UiO : University of Oslo

FYS3240- 4240
Data acquisition & control

Time and synchronization

Spring 2019– Lecture #11

Bekkeng, 28.12.2018

Why is time and synchronization so important?

- Some examples:
  - 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

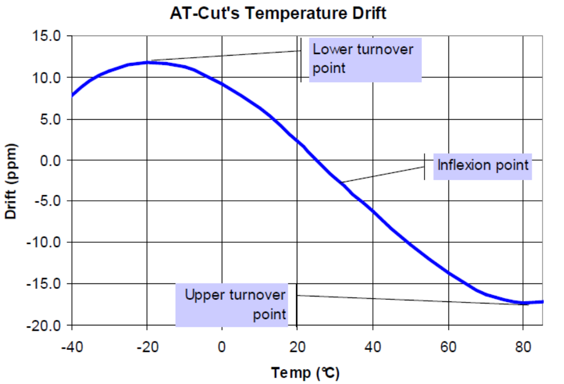
How good is a crystal oscillator (XO) ?

- **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)
  - Oven controlled crystal oscillator (OCXO)
    - the oscillator is enclosed in a temperature controlled oven

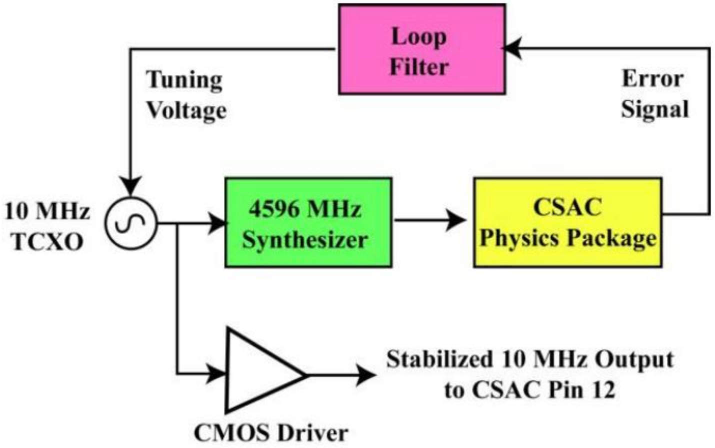
- Some DAQ card accuracy examples:
  - TCXO : 1 ppm
  - OCXO: 50 ppb



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 which is incremented synchronously with the rising edge of the 1 PPS output
  - Can set the TOD

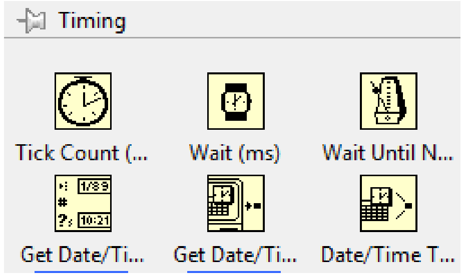


The frequency of the TCXO is continuously compared and corrected to ground state hyperfine frequency of the cesium atoms, contained in the “physics package”, which thereby improves the stability and environmental sensitivity of the TCXO.

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).

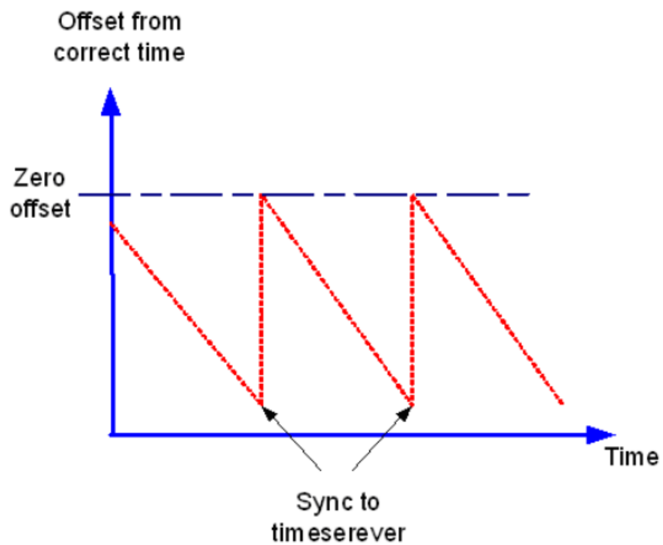
- Software clocks
  - Maintained by the operating system, based on the RTC interrupts.
  - When the system starts it sets the system time to a value based on the real-time clock of the computer and then regularly updates the time based on interrupts from the RTC.



