ITOC: International Timescales with Optical Clocks

EMRP
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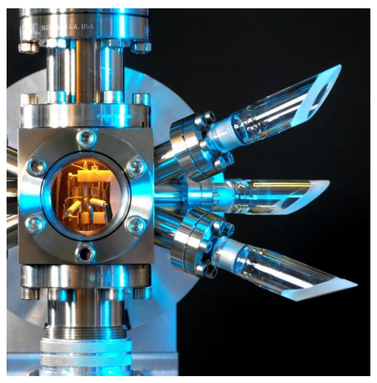
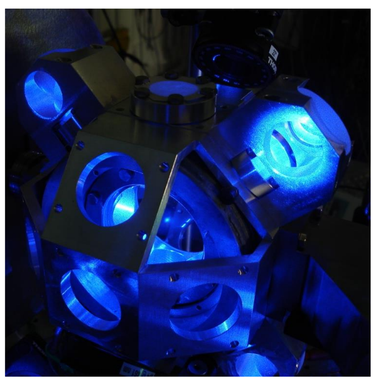
www.optical-time.eu

Rationale for the project



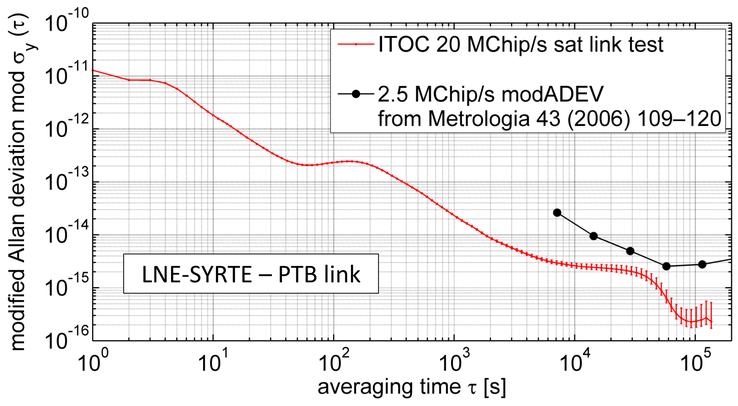
The most advanced optical atomic clocks have reached levels of stability and accuracy that surpass the performance of the best Cs fountain primary standards. However before an optical redefinition of the SI second can be implemented, it is necessary to:

- Develop improved methods for comparing optical clocks developed in different laboratories;
- Carry out a coordinated programme of clock comparisons to validate the uncertainty budgets of the optical clocks, to anchor their frequencies to the present definition of the second, and to establish the leading contenders for a new definition;
- Evaluate relativistic effects influencing comparisons between clocks at an improved level of accuracy, including the gravitational redshift of the clock transition frequency;
- Establish a framework and procedures for the optical clocks to be integrated into international timescales.



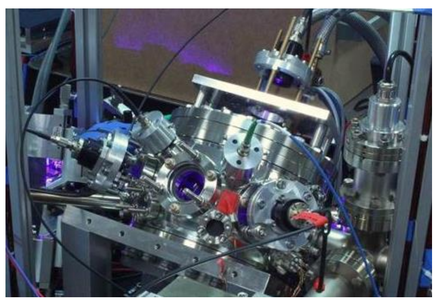
Coordinated programme of optical clock comparisons

Optical frequency comparisons using broad bandwidth TWSTFT

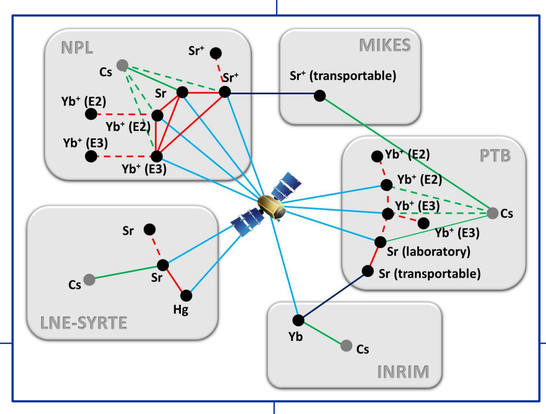


- In October 2014, a one-week satellite link test campaign at 20 Mchip/s was carried out via the SES ASTRA 3B satellite.
- Short-term instabilities of $1 – 2 \times 10^{-11}$ at 1 s averaging time were observed.
- Instabilities of a few parts in 10^{16} at one day (MDEV) are reached, limited by the stability of the hydrogen masers used as references.
- It may be possible to reduce some of the disturbances observed on the TWSTFT link, e.g. diurnals due to daily temperature variations, by modelling and subtraction.

