Atomic Clocks

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What is an Atomic Clock?

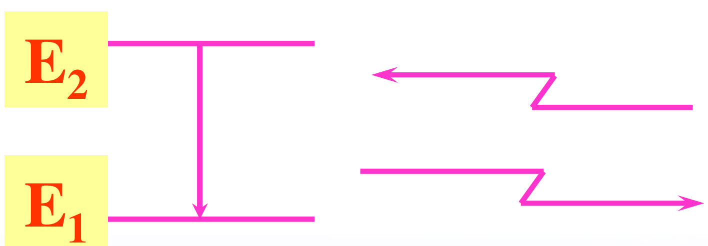
The Most Accurate Man Made Machine!

The Atom is the Pendulum of the Clock

1 second in 1000's years (Rb)

1 second in 3 million years for Cs fountain

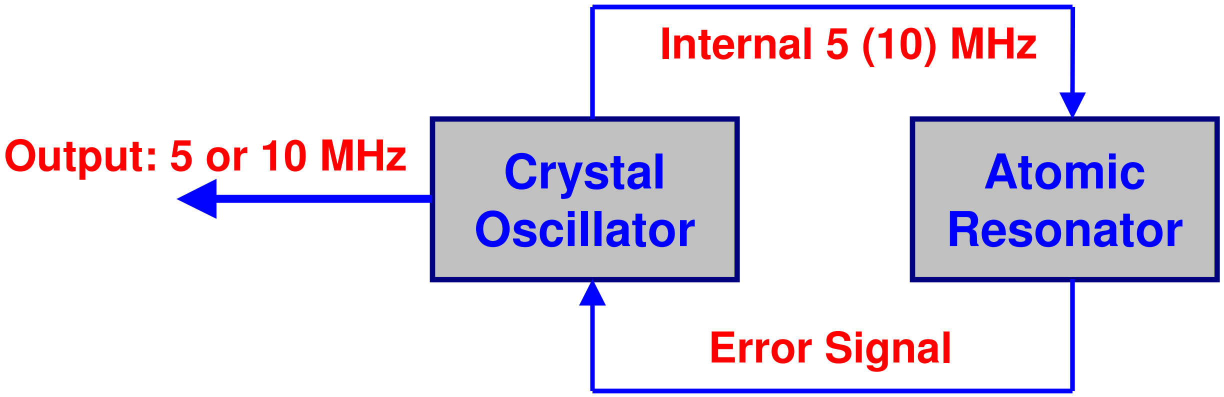
Based on a quantum transition which occurs in the atom



Planck's law

$E_1 - E_2 = h\nu$

Stability of Passive Atomic Standards



The RF output (5 or 10MHz) is derived from the Crystal Oscillator.
On the short term ($t < t_l$) the output follows the Crystal Oscillator.
On the long term ($t > t_l$) the output follows the Atomic Resonator.
t_l = loop time constant. For Rb: t_l =10 to100msec, for Cs: t_l =100ms to 1s.

This transition of stability from the Crystal to the Atomic Resonator is seen in Phase-Noise and Allan Deviation plots.

The same happens for Vibration/Acceleration Sensitivity: For fast acceleration, the Crystal determines the output, and for slow acceleration the Atomic Resonator counts.

