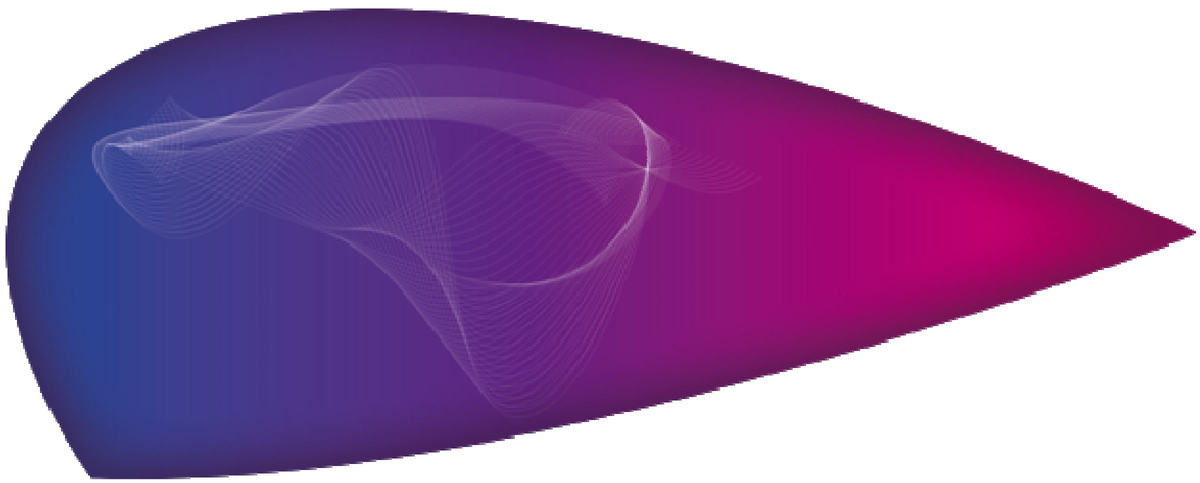
Fundamentals: Frequency & Time Generation



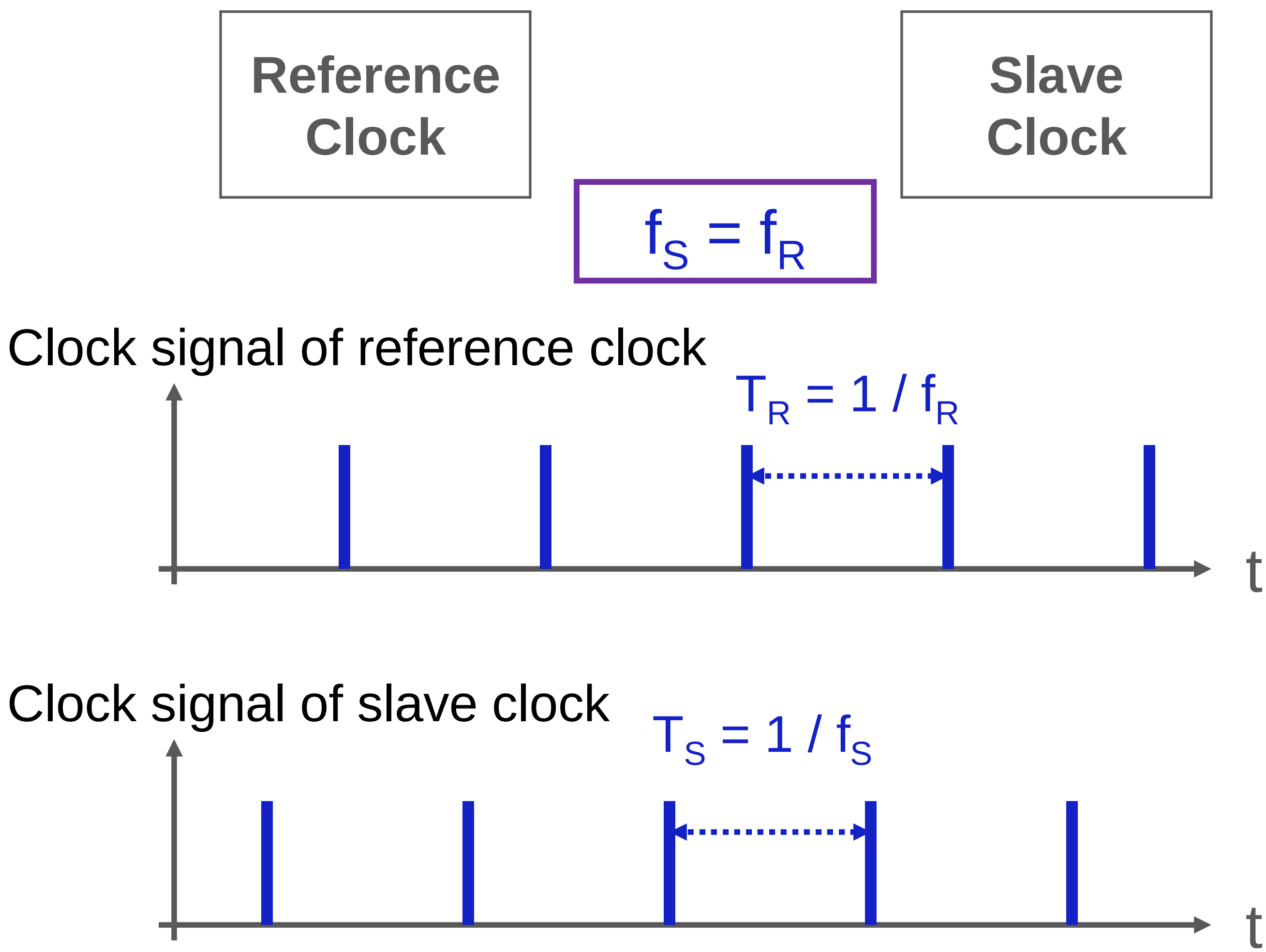
Dominik Schneuwly

Oscilloquartz SA

Content

1. Fundamentals

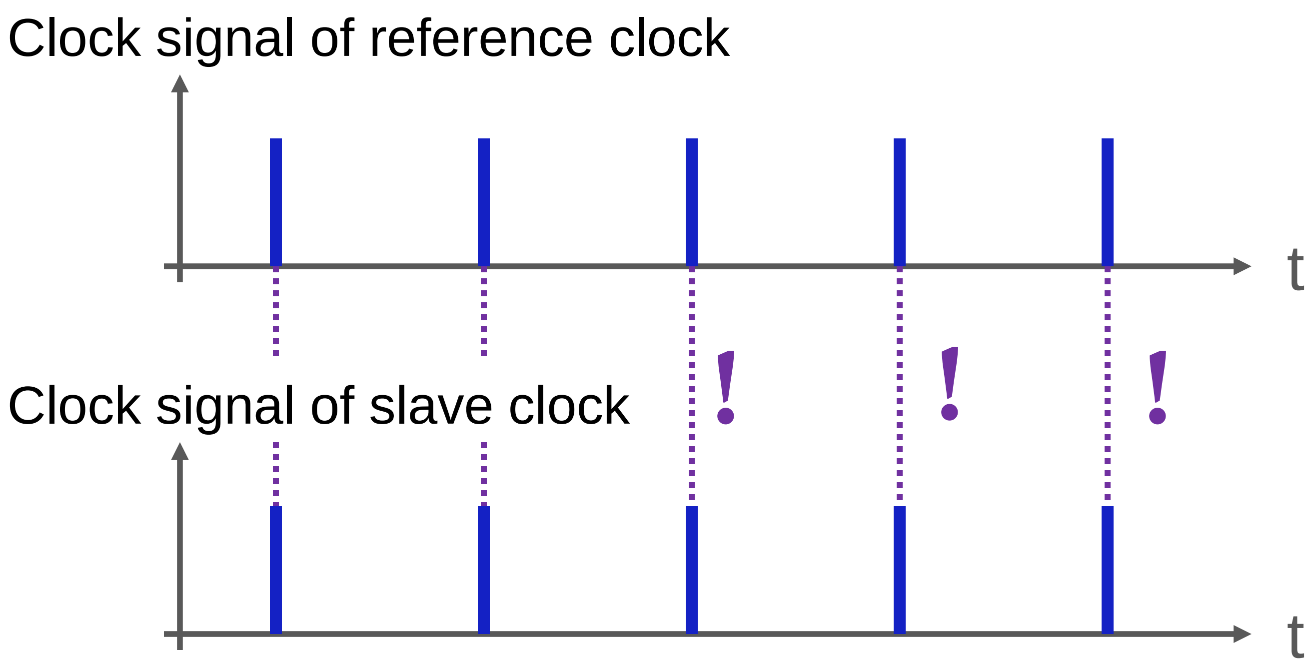
Frequency Synchronization (Syntonization)



