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JRC TECHNICAL REPORT

Next-Generation Chip Scale Atomic Clocks

Assessing the emerging physical platforms: microwave transitions in cold atoms and in trapped ions, and optical transitions in warm vapours

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It is a pleasure to acknowledge the help received by Kristina Zamudio, Stella Strataki and Gilles Lequeux at DG DEFIS for the organization of these on-line presentations on Next-Generation Chip Scale Atomic Clocks. I am also grateful to the audience for the interest expressed during the talks, and to my JRC colleague Adam Lewis for several useful suggestions on the presentations slides and on this Report.

Executive summary

Chip-scale atomic clocks (CSACs) were first made commercially available in 2011, as the result of more than 20 years of continuous support by the USA Defense Advanced Research Projects Agency (DARPA). As detailed in a previous Technical Report, the typical applications of CSACs can be found in battery-operated backpack equipment for the defence sector (e.g. man-portable military radios, jammers, GNSS receivers, etc.), although lately the commercialization of devices with radiation-hardened electronics has opened the possibility of deployment in space, e.g. to synchronize large constellations of LEO nano- or micro-satellites. CSACs are based on microwave transitions in warm vapours of alkali metals, and exploits a phenomenon called coherent population trapping (CPT) which allows eliminating the microwave cavity, thus ensuring a very favourable size, weight and power (SWaP) footprint. The drawback is a relatively poor long-term stability, which limits the application domain of these devices and prevents their use as primary frequency standards. Also the high cost (in the range of $ thousands, as compared with $ hundreds for conventional compact Rubidium clocks, which typically perform better) means that CSACs are used in applications which dictate the use of an extremely small, lightweight, and battery-operated device.

Even before the commercialization of current-generation CSACs, a targeted effort was initiated by DARPA to support the development of devices with similar SWaP properties but a long-term stability improved by approximately three orders of magnitude. Such Next Generation CSACs (NG-CSACs) must leverage completely different physical phenomena, since present-day commercial devices can not lead to the desired performance level by technological improvements only. Several different physical platforms are being explored, and have reached different level of maturity. A first relatively low-risk approach consists in the miniaturization of mercury ions clocks, which exploit a microwave transition in electromagnetically-confined ions and have more than 30 years of heritage. A more ambitious approach make use of the same CPT effect employed in current-generation devices, but exploits laser-cooled atoms instead of warm vapours to avoid the long-term instabilities of the atomic cell. The most challenging efforts involve using optical transitions in warm atomic or molecular vapours, with Doppler broadening suppression achieved by nonlinear optical phenomena such as two photon absorption or coherent modulation transfer.

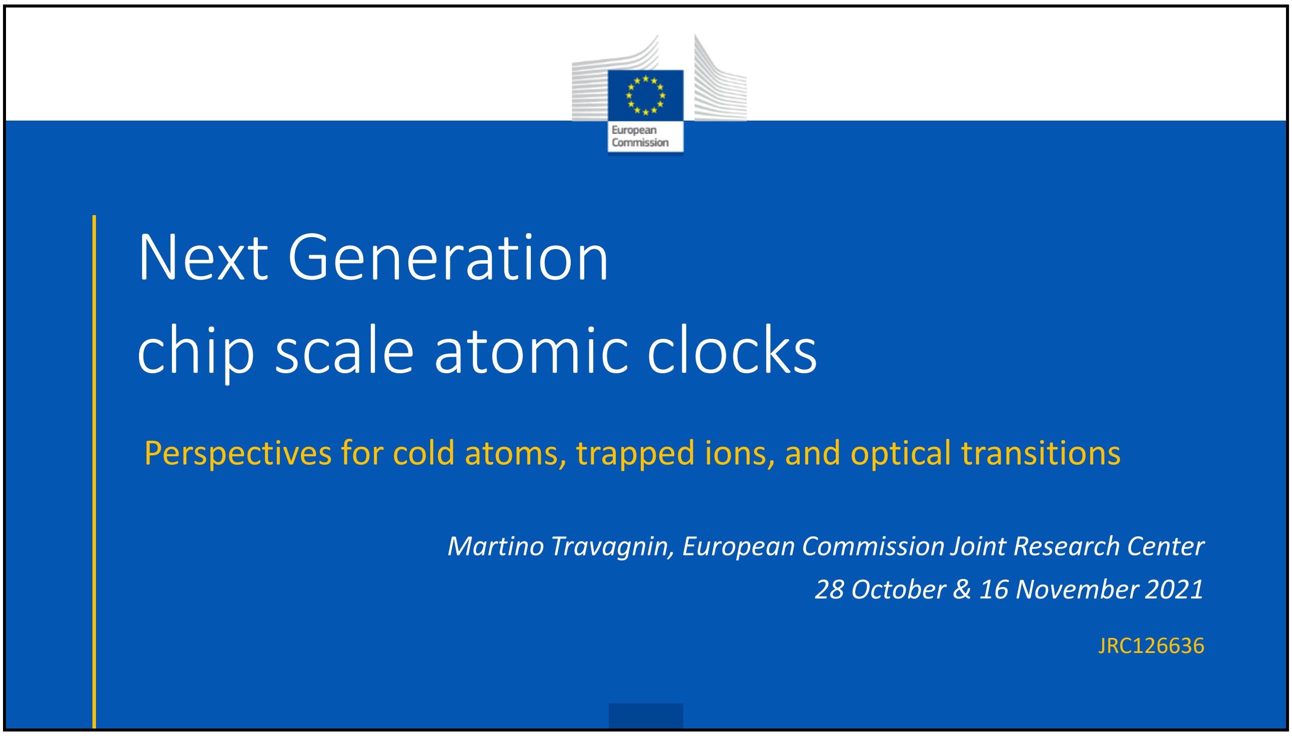
A survey of the available literature allows to assess the TRL reached by these different research line, and clearly shows that the USA is at the leading edge of their development. In particular, a chip-scale clock derived from the miniaturization of the mercury-ion Deep Space Atomic Clock launched in space in 2019 could reach the fully-integrated prototype stage in the next five years. Despite outstanding research capabilities, Europe seems presently to be lacking a focused and coordinated effort for the development of NG-CSACs. The EU is therefore running the risk of one day finding itself in the same position it is now with regards to CSACs, where it has to rely on imported devices, despite having developed very promising prototypes. The industrial production and the commercialization of CSACs constitutes indeed for manufactures a considerable investment risk, given the high cost of the technologies involved and the peculiarities of their main market, i.e. the defence one. The overall situation clearly calls for a coordinated EU support action, given the relevance that these devices will have for the EU strategic autonomy.

Abstract

Following the four talks given in April/May 2021 on Chip Scale Atomic Clocks and summarized in a JRC Technical Report (1), we here relate two presentations devoted to Next-Generation Chip Scale Atomic Clocks (NG-CSACs) organized and chaired by DG DEFIS Unit B.2 and given in October/November 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 (2).

The driving motivation for the development of a novel CSAC with a stability performance significantly improved with respect to the available products is to obtain a miniature primary frequency standard, that is a device with a frequency stability similar to that of a Caesium beam tube and the typical size, weight and power footprints of a chip-scale atomic clock. Such a device would have an application space much wider than the one attainable by CSACs of the current generation, which because of their high cost and their relatively poor long term stability can be regarded as niche items primarily aimed at high-end backpack military applications.

In this report we provide an overview of the research efforts for the development of NG-CSACs: we describe the different physical platforms which are being investigated, analysing the technical bottlenecks and assessing their technological readiness level. Continuous progress both in core and in enabling technologies is taking place, driven in particular by the US DARPA support over the last ten years, and physical packages with very promising properties are being developed. However, a fully-integrated commercially viable NG-CSAC has yet to emerge.



European Commission

Next Generation

chip scale atomic clocks

Perspectives for cold atoms, trapped ions, and optical transitions

Martino Travagnin, European Commission Joint Research Center

28 October & 16 November 2021

JRC126636

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(1) M. Travagnin, "Chip-Scale Atomic Clocks: physics, technologies, and applications", JRC Technical Report EUR 30790 EN, 2021 https://publications.jrc.ec.europa.eu/repository/handle/JRC125394

(2) 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

Currently available miniature atomic clocks (MACs) and chip scale atomic clocks (CSACs) exploit coherent population trapping in warm alkali metal vapour, in a highly integrated package ([3]). The main difference among MACs and CSACs is that the first have better stability performance but a larger size, weight and power footprint. A CSAC can be battery-operated, but its high cost limits the application space mostly to backpack man-portable military devices. A handful of commercial CSACs products (manufactured in the US and in China) do exist, and some advanced prototypes have been developed (in the EU, Switzerland, United Kingdom and Japan), which market future is rather uncertain in the absence of a significant public support (e.g. in the form of procurement for military equipment). The main motivation for a NG-CSAC is that a miniature primary frequency standard would have a large application space and market uptake, which would allow scaling down manufacturing costs and thus guarantee a successful commercial device.

It has been long recognized that technological evolution of existing CSACs and MACs will not lead to substantially better long term stability while maintaining low size & power footprints: different physics must be exploited to obtain a Next-Generation Chip Scale Atomic Clock with significantly better long-term stability performance. We here provide an overview on applied research on this field, within these flexible boundaries:

- Reached the experimental proof of concept stage, i.e. Technological Readiness Level of at least 3
- Demonstrated physical package < 1,000cm^3 (1L)
- Potential for further miniaturization and battery operation
- Potential for performance similar to Caesium Beam Tube primary standards

A review of the research activities allows positioning the NG-CSAC candidates in the atomic clocks landscape, and identifying the physical principles which can be leveraged for their development. The available scientific literature shows that a substantial improvement in long-term stability can be obtained in a compact device by using microwave transitions in cold atoms or in trapped ions, or optical transition with sub-Doppler properties in warm atomic vapours. Three different lines of work seem therefore the most promising:

1. Microwave transitions in laser-cooled alkali metals (Rb, Cs)
    - Double Optical-Microwave Resonance
    - Coherent Population Trapping (CPT)
2. Line II: Microwave transition in double-resonance trapped ions
    - $^{171}Yb^+$, laser pumped
    - $^{199}Hg^+$, lamp pumped
3. Line III: Optical transitions in warm atomic/molecular vapours
    - Modulation Transfer spectroscopy (I_2, Rb)
    - Two Photon Transition (Rb)

We review the progress achieved in these three areas, and try to establish the technological readiness level which has been reached. Trapped-ion systems have reached the highest maturity, although considerable technological development is still needed to miniaturize and integrate all the necessary components. Due to several technical constraints, CPT in laser-cooled atoms has yet to demonstrate its full potential, while system based on optical transitions need the development of several critical micro-fabricated components to yield a suitably compact system.

The overall conclusion is that a commercially viable NG-CSAC has yet to emerge. Several physical platforms are being investigated which present distinctive properties, and it is still impossible to assess whether one among them will yield a clear winner. A probable outcome is that different devices exploiting a variety of working principles will be developed in the next three to ten years, to suit applications requiring different properties and performance levels. Still, the development of some of the required manufacturing technologies, as well as the miniaturization and the integration of several customized components still constitutes an open challenge.

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[3] The present Report is to be considered as a supplement to M. Travagnin, "Chip-Scale Atomic Clocks: physics, technologies, and applications", JRC Technical Report EUR 30790 EN, 2021, https://publications.jrc.ec.europa.eu/repository/handle/JRC125394, to which the reader is referred for an essential background.

Historical Note

In November 2021 Robert Lutwak from Microchip contacted the author to provide some remarks on the JRC Technical Report EUR 30790 EN, “Chip-Scale Atomic Clocks: physics, technologies, and applications”, published in 2021. I gratefully acknowledge the additional information he offered on the history of CSACs development, and take the chance to share it with a wider audience.

1) DARPA actually began investing in CSACs in 1990, primarily at Westinghouse Corporation. The subsequent 2000 DARPA program, which was ultimately successful, was a reboot of the 1990 program. The Westinghouse team, led by Peter Chantry and Irv Lieberman, did some of the earliest and best work characterizing the physics of small vapour cells. On this project they also developed the first single-transverse-mode VCSEL at MODE Corporation (now a division of Emcore). This work, through the 1990's, did not lead to a product, primarily because the microwave electronics did not become available until the cell phone industry brought them to bear 10 years later. Nevertheless, the early contributions of the Westinghouse teams and of Lt. Col. Beth Kaspar, the original DARPA Program Manager, have been crucial for the successive developments.

2) Symmetricom (then Datum) was initially funded by the US Army to review the Westinghouse effort in 1998 and entered into contract with DARPA in 2000. The collaboration among Draper, Sandia, and Symmetricom allowed fundamental work for the development of CSACs to be performed: in particular, John Leblanc at Draper developed the first anodically-bonded MEMS vapour cells, Mark Mescher, also at Draper, developed the polyimide thermomechanical suspension system, Darwin Serkland, at Sandia, developed the first high-efficiency narrow-linewidth VCSELs at the Caesium D1 line, and Robert Lutwak’s team at Symmetricom developed the electronics and algorithms and demonstrated the first fully-autonomous CSAC.

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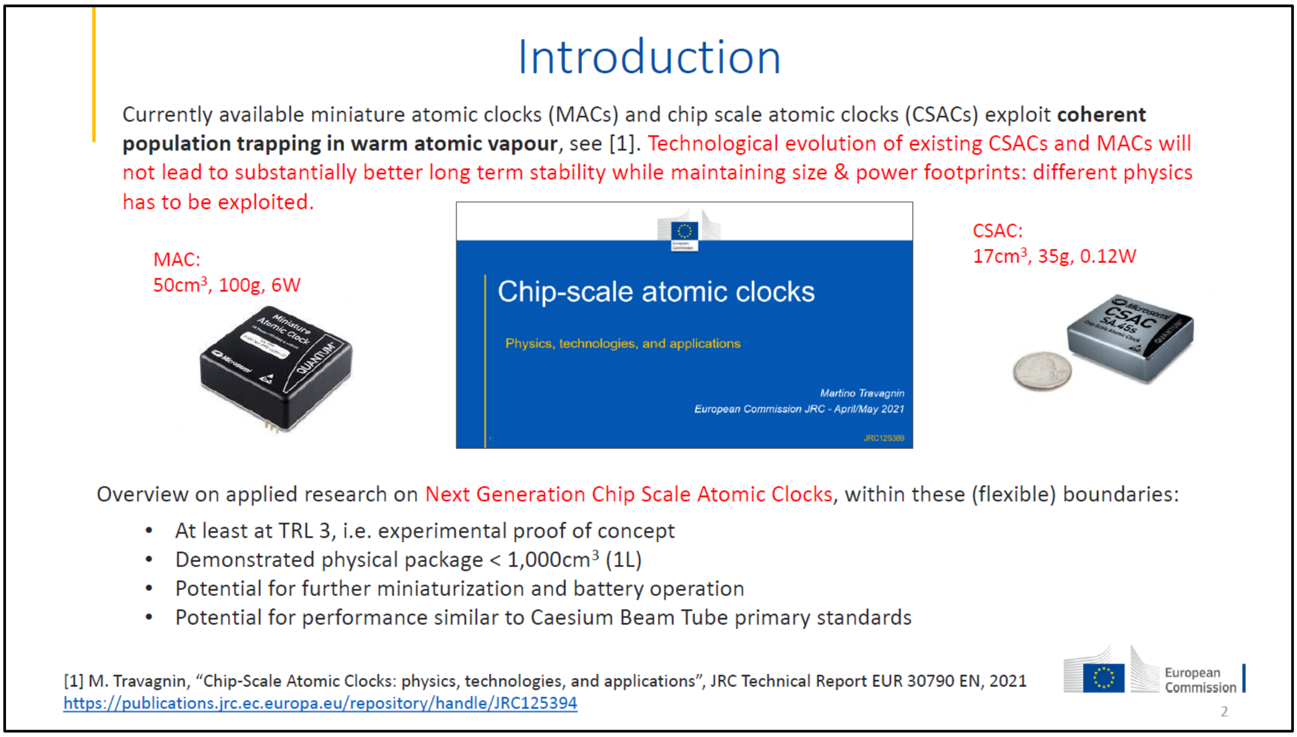
2 Next-Generation Chip Scale Atomic Clocks

2.1 Drivers, programmes, and technical overview

In this Section we explain the motivations that drive the quest for NG-CSACs, we present the main support programmes sponsored by DARPA, and to exemplify their outcomes we give a quick preview of the main actions undertaken at Sandia, so that the reader can appreciate how challenging the final target is. We then show the place of NG-CSACs in the overall panorama of existing and emerging atomic frequency standard, by presenting a compact list of clocks which are being developed and are expected to become available in the next 5 to 10 years. This work allows identifying the three most promising research lines along which the development of NG-CSACs is progressing, namely microwave transition in laser-cooled alkali metals, microwave transition in trapped ions, and optical transition in warm atomic and molecular vapours. Some essential nomenclature is presented as a final step, to explain the meaning of terms such as double resonance, coherent population trapping, Rabi and Ramsey interrogation schemes, which are an essential pre-requisite to understand the material of the following Sections.

A reader looking for a basic introduction on CSACs is direct to the NIST webpage[4], while a more scientific treatment is given by [Knappe 2007][5]; an updated review on the emerging frequency standard is provided by [Schmittberger 2021][6].



Introduction

Currently available miniature atomic clocks (MACs) and chip scale atomic clocks (CSACs) exploit **coherent population trapping in warm atomic vapour**, see [1]. Technological evolution of existing CSACs and MACs will not lead to substantially better long term stability while maintaining size & power footprints: different physics has to be exploited.

MAC:
50cm^3, 100g, 6W

Chip-scale atomic clocks

Physics, technologies, and applications

Martino Travagnin
European Commission JRC - April/May 2021

JRC125389

CSAC:
17cm^3, 35g, 0.12W

Overview on applied research on Next Generation Chip Scale Atomic Clocks, within these (flexible) boundaries:

- At least at TRL 3, i.e. experimental proof of concept
- Demonstrated physical package < 1,000cm^3 (1L)
- Potential for further miniaturization and battery operation
- Potential for performance similar to Caesium Beam Tube primary standards

[1] M. Travagnin, "Chip-Scale Atomic Clocks: physics, technologies, and applications", JRC Technical Report EUR 30790 EN, 2021
https://publications.jrc.ec.europa.eu/repository/handle/JRC125394

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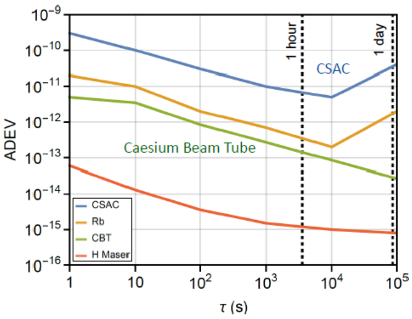
[4] https://www.nist.gov/noac/success-story-chip-scale-atomic-clock

[5] https://tsapps.nist.gov/publication/get_pdf.cfm?pub_id=50424

[6] https://ieeexplore.ieee.org/document/9316270

Motivation: why going beyond current CSACs?

CSAC-MAC size & power range: 10 to 50 cm^3, 20 to 100 grams, 100mW to 5W
Smartphone: 100cm^3, 150 grams, 2.5W
Smartwatch: 20cm^3, 40 grams, 100mW



Main CSACs limitations:

- long-term stability: Allan Deviation ADEV > 10^{-11} for $\tau \gtrsim$ 1 hour
- manufacturing costs
- market size

Long-term drifts prevent using a CSAC in applications (e.g. telecom network synchronization) which require long-term 10^{-11} stability
In these applications CSACs would require frequent recalibrations (hours) and can't be used as primary reference standards

→ CSACs usage limited mostly to portable (backpack) military applications
→ A handful of commercial CSACs products (USA, China)
→ Some advanced prototypes (EU, CH, UK, JP), with uncertain market future

Rationale for NG-CSACs: a miniature primary frequency standard would have a large application space and market uptake, allowing to scale down manufacturing costs.

Microsemi 5071A

~30000cm^3 (30L)

~50cm^3

Miniature primary frequency standard

DARPA Micro-PNT and IMPACT (2009-2015)

"In 2009 the U.S. Defense Advanced Research Projects Agency (DARPA) initiated the Integrated Miniature Primary Atomic Clock Technology (IMPACT) effort of the micro-PNT program with the ambitious goal of developing chip-scale atomic clocks with performance comparable to today's Cesium Frequency Standard technology. The ultimate objective of the program is a clock with volume < 5 cm^3, power consumption < 50 mW, and timing error of < 32 ns at one month."

