EMRP
European Metrology Research Programme
Programme of EURAMET

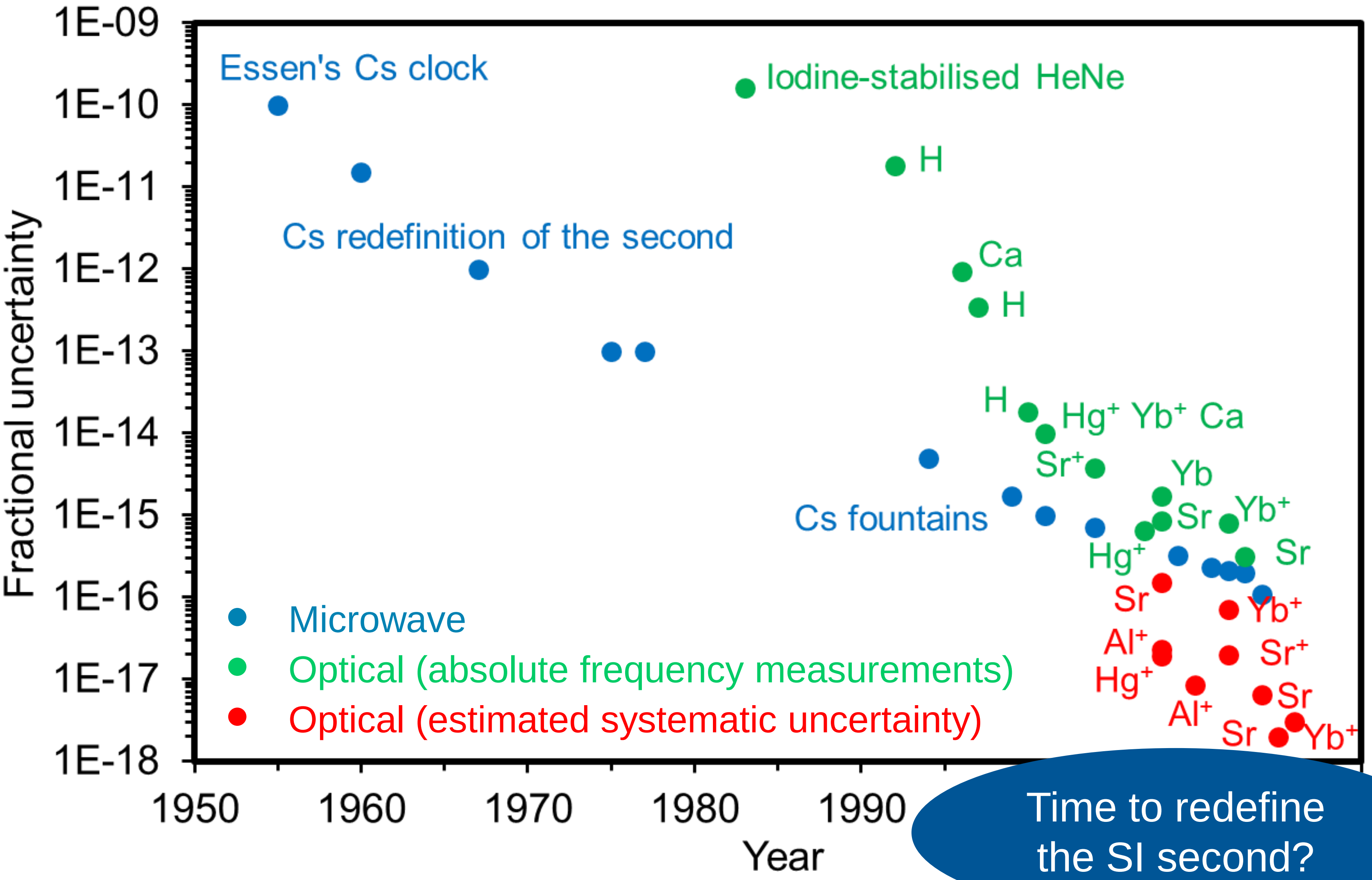
The EMRP is jointly funded by the EMRP participating countries within EURAMET and the European Union

Overview of the ITOC project

Helen Margolis

Optical Clocks: Quantum Engineering and International Timekeeping
University of York, UK (8th April 2016)

Improvements in optical clocks



Time to redefine the SI second?

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Optical secondary representations of the second

- Frequency standards that can be used to realise the SI second (although uncertainty cannot be better than Cs primary standard)

Atom or ion	Transition	Wavelength	Recommended fractional uncertainty (2015)
$^{87}\mathrm{Sr}$	$^{1}S_{0} - {}^{3}P_{0}$	698 nm	5×10^{-16}
$^{171}\mathrm{Yb}^{+}$	$^{2}S_{1/2} - {}^{2}F_{7/2}$	467 nm	6×10^{-16}
$^{27}\mathrm{Al}^{+}$	$^{1}S_{0} - {}^{3}P_{0}$	267 nm	1.9×10^{-15}
$^{199}\mathrm{Hg}^{+}$	$^{2}S_{1/2} - {}^{2}D_{5/2}$	282 nm	1.9×10^{-15}
$^{171}\mathrm{Yb}$	$^{1}S_{0} - {}^{3}P_{0}$	578 nm	2×10^{-15}
$^{171}\mathrm{Yb}^{+}$	$^{2}S_{1/2} - {}^{2}D_{3/2}$	436 nm	6×10^{-16}
$^{88}\mathrm{Sr}^{+}$	$^{2}S_{1/2} - {}^{2}D_{5/2}$	674 nm	1.6×10^{-15}

Local optical clock comparisons: reproducibility

Comparison of two $^{27}Al^+$ standards at NIST:

$^{27}Al^+ / ^{9}Be^+$	$u_B \sim 2.3 \times 10^{-17}$
$^{27}Al^+ / ^{25}Mg^+$	$u_B \sim 8.6 \times 10^{-18}$

Fractional frequency difference

$$-1.8\ (\pm 0.7) \times 10^{-17}$$

Chou *et al*., PRL 104, 070802 (2010)

Comparison of two cryogenic ^{87}Sr lattice clocks at RIKEN:

Fractional frequency difference

$$(-1.1 \pm 2.0(\mathrm{stat}) \pm 4.4(\mathrm{syst})) \times 10^{-18}$$

Ushijima *et al*., Nature Photonics 9, 183 (2015)

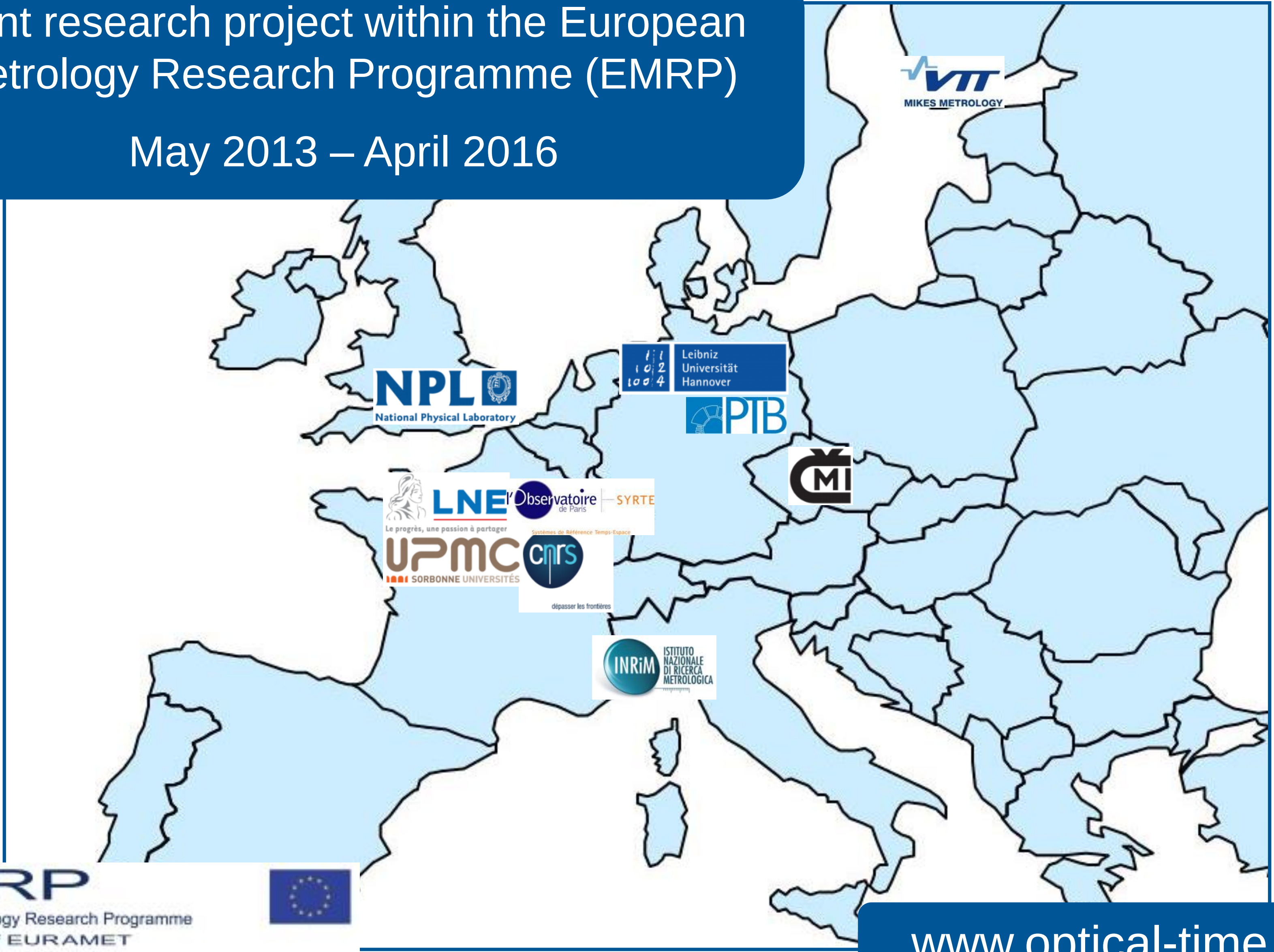
Prerequisites for a redefinition of the second