- Timers/Counters
  - 8253/8254 PIT (Programmable Interval Timer)
  - APIC (Advanced Programmable Interrupt Controller)
  - ACPI (Advanced Configuration Programmable Interrupt)

Computer clock drift

- The software clock is a bad timekeeper!
- 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).
- Could update the computer clock often, or read UTC time directly from **a timing card** connected to a GPS antenna, IRIG-B signal or an IEEE1588 signals.



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

High-Resolution Timers/Counters

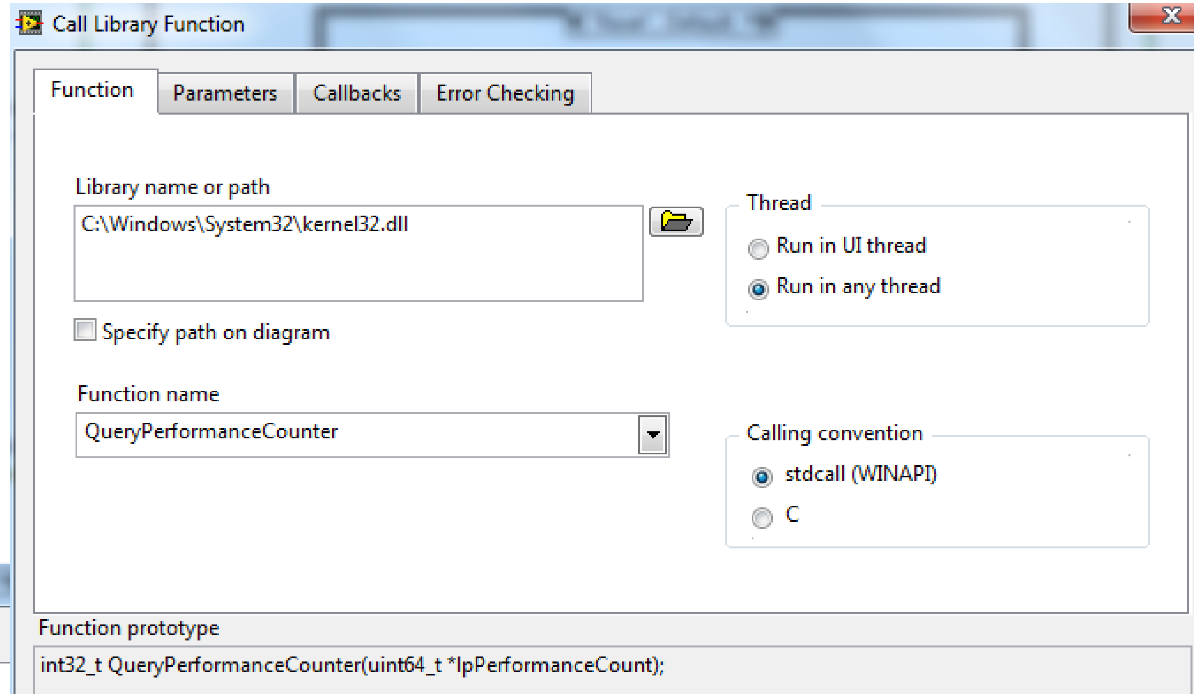
- **High Precision Event Timer (HPET)** is a 64-bit up-counter with a frequency higher than 10 MHz.

