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

<table>
<thead>
<tr>
<th>Optical frequency comparisons using broad bandwidth TWSTFT</th>
<th>Frequency comparisons using transportable optical clocks</th>
</tr>
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<tbody>
<tr>
<td>In October 2014, a one-week satellite link test campaign at 20 Mchip/s was carried out via the SES ASTRA 3B satellite.</td>
<td>Two transportable systems are being developed: a strontium optical lattice clock at PTB and a strontium ion optical clock at MIKES.</td>
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<tr>
<td>Short-term instabilities of $\sim 2 \times 10^{-17}$ at 1 s averaging time were observed.</td>
<td>The $^{87}$Sr transition has been resolved with below 10 Hz linewidth and high contrast.</td>
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<tr>
<td>Stability and accuracy limited by the stability of the hydrogen masers used as references.</td>
<td>The observed stability in preliminary comparisons against a laboratory lattice clock are well within design expectations.</td>
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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 / $^{171}$Yb (E2) at NPL [1], $^{171}$Yb / $^{87}$Sr at PTB).
- Situabilities of a few parts in $10^{-19}$ 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. diurnal due to daily temperature variations, by modelling and subtraction.

Gravity measurements

To determine gravitational redshift corrections for clocks of $10^{-15}$ 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:

- Check the level of internal consistency within the complete body of data;
- Derive optimal values for the ratios between the operating frequencies of the clocks.

- 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.

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 $\sim 1000$ m
- Gravitational redshift $\sim 10^{-15}$

**Targets:**

- Clock accuracy $5 \times 10^{-17}$
- Clock instability $1 \times 10^{-15}$

- Optical link tested using INRIM-LSM-INRIM loop:
  - Instability $10^{-15}$ @ 1 s
  - No frequency offsets observed at the $3 \times 10^{-15}$ level

- Optical link tested using INRIM-LSM-INRIM loop and tens of cm resolution in a few hours