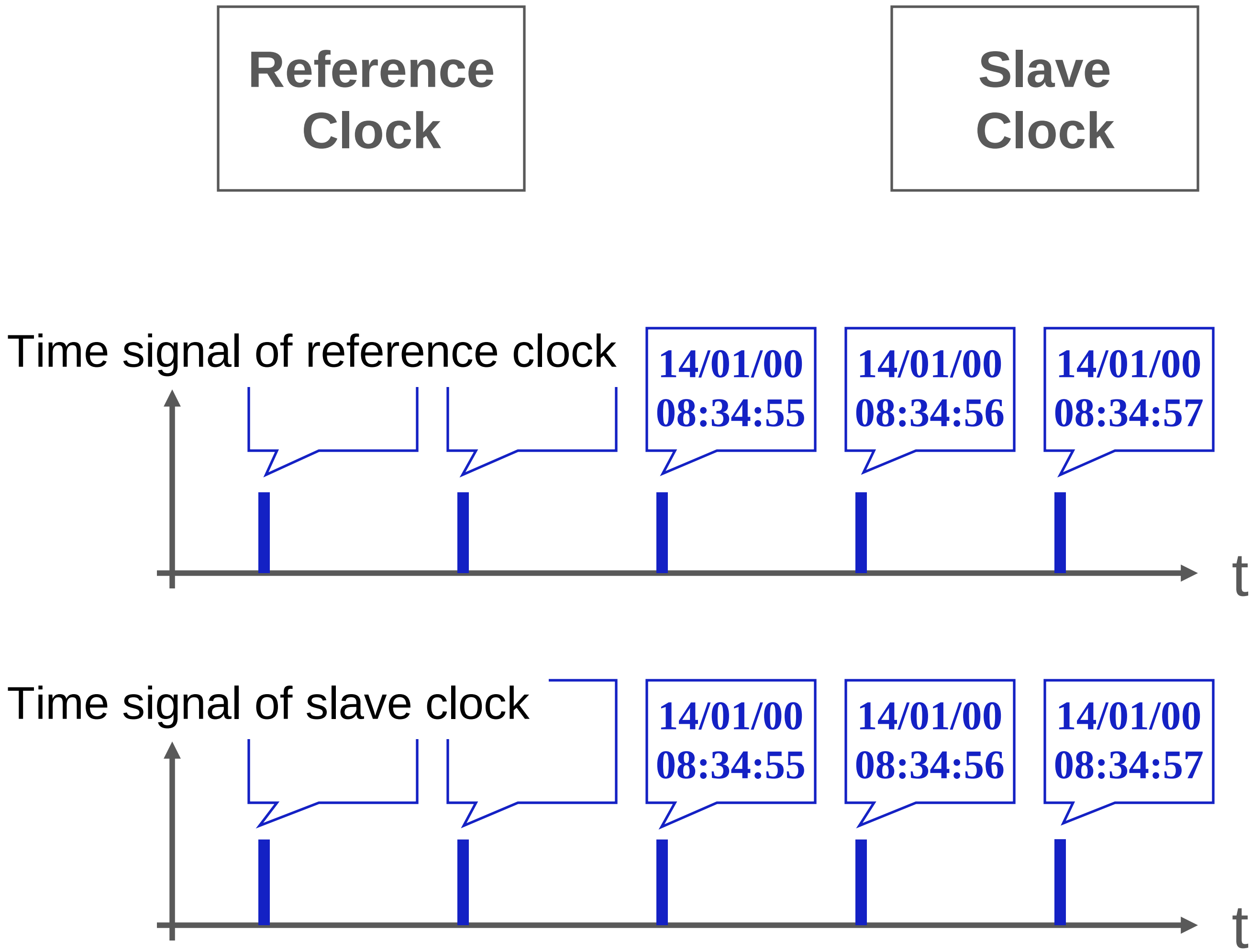
Phase Synchronization

Reference Clock

Slave Clock

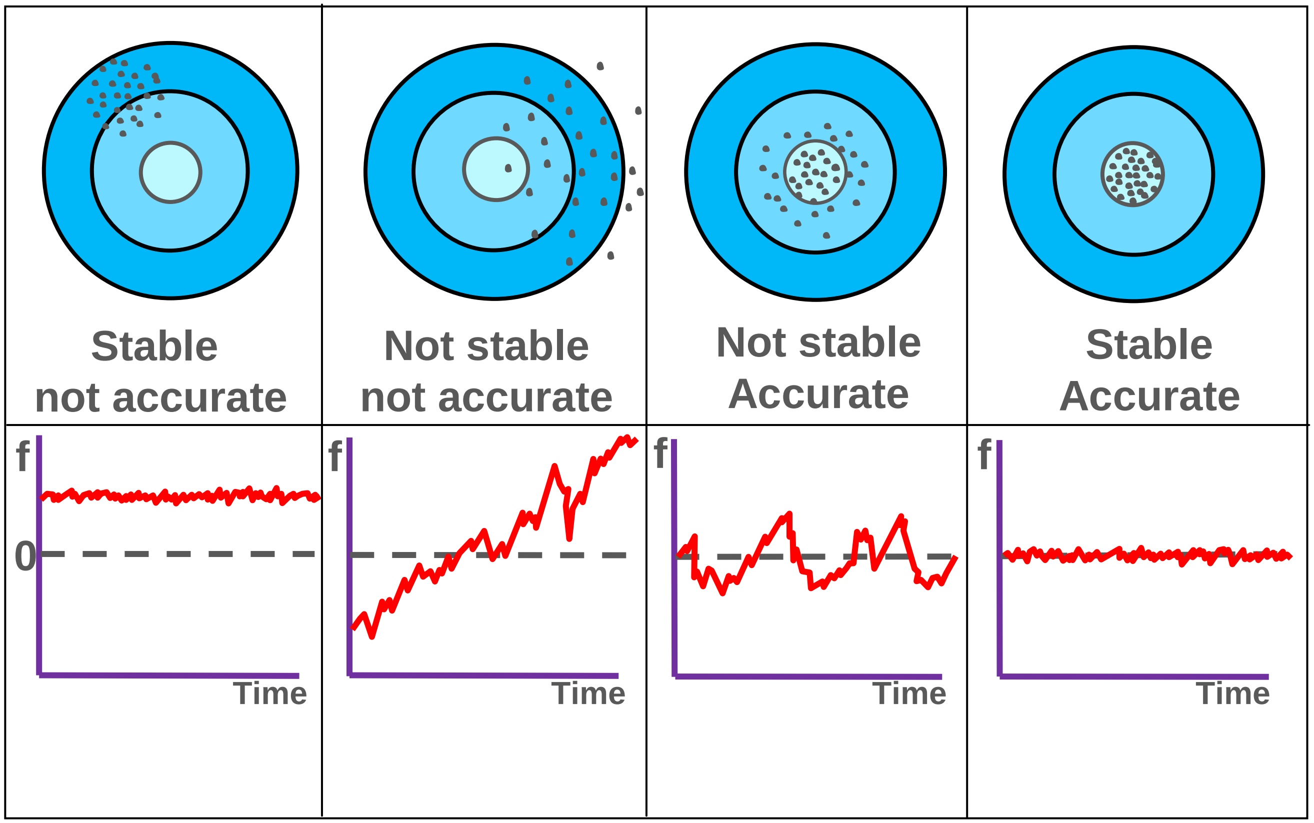


Time Synchronization

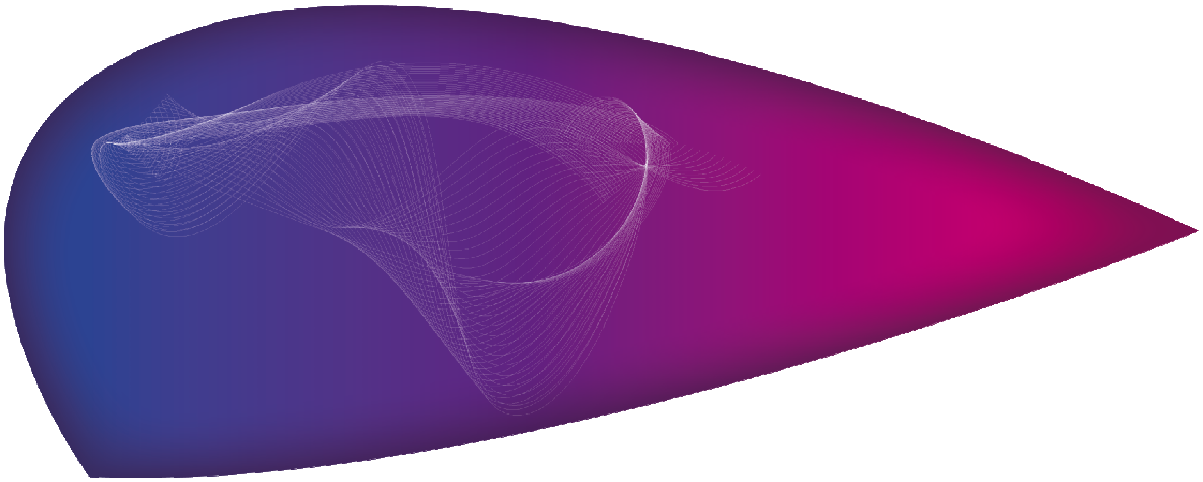


Accuracy and Stability

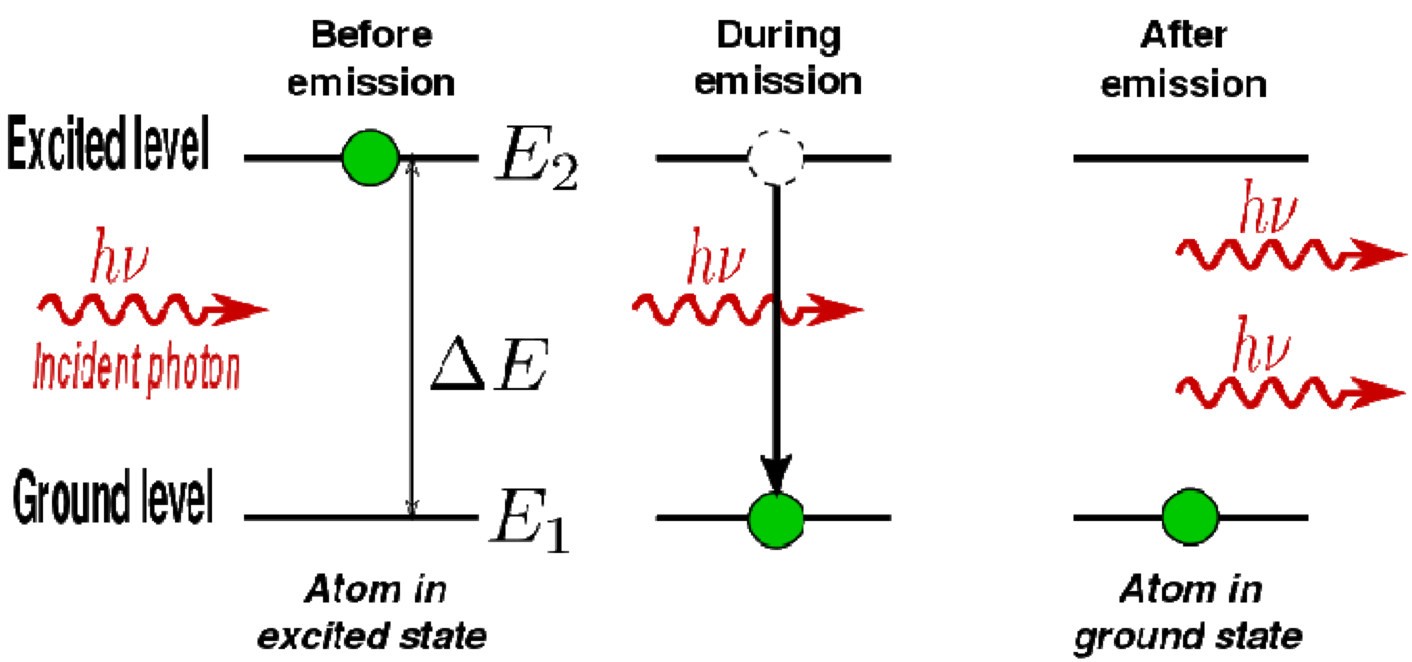
- **Accuracy**: Maximum (freq., phase or time) error over the entire life of the clock
- **Stability**: (Freq., phase or time) change over a given observation time interval
- Stability is expressed with some statistical dispersion metric as a function of observation interval (e.g. ADEV, TDEV, MTIE, a.o.)



2. Generation of Frequency



Frequency generation: **atomic cesium clock (Cs)**
Stimulated Emission

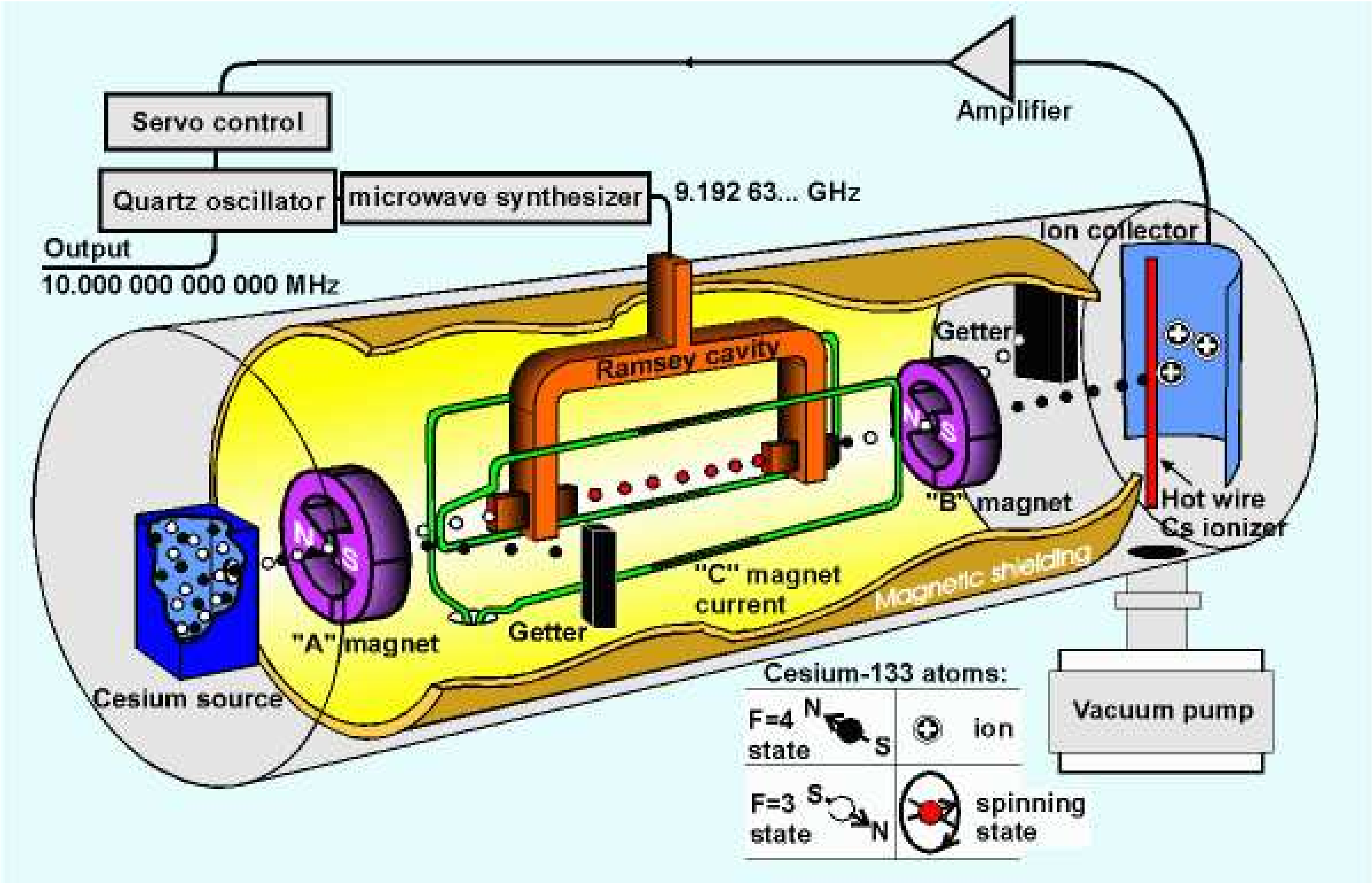


$$E_2 - E_1 = \Delta E = h\nu$$

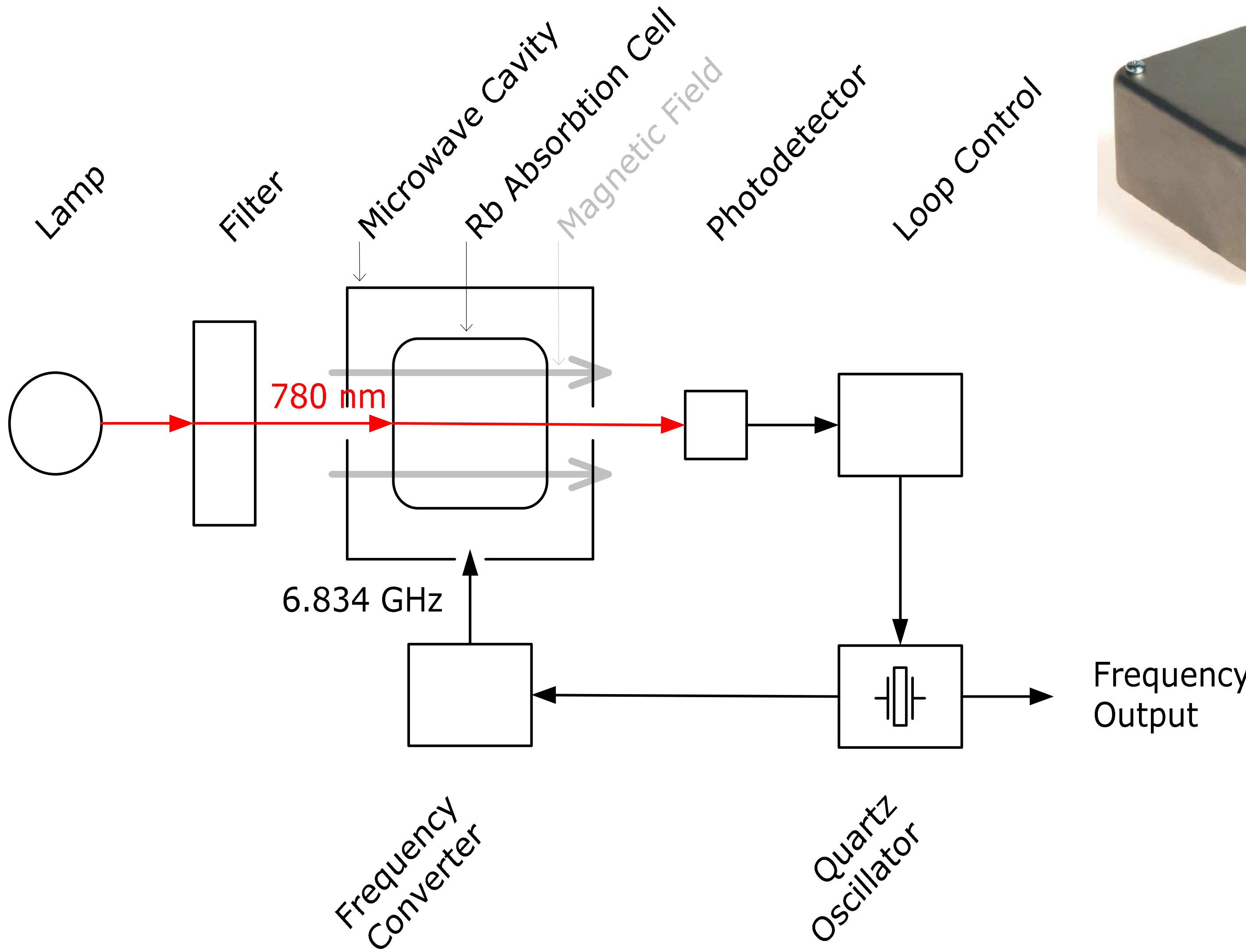
Frequency generation: **atomic cesium clock (Cs)**
Working principle

- In a cesium clock, cesium is heated to a gaseous state in an oven. A hole in the oven allows the atoms to escape at high speed.
- Magnets separate the atoms to exclude the impurities.
- The atoms that can absorb energy are directed through a microwave cavity where they are exposed to radiation with a frequency very close to 9,192,631,770 cycles per second, which is given by the Quartz Oscillator.
- These atoms are then pushed by another set of magnets toward a detector.
- This feedback tunes the microwave frequency until it exactly matches the radiation frequency of the cesium atoms, maximizing the number of atoms that reach the detector.
- Once the microwave frequency is locked into the cesium atoms' frequency, it is then divided down to a frequency that can be used to mark time accurately to a few billionths of a second.

