The SI second: present realization and path to a redefinition

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IAG WG 2.1 Relativistic Geodesy

2nd meeting 10-11 October 2018

Bureau International des Poids et Mesures

Resolutions of the 13th CGPM (1967)

- Resolution 1
  - *The second is the duration of 9 192 631 770 periods of the radiation corresponding to the transition between the two hyperfine levels of the ground state of the caesium 133 atom*.

- Resolution 2 (Freely translated from French by g.....)
  - *Considering that the cesium frequency standard is still perfectible and current experiments allow the hope of producing other standards with even better qualities to define the second,*
  - *invites expert organizations and laboratories in the field of atomic frequency standards to actively pursue their studies*.

This is happening now!

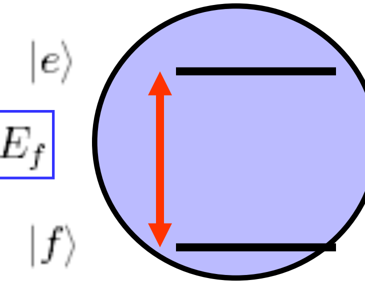
Outline

- **The present realization of the SI second and evolutions in frequency standards**
- Path to a redefinition of the SI second
- Techniques for the comparison of remote frequency standards

Present (atomic) definition of the SI second

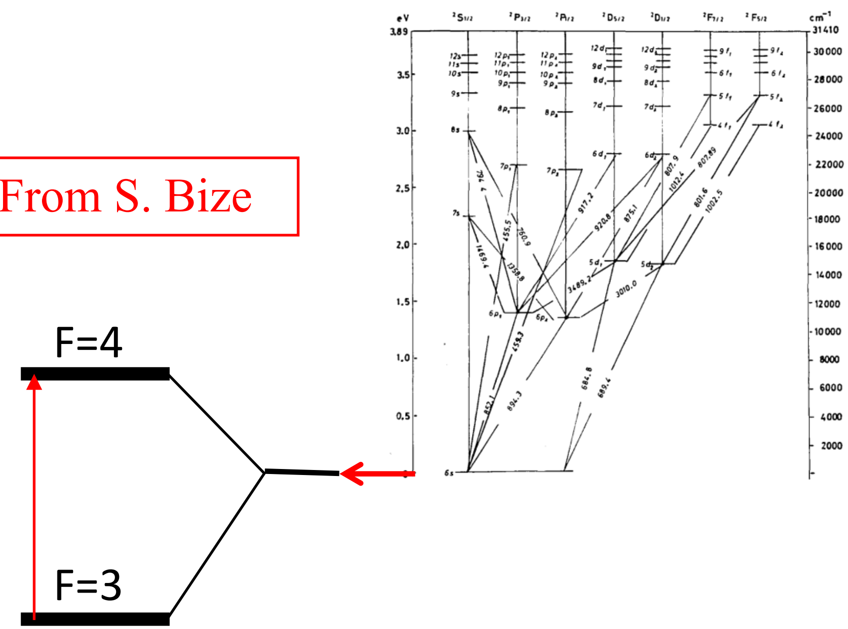
- Atoms have quantized energy levels and the energy difference between two levels corresponds to a frequency via Planck's relation

$$\boxed{\hbar\omega_{ef} = h\nu_{ef} = E_e - E_f}$$



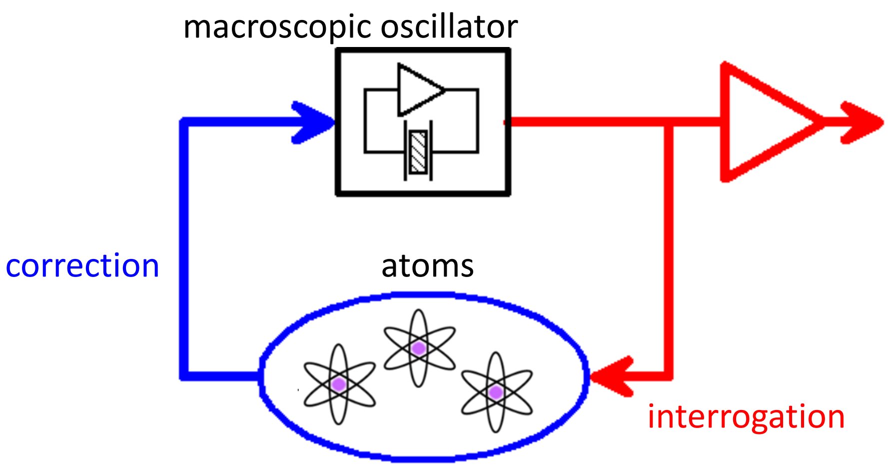
- In the definition adopted by the CGPM in 1967,
  - The two levels correspond to an hyperfine transition (interaction between nuclear spin and electronic spin) of ^{133}Cs
  - The frequency difference between the two levels is defined as 9 192 631 770 Hz

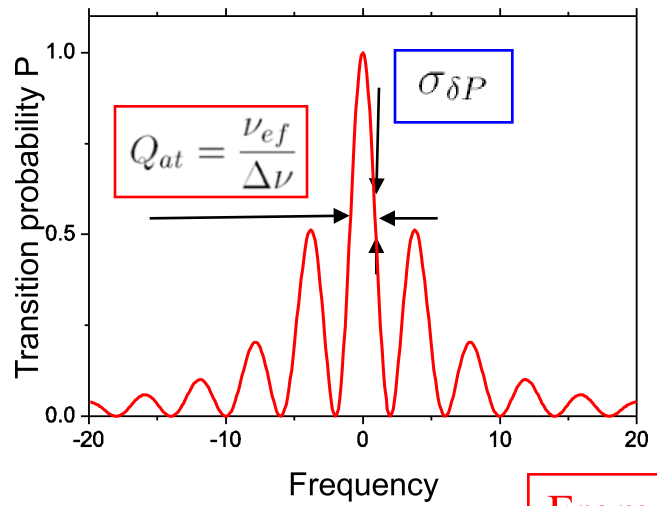
From S. Bize



Principles of atomic frequency standards

- Building blocks:





From S. Bize

- Output: An electromagnetic signal connected to the atomic transition

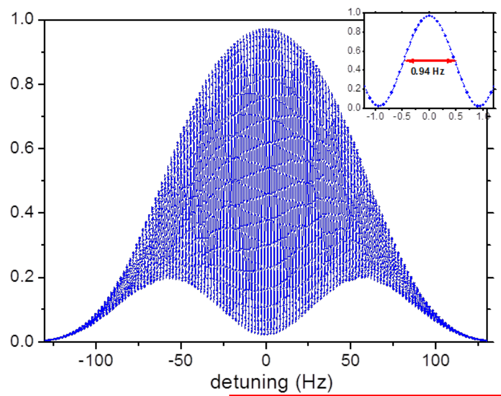
$$\omega(t) = \omega_{ef} \times (1 + \varepsilon + y(t))$$

- Properties
  - Accuracy: overall uncertainty on ε
  - Stability: statistical properties of $y(t)$, characterized with $\sigma_y(\tau)$

