Quartz Crystal Oscillators
and
Phase Locked Loops

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Content

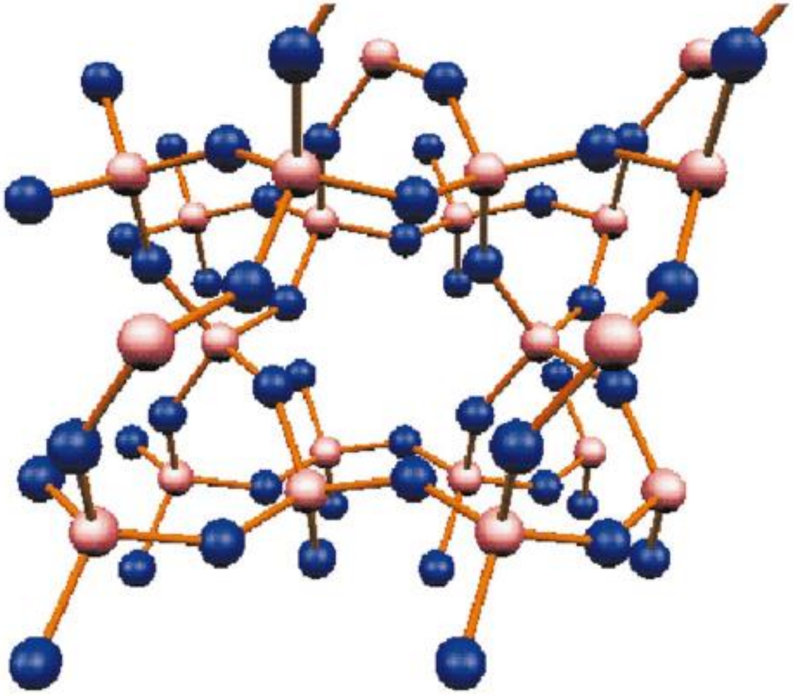
1. Quartz Crystal Resonator Technology
   - Quartz, crystal lattice and piezo-electric effect
   - Vibration modes and equivalent circuit
   - Cuts
   - Ageing mechanisms
2. Quartz Crystal Oscillator (XO) Technology
   - TCXO
   - MCXO
   - OCXO
   - DOCXO
3. XO Performance vs. Telecom Requirements
   - Frequency holdover
   - Phase holdover
4. Phase Locked Loops (PLL)

1. Quartz Crystal Resonator Technology

Quartz Crystal

Quartz = SiO_2

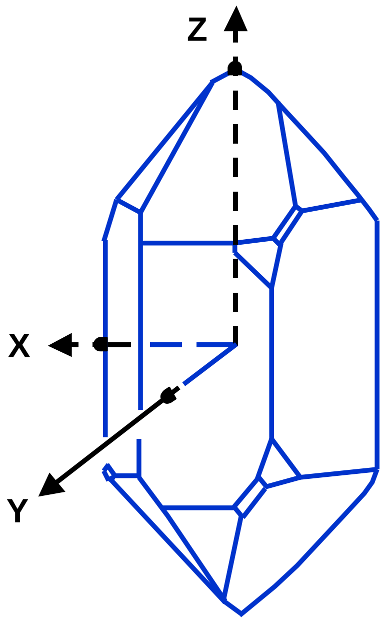
Pink = silicon atoms
Blue = oxygen atoms

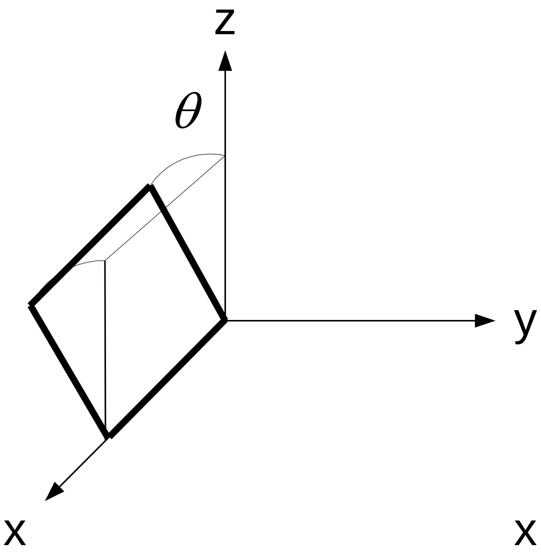


Quartz lattice

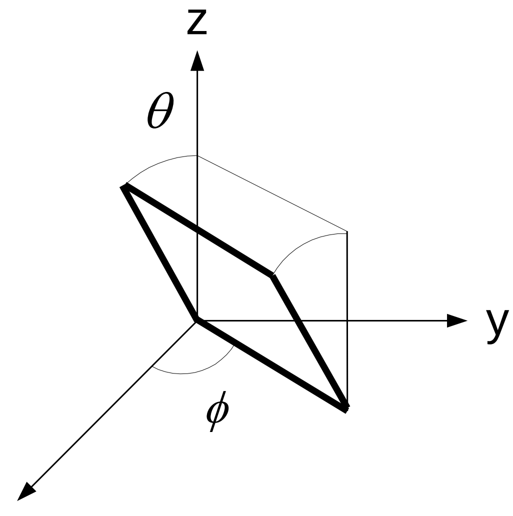
Cuts

Small disks are cut out of the crystal at given angles.





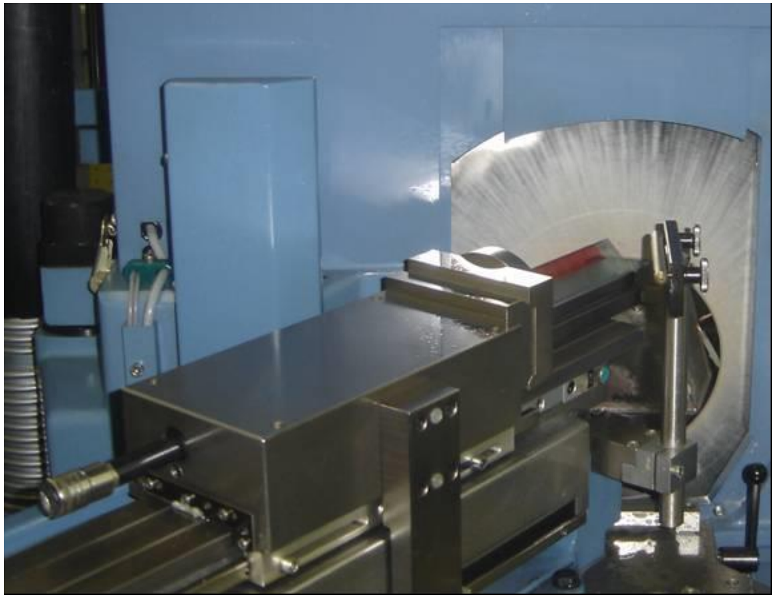
Single rotated cut
(e.g. AT-cut)



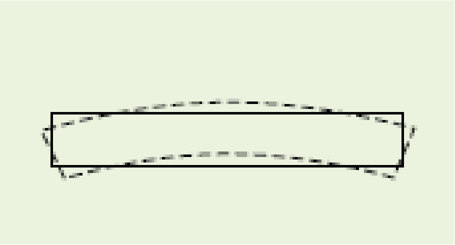
Double rotated cut
(e.g. SC-cut)

Cuts

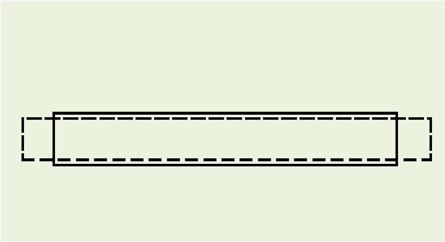
Angle accuracy: ± 10’’ (for SC-cut)



