UiO : University of Oslo

FYS3240- 4240
Data acquisition & control

Time and synchronization

Spring 2024 – Lecture #12

Bekkeng, 18.02.2024

Why is time and synchronization so important?

- Some examples:
  - Accurate time stamping of **scientific data**
  - In **financial trading** we must know the time accurately.
  - Important to reduce confusion in **shared file systems**.
  - Update **databases** (in parallel).
  - **Tracking security breaches or network usage** requires accurate timestamps in logs.
  - Used in **electric power systems** (fault recorders, billing meters, etc.).
  - Necessary in **telecommunication networks.**
  - **Global Navigation Satellite Systems (GNSS)**, such as GPS, requires very accurate clock synchronization for position calculations.

TU-artikkel : GPS mer enn bare navigasjon

How accurate much the clock be ?

- Depends on the application.

- If the clock in the GPS receiver have an error of 1 ms relative to the atomic clocks in the GPS satellites this corresponds to a position error of $\delta \mathrm{p} = \mathrm{c} * \delta \mathrm{t} = 3*10^8 \mathrm{~m/s} * 1 \mathrm{~ms} = 300 \mathrm{~km}$.

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Position, navigation & timing (PNT)

- PNT is important in many applications!

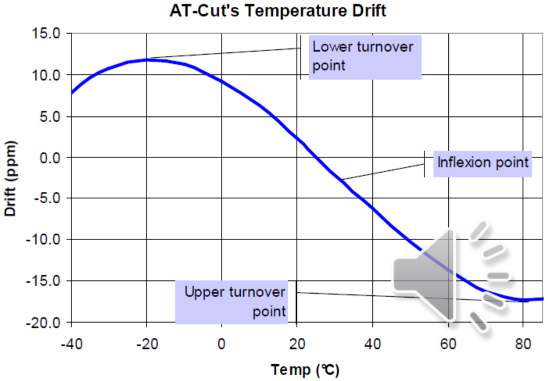
På rett sted til rett tid (regjeringen.no)

How good is a crystal oscillator (XO) ?

- **Interested in the long-term measurement stability and accuracy**

- Watch crystal oscillator: about 20 ppm, or worse
  - Error > 1.73 s in 24 hours (almost 1 minute drift in one month)

- The accuracy can be improved using a:
  - Temperature compensated crystal oscillator (TCXO)
    - based on temperature measurements.
  - Oven controlled crystal oscillator (OCXO)
    - the oscillator is enclosed in a temperature controlled oven

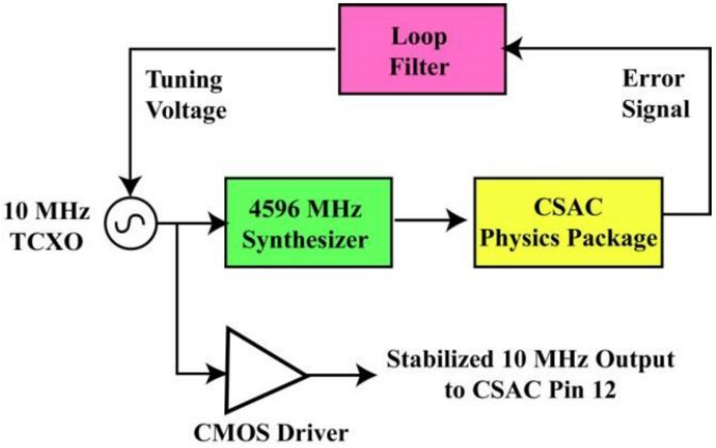


- Some DAQ card accuracy examples:
  - TCXO : 1 ppm
  - OCXO: 50 ppb

Chip Scale Atomic Clock (CSAC)

- **Two orders of magnitude better accuracy than oven-controlled crystal oscillators (OCXOs).**
- **Can keep track of the time if GPS-signals are lost (e.g. inside a building, or due to jamming).**

- Example: Microsemi CSAC
  - < 120 mW power consumption
  - < 17 cm^3 volume
  - 35 g weight
  - two outputs; a 10 MHz square wave and 1 PPS (Pulse Per Second)
  - Maintains time-of-day (TOD) as a 32-bit unsigned integer
  - Can set the TOD



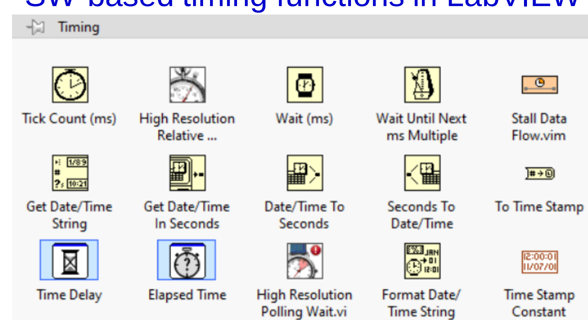
The frequency of the TCXO is continuously compared and corrected to ground state hyperfine frequency of the cesium atoms, contained in the “physics package”, which thereby improves the stability and environmental sensitivity of the TCXO.

Computer clocks

- Hardware clocks
  - **Real Time Clock (RTC)** is an integrated circuit on the motherboard.
  - The RTC has a battery backup power so that it tracks the time even while the computer is turned off.
  - Based on a 32.768 kHz quartz crystal oscillator.
  - Maximum resolution of 1 millisecond (1 kHz).

