Time and Frequency Comparisons with Optical Fiber Links

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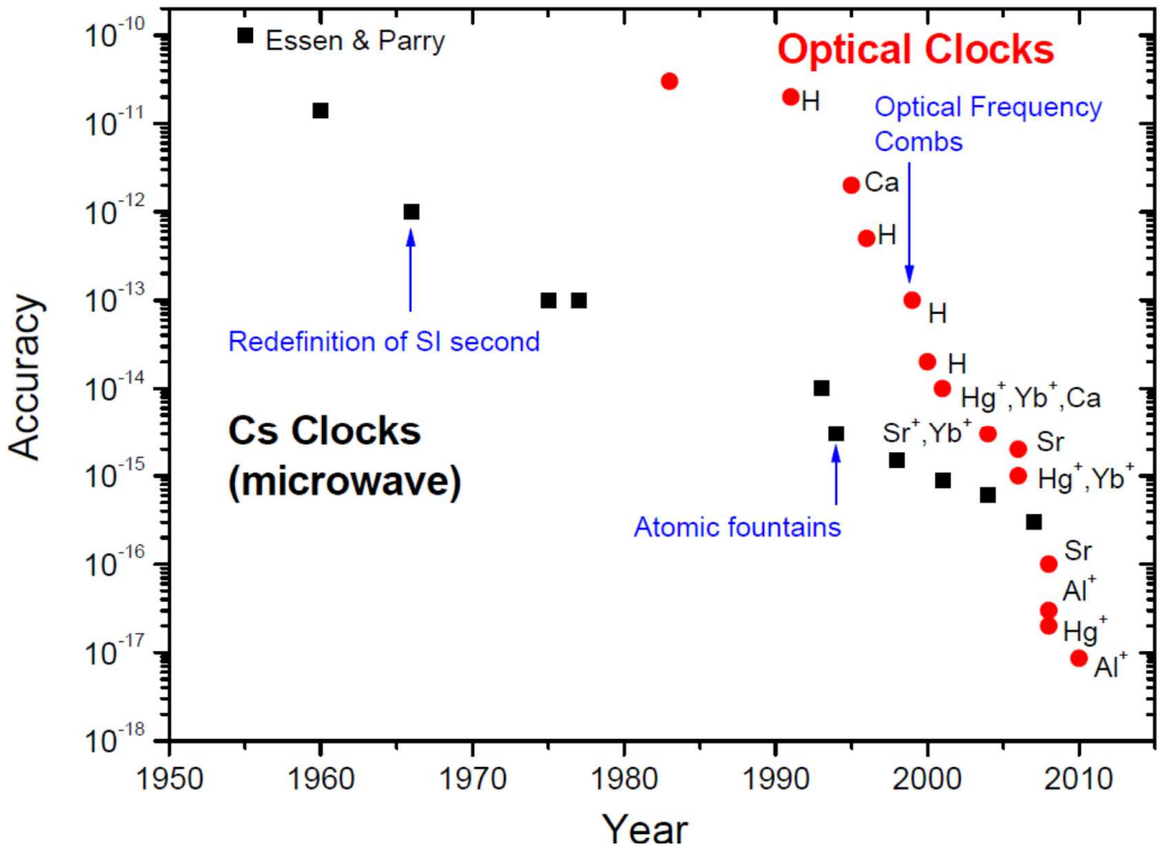
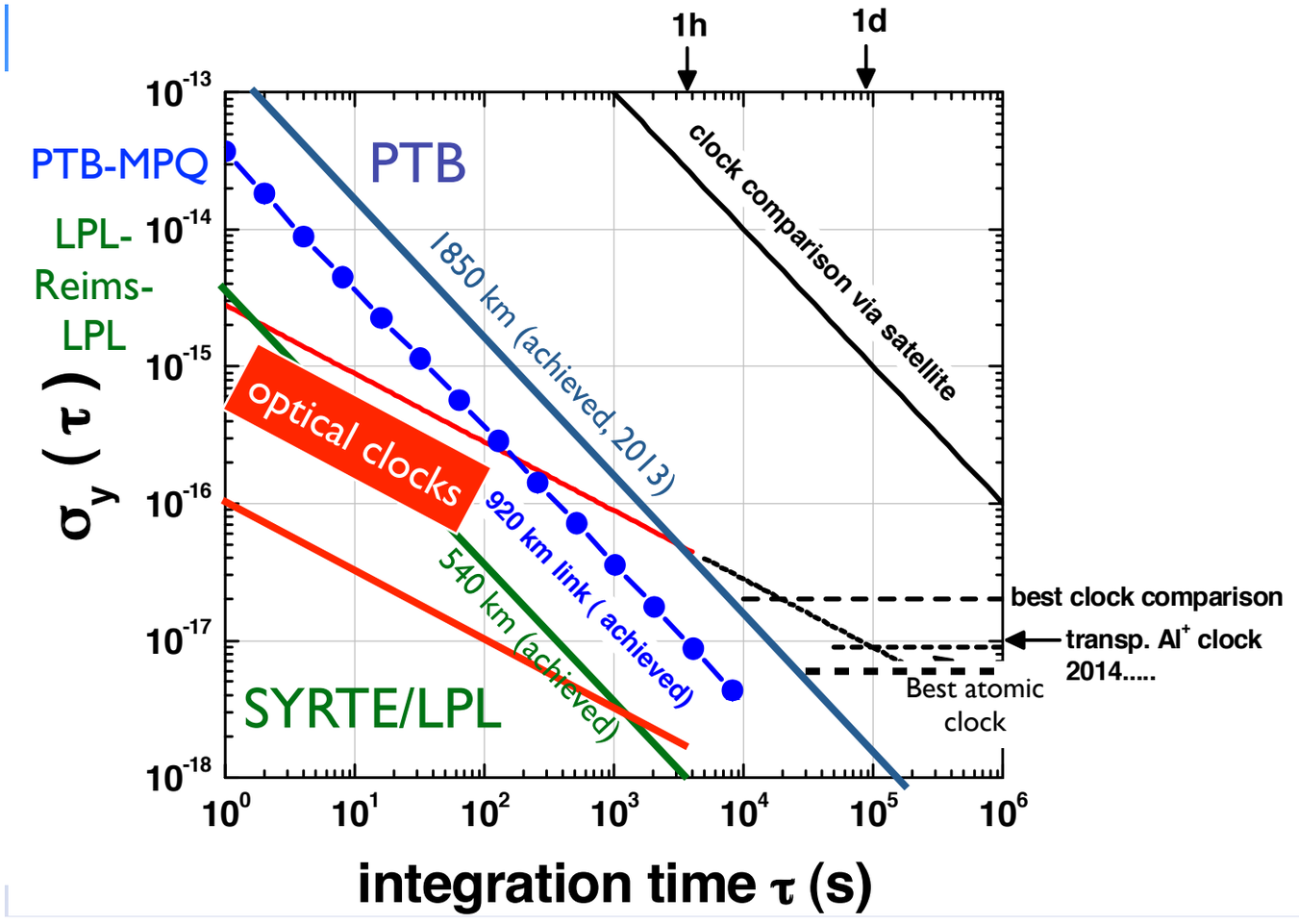
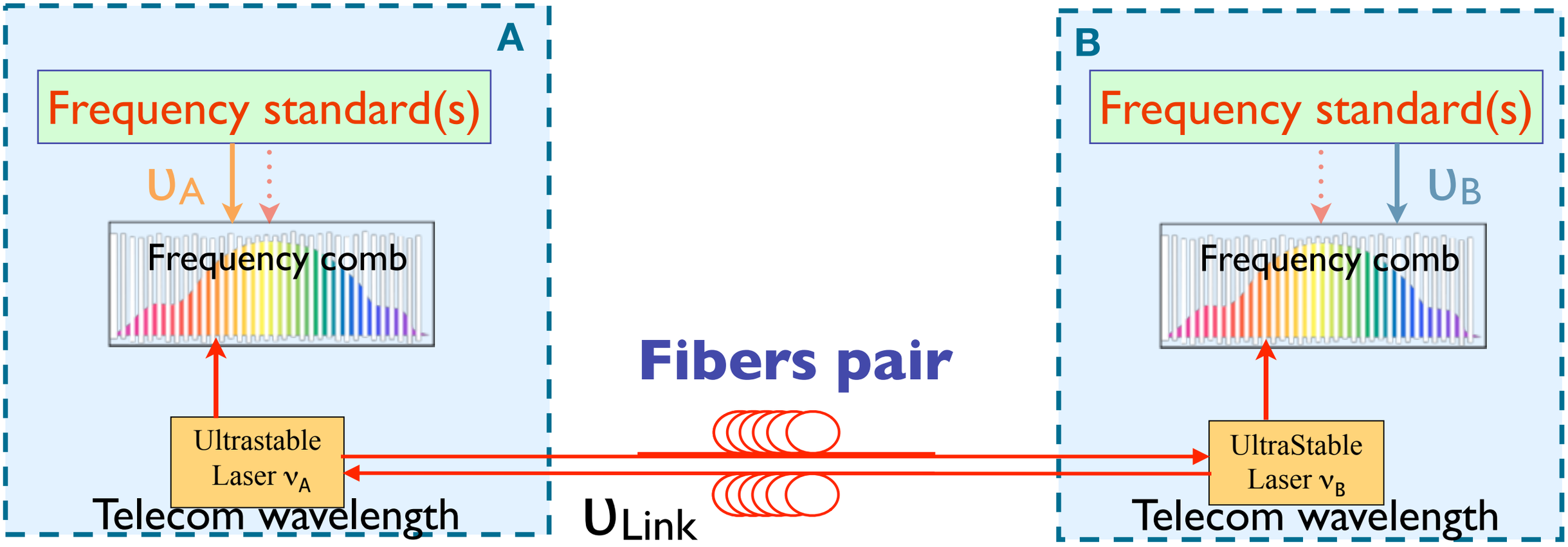
Motivations





- **Satellite links don't meet optical clocks comparisons requirements**
- **International and national clocks comparisons below 10^{-16}**
- **Frequency standard dissemination (for research labs)**

Frequency Transfer



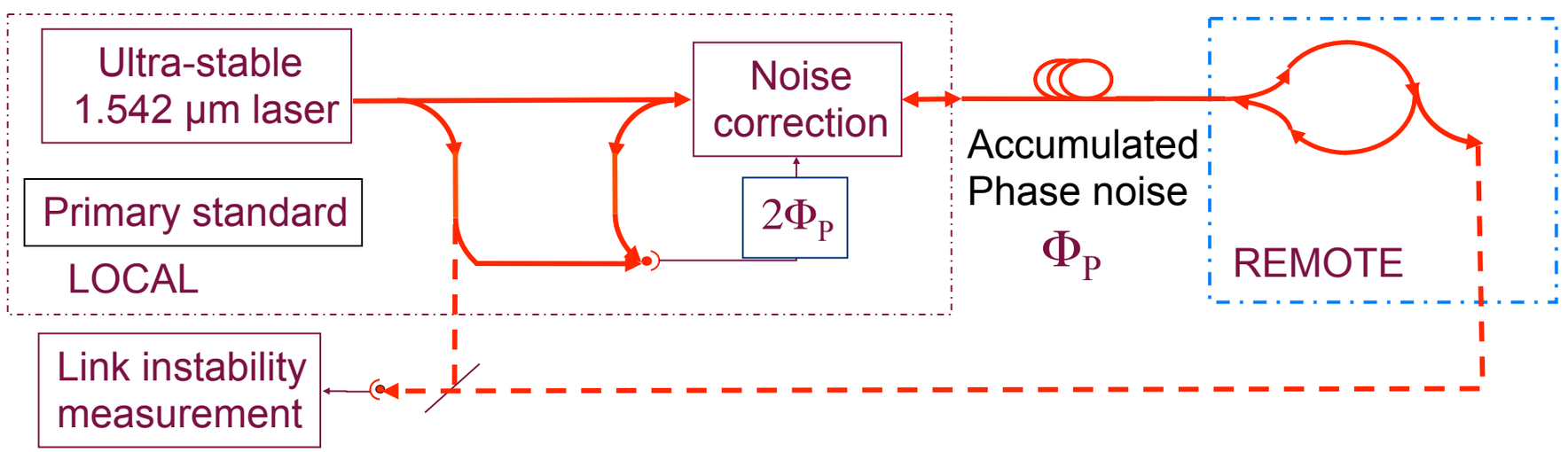
Ratio 1 = $\upsilon_{Link} / \upsilon_A$

Ratio 1/2 = υ_B / υ_A

Ratio 2 = $\upsilon_{Link} / \upsilon_B$

Basics About Fiber Links

Best results: optical frequency transfer



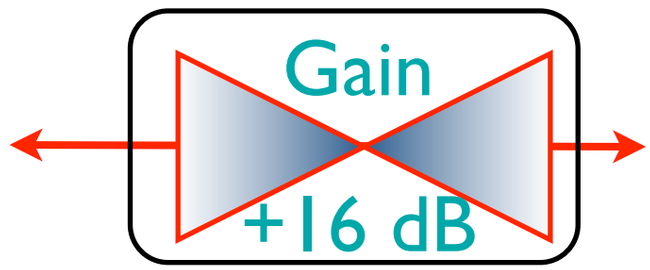
L.-S. MA & AL., OPTICS LETTERS, **19** (21) 1994

- **Transmitted frequency = carrier frequency, 194 THz**
- **No modulation**
- **Active noise compensation after one round-trip**
- Strong hypothesis : noise forth and back are the same
- 2 ends at the same place (for link stability measurements)

