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JRC TECHNICAL REPORT

Chip-Scale Atomic Clocks

Physics, technologies, and applications

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Abstract

We report on a cycle of four presentations on Chip-Scale Atomic Clocks (CSACs) organized and chaired by DG DEFIS Unit B.2 and given by the author in April/May 2021 to an audience composed by policy officers from DG JRC, DG DEFIS, DG CNECT, DG DIGIT, DG MOVE, REA, EISMEA, HaDEA, COUNCIL, EUSPA, EDA, and ESA ([1]). The presentations provide an overview of the place of CSACs in the clock landscape, their underlying working principles and enabling technologies, the available commercial devices, and the research and development initiatives going on worldwide. Applications are also covered, from which it becomes apparent the importance of CSACs for several military uses, and in some civilian domains. The aim of the report is to provide scientific and technical background for policy initiatives in an area of potential interest for strategic autonomy.

Indeed, this Technical Report shows that although the EU has a first-class research capability on CSACs and has developed advanced prototypes, the transition towards a market product with characteristics similar to those presently produced in the USA and in China needs attentive policy support. To be successful, a commercial CSAC needs to overcome the market uncertainties facing a product characterized by high manufacturing costs and an application domain falling mostly in the military and defence sector. Since in the EU accreditation and procurement of military equipment is determined by national regulations, there is a clear case for policy initiatives aimed at the institution of an EU-wide market space for CSACs, the only which can guarantee a demand large enough to enable the cost reductions associated with large-scale manufacturing.

This point clearly emerged during the discussions which followed the presentations. Indeed, policy officer from both the European Commission and the European Defence Agency hinted at the necessity of establishing a mechanism for information exchange between relevant European institutions, national governments, and manufacturers of military equipment as a precondition to raise the interest of atomic clock producers towards a device which could contribute to EU strategic autonomy. It was agreed that the JRC will continue to provide the Commission the necessary assistance, in terms of technical know-how.

([1]) The list of invitees and of participants is not disclosed in the present Report. The interested reader is invited to contact via the functional e-mail defis-qts@ec.europa.eu the Directorate General for Defence Industry and Space, Unit B.2, which will handle the request in accordance with the relevant privacy rules.

1 Introduction

Broadly speaking, an atomic clock can be seen as a hybrid device which exploits a quantum transition to discipline a classical oscillating system, i.e. to improve its long term stability. The peculiar properties and the performance level of miniature atomic clocks (MAC) and chip-scale atomic clocks (CSAC) position them in between compact atomic clocks based on rubidium cells and the best classical quartz oscillators. MACs and CSACs are devices of both commercial and military interest, and several manufacturers from USA, China, UK, Israel, France, and Switzerland are now selling devices with varying levels of technological sophistication. Continuous product improvement is supported by the US government, while research groups from Japan, China, France, UK, and Switzerland are working on advanced prototypes which hold the promises for challenging the USA technological lead in the field.

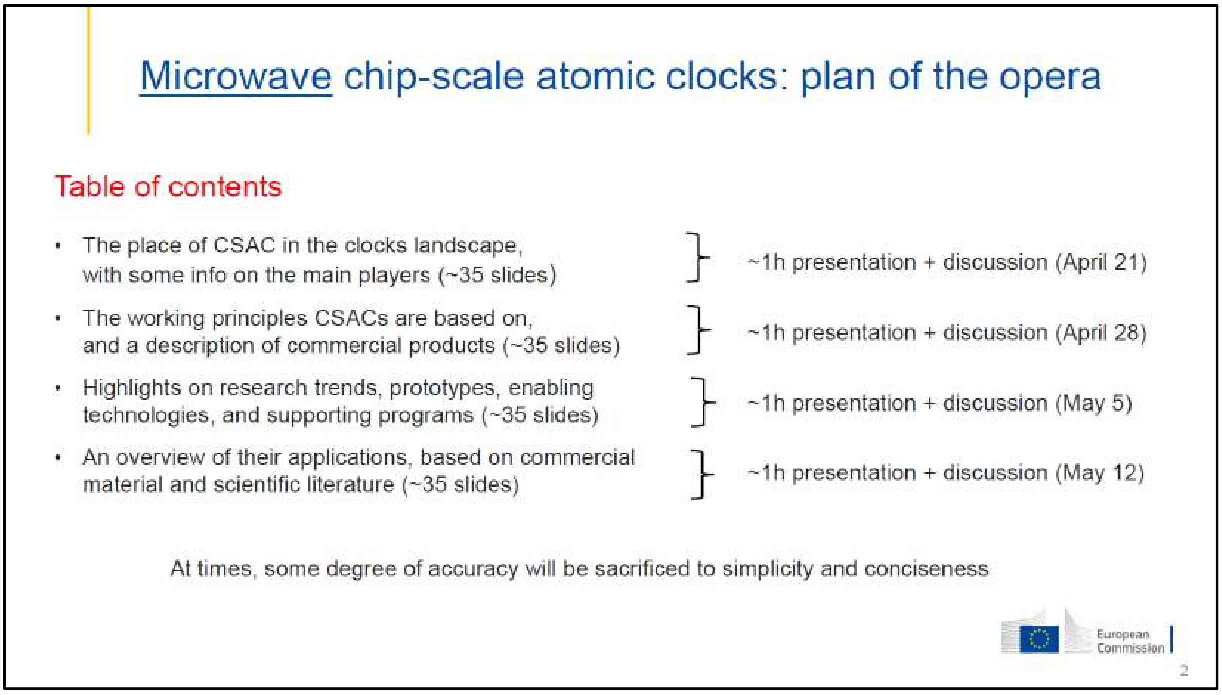
Initially spurred by military radio-communication applications, quartz has been employed as a frequency reference and for time-keeping since the 40s'. Thanks to the strong electro-mechanical coupling between mechanical vibrations and electric field, quartz constitutes a very good physical basis for an electrical circuit oscillating at a very precise frequency; however, although very stable in the short term, it suffers from instabilities induced by a number of environmental disturbances (temperature changes, vibrations, accelerations and gravity variations, etc.) and long term aging (e.g. due to radiations). Quartz-based frequency references now constitute a market estimated in 5$ billion per year, which comprehends devices of hugely different cost and performance. Also atomic clocks based on rubidium are a mature technology, whose basic principles have been established in the 1950's. By using a feedback loop they lock a quartz oscillator to a microwave atomic transition, which is detected by optically pumping and probing the Rb atoms contained in a hot vapour cell. Such a double resonance scheme, which involves both microwave and optical transitions, allows disciplining a quartz oscillator by reducing the disturbances due to uncontrollable environmental factors, thus improving the system long-term stability. Thanks to a good compromise between cost and performance, rubidium atomic clocks conquered a market large enough to support continuous exploration of physics, adoption of new techniques, and manufacturing advancements, and enjoined more than sixty years of refinements. They are by far the most widely used among atomic clocks, whose entire market is estimated at around 200$ million per year. However, the physical principles they exploit set unescapable limits to their size, weight, and power requirements, which open between the most compact Rb clocks based on double resonance and the best performing quartz systems an application space which can be covered by miniature and chip-scale atomic clocks.

Miniature and chip-scale atomic clocks are the result of the successful exploitation of a quantum physics phenomenon named coherent population trapping (CPT), which was serendipitously discovered in the 70s' and fully understood in the 90s'. CPT-based clocks exploits a quantum coherence effect, which allows one to establish whether a laser is modulated at a well-defined microwave frequency by probing the inhibition of an optical transition. In a CPT frequency reference two bulky and power-hungry elements of the classical double-resonance Rb clock, namely the lamp and the microwave cavity, are eliminated and substituted by a tiny and low-consumption Vertical Cavity Surface Emitting Laser (VCSEL), which is modulated at the microwave clock transition frequency. The use of a laser allows a wavelength flexibility which enables using also caesium, alongside rubidium, as the atomic element to be probed. The USA Defense Advanced Research Projects Agency (DARPA) early recognized the potential of CPT for a compact battery-operated atomic clock for military backpack applications and in 2000 started a multi-annual funding programme, which lead to the commercial launch of the first Miniature Atomic Clock (MAC) in 2008 and of the first Chip-Scale Atomic Clock (CSAC) in 2011. The development of a VCSEL with the suitable properties has been one of the major success of the DARPA chip-scale atomic clock initiative, and gave US commercial players to which the technology was initially reserved a decisive advantage with respect to potential competitors. Other non-trivial technological challenges which were successfully met by the DARPA program have been the manufacturing of a miniaturized hot vapour cell containing the alkali atoms and a suitable mix of buffer gas, and the control electronics which stabilized the whole system at its working point by implementing the necessary control loops.

Thanks to their better long-term stability, miniature atomic clocks (MAC) based on CPT and mains-operated can commercially compete with the best quartz-based oven controlled crystal oscillators (OCXO), provided their cost is maintained below ~1000$. By using low-cost manufacturing techniques of a typically cm-size vapour cell this has been demonstrated to be feasible, and many commercial players worldwide now sell miniature atomic clocks, having in some cases discontinued the production of the most compact among their legacy double-resonance devices. A significant enabling step in this process has been the recent commercial availability of VCSELs with the required frequency stability properties, both for Cs and Rb, which allows also atomic clock manufacturers which lack semiconductor microfabrication capabilities developing CPT-based devices by buying the suitable VCSELs from commercial vendors.

With respect to MAC, battery-operated chip-scale atomic clocks (CSACs) involve a much higher degree of miniaturization, which unavoidably implies lower stability performance. The mm-size atomic cell is typically manufactured with complex micromachining technologies, and filling it with the right gas mix requires sophisticated complementary techniques. This significantly restricts the pool of players and heavily impacts on the final cost of the device, which can easily reach several $ thousands. Presently, CSACs are mainly used for high-end backpack military application (e.g. tactical and MILSATCOM radios, military-grade GNSS receivers, Improvised Explosive Device jammers), and some niche civilian and space applications.

The next four Sections (Sections 2-5) collect the slides used for the workshops held respectively on April 21, April 28, May 5 and May 12, in which the topics detailed in the slide below have been covered. In Section 6 we present some additional technical details on military applications of high-performance clocks, in Section 7 we focus in particular on CSACs advantages, and in Section 8 we highlight some significant application of CSACs taken from the available literature. In the final Section 9 we summarize the main conclusions of this work.



Disclaimer

The citation of a specific commercial product in this report should not be regarded as an endorsement or as a recognition of the product's quality from JRC or the EC.

2 The place of Chip-Scale Atomic Clocks in the clocks landscape

Microwave chip-scale atomic clocks: plan of the opera

Table of contents

- The place of CSAC in the clocks landscape, with some info on the main players (~35 slides) } ~1h presentation & discussion (April 21)
- The working principles CSACs are based on, and a description of commercial products (~35 slides) } ~1h presentation & discussion (April 28)
- Highlights on research trends, prototypes, enabling technologies, and supporting programs (~35 slides) } ~1h presentation & discussion (May 5)
- An overview of their applications, based on commercial material and scientific literature (~35 slides) } ~1h presentation & discussion (May 12)

At times, some degree of accuracy will be sacrificed to simplicity and conciseness

2

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GNSS Galileo/Egnos clocks

- Galileo Precise Timing Facilities -> Galileo System Time
  - 2 Active Hydrogen Masers
  - 4 Caesium Atomic Clocks
  - Frequency stability: Allan Deviation ADEV ~$4 \cdot 10^{-15}$ @ 1 day
- Galileo satellites
  - 2 Passive Space Hydrogen Masers (SPHM): ADEV ~$2 \cdot 10^{-14}$ @ 1000 s
  - 2 Rubidium Atomic Frequency Standards (RAFS): ADEV ~$2 \cdot 10^{-13}$ @ 1000 s
- Egnos Ranging Integrity Monitoring Stations (RIMS)
  - Rubidium atomic clocks: ADEV ~10^{-13} @ 1 day
- GNSS receivers
  - Quartz crystal oscillators VCXO, TCXO: ADEV ~10^{-7} to ~10^{-9} @ 1 s;
  - OCXOs: ~10^{-10} to ~10^{-12} @ 1 s (for high-end applications, not backpack-portable)
  - Microwave chip-scale atomic clocks: ADEV ~10^{-10} to ~10^{-11} @ 1 s (backpack-portable: for specific military applications)
  - Compact Rb atomic clocks: ADEV ~10^{-11} @1 s, ~10^{-13} @1000 s (not portable, for very high-end applications)

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IPhone X 2017

Apple System On a Chip (since 2010):

- Central Processing Unit
- Graphic Processing Unit
- Neural Processing Unit
- Image Signal Processor
- Secure Enclave Processor
- Sensors and GNSS,
  with dedicated co-processor

A4, September 2010 (for IPhone 4)
45nm lithography, 54mm^3
0.15 billion transistors

A11, September 2017
10nm lithography, 88mm^3
4.3 billion transistors

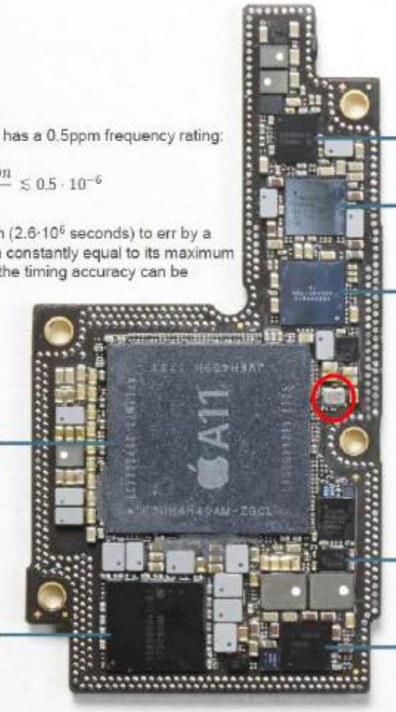
A14, September 2020
5nm lithography, 88mm^3
11.8 billion transistors

TechInsights

A typical mobile phone TCXO for GNSS has a 0.5ppm frequency rating:

$$\frac{\textit{Frequency Deviation}}{\textit{Frequency}} \lesssim 0.5 \cdot 10^{-6}$$

A 0.5ppm oscillator would take ~a month ($2.6 \cdot 10^6$ seconds) to err by a second, assuming a frequency deviation constantly equal to its maximum possible value. In one day ($8.64 \cdot 10^4$ s), the timing accuracy can be estimated in ~0.05 s.



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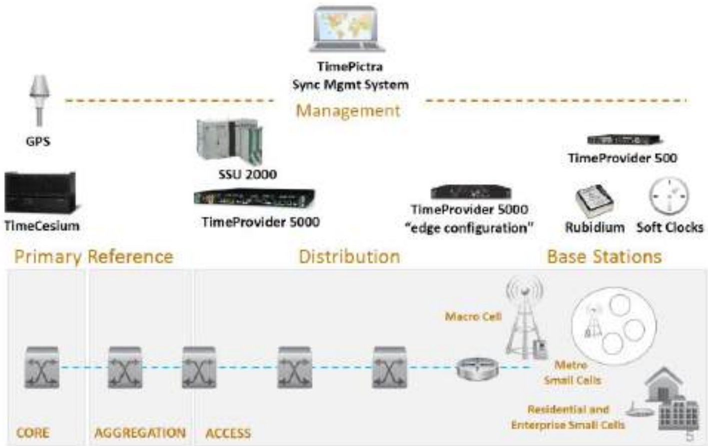
Atomic clocks in mobile telecom networks

LTE/4G Base stations: network synchronization requires timing accuracy of 1.5µs

Timing is usually provided by a GNSS-disciplined oscillator, or by a slave clock connected to a primary standard, e.g. by using the Precision Time Protocol. In either case, holdover capabilities at the base station are required, in case a fault interrupts the connection with the GNSS or with the primary reference.

Better holdover capability by the local clock allows more leeway for time-distribution faults management

Typical holdover requirement: 1.5µs/day, easily met with a compact (1000$) Rb atomic clock. Cheaper oven-controlled crystal oscillators (OCXO, 100-500$) are widely employed, which perform worse than Rb oscillators; miniature atomic clocks (MAC) are also increasingly adopted.



Slide by Symmetricom/Microsemi/Microchip

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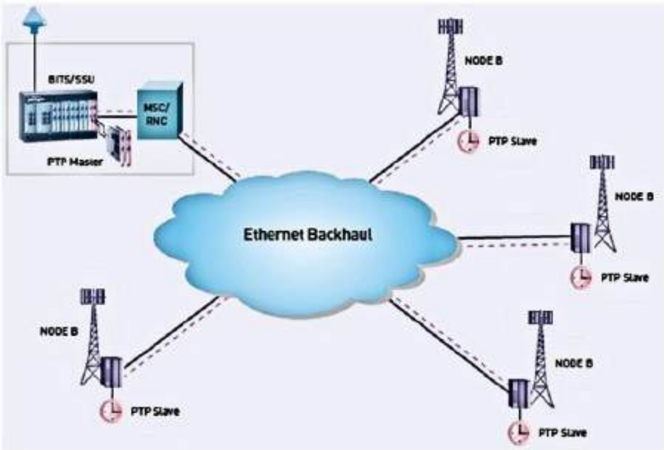
Clocks in LTE/4G base station

PTP: Precision Time Protocol



Produced by IQD Frequency Products for LTE & 4G base stations, the IQCM-100 OCXO (Oven Controlled Crystal Oscillator) module achieves a holdover specification of 1.5µs over a 24 hour period.

6.5x6.5x2=80cm³, 6W, 100$ to 1000$

Microsemi SA.22c
210cm³, 15W
Stratum 2 holdover
Discontinued May 2019
Replaced by MAC SA.5X

Microsemi SA.5X Miniature Atomic Clock: sub-microsecond holdover for 48 hour for LTE base stations, smart grid and enterprise network infrastructure

5x5x2=50cm³, 6W, 500$ to 1000$ (est.)

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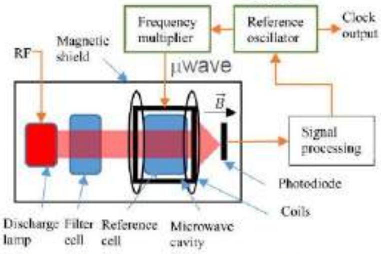
"Classical" vs chip-scale Rb atomic clock



An atomic µw resonance is optically detected and stabilizes a quartz oscillator

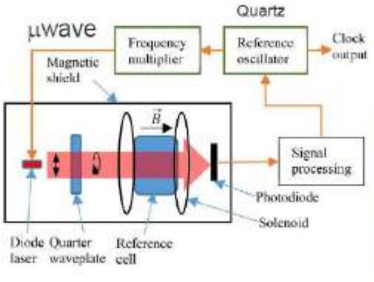
Table-top
17Kg, 30W
Year: ~1970

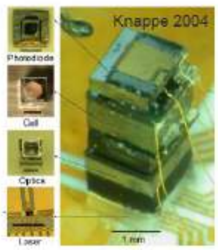
Compact
5x7.5x10=375cm³
0.6Kg, 15W
Year: 2000

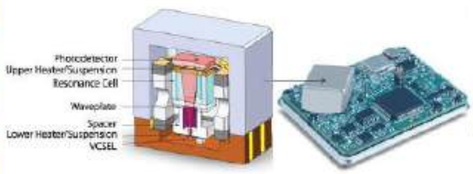
Instead of double optical-µw resonance, CSACs exploit Coherent Population Trapping

- Tiny laser (VCSEL) instead of Rb discharge lamp
- No filter cell, no microwave cavity
- Micro-machined alkali vapour reference cell

A CSAC is smaller, lighter, faster to warm-up, more power-efficient… but less stable







4x3.5x1.2=17cm³
0.035Kg, 0.120W
Year: 2011

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Miniature and chip-scale atomic clocks
China Aerospace Science and Industry Corporation
CASIC, 36cm³
Double μw-optical resonance
UK, 75cm³, 6W
CPT
USA, 5x5x2=50cm³, 100g, 6W
Chengdu XHTF1031
China, 50cm³, 6W
FR, 50cm³, 0.5W
Based on Coherent Population Trapping
IQD
Strictly specking, "CSAC" is a trademark
Chengdu XHTF1045
US, 4x3.6x2.2=32cm², 1.2W
UK, 25cm³, 1.7W
China, 17cm³, 0.25W
USA, 4x3.5x1.6=23cm³, 0.18W
USA, 4x3.5x1.2=17cm³, 35g, 0.12W
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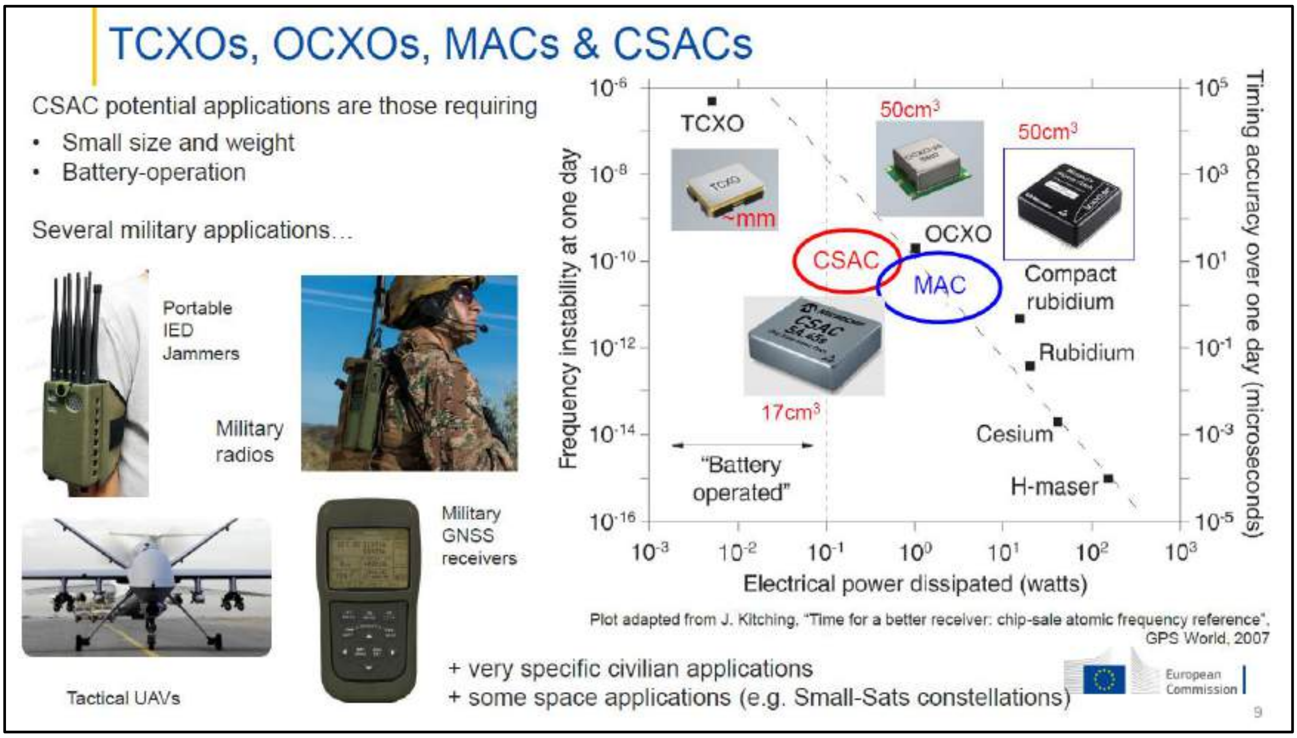
TCXOs, OCXOs, MACs & CSACs
CSAC potential applications are those requiring
• Small size and weight
• Battery-operation
Several military applications…
Portable IED Jammers
Military radios
Military GNSS receivers
Tactical UAVs
+ very specific civilian applications
+ some space applications (e.g. Small-Sats constellations)
Frequency instability at one day
Timing accuracy over one day (microseconds)
Electrical power dissipated (watts)
TCXO
~mm
50cm³
50cm³
OCXO
CSAC
MAC
Compact rubidium
Rubidium
17cm³
Cesium
H-maser
"Battery operated"
Plot adapted from J. Kitching, "Time for a better receiver: chip-sale atomic frequency reference", GPS World, 2007
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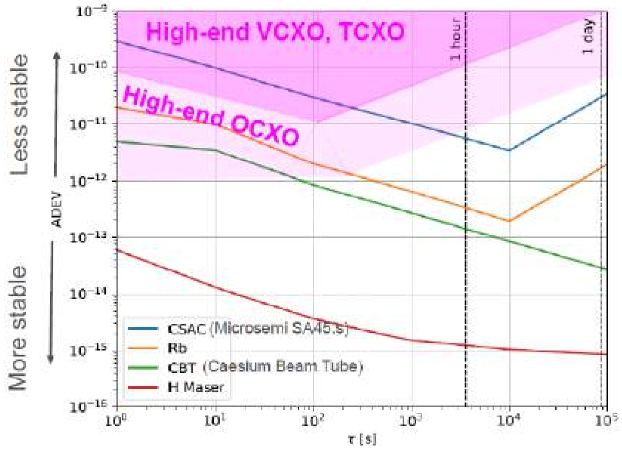
Frequency stability of quartz crystals and atomic clocks

B. L. Schmittberger et al., "A Review of Commercial and Emerging Atomic Frequency Standards", pre-published, 2021



The **Allan Deviation** ADEV(τ) measures the fractional frequency stability over a given time interval, and is a property of the clock itself.

MACs and CSACs are devised to compete with high-end quartz oscillators and OCXO in particular, for applications requiring:

- Better long-term stability
- Lower power consumption
- Smaller size and weight

CSACs are indicated for back-pack portable applications

- Accuracy measures the error of the clock with respect to a better clock (e.g. a Cesium fountain standard)
- Then there are several parameters to measure long-term stability, drifts, susceptibility to external perturbations, etc…
- Other parameters (e.g. reproducibility, relative uncertainty, etc…) must be used for optical clocks

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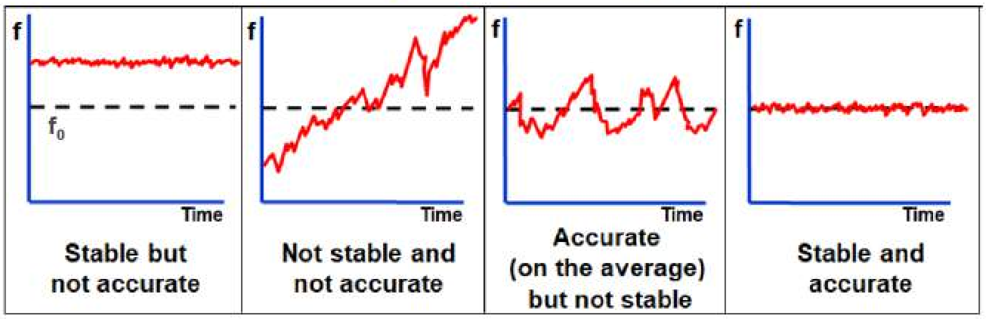
Stability and accuracy



The Allan Deviation ADEV(τ) is devised to measure the clock frequency stability on different time scales. It captures the deviations from an ideal stability behaviour which affect the device over a time interval τ.

Broadly speaking, we can say that ADEV(1s) = 10^{-11} means that we can expect a fractional frequency change of ~10^{-11} over 1 second of operation, or in other terms that the relative frequency variation will remain within a 10^{-11} range in a time interval of 1 second.

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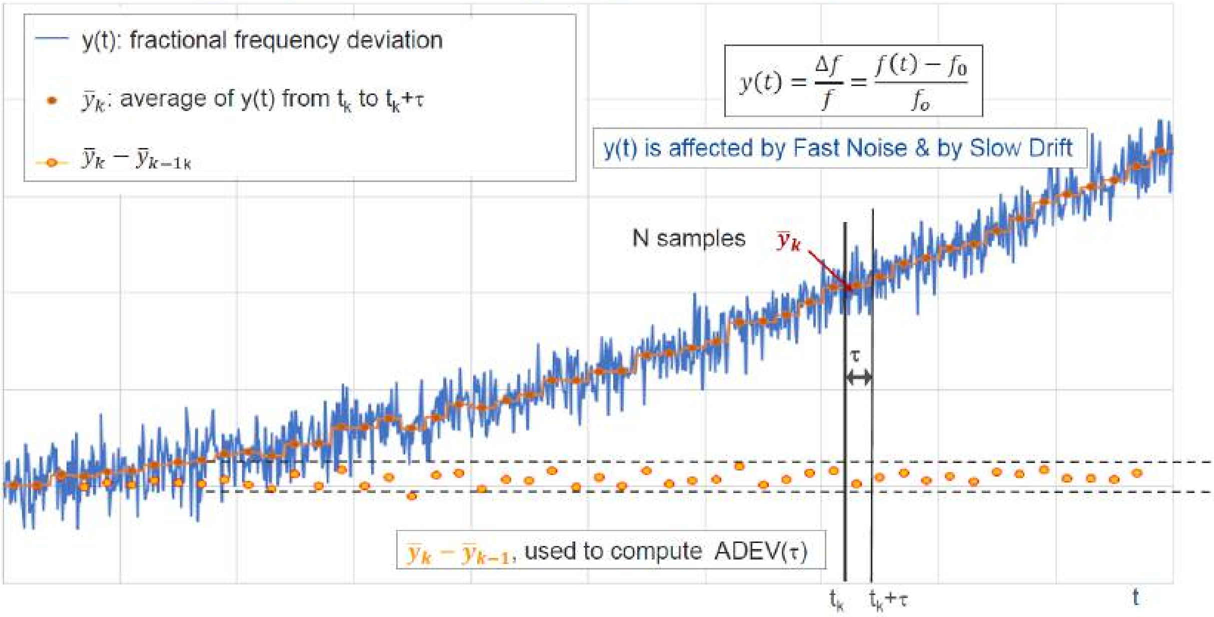
ADEV(τ) captures the frequency noise acting on a τ timescale



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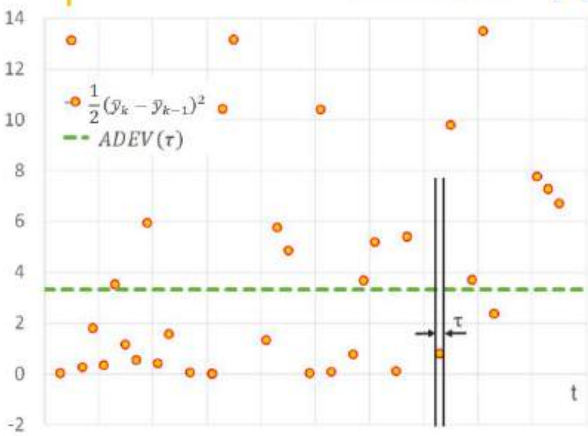
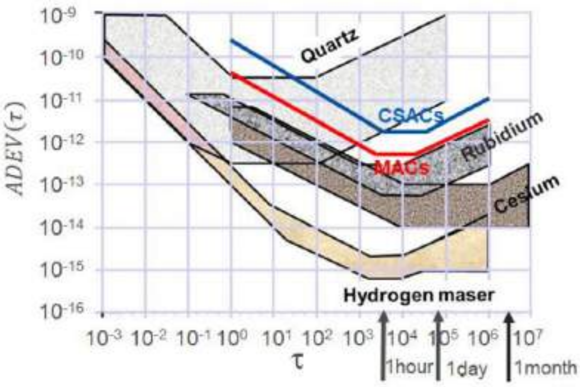
How ADEV(τ) changes with τ



$$ADEV(\tau) = \sqrt{\frac{1}{2N}\sum_{k=2}^{N}(\bar{y}_k - \bar{y}_{k-1})^2}$$

For short τ the differences $\bar{y}_k - \bar{y}_{k-1}$ are spread by "fast" noise acting on a timescale ≪ τ, so I have a broad cloud of yellow points. As τ increases the effects of a short-term noise are progressively averaged out, but "slow" drifts acting on a timescale ≫ τ start to kick in. The cloud become narrower, but it raises up.



Two competing effects affect ADEV(τ) as τ is increased:

(i) averaging out of short-term noise ⇒ ADEV(τ) ↓

(ii) larger impact of long term drifts ⇒ ADEV(τ) ↑

→ ADEV(τ) decreases, reaches a minimum, then increases again

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Quartz-based oscillating circuits

Electrostriction: applied electric field → mechanical vibrations
Piezoelectricity: mechanical vibrations → oscillating electric field
Electro-mechanical coupling in a quartz crystal:
Mechanical vibrations ↔ Oscillating electric field

Quartz is a very good physical basis for an electrical circuit oscillating at a very precise frequency

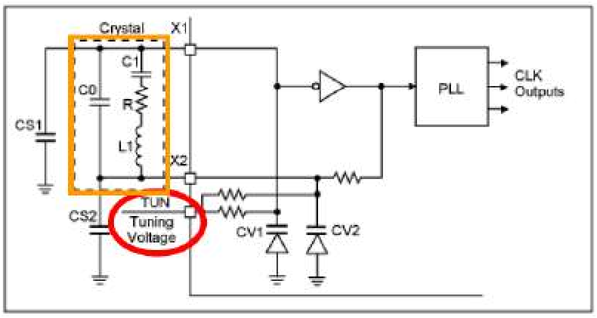
VCXO: Voltage-controlled crystal oscillating circuit
TCXO: Temperature-controlled crystal oscillating circuit
OCXO: Oven-controlled
DOCXO: Double-Oven controlled
MCXO: Microprocessor-controlled
…

Q: Oscillator quality factor: initial energy stored in the resonator divided by the energy lost in each oscillation cycle

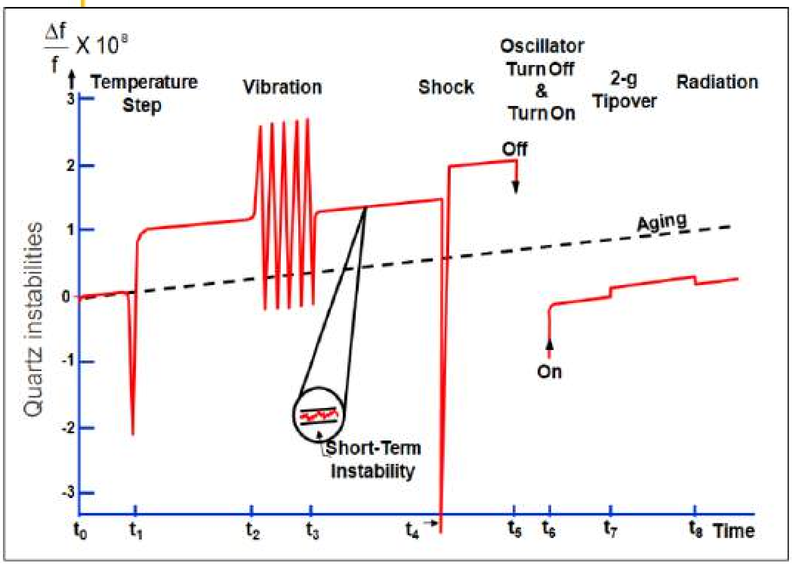
~ Number of oscillation cycles before losing energy
~ Ratio of a resonator's centre frequency to its bandwidth

Q for quartz oscillators: from 10^4 to 10^6 (for a LC circuit is ~10^2)

Example of a voltage-controlled crystal oscillator circuit



Rationale for an hybrid quartz & quantum system



Quartz:
- Good short-term stability ($t < 10^0 - 10^2$ s)

Atoms:
- Better long-term stability
- Better aging and drift
- Easier to shield from disturbances

Atomic clock basic idea: implement a feedback loop which locks the quartz oscillation to an atomic resonance.

Leverage the intrinsic stability of an atomic transition to "discipline" an oscillating circuit based on a vibrating quartz crystal.

Caveat: properties of isolated atoms depend only on fundamental and invariant constants on nature. Much of the work for atomic clocks consists in isolating atoms from environmental perturbations.

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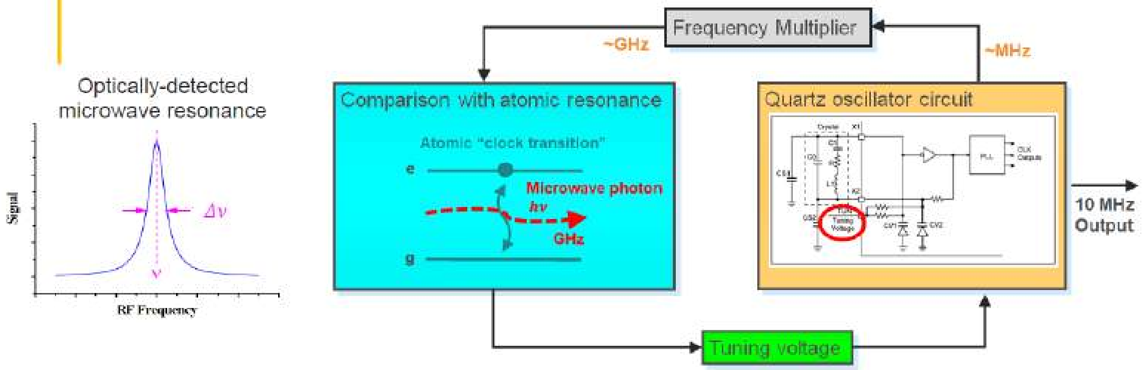
Quartz-atoms feedback loop



For the μw clock transition used in a table-top atomic Rb clock:

Atomic transition quality factor: $Q = \frac{\nu}{\Delta\nu} \cong 3 \cdot 10^7$

Signal to noise ratio: $SNR[\sqrt{Hz}\,] = \frac{Signal\ power\ [mW]}{Noise\ spectral\ power\left[{}^{mW}/_{\sqrt{Hz}}\right]}$, $(SNR)_{1\mathrm{Hz}} \cong 3000 s^{-\frac{1}{2}}$

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Allan Deviation in TCXO, OCXO, Rb clocks and CSACs

When white frequency noise dominates:

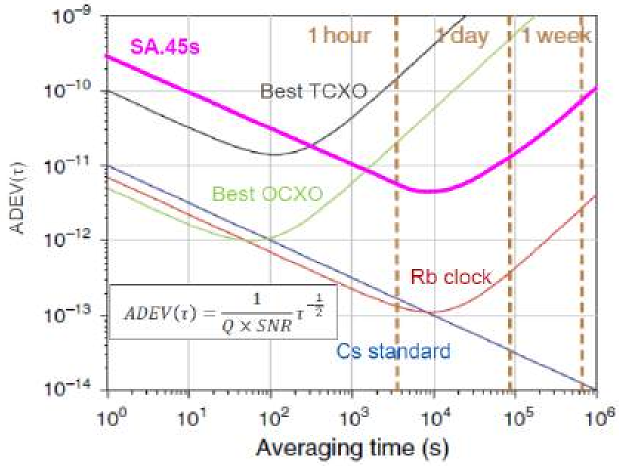
$$ADEV(\tau) = \frac{1}{Q \times SNR}\tau^{-\frac{1}{2}}$$

In a table-top Rb clock: $ADEV(1s) \cong \frac{1}{3\cdot 10^7 \times 3000} \cong 10^{-11}$

Short-term stability: $ADEV(\tau) \cong 10^{-11}\tau^{-\frac{1}{2}}$ for $1 \le \tau \le 10^4$ s

Noise floor: $ADEV(10^4 s) \cong 10^{-13}$

MACs and CSACs have worse stability performance, see plot for Microsemi SA.45s CSAC.