- Ultimate limits to the stability and accuracy of optical clocks fully investigated
- Improved methods for comparing optical clocks developed in different laboratories
- A coordinated programme of clock comparisons, to
  - Build confidence in the optical clocks
  - Anchor their frequencies to the current definition of the second
  - Establish the leading contenders for a redefinition
- Evaluation of relativistic effects at an improved level of accuracy
  - Includes the gravitational redshift of the clock frequency
- A framework and procedures for the optical clocks to be integrated into international timescales

ITOC: International timescales with optical clocks

Joint research project within the European Metrology Research Programme (EMRP)

May 2013 – April 2016



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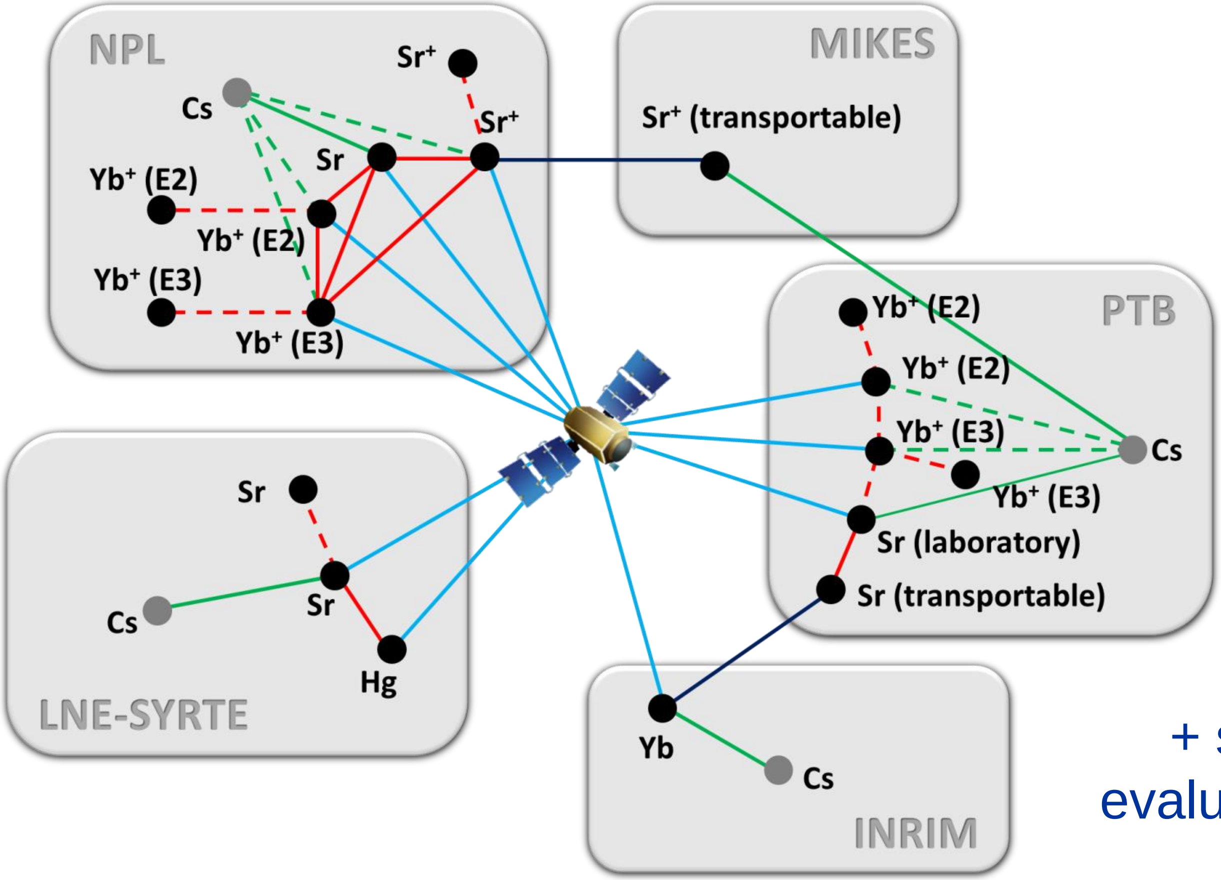
www.optical-time.eu

ITOC clock comparison programme



+ supporting work to evaluate relativistic effects

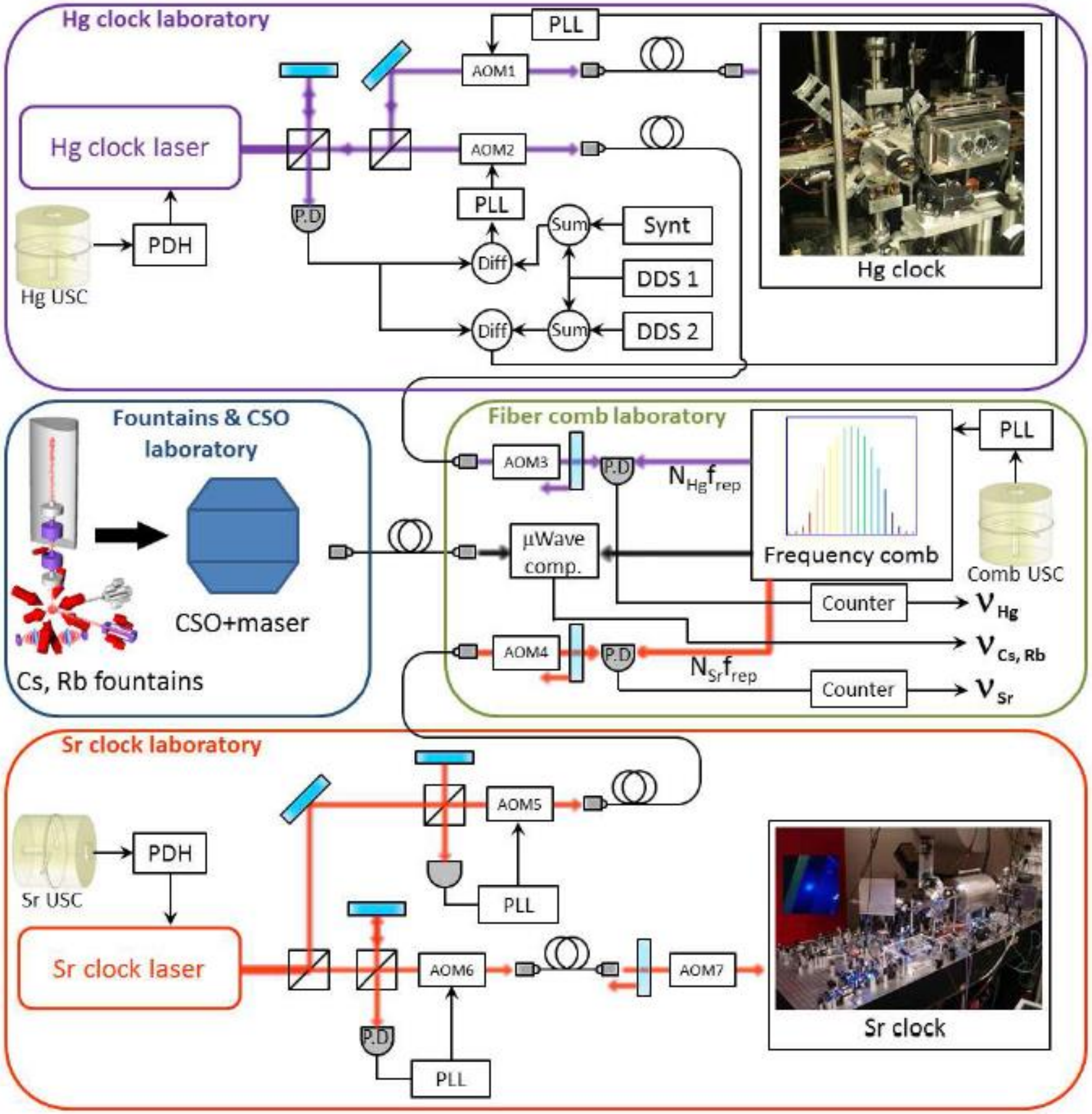
🟥 **Local optical frequency comparisons**