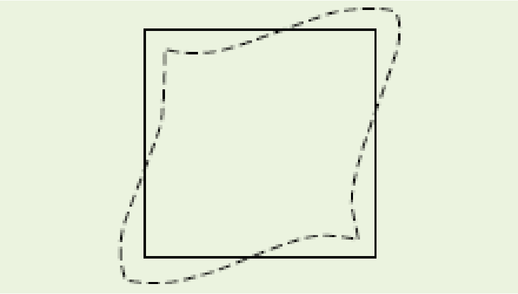
Vibration Modes



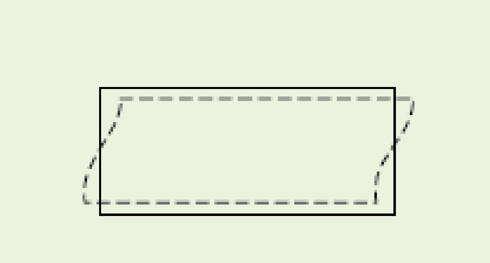
Flexure Mode



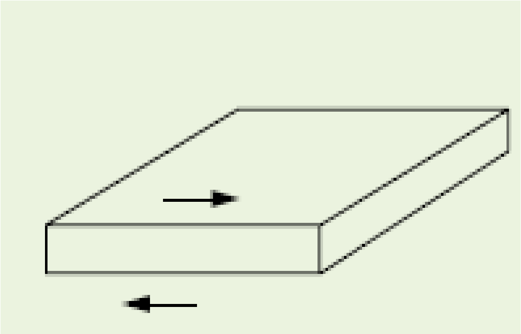
Extensional Mode



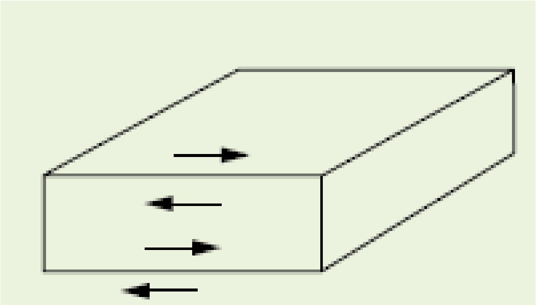
Face Shear Mode



Thickness Shear Mode



Fundamental Mode Thickness Shear

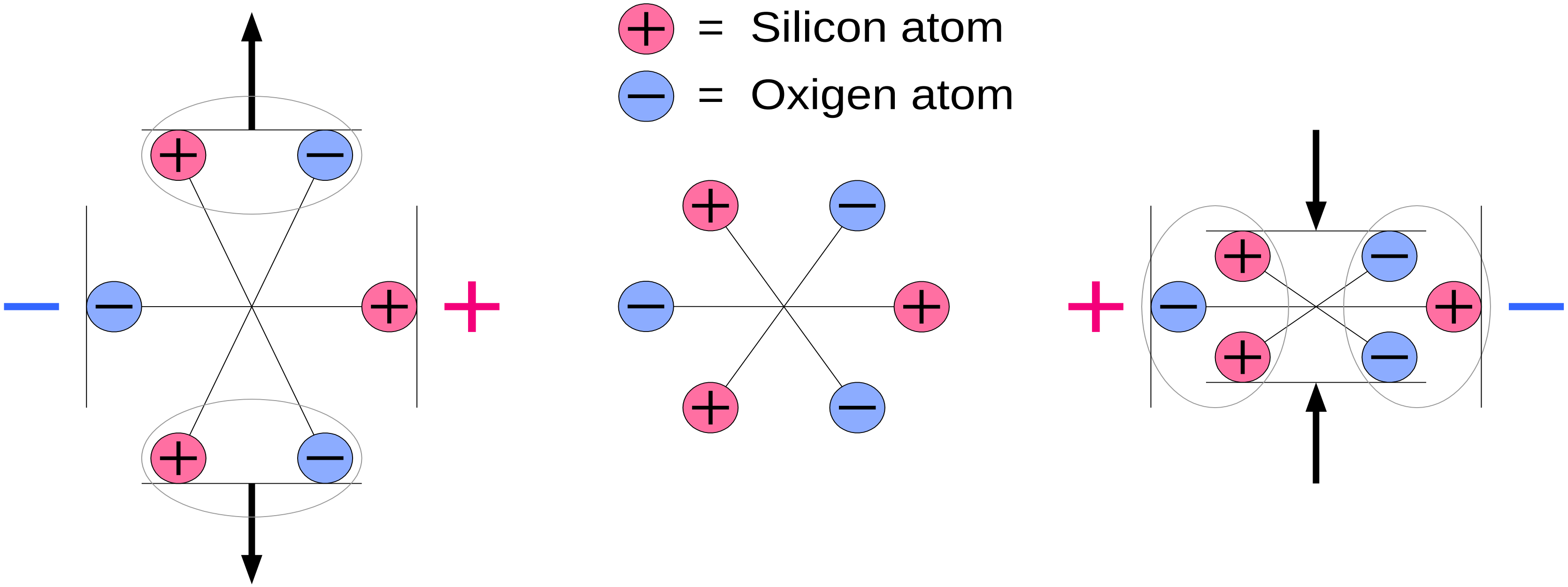


Third Overtone Thickness Shear

Piezo-electric Effect

Piezo-electric effect:

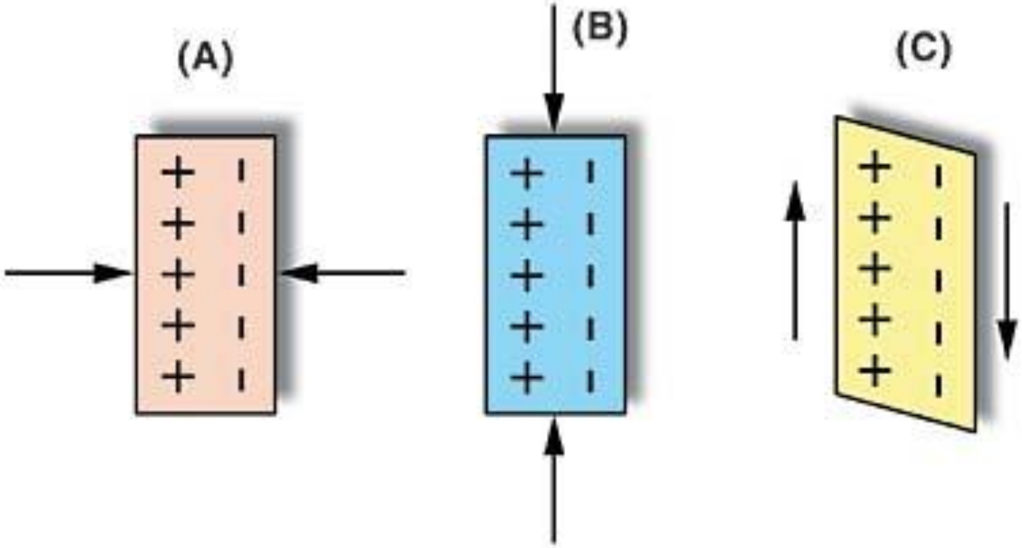
- Mechanical strain ⇒ voltage
- Voltage ⇒ mechanical deformation



