contribute to this improvement but the graph below clearly shows that this makes it possible to push the TDEV below 100 fs.

## 6.2 Conditional Filter

The Conditional Filter is a hardware feature that allows you to remove irrelevant time tags carrying no information. In a typical use case, you have a high-frequency signal applied to at least one channel. Examples include fluorescence lifetime measurements or quantum optics, where you want to capture synchronization clicks from a high repetition rate excitation laser.



The Conditional Filter distinguishes between *trigger* channels and *filtered* channels. All input channels of your Time Tagger are fully equivalent and can be used as both, trigger or filtered channels. The data rate of the filtered channels will be reduced. The reduction is controlled by the trigger channels: Every trigger opens the gate for an event of the filtered channel. All other events in the filtered channels will be discarded on the Time Tagger and do not need to be transferred via the USB connection.

Being a hardware feature, the Conditional Filter is not controlled on the level of individual measurements. It is enabled on the level of your physical device with a typical Python code looking like

```
from Swabian import TimeTagger
tagger = TimeTagger.createTimeTagger()
tagger.setConditionalFilter(trigger=[1], filtered=[8])
```

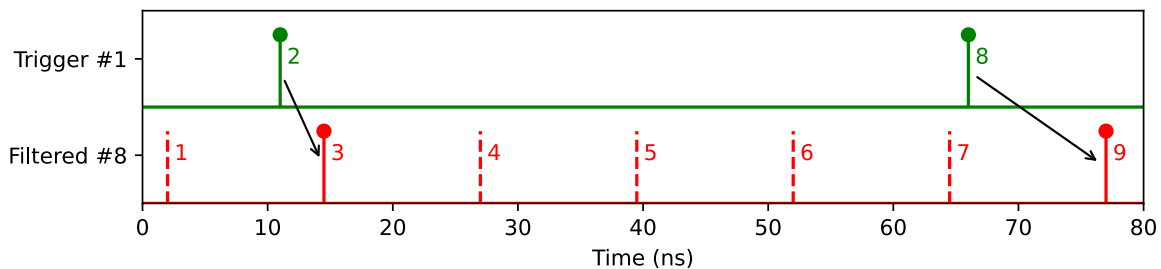
The details will be explained in the *Setup of the Conditional Filter* section.

## 6.2.1 Example configurations

### One trigger and one filtered channel

The most fundamental case involves one filtered-channel and one trigger-channel:

```
tagger.setConditionalFilter(trigger=[1], filtered=[8])
```



The Conditional Filter discards by default all signals of the filtered-channel. Only the very next event after an event on the trigger-channel is transmitted. In the example, click 2 opens the gate for click 3. When click 3 passes, it closes the gate and the subsequent events will be discarded until another event (click 8) occurs in the trigger channel.

### Multiple trigger-channels

There is the option to define more than one trigger-channel for the Conditional Filter. As a consequence, the next event on the filtered-channel is transmitted when there was a event at *any* of the trigger-channels:

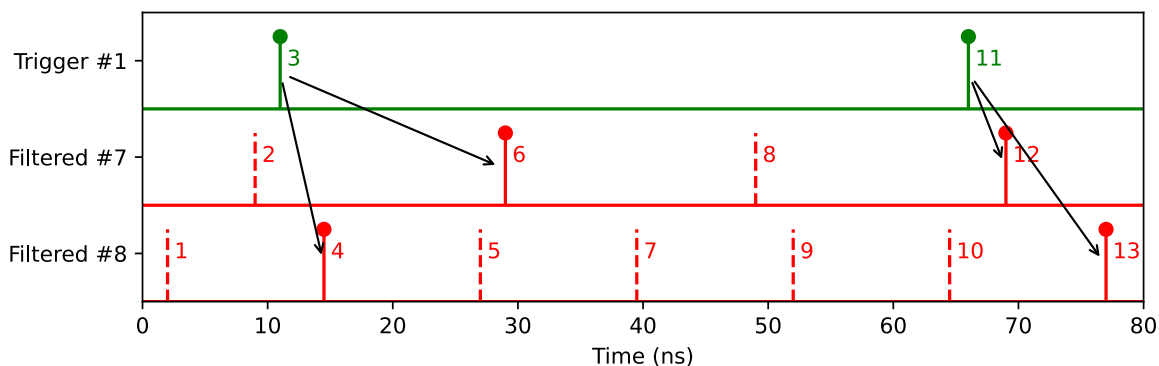
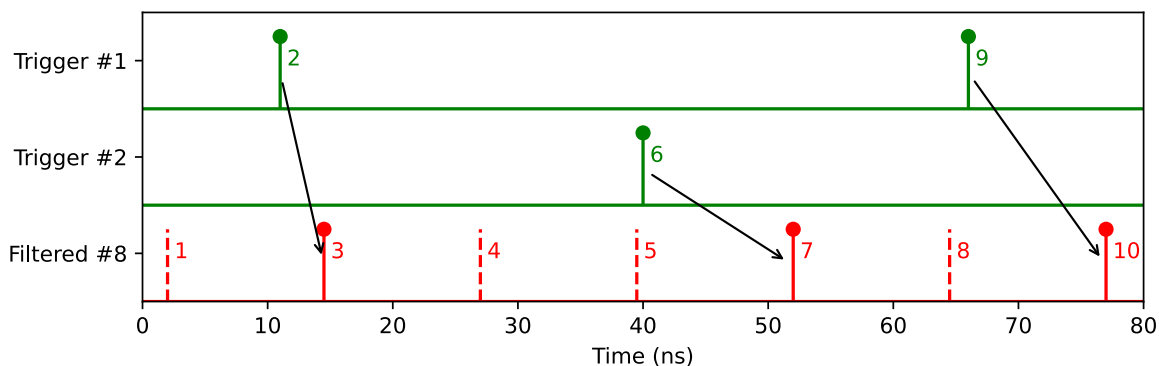
```
tagger.setConditionalFilter(trigger=[1, 2], filtered=[8])
```

This is the typical use case when you detect photons with multiple detectors and want to correlate both with the common excitation laser.

### Multiple filtered channels

It is also possible to use the Conditional Filter with one trigger-channel and several filtered-channels:

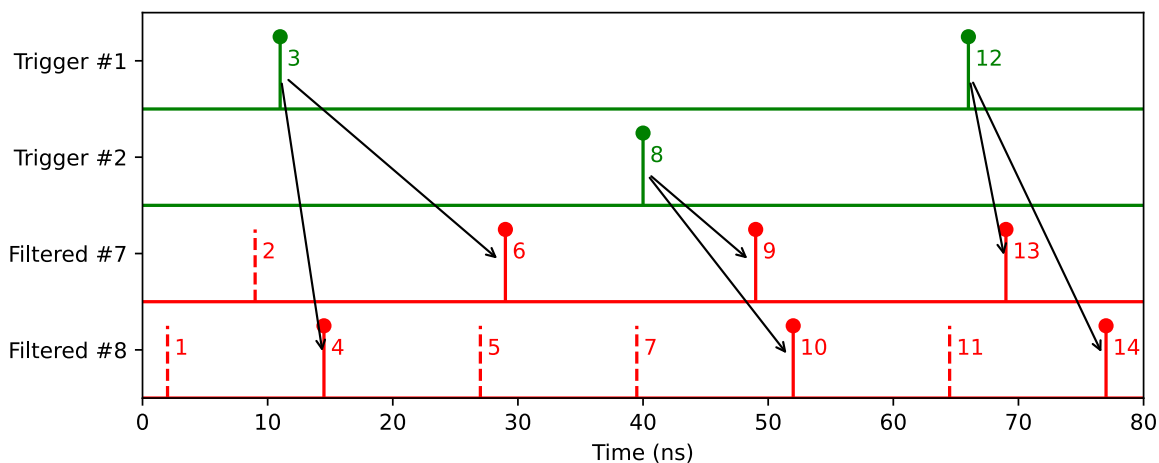
```
tagger.setConditionalFilter(trigger=[1], filtered=[7, 8])
```



### Multiple trigger and filtered channels

In general, you can also combine multiple trigger-channels and multiple filtered-channels:

```
tagger.setConditionalFilter(trigger=[1, 2], filtered=[7, 8])
```



This scheme shows two different high-frequency signals on channels #7 and #8. Such cases can occur when you want to run two completely independent experiments on a single Time Tagger. For instance, channels #1/#7 and #2/#8 may represent the two experiments. It is not possible to set up two independent Conditional Filters for these groups. The scheme shown is the only way to apply the Conditional Filter in this case - with the drawback that channel #1 (#2) may also trigger channel #8 (#7), making the filtering less efficient.

## 6.2.2 Understanding the filtering mechanism

The Conditional Filter is a hardware feature that is embedded in a sequence of processing stages. It is important to understand the order of these stages. Some unexpected results can occur when you are not aware of these mechanisms, so read the following section with care.

### Terms

#### Input time stamp

This is the time stamp *you* are interested in: It refers to the time when the input signal transits the trigger level at the input connector.

#### TDC time stamp

This is the time stamp *the Time Tagger* is interested in: It is the raw 64 bit integer the FPGA attributes to a pulse edge.

#### Hardware delay

The signal entering the input connector is routed through the Time Tagger into the FPGA where the time to digital conversion is performed. This route differs from channel to channel and so does the accumulated delay. Because of this, we need to distinguish between *Input time stamp* and *TDC time stamp*. The *hardware delay* cannot be controlled by the user, it is defined by the design of the Time Tagger hardware and the FPGA configuration (this can vary from software release to software release). Nevertheless, the Time Tagger is calibrated to compensate for this delay. This compensation is done on the device in case of the *Time Tagger Ultra* and the *Time Tagger X*. The *Time Tagger 20* can only apply the delay in software (see details below). Except for the purpose of understanding the Conditional Filter, you do not need to care about the difference.

#### External delay

Any delay introduced before the Time Tagger, e.g. by cable lengths or optical pathways.

### Processing stages

1. **Pulse enters the Time Tagger:** Up to the input connector, the user is in charge of the *external delays*. They can be controlled by changing cable lengths or optical pathways. The time tag generated by the Time Tagger should therefore represent the temporal order at the input connectors. This is the *input time stamp*.
2. **Time to digital conversion:** The pulses propagate through the Time Tagger. They are compared to the trigger level of the input stage. This results in a high or low logic level. This is still analog information that propagates to the FPGA. Here, the *TDC time stamp* is attributed to the pulse edge. The propagation length up to this time to digital conversion (TDC) differs from channel to channel. It can be compensated in one of the later stages.
3. **Adjustable hardware delay (Time Tagger Ultra and Time Tagger X only!):** The Time Tagger is able to buffer and reorder the tags before the Conditional Filter. You can set an individual delay for every input channel by `setDelayHardware()`, and independently for rising and falling channels. This behaves like an adjustable hardware delay and is calibrated by default to compensate for the physical hardware delay. It changes the behavior of the Conditional Filter tremendously, as you will see in the next stages.
4. **Adjustable deadtime:** As a first filter stage, the adjustable deadtime is applied. It acts only on the channel itself, considering rising and falling edges as two separate channels. After an event in one of the channels occurred, no other event can appear in the same channel for the defined deadtime. On the *Time Tagger 20*, the deadtime can only be set in integer multiples of the FPGA clock cycle of 6 ns with a technically required minimum of one cycle. On the other hand, on the *Time Tagger Ultra* and *Time Tagger X*, the deadtime can be set to any integer value greater than the duration of one FPGA clock cycle, which is 2 ns and 1.333 ns, respectively.
5. **Conditional Filter:** As a second filter stage, the Conditional Filter is applied. The time tags of trigger channels and filtered channels are compared. On the *Time Tagger Ultra* and the *Time Tagger X*, this comparison is based on the time stamp after the *Hardware delay* compensation and after the additional delay set by `setDelayHardware()`. On the *Time Tagger 20*, the comparison is based on the raw *TDC time stamp*. In both cases, the time order of these stamps can deviate from the order of the *input time stamps* that you are usually dealing with.

**Note**

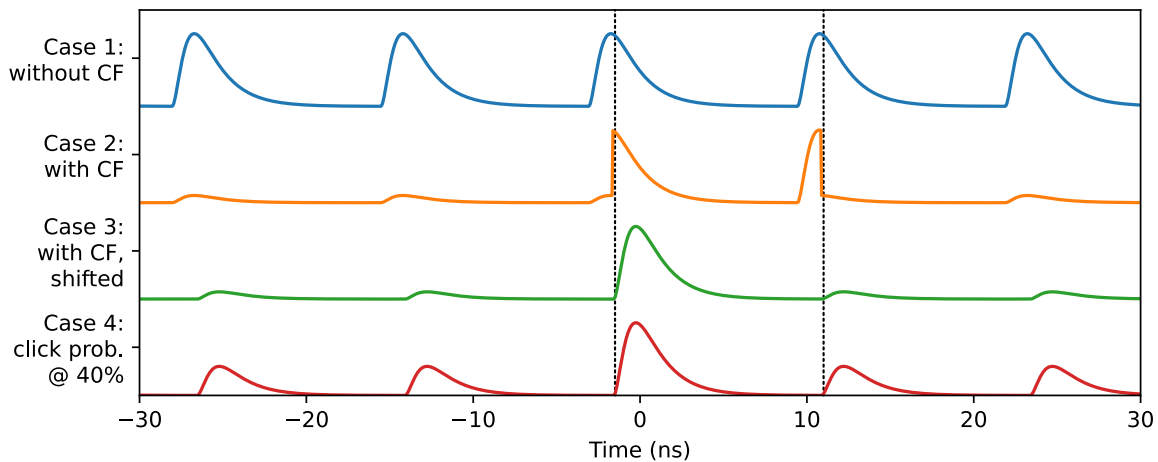
In the edge case of events arriving at the same time ( $dt=0$ ) on a trigger and filtered channel, it is not specified whether the event on the filtered channel at  $dt=0$  is passed through, or the subsequent, or both.

6. **Event Divider:** As a third filter stage, the event divider can be applied. Only one every  $n$ -th time tag of the respective channel is transmitted, all others are dismissed.
7. **The bottleneck - data transfer:** The time tags are buffered and transmitted to the PC. At this point, after applying Conditional Filter and Event Divider, it is important that the resulting data rate on average does not exceed the maximum data rate.
8. **setDelaySoftware:** From now on, the Time Tagger hardware is not involved anymore. On the *Time Tagger 20*, the software compensates now the *TDC time stamp* for the *hardware delay* to provide you the *input time stamp*. This compensation can be enabled or disabled with `setHardwareDelayCompensationActive()` (see section below). On all devices, you can modify this compensation by `setDelaySoftware()`.
9. **Delayed Channel:** The most flexible way to control the relative delay of your signals are Virtual Channels.

