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

LPL team, SYRTE team & PTB team

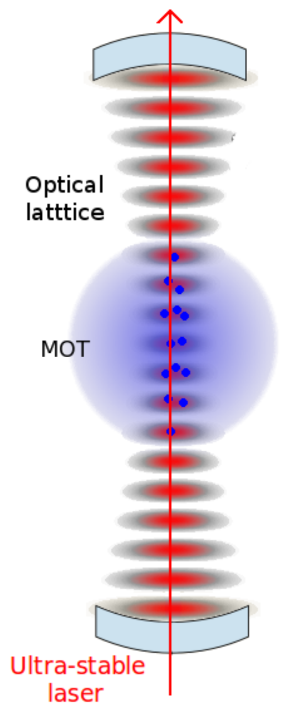
RENATER, Université de Strasbourg, LP2N

Paul-Eric Pottie, Anne Amy-Klein

Contents

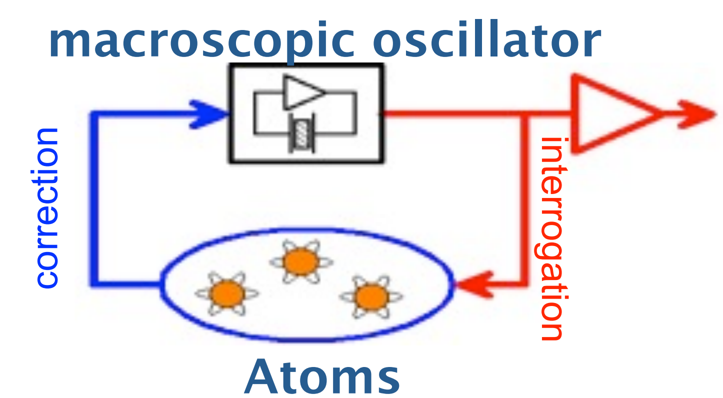
- Motivations
- Optical fiber links to compare and disseminate optical frequency standards
- An international optical clocks comparison with fiber link : a world first between PTB and SYRTE
- Outlook

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

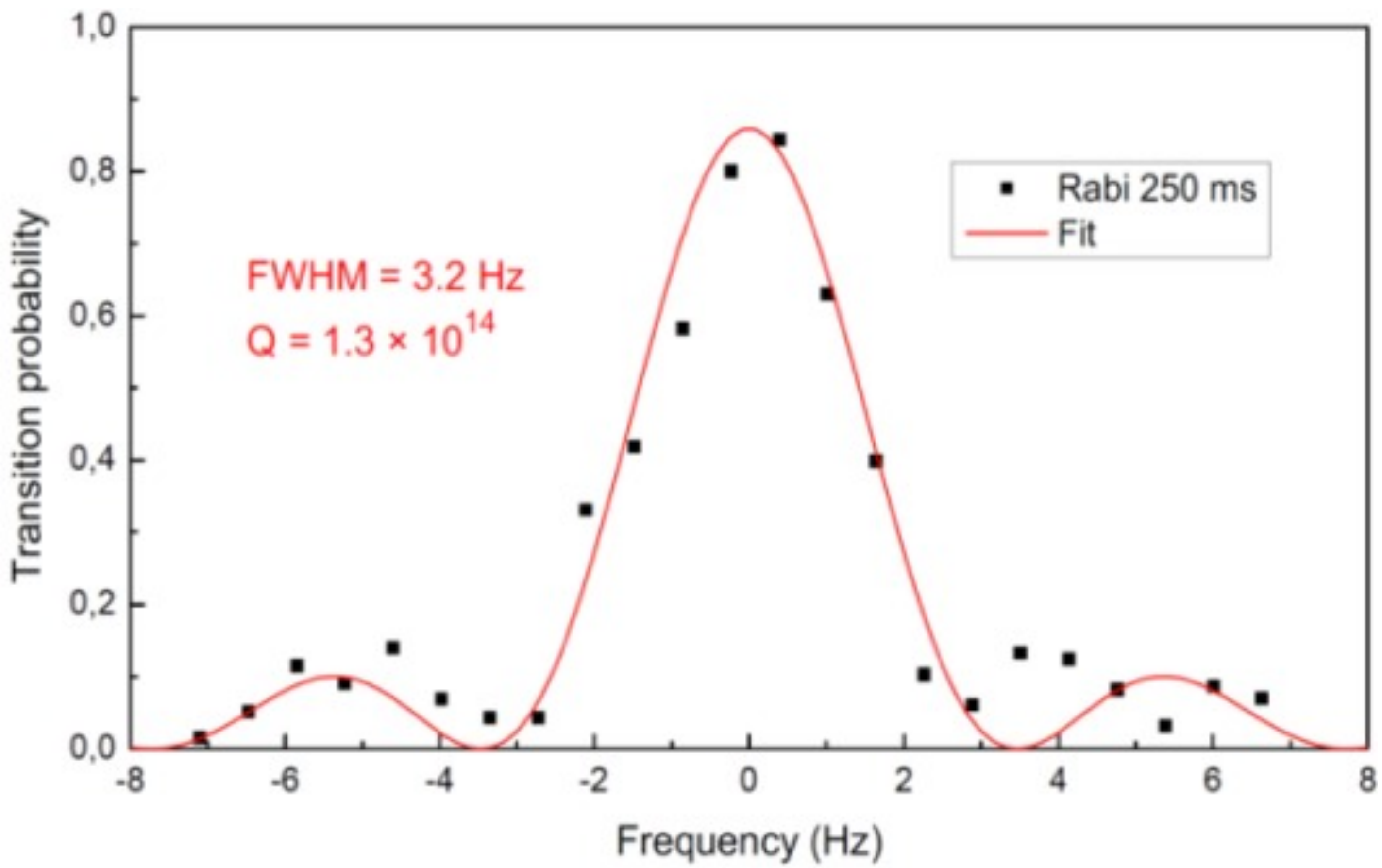
$\Rightarrow$

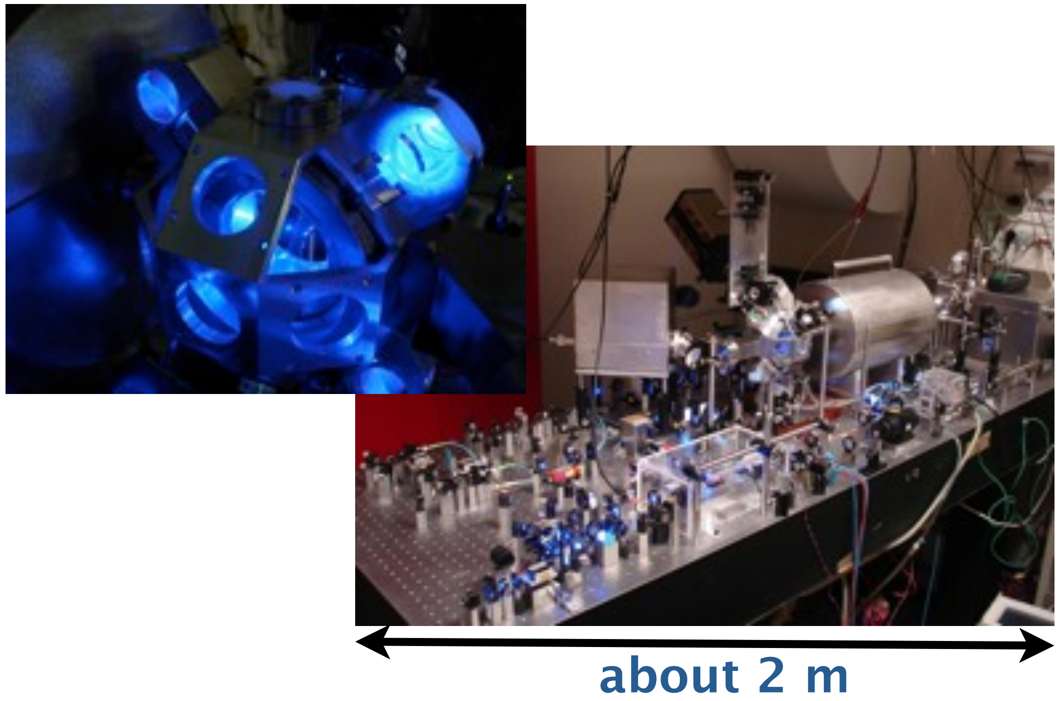
- Record frequency stability
- Record accuracy

Sr Optical lattice clock

- Cold 87Sr trapped in optical lattice
- 1S0–3P0 forbidden transition

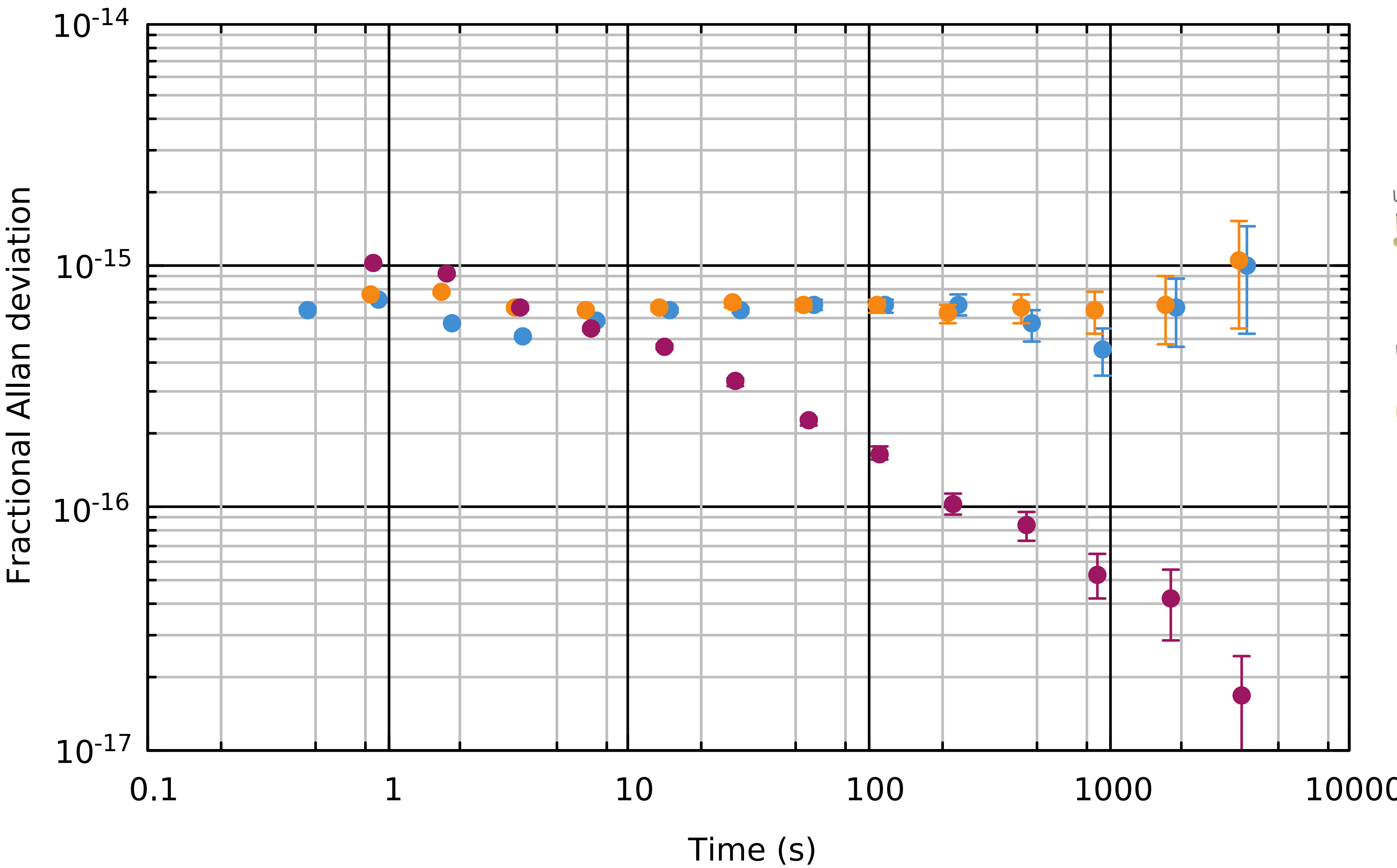
- Ultra stable laser @ 698 nm, sub Hz linewidth

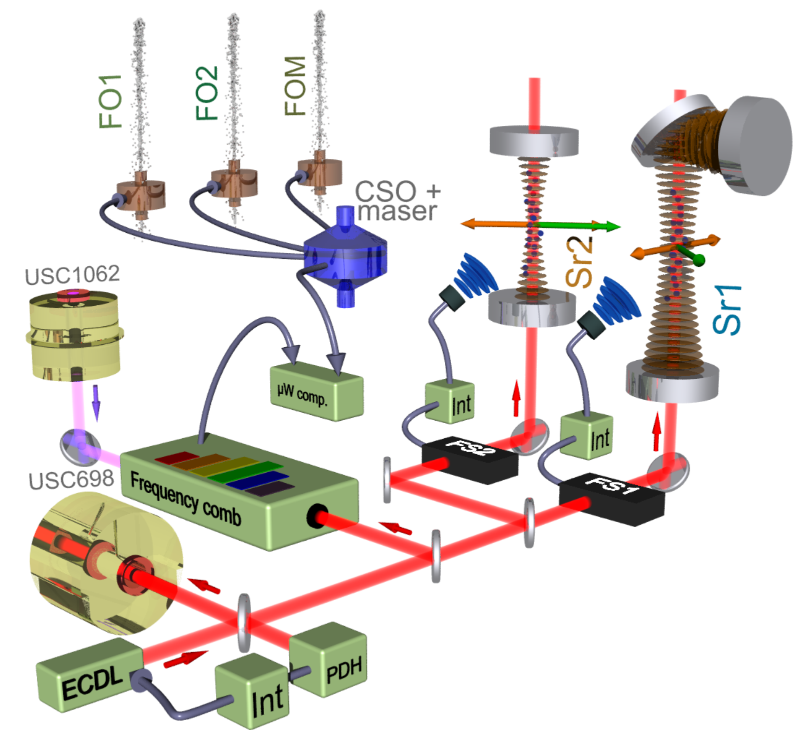




- Resonance of the clock transition
- Fourier limited at 3 Hz (250 ms)
- Laser noise dominating

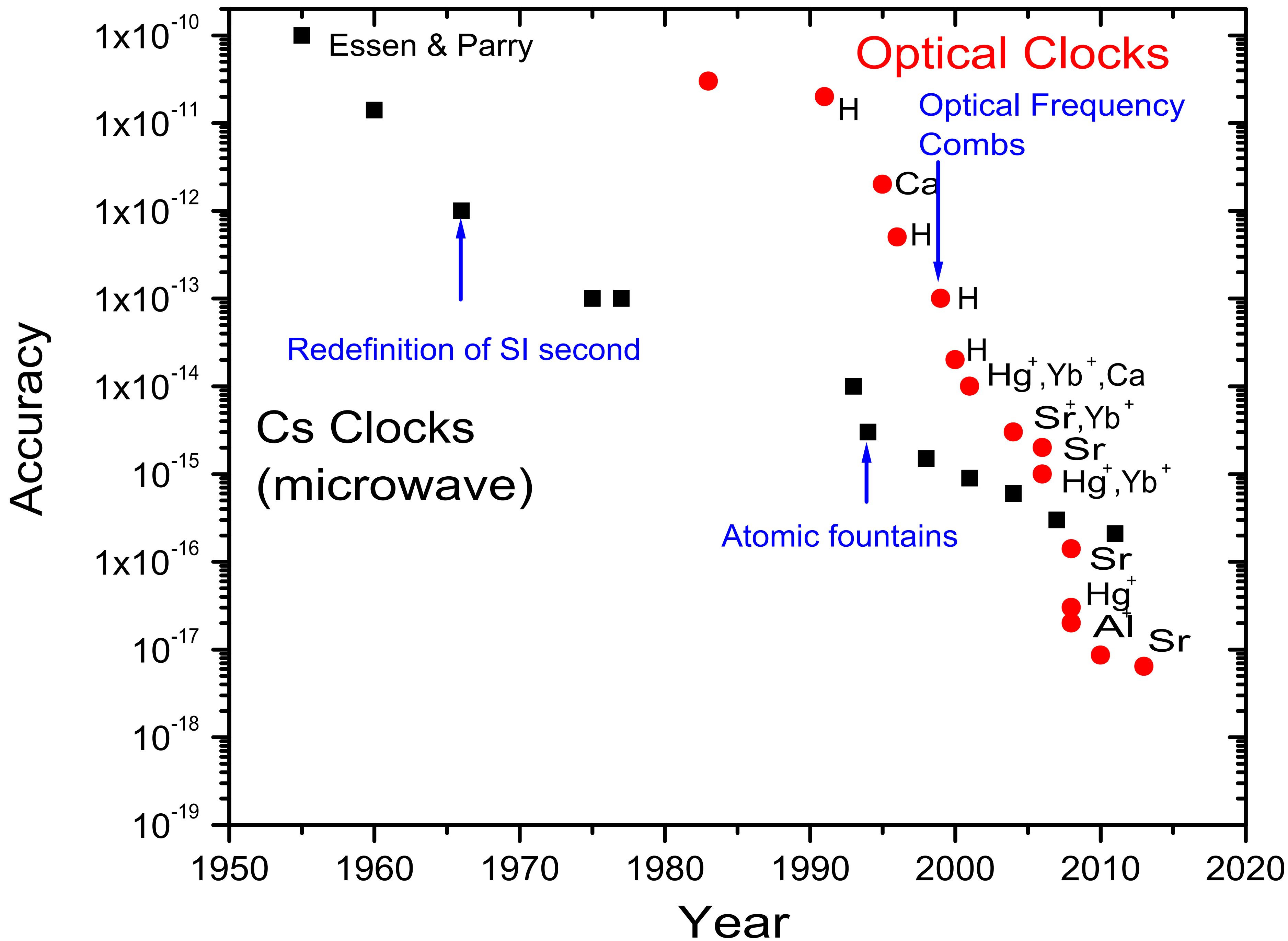
Locking the clock laser to the atomic transition





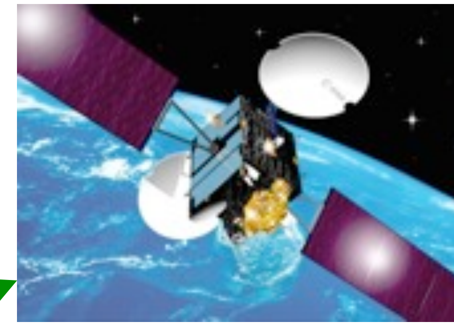
- Atoms vs cavity
  - < 5 s : limited by the atoms (Dick effect) $1 \times 10^{-15}/\sqrt{\tau}$
  - > 5 s : limited by the thermal noise of the cavity 6.5×10^{-16}
- Sr vs Sr clock comparison
  - $1.5 \times 10^{-15}/\sqrt{\tau}$
  - resolution in the low 10^{-17}

Atomic clocks performances over 70 years



Means to compare clocks

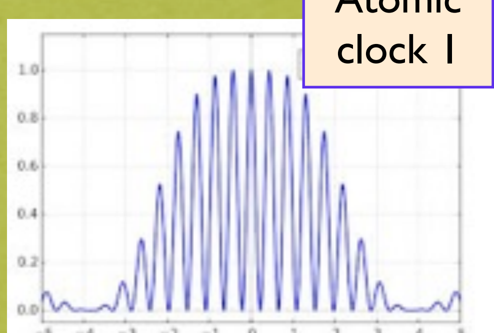
Satellite Link
10^{-11}(1s)
$2x10^{-16}$(1d)



12:47:36

NMI
A

Atomic clock 1



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

in Europe

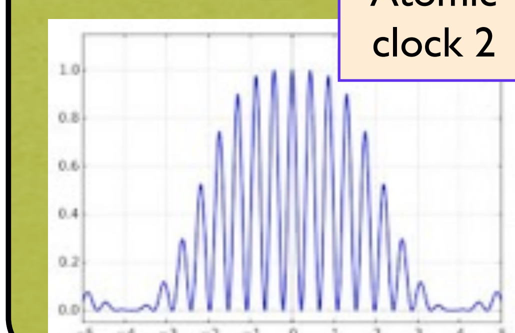
800< distance <1500 km

Transportable clock (FOM)
10^{-13}(1s)
$4x10^{-16}$(1d)