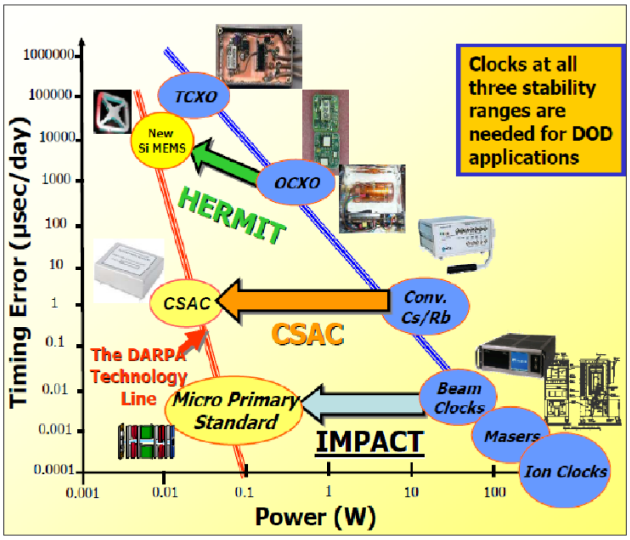
From Shah et al., "A Compact and Low-Power Cold Atom Clock", IEEE IFCS, 2012

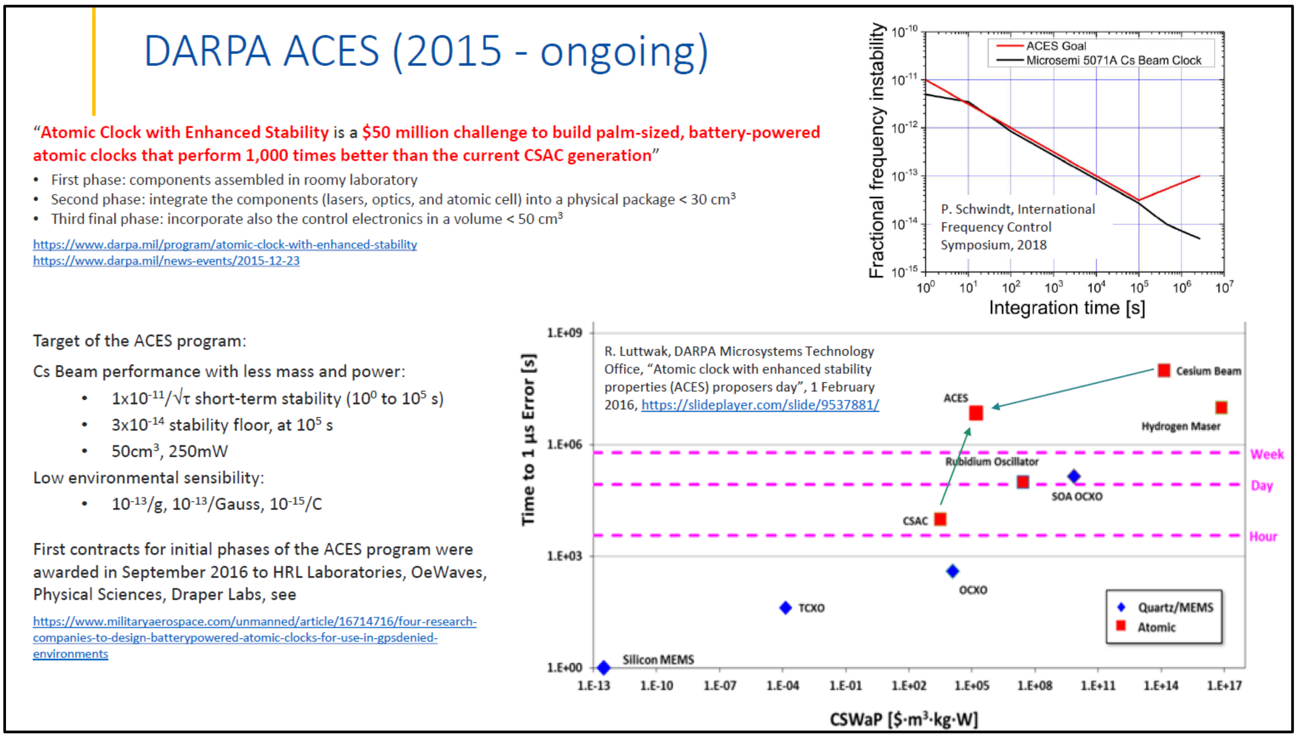
"The Integrated Micro Primary Atomic Clock Technology (IMPACT) effort is developing next-generation CSAC technology. The IMPACT requires performers to deliver a 20 cm^3, 250 mW clock demonstrating less than 160 ns time loss after one month."

https://www.darpa.mil/program/micro-technology-for-positioning-navigation-and-timing/clocks

For an overview of the Micro-PNT program see "Microtechnology Comes of Age", by Andrei M. Shkel, DARPA, 2011. It quotes Symmetricom, Sandia National Laboratories, Charles Stark Draper Laboratory, NIST, MIT, OE Waves, Avo Photonics, and Honeywell as the entities selected in the first funding round.

https://www.gpsworld.com/defense-warfighter-microtechnology-comes-age/





DARPA ACES (2015 - ongoing)

"**Atomic Clock with Enhanced Stability** is a **$50 million challenge to build palm-sized, battery-powered atomic clocks that perform 1,000 times better than the current CSAC generation**"

- First phase: components assembled in roomy laboratory
- Second phase: integrate the components (lasers, optics, and atomic cell) into a physical package < 30 cm³
- Third final phase: incorporate also the control electronics in a volume < 50 cm³

https://www.darpa.mil/program/atomic-clock-with-enhanced-stability
https://www.darpa.mil/news-events/2015-12-23

P. Schwindt, International Frequency Control Symposium, 2018

Target of the ACES program:

Cs Beam performance with less mass and power:

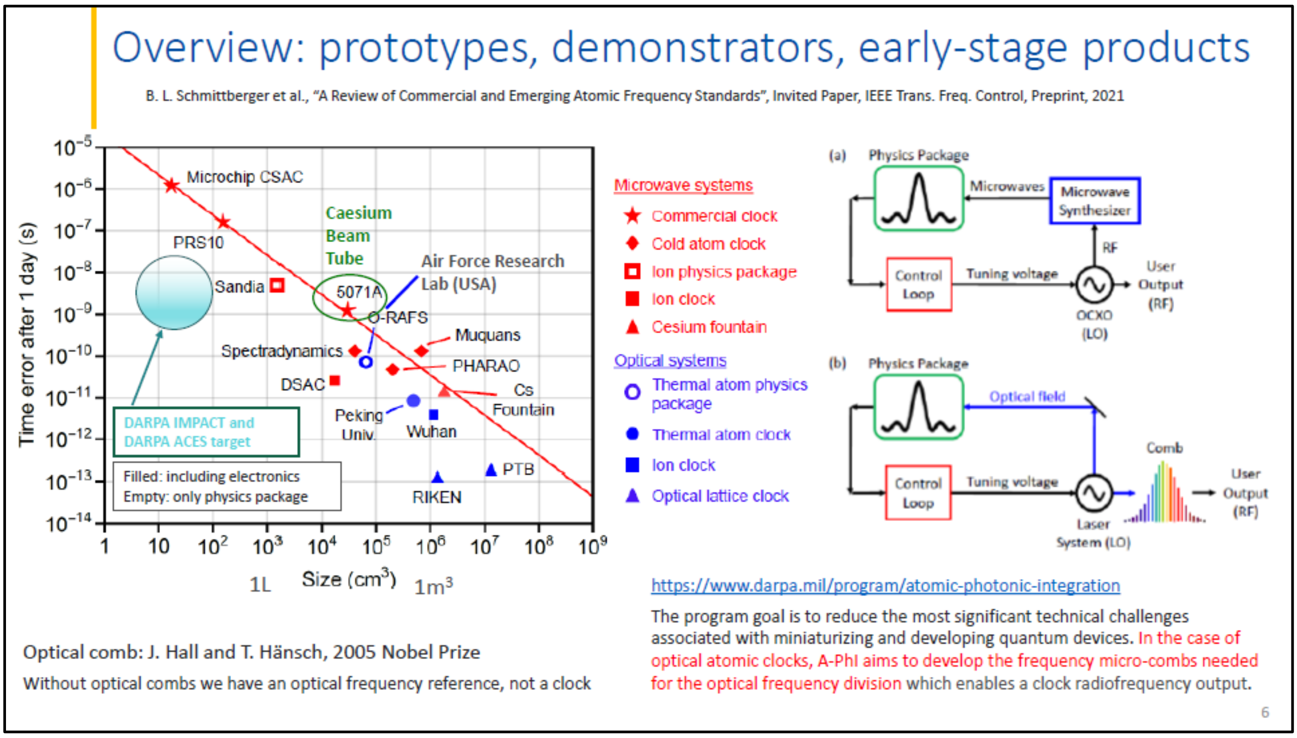
- $1\times10^{-11}/\sqrt{\tau}$ short-term stability (10^0 to 10^5 s)
- 3×10^{-14} stability floor, at 10^5 s
- 50cm³, 250mW

Low environmental sensibility:

- 10^{-13}/g, 10^{-13}/Gauss, 10^{-15}/C

First contracts for initial phases of the ACES program were awarded in September 2016 to HRL Laboratories, OeWaves, Physical Sciences, Draper Labs, see
https://www.militaryaerospace.com/unmanned/article/16714716/four-research-companies-to-design-batterypowered-atomic-clocks-for-use-in-gpsdenied-environments

R. Luttwak, DARPA Microsystems Technology Office, "Atomic clock with enhanced stability properties (ACES) proposers day", 1 February 2016, https://slideplayer.com/slide/9537881/



Overview: prototypes, demonstrators, early-stage products

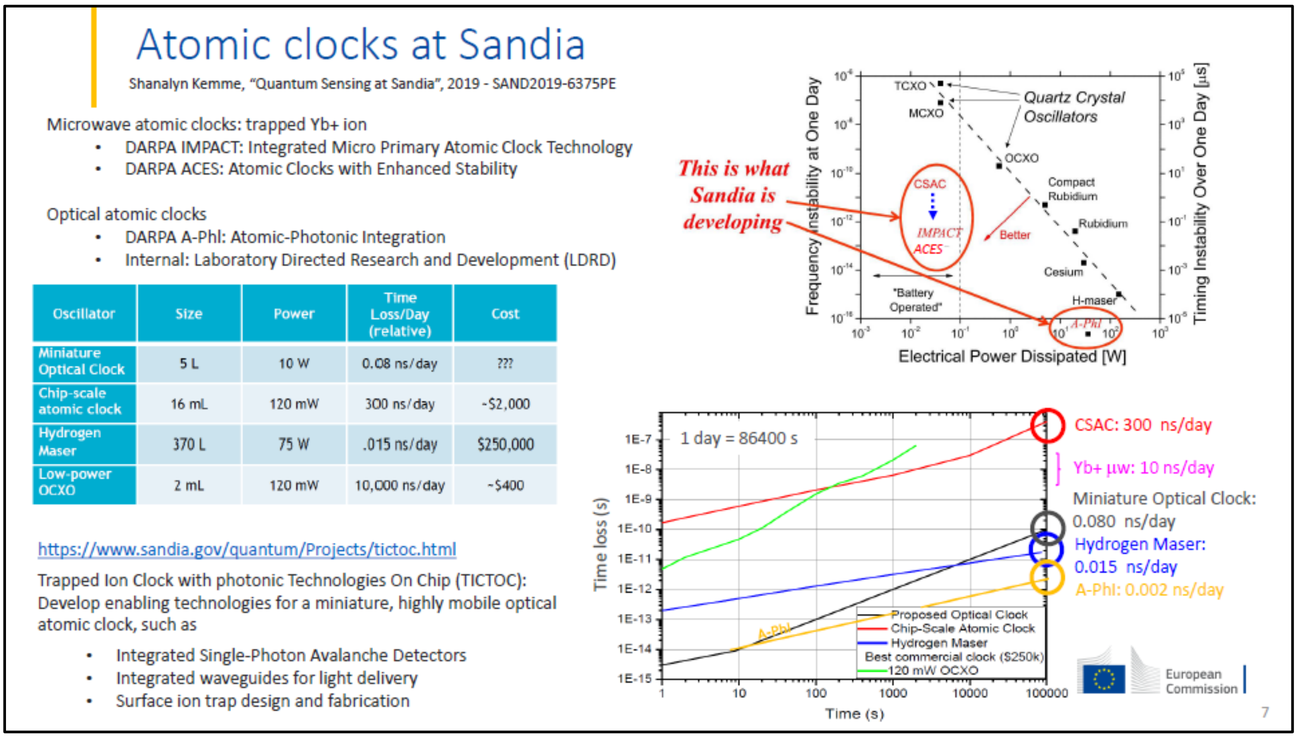
B. L. Schmittberger et al., "A Review of Commercial and Emerging Atomic Frequency Standards", Invited Paper, IEEE Trans. Freq. Control, Preprint, 2021

https://www.darpa.mil/program/atomic-photonic-integration

The program goal is to reduce the most significant technical challenges associated with miniaturizing and developing quantum devices. In the case of optical atomic clocks, A-PhI aims to develop the frequency micro-combs needed for the optical frequency division which enables a clock radiofrequency output.

Optical comb: J. Hall and T. Hänsch, 2005 Nobel Prize

Without optical combs we have an optical frequency reference, not a clock



Atomic clocks at Sandia

Shanalyn Kemme, "Quantum Sensing at Sandia", 2019 - SAND2019-6375PE

Microwave atomic clocks: trapped Yb+ ion

- DARPA IMPACT: Integrated Micro Primary Atomic Clock Technology
- DARPA ACES: Atomic Clocks with Enhanced Stability

Optical atomic clocks

- DARPA A-PhI: Atomic-Photonic Integration
- Internal: Laboratory Directed Research and Development (LDRD)

Oscillator	Size	Power	Time Loss/Day (relative)	Cost
Miniature Optical Clock	5 L	10 W	0.08 ns/day	???
Chip-scale atomic clock	16 mL	120 mW	300 ns/day	~$2,000
Hydrogen Maser	370 L	75 W	.015 ns/day	$250,000
Low-power OCXO	2 mL	120 mW	10,000 ns/day	~$400

https://www.sandia.gov/quantum/Projects/tictoc.html

Trapped Ion Clock with photonic Technologies On Chip (TICTOC): Develop enabling technologies for a miniature, highly mobile optical atomic clock, such as

- Integrated Single-Photon Avalanche Detectors
- Integrated waveguides for light delivery
- Surface ion trap design and fabrication

This is what Sandia is developing

CSAC: 300 ns/day

Yb+ µw: 10 ns/day

Miniature Optical Clock: 0.080 ns/day

Hydrogen Maser: 0.015 ns/day

A-PhI: 0.002 ns/day

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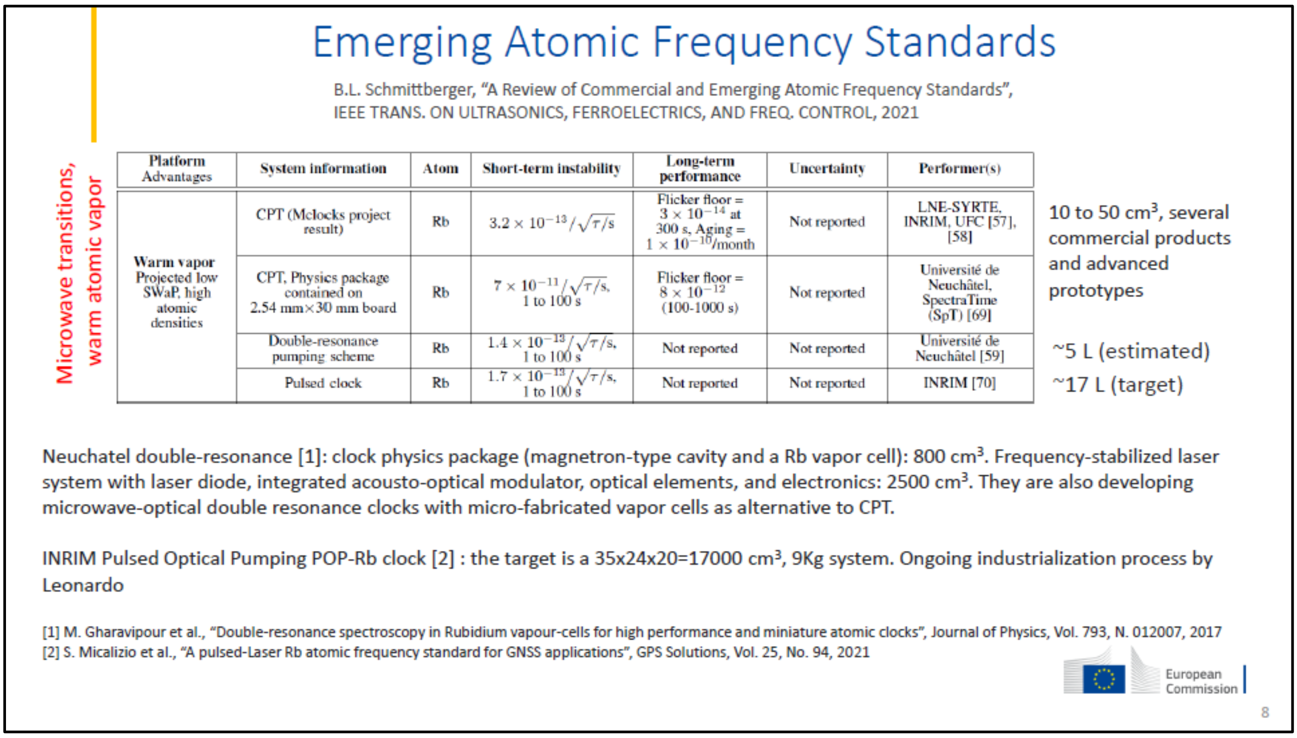

Emerging Atomic Frequency Standards

B.L. Schmittberger, "A Review of Commercial and Emerging Atomic Frequency Standards", IEEE TRANS. ON ULTRASONICS, FERROELECTRICS, AND FREQ. CONTROL, 2021

Microwave transitions, warm atomic vapor

Platform Advantages	System information	Atom	Short-term instability	Long-term performance	Uncertainty	Performer(s)
Warm vapor Projected low SWaP, high atomic densities	CPT (Mclocks project result)	Rb	$3.2 \times 10^{-13}/\sqrt{\tau/s}$	Flicker floor = 3×10^{-14} at 300 s, Aging = 1×10^{-10}/month	Not reported	LNE-SYRTE, INRIM, UFC [57], [58]
	CPT, Physics package contained on 2.54 mm×30 mm board	Rb	$7 \times 10^{-11}/\sqrt{\tau/s}$, 1 to 100 s	Flicker floor = 8×10^{-12} (100-1000 s)	Not reported	Université de Neuchâtel, SpectraTime (SpT) [69]
	Double-resonance pumping scheme	Rb	$1.4 \times 10^{-13}/\sqrt{\tau/s}$, 1 to 100 s	Not reported	Not reported	Université de Neuchâtel [59]
	Pulsed clock	Rb	$1.7 \times 10^{-13}/\sqrt{\tau/s}$, 1 to 100 s	Not reported	Not reported	INRIM [70]

10 to 50 cm^3, several commercial products and advanced prototypes

~5 L (estimated)

~17 L (target)

Neuchatel double-resonance [1]: clock physics package (magnetron-type cavity and a Rb vapor cell): 800 cm^3. Frequency-stabilized laser system with laser diode, integrated acousto-optical modulator, optical elements, and electronics: 2500 cm^3. They are also developing microwave-optical double resonance clocks with micro-fabricated vapor cells as alternative to CPT.

INRIM Pulsed Optical Pumping POP-Rb clock [2] : the target is a 35x24x20=17000 cm^3, 9Kg system. Ongoing industrialization process by Leonardo

[1] M. Gharavipour et al., "Double-resonance spectroscopy in Rubidium vapour-cells for high performance and miniature atomic clocks", Journal of Physics, Vol. 793, N. 012007, 2017

[2] S. Micalizio et al., "A pulsed-Laser Rb atomic frequency standard for GNSS applications", GPS Solutions, Vol. 25, No. 94, 2021

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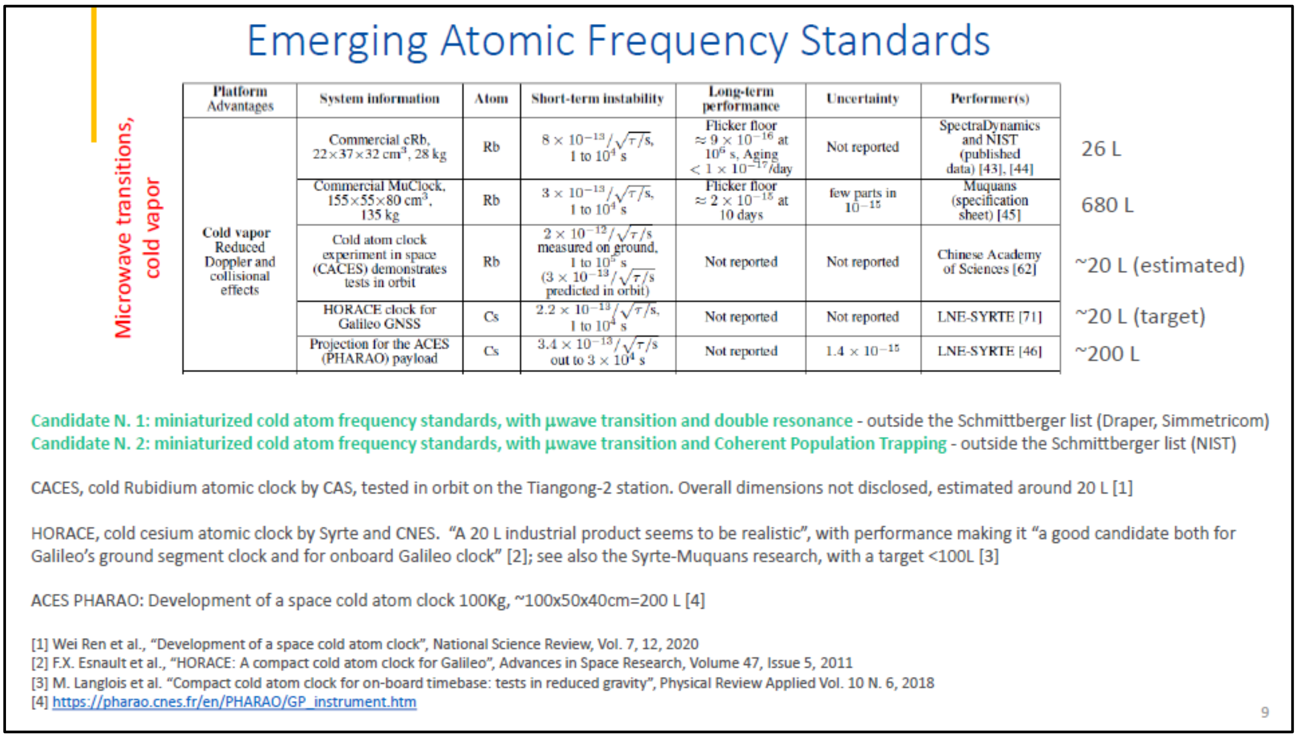


Emerging Atomic Frequency Standards

Microwave transitions,
cold vapor

Platform Advantages	System information	Atom	Short-term instability	Long-term performance	Uncertainty	Performer(s)	
Cold vapor Reduced Doppler and collisional effects	Commercial cRb, $22\times37\times32$ cm^3, 28 kg	Rb	$8\times10^{-13}/\sqrt{\tau/s}$, 1 to 10^4 s	Flicker floor $\approx 9\times10^{-16}$ at 10^6 s, Aging $< 1\times10^{-17}$/day	Not reported	SpectraDynamics and NIST (published data) [43], [44]	26 L
	Commercial MuClock, $155\times55\times80$ cm^3, 135 kg	Rb	$3\times10^{-13}/\sqrt{\tau/s}$, 1 to 10^4 s	Flicker floor $\approx 2\times10^{-15}$ at 10 days	few parts in 10^{-15}	Muquans (specification sheet) [45]	680 L
	Cold atom clock experiment in space (CACES) demonstrates tests in orbit	Rb	$2\times10^{-12}/\sqrt{\tau/s}$ measured on ground, 1 to 10^5 s ($3\times10^{-13}/\sqrt{\tau/s}$ predicted in orbit)	Not reported	Not reported	Chinese Academy of Sciences [62]	~20 L (estimated)
	HORACE clock for Galileo GNSS	Cs	$2.2\times10^{-13}/\sqrt{\tau/s}$, 1 to 10^4 s	Not reported	Not reported	LNE-SYRTE [71]	~20 L (target)
	Projection for the ACES (PHARAO) payload	Cs	$3.4\times10^{-13}/\sqrt{\tau/s}$ out to 3×10^4 s	Not reported	1.4×10^{-15}	LNE-SYRTE [46]	~200 L