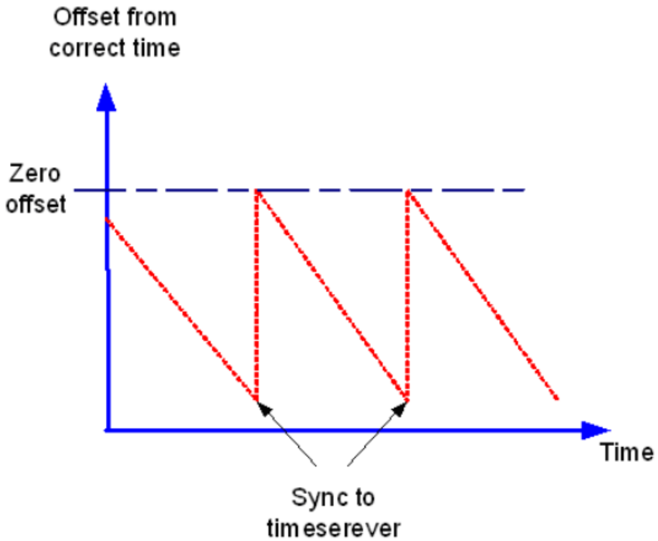
- Software (SW) clocks
  - Maintained by the operating system, based on the RTC interrupts.
  - When the system starts it sets the system time to a value based on the real-time clock of the computer and then regularly updates the time based on **interrupts from the RTC**.

SW-based timing functions in LabVIEW



Computer clock drift

- The software clock is a bad timekeeper (without corrections)!
- The computer clock drifts away from the correct time. At the time of synchronization with **a time server** the clock is reset to the "correct time" (but with a small offset).
- Can update the computer clock often (using NTP or PTP, see later slides), or read time directly from **a timing card** connected to a GPS antenna, IRIG-B signal or an IEEE1588 signals (see later slides).



Software / Operating System (OS) limits timing resolution and accuracy! The performance is system (hardware, OS) dependent.

High-Resolution Timers/Counters in PCs

- **High Precision Event Timer (HPET)** is a 64-bit up-counter with a frequency higher than 10 MHz.

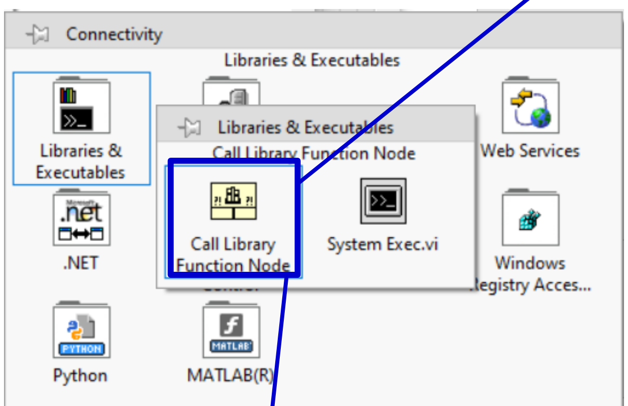
- **Time Stamp Counter (TSC)** is a 64-bit register in the CPU (cores) that increment each processor clock cycle. However, can be unreliable on a modern multicore computer due to:
  - multicore computers can have different values in their time-keeping registers.
  - variability of the CPU frequency due to power management technologies or performance technologies such as *Intel Turbo Boost Technology*.

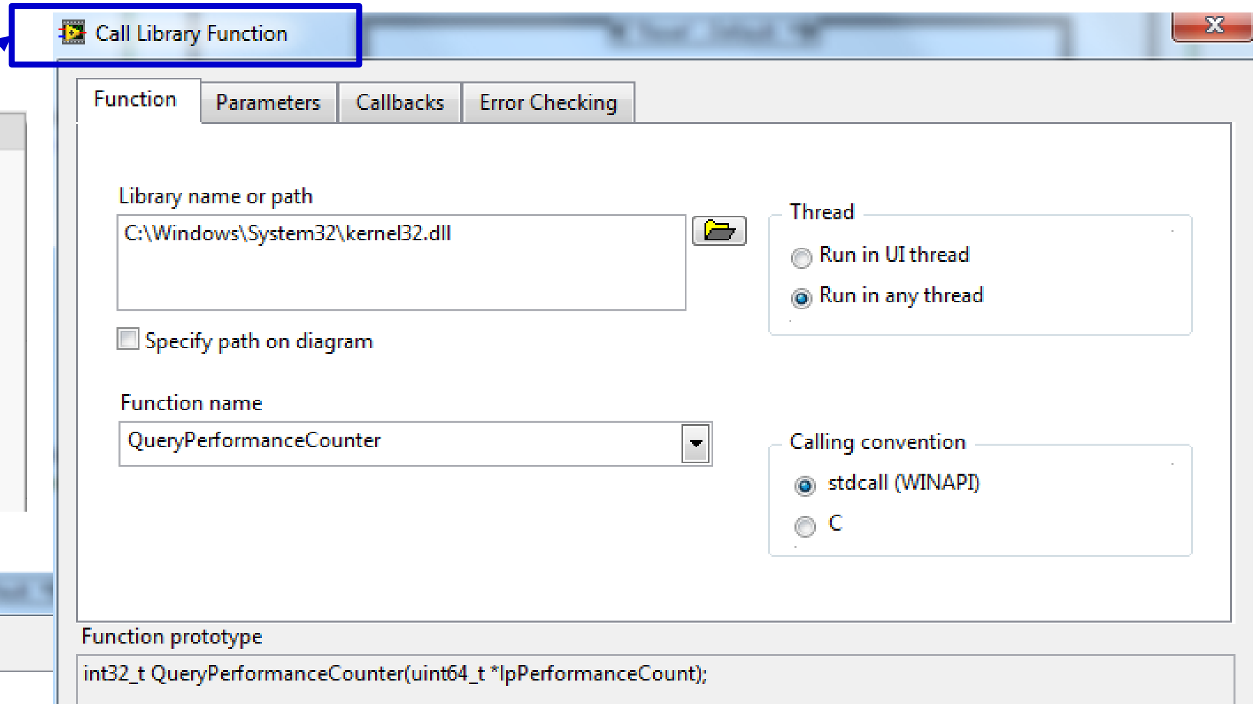
Access the TSC (or HPET) timer using the Windows API functions ***QueryPerformanceCounter*** (μs resolution) and ***QueryPerformanceFrequency***