Technical challenges

- **Attenuation**

bi-directionnal EDFA

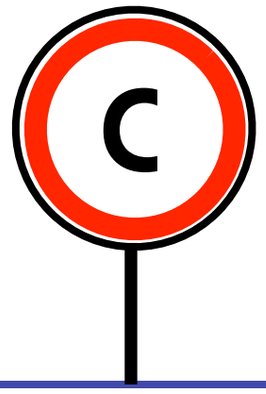


- **0,25 dB / km !**
- **Stimulated Brillouin Scattering : input power < 5 mW**
- **Coherent link : high stability laser**

$$\sigma_y(1s) \approx 10^{-15}, \quad \Delta\upsilon < 1\ \text{Hz}$$

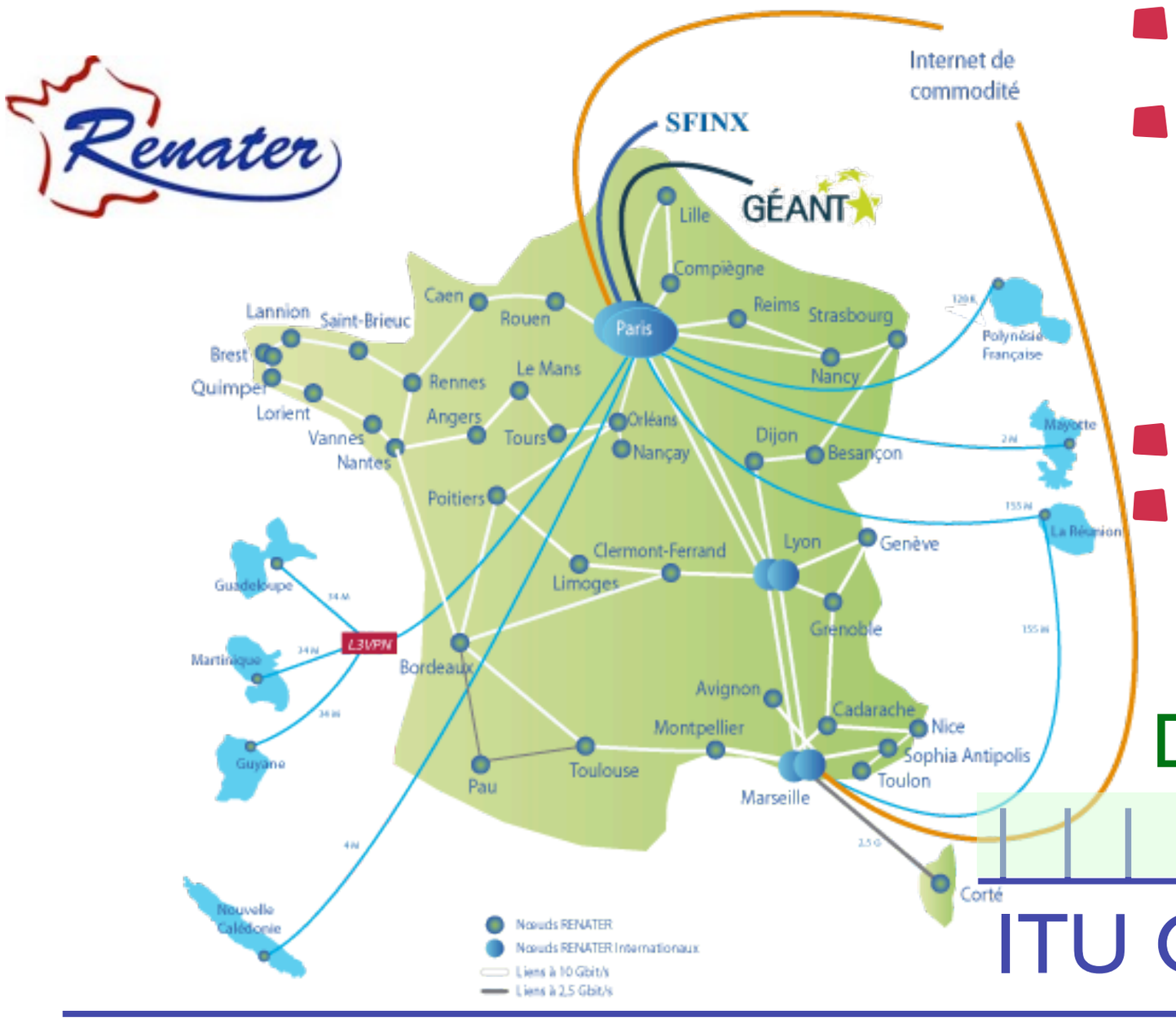
- **Finite time of propagation**

Correction
BW < 1 kHz



Cascaded links

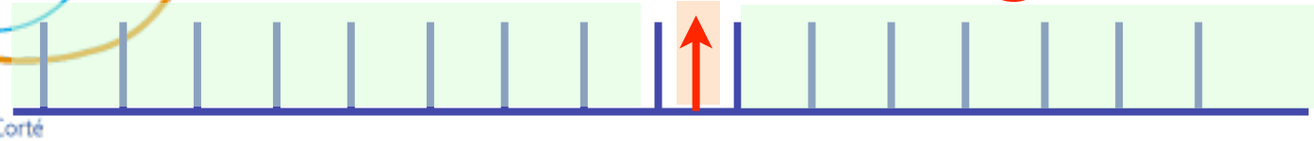
Fiber availability : the dark channel approach



- Access existing R&E networks !
- **Regeneration technique compatible with parallel data traffic**
  Optics Express, **18** (16), 16849-16857 (2010)
- Large integration time
- Equipment and development costs...

ITU 44

Data traffic CW signal



ITU GRID : 100 GHz spacing

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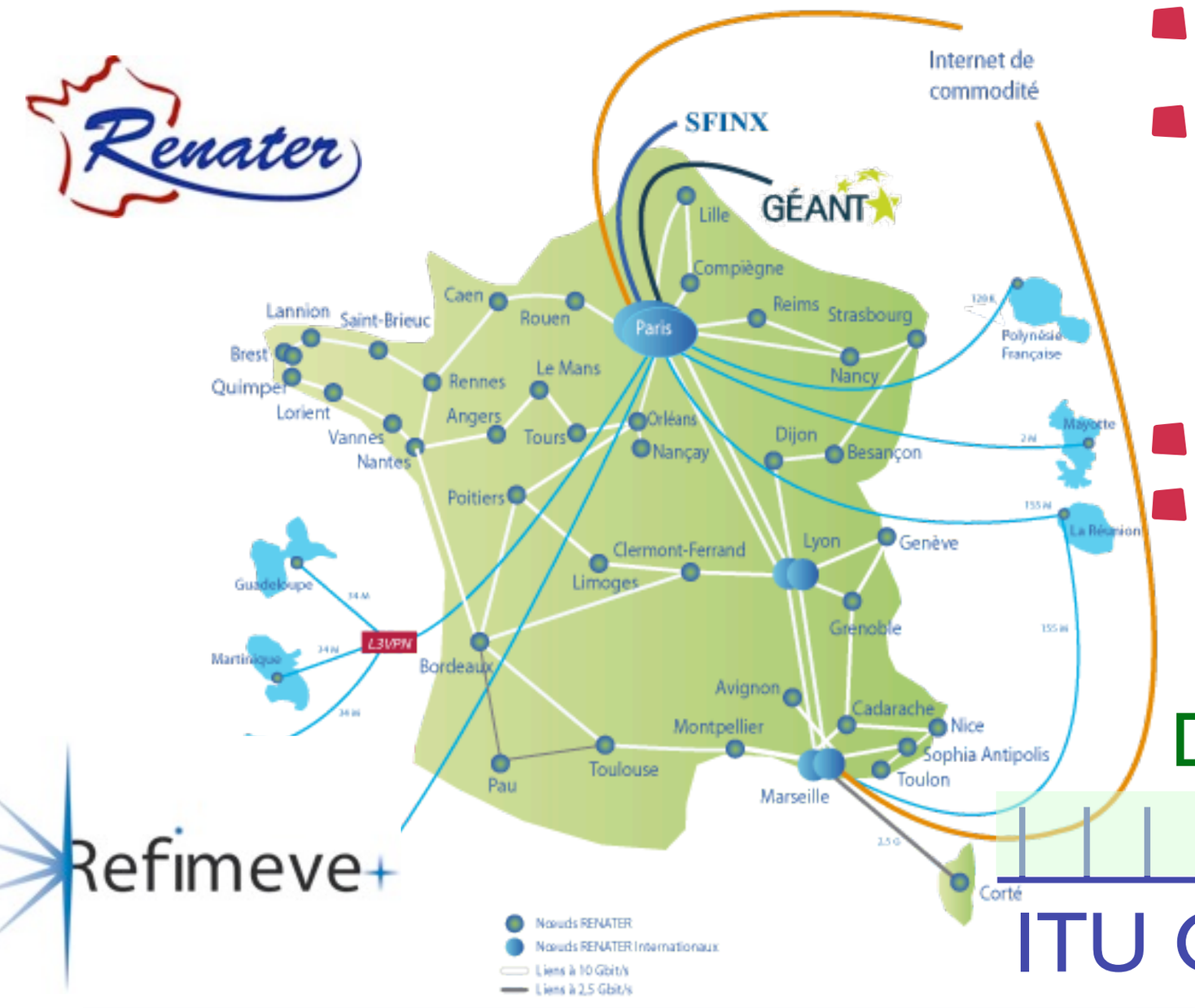

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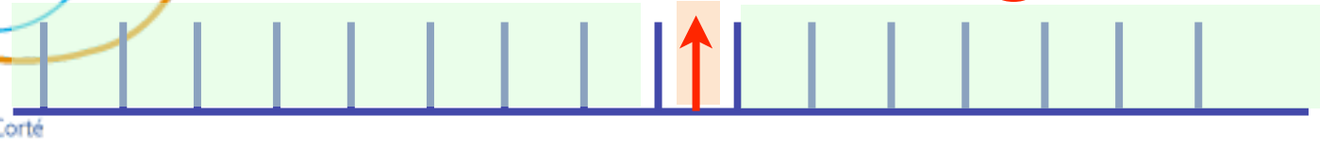

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Refimeve+

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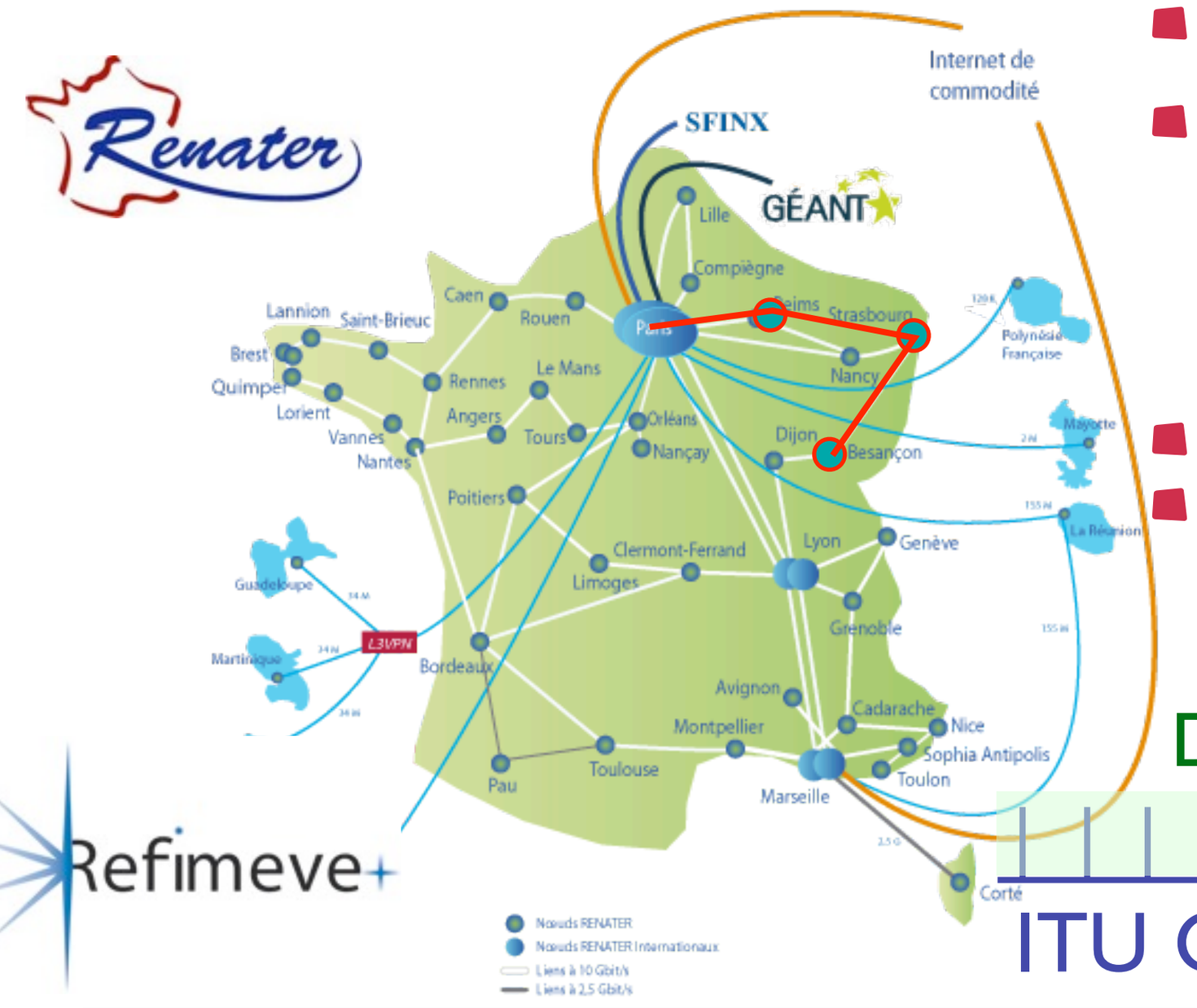