Present primary standards: Laser cooled atomic fountains

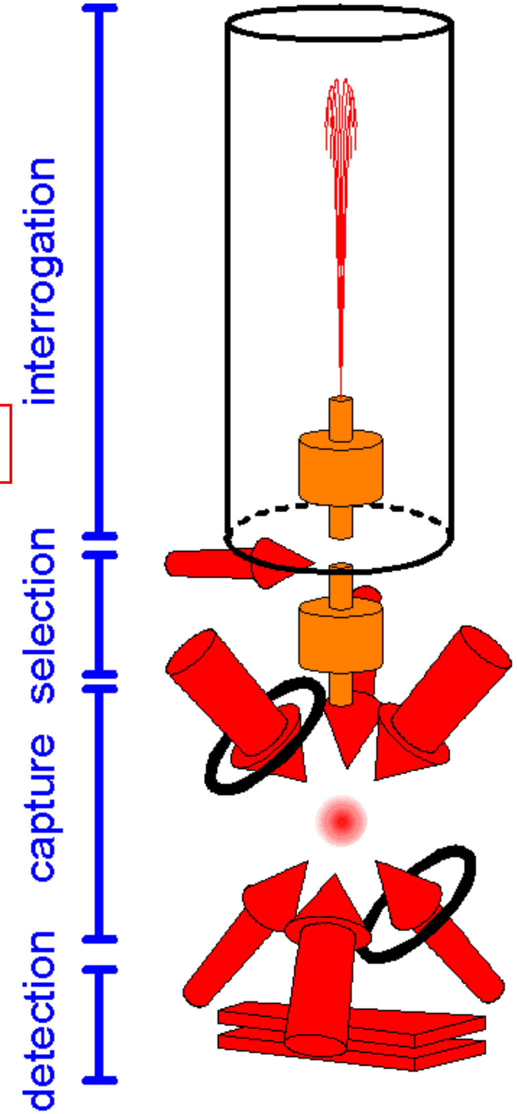
- Principle
  - Laser-cooled atomic sample currently Cs and Rb
  - Low velocity spread ~ 1 cm.s^{-1}

  => Stability can be as low as few 10^{-14} in 1 s



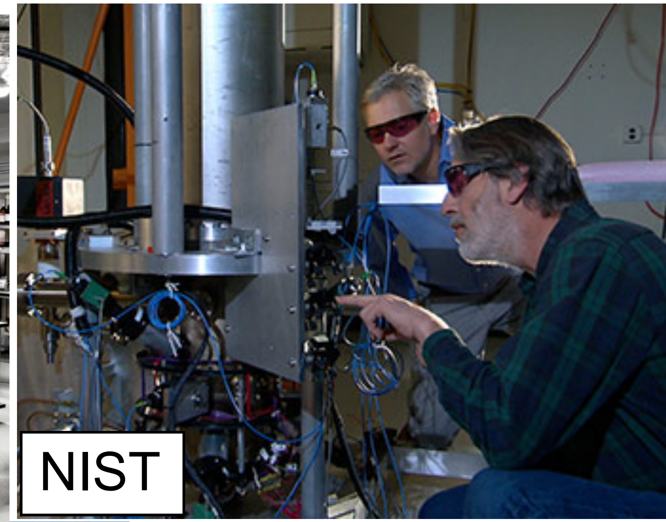
From S. Bize

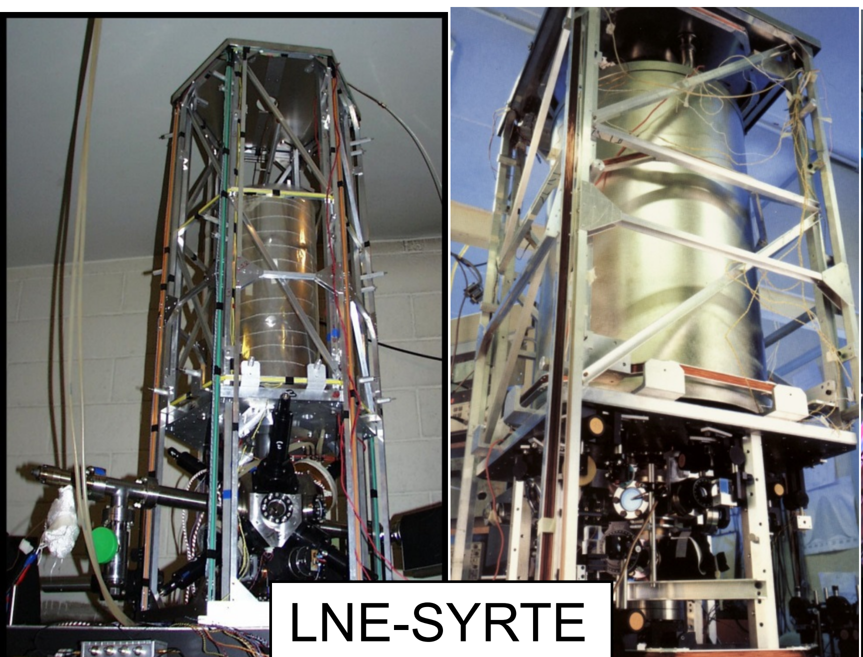
- Developed since end 1990s
- First regular reports for TAI ~2000 uncertainty order 10^{-15}
- Uncertainty budget of all systematic effects improved by one order of magnitude since that time

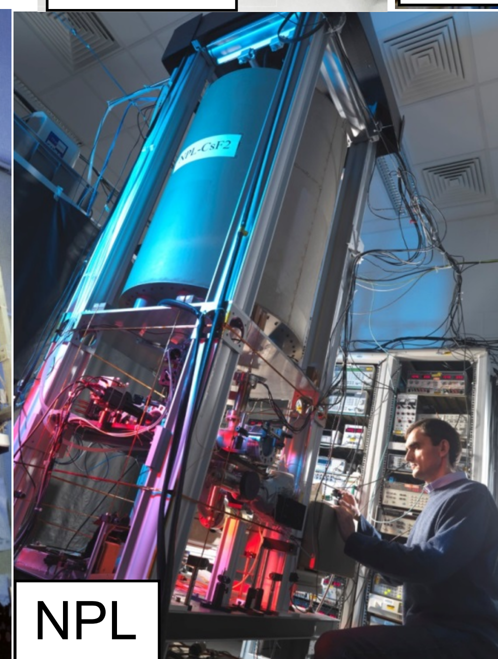


Atomic fountains now

- Now present in the main time labs for providing accuracy of TAI
- Also used to steer local times scales (OP, PTB, USNO)
- Accuracy down to $\sim 2 \times 10^{-16}$
- Also used as clocks (USNO, more to come)