12:47:36

NMI
B

Atomic clock 2



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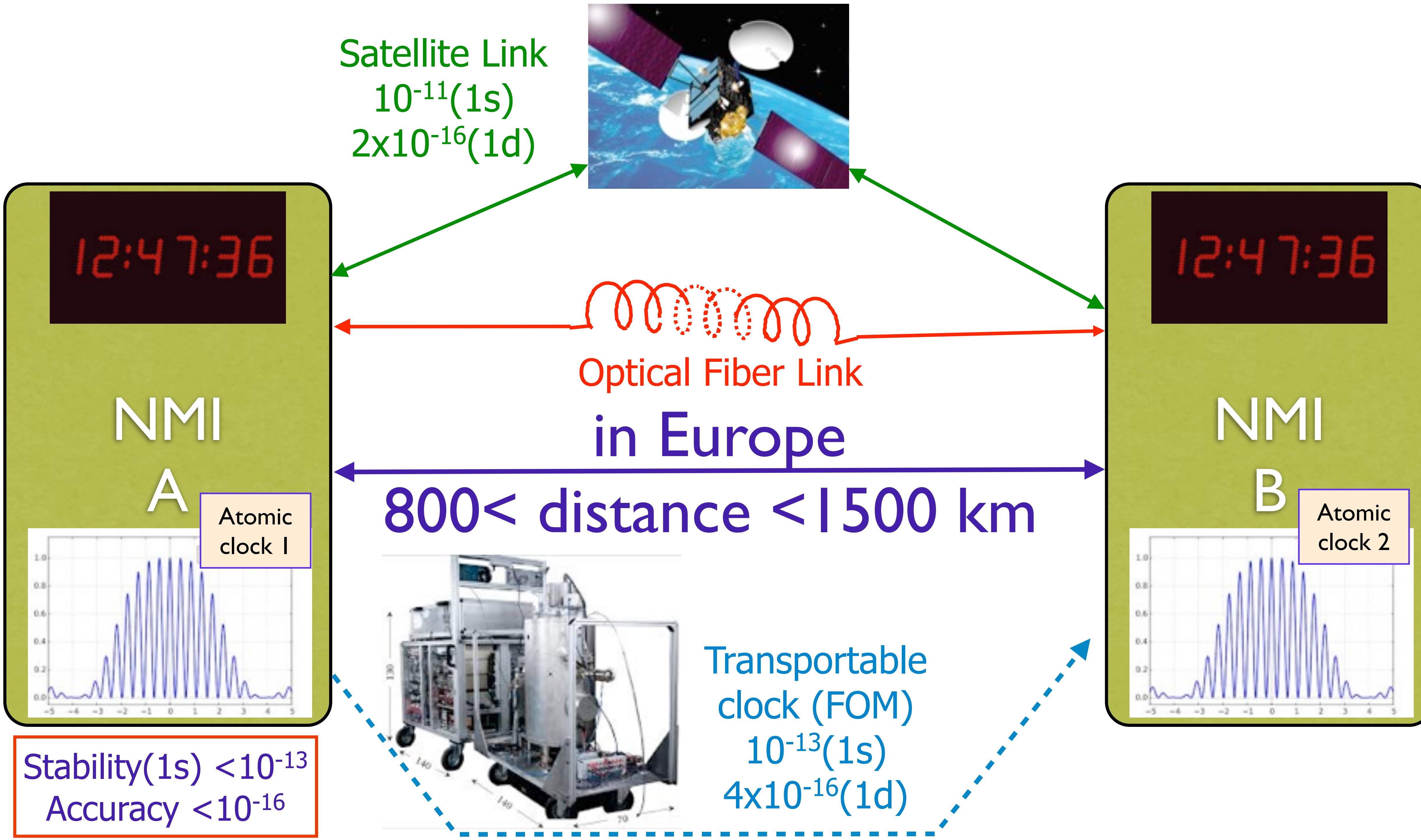
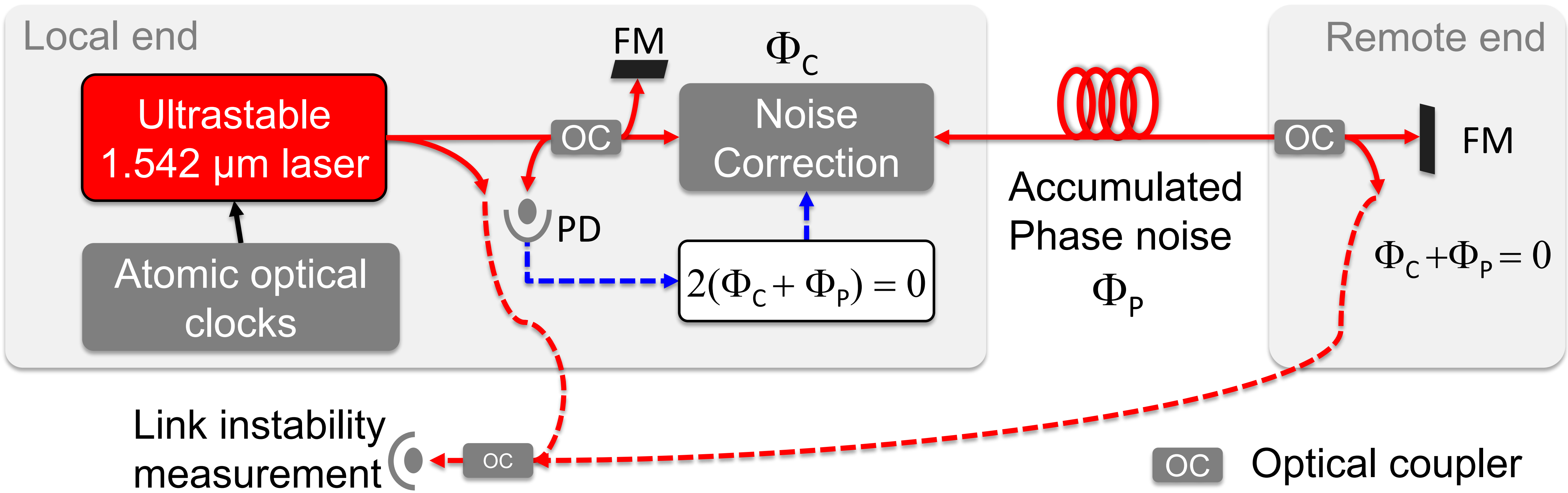
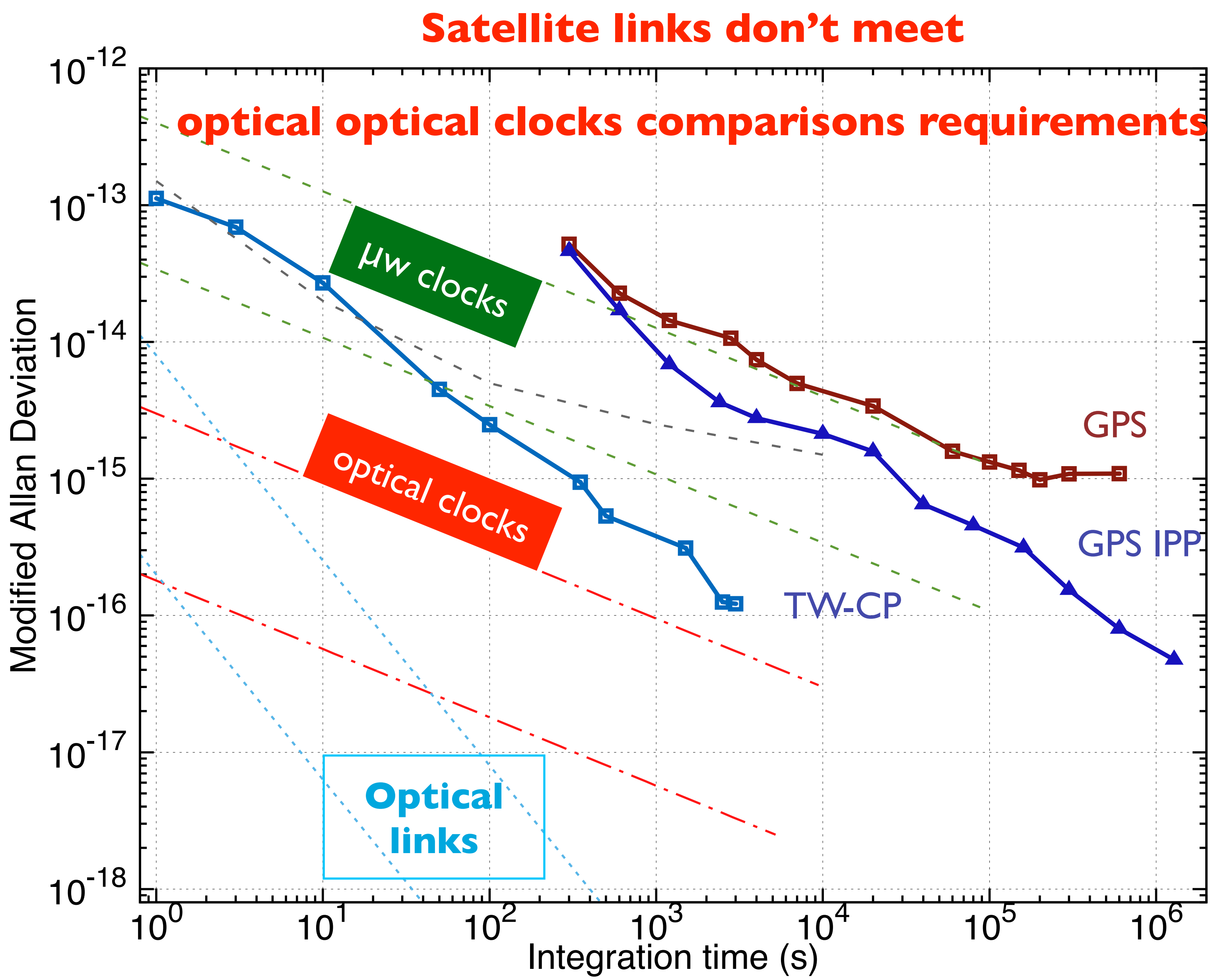


Optical fiber links

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



Motivations (in a nutshell)



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

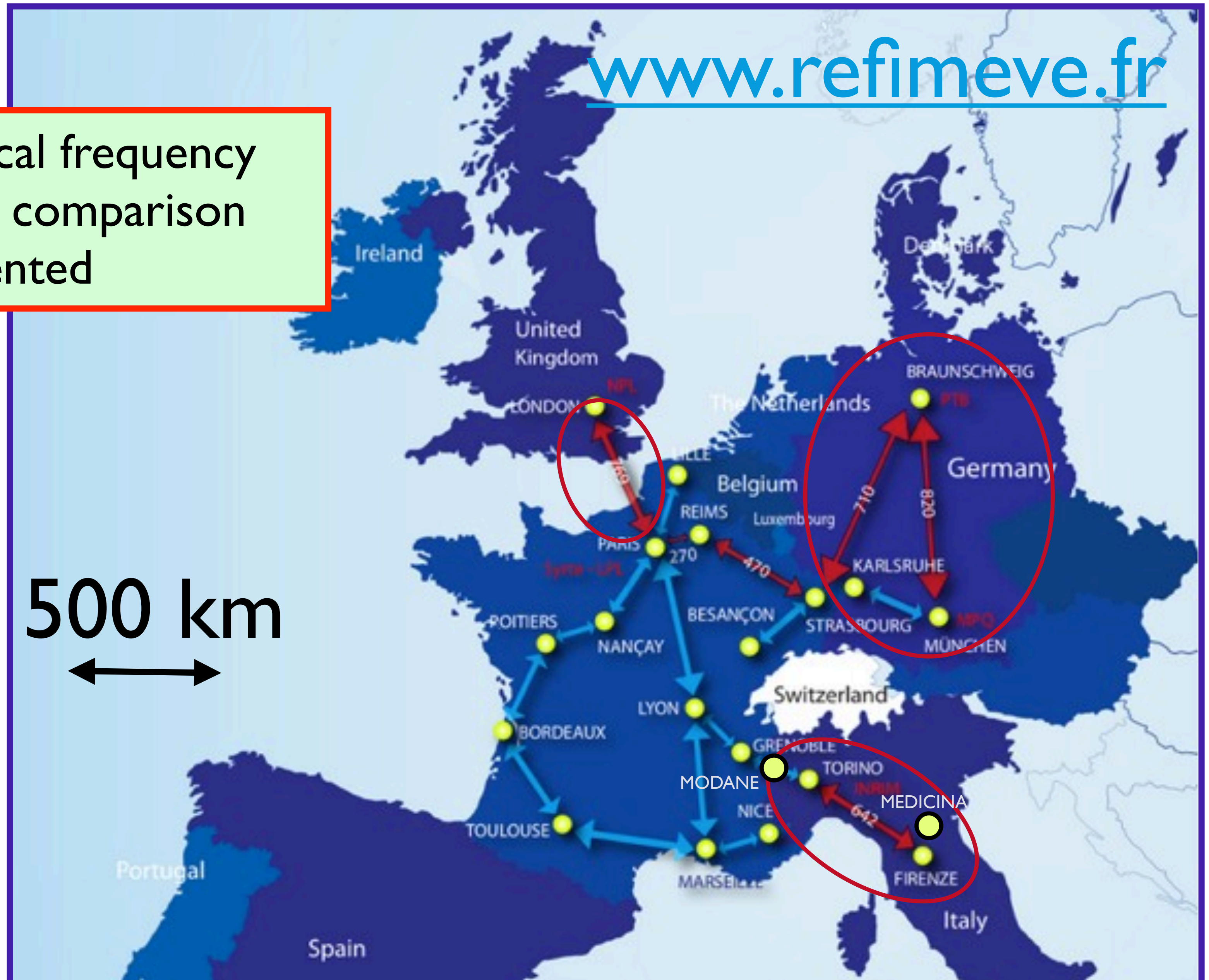
O. Lopez *et al.*, «F&T transfer for metrology and beyond (...)», C. Rendus Physique, Comptes Rendus Physique 16 (5), 459-586 (2015)

Optical Frequency transfer projects in Europe

Only CW Optical frequency dissemination / comparison represented

ICOF (GéANT)

500 km



PTB/MPQ

LIFT

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

target optical frequency dissemination > 4000 km

Challenges for long haul fiber links

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- **Fiber availability !**

Challenges for long haul fiber links

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  Partnership with NRENs / Contract with private Cie

Challenges for long haul fiber links

- **Fiber availability !**

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CONNECTEUR DE SAVOIRS
GÉANT
NORDUnet
Consortium GARR
PIONIER
FUNET
GasLINE

Challenges for long haul fiber links

- **Fiber availability !**
- **Attenuation**

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.2 to .29 dB / km

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10^{20} for 1000 km

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- **Bi-directional amplification (10<G<20 dB)**

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- **Fiber Brillouin amplification (<60 dB)**

Challenges for long haul fiber links

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.2 to .29 dB / km

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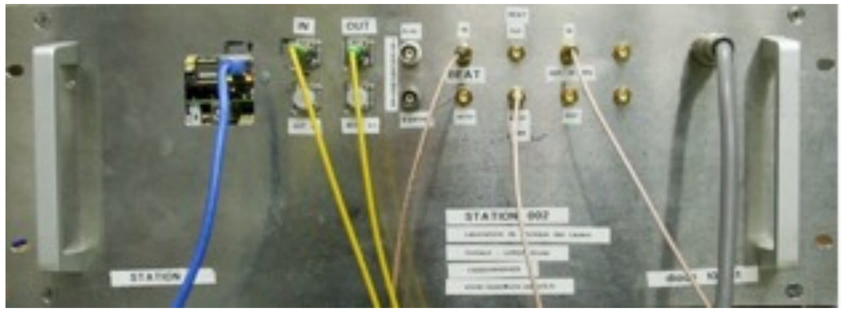
- **Bi-directional amplification (10<G<20 dB)**
- **Fiber Brillouin amplification (<60 dB)**
- **Optical regeneration (repeater laser station) : 2dBm output**



- Specific scientific equipment
- Knowledge transfer

Challenges for long haul fiber links

- **Fiber availability !**
- **Attenuation**

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- **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**

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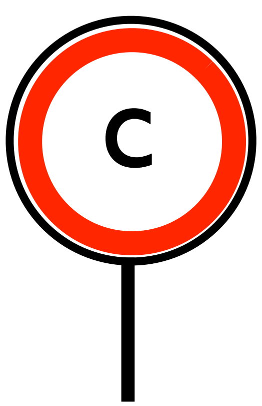
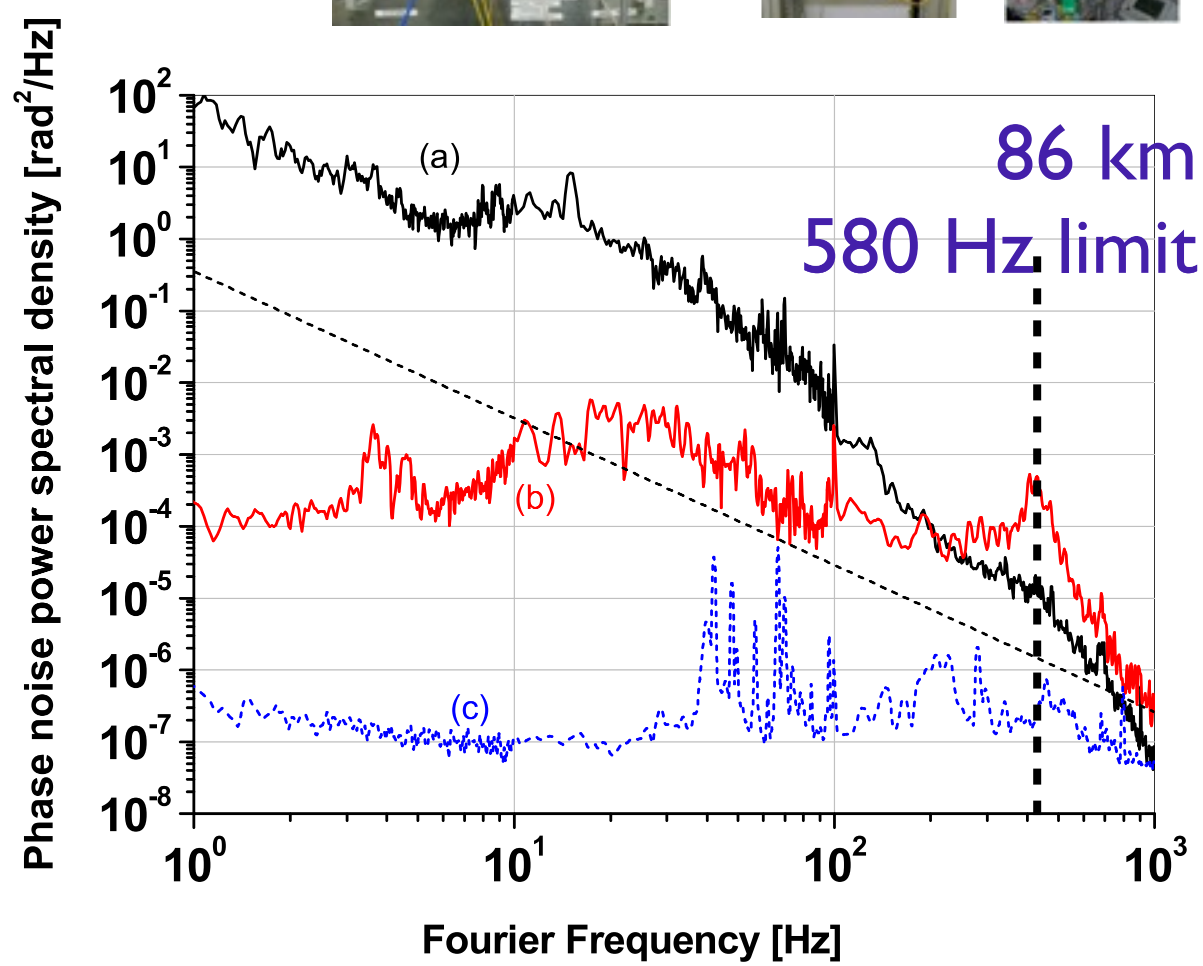


BW < 1 kHz
for L>50 km



Challenges for long haul fiber links

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

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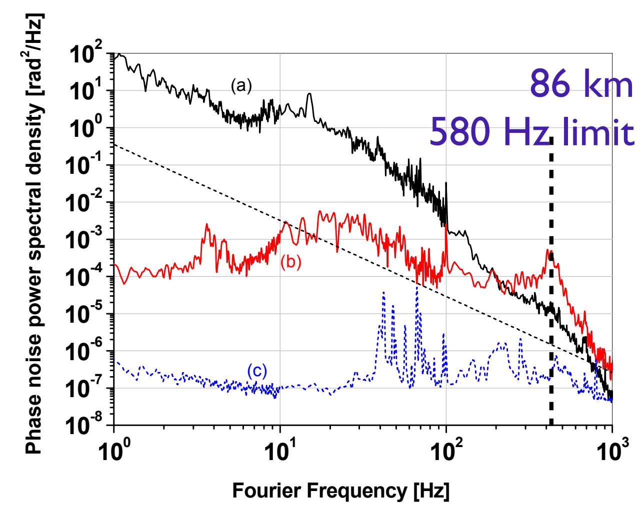
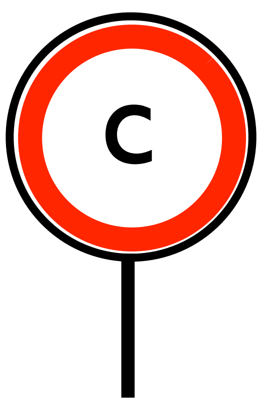
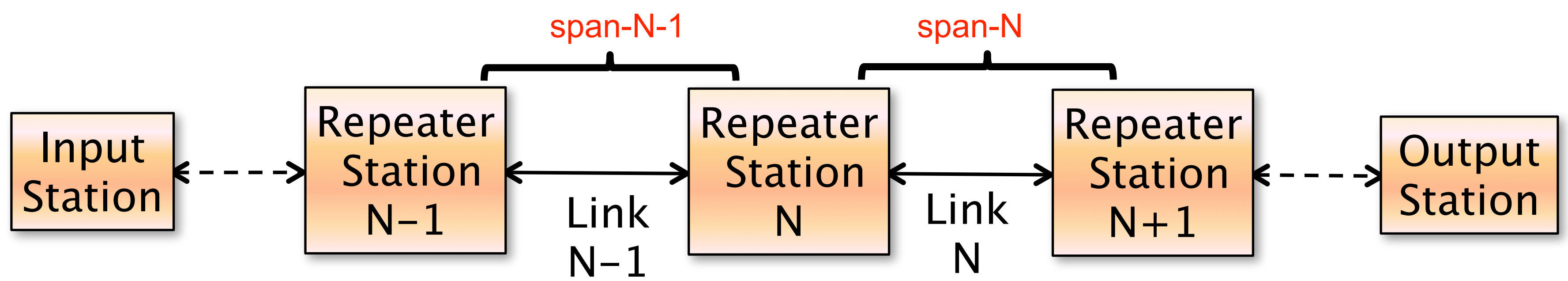




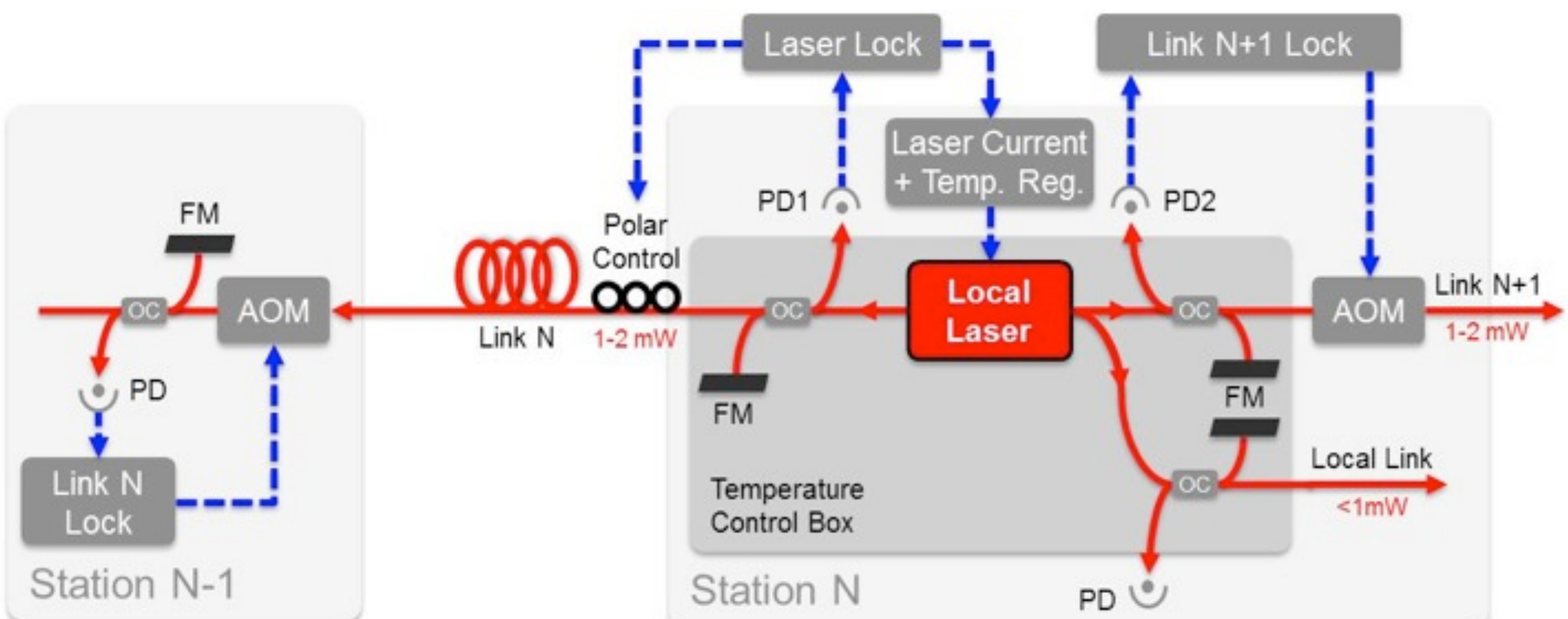
BW < 1 kHz
for L>50 km

- **Cascaded approach**

Cascaded optical fiber links



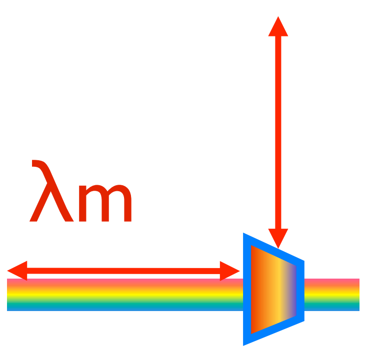
- Shorter delay and better noise rejection
- Remote control and monitoring
- Automatic operation
  - polarisation control
- No stable RF oscillator