⊕ = Silicon atom

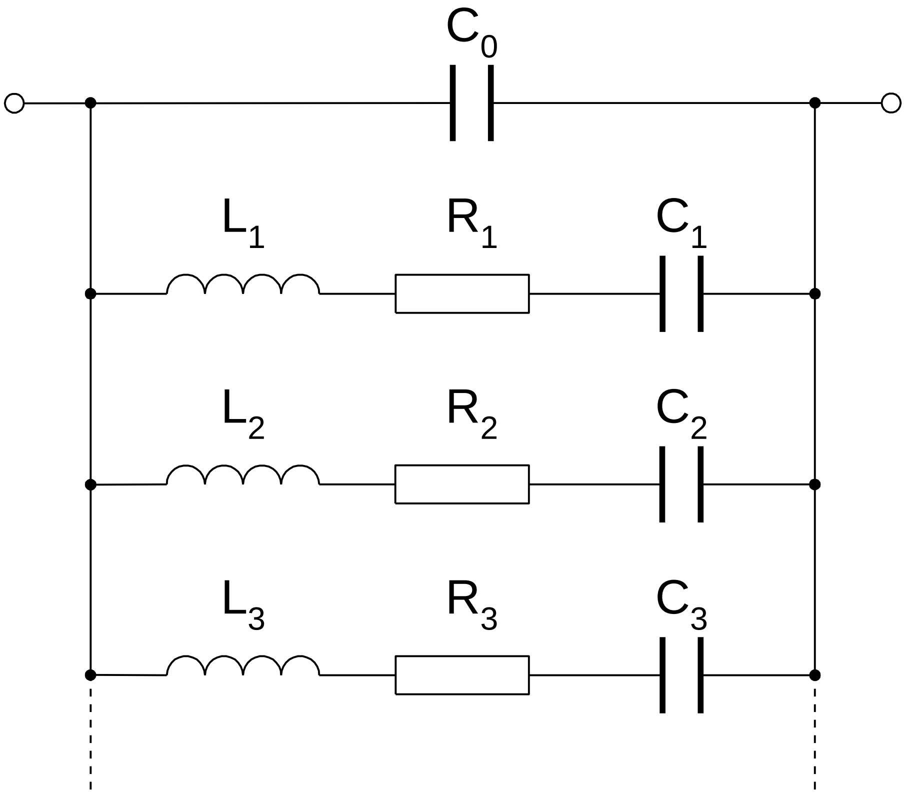
⊖ = Oxigen atom

Piezo-electric Effect



Strain Axis	Field Axis & Mode		
	(A)	(B)	(C)
x	x		x
y		x	y
z			y

Equivalent Circuit



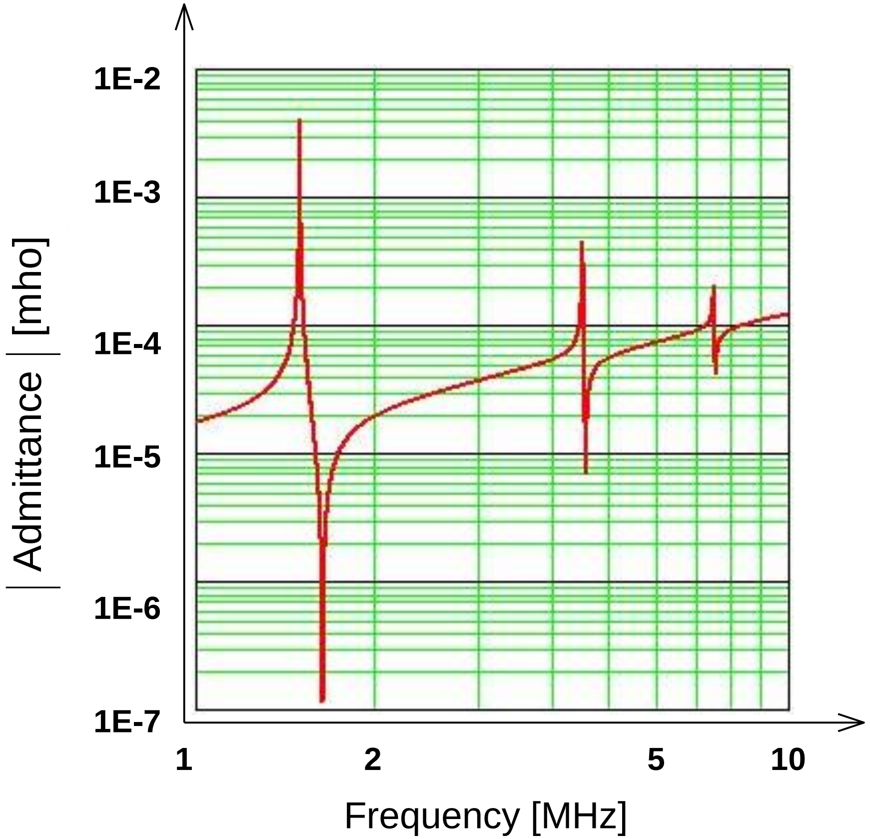
Vibration mode 1

Vibration mode 2

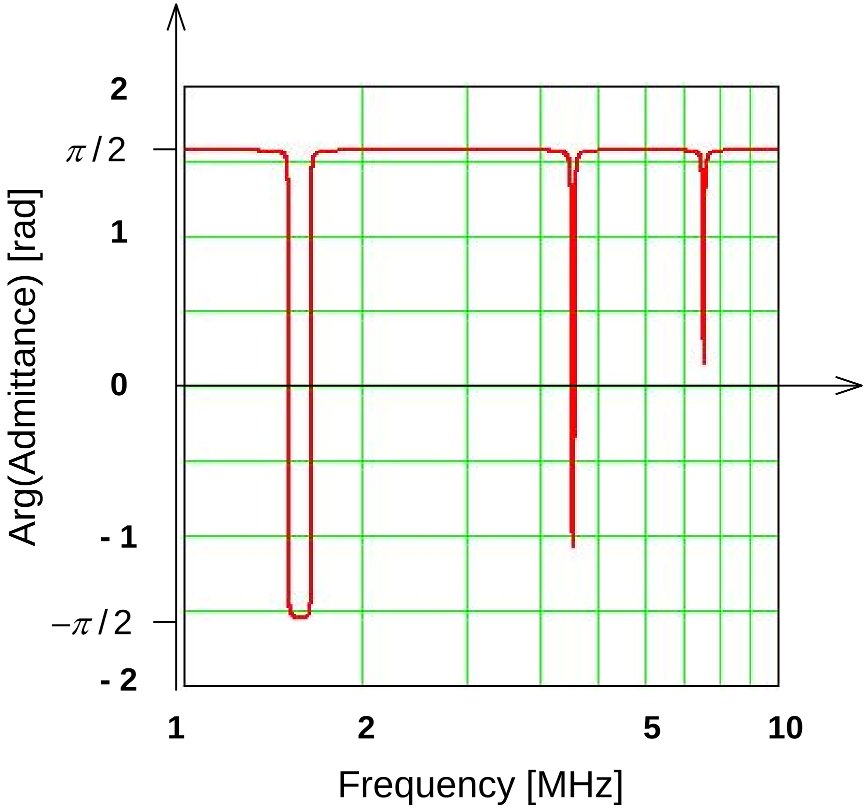
Vibration mode 3

Admittance Y(f)

$|\,Y(f)\,|$

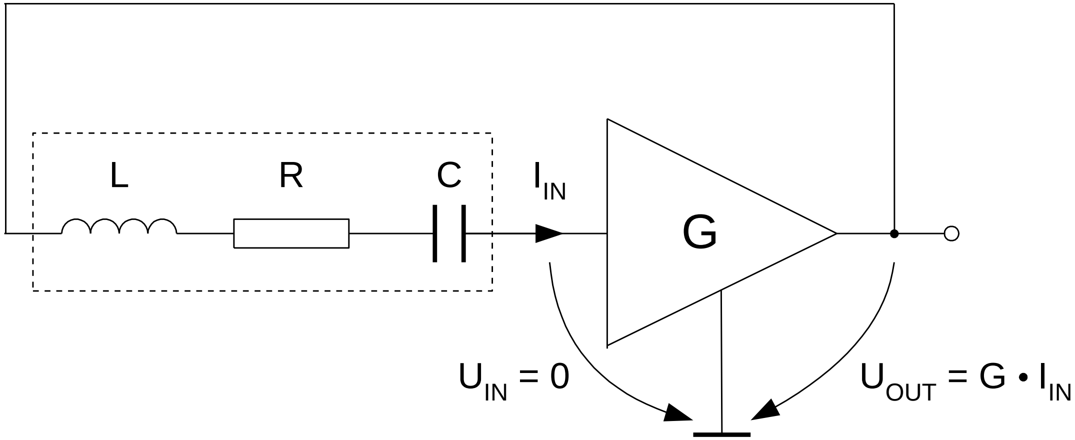


Arg (Y(f))



Note: Exaggerated resistance values R_1, R_2 and R_3 for better readability

Quartz Crystal Oscillator (XO)

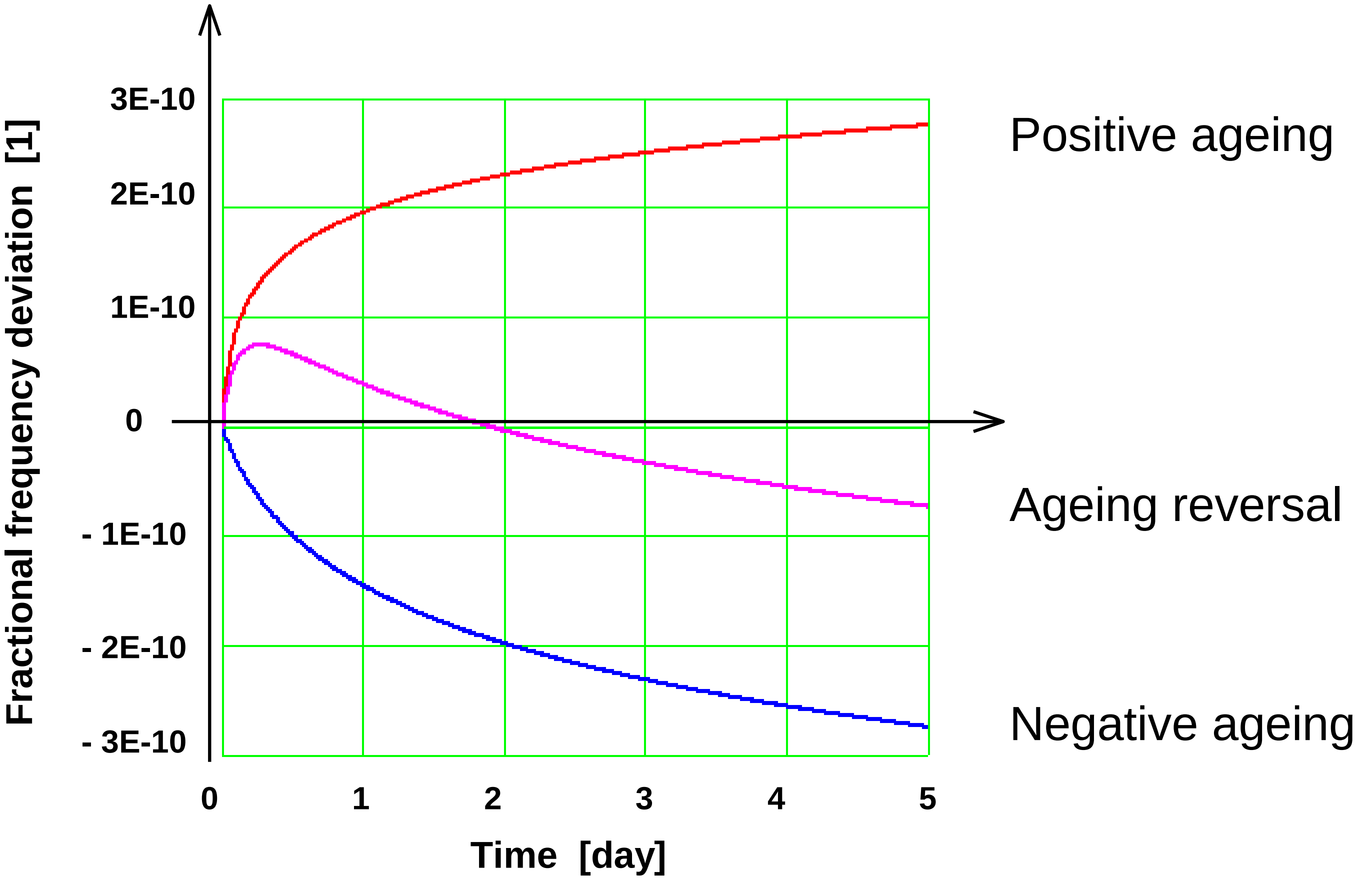


Open Loop Gain: $H(\omega) = G \cdot Y(\omega) = \dfrac{G}{j \cdot \omega \cdot L + R + \dfrac{1}{j \cdot \omega \cdot C}}$