**Consequences**

The nature of the filtering process can produce counterintuitive results that need to be handled. We will explore these cases based on the example of a fluorescence lifetime measurement. The sample is excited by a pulsed laser with a repetition rate of 80 MHz (period of 12.5 ns), the laser synchronization signal is connected to channel #8. So channel #8 is the high-frequency input that needs to be filtered. Fluorescence photons are collected by a single-photon detector connected to channel #1 that will trigger the Conditional Filter. We set up a correlation measurement and look at different cases:

```
TimeTagger.Correlation(tagger, 1, 8)
```

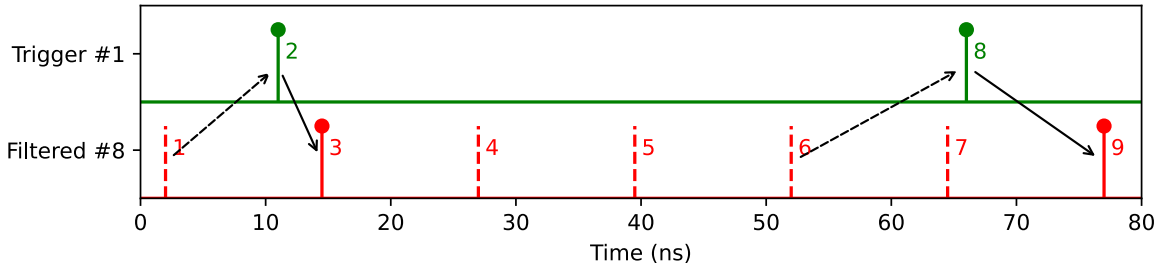


**Case 1:** Without the Conditional Filter set up, the *Correlation* measurement class provides a periodic signal. The periodicity is a result of the multi-start/multi-stop approach of the *Correlation* measurement: A click on the detector will contribute together with any laser synchronization pulse to the *Correlation*, not only with the one that actually generated the photon. Without the Conditional Filter, there will be a laser time tag every 12.5 ns. Because this high frequency might not be transferred for a long time, buffer overflows might lead to discarded data.

**Case 2:** With the Conditional Filter on, the data rate is highly reduced at the cost of losing the full periodicity of the signal:

```
tagger.setConditionalFilter(trigger=[1], filtered=[8])
```

Now we observe that the majority of the events is in the range of a few nanoseconds. However, the signal does not look like expected: Instead of a signal resembling one of the peaks from Case 1, a double peak appears. If you look carefully at the signal, you can see that the lifetime curve is cut along the dotted line and one part is shifted by one period. This indicates that the physical delay between the input channels is not designed properly. The scheme illustrates the problem:



The dashed line indicates which pulse excited the sample. If the photon is emitted early by the sample (click 2), it will trigger the first pulse (click 3) after the generating one (click 1). In the second case, the photon is emitted late and the subsequent laser pulse (click 7) has already passed. In this case, click 9 is passed and click 8 seems to be very early, although it is quite late, in fact.

**Case 3:** To align the signal properly, having the signal in between two laser events, the strategy depends on your device: With the *Time Tagger Ultra* and the *Time Tagger X*, you can use `setDelayHardware()` to align your signals. On the *Time Tagger 20*, you need to adjust your *external delays*. You might either modify optical path lengths or use cables of different lengths.

**Case 4:** This case illustrates that the height of the higher-order peaks is determined by the count rate of your detector. The relative height (compared to the center peak) is proportional to the probability for a laser synchronization pulse to pass the Conditional Filter in the higher-order period. This probability is given by the probability that a detector click occurs in the respective period and gates the synchronization click. In Case 1, without the Conditional Filter, the probability is 100% - every synchronization pulse is passed. For Case 2 and Case 3, the probability has been set to 10%, in Case 4 it has been increased to 40%.

#### Note

In Cases 3 and 4, with *external delays* well adjusted to each other, you can see a signal at negative times. How is this possible? Wouldn't this mean that the laser synchronization click arrived earlier than the photon click that gated it? Does my Time Tagger violate causality?

The answer is: No, it does not. The occurrence of negative delays is caused by the difference between the *input time stamps* and the *TDC time stamps*. Negative delays occur in *input time stamps*, but causality must only be obeyed in *TDC time stamps* (plus *adjustable onboard delays*, if available). The occurrence of negative delays indicates that the *hardware delay* of channel #8 (laser synchronization) is larger than that of channel #1 (detector).

### 6.2.3 Setup of the Conditional Filter

The `setConditionalFilter()` method expects two arguments, *trigger* and *filtered*:

```
tagger.setConditionalFilter(trigger: list[int],
                           filtered: list[int])
```

The effect of *trigger* and *filter* can be reviewed in the *Example configurations* section.

### Control hardware delay compensation

With the argument *hardwareDelayCompensation* you can decide whether the *hardware delay* is compensated or not. This means, in fact, that you can decide whether you work with *input time stamps* or with *TDC time stamps*. If your device supports *adjustable onboard delays*, you should never set this value to False and you can ignore this section.

#### hardwareDelayCompensation = True (default)

##### Pros

- Time tags are provided in the way you are used to it
- The signal position will not depend on the software version

##### Cons

- Negative time differences can occur between trigger-channel and filtered-channel and seemingly violate causality

#### hardwareDelayCompensation = False

##### Pros

- Provided time tags will be in the same temporal order as for the ConditionalFilter, no negative time differences will occur

##### Cons

- Affects all channels, not only the ones listed in *trigger* and *filtered*.
- Signal positions may change upon software (firmware) update

### Disable the Conditional Filter

To disable the Conditional Filter, you can either pass an empty lists or use the *clearConditionalFilter()* method:

```
tagger.setConditionalFilter([], [])  
# or  
tagger.clearConditionalFilter()
```

## 6.3 Raw Time-Tag-Stream access

There are several ways to access the raw time tags with the Time Tagger API. They can be split into two categories: dumping together with post-processing and on-the-fly processing. Both ways will be explained in the following. They are not exclusive so that you can combine them, also, with other measurements from our API in parallel.

### 6.3.1 Dumping and post-processing

All incoming time tags or selected channels of the Time Tagger can be stored on the hard drive via the *FileWriter*. Please visit the documentation and the provided programming examples of *FileWriter* for further details.

There are two ways for post-processing the dumped data:

#### File Reader

By reading in the stored time tags with the *FileReader*, the tags stored can be processed natively in your preferred programming language. You find examples of how to use the *FileReader* in your examples folder.



## Virtual Time Tagger

The second option to process stored time tags is the *Time Tagger Virtual*. The *Time Tagger Virtual* allows you to use the full Time Tagger API to post-process your data. You find examples of how to use the *Time Tagger Virtual* in your examples folder.

### 6.3.2 On-the-fly processing

There are two options to process raw incoming data, the *TimeTagStream* and the *CustomMeasurement*, which will be explained in the following:

#### TimeTagStream - high-level, lower performance

The *TimeTagStream* buffers the incoming raw data for on-the-fly processing. The *TimeTagStream* buffer must be polled to retrieve the tags. You find examples of how to use the *TimeTagStream* in your examples folder.

#### CustomMeasurement - low-level, higher performance

The *CustomMeasurement* functionality allows you to access the raw time tag stream with very little overhead. By inheriting from *CustomMeasurement*, you can implement your fully customized measurement class. The `process(incoming_tags, begin_time, end_time)` method of this class will be invoked as soon as new data is available. Note that this functionality is only available for C++, C#, and Python. You find examples of how to use the *CustomMeasurement* in your examples folder.

#### CustomVirtualChannel - modify the time tag stream - C++ only

It is now possible for you to modify the time tag stream, like our API does by inserting time tags, e.g., via *Coincidence* or *DelayedChannels*. If you want to use this functionality, please contact Swabian Instruments support.

#### IteratorBase - C++ only

All measurements and virtual channels are derived from the *IteratorBase* class. You can see how to access the time tag stream on the deepest level with the provided C++ examples.

## 6.4 Synchronization of the Time Tagger pipeline

In order to achieve a real-time evaluation of the events with high data rates, the Time Tagger series uses a pipeline based parallel processing.

The hardware records a timestamp for every incoming event and stores it in a large on-device buffer. The size of this buffer can be configured with `setHardwareBufferSize()`. The buffer contents are read by computer over USB, typically in blocks of one million of events or when the time between the blocks exceeds 20 ms. Waiting until a block of data is available is aimed at optimizing the USB throughput while limiting the time between consecutive block allows for reducing data latency on slow event rates. The block size can be tuned by a user with `setStreamBlockSize()`. On the computer, the blocks of data are processed by all running measurements in the order in which the measurements were created. Only one measurement has access to a block at any given time. Once a measurement has finished processing the block, it is ready to process the next block while the previous block becomes available to the next measurement.

Naturally, the transferring and processing of the data takes time and results in the latency. The latency between signal arrival and its appearance in the measurement data is usually below 100 ms; however, it can become as large as a few seconds if the on-device buffer fills up faster than the computer can transfer and process the data.

Proper operation of the pipeline and the control of the device parameters requires a suitable synchronization method. Time Tagger uses the concept of fencing. A fence is a unique identifier that is sent by the software to the hardware. It is added at the end of the on-device buffer data, streamed back to the computer along with timestamp data, and processed by all measurement classes. Once the Time Tagger software detects the fence, it knows that it is located at the data position which was in the buffer when the fence was created. The usefulness of fencing is easily demonstrated with a

following example. When you create a measurement, you expect that it starts processing data from that very instance of time; however, it starts processing the data, which was recorded earlier and is already available in the buffer. With fencing, the measurement creates a fence and begins data accumulation only when it receives the fence back. In this way, the measurement is dealing with the data recorded as close to the measurement creation as possible and avoids processing of the older data.

You can use the fencing mechanism manually. First, you have to create a new fence with `getFence()` and then wait for it to be signaled with `waitForFence()` at any time later. If you want to create a fence and immediately wait for it then using the `sync()` method is more convenient.

## 6.5 10 Gbit/s Ethernet Link

The *Time Tagger X* provides multiple interfaces for transferring time-tag data. For standard operation, the recommended configuration is to transfer time tags to the host PC via USB (Universal Serial Bus) 3.0, which provides a specified data transfer rate up to 90 MTags/s. For applications requiring higher sustained throughput or lower latency, the *Time Tagger X* also provides SFP+ and QSFP+ interfaces. These interfaces are also discussed in the [FPGA Link](#) in-depth guide, where they are employed to stream time tags to external FPGA hardware through an Ethernet-based protocol.

This guide describes how to use the SFP+ interface as a 10 Gbit/s Ethernet (10 GbE) link for streaming time tags directly from the *Time Tagger X* to an acquisition PC. The data stream is received and processed by the Time Tagger software.

The 10 GbE interface supplements rather than replaces the USB connection: USB remains required for device configuration and control, while the time-tag data stream is routed over the SFP+ interface. At any given time, all time-tag data is transferred over a single data interface; it is not possible to route data from some channels over USB and from others over the SFP+ interface simultaneously.

### Note

The 10 GbE link is intended for applications with sustained time-tag rates that exceed what can be transferred consistently over the USB interface. For lower data rates, the USB interface is simpler and therefore recommended.

### Note

10 GbE data transfer is available to all users at up to 100 MTags/s. With the *High Rate* hardware license, the full transfer rate of up to 300 MTags/s over SFP+ is enabled. To upgrade your license, contact [sales@swabianinstruments.com](mailto:sales@swabianinstruments.com). The license can then be updated using the standard procedure described in [Hardware License Upgrades](#).

**Warning**

10 GbE streaming is not supported in synchronized multi-device setups using the *Synchronizer*. In that configuration, USB remains the only supported interface for time-tag data transfer from all devices.

The following sections describe the setup requirements and provide step-by-step guidance for configuring and validating the connection.

### 6.5.1 Setup overview and requirements

The acquisition PC must be equipped with a dedicated 10 GbE network adapter with an SFP+ port, either an internal PCIe (Peripheral Component Interconnect Express) card or an external adapter, and connected to the *Time Tagger X* via two independent interfaces: USB 3.0 for device configuration and control, and the SFP+ interface for the time-tag data stream. The recommended physical setup is a direct point-to-point connection between the SFP+ port of the *Time Tagger X* and the 10 GbE adapter. For the connection itself, a Direct Attach Copper (DAC) Cable or optical SFP+ transceivers shall be used, RJ45 (10GBASE-T) SFP+ transceivers are not supported. The acquisition PC must run Time Tagger software version 2.22 or later.

**Note**

The following 10 GbE accessories are recommended for use with the *Time Tagger X*:

- **QNAP QNA-UC10G1SF**: 10 GbE SFP+ network adapter (USB4 Type-C), compatible with USB 4 and Thunderbolt 3/4.
- **10Gtek 10Gb PCIe SFP+ NIC** (Intel 82599ES, X520-DA2 compatible).
- **10Gtek 10Gb PCIe SFP+ NIC** (Intel X710-BM2, X710-DA2 compatible).
- **10Gtek SFP+ DAC Twinax cable**: passive, compatible with Cisco SFP-H10GB-CU-series DAC cables, available in multiple lengths.

The time-tag data stream uses UDP (User Datagram Protocol). Because the *Time Tagger X* generates Ethernet frames directly without relying on ARP (Address Resolution Protocol), the IPv4 address and MAC (Media Access Control) address of the receiving network interface must be supplied explicitly when enabling the stream via the Time Tagger API. How to identify these values is described in the next section.

The achievable time-tag transfer rate depends strongly on the MTU (Maximum Transmission Unit), which defines the maximum packet size used for the UDP data stream. Standard Ethernet operation uses an MTU of 1500 bytes. Larger MTU values require support for larger-than-standard Ethernet frames, commonly referred to as jumbo frames. The Time Tagger API uses an MTU of 9000 bytes by default. For high-rate operation, the receiving network interface must therefore be configured to accept Ethernet frames large enough to carry UDP packets with this MTU, as described in the following section.

If the network path does not support an MTU of 9000 bytes, the Time Tagger MTU parameter must be reduced to the maximum value accepted by all components in the path. At the standard Ethernet MTU of 1500 bytes, the achievable transfer rate is significantly reduced because the same data must be carried by many more, smaller UDP packets; in this case, we recommend using the USB interface instead.

The following table lists hardware configurations validated for 10 GbE streaming, together with the achieved sustained transfer rates at MTU 9000 bytes. Comparable rates may be achievable with MTU values above approximately 5000 bytes.

| 10 GbE SFP+ interface            | CPU                    | OS                        | Transfer rate (MTags/s) |
|----------------------------------|------------------------|---------------------------|-------------------------|
| Intel X520 (PCIe)                | AMD Ryzen 9 9950X      | Windows 11 / Ubuntu 24.04 | 300 / 260               |
| Intel X710 (PCIe)                | AMD Ryzen 9 9950X      | Ubuntu 24.04              | 264                     |
| QNAP QNA-T310G1S (Thunderbolt 3) | AMD Ryzen 9 9950X      | Windows 11                | 300                     |
| QNAP QNA-T310G1S (Thunderbolt 3) | AMD Ryzen 7 PRO 8840HS | Windows 11                | 300                     |
| QNAP QNA-T310G1S (Thunderbolt 3) | Intel Core i7-1360P    | Windows 11                | 300                     |

All measurements were performed with Time Tagger software version 2.22 using a modified version of the `transfer_rate.py` example found in the 6-Various-Examples folder of the Time Tagger installation, with 8 channels enabled.