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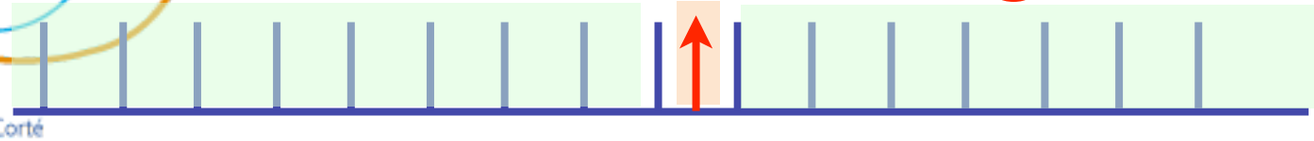

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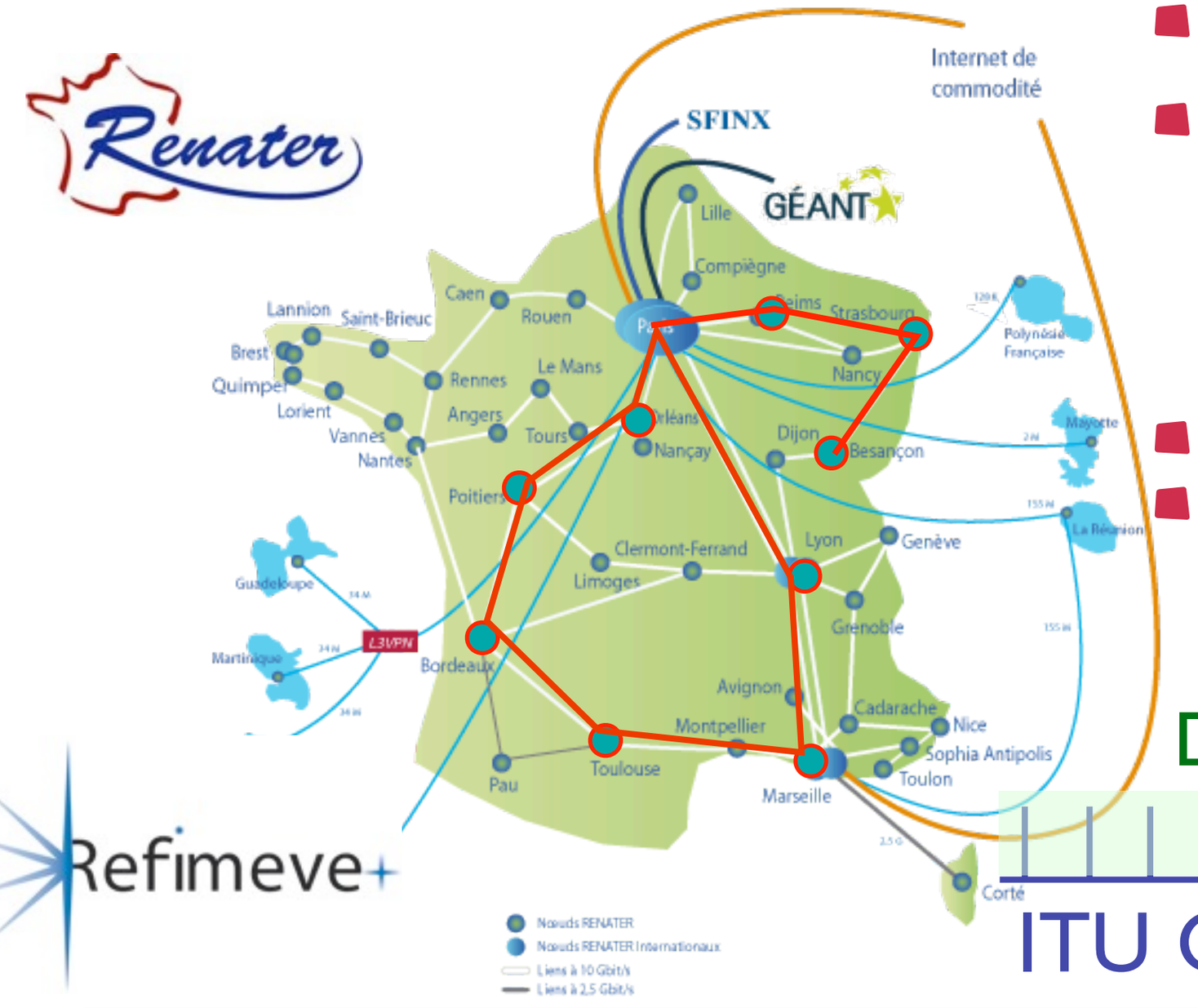

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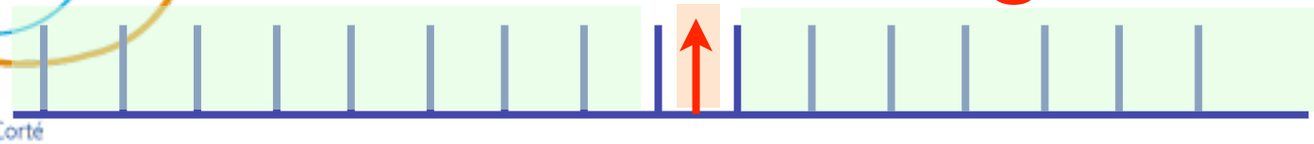

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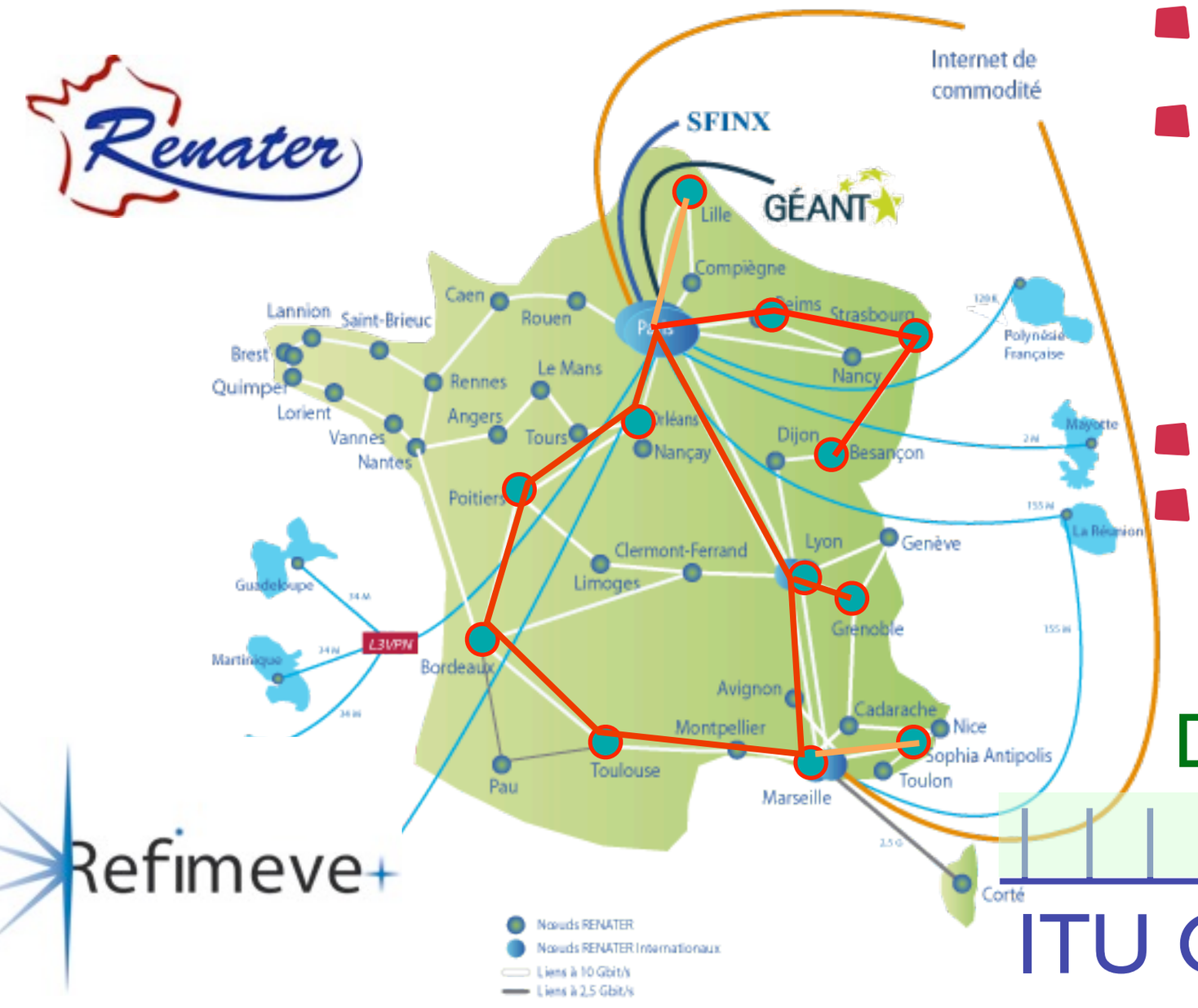

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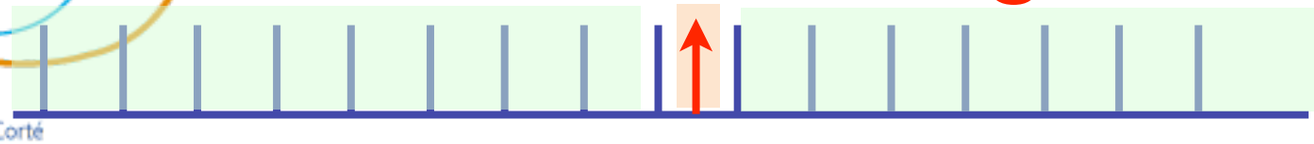

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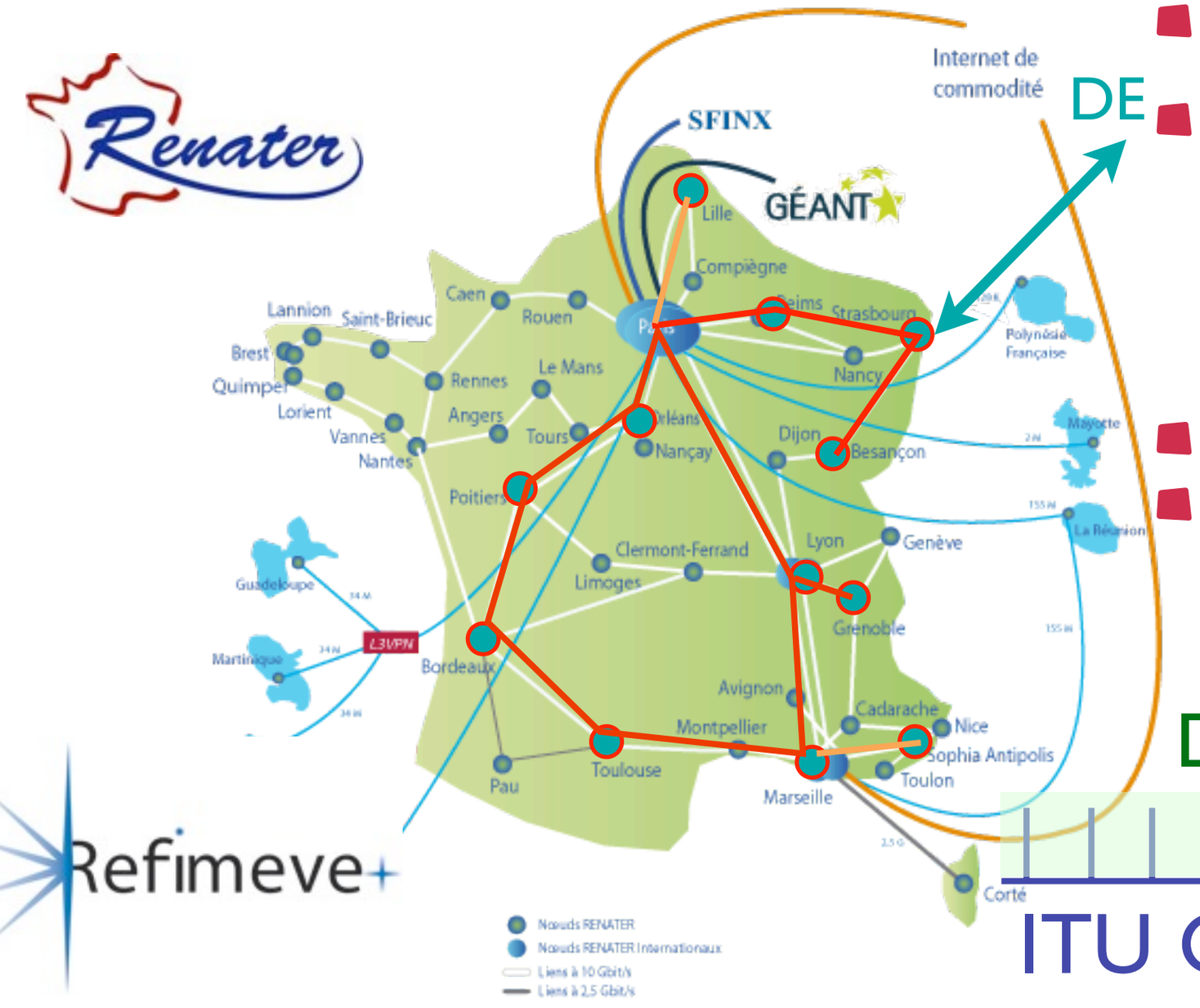

