Remote comparisons of two Sr-optical lattice clocks with a long haul optical fiber link

LPL team, SYRTE team & PTB team

RENATER, Université de Strasbourg, LP2N

Paul-Eric Pottie, Anne Amy-Klein
Contents

- Motivations
- Optical fiber links to compare and disseminate optical frequency standards
- An international optical clocks comparison with fiber link: a world first between PTB and SYRTE
- Outlook
**Optical lattice clock**

- 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

**Experiments co-funded by nano-K**

**Combine several advantages:**

- Optical clock
- Lamb-Dicke regime insensitive to motional effects
- Large number of atoms

- Record frequency stability
- Record accuracy
Sr Optical lattice clock

- Cold $^{87}\text{Sr}$ trapped in optical lattice
- $1S_0-3P_0$ forbidden transition
- Ultra stable laser @ 698 nm, sub Hz linewidth

- Resonance of the clock transition
- Fourier limited at 3 Hz (250 ms)
- Laser noise dominating

Remote comparisons Sr-Sr OLC with a long haul optical fiber link
GdR ATF/Nano-k - Paris, November 5, 2015
Locking the clock laser to the atomic transition

- Atoms vs cavity
  - $< 5 \text{s}$: limited by the atoms (Dick effect) $1 \times 10^{-15}/\sqrt{\tau}$
  - $> 5 \text{s}$: limited by the thermal noise of the cavity $6.5 \times 10^{-16}$

- Sr vs Sr clock comparison
  - $1.5 \times 10^{-15}/\sqrt{\tau}$
  - Resolution in the low $10^{-17}$

Remote comparisons Sr-Sr OLC
with a long haul optical fiber link
GdR ATF/Nano-k - Paris, November 5, 2015
Remote comparisons Sr-Sr OLC with a long haul optical fiber link

Atomic clocks performances over 70 years

Redefinition of SI second

Optical Frequency Combs

Atomic fountains

Cs Clocks (microwave)

Optical Clocks

Accuracy

Year


1x10^-10 1x10^-11 1x10^-12 1x10^-13 1x10^-14 1x10^-15 1x10^-16 1x10^-17 1x10^-18 1x10^-19
Means to compare clocks

Remote comparisons Sr-Sr OLC with a long haul optical fiber link

Satellite Link
$10^{-11}(1s)$
$2 \times 10^{-16}(1d)$

Transportable clock (FOM)
$10^{-13}(1s)$
$4 \times 10^{-16}(1d)$

NMI A
Stability$(1s) < 10^{-13}$
Accuracy $< 10^{-16}$

NMI B

in Europe
$800 < \text{distance} < 1500 \text{ km}$

GdR ATF/Nano-k - Paris, November 5, 2015
Means to compare clocks

Satellite Link
\[ 10^{-11}(1s) \]
\[ 2 \times 10^{-16}(1d) \]

Optical Fiber Link
\[ 10^{-13}(1s) \]
\[ 4 \times 10^{-16}(1d) \]

Transportable clock (FOM)

in Europe

800 \textless distance \textless 1500 km
Optical fiber links

- Seminal works: Primas et al, Proc 20\textsuperscript{th} PTTI, 1988, Ma et al., OL 1994
- Active noise compensation after one round-trip
- Strong hypothesis: noises forth and back are the same
- At the same place (for link stability measurement)

Active noise compensated link

Seminal works:
- Primas et al, Proc 20\textsuperscript{th} PTTI, 1988
- Ma et al., OL 1994

Active noise compensation after one round-trip

Strong hypothesis: noises forth and back are the same at the same place (for link stability measurement)

Ultrastable 1.542 µm laser

Atomic optical clocks

Link instability measurement

Remote end

Accumulated Phase noise $\Phi_p$

Optical coupler

Local end

FM

OC

PD

Noise Correction

$2(\Phi_c + \Phi_p) = 0$

Remote comparisons Sr-Sr OLC with a long haul optical fiber link

GdR ATF/Nano-k - Paris, November 5, 2015
Motivations (in a nutshell)