■ **Frequency comparisons using transportable optical clocks**

🟦 **Optical frequency comparisons using broad bandwidth TWSTFT**

🟩 **Absolute frequency measurements**

^{199}Hg / ^{87}Sr optical frequency ratio measured at LNE-SYRTE



^{199}Hg lattice clock

Systematic uncertainty 1.7×10^{-16}

Synchronous counting of beat notes on fibre-based frequency comb

^{87}Sr lattice clock

Systematic uncertainty 4.1×10^{-17}

^{199}Hg / ^{87}Sr optical frequency ratio measured at LNE-SYRTE

ν_{Hg}/ν_{Sr} = 2.629 314 209 898 909 15(46)

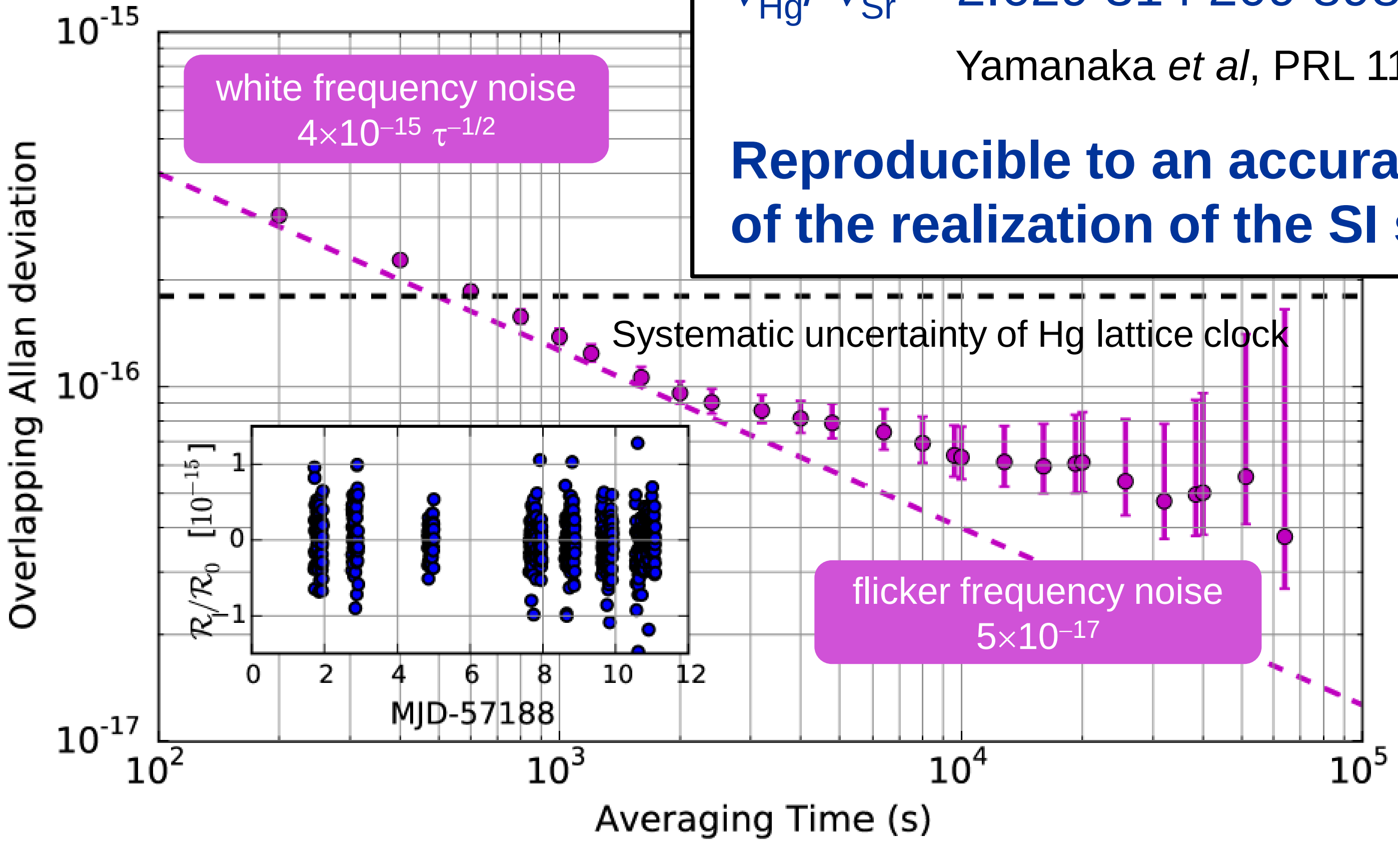
Tyumenev *et al*, arXiv:1603.02026v1 (2016)

In good agreement with

ν_{Hg}/ν_{Sr} = 2.629 314 209 898 909 60(22)

Yamanaka *et al*, PRL 114, 230801 (2015)

Reproducible to an accuracy beyond that of the realization of the SI second



white frequency noise
$4\times10^{-15}\ \tau^{-1/2}$

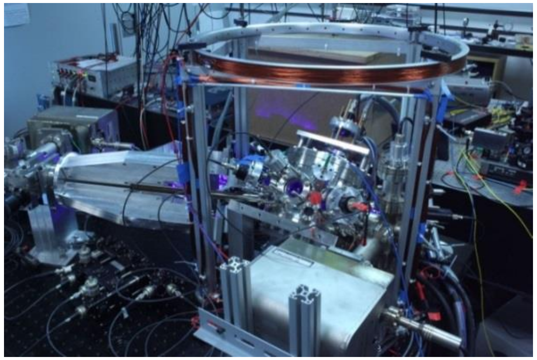
Systematic uncertainty of Hg lattice clock