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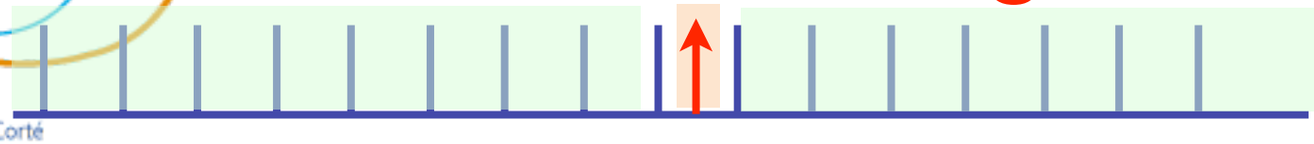

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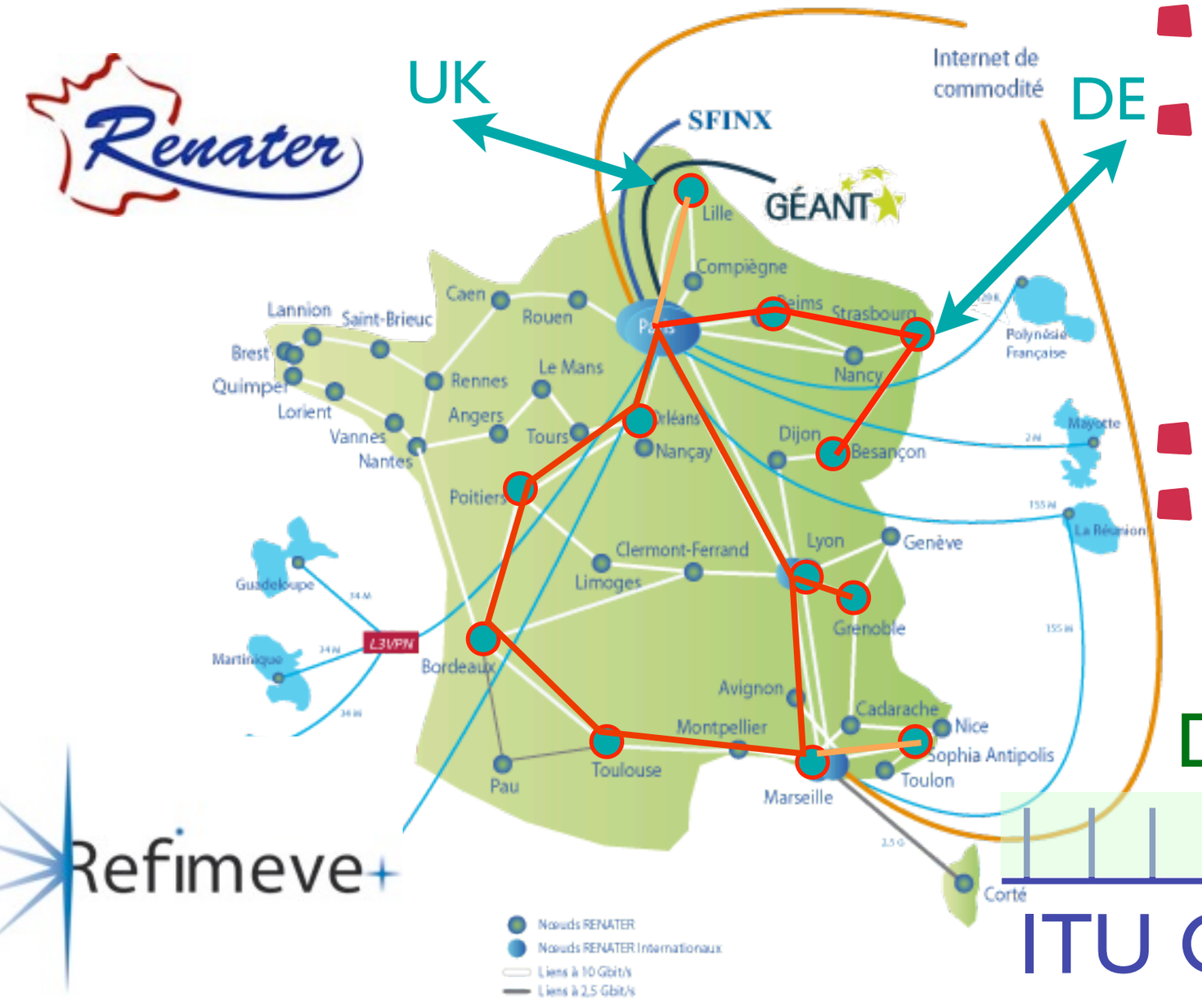

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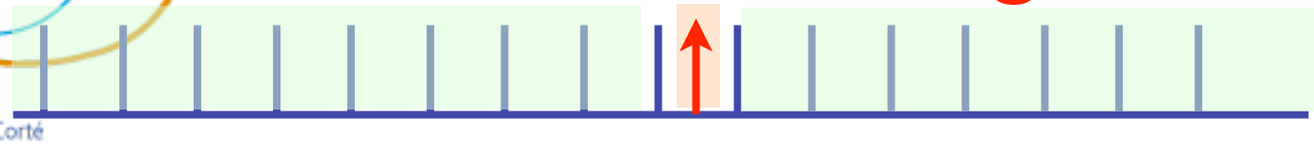

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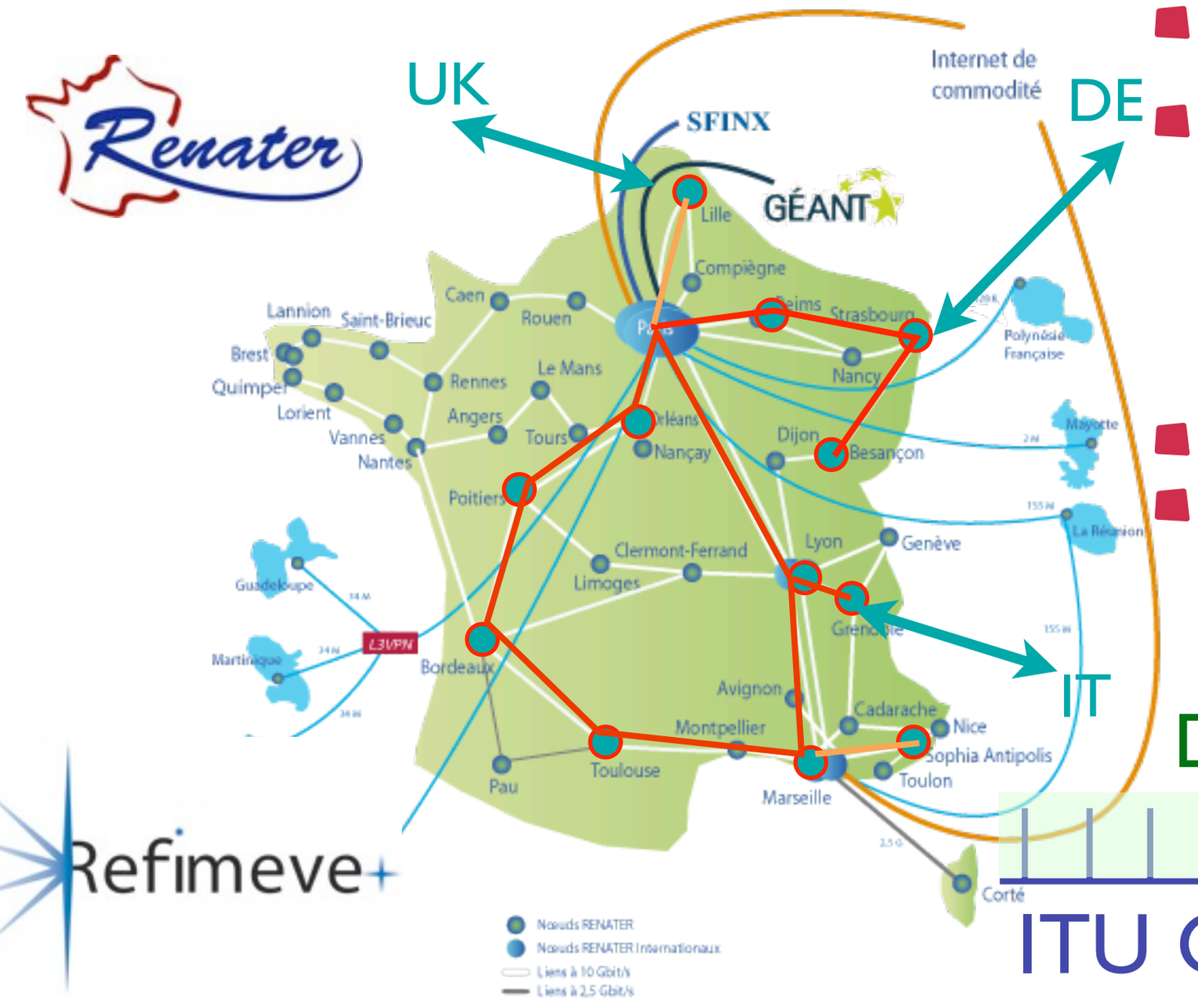

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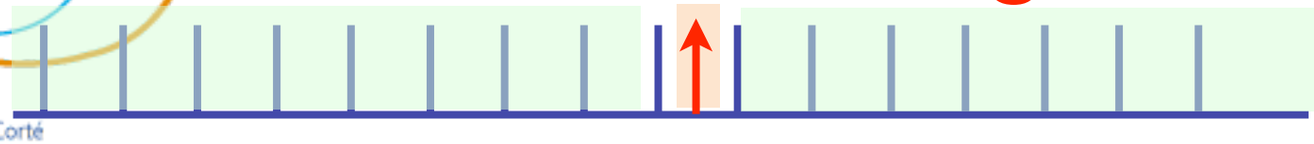

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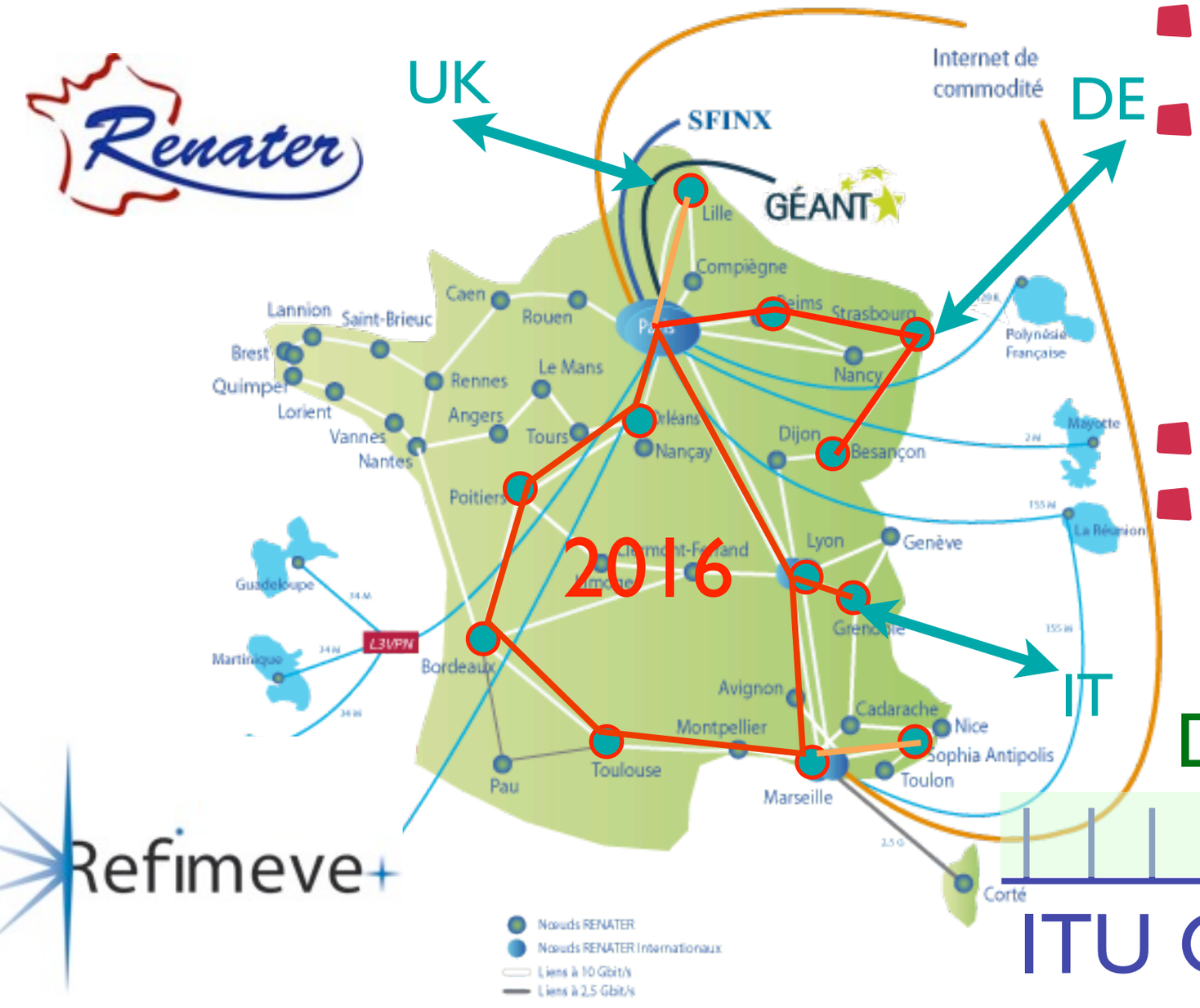

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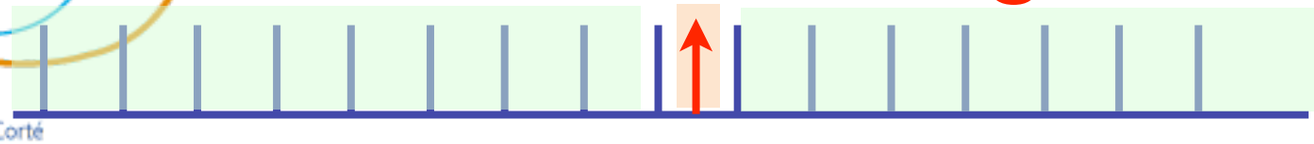