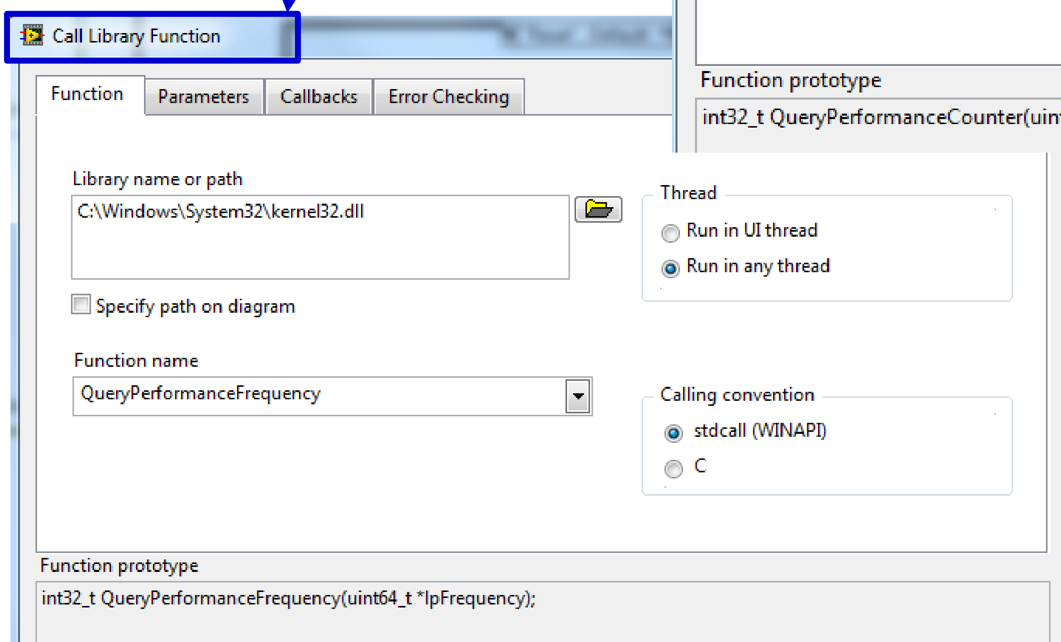
$$\Delta T = \frac{\mathrm{QueryPerformanceCounter(n)} - \mathrm{QueryPerformanceCounter(n-1)}}{\mathrm{QueryPerformanceFrequency}}$$

