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Optical clock comparisons in Europe

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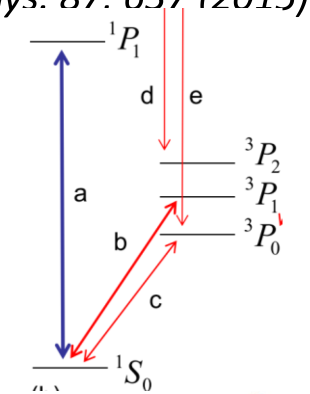
Principle of optical frequency standards

❑ A reference transition in the optical domain

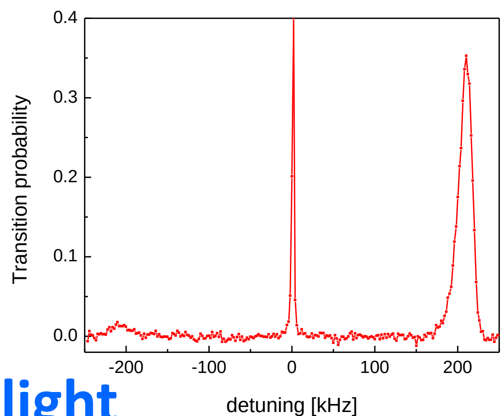
Rev. Mod. Phys. 87, 637 (2015)

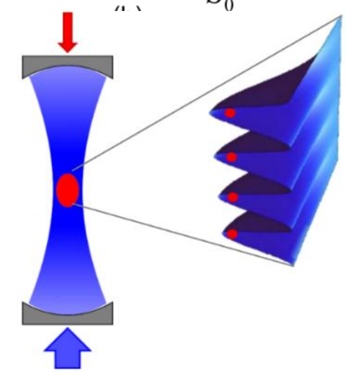


- Frequency ~10^{15} Hz
- Forbidden transitions with natural linewidth <<1 Hz

❑ Laser-cooled & tightly bound ion / atoms

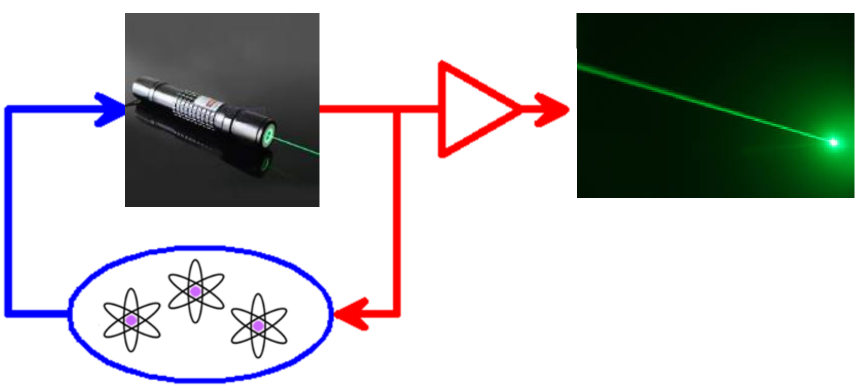
- To mitigate motional effects
- Two types
  - (single) ion clocks
  - optical lattice clocks

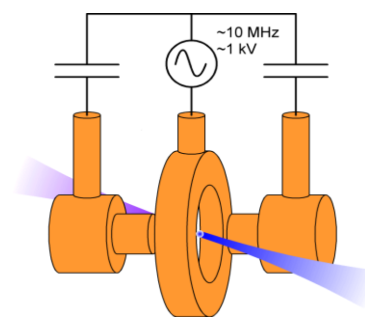




❑ Probed with ultra-stable laser light

- Fundamental signal: the phase of laser light





Physical effects inducing noise and shifts

❑ Main sources of noise

- Noise from the interrogation oscillator
- Detection of the internal state of N atoms
  - Limit for uncorrelated atoms: quantum projection
  - Can be overcome with entangled atoms

$$\left(\frac{|g\rangle + |e\rangle}{\sqrt{2}}\right)^N$$

$$\sigma_{\delta P} = \frac{\sqrt{P(1-P)}}{\sqrt{N_{det}}}$$

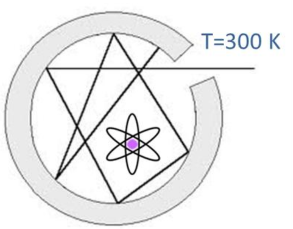
❑ Effects of trapping

- Effects of micro-motion and of oscillating fields
- Residual lattice light shifts
  - Tensor shifts, E2/M1 shifts, hyperpolarizability
  - Spectrum of the trapping light

❑ Effects of thermal radiation

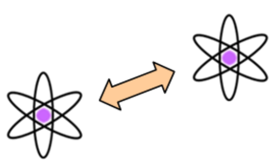
- Described by Planck's law, Stefan-Boltzmann's law, etc.

$$h\Delta f_{\mathrm{BBR}} = -\frac{\Delta\alpha_s \langle E^2(T)\rangle}{2}[1+\eta(T^2)] \qquad \langle E^2\rangle = K_E\left(\frac{T}{T_0}\right)^4$$



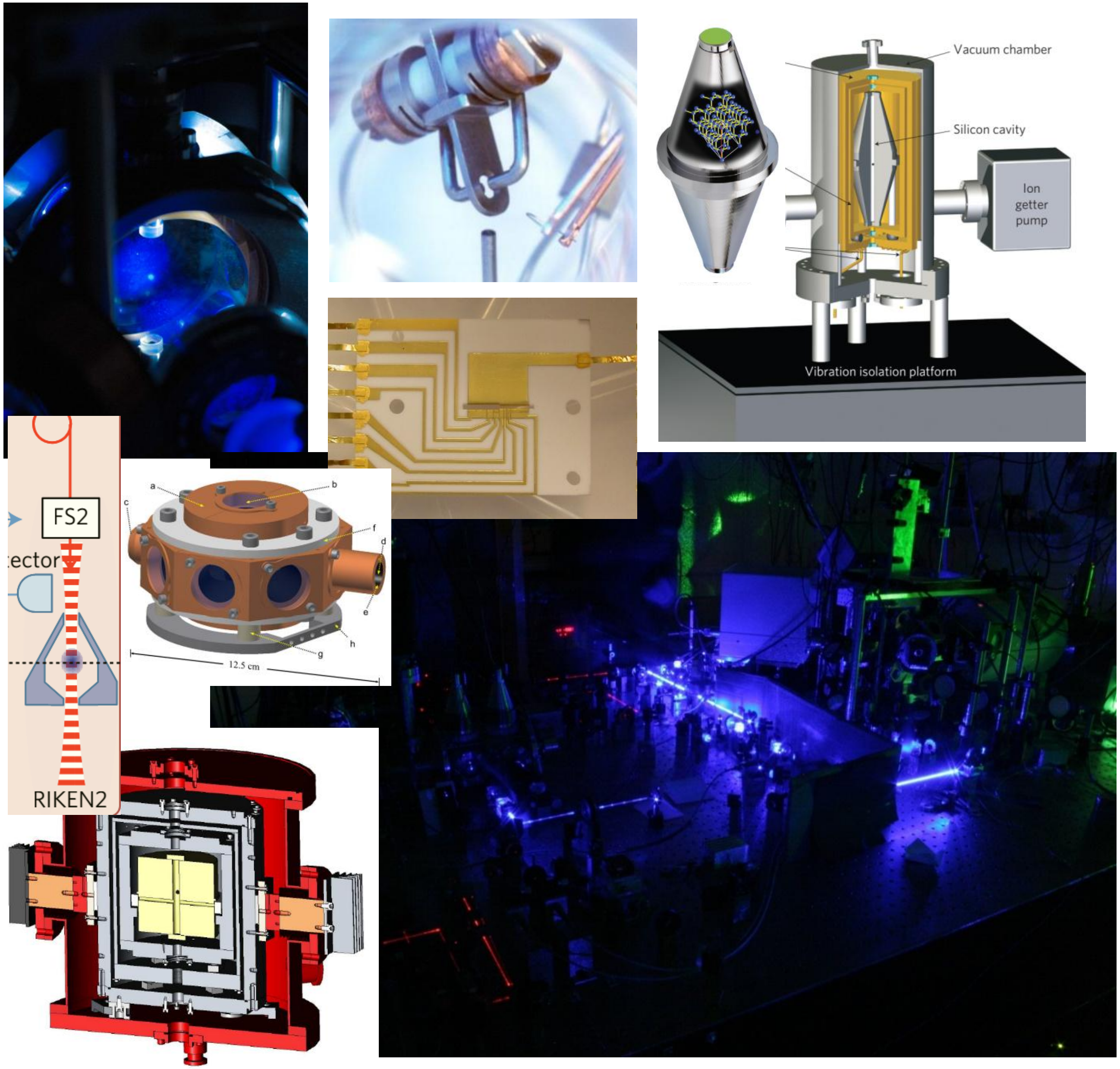
❑ Interactions between atoms

- Depends on atomic density, complex in ultra-cold regime



❑ Many other physical and technical effects

Realization of optical frequency standards



RIKEN/UT, NIST, LTE, PTB, JILA, etc.