## 6.5.2 Preparing the receiving network interface

Before enabling 10 GbE streaming, the receiving network interface must be configured to accept packets with an MTU of at least 9000 bytes, which matches the default MTU used by the Time Tagger API. The IPv4 address and MAC address of the receiving interface must also be identified. The exact steps depend on the operating system and on the network-adapter driver.

### Windows

#### Identifying the 10 GbE interface

Open a PowerShell window and run:

```
Get-NetAdapter
```

The output lists all available network adapters with their name, description, and link state. Connect the cable between the *Time Tagger X* SFP+ port and the 10 GbE adapter; the corresponding entry will change from **Disconnected** to **Up**. Note the adapter name; it is used in the following steps.

#### Configuring jumbo frames / MTU

1. Open **Device Manager** and expand **Network Adapters**.
2. Right-click the 10 GbE adapter and select **Properties**.
3. Go to the **Advanced** tab and locate the **Jumbo Packet** (or **Jumbo Frame**) property.
4. Set the value to **9014 Bytes** or the highest available value of at least 9000 bytes.
5. Click **OK**.

#### Finding the IPv4 address and MAC address

Open a Command Prompt and run:

```
ipconfig /all
```

Locate the entry for the adapter name identified above. The **IPv4 Address** and **Physical Address** (MAC address) fields provide the values required by the Time Tagger API.

Alternatively, open *Settings* → *Network & Internet*, select the adapter, and click **Properties**. Both the **IPv4 address** and the **Physical address (MAC)** are listed there.

## Linux

### Identifying the 10 GbE interface

Run the following command to list all network interfaces:

```
ip link show
```

The output lists all interfaces with their current state. The 10 GbE interface connected to the *Time Tagger X* can be identified by its state changing from **DOWN** to **UP** when the cable is plugged in. Note the interface name (e.g. `enp3s0` or `eth0`); it is used in all subsequent commands.

### Configuring the MTU

Set the MTU to 9000 bytes, replacing `<interface>` with the name identified above:

```
sudo ip link set <interface> mtu 9000
```

Verify that the MTU has been applied:

```
ip link show <interface>
```

The output should contain `mtu 9000`. This change takes effect immediately but might not be persistent across reboots.

### Finding the IPv4 address and MAC address

```
ip addr show <interface>
```

The MAC address appears on the `link/ether` line and the IPv4 address on the `inet` line. These are the values to supply to the Time Tagger API.

## 6.5.3 Enabling 10 GbE streaming

After the receiving network interface has been prepared, 10 GbE streaming is enabled via the Time Tagger API. The *Time Tagger X* must first be connected and initialized over USB, as in normal operation.

Call `xtra_enableStreamInterfaceUDP()` with the following parameters:

- `pc_ip`: the IPv4 address of the receiving network interface, identified in the previous section.
- `pc_mac`: the MAC address of the receiving network interface, identified in the previous section.
- `tagger_ip`: a user-chosen IPv4 address for the *Time Tagger X*'s SFP+ interface. This address must be on the same subnet as `pc_ip`. A simple choice is to take the PC's IP address and change the last octet to an unused address in the same subnet, as shown in the example below.
- `MTU`: the MTU in bytes (default: 9000 bytes). Must not exceed the MTU configured on the receiving adapter and is limited to a maximum of 9500 bytes.

Replace the values in the example below with the values used in your setup.

```
from Swabian import TimeTagger

PC_IP      = '169.254.99.217'
```

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```

PC_MAC      = '24:5E:BE:44:26:AF'
TAGGER_IP   = '169.254.99.216' # user-chosen; must be on the same subnet as PC_IP

tagger = TimeTagger.createTimeTagger()

tagger.xtra_enableStreamInterfaceUDP(pc_ip=PC_IP,
                                     pc_mac=PC_MAC,
                                     tagger_ip=TAGGER_IP,
                                     MTU=9000)

```

Once the UDP stream is enabled, Time Tagger measurements can be started as usual.

When 10 GbE streaming is no longer required, call `xtra_disableStreamInterfaceUDP()` to return the time-tag data path to the default USB interface.

```
tagger.xtra_disableStreamInterfaceUDP()
```

## 6.5.4 Performance considerations

At high data rates, each time tag is compressed to 32 bits, enabling a maximum transfer rate of 300 MTags/s over the 10 Gbit/s link. On reception, the software expands each tag to a 128-bit internal representation, producing a sustained in-memory data rate of approximately 4.8 GB/s, a substantial volume that underlines the scale of the data being processed.

The raw time-tag transfer rate given in the hardware comparison table is measured with a minimal custom measurement that accumulates the size of each received tag block without processing individual tags. Under these conditions, the achievable rate reflects the capacity of the network adapter and the host to sustain high-speed data reception.

When measurements are running, every received time tag must be processed by each active measurement object. Running multiple measurements simultaneously means their processing costs add up within each data block, and the combined cost determines the achievable throughput. The Time Tagger measurement backend is highly optimized to handle this stream efficiently, sustaining high throughput across most measurement types even when individual measurements do not reach the maximum transfer rate.

The computational cost per tag varies substantially across measurement types. The throughput figures below were obtained on an AMD Ryzen 9 9950X with an Intel X520 PCIe adapter and should be interpreted as indicative rather than as specifications; actual values depend on hardware, operating system, and measurement parameters.

*FileWriter* achieves the full hardware transfer rate, independently of the number of channels. Although it does not perform per-tag analysis, it must batch time tags into blocks, compress each block, and write the result to disk. Its throughput is sensitive to thread scheduling: when simultaneous multi-threading (SMT) is enabled, the data-conversion and the file-writing threads may be placed on logical cores sharing the same physical core, reducing throughput substantially down to 200-250 MTags/s. Disabling SMT recovers the full transfer rate.

Lightweight measurements such as *Counter* and *Countrate* add minimal overhead and achieve close to the full hardware transfer rate.

*Correlation* is considerably more expensive. For each incoming tag, the algorithm compares it against all previously received tags on the correlated channel that fall within the correlation time window, defined as  $\text{binwidth} \times \text{n\_bins}$ . The computational cost per tag therefore scales with the number of historical tags retained in that window. When multiple peaks of the correlation function fall within this window, all inter-peak tags must be retained and examined for each new tag, multiplying the cost accordingly. Even in a single-peak configuration, throughput is typically limited to approximately 240 MTags/s. To maximize throughput, set the time window to the minimum value that covers the region of interest and ensure that at most one peak falls within the window.

*FrequencyStability* can approach the full transfer rate when the averaging parameter is large (e.g. `average = 1000`); throughput is slightly dependent on the number of active channels. *PhaseNoise* performs an FFT (Fast Fourier

Transform)-based analysis; throughput improves as more channels share the computation, with a practical upper limit of approximately 200 MTags/s.

*HistogramLogBins* must search across all bin edges for each detected stop event, a cost that grows with the number of bins and the span of the time axis; despite a multi-threaded implementation, it remains one of the most computationally intensive common measurement types.

The achievable throughput for a given setup depends on a combination of factors: the network adapter and host hardware, the operating system, the number of active channels, the number and type of simultaneous measurements, and their individual parameters. For guidance on a specific configuration, please contact [support@swabianinstruments.com](mailto:support@swabianinstruments.com).

## 6.6 FPGA Link

### Warning

The reference design and the on-the-wire format are not stable and will be subject to incompatible changes with further development.

The FPGA link output of the *Time Tagger X* allows you to connect an FPGA of your own design to the *Time Tagger X* via an Ethernet-based protocol and benefit from higher data throughput and lower latency compared to USB.

In a typical use case, you want to use either process tags at a higher rate than the USB connection to the PC allows or integrate the measurements into a test fixture and trigger events based on the measurements.

The SFP+ port on the *Time Tagger X* can be used either with a DAC or fiber transceivers to connect to your own FPGA. For the DAC connection, we recommend the [10Gtek SFP+ DAC Twinax cable](#). We also recommend using the [OpalKelly XEM8320](#) for your custom design.

The QSFP+ port on the *Time Tagger X* should be used with a fiber transceiver to connect to your own FPGA. We also recommend using the [OpalKelly XEM8320](#) together with the [SZG-QSFP](#) for your custom design.

### Note

We recommend using the SFP+ port unless the higher bandwidth is necessary.

### Warning

There is currently no retransmission support so if corruption occurs during transmission, tags will be permanently lost. Please verify that your data link is of high quality or that tag loss can be tolerated.

### 6.6.1 Getting Started with SFP+

To enable the FPGA link output of the Time Tagger use `enableFpgaLink()`. Start by enabling the FPGA link on channel 1:

```
from Swabian import TimeTagger
tagger = TimeTagger.createTimeTagger()
tagger.enableFpgaLink([1], "", TimeTagger.FpgaLinkInterface.SFPP_10GE)
```

To receive the tags, use our [Time Tagger FPGA link reference design](#). Follow the instructions in the [XEM8320 README](#) to build the reference design. Connect the SFP+ port on the *Time Tagger X* to the SFP 1 port on the

XEM8320 and load the bitstream on the XEM8320. You should now be able to observe the LED D1 on the XEM8320 matching the input state on channel 1 of the *Time Tagger X*.

To verify the link quality, activate a test signal as follows:

```
tagger.setTestSignal([1], True)
```

and reload the bitstream on the XEM8320. LED D6 should stay dark, indicating that the channel 1 events are arriving at the expected time without drops.

## 6.6.2 Using QSFP+

QSFP+ is quite similar to using SFP+. Start by enabling the FPGA link for the QSFP+ interface for input channel 1 of the *Time Tagger X*:

```
from Swabian import TimeTagger
tagger = TimeTagger.createTimeTagger()
tagger.enableFpgaLink([1], "", TimeTagger.FpgaLinkInterface.QSFPP_40GE)
```

Similarly use our [Time Tagger FPGA link reference](#) design, but follow the instructions in the [README](#) for the QSFP+ interface.

Connect the QSFP+ port of the *Time Tagger X* with the SZG-QSFP module which has to be connected to Port E of the XEM8320. You should now be able to observe the LED D1 on the XEM8320 matching the input state on channel 1 of the *Time Tagger X*.

### Note

Using the reference design with QSFP+ requires the Xilinx *EF-DI-LAUI-SITE* IP core license. We recommend starting with the SFP+ connection.

### Warning

Only one output is active at the same time. Enabling the QSFP+ port disables the SFP+ port and vice-versa.

## 6.6.3 Modifying the reference design

Follow the instructions in [Building you own design](#).



## SYNCHRONIZER

### 7.1 Overview

The Swabian Instruments' Synchronizer allows for connecting up to 8 *Time Tagger Ultra* / *Time Tagger X* devices to expand the number of available channels. The Synchronizer generates a clock and synchronization signal to establish a common time-base on all connected Time Taggers. The Time Tagger software engine creates a layer of abstraction: the synchronized Time Taggers appear as one device with a combined number of input channels.

### 7.2 Key applications

The Synchronizer offers numerous advantages beyond its capability to extend the number of input channels up to 160, when connected to 8 Time Taggers, without introducing any additional time jitter.

#### 7.2.1 Crosstalk elimination

Employing synchronized Time Taggers provides the benefit of effectively suppressing analog crosstalk in comparison to measurements involving a single device unit. In experiments such as interferometry, for instance, the crosstalk pickup in correlation measurements hinders the identification of the physical signal from the electronic noise around zero. A commonly adopted solution consists on delaying signals with respect to each other by using cables of different lengths. Nevertheless, this approach might introduce additional complexities, e.g. the length difference fluctuates over time due to temperature variations. In this regard, the Synchronizer represents a more robust solution.

#### 7.2.2 High transfer rate

The data transfer rate from a single Time Tagger to the PC is limited to 90 MTags/s by the single-core CPU performance. Utilizing more than one Time Tagger allows to use multiple USB controllers and CPU threads, significantly increasing the total transfer rate (up to 90 MTags/s per device), as far as the Time Tagger and PC processing capabilities are not overcome.

#### 7.2.3 Multi-room experiment

In some experiments, Time Taggers need to be placed far apart. The cable length between the Synchronizer and the Time Tagger can be as long as 50 m, without any additional time jitter caused. Different Sync cables result only in a constant time offset between the signals.

#### 7.2.4 Synchronizer with a single Time Tagger

You can benefit from the Synchronizer with a single Time Tagger at least in the following two application scenarios:

1. **Long term clock stability**

The Synchronizer contains a highly stable clock oscillator which you can benefit from even when you have only one Time Tagger. Just connect any clock output of the Synchronizer to the *CLK IN* input of the Time Tagger and enjoy the clock stability provided by the Synchronizer, which matters especially measuring long time differences.

## 2. Absolute clock timestamps

By connecting all signals from the Synchronizer as shown in [Cable connections](#) the timestamps in the Time Tag stream will be referenced to the power-up time of the Synchronizer. Even when you disconnect the Time Tagger from your PC, e.g., in case of power down, USB timeout, or software restart, the time tags returned by the Time Tagger will remain referenced to the start time of the Synchronizer. To verify that this configuration is active, you will see a warning message in the console on `createTimeTagger()` that you are using the Synchronizer with only one Time Tagger.

## 7.3 Requirements

Successful synchronization of your Time Taggers requires:

- You have obtained the Synchronizer hardware.
- Your *Time Tagger Ultra* has hardware version 1.2 or higher. In case you have an older device and want to synchronize it with more units, please contact our support or sales team [www.swabianinstruments.com/contact](http://www.swabianinstruments.com/contact).
- Your PC has a sufficient number of USB3 ports for direct connection of every Time Tagger. The Synchronizer itself does not require a USB connection.
- You have a sufficient number of SMA cables of the same length. You need three cables for each Time Tagger. For more details, see in the section [Cable connections](#).
- You have installed the Time Tagger software version 2.6.6 or newer.

## 7.4 Cable connections

The Synchronizer provides a common clock signal for every Time Tagger as well as the synchronization signals. Furthermore, Time Taggers have to be connected to each other in a loop. The connection sequence in the loop defines the channel numbering order. An additional feedback signal is required to identify which of the Time Taggers in the loop is the first.

Using a single Time Tagger with Synchronizer is also possible and you shall connect *LOOP IN* and *LOOP OUT* together on the same device.

### Note

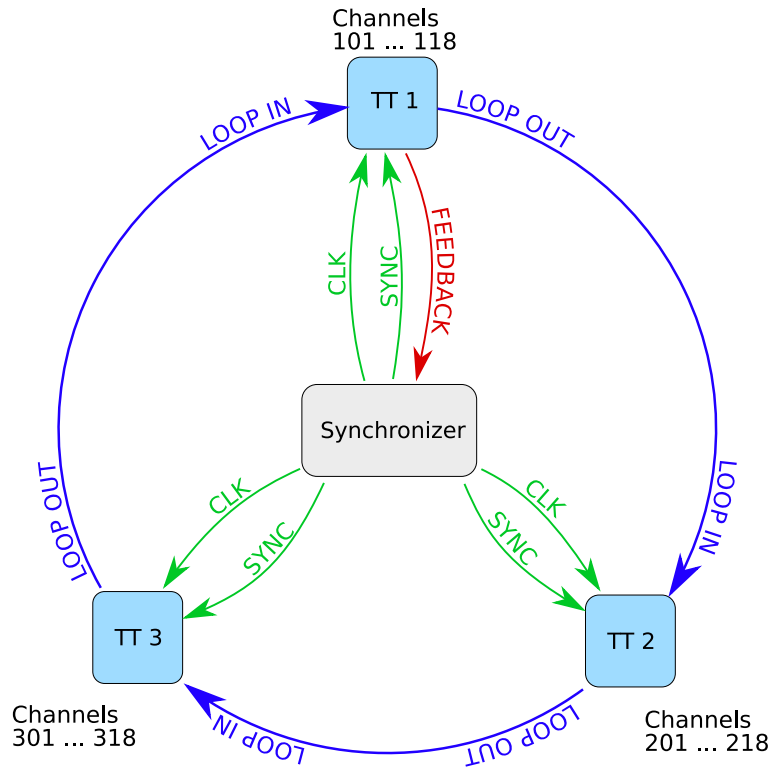
After the release of the Synchronizer, we have changed the connector labels on the front panel of *Time Tagger Ultra*. In this section, we use the new labeling scheme, while showing the corresponding old labels in brackets: *NEW\_LABEL (OLD\_LABEL)*.

Table 1: Connections between the Synchronizer and Time Taggers

| Synchronizer        | Time Tagger                 | Description                   |
|---------------------|-----------------------------|-------------------------------|
| <i>CLK OUT</i> <N>  | <i>CLK IN (CLK)</i>         | 500 MHz clock                 |
| <i>SYNC OUT</i> <N> | <i>SYNC IN (AUX IN 1)</i>   | Synchronization data          |
| <i>FDBK IN</i>      | <i>FDBK OUT (AUX OUT 2)</i> | Feedback from one Time Tagger |

Every Time Tagger should have its *LOOP OUT (AUX OUT 1)* connected to the *LOOP IN (AUX IN 2)* of next Time

Tagger, eventually forming a signal loop. The following diagram visualizes the connections required for the synchronization of three Time Taggers.



#### Warning

For reliable synchronization, the cables for *CLK* and *SYNC* signals shall have a length difference below 4 cm. We recommend using the same cable type for these two signals.

Additionally, we recommend connecting every Time Tagger directly to a USB3 port on the same computer. If your computer does not have a sufficient number of USB3 ports, avoid using USB hubs as they limit the data bandwidth available for every Time Tagger. Instead, please install an additional USB controller card into your computer. While there is a wide variety of USB3 controllers, you have to look for one that can deliver full USB3 bandwidth at every USB port simultaneously. Typically, such USB controllers have an individual chip for each USB port and require a PCIe x4 slot on the computer's motherboard.

### 7.4.1 Using an external reference clock

The Synchronizer has a built-in high accuracy and low noise reference oscillator and distributes the clock signals to all attached Time Taggers. In case you want to use your external reference clock, you have to connect it to the *REF IN* connector of the Synchronizer. Additionally, the Synchronizer can supply 10 MHz reference signal through its *REF OUT* output. Note that *REF OUT* is disabled when an external reference signal is present at the *REF IN*.

Table 2: Requirements to the reference signal at *REF IN*.

| Parameter | Value           |
|-----------|-----------------|
| Coupling  | AC              |
| Amplitude | 0.3 ... 5.0 Vpp |
| Frequency | 10 MHz          |
| Impedance | 50 Ohm          |

Table 3: Signal parameters at *REF OUT*.

| Parameter | Value                    |
|-----------|--------------------------|
| Coupling  | AC                       |
| Amplitude | 3.3 Vpp (1 Vpp @ 50 Ohm) |
| Frequency | 10 MHz                   |

## 7.5 Software and channel numbering

The Time Tagger software engine automatically recognizes if a Time Tagger belongs to a synchronized group. It will also automatically open a connection to all other Time Taggers in the group and present all devices as a single Time Tagger. There is no specific “master” device, and the connection to the synchronized group can be initiated from any of the member Time Taggers.

The connection is opened as usual using `createTimeTagger()`, and optionally you can specify the serial number of the Time Tagger.

```
tagger = createTimeTagger()
```

The *tagger* object provides a common interface for the whole synchronization loop, and all programming is done in the same way as for a single Time Tagger. Note that, compared to a single Time Tagger, the channel numbering scheme is modified for easy identification by a user. The channel number consists of the Time Tagger number in the loop and the input number on the front panel. The channel number formula is

```
CHANNEL_NUMBER = TT_NUMBER*100 + INPUT_NUMBER
```

As an example, let us assume we have three *Time Tagger Ultra 18* in a synchronization loop. The Time Tagger that provides the feedback signal to the Synchronizer has sequence number 1, and its channel numbers will be from 101 to 118. The channels of the next Time Tagger will have numbers from 201 to 218, and so forth.

You can request the complete list of available channels with the `getChannelList()` method.