Extra

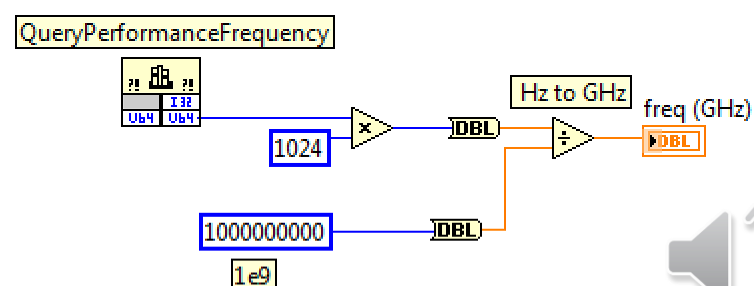
QueryPerformance from LabVIEW



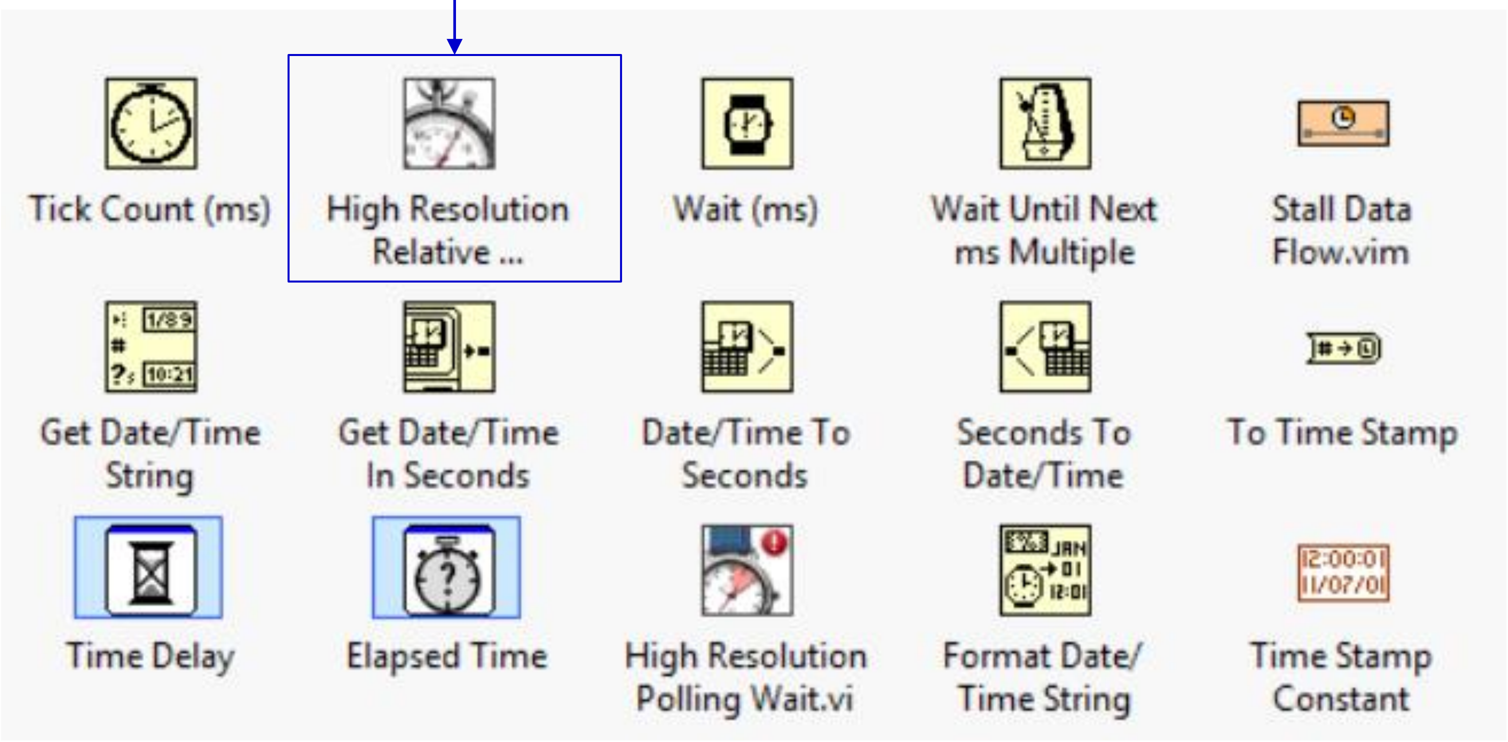




Example: get TSC frequency



Use the difference between two successive values to measure the elapsed time between the calls. Gives sub-millisecond resolution.



LabVIEW - Timing

TAI and UTC time

- **International Atomic Time (TAI)** as a time scale is a weighted average of the time kept by over 300 atomic clocks in over 60 national laboratories worldwide.

- **Coordinated Universal Time** (**UTC**) is the primary time standard by which the world regulates clocks and time, and is based on **TAI** but with leap seconds added at irregular intervals to compensate for the slowing of the Earth's rotation.

- UTC is the time standard used for many internet and World Wide Web standards. The Network Time Protocol (NTP), designed to synchronize the clocks of computers over the Internet, encodes times using the UTC system.

Leap seconds

- **Time is now measured using stable atomic clocks**

- A **leap second** is a one-second adjustment that is occasionally applied to UTC time in order to keep its time of day close to the **mean solar time**.
  - Solar time is a reckoning of the passage of time based on the Sun's position in the sky.

- Leap seconds are necessary partly because the length of the mean solar day is very slowly increasing, and partly because the atomic, fixed-length SI second, when adopted, was already a little shorter than the current value of the second of mean solar time.

Since 1967, the second has been defined to be the duration of **9,192,631,770 periods** of the radiation corresponding to the transition between the two hyperfine levels of the ground state of the **cesium 133 atom**

GPS time

- GPS time is the atomic time scale implemented by the atomic clocks in the GPS ground control stations and the GPS satellites themselves.
- Periodic corrections are performed to the on-board satellite clocks to keep them synchronized with ground station clocks.
- **GPS time is NOT corrected for leap seconds.**
- **GPS time is NOT equal to UTC or TAI time.**
  - GPS time is 18 seconds ahead of UTC because of the leap seconds added to UTC.
  - GPS time was set to match UTC in 1980
- **However, the time offset from UTC is contained in the GPS broadcast message and is usually applied automatically by GPS receivers.**

A GPS satellite clock run faster (about 38 μs a day) due to **velocity** and **gravity** effects (follows the Relativity theory)

Time dilation

From: http://leapsecond.com/java/gpsclock.htm

local	2021-01-01 20:44:50	Friday	day 001	timezone UTC+1
UTC	2021-01-01 19:44:50	Friday	day 001	MJD 59215.82280
GPS	2021-01-01 19:45:08	week 2138	503108 s	cycle 2 week 0090 day 5
Loran	2021-01-01 19:45:17	GRI 9940	145 s until	next TOC 19:47:15 UTC
TAI	2021-01-01 19:45:27	Friday	day 001	10 + 27 leap seconds = 37

Time stamping of data

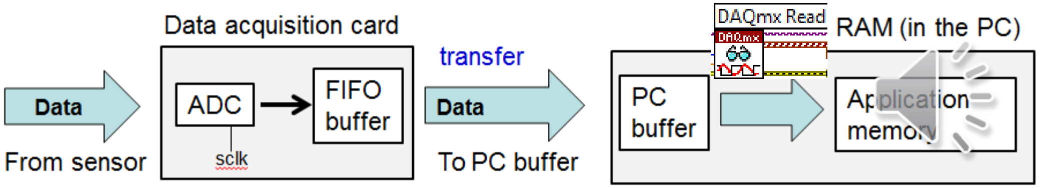
- We often need to timestamp an image in a video stream or a block of data from a DAQ-card to GPS (UTC) time; e.g. for use in data fusion in post-analysis.