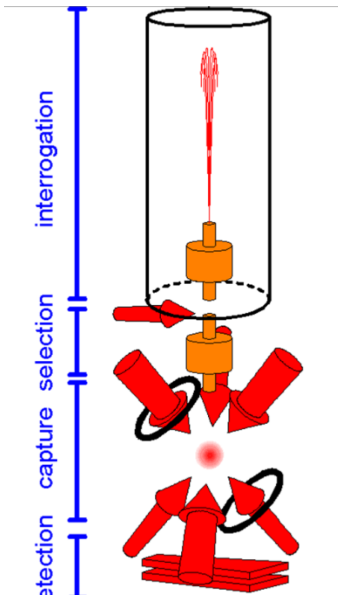


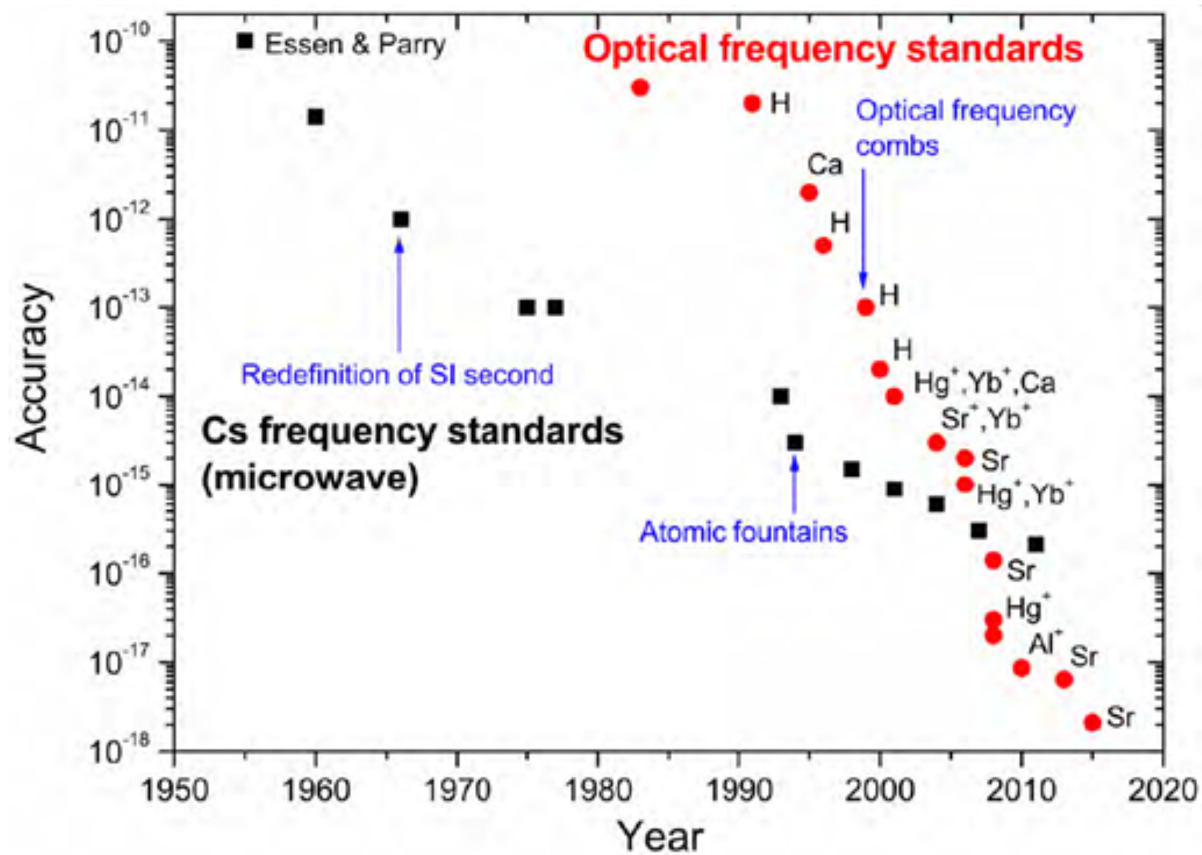




Progresses of frequency standards

- Cs fountains now at $1\text{x}10^{-16}$, close to their limit.





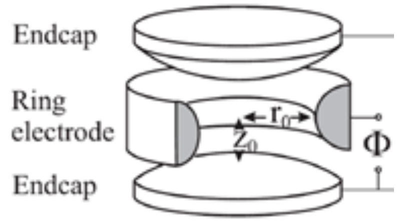
From S. Bize

- Optical frequency standards have been easy to handle since frequency combs appeared. They are now in the low $\text{x}10^{-18}$.

Optical frequency standards

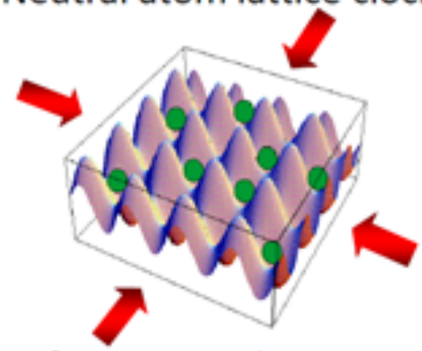
- Two main types of optical frequency standards
  - (Single) ion in an EM trap
    - Low SNR
    - Lots of studied ions
  - (Many) neutral atoms trapped in a lattice
    - High SNR
    - Reduce shifts / interactions between atoms
- If the uncertainty budget of all systematic effects can be characterized, such optical clocks are termed secondary frequency standards.
- The frequency comb allows to measure the frequency of optical transitions with respect to the Cs transition, within the limits of Cs primary frequency standards.

Single ion clock



Electrodynamic (Paul) trap

Neutral atom lattice clock



CCL-CCTF Working Group on Frequency Standards

Mission (Terms of Reference)

a) to make recommendations to the CCL for radiations to be used for the realization of the definition of the meter and to make recommendations to the CCTF for radiations to be used as secondary representations of the second,

b) to maintain, together with the BIPM, the list of recommended frequency standard values and wavelength values for applications including the practical realization of the definition of the meter and secondary representations of the second,

c) to take responsibility for key comparisons of standard frequencies such as CCL-K11,

d) to respond to future needs of both the CCL and CCTF concerning standard frequencies relevant to the respective communities.

The list of the CCL-CCTF WG on FS

Metrologia 55 (2018) 188 F Riehle *et al*

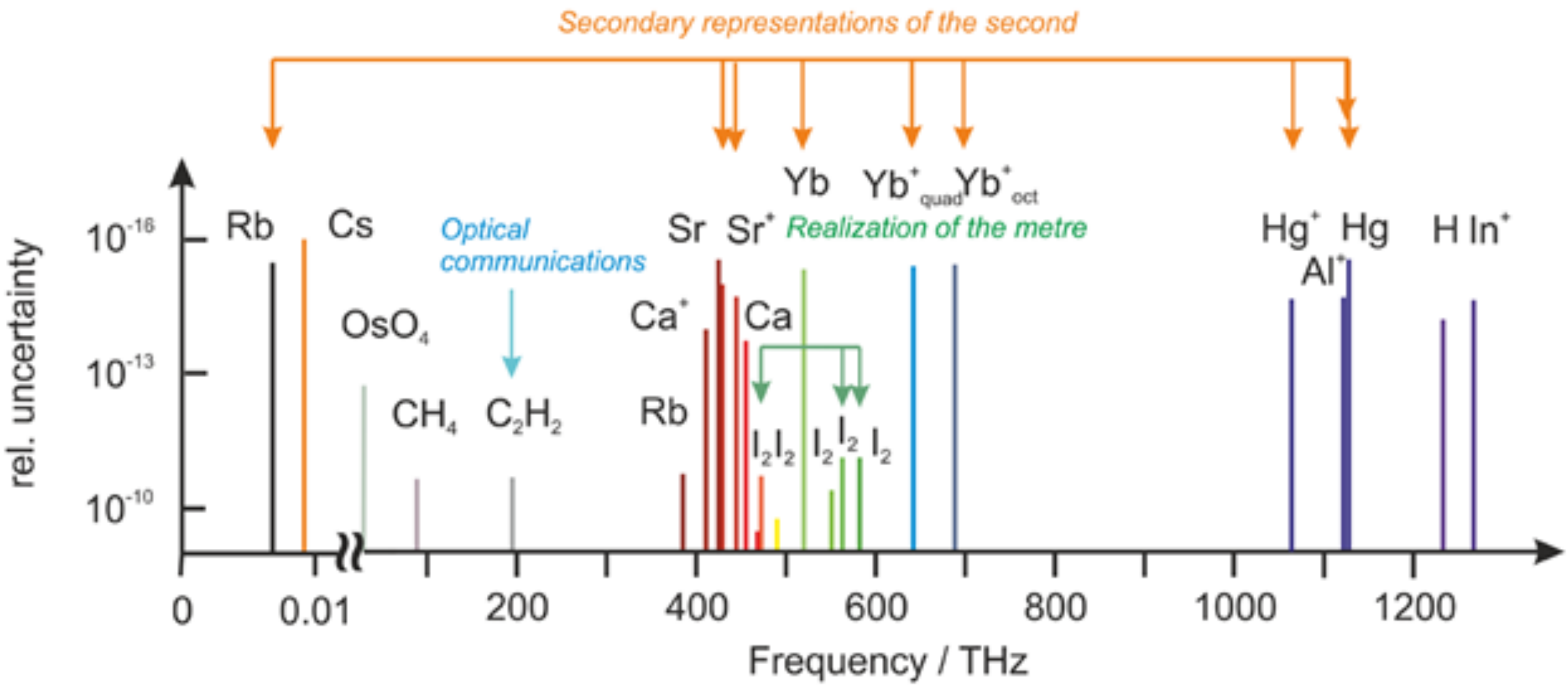
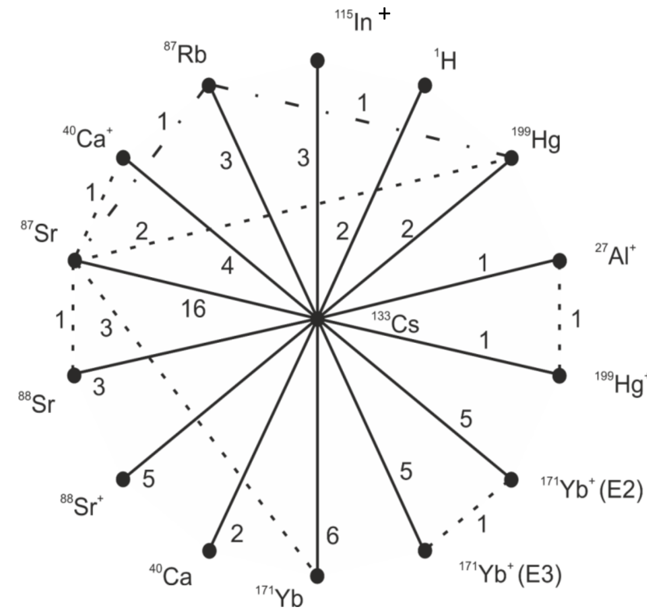


Figure 3. Graphical summary of the recommended frequency standard values (as of 2017) and their specific use for optical communications, for the realization of the metre, or for SRS.