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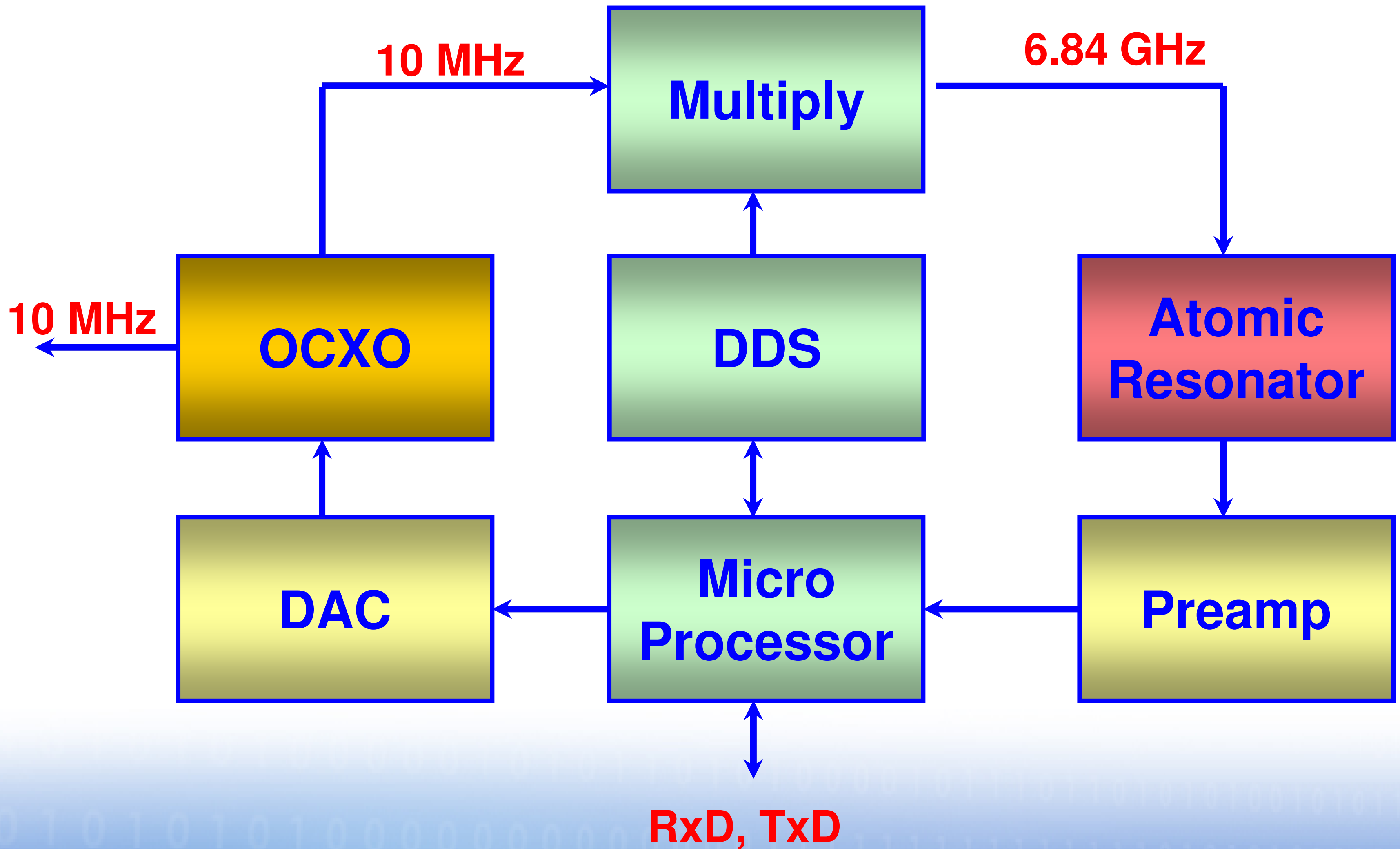
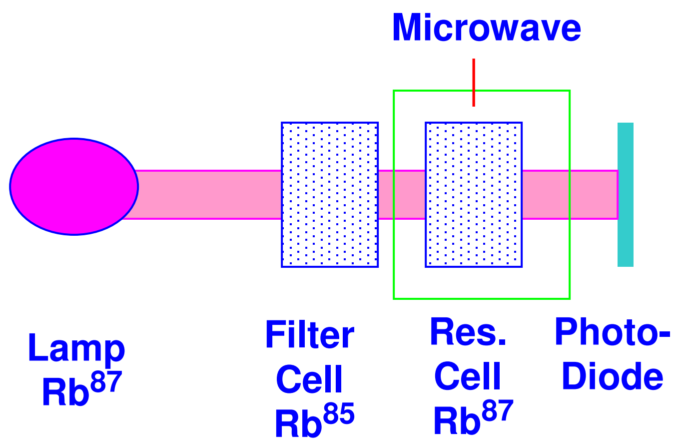
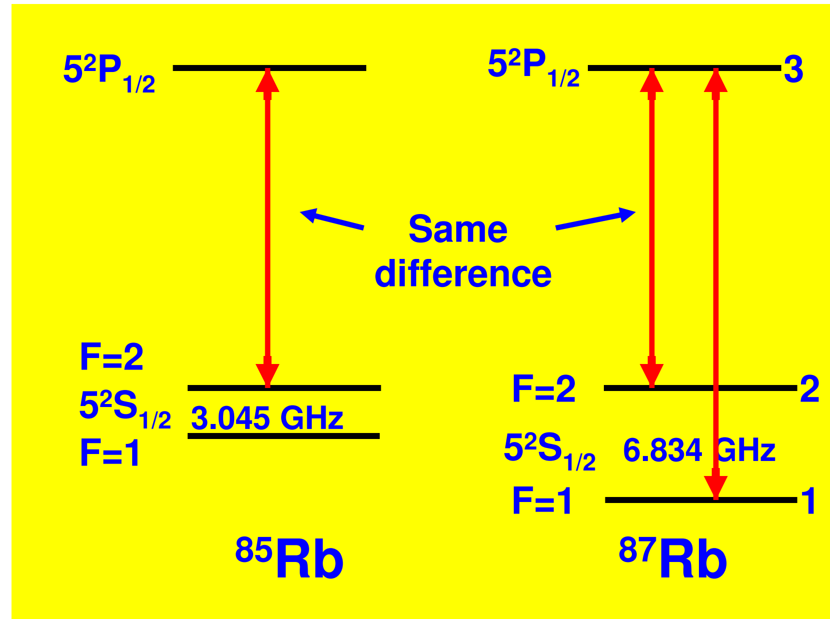
AccuBeat's Digital Loop