- If the data samples has a deterministic (regular) interval, such as samples from a DAQ-card, it is sufficient to time stamp the first sample at time t_0:

$$t = t0 + n * \Delta t$$

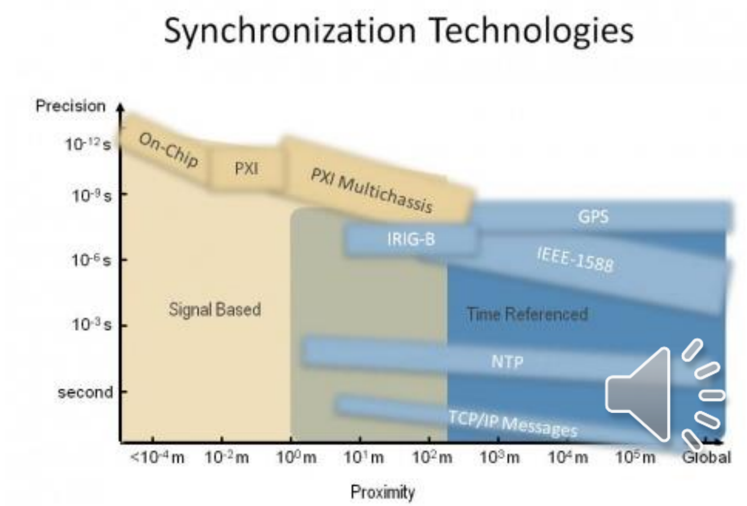
$$\Delta t = \frac{1}{fs}$$

- If the data samples are not deterministic (regular), e.g. video frames from a camera, each data point/video frame must include a timestamp.

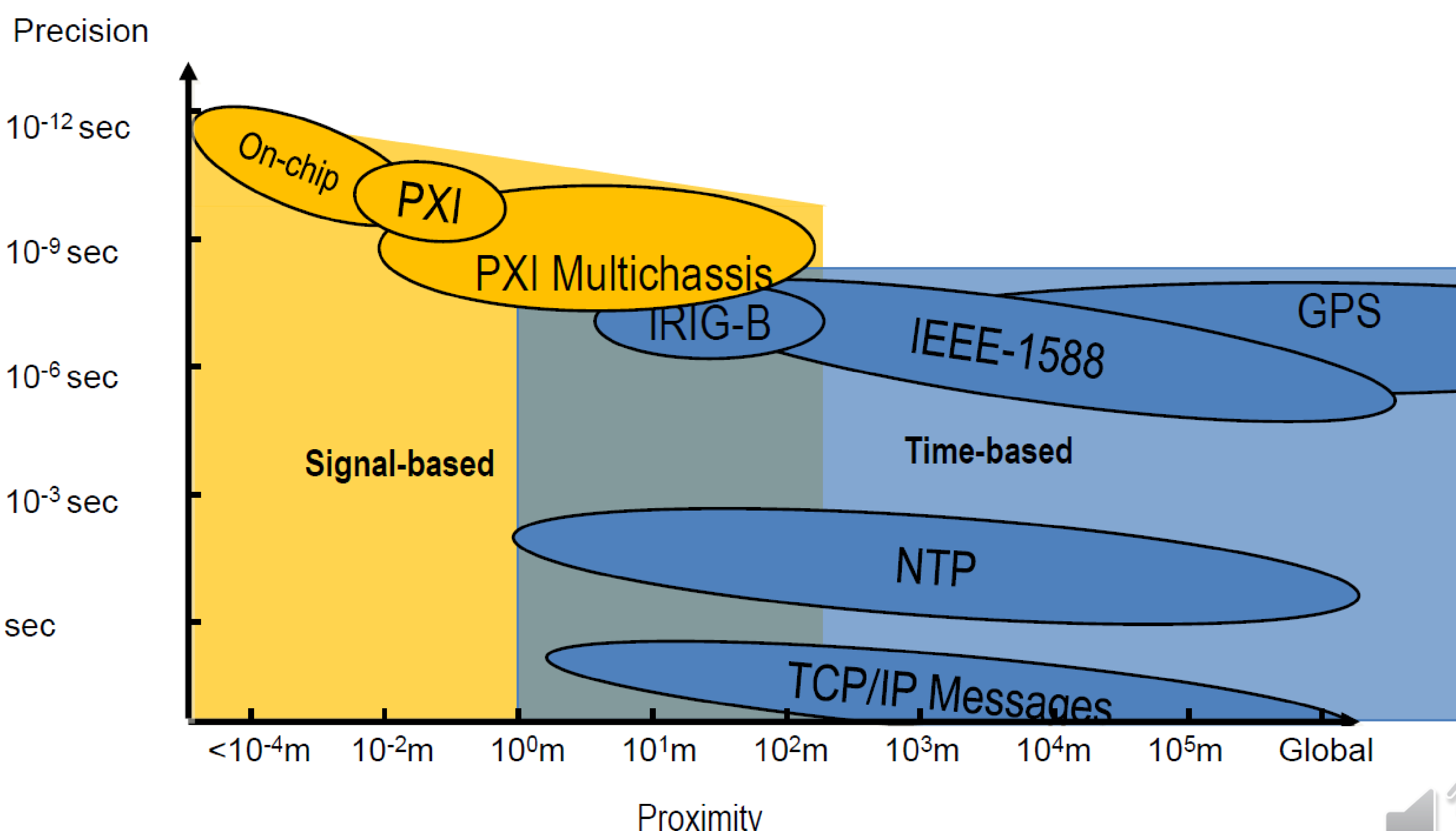


Signal based vs. time-based synchronization

- **Signal-based synchronization** involves sharing signals such as clocks and triggers directly (wires) between nodes that need to be synchronized.
- **Time-based synchronization** involves nodes independently synchronizing their individual clocks based on some time source, or time reference.
- There are advantages and disadvantages to both methods of device synchronization.