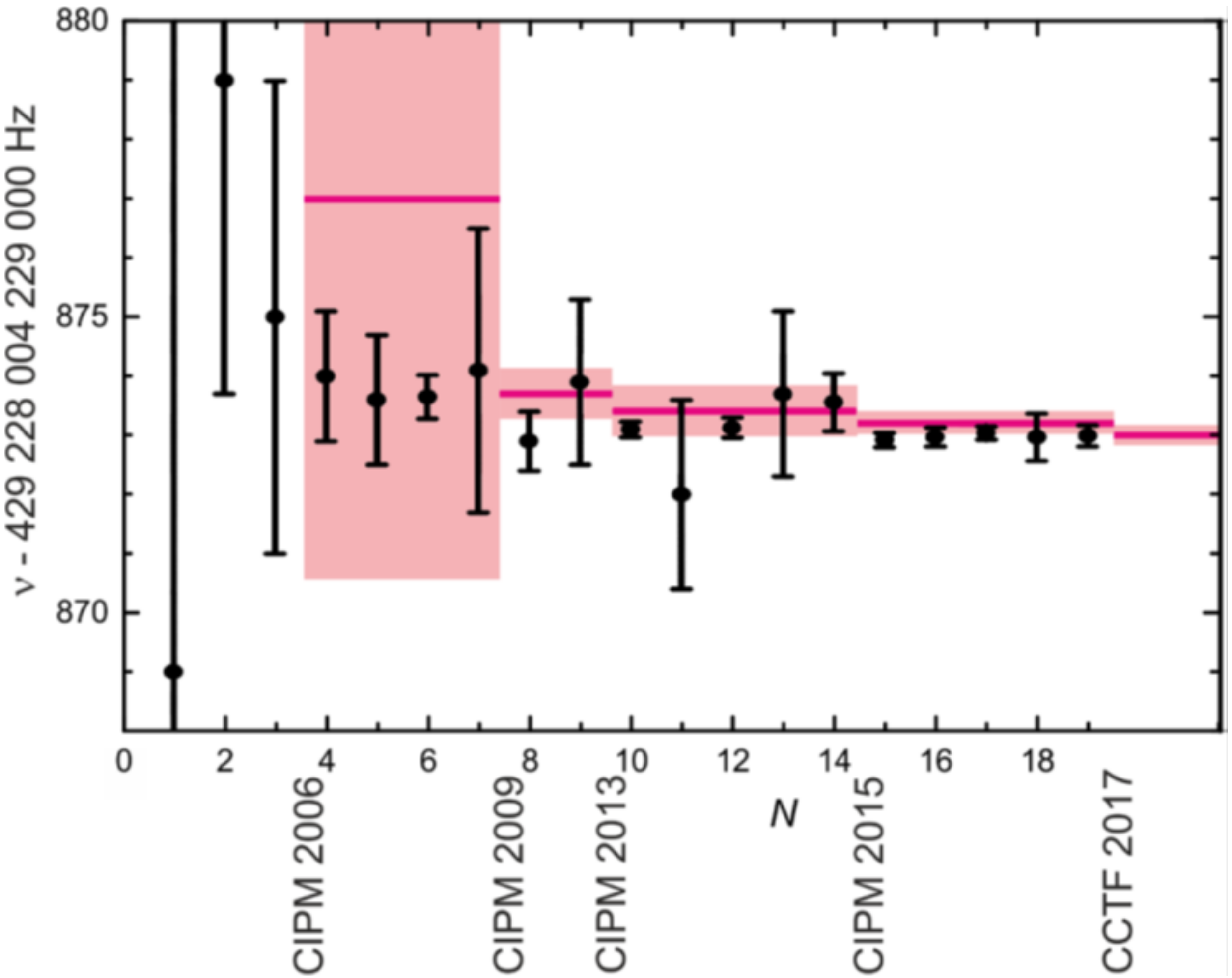
- For the secondary representations of the second, typically revises the list of transitions and recommended values for each session of the CCTF (every 2-3 years)

Results of the 2017 adjustment by the WGFS



- The adjustment procedure provides a self-consistent set of recommended values of the transition frequencies, based on a redundant set of data.
- 2017 situation
  - 14 frequencies to determine
  - 59 absolute measurements
  - 11 ratios
- Stated uncertainties are estimated by the working group "by consensus".
- Results presented to the CCTF in June 2017
- Methods of the working group described in Riehle, F., Gill, P., Arias, F., Robertsson, L.: Recommended frequency standard values for applications including the practical realisation of the metre and secondary representations of the second; Metrologia 2018

Example: the case of ^{87}Sr



Riehle et al. 2018

Figure 4.
Frequency measurements of the unperturbed ^{87}Sr transition in an optical lattice (points) and associated uncertainties for N measurements together with the frequency values (purple bars) recommended by the CIPM and the associated uncertainty bands (pink bands).

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Path towards the re-definition of the second

CCTF 21st meeting

June 2017

RECOMMENDATION CCTF 1 (2017)

Recommendations for operating, comparing and reporting frequency standards as secondary representations of the second in preparation for a redefinition of the second by optical transitions

The Consultative Committee for Time and Frequency (CCTF), at its 21st session in 2017,

considering that

- a list of secondary representations of the second (SRS) has been maintained following the recommendations of the CIPM,
- different optical SRS have estimated fractional frequency uncertainties nearly two orders of magnitude lower than those of the best caesium primary standards,
- improvements in uncertainty associated with optical frequency standards are ongoing,
- a roadmap for a future redefinition of the second using optical frequency standards has been agreed by the CCTF;

recommends that

- the institutes put effort into operating their frequency standards to realize SRS in such a way that they routinely contribute to TAI via reporting to the BIPM,
- the optical standards be compared with uncertainties that are comparable to the estimated uncertainties of the standards themselves,
- the institutes measure the frequencies of the realizations of their SRS with respect to the best primary caesium standards as a necessary requirement for a possible future redefinition of the second in terms of optical transitions,
- the relevant CCTF working groups finalize the milestones for a redefinition and regularly inform the CIPM about the progress towards meeting these milestones.

A roadmap towards the redefinition of the second

The Consultative Committee for Time and Frequency adopted in 2017 a roadmap towards the redefinition of the second (Riehle 2016):

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

Milestone 1

1. ... at least three different optical clocks (……) have demonstrated validated uncertainties of about two orders of magnitude better than the best Cs atomic clocks at that time.

- Well under way: For some of the transitions studied by the WGFS, the uncertainty on the estimation of systematic shifts is much lower than for Cs.

Atom / ion	Clock type	Clock ν THz	Clock λ nm	Lowest published clock systematic uncertainty	Uncertainty of CIPM ν value
^{87}Sr	Lattice	429	698	2.1×10^{-18}	5×10^{-16}
$^{171}Yb^{+}$	Ion octopole	642	467	3.2×10^{-18}	6×10^{-16}
$^{27}Al^{+}$	Ion, quantum logic	1121	267	8.6×10^{-18}	1.9×10^{-15}
$^{88}Sr^{+}$	Ion quadrupole	445	674	1.2×10^{-17}	1.6×10^{-15}
$^{199}Hg^{+}$	Ion quadrupole	1065	282	1.9×10^{-17}	1.9×10^{-15}
$^{40}Ca^{+}$	Ion quadrupole	411	729	3.4×10^{-17}	1.2×10^{-14}
^{199}Hg	Lattice	1129	266	7.2×10^{-17}	6×10^{-16}
$^{171}Yb^{+}$	Ion quadrupole	688	436	1.1×10^{-16}	6×10^{-16}
^{171}Yb	Lattice	518	578	3.4×10^{-16}	2×10^{-15}
^{1}H	Cryogenic beam	1233	243	4.2×10^{-15}	9×10^{-15}

From Gill (2017)

Milestone 2

2. … at least three independent measurements of at least one optical clock were compared in different institutes (e.g. $\Delta\nu/\nu < 5 \times 10^{-18}$) … by transportable clocks, advanced links, ….