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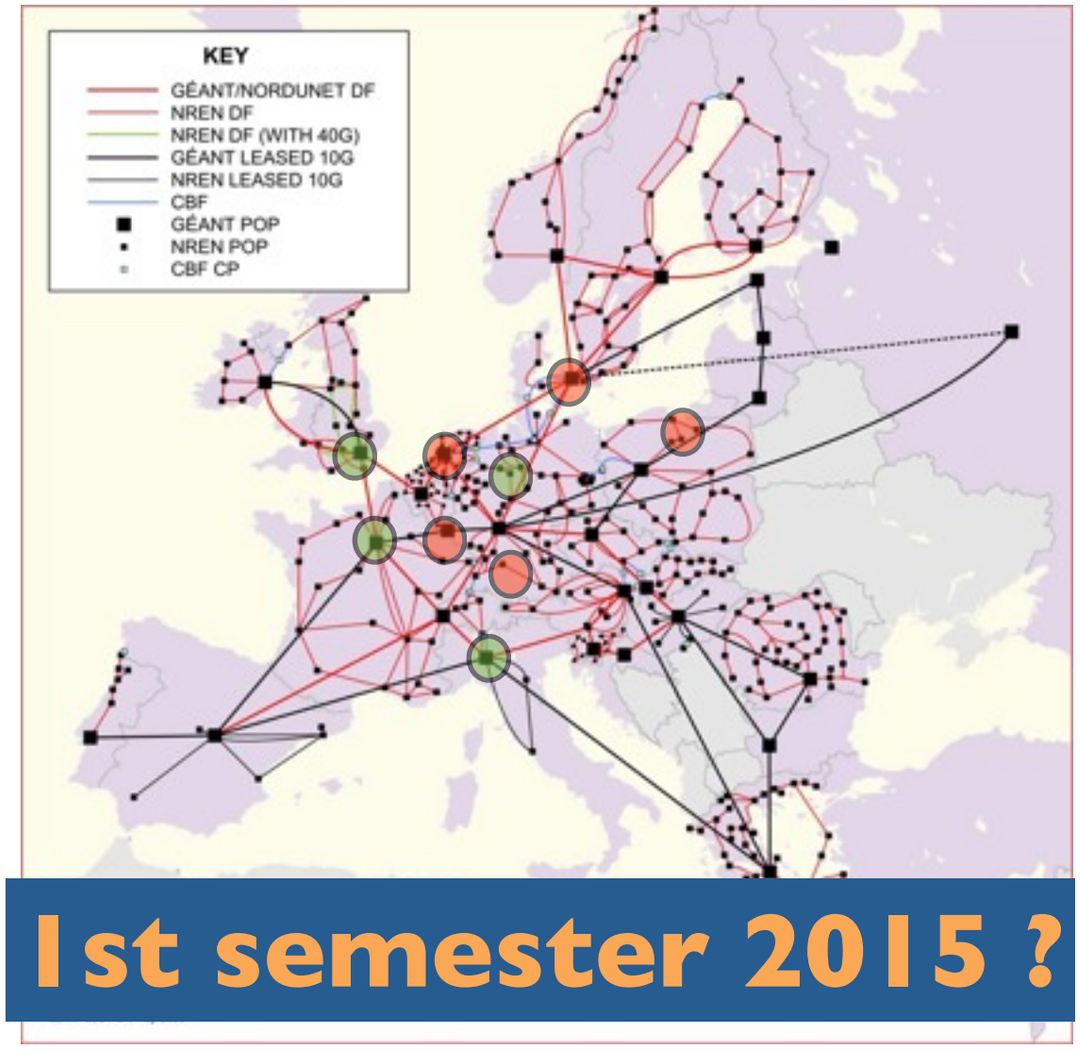
Clocks comparisons

Braunschweig - Paris - London (PTB - SYRTE/LPL - NPL)



1st semester 2015 ?

Local comparisons

id. with transportable clocks

Remote comparisons with optical links

x : done

o : goal

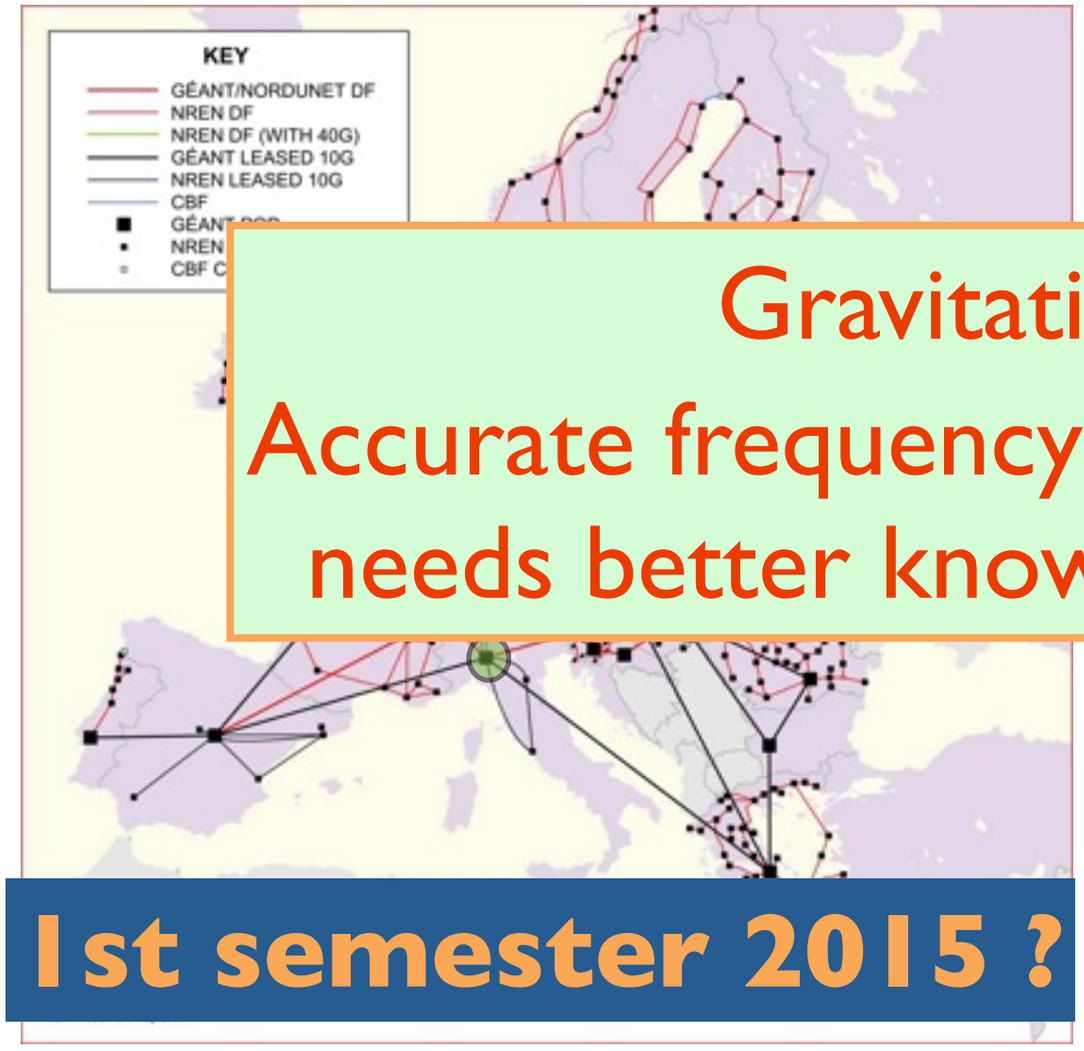
		Cs	Rb	Al^+	Hg^+	Sr^+	Yb^+ (E2)	Yb^+ (E3)	Sr	Yb	Hg
	Cs	X									
FR	Rb	X	X								
DE	Al^+	X		X							
	Hg^+	X		X							
UK	Sr^+	X				X					
DE,UK	Yb^+ (E2)	X		O		O	X				
DE	Yb^+ (E3)	X		O		O	O	O			
DE,FR,IT	Sr	X		O		O	X	X	X		
IT	Yb	X							O		
FR	Hg	X									
SI second		Cs	Rb	Al^+	Hg^+	Sr^+	Yb^+ (E2)	Yb^+ (E3)	Sr	Yb	Hg

Secondary representations

FROM REPORT OF THE 19TH MEETING OF THE CCTF (2012)

Clocks comparisons

Braunschweig - Paris - London (PTB - SYRTE/LPL - NPL)



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Local comparisons
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x : done
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FR	Cs	X									
	Rb	X	X								
DE	Al^+	X		X							
IT	Yb	X							O		
FR	Hg	X									
	SI second	Cs	Rb	Al^+	Hg^+	Sr^+	Yb^+ (E2)	Yb^+ (E3)	Sr	Yb	Hg

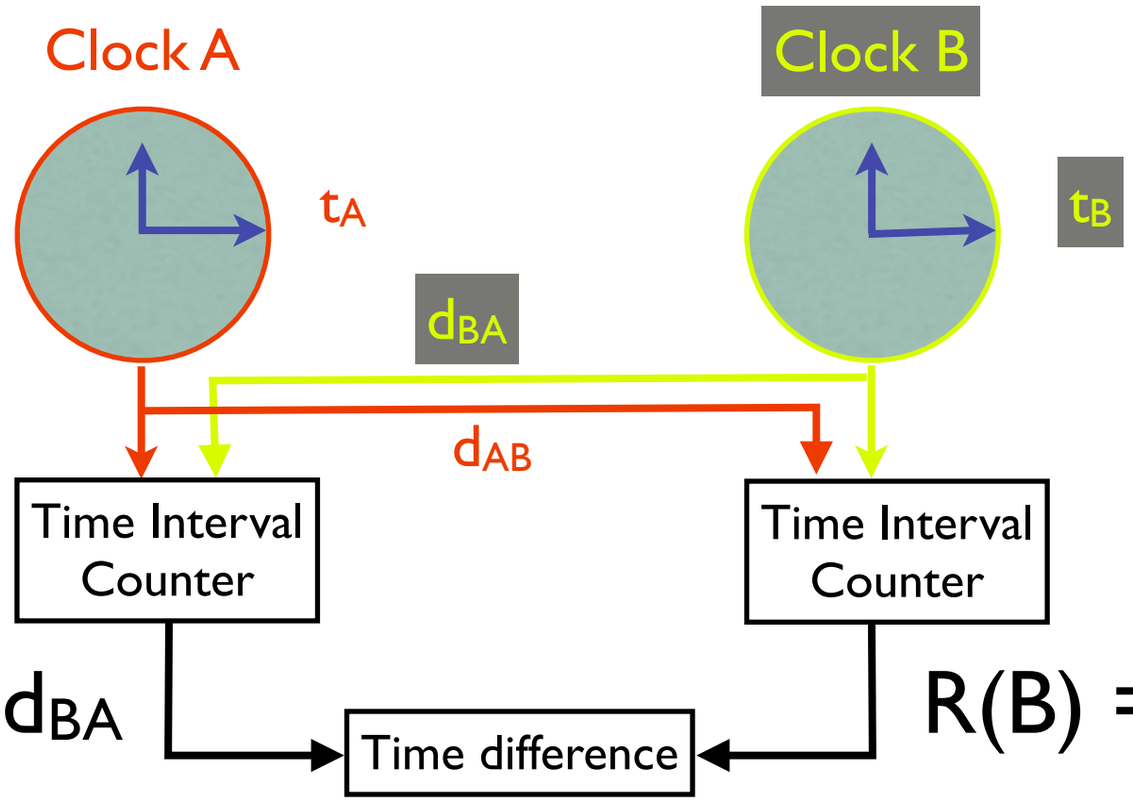
Secondary representations

FROM REPORT OF THE 19TH MEETING OF THE CCTF (2012)

Gravitational shift ~ 10^{-16}/m

Accurate frequency comparison at 10^{-17} or below needs better knowledge of geodetic potential !