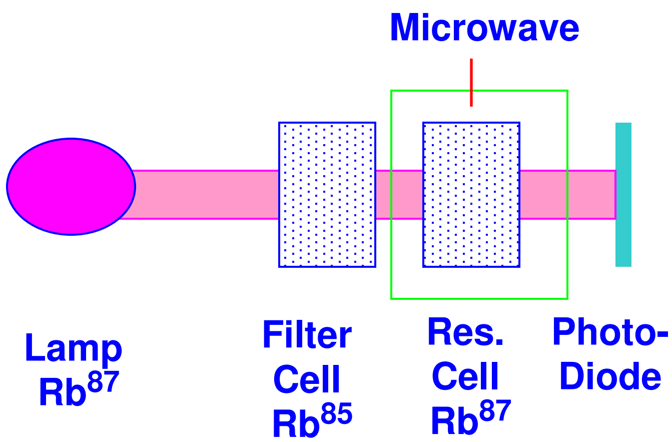
Rb Vapor Cell Principles - 1

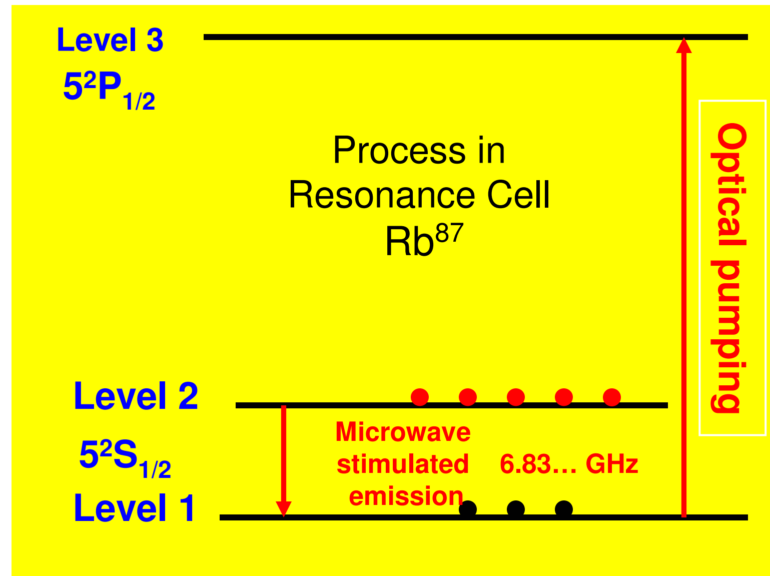




1. Light from ^{87}Rb lamp contains both 1-3 and 2-3 lines.
2. ^{85}Rb Cell filters out the 2-3 line and transmits the 3-1 line