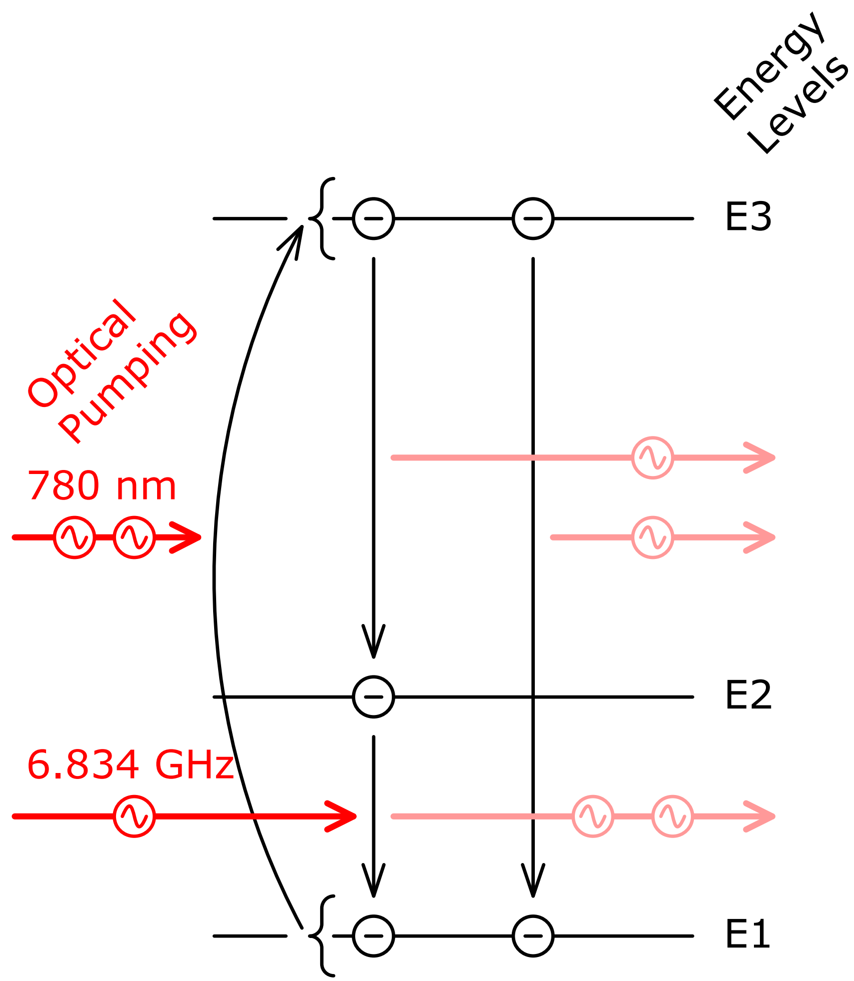
Frequency generation: **atomic cesium clock (Cs)**
Magnetic Cesium Beam Tube



Frequency source: **atomic rubidium oscillator (Rb)**



Frequency source: **atomic rubidium oscillator (Rb)**



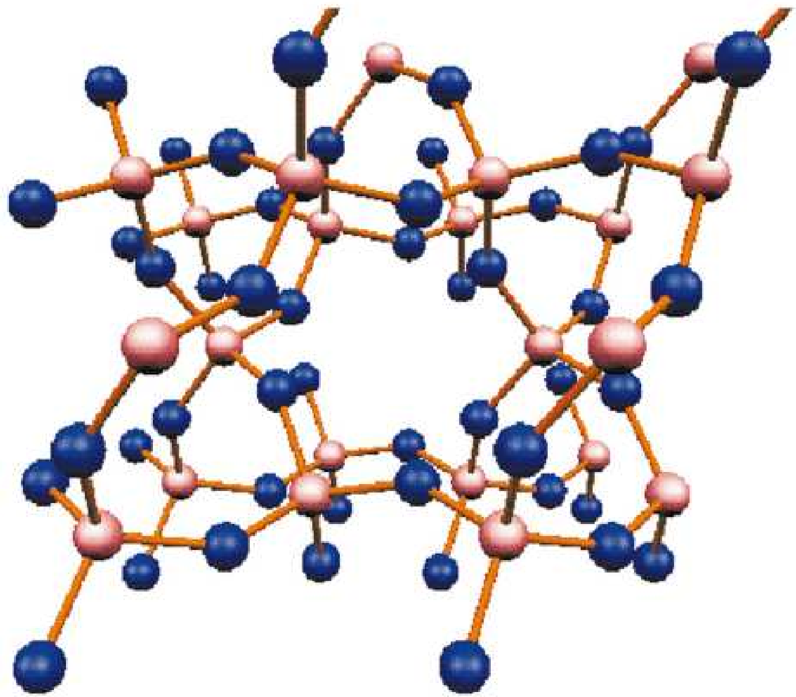
Frequency generation: **atomic rubidium oscillator (Rb)**
Working principle

- Light from ^{87}Rb lamp contains both 3-1 and 2-1 lines.
- ^{85}Rb cell filters out the 2-1 line and transmits the 3-1 line.
- The filtered light “optically pumps” ^{87}Rb atoms in the resonance cell from level 1 to 3.
- The injected microwave frequency at 6.834 GHz induces transition from level 2 to 1.
- When the injected frequency matches the difference 2-1, the photo-diode detects a reduction in the amount of light.
- This feedback tunes the microwave frequency until it exactly matches the 2-1 difference.
- Once the microwave frequency is locked to the rubidium atoms' frequency, it is then divided down to a lower frequency.
- There exist other variants of Rubidium oscillators with a slightly different working principle (tuned laser diode instead of ^{87}Rb lamp, no microwave cavity).

Frequency generation: **quartz crystal oscillator (XO)**
Quartz crystal

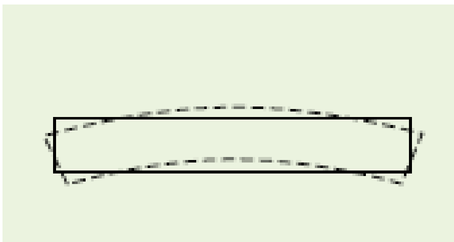
Quartz = SiO_2

Pink = silicon atoms
Blue = oxygen atoms

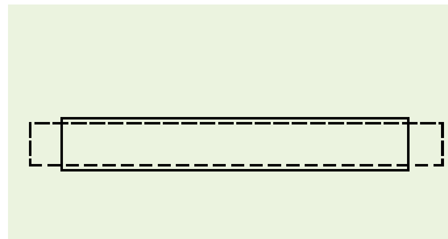


Quartz lattice

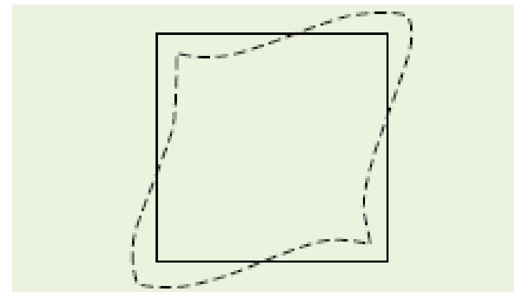
Frequency generation: **quartz crystal oscillator (XO)**
Vibration modes of quartz plates