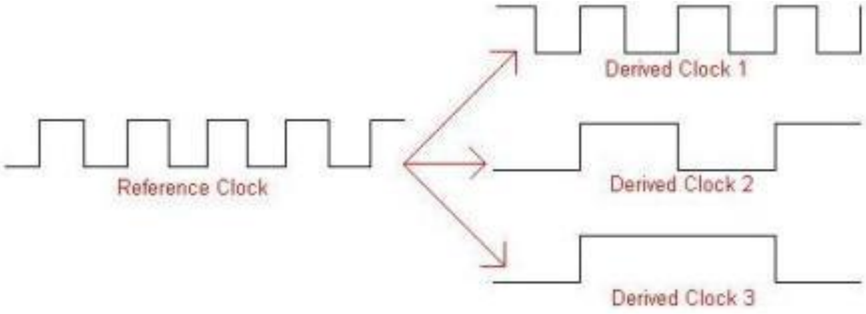
Synchronization technologies

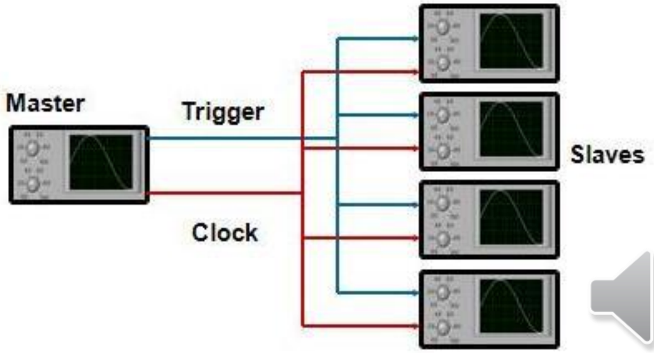


Signal-based synchronization

- In systems where the devices are near each other, sharing a common timing signal is generally the easiest and most accurate method of synchronization.

- To accurately use a common timing signal, a device must be calibrated to account for the <u>signal propagation delay from the timing source to the device</u>