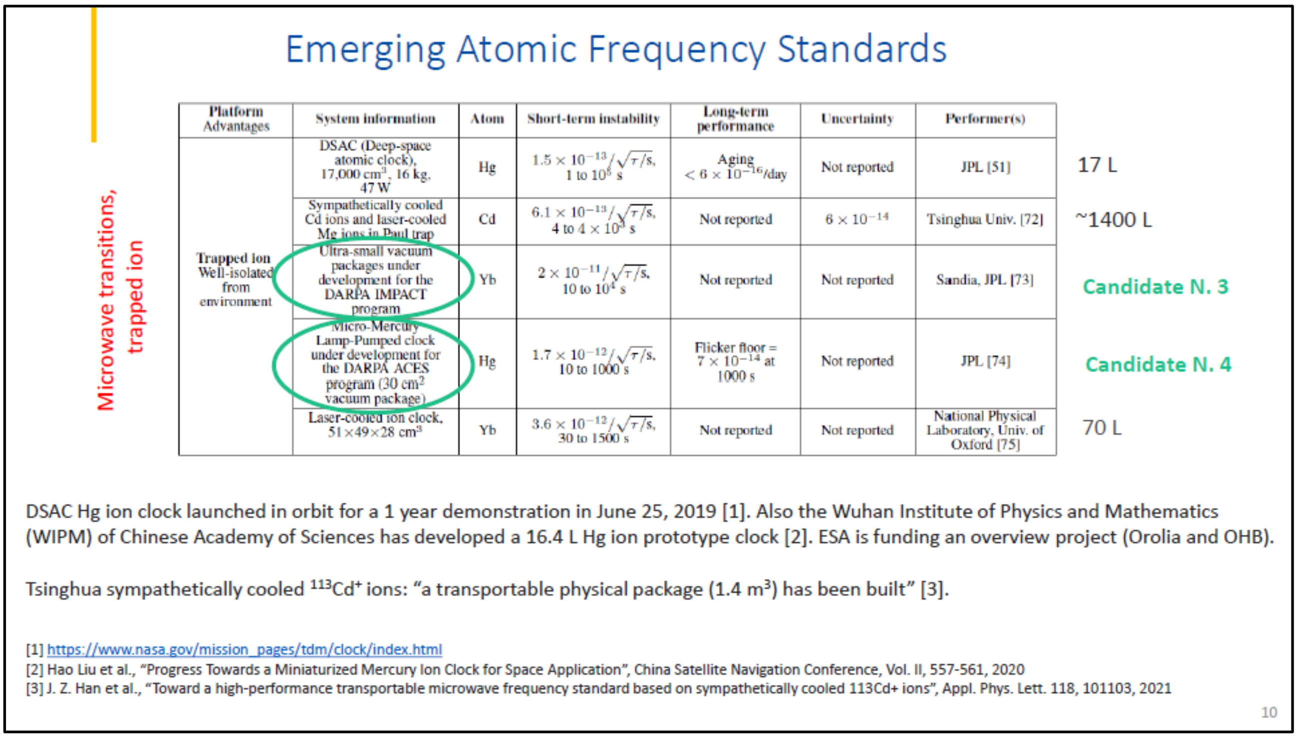
Candidate N. 1: miniaturized cold atom frequency standards, with µwave transition and double resonance - outside the Schmittberger list (Draper, Simmetricom)
Candidate N. 2: miniaturized cold atom frequency standards, with µwave transition and Coherent Population Trapping - outside the Schmittberger list (NIST)

CACES, cold Rubidium atomic clock by CAS, tested in orbit on the Tiangong-2 station. Overall dimensions not disclosed, estimated around 20 L [1]

HORACE, cold cesium atomic clock by Syrte and CNES. "A 20 L industrial product seems to be realistic", with performance making it "a good candidate both for Galileo's ground segment clock and for onboard Galileo clock" [2]; see also the Syrte-Muquans research, with a target <100L [3]

ACES PHARAO: Development of a space cold atom clock 100Kg, ~100x50x40cm=200 L [4]

[1] Wei Ren et al., "Development of a space cold atom clock", National Science Review, Vol. 7, 12, 2020
[2] F.X. Esnault et al., "HORACE: A compact cold atom clock for Galileo", Advances in Space Research, Volume 47, Issue 5, 2011
[3] M. Langlois et al. "Compact cold atom clock for on-board timebase: tests in reduced gravity", Physical Review Applied Vol. 10 N. 6, 2018
[4] https://pharao.cnes.fr/en/PHARAO/GP_instrument.htm



Emerging Atomic Frequency Standards

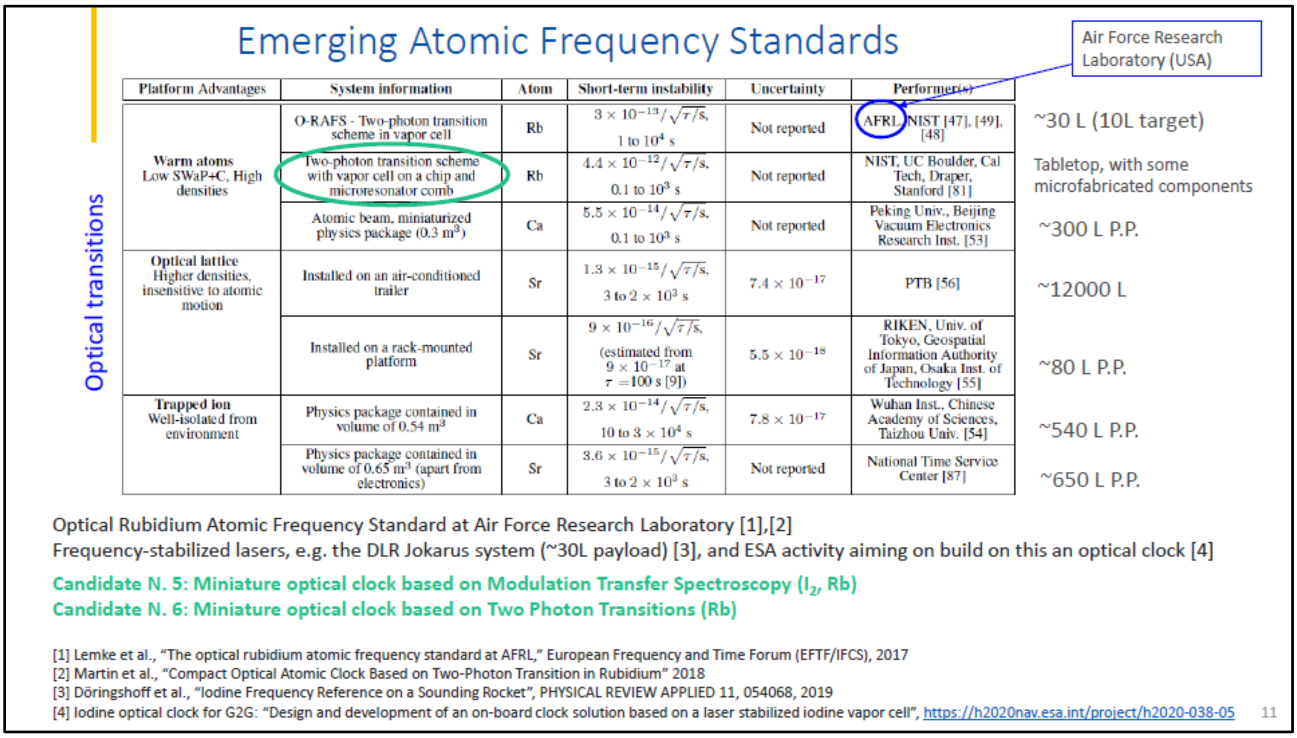
Microwave transitions,
trapped ion

Platform Advantages	System information	Atom	Short-term instability	Long-term performance	Uncertainty	Performer(s)	
Trapped ion Well-isolated from environment	DSAC (Deep-space atomic clock), 17,000 cm^3, 16 kg, 47 W	Hg	$1.5\times10^{-13}/\sqrt{\tau/s}$, 1 to 10^5 s	Aging $< 6\times10^{-16}$/day	Not reported	JPL [51]	17 L
	Sympathetically cooled Cd ions and laser-cooled Mg ions in Paul trap	Cd	$6.1\times10^{-13}/\sqrt{\tau/s}$, 4 to 4×10^3 s	Not reported	6×10^{-14}	Tsinghua Univ. [72]	~1400 L
	Ultra-small vacuum packages under development for the DARPA IMPACT program	Yb	$2\times10^{-11}/\sqrt{\tau/s}$, 10 to 10^4 s	Not reported	Not reported	Sandia, JPL [73]	**Candidate N. 3**
	Micro-Mercury Lamp-Pumped clock under development for the DARPA ACES program (30 cm^2 vacuum package)	Hg	$1.7\times10^{-12}/\sqrt{\tau/s}$, 10 to 1000 s	Flicker floor = 7×10^{-14} at 1000 s	Not reported	JPL [74]	**Candidate N. 4**
	Laser-cooled ion clock, $51\times49\times28$ cm^3	Yb	$3.6\times10^{-12}/\sqrt{\tau/s}$, 30 to 1500 s	Not reported	Not reported	National Physical Laboratory, Univ. of Oxford [75]	70 L

DSAC Hg ion clock launched in orbit for a 1 year demonstration in June 25, 2019 [1]. Also the Wuhan Institute of Physics and Mathematics (WIPM) of Chinese Academy of Sciences has developed a 16.4 L Hg ion prototype clock [2]. ESA is funding an overview project (Orolia and OHB).

Tsinghua sympathetically cooled ^{113}Cd$^+$ ions: "a transportable physical package (1.4 m^3) has been built" [3].

[1] https://www.nasa.gov/mission_pages/tdm/clock/index.html
[2] Hao Liu et al., "Progress Towards a Miniaturized Mercury Ion Clock for Space Application", China Satellite Navigation Conference, Vol. II, 557-561, 2020
[3] J. Z. Han et al., "Toward a high-performance transportable microwave frequency standard based on sympathetically cooled 113Cd+ ions", Appl. Phys. Lett. 118, 101103, 2021



Emerging Atomic Frequency Standards

Optical transitions

Air Force Research Laboratory (USA)

Platform Advantages	System information	Atom	Short-term instability	Uncertainty	Performer(s)	
Warm atoms Low SWaP+C, High densities	O-RAFS - Two-photon transition scheme in vapor cell	Rb	$3 \times 10^{-13}/\sqrt{\tau/s}$, 1 to 10^4 s	Not reported	AFRL, NIST [47], [49], [48]	~30 L (10L target)
	Two-photon transition scheme with vapor cell on a chip and microresonator comb	Rb	$4.4 \times 10^{-12}/\sqrt{\tau/s}$, 0.1 to 10^3 s	Not reported	NIST, UC Boulder, Cal Tech, Draper, Stanford [81]	Tabletop, with some microfabricated components
	Atomic beam, miniaturized physics package (0.3 m^3)	Ca	$5.5 \times 10^{-14}/\sqrt{\tau/s}$, 0.1 to 10^3 s	Not reported	Peking Univ., Beijing Vacuum Electronics Research Inst. [53]	~300 L P.P.
Optical lattice Higher densities, insensitive to atomic motion	Installed on an air-conditioned trailer	Sr	$1.3 \times 10^{-15}/\sqrt{\tau/s}$, 3 to 2×10^3 s	7.4×10^{-17}	PTB [56]	~12000 L
	Installed on a rack-mounted platform	Sr	$9 \times 10^{-16}/\sqrt{\tau/s}$, (estimated from 9×10^{-17} at τ =100 s [9])	5.5×10^{-18}	RIKEN, Univ. of Tokyo, Geospatial Information Authority of Japan, Osaka Inst. of Technology [55]	~80 L P.P.
Trapped ion Well-isolated from environment	Physics package contained in volume of 0.54 m^3	Ca	$2.3 \times 10^{-14}/\sqrt{\tau/s}$, 10 to 3×10^4 s	7.8×10^{-17}	Wuhan Inst., Chinese Academy of Sciences, Taizhou Univ. [54]	~540 L P.P.
	Physics package contained in volume of 0.65 m^3 (apart from electronics)	Sr	$3.6 \times 10^{-15}/\sqrt{\tau/s}$, 3 to 2×10^3 s	Not reported	National Time Service Center [87]	~650 L P.P.

Optical Rubidium Atomic Frequency Standard at Air Force Research Laboratory [1],[2]

Frequency-stabilized lasers, e.g. the DLR Jokarus system (~30L payload) [3], and ESA activity aiming on build on this an optical clock [4]

Candidate N. 5: Miniature optical clock based on Modulation Transfer Spectroscopy (I_2, Rb)

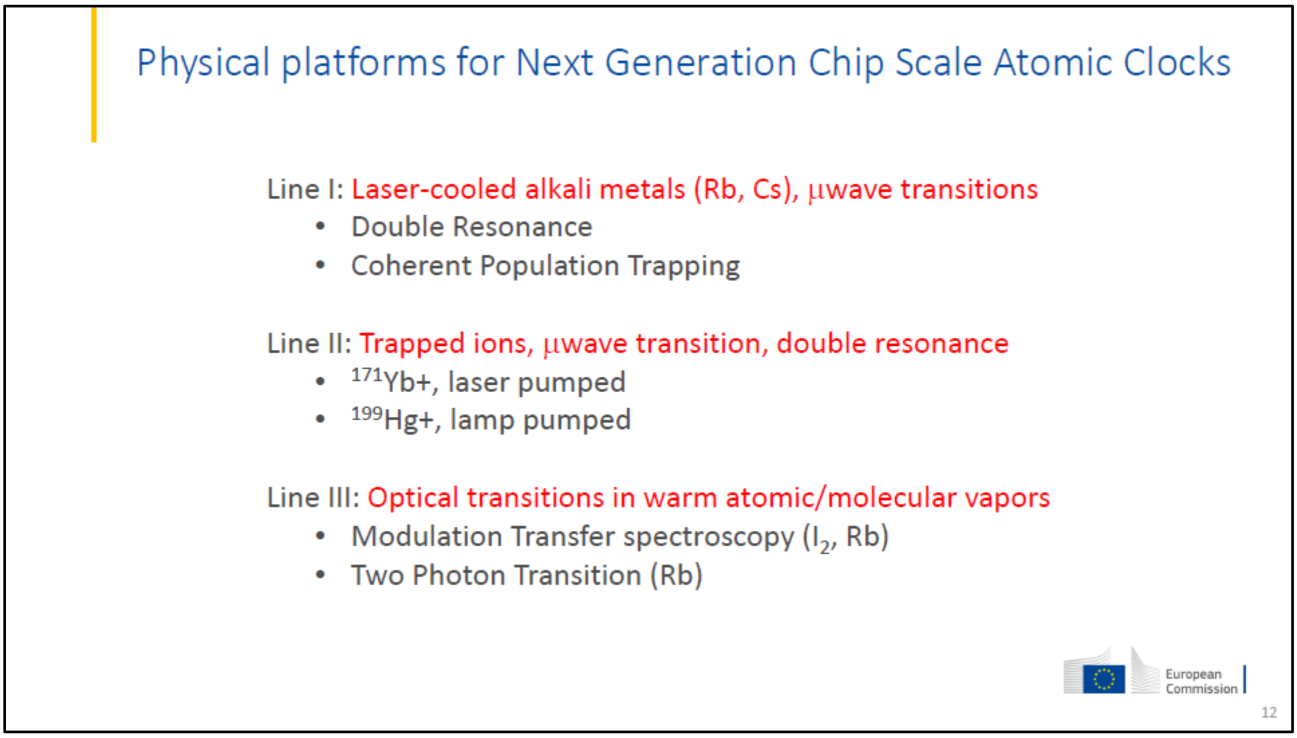
Candidate N. 6: Miniature optical clock based on Two Photon Transitions (Rb)

[1] Lemke et al., "The optical rubidium atomic frequency standard at AFRL," European Frequency and Time Forum (EFTF/IFCS), 2017

[2] Martin et al., "Compact Optical Atomic Clock Based on Two-Photon Transition in Rubidium" 2018

[3] Döringshoff et al., "Iodine Frequency Reference on a Sounding Rocket", PHYSICAL REVIEW APPLIED 11, 054068, 2019

[4] Iodine optical clock for G2G: "Design and development of an on-board clock solution based on a laser stabilized iodine vapor cell", https://h2020nav.esa.int/project/h2020-038-05



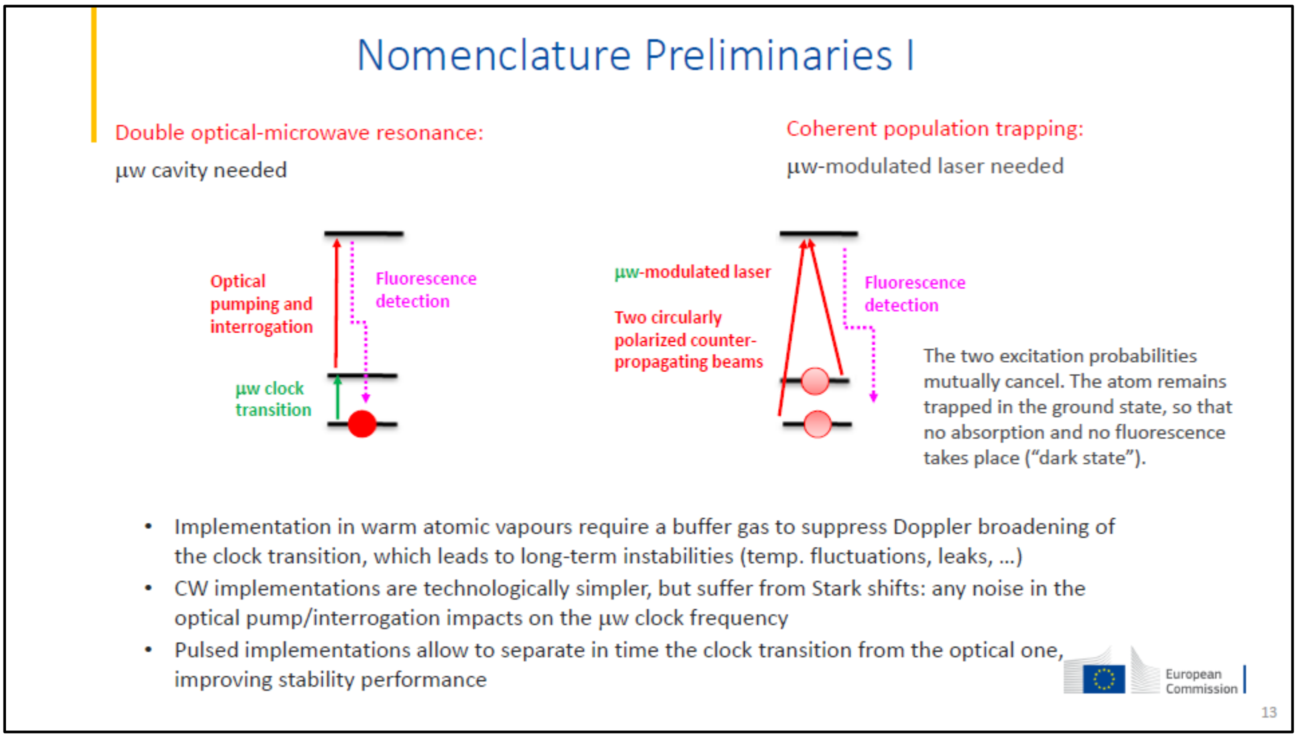
Physical platforms for Next Generation Chip Scale Atomic Clocks

Line I: Laser-cooled alkali metals (Rb, Cs), μwave transitions
- Double Resonance
- Coherent Population Trapping

Line II: Trapped ions, μwave transition, double resonance
- ^{171}Yb+, laser pumped
- ^{199}Hg+, lamp pumped

Line III: Optical transitions in warm atomic/molecular vapors
- Modulation Transfer spectroscopy (I_2, Rb)
- Two Photon Transition (Rb)

European Commission



Nomenclature Preliminaries I

Double optical-microwave resonance:

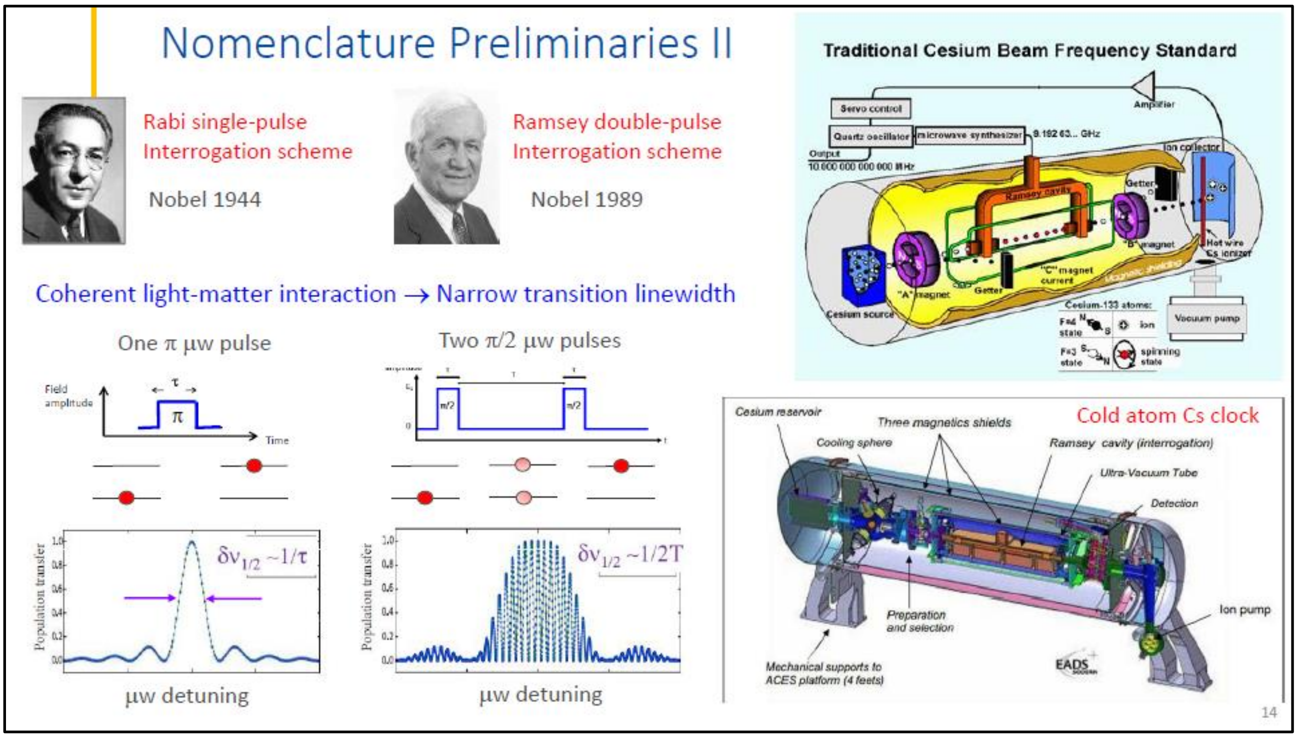
μw cavity needed

Coherent population trapping:

μw-modulated laser needed

The two excitation probabilities mutually cancel. The atom remains trapped in the ground state, so that no absorption and no fluorescence takes place ("dark state").