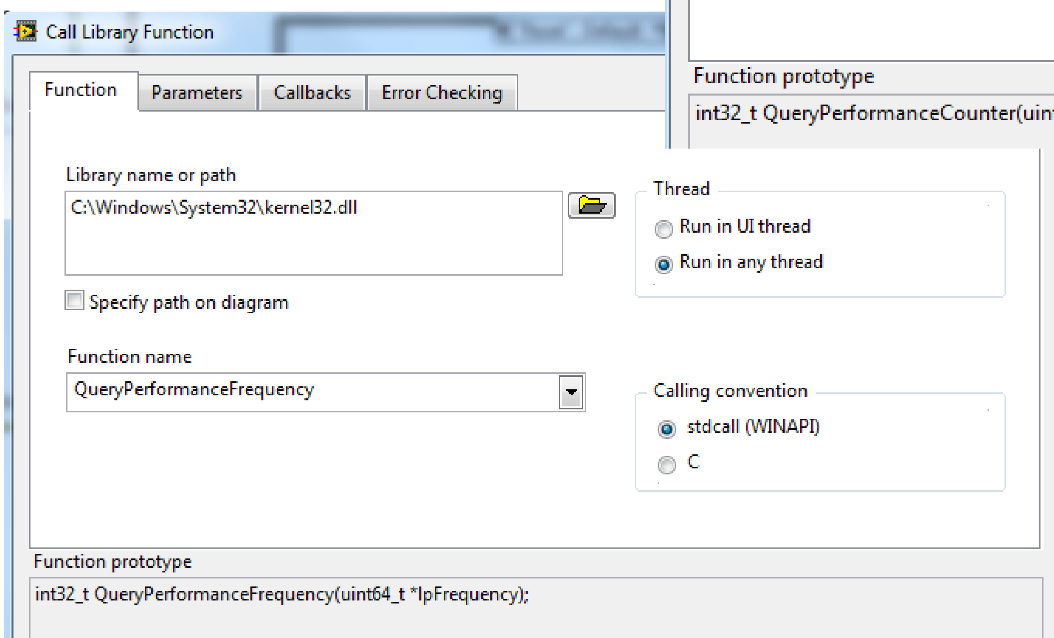
- **Time Stamp Counter (TSC)** is a 64-bit register in the CPU (cores) that increment each processor clock cycle. However, can be unreliable on a modern multicore computer due to:
  - multicore computers can have different values in their time-keeping registers.
  - variability of the CPU frequency due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

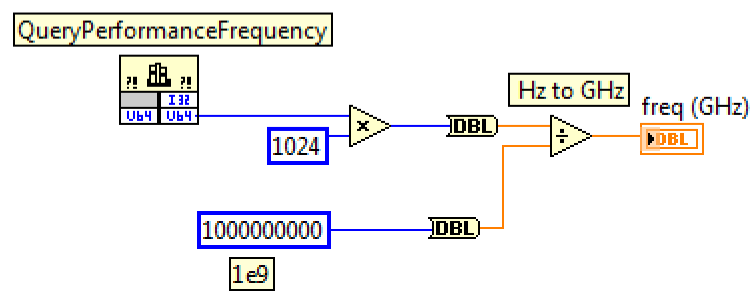
$$\Delta T = \frac{\mathrm{QueryPerformanceCounter(n)} - \mathrm{QueryPerformanceCounter(n-1)}}{\mathrm{QueryPerformanceFrequency}}$$

QueryPerformance from LabVIEW





TSC example



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.

- Since 30 June 2012 when the last leap second was added TAI has been exactly 35 seconds ahead of UTC. The 35 seconds results from the initial difference of 10 seconds at the start of 1972, plus 25 leap seconds in UTC since 1972.

- 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 remains at a constant offset of 19 seconds with TAI.
  - GPS time is now **18 seconds ahead** of UTC because of the leap seconds added to UTC.
  - A new leap second correction was added to UTC in 2016
  - 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.

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

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

Time dilation

local	2018-12-28 19:17:53	Friday	day 362	timezone UTC+1
UTC	2018-12-28 18:17:53	Friday	day 362	MJD 58480.76241
GPS	2018-12-28 18:18:11	week 2033	497891 s	cycle 1 week 1009 day 5
Loran	2018-12-28 18:18:20	GRI 9940	217 s until	next TOC 18:21:30 UTC
TAI	2018-12-28 18:18:30	Friday	day 362	37 leap seconds

Time stamping of data

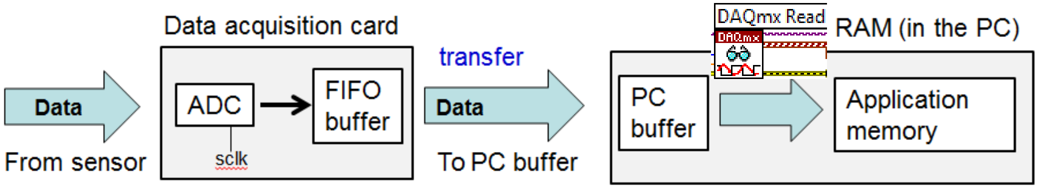
- Often need to timestamp an image in a video stream or a block of data from a DAQ-card to GPS (UTC) time; e.g. for use in data fusion in post-analysis.
- If the data samples has a deterministic (regular) interval, such as samples from a DAQ-card, it is sufficient to time stamp the first sample at time t_0:

  - $t_0 = T_{ReadFinished} - \Delta t * (number\ of\ samples) - t_{delay}$
  - Given t_0 the time of the remaining samples are found from:

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

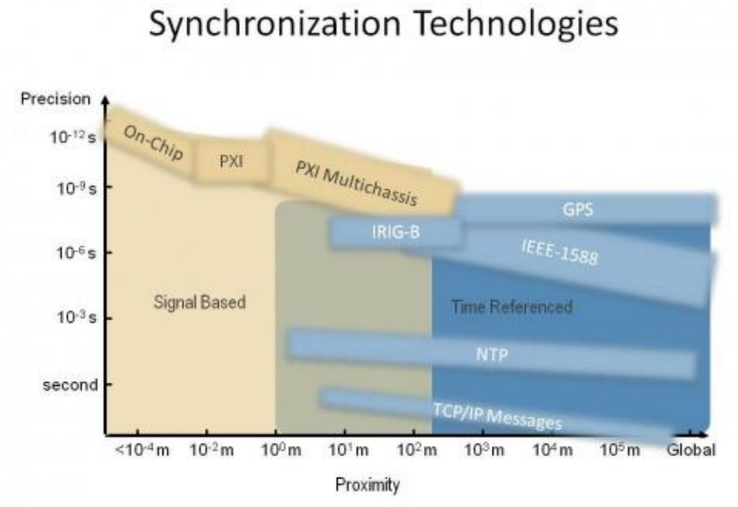
$$\Delta t = \frac{1}{fs}$$

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

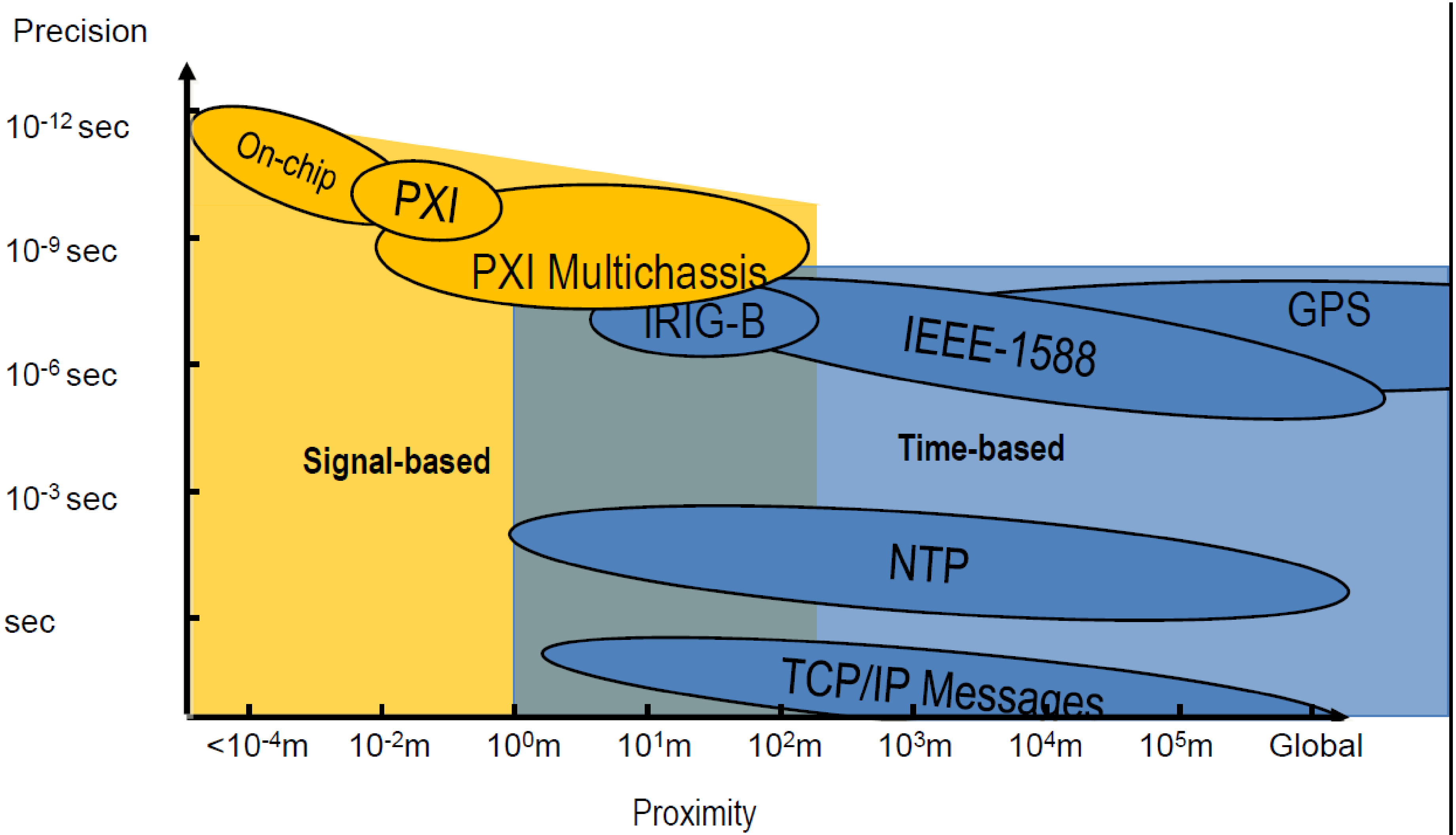


Signal based vs. time-based synchronization

- **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.