- Not yet done at this level but potentially OK
  - cf. ITOC campaigns involving comparisons by fiber links between SYRTE, PTB, NPL with Sr lattice in all laboratories
  - New project ROCIT
  - etc…
- Potential question: How will the T/F community react as long as this level of performance cannot be achieved on intercontinental links?

Milestone 3

3. … there are three independent measurements of the optical frequency standards listed in milestone 1 with three independent Cs primary clocks, … limited essentially by the uncertainty of these Cs fountain clocks (e.g. $\Delta\nu/\nu < 3 \times 10^{-16}$).

- In the 2017 list of frequencies, six transitions have uncertainties with respect to Cs that are in the 10^{-16} region:
  - ν (^{87}Sr) 4×10^{-16}
  - ν (^{171}Yb) 5×10^{-16}
  - ν (^{199}Hg) 5×10^{-16}
  - ν (^{88}Sr^{+}) 6×10^{-16}
  - ν (^{171}Yb^{+} qu) 6×10^{-16}
  - ν (^{171}Yb^{+} oc) 6×10^{-16}
- Uncertainty will go to $<3\times10^{-16}$ with larger number of comparisons, and longer operation of the optical clocks

Milestone 4

4. … optical clocks (secondary representations of the second) contribute regularly to TAI.

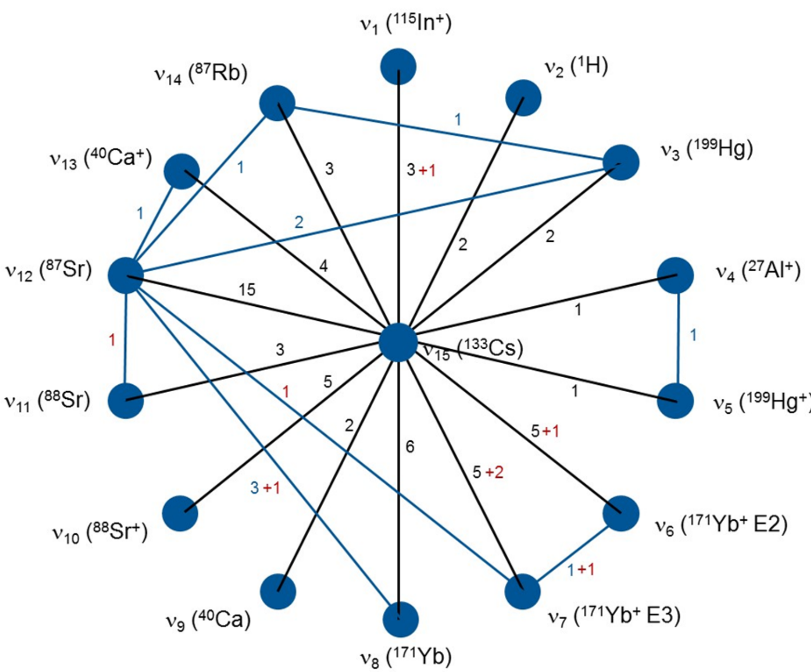
- In February 2017 were published the first contributions to TAI by optical clocks: Four evaluations by SYRTE Sr2, one by SYRTE SrB

- That’s it for the moment….

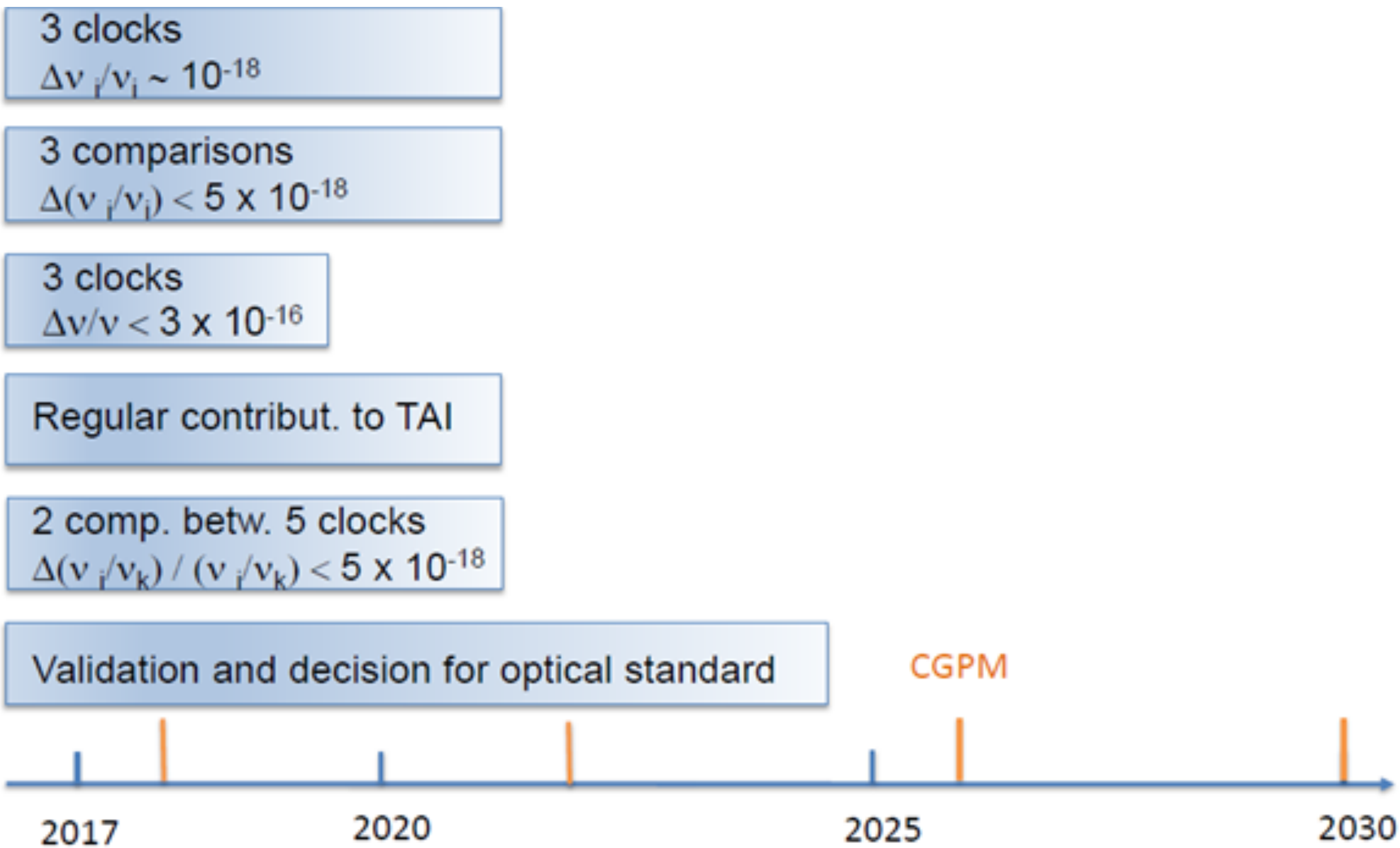
Milestone 5

5. …optical frequency ratios between a few (at least 5) other optical frequency standards have been performed (…..) at least twice by independent laboratories and agreement was found e.g. $\Delta\nu/\nu < 5 \times 10^{-18}$.