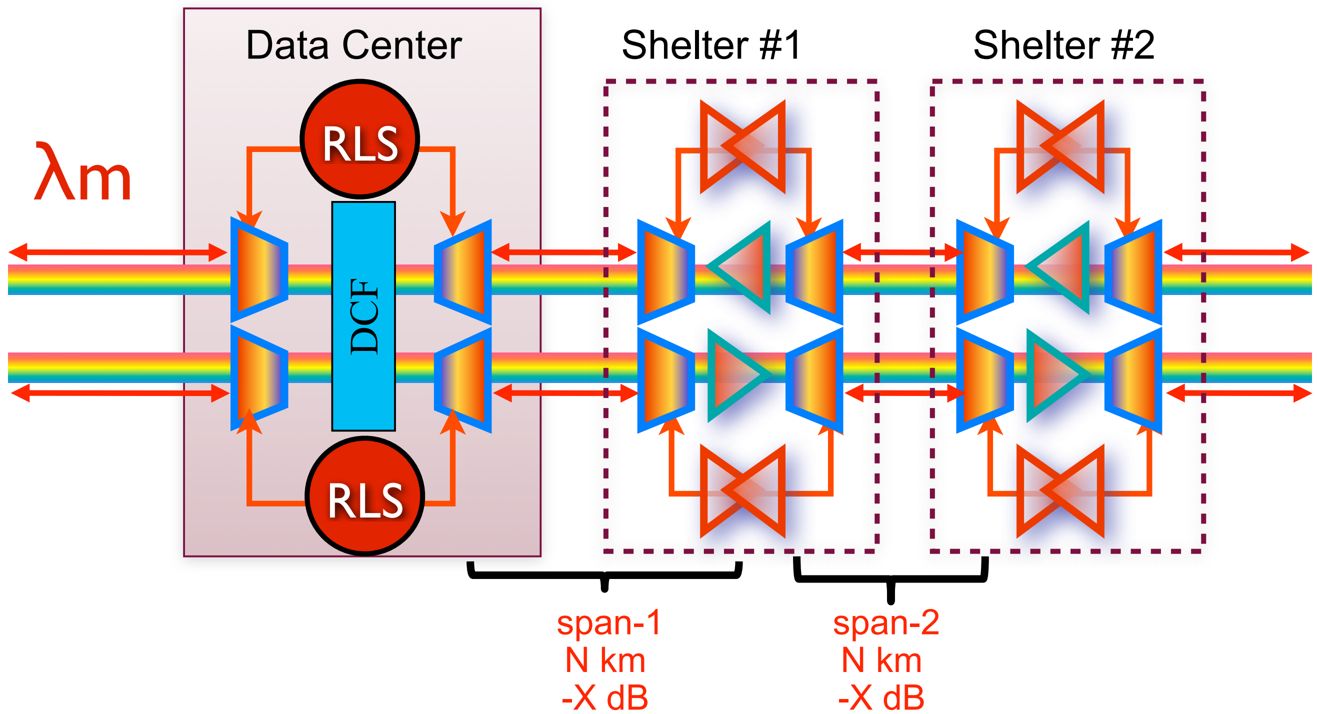
O. Lopez *et al.*, Optics Express 18 16849-16857 (2010)
O. Lopez et al, «Cascaded optical link(...), Proc. OPTO, Photonic West (2015)

Optical fiber links with ∥ data traffic

- French optical link is using a dedicated frequency channel of the academic network
- Parallel data traffic
- Optical Add-Drop Multiplexer
  - Used to go on/off the network.
  - Additional optical losses of ~1.6 dB/span

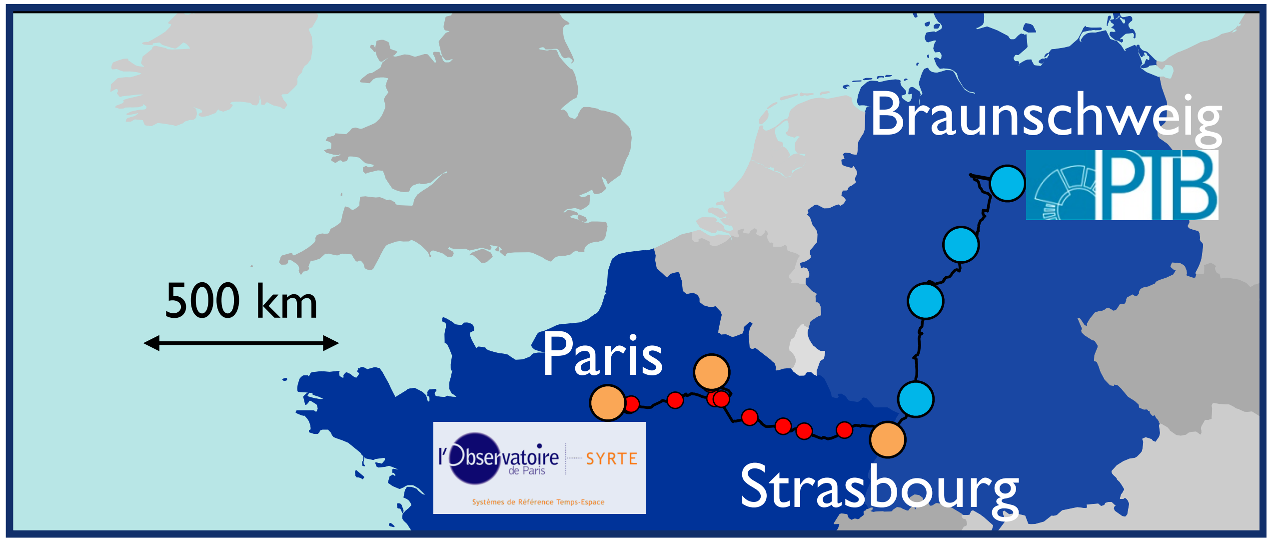


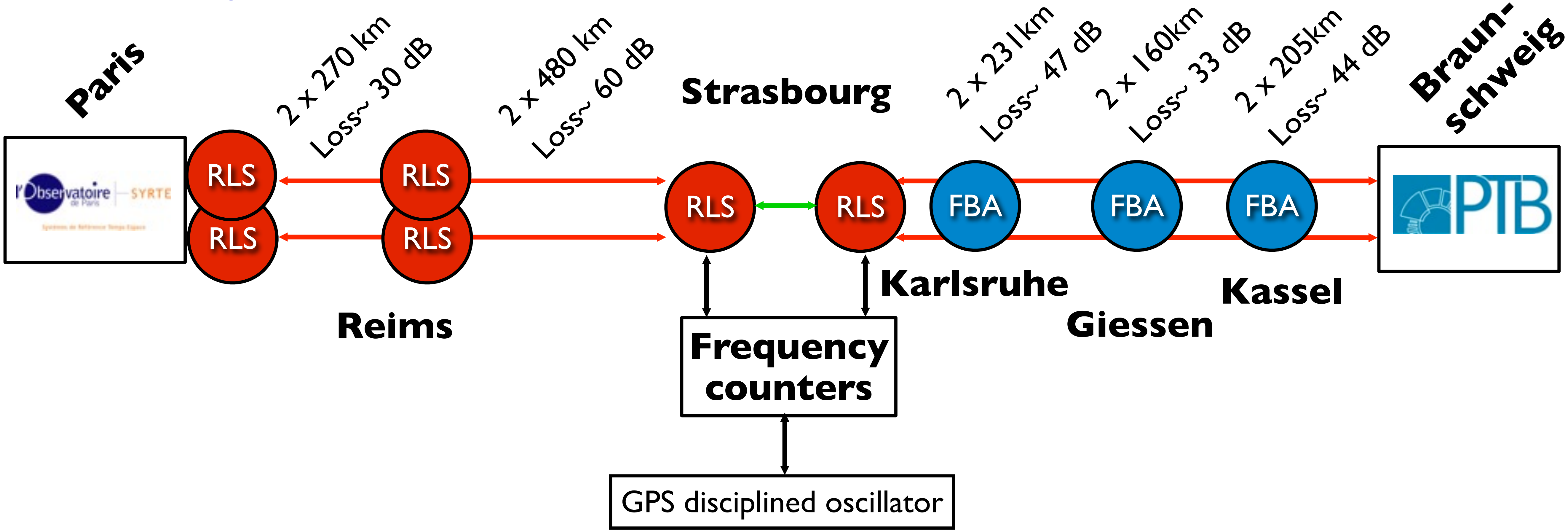
- Cascaded optical link with repeater laser stations
  - Pin on the network <2 mW
  - High gain (up to 60 dB)
  - Narrow band, tunable
  - User output

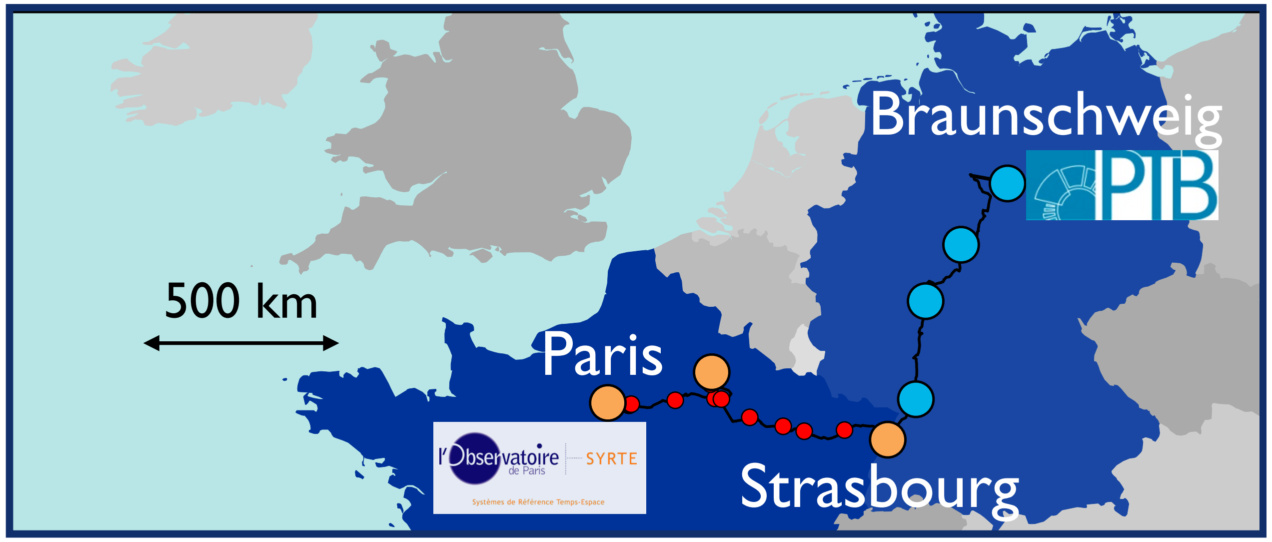


Inter-connexion FR-DE links

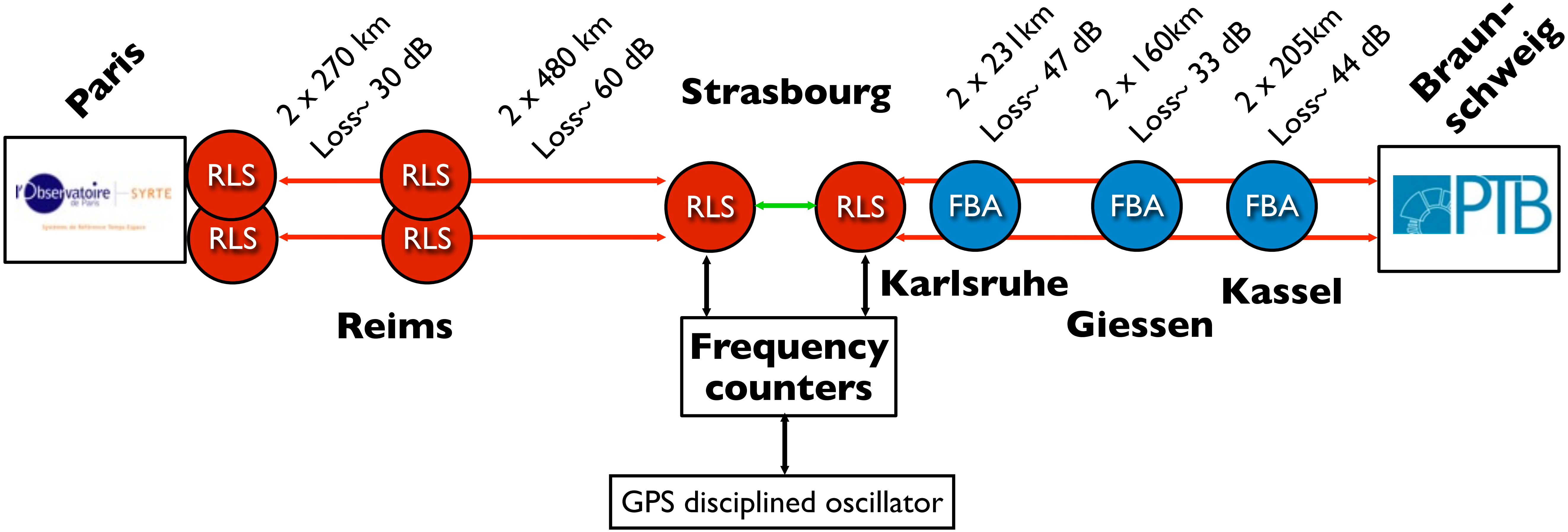
- Two-way frequency comparison between the RLS
- Optical beat note vs GPS-disciplined ultra-stable oscillator
- Remote control and monitoring FBA and RLS





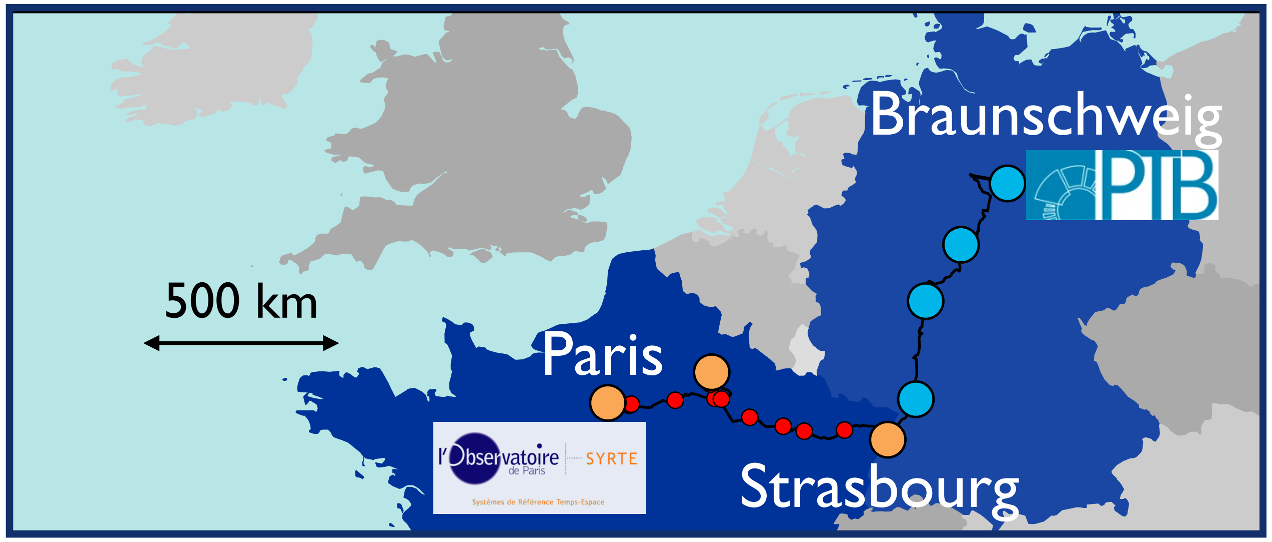


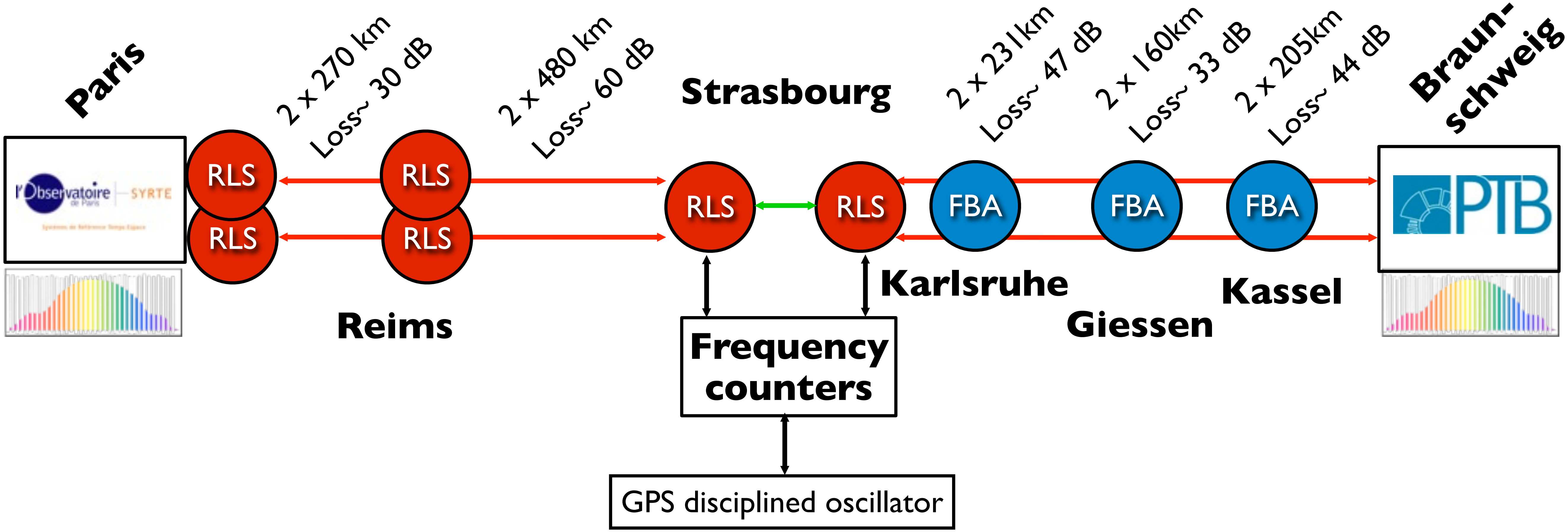
Braunschweig
PTB
500 km
Paris
Strasbourg
l'Observatoire de Paris SYRTE



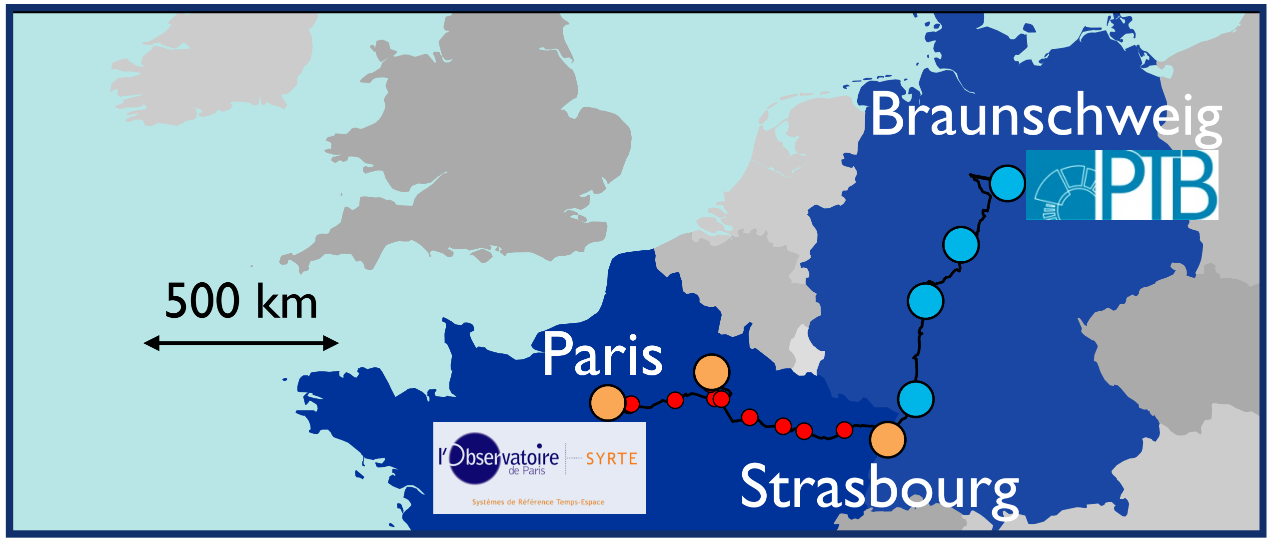
Paris
2 x 270 km
Loss~ 30 dB
2 x 480 km
Loss~ 60 dB
Strasbourg
2 x 231km
Loss~ 47 dB
2 x 160km
Loss~ 33 dB
2 x 205km
Loss~ 44 dB
Braun-schweig
RLS
RLS
RLS
RLS
RLS
RLS
FBA
FBA
FBA
PTB
Reims
Karlsruhe
Giessen
Kassel
Frequency counters
GPS disciplined oscillator