If $G = \dfrac{1}{R}$ and $\omega = \omega_0 = \dfrac{1}{\sqrt{L \cdot C}}$ then $H(\omega = \omega_0) = 1$

$f_0 = \dfrac{\omega_0}{2 \cdot \pi} =$ resonance frequency

Frequency Drift Due to Ageing

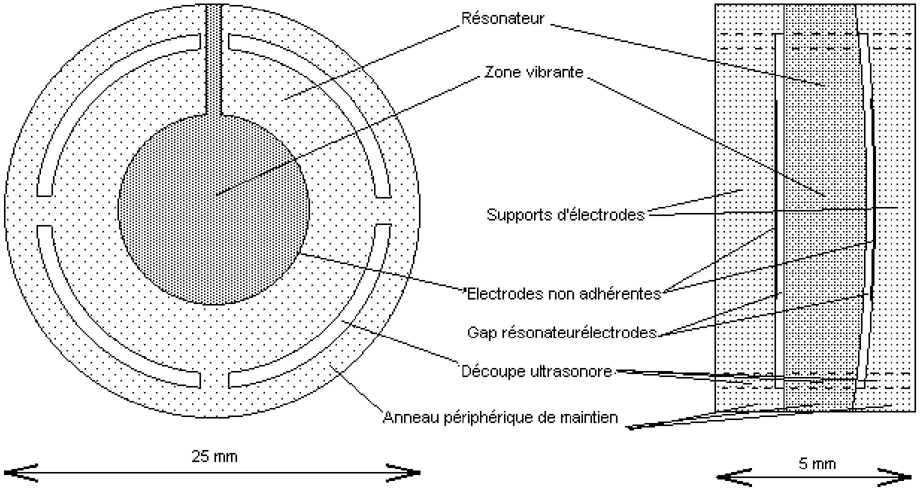


Ageing Mechanisms

- Mass transfer due to contamination (e.g. electrode metal atoms into the crystal
- Stress relief in the resonator's mounting and bonding structure, electrodes, and in the quartz
- Other mechanisms:
  - Quartz outgassing
  - Diffusion effects
  - Chemical reaction effects
  - Pressure changes in resonator enclosure (leaks and outgassing)
  - Oscillator circuit aging (load reactance and drive level changes)
  - Electric field changes (doubly rotated crystals only)
  - Oven-control circuitry aging

BVA Resonator

- Electrodes not in direct contact with the resonator body ⇒ contamination of the resonator body is stopped ⇒
- Ageing improves by a factor of 10 or more
- Other performance parameters improve also (Q, temperature sensitivity, phase noise, etc.)



Courtesy Jean-Pierre Aubry

AT-cut Resonator

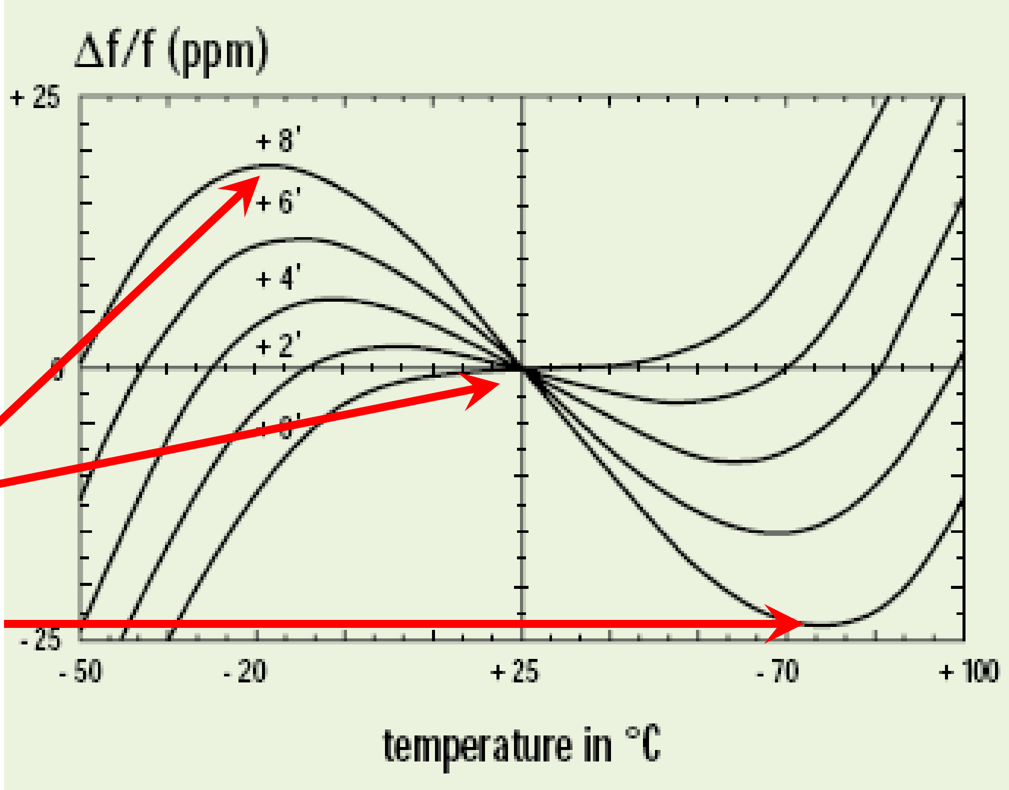
AT-cut:

- $\Theta = 35°$
- $\Phi = 0$

Δf/f as a function of temperature

(parameter: *ΔΘ* = deviation from reference angle)

- Lower Turnover Point (LTP)
- Inflection Point (IP)
- Upper Turnover Point (UTP)



SC-cut Resonator

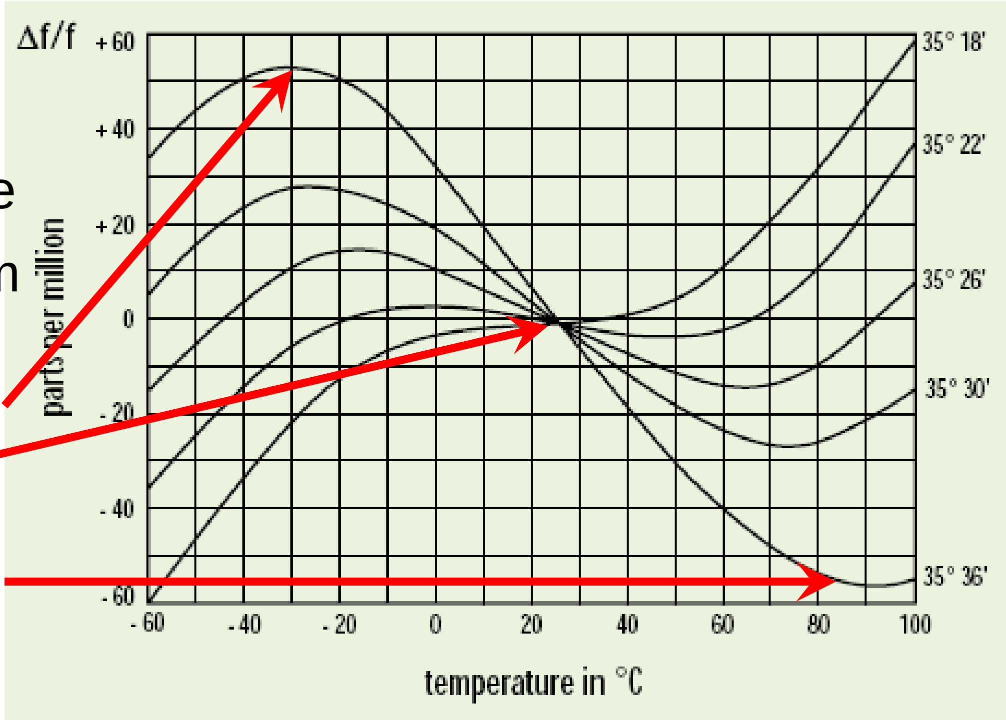
SC-cut:

- $\Theta = 34^\circ$
- $\Phi = 22^\circ$

$\Delta f/f$ as a function of temperature

(parameter: $\Delta\Theta$ = deviation from reference angle)

- Lower Turnover Point (LTP)
- Inflection Point (IP)
- Upper Turnover Point (UTP)



SC- versus AT-cut

Advantages of the SC-cut

- Thermal transient compensated (allows faster warm-up OCXO)
- Static and dynamic f(T) allow higher stability OCXO
- Planar stress compensated; lower Δf due to edge forces and bending
- Better f(T) repeatability allows higher stability OCXO (less Δf for oscillator reactance changes)
- Lower drive level sensitivity
- Higher Q for fundamental mode resonators of similar geometry
- Higher capacitance ratio (less Δf for oscillator reactance changes)
- Less sensitive to plate geometry - can use wide range of contours
- Far fewer activity dips
- Lower sensitivity to radiation

Disadvantages of the SC-cut

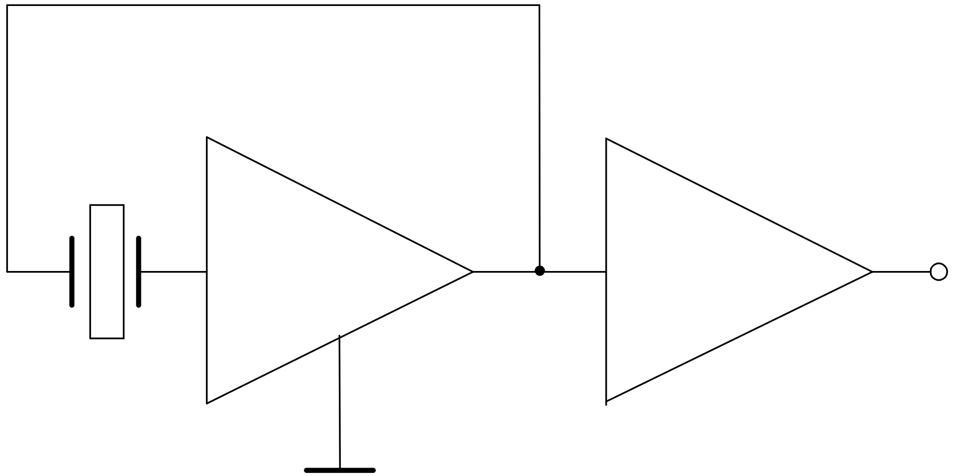
- More difficult to manufacture

2. Quartz Crystal Oscillator (XO) Technology

XO Categories rel. Temp. Control

XO, Crystal Oscillator:

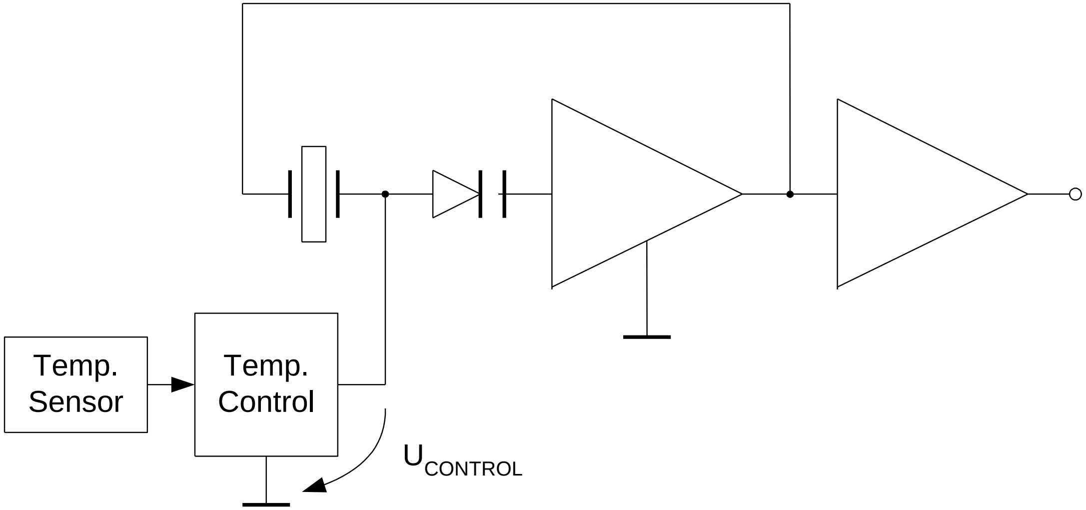
- LTP centered in the operation temperature range
- > 1E-7 / °C



XO Categories rel. Temp. Control

TCXO, Temperature Compensated XO:

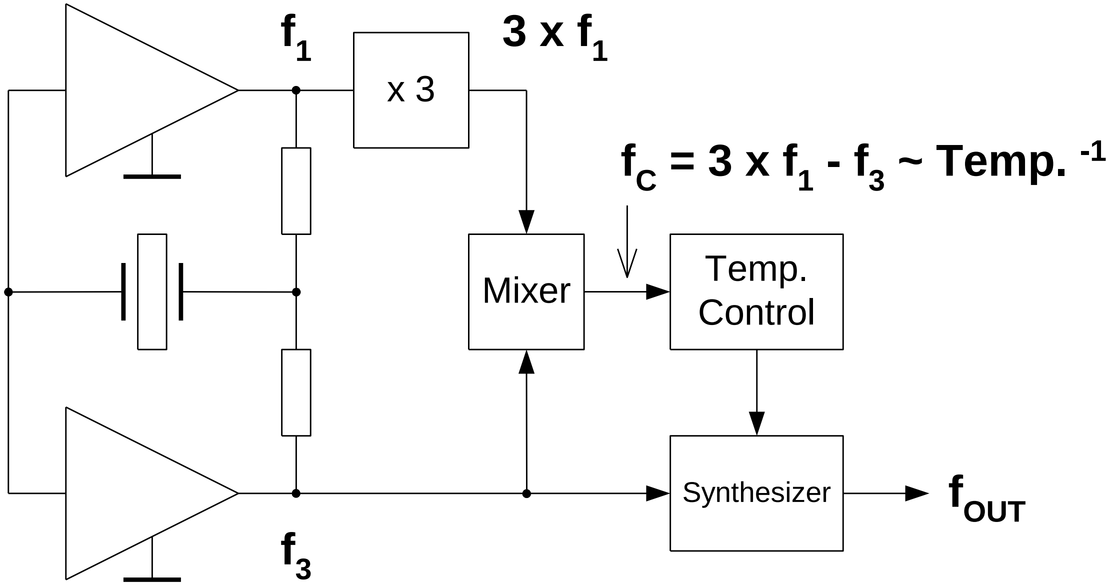
- Resonance frequency is modified by a varactor diode so as to compensate temperature sensitivity
- 5E-8 to 5E-7 over [-55°C to 85°C]



XO Categories rel. Temp. Control

MCXO, Microcomputer Compensated XO:

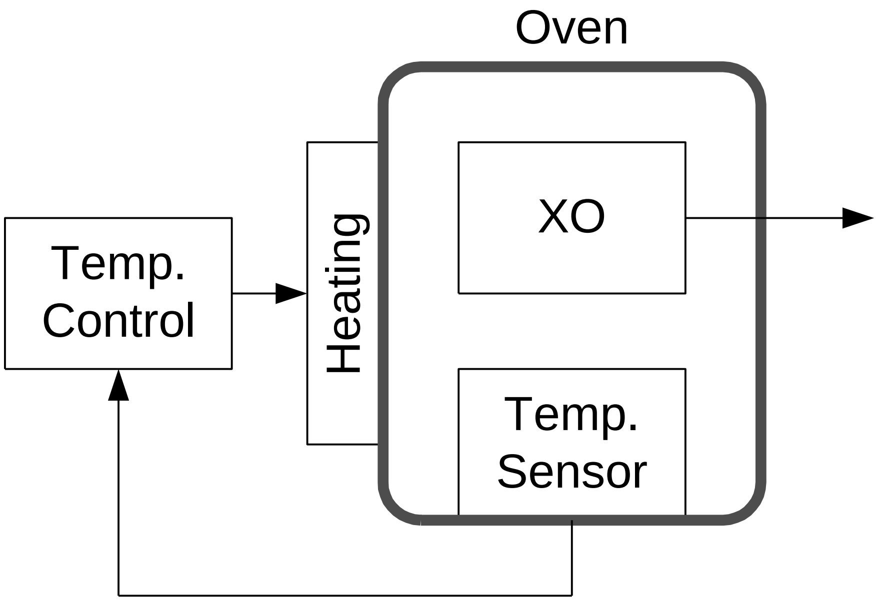
- Dual mode oscillator generating fundamental (f_1) and third overtone (f_3).
- Difference between f_3 and 3 x f_1 is used to measure temperature and compensate temperature sensitivity of f_3.