Other Specs:

Accuracy	Sensitivity to: temperature
Phase noise	electric fields
Drift	magnetic fields
Retrace	vibrations
Size, Weight, Power	accelerations
Lifetime	gravity variations
Radiation resistance	

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Commercial atomic clocks

MAC, CSAC < 100 cm³

- 3×10^{-11} < ADEV@1s < 3×10^{-10}
- 0.12W < Power < 6W
- 17cm³ < Size < 100cm³

Compact < 1000 cm³

Table Top < 30000 cm³ (3U rack)

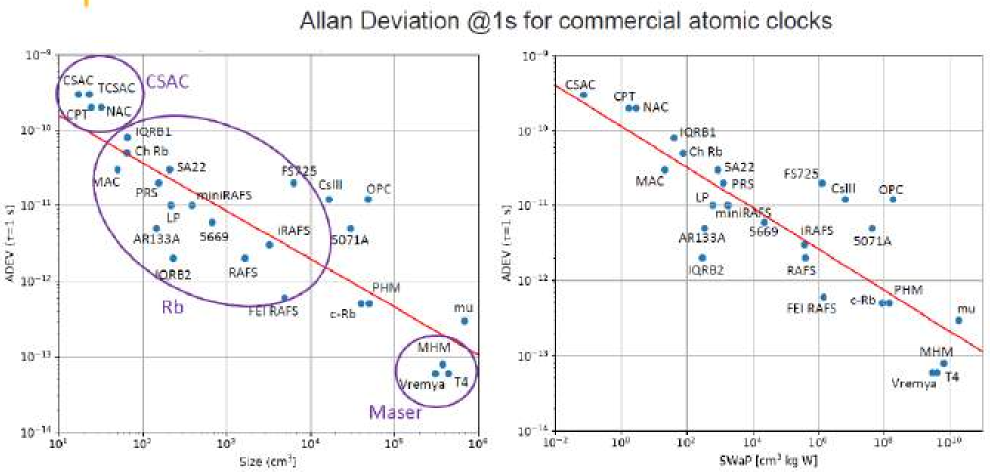
CSAC Chip Scale Atomic Clock
CPT Coherent Population Trapping
CBT Caesium Beam Tube
OPC Optical Pump Caesium
PHM Passive Hydrogen Maser

Table from B. L. Schmittberger et al., "A Review of Commercial and Emerging Atomic Frequency Standards", IEEE TRANSACTIONS ON ULTRASONICS, FERROELECTRICS, AND FREQUENCY CONTROL, pre-published, 2021

Vendor	Product	Type	ADEV (1 s)	$\mathscr{L}$ (10 Hz)	Aging (month)	Retrace	T_{min} (°C)	T_{max} (°C)	Tempco	Power (W)	Weight (kg)	Size (cm³)
Microsemi	SA45.s	CSAC	3×10^{-10}	-70	9×10^{-10}	5×10^{-10}	-10	70	1×10^{-9}	0.12	0.035	17
Teledyne	TCSAC	CSAC	3×10^{-10}	-85	3×10^{-10}	3×10^{-10}	-10	60	1×10^{-9}	0.18	0.042	23
Chengdu Spaceon	CPT	CSAC	2×10^{-10}	-90	9×10^{-10}	5×10^{-11}	-45	70	5×10^{-10}	1.6	0.045	24
Accubeat	NAC	CSAC	2×10^{-10}	-86	3×10^{-10}		-20	65	2×10^{-9}	1.2	0.075	32
Microsemi	SA35 MAC	CPT	3×10^{-11}	-87	5×10^{-11}	5×10^{-11}	-10	75	5×10^{-11}	6.3	0.1	46
Spectratime	mRO-50 (EAS)	CSAC	4×10^{-11}	-76	1.5×10^{-10}	1×10^{-10}	-10	65	4×10^{-10}	0.36	0.075	50
Chengdu Spaceon	XHTF1031 Rb	CPT	5×10^{-11}	-95	5×10^{-11}		-30	65	2×10^{-10}	6	0.2	65
IQD	IQRB-1	Rb	5×10^{-11}	-95	5×10^{-11}	2×10^{-11}	0	50	5×10^{-10}	6	0.105	66
Accubeat	AR133A	Rb	5×10^{-12}	-116	1×10^{-11}	5×10^{-11}	-20	65	1×10^{-10}	8.25	0.295	146
SRS	PRS10	Rb	2×10^{-11}	-130	5×10^{-11}	5×10^{-11}	-20	65	2×10^{-10}	14.4	0.6	155
Spectratime	LP Rb	Rb	1×10^{-11}	-100	3×10^{-11}	5×10^{-11}	-25	55	2×10^{-10}	10	0.29	216
IQD	IQRB-2	Rb	2×10^{-12}	-138	4×10^{-11}	2×10^{-11}				6	0.22	230
Spectratime	miniRAFS	Rb	1×10^{-11}	-84	3×10^{-11}		-15	55		10	0.45	388
Microchip	XPRO (low drift)	Rb	1×10^{-11}	-90	1×10^{-11}	3×10^{-11}	-25	70	6×10^{-10}	13	0.5	455
FEI	FE-5669	Rb	6×10^{-12}	-140	1×10^{-11}	2×10^{-11}	-20	60	5×10^{-11}	20	1.69	669
Excelitas	RAFS	Space Rb	2×10^{-12}	-105	3×10^{-12}	5×10^{-12}	-20	45		39	6.35	1645
Spectratime	iSpace RAFS	Space Rb	3×10^{-12}	-120	8.3×10^{-12}		-5	10		35	3.4	3224
FEI	FEI RAFS	Space Rb	6×10^{-13}	-138	9×10^{-13}	5×10^{-12}	-4	25		39	7.5	4902
Microsemi	CsIII 4310B	CBT	1.2×10^{-11}	-130			0	50		30	13.5	16544
Oscilloquartz	OSA 3235B Cs	CBT	1.2×10^{-11}	-120						60	15	23021
Microsemi	5071A	CBT	5×10^{-12}	-130			0	55		50	30	29700
Spectradynamics	c-Rb	cold Rb	5×10^{-13}	-138						75	30.5	39806
Chengdu Spaceon	TA1000	OPC	1.2×10^{-11}	-125						100	40	48266
T4Science	pHMaser	PHM	5×10^{-13}	-130	6×10^{-14}					90	33	49820
Vremya	VCH-1003M	Maser	6×10^{-14}	-135	9×10^{-15}					100	100	305525
Microsemi	MHM 2020	Maser	8×10^{-14}	-138	9×10^{-15}					75	246	374072
T4Science	iMaser-3000	Maser	6×10^{-14}	-136	6×10^{-15}					100	100	436800
Muquans	MuClock	cold Rb	3×10^{-13}	-151						200	135	682000

18

Commercial atomic clocks – ADEV versus size and SWaP



Legend

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

D.R. Scherer et al, "Current and future atomic clocks: roadmap and application", Civil GPS Service Interface Committee meeting, co-located with ION GNSS+, September 2019 - MITRE Corporation

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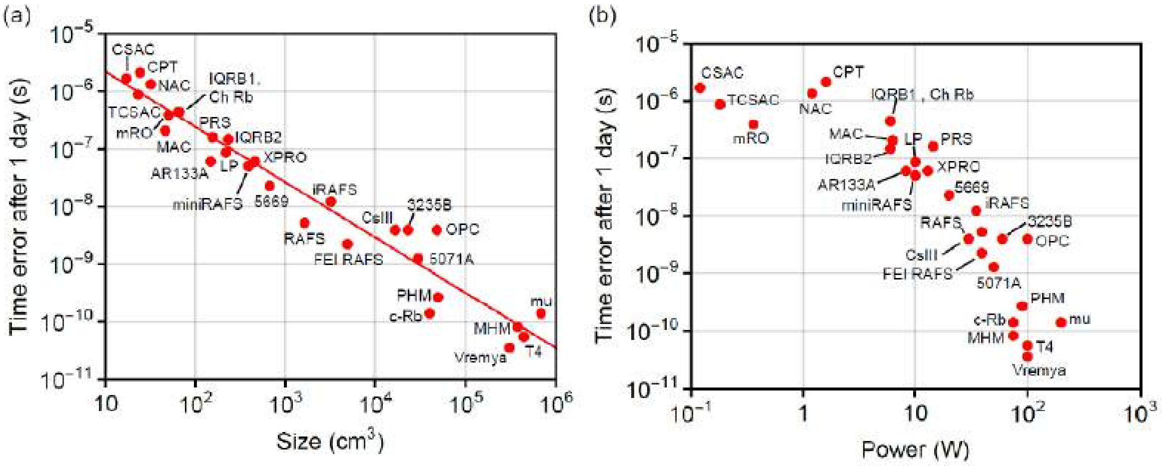
Commercial atomic clocks – time error versus size and power



B. L. Schmittberger et al., "A Review of Commercial and Emerging Atomic Frequency Standards", IEEE TRANSACTIONS ON ULTRASONICS, FERROELECTRICS, AND FREQUENCY CONTROL, pre-published, 2021

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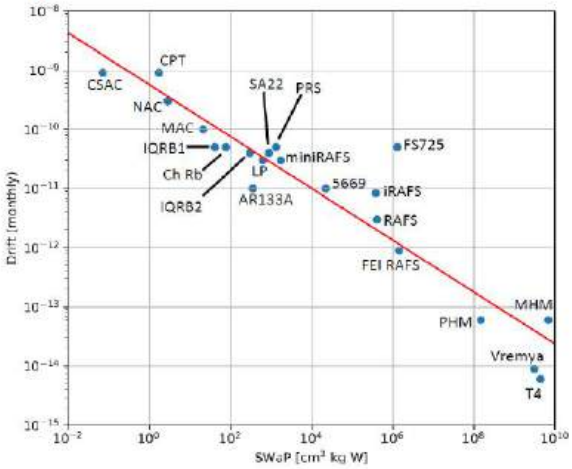
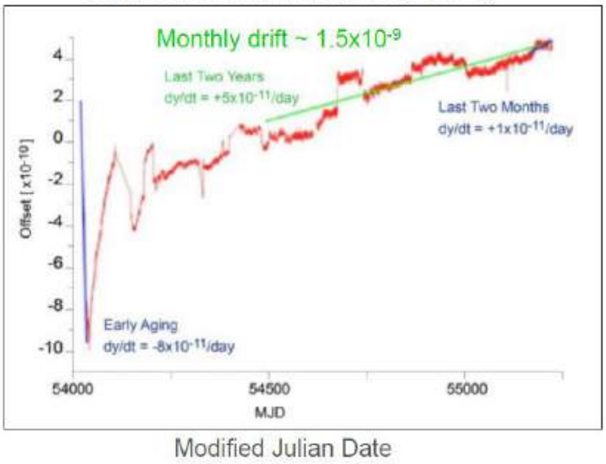
Commercial atomic clocks – long term drift in fractional frequency stability



Microsemi SA.45s
Long-term fractional frequency stability



D.R. Scherer et al, "Current and future atomic clocks: roadmap and application", Civil GPS Service Interface Committee meeting, co-located with ION GNSS+, September 2019 - MITRE Corporation

https://www.microsemi.com/blog/2018/04/24/chip-scale-atomic-clock-benchmarks-initial-accuracy-short-term-stability-and-aging/

21

https://www.researchandmarkets.com/reports/4997175/atomic-clock-markets-a-ten-year-market-forecast

Chapter Three: Profiles of Atomic Clock Companies

3.1.1 Accubeat (staff: 30, revenue: $2M/y, **Israel**)
3.1.2 CASIC China Aerospace Science and Industry Corporation (145000, $30B/y, **China**)
3.1.3 Chengdu Spaceon Electronics (600, $120M/y, **China**)
3.1.4 Excelitas (6500, $1B/y, **USA**)
3.1.5 Frequency Electronics (300, $50M/y, **USA**)
3.1.6 Microsemi (5000, $1.7B/y, **USA**)
3.1.7 MTI Milliren (30, $5M/y, **USA**)
3.1.8 Orolia Group (400, $900M/y, **France**)
3.1.9 Stanford Research Systems (140, $50/y, **USA**)
~~3.1.10 Zurich Instruments (Switzerland)~~
3.1.11 Oscilloquartz (130, $27M/y, **CH**; Acq. by ADVA **DE** 2014)
~~3.1.12 Shanghai Astronomical Observatory (China)~~
3.1.13 Vremya (200, $20M/y, **RU**)
3.1.14 Quartzlock (10, $10M/y, **UK**)
3.1.15 NIST (4000, $1.2B/y budget, **USA**)
3.1.16 Teledyne E2V (1600, $1.5B/y, **USA;** UK E2V acquired in 2017)

From www.Orolia.com: "Orolia is the world leader in Resilient Positioning, Navigation and Timing (PNT) solutions that improve the reliability, performance and safety of critical, remote and high-risk operations, even in GPS/GNSS denied environments. With a presence in more than 100 countries, Orolia provides virtually fail-safe GNSS and PNT solutions for military and commercial applications worldwide."

1995: Temex Neuchâtel Time created (CH)
2006: Orolia (FR) created from Temex (CH) and T4Science (CH)
2007: Temex renamed SpectraTime
2007: Orolia acquires Spectracom (US); IPO (NYSE& EURONEXT)
2016: Eurazeo (Paris-based private equity and venture capital firm) becomes Orolia's majority shareholder

IQD (55, $5M/y – **UK)**. Previously a division of Rakon (NZ), now part of Würth Elektronik

https://www.microwavejournal.com/articles/34584-executive-interview-jean-yves-courtois-ceo-of-orolia
September 14, 2020

Strikethroughs indicate companies which do not produce atomic clocks
Underlines indicate companies which produce CSACs
Data for staff and revenue should be considered indicative

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Commercial CSACs

Manufacturer/Model	Country	ADEV (1s)	Steady state power (W)	Size (cm^3)	Notes
Microsemi SA45.s	US	$3x10^{-10}$	0.12	17	Miniaturized CPT in several versions, from 2011. Radiation-hardened for space available from 2019.
Chengdu Spaceon XHTF1045	China	$3x10^{-10}$	0.25	17	Preproduction samples in 2020 (?). CPT.
Teledyne TCSAC	US	$3x10^{-10}$	0.18	23	Commercial since end 2020. CPT.
Chengdu Spaceon XHTF1040	China	$3x10^{-10}$	1.6	24	Advertised as the low-cost alternative to SA45.s No vacuum sealing. CPT.
IQD ICPT-1	UK	$9x10^{-11}$	1.65	25	Since January 2021, CPT. No published details.
Accubeat NAC1	Israel	$2x10^{-10}$	1.2	32	Since 2018, CPT.
Microsemi MAC SA.5X	US	$3x10^{-11}$	6.3	47	Since ~2020 / optionally with OCXO. CPT.
Microsemi MAC SA.3Xm	US	$3x10^{-11}$	5	50	Since 2008, CPT. Superseded by SA.5x.
Orolia Spectratime mRO-50	CH/FR	$4x10^{-11}$	0.45	50	Launched June 2020, no CPT. VCSEL instead of lamp.
Chengdu Spaceon XHTF1031	China	$5x10^{-11}$	6	50	"Our conventional CSAC", no CPT.
Precision Test Systems RFS2	UK	$3x10^{-11}$	6	65	Since 2012, no CPT.
Quartzlock E10-MRX	UK	$5x10^{-11}$	6	65	Since 2012, no CPT.
Seiko Epson AO6860LAN	JP	$3x10^{-11}$	3	75	Since 2015, probably only prototypes. CPT.
Jackson Labs CSAC GPSDO	US	$1x10^{-10}$	1.4	85	Includes GPS receiver, based on Microsemi SA45.s.
China Aerospace Science and Industry Corporation (CASIC)	China	?	?	98	Publicized with grand fanfare in 2020, no details.

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Size and performance - RFS

Rubidium gas cell Atomic Frequency Standards are the device of choice when better stability than a crystal oscillator is needed. They are the most widely used among atomic clocks, and their market has been large enough to support more than 60 years of continuous innovation:

- Smallest, lightest, lowest power, least complex, least expensive, longest life
- Excellent performance, stability & reliability for a wide range of applications

HP 5065 A

PRS 10

5x7.5x10=375cm^3

FE 5680A

2.5x9x12=270cm^3

5x5x2=50cm^3

4x3.5x1.2=17cm^3

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The birth of the first CSAC: a 10-year gestation

Historically, advancements in frequency control technology have been driven by military needs. In the USA, the genesis of the quartz crystal industry can be traced to the decision in 1939 to make large-scale use of crystal control in military communication systems, and the first large-scale application of quartz-based oscillators was to control the carrier frequency of military radios [1].

Also the development of CSACs is rooted in military applications. From 2000, DARPA funded a multi-year program to develop a commercial CSAC based on coherent population trapping in support of military needs for secure wireless communication and jam-resistant portable GPS receivers. Additional potential applications were underwater timing and navigation, ad hoc self-assembling navigation networks for first responders and military operations, automobile collision avoidance systems, time and frequency sources for use in high-vibration environments [2].

Several teams were formed from 12 institutions:

National Institute of Standards and Technology (NIST) / University of Colorado / Symmetricom (then Microsemi, now Microchip) / Draper Laboratory / Sandia National Laboratories / Teledyne Scientific / Rockwell Collins / Agilent / Honeywell Aerospace / Sarnoff / Princeton University / Frequency Electronics.

MAC - Miniature Atomic Clock: commercial launch in 2008 by Symmetricom
CSAC - Chip-Scale Atomic Clock: commercial launch in 2011 by Symmetricom

[1] From V.E. Bottom "A history of the quartz crystal industry in the USA", 1981
[2] https://www.nist.gov/noac/success-story-chip-scale-atomic-clock

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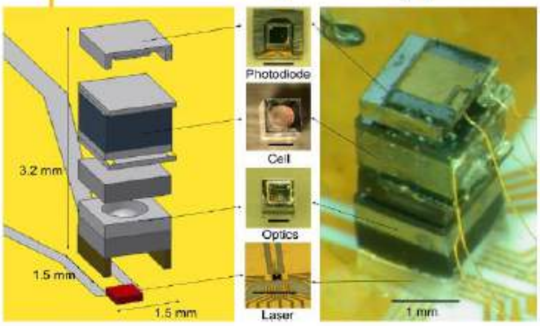
From prototype to product



S. Knappe (NIST), "A microfabricated atomic clock", Applied Physics Letters, 2004

R. Lutwak (Symmetricom), "The SA.45S chip-scale atomic clock: early production statistics", Proceedings of the 43rd Annual Precise Time Meeting, 2011

P. Cash (Microsemi) "Microsemi Chip Scale Atomic Clock (CSAC): Technical Status, Applications, and Future Plans", European Frequency and Time Forum, 2018
"Microsemi has delivered more the 95,000 CSACs to customers over the past seven years. Sophisticated data storage is utilized, so that information for every production device is maintained".
"Microsemi along with assistance from the US government continues to improve the performance of CSAC".

ULTRAFAST SCIENCE | RESEARCH UPDATE **Physics world, May 2011**

Atomic clock is smallest on the market

11 May 2011 Tushna Commissariat

4x3.5x1.2=17cm³
35grams
115mW

Commercial launch: January 18, 2011

Symmetricom's SA.45s Chip Size Atomic Clock

Researchers in the US have developed the world's smallest commercial atomic clock. Known as the SA.45s Chip Scale Atomic Clock (CSAC), it could be yours for just $1500. The clock, initially developed for military use, is about the size of a matchbox, weighs about 35 grams and has a power requirement of only 115 mW. Not your everyday timekeeper, the team behind the clock claim that it could have varied and wide-ranging applications, from disabling bombs to searching for oil.

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And what about money?

Technology	Units/year	Unit price, typical range	Worldwide sales, $/year	Performance
Quartz crystals	~5x10⁹	~$0.1 to $2,000	~$5B	Very low to medium
CSACs	~12,000 (?)	~$500 (?) to $5000 (?)	~$15M (?)	Medium
Rubidium cells	~30,000	~$1,000 to $10,000	~$150M	High
Caesium beam	~500	~$40,000 to 100,000	~$40M	Very high
Hydrogen masers	~20	More than ~$100,000	~$4M	The best

https://www.globenewswire.com/news-release/2020/03/05/1995987/0/en/Atomic-Clock-Markets-A-Ten-Year-Market-Forecast-Featuring-Accubeat-Excelitas-and-Microsemi-Among-Others.html

Atomic Clock Markets: A Ten-Year Market Forecast

ID: 4997175 | Report | February 2020 | Region: Global | Inside Quantum Technology

CSAC market forecast: "Million of units" per year in 2029

Actually, Microsemi sold ~95,000 CSACs in 2011-2018, i.e. ~12,000 per year, see Cash 2018

DESCRIPTION | TABLE OF CONTENTS | SAMPLES | COMPANIES MENTIONED | METHODOLOGY

Sources: Vig 2012, NIST, Microsemi

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Some $ figures – USA public funding for CSACs

According to NIST, in 2020 "the entire market for atomic clocks is on the order of $200 million a year", see [1]
Darpa initial funding for NIST in 2000 for CSAC development was $20 million [2], while [3] reports a $15 million figure

In 2005 Symmetricom was awarderd by Darpa $3.4 million "to develop miniature low power atomic clocks based on its proprietary coherent population trapping (CPT) atomic interrogation technology and microelectromechanical systems (MEMS) fabrication techniques" [4]

Department of Defense awarded to CSACs development ~$4.4 million in 2011, ~$7.1 million in 2012, and ~$3.5 million in 2013 [5], see also next slide

In 2016 HRL Laboratories was awarded by Darpa $1.5 million to develop an ultra-low power oven controlled crystal oscillator (OCXO) for use as a frequency reference for new high-performance, low-power atomic clocks [6]

Probably several tens of $ millions of public money were spent by the USA for the development of CPT-based MACs and CSACs. Apparently the most compact chip-scale SA.45s version is still an heavily subsidized product, and reducing production costs seems to be very difficult, see next slides

[1] https://www.nist.gov/noac/success-story-chip-scale-atomic-clock
[2] W. Gibbs "Ultimate Clocks", Scientific American 287 (3), October 2002, https://www.researchgate.net/publication/11191418_Ultimate_Clocks
[3] R. Choutani 2011 PhD Thesis "Design, technology and packaging for cesium vapor cells for MEMS atomic clocks", https://tel.archives-ouvertes.fr/tel-01337614/document
[4] Symmetricom press release, 23 August 2005, https://www.militaryaerospace.com/computers/article/16712541/symmetricom-wins-darpa-funding-for-atomic-clock
[5] https://comptroller.defense.gov/Portals/45/Documents/defbudget/fy2013/budget_justification/pdfs/03_RDT_and_E/Office_Secretary_of_Defense_PB_2013_1.pdf
[6] https://www.nextbigfuture.com/2016/12/darpa-awards-15-million-to-hrl-labs-for.html

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How much has Uncle Sam spent for CSAC development?

Department of Defense Fiscal Year 2013 President's Budget Submission
Office of Secretary Of Defense - Research, Development, Test & Evaluation, Defense-Wide

C4IRS:
Command,
Control,
Communications,
Computers,
Intelligence,
Surveillance and
Reconnaissance

B. Accomplishments/Planned Programs ($ in Millions)	FY 2011	FY 2012	FY 2013
Title: Chip Scale Atomic Clock	4.405	7.109	3.493
Description: Advanced Electronics Manufacturing: Command, Control, Communications, Computers, Intelligence, Surveillance, and Reconnaissance (C4ISR) systems require precise timekeeping even if the Global Positioning System (GPS) is unavailable. The size, weight, power, and cost components of conventional atomic clocks are too high for tactical applications. Chip Scale Atomic Clock (CSAC) provides improved long-term frequency stability that gets integrated into long-term time accuracy. The focus of this project is to leverage DARPA investments in the CSAC technology to reduce operational costs and transition beyond custom fabrication of the current CSAC. Objectives include improving the existing batch manufacturing processes such as atomic cell filling, cell sealing, physics package assembly, and sub-system testing to reduce the "touch hours" required for CSAC assembly and testing. Development of a network of multiple vendors to foster competition and ensure a viable supply base is a complementary goal. Current manual assembly processes can produce CSAC in small quantities with low yield at high cost ($8,000 / unit). The DMS&T funding will enable producibility at an affordable cost ($100 – 300 / unit). Successful performance will enable an environment of continued operation of critical C4ISR systems, regardless of the presence or absence of GPS. The ability to rapidly reacquire GPS military code in a hostile Electro Magnetic Interference (EMI) environment is an additional targeted benefit.			
FY 2011 Accomplishments: Demonstrated a production-ready manufacturing process for resonance cell and physics package fabrication on chip scale atomic clocks.			
FY 2012 Plans: Advance the manufacturing process toward an automated assembly phase, achieving an end-of-project objective of a TRL7 and MRL8. Conduct laboratory testing in relevant environments at the end of each phase, sending samples for system integration and system-level testing.			
FY 2013 Plans: Complete development of the physics package fabrication process (batch processes/automated assembly). At completion of Phase II (Jul-Aug 2013), the contractors will each deliver 100 CSACs demonstrating their pilot line capability and validating their readiness for low-rate initial production (MRL 8). CSAC in LRIP quantities will be available to system integrators for DoD products.			

PE 0603680D8Z: *Defense Wide Manufacturing Science and Technology ...*
Office of Secretary Of Defense

UNCLASSIFIED
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R-1 Line #44

Volume 3 - 241

https://comptroller.defense.gov/Portals/45/Documents/defbudget/fy2013/budget_justification/pdfs/03_RDT_and_E/Office_Secretary_of_Defense_PB_2013_1.pdf

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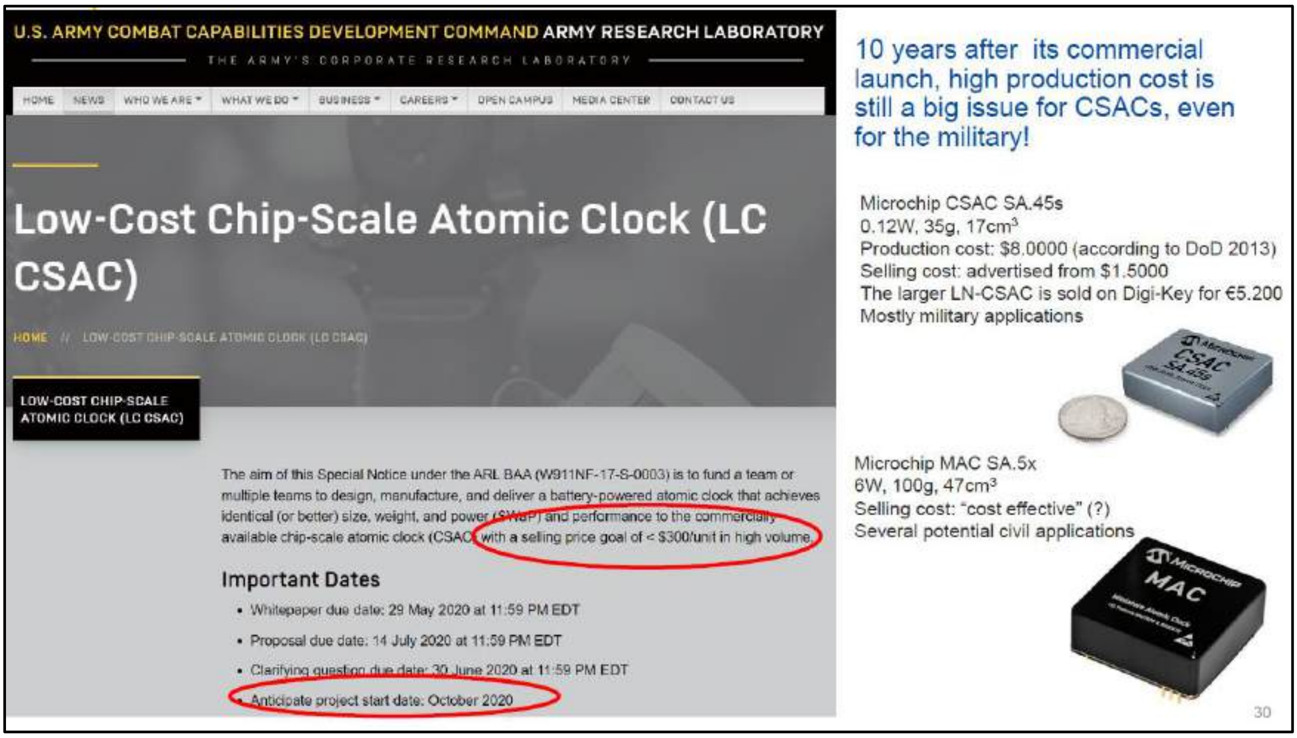
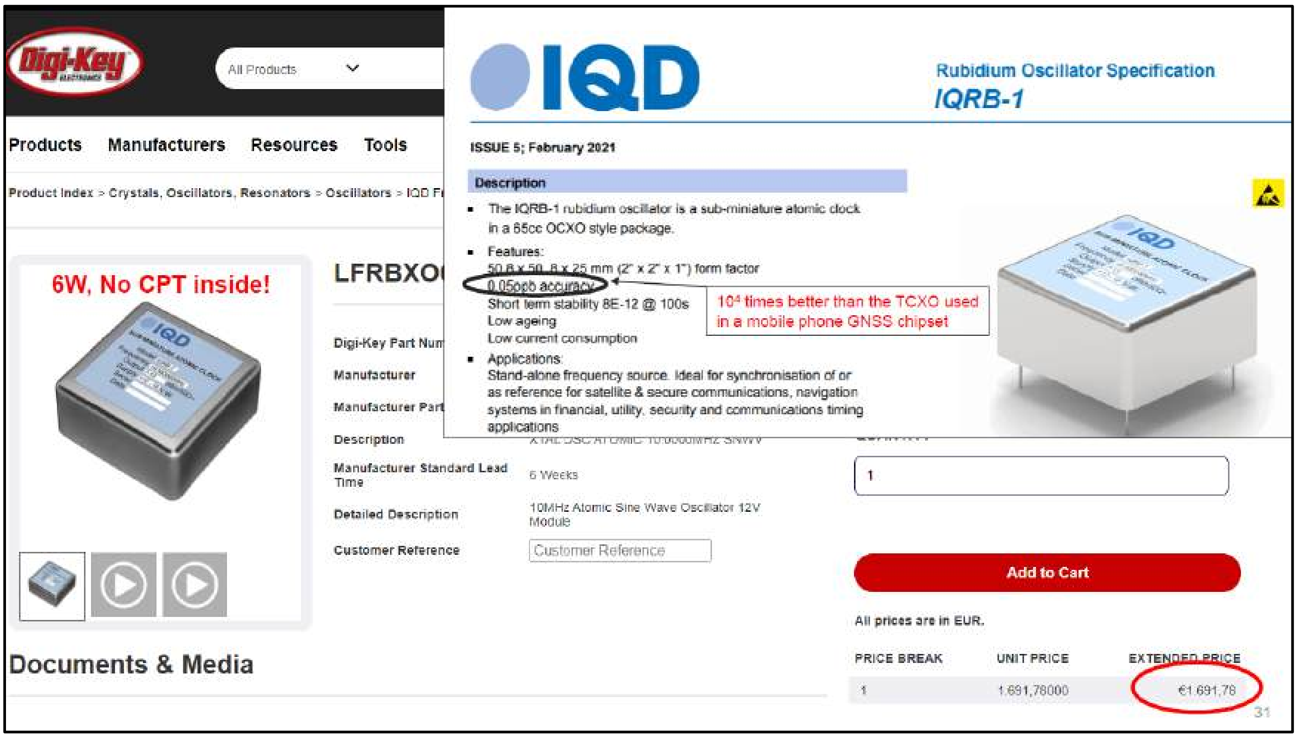
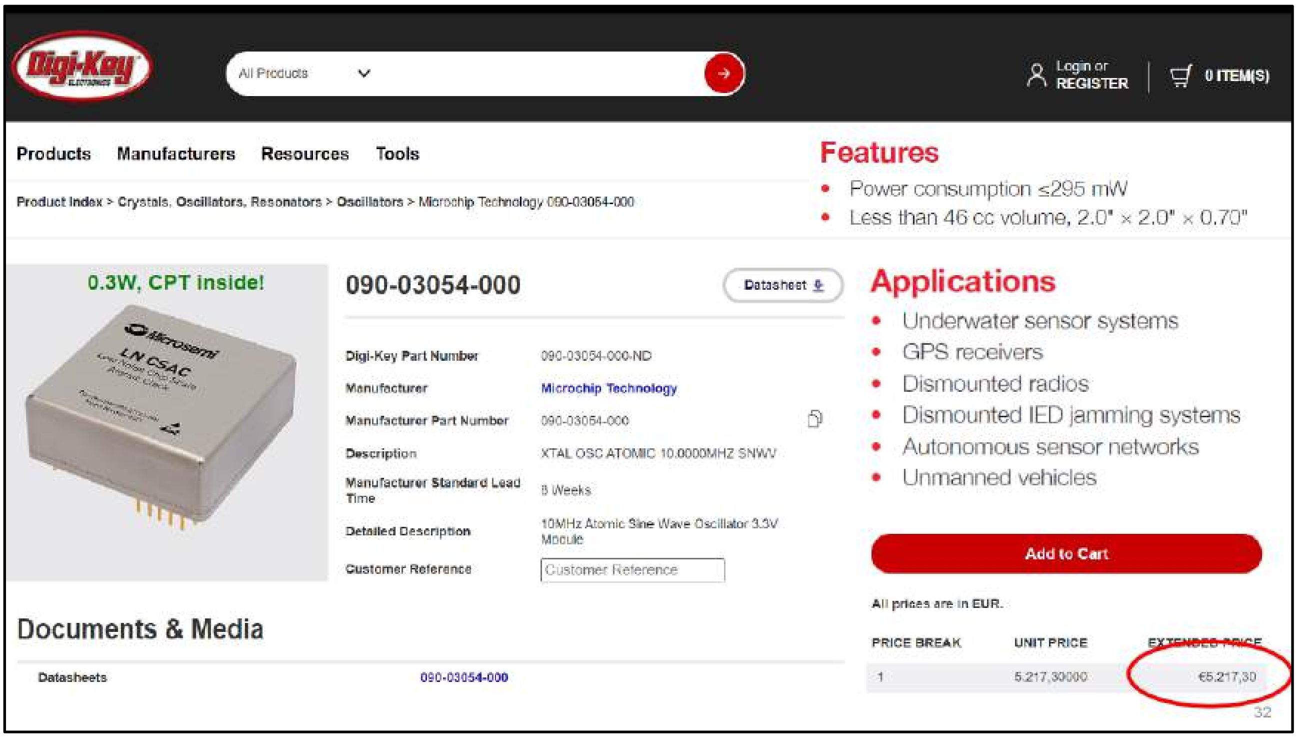

U.S. ARMY COMBAT CAPABILITIES DEVELOPMENT COMMAND ARMY RESEARCH LABORATORY
THE ARMY'S CORPORATE RESEARCH LABORATORY
Low-Cost Chip-Scale Atomic Clock (LC CSAC)
LOW-COST CHIP-SCALE ATOMIC CLOCK (LC CSAC)
The aim of this Special Notice under the ARL BAA (W911NF-17-S-0003) is to fund a team or multiple teams to design, manufacture, and deliver a battery-powered atomic clock that achieves identical (or better) size, weight, and power (SWaP) and performance to the commercially available chip-scale atomic clock (CSAC) with a selling price goal of < $300/unit in high volume.
Important Dates
Whitepaper due date: 29 May 2020 at 11:59 PM EDT
Proposal due date: 14 July 2020 at 11:59 PM EDT
Clarifying question due date: 30 June 2020 at 11:59 PM EDT
Anticipate project start date: October 2020
10 years after its commercial launch, high production cost is still a big issue for CSACs, even for the military!
Microchip CSAC SA.45s
0.12W, 35g, 17cm³
Production cost: $8.0000 (according to DoD 2013)
Selling cost: advertised from $1.5000
The larger LN-CSAC is sold on Digi-Key for €5.200
Mostly military applications
Microchip MAC SA.5x
6W, 100g, 47cm³
Selling cost: "cost effective" (?)
Several potential civil applications
30


Products Manufacturers Resources Tools
6W, No CPT inside!
LFRBXO
Digi-Key Part Num
Manufacturer
Manufacturer Part
Description
Manufacturer Standard Lead Time
6 Weeks
Detailed Description
10MHz Atomic Sine Wave Oscillator 12V Module
Customer Reference
Documents & Media
IQD
Rubidium Oscillator Specification
IQRB-1
ISSUE 5; February 2021
Description
The IQRB-1 rubidium oscillator is a sub-miniature atomic clock in a 65cc OCXO style package.
Features:
50.8 x 50.8 x 25 mm (2" x 2" x 1") form factor
0.05ppb accuracy
Short term stability 8E-12 @ 100s
Low ageing
Low current consumption
Applications:
Stand-alone frequency source. Ideal for synchronisation of or as reference for satellite & secure communications, navigation systems in financial, utility, security and communications timing applications
10⁴ times better than the TCXO used in a mobile phone GNSS chipset
Add to Cart
All prices are in EUR.
PRICE BREAK UNIT PRICE EXTENDED PRICE
1 1.691,78000 €1.691,78
31


Digi-Key
All Products
Login or REGISTER
0 ITEM(S)
Products Manufacturers Resources Tools
Product Index > Crystals, Oscillators, Resonators > Oscillators > Microchip Technology 090-03054-000
Features
Power consumption ≤295 mW
Less than 46 cc volume, 2.0" × 2.0" × 0.70"
0.3W, CPT inside!
Microsemi
LN CSAC
090-03054-000
Datasheet
Digi-Key Part Number 090-03054-000-ND
Manufacturer Microchip Technology
Manufacturer Part Number 090-03054-000
Description XTAL OSC ATOMIC 10.0000MHZ SNWV
Manufacturer Standard Lead Time 8 Weeks
Detailed Description 10MHz Atomic Sine Wave Oscillator 3.3V Module
Customer Reference
Applications
Underwater sensor systems
GPS receivers
Dismounted radios
Dismounted IED jamming systems
Autonomous sensor networks
Unmanned vehicles
Add to Cart
All prices are in EUR.
PRICE BREAK UNIT PRICE EXTENDED PRICE
1 5.217,30000 €5.217,30
Documents & Media
Datasheets 090-03054-000
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MAC and CSAC applications
6W, 100g, 47cm³
MICROCHIP
MAC
Applications
Stand-alone (free-run) stable frequency source for audio equipment, LTE base stations, smart grid and enterprise network infrastructure
Extended holdover for base stations
Portable test equipment
Autonomous sensor networks
CSAC
0.12W, 35g, 17cm³
Applications
GPS receivers
Backpack radios
Anti-IED jamming systems
Autonomous sensor networks
Unmanned vehicles
Underwater sensor systems
Atomic-clock quality timing and synchronization underpin a broad range of technologies and infrastructure.
GNSS, telecom, power distribution, mineral exploration, military and space applications would benefit from fieldable, low-SWaP atomic-clock timing with 10-11 to 10-10 uncertainty.
European Commission
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The place of MACs and CSACs in the clock landscape

Main Conclusions

Miniature atomic clocks (50-100cm^3, ~5W) have several commercial applications, e.g. they can compete with OCXO in mobile networks base stations. They are too power-hungry and too bulky to be used for hand-held or backpack applications, which are typically of military interest. Several commercial manufacturers sell miniature atomic clocks (US, China, UK, Israel, EU).