NIST, McGrew et al., Nature 564 (2018) 87–90

Shift ($10^{-18} \times \nu_{clock}$)	Yb-1 Shift	Yb-1 Uncertainty
Background gas collisions	-5.5	0.5
Spin polarization	0	<0.3
Cold collisions*	-0.21	0.07
Doppler	0	<0.02
Blackbody radiation*	-2,361.2	0.9
Lattice light (model)	0	0.3
Travelling wave contamination	0	<0.1
Lattice light (experimental)	-1.5	0.8
Second-order Zeeman*	-118.1	0.2
DC Stark	0	<0.07
Probe Stark	0.02	0.01
Line pulling	0	<0.1
Tunnelling	0	<0.001
Servo error	0.03	0.05
Optical frequency synthesis	0	<0.1
Total	**-2,486.5**	**1.4**

Validation of optical clocks

❑ Validation is needed

- From the scientific and metrological point of view
- In view of a redefinition of the SI second (see Metrologia 61, 012001 (2024))
- In view of certain applications

❑ Accuracy

- Comparisons of standards based on same transition are expected to give a ratio of 1.
- Measurements of the same ratio are expected to give the same result.
- A global fit to all ratio measurements should be consistent as given by statistical indicators
  - Xx/Yy * Yy/Zz * Zz/Xx should be equal to 1

❑ Operability

- Unattended operation of long duration
- Operation on time when planned
- Transportability

CCTF criteria for a redefinition of the second

Mandatory criteria **To be achieved** before changing the definition

Achieved

- **Validation that Optical Frequency Standards are at a level 100 times better than Cs**
- **Continuity with the definition based on Cs**
- **Regular contributions of OFS to TAI as secondary representations of the second**
- **Availability of sustainable techniques for OFS comparisons**
- **Knowledge of the local geopotential with an adequate uncertainty level**
- **Definition allowing future more accurate realizations**
- **Access for NMIs to primary or secondary realizations of the new definition**

Mandatory achievements frontier

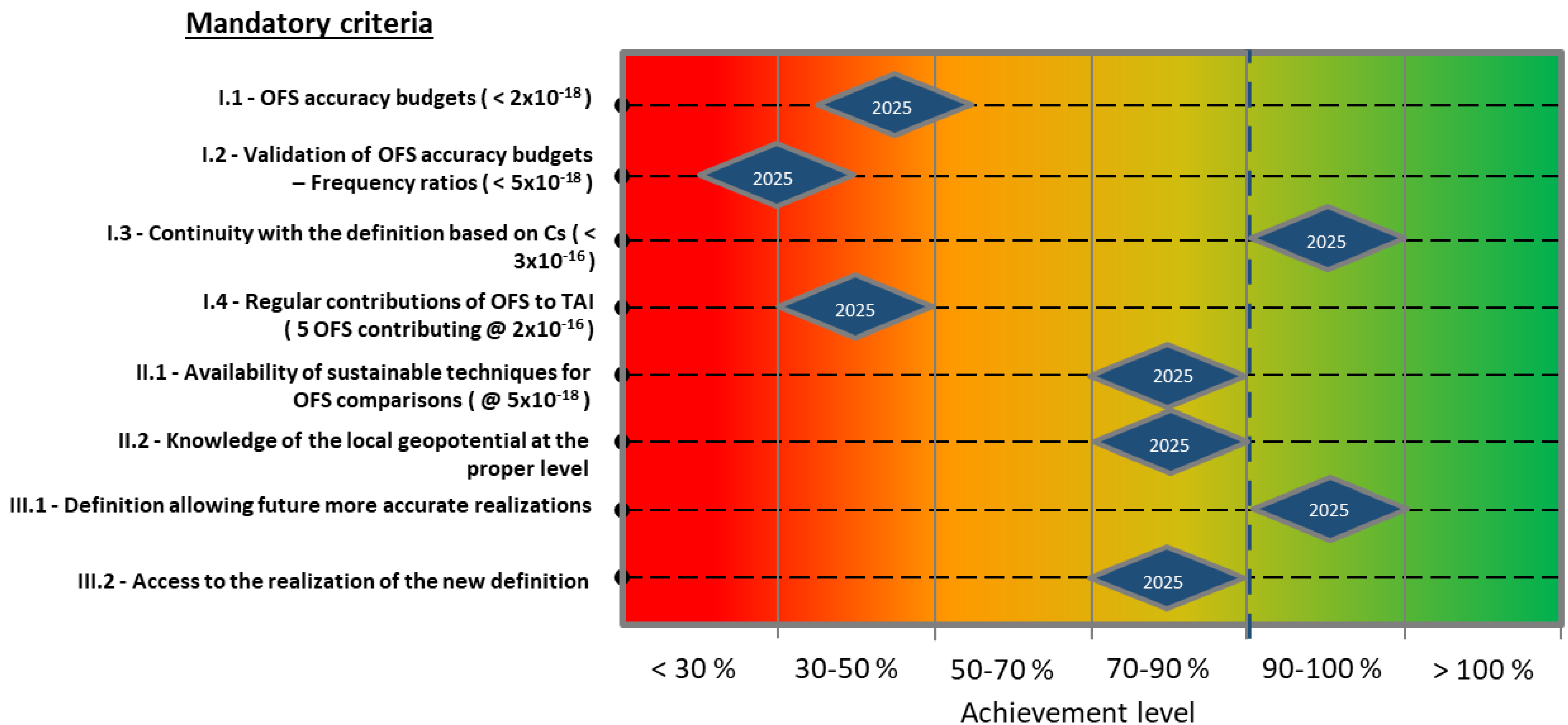
Ancillary conditions corresponding to essential **Work still in progress** when the definition is changed

In progress

- **High reliability of optical frequency standards**
- **High reliability of ultra high stability T/F links**
- **Continuous improvement of the realization and time scales after redefinition**
- **Regular contributions of optical clocks to UTC(k)**
- **Availability of commercial optical clocks**
- **Improved quality of the dissemination towards users**

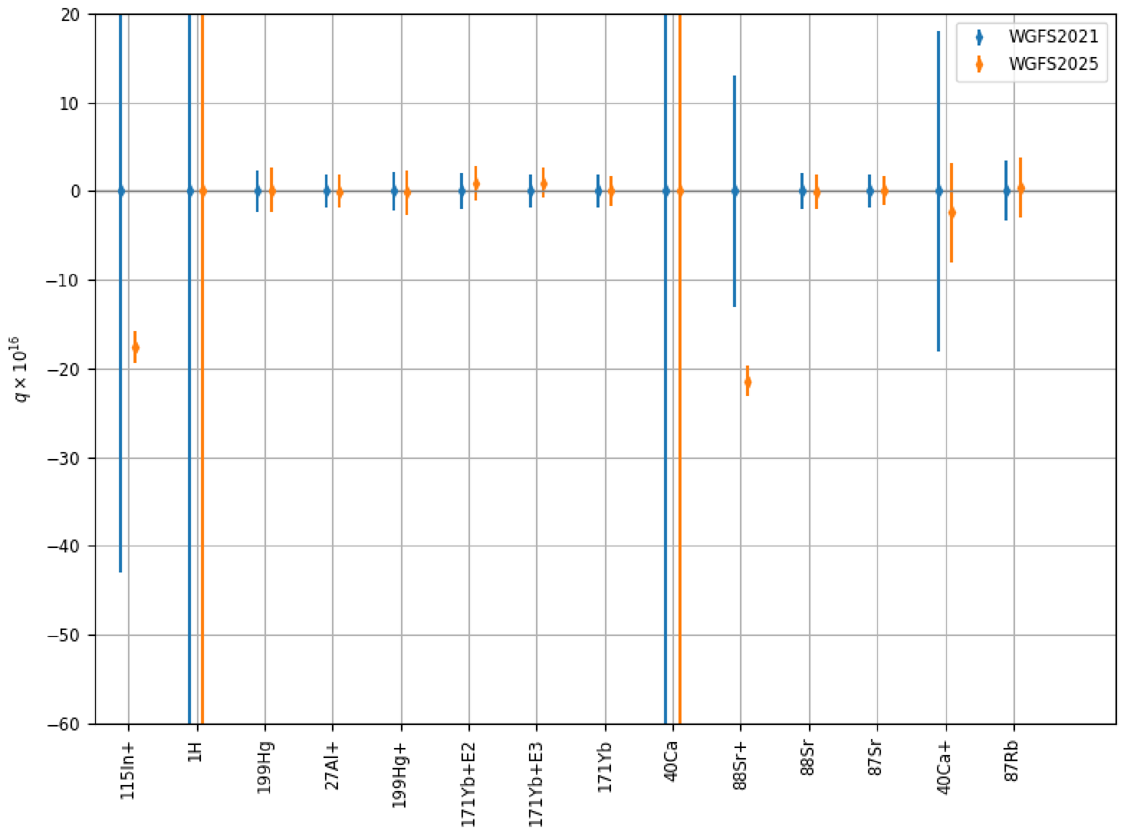
Metrologia 61, 012001 (2024)