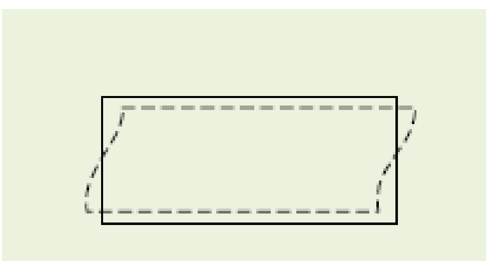
Flexure Mode



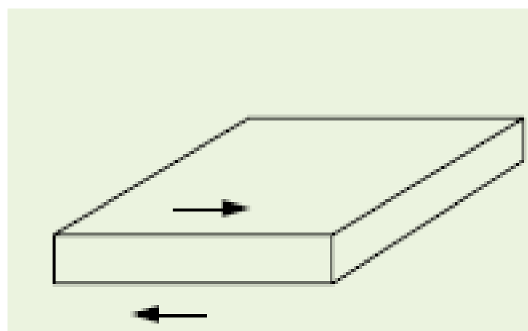
Extensional Mode



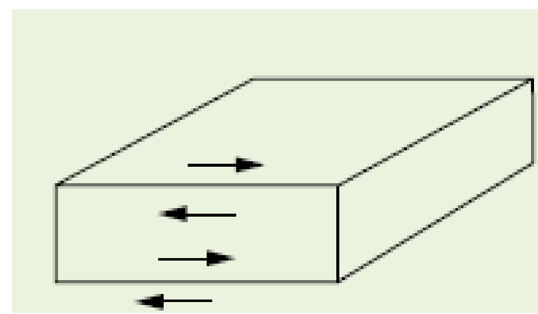
Face Shear Mode



Thickness Shear Mode



Fundamental Mode Thickness Shear

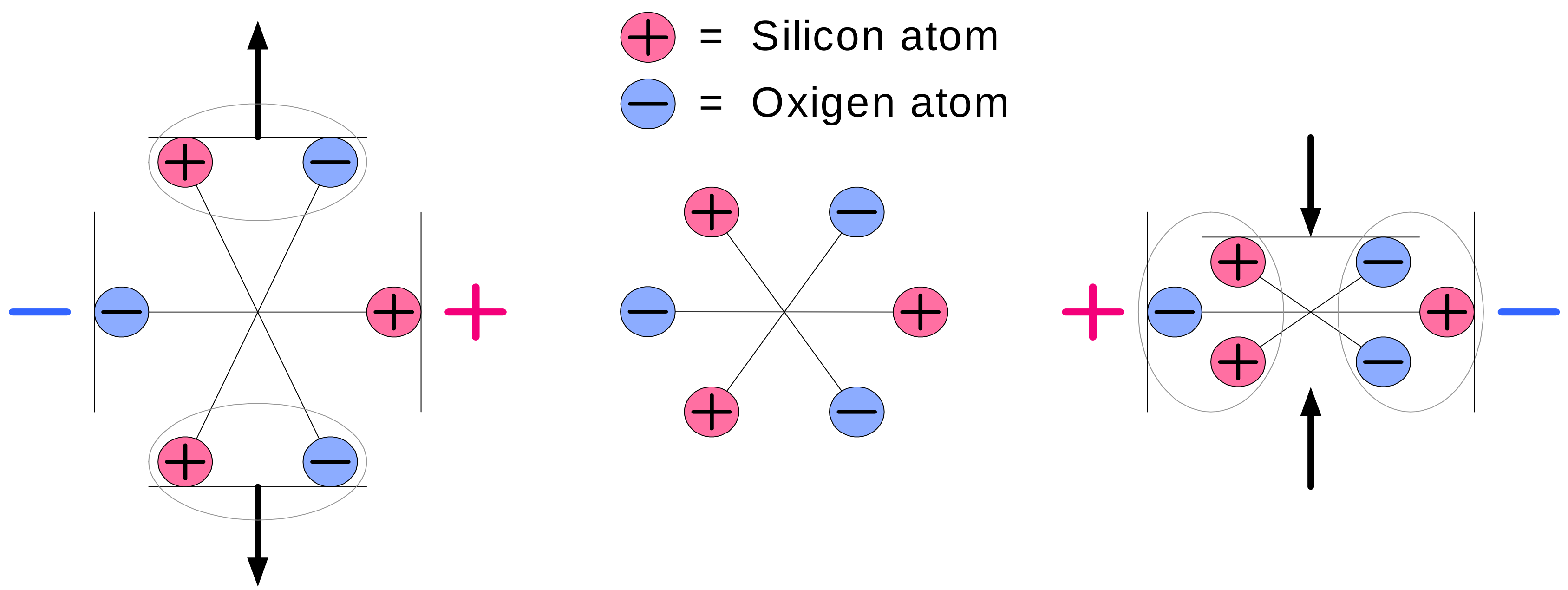


Third Overtone Thickness Shear

Frequency generation: **quartz crystal oscillator (XO)**
Piezo-electric effect in quartz

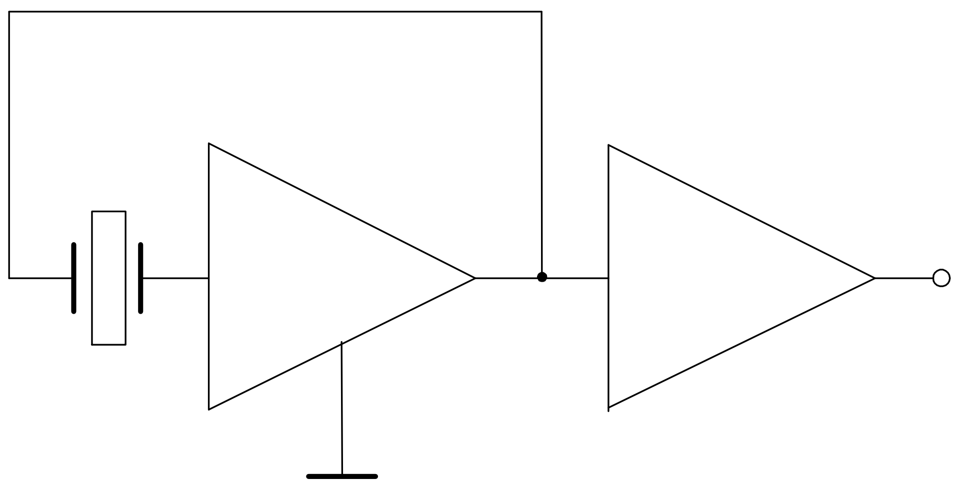
Piezo-electric effect:

- Mechanical strain ⇒ voltage
- Voltage ⇒ mechanical deformation



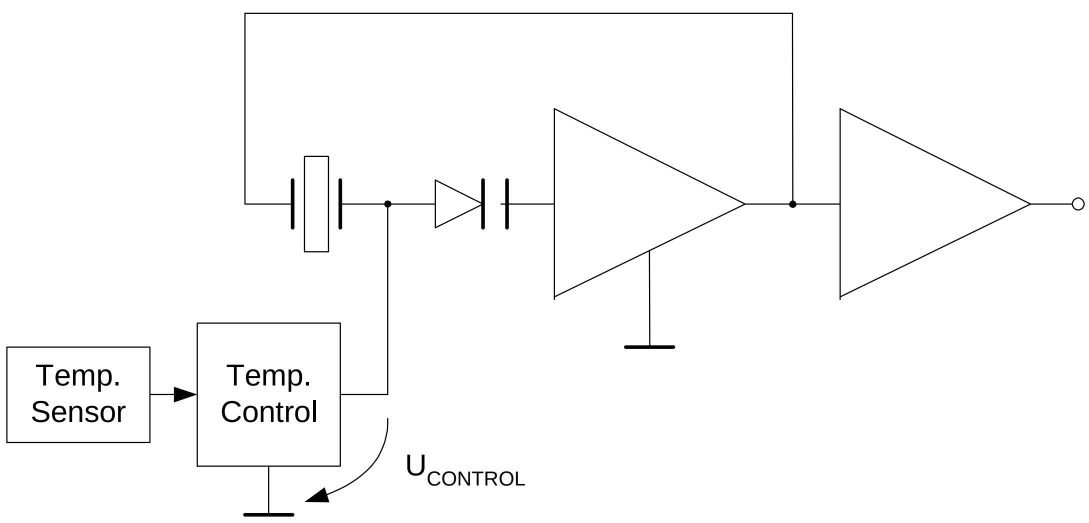
Frequency generation: **quartz crystal oscillator (XO)**
Simple XO

- Quartz resonator in a feedback loop
- Resonance frequency depends somewhat on temperature
- Resonator is cut in such a way as to mimimize temperature dependency
- Temp. sens. of fractional freq.: > 1E-7 / °C



Frequency generation: **quartz crystal oscillator (XO)**
Temperature Compensated XO (TCXO)

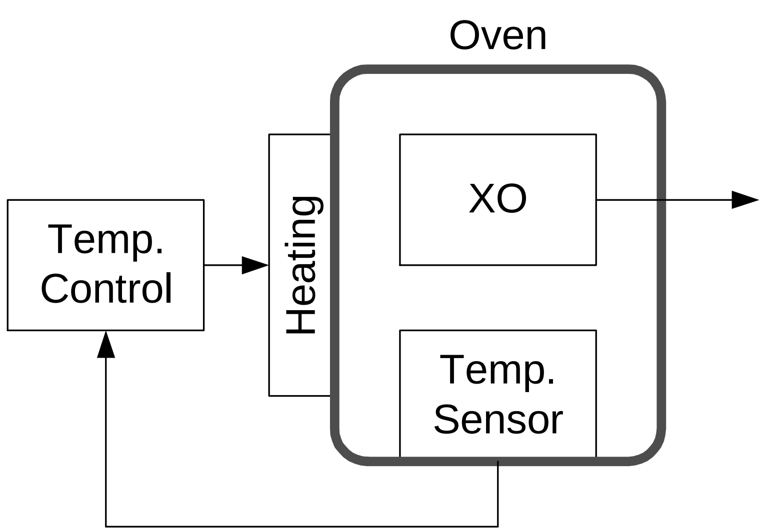
- Resonance frequency is modified by a varactor diode so as to compensate temperature sensitivity
- Temp. sens. of fractional freq.: 5E-8 to 5E-7 over [-55°C to 85°C]

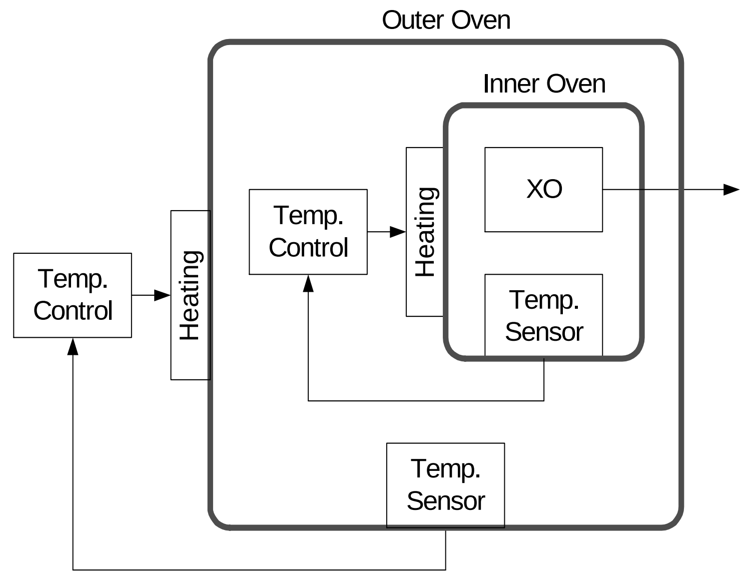


Frequency generation: **quartz crystal oscillator (XO)**
Oven-controlled XO (OCXO)