Two-way time transfer



$$R(A) = t_A - t_B + d_{BA}$$

$$R(B) = t_B - t_A + d_{AB}$$

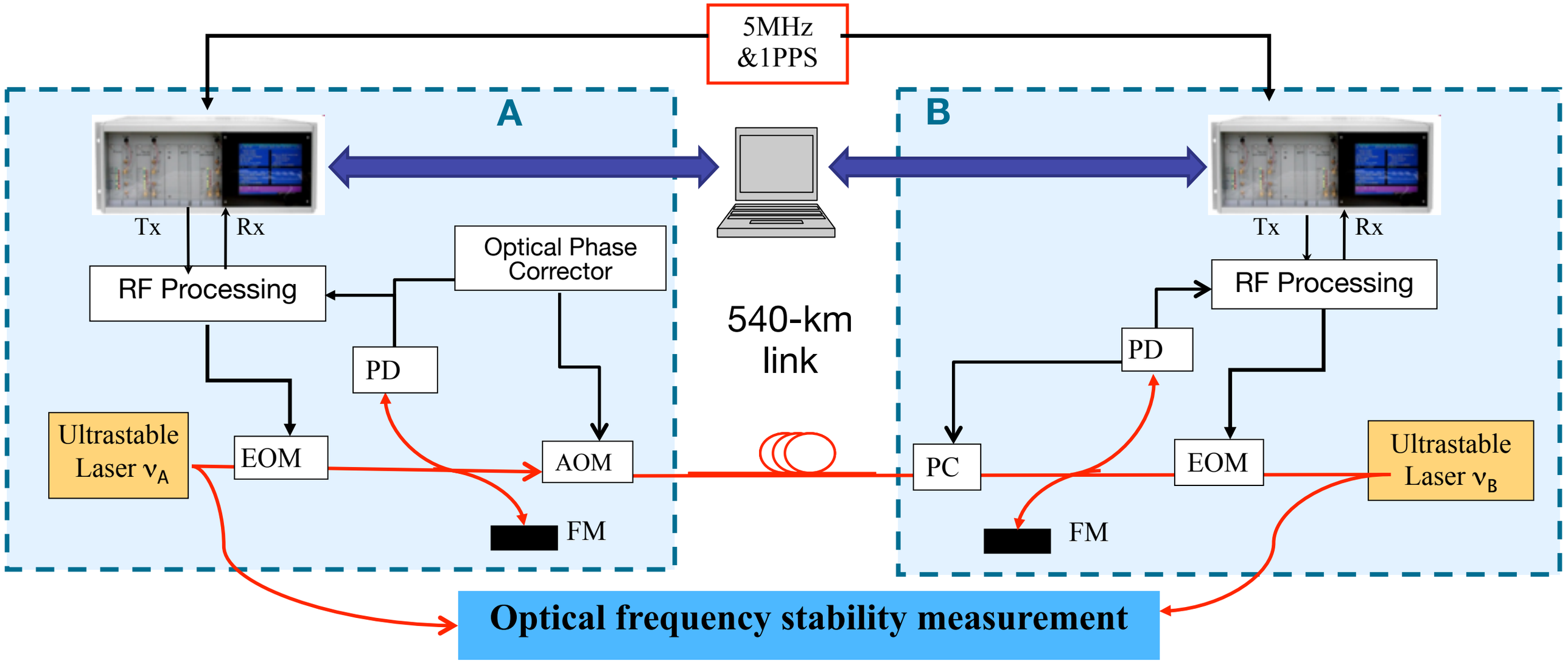
$$R(A)-R(B) = 2\,(t_A - t_B) + (d_{BA} - d_{AB})$$

Delay d_{ba}-d_{ab} = propagation delay + instrumental delay + Sagnac

Calibrated/Calc — Calibrated — Calculated

FROM D. W. HANSON, 43RD ANNUAL FREQUENCY CONTROL SYMPOSIUM, PP. 174-178, 1989

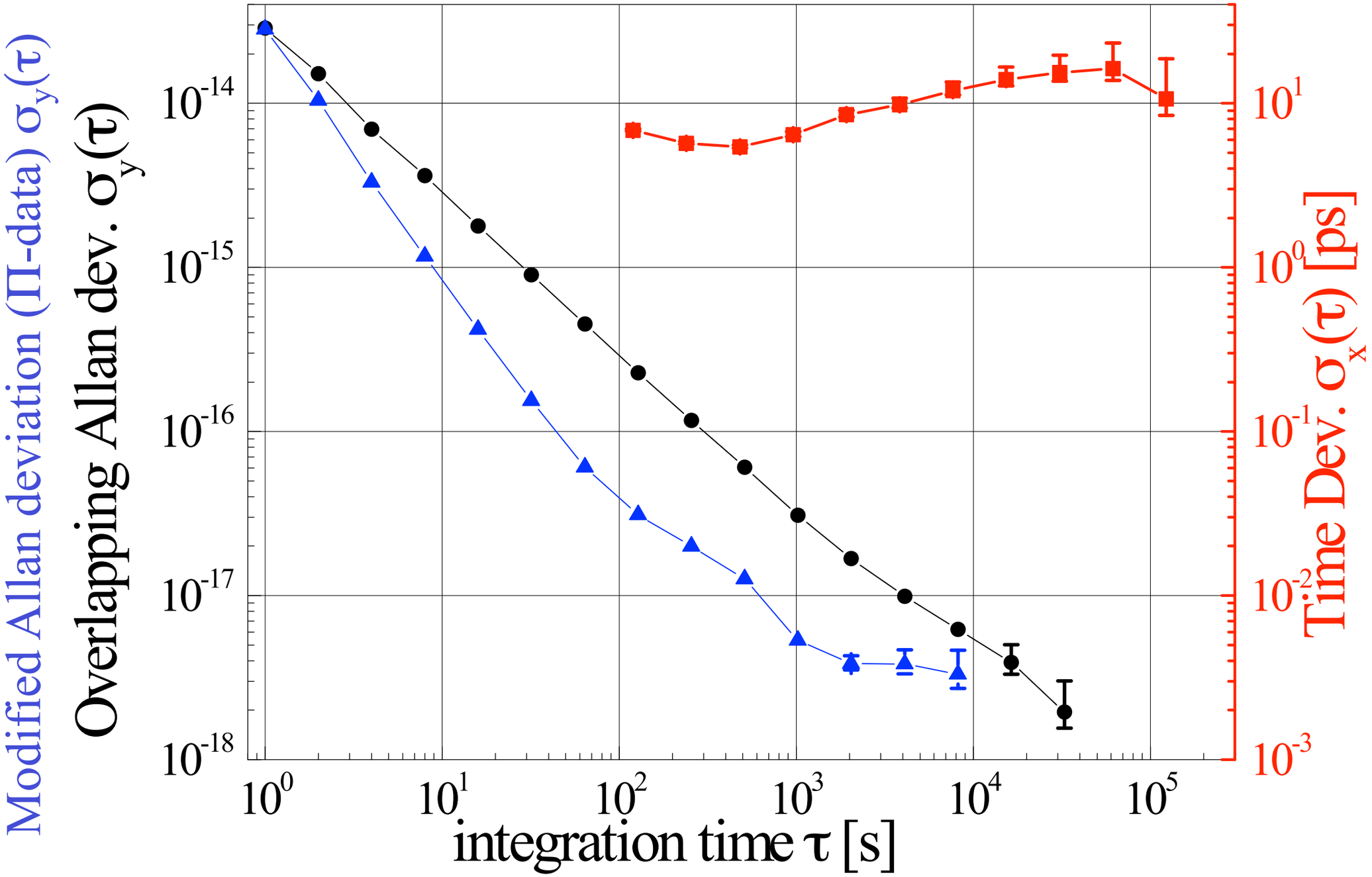
2-way Time transfer over Optical Fiber



- Frequency transfer with « round-trip » method for fiber noise compensation
- Two-way time transfer using Satre modems

EOM : Electro-Optic Modulator
AOM : Acousto-Optic Modulator
FM : Faraday Mirror
PD : PhotoDiode
PC : Polarization controler

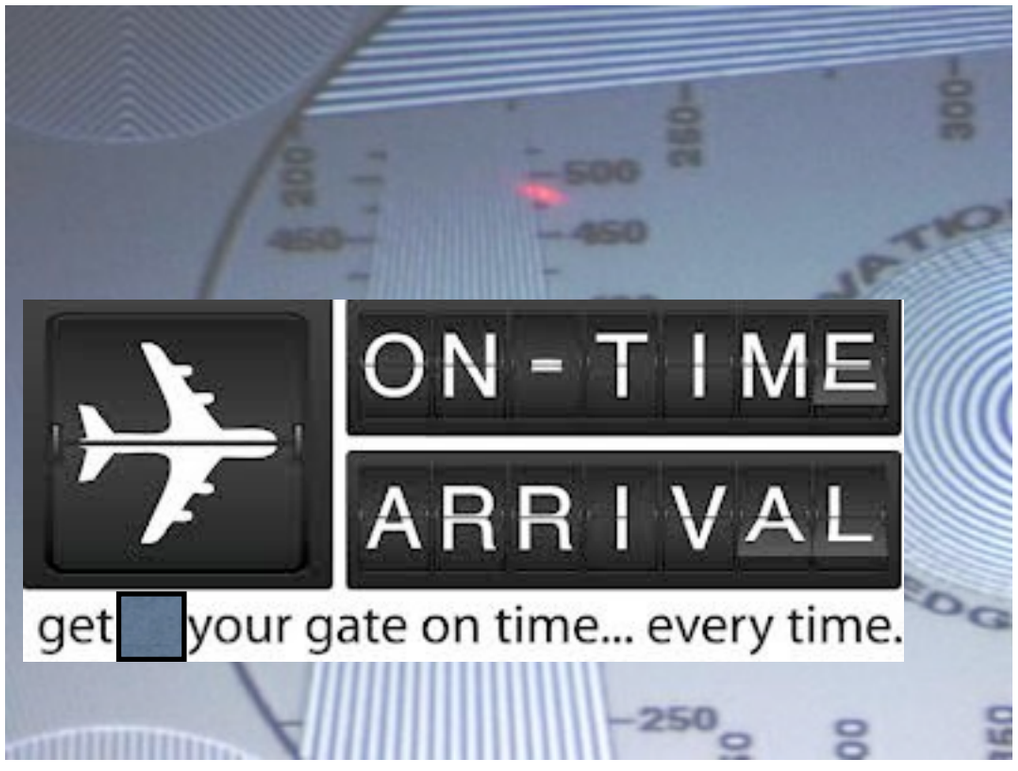
Frequency and Time transfer stability



APPL. PHYS. B, **110** (1) , PP 3-6 (2013)

Uncertainty budget

- Delay calibration: Link's length was varied from 10 m to [94; 400; 540] km
  - Constant overall attenuation (±2 dB).
  - Procedure repeated with [25; 50; 75; 100] km fiber spools
  - **Differential delay variation < 50 ps**
- Power sensitivity < 15ps/dB
- Fiber chromatic dispersion < 25 ps
- Polarisation mode dispersion (PMD)
  - < 20 ps (network characteristics)
  - < 50 ps (measurement)
- Sagnac = 0
- **Total < 250 ps**

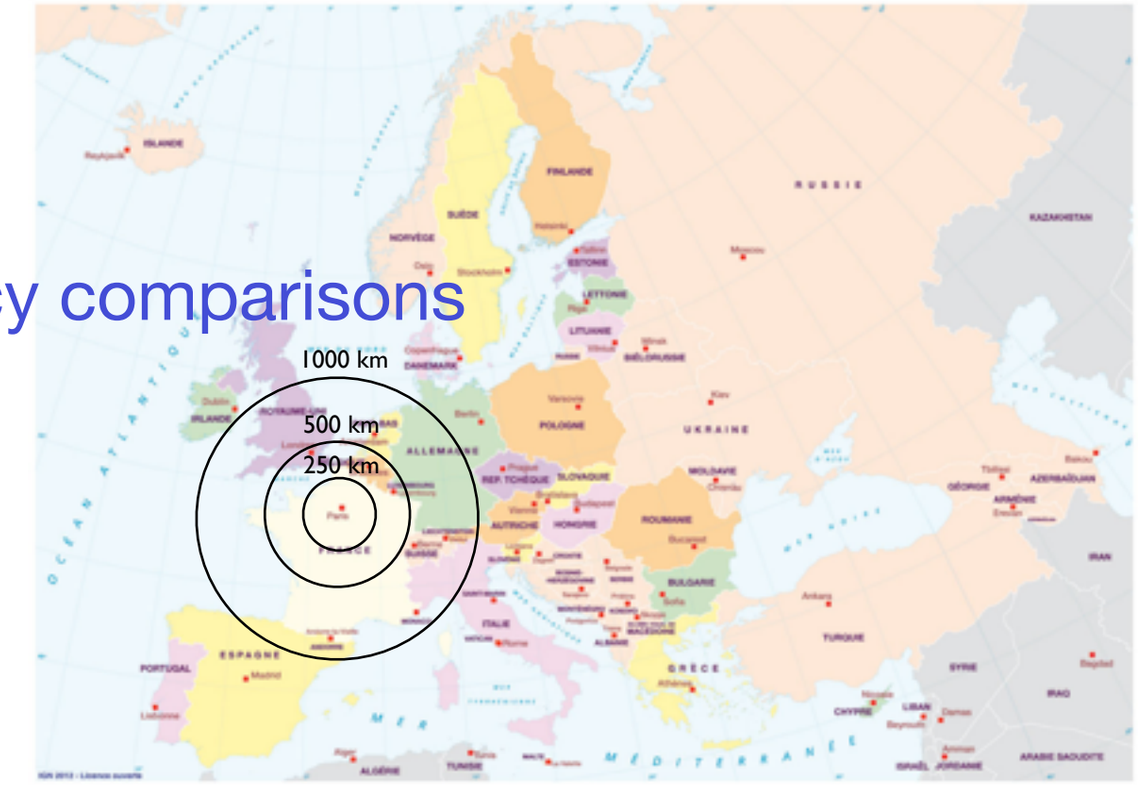


Time transfer through optical fiber links

	AGH	PTB	SYRTE/LPL
Carrier	RF + pps	Optical	Optical
Uncertainty (ps)	112	74	250
TDEV (ps) (@1day)	.9	20	20
Range (km)	421	73	540
	Metrologia 50 (2013) 133–145.	**Metrologia 49 (2012) 772-778**	**Appl. Phys. B 110 (2013) Issue 1 , pp 3-6**

Outlook

- Time and frequency transfer on a 540-km public fiber link
  - Frequency stability (1d) ~10^{-18}
  - Time stability (1d) ~20ps
  - Accuracy ~250ps
- International clock frequency comparisons
  - Optical clocks
  - ACES
  - MWL, T2L2
- Geodesy
- Time scale with optical clocks
  - Radioastronomy, VLBI



Contributors

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Thank you for attention !