CCTF fulfillment level of mandatory criteria (2025)



CIPM list of recommended values – 2025 updates

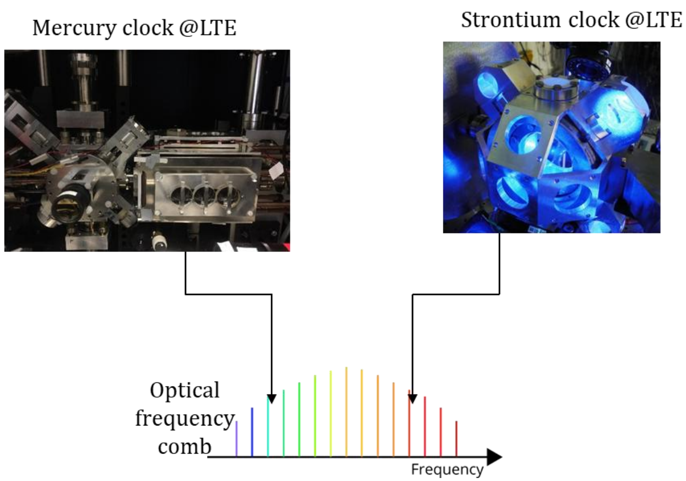
❑ Updates to the CIPM list of recommended values



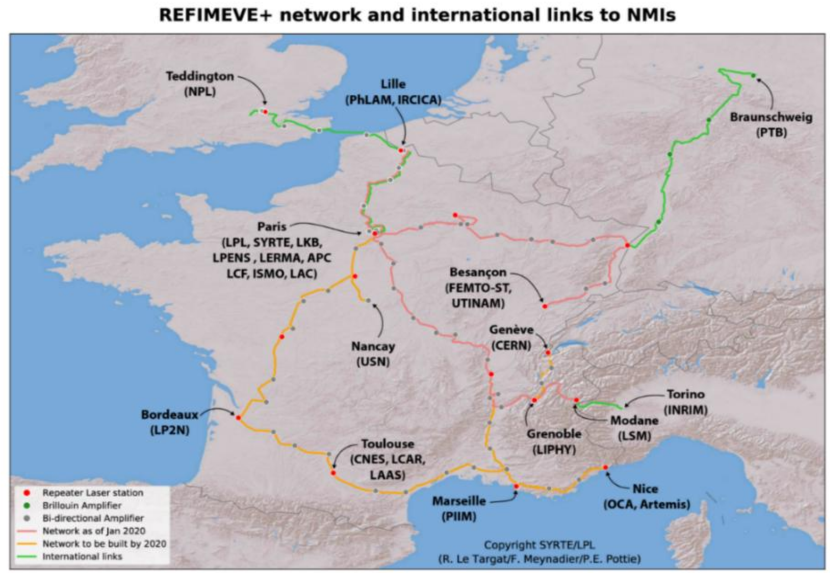
- 146 measurements as inputs. Several inconsistencies to be dealt with.
  - Global fit indicates inconsistencies at the level of 5.3E-17
- Best recommended uncertainty: 1.7E-16 (limited by Cs)
- In+ becomes a SRS
- Lu+ enters the LoR (noting that it is the mean of the frequency of 3 transitions)

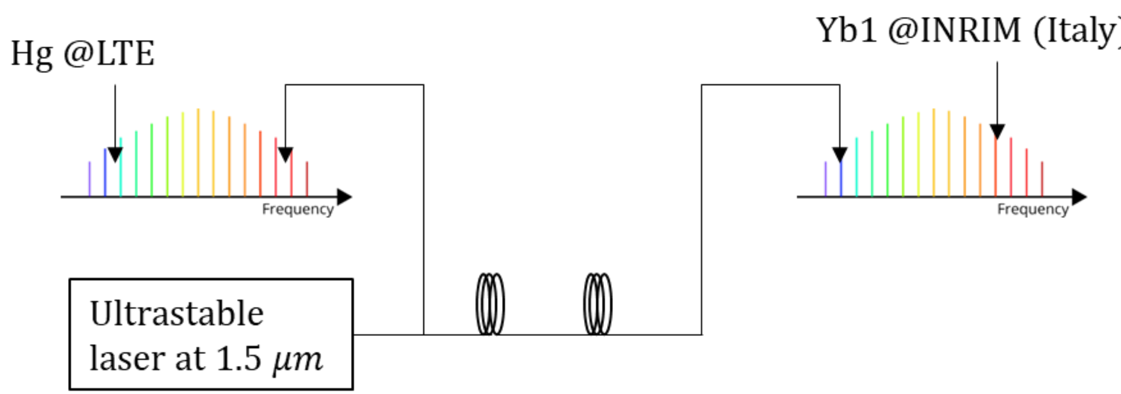
Comparisons via coherent optical fiber links

Local comparison



Remote via fiber links





Additional noise from links is negligible
Links support comparisons to <1E-19

Comparisons with coherent optical links in Europe

❑ Comparisons involving optical frequency standards

- 2013 LPL- LTE OsO4 vs Cs New J. Phys. 15, 073003 (2013)
- 2013 MPQ – PTB H(1S-2S) vs Cs Phys. Rev. Lett. 110, 230801 (2013)

- 2015 LTE – PTB Sr vs Sr Nat Comm. 7, 12443 (2016)
- 2017 LTE-PTB Cs and Rb fountains Metrologia 54, 348 (2017)
- 2018 PTB Sr transportable at INRIM and LSM Nature Physics 14, 437 (2018)
- 2020 LTE, PTB, NPL 6 clocks Sr, Hg, Yb+, New. J. Phys. 22, 093010 (2020)
- 2022 LTE-INRIM Rb, Cs and Yb, Phys. Rev. Applied 18, 054009 (2022)
- 2022 10 clocks at LTE, PTB, INRIM, NPL Optica 12, 843 (2025)
- 2023 Sr transportable clocks from PTB and RIKEN, at NPL and PTB, arXiv:2410.22973
- 2023 7 other clocks at LTE, PTB, INRIM, NPL, *to be submitted*
- 2025 >5 clocks at LTE, PTB, INRIM, NPL

Organizing frequency comparisons in clock networks

❑ Computing frequency ratios

$$\rho_{n,0} = \left(\prod_{i=1}^{n} \rho^0_{i,i-1}\right)\left(1+\sum_{i=1}^{n} R_{i-1\to i}\right),$$