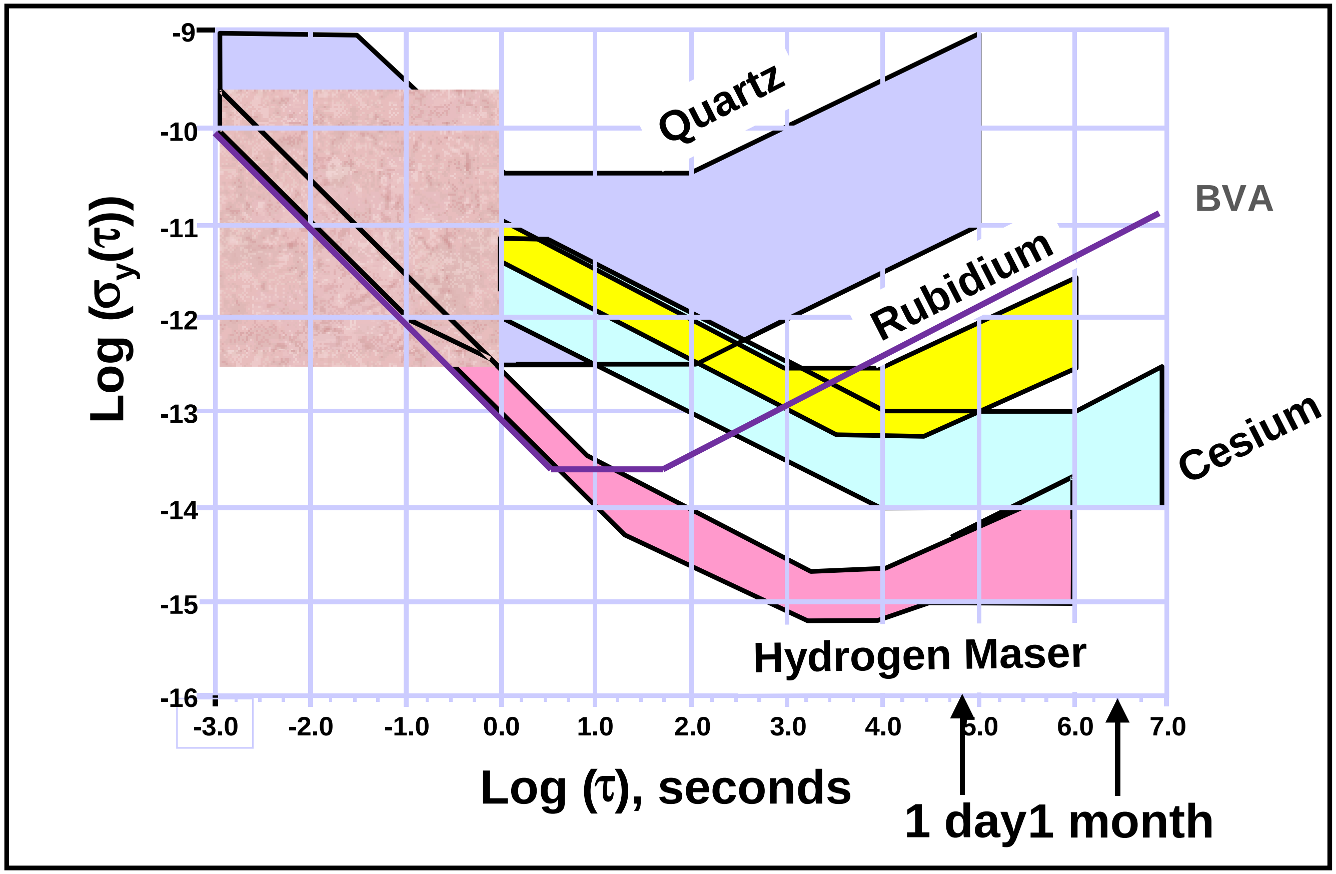
- A control loop maintains the oven containing the XO at (nearly) constant temperature.
- One or two ovens
- Single oven OCXO: 5E-9 to 5E-8 over [-30°C to 60°C]
- Double oven OCXO: 1E-10 to 5E-9 over [-30°C to 60°C]
- Double oven OCXO with BVA: 1E-10 over [-30°C to 60°C], 5E-11 over [-15°C to 60°C]

Note 1: BVA = high tech resonator with improved ageing





Frequency generation: **comparison** between XO, Rb, Cs & H



Abscissa: observation interval

Ordinate: ADEV, a frequency stability metric

Frequency generation: **comparison** between XO, Rb & Cs

	OCXO	Rb	Cs
Fractional Frequency Drift	$5 \cdot 10^{-12}$/day to $2 \cdot 10^{-9}$/day	$4 \cdot 10^{-11}$/month to $3 \cdot 10^{-10}$/month	0
Fractional Frequency Accuracy	-	-	$1 \cdot 10^{-12}$ to $5 \cdot 10^{-13}$
Temperature Sensitivity	$7 \cdot 10^{-13}$/°C to $5 \cdot 10^{-10}$/°C	$1 \cdot 10^{-12}$/°C to $1 \cdot 10^{-11}$/°C	$1 \cdot 10^{-13}$/°C to $1 \cdot 10^{-14}$/°C

3. Time Scale Genearation

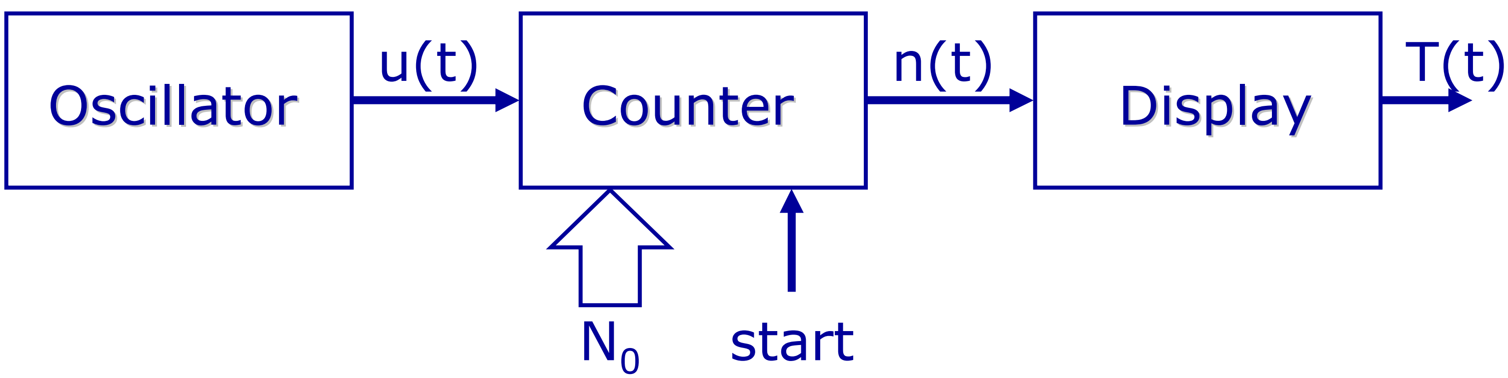
Time scale generation: **clocks and time scales**

A time scale is defined by:
1) a time unit
2) a time origin

A date is a number of units on the time scale

A clock consists of:

1) a periodic phenomenon which can be observed
2) a counter which counts the number of periods
3) a means for setting the counter to a preset value
4) a display of the registered count



Time scale generation: **definition of the second**

The second is the time unit of the International System of Units (SI).

Definition:

The second is the duration of 9 192 631 770 periods of the radiation corresponding to the transition between the two hyperfine levels of the fundamental state of the Cesium 133 atom.

Time scale generation: **atomic time scales**

Origin of Atomic Time Scales :

1 January 1958, on 0 h 0 min 0 s UT2

International Atomic Time (TAI) :

Time scale based on the definitions of the second and of the origin of Atomic Time Scales (as mentioned above), and implemented by a network of atomic clocks located all over the earth and operated by the Bureau International de l'Heure (BIH) in Paris .

Time scale generation: **atomic time scales**

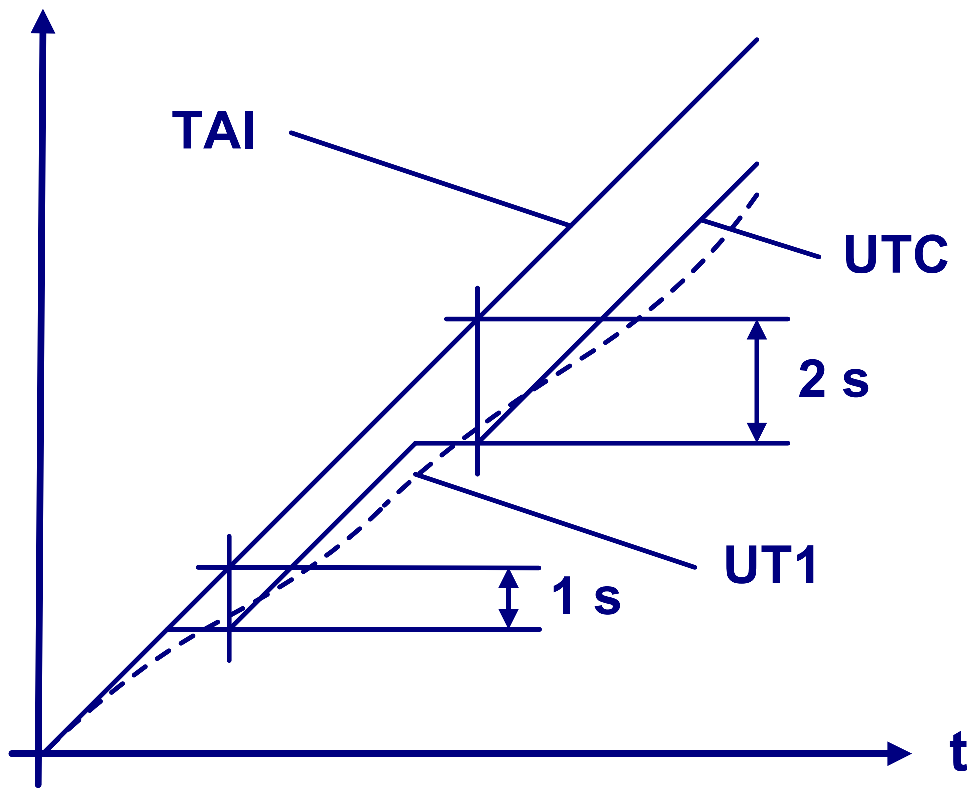
Coordinated Universal Time (UTC) :

Timescale based on the time unit of TAI, but adjusted by means of leap seconds so as to keep within 0.9 seconds of UT1; UTC differs from TAI by an integer number of seconds; leap seconds are added or subtracted when necessary at the end of the last day of a month.