flicker frequency noise
5×10^{-17}

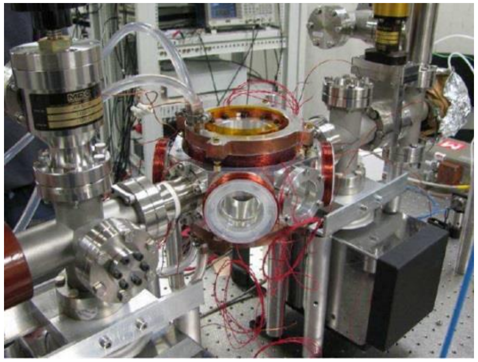
Transportable optical clocks

Transportable optical clocks

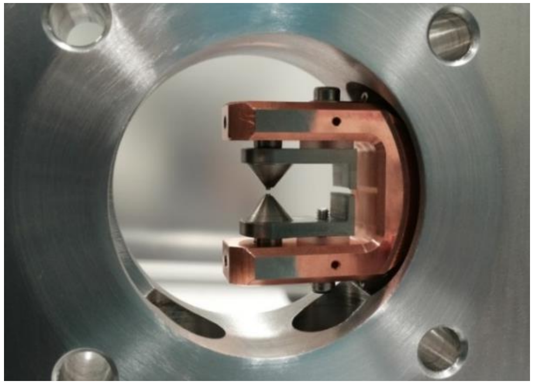
Stationary optical clocks



Strontium lattice, PTB



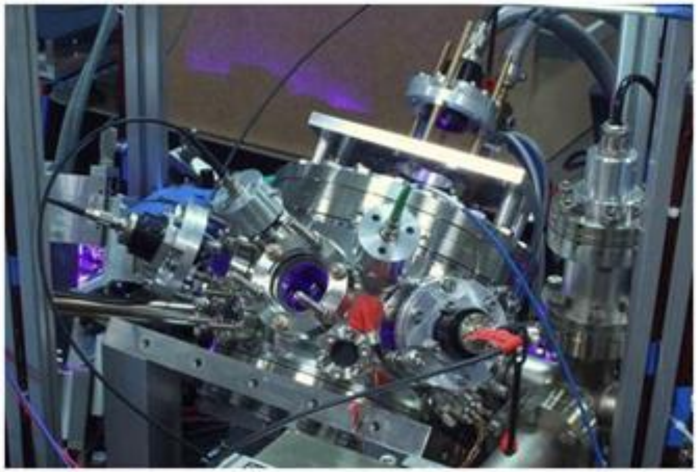
Ytterbium lattice, INRIM

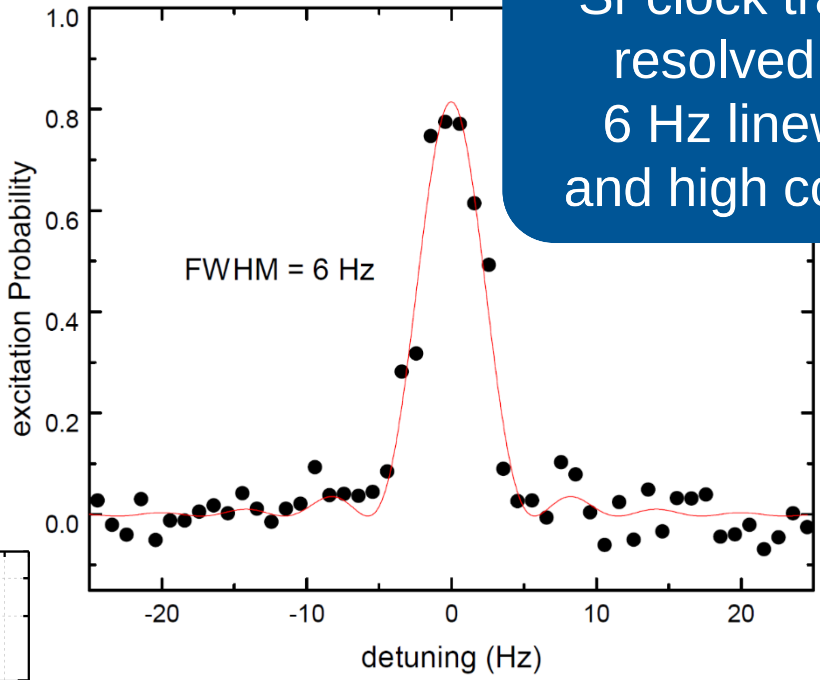


Strontium ion, MIKES

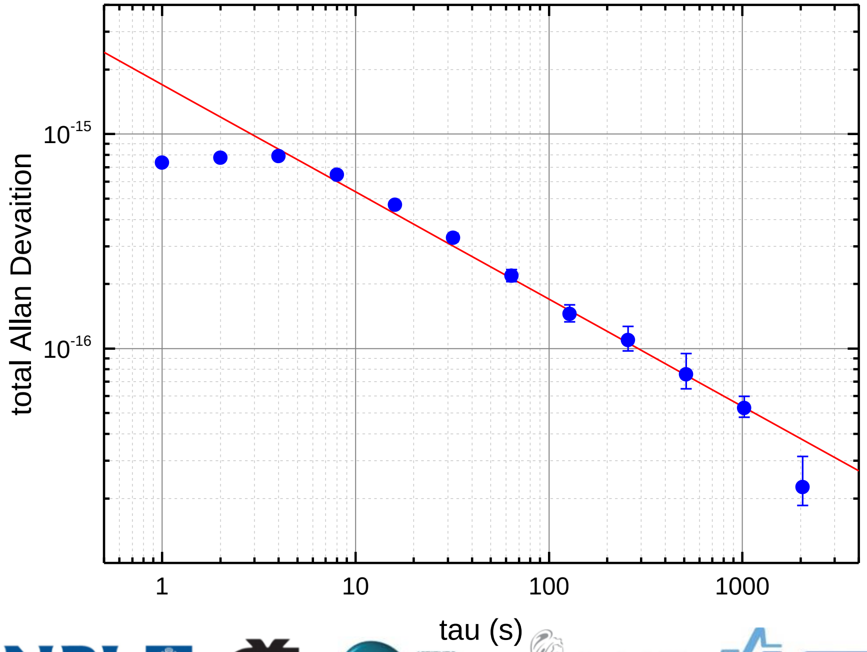
Strontium ion, NPL

PTB transportable strontium lattice clock





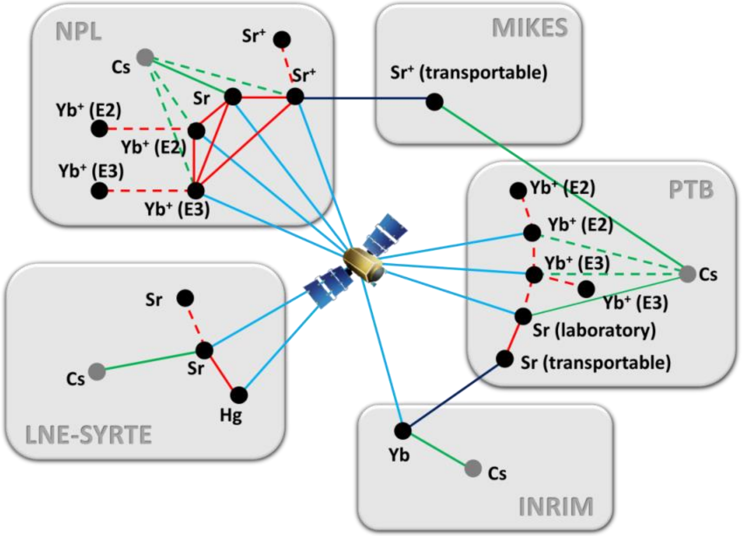
^{87}Sr clock transition resolved with 6 Hz linewidth and high contrast



Observed stability in comparisons against laboratory lattice clock well within design expectations

More details in poster 5 this afternoon (Stefan Vogt, Jacopo Grotti, Christian Lisdat)

Clock comparisons via broadband TWSTFT



- Investigation of improved TWSTFT technique based on an increased chip rate

  1 Mchip / s → 20 Mchip / s

- Goal is a gain in stability of one order of magnitude compared to state-of-the-art satellite-based methods

  10^{-15} @ 1 day → 10^{-16} @ 1 day

- Link test (7 days, October 2014) followed by optical clock comparisons (21 days, June 2015)

- Comparisons of clocks in all four laboratories with TWSTF capability (INRIM, LNE-SYRTE, NPL, PTB)

  Cs fountains as well as optical clocks

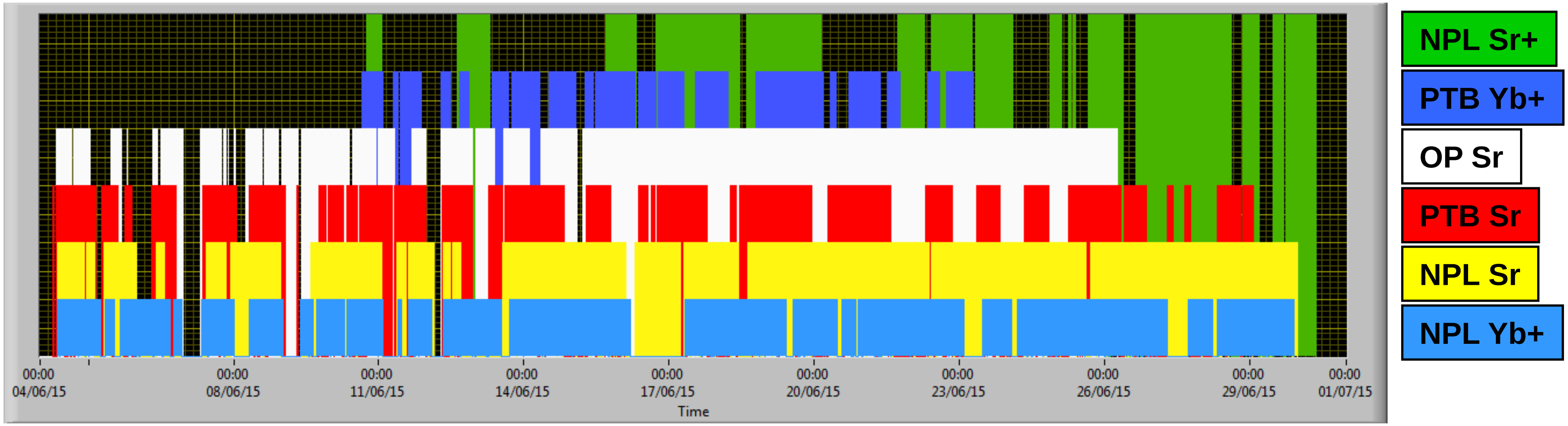
Clock comparisons via broadband TWSTFT

NPL	Yb$^+$ E3, Sr
PTB	Yb$^+$ E3, Sr
OP	Sr, Hg
INRIM	Yb

4th – ~~25th~~ June 2015

29th

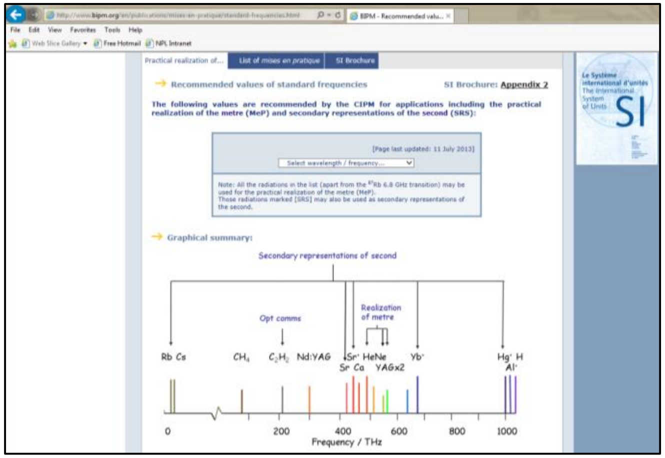
Duty cycles for optical clocks were typically in the range 60–80%:



Results will be presented in Franziska Riedel’s talk

Secondary representations of the second

- Recommended frequencies and uncertainties are assigned by the Frequency Standards Working Group (WGFS) of the CCTF and CCL



Recommended values of standard frequencies

SI Brochure: Appendix 2

The following values are recommended by the CIPM for applications including the practical realization of the metre (MeP) and secondary representations of the second (SRS):

[Page last updated: 11 July 2013]

Select wavelength / frequency...

Note: All the radiations in the list (apart from the ^{87}Rb 6.8 GHz transition) may be used for the practical realization of the metre (MeP).
Those radiations marked [SRS] may also be used as secondary representations of the second.