```
from Swabian.TimeTagger import createTimeTagger, TT_CHANNEL_RISING_EDGES

# Connect to any of the synchronized Time Taggers
tagger = createTimeTagger()

# Request a list of all positive edge channels
chan_list = tagger.getChannelList(TT_CHANNEL_RISING_EDGES)
print(chan_list)
>> [101, 102, ... , 317, 318]
```

### 7.5.1 Incomplete cable connections

The software engine attempts to detect incorrect or incomplete connections of the cables in the synchronization loop. In case some connections are missing or were disconnected during operation, the software engine will show a warning and the data transmission from the disconnected Time Tagger will be filtered out until a valid connection is restored. Issues with the cable connections and synchronization status are indicated using the status LEDs on the front panel of the Synchronizer and the Time Tagger. See more in section [Status LEDs and troubleshooting](#).

### 7.5.2 Buffer overflows

The synchronization loop also propagates the buffer overflow state from any Time Tagger to all members of the loop. On the software side, the buffer overflow has the same effect as for a single Time Tagger. See, [Overflows](#).

## 7.6 Limitations

### 7.6.1 Conditional filter

The conditional filter cannot be applied across synchronized devices. However, it can still be enabled for each Time Tagger independently.

In case you want to use the conditional filter across devices, you have to send the signal to be filtered (for example, your laser sync) to every Time Tagger where trigger signals are connected. In software, you have to choose the corresponding input for time difference measurements.

### 7.6.2 Internal test signal

The internal test-signal generator is a free-running oscillator independent from the system clock. Therefore, the test signals are not correlated between different Time Taggers, even if the synchronization loop is set up correctly. If you try to measure a correlation with the internal test signal across two different Time Taggers, you will see a flat histogram. On the other hand, performing the same measurement with two input channels of the same Time Tagger will result in a jitter-limited correlation peak.

**Note**

If you are synchronizing *Time Tagger Ultra* and *Time Tagger X* devices together, the internal test signal frequency of some of them may be different than expected. The reason for this is that a single `testSignalDivider` is applied to the synchronized group, and the internal oscillators of the *Time Tagger Ultra* and *Time Tagger X* run at different frequencies, see: `setTestSignalDivider()`. Apart from the test signal frequency change, the functionality of the Time Taggers is not affected.

## 7.7 Status LEDs and troubleshooting

The front panel of the Synchronizer has several LEDs that indicate operation status.

| LED     | Color       | Description                                             |
|---------|-------------|---------------------------------------------------------|
| Power   | dark        | No power provided                                       |
| –       | solid green | Powered on                                              |
| Status  | dark        | Warming up                                              |
| –       | solid green | Normal operation.                                       |
| FDBK IN | solid green | Normal operation                                        |
| –       | solid red   | Invalid feedback signal                                 |
| REF IN  | dark        | No external reference signal                            |
| –       | solid green | Valid 10 MHz reference signal                           |
| –       | solid red   | Invalid reference signal                                |
| REF OUT | dark        | Output is disabled when using external reference signal |
| –       | solid green | Output enabled                                          |

The LEDs of the *Time Tagger Ultra* also indicate the state of the synchronization loop. See more details in section [LEDs](#).

## SAFETY & COMPLIANCE

### 8.1 Safety and Compliance Guidelines

This section provides essential safety information, operating conditions, and compliance guidelines for the proper use and handling of all Swabian Instruments *Time Tagger* devices. Please review this section carefully before installation, operation, or maintenance of the device.

#### 8.1.1 Symbols

|                                                                                     |                          |
|-------------------------------------------------------------------------------------|--------------------------|
|    | Caution: general warning |
|   | Caution: high voltage    |
|  | Functional earth         |

#### 8.1.2 Operation environment

The *Time Tagger* is designed for operation in a clean and dry indoor laboratory environment by qualified personnel. The product or its external components shall not be exposed to corrosive and/or flammable substances, liquids, or extreme heat. Do not operate with high dust and humidity levels.

Table 1: Operation environment conditions

| Parameter         | Value                   |
|-------------------|-------------------------|
| Temperature       | +5 °C to +45 °C         |
| Relative humidity | < 80 %, no condensation |
| Maximum altitude  | 2000 meters             |
| Protection level  | IP 20 (IEC 60529)       |

#### 8.1.3 Electrostatic-sensitive device

The *Time Tagger* is a sensitive electronic device and must be handled with care. The input and output circuitry of the *Time Tagger* may be damaged by an electrostatic discharge, or their functionality may be impaired. Take appropriate precautions to minimize the risk of an electrostatic discharge into the connections or signal wiring during the installation and operation of the *Time Tagger*.

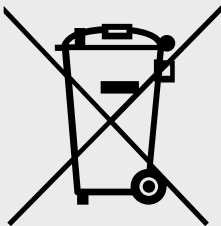


The *Time Tagger* is sensitive to electrostatic discharge! Take appropriate protective measures when performing system installation or maintenance.

## Cleaning

Before cleaning the *Time Tagger*, please make sure that it has been switched off and disconnected from all electrical connections. Clean the outer housing with a soft, lint-free dust cloth. No parts of the *Time Tagger* may be cleaned with chemical cleaning agents.

### 8.1.4 Disposal and recycling



Never dispose of the *Time Tagger* with the household waste. Please inform yourself about the local rules for the separate collection of electrical and electronic products.

### 8.1.5 Contact, support and service

Swabian Instruments GmbH can be reached directly via phone, email or per post.

Swabian Instruments GmbH  
Stammheimer Straße 41  
70435 Stuttgart  
Germany

+49 711 400 479-0  
[info@swabianinstruments.com](mailto:info@swabianinstruments.com)  
<https://www.swabianinstruments.com>

## 8.2 *Time Tagger X* Safety Notice

Swabian Instruments' *Time Tagger X* is a high-resolution streaming time-to-digital converter in a 19-inch rack mountable housing. This section gives further information on the *Time Tagger X* and its operation.



## 8.2.1 Electrical characteristics

Table 2: Power supply ratings

| Parameter       | Value                         |
|-----------------|-------------------------------|
| Nominal voltage | 100 - 240 V AC ( $\pm 10\%$ ) |
| Frequency       | 47-63 Hz                      |
| Power           | max. 60 W                     |

The maximum voltage and current ratings of the signal inputs and outputs are specified on the *Time Tagger X*'s housing and must not be exceeded. The details on the characteristics of the input channels can be found in the dedicated section *Input channels*.

## 8.2.2 Equipment installation

The *Time Tagger X* does not require assembly and is supplied fully assembled. It can be installed as a table top instrument or in a standardized 19-inch rack. Any operating position shall provide adequate space for cable connections and air circulation.

A table top installation requires an even and horizontal surface with enough space for easy access to the device.

Installation in a standardized 19-inch rack requires 2 height units. The rack shall provide sufficient ventilation and must not obstruct the ventilation openings of the *Time Tagger X*'s rear panel.

Position the *Time Tagger X* in a manner that allows the user to disconnect the device from the mains at any time and without restrictions.

Before connecting to the mains, inspect the product and the power cord for visible damage. Connection to the mains shall be done only with the supplied detachable power cord. In case of doubt, do not operate the product and seek assistance from a qualified electrician or a person responsible for electrical safety.



### Safe operation can no longer be assumed:

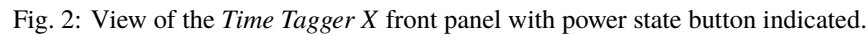
- after rough handling during transport or installation,
- in case of visible damage to the product or its power cord,
- in case of loose internal parts being noticed,
- in case of ingress of any liquids inside the product's housing.

The *Time Tagger X* provides one functional ground terminal on the rear panel located next to the power cord receptacle. All connectors that feature ground terminals are electrically connected to the *Time Tagger X* housing and to the functional ground terminal. This includes shield terminals on the SMA connectors and the USB-C connector.

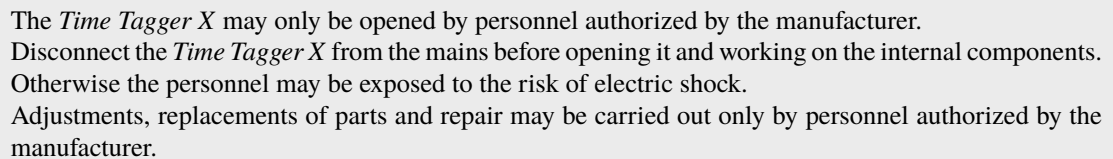
Take care of appropriate grounding practices and ensure that all connected accessory and equipment shares common ground with the *Time Tagger X*. Connection of additional accessories or equipment that are grounded to an independent grounding circuit has the potential risk of electrical shock. An inappropriately grounded *Time Tagger X* and/or connected equipment may result in product damage, malfunction, degraded performance or poor signal quality.

After connecting the *Time Tagger X* to the mains, it will be in a "Standby" power mode, as indicated by the power button light pulsating blue. Press the power button to switch the product into the "Ready" state - the power button light will turn green. By pressing the power button again, the *Time Tagger X* can be switched back into the "Standby" power mode.

The *Time Tagger X* produces waste heat during regular operation. Long-term continuous operation at elevated environment temperatures may lead to a warm product surface, this is not a malfunction. Stop operation immediately and contact the manufacturer in case the product's surface temperature exceeds 55 °C (hot on brief touch).



The *Time Tagger X* does not contain any user-serviceable or user-repairable parts. In case of malfunction or damage, stop operating the *Time Tagger X*, disconnect it from the mains and contact the manufacturer.



## Power cord

It is strictly forbidden to use a damaged power cord or a cord with inadequate ratings. In case of doubt, do not operate the product and contact the manufacturer or seek for assistance from a trained electrician or a person responsible for electrical safety.

## Safety fuse

The *Time Tagger X* is equipped with a mains fuse located on the rear panel beneath the power cord receptacle. The fuse compartment can only be accessed when the power cord is detached from the *Time Tagger X*. The fuse type and fuse rating must comply with the specification in the table [Safety fuse ratings](#) and the labeling on the *Time Tagger X*.

Table 3: Safety fuse ratings

| Parameter      | Value     |
|----------------|-----------|
| Voltage Rating | 250 V AC  |
| Current Rating | 500 mA    |
| Dimensions     | 5 x 20 mm |
| Response Time  | Slow Blow |



## REVISION HISTORY

### 9.1 V2.22.6 - 08.09.2026

#### Bug Fixes

- Fixes a bug where *HistogramLogBins* in *Time Tagger Lab* passed the selected Start Channel and Click Channel to the backend in reverse.

### 9.2 V2.22.4 - 27.07.2026

#### Bug Fixes

- Fixes a bug in *fetchDeviceLicenseUpdate()* which affected the Python example script *hardware\_license\_update.py*.

### 9.3 V2.22.2 - 09.07.2026

#### Improvements

- Adds a dialog to the network client in *Time Tagger Lab* to prevent server-side channel settings from being overwritten automatically.

#### Bug Fixes

- Fixes a possible network client crash in *Time Tagger Lab* when using the multiple-server time tag stream merger.
- Adds several minor UI fixes.

### 9.4 V2.22.0 - 26.06.2026

#### Highlights

- Adds support for streaming time tags at up to 300 MTags/s over 10 Gigabit Ethernet via the SFP+ port of the *Time Tagger X*.
- Adds the option to plot multiple measurements of the same type together on one chart in *Time Tagger Lab*.
- Adds a switch to automatically save measurement data to file for selected measurements in *Time Tagger Lab*.

## Features and improvements

- Adds a secondary (temporary) hardware license slot, with updated Python example *hardware\_license\_update.py* and support in *Time Tagger Lab*.
- Adds the ability to upgrade hardware licenses for devices connected to a Synchronizer.
- Adds the virtual channel *GatedChannels* as a generalized multi-channel version of *GatedChannel*.
- Adds the measurement *GatedCounter* as a generalized multi-channel version of *CountBetweenMarkers*.
- Improves performance of the software delay and data processing pipelines for *Time Tagger Ultra* and *Time Tagger X*.
- Improves default measurement parameters for *FrequencyCounter*, *FrequencyStability*, *HistogramLogBins* and *TimeDifferences* in *Time Tagger Lab*.
- Adds support for setting a custom Time Tagger application data directory via the `TIMETAGGER_CONFIG_DIR` environment variable.
- Many improvements and fixes in the documentation and programming examples.
- Improves the file structure in the distributed packages for Ubuntu, Debian and AlmaLinux.

## Bug Fixes

- Fixes instabilities in *TimeTaggerNetwork*, especially when connecting multiple clients to a server and transferring high data rates.
- Fixes possible error in *CounterData::getDataTotalCounts()* for very small binwidths and improves *Counter* restarting behavior after an Error event.
- Fixes several memory leaks and reduces overall memory usage in *Time Tagger Lab*.
- Fixes a deadlock when *startFor()* is called with a very high repetition rate.
- Fixes a bug where *getConditionalFilterFiltered()* returned unfiltered rather than filtered channels in *TimeTaggerVirtual*.
- Fixes a bug where *setConditionalFilter()* accepted an empty trigger list and silently dropped all filtered events *TimeTaggerVirtual*.
- Fixes a bug in *FrequencyCounter*, where the first bin was one ps too long and was not returned when running for exactly one *fitting\_window* of time.
- Fixes crashes when using `binwidth = 0` for *Correlation*, *CorrelationPairs*, *Flim*, *StartStop*, *TimeDifferences* and *TimeDifferencesND*.
- Fixes incorrect output of *FrequencyStabilityData::getSTDD()*.
- Fixes incorrect output channels of *DelayedChannels* when duplicate input channels are used.
- Fixes a crash after finishing capturing data in *CountBetweenMarkers* when in overflow mode.
- Fixes retriggering *Scope* when in overflow mode.
- Fixes incorrect counts in *getRollovers()* and *setMaxRollovers()* in *TimeDifferencesND*.
- Fixes multiple rare instabilities in *PulsePerSecondMonitor*, especially when in overflow mode.

## Support and compatibility

- Adds Python libraries for Windows to PyPI.
- Adds support for Ubuntu Long Term Support release 26.04.
- Adds Arm64 libraries to the Windows installer.
- Moves *PulsePerSecondMonitor* out of the *Experimental* namespace. Deprecated aliases for this measurement remain, except for C# and LabVIEW bindings for which this is a breaking change.
- This release changes how settings are stored in *Time Tagger Lab*: workspaces saved with version  $\geq 2.22.0$  may not fully work when opened with older software versions.
- Removes the deprecated *channel numbering scheme* which existed for backward compatibility with devices with channel numbers starting at 0.

## 9.5 V2.21.2 - 26.03.2026

### Improvements

- Reverts the default *TestSignalSource* to *Digital* for the *Time Tagger X* to maintain backwards compatibility.

### Bug Fixes

- Fixes the Python example *hardware\_license\_update.py*.
- Fixes a bug that may prevent starting a measurement in *Time Tagger Lab* when multiple measurements depend on the same processor.
- Fixes a bug that prevented loading a workspace with floating measurement windows in *Time Tagger Lab*.
- Includes various other UI fixes and stability improvements in *Time Tagger Lab*.
- Fixes a bug in the Linux Python libraries distributed through PyPI that caused a crash of the server created by *TimeTagger::startServer()* upon connection attempts.
- Fixes a bug in the Linux Python libraries distributed through PyPI that checked wrong paths for SSL CA files on some systems, which caused the license download to fail.

## 9.6 V2.21.0 - 19.02.2026

### Highlights

- Support for the *StartStop* measurement class in *Time Tagger Lab*.

### Improvements

- Adds *TestSignalSource*, *setTestSignalSource()*, and *getTestSignalSource()* to define, set, and retrieve the source of the Time Tagger on-device test signal (available only for *Time Tagger X* hardware revision  $\geq v1.3$ ).
- Adds *capture\_duration* to *HistogramLogBinsData*.
- Increases the delay hardware range for the *Time Tagger X* to  $\pm 2500000$  ( $\pm 2.5 \mu\text{s}$ )
- Adds *fetchDeviceLicenseUpdate()* and python example *hardware\_license\_update.py*.
- Adds performance improvements in *Time Tagger Lab*.
- Many improvements and fixes in the documentation and programming examples.

## Bug Fixes

- Fixes a rare bug causing a 2 ns offset between Time Taggers when using the Synchronizer.
- Fixes a bug in *SynchronizedMeasurements* where some data are missing at the start of the measurement if the channels were not previously registered.
- Fixes a possible client-side crash in *Time Tagger Lab* when the Time Tagger Network server disconnects.
- Fixes the allowed reference frequency for reference clock by taking into account the event divider in *Time Tagger Lab*.