Truly chip-scale atomic clocks (<50cm^3, <1W) have essentially military applications, when they leverage their superiority in size, weight, and power consumption footprint. However, performance decreases as size is reduced, while manufacturing difficulties and cost increase. The market is dominated by US players (Microchip from 2011, Teledyne from 2020), although also China's Chengdu Spaceon claims to have commercial CSACs. China, UK (IQD) and Israel (Accubeat) sell quasi-CSAC (>1W) miniature atomic clocks.

No EU commercial vendor of CSACs exist. Orolia is the only EU manufacturer which sells a borderline model (50cm^3, 0.5W, launched in 2020). This clock can't be further miniaturized, since it is not based on Coherent Population Trapping.

Details on the physics exploited by CSACs will be given in the next lecture.

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3 The working principles of commercial products

Microwave chip-scale atomic clocks: plan of the opera

Table of contents

- The place of CSAC in the clocks landscape, with some info on the main players (~35 slides) — ~1h presentation & discussion (April 21)
- The working principles CSACs are based on, and a description of commercial products (~35 slides) — ~1h presentation & discussion (April 28)
- Highlights on research trends, prototypes, enabling technologies, and supporting programs (~35 slides) — ~1h presentation & discussion (May 5)
- An overview of their applications, based on commercial material and scientific literature (~35 slides) — ~1h presentation & discussion (May 12)

At times, some degree of accuracy will be sacrificed to simplicity and conciseness

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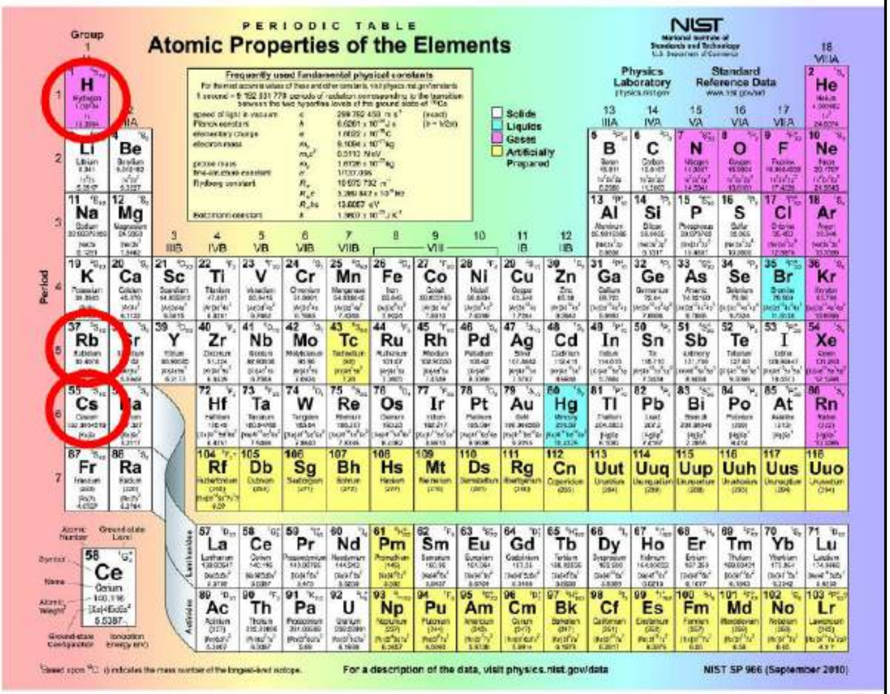
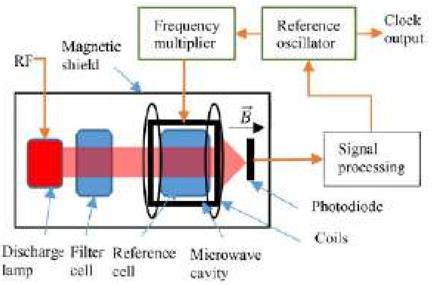
Some physics…

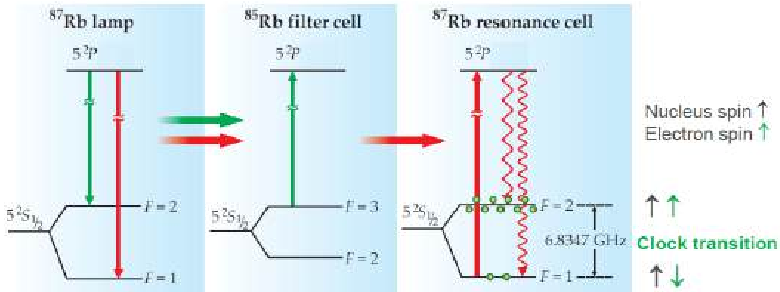
All commercial atomic clocks exploit a microwave transition of the single valence electron of one element of the first group (namely Hydrogen, Caesium, and Rubidium), leveraging the following properties:

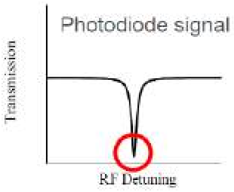
1. Non-zero nuclear spin -> ground state hyperfine splitting at ~GHz -> use of standard RF electronics
2. Simple electronic structure and large optical absorption cross sections -> optical pumping and optical detection of microwave transitions
3. High vapor pressure at a given T -> large spectroscopic signals



The double optical-microwave resonance







Selective pumping from F=1 plus dipole transitions rules for circularly polarized σ_+ photons will induce a population unbalance between ground states F=1 and F=2, depleting the F=1 state.

If the right 6.834… GHz frequency is applied to the microwave cavity, the atoms will switch from the F=2 to the F=1 state, thus making themselves again available for optical absorption. As a consequence, the light transmitted across the ^{87}Rb reference cell diminishes and there will be a dip in the photodetector signal.

In this way the quartz-based oscillating circuit can be “disciplined”, meaning that its frequency is locked to an atomic microwave transition, providing better long-term stability.

Cs has not traditionally been used in vapor cell atomic clocks because there is no good way of spectrally filtering the light generated by a discharge lamp to achieve hyperfine optical pumping.

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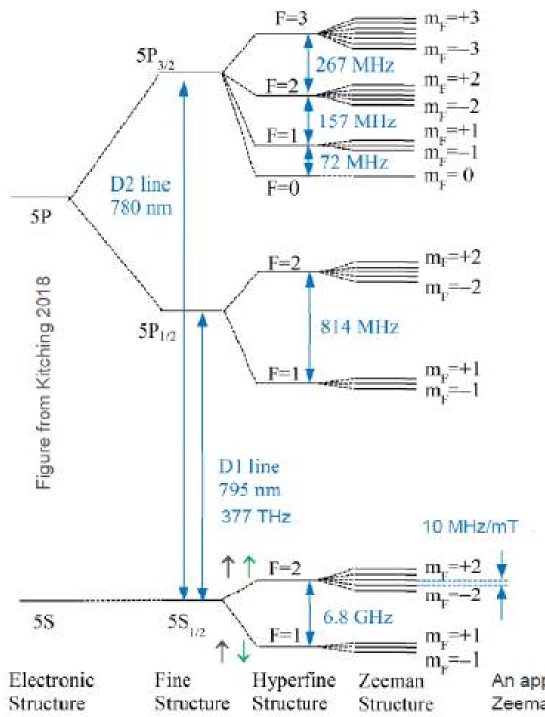

The ^{87}Rb quantum levels

Electronic structure: 5S and 5P orbitals

Fine structure (electronic spin – electronic orbit interaction):
5S not split because of its symmetry $5S_{1/2}$
5P split in $5P_{1/2}$ and $5P_{3/2}$

D1 line: optical transition $5S_{1/2} \rightarrow 5P_{1/2}$ 795nm, 377×10^{12} Hz
D2 line: optical transition $5S_{1/2} \rightarrow 5P_{3/2}$ 780nm

Hyperfine structure (electronic spin ↑ – nuclear spin ↑ interaction)
$5S_{1/2}$, F=1 means that electronic and nuclear spin are antiparallel
$5S_{1/2}$, F=2 means that electronic and nuclear spin are parallel
A microwave Electronic Spin Resonance transition inverts the electron spin

An external magnetic field splits each F level into 2F+1 sub-levels labeled by the quantum number m_F, therefore changing the clock frequency. The atomic cell must be shielded from magnetic disturbances, and a control magnetic field ("c-field") can be used to calibrate the clock:

Microwave "clock" transition at 6.8×10^9 Hz within the $5S_{1/2}$ ground state of ^{87}Rb:
F=1, m_F=0 ↔ F=2, m_F=0

Caesium: D1 line 895nm, D2 line 852nm, clock transition 9.2GHz → SI second

An applied magnetic field splits the F level in m_F=0, ±1, ±2, … ±F
Zeeman splitting ~10MHz/mT

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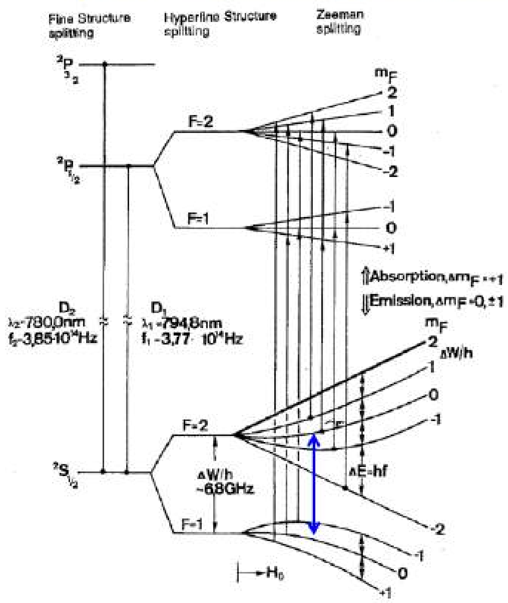
Optical pumping of Rubidium: predicted in 1950, demonstrated in 1952 - Alfred Kastler Nobel prize in 1966
Claude Cohen-Tannoudji Nobel prize 1977 for laser cooling was one AK's students…
Serge Haroche Nobel prize 2012 for quantum manipulation was one of CC-T's students...



Optical pumping of Rubidium is governed by dipole transition selection rules:

1. Rb excitation by absorption of circularly polarized σ+ photon → Δm_F=+1
2. Rb relaxation → spontaneous emission of a photon with random polarization → Δm_F=0, Δm_F=+1, Δm_F=-1 with equal probabilities. On the average, Δm_F=0

⇒ At each absorption/emission cycle between $2S_{1/2}$ and $2P_{1/2}$, m_F increases by 1

Optical pumping by σ+ photons creates an excess of atoms in the state with the highest possible value of m_F, that is F=2, m_F=2. Dipole selection rules prohibit them from absorbing any more σ+ photons, since there exist no excited state with m_F =3

⇒ The Rb cell becomes more transparent
⇒ The state F=1 is depopulated with respect to F=2

Let's add a resonant microwave field to induce transitions from F=2 to F=1

⇒ The resonance frequency is revealed by an increase in the optical absorption
⇒ The clock transition involves the first-order magnetically insensitive m_F = 0 levels of the hyperfine ground states. These levels have a second-order magnetic field induced shift which is exploited for fine-tuning and calibration by using a magnetic control field ("c-field").

ın splitting induced by an applied magnetic field is of the order of
T. Levels m_F=0 are to first order unaffected by the magnetic field.

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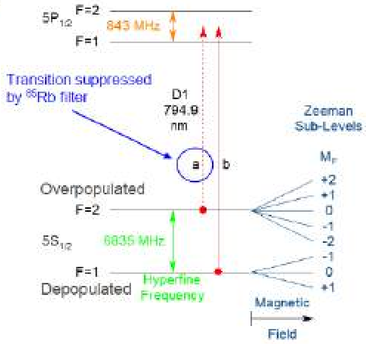
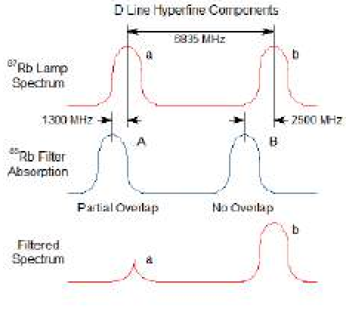
A stroke of good luck

- The efficiency of the optical pumping is enhanced by a fortuitous overlap between the optical absorption lines of the two naturally-occurring isotopes, ^{85}Rb and ^{87}Rb, which eliminates excitation transitions from the upper F=2 level. For this reason, a filter cell with ^{85}Rb is inserted between the ^{87}Rb lamp and the ^{87}Rb reference cell. Cs has not traditionally been used in vapor cell atomic clocks because there is no good way of spectrally filtering the light generated by the lamp to achieve hyperfine optical pumping. The use of a single-mode narrow-linewidth laser allows using also Cs as the reference atom.



Energy Levels of Rubidium 87



Isotopic Filtering of Rubidium 87 D Lines

- Microwave atomic clocks typically use the first-order magnetically insensitive transition between the $m_F = 0$ levels of the hyperfine ground states. This transition has a second-order magnetic field induced shift which is exploited for fine-tuning and calibration by using a magnetic control field ("c-field").
- At typical Rb cell pressures (500Torr) the homogeneous broadening of the optical transition is higher than the hyperfine splitting, and the two hyperfine-split levels F=1 and F=2 separated by 6.8Ghz are actually unresolved. However F=2 is more populated than F=1, since it contains the state with highest m_F (i.e. m_F=2).

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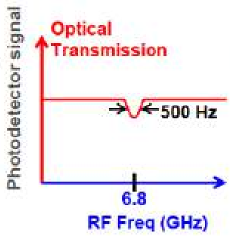
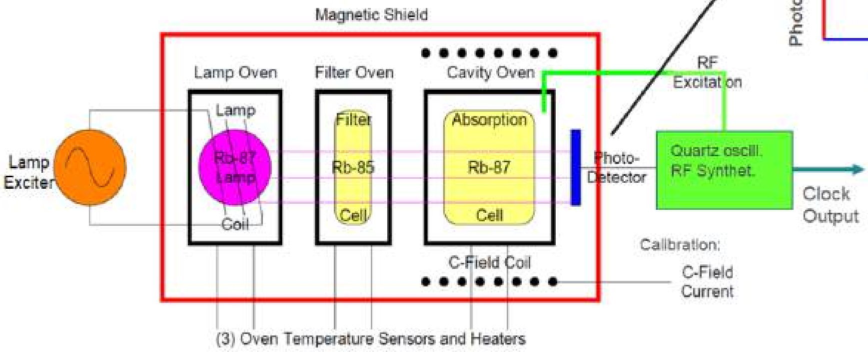
A typical Rubidium Frequency Standard

Very mature technologies: basic principles little changed since late 1950's.
Double resonance: optical pumping & detection, μwave interrogation.

60 years of refinements, thanks to a market large enough to support continuous exploration of physics, adoption of new techniques, and advancements in manufacturing.



Width and visibility of the microwave clock transition are of crucial importance for clock performance



Power requirements (10 to 30W):

- 10% Lamp Exciter
- 10% 6.8GHz RF Excitation
- 10% Electronics
- 70% Thermal stabilization of ovens

Even if a laser substitutes the lamp+filter, thermal stabilization of the RF cavity requires sizable power, especially during warm-up. Minimum RF cavity dimension $\lambda/2 = c/2\nu = 2.2$cm.

New miniaturize cavity designs are being studied: S. Micalizio (INRIM), M. Violetti (EPFL), G. Mileti (University of Neuchatel), T. Cao (Electronic Spaceon Company, Chengdu). More details in the next presentation.

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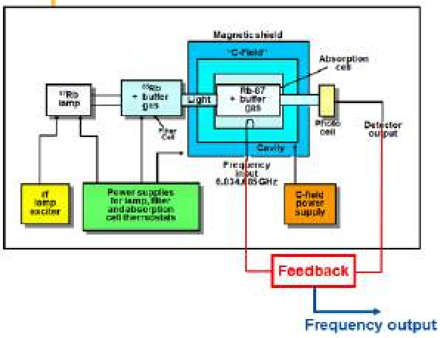
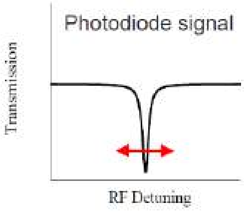
Stark shift: optical instabilities → microwave instabilities



Stark effect: dependence of atomic energy levels on applied electric fields. Because of Stark shifts, any variations in light intensity and/or spectrum will cause a broadening of the RF clock transition



The position of the dip depends on both intensity, frequency, and spectral profile of the light propagating in the ^{87}Rb cell and used for optical pumping

Transition quality factor: $Q = \frac{\nu}{\Delta\nu}$

The light in the resonance cell perturbs ^{87}Rb's energy-level structure -> the clock microwave transition frequency depends on intensity, frequency, and spectral profile of the light used for optical pumping. Lamp's spectral emission and filter cell properties must remain stable (in intensity and spectral profile) over time, otherwise there will be a quality-degrading transition broadening.

Somewhat counter-intuitively, the use of a laser instead of a ^{87}Rb lamp plus a ^{85}Rb filter does not guarantee better noise properties, mainly because of the laser frequency noise. The performance of traditional lamp-pumped vapor cell atomic frequency standards is predominantly limited by statistical shot noise of the detected photocurrent, and the vast majority of commercial double-resonance Rb clocks still use the "classical" lamp+filter.
Research on Pulsed Optically Pumped clock (INRIM, FEMTO-ST, Univ. Franche Comté, Univ. Neuchâtel, ESA → Instead of PHM in Galileo satellites)

For CPT-based CSACs a fast modulated laser is needed, and for typical CSAC components and operating conditions, the principal noise mechanism is the laser frequency noise. The availability of low-noise VCSEL has been one of the major obstacle for CSACs.

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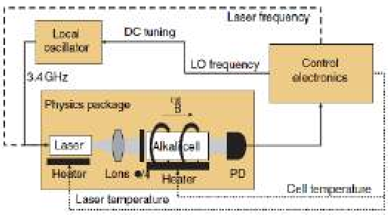
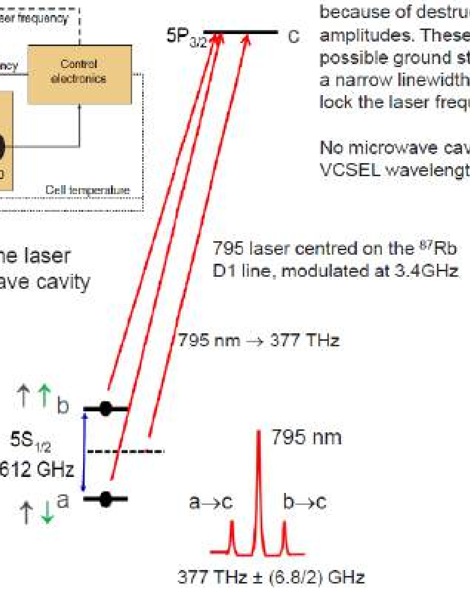
The basis of CSAC: Coherent Population Trapping



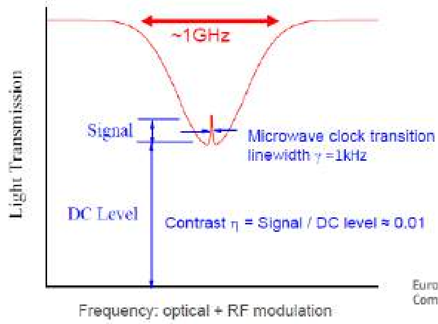
Coherent population trapping (CPT): a fraction of the alkali atoms become "trapped" in a coherent superposition of the ground states a and b, which can not absorb light because of destructive interference between the ac and bc transition probability amplitudes. These atoms are "trapped" in a coherent superposition of the two possible ground states from which they can't be excited out by a photon: therefore, a narrow linewidth peak in the transmitted light occurs. This peak can be used to lock the laser frequency modulation exactly at 3.4GHz.

No microwave cavity → less volume, less power for thermal stabilization
VCSEL wavelength flexibility → use of different transitions in both Rb and Cs

Direct modulation of the laser
→ CPT → No microwave cavity



CPT transition Figure of Merit is determined by contrast η (the higher the better) and linewidth γ (the lower the better).



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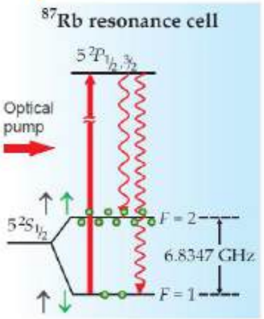
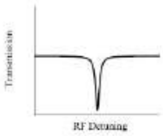
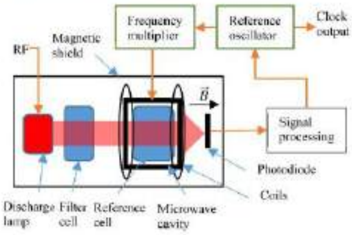
Double resonance vs CPT

Double optical-microwave resonance

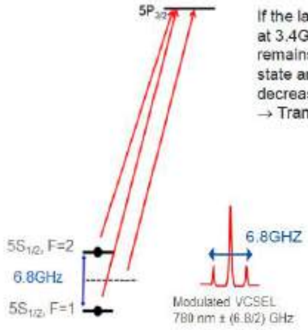


μw cavity resonance at 6.8GHZ increases population in F=1, thus increasing absorption
→ Transmission trough

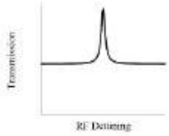


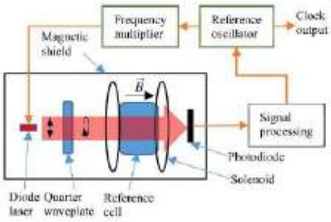


Coherent Population Trapping



If the laser is modulated at 3.4GHZ, some atoms remains trapped in $5S_{1/2}$ state and absorption decreases
→ Transmission peak





No microwave cavity needed anymore!
Less volume, less power needed for thermal stabilization

Use of VCSEL (Vertical Cavity Surface Emitting Laser) allows optical wavelength flexibility, making possible use of different transitions in both Rb and Cs

Potential for ultra-miniaturization

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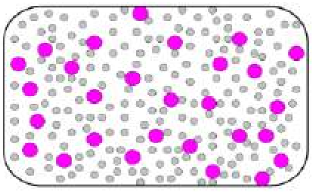
Role of buffer gas mixture



Mixture of N_2, Ne, Ar, He
Rubidium

The reference cells contains a mixture of different gases in addition to Rb. Their composition, temperature and pressure is the result of several balancing processes, aimed at optimizing the properties of the atomic transitions involved in the clock working principles and making them as independent as possible from pump light and environmental disturbances.

Collisions with untreated glass cell walls completely depolarize the spin of the atoms -> any population inversion between the two levels of the clock transition would quickly disappear. In addition, Doppler broadening due to the Rb velocity distribution increases the microwave transition linewidth. A mixture of "buffer" gases is added into the cell to avoid collisions with the walls and to ensure a narrower transition linewidth.

Gases such as N_2, Ne, Ar, and He interact only very weakly with the spin of the alkali atoms and hence the atoms can undergo many collisions with the buffer gas before the spin depolarizes. Adding a buffer gas at the right pressure ensures that the Rb atoms undergo diffusive motion and interact less frequently with the cell walls.

In addition, it is known that frequent velocity-changing coherence-preserving collisions decrease the Doppler width ("Dicke narrowing", 1953). A buffer gas at the right pressure/temperature decreases the mean-free-path of Rb, suppressing the Doppler broadening due to the atoms' thermal motion.

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Optimization of the gas mixture in the Rb cell

N_2 is added in the Rb cell to avoid "radiation trapping", a common phenomenon in alkali metals which tend to reabsorb their own fluorescent photons. Because of radiation trapping ^{87}Rb atoms are excited out of the $5S_{1/2}$, F=2 hyperfine level, and this reduces the population inversion with F=1.

If N_2 is added, excited Rb atoms will decade non-radiatively to the ground state by transferring energy to the rotovibrational modes of the N_2 molecules. No florescence photons are emitted, thus suppressing radiation trapping.

Interactions with a buffer gas induce in the Rb transition 6.834GHz a frequency shift which depends on temperature and on the gas itself. By using proper combinations of buffer gases (He, Ne, Ar) and stabilizing the vapor cell at the right temperature, the sensitivity of the hyperfine frequency to temperature variations is reduced, which improves the stability of the clock.

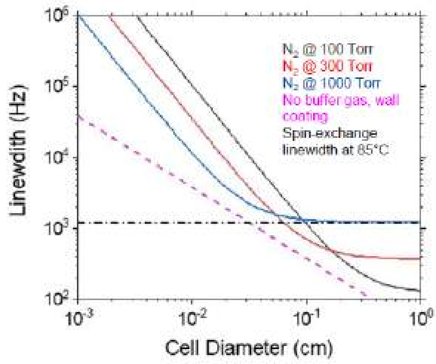

Figure from J. Kitching "Chip-scale atomic devices" Applied Physics Reviews 5, 031302 (2018)

Composition, pressure, temperature of the buffer gas mix result from over 60 years of theoretical and applied research.

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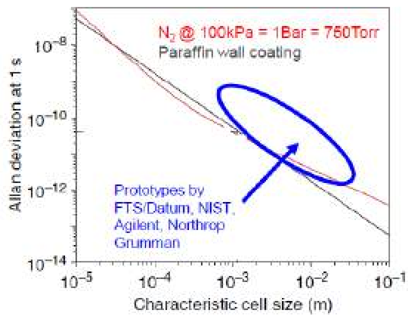
Buffer gas in the CSAC Rb cell

The cell size reduction in CSAC introduces new factors in the tradeoffs balancing.

Higher alkali densities are needed to give detectable optical signals
→ more frequent spin-exchange collisions between alkali atoms
→ line broadening proportional to the alkali atom density

More frequent wall collisions -> line-broadening -> a suitable coating is usually applied on the walls. High Rb cell temperatures degrade these coatings -> shorter cell lifetime.

Both Q and S/N decrease with decreasing cell size. $Q = {}^{\nu}/_{\Delta\nu}$ decreases because more frequent collisions with cell walls increase the hyperfine linewidth $\Delta\nu$. S/N decreases because smaller size implies a smaller optical signal to be detected and therefore an increased shot noise level.



Smaller cell → Higher $ADEV(\tau) = \frac{1}{Q \times SNR}\tau^{-\frac{1}{2}}$

Figure from S. Knappe "MEMS atomic clocks", Comprehensive Microsystems, Vol. 3, 2007
Experimental data presented by E. Donley, "Chip-Scale, Micro-fabricated Atomic Clocks", International Timing and Synchronization Forum (ITSF), 2008

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Main factors impacting on RFS stability

Short term stability: optimize clock transition linewidth and S/N

- Lamp output: gas mix, RF drive, temperature
- Filter cell: gas mix, temperature
- Resonance cell: gas mix, temperature, microwave phase stability
- If laser pump: laser frequency noise

Medium-term stability:

- Thermal control circuits and thermal isolation
- Magnetic shielding
- Ambient pressure effects

Long term stability and aging

- Stability of buffer gas mixture
- Rb or Cs migration (drop or induced by thermal gradients)
- Rb or Cs interaction with residual impurities
- Lamp duration (internal glass surface)
- Diffusion of gases (He in particular) in and out the glass wall

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Hewlett Packard HP 5065A and Stanford Research Systems PRS-10

HP 5065A (~1970)
Tabletop, 17Kg, 33W
ADEV(1s) < $5x10^{-12}$
Drift < $2x10^{-11}$ /month
2nd hand operating items available

SRS PRS-10 (launched 2001)
$5x7.5x10=375cm^3$
0.6Kg, 12W
ADEV (1s) < $5x10^{-11}$
Drift < 5×10^{-11} /month
20 years lifetime
Holdover 72 hour Stratum 1 level
New: ~2000$, depending on options
Working items available for ~200$ on E-Bay

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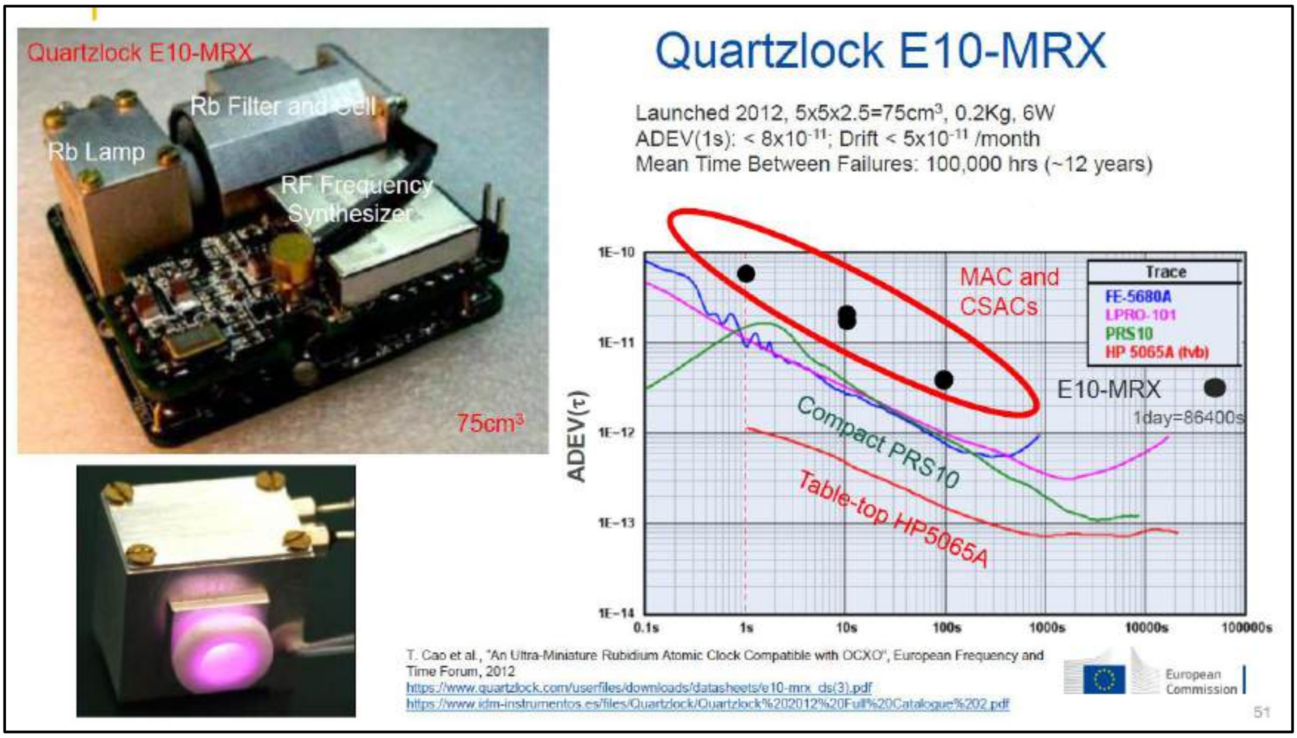

Quartzlock E10-MRX
Launched 2012, 5x5x2.5=75cm³, 0.2Kg, 6W
ADEV(1s): < 8x10⁻¹¹; Drift < 5x10⁻¹¹ /month
Mean Time Between Failures: 100,000 hrs (~12 years)
Quartzlock E10-MRX
Rb Filter and Cell
Rb Lamp
RF Frequency Synthesizer
75cm³
MAC and CSACs
Trace
FE-5680A
LPRO-101
PRS10
HP 5065A (tvb)
E10-MRX
1day=86400s
Compact PRS10
Table-top HP5065A
ADEV(τ)
1E-10
1E-11
1E-12
1E-13
1E-14
0.1s
1s
10s
100s
1000s
10000s
100000s
T. Cao et al., "An Ultra-Miniature Rubidium Atomic Clock Compatible with OCXO", European Frequency and Time Forum, 2012
https://www.quartzlock.com/userfiles/downloads/datasheets/e10-mrx_ds(3).pdf
https://www.idm-instrumentos.es/files/Quartzlock/Quartzlock%202012%20Full%20Catalogue%202.pdf
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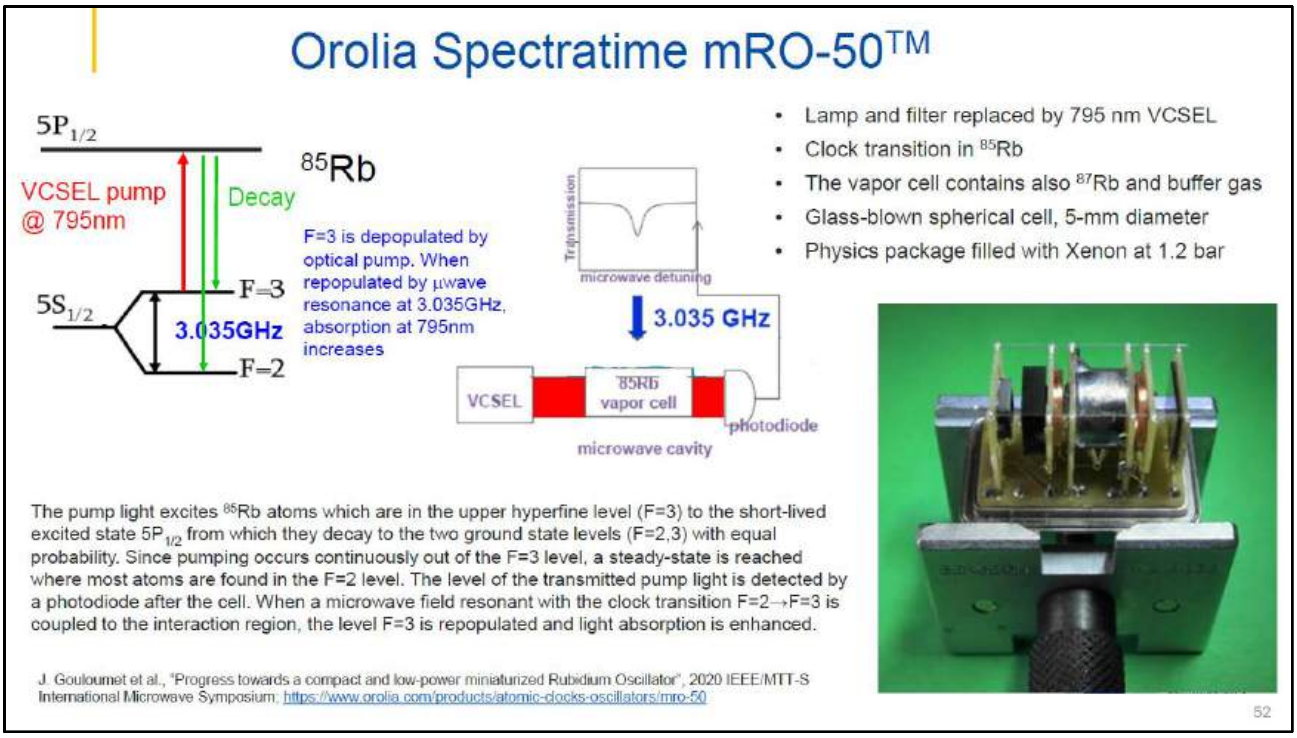

