











Optical fiber links for optical clocks comparisons

P.-E. Pottie + about 50 co-workers











- Short introduction on fiber links
- Overview and progresses of fiber links in Europe
- PTB SYRTE optical clocks comparison with fiber link : a world first
- Related publications and topics : Chronometric geodesy and Test of GR
- Next campaigns





Means to compare clocks



Systèmes de Référence Temps-Espace

Means to compare clocks

Systèmes de Référence Temps-Espace



Comparing the mean of comparisons





Systèmes de Référence Temps-Espaci



Challenges for long haul fiber links

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

Noise scale as sqrt(Length of link) More noise in urban area 20 to 45 dBc / Hz @ 1 Hz



























T&F Fiber links: a very active field

Time &/or Frequency transfer :

- Combs
- NPL : 118 km
- RF + pps
 - GUM-AOS : 420 km
- SONET, SDH, WR
 - SP-MIKES : 1000 km
 - MIKES-Kajaani : 1000 km
 - UFE-BEV : 540 km
 - VSL-VUA : 208 km

New EU-project : CLONETS

towards Research Infrastructures

<u>Review article</u> O. Lopez *et al.*, Comptes Rendus Physique, 16 (5), pp. 459-586 (2015)

bservatoire SYRTE

Systèmes de Référence Temps-Espace



- NICT, NMIJ, UT (Japan) 120km optical carrier phase
- JILA-NIST (USA) optical & frequency comb transfer
 NIM, Tsinghua Univ., Bejing Univ. μwave
- UWÁ, Adelaide Univ. NMI (Australia) optical & μ wave



CLOck NETwork Services



- Consortium of 16 partners : 1/3 academics, 1/3 Telecom Network, 1/3 Industrials
- **Expected outcomes** :
 - Review techniques and their evolutions, compatibility, needs for Research Infrastructures (NMIs, research labs, large research facilities as VLBI, accelerators...)
 - Survey potential application outside Research Infrastructure, economic and societal impact
 - Education and training
 - Define a strategic roadmap for RI

Mid-term goal :

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Secured accessed to the fiber network

NPLO

Increase technical readiness level, offer « on the shelf » solutions and procedures to establish a fiber link

🗊 RENATER

Project CLONETS involved 16 partners from 7 European countries. Partners represent 4 main areas:

- National Measurement Institutes: OBS PARIS (FR), NPL (UK), PTB (DE), INRIM (IT)
- National Research and Education Network: RENATER (FR), CESNET (CZ), PSNC (PL), GARR* (IT),
- Academic Laboratories: AGH (PL), UP13 (FR), UCL (UK), ISI (CZ), CNRS* (FR)
- Industrial: MUQUANS (FR), MENLO (DE), PIKTIME (PL), SEVEN SOL (SP), OPTOKON (CZ), TOP-IX* (IT)





Optical Fiber Links: a worldwide snapshot











Fiber link « side impact »

Link impact outside primary metrology









Fibre link for Radioastronomy: Italy (coherent transfer)

✓ Towards a common-clock VLBI experiment

- → Ongoing extension on Italian link to connect 2 telescopes
- → Low-noise microwave generation stage in progress
- → 2 VLBI campaigns with fiber-disseminated INRIM clock to Medicina already performed

C. Clivati, Sci. Rep. 7, 40992 (2017)

Next Steps: also White Rabbit











AEROSPACE: LIFT+

1800 km Frejus-Turin-Matera Realization: 2017

Fucino: Esperimentation of Trace Galileo GCC To UTC via fibre link (accuracy target <1ns)









Chronometric geodesy

Courtesy of Davide Calonico



Yamaguchi, et al., Appl. Phys. Express 4, 082203(2011).





All-optical direct comparison between Riken & UT clock (2016)







Sr-Sr comparison by fiber links







An optical methodology





Clock comparison accuracy budget

Ratio SrptB/SrsyRtE	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

C. Lisdat et al., Nature Comm. (2016), 12443 (2016), doi:10.1038/ncomms12443





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First international comparison of fountain primary frequency standards via a long distance optical fiber link

Jocelyne Guéna, Stefan Weyers, Michel Abgrall, Christian Grebing, Vladislav Gerginov, Peter Rosenbusch, Sebastien Bize, Burghard Lipphardt, Heiner Denker, Nicolas Quintin, Sebastian Raupach, Daniele Nicolodi, Fabio Stefani, Nicola Chiodo, Sebastian Koke, Alexander Kuhl, Fabrice Wiotte, Frederic Meynadier, Emilie Camisard, Christian Chardonnet, Yann Lecoq, Michel Lours, Giorgio Santarelli, Anne Amy-Klein, Rodolphe Le Targat, Olivier Lopez, Paul-Eric Pottie, Gesine Grosche



Accepted: 10 March 2017



IAG - Ist Joint Working Group 2.1

Hanover, May 15, 2017



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An international link over GéANT



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PB

End-to-end NPL-LPL-NPL 2x770 km

Noise source under investigation...