- Implementation in warm atomic vapours require a buffer gas to suppress Doppler broadening of the clock transition, which leads to long-term instabilities (temp. fluctuations, leaks, …)
- CW implementations are technologically simpler, but suffer from Stark shifts: any noise in the optical pump/interrogation impacts on the μw clock frequency
- Pulsed implementations allow to separate in time the clock transition from the optical one, improving stability performance



Nomenclature Preliminaries II

Rabi single-pulse Interrogation scheme

Nobel 1944

Ramsey double-pulse Interrogation scheme

Nobel 1989

Coherent light-matter interaction → Narrow transition linewidth

One π μw pulse

Two π/2 μw pulses

Traditional Cesium Beam Frequency Standard

Cold atom Cs clock

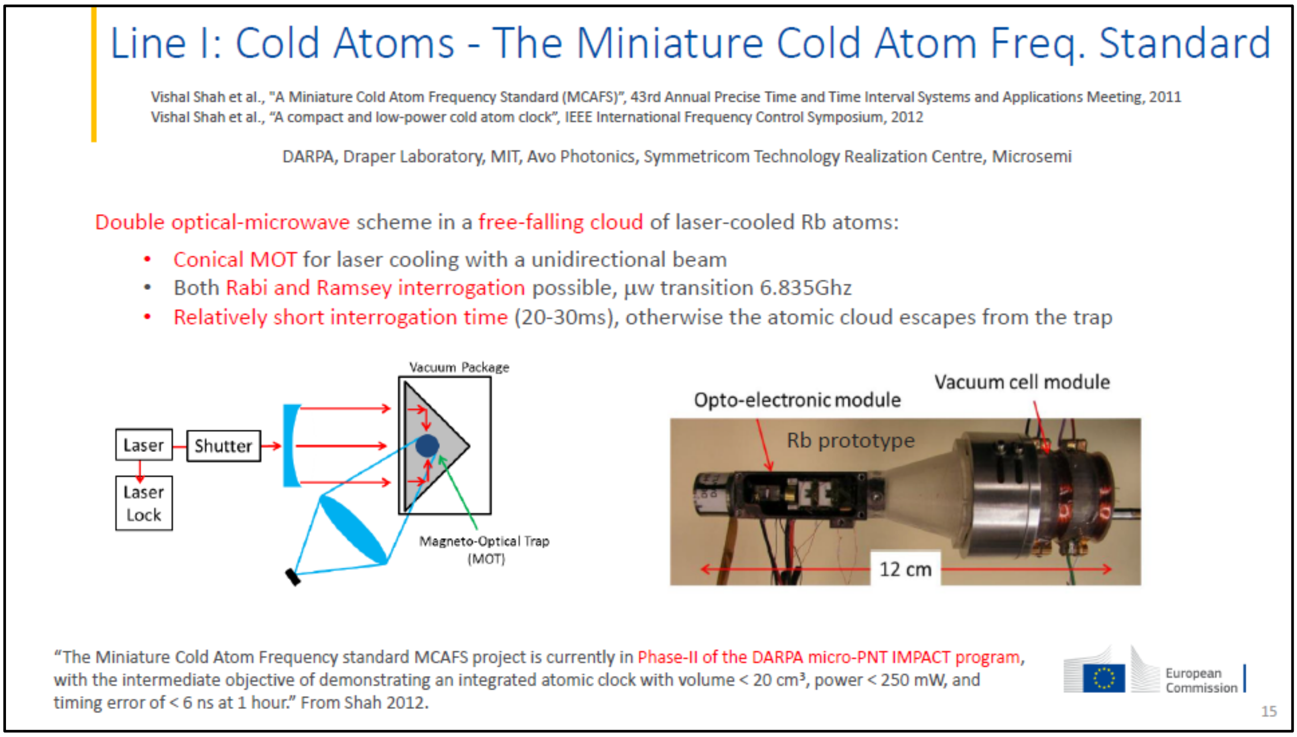
2.2 Microwave transitions in laser-cooled alkali metals

A first possibility to improve the performance of present-generation commercial CSACs relies on laser cooling the atoms which undergo the clock transition, in order to supress the instabilities associated with the vapour atomic cell which contains the alkali metal atoms and the buffer gas used to quell the Doppler broadening.

A first approach was initiated by Draper Laboratories and collaborators more than 10 years ago, and employed a conical magneto-optical trap in the conventional double optical-microwave scheme used in standard Rubidium clocks. Unfortunately, all the prototypes which have been developed failed to reach the stability performance required by the DARPA programmes, and there has been no research work published in the last 6 years. The main references for this work are [Shah 2011], [Shah 2012], and [Scherer 2014].

A second approach exploits laser cooling in the same coherent population trapping scheme on which current-generation CSACs are based. Several groups are working along this line, but the most advanced table-top implementations are being developed at NIST. Despite very impressive proof-of-principle demonstrations, we are still quite far from a fully-integrated prototype, and several technical issues must be resolved to reach the desired performance level. The interested reader can find in [Liu 2017] and [Elgin 2019] a not-too-technical description of the status of the art.

To conclude this Subsection we present an overview of the funding programs targeting cold atom technologies and in particular frequency standards based on laser-cooled atoms. Although portable cold atom clocks do exist as commercial products, their miniaturization to chip-scale dimensions represent a non-trivial challenge.



Line I: Cold Atoms - The Miniature Cold Atom Freq. Standard

Vishal Shah et al., "A Miniature Cold Atom Frequency Standard (MCAFS)", 43rd Annual Precise Time and Time Interval Systems and Applications Meeting, 2011
Vishal Shah et al., "A compact and low-power cold atom clock", IEEE International Frequency Control Symposium, 2012

DARPA, Draper Laboratory, MIT, Avo Photonics, Symmetricom Technology Realization Centre, Microsemi

Double optical-microwave scheme in a free-falling cloud of laser-cooled Rb atoms:

- Conical MOT for laser cooling with a unidirectional beam
- Both Rabi and Ramsey interrogation possible, µw transition 6.835Ghz
- Relatively short interrogation time (20-30ms), otherwise the atomic cloud escapes from the trap

"The Miniature Cold Atom Frequency standard MCAFS project is currently in Phase-II of the DARPA micro-PNT IMPACT program, with the intermediate objective of demonstrating an integrated atomic clock with volume < 20 cm³, power < 250 mW, and timing error of < 6 ns at 1 hour." From Shah 2012.

European Commission

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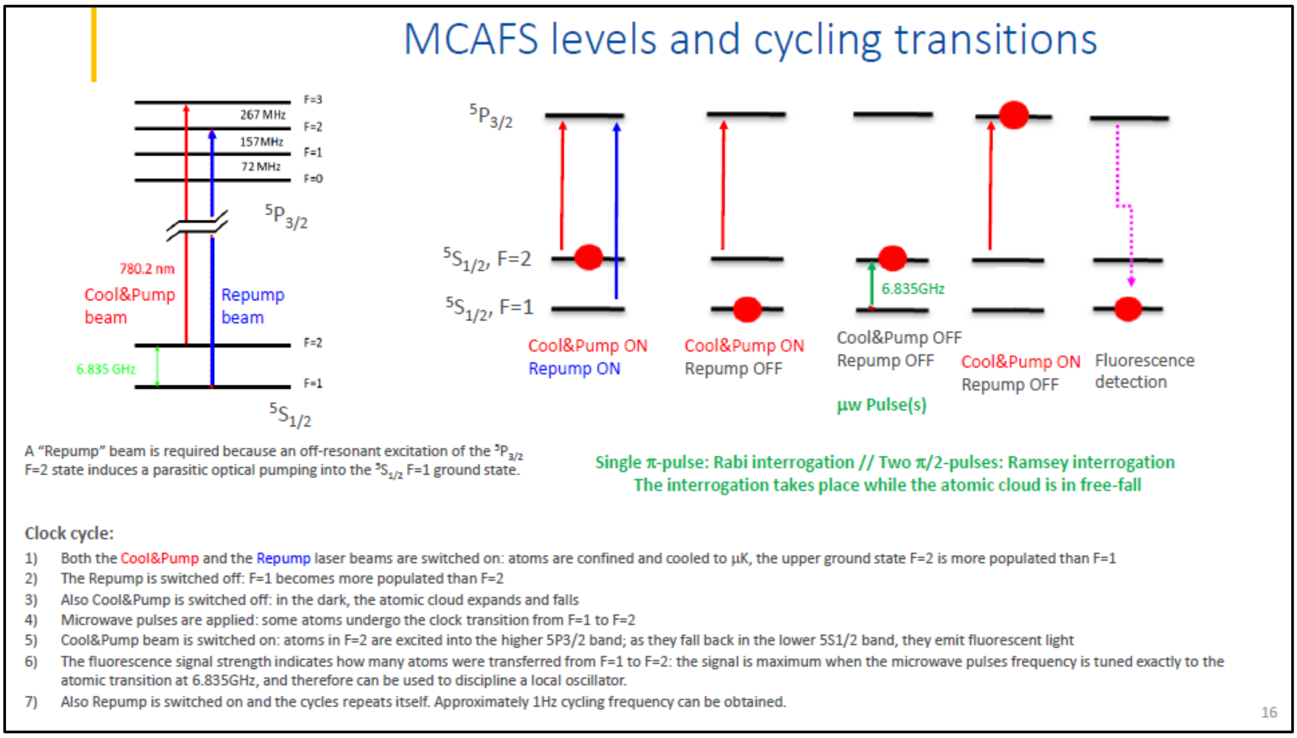


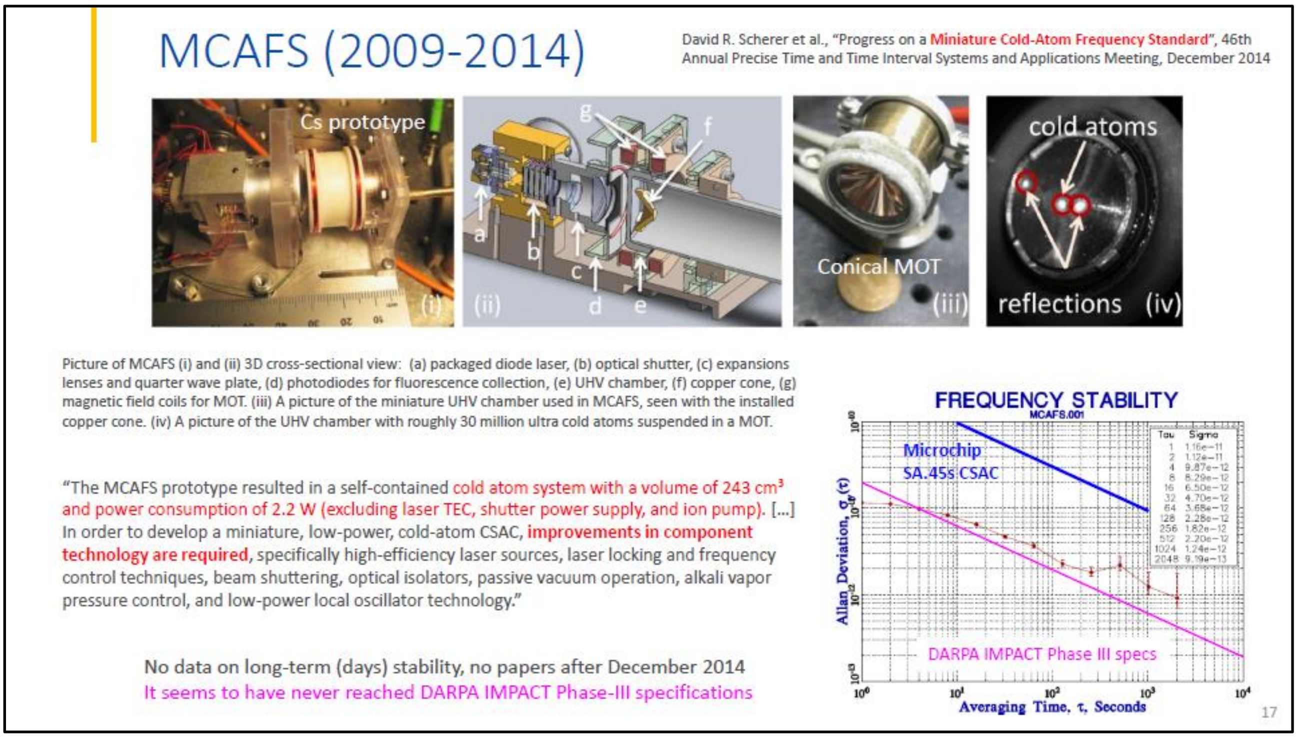
MCAFS levels and cycling transitions

A "Repump" beam is required because an off-resonant excitation of the $^5P_{3/2}$ F=2 state induces a parasitic optical pumping into the $^5S_{1/2}$ F=1 ground state.

Single π-pulse: Rabi interrogation // Two π/2-pulses: Ramsey interrogation
The interrogation takes place while the atomic cloud is in free-fall

Clock cycle:

1) Both the Cool&Pump and the Repump laser beams are switched on: atoms are confined and cooled to μK, the upper ground state F=2 is more populated than F=1
2) The Repump is switched off: F=1 becomes more populated than F=2
3) Also Cool&Pump is switched off: in the dark, the atomic cloud expands and falls
4) Microwave pulses are applied: some atoms undergo the clock transition from F=1 to F=2
5) Cool&Pump beam is switched on: atoms in F=2 are excited into the higher 5P3/2 band; as they fall back in the lower 5S1/2 band, they emit fluorescent light
6) The fluorescence signal strength indicates how many atoms were transferred from F=1 to F=2: the signal is maximum when the microwave pulses frequency is tuned exactly to the atomic transition at 6.835GHz, and therefore can be used to discipline a local oscillator.
7) Also Repump is switched on and the cycles repeats itself. Approximately 1Hz cycling frequency can be obtained.



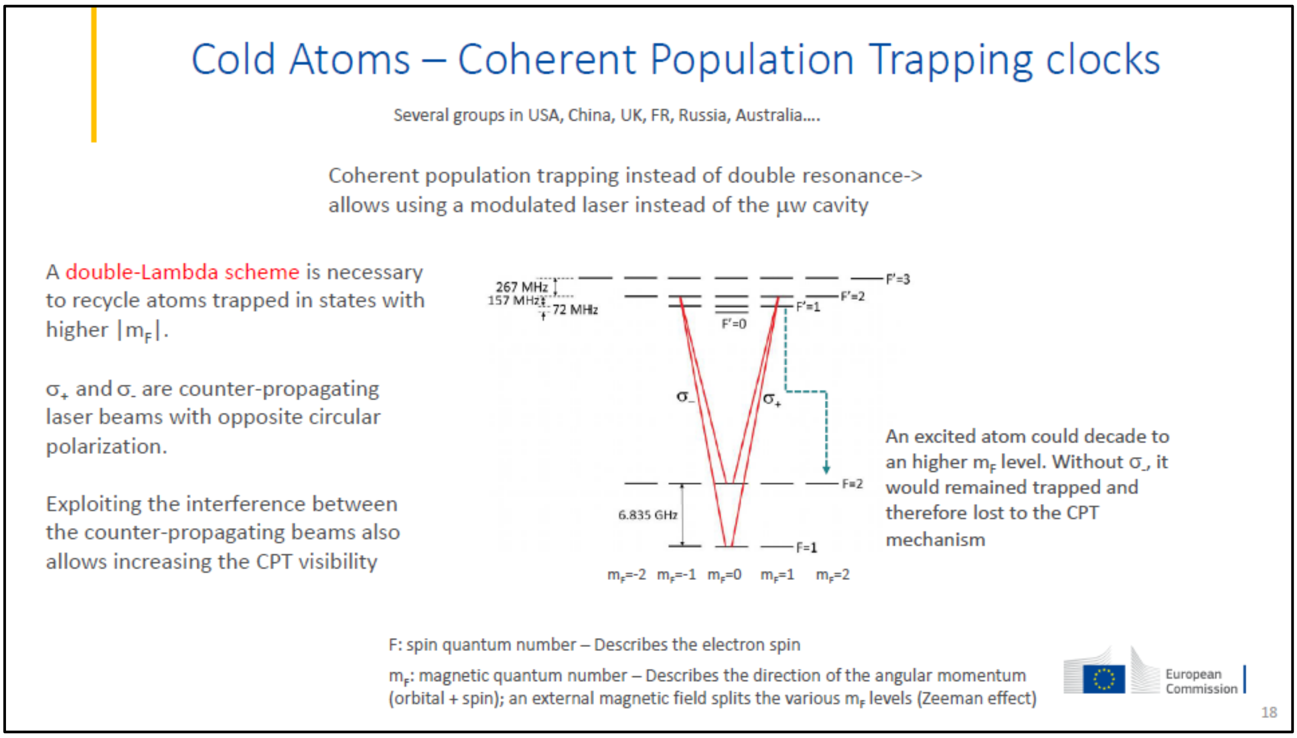
MCAFS (2009-2014)

David R. Scherer et al., "Progress on a **Miniature Cold-Atom Frequency Standard**", 46th Annual Precise Time and Time Interval Systems and Applications Meeting, December 2014

Picture of MCAFS (i) and (ii) 3D cross-sectional view: (a) packaged diode laser, (b) optical shutter, (c) expansions lenses and quarter wave plate, (d) photodiodes for fluorescence collection, (e) UHV chamber, (f) copper cone, (g) magnetic field coils for MOT. (iii) A picture of the miniature UHV chamber used in MCAFS, seen with the installed copper cone. (iv) A picture of the UHV chamber with roughly 30 million ultra cold atoms suspended in a MOT.

"The MCAFS prototype resulted in a self-contained cold atom system with a volume of 243 cm³ and power consumption of 2.2 W (excluding laser TEC, shutter power supply, and ion pump). [...] In order to develop a miniature, low-power, cold-atom CSAC, **improvements in component technology are required**, specifically high-efficiency laser sources, laser locking and frequency control techniques, beam shuttering, optical isolators, passive vacuum operation, alkali vapor pressure control, and low-power local oscillator technology."

No data on long-term (days) stability, no papers after December 2014
It seems to have never reached DARPA IMPACT Phase-III specifications



Cold Atoms – Coherent Population Trapping clocks

Several groups in USA, China, UK, FR, Russia, Australia….

Coherent population trapping instead of double resonance->
allows using a modulated laser instead of the µw cavity

A double-Lambda scheme is necessary to recycle atoms trapped in states with higher $|m_F|$.

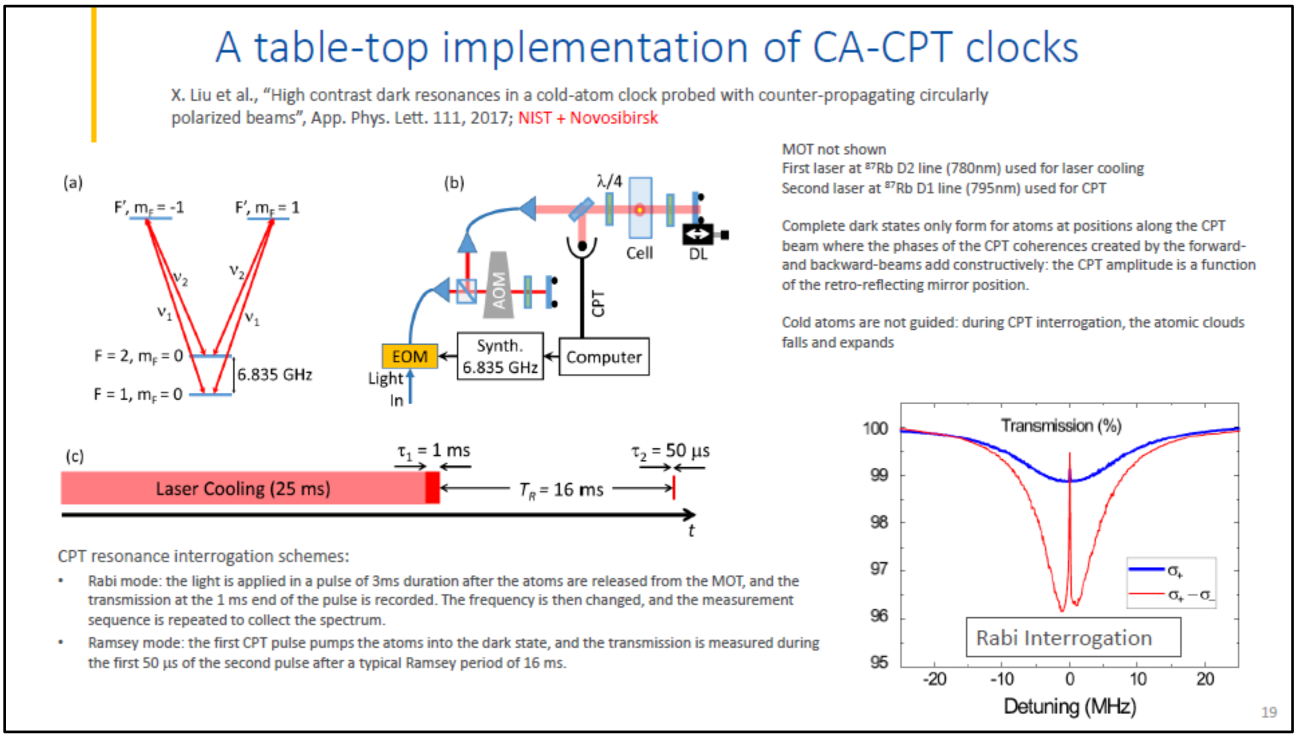
σ_+ and σ_- are counter-propagating laser beams with opposite circular polarization.