- Some frequency ratios are being measured with much smaller uncertainty than Cs e.g.
  - $\nu\,(^{27}Al^{+}) / \nu\,(^{199}Hg^{+})$ 5.5×10^{-17} (Rosenband et al. 2008)
  - $\nu\,(^{171}Yb) / \nu\,(^{87}Sr)$ 5.5×10^{-17} (Nemitz et al. 2016)
  - $\nu\,(^{88}Sr) / \nu\,(^{87}Sr)$ 2.3×10^{-17} (Takano et al. 2017)
  - A few more + others in preparation
- These are mostly in same lab but it should be OK for this milestone



Possible roadmap (Riehle, 2016)



Outline

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- **Techniques for the comparison of remote frequency standards**

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Frequency transfer 1: Present satellite techniques

- Standard techniques

’Classical’ GNSS and Two Way time /frequency transfer limited to ~few 10^{-16} after several days averaging.

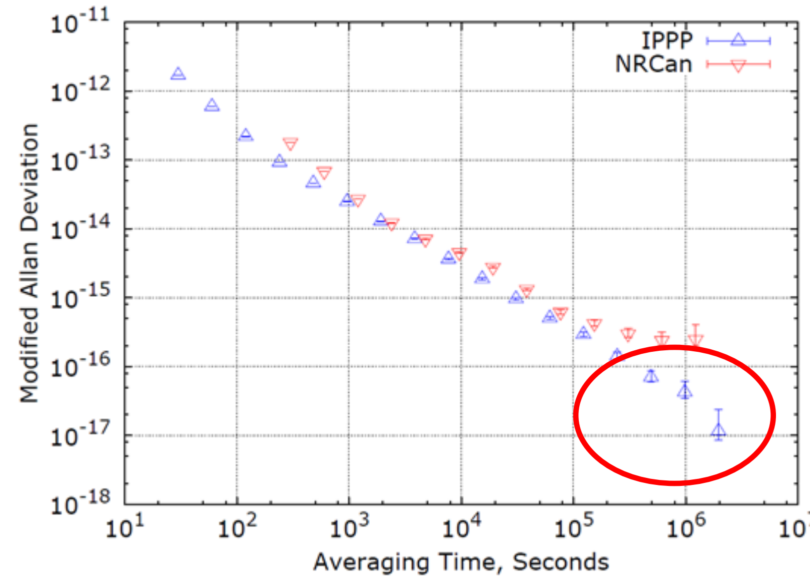
- Advanced techniques

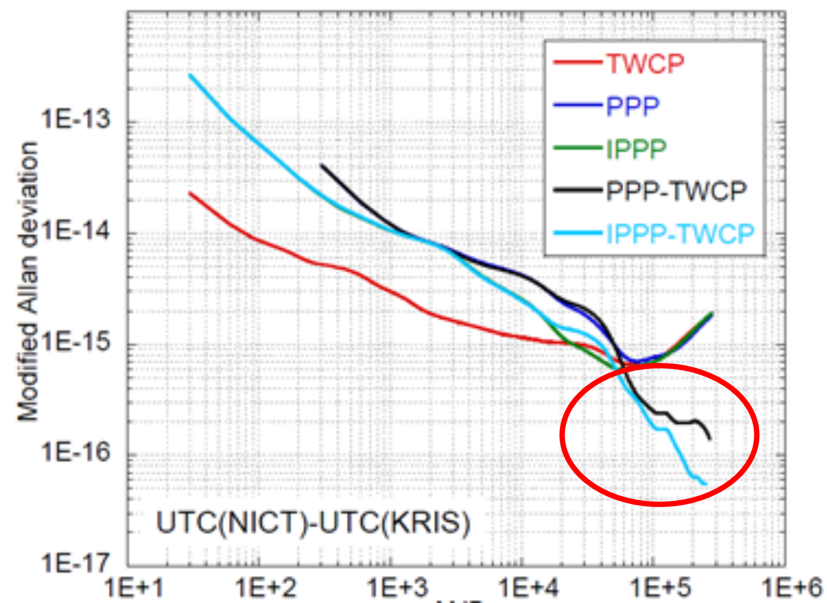
Using phase measurements improves much over standard code techniques, but requires phase continuity:

- GPS IPPP (integer ambiguities) provides 1×10^{-16} at 3 days, low 10^{-17} at 20 days. Checked vs. 420 km fiber link.

- TWCP should be even better but phase continuity may be more difficult to ensure.

See talk tomorrow

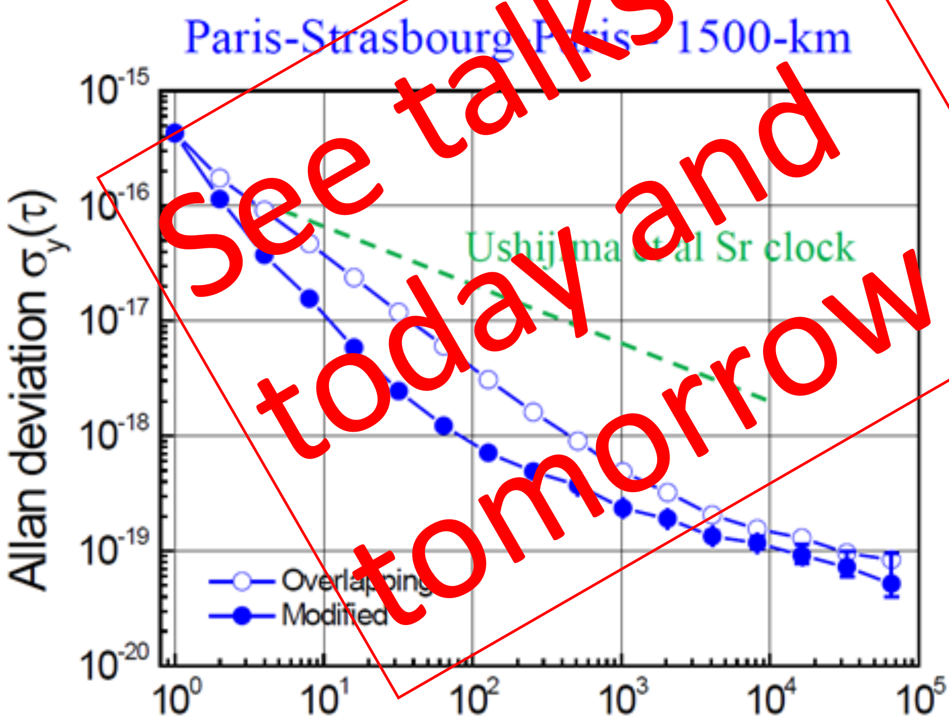




Frequency transfer 2: Fiber links

- Better than 10^{-18} within hours.
- 1500 km link demonstrated on public telecom network.
- Requires hardware installation (bi-directional amplifiers, multiplexers, regenerating stations) and a lot of negotiations with operators.
- Continental networks are emerging.