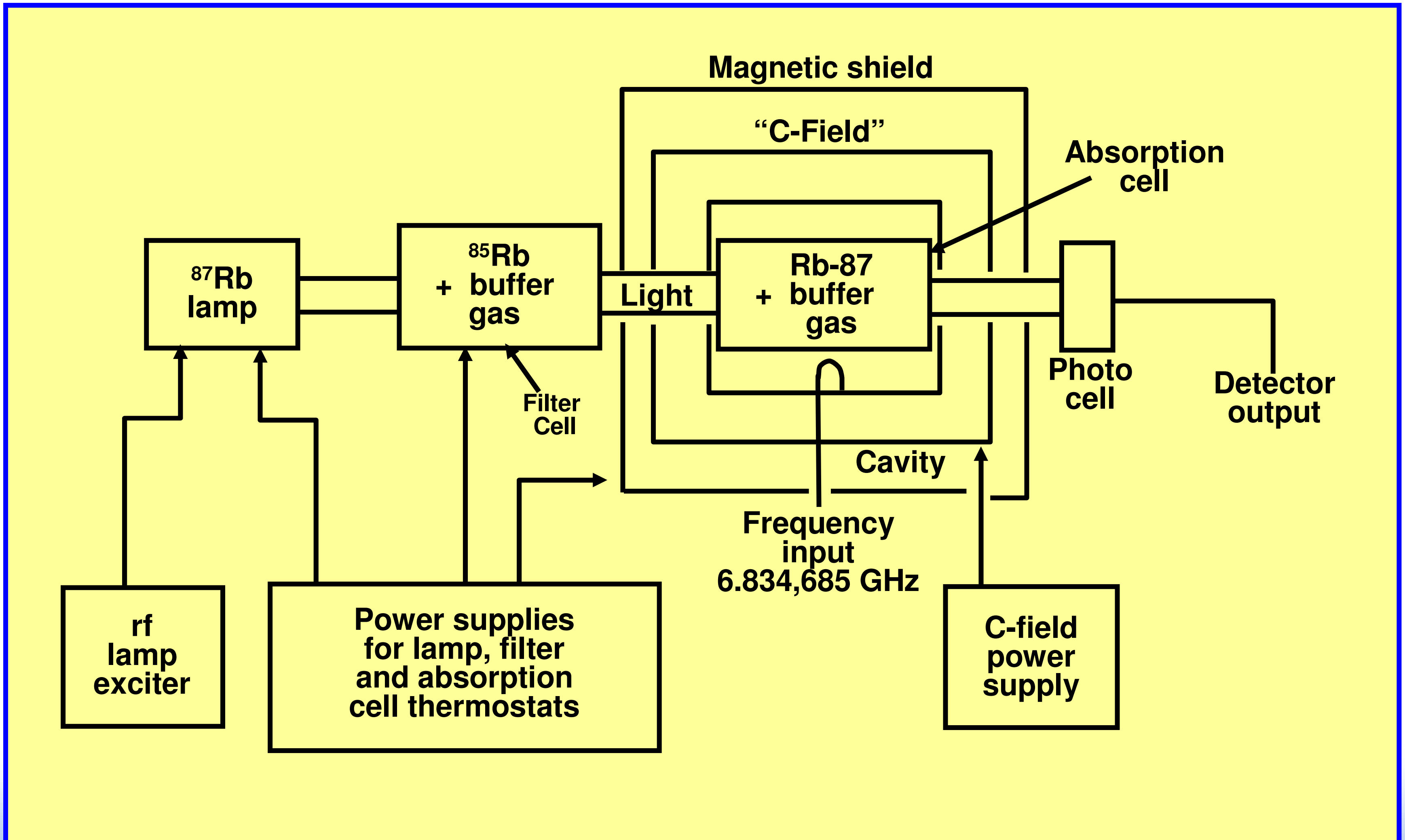
Rb Vapor Cell Principles - 2



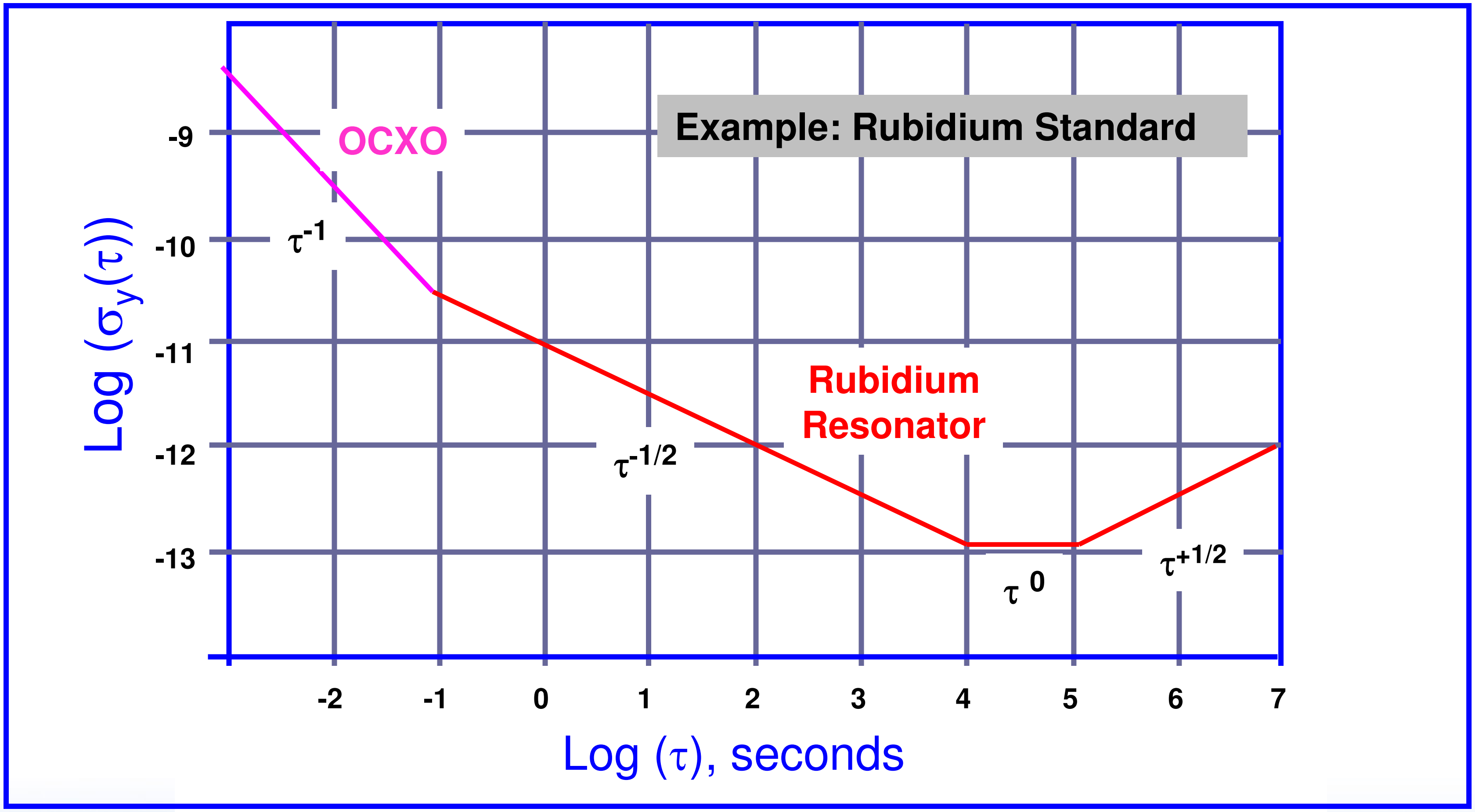


1. The filtered light "optically pumps" ^{87}Rb atoms in the Resonance Cell from level 1 to 3.
2. The injected microwave frequency at 6.84..GHz induces transition from level 2 to 1.
3. When the injected frequency matches the difference 2-1, the photo-diode detects a reduction in the amount of transmitted light.

Vapor Cell Atomic Clock



Short-Term-Stability of Passive Atomic Standards



For times shorter than the Loop Time Constant the stability follows the OCXO

For times longer than the Loop Time Constant the stability follows the RUBIDIUM resonator