Exploiting the interference between the counter-propagating beams also allows increasing the CPT visibility

An excited atom could decade to an higher m_F level. Without σ_- it would remained trapped and therefore lost to the CPT mechanism

F: spin quantum number – Describes the electron spin

m_F: magnetic quantum number – Describes the direction of the angular momentum (orbital + spin); an external magnetic field splits the various m_F levels (Zeeman effect)



A table-top implementation of CA-CPT clocks

X. Liu et al., "High contrast dark resonances in a cold-atom clock probed with counter-propagating circularly polarized beams", App. Phys. Lett. 111, 2017; NIST + Novosibirsk

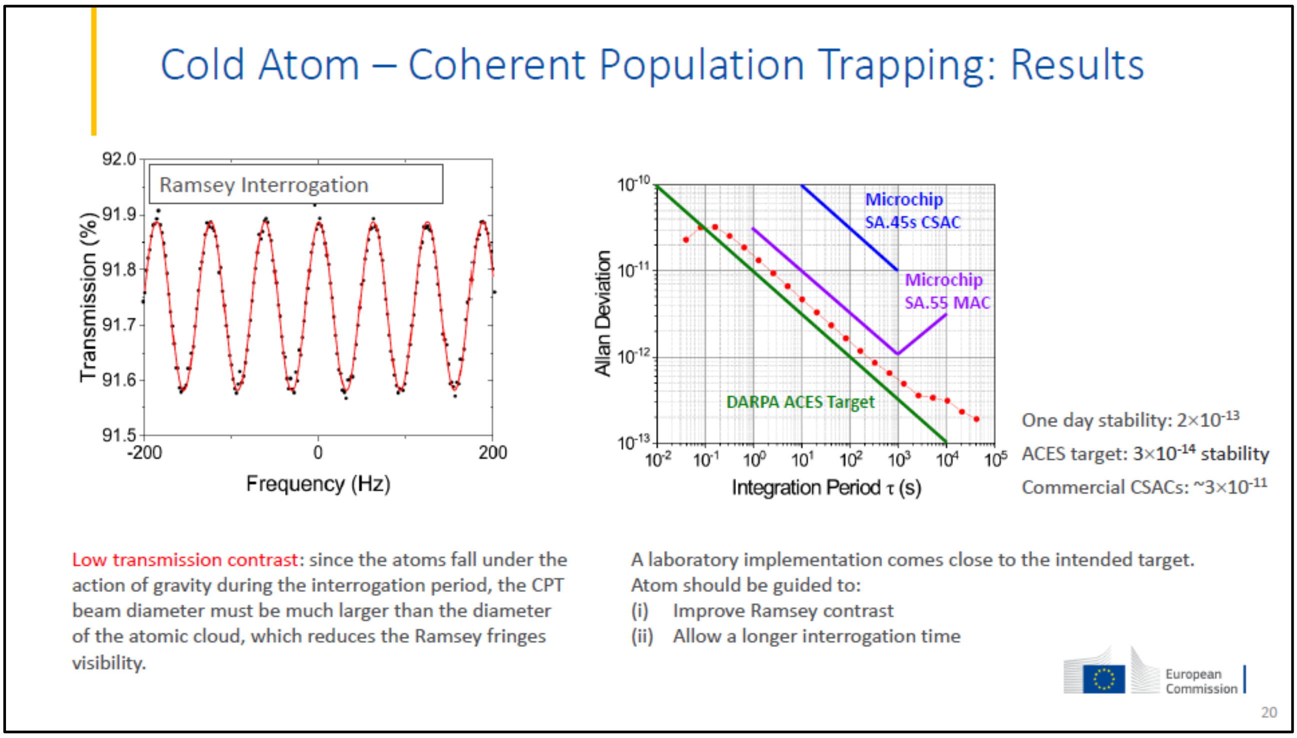
MOT not shown
First laser at ^{87}Rb D2 line (780nm) used for laser cooling
Second laser at ^{87}Rb D1 line (795nm) used for CPT

Complete dark states only form for atoms at positions along the CPT beam where the phases of the CPT coherences created by the forward- and backward-beams add constructively: the CPT amplitude is a function of the retro-reflecting mirror position.

Cold atoms are not guided: during CPT interrogation, the atomic clouds falls and expands

CPT resonance interrogation schemes:

- Rabi mode: the light is applied in a pulse of 3ms duration after the atoms are released from the MOT, and the transmission at the 1 ms end of the pulse is recorded. The frequency is then changed, and the measurement sequence is repeated to collect the spectrum.
- Ramsey mode: the first CPT pulse pumps the atoms into the dark state, and the transmission is measured during the first 50 µs of the second pulse after a typical Ramsey period of 16 ms.



Cold Atom – Coherent Population Trapping: Results

One day stability: 2×10^{-13}

ACES target: 3×10^{-14} **stability**

Commercial CSACs: ~3×10^{-11}

Low transmission contrast: since the atoms fall under the action of gravity during the interrogation period, the CPT beam diameter must be much larger than the diameter of the atomic cloud, which reduces the Ramsey fringes visibility.

A laboratory implementation comes close to the intended target.
Atom should be guided to:
(i) Improve Ramsey contrast
(ii) Allow a longer interrogation time

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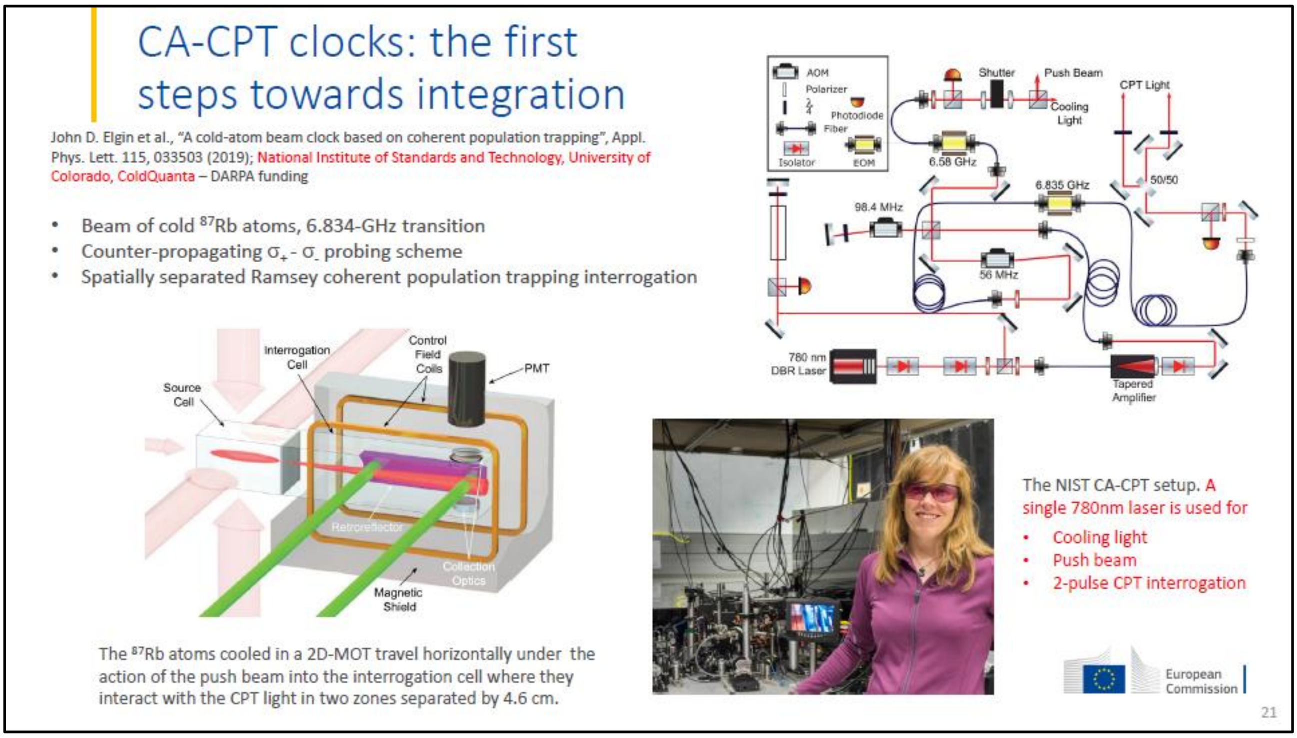


CA-CPT clocks: the first steps towards integration

John D. Elgin et al., "A cold-atom beam clock based on coherent population trapping", Appl. Phys. Lett. 115, 033503 (2019); National Institute of Standards and Technology, University of Colorado, ColdQuanta – DARPA funding

- Beam of cold ^{87}Rb atoms, 6.834-GHz transition
- Counter-propagating σ_+ - σ_- probing scheme
- Spatially separated Ramsey coherent population trapping interrogation

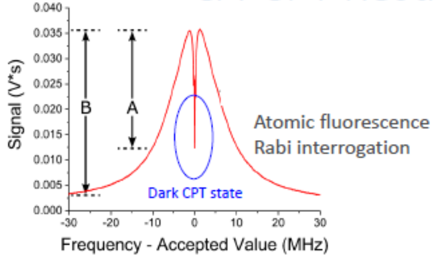
The ^{87}Rb atoms cooled in a 2D-MOT travel horizontally under the action of the push beam into the interrogation cell where they interact with the CPT light in two zones separated by 4.6 cm.

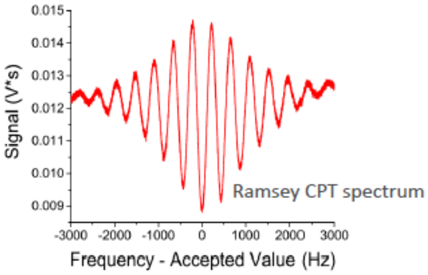
The NIST CA-CPT setup. A single 780nm laser is used for

- Cooling light
- Push beam
- 2-pulse CPT interrogation

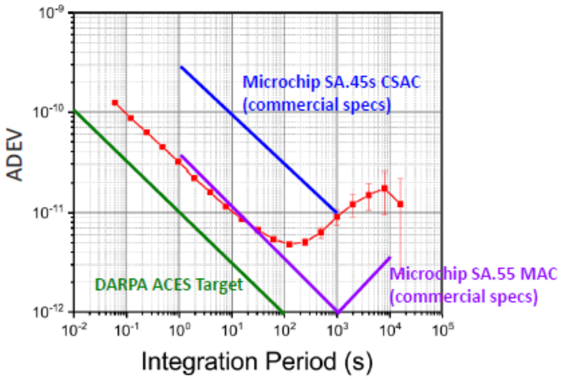
European Commission

CA-CPT Results – with a single laser





Using separate zones for the two pulses allows reducing the CPT beam diameters to match the dimension of the atomic cloud, thus increasing the contrast in the Ramsey fringes



"A cold-atoms beam Ramsey CPT clock is a unique platform for further development of compact atomic-clocks. [...] **While the current performance of the clock is not competitive with more well studied vapor-cell clocks, the current results indicate that the clock's performance is limited by the specifics of the experimental implementation**, including pressure drifts of the atom source, imperfections in the CPT optical implementation, and technical noise on the lasers"

European Commission

USA for ColdQuanta

Muquans https://www.muquans.com/product/muclock/ (Acquired by IXBlue in May 2021)
Spectradynamics https://spectradynamics.com/product-sheets/cRb-Clock-2019.pdf
ColdQuanta https://coldquanta.com/devices

[1] October 15, 2019 **ColdQuanta today announced it has been awarded $1M from NASA's Civilian Commercialization Readiness Pilot Program** (CCRPP). The program will enable ColdQuanta to develop significantly smaller cold atom systems with a high level of ruggedness. This award expands on the success of ColdQuanta's Quantum Core technology which was developed with the Jet Propulsion Laboratory (JPL) and is currently operating aboard the International Space Station (ISS).

[2] October 29, 2019. ColdQuanta today announced it has been awarded $2.8M across four separate programs from DARPA, NASA, and the U.S. military. These programs will advance the development of ColdQuanta's cold atom technology for quantum positioning (gyroscopes and atomic clocks), quantum sensors (radiofrequency detectors), and quantum communication systems. Following the recent announcement of a $1M award from NASA, **these awards put ColdQuanta's cumulative R&D funding at over $30M**.

- **DARPA awarded ColdQuanta $721k in partnership with the University of Virginia under its A-PhI (Atomic-Photonic Integration) program.** The A-PhI program is focused on combining the high accuracy of atomic systems with the portability, manufacturability, and robustness of photonic integrated chips for high-performance position, navigation, and timing (PNT) devices as an alternative to today's Global Positioning System (GPS). DARPA's goal is to produce the world's best sensors (atomic clocks and gyroscopes) with a size, weight, and power consumption that make them suitable for widespread deployment ranging from ships to aerial vehicles to dismounted soldiers.
- **NASA Ames awarded ColdQuanta $684k under the Space Technology Mission Directorate's Transformational Communications Technology effort.** This effort advances quantum-enabled and secure communications as well as quantum computer networking through the development of a novel quantum memory device based on storing quantum information in a lattice of cold atoms.
- **A branch of the U.S. military awarded two contracts to ColdQuanta, totaling $1.4 million in funding.** The projects involve atomic clock technology and radiofrequency sensors.

[3] April 16, 2021. **The Air Force Research Laboratory (AFRL) awarded ColdQuanta $750K for the development of a high-performance miniature ion trap system.** The system maximizes performance and robustness while minimizing size, weight, and power consumption (SWaP). The new AFRL award will build on the success of this prototype to increase performance, reduce cost, and create a robust architecture for deployable quantum platforms.

[1] https://www.businesswire.com/news/home/20191015005151/en/NASA-Awards-1M-to-ColdQuanta-to-Accelerate-Commercial-Deployment-of-Quantum-Atomic-Systems
[2] https://www.gpsworld.com/coldquanta-awarded-us-government-contracts-for-atomic-clock/
[3] https://www.businesswire.com/news/home/20191029005056/en/ColdQuanta-Awarded-2.8M-from-the-U.S.-Government-to-Advance-its-Quantum-Core-Technology

European Commission

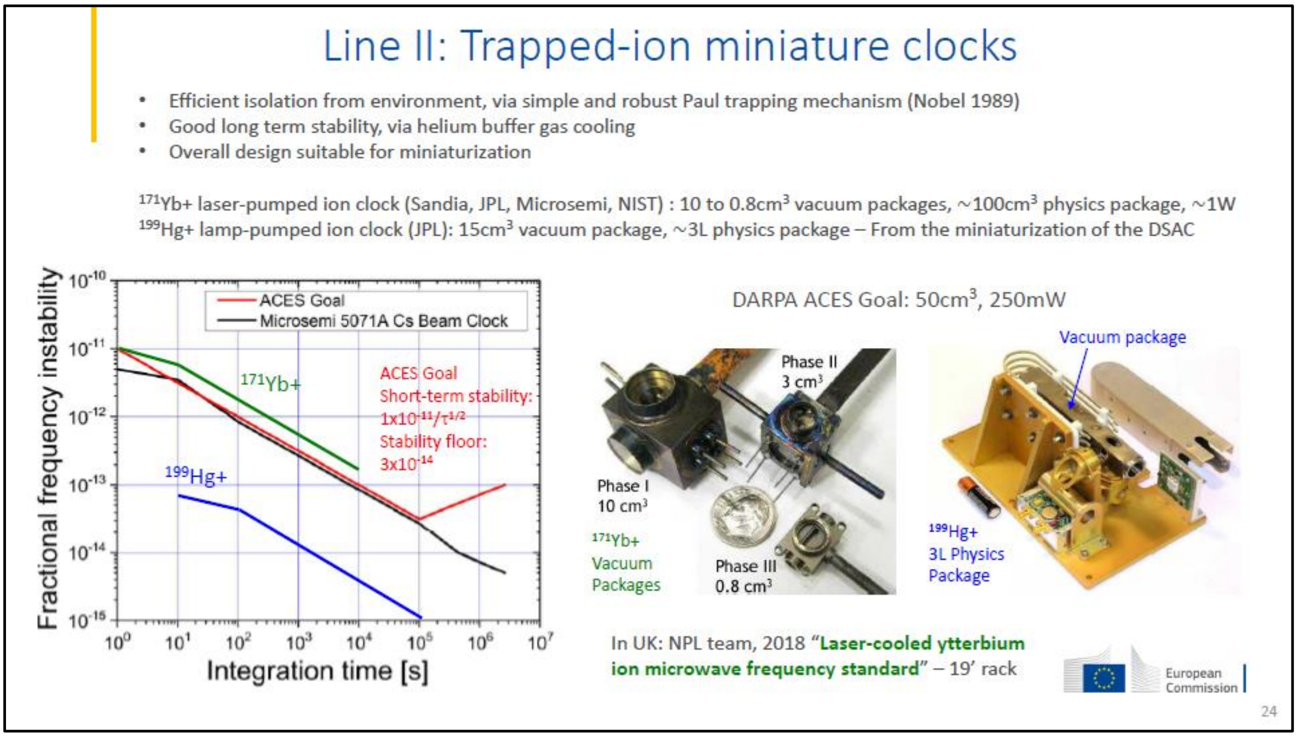
2.3 Microwave transitions in trapped ions

The invention of Paul trap (Nobel prize in Physics, 1989) provided a simple and robust way to isolate ions from environmental disturbances, and among several applications spurred the development of trapped-ion clocks. Such clocks lends themselves quite naturally to miniaturization, since a simple and efficient Doppler suppression mechanism can be ensured by using helium as a buffer gas. In the last 10 years, miniaturization efforts focused mostly on clocks exploiting microwave transitions in Ytterbium and in Mercury ions.

The player which has advanced the most towards a miniaturized Yb+ clock is Sandia with its partners. Several vacuum packages with volumes down to 0.8cm^3 have been developed, in a double-resonance scheme which requires two different lasers. The behaviour of the laser at 369nm seems to represent the main obstacle to reaching the desired stability performance, and also the presence of a parasitic state which capture the ions is an issue to be resolved. A complete idea of the progress being done can be gathered from [Schwindt 2015], [Schwindt 2016], [Schwindt 2017], and [Schwindt 2018].

JPL is miniaturizing his Deep Space Atomic Clock, which has been tested in space in 2019, see [Burt 2021]. A vacuum package of 15cm^3 has been developed, and an Hg discharge lamp is use to avoid laser-induced instabilities. Work is now progressing to miniaturize and integrate in a physical package all the clock component without compromising the outstanding stability level which has been measured. The work done by JPL is described in [Gulati 2018], [Hoang 2019], and [Hoang 2020]. It is worth noting that also China is funding the development of an Hg+ clock, see [Liu 2020].

Overall, microwave clocks based on trapped ions presently represent the most mature physical platform for the development of NG-CSACs.



