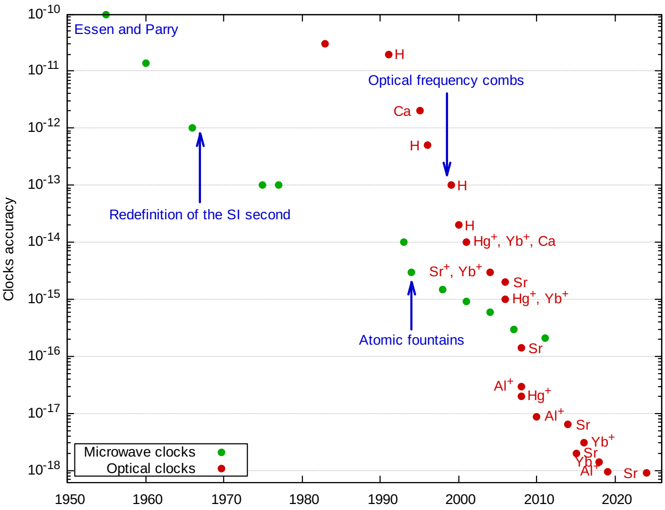
Horloges à réseau optique : vers une redéfinition de la seconde SI

Jérôme Lodewyck, Équipe “Métrologie des fréquences optiques”

History of atomic clocks

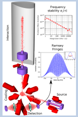


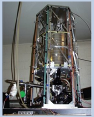
Optical clocks: going to optical transitions

Microwave clocks ⟶ **Optical clocks**

Cold atom clocks

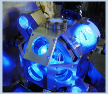
- Cs and Rb atomic fountains





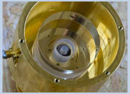
⟶

- Optical lattice cocks (Sr, Hg, Yb)



Ultra-stable oscillators

- Maser, CSO, Quartz



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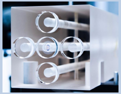
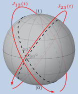
- Cavities, Spectral hole burning



Comparison tools

- Satellites (GNSS) 10^{-16} @ 1 week



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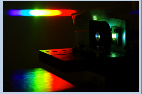
- Fiber links, combs 10^{-19} @ 3 hour



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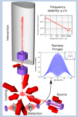
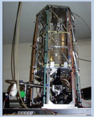

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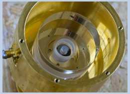

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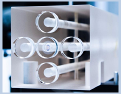


Open questions
Ultimate performances?
Operational?

Comparison tools

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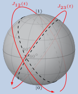

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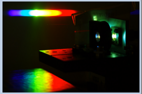
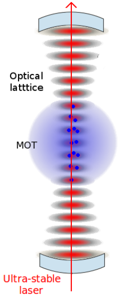


Content

Content

Optical lattice clocks



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- Stabilize the clock laser on the narrow resonance

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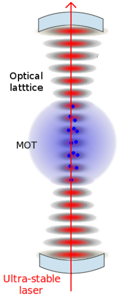

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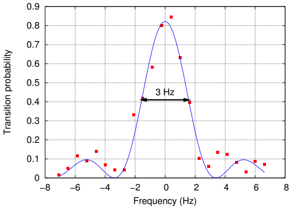
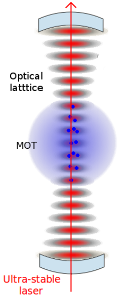
Combine several advantages:

- Optical clock
- Large number of atoms (10^4)



$Q = 10^{14}$

Optical lattice clocks



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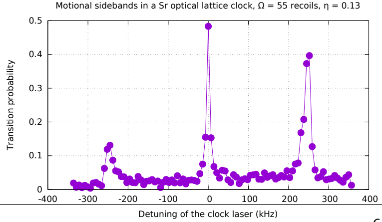

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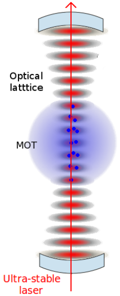

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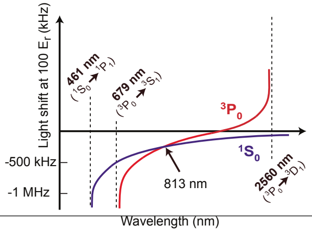
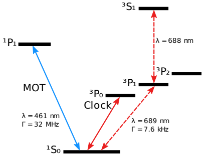
Combine several advantages:

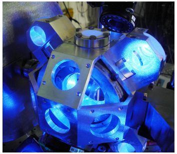
- Optical clock
- Large number of atoms (10^4)
- Lamb-Dicke regime: insensitive to motional effects
- Magic wavelength for unperturbed trapping



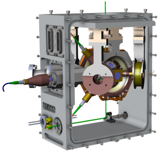
Strontium optical lattice clocks at SYRTE



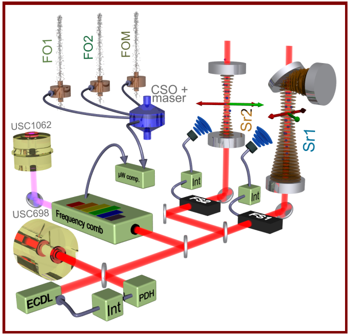
SrB



Sr2



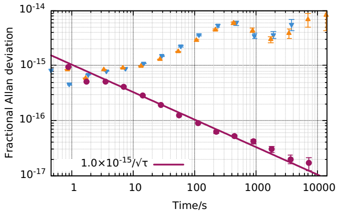
SrC



Accuracy

Effect	Uncertainty in 10^{-18}
Black-body radiation shift	12
Quadratic Zeeman shift	5
Lattice light-shift	3
Lattice spectrum	1
Density shift	8
Line pulling	6
Background collisions	4
Static charges	1.5
Total	**17** $\times 10^{-18}$

Stability



Hg optical lattice clock

Hg lattice clock

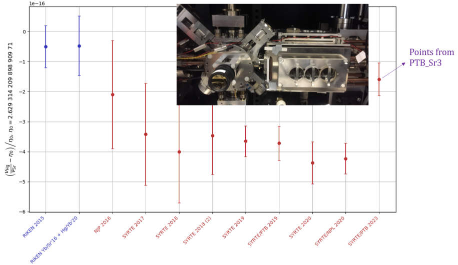
- Low sensitivity to BBR
- Trapping and probe lasers in the UV
- Current accuracy at 5.4×10^{-17}.

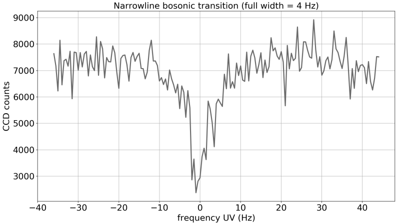
Clock comparisons

- Comparisons with Sr clocks (SYRTE, Europe)
- Comparisons with Yb^+ (PTB, NPL)

Bosonic isotope

- Larger lifetime
- Needs finer control of mag. field, collisions

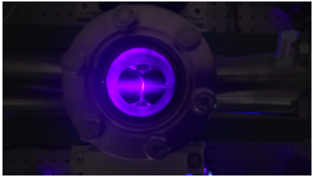


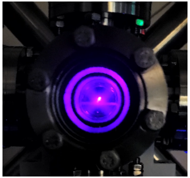


Transportable clocks

The SYRTE Transportable Yb optical lattice clock (Roymage, Razpoutyne)

- Transp. clock for applications in geodesy (measuring gravitation with the red-shift)
- Collaboration with IPGP, SHOM, IGN
- Original design with two science chambers





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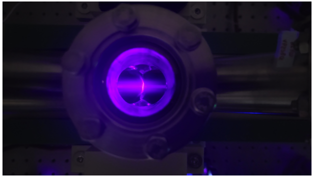
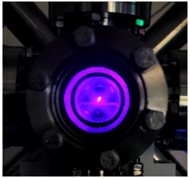
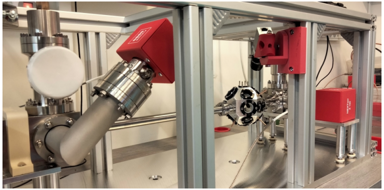




The AQuRA european transportable Strontium clock

- European quantum flagship project
- PI: University of Amsterdam
  Industry partners, inc. EXAIL, Menlo systems
- Transp. Sr clock with 5×10^{-18} accuracy
- At SYRTE: Physics package
  Collaboration with MUTA



Content

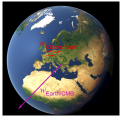
International comparisons by optical fibre links

Comparisons

- Yearly comparisons with PTB, NPL, INRIM
- Involves up to 10 optical clocks
  + frequency combs + links
- Resolution below 10^{-17}
- Operation over weeks

