Chip Scale Atomic Clocks Sources

Technology comparison

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Agenda

1. Key Parameters
2. Technology comparison
3. Conclusion

Recap from "Working principles"

General idea: leverage the intrinsic stability of atomic transitions to discipline an oscillating circuit based on a vibrating quartz crystal.

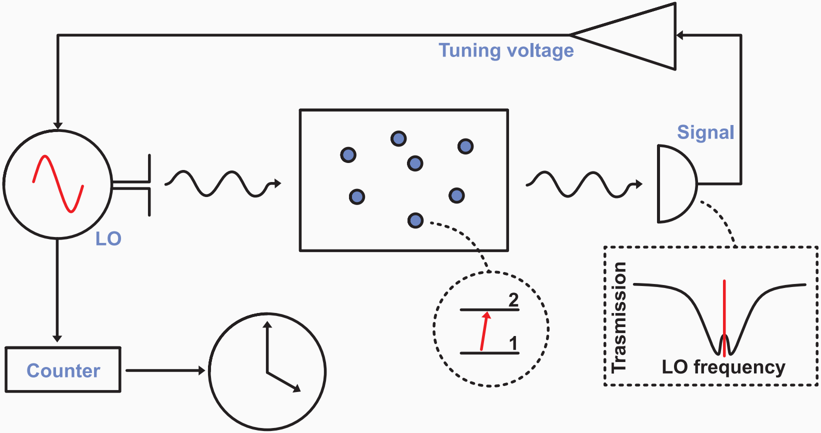
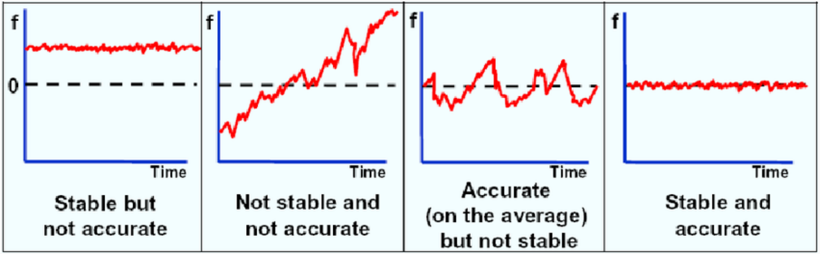


Figure 1: Chip Scale Atomic Clock scheme.

Key Parameters

Stability and Accuracy

The second, symbol s, is the SI unit of time. It is defined by taking the fixed numerical value of the Cs frequency $\Delta\nu_{Cs}$, the unperturbed ground-state hyperfine transition frequency of the ^{133}Cs atom, to be 9.192.631.770 when expressed in the unit Hz, which is equal to s^{-1}.

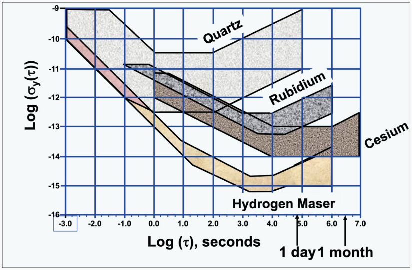


Short term stability (Allan deviation $\sigma_y(\tau)$)

Allan deviation is a measure of the stability of a frequency standard.

$$y(t) = \frac{f(t) - f_0}{f_0}$$

$$\sigma_y(\tau) = \sqrt{\frac{1}{2M}\sum_{i=2}^{M}(\bar{y}(\tau)_i - \bar{y}(\tau)_{i-1})^2}$$



It captures the frequency **Fast Noise (mainly caused by the Local Oscillator (LO))** & the Slow Drift (next slide)

[0] $\sigma_y(\tau = 1s) = 3 \times 10^{-9}$ is equivalent to an instability in frequency between two observations 1 second apart with a (RMS) value of 3×10^{-9}. For a $10MHz$ clock, this would be equivalent to $30mHz$ RMS movement.

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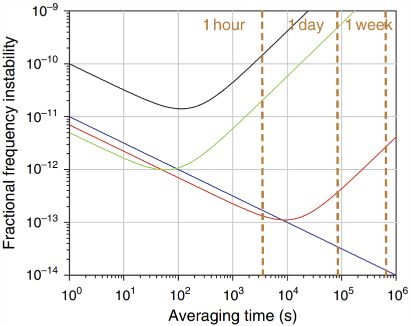

Figure 2: CBT, Rb, OCXO, TCXO

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Medium term stability (Allan deviation $\sigma_y(\tau)$)

After the flicker floor, the **Slow Drift** became the dominant noise source and Allan deviation can be expressed as:

$$\sigma_y(\tau) = \frac{1}{Q \times SNR}\tau^{-1/2}, \text{ where } \begin{cases} Q \text{ Line quality} & = \frac{\nu_0}{\Delta\nu} \\ SNR \text{ Signal-to-noise ratio} & = \frac{P_{signal}}{P_{noise}} \end{cases} \quad (1)$$

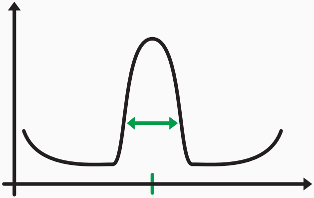


Figure 3: ν_0 and $\Delta\nu$.