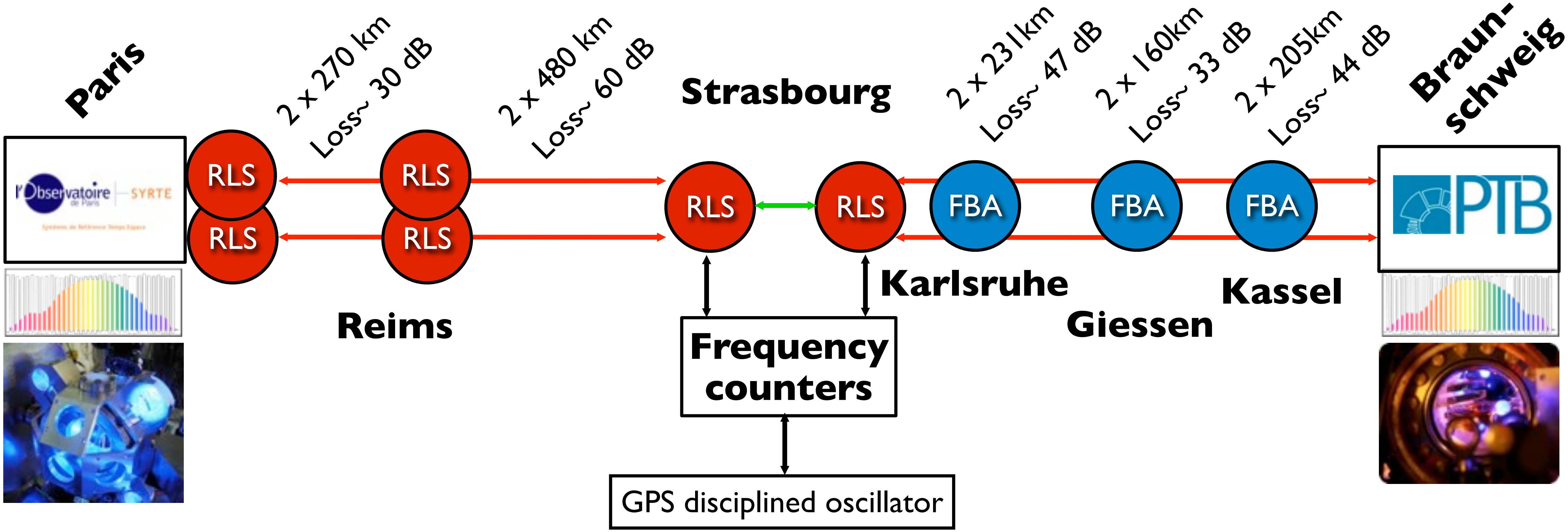
■ Frequency combs, coherent regime





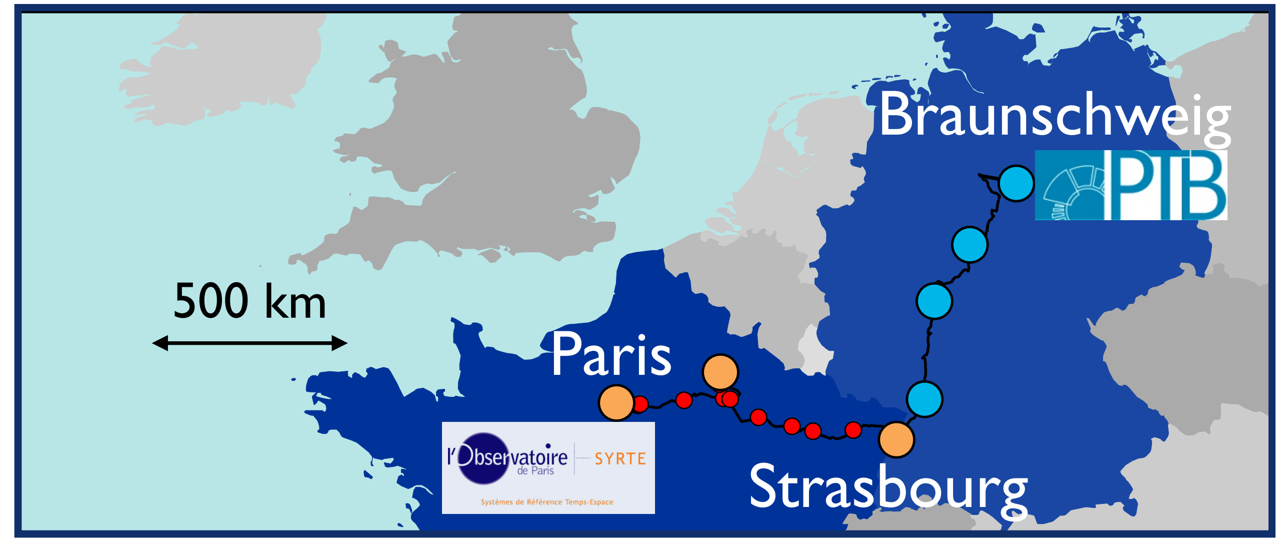
- Frequency combs, coherent regime
- Two independent Sr-lattice clock
- «All-optical» frequency comparison

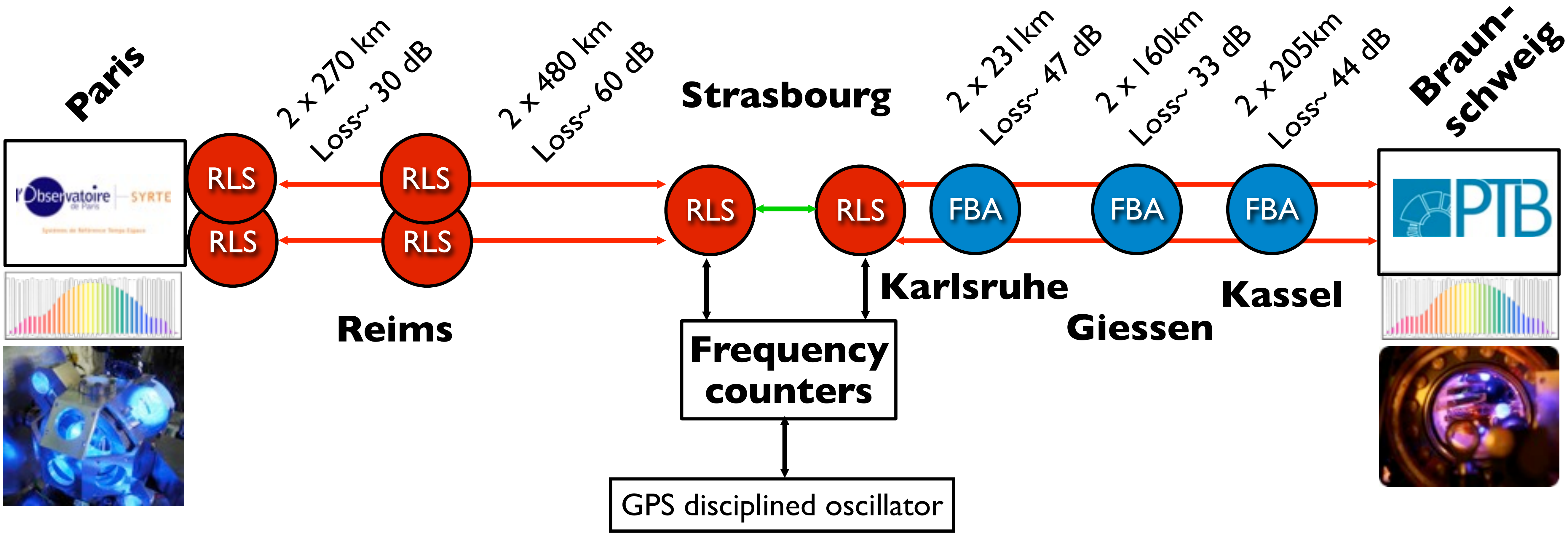




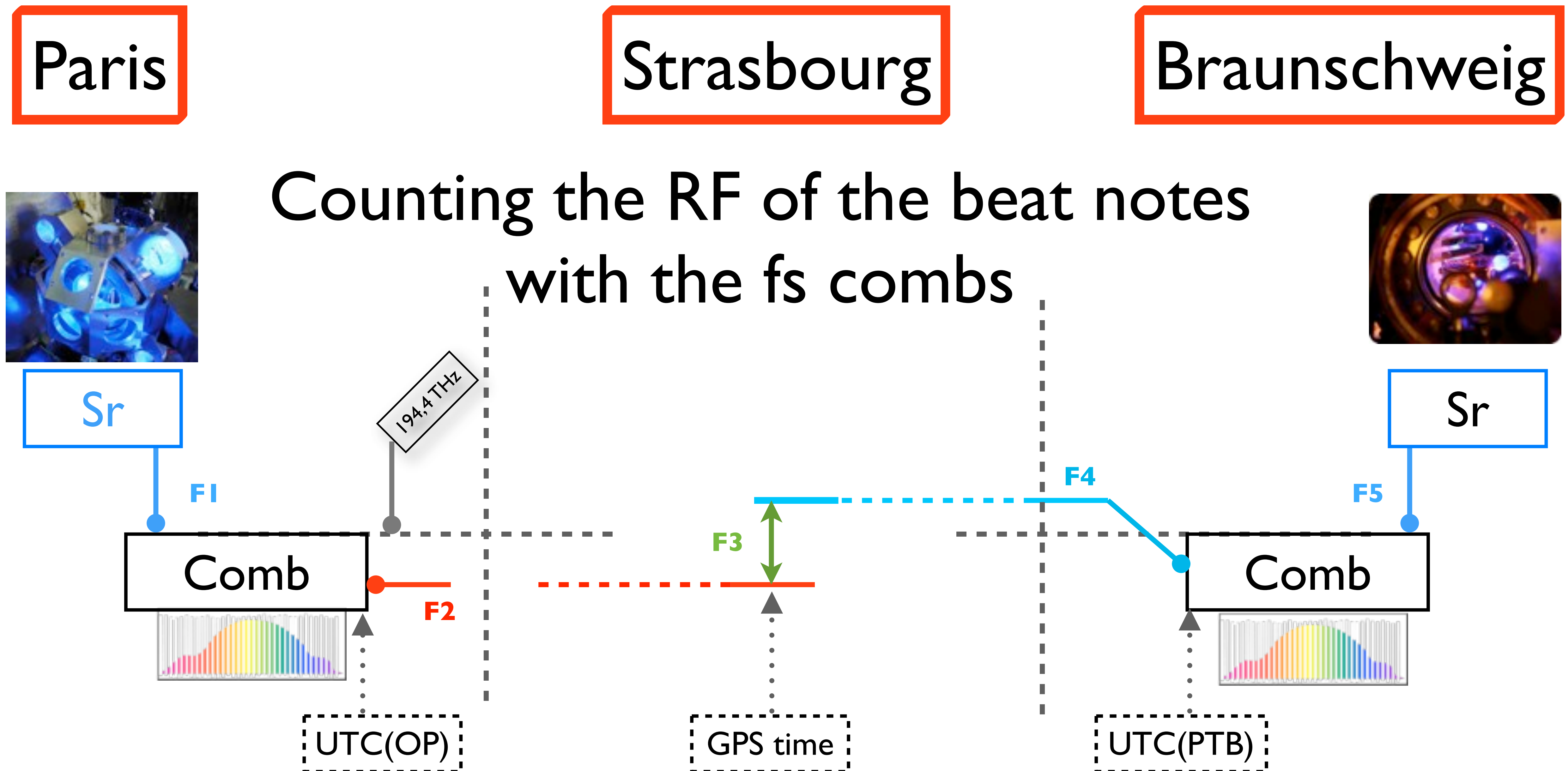
The 1st Sr-Sr comparison by long haul fiber links

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



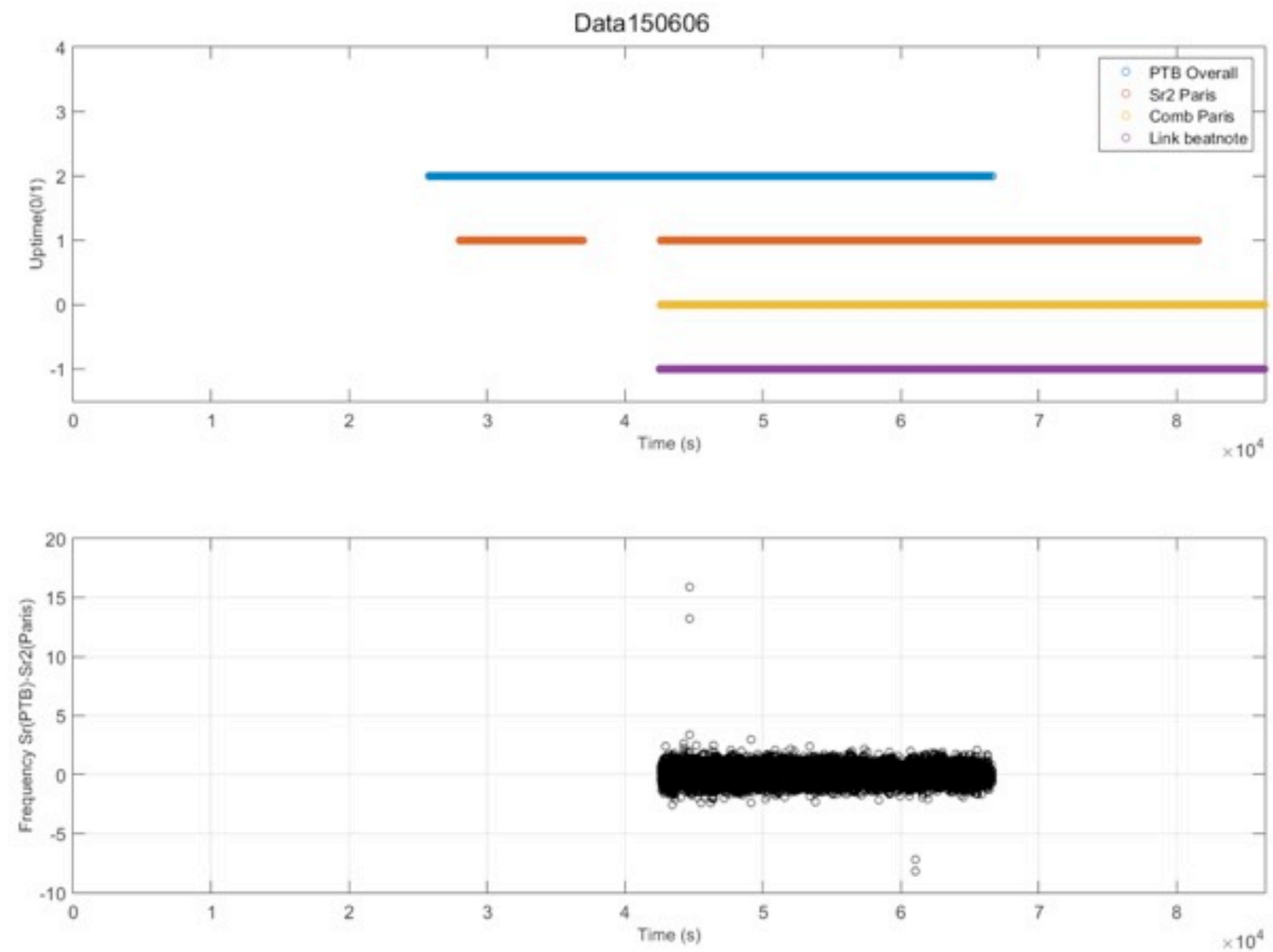


An optical methodology



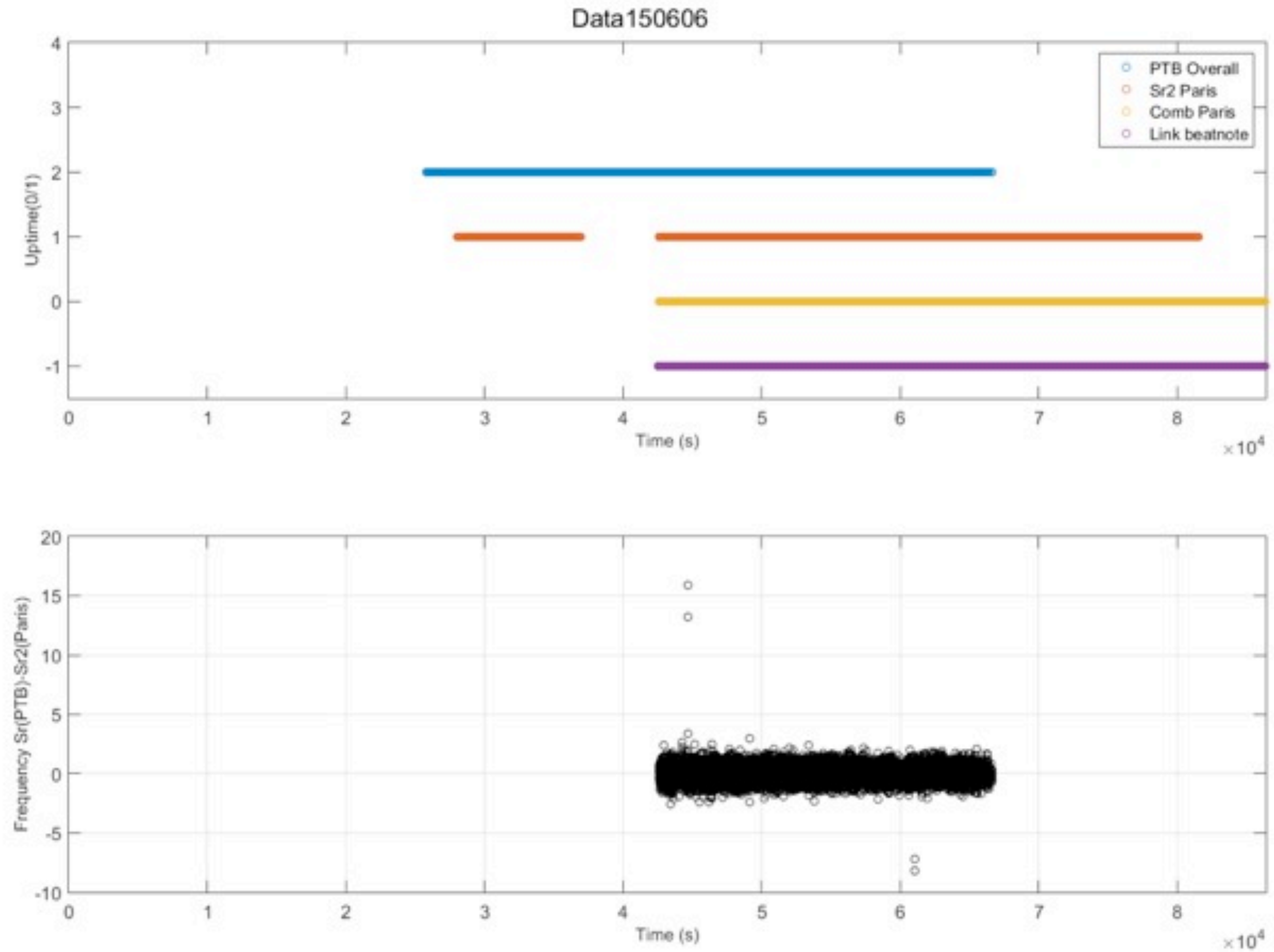
Absolute frequency difference without SI-Hz

Experimental results : raw trace



Experimental results : raw trace

- Combination of Sr/Combs/ link at both side
- two runs :



Experimental results : raw trace

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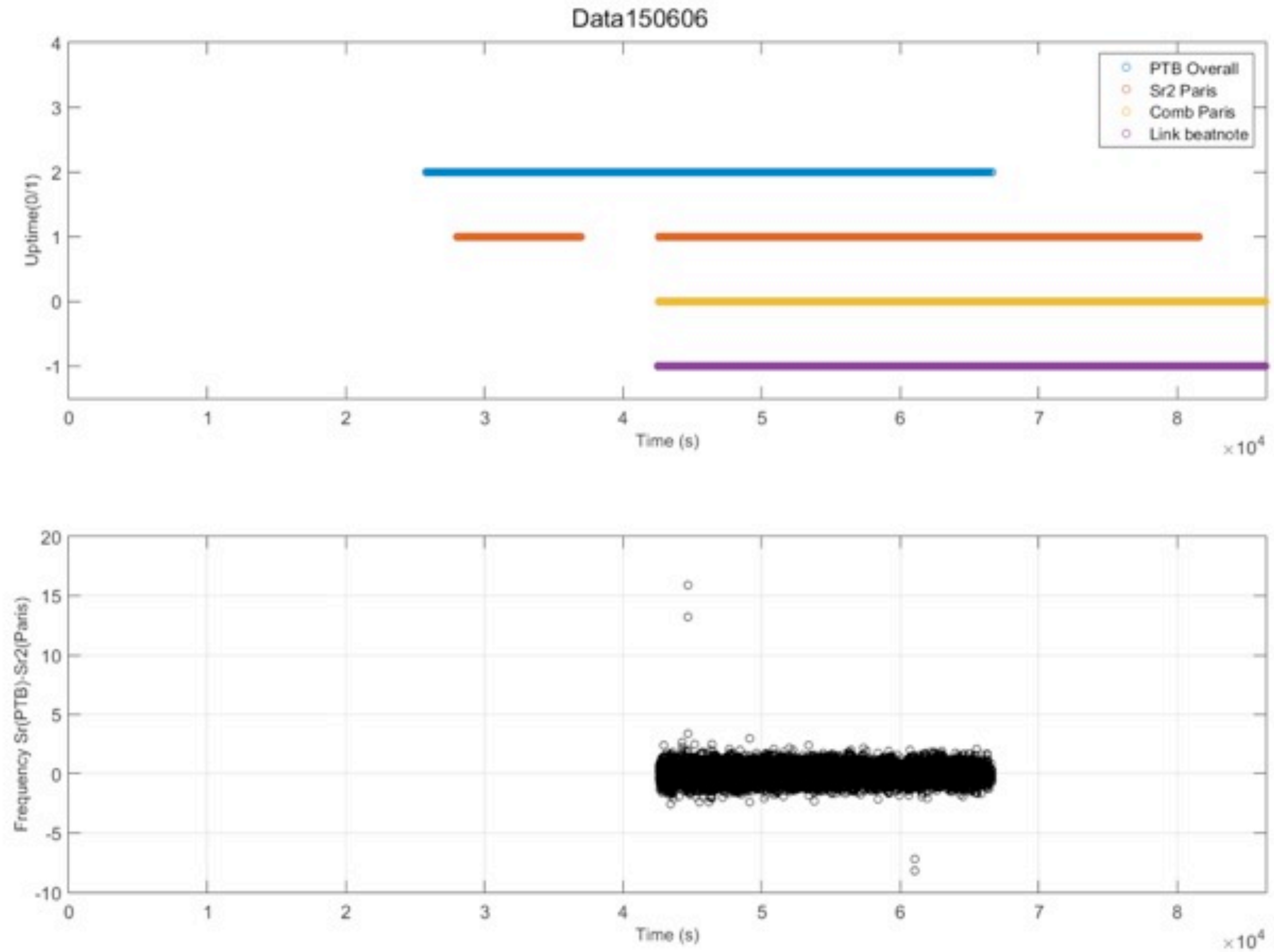
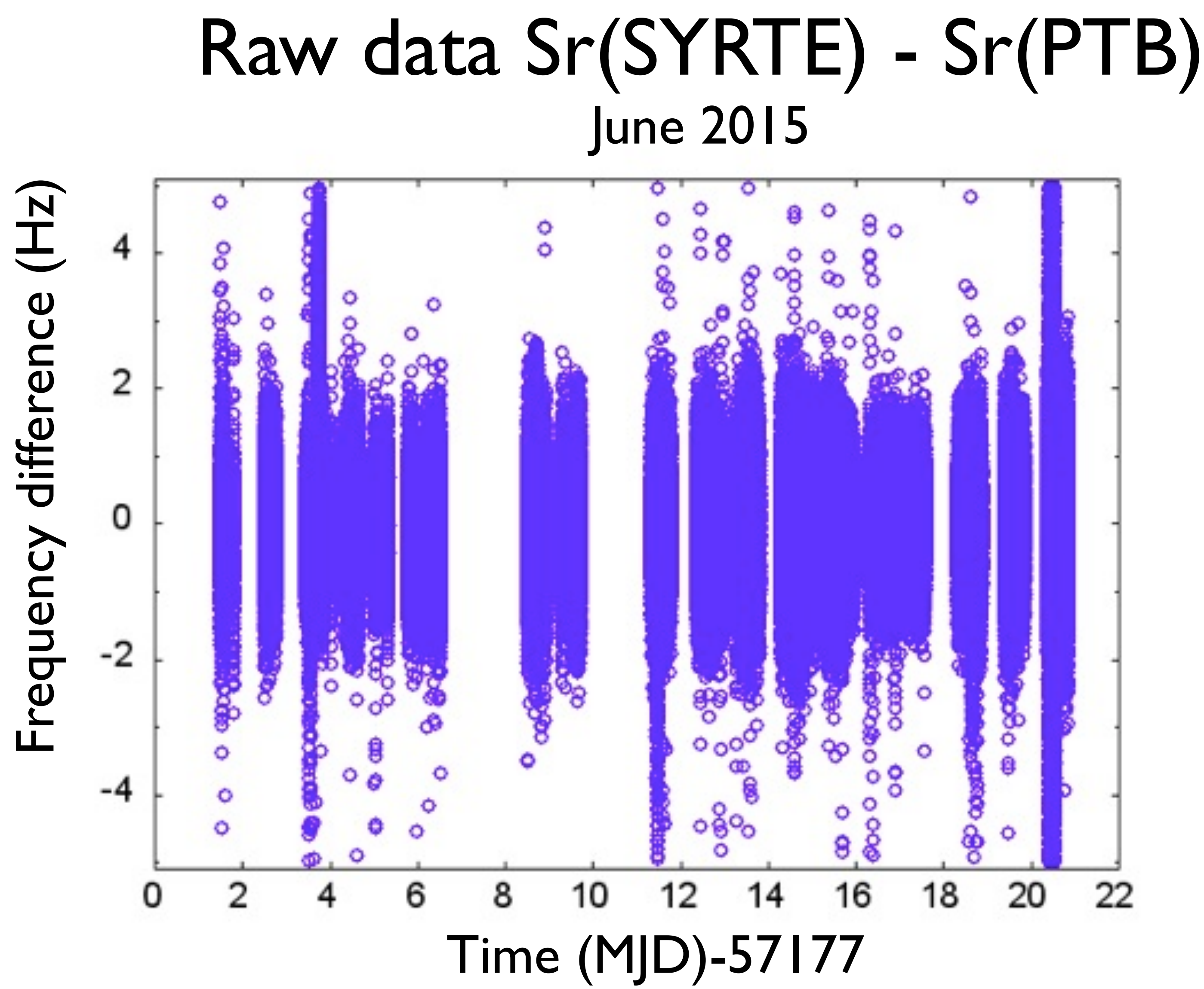
  - 3 days in March