XO Categories rel. Temp. Control

OCXO, Oven Controlled XO:

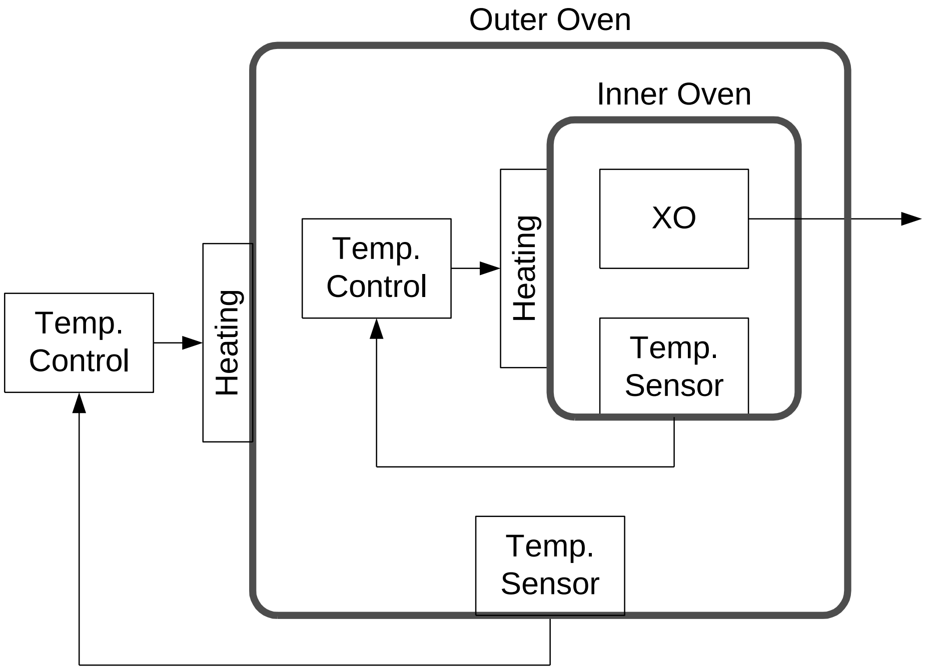
- A control loop maintains the oven containing the XO at (nearly) constant temperature.
- 5E-9 to 5E-8 over [-30°C to 60°C]



XO Categories rel. Temp. Control

DOCXO, Double Oven Controlled XO:

- Two temperature controlled ovens, one inside the other.
- 2E-10 to 5E-9 over [-30°C to 60°C]
- BVA resonator: 1E-10 over [-30°C to 60°C], 5E-11 over [-15°C to 60°C]



Typical XOs

SOCXO:

DOCXO:

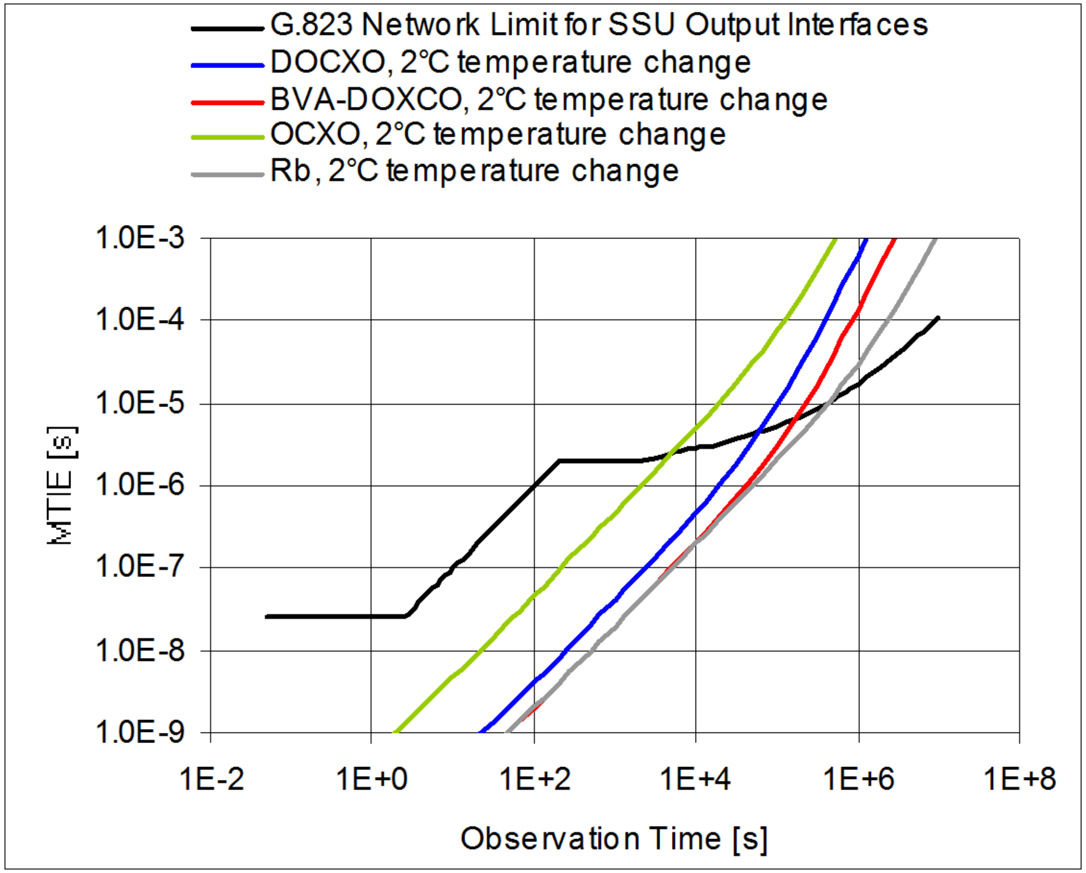
…mm

BVA-DOCXO:

3. XO Performance vs. Telecom Requirements

Frequency Holdover Autonomy

How long can the SSU stay in holdover mode until the MTIE hits the Network Limit for PRC-traceable SSU outputs (G.823)?



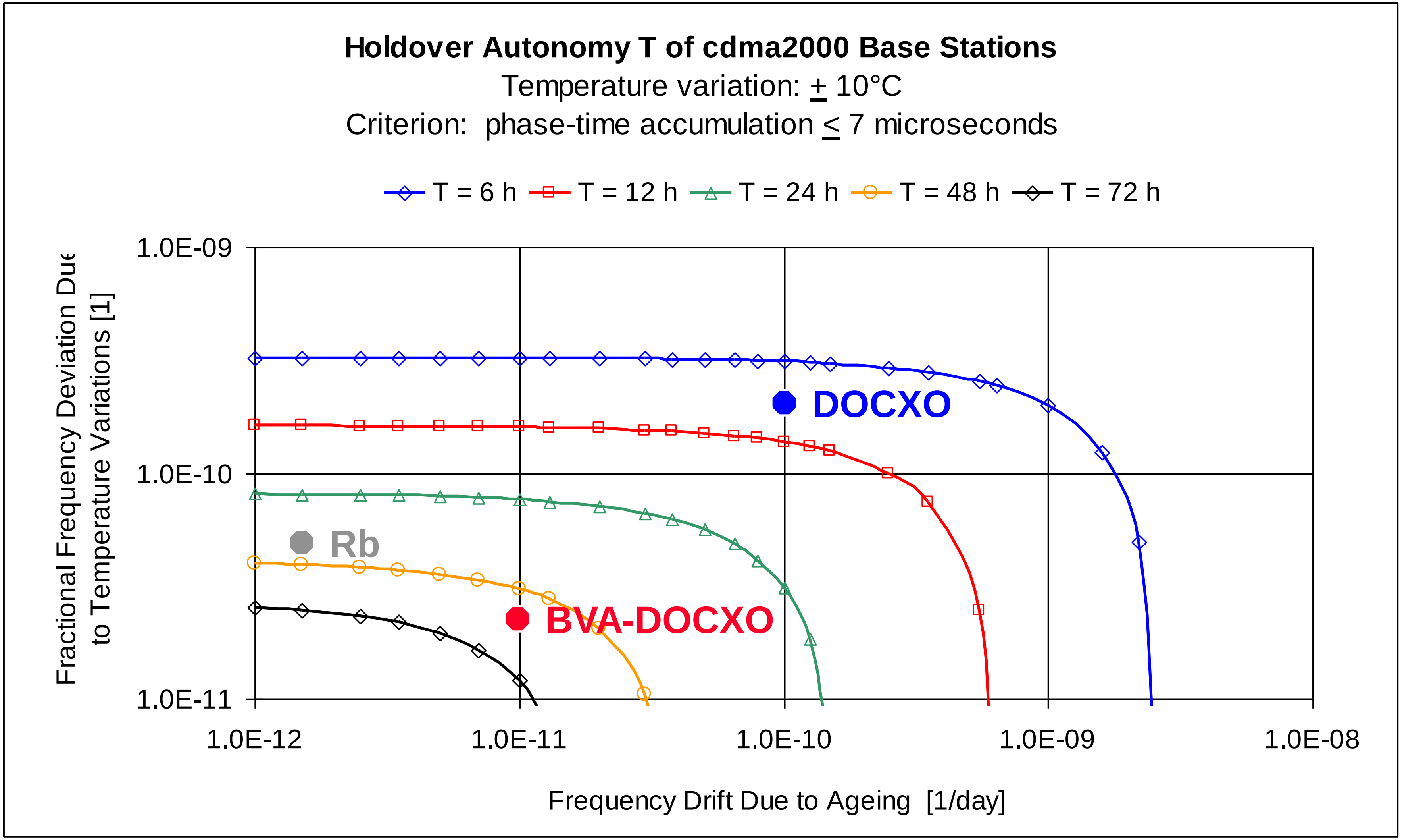
Frequency Holdover Autonomy

Holdover autonomy for different oscillator types and for different temperature conditions (temp. change during holdover):