Line II: Trapped-ion miniature clocks

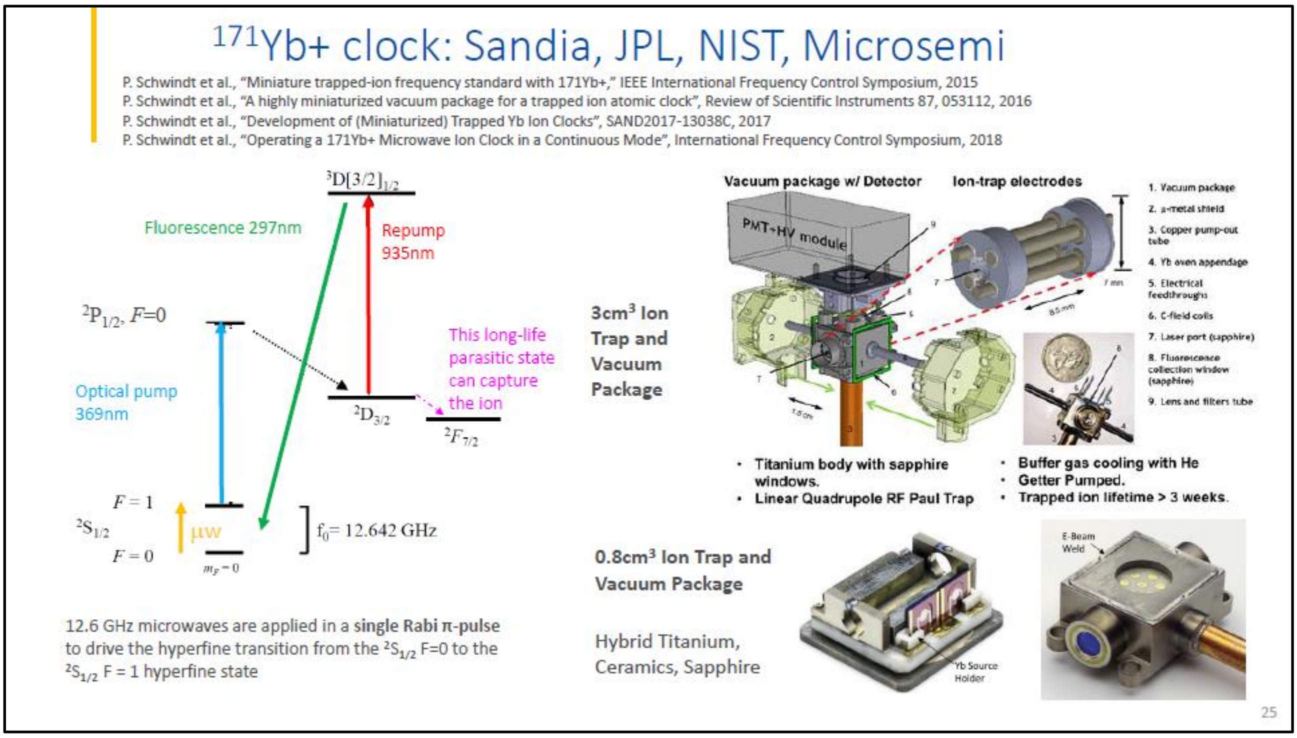
- Efficient isolation from environment, via simple and robust Paul trapping mechanism (Nobel 1989)
- Good long term stability, via helium buffer gas cooling
- Overall design suitable for miniaturization

^{171}Yb+ laser-pumped ion clock (Sandia, JPL, Microsemi, NIST) : 10 to 0.8cm^3 vacuum packages, ~100cm^3 physics package, ~1W
^{199}Hg+ lamp-pumped ion clock (JPL): 15cm^3 vacuum package, ~3L physics package – From the miniaturization of the DSAC

DARPA ACES Goal: 50cm^3, 250mW

In UK: NPL team, 2018 "**Laser-cooled ytterbium ion microwave frequency standard**" – 19' rack

European Commission



^{171}Yb+ clock: Sandia, JPL, NIST, Microsemi

P. Schwindt et al., "Miniature trapped-ion frequency standard with 171Yb+," IEEE International Frequency Control Symposium, 2015
P. Schwindt et al., "A highly miniaturized vacuum package for a trapped ion atomic clock", Review of Scientific Instruments 87, 053112, 2016
P. Schwindt et al., "Development of (Miniaturized) Trapped Yb Ion Clocks", SAND2017-13038C, 2017
P. Schwindt et al., "Operating a 171Yb+ Microwave Ion Clock in a Continuous Mode", International Frequency Control Symposium, 2018

12.6 GHz microwaves are applied in a **single Rabi π-pulse** to drive the hyperfine transition from the $^2S_{1/2}$ F=0 to the $^2S_{1/2}$ F = 1 hyperfine state

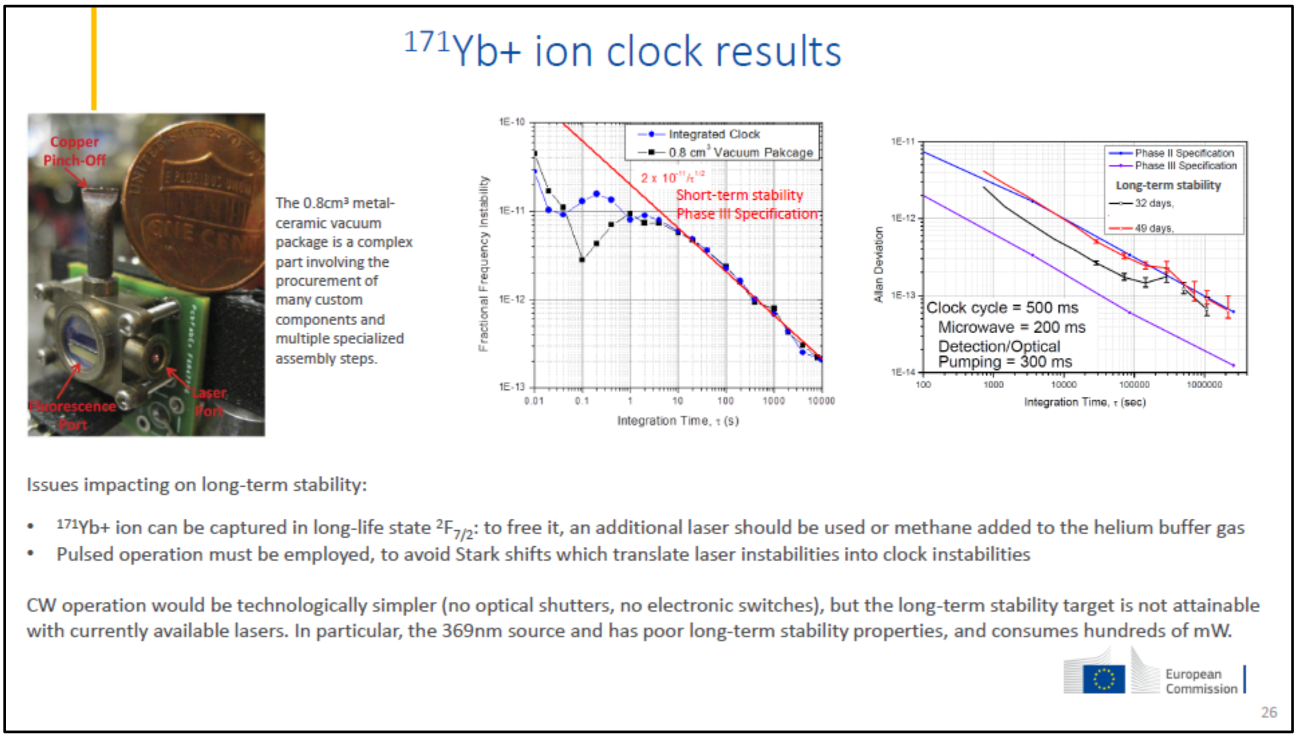
3cm^3 Ion Trap and Vacuum Package

- **Titanium body with sapphire windows.**
- **Linear Quadrupole RF Paul Trap**

- **Buffer gas cooling with He**
- **Getter Pumped.**
- **Trapped ion lifetime > 3 weeks.**

0.8cm^3 Ion Trap and Vacuum Package

Hybrid Titanium, Ceramics, Sapphire



^{171}Yb+ ion clock results

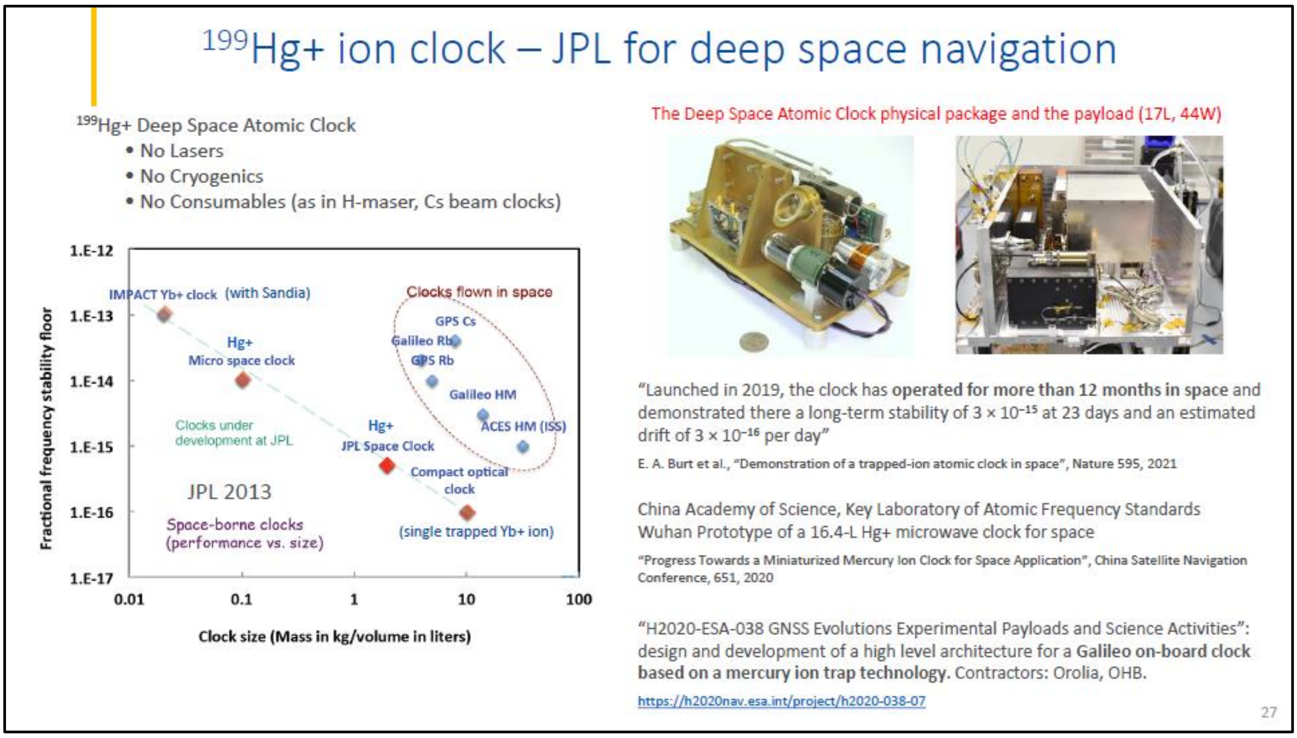
The 0.8cm³ metal-ceramic vacuum package is a complex part involving the procurement of many custom components and multiple specialized assembly steps.

Issues impacting on long-term stability:

- ^{171}Yb+ ion can be captured in long-life state $^2F_{7/2}$: to free it, an additional laser should be used or methane added to the helium buffer gas
- Pulsed operation must be employed, to avoid Stark shifts which translate laser instabilities into clock instabilities

CW operation would be technologically simpler (no optical shutters, no electronic switches), but the long-term stability target is not attainable with currently available lasers. In particular, the 369nm source and has poor long-term stability properties, and consumes hundreds of mW.

European Commission



^{199}Hg+ ion clock – JPL for deep space navigation

^{199}Hg+ Deep Space Atomic Clock
- No Lasers
- No Cryogenics
- No Consumables (as in H-maser, Cs beam clocks)

The Deep Space Atomic Clock physical package and the payload (17L, 44W)

"Launched in 2019, the clock has **operated for more than 12 months in space** and demonstrated there a long-term stability of 3×10^{-15} at 23 days and an estimated drift of 3×10^{-16} per day"

E. A. Burt et al., "Demonstration of a trapped-ion atomic clock in space", Nature 595, 2021

China Academy of Science, Key Laboratory of Atomic Frequency Standards
Wuhan Prototype of a 16.4-L Hg+ microwave clock for space

"Progress Towards a Miniaturized Mercury Ion Clock for Space Application", China Satellite Navigation Conference, 651, 2020

"H2020-ESA-038 GNSS Evolutions Experimental Payloads and Science Activities": design and development of a high level architecture for a **Galileo on-board clock based on a mercury ion trap technology.** Contractors: Orolia, OHB.

https://h2020nav.esa.int/project/h2020-038-07

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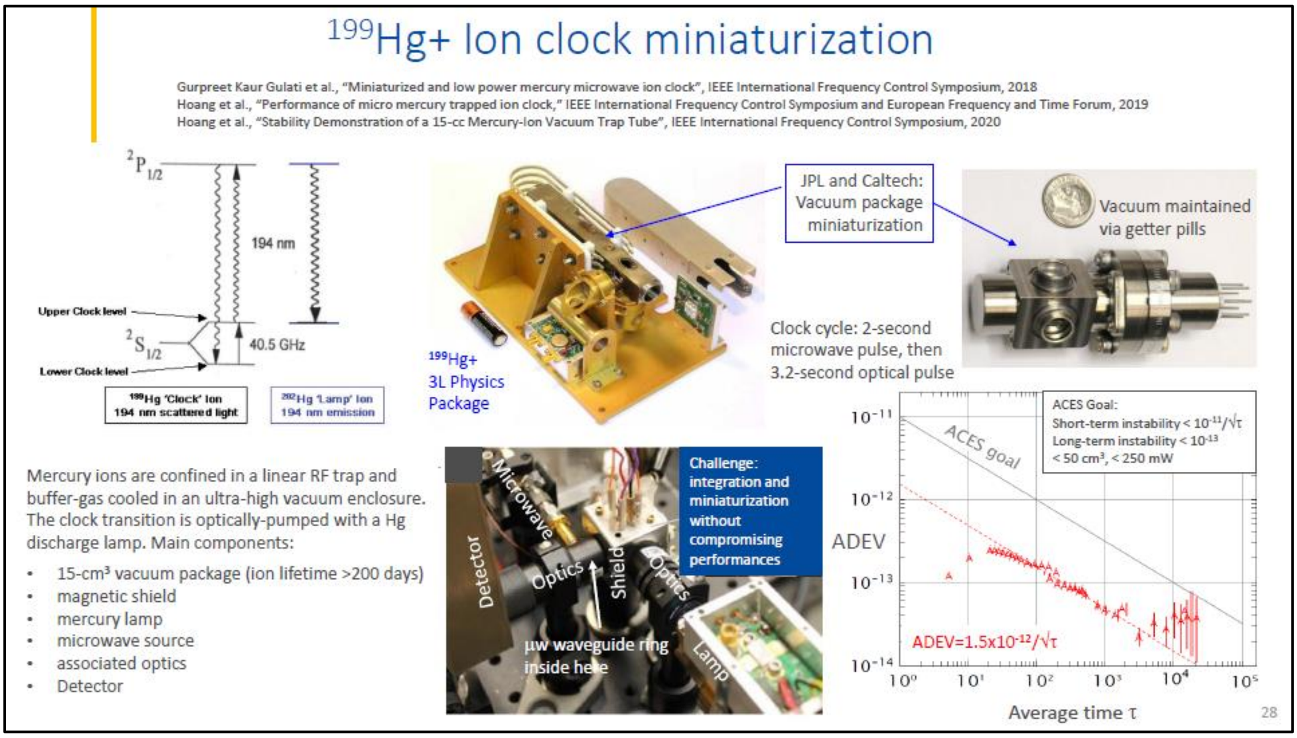

^{199}Hg+ Ion clock miniaturization

Gurpreet Kaur Gulati et al., "Miniaturized and low power mercury microwave ion clock", IEEE International Frequency Control Symposium, 2018
Hoang et al., "Performance of micro mercury trapped ion clock," IEEE International Frequency Control Symposium and European Frequency and Time Forum, 2019
Hoang et al., "Stability Demonstration of a 15-cc Mercury-Ion Vacuum Trap Tube", IEEE International Frequency Control Symposium, 2020

Clock cycle: 2-second microwave pulse, then 3.2-second optical pulse

Mercury ions are confined in a linear RF trap and buffer-gas cooled in an ultra-high vacuum enclosure. The clock transition is optically-pumped with a Hg discharge lamp. Main components:

- 15-cm³ vacuum package (ion lifetime >200 days)
- magnetic shield
- mercury lamp
- microwave source
- associated optics
- Detector

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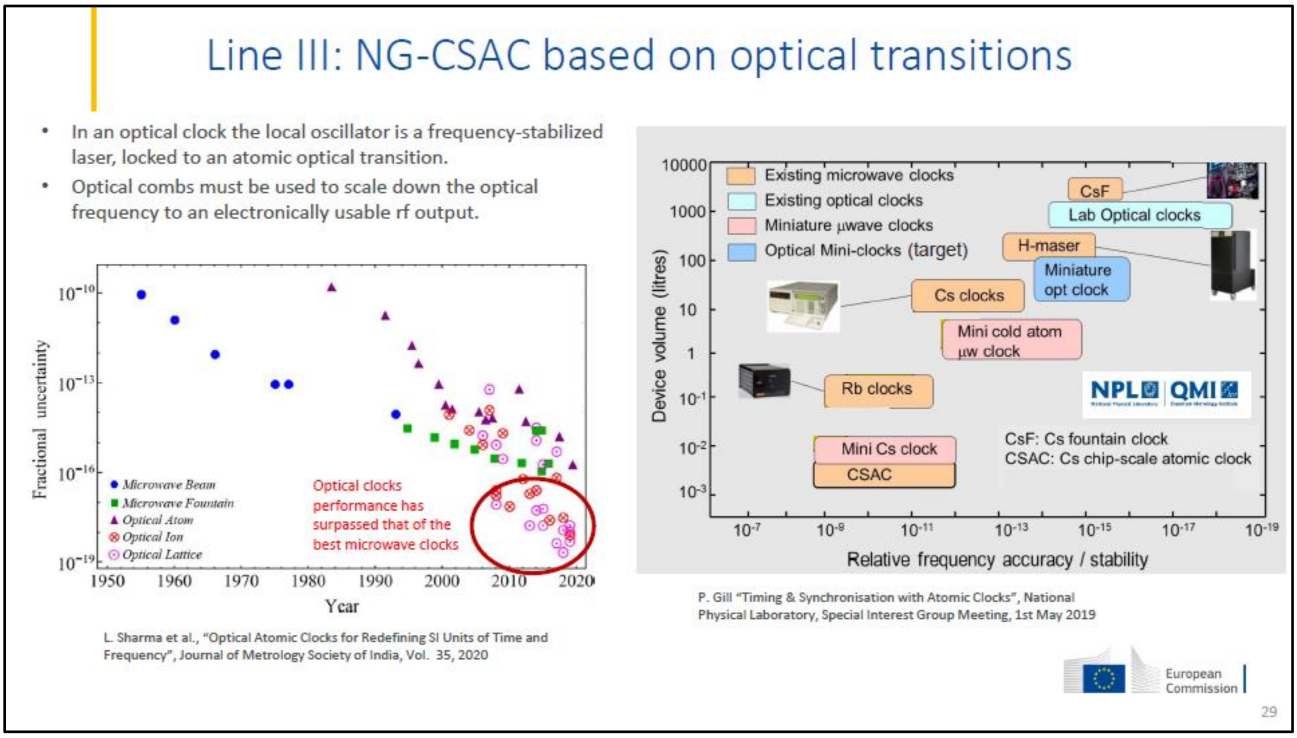
2.4 Optical transitions in warm vapours

In the last 15 years, atomic clocks based on optical transitions which outperform those based on microwave ones have emerged [Sharma 2020], [Gellesh 2020]. In such clocks the local oscillator is a laser stabilized to an optical atomic transition, and devices called frequency combs are required to derive an electronically usable radiofrequency signal from the stabilized optical tone. Generally speaking, optical clocks are large and complex devices, and do not lend themselves naturally to miniaturization. There is however the possibility of compact implementations in which sub-Doppler spectroscopic lines are obtain in warm atomic cells by using nonlinear optical effects that do not require complex laser cooling or confinement mechanisms such as ion trap or optical lattices. Two such effects have indeed been discovered in the 70s' and in the 80s', namely modulation transfer spectroscopy and two-photon transitions.

Modulation transfer spectroscopy has been used in Rubidium to develop a table-top optical clock (see e.g. [Zhang 2017]) and in Iodine to build an optical frequency standard which has also been tested in a sounding rocket [Schkolnik 2017], having spatial applications in mind. Two photon transition is being used both with the aim of developing a relatively compact (10-liters) clock [Martin 2018] and in the longer term for a fully miniaturized system [Newman 2019], [Maurice 2020].

Major obstacles for an optical CSAC are the development of integrated custom components such as fast-frequency-tunable lasers and frequency microcombs. Several programs aimed at developing the necessary enabling technologies are being funded, e.g. by DARPA, ESA and the EC.

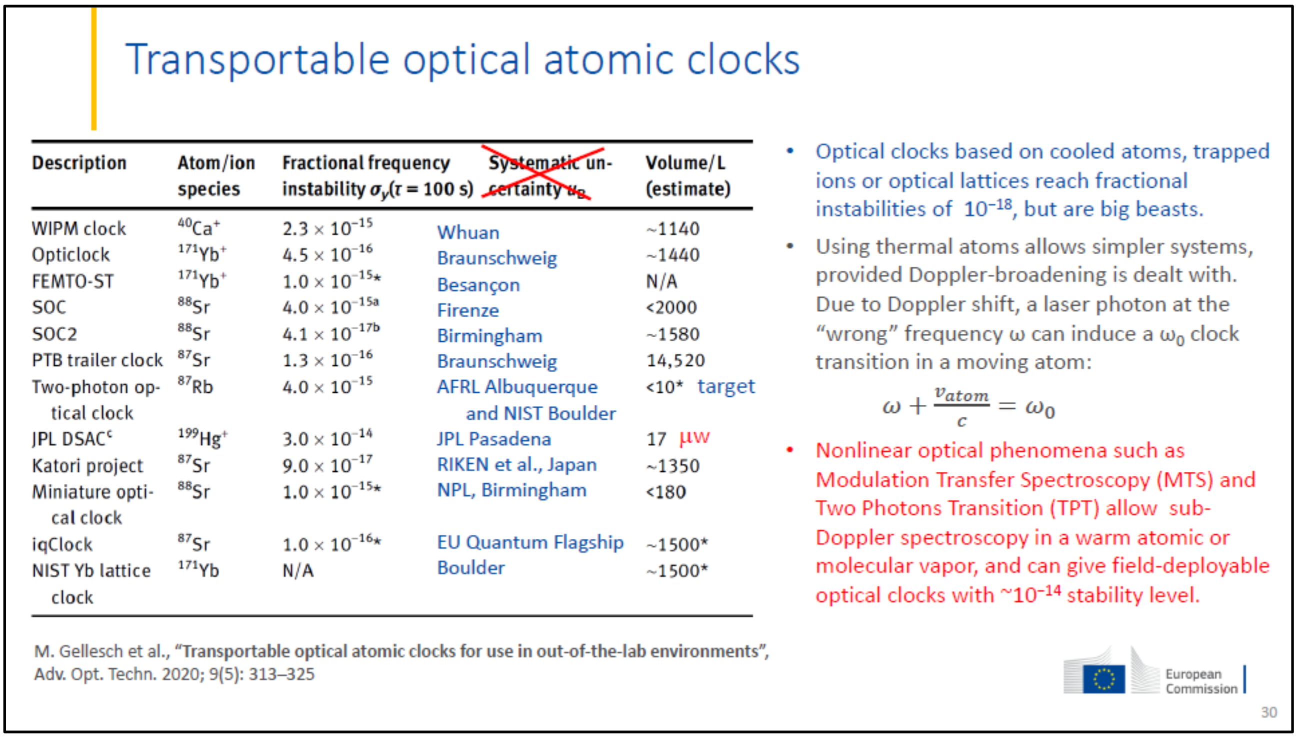


Line III: NG-CSAC based on optical transitions

- In an optical clock the local oscillator is a frequency-stabilized laser, locked to an atomic optical transition.
- Optical combs must be used to scale down the optical frequency to an electronically usable rf output.