UT1: based on the rotation of the Earth around its axis

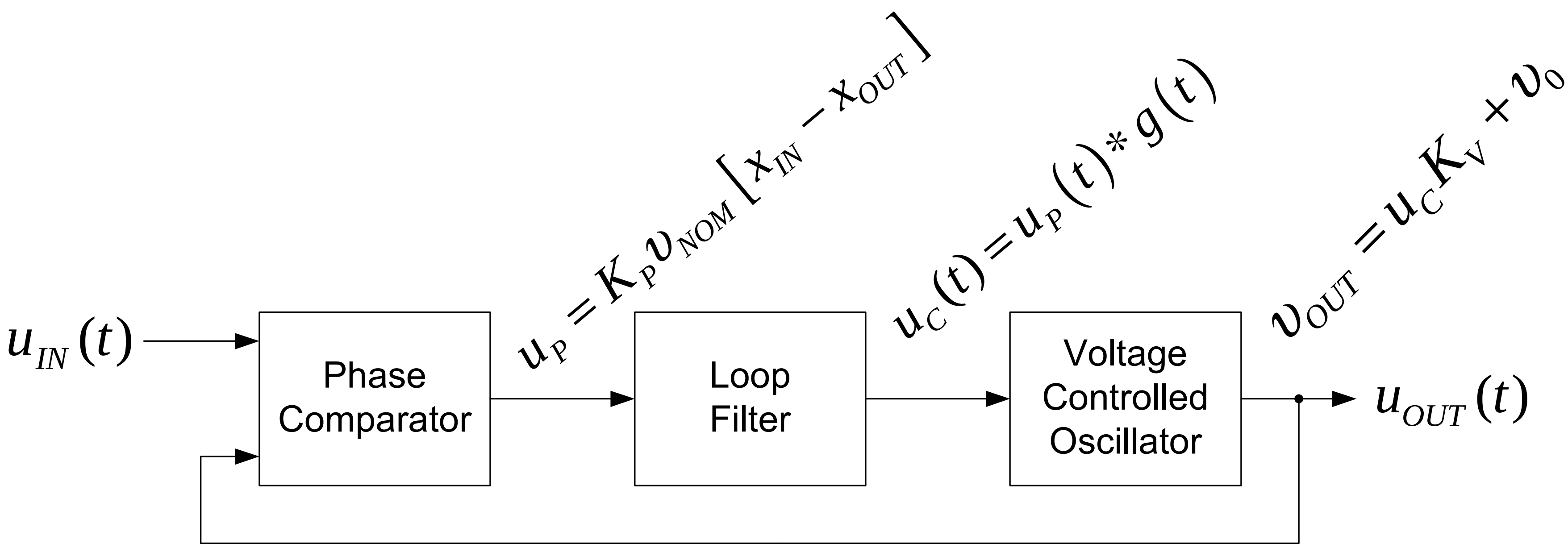
UT2: based on the rotation of the Earth around the sun

Time scale generation: **atomic time scales**



4. Phase Locked Loop (PLL)

PLL: Working principle



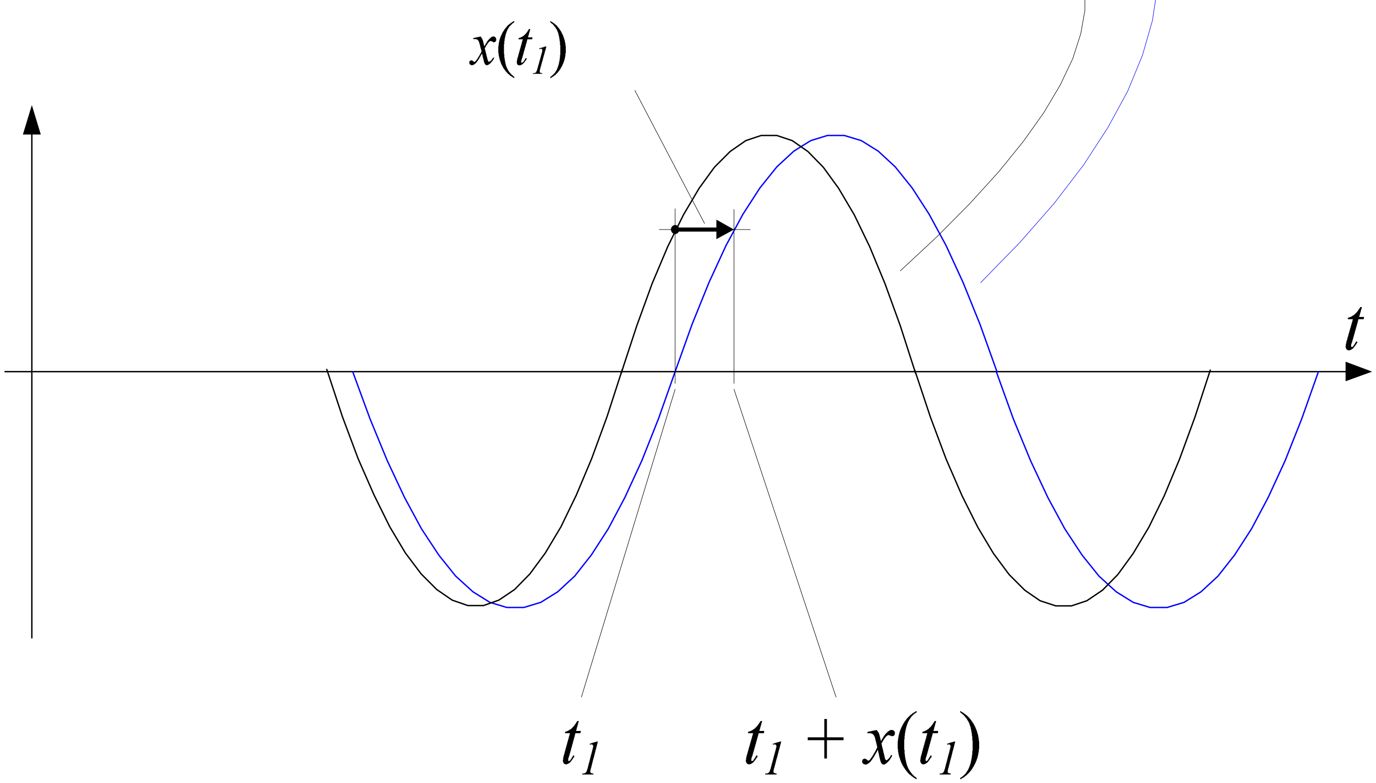
$$u_{IN}(t) = A \cdot \sin\left\{2\pi\upsilon_{NOM}\left[t + x_{IN}(t)\right]\right\} = A \cdot \sin\left\{2\pi\upsilon_{IN}(t) + \varphi_{0,IN}\right\}$$

$$u_{OUT}(t) = A \cdot \sin\left\{2\pi\upsilon_{NOM}\left[t + x_{OUT}(t)\right]\right\} = A \cdot \sin\left\{2\pi\upsilon_{OUT}(t) + \varphi_{0,OUT}\right\}$$

PLL: Phase-time deviation x(t)

$$\text{nominal signal} = \sin\left\{2\pi\upsilon_{NOM}t\right\}$$

$$\text{actual signal} = \sin\left\{2\pi\upsilon_{NOM}\left[t + x(t)\right]\right\}$$