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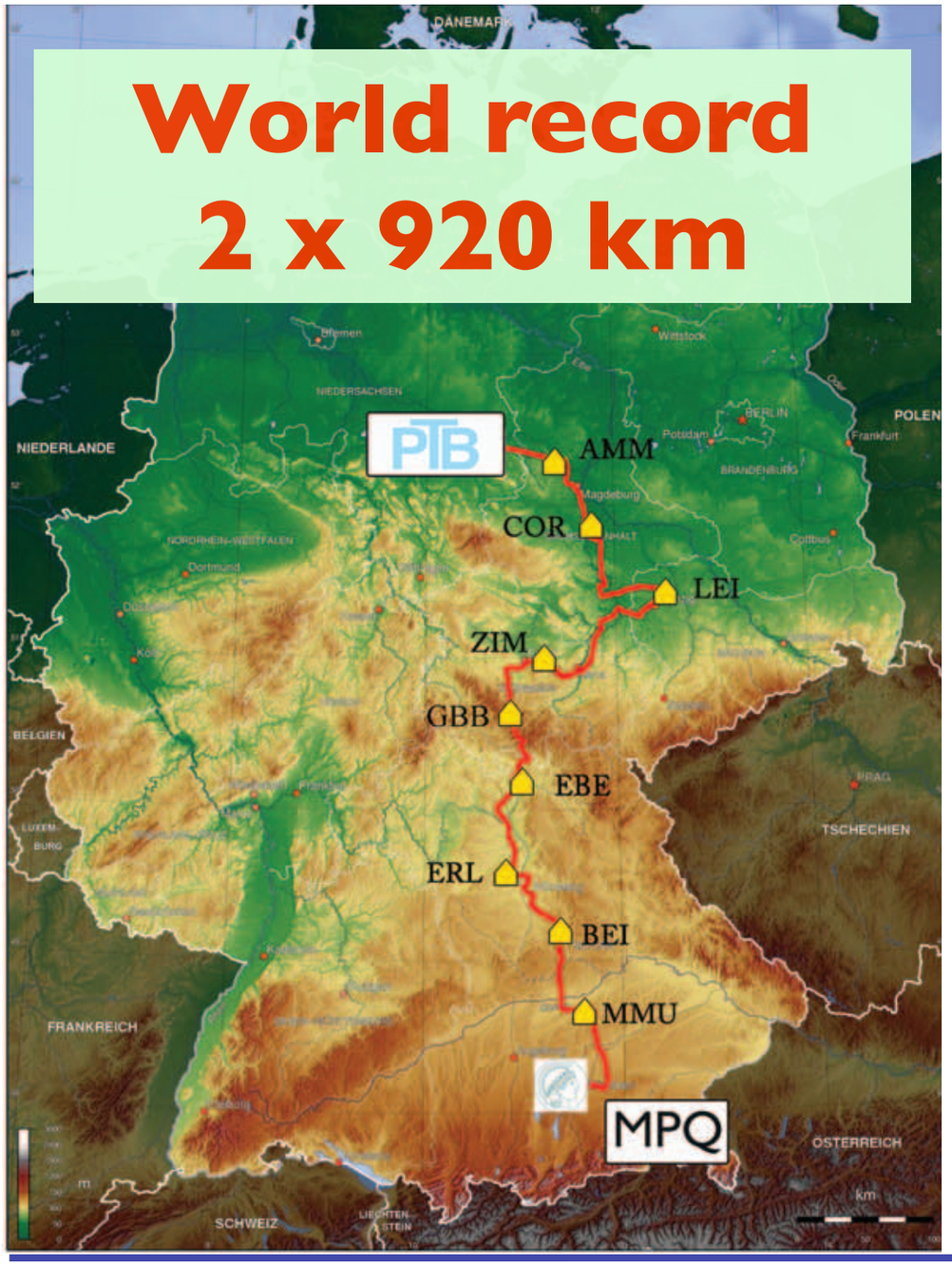
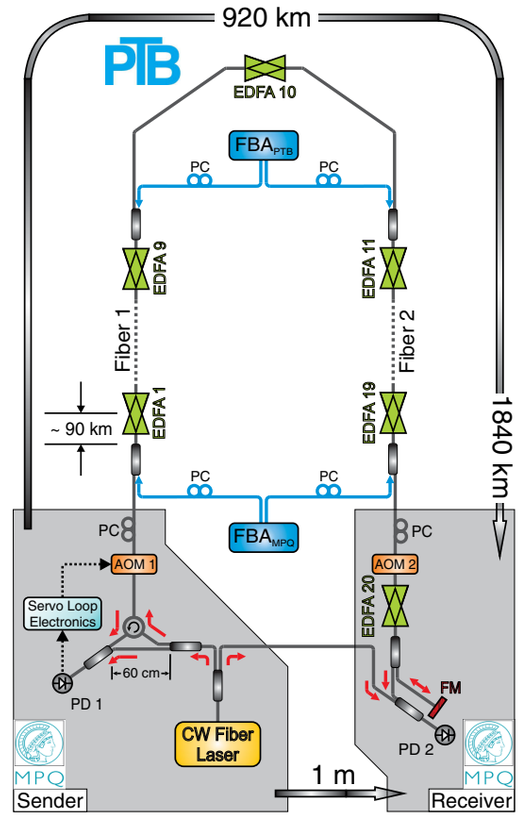
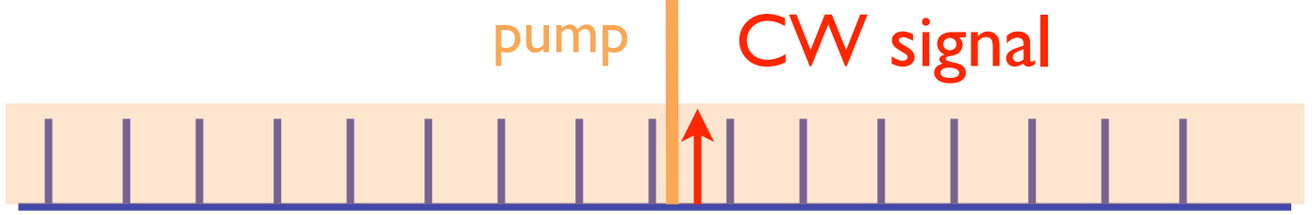


- High gain : 50-60 dB
- **Brillouin amplification : incompatible with parallel data traffic**
- Rental costs...

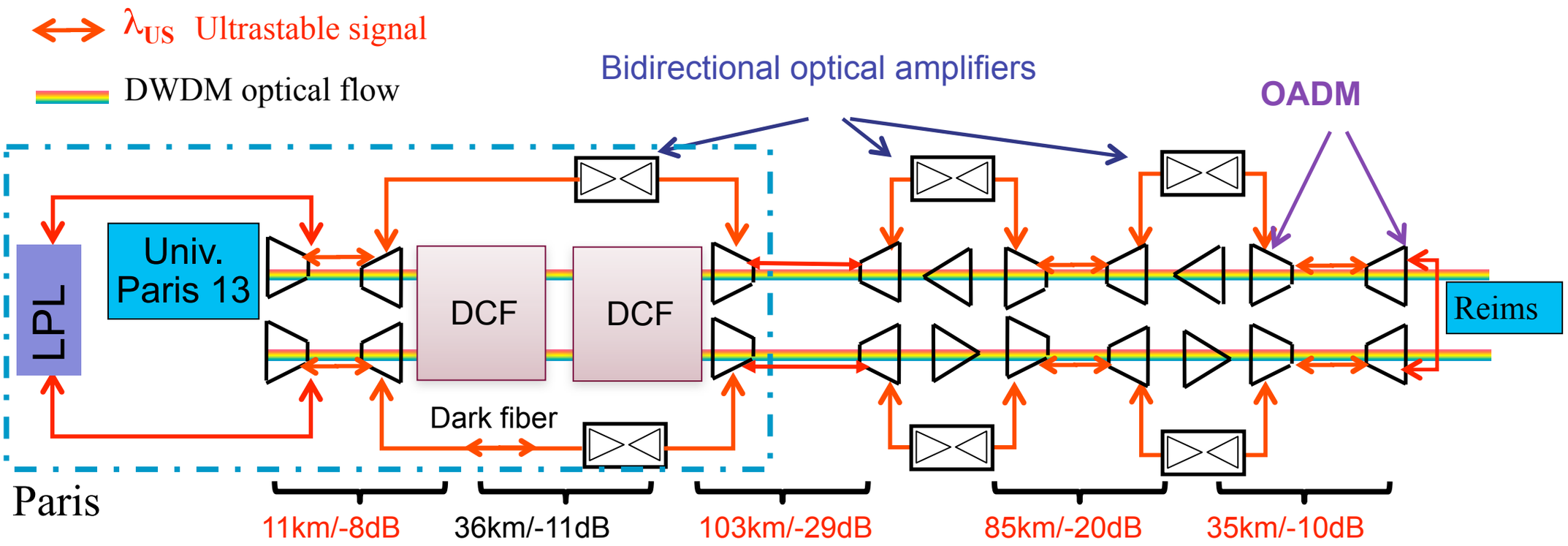




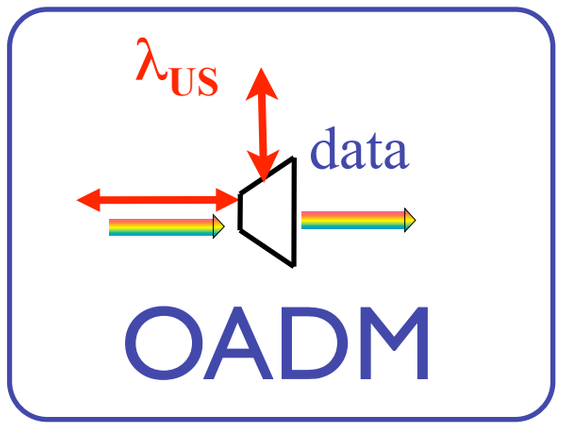
ITU GRID : 100 GHz spacing

DROSTE @ AL., PRL 111, 110801 (2013)
K. PREDEHL ET AL. SCIENCE 336, 441 (2012)

540-km link architecture

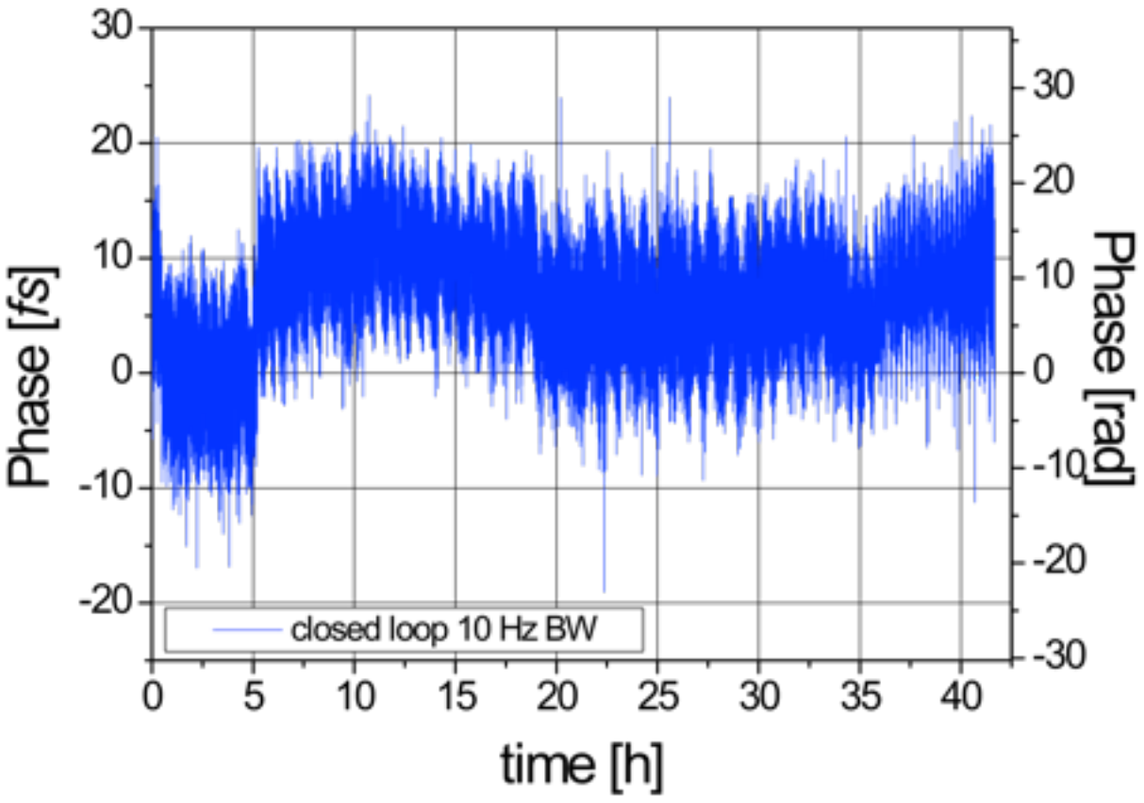


- OADMs (optical add drop multiplexer) to add and extract signal (100 GHz filter)
- Bidirectional amplifiers
- Continuous propagation
- One way attenuation / 540 km >160 dB, 6 bidirectional EDFA (gain~100 dB)