L. Sharma et al., "Optical Atomic Clocks for Redefining SI Units of Time and Frequency", Journal of Metrology Society of India, Vol. 35, 2020

P. Gill "Timing & Synchronisation with Atomic Clocks", National Physical Laboratory, Special Interest Group Meeting, 1st May 2019



Transportable optical atomic clocks

Description	Atom/ion species	Fractional frequency instability $\sigma_y(\tau = 100\ \mathrm{s})$	~~Systematic uncertainty u_B~~	Volume/L (estimate)
WIPM clock	$^{40}Ca^+$	2.3×10^{-15}	Whuan	~1140
Opticlock	$^{171}Yb^+$	4.5×10^{-16}	Braunschweig	~1440
FEMTO-ST	$^{171}Yb^+$	$1.0 \times 10^{-15*}$	Besançon	N/A
SOC	^{88}Sr	4.0×10^{-15a}	Firenze	<2000
SOC2	^{88}Sr	4.1×10^{-17b}	Birmingham	~1580
PTB trailer clock	^{87}Sr	1.3×10^{-16}	Braunschweig	14,520
Two-photon optical clock	^{87}Rb	4.0×10^{-15}	AFRL Albuquerque and NIST Boulder	<10* target
JPL DSAC[c]	$^{199}Hg^+$	3.0×10^{-14}	JPL Pasadena	17 µW
Katori project	^{87}Sr	9.0×10^{-17}	RIKEN et al., Japan	~1350
Miniature optical clock	^{88}Sr	$1.0 \times 10^{-15*}$	NPL, Birmingham	<180
iqClock	^{87}Sr	$1.0 \times 10^{-16*}$	EU Quantum Flagship	~1500*
NIST Yb lattice clock	^{171}Yb	N/A	Boulder	~1500*

M. Gellesch et al., “Transportable optical atomic clocks for use in out-of-the-lab environments”, Adv. Opt. Techn. 2020; 9(5): 313–325

- Optical clocks based on cooled atoms, trapped ions or optical lattices reach fractional instabilities of 10^{-18}, but are big beasts.
- Using thermal atoms allows simpler systems, provided Doppler-broadening is dealt with. Due to Doppler shift, a laser photon at the “wrong” frequency ω can induce a ω_0 clock transition in a moving atom:

$$\omega + \frac{v_{atom}}{c} = \omega_0$$

- Nonlinear optical phenomena such as Modulation Transfer Spectroscopy (MTS) and Two Photons Transition (TPT) allow sub-Doppler spectroscopy in a warm atomic or molecular vapor, and can give field-deployable optical clocks with ~10^{-14} stability level.

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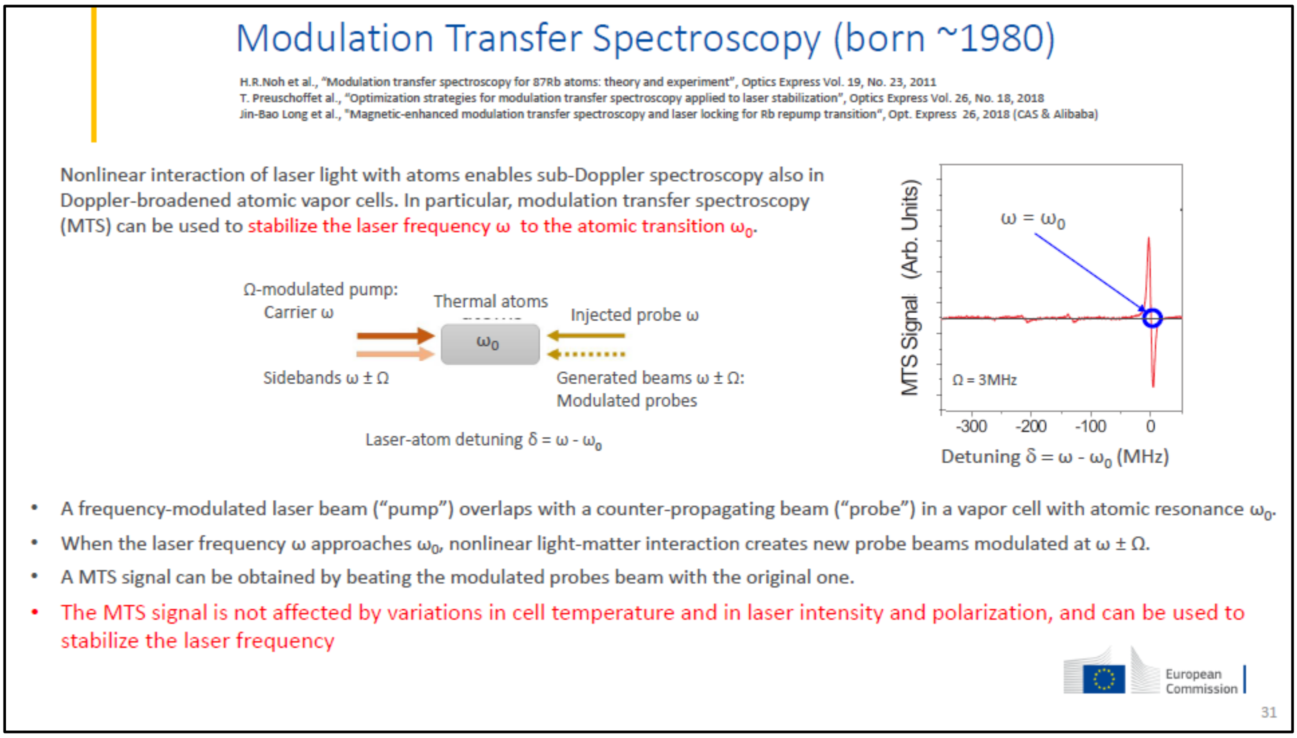

Modulation Transfer Spectroscopy (born ~1980)

H.R.Noh et al., “Modulation transfer spectroscopy for 87Rb atoms: theory and experiment”, Optics Express Vol. 19, No. 23, 2011
T. Preuschoffet al., “Optimization strategies for modulation transfer spectroscopy applied to laser stabilization”, Optics Express Vol. 26, No. 18, 2018
Jin-Bao Long et al., "Magnetic-enhanced modulation transfer spectroscopy and laser locking for Rb repump transition“, Opt. Express 26, 2018 (CAS & Alibaba)

Nonlinear interaction of laser light with atoms enables sub-Doppler spectroscopy also in Doppler-broadened atomic vapor cells. In particular, modulation transfer spectroscopy (MTS) can be used to stabilize the laser frequency ω to the atomic transition ω_0.

- A frequency-modulated laser beam (“pump”) overlaps with a counter-propagating beam (“probe”) in a vapor cell with atomic resonance ω_0.
- When the laser frequency ω approaches ω_0, nonlinear light-matter interaction creates new probe beams modulated at ω ± Ω.
- A MTS signal can be obtained by beating the modulated probes beam with the original one.
- The MTS signal is not affected by variations in cell temperature and in laser intensity and polarization, and can be used to stabilize the laser frequency

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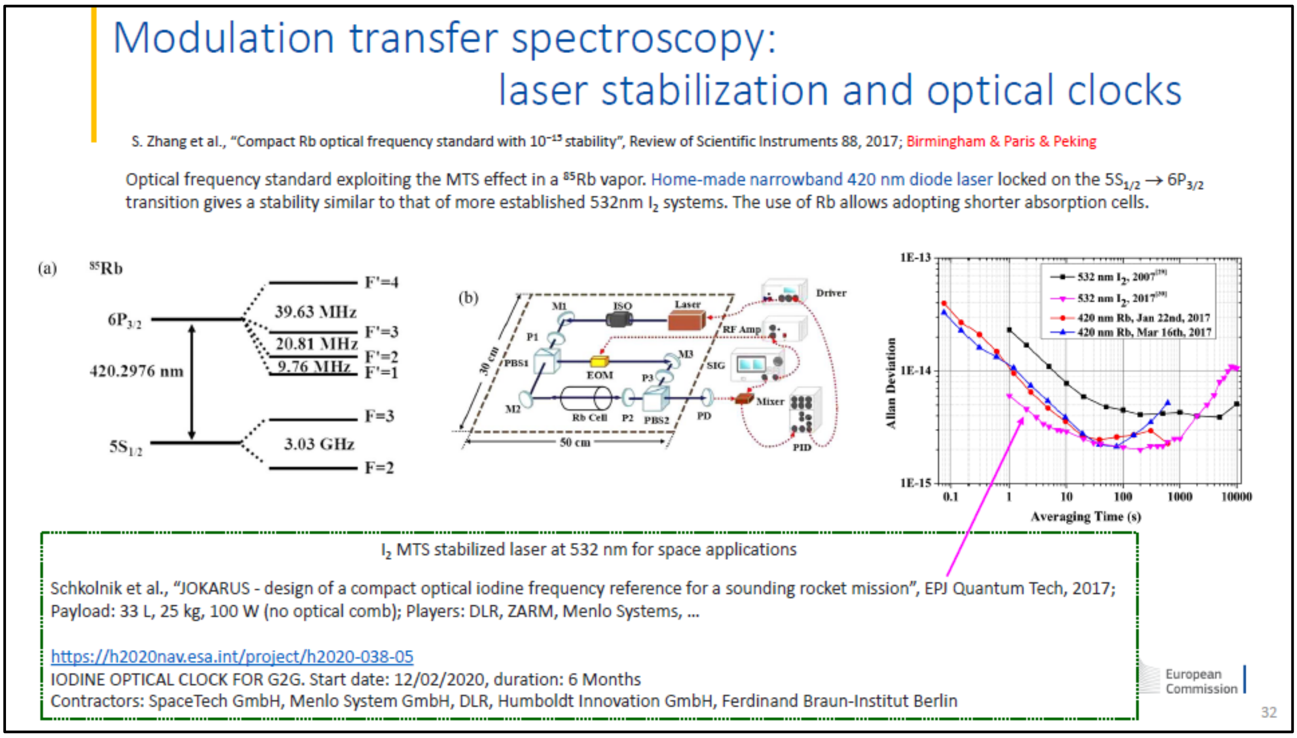

Modulation transfer spectroscopy: laser stabilization and optical clocks

S. Zhang et al., “Compact Rb optical frequency standard with 10^{-15} stability”, Review of Scientific Instruments 88, 2017; Birmingham & Paris & Peking

Optical frequency standard exploiting the MTS effect in a ^{85}Rb vapor. Home-made narrowband 420 nm diode laser locked on the $5S_{1/2} \rightarrow 6P_{3/2}$ transition gives a stability similar to that of more established 532nm I_2 systems. The use of Rb allows adopting shorter absorption cells.

I_2 MTS stabilized laser at 532 nm for space applications

Schkolnik et al., “JOKARUS - design of a compact optical iodine frequency reference for a sounding rocket mission”, EPJ Quantum Tech, 2017; Payload: 33 L, 25 kg, 100 W (no optical comb); Players: DLR, ZARM, Menlo Systems, ...

https://h2020nav.esa.int/project/h2020-038-05
IODINE OPTICAL CLOCK FOR G2G. Start date: 12/02/2020, duration: 6 Months
Contractors: SpaceTech GmbH, Menlo System GmbH, DLR, Humboldt Innovation GmbH, Ferdinand Braun-Institut Berlin

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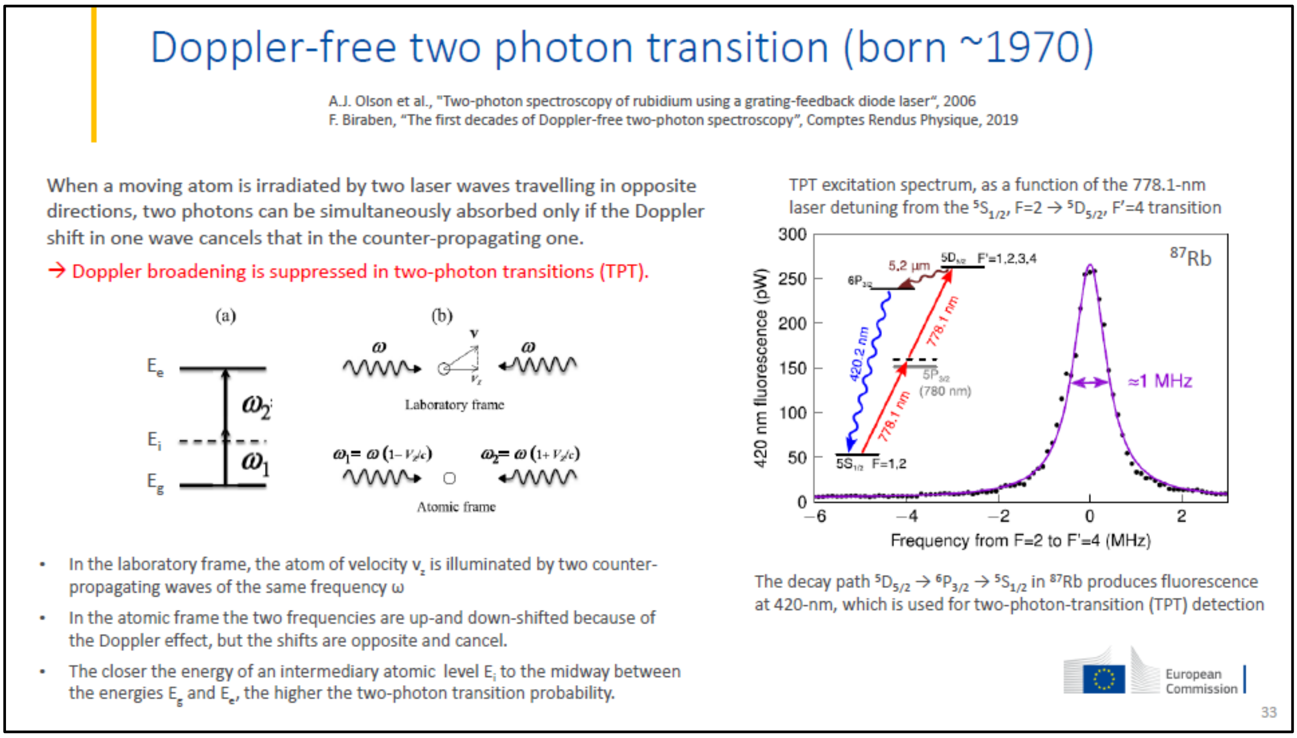

Doppler-free two photon transition (born ~1970)

A.J. Olson et al., "Two-photon spectroscopy of rubidium using a grating-feedback diode laser“, 2006
F. Biraben, “The first decades of Doppler-free two-photon spectroscopy”, Comptes Rendus Physique, 2019

When a moving atom is irradiated by two laser waves travelling in opposite directions, two photons can be simultaneously absorbed only if the Doppler shift in one wave cancels that in the counter-propagating one.

→ Doppler broadening is suppressed in two-photon transitions (TPT).

- In the laboratory frame, the atom of velocity v_z is illuminated by two counter-propagating waves of the same frequency ω
- In the atomic frame the two frequencies are up-and down-shifted because of the Doppler effect, but the shifts are opposite and cancel.
- The closer the energy of an intermediary atomic level E_i to the midway between the energies E_g and E_e, the higher the two-photon transition probability.

TPT excitation spectrum, as a function of the 778.1-nm laser detuning from the $^5S_{1/2}$, F=2 → $^5D_{5/2}$, F'=4 transition

The decay path $^5D_{5/2} \rightarrow {}^6P_{3/2} \rightarrow {}^5S_{1/2}$ in ^{87}Rb produces fluorescence at 420-nm, which is used for two-photon-transition (TPT) detection

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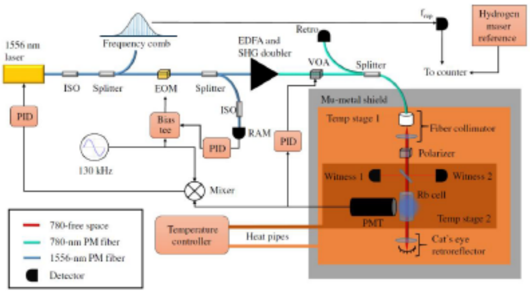
Two Photon Transition optical clock (AFRL)

K.W. Martin et al., "Compact Optical Atomic Clock Based on a Two-Photon Transition in Rubidium", Physical Review Applied, Vol. 9, No. 014019, 2018
Applied Technology Associates, USA / Air Force Research Laboratory, USA / Space Dynamics Laboratory, USA / National Institute of Standards and Technology, USA

Optical clock based on the 778-nm two-photon transition in rubidium, developed from existing vapor-cell and laser technologies and from commercial components.

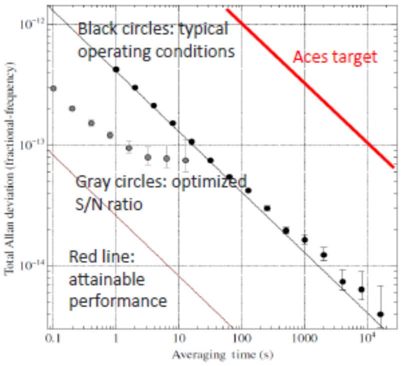
Target: ADEV 1×10^{-13} at 1 s and 1×10^{-15} at 1 day, ≲10 L, ≲20 W



~30 L setup

778.1-nm light: second-harmonic generation from telecom laser

Rb vapor cell: 5×5×25 mm, 100 °C



Black circles: typical operating conditions

Aces target

Gray circles: optimized S/N ratio

Red line: attainable performance

Next steps:

- Improving detection and stability of laser power
- Removing helium contamination in vapor cell (via vacuum chamber or helium-resistant cell)
- Increasing the efficiency of the fluorescence detection
- Increasing the effective length of the cell (with multiple passes and/or higher vapor density)
- Increasing the laser beam radius and laser power
- Miniaturizing and harden the laser and the frequency comb for future field deployment
- Automating the locking electronics and simplifying the control loop architecture
- Reducing power consumption of the frequency comb (currently needs four pump lasers)
- For space use: overcoming radiation-induced darkening of optical components

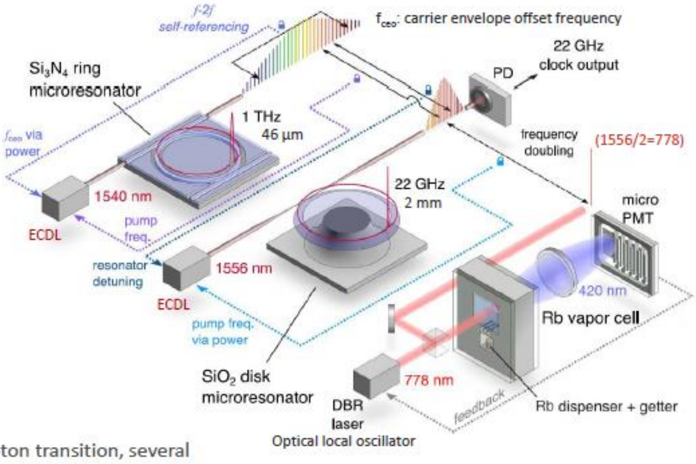
Chip-scale optical atomic clock – NIST et al.

Z.L. Newman et al., Architecture for the photonic integration of an optical atomic clock, OPTICA, 2019 - NIST Boulder Colorado, Univ. Colorado, CalTech, Charles Draper Labs, Stanford Univ., Centre for nanoscale science and technology (NIST Maryland); Funding: DARPA & U.S. Department of Defense (DoD)

A semiconductor DBR laser is frequency-stabilized by the photomultiplier tube (PMT) signal to the optical two-photon transition at 385.284 THz (780nm) in a micro-fabricated rubidium vapor cell.

The optical tone is coherently divided into a 22 GHz clock by two interlocked Kerr-micro-resonator frequency combs realized with silicon photonics.

Two interlocked microcombs are needed: a wideband comb to eliminate the frequency offset (1Thz spacing), and a narrowband comb (22GHz spacing) to produce an electronically detectable output.



In order to stabilize the 22Ghz output to the atomic two-photon transition, several feedback loops must be implemented to cascade the two optical combs and to lock the microcombs' pump lasers to the DBR local oscillator.