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Systèmes de Référence Temps-Espace

Preliminary accuracy : 1E-18 (limited by statistics)

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Sr clocks comparison NPL-SYRTE

Chronometric geodesy with clocks and

gravimeters

Determination of a high spatial resolution geopotential model using atomic clock comparisons

G. Lion^{*1,2}, I. Panet², P. Wolf¹, C. Guerlin^{1,3}, S. Bize¹ and P. Delva¹

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G. Lion et al., Journal of Geodesy, pp 1-15 (2017) arXiv:1612.03833v2 [physics.geo-ph]

Main conclusion (for a naive as me) : A few number of clock measurements can help !

Figure 9: Accuracy of the disturbing potential T reconstruction on a regular 10-km step grid in Massif Central, obtained by comparing the reference model and the reconstructed one. In Figure (a), the estimation is realized from the 4374 gravimetric data δg only, and in Figure (b) by adding 33 potential data T to the gravity data.

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Figure 10: Accuracy of the disturbing potential T reconstruction on a regular 10-km step grid in Massif Central, obtained by comparing the reference model and the reconstructed one. In Figure (a), the estimation is realized from the 4959 gravimetric data δg only, and in Figure (b) by adding 32 potential data T to the gravity data.

Test of special relativity

Test of special relativity using a fiber network of optical clocks

P. Delva¹,* J. Lodewyck¹, S. Bilicki¹, E. Bookjans¹, G. Vallet¹, R. Le Targat¹, P.-E. Pottie¹, C. Guerlin^{2,1}, F. Meynadier¹, C. Le Poncin-Lafitte¹, O. Lopez³, A. Amy-Klein³, W.-K. Lee^{1,4}, N. Quintin³, C. Lisdat⁵, A. Al-Masoudi⁵, S. Dörscher⁵, C. Grebing⁵, G. Grosche⁵, A. Kuhl⁵, S. Raupach⁵, U. Sterr⁵, I. R. Hill⁶, R. Hobson⁶, W. Bowden⁶, J. Kronjäger⁶, G. Marra⁶, A. Rolland⁶, F. N. Baynes⁶, H. S. Margolis⁶, and P. Gill⁶ ¹SYRTE, Observatoire de Paris, PSL Research University, CNRS, Sorbonne Universités, UPMC Univ. Paris 06, LNE, 61 avenue de l'Observatoire 75014 Paris, France ²Laboratoire Kastler Brossel, ENS-PSL Research University, CNRS, UPMC-Sorbonne Universités, Collège de France, 75005 Paris, France ³Laboratoire de Physique des Lasers, Université Paris 13, Sorbonne Paris Cité, CNRS, 99 Avenue Jean-Baptiste Clément, 93430 Villetaneuse, France ⁴Korea Research Institute of Standards and Science, Daejeon 34113, South Korea ⁵Physikalisch-Technische Bundesanstalt, Bundesallee 100, 38116 Braunschweig, Germany and ⁶National Physical Laboratory, Hampton Road, Teddington, TW11 0LW, UK

- Tides give time-variable gravity potential components
- Approximately diurnal peak-to-peak fractional frequency variations
- PTB-SYRTE : 1.3 × 10⁻¹⁷
- NPL-SYRTE: 5 × 10⁻¹⁸
- Tide is modeled at the level of 2 × 10⁻¹⁸

period of one sidereal day

negligible

- vA and vB are respectively the velocities of clocks
 A & B in the non-rotating geocentric celestial
 reference system (GCRS)
- w is the velocity of the Earth with respect to a preferred frame, taken as the rest frame of the cosmological microwave background (CMB)

- LI violating parameter α of the RMS framework <1.1 × 10-8
- 2 times better constrained than using accelerated ions,
- 2 orders of magnitude better than previous data using atomic clocks,
- Some effect of temperature on clock frequency was revealed and needed to be mitigated

Outlook

Optical clock comparison using fiber links is a reality : NPL-SYRTE-PTB

IAG - Ist Joint Working Group 2.1

Hanover, May 15, 2017

<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
 - Chronometric geodesy
- Linking NMIs with fiber links
 - SYRTE-PTB achieved

SYRTE

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Systèmes de Référence Temps-Espace

- SYRTE-NPL : established
- SYRTE-INRIM, PTB-GUM : next !
- Next campaign NPL-SYRTE-PTB : June 2017

Thanks to people in PTB, NPL, LPL RENATER and Uni. Strasbourg

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Thank you for attention !

