Optical clocks and fibre links

Jérôme Lodewyck
Realization of the SI second

With microwave atomic clocks

Cs fundamental state

\[ \omega_0 = \frac{\Delta E}{\hbar} = 2\pi \times 9192631770 \text{ Hz} \]

Primary Cs standard
Realization of the SI second

With microwave atomic clocks

- Calibration of TAI
- Realization of SI
- Links for remote comparisons
- Frequency ratios

- Secondary Rb standard
- Primary Cs standard
- Reliably and reproducible clocks

Applications: test of SRT/GRT, standard model, quantum physics, international time scales... See this session’s talks
Realization of the SI second

With microwave atomic clocks

Performances: $10^{-16}$

- Clock’s statistics
- Clock’s systematics
- Comparison methods

Applications: test of SRT/GRT, standard model, quantum physics, international time scales. . . See this session’s talks
Realization of the SI second

With optical clocks?

Electronic states (Sr, Yb, Hg, Al$^+$, Yb$^+$, Sr$^+$, ...)

\[ |f\rangle \xrightarrow{\omega_0 = \frac{\Delta E}{\hbar} \approx 2\pi \times 10^{15} \text{ Hz}} |e\rangle \]
Realization of the SI second

With optical clocks?

Electronic states \( (\text{Sr, Yb, Hg, Al}^{+}, \text{Yb}^{+}, \text{Sr}^{+}, \ldots) \)

Performances: \( 10^{-17}, 10^{-18}, \ldots \)

- Measure in 1 s what a \( \mu \text{W} \) clock measured in 1 day!
- No clear show-stopper

\[ \omega_0 = \frac{\Delta E}{h} \approx 2\pi \times 10^{15} \text{ Hz} \]

\[ e | e \rangle \langle e | f \rangle = \omega_0 \]

J. Lodewyck — Optical clocks and fibre links – Rencontres de Moriond, March 2017
Realization of the SI second
With optical clocks?

Boost applications
New applications: geodesy
1 Optical clocks

2 An architecture for optical clocks
   - Reliable optical clocks
   - Local frequency ratios
   - Remote clock comparisons
   - Contributing to TAI
1 Optical clocks

2 An architecture for optical clocks
   ■ Reliable optical clocks
   ■ Local frequency ratios
   ■ Remote clock comparisons
   ■ Contributing to TAI
A quick overview of atomic clocks

Atomic clock:

1: Local oscillator

\[ \omega(t) \]

2: Atomic resonance

\[ |e\rangle \quad |f\rangle \]

Quantifying the clock performances

Stability: residual noise

Accuracy: uncertainty on systematic effects

In practice, for optical clocks:

Local oscillator: laser with sub Hz linewidth

Atomic sample: single ion or neutral atoms tightly confined (no Doppler effect \( \delta \omega/\omega = \frac{v}{c} \))
A QUICK OVERVIEW OF ATOMIC CLOCKS

ATOMIC CLOCK:

1: Local oscillator

2: Atomic resonance

Lock of the LO on the atom:
\[ \omega(t) = \omega_0(1 + \epsilon + y(t)) \]

QUANTIFYING THE CLOCK PERFORMANCES

- Stability: residual noise \( y(t) \)
- Accuracy: uncertainty on systematic effects \( \epsilon \)

In practice, for optical clocks
Local oscillator: laser with sub Hz linewidth
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**Clock laser for optical clocks**

**Principle:** laser locked on a Fabry-Perot cavity \( \Rightarrow \frac{\delta \omega}{\omega} = \frac{\delta L}{L} \)

**Goal:** reduce length fluctuations \( \delta L/L \) (currently \( \simeq 10^{-16} \))
**Clock laser for optical clocks**

**Principle:** Laser locked on a Fabry-Perot cavity $\Rightarrow \frac{\delta \omega}{\omega} = \frac{\delta L}{L}$

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**Noise sources**

- Thermal noise
- Vibrations
- Temperature and pressure
- Shot noise

J. Lodewyck — Optical clocks and fibre links — Rencontres de Moriond, March 2017
**Clock laser for optical clocks**

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**Noise sources**
- Thermal noise
- Vibrations
- Temperature and pressure
- Shot noise