Applications

- Metrology
  - Verify the accuracy of clocks
  - (Re-)measure frequency ratios (Sr and Hg at SYRTE)
- Tests of fundamental physics
  - Collaboration with the "Théorie et Metrologie" team
  - Tests of Local Lorentz Invariance



  - Search for dark matter

CONTRIBUTING TO TAI WITH AN OPTICAL CLOCK

TAI = Temps Atomique International

- Long, quasi-continuous, operations of optical clocks (slots of 5 days)
- Calibration of a H-maser connected to UTC → Collaboration with the "RefMet" team
- Calibration of TAI submitted to BIPM, included in Circular T 350 (Feb. 2017) as a non-steering contribution,

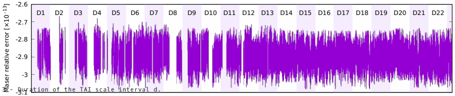
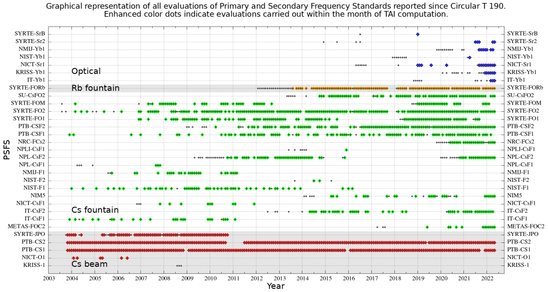


Table 1: Estimate of d by individual PSFS measurements and corresponding uncertainties.
All values are expressed in 10**-15 and are valid only for the stated period of estimation.

Standard	Period of Estimation		d	uA	uB	ul/Lab	ul/Tai	u	uSrep	Ref(uS)	Ref(uB)	uB(Ref)	Steer	Note
PTB-CS1	57784	57809	-18.71	6.00	8.00	0.00	0.15	10.00	PFS/NA		T148	8.	Y	(1)
PTB-CS2	57784	57809	-0.28	3.00	12.00	0.00	0.15	12.37	PFS/NA		T148	12.	Y	(1)
SYRTE-FO2	57784	57809	-1.30	0.40	0.32	0.11	0.32	0.61	PFS/NA		T301	0.23	Y	(2)
SYRTE-FORb	57784	57809	-0.91	0.20	0.29	0.11	0.32	0.49	0.7	[1]	T328	0.34	Y	(2)
SYRTE-SR2	56954	56964	0.81	0.20	0.04	0.10	0.53	0.57	0.5	[1]	[2]	0.05	N	(3)
SYRTE-SR2	57179	57199	0.46	0.20	0.04	0.10	0.28	0.36	0.5	[1]	[2]	0.05	N	(3)
SYRTE-SR2	57469	57479	-1.39	0.25	0.20	0.11	0.53	0.63	0.5	[1]	[2]	0.05	N	(3)
SYRTE-SR2	57539	57554	-1.24	0.30	0.04	0.11	0.37	0.49	0.5	[1]	[2]	0.05	N	(3)
SYRTE-SRB	57539	57554	-1.22	0.25	0.05	0.10	0.37	0.46	0.5	[1]	[2]	0.05	N	(3)
PTB-CSF2	57779	57809	-1.36	0.09	0.20	0.03	0.13	0.26	PFS/NA		T287	0.41	Y	(4)



QUANTUM EFFECTS IN OPTICAL LATTICE CLOCKS

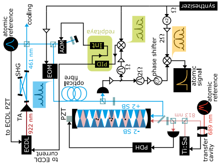
QUANTUM PROJECTION NOISE:

Noise on the measurement of p due to the quantum nature of the atoms:

$$\delta N_{\mathrm{QPN}} \simeq \sqrt{N}$$

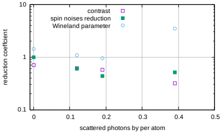
NON-DESTRUCTIVE DETECTION

- Measure the number of atoms N with a cavity
- Noise-immune heterodyne detection system
- Can resolve a “single” atom and recycle them



MEASURING UNDER THE QUANTUM PROJECTION NOISE

- SNR below QPN
- Observation of quantum correlations



Content

Redefinition of the SI second: roadmap

Current situation

- The SI second is based on Cs, now 2 orders of magnitude behind optical clocks
- System of recommended frequency "floating" with respect to the SI second
- Optical frequency standards with significant contributions to TAI