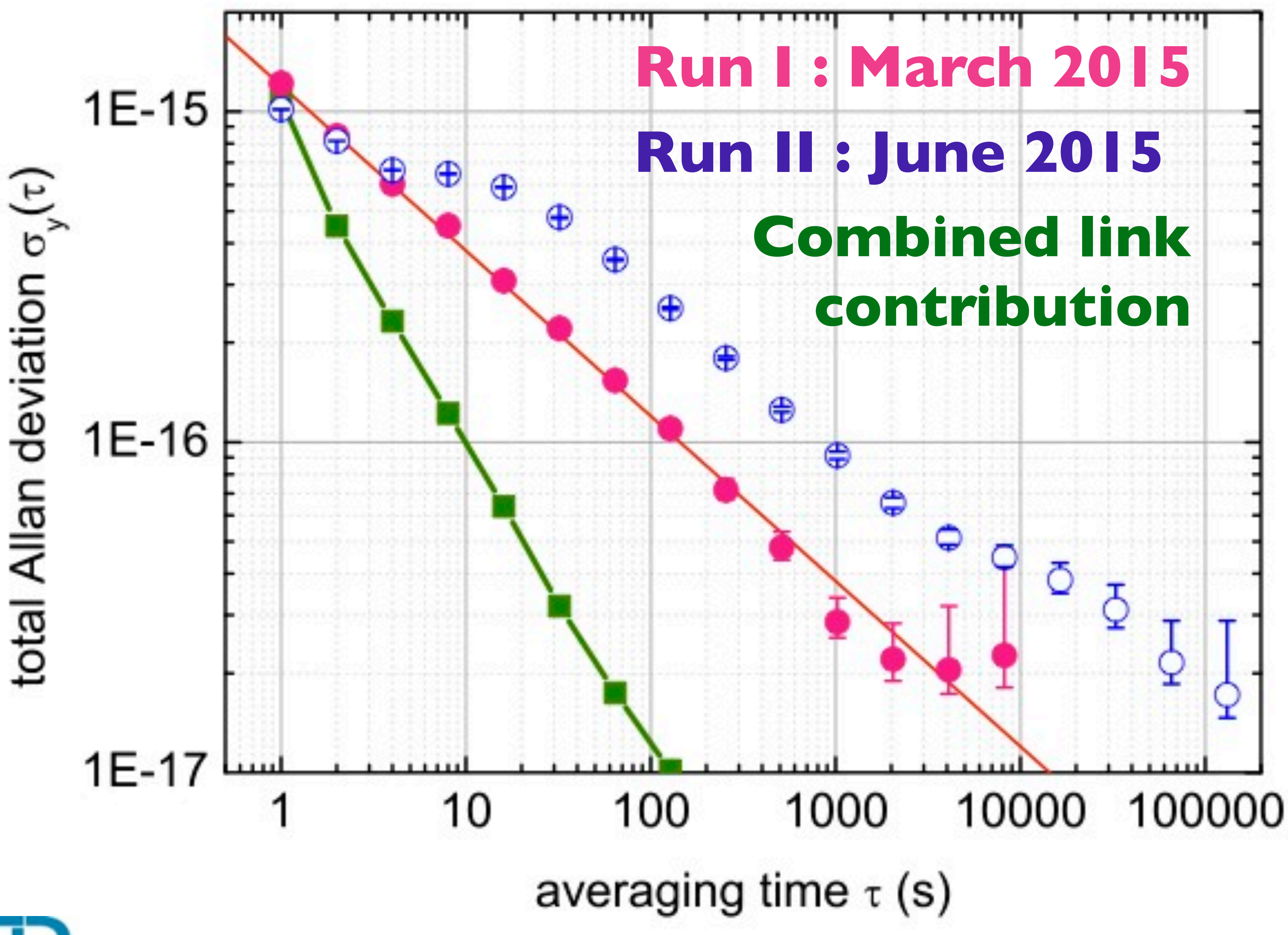


Experimental results : raw trace

- 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



Sr-clocks comparison SYRTE-PTB



Clock accuracy budget

PTB

Clock uncertainty	Sr lattice clock Paris		Sr lattice clock Braunschweig	
Effect (x 10^{-17})	Correction	Uncertainty	Correction	Uncertainty
Residual lattice light shift	0	2.5	-1.1	1.0
Black-body radiation	515.5	1.8	492.9	1.3
Black-body radiation oven	0	1.0	0.9	0.9
Density shift	0	0.8	0	0.1
Quadratic Zeeman shift	134.8	1.2	3.6	0.15
Line pulling	0	2.0	0	<< 0.1
Lock error	0	0.3	0	0.2
DC Stark shift	0	0.5	0	<< 0.1
Tunneling	0	<< 0.	0	0.1
Probe light shift	0	<< 0.	0	<< 0.1
Total clocks (x 10^{-17})	**650.3**	**4.1**	**496.4**	**1.9**

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Clock comparison accuracy budget

Ratio Sr_{PTB}/Sr_{SYRTE}	Run I	Run II
	Uncertainty (x 10^{-17})	
Systematics Sr_{SYRTE}	4.1	4.1
Systematics Sr_{PTB}	2.1	1.9
Statistical uncertainty	3	2
fs combs	0.1	0.1
Link uncertainty	<.1	<0.1
Counter synchronization	10	0.1
Gravity potential corr.	0.4	0.4
Total clock comparison	**11.4**	**5.0**

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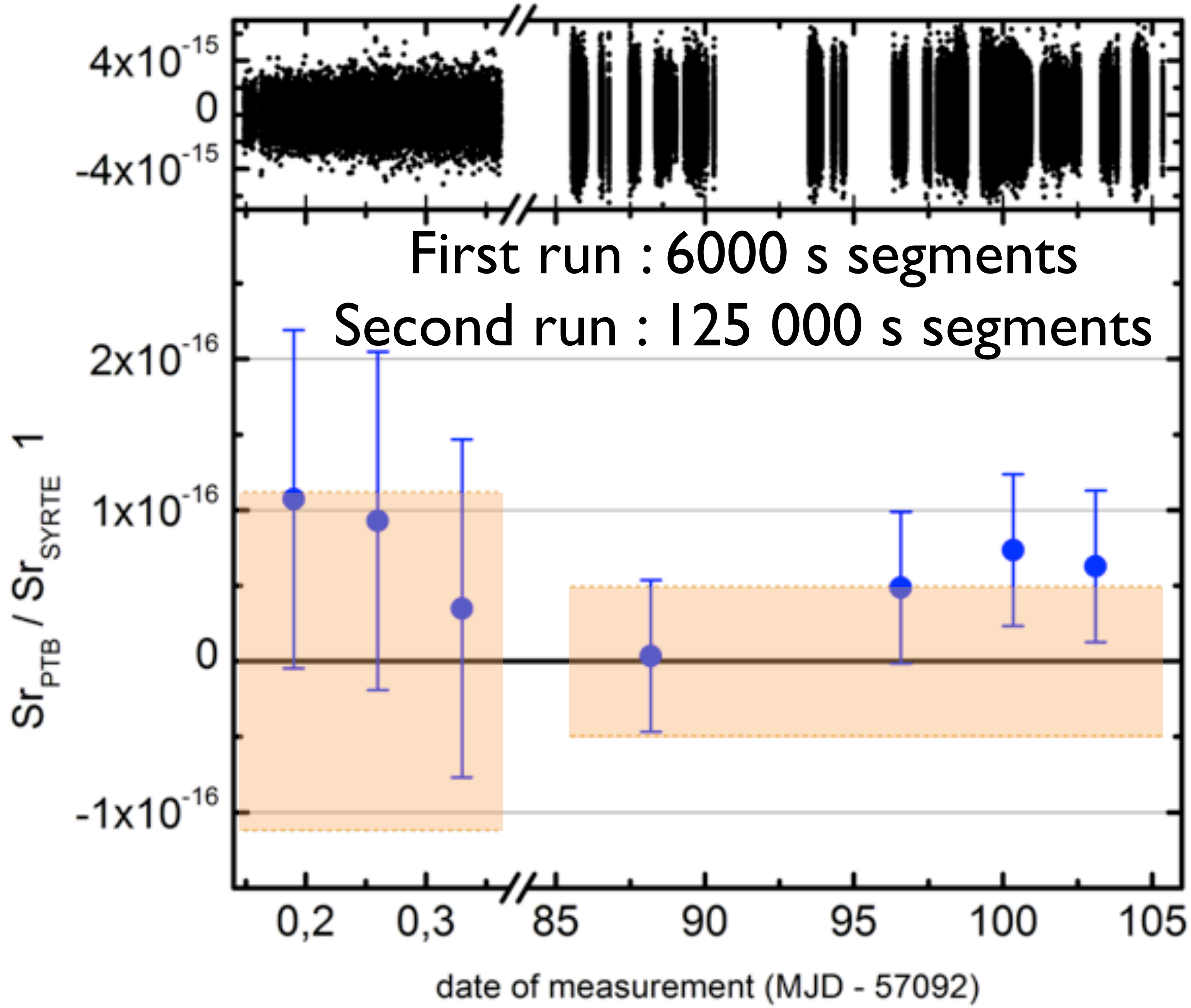

Sr-clocks comparison SYRTE-PTB

- Frequency instability Sr^{PTB}-Sr^{SYRTE}

  2×10^{-17} (5000 to 50000 s)

- Accuracy : Sr^{PTB}-Sr^{SYRTE} agreement

  $(4.7 \pm 5) \times 10^{-17}$

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  $(4.7\pm5)\times10^{-17}$

- Two fully independent system in agreement within the statistical error bars.

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  $(4.7 \pm 5) \times 10^{-17}$

- Two fully independent system in agreement within the statistical error bars.
  - Black body shift, light shift, AC Stark shift and collisions well controled on two different setups

Sr-clocks comparison SYRTE-PTB

- Frequency instability Sr^{PTB}-Sr^{SYRTE}

  $2x10^{-17}$ (5000 to 50000 s)

- Accuracy : Sr^{PTB}-Sr^{SYRTE} agreement

  $(4.7 \pm 5)x10^{-17}$

- Two fully independent system in agreement within the statistical error bars.
  - Black body shift, light shift, AC Stark shift and collisions well controled on two different setups
- Optical links demonstrates their ability to compare clock with superior abilities to any other methods

Sr-clocks comparison SYRTE-PTB

- Frequency instability Sr^{PTB}-Sr^{SYRTE}

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- Two fully independent system in agreement within the statistical error bars.
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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

Outlook

- **A world first ! Optical clock comparison SYRTE-PTB**
  - <3x10^{-17} statistical uncertainty @1day
  - 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 po
  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)

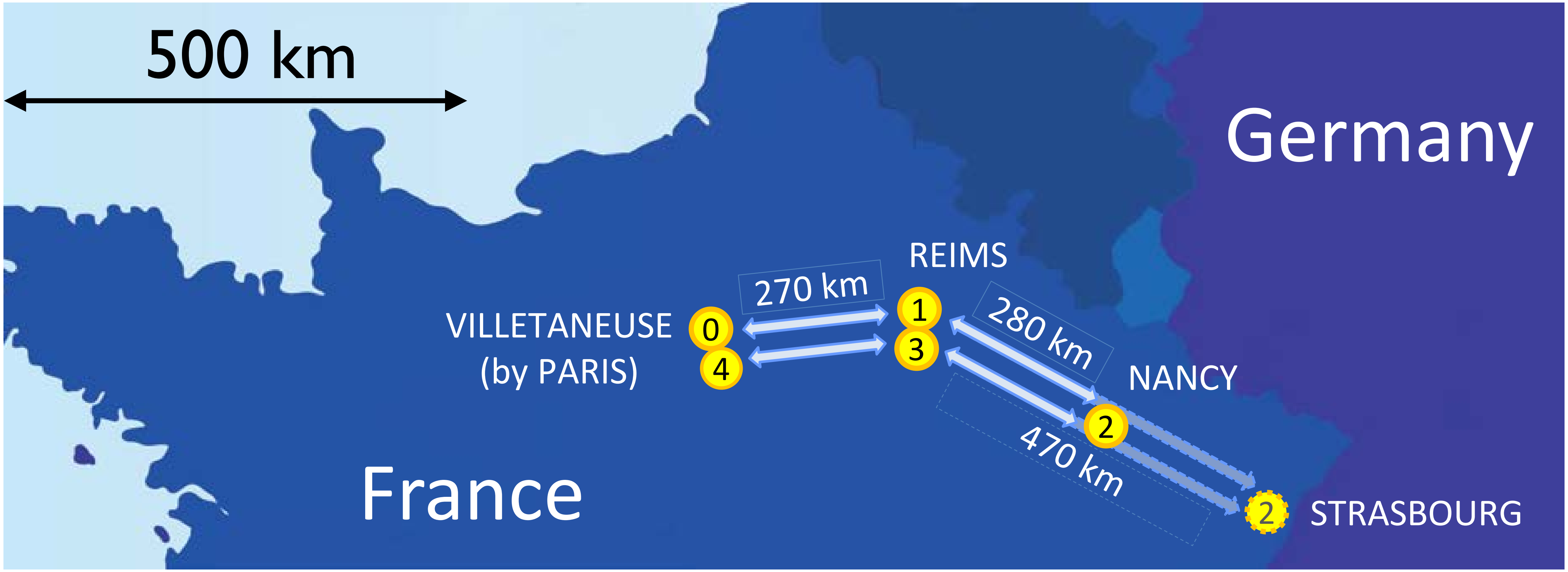
RENATER, Université de Strasbourg (network),

are :

M. Abgrall, A. Al-Masoudi, A. Amy-Klein, E. Bookjans, S. Bilicki, E. Camisard, C. Chardonnet, N. Chiodo, S. Dörscher, C. Grebing, G. Grosche, S. Häfner, A. Koczwara, S. Koke, A. Kuhl, Y. Le Coq, T. Legero, R. Le Targat, C. Lisdat, J. Lodewyck, M. Lours, O. Lopez, F. Meynadier, B. Moya, D. Nicolodi, P.-E. Pottie, N. Quintin, S. Raupach, J.-L. Robyr, G. Santarelli, C. Shi, H. Schnatz, F. Stefani, U. Sterr, F. Wiotte

Thank you for attention !

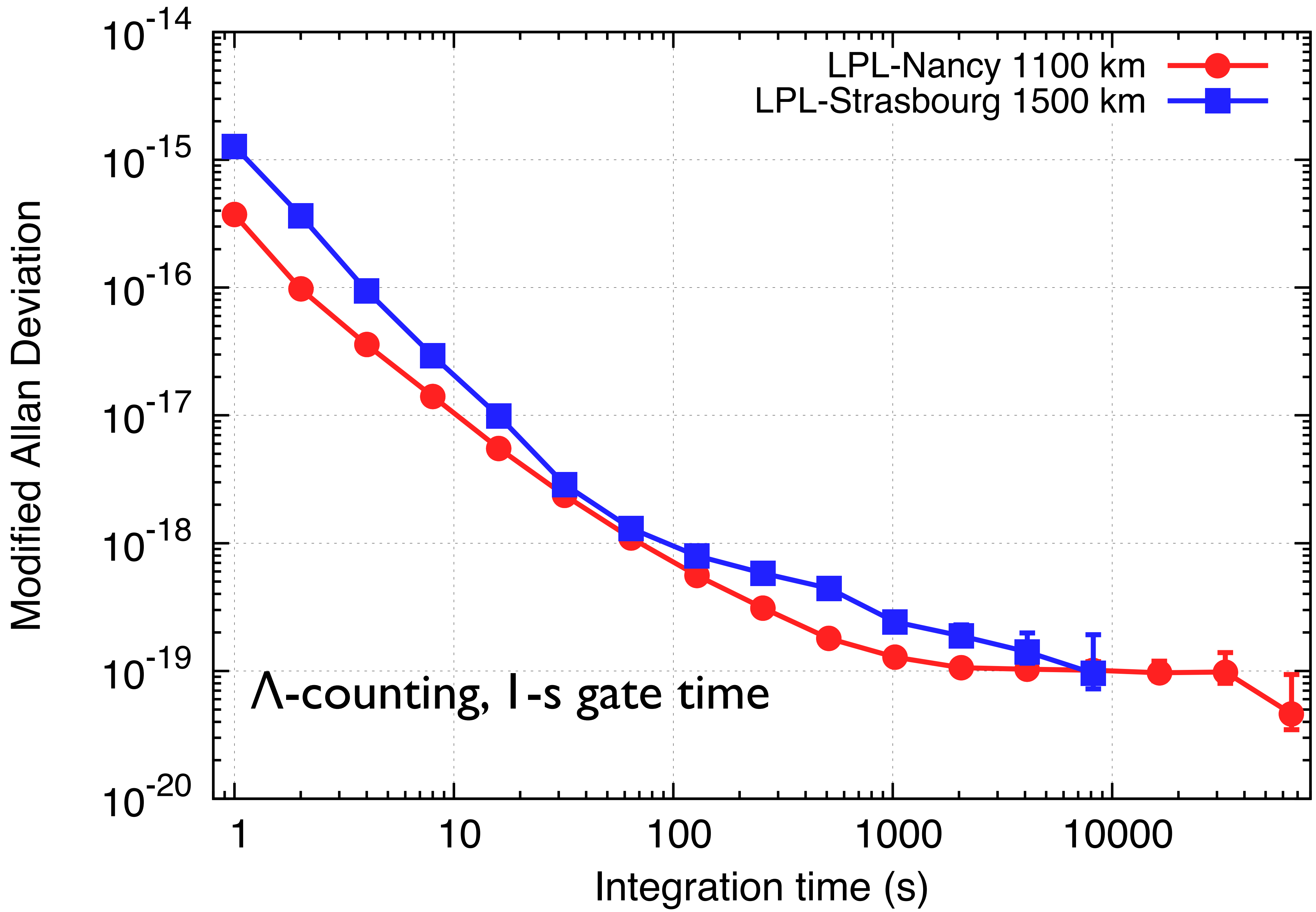
A 4-span cascaded link



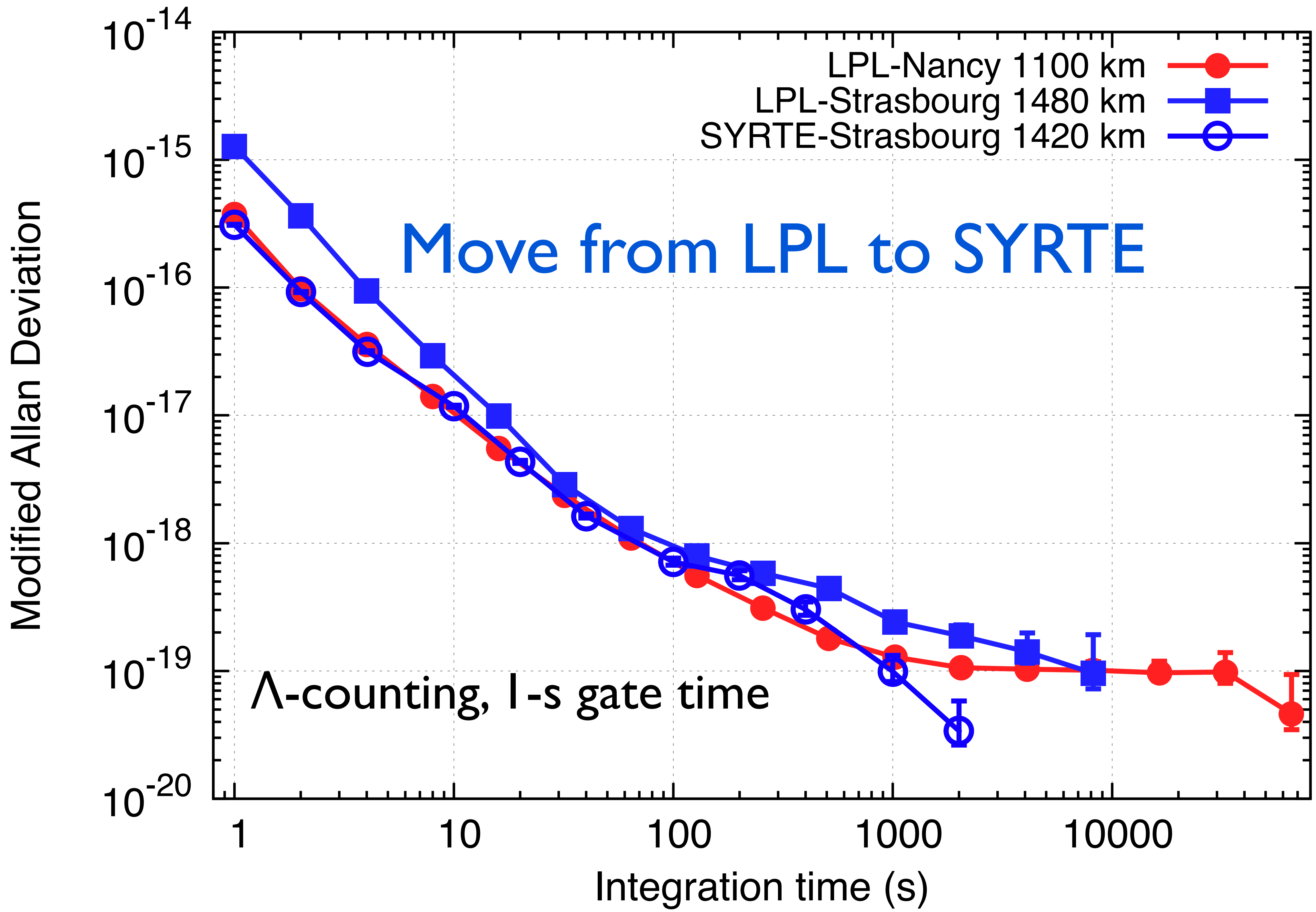
- Start and End at LPL, Paris area
- First link of 1100 km reaching Nancy and back
- Second link of 1480 km reaching Strasbourg and back
- Shift Start and End to SYRTE