- **International / national clocks comparisons below $10^{-16}$**
- **Relativistic geodesy, fundamental physics**
- **Frequency standard dissemination (for research labs: REFIMEVE+)**

Remote comparisons Sr-Sr OLC with a long haul optical fiber link

Optical Frequency transfer projects in Europe

Only CW Optical frequency dissemination / comparison represented

ICOF (GéANT)

PTB/MPQ

LIFT

500 km

2 «big» link projects in 2012: REFIMEVE+, LIFT

target optical frequency dissemination > 4000 km
Challenges for long haul fiber links
Challenges for long haul fiber links

Fiber availability!
Challenges for long haul fiber links

- Fiber availability!
  - Partnership with NRENs / Contract with private Cie

![Logos of RENATER, GÉANT, NORDUnet, Consortium GARR, PIONIER, FUNET, GasLINE]
Challenges for long haul fiber links

- Fiber availability!
Challenges for long haul fiber links

- Fiber availability!
- Attenuation
Challenges for long haul fiber links

- **Fiber availability!**
Challenges for long haul fiber links

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- Attenuation

\[0.2\text{ to } 0.29\text{ dB / km}\]
Challenges for long haul fiber links

- Fiber availability!
- Attenuation

0.2 to 0.29 dB/km

$10^{20}$ for 1000 km
Challenges for long haul fiber links

- Fiber availability!
- Attenuation
  - 0.2 to 0.29 dB/km
  - $10^{20}$ for 1000 km
- Bi-directional amplification ($10 < G < 20$ dB)
Challenges for long haul fiber links

- Fiber availability!
- Attenuation

0.2 to 0.29 dB / km
10^{20} for 1000 km

- Bi-directional amplification (10 < G < 20 dB)
- Fiber Brillouin amplification (<60 dB)
Challenges for long haul fiber links

- Fiber availability!
- Attenuation
  
  \[0.2 \text{ to } 0.29 \text{ dB / km}\]
  
  \[10^{20} \text{ for } 1000 \text{ km}\]

- Bi-directional amplification (10 < G < 20 dB)
- Fiber Brillouin amplification (<60 dB)
- Optical regeneration (repeater laser station): 2dBm output

- Specific scientific equipment
- Knowledge transfer
Challenges for long haul fiber links

- Fiber availability!
- Attenuation
  - 0.2 to 0.29 dB / km
  - $10^{20}$ for 1000 km
- Bi-directional amplification ($10 < G < 20$ dB)
- Fiber Brillouin amplification ($<60$ dB)
- Optical regeneration (repeater laser station): 2dBm output
Challenges for long haul fiber links

- Fiber availability!
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Challenges for long haul fiber links

- Fiber availability!
- Attenuation
- Accumulated noise

Noise scale as sqrt(Length of link)
More noise in urban area
20 to 45 dBc / Hz @ 1 Hz
Challenges for long haul fiber links

- **Fiber availability!**
- **Attenuation**
- **Accumulated noise**
- **Finite time of propagation**

Noise scale as $\sqrt{\text{Length of link}}$

More noise in urban area

20 to 45 dBC / Hz @ 1 Hz

BW < 1 kHz

for $L > 50$ km

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Remote comparisons Sr-Sr OLC with a long haul optical fiber link

GdR ATF/Nano-k - Paris, November 5, 2015
Challenges for long haul fiber links

- Fiber availability!
- Attenuation
- Accumulated noise
- Finite time of propagation

Noise scale as $\sqrt{\text{Length of link}}$
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BW < 1 kHz
for $L>50$ km

Cascaded approach

Remote comparisons Sr-Sr OLC
with a long haul optical fiber link
GdR ATF/Nano-k - Paris, November 5, 2015
Cascaded optical fiber links

- Shorter delay and better noise rejection
- Remote control and monitoring
- Automatic operation
- Polarisation control
- No stable RF oscillator

O. Lopez et al., Optics Express 18 16849-16857 (2010)
Optical fiber links with data traffic

- French optical link is using a dedicated frequency channel of the academic network
  
  ![RENATER](image)

- Parallel data traffic
- Optical Add-Drop Multiplexer
  
  Used to go on/off the network.