- Fixes the trigger level control within the channel configurator of a measurement or processor in *Time Tagger Lab*.
- Reverts status LEDs to being on by default for *Time Tagger Ultra* and *Time Tagger X* in *Time Tagger Lab*.

## Support and compatibility

- Adds support for *Time Tagger Ultra* with hardware revision 2.0.
- Adds support for *Time Tagger X* with hardware revision 1.4.
- Adds support Debian Trixie for amd64 and ARM.
- Adds support for AlmaLinux 10.
- Drops the deprecated WebApp user interface.

## 9.7 V2.20.2 - 17.12.2025

### Bug Fixes

- Fixes an error when saving a *Time Tagger Lab* workspace in a OneDrive synchronized folder.

### Improvements

- Adds Python libraries for Arm64 Linux to PyPI.
- Adds a description to the Python libraries distributed through PyPI.

## 9.8 V2.20.0 - 11.12.2025

### Highlights

- Introduces *TimeTaggerNetwork* functionality in *Time Tagger Lab*.
- Support for *Virtual Channels Combinations* and *Combiner* in *Time Tagger Lab*.
- Support for the *PhaseNoise* measurement class in *Time Tagger Lab*.
- New measurement classes *CorrelationPairs* and *HistogramCustomBins*.
- New tutorial on *Fluorescence Correlation Spectroscopy (FCS)* in the documentation.

### Improvements

- Adds methods *setMaxRollovers()*, *getRollovers()*, and *getHistogramIndex()* to the measurement class *TimeDifferencesND*.
- Adds method *getChannelByMask()* to the virtual channel class *Combinations*.
- Many improvements and fixes in the documentation and programming examples.



### Bug Fixes

- Tag streaming over network or USB is now halted for unused channels after `stop()` is called.

### Support and compatibility

- Python libraries for Linux are now distributed through PyPI under the name `Swabian-TimeTagger` and can be installed with `pip`.
- The Python namespace is changed to `Swabian.TimeTagger`. The `TimeTagger` namespace is deprecated but continues to be supported.
- This software version will be the last to include the deprecated WebApp user interface.

## 9.9 V2.19.0 - 29.07.2025

### Highlights

- New measurement class `PhaseNoise` provides a phase noise estimator for periodic signals.

### Improvements

- Adds performance improvements for `FrequencyStability`, especially for CPUs supporting AVX512 instructions.
- Improves and expands the *FLIM tutorial* in the documentation.
- New method `TimeTagger::getConnectedClients()` to list the clients connected to a Time Tagger Network server.

### Bug fixes

- Fixes performance limitations that led to USB3 transfer rates below 90 MTags/s in Linux builds.
- Fixes the broken `CoincidencesFactory` constructor in LabVIEW.
- Fixes incorrect channel numbering in Time Tagger Network clients for the specific case of multiple servers streaming at low data rates.
- Fixes a rare crash when copying log messages to the clipboard in *Time Tagger Lab*.

### Support and compatibility

- This release breaks backward compatibility for Time Tagger Network. This means that clients connecting to servers with version  $\geq 2.19.0$  must also be of version  $\geq 2.19.0$ .
- Drops support for Ubuntu 20.04.

## 9.10 V2.18.2 - 07.05.2025

### Bug fixes

- Fixes a crash when aborting a `HistogramLogBins` measurement.
- Fixes a memory leak when starting a Time Tagger Network server in *Time Tagger Lab*.
- Fixes a crash when resetting a *Time Tagger Lab* workspace saved in a OneDrive synchronized folder.
- Fixes a channel mapping bug in Time Tagger Network when transferring low data rates in a multi-server configuration.

## 9.11 V2.18.0 - 23.04.2025

### Highlights

- Support for *Virtual Channels Coincidences*, *GatedChannel* and *DelayedChannel* in *Time Tagger Lab*.
- Multi-server time tag stream merger with *TimeTaggerNetwork*.
- 20 channel support for the *Time Tagger X*.

### Time Tagger

- Introduces ReferenceClock as an improvement over SoftwareClock to allow for synchronization with 1PPS signals and reconstruction of the original frequency.
- Adds a Raspberry Pi installer for TimeTagger software.
- Documentation: unifies the online user manual and the C++ API user manual into a single document.
- Documentation is now built into our Python and C# wrappers (via pydoc and XML).
- New tutorials for *Time Tagger Lab* and *Remote synchronization*.

### Time Tagger Lab

- Introduces manually adjustable plot limits.
- Adds option to switch between *Counter* and *FrequencyCounter* as the auxiliary graph.
- Fixes unreliable behavior when using multiple monitors with different screen scaling settings.
- Visual improvements when using Synchronized devices.
- Includes several smaller UI and stability improvements.

### Support and compatibility

- Removes installer for 32 bit Windows.
- Drops support for Ubuntu 18.04 and replaces CentOS 8 with AlmaLinux 8.
- Adds support Debian Bookworm (amd64 and arm64) and for AlmaLinux 9.
- Adds support for C# on Linux (not on Ubuntu 20.04 and Raspberry Pi).
- Adds support for Numpy 2.0 on all Linux distributions but Ubuntu 20.04 and AlmaLinux 8.
- This release breaks backward and forward compatibility for Time Tagger Network. This means that clients connecting to servers with version = 2.18.x must also be of version = 2.18.x.

### Improvements

- Adds the method *setServerAddress()* for binding to a single network interface.
- Adds the method *getServer()* providing a proxy object with the *TimeTaggerHardware* interface to control the Time Tagger device connected to the server.
- Adds the method *Combinations::getChannels()* to query many virtual channels at once.
- Adds the methods *getTriggerLevelRange()*, *getDeadtimeRange()* and *getDelayHardwareRange()* to query hardware limitations.
- Adds the enum *AccessMode::SynchronousListen* to Time Tagger Network for delivering data synchronously to clients while restricting control settings and exposing only a limited set of channels.

- Improves the performance of *FileWriter* and *HistogramLogBins*.
- Fixes a slowdown of *FrequencyStability* on Windows with small values for the *average* parameter.
- Fixes the instantiation of *FrequencyStability* in LabView.
- Fixes input registration and unregistration by measurements if some requested channel numbers are not available.
- Fixes the behavior of *Countrate* with Error events.
- Fixes the generation of MissedEvents in Listen mode on overload conditions for TimeTaggerNetwork.

### API changes

- New API for the Time Tagger Virtual: Specify the files in *createTimeTaggerVirtual()* and call *run()* after creating all measurements.
- Split *TimeTagger* in the two interfaces *TimeTaggerSource* for controlling the on-device timestamp manipulation modules and *TimeTaggerHardware* for controlling the physical parameters of a Time Tagger device.
- Support for *setTestSignal* and *getTestSignal* has been removed from *SynchronizedMeasurements* and deprecated in *TimeTaggerVirtual*.
- *freeTimeTagger()* no longer supports a Boolean return value in all programming interfaces (except C# and Labview, for backward compatibility reasons). This value was used to test whether a TimeTagger in singleton mode had been properly freed, however singleton mode has been deprecated since v2.7.2.
- C#: Throws *ArgumentOutOfRangeException* instead of *ApplicationException* on unsupported function arguments.
- Deprecates *getDACRange()* and *setSoftwareClock()*.
- Renames *waitForCompletion()* to *waitUntilFinished()* to match the method name of measurements.
- Splits the former single C++ measurements header in one file per measurement.

## 9.12 V2.17.6 - 21.01.2025

### Highlight

- The maximum default *block size* is increased to 1 million events on the *Time Tagger Ultra* and *Time Tagger X*. With the default settings, the respective maximum transfer rates exceed 90 MTags/s.

## 9.13 V2.17.4 - 17.07.2024

### Improvement

- Python: adds support for NumPy 2.0.0 (for Python versions on Linux that support NumPy 2.0.0, rebuilding the Python wrapper may be necessary. See our [documentation](#) for more details).

## 9.14 V2.17.2 - 02.07.2024

### Improvement

- Adds support for Ubuntu Long Term Support release 24.04.
- Adds *abort()* for a non-blocking hint to abort measurements quickly.
- Adds a tutorial for ODMR measurements.

### Time Tagger bug fixes

- Fixes wrong initial UTC time stamp in *PulsePerSecondMonitor* and improved formatting in its data export file.
- Fixes *HistogramND* for  $N > 4$ .
- Fixes a bug with missing time tags when multiple small saved files are merged and replayed.

### Time Tagger Lab bug fixes

- Fixes a crash when switching between *FileWriter* and other measurements.
- Adds missing data export option for *PulsePerSecondMonitor* and *FrequencyCounter*.
- Fixes visualization of available HighRes channels for *Time Tagger X* on the landing page.
- Fixes a bug when stopping and restarting the Logarithmic Histogram DLS simulation.
- Fixes a crash in the application's window docking manager.
- Includes several smaller UI and stability improvements.

## 9.15 V2.17.0 - 22.04.2024

### Highlights

- With the new *FrequencyCounter* measurement, the Time Tagger becomes a full feature Omega-type frequency counter.
- The new *PulsePerSecondMonitor* measurement allows to monitor the synchronicity of different PPS sources.
- The support of variable integration time per bin in *HistogramLogBins* provides the accurate g2 normalization with immediate start and gated inputs.
- Improve the performance of the Synchronizer to reach the full 80 MTags/s per device.

### Improvement

- New virtual channel *Combinations* for exclusive coincidences.
- Adds support for the Python Stable ABI to support Python 3.12 and likely many more further releases.
- Adds support for the MinGW C++ ABI for the *MINGW32* and *UCRT64* environment.

### Time Tagger Ultra and Time Tagger X

- Significantly reduced on-device latency noticeable both over USB and FPGA link.
- Support for *high priority input channels*, which will still be transmitted while in overflow domain.
- The timestamps of rising and falling events can be *averaged on hardware* for a higher precision of events.
- Enhanced version of the *deadtime filter*, which can be configured with any dead time in picosecond precision.

### Time Tagger X

- Full support for the *High-Resolution* mode on the *Time Tagger X* with a timing jitter of 1.5 ps RMS per channel.
- Support for the QSFP+ *FPGA link* with a data rate of 1200 MTags/s.
- Support for the readout of more device sensors on the hardware.

- The self verification of the hardware input stage of the built-in test signal is reverted on the *Time Tagger X*.
- All input ports stay at the *high-impedance* mode before their first usage and after *freeTimeTagger()*.
- Changes the default *hysteresis* from 1 mV to 20 mV.

### Time Tagger Ultra

- Adds support for *Time Tagger Ultra* with hardware revision 1.8.
- The improved auto-calibration for periodic signals and its error handling is backported from the *Time Tagger X* to the *Time Tagger Ultra*.
- Improves the USB performance for many aligned inputs.

### Time Tagger Lab features and enhancements

- Improved and more informative landing page layout.
- Existing measurements can now be cloned easily (by right clicking).
- The live countrate is now visible in the detailed device view.
- Application window positions and the measurement list order are now saved to workspace.
- A notification appears when the measurement dead time is automatically adjusted to a multiple of the Time Tagger clock.
- New startup command line options –select-device and –start-measurement.
- Maximum file size for the *FileWriter* measurement is now shown in megabytes.
- “Force high impedance” option for *Time Tagger X* start-up without impedance switch.
- Many smaller UI improvements and fixes.

### Time Tagger Lab bug fixes

- Fixed various crashes related to device license checks, sending feedback and exporting large data sets to file.
- Fixed occasional misaligned axis ticks and missing axis ticks when zooming in.
- Fixed limited application visibility for high screen scaling settings.
- Fixed occasionally missing chart cursor values.
- Changed logarithmic axis labels from E<sup>^</sup> to 10<sup>^</sup>.

## 9.16 V2.16.2 - 28.06.2023

### Time Tagger hardware support

- Adds support for *Time Tagger 20* with hardware revision 2.5.
- Adds support for *Time Tagger X* with hardware revision 1.2.

### Time Tagger bug fix

- Fixes *Counter* showing wrong values when the same channel is used multiple times, now throwing an exception on creating.
- Fixes *FileReader* in MATLAB not loading the .NET Assembly in its constructor. All measurement classes now load the assembly.

## Time Tagger Lab

- Fixes non-visible numbers for cursor values.
- Moved legend of Counter time trace to the top left.
- Higher precision formatting values when necessary.

## 9.17 V2.16.0 - 05.06.2023

### Highlights

- *Time Tagger Lab*: Virtual Antibunching and Fluorescence lifetime setups.

### Time Tagger Lab features and enhancements

- Antibunching and Fluorescence lifetime setups and corresponding simulation measurements. The detector signals are fully simulated for those measurements and no physical detectors are needed.
- Option to suppress counts for  $dt=0$  with autocorrelation measurements.
- Notification that software updates are available.
- Improved crash and error reporting.
- Improved ticks and labels of logarithmic plots.

### Time Tagger Lab bug fixes

- Fixed various crashes related to exporting data, opening a message box, and creating log files.
- Fixed Histogram 2D export.
- Fixed auto-restarting with no-plot measurements on configuration change.
- Missing log-y labels and ticks are added to chart display.

### Improvement

- Adds support for Python 3.11.
- The built-in test signal verifies the hardware input stage on *Time Tagger X* starting from hardware revision 1.1.

### Bug fixes

- Fixes fan information of `getSensorData()` on the *Time Tagger Ultra*.
- Fixes the support for *Time Tagger Ultra* devices with the serials starting with *I7*.
- Fixes `GatedChannel`, `FrequencyMultiplier` and `TriggerOnCounterRate` to switch to the initial state on `clear()` and `startFor()`.
- Fixes `autoCalibration()` to clear the old calibration data.
- Fixes the error handling on Linux if parts of the Python wrapper are missing.
- Fixes a one bit out of bounds memory access on verifying the hardware license.
- Fixes the jagged array handling of the MATLAB Wrapper for `Coincidences`.

## 9.18 V2.15.0 - 06.03.2023

### Highlights

- Rework of the MATLAB wrapper, now reflecting the full functionality of the Time Tagger API.

### MATLAB wrapper

- Supports class inheritance, new TT classes are closer to their C++, and Python counterparts.
- Supports creation of TimeTagger objects via `createTimeTagger`.
- Supports native MATLAB enums.
- Supports jagged arrays via conversion from/into MATLAB cells.

### Behavior change

- Disallow an event divider value of 0. Please use 1 instead.
- MATLAB: Removed MATLAB app designer examples.

### Other Changes

- Updated Opal Kelly Frontpanel library to 5.2.12.

### Bug fixes

- Python: Fix return type annotation for `createTimeTagger()`.
- Fixes certain deadlock issues in MATLAB caused by asynchronous functions.
- Fixes the overflow tracking with a USB error while in overflow.
- Fixes handling of tags with respect to <-> missed events at the timestamp of an OverflowBegin error.
- Counter: Fixes a transpose issue of the NaN generation in `getDataNormalized()`.
- FrequencyStability: Fixes an integer overflow in the MDEV / TDEV calculation.
- Fixed issue with `LicenseRequestGenerator.exe` not working on some systems.

### Time Tagger Lab features and enhancements

- Device LEDs can be switched on and off (not *Time Tagger 20*).
- Improved setting of the reference software clock for signals with an event divider greater than 1.
- *Time Tagger 20* Edu is supported.

### Time Tagger Lab bug fixes

- Fix the crash when capturing high-resolution counter-time traces.
- Fix the crash when the USB connection to the device is unstable.
- Fix the crash when exporting large Scope measurement data.
- Fix the crash when exporting a plot to a PNG file.
- Fix the crash when measurements require too much memory on initialization.
- User interface issues with small screens are solved.

## 9.19 V2.14.0 - 23.12.2022

### Time Tagger X

- Adds support for *Time Tagger X* with hardware revision 1.1.
- Adds support for Synchronizer with *Time Tagger X* and also mixed setups with *Time Tagger Ultra*.
- Provides preliminary Ethernet support on the SFP+.
- Improves the auto-calibration for periodic signals.
- Better CPU performance for aligned tags.
- Improves the channel LED blinking for 1pps signals.
- Shows calibration errors on the channel LED in red.
- Fixes a random skew jump of 1333 ps per input channel on USB errors.
- Fixes the channel LED indication for falling events.

### Bug fix

- Fix Power LED turning off after calling `freeTimeTagger()` on the *Time Tagger Ultra*.

## 9.20 V2.13.2 - 22.11.2022

### Highlight

- Release of *Time Tagger Lab* - the native UI for Windows.

## 9.21 V2.12.4 - 09.11.2022

### Improvement

- Adds support for *Time Tagger Ultra* with hardware revision 1.7.

### Bug fix

- Fixed webapplication data export for *HistogramLogBins*.

## 9.22 V2.12.2 - 04.10.2022

### Bug fixes

- Fixes wrong `Tag::Type::Error` event generation and channel detection in `mergeStreamFiles()`.
- Fixes host license querying for *TimeTaggerNetwork* clients (broken in v2.12.0)
- Python: Fixes the decoding of the return values of `getDeviceLicense()` and `getSensorData()` of *TimeTaggerNetwork*.
- C++: Fixes `std::string` unmarshalling within the Network Time Tagger.



### Various improvements

- Adds method `getTraceFrequencyAbsolute()` to *FrequencyStability*.
- Adds method `getChannelList()` to *FileReader*.

## 9.23 V2.12.0 - 01.09.2022

### Highlights

- Add support for our new high precision measurement device, the *Time Tagger X*, with a typical timing resolution of 2.0 picoseconds.

### WebApp

- Change default access mode to `AccessMode::Control` for Time Tagger Network.