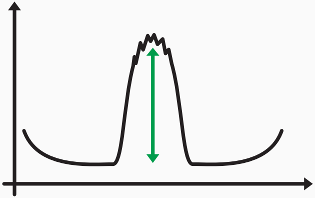
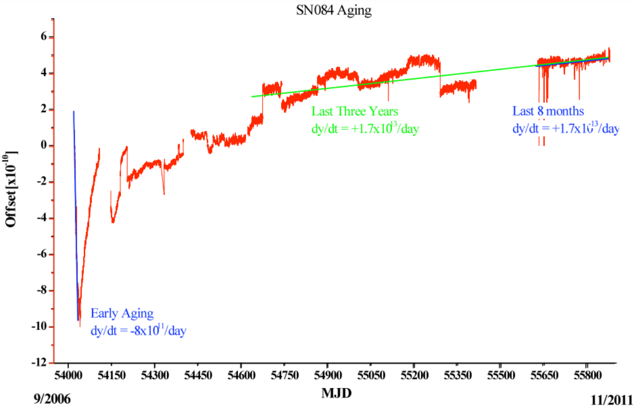


Figure 4: P_{signal} and P_{noise}.

MODR-based: lower Q but higher SNR.
CPT-based: higher Q but lower SNR.

Long term stability (Drift)

Drift is a measure of the long term stability of the clock which is caused by variation in the atomic reference frequency due to aging and environmental factors.

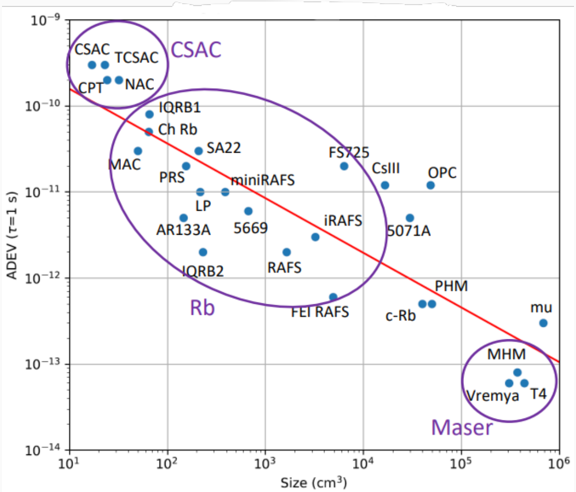


[0] MJD: Modified Julian Dates, are a count of days since November 17, 1858.

Technology comparison

ADEV@1s vs. Size

Empirical correlation[1]: $\sigma_y(\tau = 1) = 6.85 \times 10^{-10} + \text{volume}^{-0.64}$



Legend
CSAC = Microsemi SA.45s CSAC
TCSAC = Teledyne CSAC (preliminary)
CPT = Chengdu Spaceon CPT
NAC = Accubeat Rb NAC1
IQRB1 = IQD IQRB-1
Ch Rb = Chengdu Spaceon XHTF1031
MAC = Microsemi SA.35m
SA22 = Microsemi SA.22c
PRS = SRS PRS10
LP = Spectratime low profile Rb
AR133A = Accubeat AR133A Rb
miniRAFS = Spectratime miniRAFS
IQRB2 = IQD IQRB-2
5669 = FEI FE-5660 Rb
FS725 = SRS FS725
RAFS = Excelitas space RAFS
iRAFS = Spectratime iSpace RAFS
CsIII = Microsemi CBT 4310B CsIII
FEI RAFS = FEI RAFS
5071A = Microsemi 5071A CBT
OPC = Chengdu Spaceon TA1000 OPC
c-Rb = Spectradynamics cold Rb c-Rb
PHM = T4Science pHMaser 1008
mu = Muquans cold-atom MuClock (preliminary)
MHM = Microsemi MHM 2010 H Maser
Vremya = Vremya VCH-1003M H Maser
T4 = T4Science iMaser-3000 H Maser