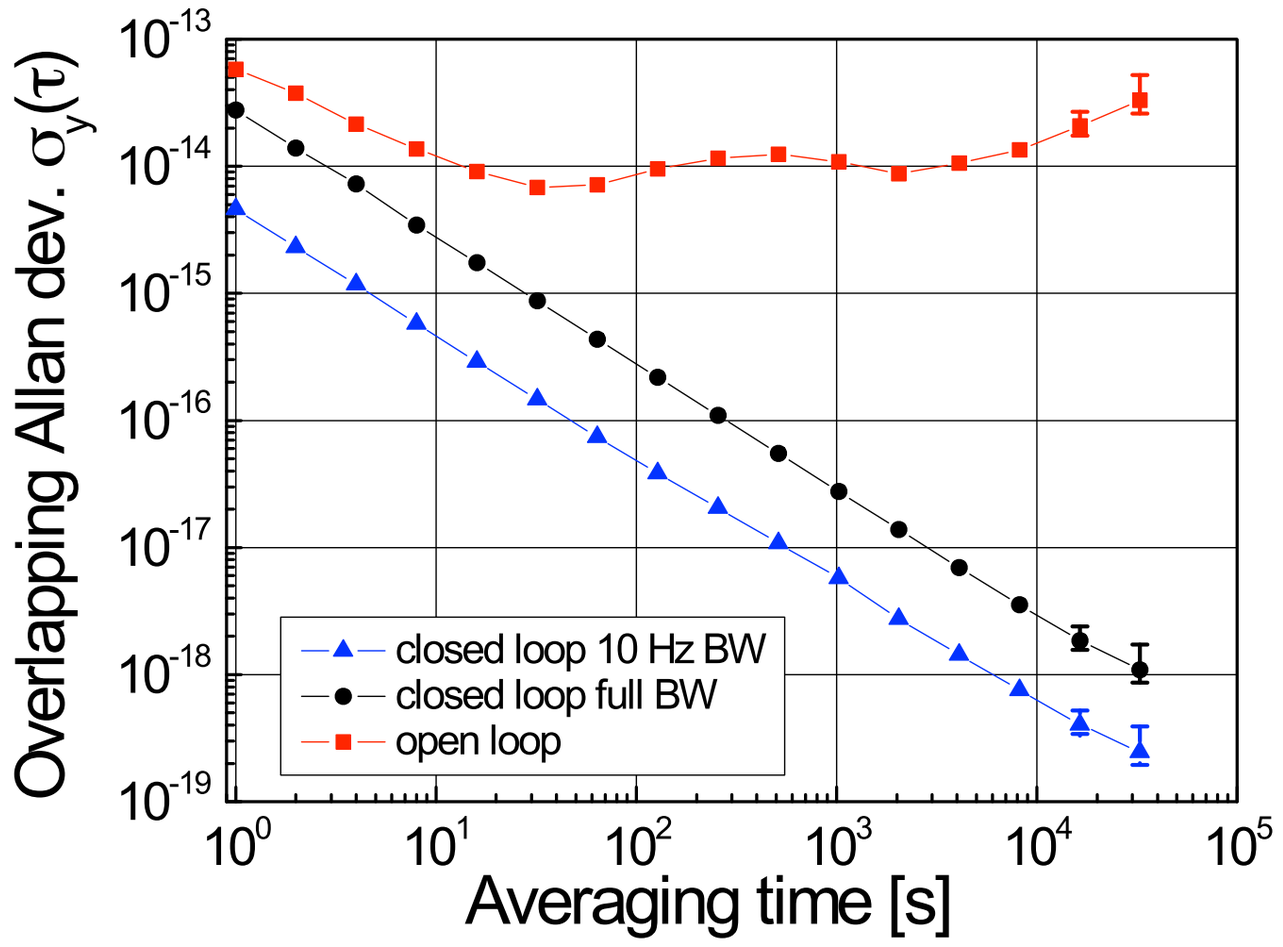


Frequency transfer : 540-km link

End-to-end phase variation (compensated)



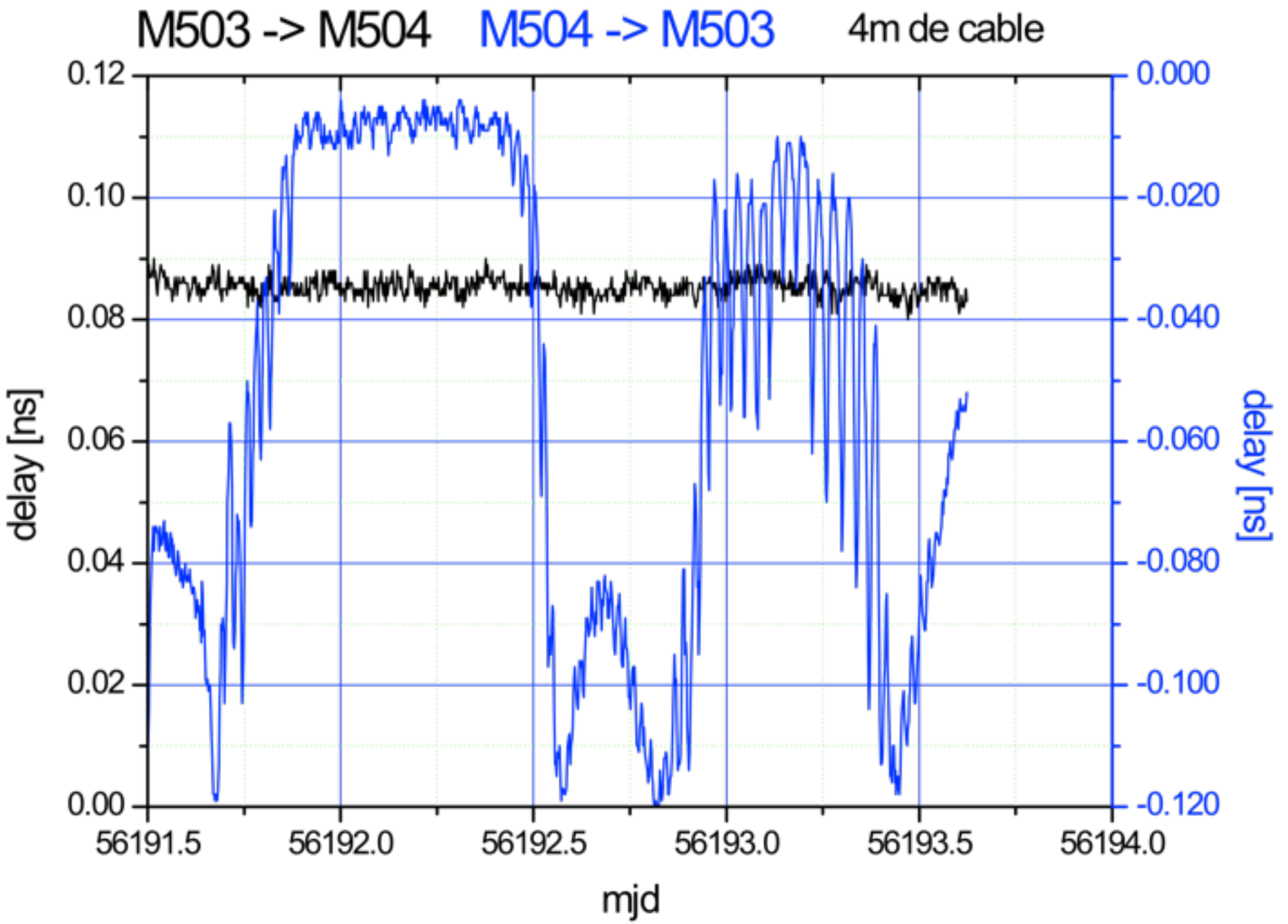
End-to-end stability



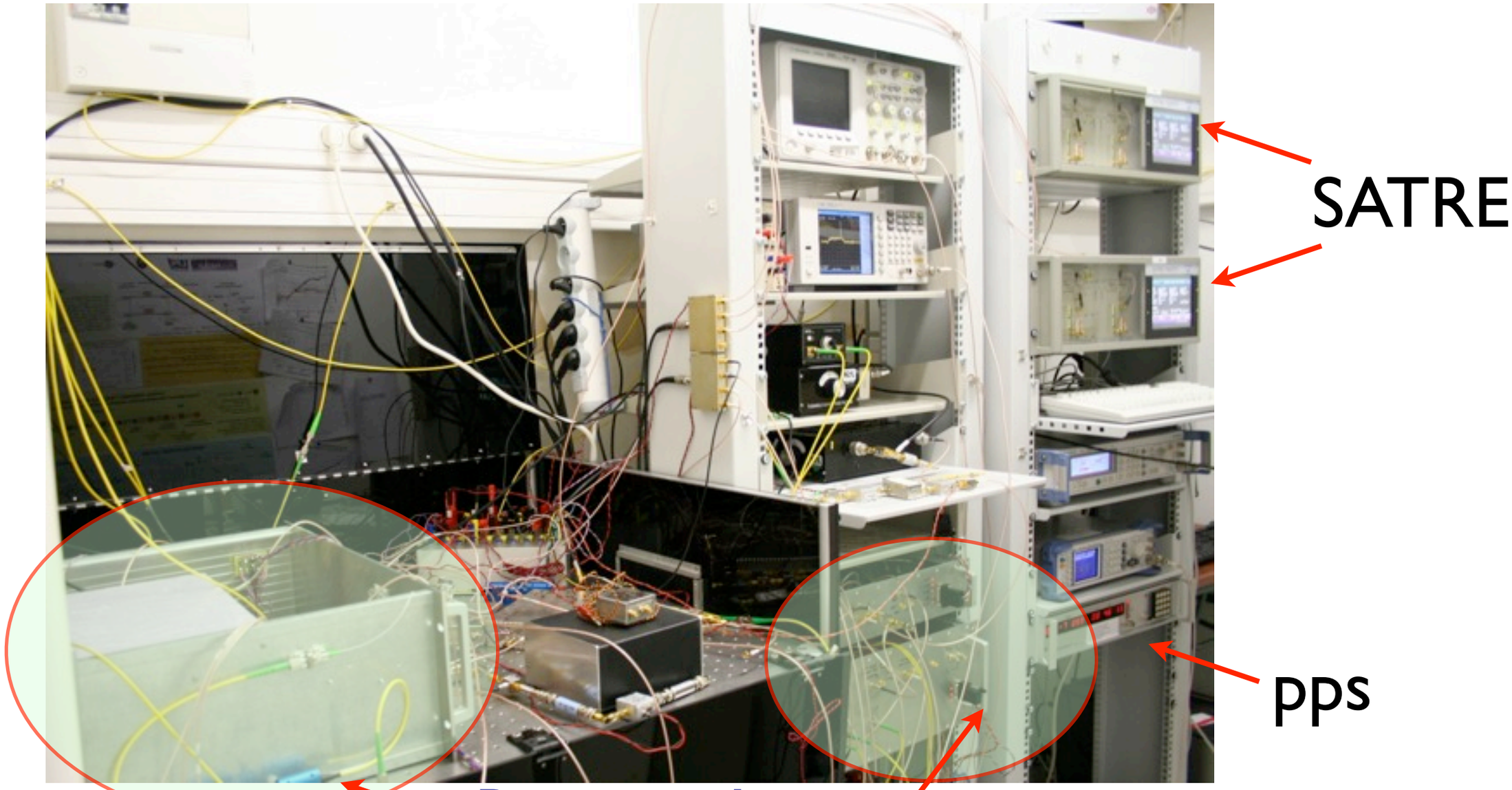
PTB : 920 km, Science 27 **336** (6080), 441-444 (2012)
670 km link just established at INRIM-LENS

Optics Express, **20** (21), 23518-23526 (2012)

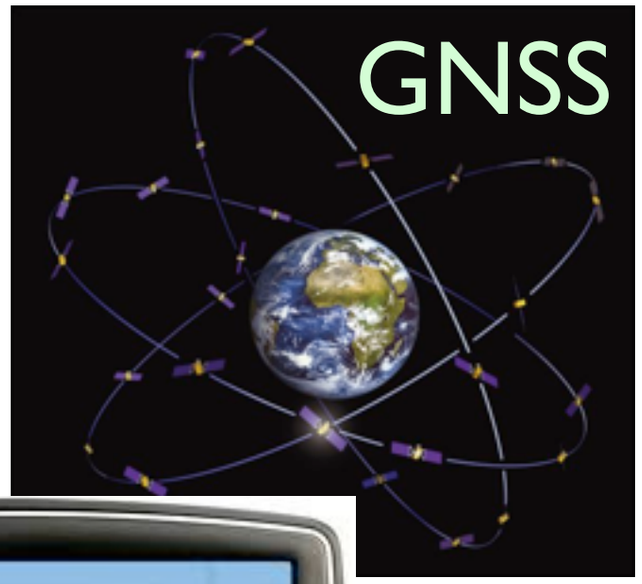
Modem stability

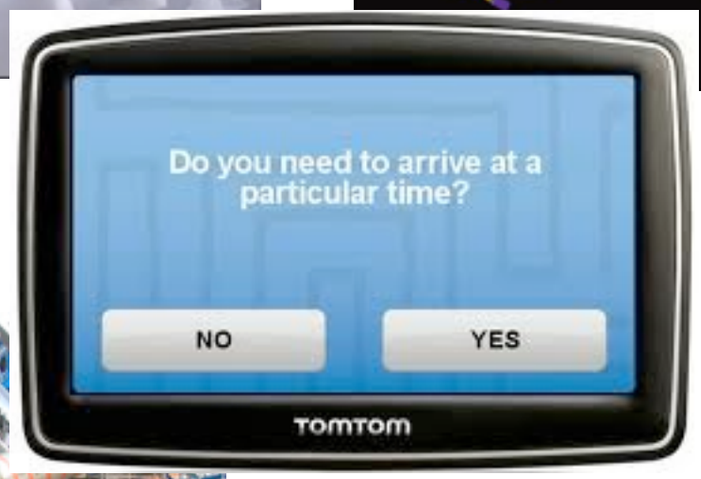


Picture of the experiment



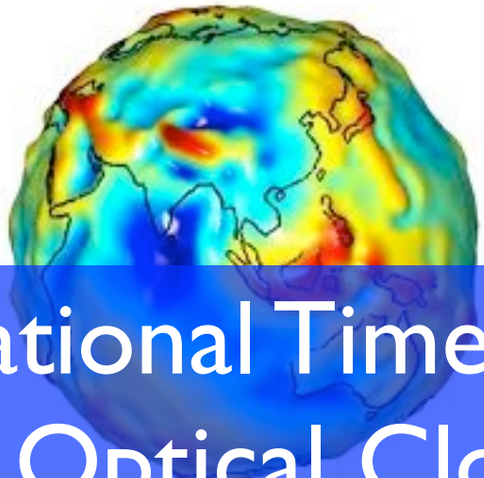
Time and Frequency Comparisons





Accelerators

Geodesy



International Time Scale with Optical Clocks