Orolia Spectratime mRO-50™
5P1/2
85Rb
VCSEL pump @ 795nm
Decay
F=3 is depopulated by optical pump. When repopulated by μwave resonance at 3.035GHz, absorption at 795nm increases
5S1/2
F=3
3.035GHz
F=2
Transmission
microwave detuning
3.035 GHz
VCSEL
85Rb vapor cell
photodiode
microwave cavity
Lamp and filter replaced by 795 nm VCSEL
Clock transition in 85Rb
The vapor cell contains also 87Rb and buffer gas
Glass-blown spherical cell, 5-mm diameter
Physics package filled with Xenon at 1.2 bar
The pump light excites 85Rb atoms which are in the upper hyperfine level (F=3) to the short-lived excited state 5P1/2 from which they decay to the two ground state levels (F=2,3) with equal probability. Since pumping occurs continuously out of the F=3 level, a steady-state is reached where most atoms are found in the F=2 level. The level of the transmitted pump light is detected by a photodiode after the cell. When a microwave field resonant with the clock transition F=2→F=3 is coupled to the interaction region, the level F=3 is repopulated and light absorption is enhanced.
J. Gouloumet et al., "Progress towards a compact and low-power miniaturized Rubidium Oscillator", 2020 IEEE/MTT-S International Microwave Symposium; https://www.orolia.com/products/atomic-clocks-oscillators/mro-50
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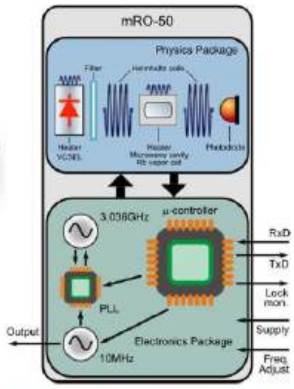
Orolia mRO-50™

5x5x2=50cm³ / 75g / 0.45W;
Since July 2020



- Clock-functions handled by low power micro-controller
- Microwave at 3GHZ generated by VCXO and phase-locked loop (PLL)
- Cell immersed in static control magnetic field to resolve the Zeeman sub-transitions and select the one with the least magnetic sensitivity
- The physics package is placed inside a magnetic shield

ENVIRONMENTAL

Type	mRO-50
Magnetic field sensitivity	$< 1 \times 10^{-10}$ / Gauss
Storage Temperature	- 55°C to + 85°C
Operating Temperature	-10°C to +60°C (+65°C option E) (maximum temperature of the thermal chamber with air flow around the unit)
Overall Environment Effects Altitude (qualification ongoing) Vibration Shocks (qualification ongoing)	Meets or exceeds: MIL-STD-810H, Method 500.6 MIL-STD-810H, Method 514.8 annex C general exposure 4 G MIL-STD-202, 30g, 11 ms, half sinus
Humidity (qualification ongoing)	MIL-STD-810H, Method 507.6 35°C, 95% relative humidity
g-tip-over test	2×10^{-12} / g on worst sensitive axis

Drift		$< 1 \times 10^{-11}$ / day
ADEV	1 sec	$\leq 1 \times 10^{-10}$
	10 sec	$\leq 3 \times 10^{-11}$
	100 sec	$\leq 1 \times 10^{-11}$

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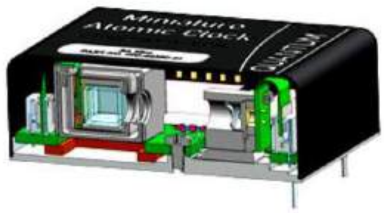
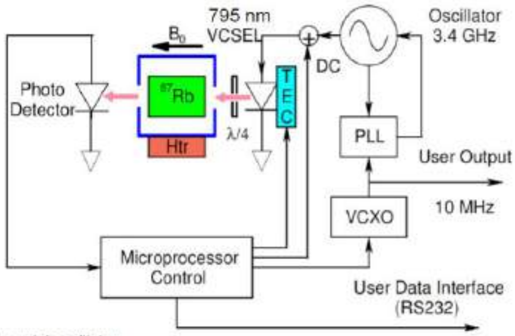
Simmetricom Miniature Atomic Clock MAC SA.3Xm

- Interrogation of ^{87}Rb D1 line @795nm via Coherent Population Trapping
- CPT by modulated VCSEL
- Photodiode detects CPT resonance
- 10MHz VCXO synthetizes 3.4 GHz microwaves
- Microwave frequency locked to CPT resonance to stabilize 10MHz output





Size 18.3mm × 50.8mm × 50.8mm
Commercial since 2008

Applications

- Stand-alone (free-run) stable frequency source for audio equipment, LTE base stations, smart grid and enterprise network infrastructure
- Extended holdover for base stations
- Portable test equipment
- Autonomous sensor networks

VCXO: voltage-controlled crystal oscillator
PLL: phase-locked loop
VCSEL: Vertical cavity surface emitting laser
TEC: Thermoelectric controller

Jinquan Deng et al. "A commercial CPT Rubidium clock", EFTF 2008

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Evolution towards MAC SA.5X

Symmetricom -> Microsemi -> Microchip

SA.3Xm – from October 4, 2008
Size 50.8 mm × 50.8 mm × 18.3 mm
Volume <49.5 cm³
Weight <85 g

Short-Term Stability (Allan Deviation)

Type	SA.35m/ SA.33m	SA.31m
τ = 1 s	$\leq 3 \times 10^{-11}$	$\leq 5 \times 10^{-11}$
τ = 10 s	$\leq 1.6 \times 10^{-11}$	$\leq 2.5 \times 10^{-11}$
τ = 100 s	$\leq 8 \times 10^{-12}$	$\leq 1 \times 10^{-11}$

SA.5X – from November 25, 2019
Same size as SA.3Xm, Weight < 100 g
MTBF 150,000hrs (18 years)

Stability

ADEV	SA55 (Hz/Hz)	SA53 (Hz/Hz)
τ = 1 S	$< 3 \times 10^{-11}$	$< 5 \times 10^{-11}$
τ = 10 S	$< 1 \times 10^{-11}$	$< 1.6 \times 10^{-11}$
τ = 100 S	$< 3 \times 10^{-12}$	$< 5 \times 10^{-12}$
τ = 1,000 S	$< 1 \times 10^{-12}$	
τ = 10,000 S	$< 3 \times 10^{-12}$	
Aging	**SA55 (Hz/Hz)**	**SA53 (Hz/Hz)**
Monthly***	$< 5 \times 10^{-11}$	$< 1 \times 10^{-9}$
Yearly	$< 6 \times 10^{-10}$	$< 1.5 \times 10^{-8}$
Daily***	$< 2.5 \times 10^{-11}$	$< 2.5 \times 10^{-11}$

Environmental

	Operating
Temperature Range	-40°C to +75°C*
Magnetic Sensitivity (frequency change)	< 2 Gauss (≤7 × 10⁻¹¹ Hz/Hz /Gauss)
Voltage Sensitivity (frequency change)	± 1VDC (<1 × 10⁻¹¹ Hz/Hz, p-p)
Vibration	7.7 Grms/axis per MIL-STD-810, Fig 514.7E-1, Category 24 (General Minimum Integrity Exposure); no loss of lock.
Shock	30g, 11 msec half-sine pulse per MIL-STD-202, Method 213, Test Condition J, 18 shocks (3+ & 3- per axis); no loss of lock, ≤ 4x10-8 Hz/Hz frequency perturbation momentary
Humidity	GR-63-CORE, issue 4, April 2012, section 4.1.2
Altitude	50,000 feet

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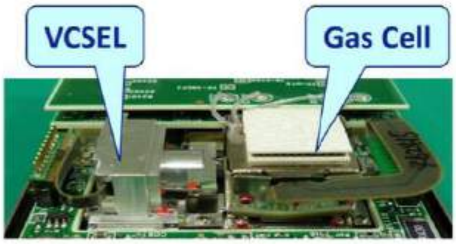
Seiko Epson AO6860LAN

CPT, Caesium D1 transition, VCSEL @895nm;
TCXO, Physics package, and IC by Epson

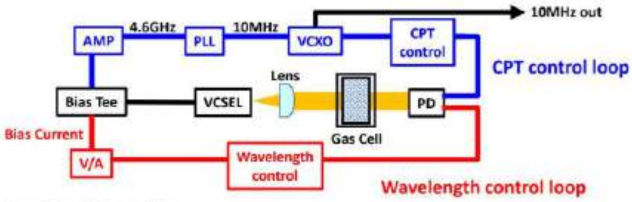
6x6.8x1.8 = 74cm³, 3W
ADEV(1s) ≤ 5x10⁻¹¹

Did it remain a prototype?

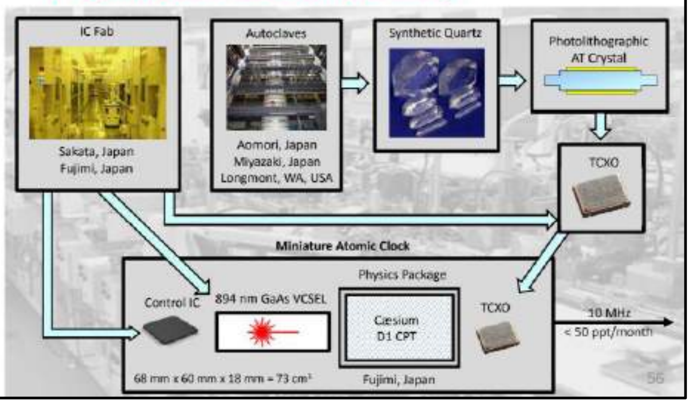


Hiroyuki Yoshida "A new compact high-stability oscillator", Proceedings of the International Timing and Sync Forum ITSF 2015; Edinburgh, Nov. 4, 2015
http://www.telecom-sync.com/files/pdfs/itsf/2015/day2/1345_Epson_MAC_%20ITSF_16x9.pdf

CPT control loop
- **Controls modulation to match the CPT spectrum.**



Wavelength Control Loop
- **Adjusts VCSEL bias current to center the wavelength.**



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Accubeat NAC-1 CPT

VCSEL laser, 795nm (^{87}Rb D1 line) + RF modulation

Six feedback control loops are implemented to stabilize the devices parameters versus environmental changes (e.g VCSEL wavelength and intensity, RF modulation)

ADEV(1s) < $2 \cdot 10^{-10}$
ADEV(10s) < $8 \cdot 10^{-11}$
ADEV(100s) < $2 \cdot 10^{-11}$

- The cell is a ~1cm glass sphere filled with ^{87}Rb and buffer gas. It is covered in the center with a partially transparent coating with high electrical resistance and on the caps with an opaque coating of lower resistance, to optimize SNR and CPT linewidth and to minimize heating power.
- By using traditional and mature low-cost glass technology and avoiding vacuum packaging high reliability (no leaks and outgassing) over a wide temperature range (-40°C to 75°C) are possible.

Applications
- ◊ GPS receivers
- ◊ UAV's
- ◊ Autonomous sensors
- ◊ Backpack secure communication radios

Avinoam Stern et al., "The NAC – A Miniature CPT Rubidium Clock", European Frequency and Time Forum (EFTF), 2016
Shemi Prazot et al. "The Medium and Long Term Stability of the NAC Atomic Clock", Joint Conference of the European Frequency and Time Forum and IEEE International Frequency Control Symposium (EFTF/IFCS), 2017
https://www.accubeat.com/product-item/nano-atomic-clock-nac1/

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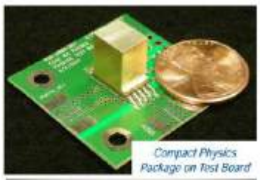
Teledyne TCSAC

ADEV(1s)=$3 \cdot 10^{-10}$
ADEV(10s)=$1 \cdot 10^{-10}$
ADEV(100s)=$3 \cdot 10^{-11}$
ADEV(1000s)=$1 \cdot 10^{-11}$

4x3.5x1.6=23cm^3
47g / 180 mW
MTBF > 100,000 hrs


Compact Physics Package on Test Board


Compact Control Electronics

APPLICATIONS
- GPS-challenged Environments
- Land, Undersea
  - Unmanned Vehicles
  - Seismic Exploration
- Sensor Networks
- Undersea Scientific Applications
- Anti-IED Jamming Systems

Commercial since end 2020

2008: Teledyne / Rockwell Collins / Agilent Laboratories

CSAC prototypes tested for compliance with MIL-STD test protocols at Rockwell Collins, producer of crystal-based military frequency standards used in GPS, radio and SATCOM systems.

1) MIL-STD-810F "Environmental Engineering Considerations and Laboratory Tests"
2) MIL-STD-202G "Test Method Standard for Electronic and Electrical Component Parts."

Shock / Vibration: Use of robust thermo-mechanical supports to suspend and thermally isolate the physics package will ensure survival under shock and high vibration environments.

Humidity: The CSAC physics package is sealed under vacuum, and not impacted by humid ambient. A secondary hermetic enclosure around the physics package and circuit is used, backfilled with dry inert gas to ensure immunity to humid ambient

Two-layer magnetic shielding to preserve stable CPT operation

Aim: "ensure compatibility with the accepted test procedures for military frequency standards to allow transition to a large number of DoD platforms"

J.F. DeNatale et al "Compact, low power chip scale atomic clock", Proceedings of IEEE/ION PLANS 2008, May 6 - 8, 2008
http://www.teledyne-si.com/products/Documents/TCSAC%20Data%20Sheet%2010Mar2020.pdf

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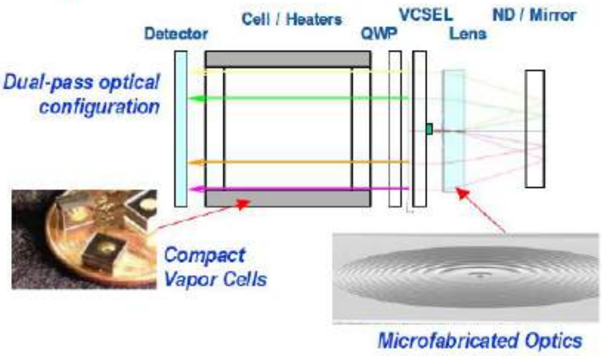
Teledyne TCSAC dual-pass reflective configuration

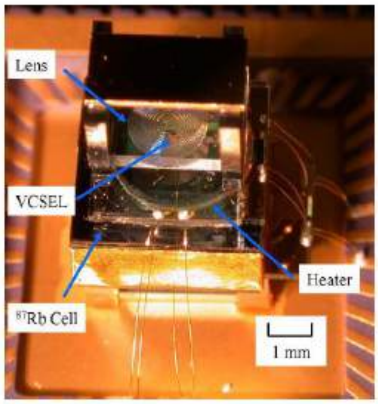


Central microlens expands the beam, outer rings collimate the reflected beam

Microfabricated optics →

Common heater for VCSEL and vapor cell
Heat dissipated by VCSEL is recoupled into the heater

→ Lower power consumption



A 795nm VCSEL tuned to the D1 transition of ^{87}Rb is RF modulated to create the proper optical fields, which are passed through beam conditioning optics and through a vapor cell containing ^{87}Rb and controlled pressure of buffer gas. The transmitted light is detected by a photodetector that is used to monitor the creation of the microwave resonance of the CPT operation. Electronic control loops are used to lock the modulation frequency to this resonant signal and stabilize the VCSEL wavelength.

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The first CSAC: Microsemi SA.45s

Atomic spectroscopy + semiconductor laser technology + silicon micromachining

- Vertical Cavity Surface Emitting semiconductor Laser (small, low frequency noise, direct RF current drive at GHz
- Alkali-vapour microcell: different techniques for manufacturing and filling have been tried.

DARPA and DoD funding to: National Institute of Standards and Technology (NIST) / University of Colorado / Symmetricom (then Microsemi, now Microchip) / Draper Laboratory / Sandia National Laboratories / Teledyne Scientific / Rockwell Collins / Agilent / Honeywell Aerospace / Sarnoff / Princeton University / Frequency Electronics.

Not ITAR-controlled; Commercial since 2011; 1000$ to 2000$ each (really?)
Production cost is likely much higher, with the difference covered by public subsidies.
COTS electronics, not space-qualified. Space version available since 2019.
Also a low-noise version (with OCXO instead of TCXO) available (5.300 euro on DigiKey).

Applications[1]

- GPS receivers
- Backpack radios
- Anti-IED jamming systems
- Autonomous sensor networks
- Unmanned vehicles
- Underwater sensor systems
- Stability for various other communication and transmission applications

Short-Term Stability (Allan Deviation)

Type	SA.45s
τ = 1 s	3×10^{-10}
τ = 10 s	1×10^{-10}
τ = 100 s	3×10^{-11}
τ = 1000 s	1×10^{-11}

Physical package

4x3.5x1.2cm - 17cm^3 - 35g -120mW

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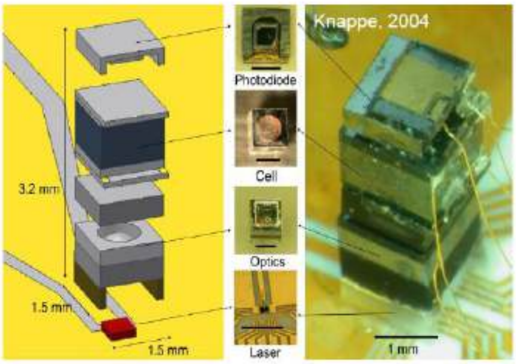
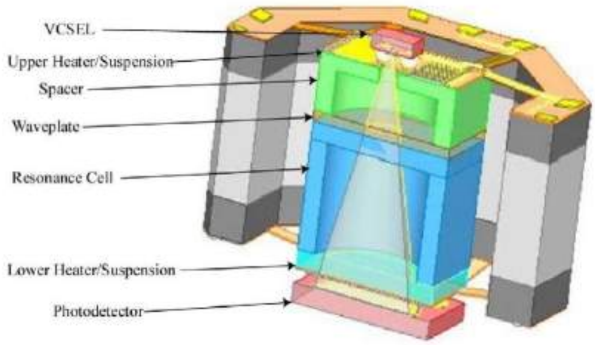
Microsemi CSAC physical package

- VCSEL originally developed by Sandia, tuned on the 895nm Caesium D1 line; ~3mW
- VCSEL + Optics + Cell + Detector suspended in vacuum to minimize heating power
- Mu-metal shield to protect the cell from external magnetic fields
- Small biasing magnetic field separates the $m_F \neq 0$ transitions from the desired one at $m_F=0$
- Resonance cell at ~80°C, Caesium + optimized buffer glass (Ar, Ne, N_2), ~2 mm^3 (NIST)
- The entire physics package (Draper) is ~0.35 cm^3, and needs ~10mW to operate





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The past challenges and future evolution of Microsemi CSAC

Past:

Main challenges which had to be solved: (1) development of the VCSEL source (2) microfabrication of the atomic vapour cell

Present:

"Microsemi has delivered more the 95,000 CSACs to customers over the past seven years"
"Microsemi along with assistance from the US government continues to improve the performance of CSAC"

Future:

"An updated CSAC B will operate from -40 to 80 °C, with longer lifetime, reduced sensitivity to temperature and voltage changes, improvements in phase noise, Allan Deviation, and warm-up time. The TCXO used in the frequency synthesis chain can optionally be replaced by a low-phase-noise OCXO, in a larger enclosure."

"Traditional space applications in high altitude orbits with extreme radiation conditions are not suited for the commercial electronics used in CSAC. To meet recent trends towards smaller LEO satellites requiring state of the art technology, rapid design and deployment, a space-qualified CSAC has been developed. Its targets include several low-orbit scenarios such as crosslinking, earth science, data collection, and communication. CSAC and Space CSAC are already utilized in space and are deployed in critical government space missions."

From P. Cash *et al.*, "Microsemi Chip Scale Atomic Clock (CSAC) technical status, applications, and future plans," *2018 European Frequency and Time Forum*

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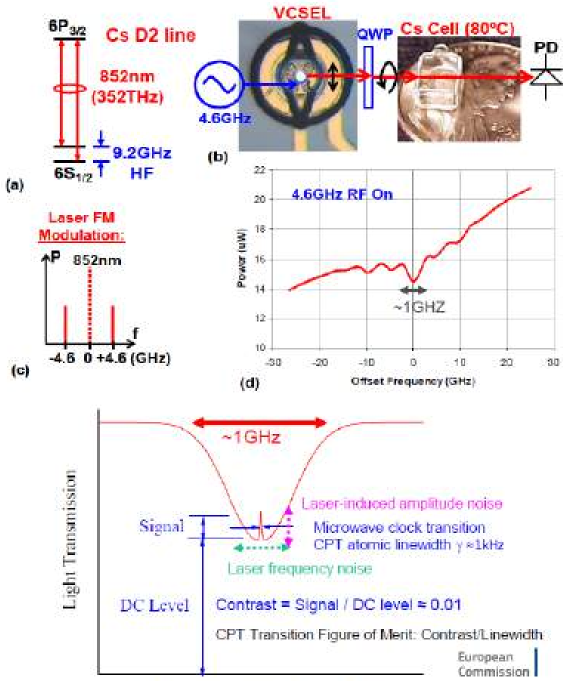
Impact of VCSEL linewidth

R. Lutwak et al., "The Chip-Scale Atomic Clock – Recent Development Progress", 34th Annual Precise Time and Time Interval Systems Applications Meeting, 2003;

D.K. Serkland et al., "VCSELs for atomic clocks", Proc. SPIE 6132, 2006



As the wavelength of a RF-modulated VCSEL is varied, the transmitted optical power exhibits a 1-GHz-wide absorption dip when the laser is tuned to the mid-point between the f_{ac} and f_{bc} frequencies. Once the lasing wavelength is stabilized at the bottom of the dip, the RF frequency is finely adjusted to give rise to the CPT transmission peak, and then locked to it.

The laser frequency noise strongly impact on clock performance: the slope of the transmission vs frequency curve around the CPT peak converts frequency noise into amplitude noise at the detector, reducing the visibility of the CPT peak.

The laser frequency should change by less than 10% of the approximately 1-GHz-wide absorption dip, that is <100MHz. This is a manufacturing challenge, since a typical telecom VCSEL has a linewidth of several hundreds MHz.

Because of the strong dependence of VCSEL frequency on drive current, we also need very stable current sources to drive the VCSEL.

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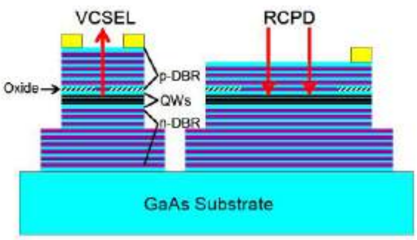
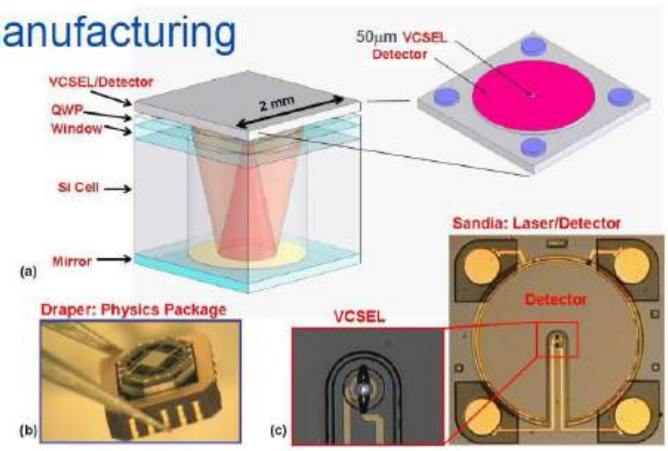
The challenge of VCSEL manufacturing





VCSEL requirements:

- Low power, modulability at 5Ghz
- Operation at high temperature (85°C), for 10 years
- Stable wavelength, polarization, single frequency
- **Low frequency noise: laser linewidth <100MHz**
- High stability current source
- Impedance matching with RF source

Serkland et al. "VCSELs for atomic clocks," Proc. SPIE 6132, Vertical-Cavity Surface-Emitting Lasers X, 613208, 2006

Required layer accuracy: 0.15nm over a 3-inch AsGa wafer - 10x more demanding than standard epitaxial manufacturing processes
Required transverse oxidising accuracy: 0.1µm - 2x more demanding than standard epitaxial manufacturing processes

Even with exceptionally accurate epitaxial growth and manufacturing capability, only a small percentage (<<10%) of devices will meet these requirements. Low manufacturing yield → High cost!

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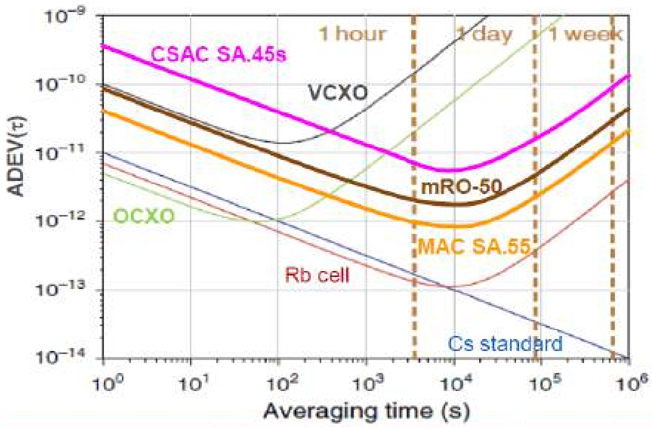
Comparison of main commercial solutions



Chengdu Spaceon, only commercial specs available

ADEV XHTF1045 (CPT) – 0.25W – 17cm^3 – 35g
$3 \cdot 10^{-10}$/1s
$1 \cdot 10^{-10}$/10s
$3 \cdot 10^{-11}$/100s
as SA.45s, but more power hungry

ADEV XHTF1040 (CPT) – 1.6W – 24cm^3 – 45g
$3 \cdot 10^{-10}$/1s
$1 \cdot 10^{-10}$/10s
$3 \cdot 10^{-11}$/100s
as SA.45s, but larger, heavier and much more power hungry

ADEV XHT1031 (no CPT) – 6W – 65cm^3 – 200g
$5 \cdot 10^{-11}$/1s
$1.6 \cdot 10^{-11}$/10s
$5 \cdot 10^{-12}$/100s
as SA.55, but larger and heavier

Manufacturer/Model	Country	Power (W)	Size (cm^3)	Weight (g)	Notes
Microsemi CSAC SA.45s	US	0.12	17	35	Commercial since 2011 – CPT – high integration. Continuously evolving: e.g. low-noise version in 2015, space version in 2019; wide temp. range to be launched
Teledyne TCSAC	US	0.18	23	47	Launched March 2020 – CPT – Same ADEV as SA45.s
Orolia Spectratime mRO-50	CH/FR	0.45	50	75	Launched June 2020 – Double resonance, VCSEL-pumped
Microsemi MAC SA.55	US	6.3	47	100	First commercial CPT (SA.3Xm) in 2008; SA.55 version launched in 2020

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Conclusions on CSAC principles and products

A CSAC is based on Coherent Population Trapping, not on the traditional double resonance scheme. It needs a special-purpose laser of the VCSEL kind, and a micro-fabricated atomic cell. While VCSELs suitable for CPT CSACs are becoming commercially available both for Rb and Cs, the microfabrication of the atomic cell is still an open research area.

CSAC is a Darpa's creature, which since 2000 gave funding to NIST, Sandia, Draper, and several other American teams, both from universities and private companies. The best commercial models are manufactured by USA firms, namely Microchip (since 2011) and Teledyne (since 2020). A Chinese player (Chengdu Spaceon) sells commercial devices, but gives very few technical details on them.

Firms from UK, IS and FR sell miniaturized atomic clocks, but they are less technologically advanced than the USA's CASCs. They are bulkier, heavier and more power-hungry, and thus ill-suited for backpack military applications.

Several countries are pursuing research programs to catch up with the US leadership in the field: China, Japan, France, and Switzerland have first-class advanced prototypes of CSAC.

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4 Critical technologies, research trends, prototypes and programmes

Microwave chip-scale atomic clocks: plan of the opera

Table of contents

- The place of CSAC in the clocks landscape, with some info on the main players (~35 slides) — ~1h presentation & discussion (April 21)
- The working principles CSACs are based on, and a description of commercial products (~35 slides) — ~1h presentation & discussion (April 28)
- Highlights on critical technologies, research trends, prototypes, and supporting programs (~40 slides) — ~1h presentation & discussion (May 5)
- An overview of their applications, based on commercial material and scientific literature (~35 slides) — ~1h presentation & discussion (May 12)

At times, some degree of accuracy will be sacrificed to simplicity and conciseness

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Critical technologies for CPT-based atomic clocks

Laser source, i.e. VCSELs at the right wavelength and with suitable characteristics. First developed by Sandia, with DARPA funding, from ~ 2000 to ~2007. Commercially available at 795 (^{87}Rb D1 line) since ~10 years (e.g. Oclaro, now Lumentum, USA), and at 895 nm (Cs D1 line) since 2021 (Vixar, Honeywell spinoff, USA). Europe has developed research prototypes (DE, CH) and has acquired know-how developed in USA, thanks to the acquisition by OSRAM (DE) and AMS (AT) (now together) of Princeton Electronics (USA) and Vixar (USA). Important results have recently been obtained by the UK Quantum Technologies National Programme (Kairos project). Also China and Japan (Ricoh) are capable of indigenous solutions, at least at the pre-production level.

Atomic microcell. Still an hot research topic (teams in USA, China, Japan, Russia, Europe), with several different approaches being explored for manufacturing and filling the cell with the right mix of alkali atoms and buffer gas. A standard privileged technique has not yet been established: anodic bonding seems a good practice for manufacturers with deep pockets and high-tech capabilities, but it has a sizable impact on the final device cost. Also the **vacuum-sealing** and the **device packaging** processes have not yet scaled up for mass production and contribute significantly to the selling price.

All main players are working also on the **electronics and microelectronics** aspects, such as low-noise driving source for lasers, complementary metal-oxide semiconductor (CMOS)-based integrated circuits, radiation-hardened electronics.

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Commercial availability of VCSELs for CSACs

VCSELs tuned on the ^{87}Rb D1 line at 795nm to be used for CPT-based clocks were the first ones to be developed and become commercially available, see press release "Oclaro to supply VCSELs for Symmetricom Miniature Atomic Clocks" of January 26th, 2011 [1]. A commercial VCSEL for atomic clock at 795nm manufactured by Oclaro (now part of Lumentum) which was recently made available is [2].

Another manufacturer VCSELs at 795nm to be used for CPT-based clocks is Princeton Optronics, part of Austria-based AMS since 2017/03/16 [3].

For the Cs D1 line at 895nm (the one used for Symmetricom CSAC), commercial VCSELs have long been not available, see quotation from [4]:

"Sandia National Laboratories has developed high performance 895 nm VCSELs in the frame of the DARPA CSAC project. To our knowledge, this technology was industrially transferred but remains only accessible for specific customers. VCSEL prototypes tuned on the Cs D1 line developed by Ricoh were used in MAC experiments [5] but remain, to our knowledge, unavailable. In Europe, Ulm University has reported the technology description, polarization stability, and small-signal characteristics of novel custom designed single-mode VCSELs emitting at 894.6 nm wavelength, which have also demonstrated their potential for CSACs applications, see [6]. However, to our knowledge, this technology was not industrially transferred and is not commercially available to date."

Recently, a novel 894.6 nm VCSEL product dedicated to Cs D1 line spectroscopy, has been proposed by Vixar Inc., see [7]

[1] https://www.laserfocusworld.com/lasers-sources/article/16562278/oclaro-to-supply-vcsels-for-symmetricom-miniature-optical-clocks
[2] https://www.laserdiodesource.com/shop/795nm-1mW-TO-can-Oclaro
[3] https://ams.com/-/ams-signs-agreement-to-acquire-vcsel-technology-leader-princeton-optronics, https://ams.com/vcsel
[4] E. Kroemer et al., "Characterization of commercially available vertical-cavity surface-emitting lasers tuned on Cs D1 line at 894.6 nm for miniature atomic clocks", Applied Optics, Vol. 55, Issue 31, (2016). https://www.osapublishing.org/ao/abstract.cfm?uri=ao-55-31-8839
[5] Yuichiro Yano et al., "Two-step pulse observation to improve resonance contrast for coherent population trapping atomic clock", Applied Physics B, Vol. 123, N. 67, 2017
[6] https://www.uni-ulm.de/fileadmin/website_uni_ulm/iui.inst.140/Jahresbericht/2008/ar2008_diw.pdf
[7] http://vixarinc.com/products/vcsel-die, http://vixarinc.com/wp-content/uploads/2021/02/V00140.pdf

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Vixar Inc. Overview

Headquarters: Plymouth, Minnesota, USA

Founded	Acquired	Strong cooperation
Spinout from Honeywell	OSRAM Opto Semiconductors	Expanding business Ops
Jan 2005	July 2018	July 2019

VCSEL Technology: Laser Performance / Cost Structure of LEDs

Magnetometry

LI & IV	Wavelength
Single-mode Power	RIN
Polarization	SMSR

CPT Clocks

LI & IV	Wavelength
Stable Polarization	Linewidth (<50MHz)
Side-band Symmetry	Modulation Efficiency
SMSR	Divergence

Presentation by Klein Johnson, "VCSELs for Atomic sensors", at the EPIC technology meeting on Atomic Clocks and Quantum Sensors, April 3 2020

Market leader across a diversified VCSEL product portfolio

- Wavelengths from 670 nm to 980 nm
- Single-mode to high power arrays > 100's W
- Bare die
- Low cost surface mount packaging
- High-value custom packaging
- Custom subassemblies and optics integration

Vixar AN OSRAM Opto Semiconductors COMPANY

Manufacturing infrastructure and supply chain

- World-class supply chain
- Scalable manufacturing for hundreds of millions of units per year
- Production on both 4" and 6" wafer platforms for cost-efficient manufacturing
- Both domestic and off-shore packaging capacity
- Rapid customization

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Princeton Optronics → AMS

Premstaetten, Austria (3 July 2017) - AMS, a leading worldwide supplier of high-performance sensor solutions, announces the completion of the transaction to acquire 100% of the shares in Princeton Optronics, Inc., a leading provider of high performance Vertical Cavity Surface-Emitting Lasers which offer specific differentiation for mobile, consumer, automotive, and industrial applications.

ams OSRAM Let's start the journey together.

The ams brand, owned by ams AG, the OSRAM brand, owned by OSRAM GmbH, are separately registered trademarks.

Premstaetten, Austria (9 July 2020) - AMS announces the successful closing of the OSRAM Licht AG (OSRAM) acquisition. The takeover offer has been fully settled today and the offer price paid to the holders of the tendered shares.

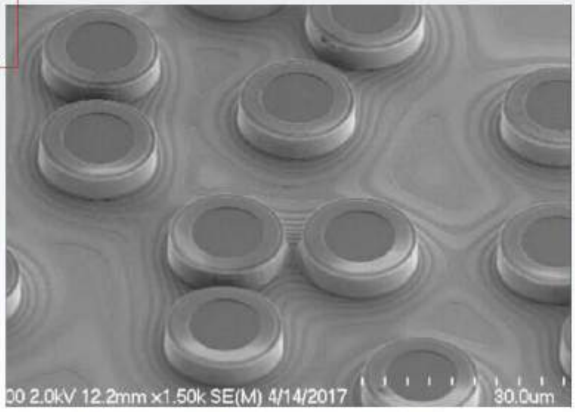
VCSEL

Vertical-cavity surface-emitting lasers (VCSELs) have various advantages over other types of lasers. These include:

- surface emission, which offers design flexibility in addressable arrays
- low temperature dependence of the lasing wavelength
- superior reliability
- a wafer-level manufacturing process

These features make VCSELs better suited to a wide range of applications than conventional edge-emitting diode lasers and LEDs.

The ams VCSEL (Vertical-cavity surface-emitting laser) technology includes the epitaxial structure and chip design, epitaxial growth, front- and back-end processing, packaging and advanced testing and simulations. ams VCSELs are rated for operation at ambient temperatures as high as 150°C.