**Ongoing research**
- Long cavities
- High-order modes
- Crystalline coatings
- Single crystal cryogenic Si
- Spectral hole burning
Optical lattice clocks

- Atoms loaded from a MOT to an optical lattice formed by a 1D standing wave
- Probing a narrow optical resonance with an ultra-stable “clock” laser
- Stabilize the clock laser on the narrow resonance

![Graph showing transition probability vs. frequency](image)
Optical lattice clocks

- Atoms loaded from a MOT to an optical lattice formed by a 1D standing wave
- Probing a narrow optical resonance with an ultra-stable “clock” laser
- Stabilize the clock laser on the narrow resonance

Combine several advantages:

- Optical clock
- Large number of atoms \((10^4)\)
- Lamb-Dicke regime insensitive to motional effects
- Magic wavelength for unperturbed trapping
- Developed in many laboratories (Sr)
  \[ \Rightarrow \text{good candidates for a new SI second} \]
Strontium optical lattice clocks at SYRTE

Sr1

Sr2

<table>
<thead>
<tr>
<th>Fractional Allan deviation</th>
<th>Time (s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$10^{-17}$</td>
<td>0.1</td>
</tr>
<tr>
<td>$10^{-16}$</td>
<td>1</td>
</tr>
<tr>
<td>$10^{-15}$</td>
<td>10</td>
</tr>
<tr>
<td>$10^{-14}$</td>
<td>100</td>
</tr>
<tr>
<td>$10^{-13}$</td>
<td>1000</td>
</tr>
<tr>
<td>$10^{-12}$</td>
<td>10000</td>
</tr>
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</table>

Accuracy (in $10^{-18}$)

<table>
<thead>
<tr>
<th>Effect</th>
<th>Uncertainty</th>
</tr>
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<tbody>
<tr>
<td>Black-body radiation shift</td>
<td>20</td>
</tr>
<tr>
<td>Quadratic Zeeman shift</td>
<td>12</td>
</tr>
<tr>
<td>Lattice light-shift</td>
<td>-30</td>
</tr>
<tr>
<td>Lattice spectrum</td>
<td>1</td>
</tr>
<tr>
<td>Density shift</td>
<td>8</td>
</tr>
<tr>
<td>Line Pulling</td>
<td>20</td>
</tr>
<tr>
<td>Probe light-shift</td>
<td>0.4</td>
</tr>
<tr>
<td>AOM phase chirp</td>
<td>-8</td>
</tr>
<tr>
<td>Servo error</td>
<td>3</td>
</tr>
<tr>
<td>Static charges</td>
<td>1.5</td>
</tr>
<tr>
<td>Black-body radiation oven</td>
<td>10</td>
</tr>
<tr>
<td>Background collisions</td>
<td>8</td>
</tr>
<tr>
<td>Total</td>
<td>6487.4</td>
</tr>
</tbody>
</table>

J. Lodewyck — Optical clocks and fibre links – Rencontres de Moriond, March 2017
Strontium optical lattice clocks at SYRTE

Sr1

Sr2
Strontium optical lattice clocks at SYRTE

Stability

Accuracy (in $10^{-18}$)

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<td>5208</td>
<td>20</td>
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</tr>
<tr>
<td>Total</td>
<td>6487.4</td>
<td>41</td>
</tr>
</tbody>
</table>

J. Lodewyck — Optical clocks and fibre links – Rencontres de Moriond, March 2017
Other groups

Rapid progress for optical lattice clocks

- JILA: Sr optical lattice clock with $2 \times 10^{-18}$ accuracy

- NIST: Stability down to $1.6 \times 10^{-18}$ after 7 h between 2 Yb clocks

- PTB: Sr optical lattice clock with $1.9 \times 10^{-17}$ accuracy
  
  ultra-stable laser with $8 \times 10^{-17}$ noise floor

- Riken: Comparison between to cryogenic Sr clocks with $7.2 \times 10^{-18}$ accuracy.
1 Optical clocks