- Additional optical losses of ~1.6 dB/span

- Cascaded optical link with repeater laser stations
  
  - Pin on the network <2 mW
  - High gain (up to 60 dB)
  - Narrow band, tunable
  - User output

---

Remote comparisons Sr-Sr OLC with a long haul optical fiber link

GdR ATF/Nano-k - Paris, November 5, 2015
Inter-connexion FR-DE links

- Two-way frequency comparison between the RLS
- Optical beat note vs GPS-disciplined ultra-stable oscillator
- Remote control and monitoring FBA and RLS

Remote comparisons Sr-Sr OLC with a long haul optical fiber link

GdR ATF/Nano-k - Paris, November 5, 2015
Remote comparisons Sr-Sr OLC with a long haul optical fiber link
GdR ATF/Nano-k - Paris, November 5, 2015
Frequency combs, coherent regime

Remote comparisons Sr-Sr OLC with a long haul optical fiber link

GdR ATF/Nano-k - Paris, November 5, 2015
- Frequency combs, coherent regime
- Two independent Sr-lattice clock
- «All-optical» frequency comparison
The 1st Sr-Sr comparison by long haul fiber links

- Frequency combs, coherent regime
- Two independent Sr-lattice clock
- «All-optical» frequency comparison

Remote comparisons Sr-Sr OLC with a long haul optical fiber link

GdR ATF/Nano-k - Paris, November 5, 2015
An optical methodology

Remote comparisons Sr-Sr OLC with a long haul optical fiber link

GdR ATF/Nano-k - Paris, November 5, 2015

Counting the RF of the beat notes with the fs combs

Absolute frequency difference without SI-Hz
Experimental results: raw trace

Remote comparisons Sr-Sr OLC with a long haul optical fiber link

GdR ATF/Nano-k - Paris, November 5, 2015
Experimental results: raw trace

- Combination of Sr/Combs/link at both side
- Two runs:
Experimental results: raw trace

- Combination of Sr/Combs/link at both side
- two runs:
  - 3 days in March

![Graph showing data points and lines correlating time and frequency differences](image-url)
Experimental results: raw trace

- Combination of Sr/Combs/link at both side
- Two runs:
  - 3 days in March 2015
  - 25 days in June 2015
  - Up time: 20%
  - 35 people involved
- #520k data points

Raw data Sr(SYRTE) - Sr(PTB)

June 2015

![Frequency difference (Hz) vs Time (MJD)-57177 diagram]
Remote comparisons Sr-Sr OLC with a long haul optical fiber link

Sr-clocks comparison SYRTE-PTB

Run I : March 2015
Run II : June 2015
Combined link contribution

Combined link contribution
## Sr-clocks comparison SYRTE-PTB

### Clock accuracy budget

<table>
<thead>
<tr>
<th>Effect (x $10^{-17}$)</th>
<th>Sr lattice clock Paris</th>
<th>Sr lattice clock Braunschweig</th>
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<tbody>
<tr>
<td></td>
<td>Correction</td>
<td>Uncertainty</td>
</tr>
<tr>
<td>Residual lattice light shift</td>
<td>0</td>
<td>2.5</td>
</tr>
<tr>
<td>Black-body radiation</td>
<td>515.5</td>
<td>1.8</td>
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<tr>
<td>Black-body radiation oven</td>
<td>0</td>
<td>1.0</td>
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<tr>
<td>Density shift</td>
<td>0</td>
<td>0.8</td>
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<tr>
<td>Quadratic Zeeman shift</td>
<td>134.8</td>
<td>1.2</td>
</tr>
<tr>
<td>Line pulling</td>
<td>0</td>
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</tr>
<tr>
<td>Lock error</td>
<td>0</td>
<td>0.3</td>
</tr>
<tr>
<td>DC Stark shift</td>
<td>0</td>
<td>0.5</td>
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<tr>
<td>Tunneling</td>
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<td>&lt;&lt; 0.1</td>
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<td>Systematics Sr&lt;sub&gt;SYRTE&lt;/sub&gt;</td>
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<td>Systematics Sr&lt;sub&gt;PTB&lt;/sub&gt;</td>
<td>2.1</td>
<td>1.9</td>
</tr>
<tr>
<td>Statistical uncertainty</td>
<td>3</td>
<td>2</td>
</tr>
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<td>fs combs</td>
<td>0.1</td>
<td>0.1</td>
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Remote comparisons Sr-Sr OLC with a long haul optical fiber link