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

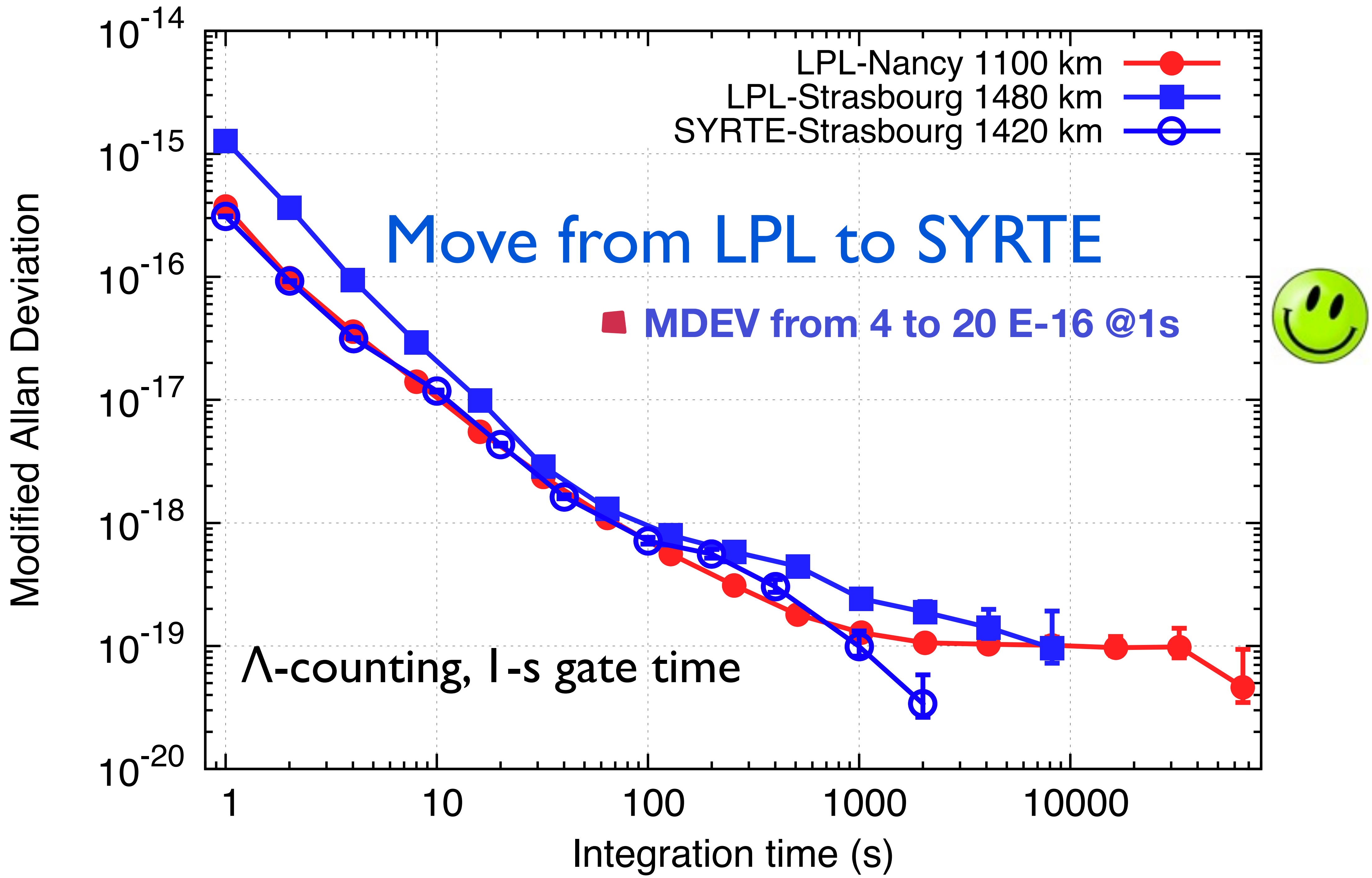
Relative frequency instability



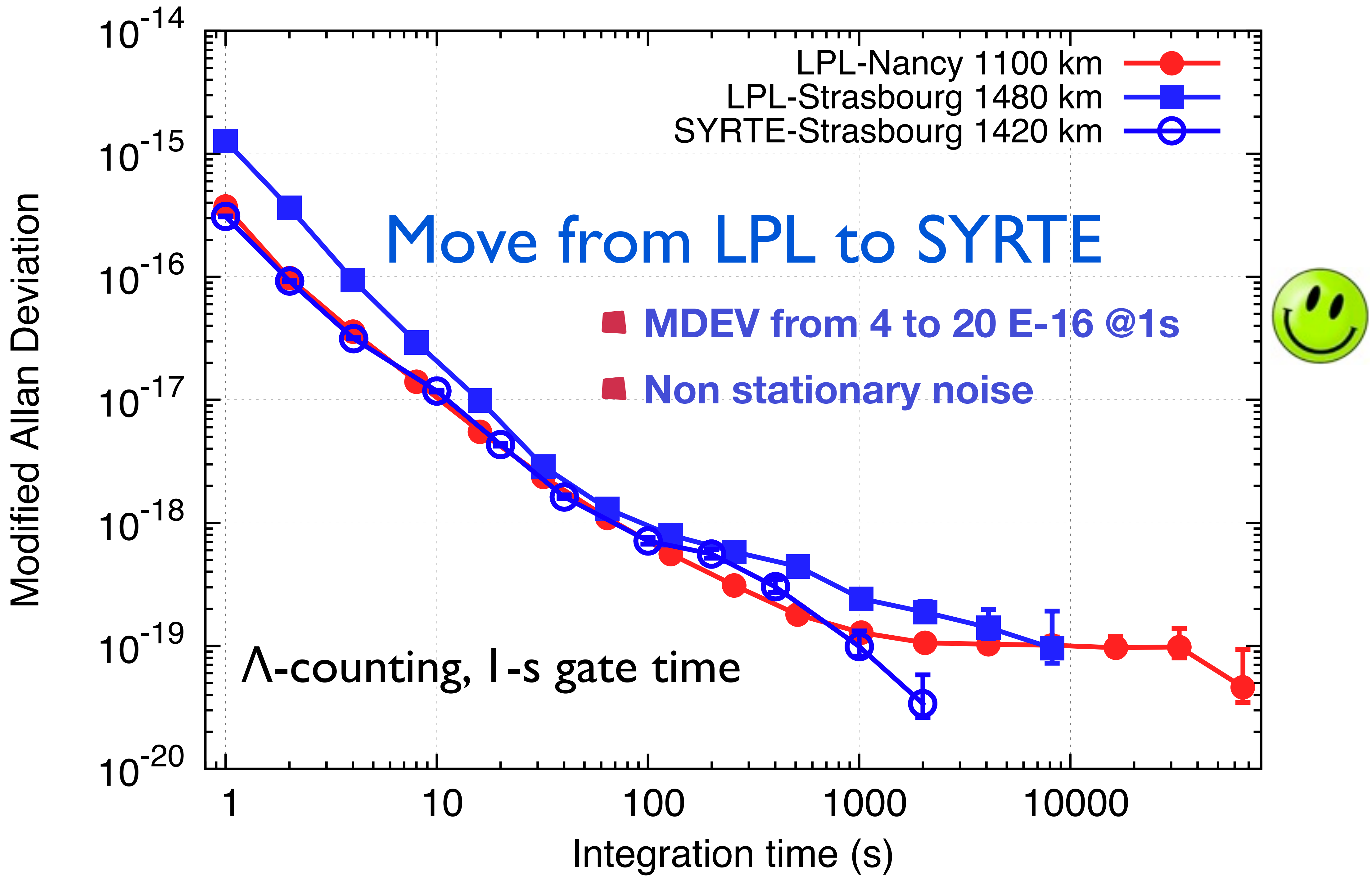
Relative frequency instability



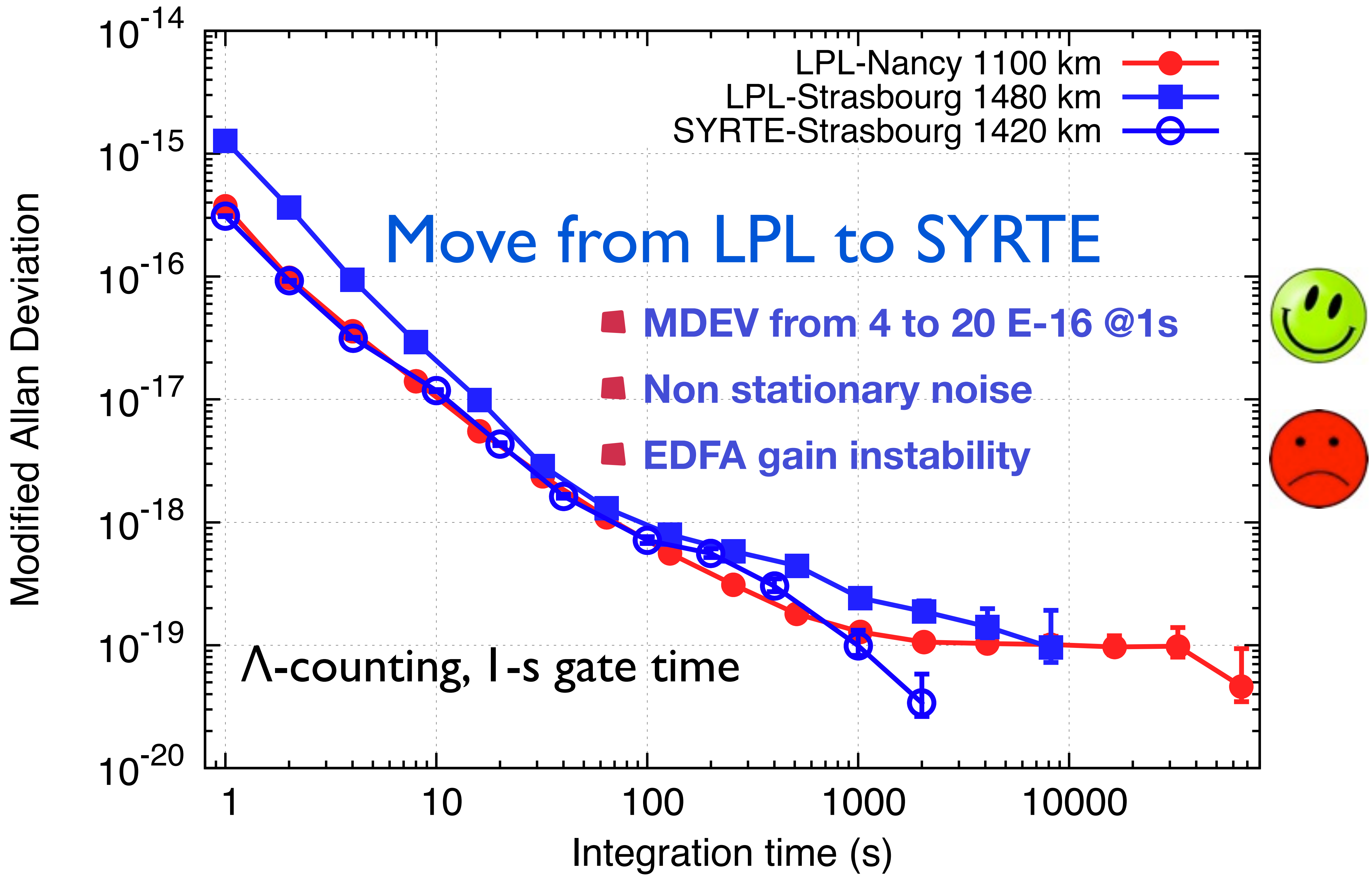
Relative frequency instability



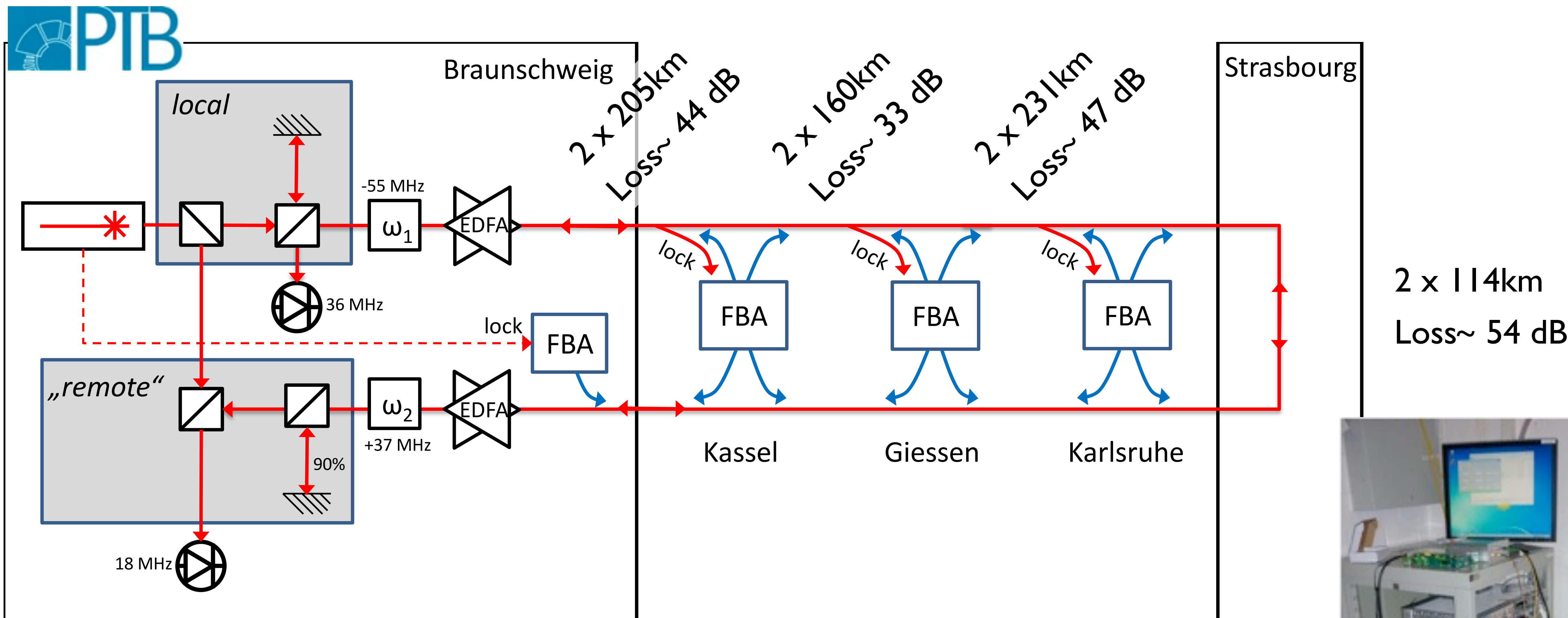
Relative frequency instability



Relative frequency instability



Long-haul fiber links with FBA



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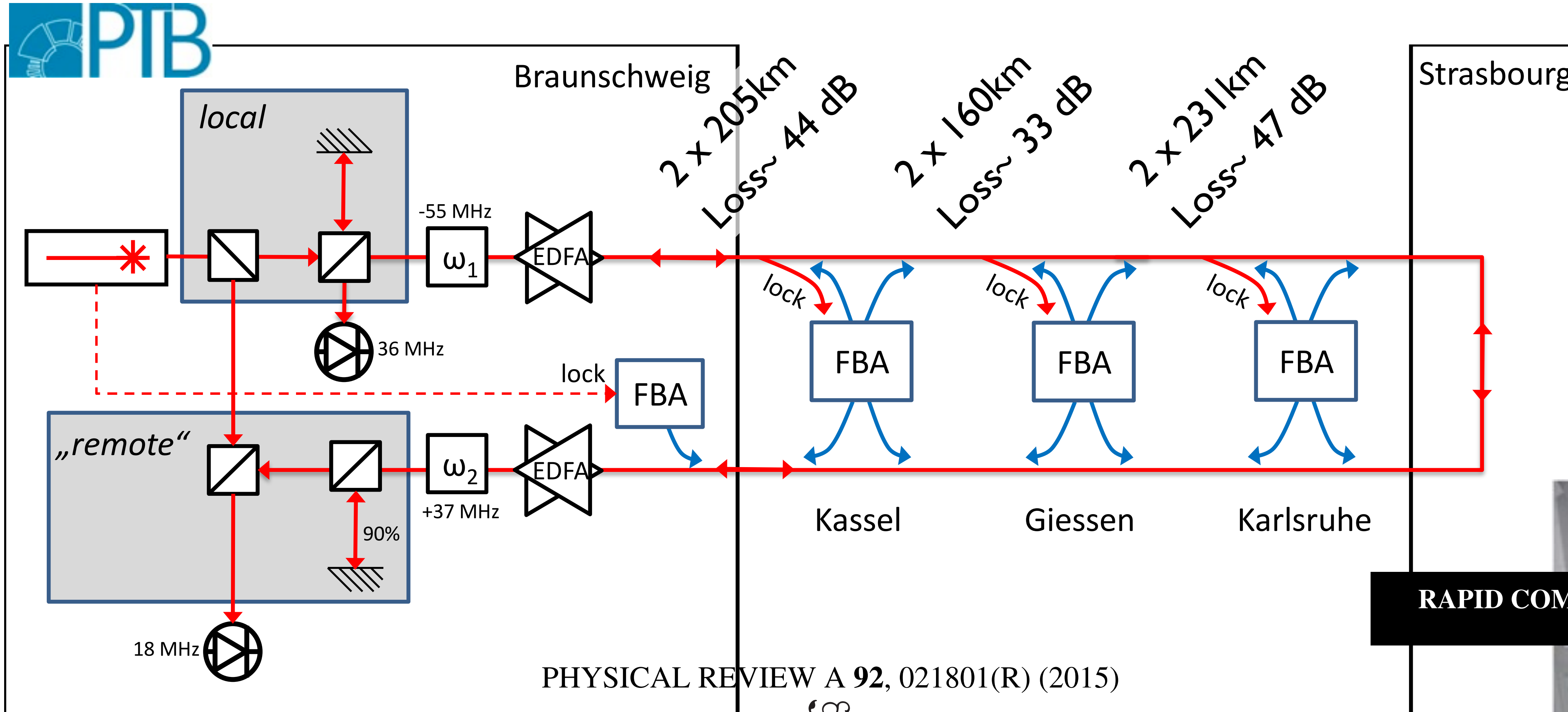


RAPID COMMUNICATIONS

PHYSICAL REVIEW A **92**, 021801(R) (2015)

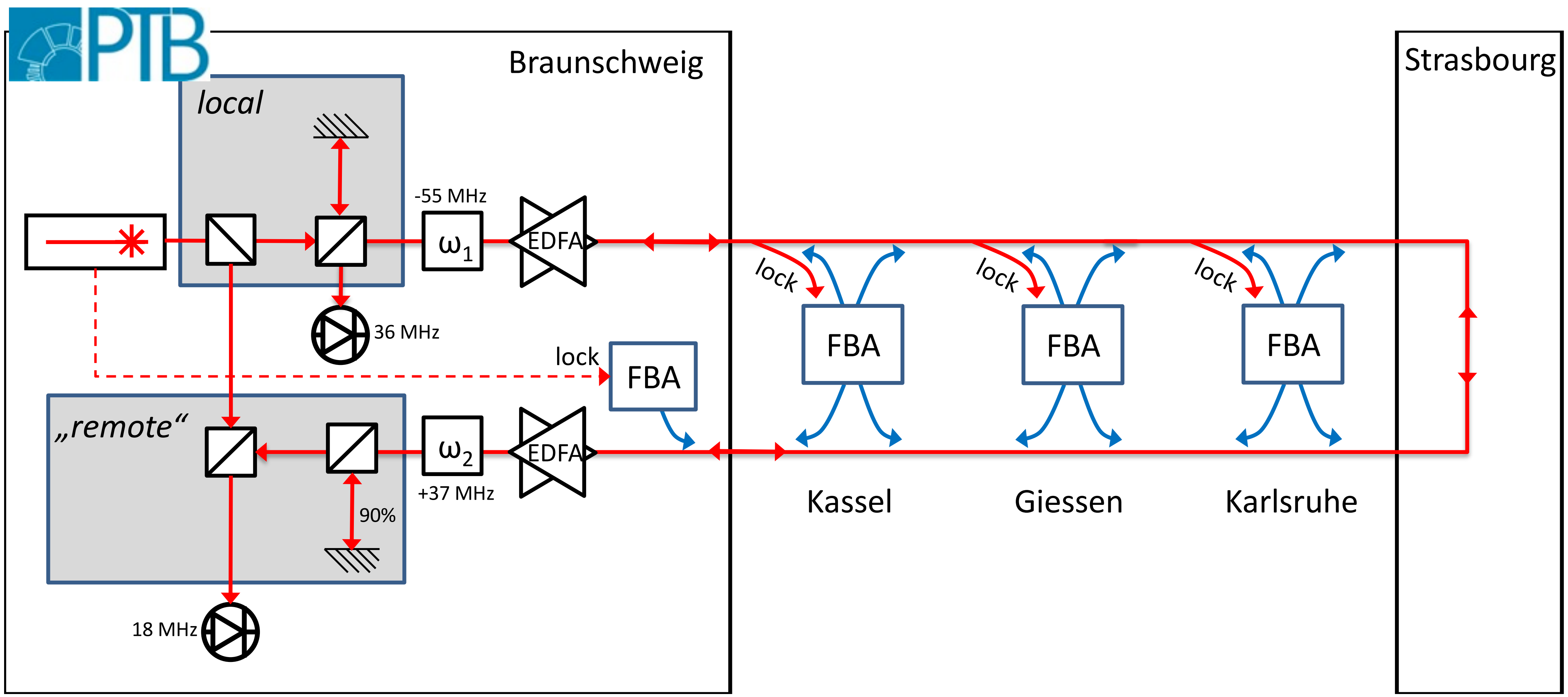
Brillouin amplification supports 1 × 10^{-20} uncertainty in optical frequency transfer over 1400 km of underground fiber