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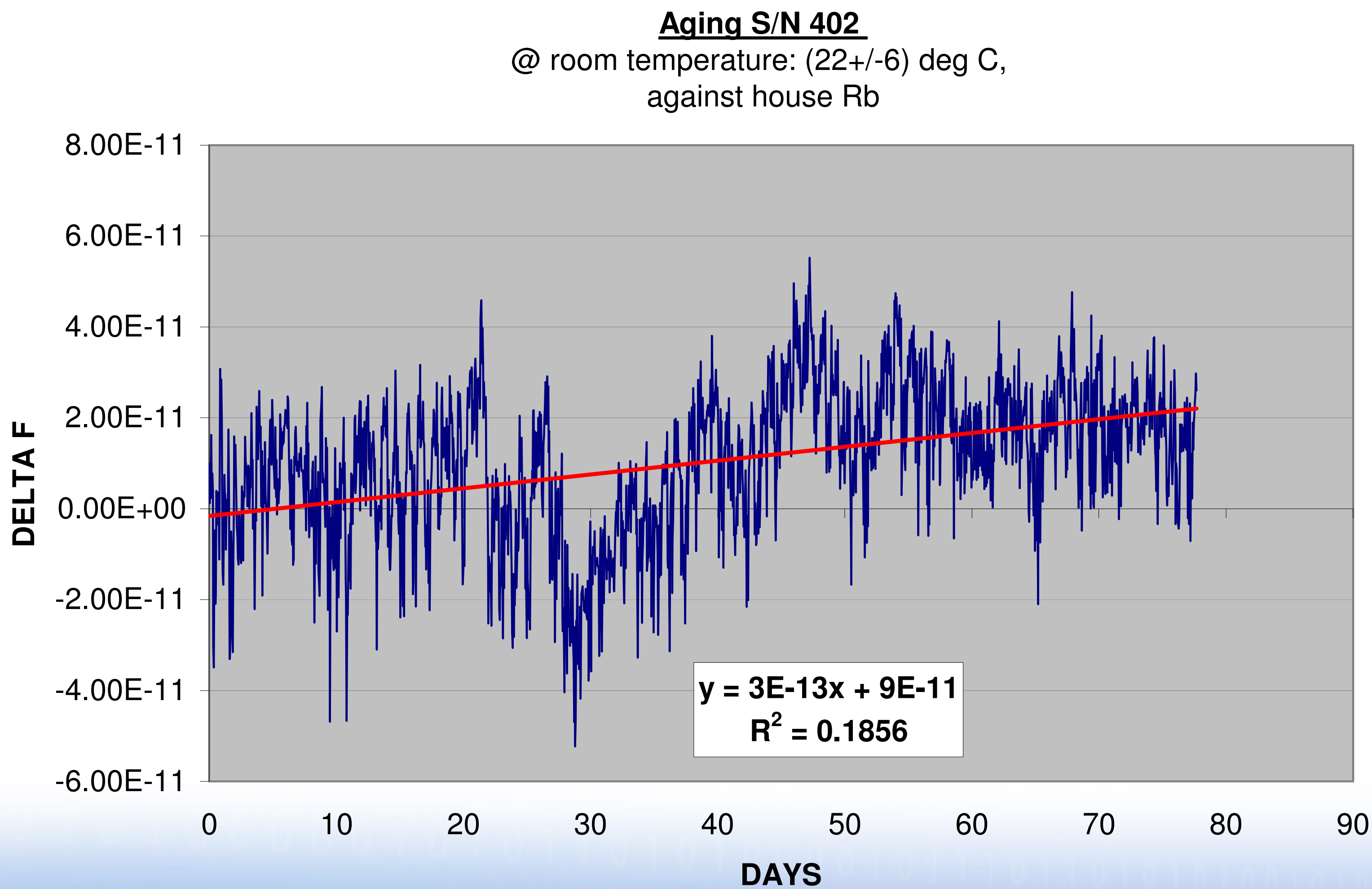