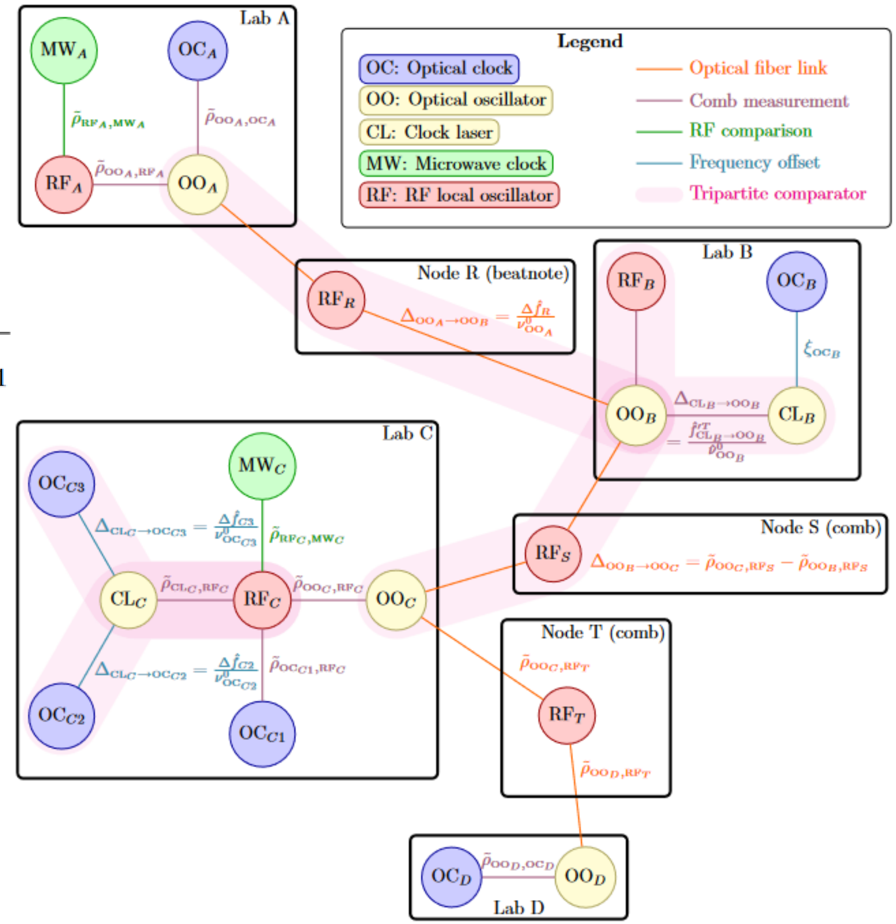
$$R_{i-1\to i} \simeq \Delta_{i-1\to i}\frac{s_i/\hat{\nu}_0^0}{\prod_{k=1}^{i}\rho^0_{k,k-1}} = -\Delta_{i\to i-1}\frac{s_{i-1}/\hat{\nu}_0^0}{\prod_{k=1}^{i-1}\rho^0_{k,k-1}}$$

❑ 3 types of data

- Frequency corrections (from lock to atomic transition)
- Frequency counting (combs)
- Frequency offsets (links, combs)

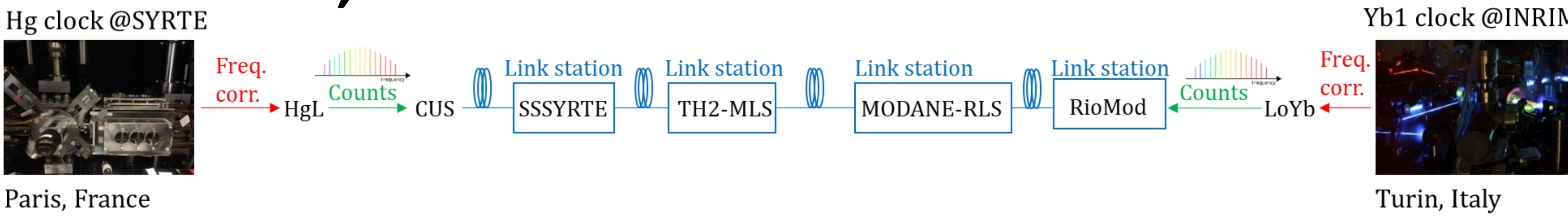
❑ + gravitational redshift

- wrt a reference potential W_0=62 636 856.0 $m^2.s^{-2}$
- See Resolution 2 – CGPM 2018



Physical Review Research 2, 043269 (2020)

User's view, user's role



1 Create file in share repository

Folder name :
INSTITUTEB_OSCB-INSTITUTEA_OSCA

2 Create .yaml header file for your segment


```
- name: "SYRTE_HgL-SYRTE_Hg"  # comparator name, in the form INSTITUTEB_OSCB-INSTITUTEA_OSCA
  numrhoBA: 1                  # numerator of the NFR rho^0_BA (arbitrary precision floating point)
  denrhoBA: 1                  # denominator of the linkage NFR rho^0_BA  (arbitrary precision floating point)
  sB: -1        # scaling factor sB (double precision floating point)
  grsA: -6.0897e-15            # GRS correction for the oscillator A to the Geoid, in relative units (optional)
  nuOA: 1128575290808154.4     # recommended value \nu^0_A for the nominal frequency of A. (optional)
  uA_sys: 1.7e-17              # uncertainty of the oscillator A (optional)
  ref_osc: "SYRTE_H810"
```


3 Load your files

Data rate: 1 / s
Synchronized to UTC

$\Delta_{A \to B}$

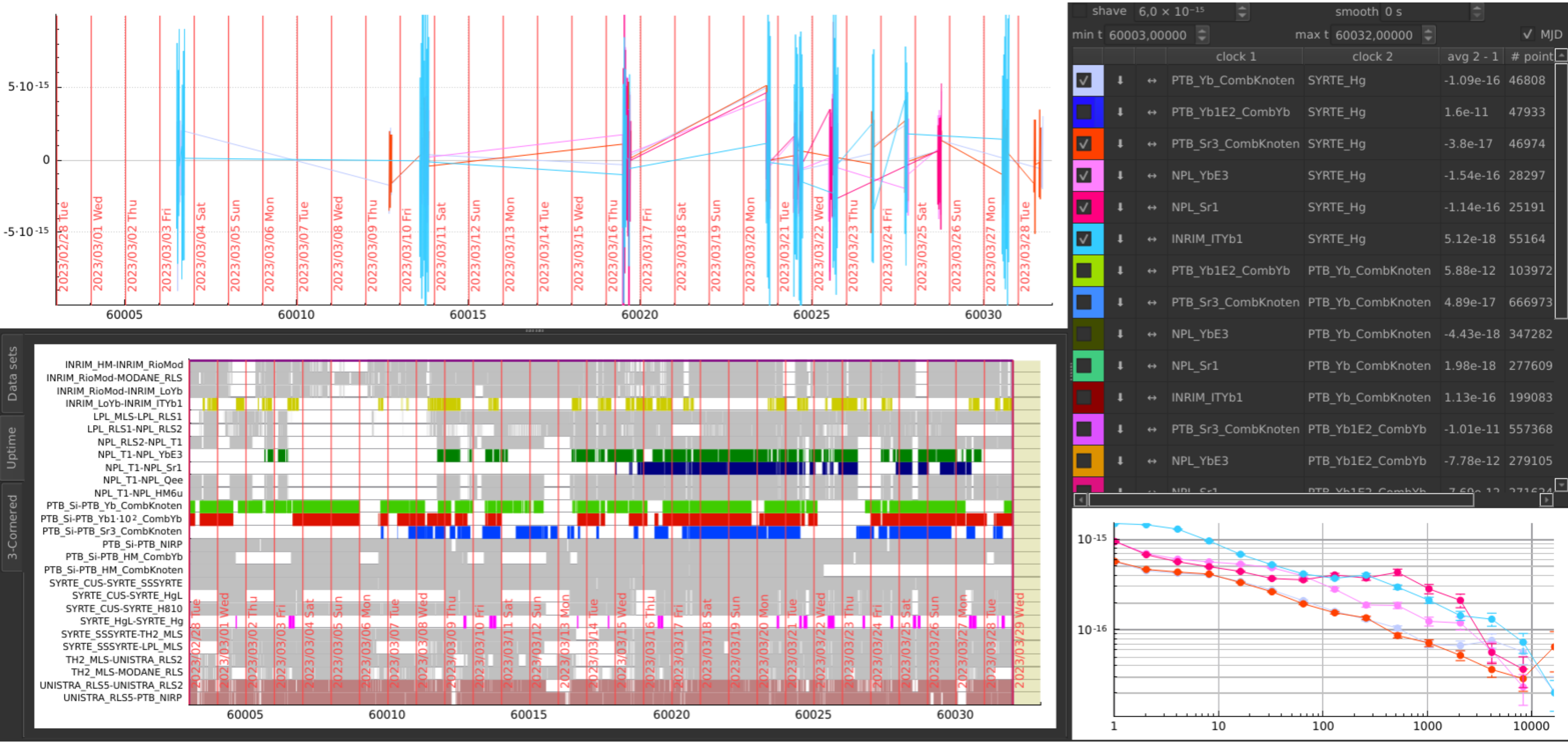
Validity

```
# Systematic correction already applied :
# uncertainty on correction : +/- 26.14e-1
# GRS not applied yet. Lattice depth = 92.
# total cycle time = 1.08660 s, loading =
60059.000000    0.000000      0
60059.000012    0.000000      0
60059.000023    0.000000      0
...
60059.627245    0.000000      0
60059.627257    0.000000      0
60059.627269    0.000000      0
60059.627280    0.000000      0
60059.627292    0.000000      0
60059.627303    -6392870.060744    1
60059.627315    -6392870.023917    1
60059.627326    -6392870.157011    1
60059.627338    -6392870.075268    1
60059.627350    0.000000      0
60059.627361    -6392869.969357    1
60059.627373    -6392869.923739    1
60059.627384    -6392869.858319    1
60059.627396    -6392870.024806    1
60059.627407    -6392870.088699    1
60059.627419    -6392870.078069    1
60059.627431    -6392869.993126    1
60059.627442    -6392870.048012    1
60059.627454    -6392869.899042    1
```