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1 Optical clocks

2 An architecture for optical clocks
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Operation of the full metrological chain

Feb. 2014 Attended operation of 5 days, 87% uptime

Oct. 2014 Unattended operation of 10 days, 92% uptime (ITOC JRP)

Jun. 2015 Unattended operation of 21 days, 83% uptime (ITOC JRP)

March 2016 Unattended operation of 10 days, 67% uptime

June 2016 Unattended operation of 15 days, 75% uptime (Sr2 + SrB)

J. Lodewyck et al., Metrologia 53, 1123 (2016)
1 Optical clocks

2 An architecture for optical clocks
   - Reliable optical clocks
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**Local optical to optical comparison**

**Sr vs. Sr**

- First agreement between OLCs

\[
Sr_2 - Sr_1 = 1.1 \times 10^{-16} \pm 2 \times 10^{-17} \text{ (stat)} \pm 1.6 \times 10^{-16} \text{ (sys)}
\]

R. Le Targat *et al.* Nat. Commun. 4 2109 (2013)

- Repeated agreement:

\[
Sr_2 - Sr_1 = (2.3 \pm 7.1) \times 10^{-17}
\]
**Local optical to optical comparison**

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  \text{Sr}_2 - \text{Sr}_1 = 1.1 \times 10^{-16} \pm 2 \times 10^{-17} \text{(stat)} \pm 1.6 \times 10^{-16} \text{(sys)}
  \]


- **Repeated agreement:**

  \[
  \text{Sr}_2 - \text{Sr}_1 = (2.3 \pm 7.1) \times 10^{-17}
  \]

**Sr vs. Hg**

- **Optical to optical frequency measurement**

- **Best reproduced frequency ratio (with RIKEN, Tokyo)**

  \[
  \text{Hg/Sr} = 2.62931420989890915 \pm 5 \times 10^{-17} \text{(stat)} \pm 1.7 \times 10^{-16} \text{(sys)}
  \]
**Sr vs microwave atomic fountains: stability**

**Absolute frequency measurements**

<table>
<thead>
<tr>
<th>Fractional Allan deviation</th>
<th>Time (s)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0.1</td>
</tr>
<tr>
<td>$3.4 \times 10^{-14}/\sqrt{\tau}$</td>
<td></td>
</tr>
<tr>
<td>$3.9 \times 10^{-14}/\sqrt{\tau}$</td>
<td></td>
</tr>
</tbody>
</table>

**Sr vs Cs and Rb**

- Frequency stability **limited by the QPN** of the microwave fountains
- $10^{-16}$ resolution after 12 h
- **mid** $10^{-17}$ resolution after 7 days

**Sr vs Rb**

(best $\mu$Wave vs optical stability)

- $2.8 \times 10^{-14}/\sqrt{\tau}$
SR vs microwave atomic fountains: accuracy

Sr/µwave frequency ratios at SYRTE

Sr2 vs FO1
Sr2 vs FO2-Cs
Sr2 vs FO2-Rb
SrB vs FO2-Cs
SrB vs FO2-Rb

SI recommendation

(wrt SI recommendations)

J. Lodewyck et al.,
Metrologia 53, 1123 (2016)

Sr/Cs, international

Excellent agreement, limited by the accuracy of the Cs fountains
1 Optical clocks

2 An architecture for optical clocks

- Reliable optical clocks
- Local frequency ratios
- Remote clock comparisons
- Contributing to TAI
INTERNATIONAL CLOCK COMPARISONS BY SATELLITE

Comparison Sr vs. Yb\(^+\) (PTB, NPL) via satellite (TWSTFT)
ITO C JRP project

RESULTS

- Statistical resolution in the mid 10\(^{-16}\) after 7 days of measurement
- Frequency ratio compatible with independent local measurements