GdR ATF/Nano-k - Paris, November 5, 2015
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- Frequency instability $\text{Sr}^{\text{PTB}}-\text{Sr}^{\text{SYRTE}}$
  
  $2 \times 10^{-17}$ (5000 to 50000 s)

- Accuracy: $\text{Sr}^{\text{PTB}}-\text{Sr}^{\text{SYRTE}}$ agreement
  
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- Optical links demonstrates their ability to compare clock with superior abilities to any other methods
- Gravitational redshift is taken into account. Confirm the proper correction of relativistic effects and results from precise levelling campaign of the clocks
A world first! Optical clock comparison SYRTE-PTB

- $<3 \times 10^{-17}$ statistical uncertainty @1 day
- Comparison uncertainty below the SI limit
- Outperform by order of magnitudes the abilities of satellite based methods
- Open a new era of clock’s comparisons
- Linking NMIs with fiber links on going
- Precise frequency measurements will be possible with unprecedented stability and accuracy.
- The french touch: parallel to data traffic
A large collaboration

PTB Team (Sr clock, combs and links)
SYRTE Team (Sr clocks, combs and links),
LPL Team (links), LP2N (links)
RENATER, Université de Strasbourg (network),

are:

Remote comparisons Sr-Sr OLC with a long haul optical fiber link
GdR ATF/Nano-k - Paris, November 5, 2015

Thank you for attention!
A 4-span cascaded link

- Start and End at LPL, Paris area
- First link of 1100 km reaching Nancy and back

N. Chiodo et al, «Cascaded optical fiber link using the Internet network for remote clocks comparison», submitted (2015)

- Second link of 1480 km reaching Strasbourg and back
- Shift Start and End to SYRTE

Remote comparisons Sr-Sr OLC with a long haul optical fiber link

GdR ATF/Nano-k - Paris, November 5, 2015
Remote comparisons Sr-Sr OLC with a long haul optical fiber link
GdR ATF/Nano-k - Paris, November 5, 2015

Relative frequency instability

![Graph showing Modified Allan Deviation vs Integration time for LPL-Nancy 1100 km and LPL-Strasbourg 1500 km.]

- Modified Allan Deviation
- Integration time (s)
- LPL-Nancy 1100 km (red)
- LPL-Strasbourg 1500 km (blue)

\[ \Lambda \text{-counting, 1-s gate time} \]
Relative frequency instability

Move from LPL to SYRTE

Modified Allan Deviation

Integration time (s)

LPL-Nancy 1100 km
LPL-Strasbourg 1480 km
SYRTE-Strasbourg 1420 km

\( \Lambda \)-counting, 1-s gate time
Relative frequency instability

Move from LPL to SYRTE

MDEV from 4 to 20 E-16 @1s

LPL-Nancy 1100 km
LPL-Strasbourg 1480 km
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Modified Allan Deviation

Integration time (s)

Modified Allan Deviation

Integration time (s)

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Remote comparisons Sr-Sr OLC
with a long haul optical fiber link
GdR ATF/Nano-k - Paris, November 5, 2015
Remote comparisons Sr-Sr OLC with a long haul optical fiber link

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Modified Allan Deviation

Integration time (s)

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MDEV from 4 to 20 E-16 @1s
Non stationary noise

Λ-counting, 1-s gate time
Relative frequency instability

Move from LPL to SYRTE
- MDEV from 4 to 20 E-16 @1s
- Non stationary noise
- EDFA gain instability

\[\text{Modified Allan Deviation} \]
- \(\Lambda\)-counting, 1-s gate time

Integration time (s)

Relative frequency instability

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GdR ATF/Nano-k - Paris, November 5, 2015
Long-haul fiber links with FBA