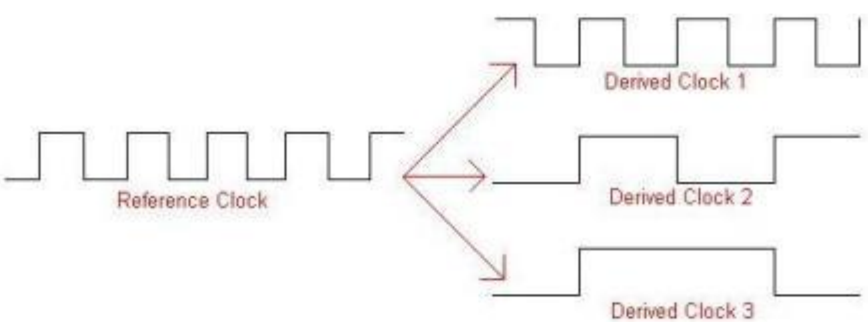


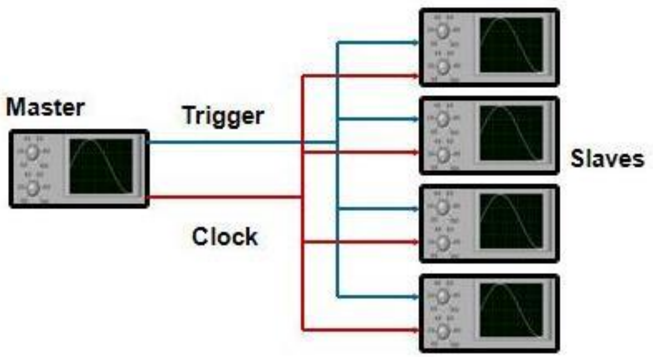
Synchronization technologies



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.
- For example, modular instruments in a PXI chassis all share a common 10 MHz clock signal from the PXI backplane.
- To accurately use a common timing signal, a device must be calibrated to account for the signal propagation delay from the timing source to the device