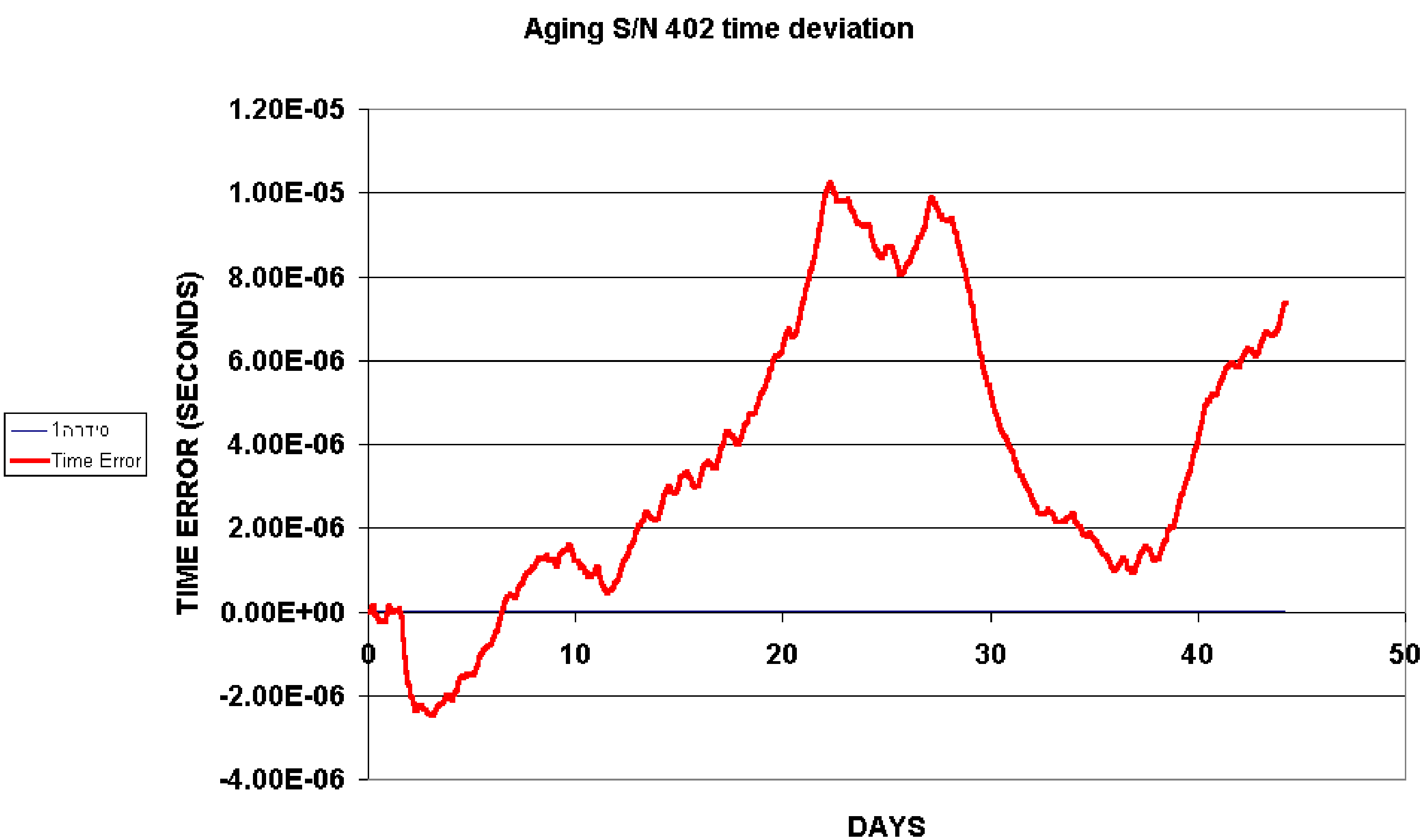
Rubidium Performance Summary