Data analysis

❑ Participants can compute all possible ratios

- In practice, done several times independently for verification



2022 comparison campaign

Research Article Vol. 12, No. 6 / June 2025 / *Optica* 843

OPTICA

Coordinated international comparisons between optical clocks connected via fiber and satellite links

Thomas Lindvall,[1,†] Marco Pizzocaro,[2,†] Rachel M. Godun,[3,*] Michel Abgrall,[4] Daisuke Akamatsu,[5,6] Anne Amy-Klein,[7] Erik Benkler,[8] Nishant M. Bhatt,[8] Davide Calonico,[2] Etienne Cantin,[7] Elena Cantoni,[2] Giancarlo Cerretto,[2] Christian Chardonnet,[7] Miguel Angel Cifuentes Marin,[4] Cecilia Clivati,[2] Stefano Condio,[2] E. Anne Curtis,[3] Heiner Denker,[9] Simone Donadello,[2] Sören Dörscher,[8] Chen-Hao Feng,[3] Melina Filzinger,[8] Thomas Fordell,[1] Irene Goti,[2] Kalle Hanhijärvi,[1] H. Nimrod Hausser,[8] Ian R. Hill,[3] Kazumoto Hosaka,[5] Nils Huntemann,[8] Matthew Y. H. Johnson,[3] Jonas Keller,[8] Joshua Klose,[8] Takumi Kobayashi,[5] Sebastian Koke,[8] Alexander Kuhl,[8] Rodolphe Le Targat,[4] Thomas Legero,[8] Filippo Levi,[2] Burghard Lipphardt,[8] Christian Lisdat,[8] Hongli Liu,[8] Jérôme Lodewyck,[4] Olivier Lopez,[7] Maxime Mazouth-Laurol,[4] Tanja E. Mehlstäubler,[8,10] Alberto Mura,[2] Akiko Nishiyama,[5] Tabea Nordmann,[8] Adam O. Parsons,[3] Gérard Petit,[11] Benjamin Pointard,[4] Paul-Eric Pottie,[4] Matias Risaro,[2] Billy I. Robertson,[3] Marco Schioppo,[3] Haosen Shang,[4] Kilian Stahl,[8] Martin Steinel,[8] Uwe Sterr,[8] Alexandra Tofful,[3] Mads Tønnes,[4] Dang-Bao-An Tran,[3] Jacob Tunesi,[3] Anders E. Wallin,[1] and Helen S. Margolis[3]

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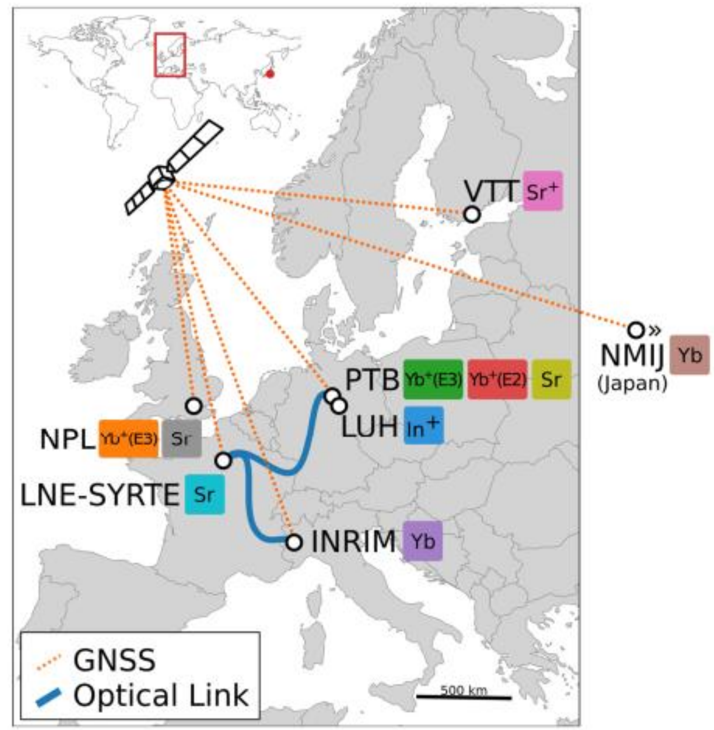


2022 comparison campaign

❑ 10 optical clocks involved

- 12 ratios local or via fiber links. 26 via GNSS (Optica 12, 843 (2025))

Uptime of clocks and links

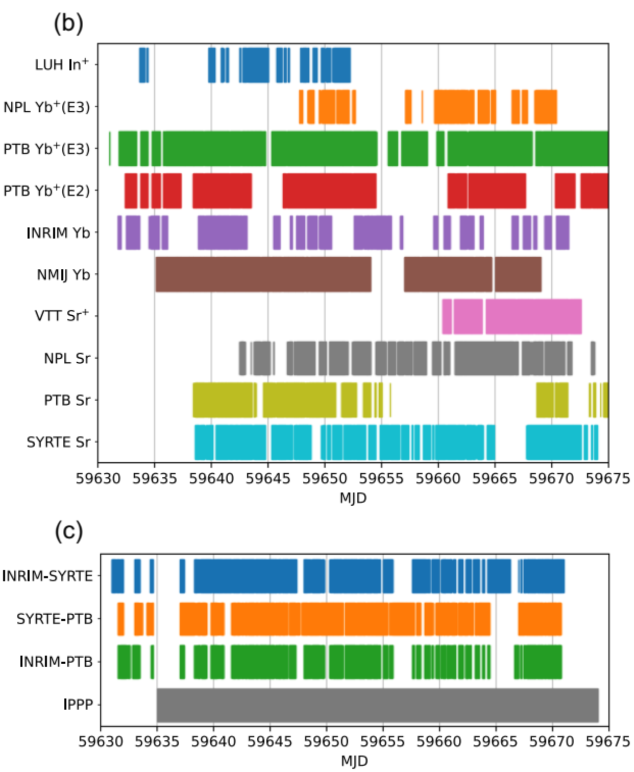


Table 2. Summary of the Frequency Ratios Measured in this Campaign, Shown with the Estimated Uncertainties for Each Measurement[a]