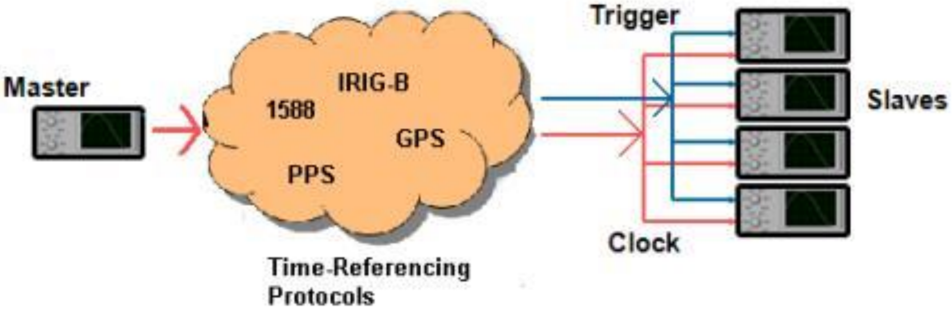




Time-based synchronization

- Necessary for long distances

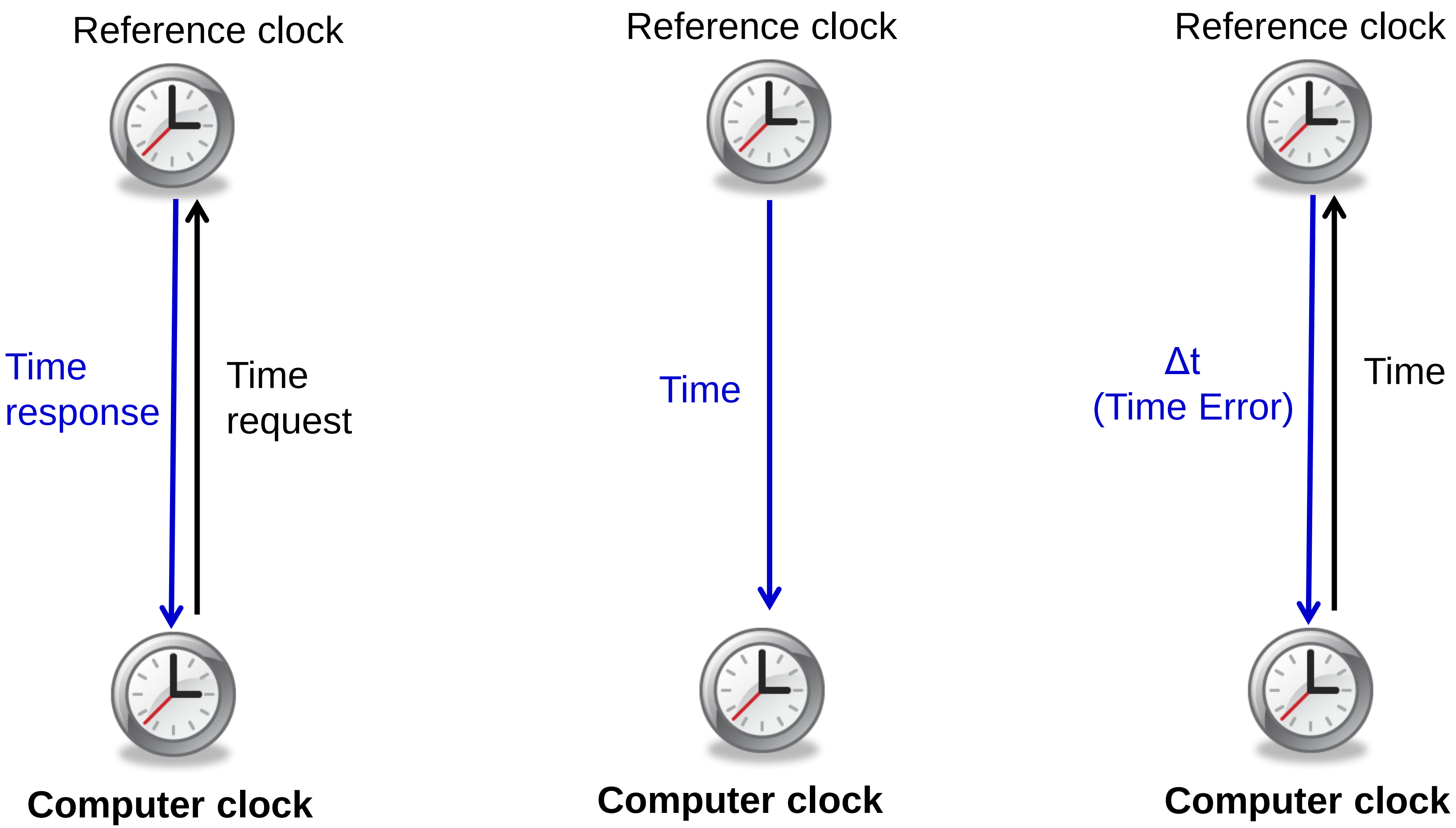
- Because of the inherent instabilities in (crystal oscillator) clocks, distributed clocks must be synchronized continuously to a time refererence to match each other in frequency and phase.