Graphical summary:

- Values are periodically updated and published at www.bipm.org/en/publications/mises-en-pratique/standard-frequencies.html

- Almost all data considered so far comes from absolute frequency measurements relative to Cs primary standards

- Future information about reproducibility of optical standards will come mainly from direct optical frequency ratio measurements

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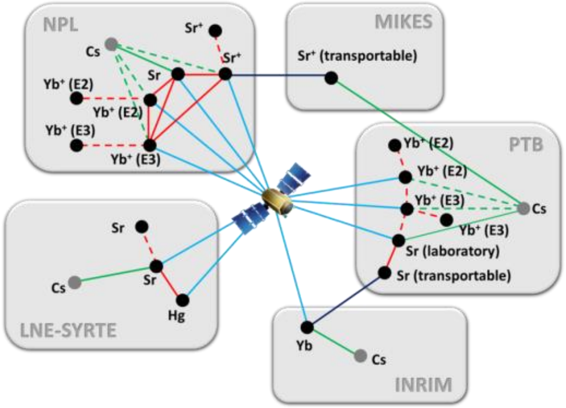
Over-determined sets of clock comparison data

- Within the ITOC project, we will end up with
  - A set of frequency ratio measurements between optical clocks
  - A set of Cs-limited absolute frequency measurements



- It will be possible to deduce some frequency ratios from several different measurements

- For example, ν_{Yb+} / ν_{Sr} could be measured either directly, or indirectly by combining two or more other frequency ratio measurements, e.g. $\nu_{Yb+} / \nu_{Sr} = (\nu_{Yb+} / \nu_{Yb})(\nu_{Yb} / \nu_{Sr})$ or $\nu_{Yb+} / \nu_{Sr} = (\nu_{Yb+} / \nu_{Cs})(\nu_{Cs} / \nu_{Sr})$

- Multiple routes to deriving each frequency ratio value mean that it will no longer be possible to treat each optical clock in isolation when considering the available data

Analysis of the frequency ratio matrix

- New methods have been developed for analysing such over-determined sets of clock comparison data
  - a) To check the level of internal self-consistency
  - b) To derive optimal values for the ratios between the operating frequencies of the clocks

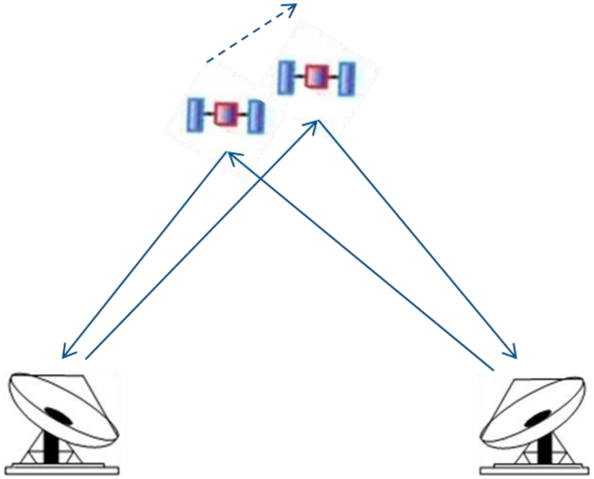
H. S. Margolis and P. Gill, Metrologia 52, 628 (2015)

- Use a least-squares adjustment procedure, based on the approach used by CODATA to provide a self-consistent set of recommended values of the fundamental physical constants
- All data stored as frequency ratios (optical frequency ratios, microwave frequency ratios or optical-microwave frequency ratios)
- Correlations between measured quantities are included in analysis
- Methods used by WGFS to update recommended frequency values in September 2015

For more details see poster 14 (Helen Margolis, Patrick Gill)

Relativistic effects in TWSTFT

GEO orbit is not perfect – residual motion of satellite has a period of one day



Sagnac effect

- Magnitude determined by satellite and ground station positions, therefore varies with a period of one day
- Imposes requirements on knowledge of satellite position

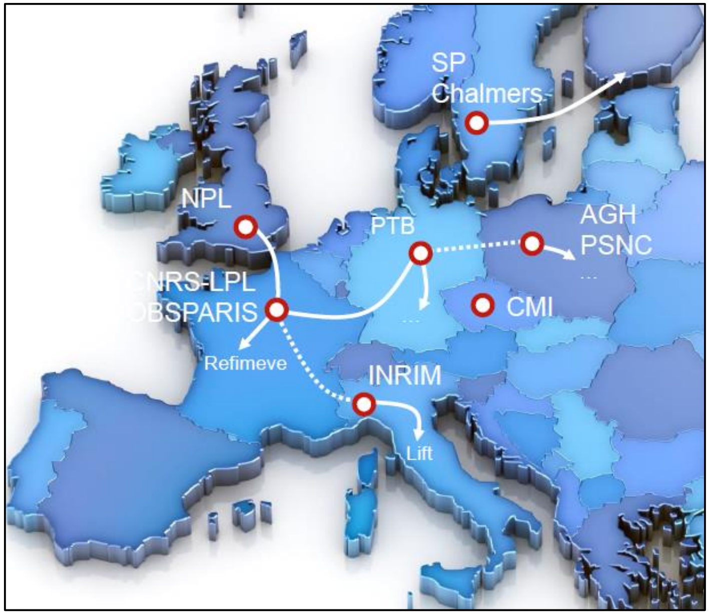
Path variation effects

- 1 PPS signals arrive at the satellite at slightly different times, corresponding to slightly different satellite positions
- Difference varies with time leading to frequency instability in the transfer
- Can be reduced by applying an offset Δt between the 1 PPS transmit times of the two stations

For more details see poster 17 (Setnam Shemar)

Relativistic corrections for time and frequency transfer in optical fibres

- Relativistic corrections derived for one-way and two-way time and frequency transfer over optical fibres
- All terms evaluated that exceed 1 ps in time and 10^{-18} in fractional frequency, estimating uncertainties due to imperfect knowledge of fibre route



- NPL-SYRTE and PTB-SYRTE fibre links studied as specific examples

J. Gersl, P. Delva and P. Wolf, Metrologia 52, 552 (2015)

See also poster 21 (Jan Geršl)

Gravity potential for optical clock comparisons

- Clocks are affected by the gravitational field and the velocity of the clocks
- Relativistic redshift between two Earth-bound clocks at rest is

$$\frac{\Delta f}{f} = \frac{\Delta W}{c^2}$$

W = gravity potential

(includes a gravitational and a centrifugal component)

Correction terms < 10^{-18} as long as time-variable effects are considered

- Absolute potentials are needed for contributions to international timescales (relative to conventional W_0)
- Potential differences ΔW are sufficient for clock comparisons

GNSS / levelling observations

- Geometric levelling is a differential technique – gives only potential differences
- Sub-mm accuracy over short distances, but systematic errors accumulate over larger distances

NPL

PTB

- GNSS / geoid approach can deliver absolute potential values
- Accuracy is about 0.25 m^2/s^2 (equivalent to 2.5×10^{-18} in fractional frequency)

ITOC gravity campaigns

INRIM (September 2013)

- One absolute gravity measurement
- 35 relative gravity measurements

OBSPARIS (October 2014)

- 3 absolute gravity measurements
- 99 relative gravity measurements

NPL (March 2014)

- 2 absolute gravity measurements
- 64 relative gravity measurements

PTB (March and October 2014)

- 1 absolute gravity measurements
- 83 relative gravity measurements

ITOC gravity campaigns

NPL (March 2014)

- 2 absolute gravity measurements
- 64 relative gravity measurements

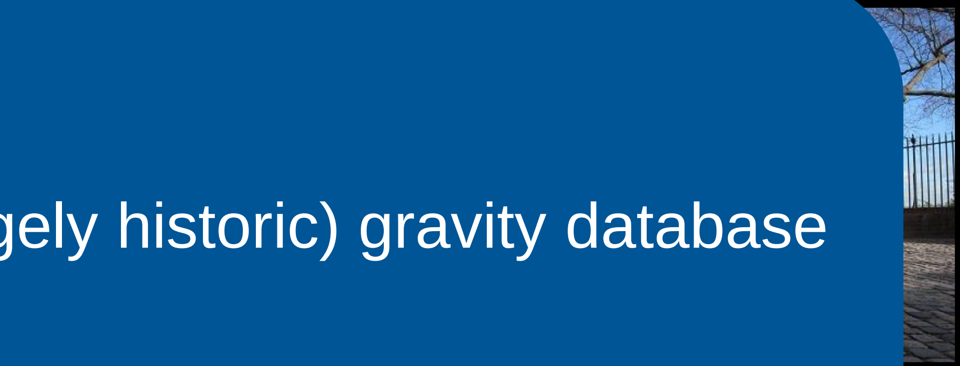
Aims:

- Evaluate the existing (largely historic) gravity database

  → *Consistency check*

- Fill areas void of gravity data

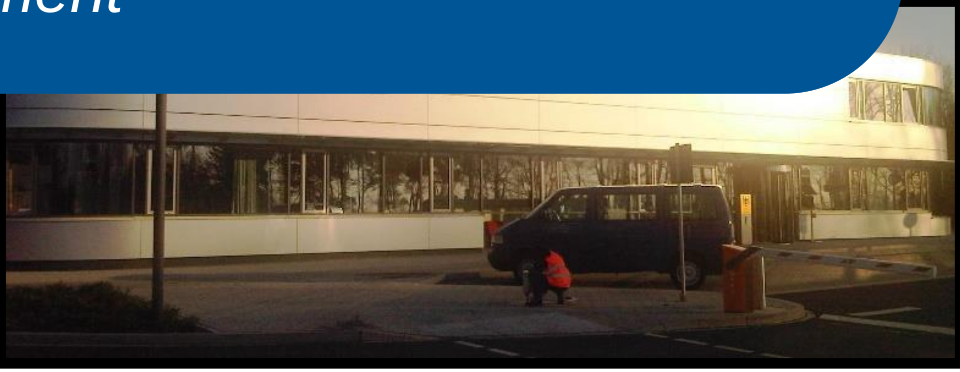
  → *Coverage improvement*



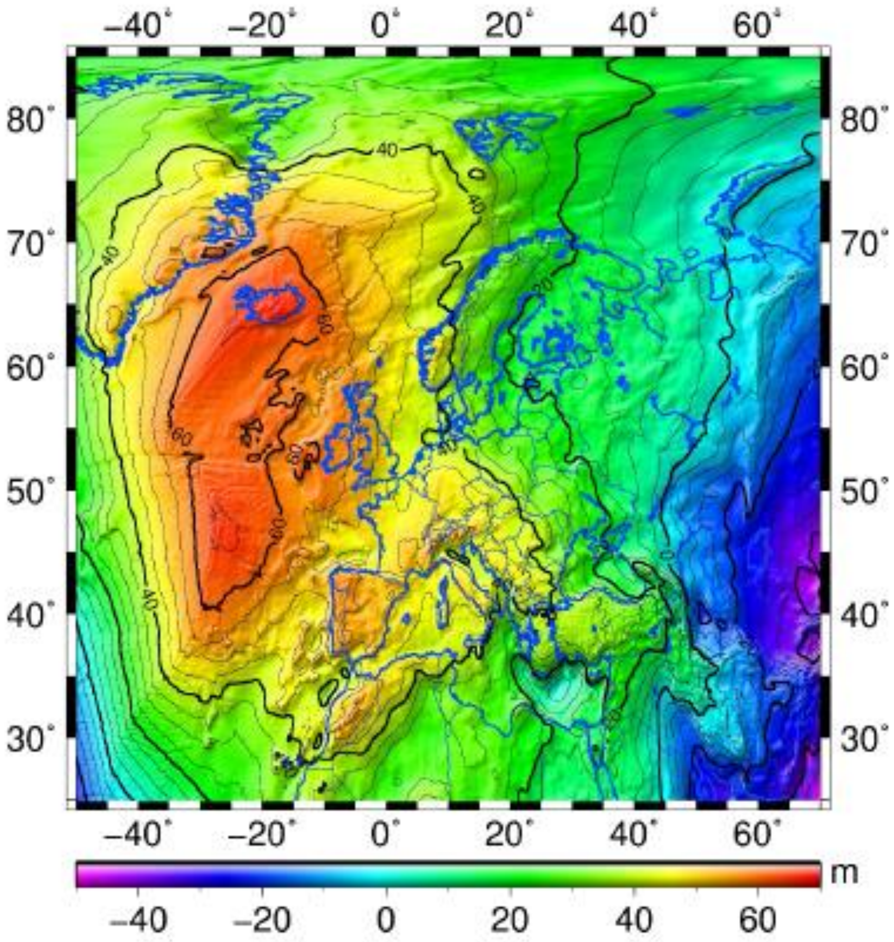
IN

OBSPARIS (October 2014)

- 3 absolute gravity measurements
- 99 relative gravity measurements



New European Gravimetric (Quasi)Geoid EGG2015



- Long wavelength components computed from a global Earth gravity model
- Short wavelength components computed from high resolution digital elevation models
- Medium wavelength structures recovered from terrestrial gravity data

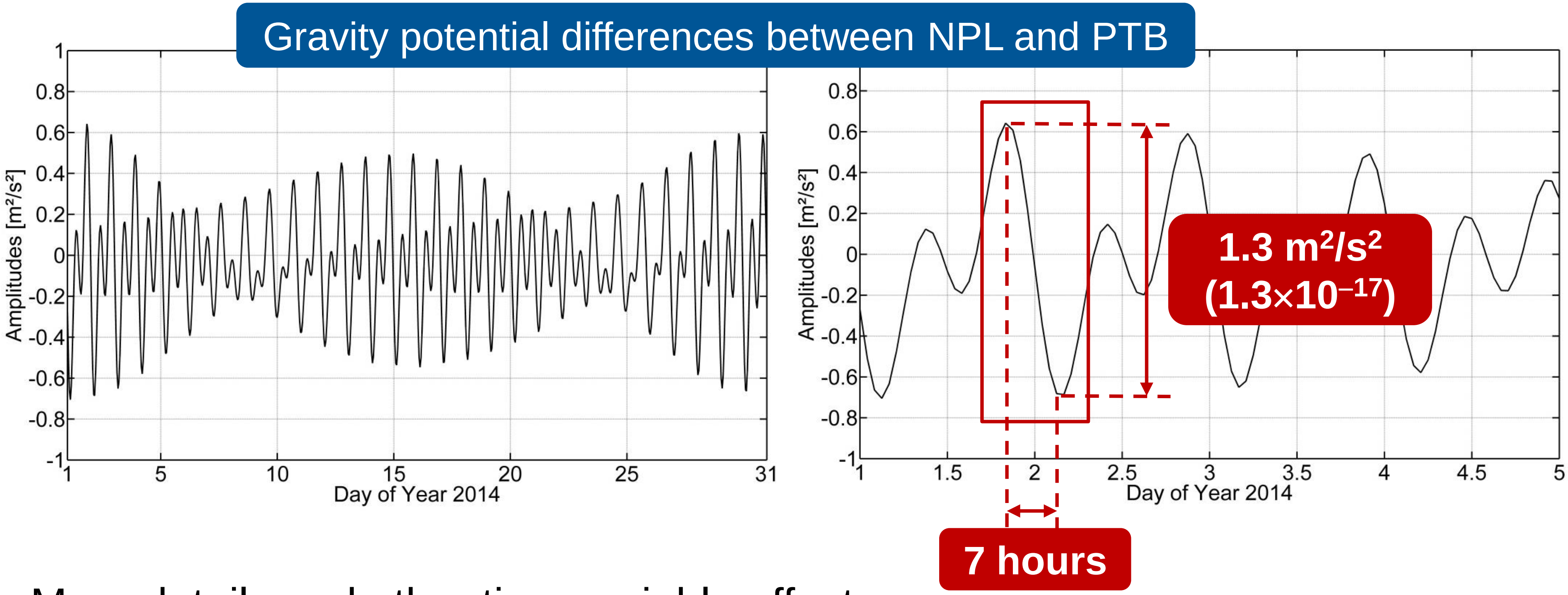
Accuracy ~ few cm

For more details see poster 18 (Heiner Denker, Ludger Timmen)

Time-variable components of the gravity potential

Largest effect is from Solid Earth tides

- Peak-to-peak range ~ 5 m^2/s^2
- Potential differences increase with increasing East-West separation



Gravity potential differences between NPL and PTB

$1.3\ m^2/s^2$
(1.3×10^{-17})

7 hours

More details and other time-variable effects
discussed in poster 19 (Heiner Denker, Ludger Timmen)

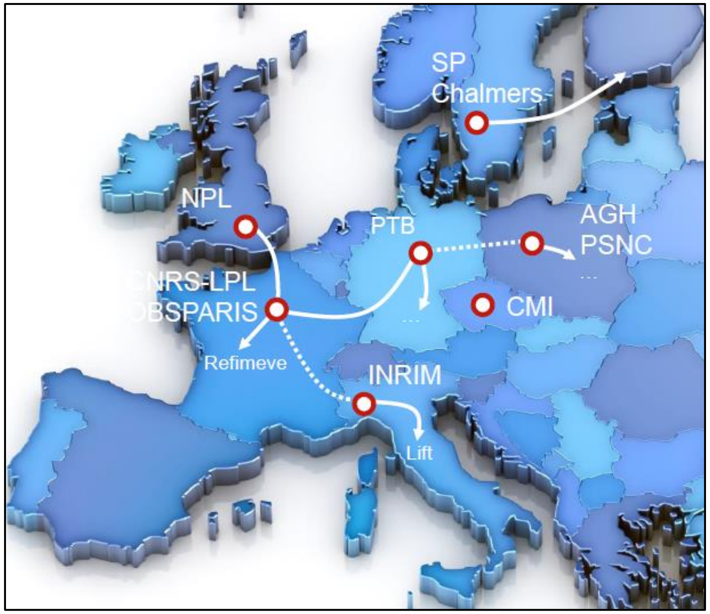
Clock-based geodesy

Direct measurement of the earth’s gravity potential with high resolution by using the gravitational redshift.