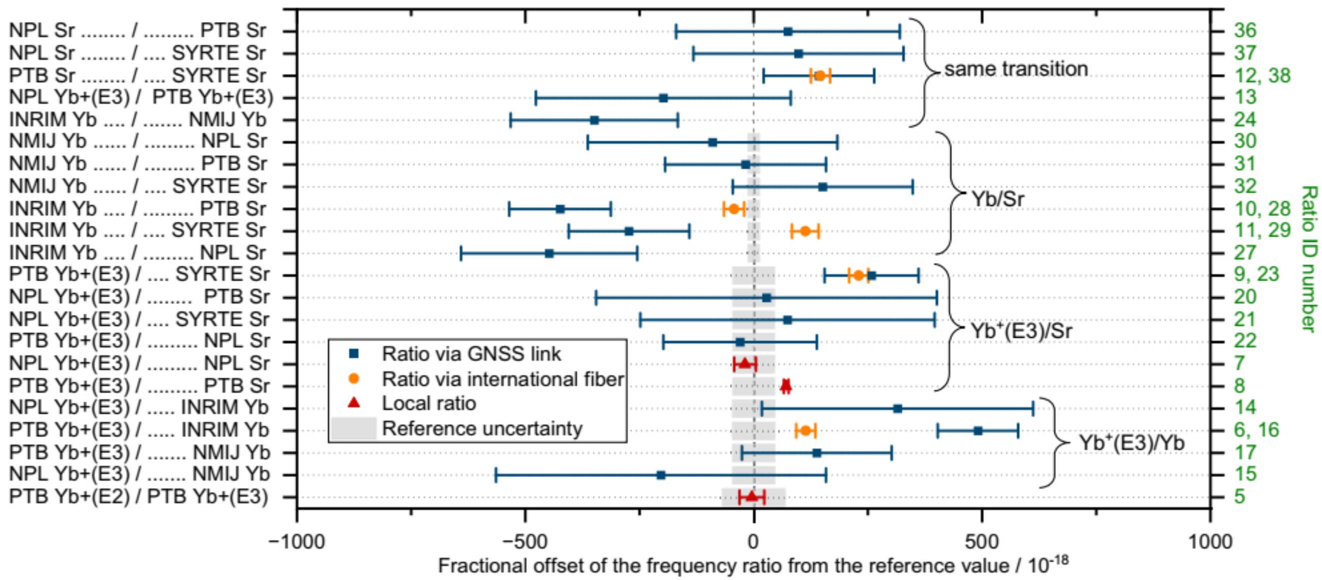
No.	Frequency Ratio with Total Uncertainty in Parentheses	Total Fractional Uncertainty	Link	Clock 1	Clock 2
1	1.973 773 591 557 215 789(9)	4.4×10^{-18}	Local	LUH In^+	PTB Yb^+(E3)
2	2.445 326 324 126 950 199(58)	2.4×10^{-17}	Fiber	LUH In^+	INRIM Yb
3	2.952 748 749 874 860 909(15)	5.1×10^{-18}	Local	LUH In^+	PTB Sr
4	2.952 748 749 874 861 332(72)	2.4×10^{-17}	Fiber	LUH In^+	SYRTE Sr
5	1.072 007 373 634 205 468(29)	2.7×10^{-17}	Local	PTB Yb^+(E2)	PTB Yb^+(E3)
6	1.238 909 231 832 259 569(26)	2.1×10^{-17}	Fiber	PTB Yb^+(E3)	INRIM Yb
7	1.495 991 618 544 900 525(36)	2.4×10^{-17}	Local	NPL Yb^+(E3)	NPL Sr
8	1.495 991 618 544 900 659(8)	5.4×10^{-18}	Local	PTB Yb^+(E3)	PTB Sr
9	1.495 991 618 544 900 897(32)	2.1×10^{-17}	Fiber	PTB Yb^+(E3)	SYRTE Sr
10	1.207 507 039 343 337 793(26)	2.2×10^{-17}	Fiber	INRIM Yb	PTB Sr
11	1.207 507 039 343 337 981(36)	2.9×10^{-17}	Fiber	INRIM Yb	SYRTE Sr
12	1.000 000 000 000 000 146(21)	2.1×10^{-17}	Fiber	PTB Sr	SYRTE Sr
13	0.999 999 999 999 999 80(28)	2.8×10^{-16}	GNSS	NPL Yb^+(E3)	PTB Yb^+(E3)
14	1.238 909 231 832 259 82(37)	3.0×10^{-16}	GNSS	NPL Yb^+(E3)	INRIM Yb
15	1.238 909 231 832 259 18(45)	3.6×10^{-16}	GNSS	NPL Yb^+(E3)	NMIJ Yb
16	1.238 909 231 832 260 04(11)	8.8×10^{-17}	GNSS	PTB Yb^+(E3)	INRIM Yb
17	1.238 909 231 832 259 60(20)	1.6×10^{-16}	GNSS	PTB Yb^+(E3)	NMIJ Yb
18	1.443 686 489 498 354 68(51)	3.5×10^{-16}	GNSS	NPL Yb^+(E3)	VTT Sr^+
19	1.443 686 489 498 354 89(17)	1.2×10^{-16}	GNSS	PTB Yb^+(E3)	VTT Sr^+
20	1.495 991 618 544 900 59(56)	3.7×10^{-16}	GNSS	NPL Yb^+(E3)	PTB Sr
21	1.495 991 618 544 900 66(48)	3.2×10^{-16}	GNSS	NPL Yb^+(E3)	SYRTE Sr
22	1.495 991 618 544 900 51(25)	1.7×10^{-16}	GNSS	PTB Yb^+(E3)	NPL Sr
23	1.495 991 618 544 900 94(15)	1.0×10^{-16}	GNSS	PTB Yb^+(E3)	SYRTE Sr
24	0.999 999 999 999 999 65(18)	1.8×10^{-16}	GNSS	INRIM Yb	NMIJ Yb
25	1.165 288 345 913 157 59(18)	1.6×10^{-16}	GNSS	INRIM Yb	VTT Sr^+
26	1.165 288 345 913 158 03(31)	2.7×10^{-16}	GNSS	NMIJ Yb	VTT Sr^+
27	1.207 507 039 343 337 30(23)	1.9×10^{-16}	GNSS	INRIM Yb	NPL Sr
28	1.207 507 039 343 337 33(13)	1.1×10^{-16}	GNSS	INRIM Yb	PTB Sr
29	1.207 507 039 343 337 52(16)	1.3×10^{-16}	GNSS	INRIM Yb	SYRTE Sr
30	1.207 507 039 343 337 74(33)	2.7×10^{-16}	GNSS	NMIJ Yb	NPL Sr
31	1.207 507 039 343 337 82(21)	1.8×10^{-16}	GNSS	NMIJ Yb	PTB Sr
32	1.207 507 039 343 338 03(24)	2.0×10^{-16}	GNSS	NMIJ Yb	SYRTE Sr
33	1.036 230 254 578 831 95(24)	2.4×10^{-16}	GNSS	VTT Sr^+	NPL Sr
34	1.036 230 254 578 832 29(26)	2.5×10^{-16}	GNSS	VTT Sr^+	PTB Sr
35	1.036 230 254 578 832 33(21)	2.0×10^{-16}	GNSS	VTT Sr^+	SYRTE Sr
36	1.000 000 000 000 000 08(24)	2.4×10^{-16}	GNSS	NPL Sr	PTB Sr
37	1.000 000 000 000 000 10(23)	2.3×10^{-16}	GNSS	NPL Sr	SYRTE Sr
38	1.000 000 000 000 000 14(12)	1.2×10^{-16}	GNSS	PTB Sr	SYRTE Sr

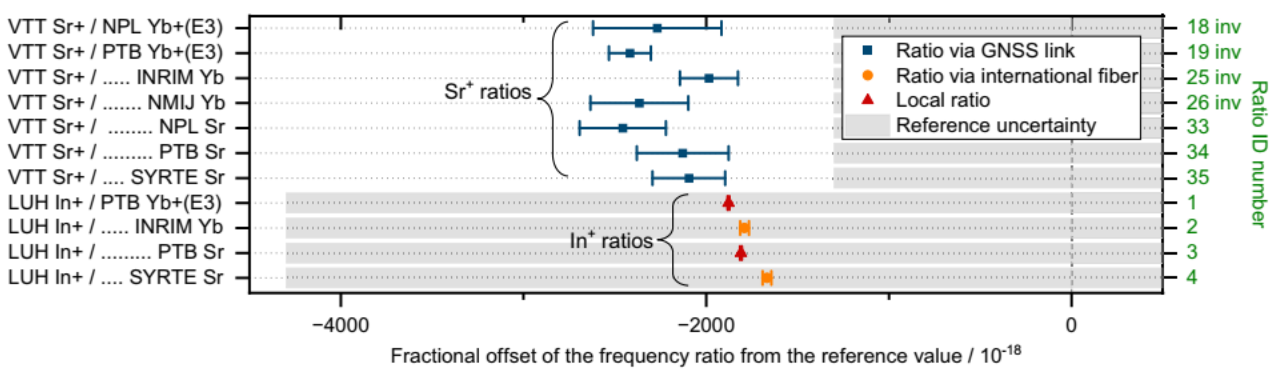
[a]It is likely, however, that some of the frequency ratios have significantly larger uncertainties than the estimates shown here. See Section 5 for further discussion of discrepancies seen in the ratios measured via GNSS with INRIM as well as ratios involving SYRTE Sr and PTB Sr.