J. Lodewyck — Optical clocks and fibre links – Rencontres de Moriond, March 2017
International clock comparisons: fibre links

Goal: high resolution comparison

- Direct comparison of optical clocks over continental scale
- Pure optical comparison, not limited by
  - Microwave transfer methods
  - Microwave oscillators
- Preserve the frequency stability over long distances
**International clock comparisons: fibre links**

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**Implementation**
- Disseminate an IR (1542 nm) “vector” narrow laser through phase-compensated optical fibres
- Optical frequency combs to measure $\nu_{\text{IR}}/\nu_{\text{clock}}$ on both sides
INTERNATIONAL CLOCK COMPARISONS: FIBRE LINKS

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IMPLEMENTATION

- Disseminate an IR (1542 nm) “vector” narrow laser through phase-compensated optical fibres
- Optical frequency combs to measure $\nu_{\text{IR}}/\nu_{\text{clock}}$ on both sides

CHALLENGES

- Fibre attenuation (e.g. 450 dB for 1500 km)
- Availability of fibres (dark channel or dark fibre)
- Propagation delays (cascaded links)
- Power limits (non-linear effects, disturbance of telecom networks)
PTB, LPL and SYRTE established a 1415 km long optical fibre link and performed in 2015 the first direct comparison of optical clocks at continental scale.
**Challenge 1: Amplification and Signal Regeneration**

**Paris ↔ Strasbourg**

- Signal along internet traffic (RENATER)
- Bidirectional amplifiers
- Regeneration stations

![Diagram of signal amplification and regeneration](image)
**Challenge 1: Amplification and signal regeneration**

**Paris ↔ Strasbourg**
- Signal along internet traffic (RENATER)
- Bidirectional amplifiers
- Regeneration stations

**Braunschweig ↔ Strasbourg**
- Dark fibre
- Fibre Brillouin amplification
Challenge 2: Fibre noise compensation

Free running link
Challenge 2: Fibre noise compensation

Free running link

Fractional frequency stability vs. averaging time (s)
Challenge 2: Fibre noise compensation

Free running link

End-to-end beatnote

Local

RF oscillator
PLL2
Filter
AOM1
39 MHz
FM

RLS

RF oscillator
PLL1
PD
Filter
Laser

540-km fiber

PC

FM

-37 MHz

AOM

PC

PLL

FM

-37 MHz

AOM
Challenge 2: Fibre noise compensation

Mod Allan deviation $\sigma_\tau(\tau)$ vs. Integration time $\tau$, s
# Comparing remote optical clocks

## Different designs of Sr clocks:

<table>
<thead>
<tr>
<th></th>
<th>PTB</th>
<th>SYRTE</th>
</tr>
</thead>
<tbody>
<tr>
<td>Loading of the atoms</td>
<td>Blue MOT-Red MOT</td>
<td>Blue+atomic drain</td>
</tr>
<tr>
<td>Lattice light</td>
<td>TiSa pumped by a multimode pump</td>
<td>TiSa pumped by a monomode pump</td>
</tr>
<tr>
<td>BBR Shield from oven</td>
<td>No direct line of sight</td>
<td>Deflected atomic beam</td>
</tr>
<tr>
<td>Lattice orientation</td>
<td>Horizontal</td>
<td>Vertical</td>
</tr>
<tr>
<td>Lattice effect</td>
<td>Retroreflected light</td>
<td>Cavity-formed + PDH lock</td>
</tr>
<tr>
<td>Clock laser</td>
<td>48 cm long cavity, flickering at $8 \times 10^{-17}$</td>
<td>10 cm long cavity, flickering at $5 \times 10^{-16}$</td>
</tr>
<tr>
<td>Density of atoms</td>
<td>1-2 atoms/site</td>
<td>5-10 atoms/site</td>
</tr>
<tr>
<td>Coils</td>
<td>In-vacuum MOT coils</td>
<td>MOT coils outside of vacuum</td>
</tr>
<tr>
<td>Gravitational redshift</td>
<td>-247.4 ($\pm 0.4) \times 10^{-17}$</td>
<td></td>
</tr>
<tr>
<td><strong>Uncertainty budgets</strong></td>
<td>$1.9 \times 10^{-17}$</td>
<td>$4.1 \times 10^{-17}$</td>
</tr>
</tbody>
</table>