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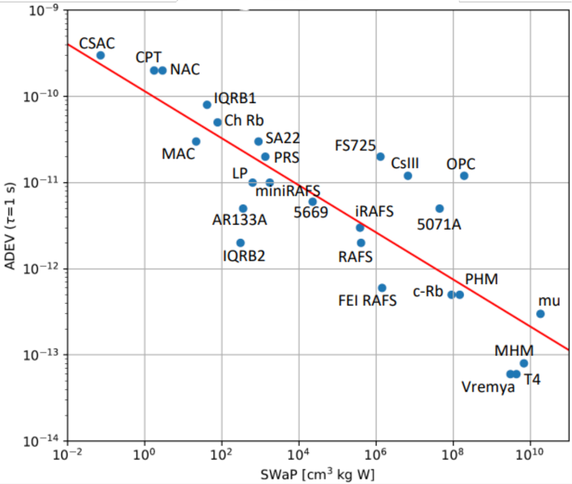
[1] Volume is expressed in [cm^3].

ADEV@1s vs. SWaP (Size, Weight and Power)

Similar correlation as before[1]: $\sigma_y(\tau = 1) = 1.15 \times 10^{-10} + \text{SWaP}^{-0.27}$



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[1] SWaP is expressed in $[cm^3 \times kg \times W]$.

Cost vs. Performance (qualitative)

Similar to what we have seen before, the cost of an atomic clock is proportional to its performance.

Technology	**Units/year**	**Unit price** (Range in \$)	**Worldwide sales** (\$/year)	**ADEV** (1 s)
Quartz crystals	5×10^9	$[0.1; 2000]$	$5B$	Low to medium
CSACs	12000	$[2000; 6000]$	$15M$	Medium to high
Rubidium cells	30000	$[1000; 10000]$	$150M$	High
Caesium beam	500	$[40000; 100000]$	$40M$	Very high
Hydrogen masers	20	> 100000	$4M$	The best

Table 1: All data must be taken as indicative.

For a CSAC, the cost is mainly driven by the packaging and assembly of the physics package.

Conclusion

Choice the right technology

The performance of an atomic clock can be evaluated (simplistically) as:

$$\text{Better performance} \Leftrightarrow \text{Higher SWaP \& Cost} \tag{2}$$

Both **MODR**-based[1] and **CPT**-based[2] have comparable performance, but different SWaP and cost:

- **CSAC (MODR)**: cheaper, but larger and more power hungry.
- **CSAC (CPT)**: more expensive, but smaller and more power efficient.

The right balance between performance, size, power consumption and cost depends on the specific application.

[1] Microwave Optical Double-Resonance
[2] Coherent Population Trapping

Extra slides

Commercial CSACs

Manufacturer/Model	Country	ADEV (1 s)	Power (W)	Size (cm^3)
Jackson Labs CSAC GPSDO	US	1E-10	1,4	85
Seiko Epson A06860LAN	JP	3E-11	3,0	75
Precision Test Systems RFS2	UK	3E-11	6,0	65
Quartziock EI O-MRX	UK	5E-11	6,0	65
Microsemi MAC SA.3Xm	US	3E-11	5,0	50
Orolia Spectratime mRO-50	CH/FR	4E-11	0,5	50
Chengdu Spaceon XHTF1031	China	5E-11	6,0	50
Microsemi MAC SA.5X	US	3E-11	6,3	47
Accubeat NAC1	Israel	2E-10	1,2	32
IQD ICPT-1	UK	9E-11	1,7	25
Chengdu Spaceon XHTF1040	China	3E-10	1,6	24
Teledyne TCSAC	US	3E-10	0,2	23
Microsemi SA45.s	US	3E-10	0,1	17
Chengdu Spaceon XHTF1045	China	3E-10	0,3	17

[0] Data ordered by size.