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



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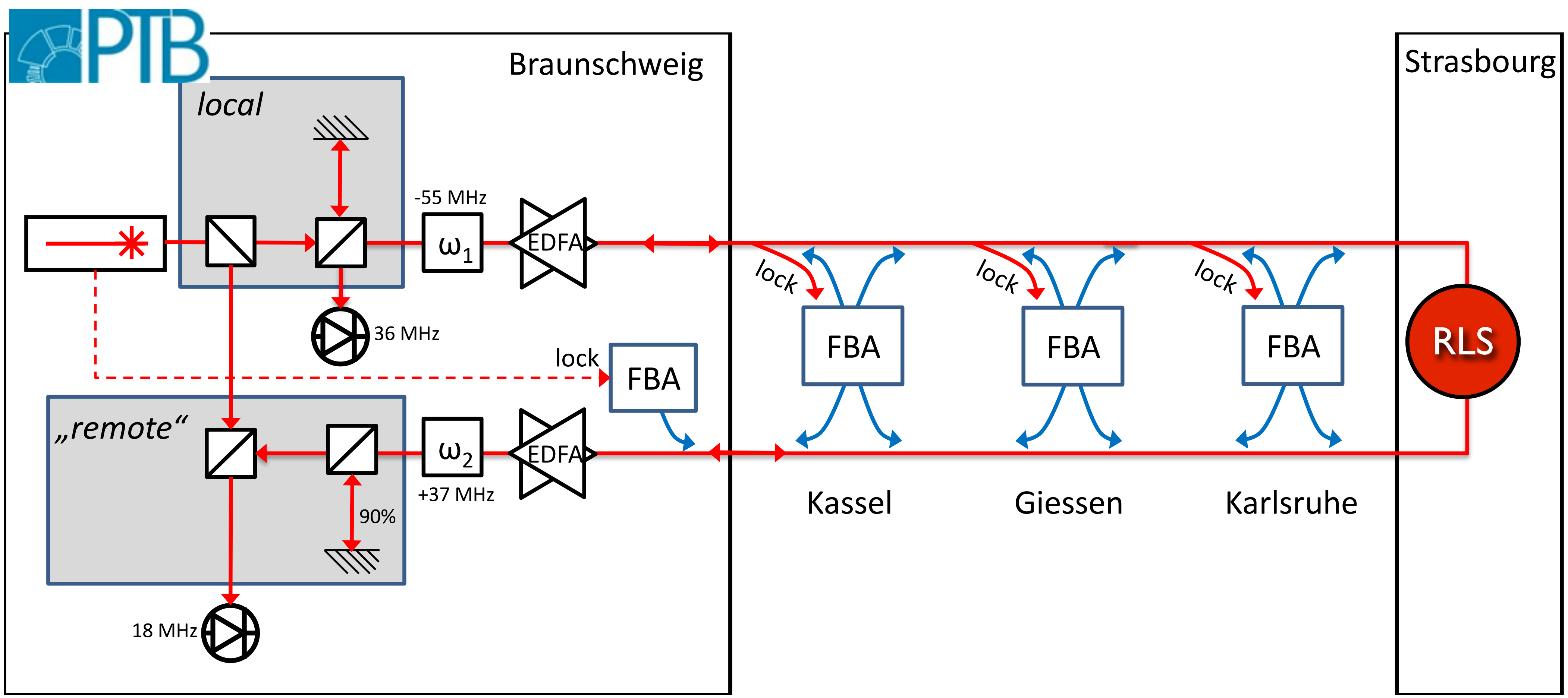

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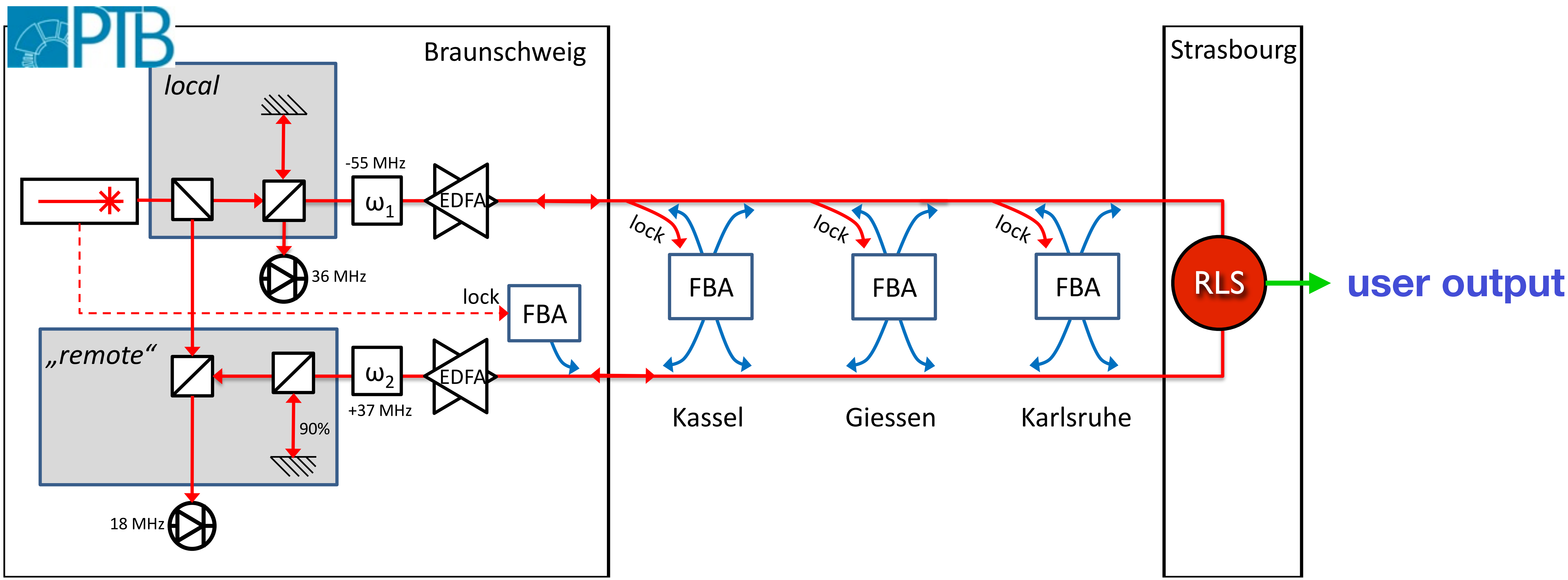
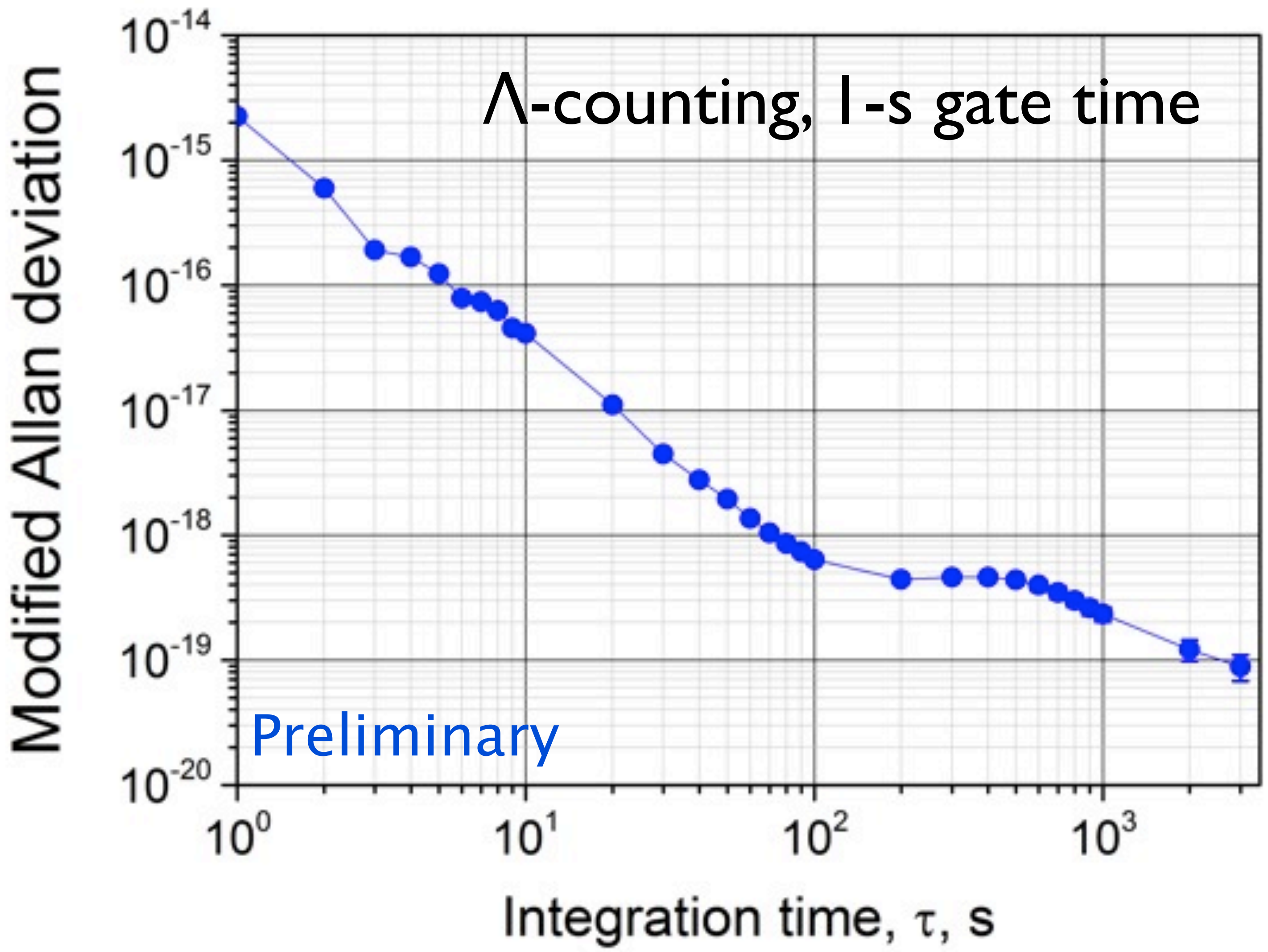


On interferometer noise, see : F. Stefani *et al*, «Tackling the limits of optical fiber links», JOSA B 32, 787-797 (2015)

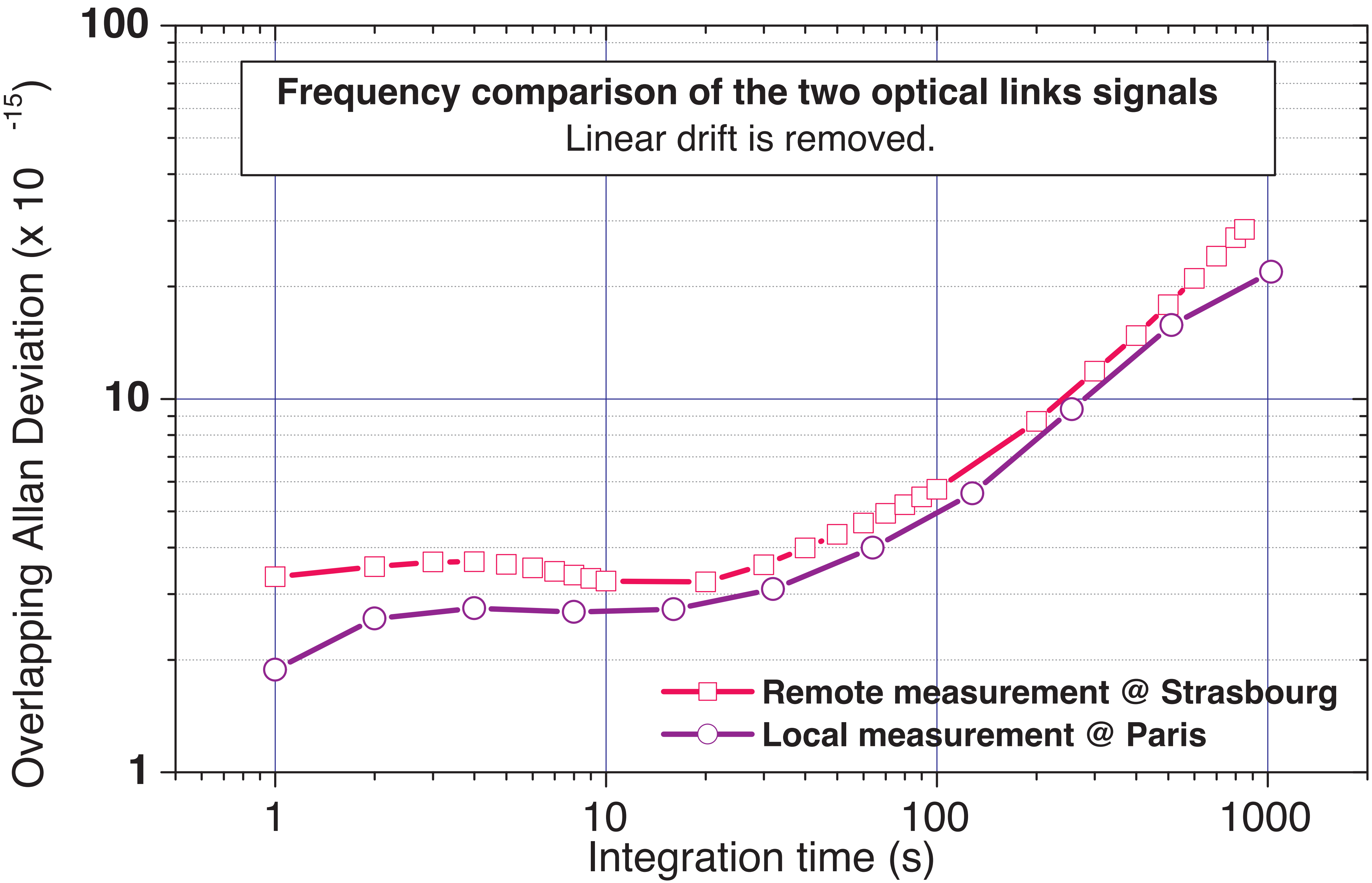
Relative frequency stability



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

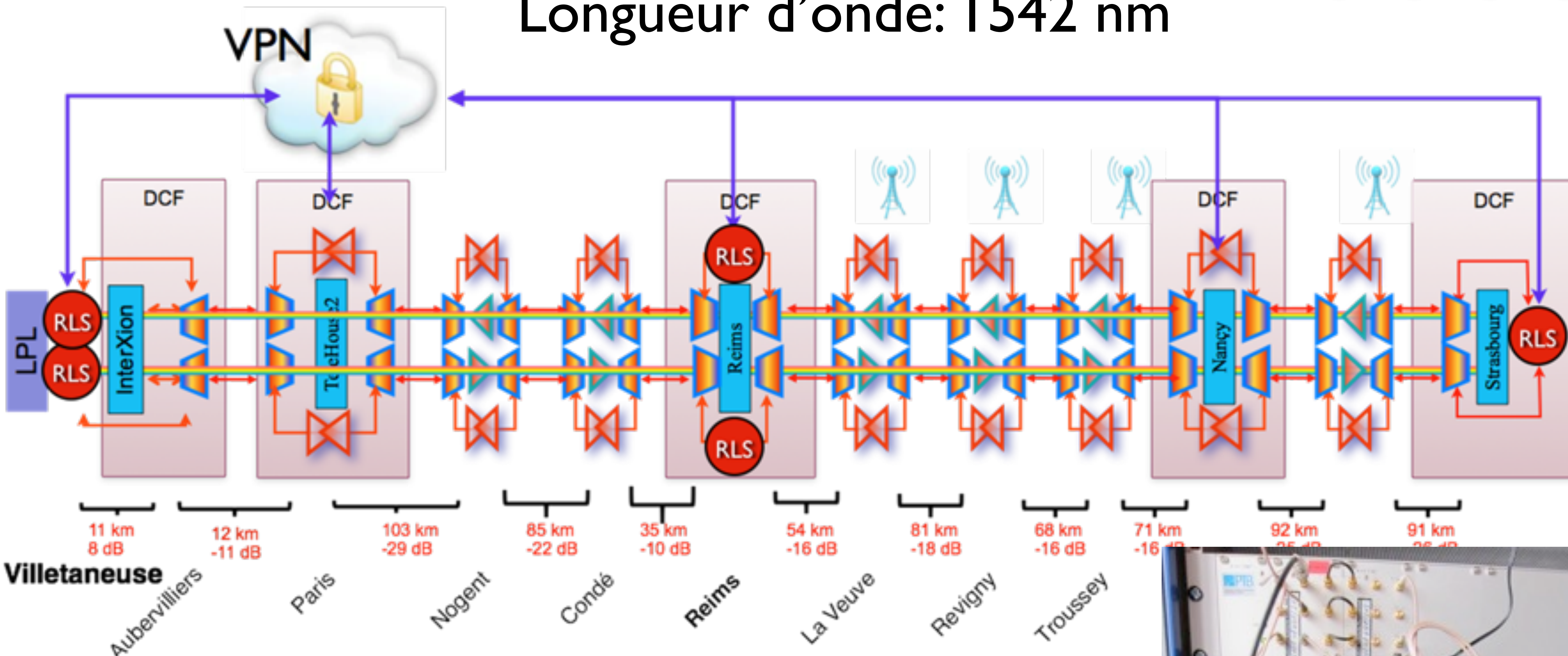
O. Lopez et al, «Towards international optical frequency transfer by fiber link between two metrology institutes, PTB and LNE-SYRTE», EFTF-IFCS poster presentation (2015).

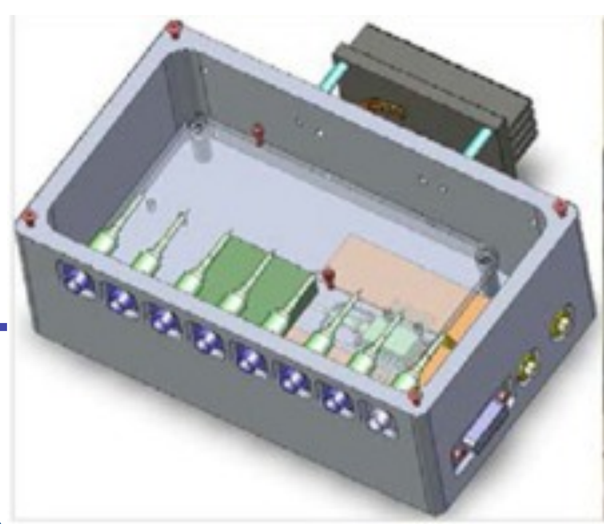
Experimental results

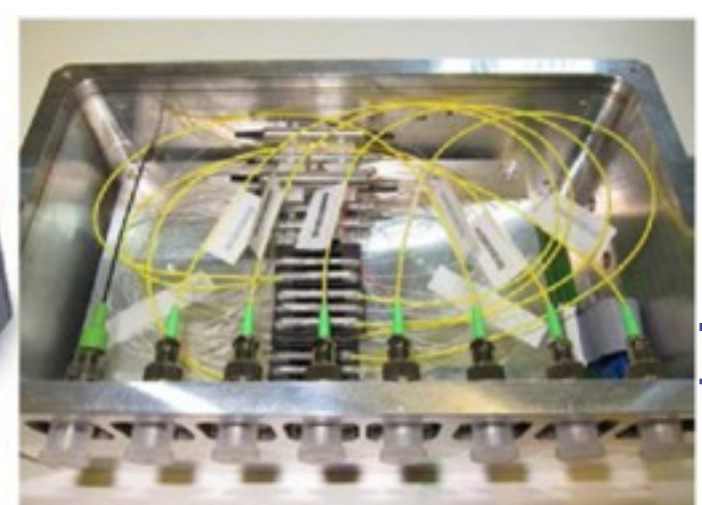


Implémentation du lien optique

Longueur d'onde: 1542 nm

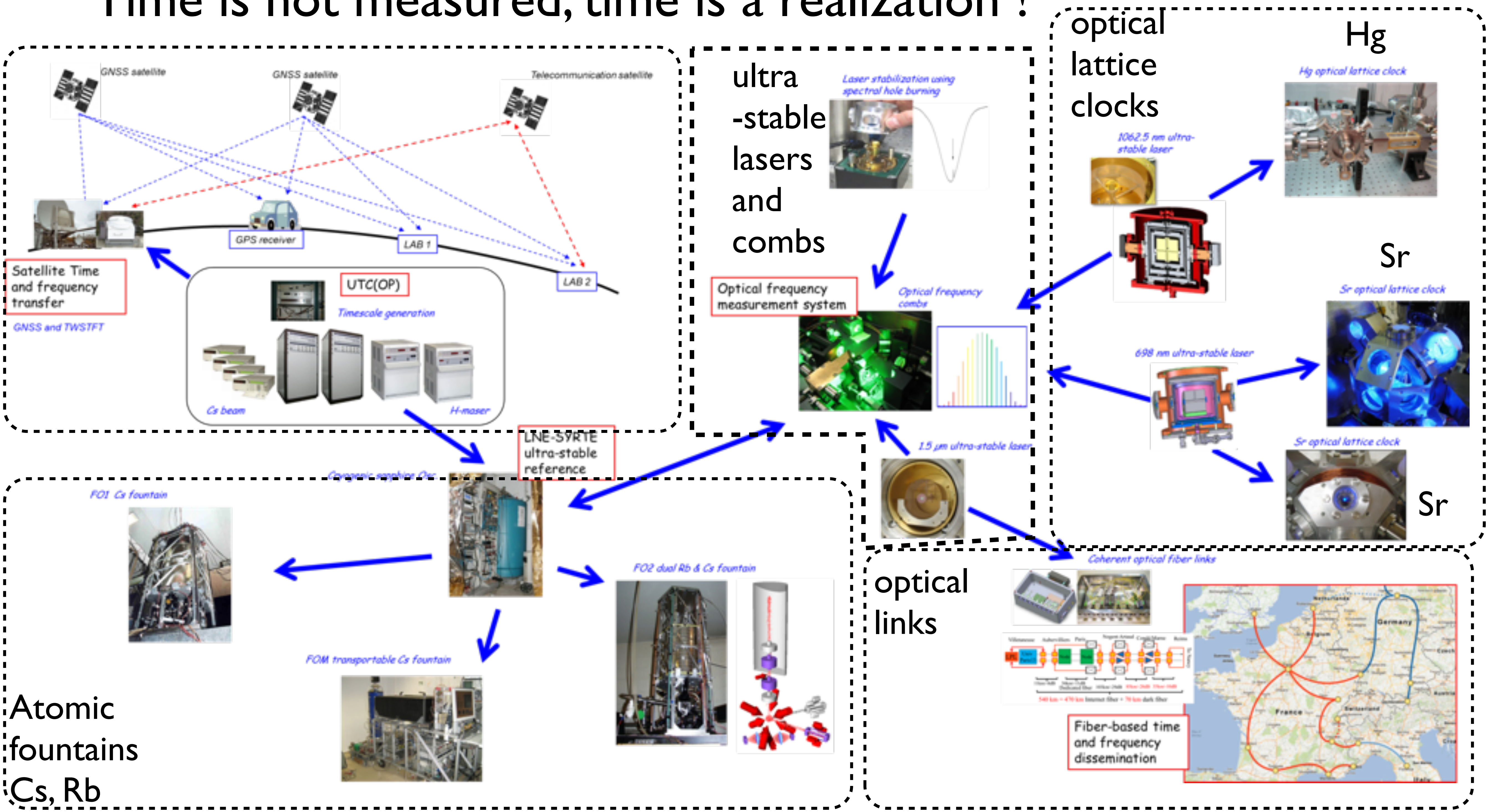






LNE-SYRTE clock ensemble

Time is not measured, time is a realization !