### Features

- Improve the performance of the Synchronizer. Two *Time Tagger Ultra* devices now can achieve a total data rate of over 100 Mtags per second.
- Add support for the new Ubuntu Long Term Support release 22.04 Jammy Jellyfish.

### Behavior change

- All provided strings to the C++ API must be encoded as UTF-8, returning strings are also UTF-8 encoded.
- Rename `getLicenseInfo()` to `getDeviceLicense()`. It returns a JSON formatted string for easier processing.
- Drop support for obsolete Python versions 2.7 and 3.5 and for the obsolete Linux distributions CentOS 7 and Ubuntu 16.04.

### Examples

- Jitter verification requests the specified jitter values directly from the Time Tagger backend.
- FLIM example is now available for MATLAB

### Various Fixes and Improvements

- Fix Unicode characters in all filenames of *FileWriter* and *FileReader*.
- Fix CoincidenceFactory for MATLAB and Labview.
- Fix the *Flim* measurement for MATLAB.
- Fix the crash on a failing license download within the initialization of the Network Time Tagger.
- Prefer a host-locked license over a user-locked license in the Virtual Time Tagger. This reduces the chance of a false-positive anti-virus warning.
- Improve the rounding behavior of `getTriggerLevel()`.
- Update of the USB driver for various fixes.

## 9.24 V2.11.0 - 22.04.2022

### Highlights

- Introduced `mergeStreamFiles()` to combine several *FileWriter* files into one.

## Time Tagger Network

- New Protocol version 3.1 with a new set of features. Backward compatible with 3.0.
- Improved messages for connection loss and disconnection. Additionally, messages for connecting to new and old versions of TTN will be presented.
- Fixed issue related to implicit call of `sync()` on measurement creation in `AccessMode::Listen` mode.
- Server and network information has been added to `getConfiguration()`.
- Fixed crashes when streaming over 250 channels.
- Various race conditions and possible freezes have been fixed.
- Faster initialization of measurements with many channels.
- Fixed error handling on disconnection.
- Reduced connection timeout to 10 seconds.
- Fixed an issue where channels used by a client remained registered after a disconnect.
- `setTimeTaggerNetworkStreamCompression()` can be utilized to double the maximum transfer rate in a very slow network environment ( $\leq 100$  Mbit/s).

## Time Tagger Virtual

- The `TimeTaggerVirtual` will now wait for a test signal channel to be registered before starting to stream it (behavior identical to a hardware Time Tagger).

## GatedChannel

- Optional constructor argument `initial` of type `GatedChannelInitial` to initialize the gate optionally in an open state.
- Changed behavior if `input_channel` equals `gate_start_channel` or `gate_stop_channel` to allow for operation similar to the `ConditionalFilter`.

## FrequencyStability

- Fixed `getTraceFrequency()`; now it returns the relative frequency error instead of the relative period error.
- Traces are no longer truncated to the length of the maximum steps.
- Corrected behavior if stopped and restarted without clearing.

## Other measurement classes

- `HistogramLogBins`: Removed bins which have a bin width of 0 ps.
- `SynchronizedMeasurements`: Methods calls on a `SynchronizedMeasurements` object without any registered measurements will no longer generate an exception but a warning.
- `TimeDifferences`: Added `getHistogramIndex()` to return the index of the histogram being processed currently.
- Exposed `Tag::Type` to be used with `TimeTagStream` and `CustomMeasurement`.

### Synchronizer

- Improved error messages.
- Fixed USB errors occurring under very high data rates.

### Examples

- Added Visual Basic .NET example

### Various Fixes

- Fixed crash on `createTimeTagger()` during a USB error.
- Fixed an issue where `startFor()` could run further than the specified time on `HistogramLogBins` and `FileWriter`.
- WebApp: Fixed argument handling on Linux.
- MATLAB: Supports now `Resolution` for HighRes.
- MATLAB: Verifies that the version of the installed backend matches the wrapper version.

## 9.25 V2.10.6 - 16.03.2022

### Improvements

- Adds support for *Time Tagger Ultra* with hardware revision 1.6b.

## 9.26 V2.10.4 - 23.02.2022

### WebApp

- Fixed Input Delay for negative values.
- Fixed adding new channels for `Countrate` measurement.
- Fixed `HistogramLogBins` for low start times (< 10ps).
- Fixed units for data export of `Counter`, `Correlation`, `Histogram2D`, and `HistogramLogBins` measurements.

## 9.27 V2.10.2 - 31.12.2021

### Improvements

- Added support for Python 3.10.

### Fixes for issues since v2.10.0

- Fixed `HistogramLogBins` in the Web Application.
- Fixed `DelayedChannel` for negative delays.
- Fixed an issue with `Counter::getDataTotalCounts()` not resetting to 0 on `clear()`.
- Fixed some MATLAB examples not being compatible with 2016b or older.

## 9.28 V2.10.0 - 22.12.2021

### Highlights

- Time Tagger Network: All Time Tagger devices and the acquired data can be accessed via the network from multiple clients or locally across the different programming languages. The clients can use all TimeTagger measurement classes and may optionally control the settings of the physical Time Tagger.
- A new frequency stability toolbox: It offers on-the-fly evaluation of periodic signals by calculating several analysis metrics, including, for example, the Allan deviation (ADEV) and time deviation (TDEV).
- Software Clock: The new recommended method for using an external clock on the *Time Tagger Ultra*. The time tag stream is rescaled on the software side with respect to the connected clock. It allows for a broad input frequency range and also calculates phase error estimators. In addition, the input jitter of the clock channel will be averaged out, resulting in a lower jitter for measurements including the clock channel directly.

### Features

- Counter: New `getDataObject()` returning data as an object of `CounterData` and allowing for continuous chunkwise data acquisition. This object contains the Counter data, timing information and overflow flags.
- New `HistogramND` measurement, which is a multidimensional generalization of the older `Histogram2D`.
- New `Sampler` measurement class for a triggered sampling of the current state of other channels.
- Measurement and virtual channel settings can now be requested with `getConfiguration()` method. The settings of all measurements are also available in the return value of `getConfiguration()` method.

### WebApp

- A *Time Tagger Network* server can be activated in the settings.
- Includes the *Software Clock* feature.
- Adds *Event Divider* settings.
- Shows specified RMS jitter for each channel in HighRes mode.
- It is now possible to specify the integration time in a single-shot or cyclic mode (internally uses `startFor()`) for all available measurement classes.

### Performance

- Improved performance of `Counter`, `Countrate`, `TimeTagStream`, `Combiner`, `DelayedChannel` for many channels.
- `HistogramLogBins` with an improved algorithm, multithreading, and AVX2+AVX512 tuning.
- `Coincidences` improved for high input rates with low coincidence rates.

### Behavior change

- `TimeTagStream` now always requires a list of channels.
- `CustomMeasurement` in Python: with `self.mutex` replaces `self.lock` and `self.unlock`.
- A Synchronizer with only one Time Tagger will use the timestamps of the Synchronizer but the channel identifiers of the single device itself.
- No messages on the INFO level will be shown in MATLAB to avoid running into deadlocks.
- `std::invalid_argument` exceptions are now wrapped as `ValueError` in Python.

## Examples

- New Python example to measure the maximum transfer rate and the jitter.
- New Python example to show coincidence counting applications.
- New example to show the use of the software clock and measure the frequency stability of the test signal in Python, MATLAB and LabVIEW.
- Update the *Counter* example in Python and MATLAB to show the use of the new *CounterData*.

## Fixes

- Skips an unlikely blocking *freeTimeTagger()* call for up to 10 seconds.
- Fixes the 64-bit signed integer overflow after 106 days on Linux.
- Stops playing the last sound of *setSoundFrequency()* after *freeTimeTagger()*.
- Fixes the timing of *TimeTagStreamBuffer::tGetData* in the last block of *FileReader*.
- Adds support for TTU HW revision 1.6 and TT20 Value.
- Fixes the empty configuration and channel list in *FileReader* before fetching the first time tag.
- Fixes a race condition on the *Time Tagger Ultra*, which may yield one invalid time tag after USB connection errors.
- Fixes a crash on using *with CustomMeasurement()* as *c* in Python.
- Fixes incorrectly displayed units in the WebApp if measurement settings changed during a measurement.
- Fixes the behavior of Histogram2D if start\_channel matches a stop channel.
- Fixes the behavior of Countrate with startFor if it ends within an overflow interval.

## 9.29 V2.9.0 - 07.06.2021

### Highlights

- Reduced communication latency of all Time Taggers.
- Reduced *Time Tagger 20* crosstalk on channel 1 and 2.
- Improved USB connection stability for *Time Tagger 20*.
- Optional collection and reporting of pseudonymous usage statistics. *Improvement program*.
- Please use at least v2.9.0 for devices shipped from 2021 on.

### Changes

- *getConfiguration()* and *getSensorData()* return a JSON string with partially renamed sensor names.
- Altered *Countrate::getData()* to return NaN (Not a Number) for zero capture durations.
- Uses *enum.Enum* as base class for all enumerators in the Python wrapper (Python >= 3.5).
- Improved the format of the Time Tagger error messages.

## Features

- Added `setHardwareBufferSize()` for the *Time Tagger 20*.
- Added an example and tutorial on how to work with a remote Time Tagger using Python and the Pyro5 package.
- License upgrades can be flashed now for the *Time Tagger 20* via the web application.

## Bug fixes

- Fixed `setStreamBlockSize()` block size heuristic while uploading new configuration.
- Fixed slow performance of `freeTimeTagger()` in overflow mode.
- Fixed `waitUntilFinished()` invoke nodes in LabVIEW examples.
- Fixed error message in the Web Application for non compatible devices.
- Fixed `getConfiguration()`. Now it is returning configuration data for *TimeTaggerVirtual* class.
- Fixed a possible crash on Python interpreter exit while running *CustomMeasurement*.
- Fixed `sync()` signaling one block too late. The fix reduces the sync, measurement start and clear times.

## 9.30 V2.8.4 - 04.05.2021

- Fixed the initialization for a Virtual Time Tagger in the Web Application

## 9.31 V2.8.2 - 26.04.2021

- Fixed non appearing option to initialize in HighRes mode after upgrading/flashing the device in the Web Application.

## 9.32 V2.8.0 - 29.03.2021

### Highlights

- High-resolution options for the *Time Tagger Ultra* series with a timing jitter of down to 4 ps RMS per channel.
- Hardware input delay on the *Time Tagger Ultra* series with picoseconds accuracy before the conditional filter.
- Reduced CPU load for *Time Tagger Ultra*.

### Note

The release is fully compatible with all *Time Tagger 20* devices. It is compatible with all *Time Tagger Ultra* devices shipped from March 2021 and all earlier *Time Tagger Ultra* devices with 8 or less channels without HighRes option. If you received *Time Tagger Ultra* before March 2021 and it has more than 8 channels or HighRes, it is not compatible with the release. Please contact support to get a free device exchange to be fully compatible again.

### New Time Tagger Ultra features

- Reduced crosstalk and thermal drift on all channels.
- The Time Tagger hardware sound module can be activated and set via `setSoundFrequency()`. It can be used, e.g., for optical alignment purposes (count rate -> frequency).

## Changes

- Split `setInputDelay()` into `setDelayHardware()` and `setDelaySoftware()`.
- `getChannelList()` filter enum renamed to `ChannelEdge`.
- `setNormalization()` can now be configured per channel.
- Changed the default port of the WebApp to 50120 to avoid collision with Jupiter Notebooks.
- Maximum input frequency of the *Time Tagger Ultra* is reduced to 475 MHz.
- The deadtime specification of the *Time Tagger Ultra* changed to 2.1 ns. It can detect events separated by 2 ns with possible loss of some events.

## Features

- Added a `TriggerOnCountRate` virtual channel that generates events when a count rate crosses the given threshold value.
- Added support for Python 3.9.
- `waitUntilFinished()` and `sync` have an optional timeout parameter.

## Examples

- Mathematica: Added example for `FileWriter` and `TimeTaggerVirtual`.
- LabVIEW: Fixed broken example (#14) and added it to the LabVIEW project.
- C++: Added an example for Custom Virtual Channel.

## Bug fixes

- Histogram can be used with `waitUntilFinished()` and `SynchronizedMeasurements`. `Histogram` is now derived from `IteratorBase`.
- Displaying the singleton warning of `createTimeTagger` just once.
- Fixed string conversion issue for old MATLAB versions.
- Hide “unused argument” warnings in the TimeTagger C++ headers.

## 9.33 V2.7.6 - 26.04.2021

- Fixed RuntimeError “Got the USB error ‘UnsupportedFeature’” when calling `createTimeTagger()`

## 9.34 V2.7.4 - 19.04.2021

- Fixed a bug for old *Time Tagger Ultra* devices, where the Web Application could not apply the license upgrade.

## 9.35 V2.7.2 - 22.12.2020

### Highlights

- Reworked `Flim` implementation. Versatile high-level functionality with `Flim` and low-level CPU- and memory-efficient access via `FlimBase` and callbacks.
- Highly improved `TimeTaggerVirtual` performance taking use of multithreading.

- Support for direct time tag stream access via *CustomMeasurement* in C# and Python - see examples in the installation folder.

### Improvements

- Added AnyCPU targeted .NET Assembly for C# wrappers. Available in GAC\_MSIL and the installation folder.
- More detailed error handling and human-readable error messages.
- Added *Conditional Filter* for *TimeTaggerVirtual*.
- Removed Intel's *libmmd.dll* library dependency.
- All measurements have the new common method *waitUntilFinished()*, which can be used with *startFor()*.
- Warnings are printed with time information.
- Cleanup of the C++ measurements' header file.
- Remote license upgrades can be performed via the web application.
- Reworked Python and C# examples.

### Fixes

- *Countrate* no longer clears total counts on *start()*.
- Implemented *getChannellist()* and *waitForFence()* in MATLAB.
- Fixed *setDeadtime()* for the *TimeTaggerVirtual* using *setTestSignal()*.
- Fixed a frequent crash in *FileWriter* with high data rates and multiple files.
- Fixed a crash in deleting measurements still registered to *SynchronizedMeasurements*.
- Fixed an unlikely race condition of freeing measurements.

### API changes

- The old *FLIM* class is replaced by a new implementation: *Flim*. In case you need the old implementation, there is a 1 to 1 replacement, see [here](#).
- All methods and measurements now throw exceptions instead of warning on wrong arguments like invalid channels or out-of-range parameters.
- Automatically call *freeTimeTagger* on *del/clear/Dispose* in Python/MATLAB/LabVIEW/C# .
- Removed the *freeAllTimeTagger()* method.
- Deprecate the multiple use of *createTimeTagger()* for one physical device. Pass on the *timetagger* object instead.
- *\_Log* is renamed to *LogBase*.
- Our libraries are compiled with VS 2019 now, so at least version 142 of the VC runtime is required in the final application.

## 9.36 V2.7.0 - 01.10.2020

### Highlights

- New measurements are automatically synchronized to the hardware. All data analyzed is guaranteed to be temporal later than the measurement's initialization, start, or clear. Data coming from the internal buffer, which was



acquired before the measurement was initialized, started, or cleared, will not be analyzed. Before this release, the `.sync()` method was required for these tasks.

### Fixes and improvements

- Added a MATLAB example for SynchronizedMeasurements.
- Fixed a bug in MATLAB, creating synced measurements via SynchronizedMeasurements and `.getTagger()`.
- The last datapoint from a scope measurement is not marked as invalid any more.

## 9.37 V2.6.10 - 07.09.2020

### Fixes and improvements

- Fixes input delay, deadtime and test signal generator for the TimeTaggerVirtual.
- Fixes `getInvertedChannel` with the Swabian Synchronizer and with *Time Tagger Ultra* 8 devices with the old channel numbering schema.
- x axis is zoomable with Scope measurement.
- Better error handling for non-existent files with TimeTaggerVirtual and FileReader.

### Python

- Changed the constants `CoincidenceTimestamp_` to a Python enum (e.g., `CoincidenceTimestamp_First` is now `CoincidenceTimestamp.First`).

### MATLAB

- Enum for timestamp argument for `Coincidence(s)` is available via `TTCoincidenceTimestamp`.

### Linux

- Fix for slow Linux device opening.

## 9.38 V2.6.8 - 21.08.2020

### Highlights

- Support for the Time Tagger Value edition. This is an upgradeable and cost-efficient version of the *Time Tagger Ultra* for applications with moderate timing precision requirements.

### Webapp

- Added *Histogram2D* to the measurement list.
- Improved performance and responsiveness for large datasets.
- 32-bit version of the Web Application works again.
- Fixed a bug that data of stopped measurements could not be saved.
- Fixed a bug that settings saved had the file extension `.json` instead of `.ttconf` ending.
- Fixed a bug when using falling edges for Time Tagger starting with channel 0.

### Python

- Fixed a bug that some named arguments could not be used anymore.

### API

- Added the method `SynchronizedMeasurements::unregisterMeasurement()` to remove measurements from `SynchronizedMeasurements`.

### Backend

- Improved performance of the FileWriter, exceeding 100 M tags/s on high-end CPUs.
- Improved binning performance of all histogram measurements: Correlation, FLIM, Histogram, StartStop, TimeDifferences, TimeDifferencesND.
- Fixes a deadlock in the virtual Time Tagger if a measurement accesses some public methods of the Time Tagger.