	OCXO[1]	DOCXO[2]	BVA-DOCXO[3]	Rb[4]
Const. Temp.	9 h	21 h	51 h	9 days
2°C	1.4 h	17 h	46 h	5.5 days
5°C	30 min	13 h	39 h	67 h
10°C	15 min	8.3 h	31 h	33 h

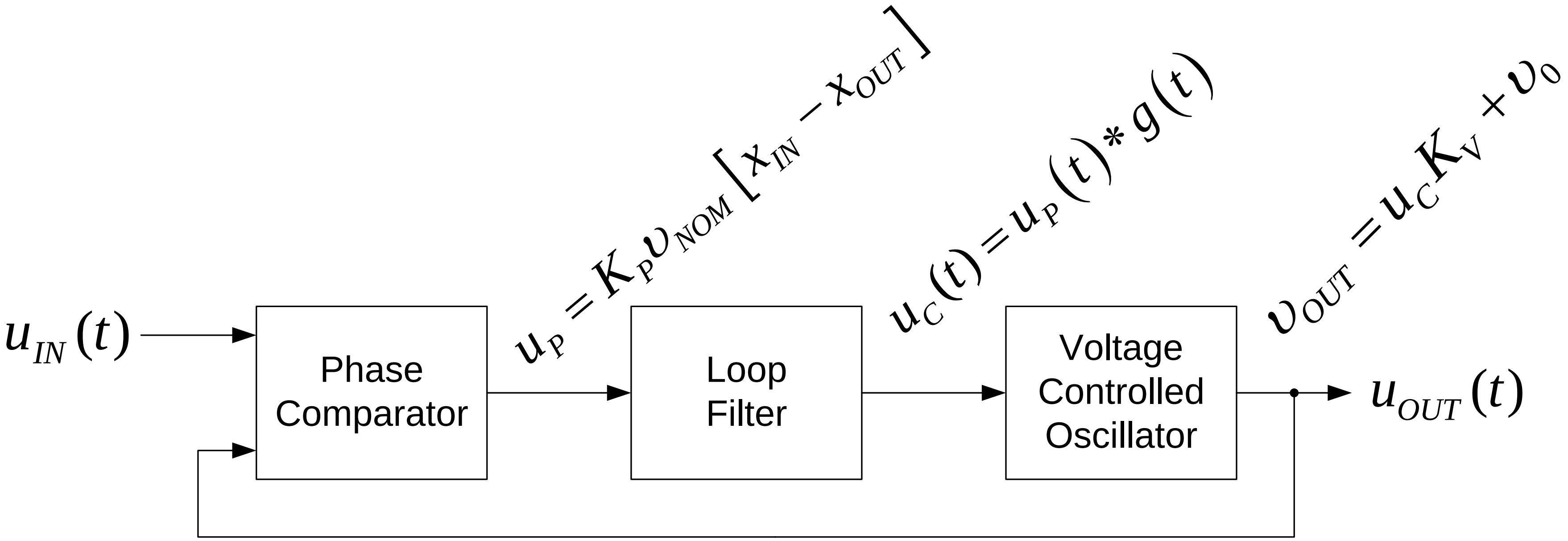
Notes: 1) OSA 8741 2) OSA 8663 3) OSA 8600 4) TNT RMO

Phase Holdover Autonomy (e.g. 1PPS)



4. Phase Locked Loops (PLL)

PLL: Working principle



$u_{IN}(t)$

Phase Comparator

$u_P = K_P \upsilon_{NOM} [x_{IN} - x_{OUT}]$

Loop Filter

$u_C(t) = u_P(t) * g(t)$

Voltage Controlled Oscillator

$\upsilon_{OUT} = u_C K_V + \upsilon_0$

$u_{OUT}(t)$

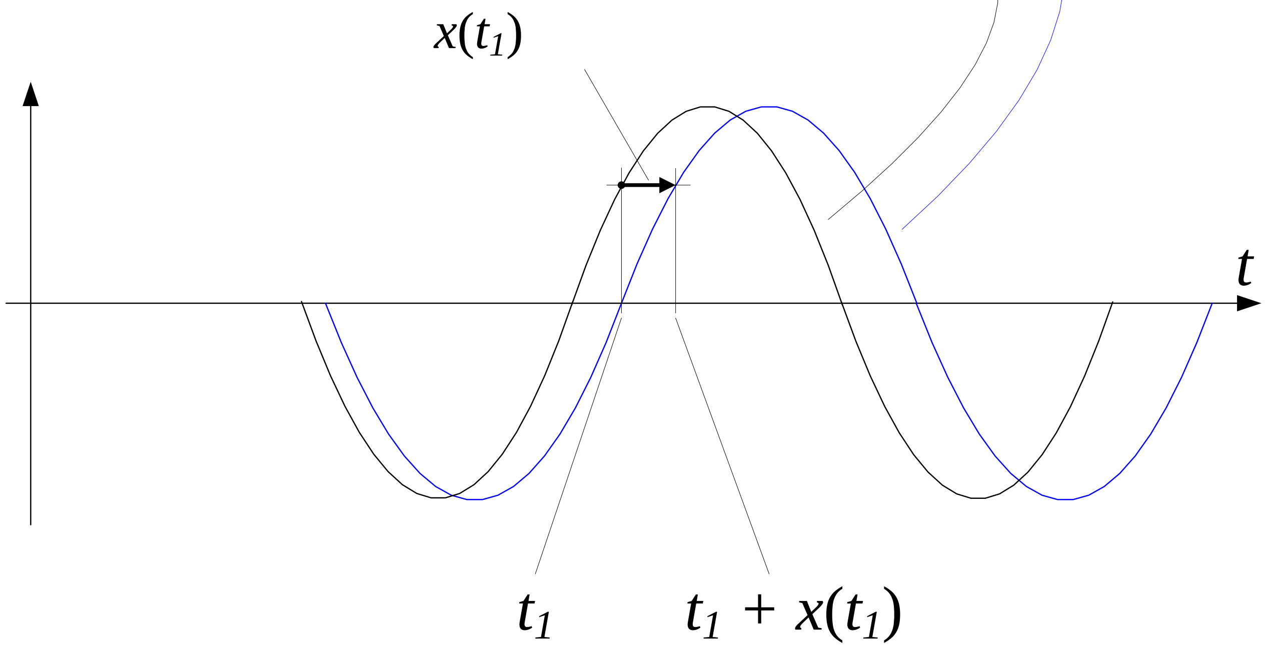
$$u_{IN}(t) = A \cdot \sin\left\{2\pi\upsilon_{NOM}\left[t + x_{IN}(t)\right]\right\} = A \cdot \sin\left\{2\pi\upsilon_{IN}(t) + \varphi_{0,IN}\right\}$$