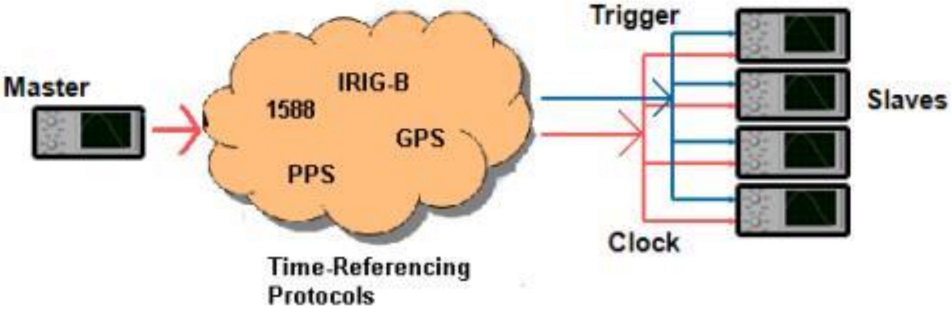


Time-based synchronization

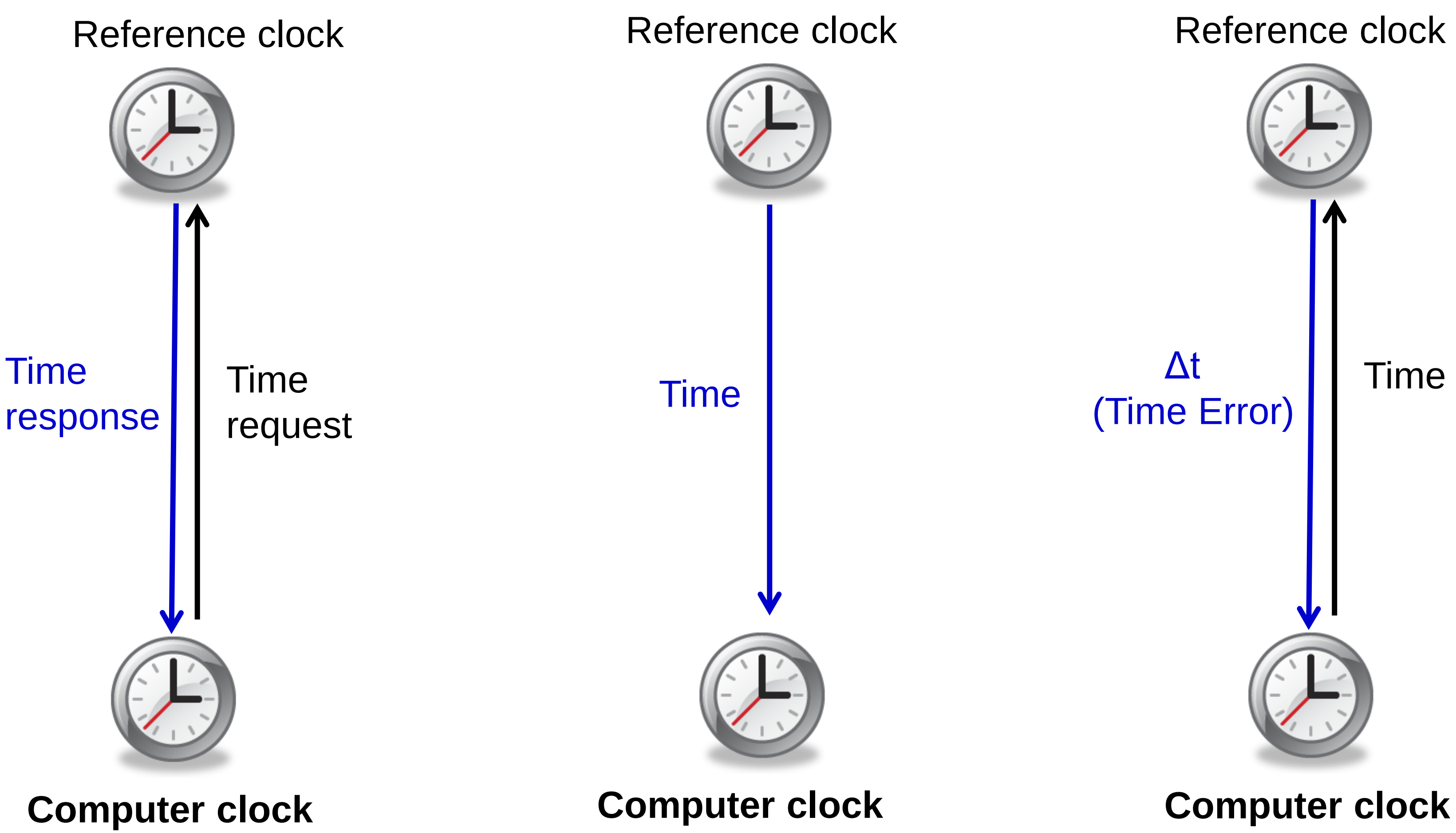
- Necessary for long distances

- Because of the inherent instabilities in (crystal oscillator) clocks, distributed clocks must be synchronized continuously to a time refererence to match each other in frequency and phase.

- Time references:
  - GPS
  - IEEE 1588 master
  - IRIG-B sources



Global time – possible implementations

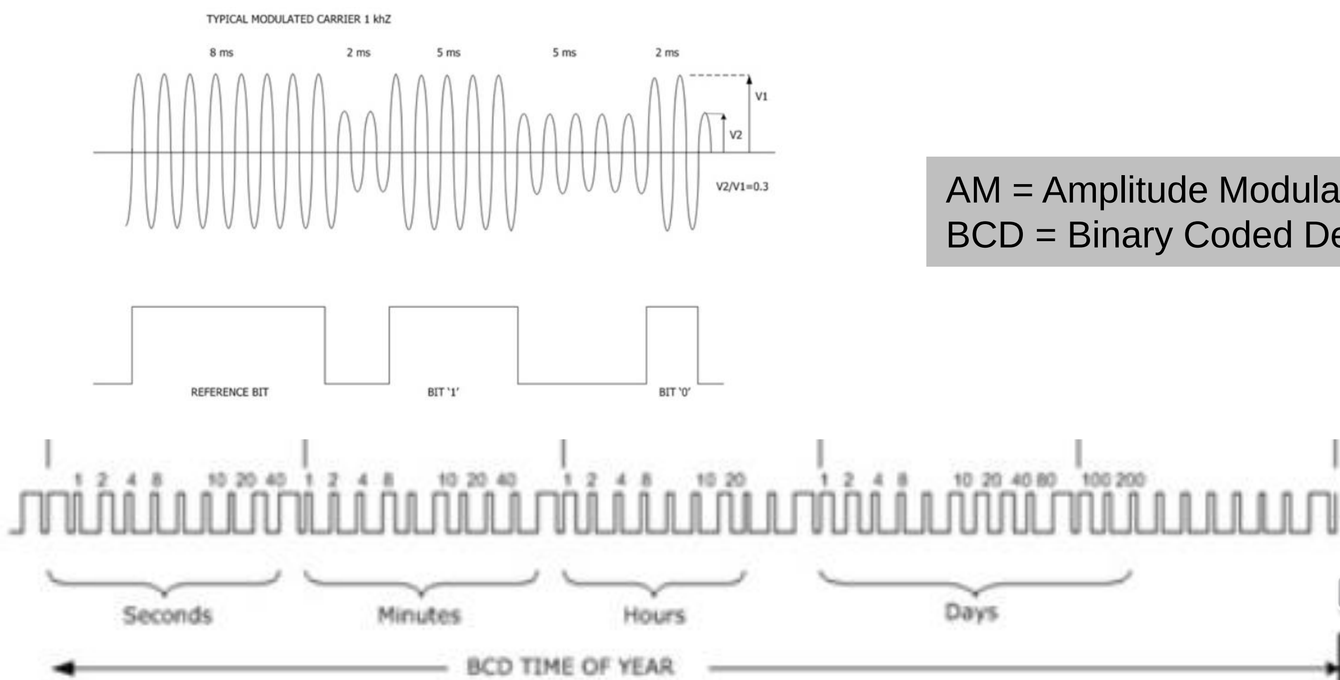


IRIG serial time codes

- IRIG = Inter Range Instrumentation Group (a standard)
- Several time codes, but **IRIG-B** is the most common
- Both AM and DC versions of the code
  - Best time accuracy with DC
  - AM best for transmission over long cables (so this is most common)
  - **Accuracies of the order of a few microseconds or better**
  - Distributed using Coax cable

IRIG-B AM

IRIG-B DC



AM = Amplitude Modulation
BCD = Binary Coded Decimal

GPS with NTP-server and IRIG-B output

Network Time Protocol (NTP)

- NTP is a protocol designed to synchronize the clocks of computers over a network.
- Can provide **accuracies of better than 10 ms over Ethernet.**
  - accuracy depends on the network (local area network vs. Internet)
- User Datagram Protocol (UDP) is used.