See e.g. L. Watkins et al., "High-power vertical-cavity surface-emitting lasers for atomic clock applications", Proc. SPIE 9616, 2015 – Princeton Optronics

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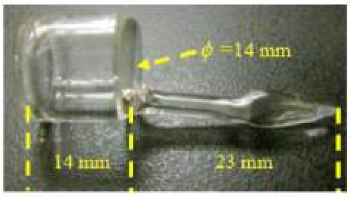
Rb cell manufacturing process

Traditional glass-blowing techniques
Melting and shaping glass with high-temperature flames. A filling tube connects the interior of the glass cell to a vacuum pump and a sealed ancillary chamber containing highly pure alkali metal. The chamber is evacuated, the ancillary chamber is opened and the alkali metal is distilled into the main chamber, which is then filled with an appropriate combination of buffer gases. Glass-blowing technique is not suitable for fabrication of cells much smaller than ~1cm^3 and for mass production.
Orolia, Accubeat



Glass-blown cells

Silicon wafer etching + anodic bonding to glass
Glass and etched silicon wafers are polished, placed in contact and heated to near 300°C, when impurity ions in the glass become mobile. A voltage (3-500 Volt) is then applied, which causes positively-charged alkali impurities in the glass to diffuse away from the glass-Si interface. As a consequence, negatively charged oxygen ions drift toward the interface where they react with the silicon to form a silica SiO_2 layer which create a strong bond between the glass and the silicon. It is an expensive high-tech method, which can be applied only between silicon and borosilicate glass, which has the right impurities and the right thermal expansion properties. Complex complementary technologies are needed also to introduce alkali metal into the cell and dicing an array of micro-cells into single cell units.
Microchip, Teledyne

Anodic-bonded cells
(Si + borosilicate glass)

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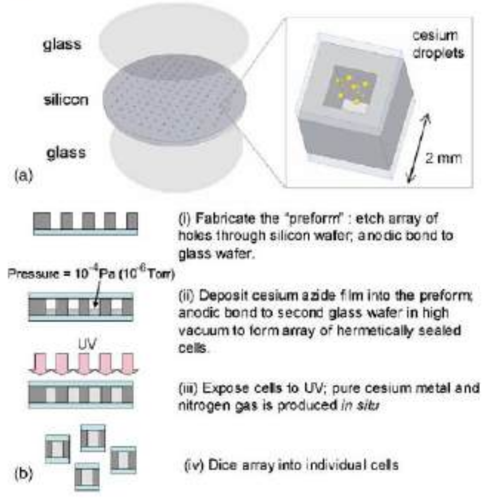
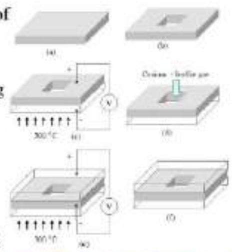
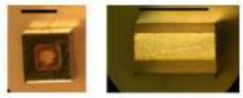
Fabricating and filling the CSAC microcell at NIST



L-A. Liew, et al., Applied Physics Letters, 90, 114106, 2007

- Preform created by wet chemical etching or DRIE of Si wafers
  - Pyrex bonded on one side with anodic bonding
- Cell preform placed in anaerobic chamber for filling with Cs
  - Cs deposited using: $BaN_6 + CsCl \rightarrow BaCl + Cs + 3N_2$
  - Chamber back-filled with buffer gas and final bonding step carried out in chamber
- Diced cells made at NIST using the anodic bonding technique
  - Interior: 1 mm x ∅ 0.9 mm
  - Exterior: 1.33 mm x $(1.45\ mm)^2$





S. Knappe et al., Opt. Lett. 30, 2351–2353, 2005

The fabrication & filling techniques presently employed for the atomic cells of the commercial Microsemi clocks CSAC SA.45s and MAC SA.5X are not disclosed

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MEMS technologies for manufacturing and filling atomic vapour cells

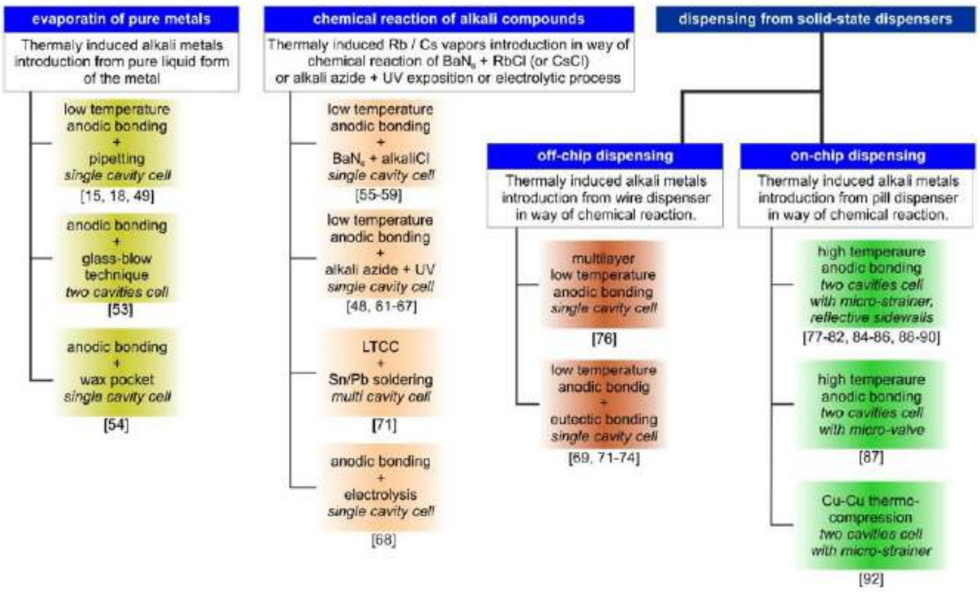

Figure taken from
P. Knapkiewicz, "Technological Assessment of MEMS Alkali Vapor Cells for Atomic References", Micromachines, 10, 25, 2019 - Wroclaw University of Science and Technology

See also
Sylvain KARLEN
PhD Thesis
"Fabrication and characterization of MEMS alkali vapor cells used in chip-scale atomic clocks and other atomic devices"
- CSEM (Swiss Center for Electronics and Microtechnology) and University of Neuchatel, 2018

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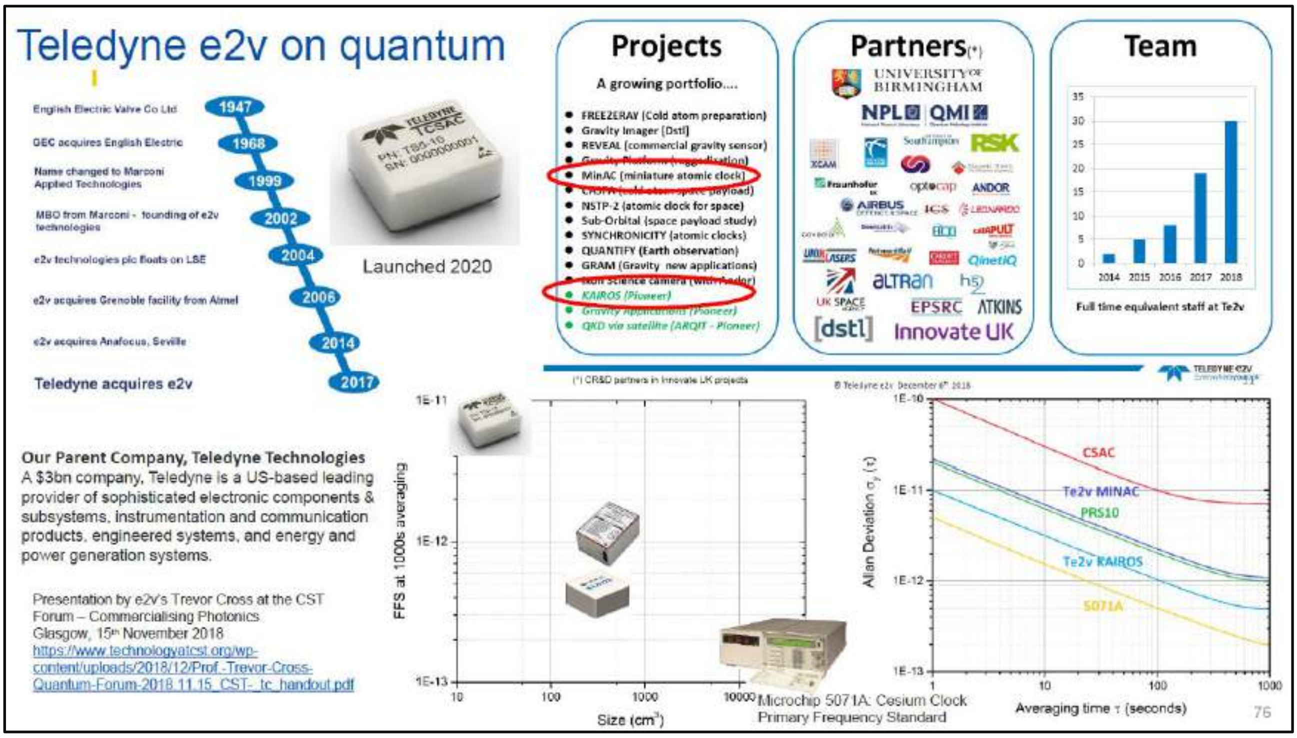

Teledyne e2v on quantum
English Electric Valve Co Ltd 1947
GEC acquires English Electric 1968
Name changed to Marconi Applied Technologies 1999
MBO from Marconi - founding of e2v technologies 2002
e2v technologies plc floats on LSE 2004
e2v acquires Grenoble facility from Atmel 2006
e2v acquires Anafocus, Seville 2014
Teledyne acquires e2v 2017
TELEDYNE TCSAC PN: T86-10 SN: 0000000001
Launched 2020
Our Parent Company, Teledyne Technologies
A $3bn company, Teledyne is a US-based leading provider of sophisticated electronic components & subsystems, instrumentation and communication products, engineered systems, and energy and power generation systems.
Presentation by e2v's Trevor Cross at the CST Forum – Commercialising Photonics
Glasgow, 15th November 2018
https://www.technologyatcst.org/wp-content/uploads/2018/12/Prof.-Trevor-Cross-Quantum-Forum-2018.11.15_CST-_tc_handout.pdf
Projects
A growing portfolio....
FREEZERAY (Cold atom preparation)
Gravity Imager (Dstl)
REVEAL (commercial gravity sensor)
MinAC (miniature atomic clock)
NSTP-2 (atomic clock for space)
Sub-Orbital (space payload study)
SYNCHRONICITY (atomic clocks)
QUANTIFY (Earth observation)
GRAM (Gravity new applications)
KAIROS (Pioneer)
Gravity Applications (Pioneer)
QKD via satellite (ARQIT - Pioneer)
Partners(*)
UNIVERSITY OF BIRMINGHAM
NPL
QMI
XCAM
Southampton
RSK
Fraunhofer UK
optocap
ANDOR
AIRBUS DEFENCE & SPACE
IGS
LEONARDO
CATAPULT
QinetiQ
altran
UK SPACE AGENCY
EPSRC
ATKINS
[dstl]
Innovate UK
Team
Full time equivalent staff at Te2v
2014 2015 2016 2017 2018
(*) CR&D partners in Innovate UK projects
© Teledyne e2v December 6th 2018
TELEDYNE e2v
FFS at 1000s averaging
Size (cm³)
Microchip 5071A: Cesium Clock Primary Frequency Standard
Allan Deviation σy (τ)
Averaging time τ (seconds)
CSAC
Te2v MINAC
PRS10
Te2v KAIROS
5071A
76

Microchip CSAC SA.45s: continuously evolving from 2011
First CSAC: 2011
Low-Noise CSAC: 2015
Space CSAC: 2019
CPT-based MAC from 2008
Institute of Navigation - Joint Navigation Conference
August 24-27, 2021, Greater Cincinnati, Ohio
Session A4: Novel Timing Technologies and Applications
Peter Cash et al., Microchip Technologies, "Militarized Chip-Scale Atomic Clock"
Microchip's Model SA.45 Chip-Scale Atomic Clock (CSAC) provides accurate low-power frequency and timing capabilities to portable, volume constrained, severe environmental applications. Microchip has updated the CSAC, to support military applications in demanding environments. The new SA.65 CSAC provides operation over a wider temperature range, improved temperature stability, longer hold-over time, improved phase noise, and reduced time to atomic lock. This paper will describe the updates to the hardware and firmware design. Design improvements include optimizing microwave coupling to the physics package, improved voltage regulation, increased heater demand power for rapid warm-up, and enhancements to the atomic clock control algorithms. In parallel, Microchip is developing a companion variant of the SA.65 CSAC with superior phase noise for radio applications. The improved phase noise is a result of incorporating a low-power Ovenized Crystal Oscillator (OCXO) in place of the Temperature-Controlled Crystal Oscillator (TCXO) as the primary local oscillator for atomic interrogation. The paper will summarize the results of environmental testing of the SA.65 CSAC, including thermal and thermal vacuum, phase noise and frequency stability performance during random vibration, mechanical shock resilience and performance, and extended high-temperature life testing.
European Commission
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KAIROS project / Funding: £4,450,251 / Funder: Innovate UK [1], UKQTNP [2] / Period: 2018-21

"This project will **develop a pre-production prototype of a miniature atomic clock for providing precise timing to a variety of critical infrastructure services**, such as reliable energy supply, safe transport links, mobile communications, data networks and electronic financial transactions. The precise measurement of time is fundamental to the effective functioning of these services, which currently rely on Global Navigation Satellite Systems (GNSS) for a timing signal. However, GNSS signals are easily disrupted either accidentally or maliciously, and in prolonged GNSS unavailability these critical services stop functioning. The next generation miniature atomic clock arising from this project fulfills demand for timing solutions that are not GNSS dependent and will find widespread application in **precision timing for mobile base stations, network servers for financial services, data centres, national power distribution networks and air traffic control systems**. Further applications arise in areas where an independent timing reference is needed on mobile platforms and especially in areas where no GNSS signal is available. A high performance compact clock would benefit a range of useful capabilities, addressing **civil and military applications**, bringing both technical and economic gains for the UK."

News on VCSELs, see e.g. press releases of March 29, 2021 [3], [4]:

"The laser design, epitaxial materials and device fabrication partners in the project have demonstrated a **UK sovereign capability in VCSELs** and delivered single-mode VCSELs with ultra-high mode-stability operating **at 894nm**, the wavelength corresponding to **the D1 transition line of Cs used in high accuracy clocks**. Demonstrated capability includes: a suite of proprietary laser design and simulation models at Cardiff University and ICS Ltd; high uniformity epitaxial layer structures realised at CSC, with < 3nm centre wavelength tolerance; polarisation insensitive, single mode VCSEL performance with a linewidth of ~30MHz and SMSR of 28dB, fabricated by ICS Ltd; and novel VCSEL characterisation processes specifically developed for quantum applications at the National Physical Laboratory (NPL). Having met stringent target performance specifications required for atomic clock applications, the supply chain partners are preparing to service future opportunities for high-specification VCSELs through several parallel activities, one of which is the **QFoundry project to upscale the manufacturability and reliability** of quantum photonic components (QPCs), also part-funded by the UK National Quantum Technologies Challenge."

KAIROS project

Lead Participant
Teledyne E2v (UK) Limited, Essex

Participants
Cardiff University, United Kingdom
Altran UK Limited, Bath
Alter Technology Tuv Nord UK Limited, Livingston
Compound Semiconductor Centre Limited, Cardiff,
Integrated Compound Semiconductors Limited, Cheadle
University of York, United Kingdom
Leonardo MW Ltd
NPL Management Limited, Teddington
HCD Research Limited, Sussex

[1] https://gtr.ukri.org/projects?ref=104614#/tabOverview
[2] UK Quantum Technologies National programme, https://uknqt.ukri.org/
[3] https://www.npl.co.uk/news/uk-project-delivers-vcsels-for-atomic-clocks
[4] https://compoundsemiconductor.net/article/112986/UK_Project_Makes_894nm_VCSELs_For_Atomic_Clocks

European Commission

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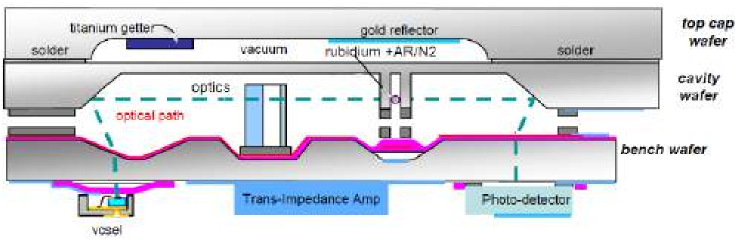
Honeywell highly integrated prototype

D. W. Youngner et al., "A manufacturable chip-scale atomic clock", Transducer and Eurosensors Conference, 2007



The cost of a CSAC is dominated by packaging and assembling. Honeywell Darpa-funded approach was trying to minimize cost by doing more of the integration and critical alignment at the wafer level.

- Lower wafer (Pyrex): VCSEL in a stress-isolated thermally-controlled cage, pit for neutral density filter and quarter wave plate, thermal isolation stage for the rubidium cell, photo-detector, and first amplification stage.
- Middle wafer (Silicon): two sloped mirrors and rubidium cavity
- Upper wafer (Pyrex): titanium getter to help preserve a vacuum around the cell.
- On both Pyrex wafers above and below the rubidium cell there are gold reflectors that reflect back heat, to minimize the power required to keep the cell at 90°C.

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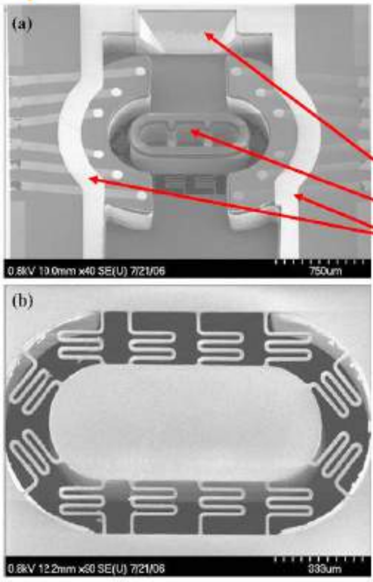
Honeywell highly integrated prototype



Light across the optical path

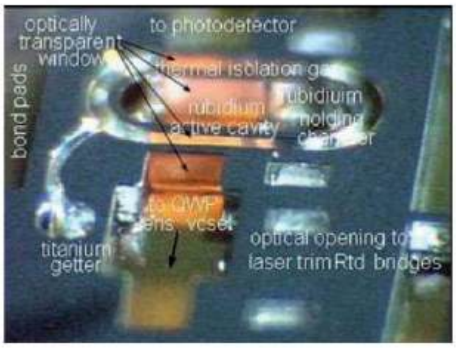
SEM photographs:

Sloped mirror
Rubidium cavity
Outer vacuum-isolation

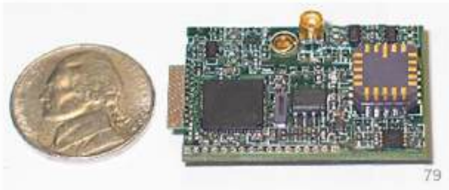
Serpentine legs: support the cavity and provide thermal isolation and shock-isolation

Tested also with an integrated GNSS-disciplining feedback

No more news after 2007…
Dead road?



Overall power requirement: ~ 60mW
Allan Deviation @1hour < 10^{-11}



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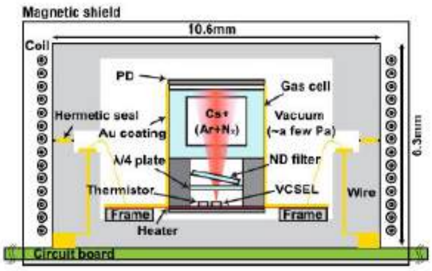
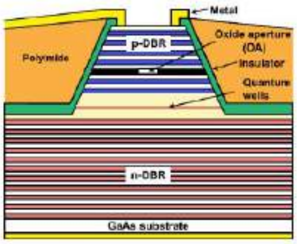
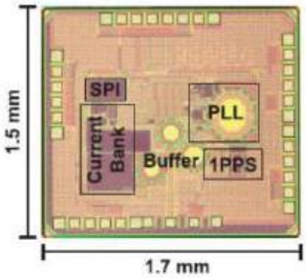
Ultra Low Power Atomic Clock - ULPAC

Haosheng Zhang et al., "ULPAC: A Miniaturized Ultralow-Power Atomic Clock", IEEE Journal of solid state circuit, Vol. 54, No. 11, 2019
JP: Tokyo Institute of Technology, Tokyo Metropolitan University, National Institute of Advanced Industrial Science and Technology (AIST), Ricoh. Sweden: Ericsson



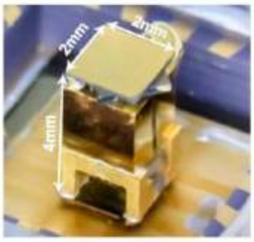


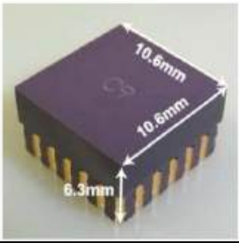
VCSEL purposely designed and manufactured by Ricoh



Quantum package: 4x2x2mm
Au-coating and suspensions

Vacuum-sealed physical package:10.6x10.6x6.3mm





Frequency-locking electronic circuit, built with 65nm standard CMOS.
Design and manufacturing suitable for LEO applications, e.g. small-sats constellations.

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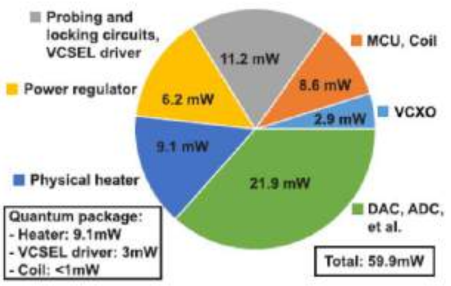
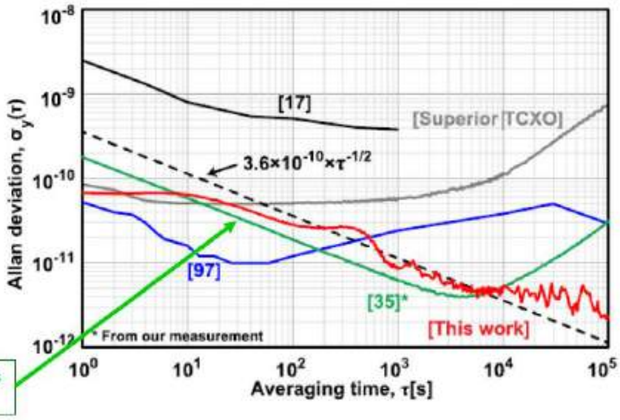
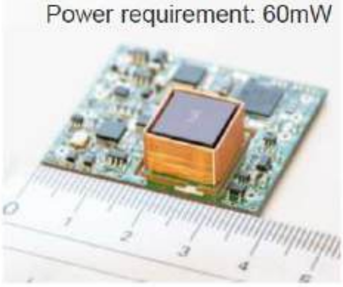
ULPAC





Total volume: 15cm^3
Power requirement: 60mW



[35] Microchip CSAC SA.45s
17cm^3, 120mW

[97] MAC clock developed at CSEM (Switzerland), see D. Ruffieux *et al.*, "Towards portable miniature atomic clocks," in *Frequency Reference, Power Management for SoC, and Smart Wireless Interfaces*, A. Baschirotto, K. A. A. Makinwa, and P. Harpe, Eds. Cham, Switzerland: Springer, 2014, Chapter 6, pp. 83–99.

[17] Molecular clock under study at MIT (USA), see C. Wang, X. Yi, M. Kim, Y. Zhang, and R. Han, "A CMOS molecular clock probing 231.061-GHz rotational line of OCS with sub-ppb long-term stability and 66-mW DC power," in *Proc. Symp. VLSI Technol. Circuits*, Jun. 2018, pp. 113–114.

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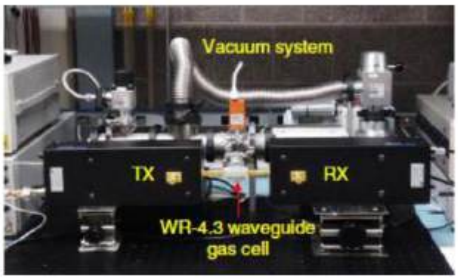
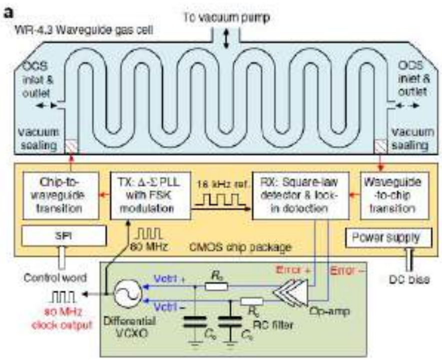
Molecular clock based on rotational spectroscopy (MIT)

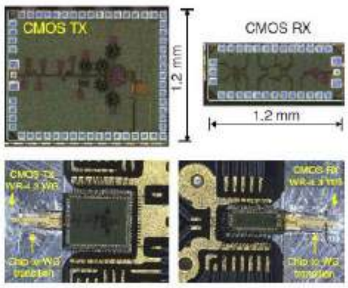
Cheng Wang et al., "An on-chip fully electronic molecular clock based on sub-terahertz rotational spectroscopy", Nature Electronics, Vol. 1, 2018 - MIT

Approach: exploit as clock reference the rotational transitions at ~ 200 - 300 GHz of linear molecules such as carbonyl sulfide (OCS). OCS is chemically stable, and its rotational spectral lines are insensitive to external electric/magnetic fields. Their sub-terahertz rotational transition can be exploited as time/frequency standards by using integrated circuits built with mature complementary metal-oxide semiconductor CMOS technologies.

- The clock requires neither an electromagnetic shield nor a gas cell heater
- It features instantaneous turn-on operation
- The limit for the clock size is the volume of the meander cell (~100 mm^3)







Conclusion: Molecular clocks provide a promising route to miniature (<1 cm^3) time-keeping devices that can be monolithically integrated with mainstream CMOS process, leading to low-cost & low-power (< 40 mW) chip-scale clocks.

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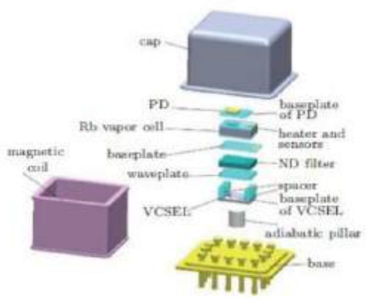
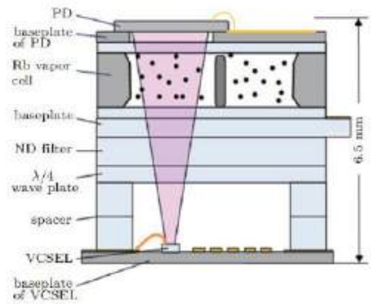
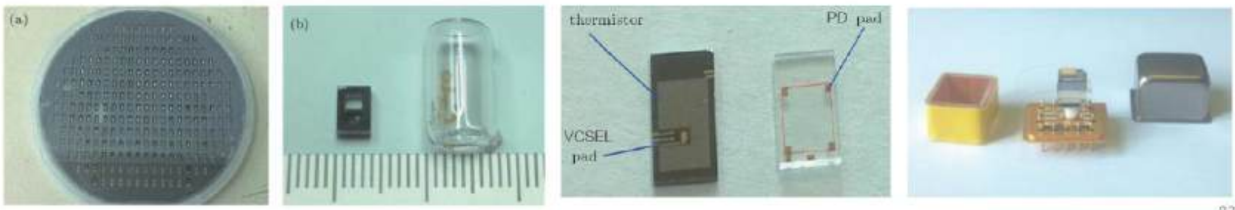
“Integrated physics package of a chip-scale atomic clock”, 2014

Li Shao-Liang et al., Chin. Phys. B, Vol. 23, No. 7, 2014
(1) State Key Laboratory of Transducer Technology, Shanghai
(2) University of Chinese Academy of Sciences, Beijing





- Physical package: cuboid of ~2.8cm^3
- Not yet vacuum-sealed
- Power dissipation ~ 150mW
- Temperature control accuracy to be improved
- ^{87}Rb vapor cell: 2-chambers batch-fabricated by MEMS technology, in-situ chemical reaction
- Short-term frequency stability: ~7x10^{-10} @1s



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Peking University and Nat. Key Lab of Sci. and Tech. (since 2013)

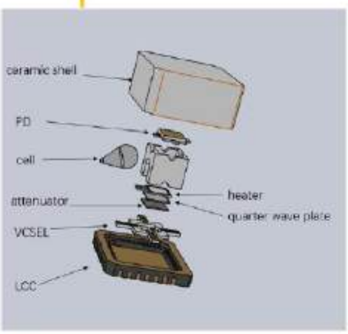
Jianye Zhao et al., “Advances of chip-scale atomic clock in Peking University”, 2015 Joint Conference of the IEEE International Frequency Control Symposium & the European Frequency and Time Forum

Jianye Zhao, et al., "Progress towards chip-scale atomic clock in Peking University," 2017 Joint Conference of the European Frequency and Time Forum and IEEE International Frequency Control Symposium

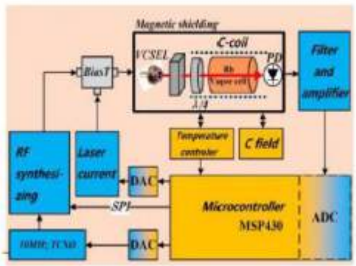
Jianye Zhao et al., “ New Progress towards Chip-Scale Atomic Clock in Peking University” 2018 IEEE International Frequency Control Symposium

Jianye Zhao et al., “Advances of Chip-Scale Atomic Clock in Peking University in 2019”, 2020 Joint Conference of the IEEE International Frequency Control Symposium

(1) Peking University
(2) National Key Laboratory of Science and Technology on Vacuum Technology & Physics (Lanzhou)
(3) China Zhongkeqidi Optoelectronic Technology (Guangzhou)

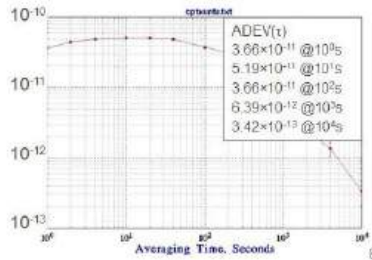


- Leadless chip carrier (LCC) base and ceramic cap
- Vacuum sealing welding between the LCC base and the sealing cap
- Getter integrated in the ceramic cap to further improve inside vacuum
- C-field generated by metal shell on the outer wall of the ceramic cap



VCSEL system and ^{87}Rb cell system stacked together
Temperature-control loop, ±2mK fluctuations after 3 min warm-up

Physical package power ~20mW
Total volume 12cm^3



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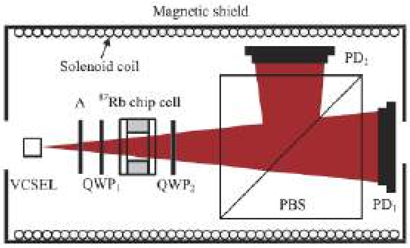
Wuhan 2019: CPT-based CSAC with differential detection

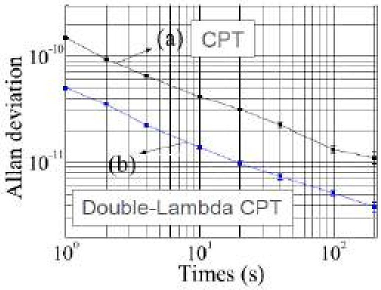
Huifang Lin et al. , "Experimental study of the application feasibility of a novel chip-scale atomic clock scheme", Rev. Sci. Instrum. 90, 053111 (2019)
(1) Wuhan National Laboratory for Optoelectronics, Wuhan Institute of Physics and Mathematics
(2) Huazhong University of Science and Technology
(3) Key Laboratory of Atomic Frequency Standards
(4) Chinese Academy of Sciences

Double – Lambda CPT resonance

Elliptically polarized light & Double detection scheme

-> Improved SNR -> better frequency stability





VCSEL Enabling Technology

Zhang Xing et al, "894 nm high temperature operating vertical cavity surface emitting laser and its application in Cs chip scale atomic clock system", Acta Physica Sinica 65, 13, 2016; State Key Laboratory of luminescence and applications (Changchun), Key laboratory of atomic frequency standards (Wuhan), University of Chinese Academy of Science (Beijing)

Jianwei Zhang et al., "High-temperature operating 894.6nm-VCSELs with extremely low threshold for Cs-based chip scale atomic clocks", Optics Express Vol. 23, Issue 11, 2015 - State Key Laboratory of Luminescence and Application, Changchun Institute of Optics

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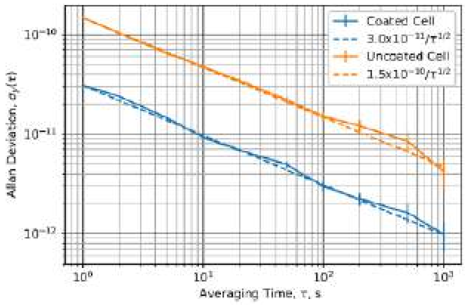
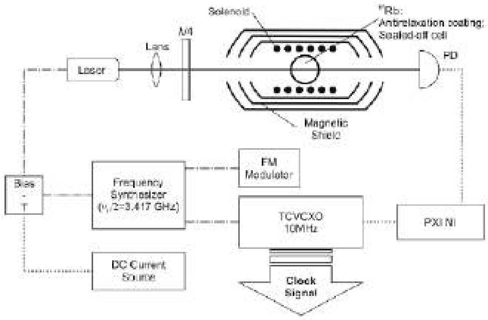
Novosibirsk: cell without buffer gas

Study of CPT resonance

Glass-blown cell, 1.3cm diameter
No buffer gas, anti-relaxation internal coating

VCSEL laser from Oclaro, 100MHz linewidth
TCVCXO from IQD FOQ GmbH
Control electronics: National Instrument PXI





S. Khripunov et al., "Atomic clock based on a coherent population trapping resonance in ^{87}Rb with improved high-frequency modulation parameters", Proc. of SPIE conference Slow Light, Fast Light, and Opto-Atomic Precision Metrology, 2015

S. Kobtsev et al., "Stability properties of an Rb CPT atomic clock with buffer-gas-free cells under dynamic excitation", Journal of the Optical Society of America B, Vol. 36, No. 10, 2019

A.O. Makarov et al., "Investigation of Commercial 894.6 nm Vertical-Cavity Surface-Emitting Lasers for Applications in Quantum Metrology", VIII International Symposium on modern problems of laser physics, 2019; VCSEL produced by VIXAR Inc.

(1) Novosibirsk State University
(2) Institute of Laser Physics (Novosibirsk)
(3) Tekhnoscan Labs

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Novosibirsk: Optical contact bonding

S. Kobtsev et al., "CPT atomic clock with cold-technology-based vapour cell", Optics and Laser Technology 119, 2019
All-Russian Scientific Research Institute of Physical-Technical and Radiotechnical Measurements, Tekhnoscan Lab, Novosibirsk State University

Optical contact bonding is a low-temperature process which allows using the same optical material (e.g. silica, quartz, glass) for all the parts to be joined. When clean polished faces of dielectric components are brought about a nanometer apart, the molecular forces existing between hydroxyl groups lead to reliable joining. For optical contact bonding it is sufficient to press accurately polished surfaces against each other, at room temperature. However, optical contact bonding is not as robust as anodic bonding: temperature variations and temperature gradients can disjoint surfaces which have been joint with optical bonding technique.

Cell made by direct optical bonding of three fused silica elements.

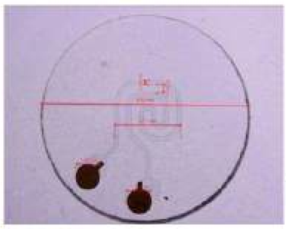
- One window is direct-bonded to the cylinder
- The cell is placed inside a vacuum chamber
- A ~1 μL micro-droplet of ^{87}Rb is introduced into the cell cavity
- The vacuum chamber is filled with the buffer gas
- The second cell window is bonded to the cylinder

Windows:
8mm diameter
1.5mm thickness

Cylinder:
5mm length
8mm outside diameter
4mm internal bore

40 cells made in a pilot facility and spectroscopically tested. Stability of CPT atomic clocks was measured, obtaining ADEV(1s) = 4×10^{-11}

Since cell windows are cooler then the rest of the cell, alkali atoms can form deposits on them, degrading the clock performance. To address this issue, a conductive heating element has been integrated in the cell windows.



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CSAC research highlights in Europe (last ~10 years)

Topics:

Miniaturization of the Rb lamp
Miniaturization of RF cavity

Manufacturing of the Rb microcell

Manufacturing of dedicated VCSEL sources for CPT
Characterization of commercial VCSEL for CPT

Integration of components
Characterization of prototypes

Players (not exhaustive list):

Université Bourgogne Franche-Comté (Besançon, FR)
Université de Neuchâtel (CH)
École polytechnique fédérale de Lausanne - EPFL (CH)
Universität Ulm (DE)
Technological University of Wroclaw (PL)
VTT Technical Research Centre of Finland (FI)
CEA/Léti Commissariat à l'énergie atomique et aux énergies alternatives / Laboratoire d'électronique et de technologie de l'information (Grenoble, FR)
CNRS / FEMTO-ST (Besançon, FR)
FranceTronics Microsystems, Crolles (FR)
CSEM Centre Suisse d'Electronique et de Microtechnique (CH)
École nat. sup. de mécanique et des microtech. (Besançon, FR)
The Swatch Group Recherche et Développement, Neuchâtel (CH)
SAES Getters (IT)
Oscilloquartz (Neuchâtel, CH)
SCHOTT Primoceler Oy (Tampere, Finland)
Ligentec (CH) – spinoff from Lausanne EPFL
INRIM Istituto Nazionale di Ricerca Metrologica (Torino, Italy)
LNE-LTFB Laboratoire national de métrologie et d'essais Laboratoire Temps Frequence de Besancon (FR)
LNE-SYRTE Laboratoire national de métrologie et d'essais - Système de Références Temps-Espace (FR)

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First European chip-scale atomic clock: 2008-2012

FP7-ICT STREP project MAC-TFC: MEMS Atomic Clocks for Timing, Frequency Control & Communications, 2008-2012, EU contribution € 3,350,000, https://cordis.europa.eu/project/id/224132/it

Develop a MEMS-based atomic clock which outperforms crystal quartz oscillators over long time scales, to provide base timing for telecommunication networks synchronization, 4G base stations, navigation or military systems. Objectives and technologies:

(i) Small size (~1cm^3 for the physical package)
(ii) Low power consumption (200 mW)
(iii) Short-term stability < 1x10^{-11} @1hr
(iv) Implementation of thick-film alkali dispensers and MEMS getters in wafer scale fabrication of Cs cells
(v) Vacuum packaging of the micro-optical bench by LTCC (Low-Temperature Co-fired Ceramic) technologies
(vi) Use of customized VCSELs for CPT operation

Université de Franche-Comté (Besançon, FR)
Université de Neuchâtel (CH)
École polytechnique fédérale de Lausanne - EPFL (CH)
Universität Ulm (DE)
Technological University of Wroclaw (PL)
VTT Technical Research Centre of Finland (FI)
CEA/Léti (Grenoble, FR)
Centre national de la recherche scientifique, FEMTO-ST (FR)
École nationale supérieure de mécanique et des microtechniques (Besançon, FR)
The Swatch Group Recherche et Développement, Neuchâtel (CH)
SAES Getters (IT)
Oscilloquartz (Neuchâtel, CH)

Fig. 13. Physics package assembled with electronics (EPFL data).

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EU FP7 STREP project MAC-TFC: towards an EU CSAC

C. Gorecki "Development of first European chip-scale atomic clocks: Technologies, Assembling and Metrology", Eurosensors XXVI, 2012

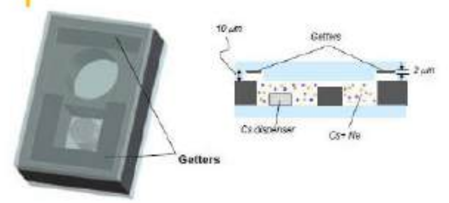


Fig. 1. Schematic of Cs microcell based on Si etch, anodic bonding and dispenser&getter technologies from SAES Getters (FEMTO-ST data).