## 9.39 V2.6.6 - 10.07.2020

### Highlights

- Swabian Synchronizer support. The Synchronizer hardware can combine 8 *Time Tagger Ultra* devices with up to 144 channels. The combined Time Tagger can be interfaced the very same as it would be only one device.
- Support for custom measurements in Python. Please see the provided programming example in the installation folder for further details.

### Webapp

- Support for the Synchronizer
- Showing error messages from setLogger API in a modal window
- Load/save settings is now supported for the Time Tagger Virtual

### Time Tagger Ultra

- Hardware revision 1.1 now with the same performance enhancement of 500 MHz maximum sync rate, 2ns dead time and better phase stability, as introduced before for Hardware revision > 1.1
- Dropped support for the very first *Time Tagger Ultra* devices, an error will be shown on initialization - free exchange program available
- More intuitive byte order of the bitmask in setLED
- Small modifications to the hardware channel to channel delay

### Backend

- Coincidence and Coincidencees have an optional parameter to select which timestamp should be inserted, the last/first completing the coincidence, the average of the event timestamps, or the first of the coincidence list.
- Fixed .net/MATLAB/LabVIEW wrappers for data with empty 2D or 3D arrays
- Provide a globally registered .NET publisher policy for C#, avoiding the 'wrong dll version' message in Labview when updating the Time Tagger software
- setConditionalFilter throws an exception when invalid arguments are applied
- Hide the warning on fetching the TimeTaggerVirtual license without an internet connection

- DelayedChannel supports a negative delay
- Performance enhancements in StartStop

## 9.40 V2.6.4 - 27.05.2020

### WebApp

- Option to enable logarithmic y-axis scaling for Counter, Histogram, HistogramLogBins and Correlation
- Redesign “Create measurement” dialog with links to the online documentation
- Fixed flickering when switching between plots
- Fixed plotting wrong data range when changing the number of data points
- Added the basic functionality of the TimeTaggerVirtual (test signal only)

### New features and improvements

- Added the test signal to TimeTaggerVirtual
- Support for Ubuntu 20.04 and CentOS 8
- LabVIEW example for FileWriter and FileReader
- Improved MATLAB API for VirtualTimeTagger, adding optional parameters
- Make the data transfer size configurable by .setStreamBlockSize
- Performance improvements for HistogramLogBins
- Slightly improved timing jitter at large time differences for the *Time Tagger 20*
- Time Tagger Application works again with 32 bit operating systems
- Connection errors are shown in the MATLAB console or can be handled with the new logger functionality
- Added custom logger examples for MATLAB/Python/C#

### Changes

- Updated the USB library
- Stop measurements when freeTimeTagger is called (e.g. closes files on dump, isRunning now returns false)
- Reduced polling rate (0.1s) for USB reconnections

### API changes

- Added .setLogger() to attach a callback function for custom info/error logging
- Rename of enumeration ErrorLevel to LogLevel
- Rename of log level constants and with new corresponding integer values

## 9.41 V2.6.2 - 10.03.2020

### Highlights

- TimeTaggerVirtual, FileWriter, and FileReader have reached a stable state
- Improved Linux support (documentation, compiling custom Python wrappers)

### New features

- Added setInputDelay, setDeadtime, getOverflows, and more to the TimeTaggerVirtual
- Add an optional parameter in setConditionalFilter for disabling the hardware delay compensation
- Infinite dumping in Dump for negative max\_count
- Create a freeAllTimeTagger() method, which is called by Python atexit
- Reimplement SynchronizedMeasurements as a proxy tagger object, which auto registers new measurements without starting them
- The new SynchronizedMeasurements.isRunning() method returns if any measurement is still running
- Python: Distribute the generated C++ wrapper source for supporting future Python revisions
- C++: New IteratorBase.getLock method returning a std::unique\_lock
- C++: Improved exception handling for custom measurements: exceptions now stop the measurement, runSynchronized forwards exceptions to the caller

### API changes

- TimeTagger.getVersion return value is changed to a string
- C++: Use 64 bit integers for the dimensions in the array\_out helpers
- C++: Rename the base class for custom measurements from \_Iterator to IteratorBase
- C++: Constructors of custom measurements shall call finishInitialization instead of IteratorBase.start
- Python 2.7: Update the numpy C headers to 1.16.1

### Examples and documentation

- Improved Histogram2D example
- Clarify setInputDelay vs DelayedChannel

### Bug fixes

- Relax the voltage supply check in the *Time Tagger Ultra* hardware revision 1.4
- Use a 1 MB buffer for Dump, FileWriter, and FileReader to achieve full speed especially on network devices
- Fix getTimeTaggerModel on an active device
- Fix deadlock within sync() while the device is disconnected
- Provide the documentation on Linux
- Several fixes and improvements for the FileWriter and TimeTaggerVirtual

### WebApp

- Improved default names for measurements
- Not relying on data stored within the browser any more
- Disabling mouse scrolling within numeric inputs
- Various buxfixes

## 9.42 V2.6.0 - 23.12.2019

### Highlights

- FileWriter: New space-efficient file writer for storing time tag stream on a disk. The file size is reduced by a factor of 4 to 8. Replaces the Dump function.
- Virtual Time Tagger allows to replay previously dumped events back into the Time Tagger software engine.
- Improved behavior in the overflow mode. The hardware now also reports the amount of missed events per input channel and provides the start and the end timestamps of the overflow interval.
- New tutorial on how to implement the data acquisition for a confocal microscope
- New measurement Histogram2D for 2-dimensional histogramming with examples
- Web App: Selectable input units (s/ms/ $\mu$ s/ps) instead of ps only

### Known issues

- FileWriter and FileReader have a low performance on network devices

### API changes

- deprecated TimeTagStreamBuffer.getOverflows() – use .getEventTypes() instead
- renamed HistogramLogBin.getDataNormalized() to .getDataNormalizedCountsPerPs()
- removed deprecated TimeTagger.getChannels() - use .getChannelList() instead
- removed deprecated CHANNEL\_INVALID - use CHANNEL\_UNUSED instead
- removed deprecated TimeTagger.setFilter() and TimeTagger.getFilter() - use .setConditionalFilter(), .getConditionalFilter(), and .clearConditionalFilter() instead
- C++: All custom measurement class constructors must be modified, such that the parameter containing the Time Tagger is of the type TimeTaggerBase. This allows for using the custom measurement within a real Time Tagger object and the Time Tagger Virtual.
- C++: The struct Tag includes the type of event and the amount of missed events. They have replaced the overflow field.
- C++/Windows: We additionally distribute binaries for the debug runtime (/MDd)
- MATLAB: TimeTagger.free() is now deprecated, use .freeTimeTagger()

### New features

- Web App: Normalization (counts/s) for the Counter measurement
- getConfiguration returns the current hardware configuration as a JSON string
- added g2 normalization for HistogramLogBins with getDataNormalizedG2
- improved overflow behavior for Countrate due to the missed event counters
- improved overflow handling for the g2 normalization of Correlation and HistogramLogBin
- support for Python version 3.8
- smaller latency on low data rates due to adaptive chunk sizes of  $\leq 20$  ms
- support for the *Time Tagger Ultra* hardware revision 1.4

## Examples

- MATLAB: Faster loading of events from disk for now deprecated Dump file format
- C++: Loading events from disk stored in the new data format
- Labview: Scope example, .NET version redirection
- Mathematica: Improved example
- Python: Added “Stop” button to the countrate figure.

## Bug fixes

- fixed static input delay error with conditional filter enabled since v2.2.4
- added missing `TimeTagger.getTestSignalDivider()` method
- Scope: Fix the output if one channel has had no events
- resolve overflows after the initialization of the *Time Tagger 20*
- fixes an issue with wrongly sorted events on the reconfiguration of input delays
- always emit an error event on plugging an external clock source
- fixes an unlikely case when the synchronization of the external clock got lost
- the new USB driver version fixes some random data abruption
- TTU1.3: Fix a bug which may select a wrong clock source in the first 21 seconds and wrongly activated ext clock LED
- MATLAB: SynchronizedMeasurements work now in MATLAB, too
- different improvements within the python and C# wrappers
- LED turns off and not red after freeing a Time Tagger
- Dump now releases the file handle after the end of the startFor duration
- Web App: Removed caching issues when up or downgrading the software

## 9.43 V2.4.4 - 29.07.2019

- reduced crosstalk between nonadjacent channels of the *Time Tagger Ultra*
- fixed a bug leading to high crosstalk with V2.4.2 for specific channels
- fixed a rare clock selection issue on the *Time Tagger 20*
- improved and more detailed documentation
- new method `Countrate::getCountsTotal()`, which returns the absolute number of events counted
- new Mathematica quickstart example
- new *Scope* example for LabVIEW
- support of the *Time Tagger 20* series with hardware revision 2.3
- release the Python GIL while in the Time Tagger engine code
- fixed a bug in `ConstantFractionDiscriminator`, which could cause that no virtual tags were generated

## 9.44 V2.4.2 - 12.05.2019

- support of the *Time Tagger Ultra* series with hardware revision 1.3
- improve performance of short pulse sequences on the *Time Tagger 20* series
- improve overflow behavior at too high input data rates
- fix the name of the ‘SynchronizedMeasurements’ measurement class

## 9.45 V2.4.0 - 10.04.2019

### Libraries

- 32 bit C++ library added
- C++ and .NET libraries renamed and registered globally

### API

- virtual constant fraction discriminator channel ‘ConstantFractionDiscriminator’ added
- ‘TimeDifferenceND’ added for multidimensional time differences measurements
- faster binning in ‘TimeDifferences’ and ‘Correlation’ measurements
- improved memory handling for ‘TimeTageStream’
- improved Python library include
- fixed ‘.getNormalizedData’ for ‘Correlation’ measurements
- various minor bug fixes and improvements

### Examples

- LabVIEW project for 32 and 64 bit
- improved LabVIEW examples

### Time Tagger Ultra

- 10 MHz EXT input clock detection enabled
- internal buffer size can be increased from 40 MTags to 512 MTags with ‘setHardwareBufferSize’
- reduced crosstalk and timing jitter
- increased maximum transfer rate to above 65 MTags/s (Intel 5 GHz CPU on 64 bit)
- various performance improvements
- reduced deadtime to 2 ns on hardware revision  $\geq 1.2$

### Time Tagger 20

- 166.6 MHz EXT input clock detection enabled

## Operating systems

- equivalent support for Windows 32 and 64 bit, Ubuntu 16.04 and 18.04 64 bit, CentOS 7 64 bit

## 9.46 V2.2.4 - 29.01.2019

- fix the conditional filter with filter and trigger events arriving within one clock cycle
- fix issue with negative input delays
- calling .stop() while dumping data stops the dump and closes the file
- fix device selection on reconnection after transfer errors
- synchronize tags of falling edges to their rising ones

## 9.47 V2.2.2 - 13.11.2018

- Removed not required Microsoft prerequisites.
- 32 bit version available

## 9.48 V2.2.0 - 07.11.2018

### General improvements

- support for devices starting with channel 1 instead of 0
- under certain circumstances, the crosstalk for the *Time Tagger 20* of channel 0-2, 0-3, 1-2, and 1-3 was highly increased, which has been fixed now
- updated and extended examples for all programming languages (Python, MATLAB, C#, C++, LabVIEW)
- C++ examples for Visual Studio 2017, with debug support
- documentation for virtual channels
- Web app included in the 32 bit installer
- Linux package available for Ubuntu 16.04
- Support for Python 3.7

### API

- 'HistogramLogBin' allows analyzing incoming tags with logarithmic bin sizes.
- 'FrequencyMultiplier' virtual channel class for upscaling a signal attached to the Time Tagger. This method can be used as an alternative to the 'Conditional Filter'.
- 'SynchronizedMeasurements' class available to fully synchronize start(), stop(), clear() of different measurements.
- Second parameter from 'setConditionalFilter' changed from 'filter' to 'filtered'.

### Web application

- full 'setConditionalFilter' functionality available from the backend within the Web application



## 9.49 V2.1.6 - 17.05.2018

fixed an error with getBinWidths from CountBetweenMarkers returning wrong values

## 9.50 V2.1.4 - 21.03.2018

fixed bin equilibration error appearing since V2.1.0

## 9.51 V2.1.2 - 14.03.2018

fixed issue installing the MATLAB toolbox

## 9.52 V2.1.0 - 06.03.2018

### Time Tagger Ultra

- efficient buffering of up to 60 MTags within the device to avoid overflows

## 9.53 V2.0.4 - 01.02.2018

### Bug fixes

- Closing the web application server window works properly now

## 9.54 V2.0.2 - 17.01.2018

### Improvements

- MATLAB GUI example added
- MATLAB dump/load example added

### Bug fixes

- dump class writing tags multiple times when the optional channel parameter is used
- Counter and Countrate skip the time in between a .stop() and a .start() call
- The Counter class now handles overflows properly. As soon as an overflow occurs the lost data junk is skipped and the Counter resumes with the new tags arriving with no gap on the time axis.

## 9.55 V2.0.0 - 14.12.2017

### Release of the Time Tagger Ultra

#### Note

The input delays might be shifted (up to a few hundred ps) compared to older driver versions.

### Documentation changes

- new section 'In Depth Guides' explaining the hardware event filter

## **Webapp**

- fixed a bug setting the input values to 0 when typing in a new value
- new server launcher screen which stops the server reliably when the application is closed

## **9.56 V1.0.20 - 24.10.2017**

### **Virtual Channels**

- DelayedChannel clones and optionally delays a stream of time tags from an input channel
- GatedChannel clones an input stream, which is gated via a start and stop channel (e.g. rising and falling edge of another physical channel)

### **API**

- startFor(duration) method implemented for all measurements to acquire data for a predefined duration
- getCaptureDuration() available for all measurements to return the current capture duration
- getDataNormalized() available for Correlation
- setEventDivider(channel, divider) also transmits every nth event (divider) on channel defined

## **Webapp**

- label for 0 on the x-axis is now 0 instead of a tiny value

### **C++ API:**

- internal change so that clear\_impl() and next\_impl() must be overwritten instead of clear() and next()

### **Other bug fixes/improvements**

- improved documentation and examples

## **9.57 V1.0.6 - 16.03.2017**

### **Web application (GUI)**

- load/save settings available for the Time Tagger and the measurements
- correct x-axis scaling
- input channels can be labeled
- save data as tab separated output file (for MATLAB, Excel, ... import)
- fixed: saving measurement data now works reliably
- fixed: 'Initialize' button of measurements works now with tablets and phones

### **API**

- direct time stream access possible with new class TimeTagStream (before the stream could be only dumped with Dump)
- Python 3.6 support
- better error handling (throwing exceptions) when libraries not found or no Time Tagger attached

- `setTestSignal(...)` can be used with a vector of channels instead of a single channel only
- `Dump(...)` now with an optional vector of channels to explicitly dump the channels passed
- `CHANNEL_INVALID` is deprecated - use `CHANNEL_UNUSED` instead
- Coincidences class (multiple Coincidences) can be used now within MATLAB/LabVIEW

### Documentation changes

- documentation of every measurement now includes a figure
- update and include web application in the quickstart section

### Other bug fixes/improvements

- no internal test tags leaking through from the initialization of the Time Tagger
- Counter class not clearing the data buffer in time when no tags arrive
- search path for bitfile and libraries in Linux now work as they should
- installer for 32 bit OS available

## 9.58 V1.0.4 - 24.11.2016

### Hardware changes

- extended event filter to multiple conditions and filter channels
- improved jitter for channel 0
- channel delays might be different from the previous version (< 1 ns)

### API changes

- new function `setConditionalFilter` allows for multiple filter and event channels (replaces `setFilter`)
- Scope class implements functionality to use the Time Tagger as a 50 GHz digitizer
- Coincidences class now can handle multiple coincidence groups which is much faster than multiple instances of Coincidence
- added examples for C++ and .net

### Software changes

- improved GUI (Web application)

### Bug fixes

- MATLAB/LabVIEW is not required to have the Visual Studio Redistributable package installed

## 9.59 V1.0.2 - 28.07.2016

### Major changes:

- LabVIEW support including various example VIs
- MATLAB support including various example scripts
- .net assembly / class library provided (32 and 64 bit)

- WebApp graphical user interface to get started without writing a single line of code
- Improved performance (multicore CPUs are supported)

**API changes:**

- `reset()` function added to reset a Time Tagger device to the startup state
- `getOverflowsAndClear()` and `clearOverflows()` introduced to be able to reset the overflow counter
- support for python 3.5 (32 and 64 bit) instead of 3.4

## **9.60 V1.0.0**

initial release supporting python

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