⇒ **need for a new definition based on optical clocks**

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- Optical frequency standards with significant contributions to TAI

$\Rightarrow$ **need for a new definition based on optical clocks**

Roadmap by the BIPM, CCTF and its WG

1. at least three different optical clocks (either in different laboratories, or of different species) have demonstrated validated uncertainties of about two orders of magnitude better than the best Cs atomic clocks of the time.
2. at least three independent measurements of at least one optical clock from milestone 1 have been compared in different institutes (with, e.g., $\Delta\nu/\nu < 5 \times 10^{-18}$) either by transportable clocks, advanced links, or frequency ratio closures.
3. three independent measurements of the optical frequency standards of milestone 1 with three independent Cs primary clocks have been performed, where the measurements are limited essentially by the uncertainty of these Cs fountain clocks (with, e.g., $\Delta\nu/\nu < 5 \times 10^{-16}$).
4. optical clocks (SRS) contribute regularly to TAI.
5. optical frequency ratios between a few (at least 5) other optical frequency standards have been performed; each ratio measured at least twice by independent laboratories and agreement was found to better than, e.g., $\Delta\nu/\nu < 5 \times 10^{-18}$.

Redefinition of the SI second: constants in the SI

Unification of physical theories

$\Rightarrow$ A unit disappears, a constant is fixed

- Thermodynamics: heat = energy $\Rightarrow$ The calorie is a derived unit, 1 cal = 4.184 J
- Relativity: space and time unified, $c = 299\,792\,458$ m/s exactly (SI, 1983)

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New SI in 2018: all units are based on fixing fundamental constant

- no more units based on artifacts
- c, h, e, k_B, $\mathcal{N}_A$ ...
- ...except $\Delta\nu_{\mathrm{Cs}}$

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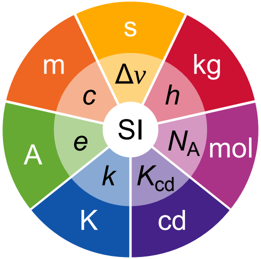
Which constant to fix?

- $G \rightarrow$ uncertainty 10^{-5}
- m_e, $R_\infty \rightarrow$ uncertainty 3×10^{-10} or 1.1×10^{-12}.

$\Rightarrow$ not suitable in practice



Redefinition of the SI second: options

Under consideration at the BIPM/CCTF working groups:

3. ~~Option 3: Setting the numerical value of a fundamental constant~~

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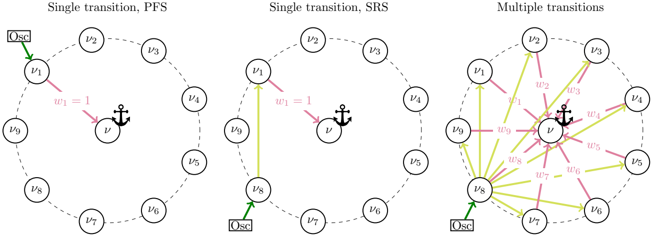
1. Option 1: Replacing Cs with an optical transition $\rightarrow \Delta\nu_{Sr} = N$ Hz
   $\rightarrow$ which one ? Sr, Yb, Yb^+, Sr^+, Ca^+, Th, . . .

3. ~~Option 3: Setting the numerical value of a fundamental constant~~

Redefinition of the SI second: options

Under consideration at the BIPM/CCTF working groups:

1. Option 1: Replacing Cs with an optical transition → $\Delta\nu_{Sr} = N$ Hz
   → which one ? Sr, Yb, Yb^{+}, Sr^{+}, Ca^{+}, Th, ...
2. Option 2: Defining the second with multiple transitions → $\prod_i \nu_i^{w_i} \equiv N\,\mathrm{Hz}$



Metrologia **56** 055009 (2019)

- Optimal generalisation of PFS / SRS
- Update of the unit possible without drift

3. ~~Option 3: Setting the numerical value of a fundamental constant~~

Redefinition of the SI second: status

- Now: working groups discussing options, pro & cons, consequences for end users
  $\rightarrow$ SYRTE involved
- Reaching a consensus
- Adoption by the CGPM (Conférence Générale des Poids et Mesures)
  $\rightarrow$ 2030 at the earliest, most likely 2034

Questions?