- agreement between completely independent optical clocks
### Results

#### 2 Measurement campaigns

<table>
<thead>
<tr>
<th>Total clocks</th>
<th>650.3</th>
<th>4.1</th>
<th>496.3</th>
<th>1.9</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Ratio Sr\textsubscript{PTB}/Sr\textsubscript{SYRTE}</strong></td>
<td><strong>Campaign I</strong> Unc. $\times 10^{-17}$</td>
<td><strong>Campaign II</strong> Unc. $\times 10^{-17}$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Systematics Sr\textsubscript{SYRTE}</td>
<td>4.1</td>
<td>4.1</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Systematics Sr\textsubscript{PTB}</td>
<td>2.1</td>
<td>1.9</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Statistical uncertainty</td>
<td>2</td>
<td>2</td>
<td></td>
<td></td>
</tr>
<tr>
<td>fs combs</td>
<td>0.1</td>
<td>0.1</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Link uncertainty</td>
<td>$0.1$</td>
<td>$0.03$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Counter synchronization$^*$</td>
<td>10</td>
<td>$&lt;0.01$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Gravity potential correction$^*$</td>
<td>0.4</td>
<td>0.4</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total clock comparison</td>
<td>11.2</td>
<td>5.0</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

C. Lisdat et al., Nature Comm. 7 12443 (2016)
## Results

### 2 Measurement campaigns

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<td>1.9</td>
</tr>
<tr>
<td>Systematics Sr&lt;sub&gt;SYRTE&lt;/sub&gt; Unc. (10&lt;sup&gt;-17&lt;/sup&gt;)</td>
<td>4.1</td>
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| **Total clocks** | 650.3  |
| **Sr(PTB)-Sr(OP), cut-off at 5 Hz** |
| Time (days after MJD 57092) | 5.0
| Time (days after MJD 57177) |

Statistical uncertainty $2 \times 10^{-17}$ after $\simeq 1$ hour

$$\frac{Sr_{PTB}}{Sr_{SYRTE}} - 1 = (4.7 \pm 5.0) \times 10^{-17}$$

C. Lisdat *et al.*, Nature Comm. 7 12443 (2016)

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J. Lodewyck — Optical clocks and fibre links – Rencontres de Moriond, March 2017

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150 hours of data
**Extending to NPL**

**Fiber link SYRTE – LPL – NPL first operated in June 2016**
Extending to NPL

Fiber link SYRTE – LPL – NPL first operated in June 2016

First tests: Sr vs. Sr

42 h of data over a few days
Sr1 and Sr2 involved

Future national and international fibre networks

J. Lodewyck — Optical clocks and fibre links – Rencontres de Moriond, March 2017
Determination of the gravitational potential
Red-shift due to gravity for remote clocks

\[ \frac{\Delta \nu}{\nu} = \frac{\Delta \phi}{c^2} \quad \phi: \text{gravitational potential} \]

On Earth: 1 m height different \(\iff 10^{-16}\)

Remote comparisons of optical clocks (SYRTE – PTB)

- Correction for the gravitational redshift: \((-247.4 \pm 0.4) \times 10^{-17}\)
  \(\iff 4 \text{ cm uncertainty of the (geodetic) height of the clocks}\)
  Work by H. Denker (LUH), P. Delva (SYRTE)

- The next generation of remote clocks comparisons will improve our knowledge of the gravitational potential of the Earth
  \(\implies\) applications to Earth science. See poster by P. Delva.
Tests of fundamentals physics

With fiber networks
Testing LLI with remote clock comparisons. See talk by P. Delva.