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

Timing and Synchronization Systems

Global time – possible implementations

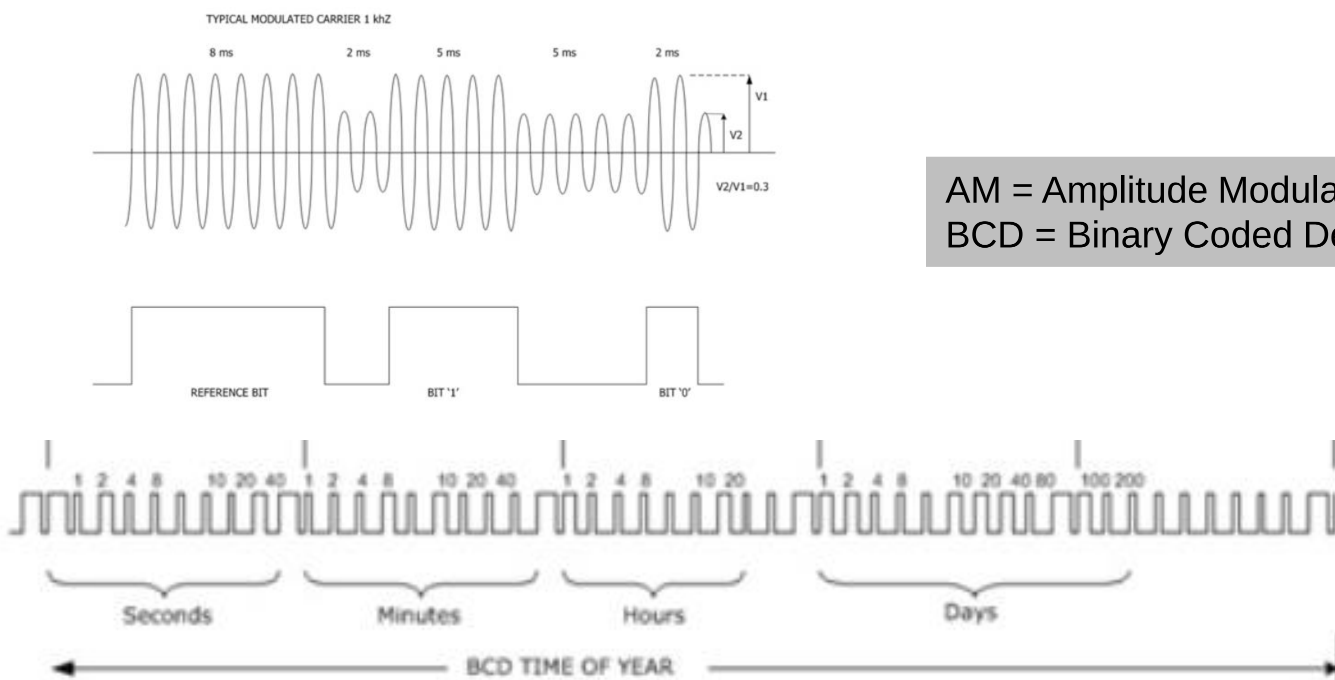


IRIG serial time codes

- 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
  - **Accuracies of the order of a few microseconds or better**