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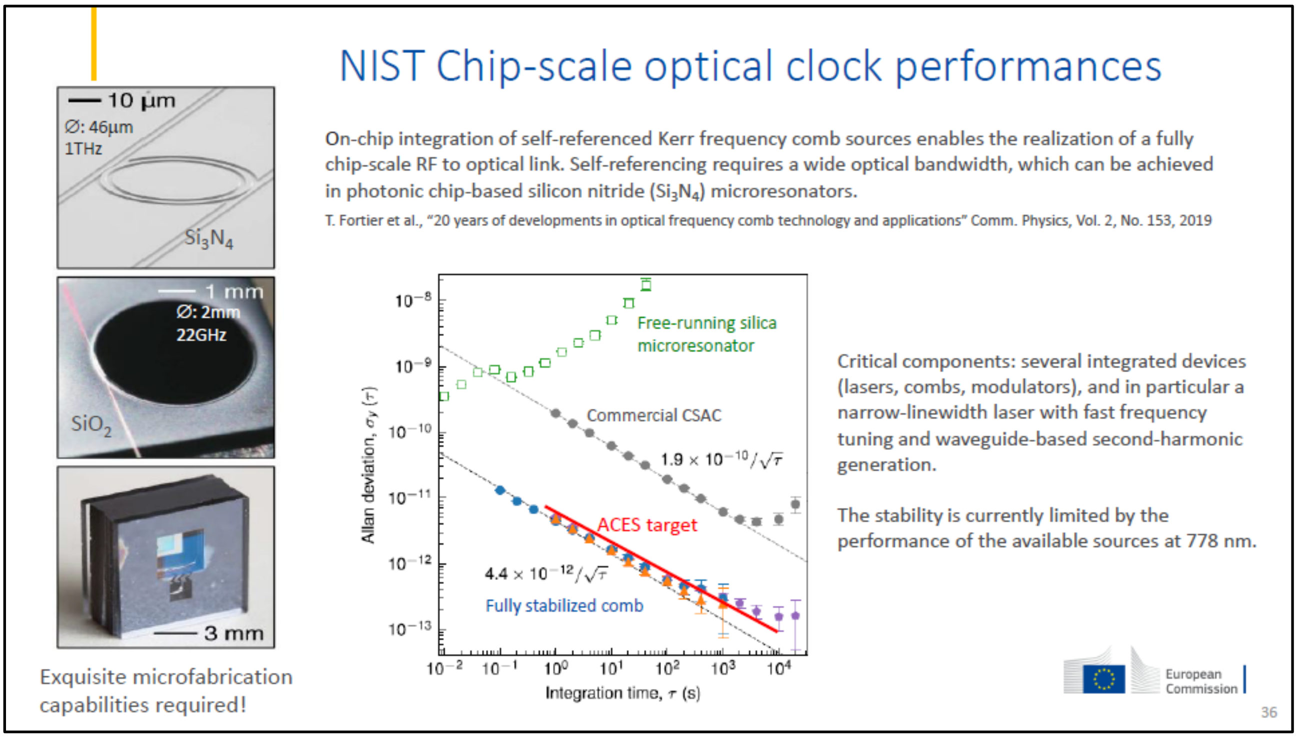


NIST Chip-scale optical clock performances

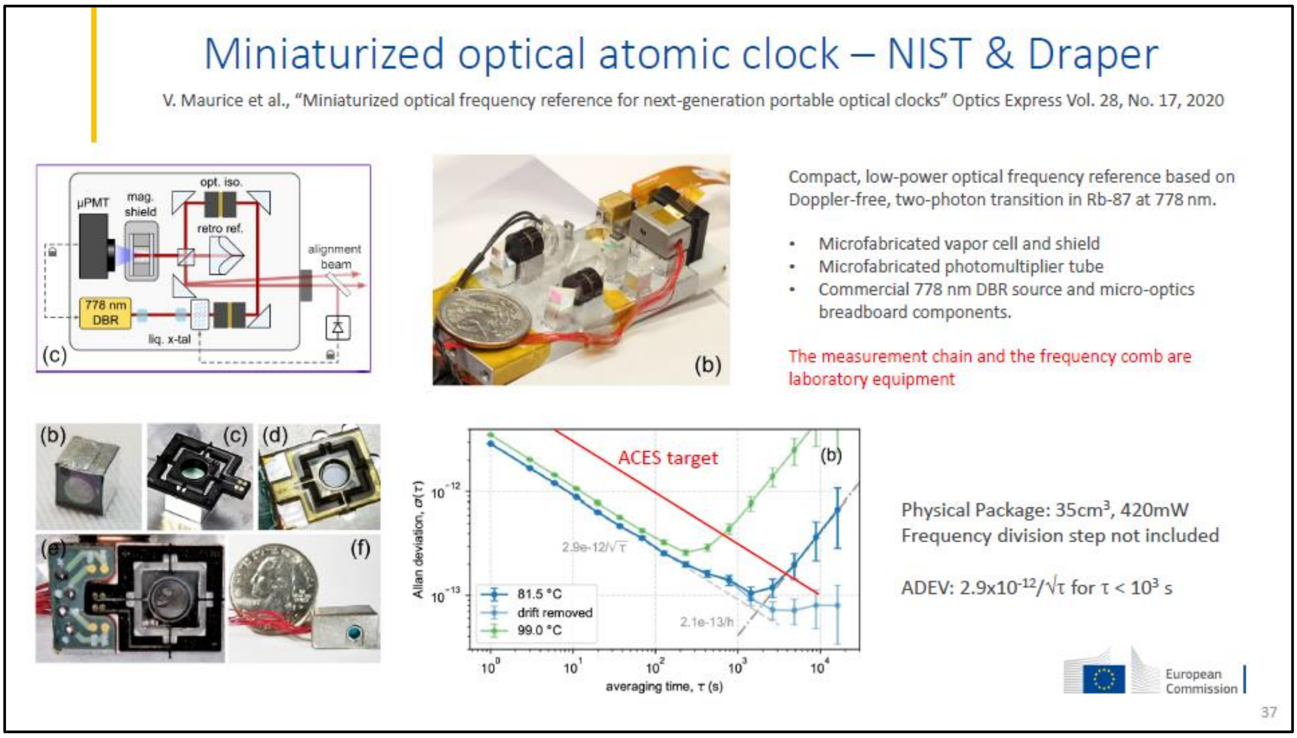
On-chip integration of self-referenced Kerr frequency comb sources enables the realization of a fully chip-scale RF to optical link. Self-referencing requires a wide optical bandwidth, which can be achieved in photonic chip-based silicon nitride (Si_3N_4) microresonators.

T. Fortier et al., "20 years of developments in optical frequency comb technology and applications" Comm. Physics, Vol. 2, No. 153, 2019

Critical components: several integrated devices (lasers, combs, modulators), and in particular a narrow-linewidth laser with fast frequency tuning and waveguide-based second-harmonic generation.

The stability is currently limited by the performance of the available sources at 778 nm.

Exquisite microfabrication capabilities required!



Miniaturized optical atomic clock – NIST & Draper

V. Maurice et al., "Miniaturized optical frequency reference for next-generation portable optical clocks" Optics Express Vol. 28, No. 17, 2020

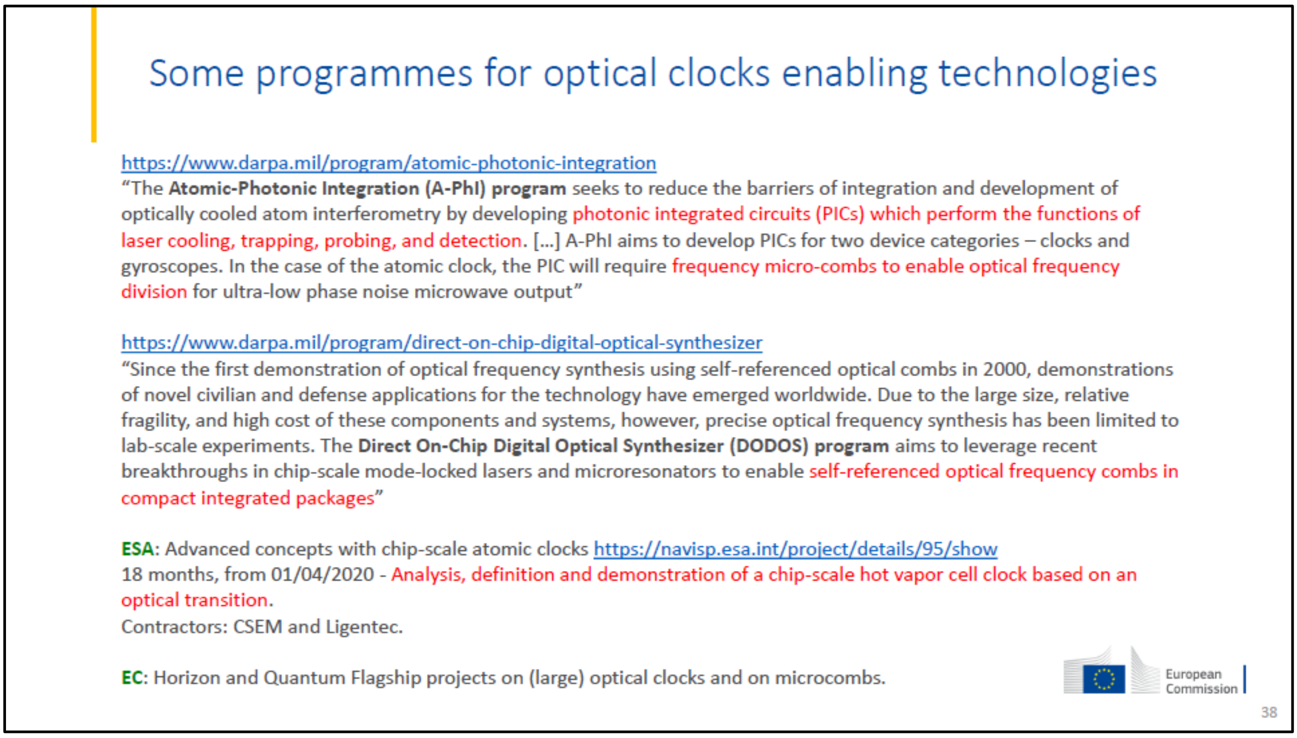
Compact, low-power optical frequency reference based on Doppler-free, two-photon transition in Rb-87 at 778 nm.

- Microfabricated vapor cell and shield
- Microfabricated photomultiplier tube
- Commercial 778 nm DBR source and micro-optics breadboard components.

The measurement chain and the frequency comb are laboratory equipment

Physical Package: 35cm^3, 420mW
Frequency division step not included

ADEV: $2.9 \times 10^{-12}/\sqrt{\tau}$ for $\tau < 10^3$ s



Some programmes for optical clocks enabling technologies

https://www.darpa.mil/program/atomic-photonic-integration
“The **Atomic-Photonic Integration (A-PhI) program** seeks to reduce the barriers of integration and development of optically cooled atom interferometry by developing photonic integrated circuits (PICs) which perform the functions of laser cooling, trapping, probing, and detection. […] A-PhI aims to develop PICs for two device categories – clocks and gyroscopes. In the case of the atomic clock, the PIC will require frequency micro-combs to enable optical frequency division for ultra-low phase noise microwave output”

https://www.darpa.mil/program/direct-on-chip-digital-optical-synthesizer
“Since the first demonstration of optical frequency synthesis using self-referenced optical combs in 2000, demonstrations of novel civilian and defense applications for the technology have emerged worldwide. Due to the large size, relative fragility, and high cost of these components and systems, however, precise optical frequency synthesis has been limited to lab-scale experiments. The **Direct On-Chip Digital Optical Synthesizer (DODOS) program** aims to leverage recent breakthroughs in chip-scale mode-locked lasers and microresonators to enable self-referenced optical frequency combs in compact integrated packages”

ESA: Advanced concepts with chip-scale atomic clocks https://navisp.esa.int/project/details/95/show
18 months, from 01/04/2020 - Analysis, definition and demonstration of a chip-scale hot vapor cell clock based on an optical transition.
Contractors: CSEM and Ligentec.

EC: Horizon and Quantum Flagship projects on (large) optical clocks and on microcombs.

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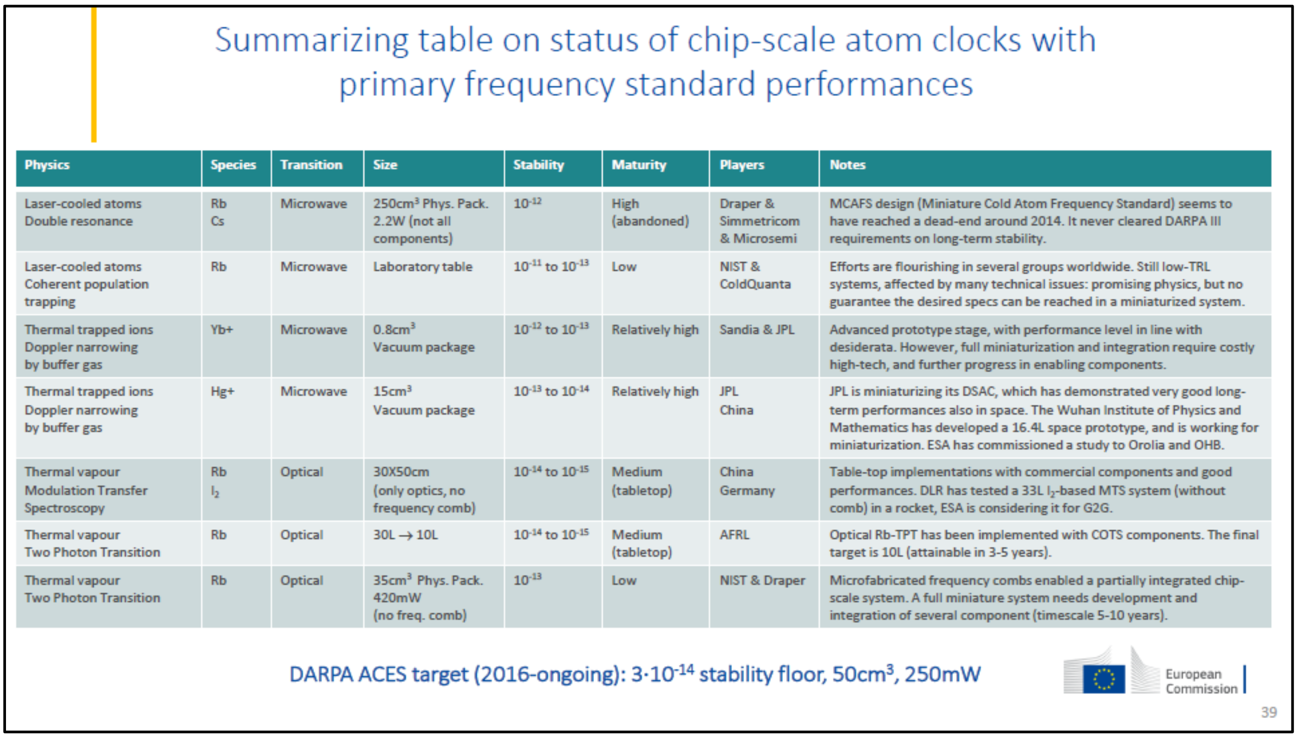
3 Conclusions

According to publicly-available information, the USA is the only country with dedicated programs aimed at developing a next-generation chip scale atomic clock, i.e. a miniaturized device with the stability performance of a primary frequency standard. DARPA sponsored NG-CSAC efforts at least since 2010, i.e. even before the first CSACs based on coherent population trapping (CPT) in warm alkali metals were made commercially available. DARPA is aiming at a device with CSAC-like CSWaP footprints (broadly speaking, a ~50cm^3 battery-operated clock at a cost of some thousands $) and the performance of a primary frequency standard (namely, a ~10^{-14} stability floor at 1 day): this constitutes an extremely challenging target, which after 10 years of efforts has not yet generated a viable product.

Systems with the highest technological maturity are based on double-resonance microwave transitions in trapped ions, for which vacuum packages have been built and characterized; however, their full integration and miniaturization requires complex customized technologies, and may impact on performances. Systems based on CPT microwave transitions in laser-cooled Rb atoms are being developed; although in principle they can reach the targeted specs, their performances are in practice still limited by several technical factors in the cold atom source and in the CPT optical implementation. Exploiting sub-Doppler optical transitions in warm atomic or molecular vapours shows that 10-L systems can be feasible in the next 3-5 years; however, a truly chip-scale atomic clock based on optical transitions requires the development of several customized micro-components and needs long-term support.

The early start of the DARPA programs on NG-CSACs allowed the USA developing substantial technical expertise and intellectual property. Conversely, Europe is presently not only dependent on imports for commercial CSACs of the current generation, but is still missing a coherent framework of support actions for the development of next-generation miniaturized clocks. Given the range and the sensitivity of the applications enabled by such devices, it can be argued that EU-27 is presently running the risk of prolonging to the next decades its strategic dependence on clocks with critical space and defence applications.

Since the physical platforms on which NG-CSACs could be based have reached very different levels of technological maturity, a wide range of support actions is likely required to foster the development of a device which in the next decade can become important for the EU-27 strategic autonomy: in particular, applied research and academic-industrial collaborations should be encouraged to foster the development of critical components and manufacturing technologies. It is worth noting that targeting a NG-CSAC can become instrumental for bringing to fruition a wide range of physical effects, which can be leveraged not only for measuring time but also to develop new miniaturized devices to be used e.g. for autonomous navigation and electromagnetic sensing. In this sense, supporting the development of NG-CSACs would be a highly consequential political decision, able to spur progress is several fields.



Summarizing table on status of chip-scale atom clocks with primary frequency standard performances

Physics	Species	Transition	Size	Stability	Maturity	Players	Notes
Laser-cooled atoms Double resonance	Rb Cs	Microwave	250cm^3 Phys. Pack. 2.2W (not all components)	10^{-12}	High (abandoned)	Draper & Simmetricom & Microsemi	MCAFS design (Miniature Cold Atom Frequency Standard) seems to have reached a dead-end around 2014. It never cleared DARPA III requirements on long-term stability.
Laser-cooled atoms Coherent population trapping	Rb	Microwave	Laboratory table	10^{-11} to 10^{-13}	Low	NIST & ColdQuanta	Efforts are flourishing in several groups worldwide. Still low-TRL systems, affected by many technical issues: promising physics, but no guarantee the desired specs can be reached in a miniaturized system.
Thermal trapped ions Doppler narrowing by buffer gas	Yb+	Microwave	0.8cm^3 Vacuum package	10^{-12} to 10^{-13}	Relatively high	Sandia & JPL	Advanced prototype stage, with performance level in line with desiderata. However, full miniaturization and integration require costly high-tech, and further progress in enabling components.
Thermal trapped ions Doppler narrowing by buffer gas	Hg+	Microwave	15cm^3 Vacuum package	10^{-13} to 10^{-14}	Relatively high	JPL China	JPL is miniaturizing its DSAC, which has demonstrated very good long-term performances also in space. The Wuhan Institute of Physics and Mathematics has developed a 16.4L space prototype, and is working for miniaturization. ESA has commissioned a study to Orolia and OHB.
Thermal vapour Modulation Transfer Spectroscopy	Rb I_2	Optical	30X50cm (only optics, no frequency comb)	10^{-14} to 10^{-15}	Medium (tabletop)	China Germany	Table-top implementations with commercial components and good performances. DLR has tested a 33L I_2-based MTS system (without comb) in a rocket, ESA is considering it for G2G.
Thermal vapour Two Photon Transition	Rb	Optical	30L → 10L	10^{-14} to 10^{-15}	Medium (tabletop)	AFRL	Optical Rb-TPT has been implemented with COTS components. The final target is 10L (attainable in 3-5 years).
Thermal vapour Two Photon Transition	Rb	Optical	35cm^3 Phys. Pack. 420mW (no freq. comb)	10^{-13}	Low	NIST & Draper	Microfabricated frequency combs enabled a partially integrated chip-scale system. A full miniature system needs development and integration of several component (timescale 5-10 years).

DARPA ACES target (2016-ongoing): $3{\cdot}10^{-14}$ stability floor, 50cm^3, 250mW

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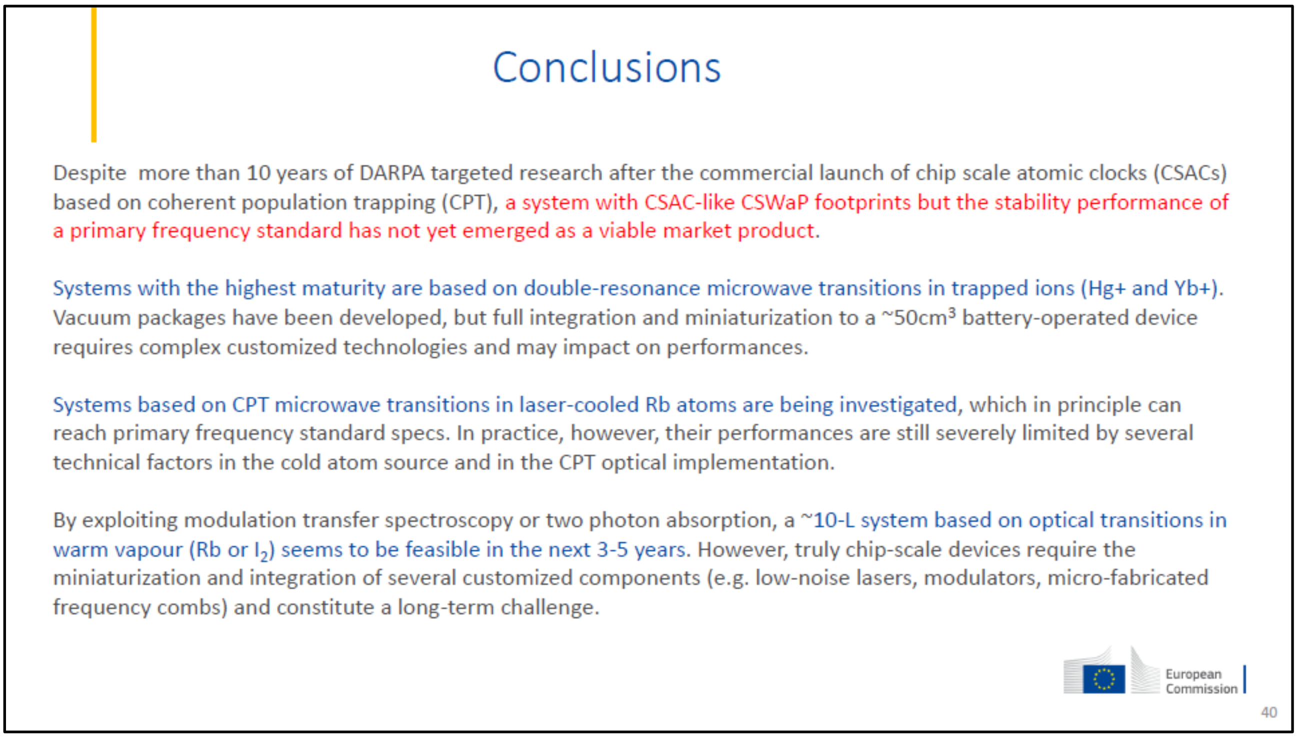

Conclusions

Despite more than 10 years of DARPA targeted research after the commercial launch of chip scale atomic clocks (CSACs) based on coherent population trapping (CPT), a system with CSAC-like CSWaP footprints but the stability performance of a primary frequency standard has not yet emerged as a viable market product.

Systems with the highest maturity are based on double-resonance microwave transitions in trapped ions (Hg+ and Yb+). Vacuum packages have been developed, but full integration and miniaturization to a ~50cm^3 battery-operated device requires complex customized technologies and may impact on performances.

Systems based on CPT microwave transitions in laser-cooled Rb atoms are being investigated, which in principle can reach primary frequency standard specs. In practice, however, their performances are still severely limited by several technical factors in the cold atom source and in the CPT optical implementation.

By exploiting modulation transfer spectroscopy or two photon absorption, a ~10-L system based on optical transitions in warm vapour (Rb or I_2) seems to be feasible in the next 3-5 years. However, truly chip-scale devices require the miniaturization and integration of several customized components (e.g. low-noise lasers, modulators, micro-fabricated frequency combs) and constitute a long-term challenge.

European Commission

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List of acronyms

AFRL Air Force Research Laboratory

CBT Caesium Beam Tube

CPT Coherent Population Trapping

CSAC Chip Scale Atomic Clock

DARPA Defense Advanced Research Projects Agency

DARPA ACES Atomic Clocks with Enhanced Stability

DARPA IMPACT Integrated Micro Primary Atomic Clock Technology

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

DLR Deutsches Zentrum für Luft und Raumfahrt, i.e. German Aerospace Center

DSAC Deep Space Atomic Clock

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

MOT Magneto Optical Trap

NG-CSAC Next Generation Chip Scale Atomic Clock

NIST National Institute for Science and Technology

OCXO Oven Controlled Crystal Oscillator

OPC Optical Pump Caesium

PHM Passive Hydrogen Maser

PNT Positioning, Navigation, and Timing

REA Research Executive Agency

RFS Rubidium Frequency Standard

SWaP Size Weight and Power

TCXO Temperature Controlled Crystal Oscillator

TRL Technology Readiness Level

VCSEL Vertical Cavity Surface Emitting Laser

VCXO Voltage Controlled Crystal Oscillator

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