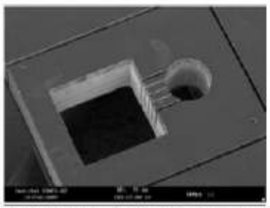
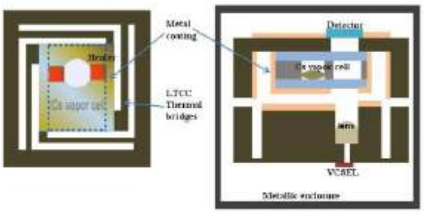


Fig. 2. Microcell cavities fabricated by DRIE (FEMTO-ST data).

DRIE: Deep Reactive-Ion Etching

Fig. 6. Glass transmissive cell (Wroclaw UT data).



Physical Package, ~1cm^3, ~ 40mW

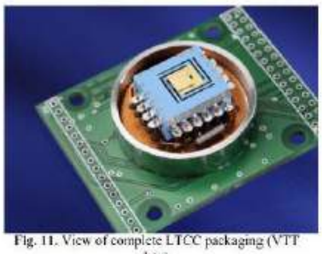
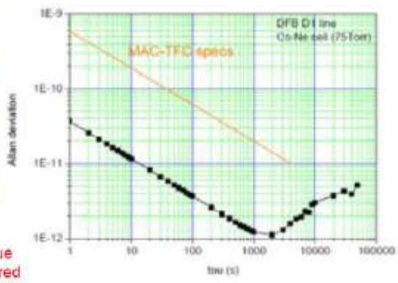


Fig. 11. View of complete LTCC packaging (VTT data).

LTCC: Low-Temperature Co-fired Ceramic - A technique to obtain robust assembly and packaging of multi-layered electronic micro-components



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Rb dielectric barrier discharge (DBD) source

V. Venkatraman et al., "Optical pumping in a microfabricated Rb vapor cell using a microfabricated Rb discharge light source", Applied Physics Letters, 104, (2014). University of Neuchatel and École Polytechnique Fédérale de Lausanne.

Swiss project MACQS : Miniature atomic clocks and quantum sensors
https://www.unine.ch/ltf/fr/home/projets/projets-termines/MACQS.html

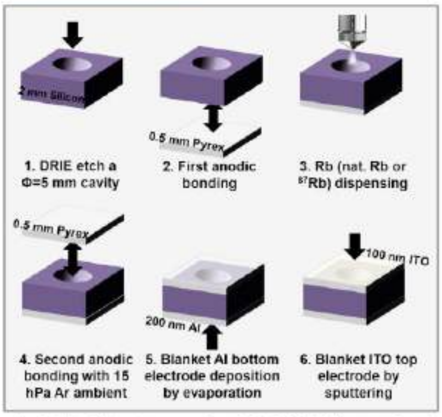
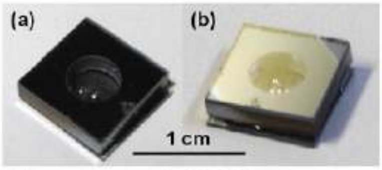
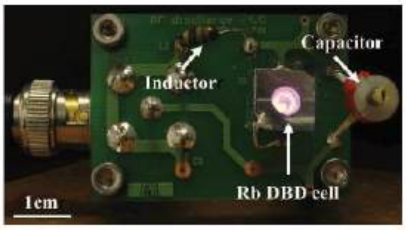


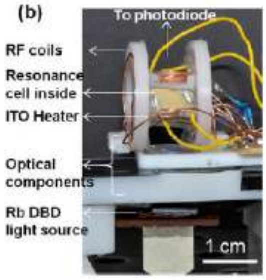
Fig. 3. Microfabrication process flow of the Rb DBD light source. Steps 1 and 2 are performed at wafer level and steps 3 to 6 are done at chip level



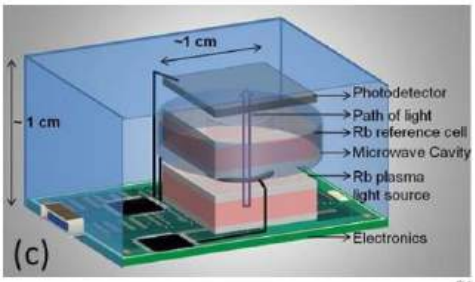
Rb resonance cell Rb DBD light source



Magnetometer prototype built with Rb Dielectric Barrier Discharge light source and Rb Resonance cell



Conceptual scheme of a miniaturized double-resonance clock



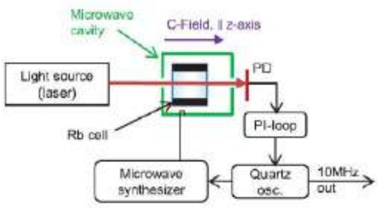
Miniature atomic clocks and quantum sensors (MACQS)

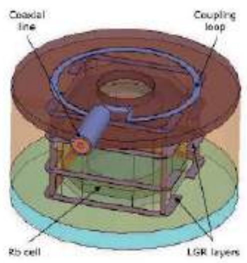
M. Violetti "The Microloop-Gap Resonator: A Novel Miniaturized Microwave Cavity for Double-Resonance Rubidium Atomic Clocks", IEEE Sensors Journal, Vol. 14, No. 9, 2014 - University of Neuchatel and Ecole Politecnique Fédérale de Lausanne

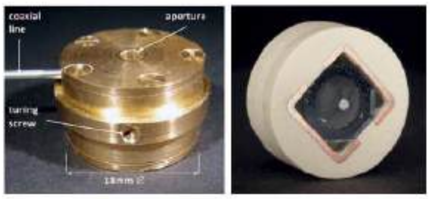
Realization of **miniature double-resonance atomic clocks**, with potential applications in satellite navigation and positioning, secure telecoms, mobile timing applications. Based on the optical-microwave double resonance scheme, which allows better stability than the coherent population trapping scheme, for a vapor cell of the same size.

Development and testing of a miniaturized microwave resonator, to apply a well-defined microwave field to a microfabricated Rb cell.

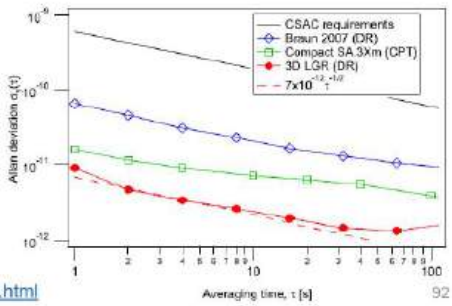
μ-LGR Micro Loop Gap Resonator with very compact dimensions, which can be fabricated and assembled with repeatable and low-cost techniques.







Resonator, with internal volume < 0.9 cm³



https://www.unine.ch/ltf/home/projets/projets-termines/MACQS.html

Double-resonance compact Rb clocks – Neuchatel

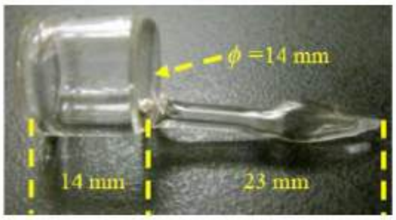
T.N. Bandi, "Double resonance studies on compact, high performance Rubidium cell frequency standards", PhDThesis, Univ. Neuchatel, 2013

Laser-microwave double-resonance spectroscopy and metrology in rubidium (^{87}Rb) vapor cells for high-performance, compact Rb-cell atomic clocks. The Rb vapor cell is confined inside a magnetron-type cavity microwave resonator (MWR).

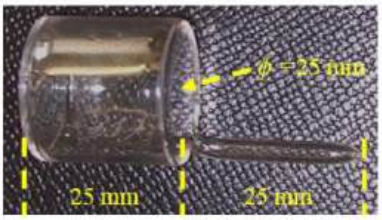
Small vapor cells with inner walls coated with anti-relaxation material. Good short-term frequency stability, medium- to long-term stability limited by the thermal stability of the coating material.

Larger cells filled with ^{87}Rb and buffer gases, placed within a newly developed MWR for a high-performance atomic standard. Demonstrated State-of-the-art short-term stability of $< 1.4\times10^{-13}\ \tau^{-1/2}$. Metrological quantitative measurements on parameters influencing the medium- to long-term stability, in view of next generation satellite navigation systems that demand a stability level of $<1\times10^{-14}$ at 10^4 s (equivalent to <1 ns/day).

ESA NAVISP-EL1-032 project; Start date: 01/03/2020; Duration: 18 Months (Neuchatel & EPFL)

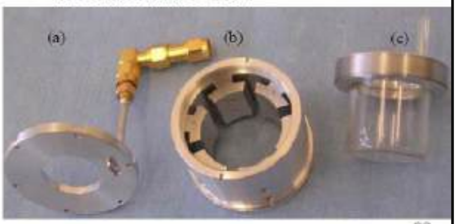


Paraffin-coated cell (inner volume 1.4 cm^3), with a reservoir stem on its right-hand side.



Buffer-gas cell with an inner volume 9.6 cm^3. The stem serves as a reservoir for metallic Rb.

Magnetron-type microwave resonator for 25mm-diameter cell

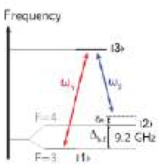


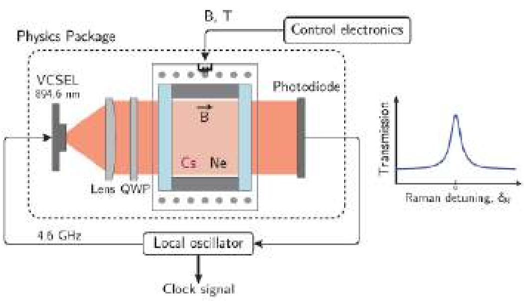
Characterization of commercial VCSELs at 895nm

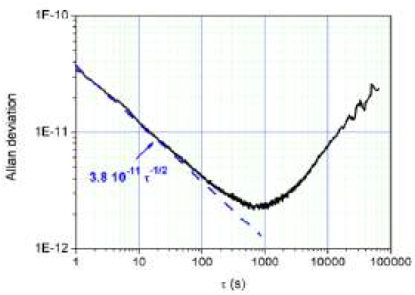
E. Kroemer et al., "Characterization of commercially available vertical-cavity surface-emitting lasers [by VIXAR] tuned on Cs D1 line at 894.6 nm for miniature atomic clocks", Applied Optics, Vol. 55 No. 31, 2016; FEMTO-ST, CNRS, UBFC – Funding by Direction Générale de l'Armement (DGA);

R. Vicarini et al., "Characterization of 894.6 nm VCSELs and application to a microcell-based atomic clock", International Frequency Control Symposium and European Frequency and Time Forum, 2017; FEMTO-ST (CNRS), Besançon

The short-term fractional frequency stability of CPT-based MACs is known to be significantly improved by using a laser tuned on the alkali D1 line. For Cs MACs, different 895 nm VCSELs were developed, but finding commercially available VCSELs at this wavelength for Cs MACs has long been a significant issue. In this study, we report the characterization of novel 894.6 nm VCSELs to be used in a Cs MAC. These measurements include output optical power versus dc current and temperature, spectral linewidth, relative intensity noise or frequency noise. A commercial VCSEL is used for a Cs microcell-based CPT atomic clock, reporting a fractional frequency stability of 3.8 $10^{-11}\ \tau^{-1/2}$ up to about 1000 s.

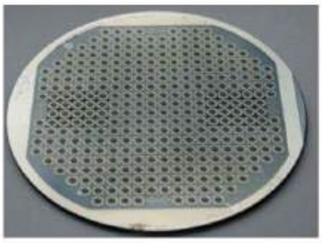


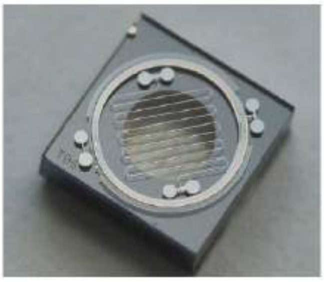




CSEM – Switzerland (1/3)

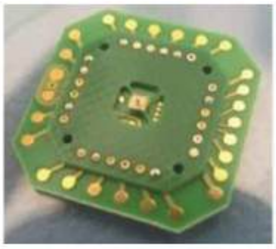
T. Overstolz et al., "Wafer scale fabrication of highly integrated rubidium vapor cells", 2014 - CSEM



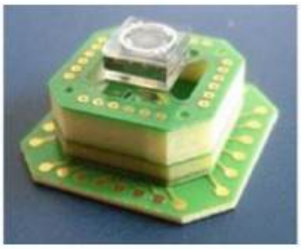


MEMS cells made of silicon and glass by using alkali azide as starting material. After full evaporation of the solvent, the cavities are sealed by anodic bonding under controlled atmosphere. Metallic rubidium and nitrogen are obtained by UV decomposition of the crystallized rubidium azide. The cells were miniaturized down to 1x1mm^2 . On the 2x2=4mm^2 cells functionalities were added to the glass windows: integrated heaters, temperature sensors and Helmholtz coils. The core physics package is realized by a stacking of Printed Circuit Board layers and measures 11x11x8.5 mm^3, including the functionalized atomic vapor cell.

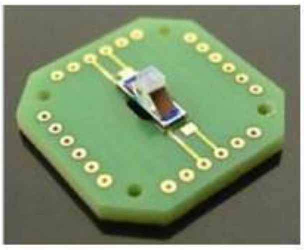
Laser (VCSEL) PCB layer



Core physics packages

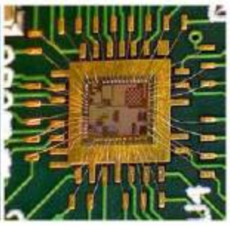


Optical PCB layer with photodetectors



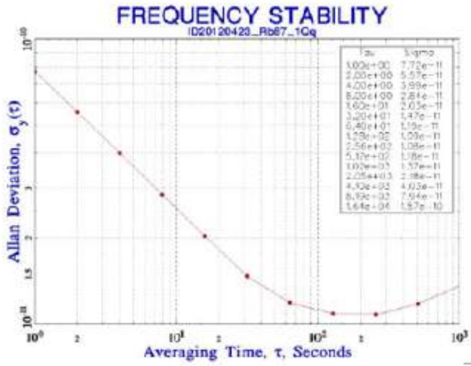
CSEM - Switzerland (2/3)

D. Ruffieux et al., "Towards Portable Miniature Atomic Clocks", 2014 – CSEM



The core physics package is mounted in a commercial ceramic package and vacuum-encapsulated. The resulting assembly is surrounded by an external magnetic shielding, the overall volume of the physics package reaching 22 cm^3.

The frequency stability of this atomic clock was measured to be below 10^{-10} at 1s integration time, showing that the developed atomic vapor cells meet the short term frequency stability specifications of miniature atomic clocks ($<6 \cdot 10^{-10}$ @ 1s). Preliminary results show that the miniature vapor cells are very close to meet the challenging long term frequency stability specifications ($<1 \cdot 10^{-11}$ @ 1day), with a frequency drift measured to be close to $1 \cdot 10^{-10}$ per month.



ESA-funded C-MAC project at CSEM (3/3)

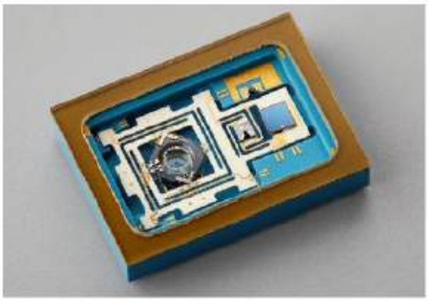
European Space Agency Contract 4000114436/15INLIMM, "Ceramic Miniature Atomic Clock (C-MAC)", started in 2015

J. Haesler et al., "Low-power and low-profile miniature atomic clock ceramic based flat form factor miniature atomic clock physics package (C-MAC)", 2017 Joint Conference of the European Frequency and Time Forum and IEEE International Frequency Control Symposium (EFTF/IFCS) - CSEM, VTT, Primoceler Oy

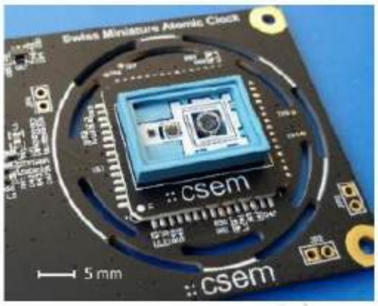
Objective: innovative and low-cost ceramic-based physics package (PP) for ultra-low power miniature atomic clocks (MACs) with flat form factor (height < 5mm) for portable devices (GNSS receiver, smartphone, tablet, laptop, etc.) and high-end demanding applications like onboard satellites.

The preliminary functional testing of the C-MAC PP as well as the low power consumption measurements in vacuum (< 40mW) are in line with the expectations. Hermetic vacuum encapsulation of the package remains the most critical process in order to successfully reach the final objectives. State-of-the-art coherent population trapping (CPT) clock signals have been measured.

Functionalized CSEM vapor cell
US patent US 8,906,470 B2 (2011)
EP application 3 244 269 A1 (2016)



21x15x5 mm³ ceramic-based miniature atomic clock physics package developed by CSEM and VTT (FI)



J. Haesler, EPIC on-line meeting on atomic clocks and quantum sensors, April 2020, https://www.epic-assoc.com/wp-content/uploads/2020/04/Jacques-Haesler_CSEM.pdf

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Activity at the FEMTO-ST (Besançon, Rodolphe Boudot)

L'institut FEMTO-ST (Franche-Comté Electronique Mécanique Thermique et Optique – Sciences et Technologies) est une unité mixte de recherche, placé sous la quadruple tutelle de l'Université de Franche-Comté (UFC), du Centre National de la Recherche Scientifique (CNRS), de l'École Nationale Supérieure de Mécanique et des Microtechniques (ENSMM) et de l'Université de Technologie Belfort-Montbéliard (UTBM). Il a plus de 750 membres a Besançon, Belfort, et Montbéliard.

https://teams.femto-st.fr/equipe-ohms/cell-based-frequency-references

Brief history of CPT-based MACs at FEMTO-ST
The study and development of CPT-based miniature atomic clocks has started at FEMTO-ST in 2005 (funding supports from CNES, Région de Franche-Comté and Agence Nationale de la Recherche). From 2008 to 2012, FEMTO-ST has piloted a European project called MAC-TFC, combining the expertise of 10 industrial and academic partners. This project has led to the demonstration of a first European miniature atomic clock prototype. Main scientific achievements of this project were the development of custom-designed 894 nm (Cs D1 line at 894.6 nm) VCSEL diode lasers (Ulm University), the demonstration of 15-mW and low phase noise 4.596 GHz synthesizers to be used as local oscillator (EPFL-IMT), and the development of an original Cs vapor microcell technology (FEMTO-ST/SAES/Wroclaw University). This project led to the beginning in France of new projects (supports from DGA, LabeX FIRST-TF, ANR, BPI). In 2014, a French industrial-academic platform has been mounted in order to develop an industrial CPT-based miniature atomic clock.

Miniature CPT-based Cs cell atomic clocks: With the help of MEMS techniques, VCSEL lasers and integrated electronics, we develop miniature atomic clocks aiming to combine a low power consumption (150 mW), a small volume (15 cm³) and a fractional frequency stability better than 10^{-11} at 1 hour, in a large temperature range (-40 to +85°C). Strong collaboration with FEMTO-ST MOEMS Group and several industrial partners.

High-performance CPT-based Cs cell atomic clock: Demonstrate a CPT-based Cs cell atomic clock, with similar size and power consumption than commercially-available Cs beam clocks and a fractional frequency stability at the level of a few $10^{-13}\ \tau^{-1/2}$. Our laboratory-prototype clock combines an optimized CPT pumping scheme and a pulsed Ramsey-based interrogation protocol.

MEMS-cell based optical frequency references: Development of new-generation chip-scale hot vapor cell-based optical frequency references. Ultimately, the objective is to demonstrate fully-miniaturized optical frequency references with frequency stability performance 50-100 times better than CPT-based microwave miniature atomic clocks, for a reasonably increased size and power consumption.

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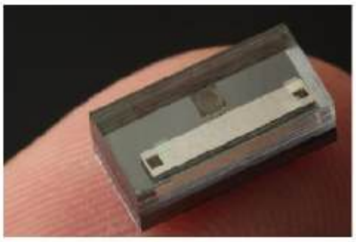
Some microcells developed at the FEMTO-ST

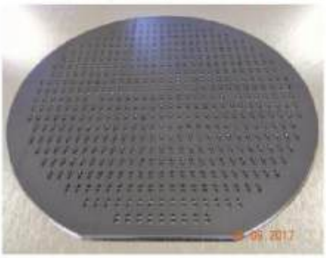
A centimeter-scale Cs vapor cells coated with octa-decyl-trichlorosilane (OTS)

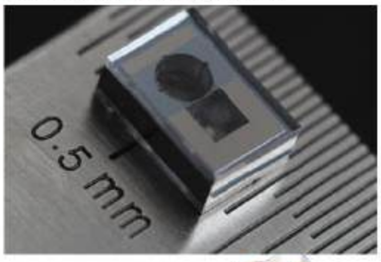


An cell that combines diffraction gratings with anisotropically etched silicon sidewalls to route a normally-incident beam in a cavity oriented along the substrate plane.

Pill-dispenser Cs vapor microcell technology. This cell consists of a silicon substrate sandwiched between two anodically-bonded glass wafers. The cell contains two cavities, connected by thin filtration channels, the first one containing a Cs pill dispenser and the second one for the CPT interaction. After complete sealing of the cell, Cs vapor is generated by laser activation of the Cs pill dispenser. In collaboration with our industrial partner Tronics Microsystems, we have reported the characterization of Cs vapor microcells based on pill dispensers and fabricated in a MEMS foundry, according to a process compatible with mass-production. More than three quarters of cells from 6-inch wafers are successfully filled with Cs vapor. Various cells of a given wafer have been characterized using CPT spectroscopy, to demonstrate that this vapor cell technology is suitable for industrial miniature quantum clocks or sensors.

CPT chamber: 2 mm diameter, 1.5mm length. Industrialized by Tronics Microsystem with single-step DRIE (Deep Reactive Ion Etching) and dual-step anodic bonding processes.





Rodolphe Boudot "Miniature Cs vapor cells and atomic clocks in FEMTO-ST", Workshop Miniature Atomic Clocks, Strathclyde, United Kingdom, 2017

European Commission

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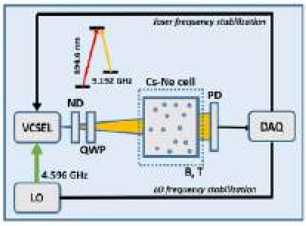
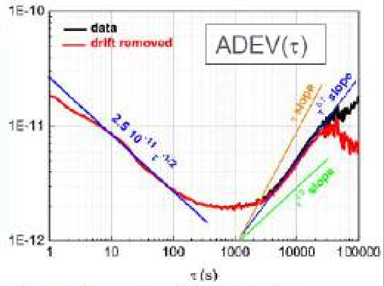
Miniature atomic clock at FEMTO-ST (Besançon) 1/2

R. Vicarini et at., "Demonstration of the mass-producible feature of a Cs vapor microcell technology for miniature atomic clocks", 2018
C. Gorecki et al., "Advanced microfabrication technologies for miniature caesium vapor cells for atomic clocks", SPIE OPTO, San Francisco, 2019

FEMTO-ST, CNRS (Besançon); FranceTronics Microsystems (Crolles)
Funding: Délégation Générale de l'Armement (DGA); Association Nationale de la Recherche et de la Technologie (ANRT)

A clock prototype was built using a fabricated microcell based on Cs pill dispensers, demonstrating a frequency stability of $2.5\times10^{-11}\,\tau^{-1/2}$ up to 200s and better than 2×10^{-11} at 10^5s, with mid-term stability mainly affected by temperature-induced light shift effects. A vapor cell technology compatible with mass-production has thus been demonstrated to be suitable for miniature quantum clocks and sensors.





MACs are based on the operation of two main servo loops (stabilization of the laser frequency and stabilization of the local oscillator onto the CPT resonance frequency). The development of MACs with improved mid- and long-term stability requires the implementation of additional servo loops to reduce temperature-induced light-shift effects. On time scales higher than ~100 s frequency shifts degrade a MAC performance, due to:

- Buffer-gas-induced temperature-dependent frequency shift of the clock transition, which is usually addressed by using an appropriate buffer gas mixture and stabilizing the cell at a so-called inversion temperature)
- Temporal evolution of the cell inner atmosphere, because of (i) residual contaminants or impurities (ii) progressive reduction of the alkali density in the cell (iii) buffer gas permeation issues through the cell glass windows (iv) alkali condensation on the cell windows.
- Light-shift effects, due to the sensitivity of the clock frequency to variations of the laser power, the laser frequency and also to the CPT sideband amplitude ratio through the microwave power of the signal that modulates the laser system.

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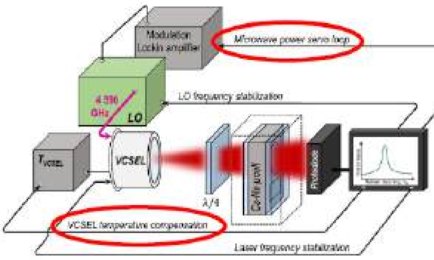
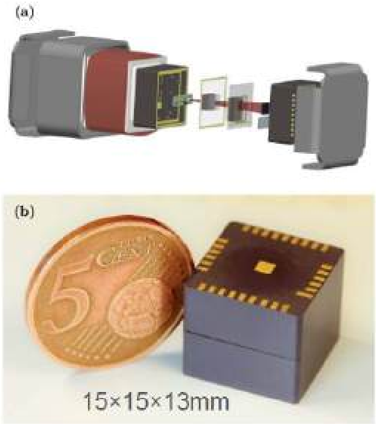
Miniature atomic clock at FEMTO-ST (Besançon) 2/2

Rémy Vicarini et al., "Mitigation of Temperature-Induced Light-Shift Effects in Miniaturized Atomic Clocks", IEEE Transactions on Ultrasonics Ferroelectrics and Frequency Control , Vol. 66, No. 12, 2019
R. Vicarini, M. Abdel Hafiz, E. Kroemer, S. Galliou and R. Boudot, "Micro-Horloge atomique et procedé de régulation associé", Patent Pending Proposal FR 187 256, 2018

Experimental demonstration of a MAC with additional stabilization loops, with a CPT-clock physics package with a MEMS microcell and a VCSEL tuned on the Cs D1 line (895 nm). Four servo loops control the laser frequency, LO frequency, VCSEL temperature, microwave power. Laboratory-prototype electronics are used, and the clock physics package is fully integrated in 15×15×13 mm^3. The clock demonstrates an Allan deviation of 7.5×10^{-11}, 5.5×10^{-12}, and 2×10^{-11} at 1, 10^3, and 10^5 s averaging times.

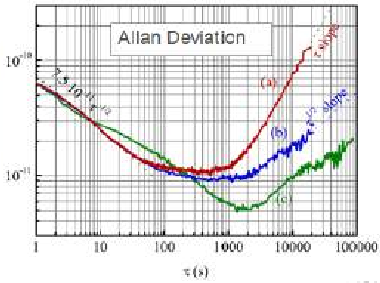


Physics package formed by two half-box ceramic shells, sealed together. The VCSEL and the microcell are each placed onto distinct suspended polyimide platforms for high thermal insulation. The vacuum sealing process of the physics package was not successful, so the physics package prototype was placed into a vacuum chamber for this experimental characterization.



(a) Basic configuration with only two active servo loops (laser and LO frequency)
(b) VCSEL temperature compensation active
(c) Both VCSEL temperature and microwave power stabilizations are active

Power consumption not specified.



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Selection of CSACs products and prototypes (TRL4-TRL5)

Manufacturer/Model	Country	Ion	ADEV (1s)	ADEV (100s)	ADEV (1000s)	Aging (month)	Power (mW)	Weight (g)	Size (cm^3)	Notes
Microsemi SA.45s [1]	USA	Cs	3×10^{-10}	3×10^{-11}	1×10^{-11}	9×10^{-10}	120	35	17	ADEV(10^5 s) = 3×10^{-11}. Commercial since 2011, 95,000 units sold in 2011-18. Low-noise version in 2015, space version in 2019, militarized version in 2021, continuous support by the US gov.
Teledyne TCSAC [2]	USA	Rb	3×10^{-10}	3×10^{-11}	1×10^{-11}	3×10^{-10}	180	47	23	Launched March 2020. Larger versions (MINAC and KAIROS) in development by e2V, funds by Innovate UK and UKNQT.
Chengdu Spaceon XHTF1045 [3]	China	?	3×10^{-10}	3×10^{-11}	?	9×10^{-11}	250	35	17	Very few technical details available. The firms seems to push a slightly larger version ("our standard CSAC"), which requires 1.6W.
Tokyo Ultra Low Power Atomic Clock ULPAC [4]	Japan	Cs	7×10^{-11}	3×10^{-11}	1×10^{-11}	?	60	?	15	ADEV(10^5 s) = 2×10^{-12}. Custom VCSEL source developed by Ricoh. The electronics control of physical package is implemented with space-ready 65-nm CMOS process.
Besançon FEMTO-ST et al. [5]	France	Cs	8×10^{-11}	2×10^{-11}	6×10^{-12}	?	?	?	~3 (only Physical Package)	ADEV(10^5 s) = 2×10^{-11}. Microcell industrialized by FranceTronics Microsystems. Funding from DGA, Région de Franche-Comté, Agence Nationale de la Recherche.
CSEM Ceramic Miniature Atomic clock C-MAC [6]	Switzerland Finland	Rb	8×10^{-11}	2×10^{-11}	?	1×10^{-10} (aim)	<500 (aim)	?	6 (P.P.) 50 (aim)	Activity funded also by ESA. The immediate aim seems to be a low-cost (aim: < 300$) miniature atomic clock, but a P.P. < 2cm^3 for a truly chip-scale atomic clock is also being developed.
Peking University et al. [7]	China	Rb	4×10^{-11}	4×10^{-11}	7×10^{-12}	?	20 (Phys. Package)	?	12 (aim)	Continuous advancements from 2013. Vacuum-sealed, very good temperature control loop.

TRL 4 – technology validated in lab
TRL 5 – technology validated in relevant environment

[1] https://www.microsemi.com/product-directory/clocks-frequency-references/3824-chip-scale-atomic-clock-csac
[2] http://www.teledyne-si.com/products-and-services/scientific-company/csac
[3] https://www.elecspn-spaceon.com/atomic-clocks/cpt-atomic-clocks/xhtf1045-chip-scale-atomic-clock.html
[4] Haosheng Zhang et al., "ULPAC: A Miniaturized Ultralow-Power Atomic Clock", IEEE Journal of solid state circuit, Vol. 54, No. 11, 2019
Tokyo Institute of Technology, Tokyo Metropolitan University, Japan National Institute of Advanced Industrial Science and Technology (AIST), Ricoh (JP), Ericsson (Sweden)
[5] R. Vicarini et al., "Mitigation of Temperature-Induced Light-Shift Effects in Miniaturized Atomic Clocks", IEEE Transactions on Ultrasonics Ferroelectrics and Frequency Control , Vol. 66, No. 12, 2019
CNRS, UBFC, ENSMM, UTBM, FEMTO-ST, Besançon, (FR); Tronics Microsystems, Crolles, (FR).
[6] J. Haesler et al., "Ceramic based flat form factor miniature atomic clock physics package (C-MAC)", ESA/ESTEC Workshop on Microwave Technology and Techniques, Noordwijk (NL), 2017
CSEM (CH) and VTT Technical Research Center of Finland
[7] Jianye Zhao et al., "Advances of Chip-Scale Atomic Clock in Peking University in 2019", 2020 Joint Conference of the IEEE International Frequency Control Symposium
Peking University, National Key Laboratory of Science and Technology on Vacuum Technology & Physics (Lanzhou), China Zhongkeqidi Optoelectronic Technology (Guangzhou)

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ESA Projects AMICC and AMICC-BIS
Advanced Concept for Chip-Scale Atomic Clocks

NAVISP-EL1-032; Start date: 01/03/2020; Duration: 18 Months - https://navisp.esa.int/project/details/90/show
Contractors: University of Neuchatel, Switzerland; EPFL, Switzerland

The AMICC project aims for evaluating and implementing an alternative but still simple architecture for CSAC, aiming at an about 10-fold improvement in clock stability. Pre-studies performed by the contractors indicate that such performance improvements can be achieved when replacing the standard CSAC scheme by direct microwave interrogation of the atoms in the microcell, using a custom-designed miniature microwave resonator. Concepts for a truly miniaturized microwave resonator have been developed previously and will serve as starting point for the AMICC project.

NAVISP-EL1-032 (bis); Start date: 01/04/2020; Duration: 18 Months - https://navisp.esa.int/project/details/95/show
Contractors: CSEM, Switzerland; Ligentec, Switzerland

The proposed activity is oriented toward the analysis, definition and demonstration of a chip-scale hot vapor cell clock based on an optical transition. The main objectives of the proposed activity are to: (i) Perform a state-of-the-art study on hot atomic vapor optical clocks and on their underlying building blocks and technologies (ii) Design and realize an atomic reference unit based on hot atomic vapor cells and of a Kerr frequency comb (iii) Testing the prototypes and outline future development

https://www.ligentec.com: Based on the ground-taking work of the laboratory of Professor Kippenberg at the Federal Institute of Technology in Lausanne (Switzerland), LIGENTEC is your manufacturing partner for Photonic Integrated Circuits (PIC). We provide next generation silicon photonics for customers in high-tech areas such as Communication, Quantum technologies, LiDAR and Sensing.

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EU projects

EMRP project Mclocks (2013 – 2016) [1], [2], [3]: transfer recent advances in laboratory compact microwave atomic clocks towards new atomic clock instruments suitable for demanding industrial and technical applications. Members: INRIM (Italy) / LNE-LTFB (France) / LNE-SYRTE (France) / UME (Turkey) / Muquans (France) / University of Neuchatel (Switzerland).
Results:

- Development of a pulsed optically pumped (POP) Rubidium vapor cell frequency standard; a prototype is undergoing further development as a potential candidate for use in the next generation of Galileo satellites
- Development of a special spherical microwave cavity, for use in a Rb cold atom pulsed microwave atomic clock (Rubiclock, then commercialized by French company Muquans)
- Spectroscopic evaluation of Cs vapor cells using Coherent Population Trapping (CPT), in view of a Cs-cell CPT atomic clock

Q-Clocks (QuantERA project, started in 2017, see [4], [5]): establish a new frontier in the quantum measurement of time by applying advanced quantum techniques to state-of-the-art optical lattice clocks, demonstrating enhanced sensitivity while preserving long coherence times and the highest accuracy.
Italy INRIM / Poland UMK / France SYRTE / Denmark KU / Italy CNR-INO / Spain ICFO

EC Quantum Flagship Project IQClock Integrated Quantum Clocks [6]: Optical lattice clocks, Superradiant clocks

[1] The EMRP (European Metrology Research Programme) is jointly funded by the EMRP participating countries within EURAMET (European Association of National Metrology Institutes) and the European Union.
[2] https://www.euramet.org/research-innovation/search-research-projects/details/project/compact-and-high-performing-microwave-clocks-for-industrial-applications/?tx_eurametctcp_project%5Baction%5D=show&tx_eurametctcp_project%5Bcontroller%5D=Project&cHash=897fec0c81dff56fb80779b886db142
[3] http://www.unine.ch/ltf/de/home/projets/Mclocks.html
[4] https://www.quantera.eu/images/QuantERA_Call_2017_Projects_Catalogue.pdf
[5] https://www.quantera.eu/co-funded-call/funded-projects/49-q-clocks
[6] https://www.iqclock.eu/about.html

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Quantum Flagship: EC-funded project macQsimal

https://www.macqsimal.eu/

J. Haesler, European Photonic Industry Consortium EPIC on-line meeting on atomic clocks and quantum sensors, April 2020, https://www.epic-assoc.com/wp-content/uploads/2020/04/Jacques-Haesler_CSEM.pdf

Funding programme: H2020-FETFLAG-2018-2020
Project Duration: 01/10/2018-30/9/2021
Project Budget: 10.2 million euro

MACQSIMAL will develop quantum-enabled sensors with outstanding sensitivity for five key physical observables: magnetic fields, time, rotation, electro-magnetic radiation and gas concentration. These sensors are chosen for their high impact and their potential to quickly advance to a product: Within MACQSIMAL all these sensors will reach TRLs between 3 and 6 and will outperform other solutions in the respective markets.

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Quantum Flagship: EC-funded project macQsimal

The common core technology in these diverse sensors is **atomic vapor cells realized as integrated microelectromechanical systems (MEMS)**.

Atomic vapor cells make coherent quantum processes available to applications. Fabricating such atomic vapor cells as MEMS allows for high-volume, high-reliability and low-cost deployment of miniaturized, integrated sensors, critical to wide-spread adoption.

J. Haesler, European Photonic Industry Consortium EPIC on-line meeting on atomic clocks and quantum sensors, April 2020, https://www.epic-assoc.com/wp-content/uploads/2020/04/Jacques-Haesler_CSEM.pdf

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Conclusions on CSAC research highlights

Commercial CSACs manufactured in the USA are the results of heavily subsidized programs spurred in 2000 by military interest, and seem at least in part to still be backed by public money. They have more than ten years of market history, and have kept evolving and adopting new technological solutions. Commercial players are Microchip and Teledyne e2v.

There are commercial products from China, but very little is publicly available on the technologies they are built with. Several Chinese research groups (from universities and state-backed "Key Laboratories") are developing CSACs: they seem slightly below the level reached by their best competitors in the USA, EU, CH, and Japan, but a clear-cut assessment is difficult.