Frequency shift

$$Z \equiv \frac{\Delta f}{f} = \frac{\Delta W}{c^2}$$

ΔW = gravity potential difference between clocks



Comparison of terrestrial clocks with 10^{-18} accuracy

Measurement of gravity potential differences with a sensitivity of ~0.1 m^2/s^2 or 1 cm in height

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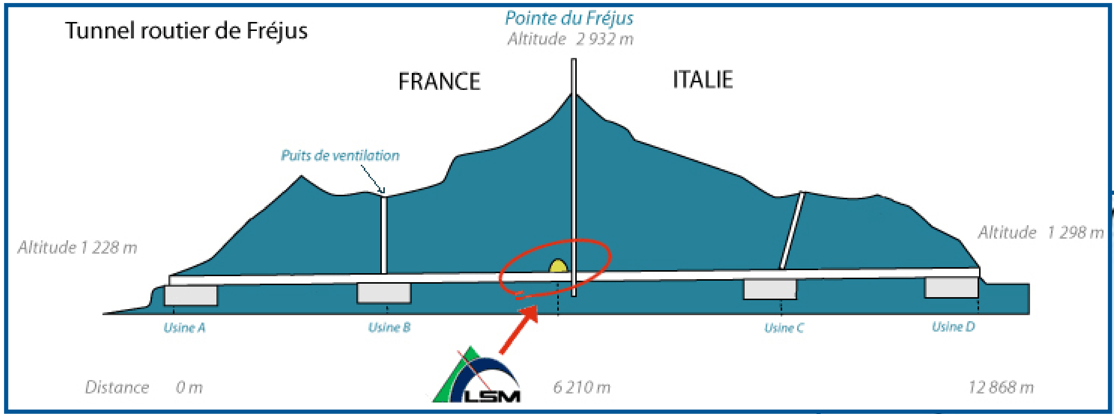
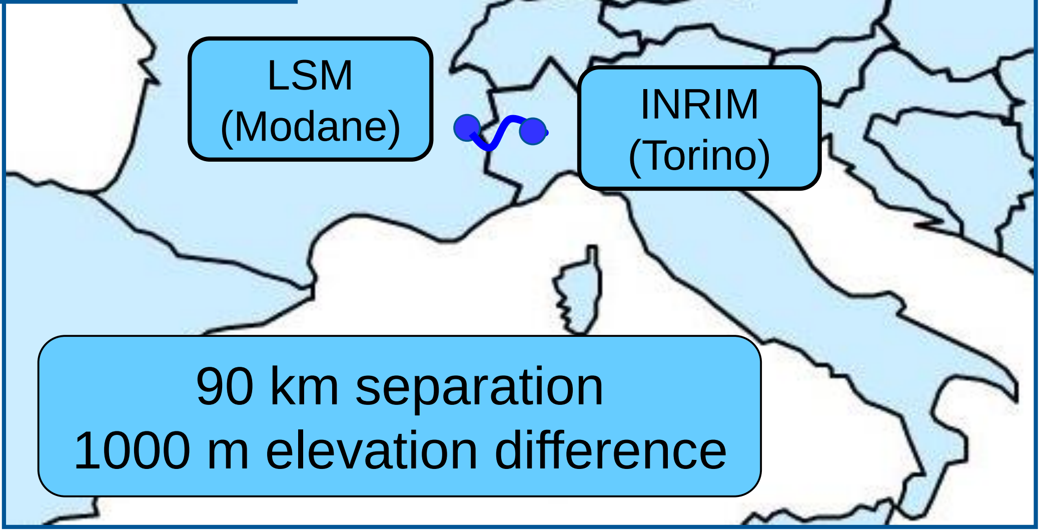
Proof-of-principle clock-based geodesy experiment

Aim: To show that optical clocks can be used to measure gravity potential differences over medium – long baselines with high temporal resolution



- One absolute gravity measurement
- 122 relative gravity measurements

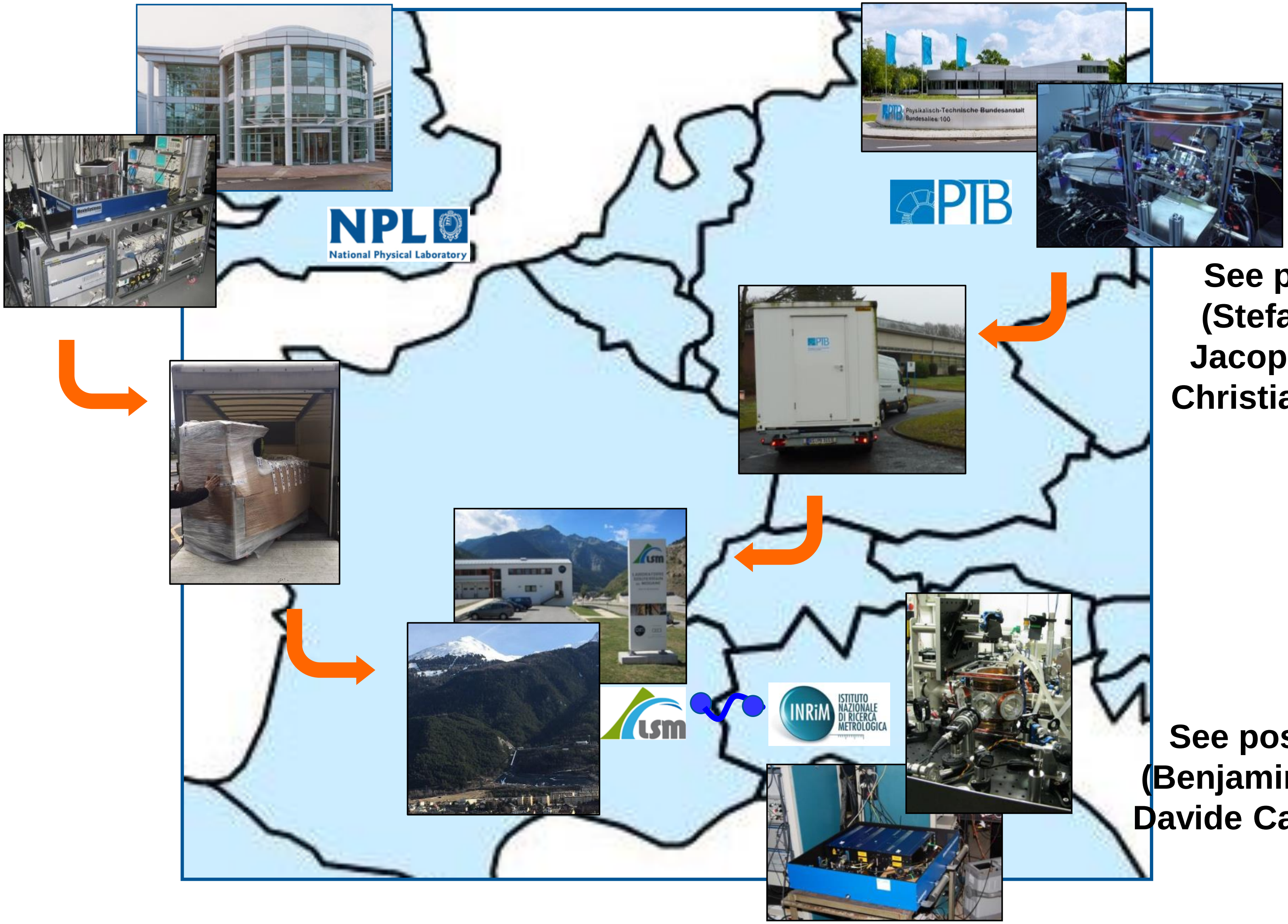


LSM (Modane)

INRIM (Torino)

90 km separation
1000 m elevation difference

Proof-of-principle clock-based geodesy experiment



See poster 5 (Stefan Vogt, Jacopo Grotti, Christian Lisdat)

See poster 2 (Benjamin Rauf, Davide Calonico)

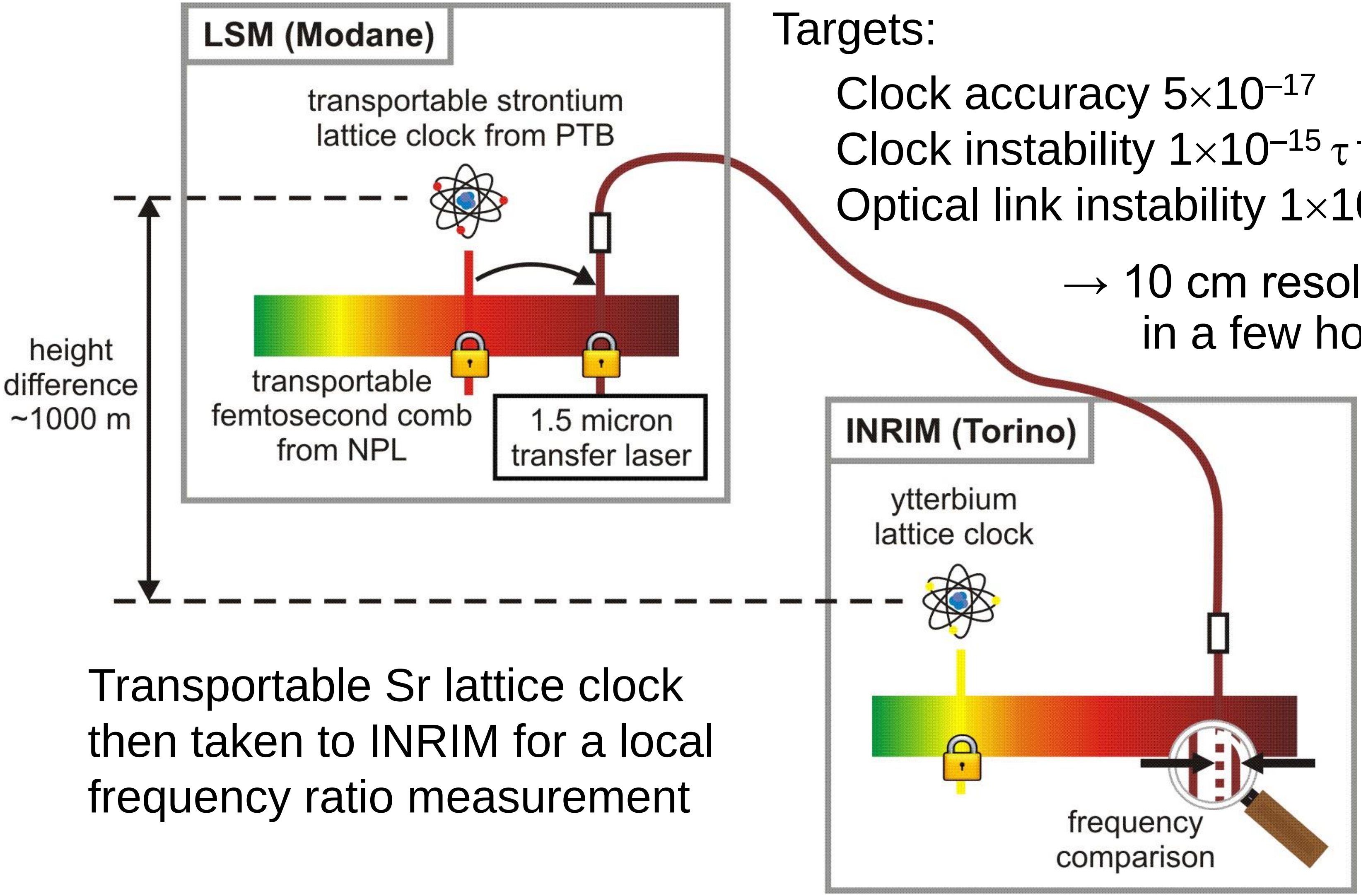
Proof-of-principle clock-based geodesy experiment