Miniature Oscillators:	18mm, 150cc
Low Aging:	$2x10^{-10}$ / Year
Wide Temp. Range:	-40°C to +78°C (+85°C)
Temp. Stability:	$5x10^{-11}$ / 0 to 50°C
Low Phase Noise	150dBc/Hz (floor)
Digital Freq. Cntrl:	$7x10^{-13}$ steps
Smart Clocks:	Hold-Over, Noise Reduction
High Reliability:	>261,000 Hrs at 25°C

Frequency Drift Example



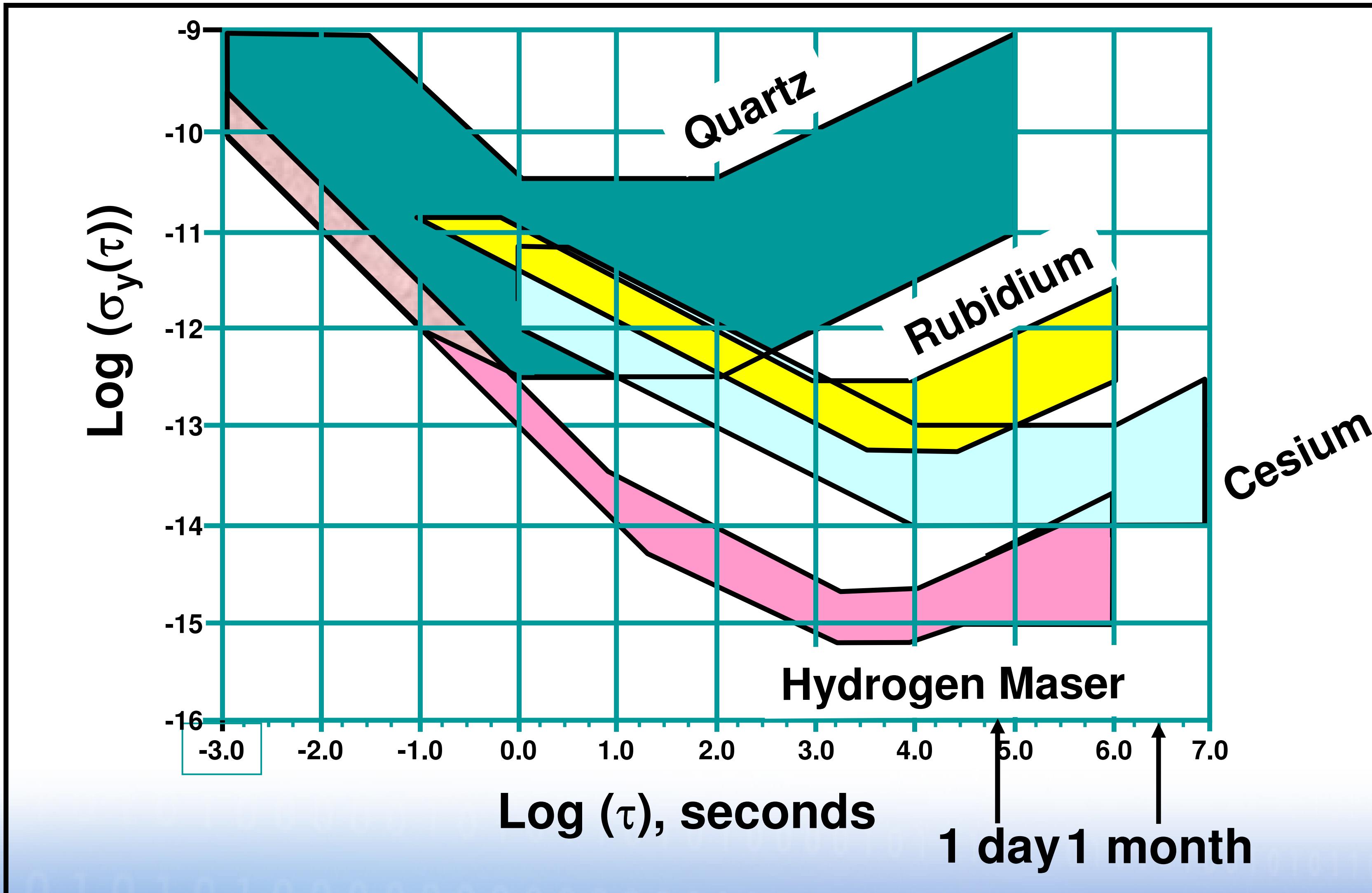
Time Drift Example (Rubidium)



Types of Atomic Standards

	Principle of Operation	Stability	Atomic Frequency	Q
Rubidium Vapor Cell	Optical pumping and transition detection in a Rb vapor cell	$10^{-9} – 10^{-11}$	6.8GHz	10^{7}
Cesium Beam	Detection of Cs beam trajectories in a magnetic field in a vacuum	$10^{-11} – 10^{-14}$	9.2GHz	10^{8}
Hydrogen Maser	Self-sustaining microwave oscillator at the atomic H freq.	$10^{-12} – 10^{-15}$	1.4GHz	10^{9}
Trapped Ions	Trapping ions in an electric field for longer interrogation and for reducing motion	$10^{-14} – 10^{-16}$	10GHz	10^{11}
Atomic Fountain	Cooled atoms (Cs, Rb) are tossed up and fall down slowly for longer interrogation	$10^{-15} – 10^{-17}$	9.2GHz	10^{12}

Short Term Stability Ranges of Various Frequency Standards



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Oscillator Comparison

	Quartz Oscillators		Atomic Oscillators		
	TCXO	OCXO	Rubidium	Rb+GPS	Cesium
Accuracy * (per year)	2×10^{-6}	1×10^{-8}	5×10^{-10}	1×10^{-13}	2×10^{-11}
Aging/Year	5×10^{-7}	5×10^{-9}	2×10^{-10}	1×10^{-13}	0
Temp. Stab. (range, ^{0}C)	5×10^{-7} (-55 to +85)	1×10^{-9} (-55 to +85)	3×10^{-10} (-55 to +71)	Stable T: 1×10^{-13}	2×10^{-11} (-28 to +65)
Stability, $\sigma_y(\tau)$ (τ = 1s)	1×10^{-9}	1×10^{-12}	3×10^{-12}	3×10^{-12}	5×10^{-11}
Size (cm^3)	10	20-200	100-800	2000	6,000
Warmup Time (minutes)	0.03 (to 1×10^{-6})	4 (to 1×10^{-8})	3 (to 5×10^{-10})	15	20 (to 2×10^{-11})
Power (W) (at lowest temp.)	0.04	0.6	7-20	15-20	30
Price (~$)	10 - 100	200-2,000	2,000-8,000	5000-10000	30,000-50,000

* Including environmental effects (note that the temperature ranges for Rb and Cs are narrower than for quartz).

COURTESY OF DR. JOHN VIG