2022 comparison campaign

❑ Significant inconsistencies

- some of them related to GNSS equipment
- Some likely from clocks, at the level of <1E-16

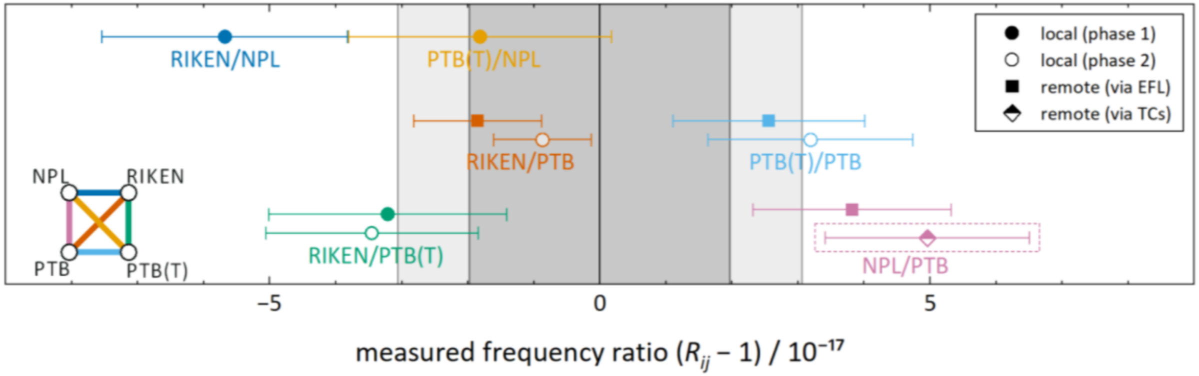


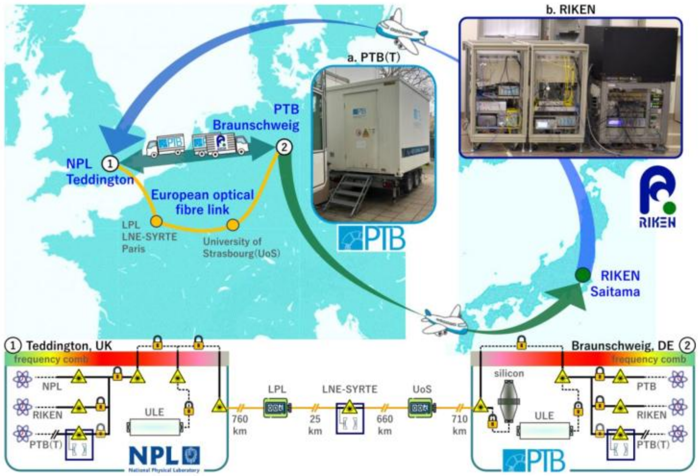


Recent campaigns

❑ 2023 with Sr transportable clocks from PTB and RIKEN

- arxiv 2410.22973





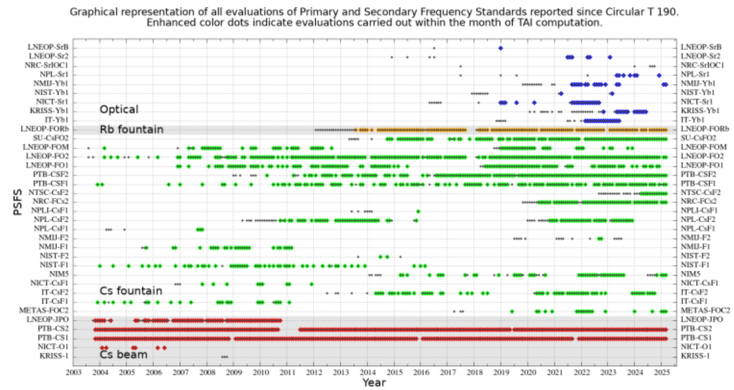
- Clocks systematic unc.

RIKEN 6×10-18
PTB(T) 1.4×10-17
PTB stationary 3×10-18
NPL stationary1.4×10-17

❑ 2023 7 clocks (INRIM, LTE, NPL, PTB) to be submitted

❑ 2025 on going analysis

Applications

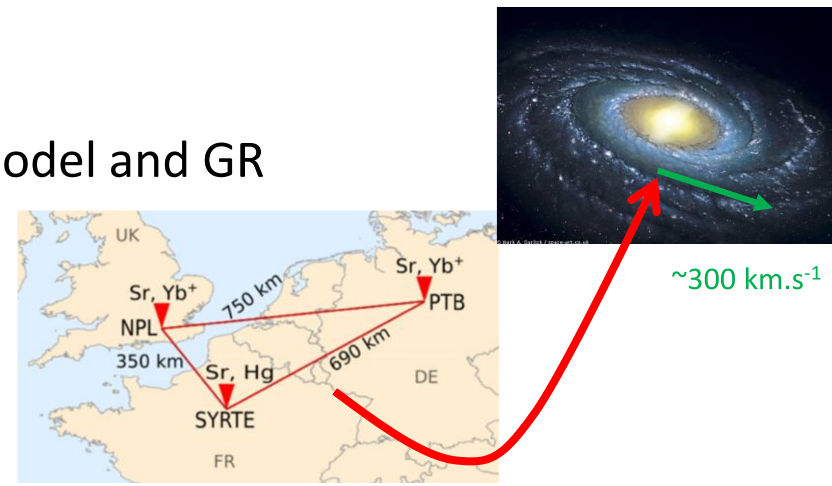


❑ Metrology

- Better time & frequency references
- Redefinition of the SI second

❑ Tests of fundamental laws

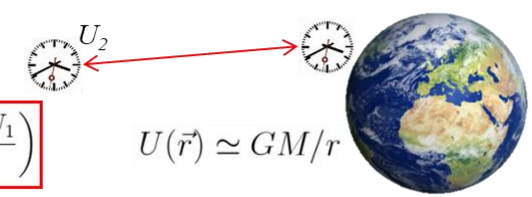
- Test of general relativity
- Search of physics beyond the standard model and GR
  - Stability of natural constants
- Search for dark matter



New. J. Phys. 22, 093010 (2020)

❑ Chronometric geodesy

- Sensitivity: 1E-18 ⇔ 1 cm
- →Transportable optical clocks
- →Optical fiber and free-space links



$$\frac{\nu_2}{\nu_1} = \left(1 - \frac{U_2 - U_1}{c^2}\right)$$

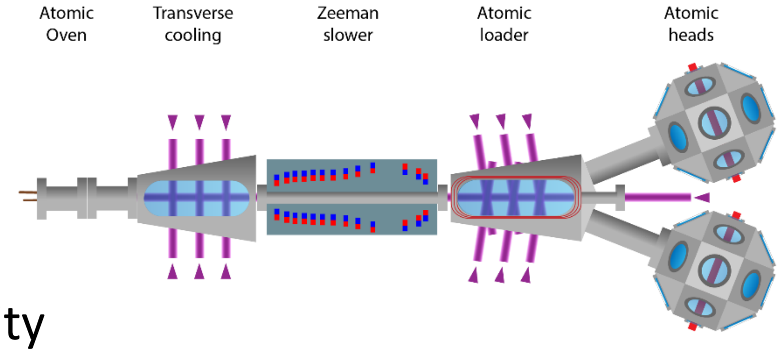
Delva, P., Denker, H., Lion, G. (2019). Chronometric Geodesy: Methods and Applications. arXiv:1804.09506

Transportable Yb lattice clock at LTE

https://roymageanr.obspm.fr/

❑ Impact of in-field operation

- Difficult to have state of the art ultra-stable laser
- More vibrations from the environment
- →degraded short term stability

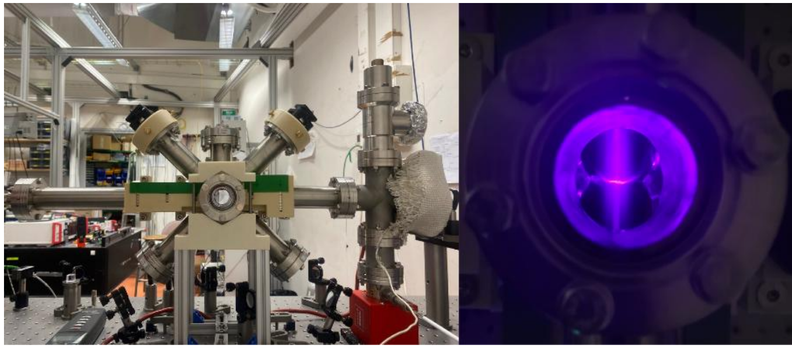


❑ Mitigate this with

- Seismometers to stabilize the reference cavity
- Ultrafast loading
- Dead-time free clock operation

❑ Goals

- Short term stability of few 1E-16 @1s in field conditions
- Total uncertainty of a few parts in 1E18