PLL: Transfert function

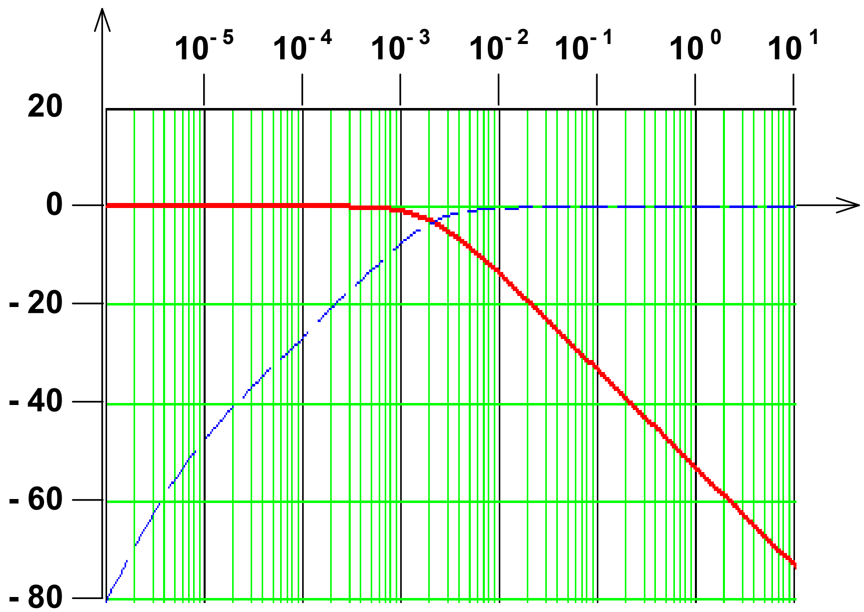
$$u_{OUT}(t) = u_{IN}(t) * h(t)$$

$$U_{IN}(s) = U_{OUT}(s) \cdot H(s)$$

where $h(t) =$ impulse response

$$H(s) = \text{ transfer function } = \text{Laplace}\{h(t)\}$$

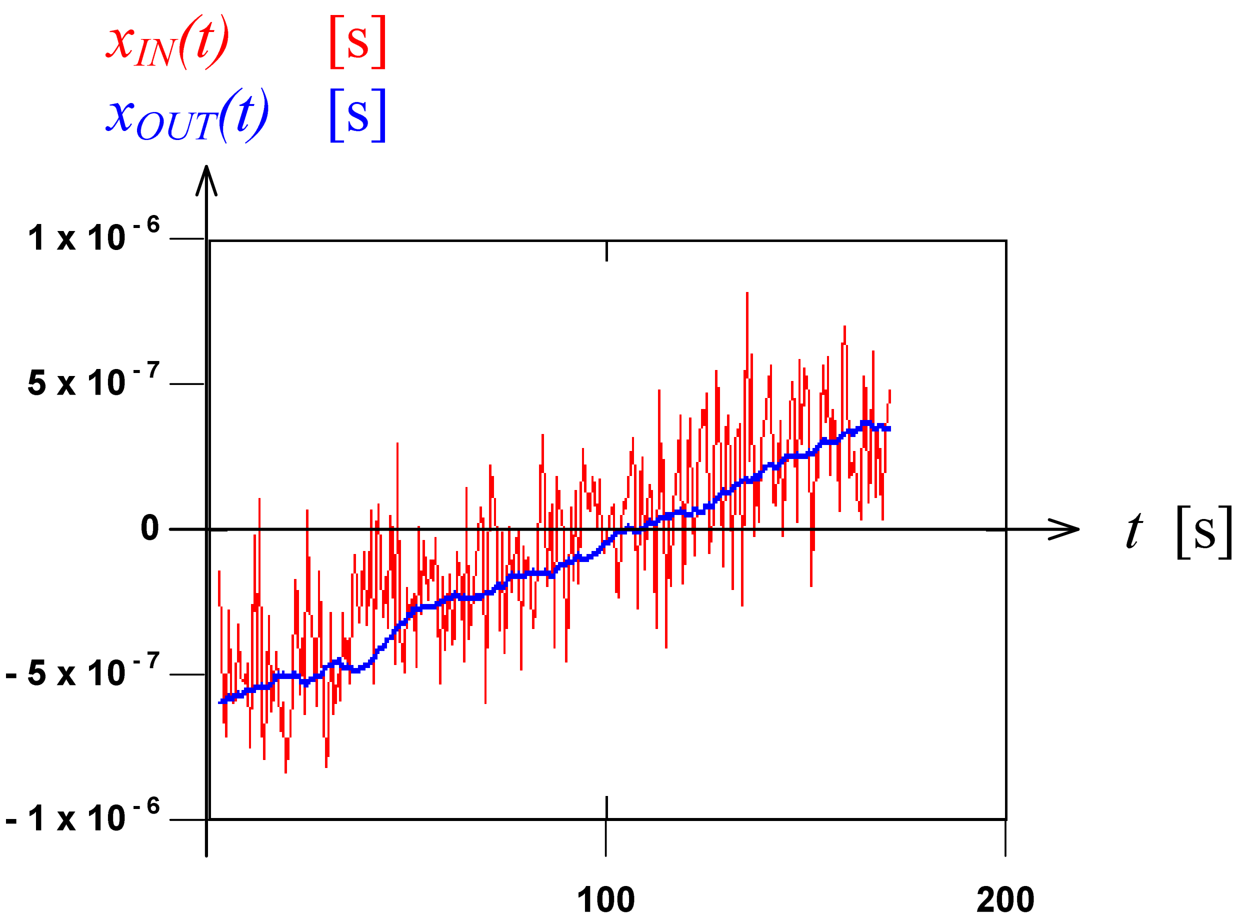
$20\log\left|H(j2\pi f)\right|$ [dB]



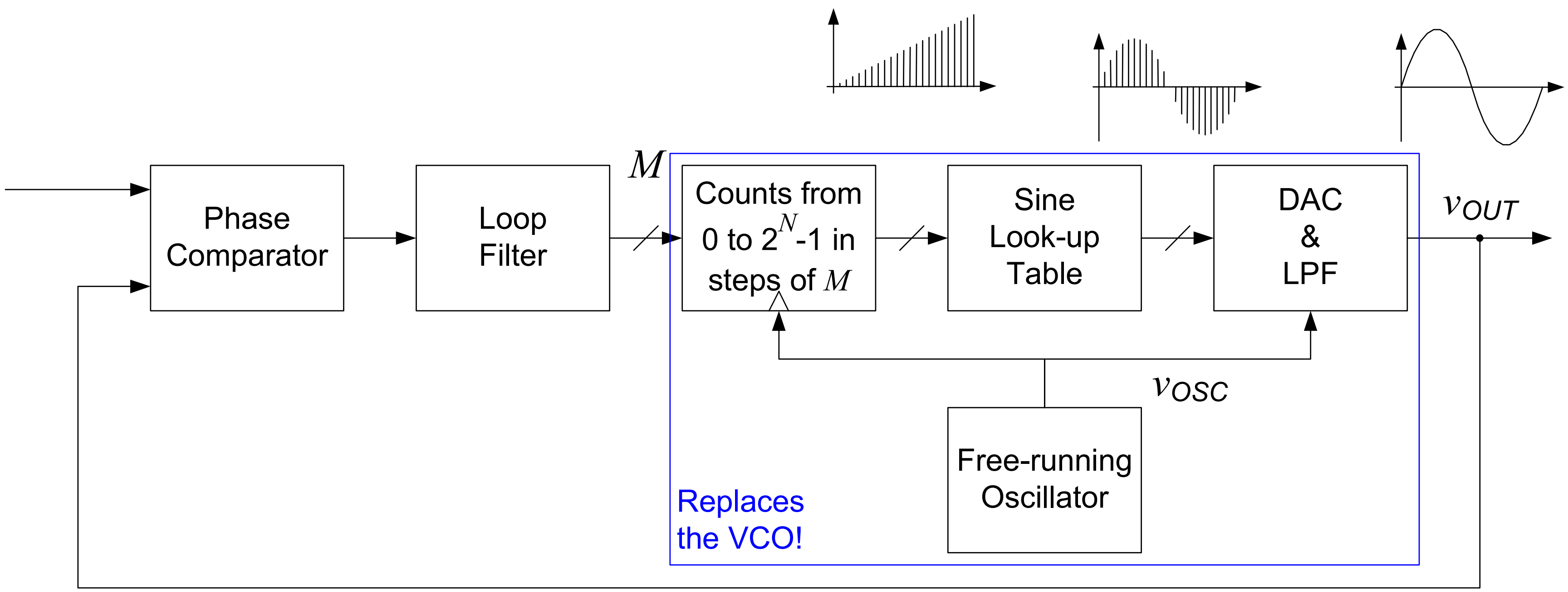
Red curve = PLL transfer function

Blue curve = transfer function for oscillator noise

PLL: Jitter filtering



PLL with Direct Digital Synthesis



DAC = Digital-to-Analog Converter

LPF = Low-pass Filter

$$\nu_{OUT} = \frac{M}{2^N} \nu_{OSC}$$

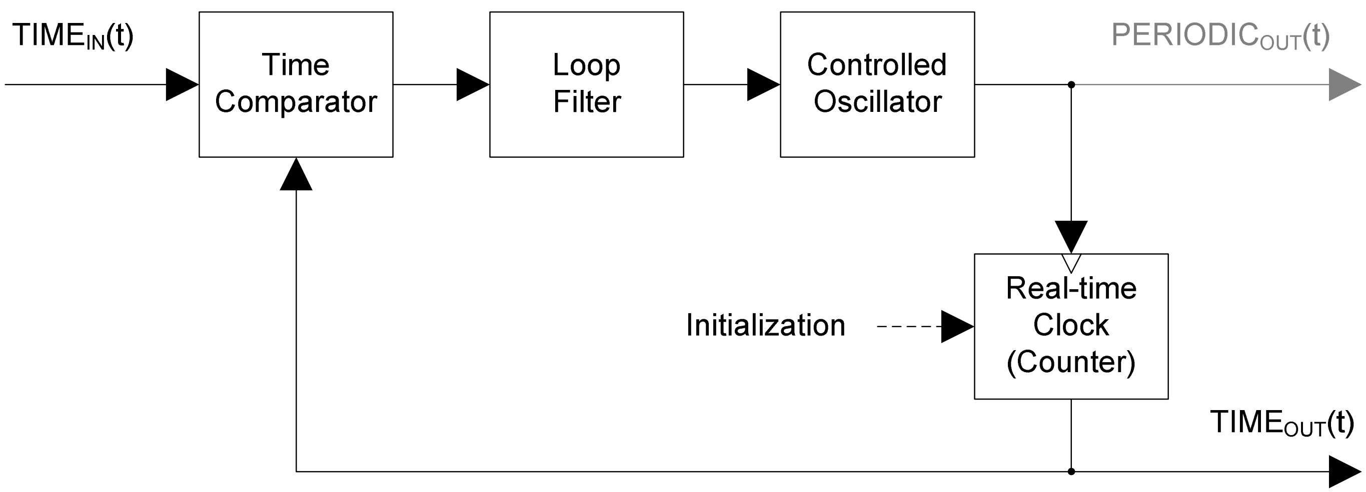
where $M =$ output of the digital loop filter (integer)

$N =$ size of the counter in bits (integer)

$\nu_{OUT} =$ frequency of output signal $u_{OUT}(t)$

$\nu_{OSC} =$ free-run frequency of the oscillator

Time Locked Loop



Thank You