Precision Time Protocol (PTP)

- The two primary problems that must be overcome in network timekeeping are oscillator drift and time transfer latency.

- PTP overcomes the Ethernet latency and jitter issues through **hardware time stamping** at the physical layer of the network.
  - The result can be an accuracy in the 10-nanosecond to 100-nanosecond range using **an Ethernet network to carry the timing packets**

[Proposal (en4tel.com)]

IEEE 1588 Protocol (using hardware)

- Gives **sub-microsecond synchronization** in distributed systems.

- IEEE 1588 provides a standard protocol for synchronizing clocks connected via a multicast capable network, such as **Ethernet**.
  - uses the **precision time protocol (PTP).**
  - eliminates the need for additional cabling.

- All participating clocks in the network are synchronized to the highest quality clock in the network.

- The highest ranking clock is called the ***grandmaste****r clock, and* synchronizes all other ***slave*** *clocks.*

IEEE 1588 example for sensor DAQ

- Consider the example of a **real-time control system** that is set up over **Ethernet** with a variety of **independent sensors**.
- Each sensor uses an onboard 1588 clock slaved to a grandmaster clock and is synchronized with the other sensors on the network to an accuracy of 1 microsecond.
- Every 5 milliseconds, each sensor takes a measurement and sends the information back to the controller, using the same LAN that is coordinating the synchronization of the sensors.
- → data is acquired synchronously from the entire system at precise time intervals.

Example from Microsemi_IEEE_1588_PTP_New_Standard_in_Time_Synchronization_White_Paper.pdf

Examples of COTS equipment that support IRIG-B and IEEE 1588

- Timing cards (such NI PXI-6683)
  - IRIG-B and IEEE 1588
- High speed cameras
  - IRIG-B
- Scientific infrared cameras
  - IRIG-B
- Machine vision cameras
  - IEEE 1588

NI PXI-6683: TCXO, GPS, IRIG-B, IEEE 1588
PXI Synchronization Module

Windows & PTP

- From Windows 10 PTP is supported in Windows.
  - Software client.
  - However, a setup of PTP is required in Windows 10!

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Comparison

Table 1 • Comparison of Synchronization Requirements of NTP, IRIG Time Code, and IEEE 1588

Protocol	Sync Accuracy	Interconnect	Required Clock Hardware and Software
NTP	1 ms to 10 ms	Ethernet LAN or WAN	Hardware or software server, software clients
IRIG	1 µs to 10 µs	Coaxial cable	Hardware master and slaves
IEEE 1588	20 ns to 100 ns	Ethernet LAN	Hardware master and slaves

Figure from Microsemi_IEEE_1588_PTP_New_Standard_in_Time_Synchronization_White_Paper.pdf

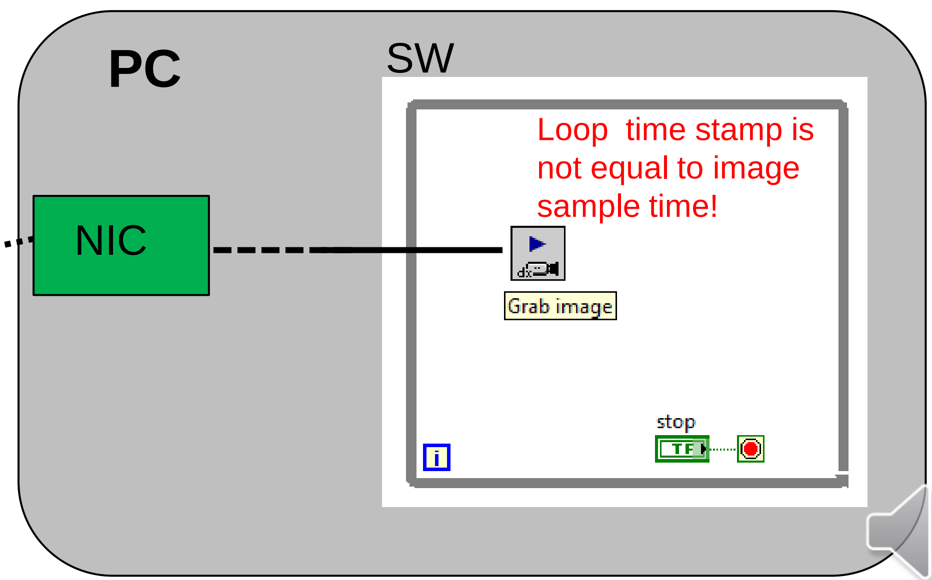
Example - Vision time stamping

Must avoid "software in the loop" to achieve the best possible time accuracy and resolution !

Remember: Data buffers both in camera and in computer RAM!

Camera

Ethernet



Synchronization of video with other data

- In many applications we need to synchronized other measurements (analog or digital data) with acquired images.

- Assume that we have a DAQ-card that samples analog signals and a machine vision camera. Some possible ways of synchronization (depending on hardware possibilities):
  1. Use a trigger from the camera (“image ready”) to trigger a new DAQ-card sampling.
  2. Use a trigger from the DAQ-card to trig acquisition of a new image from the video camera
  3. DAQ-card and camera running using the same clock or clocks that are in phase, and the first “image ready” output from the camera is used as a start trigger.
  4. Log camera synch-output (“image ready”) as an analog signal on the DAQ-card and align data by post-processing.
  5. Free running (not hardware synchronized) DAQ-card and camera, but both timestamp their data based on UTC (GPS) time
     - Combined data offline based on timestamps and interpolation.
  6. A combination of methods above.