IRIG-B AM

IRIG-B DC



AM = Amplitude Modulation
BCD = Binary Coded Decimal

GPS with NTP-server and IRIG-B output

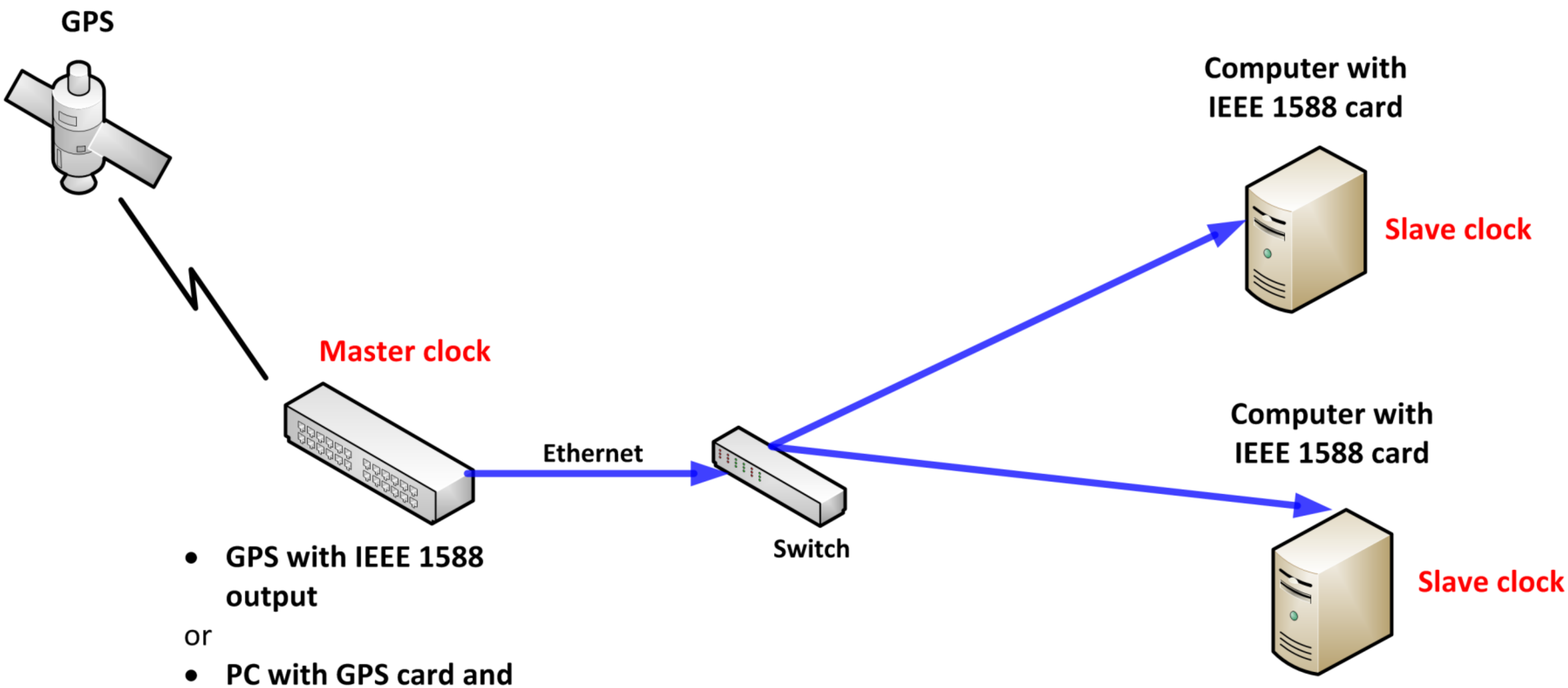
Network Time Protocol (NTP)

- 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.
- Edited from Wikipedia:
  - "NTP can usually maintain time to within tens of milliseconds over the public Internet, and can achieve better than one millisecond accuracy in local area networks under ideal conditions. Network problems can cause errors of 100 ms or more"
  - All Microsoft Windows versions since Windows 2000 and Windows XP include the **Windows Time Service**, which has the ability to sync the computer clock to an NTP server. The version in Windows 2000 and **Windows XP only implements Simple NTP (SNTP), and violates several aspects of the NTP version standard**. Beginning with Windows Server 2003 and Windows Vista, a compliant implementation of full NTP is included.

IEEE 1588 Protocol

- 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 a protocol known as the precision time protocol (PTP).
- 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.*
- The level of precision achievable using **PTP (Precision Time Protocol)** depends heavily on the jitter (the variation in latency) present in the underlying network topology.
  - Point-to-point connections provide the highest precision.

GPS & IEEE 1588 used for time synchronization of multiple PCs



- GPS with IEEE 1588 output

or

- PC with GPS card and IEEE 1588 output

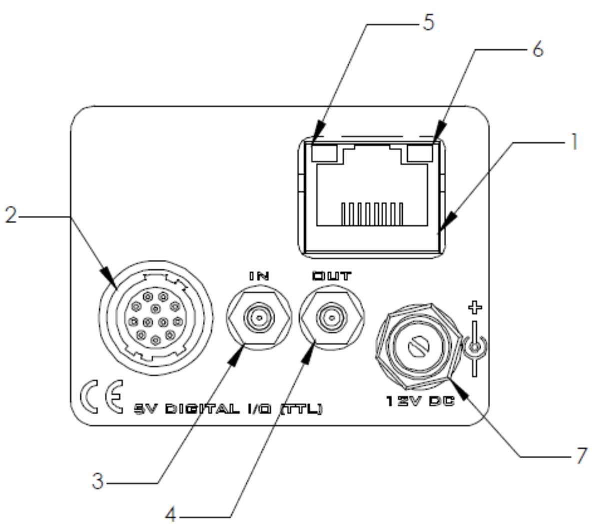
or

- PC with IRIG-B input (from a GPS) and IEEE 1588 output

IEEE1588 can be used for applications that require higher accuracy than NTP but that cannot afford the cost of a GPS receiver at each node (or for which GPS signals are inaccessible)

Example - Vision time stamping

Visual camera (205 fps)



Question: How to accurately time stamp each image from a camera to GPS time, without any delay added from the software loop?