With local frequency ratios

- Track variations of frequency ratios
- When combined to other frequency ratio measurements: bounds on the variations of fundamental constants $\alpha, m_e/m_p, \Lambda_{\text{QCD}}$
- Test of LPI by a coupling to the Sun’s gravitational potential

M. Abgraal et al., Comptes Rendus Physique 16, 461 (2015)
1 Optical clocks

2 An architecture for optical clocks
   - Reliable optical clocks
   - Local frequency ratios
   - Remote clock comparisons
   - Contributing to TAI
Contributions to TAI

Current status

- A few primary Cs standards (fountains) are used to calibrate TAI
- The Rb fountain has contributed since 2012 as a secondary representation of the SI second
- Calibration reports processed by the BIPM, and published in the “Circular T”
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Contributing Optical clocks

- Determination of the Maser/Sr frequency ratio
- Requires the quasi-continuous operation of optical clocks for several sets of 5 consecutive days
- ⇒ Requirement for a possible redefinition of the SI second
Contributions to TAI

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- Requires the quasi-continuous operation of optical clocks for several sets of 5 consecutive days
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Results

- Accumulation of 4 long operations with Sr2 + 1 with Sr1
- More and more autonomous
5 TAI calibration reports sent to BIPM:
First contribution from an optical clock

The secondary frequency standard LNE-SYRTE-SrB has been compared to the hydrogen Maser 140 0889 of the laboratory, during a measurement campaign between MJD 57539 and 57554 (31st May 2016 – 15 June 2016). The optical lattice clock operation covers ~74.1% of the total measurement duration.

The mean frequency difference at the middle date of each interval is given in the following table:

<table>
<thead>
<tr>
<th>Period (MJD)</th>
<th>Date of the estimation</th>
<th>y(H_Maser 140 0889 - SrB)</th>
<th>uB</th>
<th>uA</th>
<th>uLink/maser</th>
<th>uSecRep</th>
</tr>
</thead>
<tbody>
<tr>
<td>57539 – 57554</td>
<td>57446.5</td>
<td>-3316.5</td>
<td>0.48</td>
<td>2.5</td>
<td>1.0</td>
<td>5</td>
</tr>
</tbody>
</table>

Table 1: Results of the comparison in $1 \times 10^{-16}$.

The calibration is made using the recommended value for the $^{87}$Sr secondary representation: 429 228 004 229 873.2 Hz (20th CCTF in 2015).

$u_h$ is the $^{87}$Sr optical lattice type B uncertainty.

$u_{\text{SecRep}}$ is the recommended uncertainty of the secondary representation (20th CCTF in 2015).
Conclusion

- Optical clocks
- Microwave standards
- Reliable and reproducible clocks
- Frequency ratios
- Calibration of TAI
- Links for remote comparisons

Perspectives
- Redefinition of the SI second with optical clocks
- Improved stability and accuracy of OLCs: $10^{-19}$ feasible
- Complete European fibre network for comparison of optical clocks
- Ground segment of the Pharao/ACES space clock
- Study of quantum effects in optical lattice clocks
Conclusion

Perspectives

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Clock ensemble at SYRTE

- **2 strontium lattice clocks**
  J. Lodewyck, R. Le Targat, S. Bilicki, E Bookjans, G. Vallet

- **1 mercury lattice clock**
  S. Bize, L. De Sarlo, M. Favier, R. Tyumenev

- **Frequency combs (Ti-Sa, fiber)**
  Y. Lecoq, R. Le Targat, D. Nicolodi

- **3 atomic fountains**
  (1 Cs, 1 Cs mobile, 1 Cs/Rb)
  J. Guéna, P. Rosenbusch, M. Abgrall, D. Rovera, S. Bize, P. Laurent
Comparison with fiber links

- **LPL**
  - N. Quintin, F. Wiotte, E. Camisard, C. Chardonnet, A. Amy-Klein, O. Lopez

- **SYRTE**

- **PTB**

- **NPL**

- **LUH**
  - H. Denker, L. Timmen, C. Voigt