Brillouin amplification supports $1 \times 10^{-20}$ uncertainty in optical frequency transfer over 1400 km of underground fiber

Sebastian M. F. Raupach,* Andreas Koczwara, and Gesine Grosche

Physikalisch-Technische Bundesanstalt (PTB), Bundesallee 100, D-38116 Braunschweig, Germany

(Received 20 March 2015; published 24 August 2015)
2-span cascaded link with FBA

- Insert a Regeneration Laser Station in Strasbourg to the FBA-based link
  - worked within 1 day!
- Advantage : RLS has a stable user output, thanks to its balanced interferometric setup

Remote comparisons Sr-Sr OLC with a long haul optical fiber link
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![Diagram of optical link with FBA and RLS stations](image)

Remote comparisons Sr-Sr OLC with a long haul optical fiber link

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- worked within 1 day!

- Advantage: RLS has a stable user output, thanks to its balanced interferometric setup

On interferometer noise, see: F. Stefani et al., «Tackling the limits of optical fiber links», JOSA B 32, 787-797 (2015)
Remote comparisons Sr-Sr OLC with a long haul optical fiber link

GdR ATF/Nano-k - Paris, November 5, 2015

Relative frequency stability

- Even better short term stability due to the higher bandwidth of correction
- Very stable signal
- No cycle slips for days
- Robust, reliable

Experimental results

Frequency comparison of the two optical links signals
Linear drift is removed.

Overlapping Allan Deviation ($\times 10^{-15}$)

Integration time (s)

- Red squares: Remote measurement @ Strasbourg
- Purple circles: Local measurement @ Paris
Implémentation du lien optique

Longueur d’onde: 1542 nm

Atomes peuvent aider

Bohr frequences d’atomes non perturbs sont considerees "parfaitement" stables et universelles
LNE-SYRTE clock ensemble

Time is not measured, time is a realization!

Optical lattice clocks

Ultra-stable lasers and combs

Atomic fountains Cs, Rb

Remote comparisons Sr-Sr OLC with a long haul optical fiber link

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Passive stabilization of fiber optic transmission links, such as burial of the cable, is not sufficient for maintaining stabilities in the range required for many applications. When stabilities higher than a part in $10^{15}$ are required the link must be actively stabilized.
Seminal works: Primas et al., 1988

- **Active noise compensation after one round-trip**
- **Strong hypothesis**: noise forth and back are the same

Part in $10^{16}$ are required the link must be actively stabilized.

**Figure 1. Phase conjugation at input to optical fiber**

**Figure 3. Fiber optic frequency distribution system**

Delivering the same optical frequency at two places: accurate cancellation of phase noise introduced by an optical fiber or other time-varying path

Long-Sheng Ma, Peter Jungner, Jun Ye, and John L. Hall

Joint Institute for Laboratory Astrophysics, University of Colorado and National Institute of Standards and Technology, Boulder, Colorado 80309-0440

Received May 12, 1994

Although a single-mode optical fiber is a convenient and efficient interface/connecting medium, it introduces phase-noise modulation, which corrupts high-precision frequency-based applications by broadening the spectrum toward the kilohertz domain. We describe a simple double-pass fiber noise measurement and control system, which is demonstrated to provide millihertz accuracy of noise cancellation.
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Fig. 2. Optical field spectrum at the output of a 25-m fiber. The input optical signal approximates a delta function. The signal arrives at the far end with a 1.2-kHz width, shown in (a). In (b) the phase-noise compensation system is operational, and one regains 99.6% of the power in the sharp spectral feature. The resolution bandwidth is 15.6 Hz. In (c) the resolution bandwidth is 0.95 mHz. The carrier is reduced by only 1.3 dB from (b) to (c) because of noise near the carrier.

25-m optical fiber link
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From here this talk is focussed on optical frequency transfer, CW regime

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25-m optical fiber link
Experimental set up (Strasbourg, Kassel)

High stability quartz
GPS DO
Sp. Analyzer
Counters
Computer

RLS #1
RLS #2
FBA in Kassel
First beat note

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Cell phones!

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