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

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

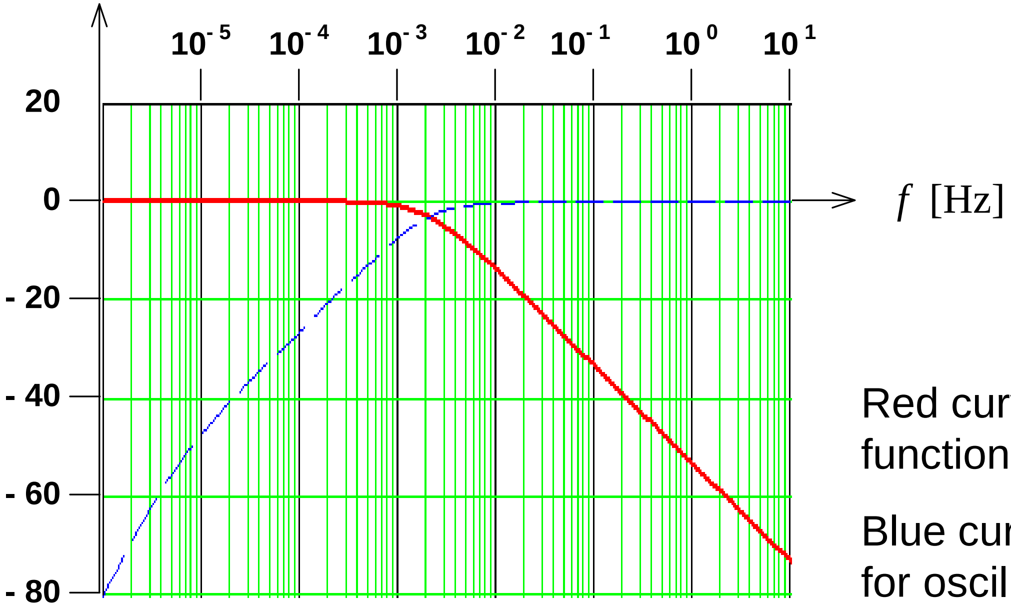
$$u_{OUT}(t) = u_{IN}(t) * h(t)$$

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

where $h(t) =$ impulse response

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

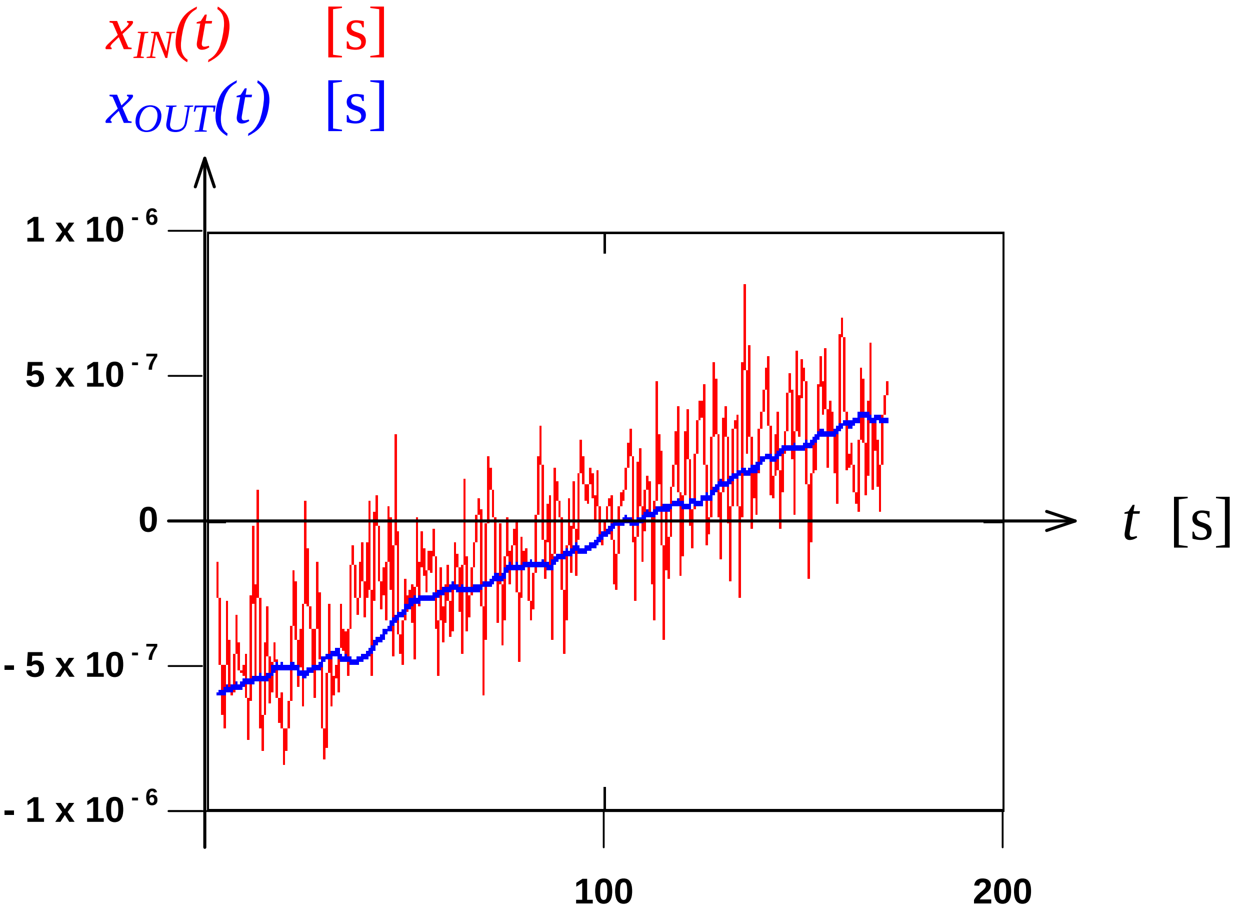
$$20\log\left|H(j2\pi f)\right| \text{ [dB]}$$



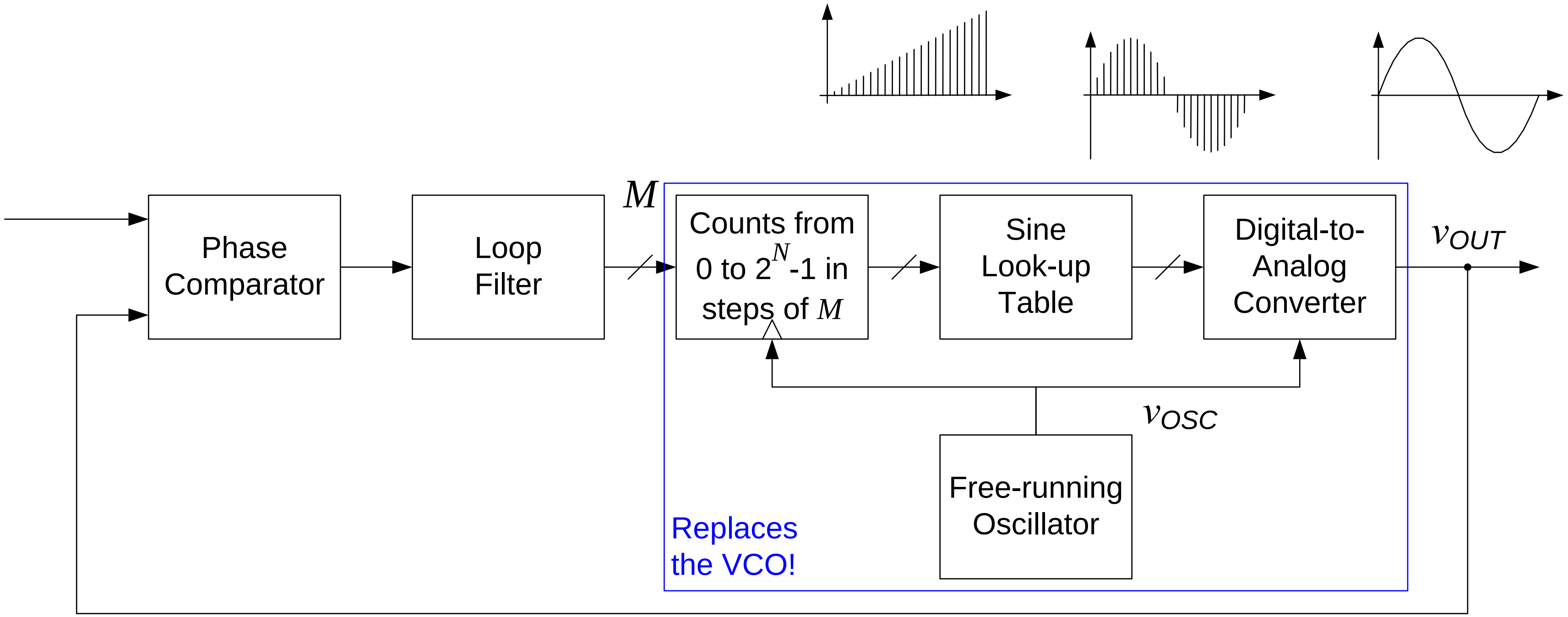
Red curve = PLL transfer function

Blue curve = transfer function for oscillator noise

PLL: Jitter filtering



PLL with Direct Digital Synthesis



M

Phase Comparator

Loop Filter

Counts from 0 to 2^N-1 in steps of M

Sine Look-up Table

Digital-to-Analog Converter

v_{OUT}

v_{OSC}

Free-running Oscillator

Replaces the VCO!

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

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

N = size of the counter in bits (integer)

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

υ_{OSC} = free-run frequency of the oscillator

PLL with VCO and with DDS compared

	Pros	Cons
PLL with VCO	•Very low phase noise	•PLL’s pull-in range depends on VCO’s pulling range •Requires VCO
PLL with DDS	•Configurable pull-in range •Requires only free-running oscillator	•Some quantization phase noise

Thank you