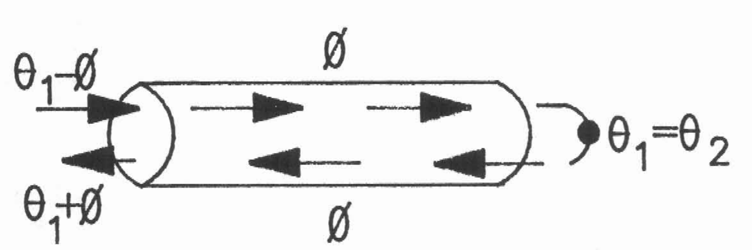


Seminal works : Primas et al., 1988

STABILIZED FIBER OPTIC FREQUENCY DISTRIBUTION SYSTEM*

Lori E. Primas
George F. Lutes
Richard L. Sydnor
Jet Propulsion Laboratory
Pasadena, California 91109

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.



$$\theta_2 = (\theta_1 - \emptyset) + \frac{(\theta_1+\emptyset)-(\theta_1-\emptyset)}{2} = \theta_1$$

FIGURE 1. PHASE CONJUGATION AT INPUT TO OPTICAL FIBER

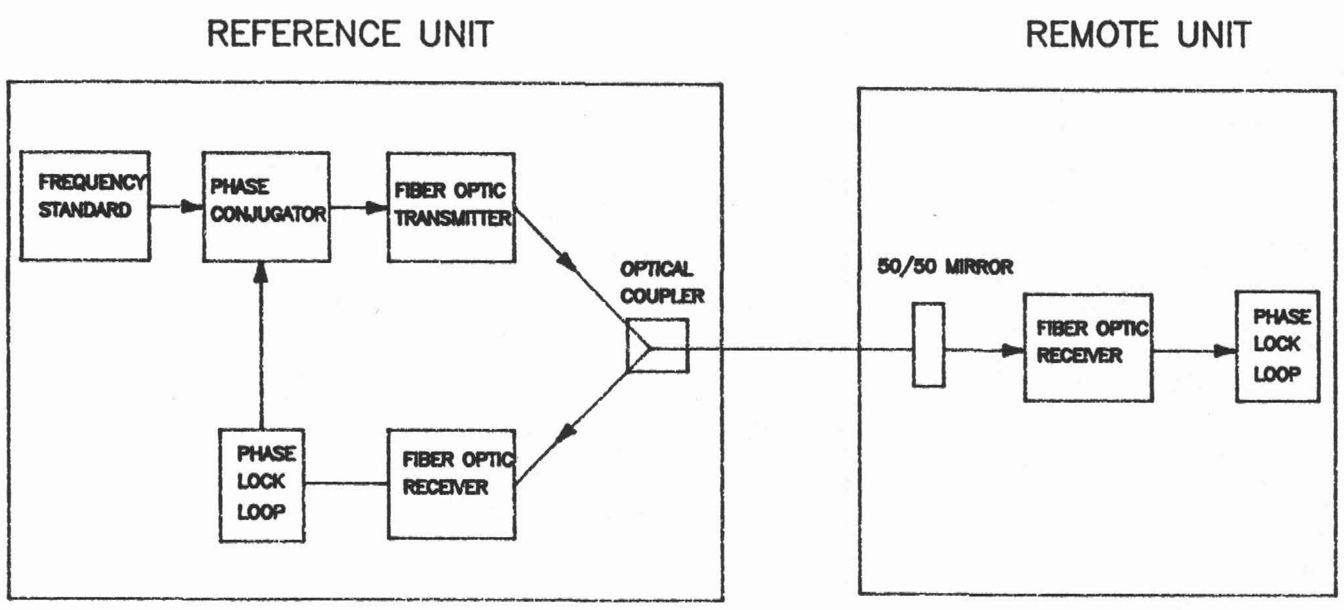


FIGURE 3. FIBER OPTIC FREQUENCY DISTRIBUTION SYSTEM

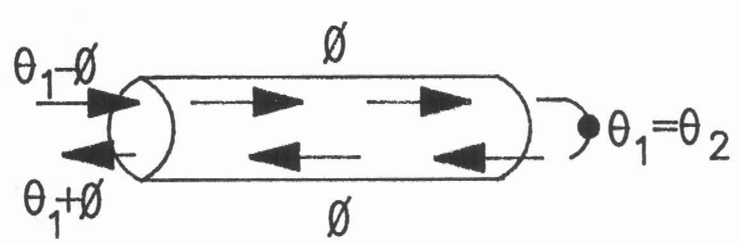
L. E. Primas *et al.*, Proc. 20th PTTI, Vienna, VA, 29 Nov - 1 Dec 1988(1988)

Seminal works : Primas et al., 1988

STABILIZED FIBER OPTIC FREQUENCY DISTRIBUTION SYSTEM*

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

part in 10^{15} are required the link must be actively stabilized.



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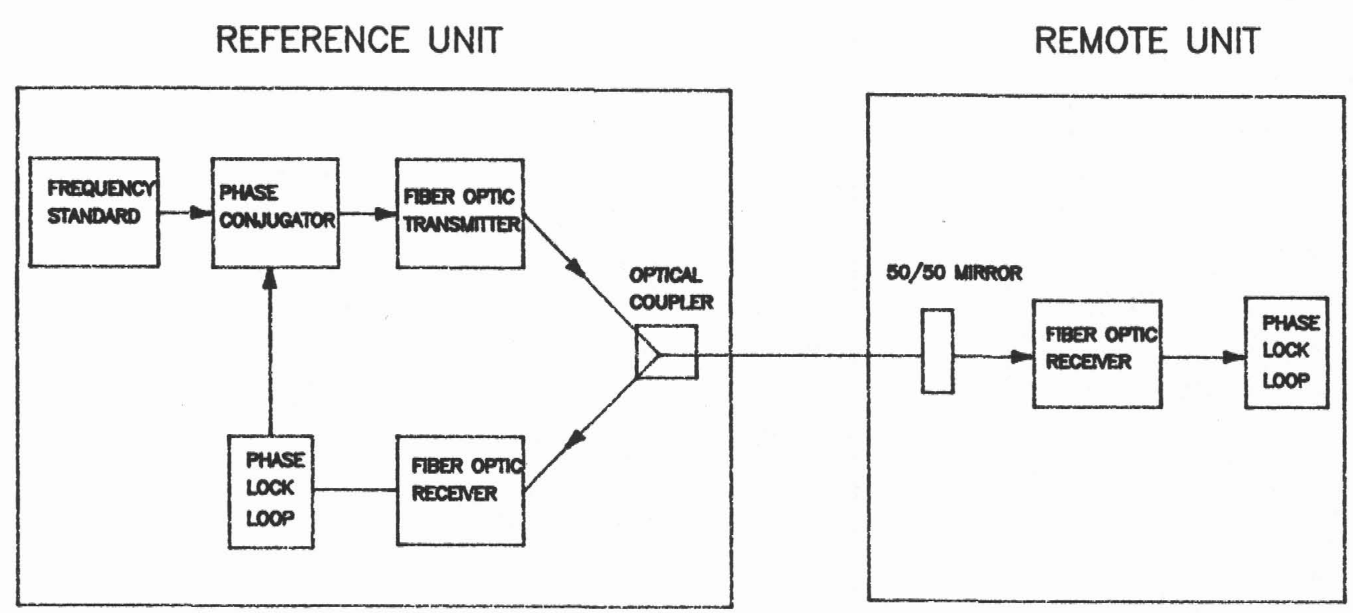

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November 1, 1994 / Vol. 19, No. 21 / OPTICS LETTERS 1777

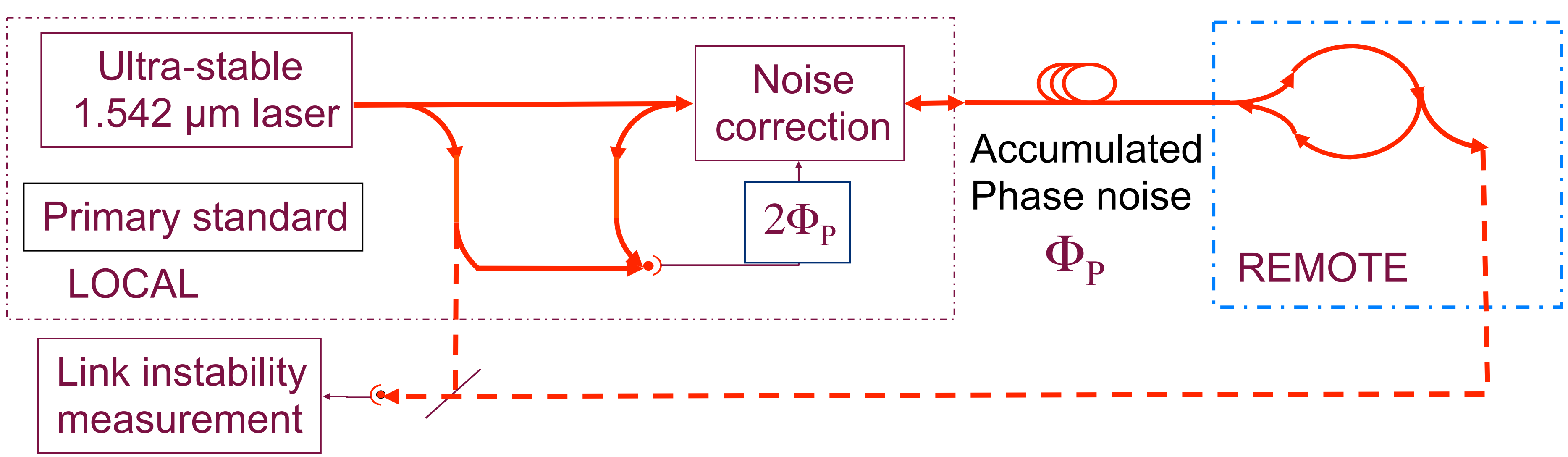
Delivering the same optical frequency at two places: accurate cancellation of phase noise introduced by an optical fiber or other time-varying path

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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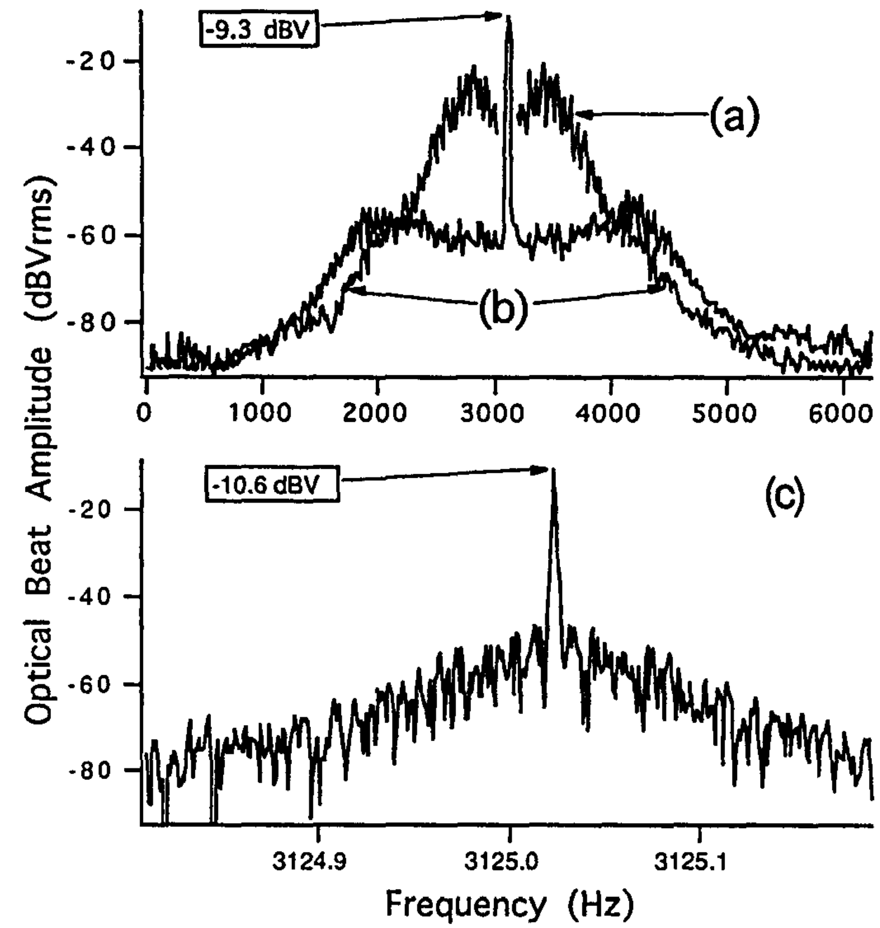
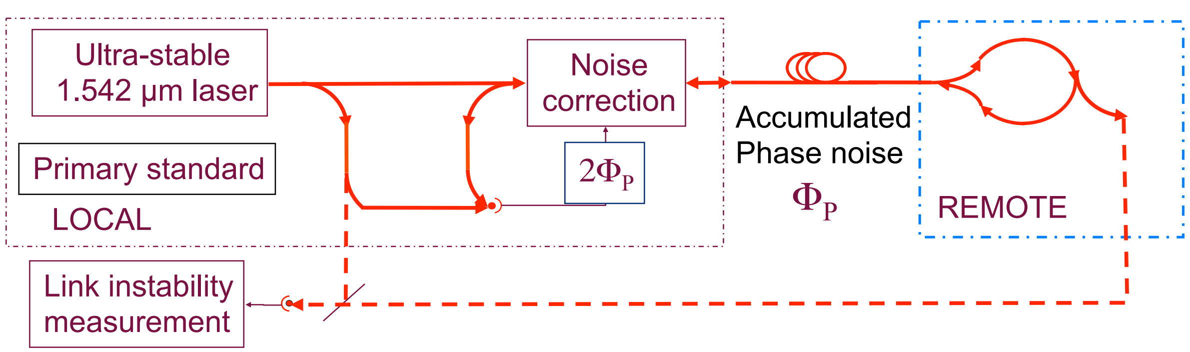


Fig. 2. Optical field spectrum at the output of a 25-m fiber. The input optical signal approximates a delta function. The signal arrives at the far end with a 1.2-kHz width, shown in (a). In (b) the phase-noise compensation system is operational, and one regains 99.6% of the power in the sharp spectral 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

Seminal works : Ma et al., 1994

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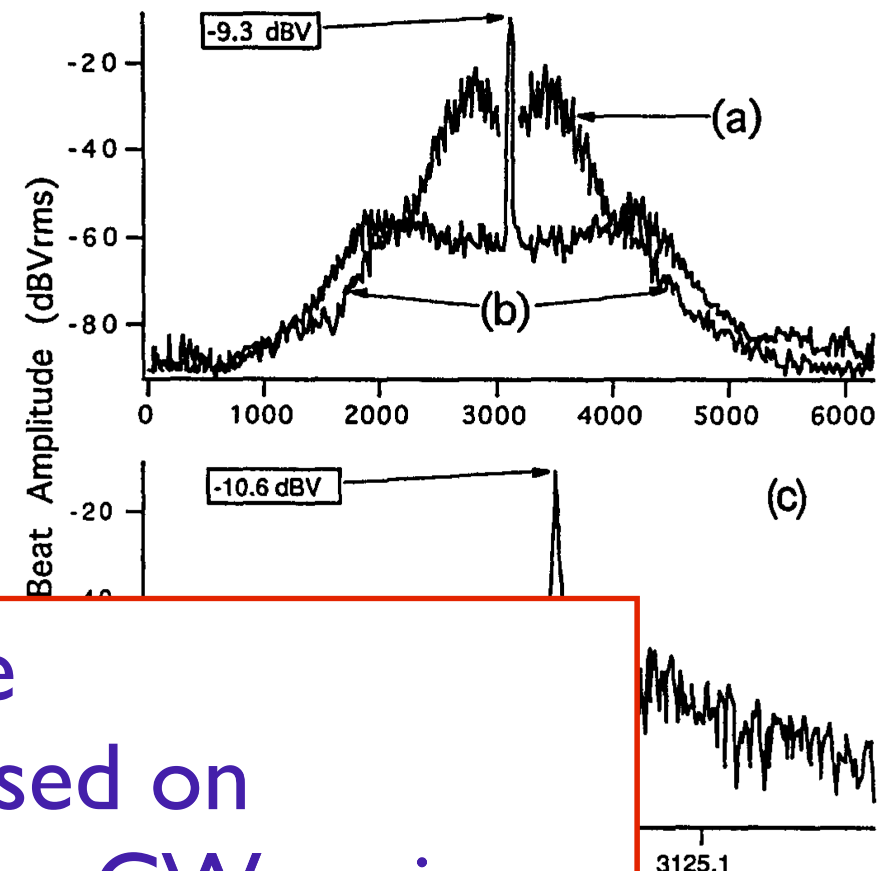
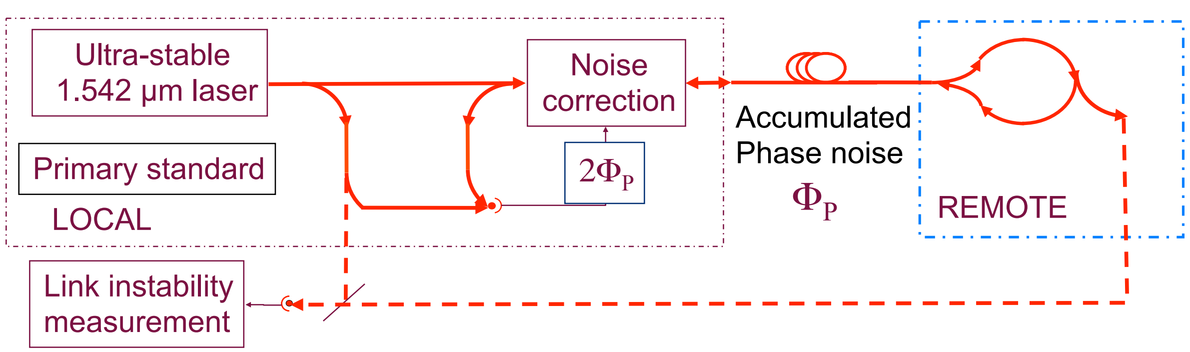


From here
this talk is focussed on
optical frequency transfer, CW regime



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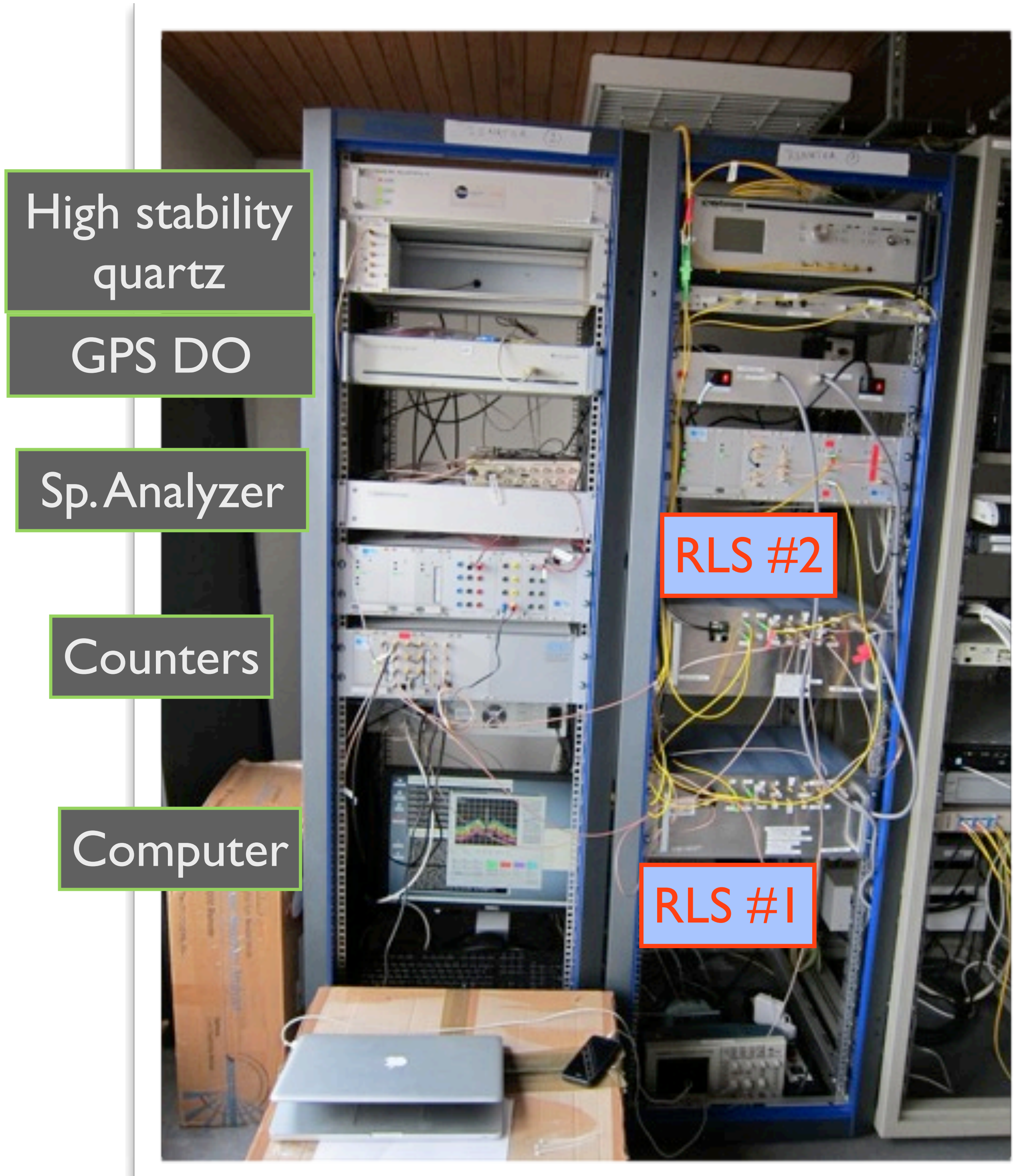
25-m optical fiber link

Experimental set up (Strasbourg, Kassel)



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