Japan, FR+EU, CH+EU, UK+US, have the technical capabilities to produce first-class (i.e. very small and with very low power requirements) CSACs. Several technological alternatives are being explored, and several prototypes have been manufactured and tested. Research seems to be backed mostly by public money, but industrial transition to a commercial product seems to be not very far (2/3 years, maybe less).

CSACs target essentially military backpack applications and a limited number of civilian and space uses, unless a way can be found to produce them at scale with low costs: in particular, the manufacture of the microcell and the overall package integration have a sizable impact on final cost. Slightly bigger Miniature Atomic Clocks have larger market potential, and can be produced at costs which are already competitive with standard compact Rb atomic clocks. Both for CSACs and for MACs, a critical component is the lasers source, i.e. a VCSEL with the right properties.

The EU27 is funding the development of high-performance atomic clocks and of atomic microcells for sensing applications, but a focused program aimed at industrial transition of EU research results on CSACs seems to be missing.

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5 An applications overview

Microwave chip-scale atomic clocks: plan of the opera

Table of contents

- The place of CSAC in the clocks landscape, with some info on the main players (~35 slides) — ~1h presentation & discussion (April 21)
- The working principles CSACs are based on, and a description of commercial products (~35 slides) — ~1h presentation & discussion (April 28)
- Highlights on research trends, prototypes, enabling technologies, and supporting programs (~35 slides) — ~1h presentation & discussion (May 5)
- An overview of their applications, based on commercial material and scientific literature (~30 slides & additional text) — ~1h presentation & discussion (May 12)

At times, some degree of accuracy will be sacrificed to simplicity and conciseness

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Properties and applications of CSACs

With respect to high-quality quartz-based OCXO:

- Better medium and long term frequency stability and time-keeping capabilities
- Smaller, lighter, less power-hungry → Backpack portability, longer battery lifetime
- Faster warm-up, better performance in harsh environments (shocks, vibrations)

Military applications:

- Faster GPS signal acquisition: P(Y) code time to lock, time to first fix
- Improved GPS navigation in low satellites visibility, via "clock coasting"
- Improved GPS navigation in tanks, planes, UAV
- Better radio-frequency spectrum utilization
- Faster frequency hopping in spread spectrum systems
- Increased jamming resistance, avoid self-jamming
- Improved spoofing detection and resistance
- Improvised Explosive Devices jammers
- Faster signal acquisition for radio-net entry
- Improved ability to hide signals
- Longer radio silence interval
- Improved identification-friend-or-foe
- Improved ability to lock-out unauthorized users from radio networks
- Improved electronic warfare capability (emitter location via TOA)
- Improved slow-moving target detection in Doppler radar
- Improved surveillance capabilities in bistatic radar
- Improved missile guidance, e.g. by on-board radar wrt ground radar

Non-military applications:

- Improved GNSS navigation in poor satellite visibility scenarios
- Synchronization of telecommunication and energy networks, with holdover capability
- Autonomous timing for distributed systems (underground and underwater sensors, LEO satellite constellations)
- Scientific payloads for CubeSats
- LEO CubeSat navigation, e.g. orbit determination with one-way radiometric measurements using an onboard CSAC as timing reference

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Microsemi Component Clocks Portfolio

Double-resonance Rubidium clocks

XPRO

SA.22c, discontinued in 2019

Coherent Population Trapping Rubidium clocks

MAC

? Price ~ 500-1000$?

SA.3x, commercial since 2008
SA.5x upgraded version, since 2020

CSAC

? Price ~ 3000-5000$?

SA.45s, commercial since 2011
LN-CSAC, commercial since 2015
Space version, available since 2019
SA.65, militarized version, from August 2021

Microsemi

Component Clocks Positioning

Quantum CPT

Spec\Type	XPRO High-Performance Rubidium	SA.22C Precision Rubidium Oscillator	~~SA.35m~~/SA.5x Miniature Atomic Clock	Quantum™ Chip Scale Atomic Clock (CSAC)
Dimensions (cm)	12.7 x 9.2 x 3.9	7.82 x 11.2 x 2.31	5.1 x 5.1 x 1.8	1.6 x 1.39 x 0.45
Volume	456 cm³	203 cm³	< 47 cm³	< 17 cm³
Power @25° C	13 W	10 W	5 W	<120 mW
ADEV @ 1 sec	< 1E-11	<3E-11	<3E-11	<2.5E-10
Differentiator	Highest Performance	Legacy Telecom	Performance Good SWaP	Best SWaP

Microsemi's atomic clocks meet a variety of application needs

Microsemi

What Applications Benefit from the CSAC?

- Application performance needs
  - Precise time for synchronization without direct connection
  - Ability to hold precise time in absence of GPS
  - Minimize Size, Weight, and Power (SWaP)

CSAC fulfills all of the above needs

- Example Applications that benefit from CSAC :
  - Portable "man-pack" equipment for the military
  - Enhanced Military GPS Receiver
  - IED Dismounted Jammers
  - Tactical UAVs
  - Underground or underwater distributed geophysical sensors

Microsemi

CSAC Opportunities

IED Dismounted Jammers

(Backpack)

Ultra-low power consumption plus high stability make the SA.45s CSAC ideal for IED jammers small enough and light enough to be carried by soldiers.

Dismounted Military Radios (Backpack)

Use TCXO's, OCXO's today

- Sometimes too much drift for GPS-denied scenarios
- Problem will worsen with higher-bandwidth waveforms
- Excellent fit for SA.45s CSAC as these new waveforms get rolled out

Quantum

Choose QUANTUM class for best-in-class stability, size, weight and power consumption.

Marine Geophysical Sensors

Oscillators inside underwater geophysical sensors must provide highly accurate timing without GPS access. The CSAC's superior aging rate and low power consumption compared to crystal oscillators mean sensors can deliver more accurate data for longer periods or conversely, with smaller, less expensive batteries

Tactical UAV's

Payloads are always stretched on Size, Weight, and Power "SWaP"

- SA.45s CSAC helps in all three areas!
- CSAC provides excellent holdover performance in GPS-denied environments

Enhanced Military GPS Receivers

- Direct Y Acquisition after extended outage
- 3 SV navigation
- GPS Tracking loop improvements
- A/J Improvements

Microsemi

Microchip GPS-2700 disciplined oscillator

"The 10 MHz 2700 CSAC-based GPS Disciplined Oscillator has a Cesium Vapor Cell Atomic Reference Oscillator packaged in a unit much smaller than legacy products, with more than an order of magnitude in power reduction, which requires less than 2 minutes warm-up to be fully operational"

Features

- 50-channel GPS receiver
- Holdover: typically 1 µs over 24 hours at 25°C
- Ultra-low power consumption: ≤1.4W at 25°C (V_{DD} = 12V)
- Fast warm-up time: <180s at 25°C
- Industry leading 1PPS accuracy: ±15 ns to UTC RMS (1-sigma), GNSS locked
- Small footprint and low profile: only 2.5" × 3" × 0.7"
- 10 MHz, 5 MHz and 1 PPS outputs
- Stationary or Mobile mode

Applications

- Unmanned Aerial Vehicles (UAV's)
- IED Jammers—fixed, mounted and dismounted
- Radar systems
- Aircraft guidance systems
- Tactical radios
- Underwater systems using GNSS for initialization

The GPS-2700 is the pre-eminent solution for demanding mobile GNSS applications. These include military man-pack radios that require very-low-g static sensitivity, MILSATCOM terminals, avionics payloads for Unmanned Autonomous Systems (UAS), and high acceleration applications such as jet fighters. All of these applications are increasingly expected to deliver mission critical performance even in GNSS-denied environments. Other applications include network timing in stationary applications such as base-stations.

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Selective Availability Anti-Spoofing Module (**SAASM**)

A Selective Availability Anti-Spoofing Module (SAASM) is used by military Global Positioning System receivers to allow decryption of precision GPS signals, while the accuracy of civilian GPS receivers may be reduced by the United States military.

SAASM Military GPSDO

2.0 x 2.85 x 0.6 inches, less than 1.1W steady state at 12V (CSAC)
Ruggedized for Airborne, Wheeled-, Tracked-Vehicle, and Man Packs

http://jackson-labs.com/index.php/products/saasm_hd_csac_gpsdo

The JLT SAASM HD GPSDO product line combines for the first time a P(Y) capable military SAASM dual-frequency GPS receiver with a chip-scale atomic clock on a ruggedized PC board. Three variants are offered with either CSAC or DOCXO oscillators. The SAASM HD GPSDO is capable of receiving L1 and L2 GPS signals with C/A and P(Y) code, and is optimized for providing a highly accurate Position, Velocity, Time, and Frequency reference under extreme environments such as could be encountered in aircraft, tracked- and wheeled-vehicles, and man-packs.

The SAASM HD GPSDO products provide Position- and Velocity information ("PVT Assured Operation") to the user operating even in hostile environments using Anti Spoofing and Anti Jamming technology. A built-in Cesium Vapor Atomic Clock provides extremely accurate timing and frequency performance when in GPS holdover mode, and allows full operational readiness within 2 minutes after power-on, with less than 1.1W total power consumption - more than one order of magnitude less than the closest legacy solutions.

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Why a CSAC in a military GPS receiver?

https://www.baesystems.com/en-us/product/defense-advanced-gps-receiver

For soldiers who need a secure and reliable military GPS handheld receiver, the Defense Advanced GPS Receiver (DAGR) is a proven, SAASM-based handheld GPS in a rugged form factor. Unlike commercial GPS receivers, DAGR provides secure, military SAASM-based GPS in the most reliable and proven handheld form available today.

- The de facto standard military GPS receiver
- Protection from jamming and spoofing using SAASM and dual-frequency encrypted signals
- Performs as a handheld receiver or integrated into a vehicle
- ICD GPS 153-compliant interface
- Powered by four AA batteries, enables continuous operation >14 hours minimum
- Compatible with PLGR integrations

SAASM: Selective Availability Anti-Spoofing Module

GNSS receivers make a search in time and frequency to maximize correlation between the satellite-received code and the receiver-generated code. If the received signal is weak, or when the satellite code is long, the uncertainties in the receiver clock (i.e. in the receiver time and frequency) this search will require more time and processing power. The better performance of CSAC relative to quartz-based time standards reduce the code search space and hence the reacquisition time and the processing power required for GNSS positioning of the receiver. The GPS P(Y) code is the encrypted precise code intended for military users: to increase resistance to jamming, the P(Y) code is longer than the civilian coarse acquisition code C/A, and it is spread to a wider bandwidth. As a consequence, even under normal conditions, the process of correlation maximization is longer for P(Y) than for C/A. In difficult receiving conditions (poor satellite visibility) the correlation search of P(Y) can become very time-consuming, and even fail. For this reason, a better clock can be important for backpack military GNSS positioning.

Let's imagine soldiers which enter a large building and lose GNSS signals. When they emerge, they may need to know their position: a CSAC permits GNSS receivers to keep such accurate time that soldiers' equipment will remain synchronized with GNSS satellites clocks even after losing the signal for several hours, allowing a quick reacquisition of GNSS positioning.

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Why a CSAC in a military tactical radio?

THALES
Building a future we can all trust

Defence and Security | Digital Identity and Security | Aerospace | Space

TRC 9110 PR4G F@stnet VHF Handheld Radio

- Simultaneous voice, data and BFT traffic (GeoMux mode)
- Software Defined Radio capability
- Three EPM protections (FFH, FCS, Mixed mode)
- High grade encryption

FlexNet Compact Vehicular Wide Band V/UHF SDR

- V/UHF vehicular 50 W SDR
- Transceiver: 30-512 MHz
- Supporting mobile ad hoc networking waveform and associated voice, data and multimedia services
- Supporting PR4G F@stnet waveform and associated voice and data services
- Compact and easy to install, PR4G vehicular form fit

The speed with which a communication link can be established strongly depends on the frequency difference between transmitter and receiver; in frequency-hopping systems it depends also on the timing error between the transmitter's clock and the receiver's clock. The larger the time and frequency differences, the longer it takes to search and acquire a communication channel: as a consequence, the time it takes for a tactical radio to enter a net increases with its frequency and time errors. In addition, if the transmitted signal is weak, also the noise of the receiver's reference oscillator affects the acquisition time. A CSAC-based GPSDO can help decreasing the net-entry time, increase hopping rate, improve spectrum utilization, and maintain time and frequency synchronization in GPS-deprived scenarios.

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Why a CSAC in a MILSATCOM radio?

February 8, 2021

The State Department has made a determination approving a possible Foreign Military Sale to the NATO Communications and Information Agency (NCIA) of UHF SATCOM radio systems and related equipment for an estimated cost of $65million. The NCIA has requested to buy 517 AN/PRC-158 Manpack UHF SATCOM radio systems. Also included are crypto fill devices, man-portable ancillaries, vehicular ancillaries, deployed Headquarter ancillaries, power support, and operator and maintenance training and other related elements of program, technical and logistics support.

https://www.microwavejournal.com/articles/35420-nato-communications-and-information-agency-uhf-satcom-radio-systems

Portable satellite communication (SATCOM) systems involve transmission of secure TDMA (time division multiple access) waveforms that must be synchronized between satellite and terrestrial terminals. The time synchronization enables the terminal to hop to the correct frequency at the appropriate time. If many users in a group such as an infantry platoon are communicating, differing times are allocated to the radios to allow transmission on the same frequency. The data packets have guard bands that protect individual packets from overlapping: a CSAC can provide such accurate timing per radio that it reduces the guard bands, allowing more information to be transmitted. In addition, by incorporating a CSAC into the SATCOM terminal a precise time base can be preserved even in the absence of GNSS, reducing substantially network acquisition time. Presently OCXO are employed, which long warm-up time can be unacceptable in the network intensive battlefield, especially in dynamic environments involving rapid force movement.

Why a CSAC in a backpack IED Jammer?

IED jammers are devices which soak an area with EM radiation to prevent the detonation signal emitted by a phone or a radio from reaching the explosive. Lot of power is required to generate EM noise, so portable devices have limited battery duration and can secure only a limited area. As a consequence, several portable IED jammers usually work together to secure a larger area. They need to be tightly synchronized to allow predefined time slots in the signals ("look windows") where friendly force communication could still get through. Use of atomic clocks allows keeping such synchronization for longer times.

https://cbnw.co.uk/northrop-grummans-ied-jammer/

Joint counter radio-controlled improvised explosive device (RCIED) electronic warfare (JCREW) is a software-programmable jammer that provides protection from device-triggered IEDs. The units are available in both a wearable, backpack design and a mounted/fixed-site version to protect warfighters on foot, in vehicles, and in permanent structures. In June 2020, Northrop Grumman delivered all contracted JCREW LRIP dismounted systems to the US Naval Sea Systems Command (NAVSEA). In June 2020, Northrop Grumman was awarded a JCREW full-rate production contract for $96.5 million. Under this contract, the company will deliver additional dismounted systems, mounted systems and spares to NAVSEA.

https://www.leonardocompany.com/it/press-release-detail/-/detail/09-09-19-leonardo-unveils-latest-jamming-technology-for-ground-forces-to-protect-from-the-improvised-explosive-threat

Roma 09 settembre 2019: Leonardo presenta la più recente tecnologia jamming per proteggere le forze di terra dalla minaccia di ordigni improvvisati radio-controllati.

Due nuove varianti della famiglia GUARDIAN Counter-Improvised Explosive Device (C-IED) di Leonardo saranno presentate alla fiera DSEI a Londra. [...] I sistemi GUARDIAN sono in servizio e collaudati in combattimento con le forze armate di tutto il mondo, con oltre 25.000 sistemi consegnati

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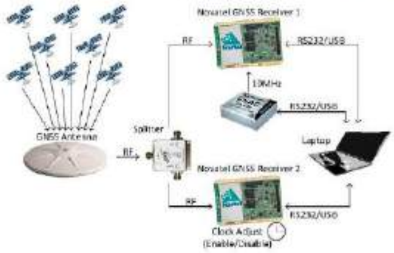
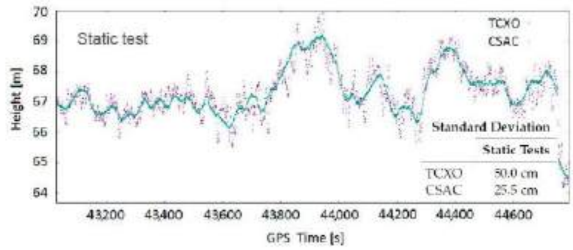
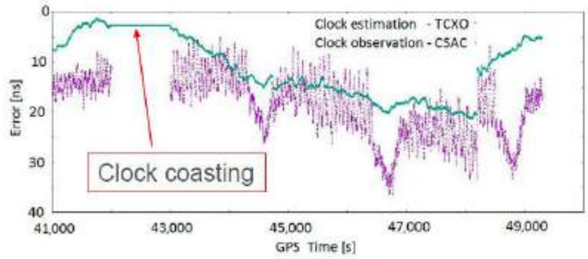
Why a CSAC for GNSS positioning and navigation?

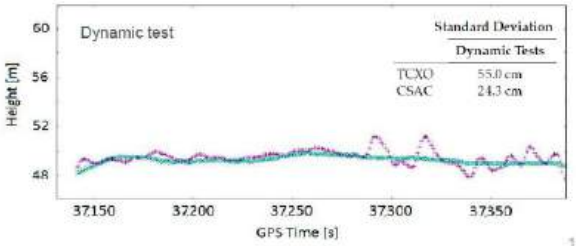
Enric Fernández et al., "CSAC Characterization and Its Impact on GNSS Clock Augmentation Performance"
Sensors, Vol. 17, No. 370, 2017 - Centre Tecnològic de Telecomunicacions de Catalunya, Spain

Replacing the internal TCXO clock of GNSS receivers with a CSAC improves the navigation solution in terms of low satellite visibility positioning accuracy, solution availability, signal recovery, and multipath mitigation. The proposed clock coasting model allows an improvement in vertical positioning precision of around 50% with only three satellites and a reduction of recovery after an holdover interval from dozens of seconds to only a few seconds.









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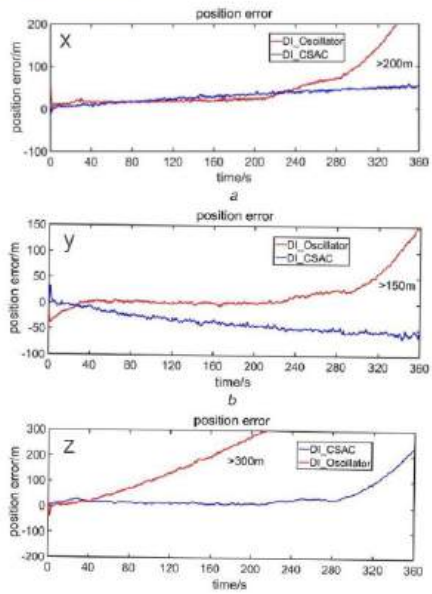
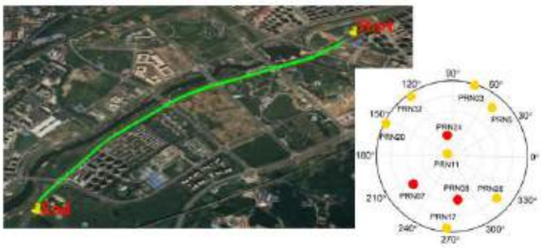
Why a CSAC in a GNSS navigation system?

Changhui Jiang et al., "Research on a chip scale atomic clock driven GNSS/SINS deeply coupled navigation system for augmented performance"
IET Radar Sonar Navig., Vol. 13, No. 2, 2019
School of Automation, Nanjing University of Science and Technology, Nanjing, People's Republic of China
Department of Remote Sensing and Photogrammetry, Finnish Geospatial Research Institute, Espoo, Finland

A GNSS receiver can determine its three-dimensional position and its clock offset and drift provided that at least four satellites are in view. Most GNSS receivers usually employ low-cost temperature compensated crystal oscillator (TXCO) as a local clock. Traditional Rb-based atomic clocks have been demonstrated to improve GNSS positioning accuracy (especially altitude) and enable positioning with only three satellites in view, but are hard to integrate into a portable GNSS receiver. A chip scale atomic clock (CSAC) provides more stable atomic frequency reference than a TCXO, and is suitable for portable devices. Comparative field tests were conducted to evaluate the performance improvement enabled by using a CSAC instead of a TXCO in a navigation system using deep-integrating vector tracking loop, in different satellite visibility scenarios. The CSAC eliminates the code tracking errors caused by local clock noise, while errors due to ionosphere delay and troposphere delay, ephemeris errors and multipath effects are modelled as clock bias variables in the state vector, and the estimated state bias is then fed back to signal to track. It is shown that a CSAC enhances the positioning performance, especially in the vertical direction and in satellite poor visibility conditions.





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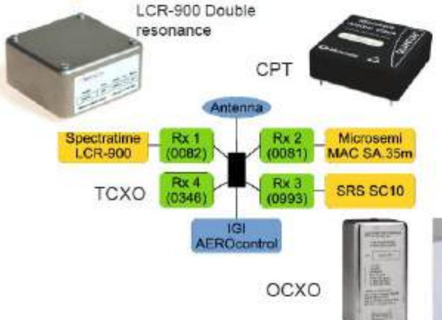
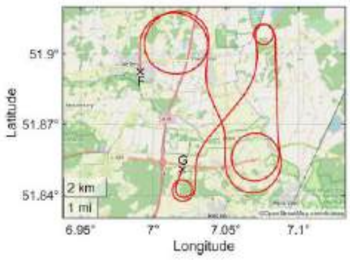
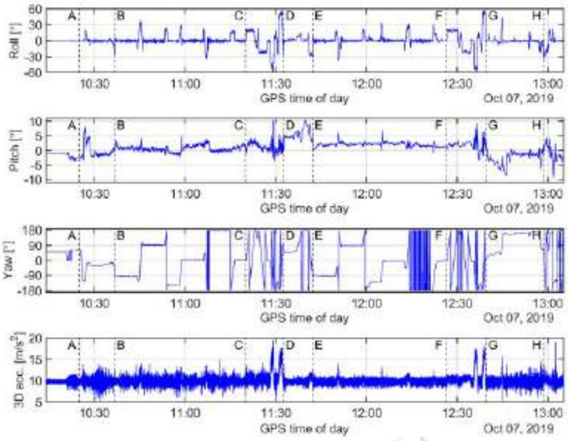
Why a CSAC in a plane?



A characterization of the frequency stability of two miniaturized rubidium clocks and of a high-precision OCXO was performed in a static laboratory environment, revealing performances in line with those declared by the manufacturers. The three oscillators were then employed in a flight experiment.





Four JAVAD GNSS receivers of type Delta TRE-G3T(H), one driven by its internal TCXO and the other three by external clocks. The IGI AEROcontrol unit (IGI2020) consists of a navigation-grade inertial measurement unit (IMU) combined with a high-precision Septentrio GNSS receiver, to compute a precise kinematic reference trajectory. The sensor pod is placed on a passively dampened mount to reduce the impact of sudden jerks, mechanical shocks and vibrations on the external oscillators.

Ankit Jain et al., "Performance of miniaturized atomic clocks in static laboratory and dynamic flight environments", GPS Solutions 25:5, 2021
Leibniz Universität Hannover, Germany; PTB, Braunschweig, Germany

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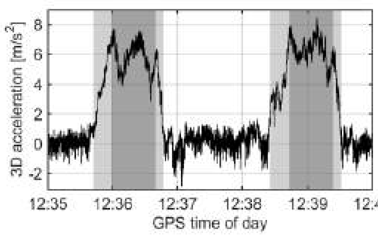
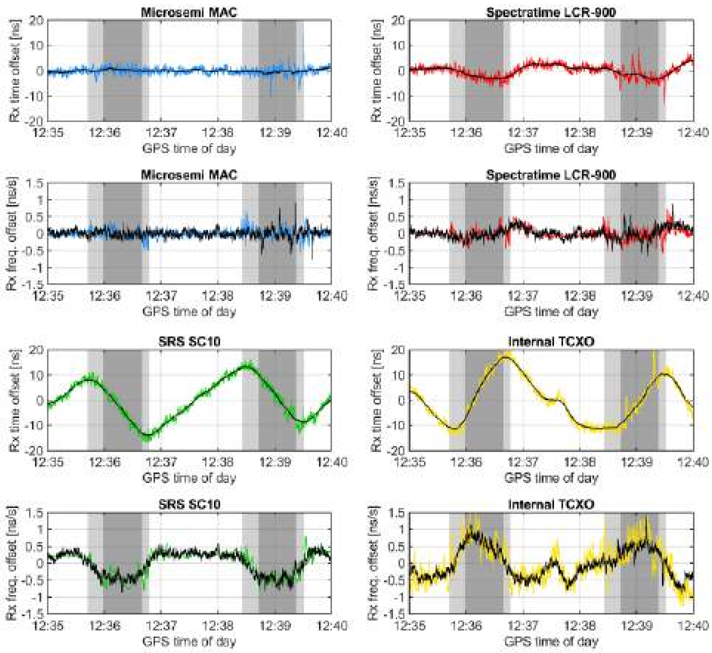
Why a CSAC in a plane?

The impact of flight turbulence at different altitudes on the clock performance is evaluated by comparison with the GNSS receivers. The frequency stability of the atomic clocks is degraded by about one order of magnitude, while the stability of the quartz oscillator is degraded by about two orders or magnitude compared to the static laboratory environment.

The impact of flight dynamics on the performance of the oscillators was also investigated. It was found that steep turn maneuvers with accelerations of up to 9 m/s² cause significant frequency shifts in the OCXO and in the receiver driven by its internal TCXO quartz oscillator. The atomic clocks do not show such behavior: they are less g-sensitive within the experienced range of accelerations, allowing receiver clock modeling to strengthen the navigation performance even in high dynamics.





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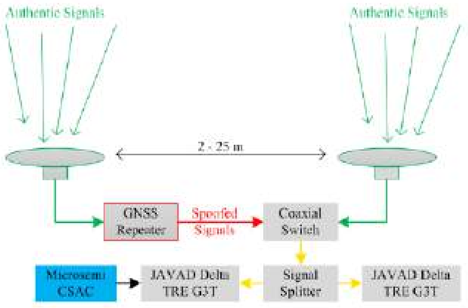
Why a CSAC in an anti-spoofing GNSS receiver?

T. Krawinkel et al., "Benefits of Chip Scale Atomic Clocks in GNSS Applications", ION 28th International Technical Meeeting of the Satellite Division, ION GNSS+2015, Tampa, FL
Leibniz Universität Hannover, Institut für Erdmessung

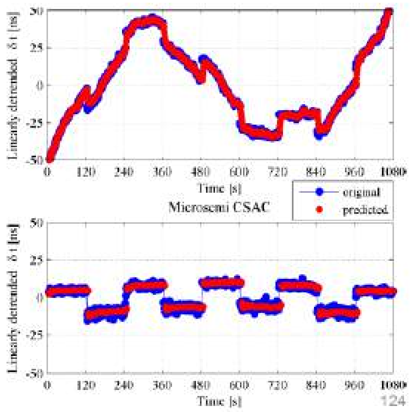
Jamming disturbs authentic GNSS signals so that a target receiver can no longer compute a navigation solution because it is not capable of acquiring them. Spoofing aims for falsifying authentic signals to mislead a target receiver in a way that it may not detect that its position and timing solution rely on non-authentic GNSS signals. Meaconing is a type of spoofing attack based on a simple replay of authentic GNSS signals in a different area. The goal of spoofing is to occupy the signal tracking loops of a target receiver, and then pull its solution away from its authentic position. In order to not be detected by the target receiver, the common delay of the spoofed signals must be smaller than the receiver's clock error estimate, so that the injected delay cannot be distinguished from the typical random frequency and time fluctuations of the oscillator driving the receiver.



Two JAVAD Delta TRE-G3T GNSS receivers, one driven by its internal quartz oscillator, and one connected to a Microsemi CSAC, both recording the same GNSS signals via a signal splitter.

JAVAD Delta-3 is a powerful and reliable receiver for high-precision navigation systems, including high dynamics systems, for machine and traffic control, as well as for high-precision surveying and geodynamics and aero-geophysics applications.

Original and predicted receiver time offset states for a receiver driven by its internal TCXO or connected to a Microsemi CSAC, respectively. The repeater antenna is located ~2 m away from the authentic antenna.



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GNSS Time and Synchronization services

Telecom networks

- Timing for satellite-based communication links, e.g. via Time Division Multiple Access (TDMA)
- Monitoring and control of services in ground networks, e.g. via Network Time Protocol (NTP)
- Synchronization of timeslots and handovers between base stations, e.g. in cellular networks

Energy networks

Phasor Measurements Units (PMU) are used as a source of Timing & Synchronization for Network Monitoring and Automatic Protection, which requires a high level of accuracy and redundancy. PMUs are deployed across remote locations of the power network, and their time references are usually based on GNSS receivers.

Financial transactions

Financial services rely on very powerful IT systems and networks requiring a high level of availability, security and reliability. GNSS is used for Synchronization and Time Stamping functions to log events or quotes in a chronologic manner.

Typical accuracy requirements: nanoseconds (10^{-9} s) for Satcom services, microseconds (10^{-6} s) for most Telecom and Energy applications, milliseconds (10^{-3} s) for finance transactions.

Global trend of continuous security improvement requires:

- GNSS authentication
- Improved robustness to interference
- Continuity of service

All distributed networks relying on GNSS timing & synchronization employ holdover local oscillators to ensure service is maintained in case the GNSS signal is temporarily lost. **Stratum levels** define for how long such local oscillators will be able to ensure service in the absence of GNSS signal.

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Clocks for network synchronization - Stratum levels

Stratum level	Stratum-1	Stratum-2	Stratum-3E	Stratum-3
Frequency accuracy	1.0×10^{-11}	1.6×10^{-8}	1.0×10^{-6}	4.6×10^{-6}
Frequency stability	N/A	1.0×10^{-10}	1.0×10^{-8}	3.7×10^{-7}
Time offset per day	0.864 µs	8.64 µs	864 µs	32 ms
Interval between cycle slips (i.e. time offset > 62.5µs)	72 days	7.2 days	104 minutes	3 minutes
Typical frequency standard	Cesium Rubidium, with periodic calibration	Rubidium MAC High Quality OCXO	CSAC OCXO	OCXO TCXO

A Stratum-1 clock is a completely autonomous source of timing, with a frequency accuracy $\Delta f/f$ better than 1×10^{-11} over any time interval. A Stratum-2 clock system tracks an input reference frequency under normal operating conditions, and provides autonomous holdover capabilities during impaired operating conditions.

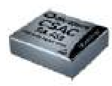
Time offset per day ≈ frequency stability x 86400s. For example, for Stratum-2: 1×10^{-10} x 86400s = 8.64×10^{-6} s = 8.64µs

A voice channel sends data at 64kbps rate, and is sampled 8000 times per second, that is every 125µs. A cycle slip occurs when the time error exceeds half this amount, that is 62.5µs. With a time offset of 8.64µs/day, the expected interval between two cycle slips is (62.5µs)/(8.64µs/day) = 7.2 days. Which are the consequences of a cycle slip?

- Voice equipment tends to re-acquire frame synchronization quickly, resulting in a pop or click. Data circuits lose some bits depending on the data rate, and on whether forward error correction is being used
- Multiplex equipment that provides add & drop services may interrupt all output trunks while a new source of synchronization is acquired. The slip causes further slips downstream, rendering a network temporarily useless.

Rb PRS10, 72-hours Stratum-1 level holdover
https://www.thinksrs.com/downloads/pdfs/catalog/PRS10c.pdf

MAC SA.5x, 48-hours sub-µs holdover
https://ww1.microchip.com/downloads/en/DeviceDoc/00003348.pdf



CSAC, few (i.e. 3-5) hours sub-µs holdover
https://www.microchip.com/en-us/about/blog/developer-insights/chip-scale-atomic-clocks-performance-part-1

Microchip GPS-2700 DO: 1µs over 24hours (at constant temperature)

Chengdu XHTF1045: ≤ 5µs over 24hours (after 1 day disciplining)

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Atomic clocks in mobile telecom networks

LTE/4G Base stations: network synchronization requires timing accuracy of 1.5µs

Timing is usually provided by a GNSS-disciplined oscillator, or by a slave clock connected to a primary standard, e.g. by using the Precision Time Protocol. In either case, holdover capabilities at the base station are required, in case a fault interrupts the connection with the GNSS or with the primary reference.

Better holdover capability by the local clock allows more leeway for time-distribution faults management

Typical holdover requirement: 1.5µs/day, easily met with a compact low-cost (1000$) Rubidium oscillator

Actually, Oven Controlled Crystal Oscillators (OCXO, 100-300$) are traditionally employed, with performance typically lower than Rb oscillators

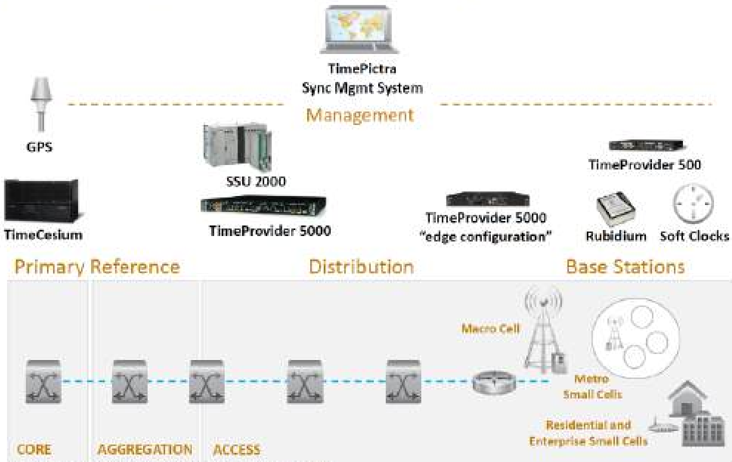

Figure by Symmetricom/Microsemi/Microchip

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Choice of clock in a NTP server

The Meinberg LANTIME M900 Network Time Protocol Timeserver can be used all around the world to synchronize even the largest networks in computer centers, industrial network infrastructures and telecom environments. The M900 is Meinbergs system platform for customized solutions and offers a wide range of possible configurations, including a wealth of choices for time and frequency inputs and outputs as well as redundancy enhancements for fail-safe synchronization needs.

	TCXO	OCXO LQ	OCXO SQ	OCXO MQ	OCXO HQ	OCXO DHQ	Rubidium (only available for 3U models)
short term stability (τ = 1 sec)	$2 \cdot 10^{-9}$	$1 \cdot 10^{-9}$	$5 \cdot 10^{-10}$	$2 \cdot 10^{-10}$	$5 \cdot 10^{-12}$	$2 \cdot 10^{-12}$	$2 \cdot 10^{-11}$
accuracy of time free run, one day	± 4.3 msec	± 865 µs	± 220 µs	± 65 µs	± 22 µs	± 4.5 µs	± 1.1 µs
accuracy of time free run, 7 days	± 128 ms	± 32 ms	± 9.2 ms	± 2.9 ms	± 1.0 ms	± 204 µs	± 34 µs
accuracy of time free run, 30 days	± 1.1 s	± 330 ms	± 120 ms	± 44 ms	± 16 ms	± 3.3 ms	± 370 µs
accuracy of time free run, one year	± 16 s	± 6.3 s	± 4.7 s	± 1.6 s	± 788 ms	± 158 ms	± 8 ms

Probably a MAC SA.5x will soon become an option, too…

https://www.microsemi.com/product-directory/embedded-clocks-frequency-references/5570-miniature-atomic-clock-mac-sa5x

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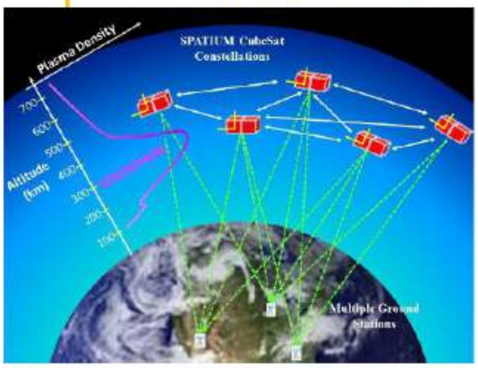
SPATIUM (Space Precision Atomic-clock Timing Utility Mission)



The signals propagating through the ionosphere interact with plasma, which causes a propagation delay. By measuring the phase difference in satellite signals between two satellites, or between satellite and ground station, the integral of the electron density distribution along the path length can be modelled using custom-designed computational modelling tools.

SPATIUM-I is the first effort in this program to validate a few key enabling technologies in orbit for a future mission, in particular the in-orbit demonstration of a COTS (Commercial Off-The-Shelf) CASC (Chip-Scale Atomic Clock) as reliable reference clock of a CubeSat mission.

Released October 2018 from JP Kibo module of ISS
https://directory.eoportal.org/web/eoportal/satellite-missions/s/spatium

SPATIUM-I is a CubeSat pathfinder mission developed jointly by Singapore NTU (Nanyang Technological University) and Japan Kyutech (Kyushu Institute of Technology). The primary scientific objective of the SPATIUM program is to develop a reliable platform that derives the three-dimensional global ionosphere plasma distribution with excellent spatial and temporal resolutions. The main objective is to model the ionosphere TEC (Total Electron Content) based on multipoint measurements of phase-shift in satellite clock signal from a constellation of CubeSats carrying a high precision timing reference.