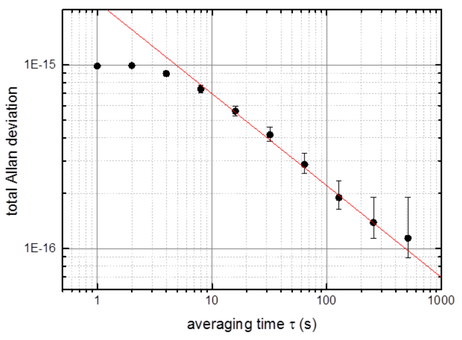
Frequency comparisons using transportable optical clocks



- Two transportable systems are being developed: a strontium optical lattice clock at PTB and a strontium ion optical clock at MIKES.
- The hardware for the transportable lattice clock has been assembled at PTB and the clock apparatus is now under evaluation.



- The ^{87}Sr clock transition has been resolved with below 10 Hz linewidth and high contrast.
- The observed stability in preliminary comparisons against a laboratory lattice clock are well within design expectations.



Local optical frequency comparisons using femtosecond combs

- Comparisons between co-located optical clocks will lead to the highest levels of stability and accuracy.
- Values for two directly measured optical frequency ratios have been provided by the EMRP project “High accuracy optical clocks with trapped ions” (^{171}Yb$^+$ (E3) / ^{171}Yb$^+$ (E2) at NPL [1], ^{171}Yb$^+$ (E3) / ^{87}Sr at PTB).

Absolute frequency measurements

- Four new absolute frequency measurements of the ^{87}Sr optical clock transition have been completed at PTB [2] and LNE-SYRTE.
- Several other new measurement results have been obtained from the EMRP project “High accuracy optical clocks with trapped ions” (^{88}Sr$^+$ at NPL [3], ^{171}Yb$^+$ E2 and E3 at NPL [1] and PTB [4,5]).

[1] R. M. Godun *et al.*, PRL 113, 210801 (2014). [2] S. Falke *et al.*, New J. Phys. 16, 072023 (2014). [3] G. P. Barwood *et al.*, PRA 89, 050501(R) (2014). [4] C. Tamm *et al.*, PRA 89, 023820 (2014). [5] N. Huntemann *et al.*, PRL 113, 210802 (2014).

Gravity measurements

To determine gravitational redshift corrections for clocks of 10^{-18} accuracy requires improved knowledge of the gravity potential at the clock locations.

- Setups have been designed to determine the static gravity potential at all clock locations (potential differences for clock comparisons, absolute potential values for timescales).
- Levelling measurements have been performed at INRIM, LNE-SYRTE, LSM, NPL and PTB.
- Gravity surveys have been carried out at all locations, including at least one absolute gravity observation on each site and between 35 and 122 relative gravity measurements around each site.

- These measurements will feed into the computation of a refined European geoid model.
- Time-variable components of the gravity potential will also be investigated.

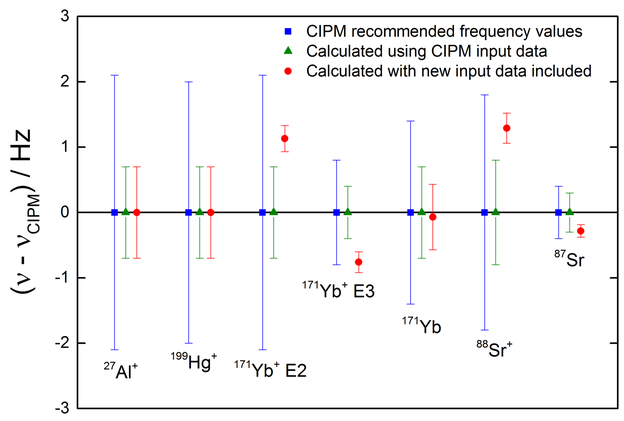
Analysis techniques

The set of clock comparison measurements will be over-determined, in the sense that it will be possible to deduce certain frequency ratios from several different measurements.