See talks today and tomorrow



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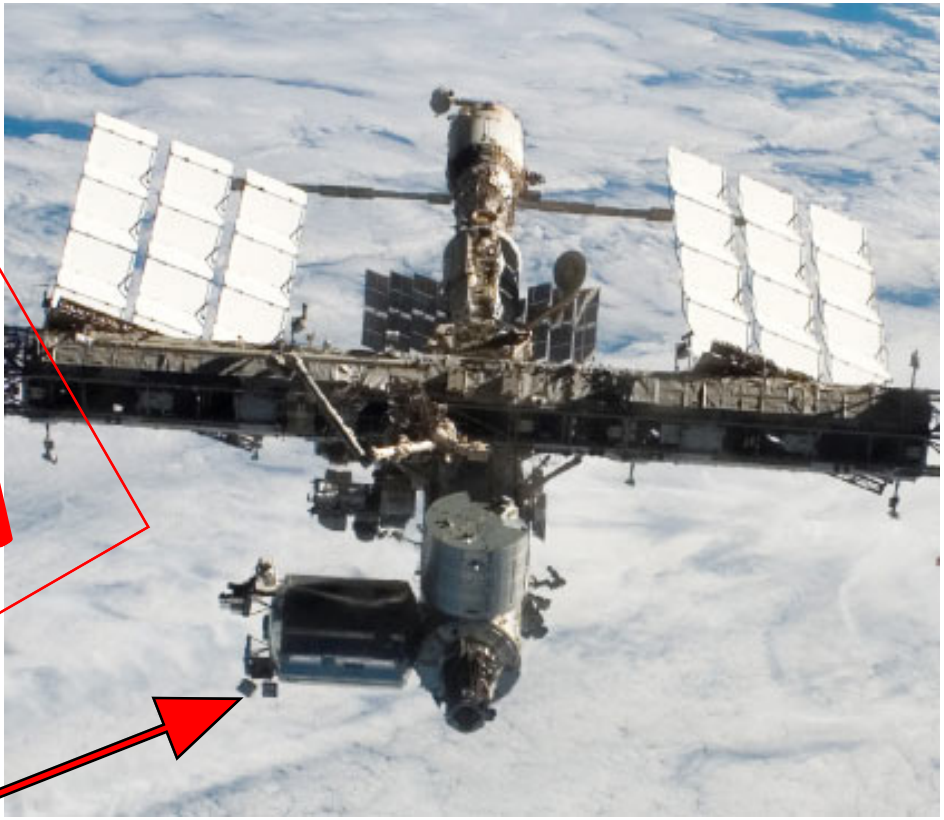
From A. Amy-Klein

Frequency transfer 3: Future ACES time link

- Atomic Clock Ensemble in Space mission
  - PHARAO Cs clock and H maser
  - Microwave link (2+1 ways)
  - Laser link
- To fly 2020 (?) on board the ISS for 18 months to 3 years

See talk tomorrow

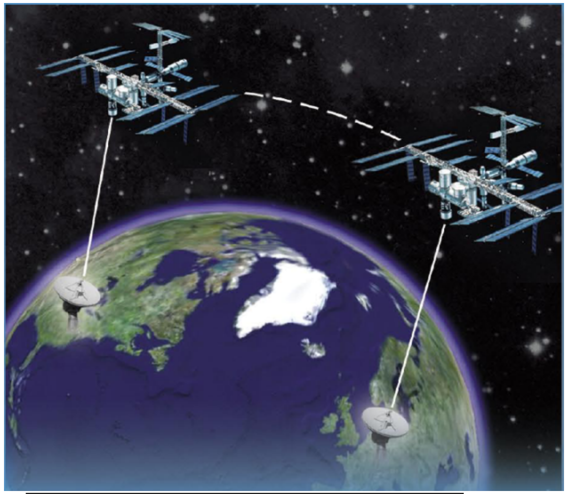


ACES

From Ch. Salomon

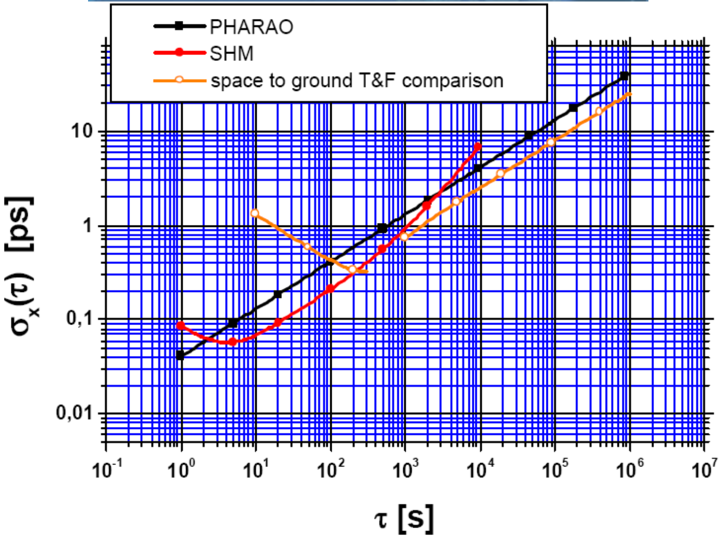
Performance of ACES frequency transfer

MWL: Ground Clock comparisons@ 10^{-17} achieved
over 1 day in Common view, over 4-5 days in non common view



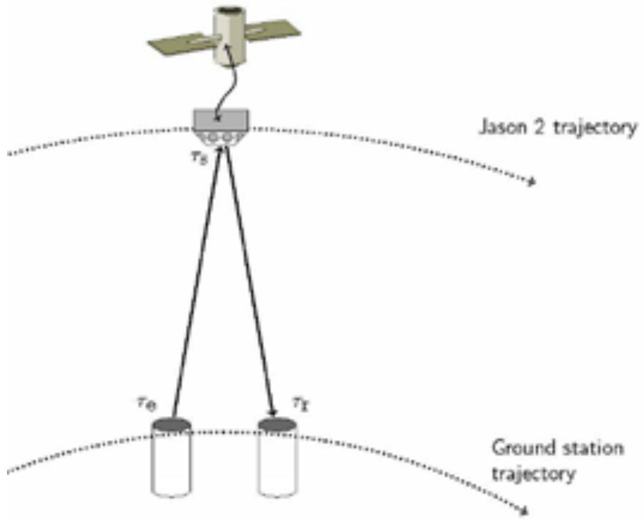
See talk tomorrow

But limited
- to the duration of the mission
- to the few ground terminals available



Frequency transfer 4: Ground-space optical links

- Time transfer by Laser Link (T2L2)
  - On board Jason 2 since 2008
  - 1×10^{-15} @ 1000 s
  - Actual measurements very discontinuous
  - Mostly an accurate system (100 ps)



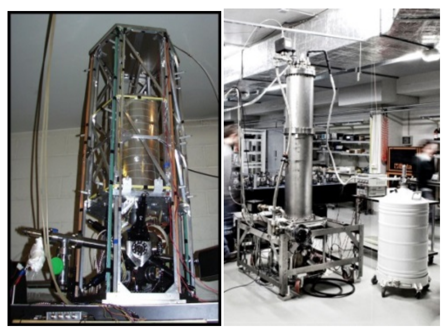
- ELT / ISOC
  - ELT with ACES on the ISS
  - ELT+ in ISOC project

- Two-way ground-satellite coherent optical links
  - Same dependence to weather
  - Turbulence, see e.g. Robert et al, 2016 J. Phys.: Conf. Ser.

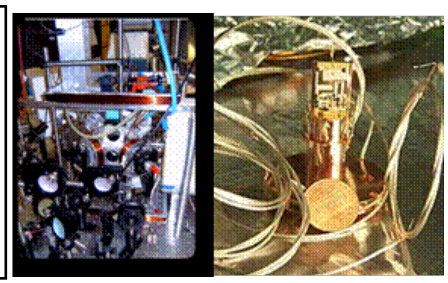
Summary

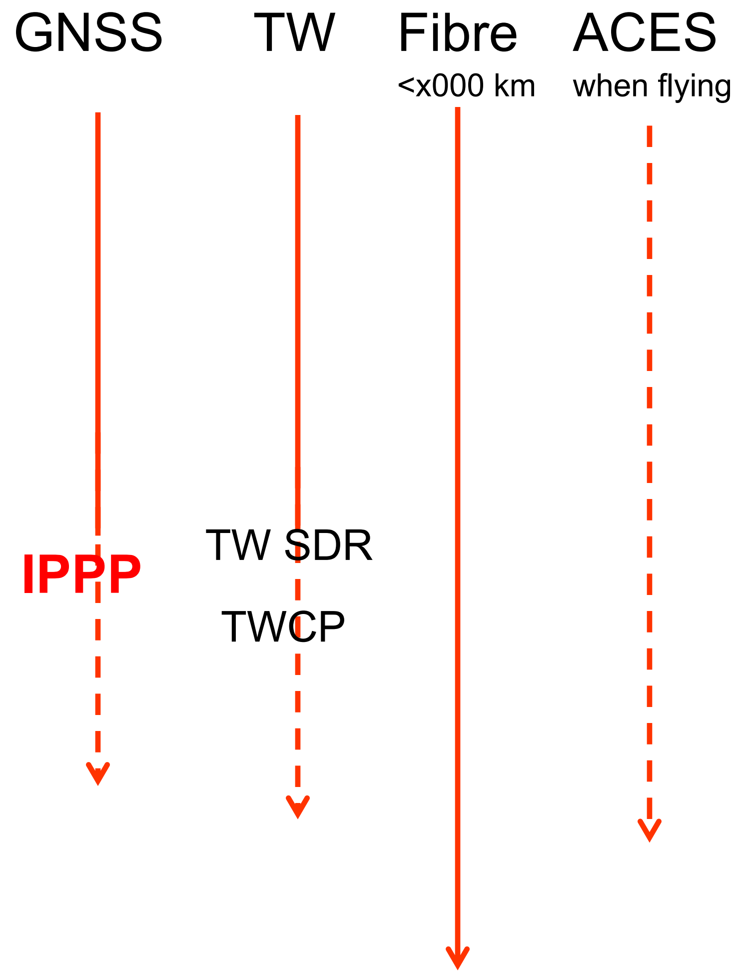
« Commercial » clocks
Cs tube, H-maser
$10^{-14} \approx$ 1 ns / 1 day
$10^{-15} \approx$ 0.1 ns / 1 day