Gravitational redshift ~ 10^{-13}

Targets:

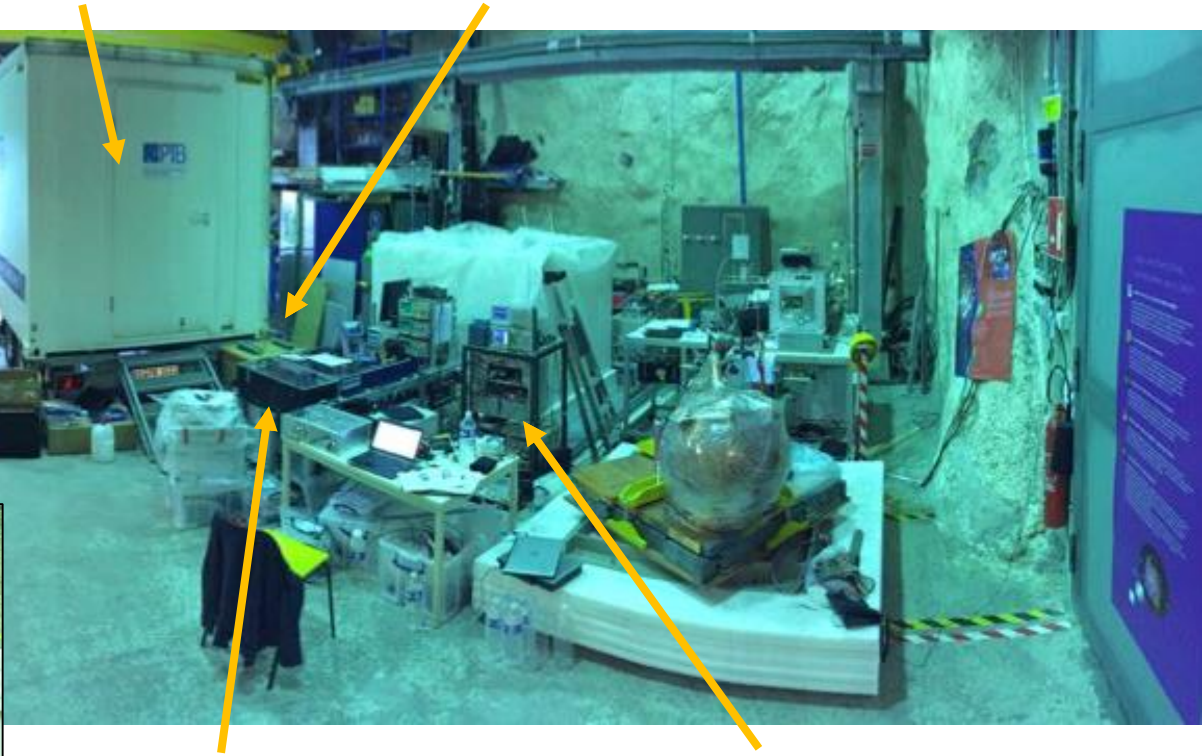
- Clock accuracy 5×10^{-17}
- Clock instability $1\times10^{-15}\,\tau^{-1/2}$
- Optical link instability $1\times10^{-14}\,\tau^{-1}$

→ 10 cm resolution in a few hours



Transportable Sr lattice clock then taken to INRIM for a local frequency ratio measurement

Experimental setup at LSM (February / March 2016)

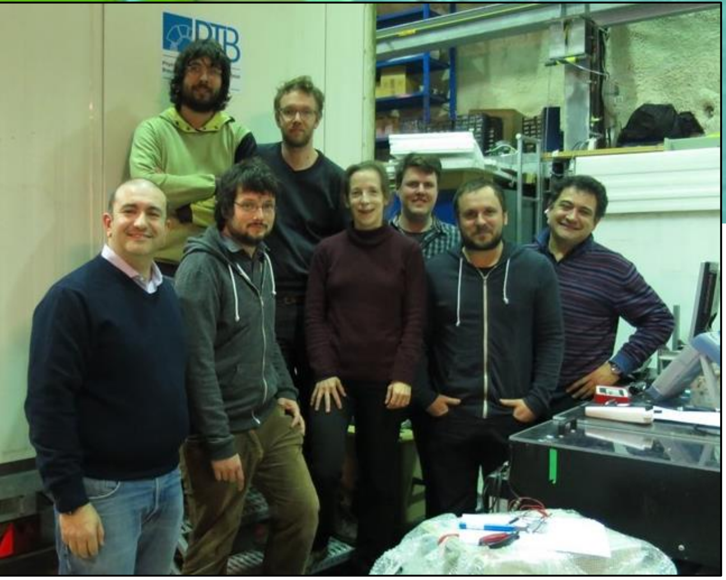


Sr lattice clock

clock laser

frequency comb

fibre link from INRIM



All 6.5 km inside the Fréjus tunnel…

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PTB

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Status of experiment

Challenges

- Tunnel environment
- Movement of overhead crane
- Limited working hours
- Explosions!

What worked

- Frequency comb at INRIM and transportable comb at LSM
- Optical fibre link from INRIM to LSM
- Transportable Sr lattice clock (after heroic effort from the PTB team)
- Yb lattice clock at INRIM (for most of the measurement campaign)
- Cs fountain at INRIM
- Team cooperation

Data analysis underway: Sr v CsF with hydrogen maser as a flywheel

Anticipated uncertainty $< 2 \times 10^{-15}$

With thanks to …

CMI	Jan Geršl
INRIM	Filippo Bregolin, Davide Calonico, Giancarlo Cerretto, Cecilia Clivati, Giovanni Antonio Costanzo, Matteo Frittelli, Filippo Levi, Alberto Mura, Marco Pizzocaro, Benjamin Rauf, Ilaria Sesia, Anna Tampellini, Patrizia Tavella, Pierre Thoumany, Massimo Zucco
LNE-SYRTE	Michel Abgrall, Joseph Achkar, Slawomir Bilicki, Sébastien Bize, Eva Bookjans, Baptiste Chupin, Pacôme Delva, Luigi De Sarlo, Maxime Favier, Jocelyne Guéna, Yann Le Coq, Guillaume Lion, Jérôme Lodewyck, Rodolphe Le Targat, Daniele Nicolodi, Jean-Luc Robyr, Peter Rosenbusch, Daniele Rovera, Chunyan Shi, Rinat Tyumenev, Peter Wolf
LUH	Heiner Denker, Delira Hanelli, Sergiy Svitlov, Ludger Timmen, Christian Voigt
MIKES	Thomas Fordell, Thomas Lindvall, Mikko Merimaa, Anders Wallin
NPL	Geoff Barwood, Fred Baynes, Charles Baynham, William Bowden, Sean Donnellan, Patrick Gill, Rachel Godun, Ian Hill, Richard Hobson, Guilong Huang, Luke Johnson, Jonathan Jones, Steven King, Hugh Klein, Andrew Lamb, Marco Menchetti, Peter Nisbet-Jones, Filip Ozimek, Antoine Rolland, Fiona Rust, Setnam Shemar, Krzysztof Szymaniec, Peter Whibberley
PTB	Ali Al-Masoudi, Erik Benkler, Sören Dörscher, Stephan Falke, Vladislav Gerginov, Christian Grebing, Jacopo Grotti, Sebastian Häfner, Nils Huntemann, Silvio Koller, Julia Leute, Burghard Lipphardt, Christian Lisdat, Ekkehard Peik, Dirk Piester, Franziska Riedel, Christian Sanner, Uwe Sterr, Christian Tamm, Stefan Vogt, Stefan Weyers
Collaborators	Michel Zampaolo, Thierry Zampieri (Laboratoire Souterrain de Modane, France) Pascale Defraigne (Royal Observatory, Belgium) Wolfgang Schäfer (TimeTech, Germany) Gérard Petit (BIPM)