2U CubeSat
20x10x10cm
2.66 kg

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SA.45s Space CSAC

Chip-Scale Atomic Clock

Features

- Power consumption <120 mW
- Less than 17 cc volume, 1.6" × 1.39" × 0.45"
- Radiation-tolerant: 20 krad
- SEL, SEU tested to 64 MeV·cm²/mg (contact factory for details)
- 10 MHz CMOS-compatible output
- 1PPS output and 1PPS input for synchronization
- RS-232 interface for monitoring and control
- Short-term stability (Allan Deviation) of 3.0×10^{-10} at TAU = 1 sec

Applications

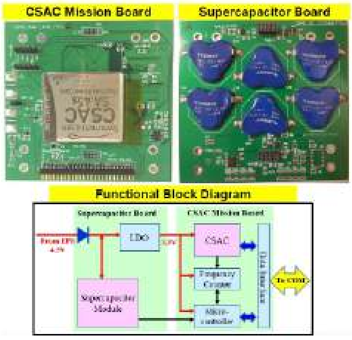
- Satellite timing and frequency control
- Satellite clock reference
- Assured Position, Navigation and Timing (PNT)
- Atomic clock accuracy
- Satellite cross-linking

Commercial since 2019

Radiation hardened electronics

Radiation hardened TCXO

SPATIUM-I



"No visible drift is observed in the count per second, indicating that the CSAC is working properly"

"SPATIUM-I is the first nanosatellite in the world to successfully demonstrate a CSAC working in Low Earth Orbit. The satellite is working as per design after more than 9 months of operation"

Chee Lap Chow et al., "Overview of Project SPATIUM – Space Precision Atomic-clock Timing Utility Mission," 33rd Annual Conference on Small Satellites, 2019

"Traditional space applications in high altitude orbits with extreme radiation conditions are not suited for the commercial electronics used in CSAC. The recent trend towards smaller satellites with lower orbits that require state of the art technology and rapid design and deployment is perfectly suited for CSAC. CSAC's precision frequency and timing keeping may be used in several in-orbit scenarios including crosslinking, earth science, data collection, and communication. CSAC and Space CSAC are already utilized in space and are deployed for critical government space missions"

A potential application of space CSACs for satellite navigation has been studies by Margaret M. Rybak et al., "Chip Scale Atomic Clock–Driven One-Way Radiometric Tracking for Low-Earth-Orbit CubeSat Navigation", Journal of spacecraft and rockets, Vol. 58, No. 1, 2021

In conventional two-way tracking, a ground station transmits a signal to a specific satellite, where it is actively or passively returned, allowing distance and velocity to be measured at the same ground station. This two-way coherent process prevents time and frequency errors in the onboard oscillator from influencing the measurements. Chip scale atomic clocks (CSACs) have the potential to provide CubeSat missions with precision timekeeping capabilities to support onboard one-way radiometric tracking, thus reducing dependence on ground support. The paper studies a baseline orbit determination scenario for a LEO CubeSat, with a timing signal uplinked from a ground station and a radiometric measurements made onboard using a CSAC timing reference.

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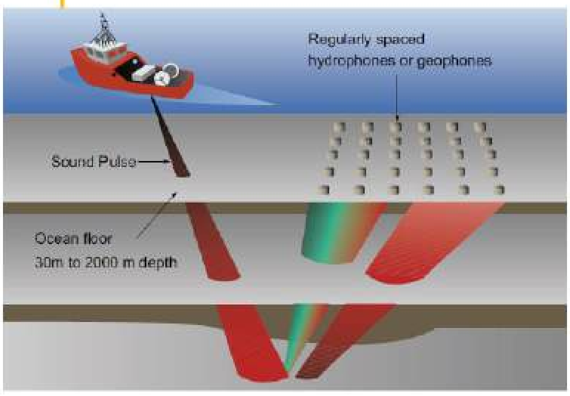
CSACs for Underwater Sensor Systems



From amplitude and <u>delay</u> of reflected sound pulses

→ Information on position and thickness of different geological layers

→ detection and assessment of hydrocarbon deposits

From Microsemi CSAC SA.45s commercial brochure:

Underwater sensors are used in seismic research, oil exploration and many other applications. Sensors designed to lie on the ocean floor will typically include a hydrophone, a geophone and a very stable clock to time-stamp the data collected by the sensor. Because GPS signals can't penetrate water, oven-controlled crystal oscillators (OCXO's) have been used to provide the accuracy needed for most time-stamping applications.

The SA.45s CSAC is a nearly ideal clock for these underwater applications. Because it consumes 1/10th to 1/30th the power of an OCXO, it requires much less battery power, resulting in smaller and lower-cost sensors, or alternatively, sensors with a much longer mission life.

The SA.45s CSAC's aging rate, which can be 1/100th of even a good OCXO, means that time-stamping errors caused by drift are greatly reduced. The SA.45s CSAC's superior temperature coefficient means that when sensors are calibrated to GPS on a warm boat deck and then dropped into cold ocean water of several hundred meters depth, the offset error produced by this temperature change is minimized.

Calibration and synchronization of clocks will be maintained during measurements missions which could last for months.

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CSACs in oil exploration

Azizur Rahman Khan et al., "Cutting-edge marine seismic technologies: some novel approaches to acquiring 3D seismic data in a complex marine environment", First Break, Vol. 35, N. 11, 2017 Saudi Aramco

Magseis Fairfield ASA, Norway - Marine Autonomous Seismic System (MASS)

It is a node-on-a-rope based Ocean Bottom Node system. Its fully automated deployment, retrieval and parallel data downloading make the survey operations and data retrieval highly efficient. Some of the features of MASS are:

- Depth rated to 3000m
- Four-component recording, one hydrophone and three component geophones
- High weight density for better coupling
- Low power consumption electronics for longer battery life up to 65 days
- **Stable CSAC clock**
- Automated battery replacement and system health check
- Compact size enables large inventory on a single vessel
- Armored cable with 20 tons breaking strength

December 17, 2018: Sales contract between Magseis ASA and China National Petroleum Corporation (CNPC) for the sale of 17,000 MASS I ocean bottom seismic nodes and four MASS Modular handling systems. First delivery is expected in late fourth quarter 2018 with last delivery expected by the end of the third quarter 2019.

https://www.offshore-energy.biz/magseis-inks-sales-contract-for-seismic-nodes-with-bgp/

Geospace Technologies, USA

The Ocean Bottom Recorder OBX-90 is designed for extended-duration seabed ocean bottom seismic data acquisition. Nodes can be deployed in depths exceeding 3,400 meters with continuous recording for up to 100 days.

- Continuous, cable-free autonomous recording
- Battery module: 100 days
- Built-in, full-resolution test generator
- Solid-state flash memory: 16 GB per channel
- **CSAC clock**

https://www.geospace.com/products/marine-exploration/obx-90/

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Conclusions on MAC and CSAC applications

Miniature atomic clocks (MACs) based on coherent population trapping (CPT) have a clear space in the commercial market. They can compete on one side with high-end OCXO, and on the other with the most compact among classical double-resonance Rb clocks – provided the selling price can be kept at around 500$. Microsemi already propose CPT-based MACs as the standard solution for mobile phone base stations.

Chip Scale Atomic Clocks (CSACs) are less stable than MAC, but they are smaller, lighter, and can be battery-operated. They were initially developed for back-pack portable military applications, and presently their high cost (several thousands $) prevents a substantial enlargement of their application space. If price can't be reduced, they are likely to remain a product for high-end military use, for some niche civilian applications (underwater and underground autonomous sensing networks), and for some space applications (synchronization of small LEO satellites constellations, CubeSat navigation, low-cost scientific payloads).

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Note: the content of slides 133 to 146 has been translated into text, and constitutes the following Section 6, Section 7, and Section 8.

6 Military applications of high-accuracy clocks

Communications Systems

In communication systems, the accuracy and stability of oscillators and clocks affect important system performance parameters, such as spectrum utilization, resistance to jamming, self-jamming avoidance, signal acquisition speed, autonomy period, and bit error rates.

Spectrum utilization

Frequency control is intimately related to frequency spectrum utilization. In both commercial and military systems, to allow for more users in a given frequency band, it is necessary to reduce the channel spacing, which requires the tightening of the frequency tolerances allowed in both the transmitters and receivers. As the number of users grew, and as technology allowed the allocation of higher frequency bands, the frequency tolerances became tighter and tighter. The noise of oscillators can also limit the capacity of communication systems: since the noise from a transmitter in one channel extends to neighbouring channels, as the number of transmitters grows, the noise can accumulate to the point where receivers can no longer function properly. This is a problem especially when users are on vibrating platforms (trucks, aircrafts…), because of vibration-induced phase noise.

Resistance to jamming

Spread spectrum techniques are widely used in military systems for communications security and for jamming rejection. Frequency hopping is a widely used spread-spectrum technique: transmitter and receiver have synchronized clocks, and hop to the same frequency at the same time. The faster the hopping time, the higher the resistance to jamming. A fast enough spectrum analyser makes it possible to jam a frequency-hopping system, since it can detect the transmission frequency and tune the jammer to this frequency before the radio hops to the next one. A good enough clock allows beating such "follower jamming" technique.

Avoid self-jamming

If there are several radio nets in the same area, self-jamming may occur when radios of neighbouring nets which operate independently occasionally hop to the same frequency at the same time. To avoid self-jamming, neighbouring nets must be synchronized and use shared codes which ensure that radios do no jump to the same frequency at the same time. Radios must therefore remain synchronized to all neighbouring nets, which requires higher clock accuracy.

Increase signal acquisition speed

The speed with which a communication link can be established strongly depends on the frequency difference between transmitter and receiver; in spread spectrum systems it depends also on the timing error between the transmitter's clock and the receiver's clock. The larger these differences, the longer it takes to search and acquire a communication channel. If the transmitted signal is weak, also the noise of the receiver's reference oscillator affects the acquisition. As a consequence, the time it takes for a tactical radio to enter a net increases with its frequency and time errors. Similarly, in a satellite communication system, the time it takes for a terminal to acquire the satellite signal depends on the terminal's frequency and time errors. In a GNSS navigation system the time to first fix strongly depends on the receiver's frequency error. During its searching phase a receiver is particularly vulnerable to interception and jamming, so minimizing acquisition time is especially important in military systems where avoiding detection is of paramount importance (e.g. submarine, special operations forces).

Increase autonomy period and radio silence interval

In order to remain undetected special operations forces must, at times, refrain from communicating over the air for extended periods. When clocks are not re-synchronized and re-tuned (i.e., frequency-recalibrated), time and frequency errors increase with increasing mission duration. The better the long-term stability of the systems oscillators, the longer the allowable autonomy period can be, and the shorter the subsequent acquisition time.

Improve digital communications

Digital communications systems must be synchronized and have the same data rates to ensure that information transfer is performed with an acceptable level of cycle "slips", which cause problems such as clicks in voice transmission, loss of encryption key in secure voice transmission, and loss of data. Shock and vibration can produce large phase deviations in oscillators, which can lead to high rates of cycle slips. Moreover, when the frequency of an oscillator is multiplied, also phase deviations get multiplied, which lead to large phase excursions which can be catastrophic to the system performance. Low-noise acceleration-insensitive oscillators are therefore very important for digital communications.

GNSS positioning and navigation

GNSS positioning and navigation exploits one-way time measurements. Since electromagnetic waves travel 0.3m per nanosecond, a timing error of e.g. a microsecond would results a positioning error of 300m. In GNSS, atomic clocks in the satellites and quartz oscillators in the receivers ensure nanosecond-level accuracies, and the resulting (worldwide) positioning accuracies are typically less than ten meters. A GNSS augmentation systems use a network of fixed ground-based reference stations to broadcast the difference between the positions indicated by the GNSS satellite system and known fixed positions in their neighbourhood. The ground stations broadcast the local difference between the measured satellite pseudoranges and the actual ranges, and users correct their pseudoranges by the same amount: such procedure ensure accuracies of centimetres, or even better. Commercial receivers contain low-cost temperature-compensated crystal oscillators (TCXO's), while military GNSS receivers typically contain more expensive oven-controlled crystal oscillators (OCXO's). The oscillator medium-term (10-1000s) stability affects the reacquisition capability, system integrity monitoring, and performance in a high jamming environment; the long-term stability affects the time-to-subsequent fix and the capability to operate with less than four satellites; the warm-up time of the oscillator affects the time to first fix; and the power requirement and the size of the oscillator affect the receiver's battery life, mission duration, and weight.

Identification-Friend-or-Foe

In modem warfare reliable identification of friend and foe is critically important, and precise timing plays a major role in solving this problem. So-called cooperative IFF systems use an interrogation/response method which employs cryptographically encoded spread spectrum signals. The interrogation signal ("challenge") sent by the identification authority and received by a friend results in a correct code being automatically sent back via a transponder located on the friendly platform. This correct code must be changed very frequently to prevent a foe from recording and transmitting it ("repeat jamming"), thereby appearing to be a friend. The code is changed at the end of what is called the code validity interval (CVI). The CVI is usually dictated by the clock accuracy achievable with low-power oscillators, such as those usually deployed on the friendly platform. A better clock on the friendly platform allows a shorter CVI and a longer autonomy period, in case it can't be resynchronized during a mission.

Electronic Warfare

The ability to locate radio emitters is important in modem warfare. One method of locating emitters is to measure the time difference of arrival of the same signal at widely separated locations. Emitter location by means of this method depends on the availability of highly accurate clocks, and on highly accurate methods of synchronizing clocks that are widely separated. The clocks of emitter locating systems must be kept synchronized to within nanoseconds in order to locate emitters with enough accuracy, and even the best available militarized atomic clocks can maintain such accuracies for periods of only a few hours without resynchronization. If GNSS signal is available, using the "GNSS common view" method of time transfer, widely separated clocks can be synchronized to the nanosecond level. A more accurate method of synchronization is "two-way time transfer" via communication satellites, which makes use of very small aperture terminals (VSAT's) and pseudonoise modems to attain subnanosecond time transfer accuracies.

Another important EW application of frequency sources is the Electronic INTelligence (ELINT) receiver, which is used to search a broad range of frequencies for signals that may be emitted by a potential adversary. The frequency source must be as noise-free as possible so as not to obscure weak incoming signals. The frequency source must also be extremely stable and accurate in order to allow accurate measurement of the incoming signal's characteristics.

Missile Guidance

A ground radar used to guide a missile is vulnerable to several countermeasures, which can be offset by placing the radar on-board the missile. This approach places much greater demands on missile components: in particular, the missile's high vibration levels will increase the reference oscillator phase noise by a wide margin. Vibration-insensitive low noise oscillators are essential for on-board radar systems.

Survivability under Radiation and High Acceleration

Survivability under ionizing radiation and high shock and vibration conditions is primarily a military (and space) requirement. Gun-hardened oscillators are required, for example, for smart munitions, air-dropped and artillery emplaced sensors, fuses, and space defence systems. Highly shock resistant oscillators have been developed which can withstand the shock of being launched from a howitzer. Radiation hardening of oscillators used to be a major issue in many military systems because a high intensity pulse of nuclear radiation stops clocks and causes large temporary and smaller permanent frequency offsets in frequency standards. With the threat of nuclear war receding, radiation hardening is less of an issue today for military systems, but remains an important issue for space systems.

Surveillance

In Doppler radars the oscillator phase noise requirements are determined primarily by the target’s velocity and by the radar frequency. Slow moving targets produce small Doppler shifts, and low phase noise close to the carrier is required. To detect fast moving targets, low noise far from the carrier is required. When a radar is on a stationary platform, the phase noise requirements can usually be met with high-quality commercial quartz-based oscillators. The problem with achieving sufficiently low phase noise occurs when the radar platform vibrates, e.g. when it is positioned in an aircraft or a missile. The vibration applies time-dependent stresses to the resonator in the oscillator which results in modulation of the output frequency. The aircraft's random vibration, thereby, degrades the phase noise, and discrete frequency vibrations (e.g., due to helicopter blade rotation) produce spectral lines which can result in false target indications.

In a coherent radar, the platform-vibration induced phase noise can reduce the probability of detection to zero. To detect stealthy targets, the radar systems must compensate for the smaller reflections by significantly increasing the transmitted power (which is often not feasible) or by significantly improving the radar receiver's sensitivity. But higher sensitivity results in receiving more clutter and false targets, and require very low-noise reference oscillators to detect targets.

A bistatic radar, in which the illuminator and receiver are widely separated, can greatly reduce the vulnerability to countermeasures such as jamming and anti-radiation weapons which can be used against monostatic radars. The transmitter can remain far from the battle area, while the receiver can remain electromagnetically silent. Timing and phase coherence problems are much more severe in bistatic than in monostatic radars, especially when the receiving platform is moving. The two reference oscillators must remain synchronized and synthonized during a mission so that the receiver knows when the transmitter emits each pulse: a combination of high-performance atomic standard on the transmitter and a CSAC at the receiving platform can be envisaged for the best results.

7 CSACs for defence systems

As miniaturized, low power devices, CSACs have military applications for high-security, ultrahigh frequency communications, jam-resistant global positioning system (GPS) receivers, sensors, and guided munitions. They are designed for low-power operations in handheld communications and personal navigation equipment, and to help spectrum-hopping radios synchronize their frequencies and access signals from navigation satellites.

Tactical military electronic systems are usually powered by batteries, and in many of these systems precise timing plays an essential role. When the system is not being used, everything except the clock can be turned off, so the power requirement of the clock is a major determinant of battery consumption. If a high performance oven-controlled crystal oscillator is employed, its power requirement may induce to switch the clock off when the system is not operated, and switch it on again only when needed. However, this implies that before the system reaches its full capabilities (i) the clock must be resynchronized and (ii) a warm-up time must be waited. It is clear that in some operational conditions these constitute major disadvantages. In the field, the benefit of lower power systems is a lighter, more mobile force, which can operate for longer periods without needing clock resynchronization or battery replenishment. In addition, the dissipation of high-power oscillators may produce infrared signatures which makes the system easier to detect by an adversary.

GNSS

GNSS receivers make a search in time and frequency to maximize correlation between the satellite-received code and the receiver-generated code. If the received signal is weak, or when the satellite code is long, the uncertainties in the receiver clock (i.e. in the receiver time and frequency) this search will require more time and processing power. The better performance of CSAC relative to quartz-based time standards reduce the code search space and hence the reacquisition time and the processing power required for GNSS positioning of the receiver. The GPS P(Y) code is the (usually encrypted) precise code intended for military users: to increase resistance to jamming, the P(Y) code is longer than the civilian coarse acquisition code C/A, and it is spread to a wider bandwidth. As a consequence, even under normal conditions, the process of correlation maximization is longer for P(Y) than for C/A. In difficult receiving conditions (poor satellite visibility) the correlation search of P(Y) can become very time-consuming, and even fail. For this reason, a better clock can be important for backpack military GNSS positioning. Let's imagine soldiers which upon entering a large building will lose GNSS signals. When they emerge, they may want to know their position to request assistance: if GNSS is unavailable, they must use maps to deduce their location. CSAC technology permits devices to keep such accurate time that soldiers' equipment will remain synchronized with GNSS satellites clocks even after losing the signal for several hours, allowing a quick reacquisition of GNSS positioning.

The improved timing will also improve GNSS jamming resistance and defence against spoofed GNSS signals, and reduce the number of satellites required for an accurate PNT solution. A CSAC timekeeper would also be useful when using electromagnetic interference to prevent telephone signals from detonating improvised explosive devices (IEDs), since it would continue working even if GPS timing signals need to be blocked. With regards to positioning precision, it is known that vertical positioning is more subject to dilution of precision, because of uncertainties in modelling atmospheric delays. A better clock which do not rely on GNSS-distributed time is expected to improve vertical positioning, especially in kinematic conditions.

MILSATCOM

Portable military satellite communication (MILSATCOM) systems can benefit from improved network acquisition via improved time uncertainty provided by the CSAC capability. The SATCOM systems involve transmission of secure TDMA (time division multiple access) waveforms that must be synchronized between satellite and terrestrial terminals. This time synchronization enables the terminal to hop to the correct frequency at the appropriate time. If many users in a group such as an infantry platoon are communicating, differing times are allocated to the radios to allow transmission on the same frequency. The data packets have guard bands that protect individual packets from overlapping: a CSAC can provide such accurate timing per radio that it reduces the guard bands, allowing twice the information to be transmitted. In addition, by incorporating a CSAC into the SATCOM terminal a precise time base can be preserved even in the absence of GNSS, reducing substantially network acquisition time. This is of great advantage in the network intensive battlefield, especially in dynamic environments involving rapid force movement, such as in comm-on-the-move, comm-on-the-halt, and comm-on-the-quickhalt operations. These CONOPS (concept of operations) are becoming increasingly important considerations in system operation as well as operational tactics, and the fast warmup time of the CSAC can provide tangible benefits to the system operation.

Networked Systems and Sensors

Timing and synchronization is a critical element of network management and operation of networked systems. The improved time base provided by CSAC can enable novel network architectures with improved robustness and bandwidth relative to traditional approaches. Further, precision time tagging of events from distributed sensors enables improved localization and data processing.

EW/IED Protection

High-energy electromagnetic jamming creates the risk of co-site interference with other RF communications, navigation, and sensing systems. Time synchronization of assets to coordinate T/R “windows” can be effective in avoiding self-jamming.

Undersea Systems

The undersea environment is inherently GPS-denied, and a number of operational advantages are enabled in marine systems as a result of improved time stability. Preserving synchronization of assets improves communications, navigation, and ranging. Similar to the benefits to ground-based GNSS systems, the CSAC can enable longer periods of autonomous operation and reduced time at surface to reacquire GNSS position.

Future GNSS satellites

In a future conflict, an adversary could harm military communications by destroying or jamming dozens of GNSS satellites. A pre-emptive measure could be launching a high number of small, inexpensive navigation satellites (nanosats) having on-board CSACs and other advanced time-keeping technologies, since a large constellation with hundreds of nanosats would be more difficult to disable.

8 Highlights from scientific literature on CSACs applications

In this Section we present some significant results taken from available scientific literature dealing with CSACs applications. The text is mostly taken from the original publication, but an attempt has been made to avoid or explain terms which would have not been widely understandable. The content has also been simplified to keep it in line with the overall technical level of the present Report.

Chip Scale Atomic Clocks: Benefits to Airborne GNSS Navigation Performance

T.S. Bruggemann et al., International Global Navigation Satellite Systems Society Symposium, 2006

In typical GPS receiver operation, the clock bias is estimated in addition to the three dimensions of position from four or more satellites. With the so-called "clock coasting" technique, the clock is "coasted" during periods of poor satellite geometry or a low number of visible satellites. The "coasting" process allows, for a stable enough oscillator with a known model error, to determine the clock bias starting from the last estimated value calculated with good geometry, i.e. with four or more satellites. With clock coasting only three satellite range measurements are required to obtain a position fix since the clock bias does not need to be solved. The application considered in this study is "clock coasting" in airborne GPS navigation. The results show that "clock coasting" with CSACs results in an improved Dilution of Precision (DOP) for up to 55 minutes under low satellite visibility or poor geometry, compared to a typical crystal oscillator.

GNSS receiver clock modeling when using high-precision oscillators and its impact on PPP

U. Weinbach, Advances in Space Research 47, 2011

Processing data from Global Navigation Satellite Systems (GNSS) always requires time synchronization between transmitter and receiver clocks. Due to the limited stability of the receiver's internal oscillator, the offset of the receiver clock with respect to the system time has to be estimated for every observation epoch or eliminated by processing differences between simultaneous observations. If, in contrast, the internal oscillator of the receiver is replaced by a stable atomic clock one can try to model the receiver clock offset, instead of estimating it on an epoch-by-epoch basis. In view of the progress made in the field of high-precision frequency standards we will investigate the technical requirements for GNSS receiver clock modeling at the carrier phase level and analyze its impact on the precision of the position estimates. Based on simulated and real GNSS data it is shown that receiver clock modeling improves the RMS of the height component of a kinematic Precise Point Positioning (PPP) by up to 70%, whereas for the static case the gain is almost negligible.

Application of Miniaturized Atomic Clocks in Kinematic GNSS Single Point Positioning

T. Krawinkel et al., European Frequency and Time Forum, 2014

Global Navigation Satellite Systems (GNSSs) are one-way ranging systems, so receiver and satellites' time scales have to be synchronized. Corrections for the satellite clock errors are made available by the system provider, e.g. via GNSS navigation message. In contrast, due to the limited long-term frequency stability of the receiver's internal quartz oscillator and its generally poor accuracy, the receiver clock error has to be estimated epoch-by-epoch together with the coordinates. This leads to very high mathematical correlations between the height component and the clock parameters: as a consequence the height component is typically determined three times worse than the horizontal component, and vulnerable to systematic effects. This situation can be improved by using more stable clocks and modelling their behaviour in a physically meaningful way instead of epoch-wise estimation. Especially kinematic single point positioning (SPP) will benefit from such receiver clock modelling (RCM) approach. Recent developments of low-priced, low power consuming miniaturized atomic clocks (MACs) and Chip Scale Atomic Clocks (CSACs), allow for usage in kinematic GNSS applications. Replacing the internal oscillator by one of these much more stable external frequency standards opens up the possibility of RCM. By investigating the performance of three different MACs (Jackson Labs LN CSAC, Symmetricom SA.45s CSAC, and Stanford Research Systems PRS10) we show that compared to the non-modelled case significant smoothing of the clock estimates and improvements of the up-coordinate precision can be seen: modelling the process receiver clock noise in pseudo-kinematic code-based GNSS SPP can reduce the estimated up-coordinates' root mean squared error up to 26.2%.

Reducing the jitters: How a chip-scale atomic clock can help mitigate broadband interference

Fang Cheng Chan et al., GPS World, May 2014

Currently installed Local Area Augmentation System (LAAS) ground receivers experience of disruptions in GPS signal tracking because the illegal use of jammers in vehicles driving by the ground installations. Popular personal privacy devices (PPDs) found in the market typically interfere with the GPS signal by using wideband signal jammers, to which GPS signal is very vulnerable. Indeed, GPS receivers use wide-bandwidth tracking loops to accommodate the change in signal frequencies and phases caused by user dynamics, and wide bandwidths allow more noise to enter into the tracking loop. As a consequence, continuity and integrity of the Ground Based Augmentation System (GBAS) can be severely degraded by wideband jammers. A general approach to mitigate wideband interference is to reduce the tracking loop bandwidth: however, a receiver employing a temperature controlled crystal oscillator (TCXO) needs to maintain a large enough loop bandwidth to track the dynamics of the clock itself. The poor stability of TCXO thus fundamentally limits the potential to reduce the tracking loop bandwidth. This limitation becomes much less constraining if an atomic clock is used at the receiver in a GBAS ground station. High frequency-stability atomic clocks naturally reduce the minimum required bandwidth for tracking clock errors, therefore reducing the system sensibility to wideband jamming. The limitations of reducing PLL tracking loop bandwidths using different qualities of receiver clocks have been analysed and compared with the experimental results. Good agreement between theoretical prediction and experimental data has been obtained for the tracking loop performance of a TCXO, while the tracking performance of a SA.45s CSAC was not as good as the theoretical prediction, which suggests that the SA.45s CSAC clock error model miss-represents the available commercial products.

A study on integrity improvement of GBAS ground subsystem using CSACs

Takayuki Yoshihara et al., ION ITM 2015, January 2015

GBAS (Ground-Based Augmentation System) is a system based on local differential correction technique to support aircraft precision approach, and its CAT-III approach service requires extremely high safety. A research prototype for a GBAS ground subsystem has been developed and operated in New Ishigaki airport to collect measurement data, with the aim of validating its safety requirements against impacts of ionospheric disturbance due to “plasma bubble”, which frequently occurs between sunset and midnight in the low magnetic latitude around spring and autumn. The prototype has been designed to optionally accept an external clock signal from a CSAC (Chip Scale Atomic Clock) as a stable reference. The study will perform a statistical analysis to investigate the prototype performance in the presence of ionospheric anomalies, and other sources of ranging errors such as obstacles leading to multipath interference.

Characterization of Chip-Scale Atomic Clock for GNSS navigation solutions

D. Calero et al., International Association of Institutes of Navigation World Congress, 2015

This work focuses on the characterization of CSACs to be used instead of TCXO in GNSS receivers. Its main conclusion is that with respect to a TCXO, the use of a CSAC shortens the time needed to re-lock satellites when signal outages longer than 1 minute occur. However, the behaviour of the CSAC is noticeably affected by variations in temperature.

Benefits of Chip Scale Atomic Clocks in GNSS Applications

T. Krawinkel et al., 28th International Technical Meeting of the Satellite Division of the Institute of Navigation, 2015

A receiver CSAC model is developed for GNSS navigation, demonstrating a decrease in the noise of the up-coordinate by up to 58% and a reliability enhancement which leads to a robust positioning even in case of partial satellite outages, leading to only three satellites in view. The benefits of a CSAC in spoofing detection are also investigated. Jamming and spoofing attacks introduce delays which can be detected if the receiver clock behavior is predictable: consequently, an accurate clock model allows warning the user about an attack. Whereas jamming intends to disturb authentic GNSS signals so that a target receiver can no longer compute a navigation solution because it is not capable of tracking and/or acquiring authentic GNSS signals, spoofing falsifies the authentic signals to mislead a target receiver in a way that it may not detect that its position and timing solution rely on non-authentic GNSS signals. A common kind of spoofing is the so-called meaconing attack, which is based on the interception of navigation signals by means of a commercial GNSS repeater and it rebroadcasting in a different area, typically with higher power than the original signal.

An important role in GNSS jamming and spoofing detection and mitigation is assigned to the receiver clock, and the benefits of a highly stable oscillator are widely recognized. The general goal of a spoofing attack is to occupy the signal tracking loops of a target receiver, and then pull its navigation solution away from its authentic position. In order to not be detected by the target receiver, the common delay of the spoofed signals must be absorbed by the receiver's clock error estimate, meaning that the injected delay has to be so small that it cannot be separated from the typical time and frequency random fluctuations of the receiver oscillator. It has been demonstrated that the use of a CSACs instead of the receiver's standard internal oscillator enhances the detectability of a spoofing attack, especially in its early stages.

CSAC Characterization and Its Impact on GNSS Clock Augmentation Performance

Enric Fernández et al., Sensors, Vol. 7, N. 2, 2017

Replacing the internal TCXO clock of GNSS receivers with a CSAC improves the navigation solution in terms of low satellite visibility, positioning accuracy, solution availability, signal recovery, holdover, multipath and jamming mitigation and spoofing attack detection. A CSAC clock allows GNSS positioning even when only three satellites are available, but it has almost no impact in planimetry performance neither for static nor dynamic trajectories, while it has a relevant impact on the performance of height estimations in both scenarios. Indeed, by adding a precise clock to a GNSS receiver, it is possible to obtain position with no need to estimate the receiver clock errors for a long period (<10,000 s) by using the clock coasting estimation method allowing the determination of a positioning solution with only three satellites, while that the combined use of CSAC and GNSS helps mitigate multipath effects, improving the quality of the navigation solution in non-favourable conditions such as poor satellite availability or difficult scenarios such as urban canyons and forests.

Research on a CSAC-driven GNSS/SINS navigation system for augmented performance

Changhui Jiang et al., IET Radar, Sonar & Navigation, 2019

This study investigates a GNSS strap-down deep-integrated (DI) inertial navigation system (INS), and evaluates the clock impact through comparative field driving tests performed both with a SA.45s CSAC and with a TXCO. Both scalar tracking loop (in which GNSS tracks each satellite signal in one channel separately) and vector tracking loop (where all of the satellite signals are simultaneously tracked and processed in one navigation filter) are investigated. With respect to the TXCO, the CSAC effectively suppress code tracking errors caused by local clock noise both in vector tracking loop and in scalar tracking loop. With vector tracking, the effects of ionosphere and troposphere delay, ephemeris errors and multipath errors can be modelled as clock bias variables, and the estimated state bias is fed back to the signal track loop to improve positioning. Under the condition that less than 4 satellites are available, the CASC effectively slows down the divergence of the position errors.

Performance of miniaturized atomic clocks in static laboratory and dynamic flight environments

A. Jain et al., GPS Solutions, Vol. 25, N. 5, 2021

Miniaturized atomic clocks with high frequency stability as local oscillators in global navigation satellite system (GNSS) receivers promise to improve real-time kinematic applications. Such oscillators have been investigated regarding their overall technical applicability, i.e., transportability, and performance in dynamic environments. The short-term frequency stability of these clocks is usually specified by the manufacturer, being valid for stationary applications. Since the performance of most oscillators is likely degraded in dynamic conditions, various oscillators are tested to find the limits of receiver clock modelling in dynamic cases and consequently derive adequate stochastic models to be used in navigation. We present the performance of three different oscillators for static and dynamic applications. The time and frequency offsets of the oscillators are characterized with regard to the flight dynamics recorded by a navigation-grade inertial measurement unit. The impact of flight turbulence at different altitudes could be seen from the noise levels of the estimated clock frequency offsets of the GNSS receivers connected to the oscillators. The frequency stability of the Microsemi MAC and the Spectratime LCR-900 is degraded by about one order of magnitude, while the stability of the SRS SC10 is degraded by about two orders or magnitude compared to the static laboratory environment. Also, the impact of flight dynamics on the performance of the oscillators was investigated. It was found that steep turn manoeuvres with accelerations of up to 9 m/s2 cause significant frequency shifts: the two quartz oscillators show a significant g-sensitivity, while the rubidium clocks are less sensitive, thus enabling receiver clock modelling and strengthening of the navigation performance even in high dynamics.

CSAC–Driven One-Way Radiometric Tracking for Low-Earth-Orbit CubeSat Navigation

Margaret M. Rybak et al., Journal of spacecraft and rockets, Vol. 58, No. 1, 2021

In conventional two-way tracking, a ground station transmits a signal to a specific satellite, where it is actively or passively returned, allowing distance and velocity (via Doppler effect) to be measured at the same ground station. This two-way coherent process prevents time and frequency errors in the onboard oscillator from influencing the measurements. Ground stations like the Deep Space Network (DSN) use high stability hydrogen maser clocks as their frequency standard, which are continuously calibrated and exhibit stabilities of approximately 2×10−15 per day. If sufficiently stable timing were available onboard, a satellite or spacecraft could measure its own range and Doppler shift using an uplinked signal from a ground station, and subsequently compute orbit determination solutions onboard. This configuration would significantly reduce a mission’s dependence on ground support. In this one-way configuration the difference between the spacecraft and ground station clocks directly affects the accuracy. Thus, the quality of clock that can be carried onboard a satellite is the limiting factor in one-way ranging performance. Space-rated CSACs have the potential to provide CubeSat missions with moderate stability of ~2.8 × 10−11 at one day, low cost, and SWaP. The goal of our study is to quantify the orbit and timing performance achievable using CSACs to make one-way tracking measurements onboard LEO CubeSats.

9 Conclusions

The exploitation of coherent population trapping to build atomic frequency standards has until now yielded two different families of products: miniature atomic clocks and chip scale atomic clocks. The boundary between them is determined by frequency stability performance, sensitivity to environmental disturbances, weight, size, and above all power consumption. Although less stable, CSACs are smaller, lighter, and much less power hungry than MACs, so that they can be battery-operated and are suitable for backpack operations. These properties make them the product of choice for several military man-portable applications. However, because of its technological complexity and its final cost, it is doubtful that a CSAC can be developed and survive as a commercial product in the absence of publicly-supported R&D programs and of a large enough assured market. Conversely, MACs can now be manufactured at a cost that make them already competitive for several industrial applications with high-quality quartz based systems on the one side, and with the most compact and cheapest legacy atomic rubidium clocks on the other.

The rationale for a public support action on CSACs can be justified by the need of securing technological autonomy in an area were strategic dependence would be better avoided. It is known that although CSACs manufactured in the USA are presently not subject to ITAR export restrictions, certain related enabling technologies (notably Vertical Cavity Surface Emitting Lasers – VCSELs - with the suitable frequency stability properties) which have been developed with DARPA funding have not been made available to commercial players from third countries. China has several governmental “Key Laboratories” and public research institutions working on CSACs and related critical technologies, and the UK has a public-sponsored miniature atomic clock development program which has recently “demonstrated UK sovereign capability in VCSELs and delivered single–mode VCSEL with ultra-high mode-stability”. Japan has a CSAC prototype which requires half the power required by the best commercially-available product, and a CMOS electronics suitable for space LEO applications. In other terms, several countries have now reached or are close to reach autonomous manufacturing capabilities of CSACs, and are clearly aiming to close their technological gap with the USA.

Presently, no EU-27 clock manufacturer offers a CSAC suitable for backpack military applications. In Europe, several advanced prototypes developed by academic groups with industrial collaborations have reached a TRL of 4 to 5, and are very close to mass manufacturability. As emerged during the discussions with the audience, the challenges on the path towards a commercial product, more than by technical difficulties, seem to be determined by the uncertainties about the market size it can aim at. In the EU, procurement of military equipment is still hindered by internal border attrition, since developers of military equipment are bounded by national rules and therefore refer primarily to domestic markets. There is a clear case for EU institutions to try and smooth inter-state dialogue and reach an assessment of the size of the market a CSAC can reach inside the EU as a whole. A supporting action aimed at establishing the right forum for exchange of information between relevant European institutions (e.g. European Commission, European Defence Agency), national governments, and manufacturers of military equipment which could make use of an EU-manufactured CSAC is therefore needed to raise the interest of atomic clock producers towards a device which could contribute to EU strategic autonomy.

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List of acronyms

CBT Caesium Beam Tube

CPT Coherent Population Trapping

CSAC Chip Scale Atomic Clock

DARPA Defense Advanced Research Projects Agency

DG CNECT Directorate-General for Communications Networks, Content and Technology

DG DEFIS Directorate-General for Defence Industry and Space

DG DIGIT Directorate-General for Informatics

DG JRC Directorate-General Joint Research Center

DG MOVE Directorate-General for Mobility and Transport

EDA European Defence Agency

EISMEA European Innovation Council and SME Executive Agency

ESA European Space Agency

EUSPA EU Agency for the Space Programme

GNSS Global Navigation Satellite System

GPS Global Positioning System

HaDEA European Health and Digital Executive Agency

LEO Low Earth Orbit

MAC Miniature Atomic Clock

OCXO Oven Controlled Crystal Oscillator

OPC Optical Pump Caesium

PHM Passive Hydrogen Maser

REA Research Executive Agency

RFS Rubidium Frequency Standard

SWaP Size Weight and Power

TCXO Temperature Controlled Crystal Oscillator

VCSEL Vertical Cavity Surface Emitting Laser

VCXO Voltage Controlled Crystal Oscillator

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