« Best » present standards
Cs fountains (in ~ 10 labs)
$10^{-16} \approx$ 0.1 ns / 10 days
10 ps / 1 day



« Future » standards
Lattice (e.g. Sr), trapped ions
$10^{-17} \approx$ 1 ps / 1 day
$10^{-18} \approx$ 1 ps / 10 days

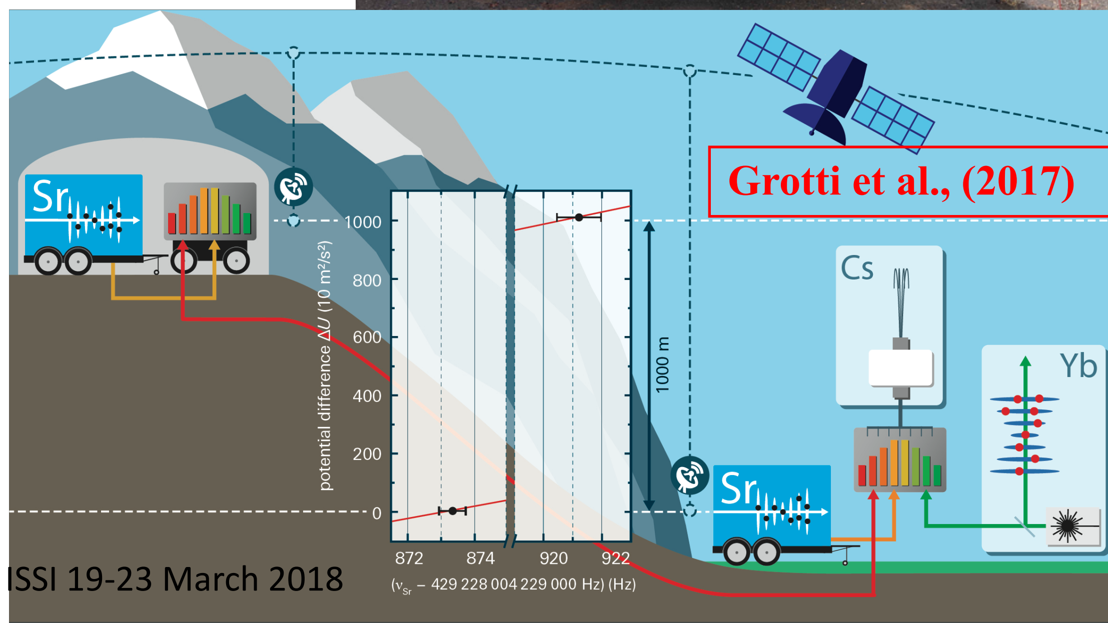




Transporting an ultra-accurate clock ?

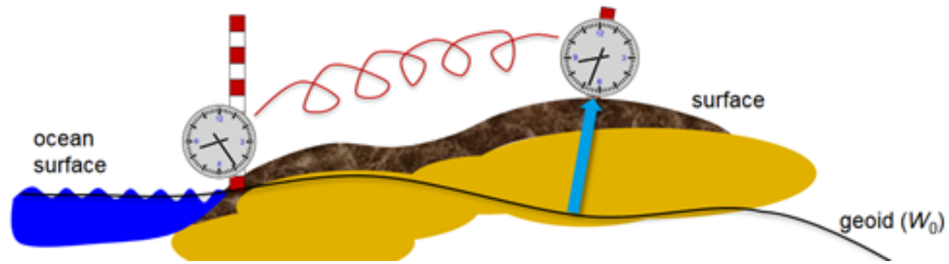
- Allows placing an accurate clock in any location and cross-checking the uncertainty budget (accuracy) of distant clocks

- But does not allow frequency comparisons as needed for relativistic geodesy



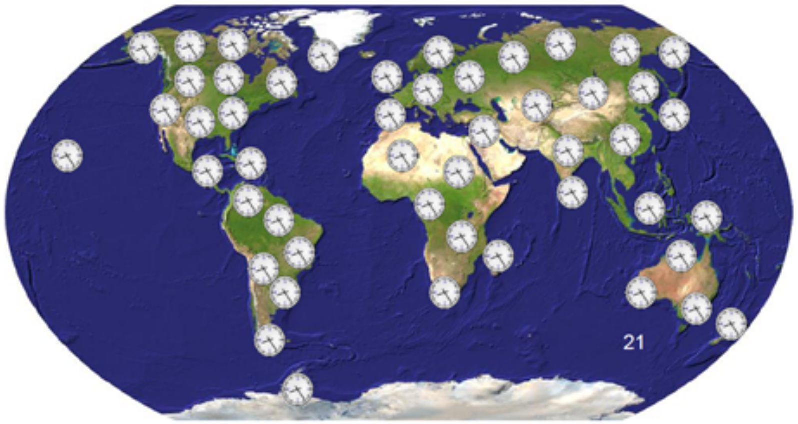
Relativistic geodesy

- Chronometric levelling directly measures the geopotential (height) difference between any two clocks (1cm $\approx 10^{-18}$) if
  - Clocks are accurate
  - Frequency difference can be measured

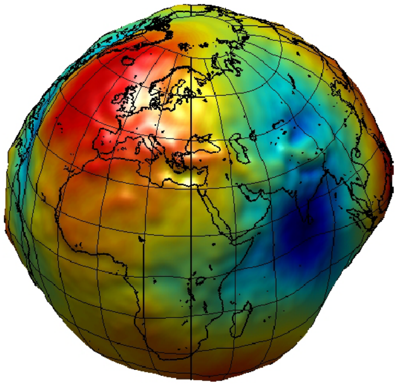


- This allows discriminating geopotential / sea level changes from other sources

- The needs of relativistic geodesy are essentially the same as those of a new definition of the second



Geodesy ↔ Clocks



- Presently clocks need geodesy to model their relativistic rate shift
  - because clocks at the $1x10^{-17}$ level (~10 cm) need to be certified before going to the $1x10^{-18}$ level (1 cm)
  - and the 10^{-18} level cannot be validated at long distance
- This WG can help, e.g. provide a « mise en pratique » to compute the shift
- Several publications provide the basis
  - Denker et al. J. Geod 2017; Voigt et al. Metrologia 2016; …………
- In the future the relationship will be more balanced / will reverse
  - because the 10^{-18} level (1 cm) will be validated
  - because reference clocks can be placed in space where the gravity potential is easier to determine

Main conclusions

- The atomic definition of the second of 1967, based on the Cs transition, reaches its limits.
- A roadmap for the redifinition of the second has been drafted.
- The work of the WG on Frequency Standards paves the way for a redefinition of the second.

- New better long distance frequency transfer techniques are needed.
  - In the meantime, do the best with existing satellite technques

- This work goes exactly in parallel to the needs of relativistic geodesy.

THANK YOU

Thanks to CCL-CCTF WG on Frequency Standards ex co-chairs F. Riehle and P. Gill

S. Bize (SYRTE) for several slides