Commercial atomic clocks

Vendor	Product	Type	ADEV (1 s)	$\mathcal{L}$ (10 Hz)	Aging (month)	Retrace	Tmin (°C)	Tmax (°C)	Tempco	Power (W)	Weight (kg)	Size (cm^3)
Muquans	MuC10ck	cold Rb	3,00E-13	-151						200,00	135,000	682000
T4Science	iMaser-3000	Maser	6,00E-14	-136	6,00E-15					100,00	100,000	436800
Microsemi	MHM 2020	Maser	8,00E-14	-138	9,00E-15					75,00	246,000	374072
Vremya	VCH-1003M	Maser	6,00E-14	-135	9,00E-15					100,00	100,000	305525
T4Science	pHMaser	PHM	5,00E-13	-130	6,00E-14					90,00	33,000	49820
Chengdu Spaceon	TA1000	OPC	1,20E-11	-125						100,00	40,000	48266
Spectradynamics	c-Rb	cold Rb	5,00E-13	-138						75,00	30,500	39806
Microsemi	5071A	CBT	5,00E-12	-130			0	55		50,00	30,000	29700
Oscilloquartz	OSA 3235B Cs	CBT	1,20E-11	-120						60,00	15,000	23021
Microsemi	csIII 4310B	CBT	1,20E-11	-130			0	50		30,00	13,500	16544
FEI	FEI RAFS	Space Rb	6,00E-13	-138	9,00E-13	5,00E-12	-4	25		39,00	7,500	4902
Spectratime	iSpace RAFS	Space Rb	3,00E-12	-120	8,30E-12		-5	10		35,00	3,400	3224
Excelitas	RAFS	space Rb	2,00E-12	-105	3,00E-12	5,00E-12	-20	45		39,00	6,350	1645
FEI	FE-5669	Rb	6,00E-12	-140	1,00E-11	2,00E-11	-20	60	5,00E-11	20,00	1,690	669
Microchip	XPRO (low drift)	Rb	1,00E-11	-90	1,00E-11	3,00E-11	-25	70	6,00E-10	13,00	0,500	455
Spectratime	miniRAFS	Rb	1,00E-11	-84	3,00E-11		-15	55		10,00	0,450	388
IQD	IQRB-2	Rb	2,00E-12	-138	4,00E-11	2,00E-11				6,00	0,220	230
Spectratime	LP Rb	Rb	1,00E-11	-100	3,00E-11	5,00E-11	-25	55	2,00E-10	10,00	0,290	216
SRS	PRS10	Rb	2,00E-11	-130	5,00E-11	5,00E-11	-20	65	2,00E-10	14,40	0,600	155
Accubeat	AR133A	Rb	5,00E-12	-116	1,00E-11	5,00E-11	-20	65	1,00E-10	8,25	0,295	146
IQD	IQRB-1	Rb	5,00E-11	-95	5,00E-11	2,00E-11	0	50	5,00E-10	6,00	0,105	66
Chengdu Spaceon	XHTF1031 Rb	CPT	5,00E-11	-95	5,00E-11		-30	65	2,00E-10	6,00	0,200	65
Spectratime	mRO-50 (EAS)	CSAC	4,00E-11	-76	1,50E-10	1,00E-10	-10	65	4,00E-10	0,36	0,075	50
Microsemi	SA55 MAC	CPT	3,00E-11	-87	5,00E-11	5,00E-11	-10	75	5,00E-11	6,30	0,100	46
Accubeat	NAC	CSAC	2,00E-10	-86	3,00E-10		-20	65	2,00E-09	1,20	0,075	32
Chengdu Spaceon	CPT	CSAC	2,00E-10	-90	9,00E-10	5,00E-11	-45	70	5,00E-10	1,60	0,045	24
Teledyne	TCSAC	CSAC	3,00E-10	-85	3,00E-10	3,00E-10	-10	60	1,00E-09	0,18	0,042	23
Microsemi	SA45.s	CSAC	3,00E-10	-70	9,00E-10	5,00E-10	-10	70	1,00E-09	0,12	0,035	17
Microsemi	SA65	CSAC	3,00E-10	-64	9,00E-10	5,00E-10	-40	80	3,00E-10	0,12	0,035	16

[0] Data ordered by size.

References i

P. Banerjee and D. Matsakis.
Frequency Stability, pages 79–108.
Springer Nature Switzerland, Cham, 2023.

BIMP.
Si base unit: second (s).
https://www.bipm.org/en/si-base-units/second.

J. H. David R. Scherer, Bonnie L. Schmittberger.
Current and future atomic clocks - roadmap and applications.
https://www.gps.gov/cgsic/meetings/2019/.

S. Knappe.
Emerging Topics MEMS Atomic Clocks.
Elsevier (Netherlands), Nov 2007.

References ii

B. L. S. Marlow and D. R. Scherer.
A review of commercial and emerging atomic frequency standards.
IEEE Transactions on Ultrasonics, Ferroelectrics, and Frequency Control, 68(6):2007–2022, 2021.

Microchip.
Microchip technology inc. (website).
https://www.microsemi.com/.

NIST.
Time and frequency from a to z.
https://www.nist.gov/pml/time-and-frequency-division/popular-links/time-frequency-z.

M. Travagnin.
Chip-scale atomic clocks: Physics, technologies, and applications.
(KJ-NA-30790-EN-N (online)), 2021.

Questions?

Thank you!