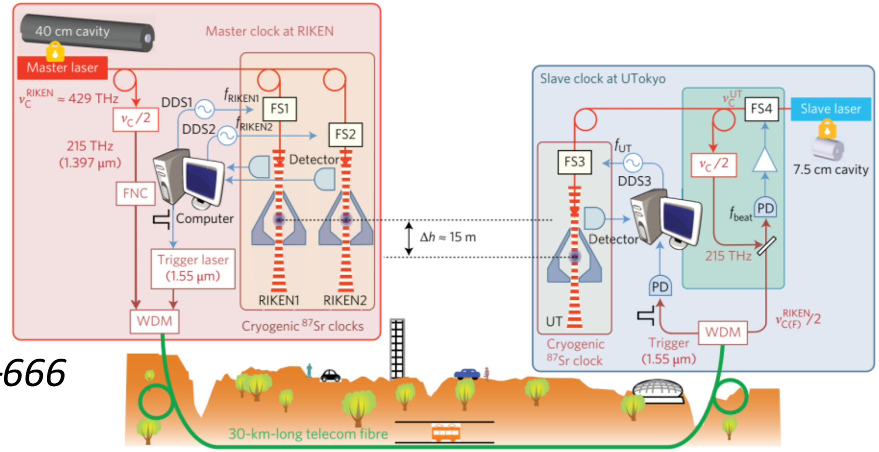


Toward chronometric geodesy

❑ Tokyo area

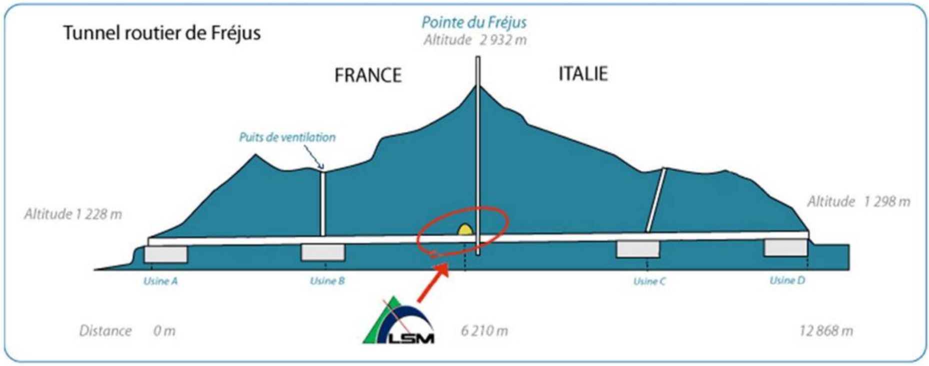
- RIKEN, UT
- Fiber: 30 km
- Spirit levelling, gravimetry: dh=5.9 mm
- u=5.9x10^{-18}

Nat. Photonics 10 (2016) 662–666



❑ Fréjus tunnel (LSM) – Torino

- PTB (Sr transp clk), INRIM, NPL
- Fiber: 150 km
- 1000 m height difference
- Underground, 1700 m rock coverage
- Geodesy + linkage: 1.8x10^{-17}
- u=1.9x10^{-15}



Nature Physics 14, 437–441 (2018)

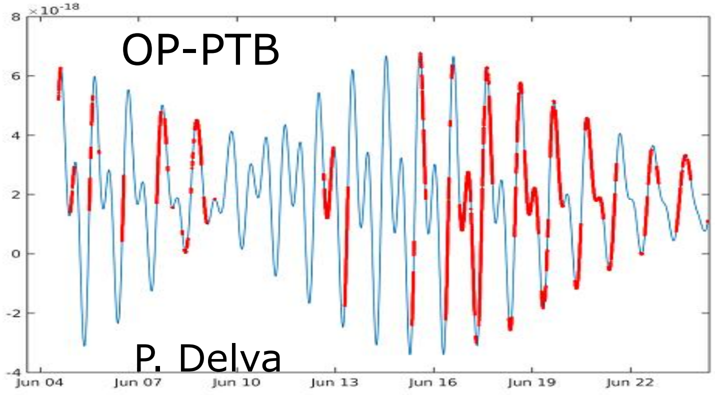
Toward chronometric geodesy

❑ PTB Sr transportable clock between PTB and MPQ

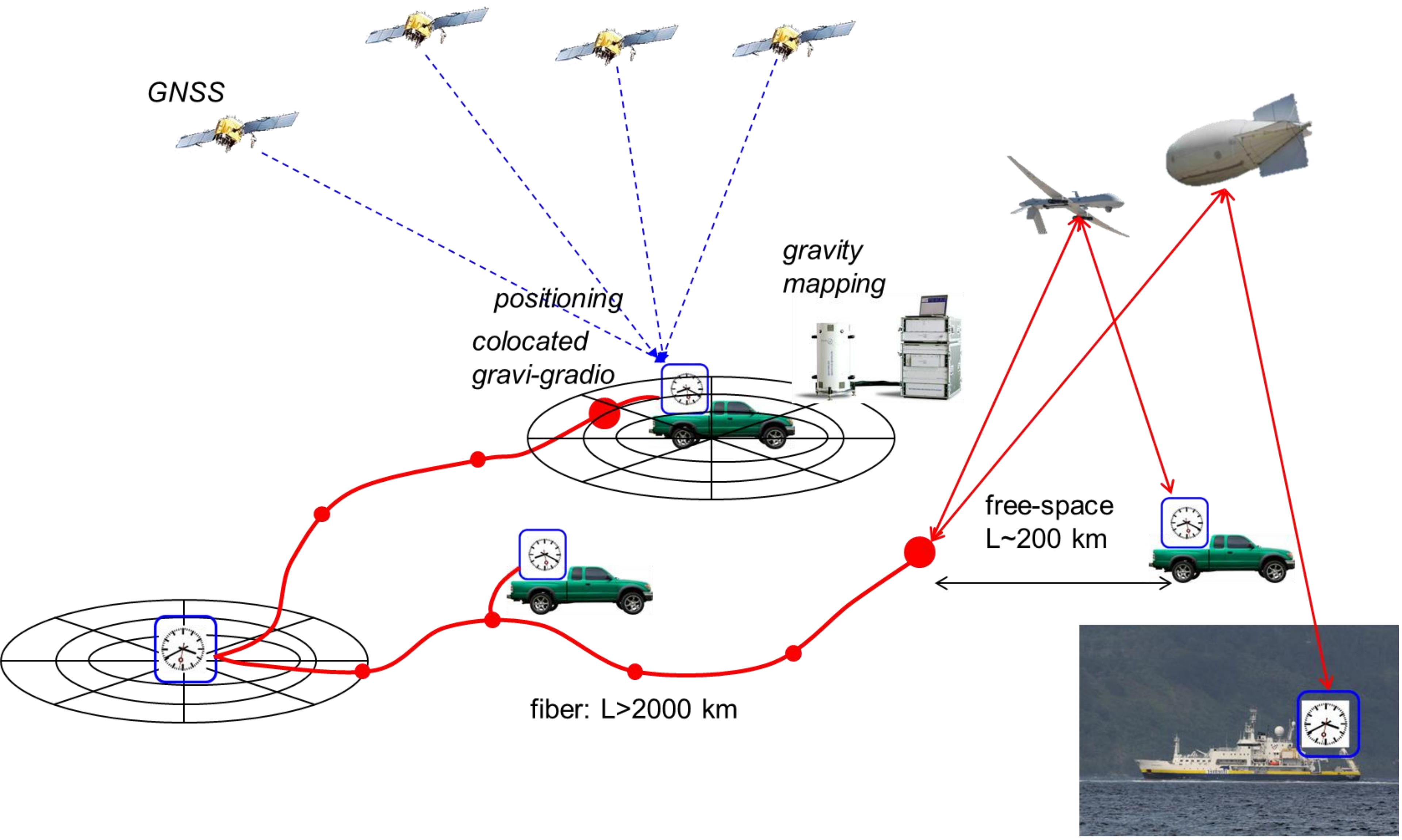
- Phys. Rev. Applied 21, L061001 (2024)
- Distance: 427 km
- Equivalent height uncertainty: 27 cm

❑ 2025 : attempt to observe the time varying potential due to tides

- Estimation of time varying potential: Metrologia 53, 1365 (2016)
- Mainly solid Earth tides and ocean tidal loading



Chronometric geodesy



Conclusions

- **Consolidation of optical clock accuracy**
  - More efforts needed to consolidate accuracy at the 5E-18 and beyond

- **Coherent optical fiber links are key to achieve this**
  - More comparison campaigns are and will be organized in the coming years.

- **Coherent optical fiber links can support comparisons to <<1E-18**
  - →Chronometric geodesy
  - →Improved fundamental physics tests