A least-squares adjustment procedure has been developed to

a) check the level of internal consistency within the complete body of data;

b) derive optimal values for the ratios between the operating frequencies of the clocks.



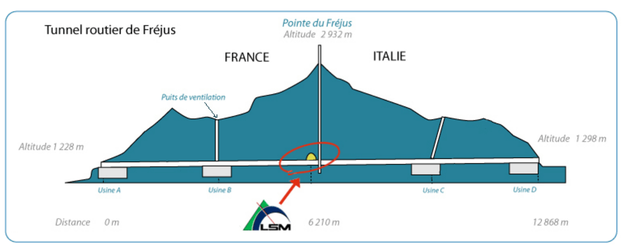
Frequency values obtained from the analysis software for the seven optical secondary representations of the second

- Analysis software reproduces the CIPM recommended frequency values, when using the same input data.
- Used to explore the effects of including more recent data in the analysis.
- Work has shown the importance of accounting for correlations between the input data.

H. S. Margolis and P. Gill, arXiv:1504.01633v1 (2015)

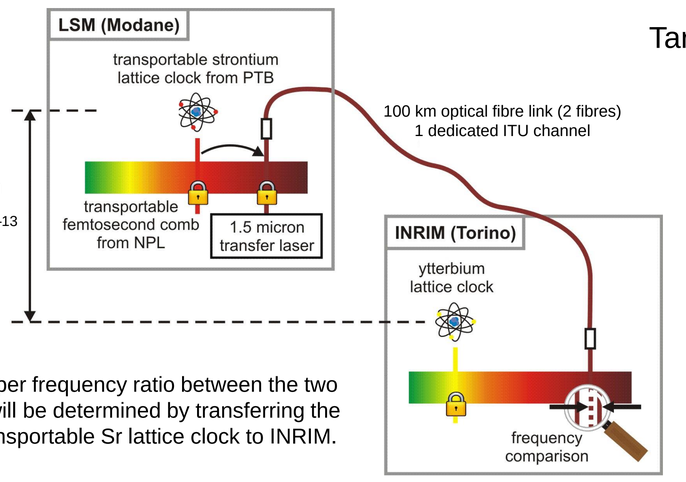
Proof-of-principle clock-based geodesy experiment

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



Height difference ~ 1000 m

Gravitational redshift ~ 10^{-13}



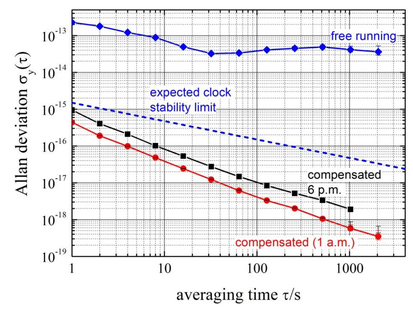
The proper frequency ratio between the two clocks will be determined by transferring the PTB transportable Sr lattice clock to INRIM.

Targets: Clock accuracy 5×10^{-17}

Clock instability $1 \times 10^{-15}\ \tau^{-1/2}$ ➡ tens of cm resolution in a few hours

Optical link tested using INRIM-LSM-INRIM loop:

- Instability 10^{-15} @ 1 s
- No frequency offsets observed at the 3×10^{-19} level



NPL National Physical Laboratory | QMI Quantum Metrology Institute | CMI | INRiM Istituto Nazionale di Ricerca Metrologica | LNE Le progrès, une passion à partager | VTT MIKES METROLOGY | l'Observatoire de Paris SYRTE Systèmes de Référence Temps-Espace | PTB | Leibniz Universität Hannover | cnrs dépasser les frontières | UPMC Sorbonne Universités