Strontium Optical Lattice Clock Comparison Over 1415 Kilometers

Joe Becker

Texas A&M Department of Physics and Astronomy

jbecker@physics.tamu.edu

September 15, 2016

Outline

1. Motivation
2. Background
3. Apparatus
4. Results
5. Conclusion

Why Compare Clocks?

Moving to an Optical Standard

- You can only measure frequency against a standard.
- The current time standard (caesium) is based on microwave frequencies.
- Current optical clock comparisons are limited to 4×10^{-16} fractional agreement due to the caesium clocks.
- In order to move to the new more accurate time standard optical clocks need to be directly compared.

Why Compare Clocks?

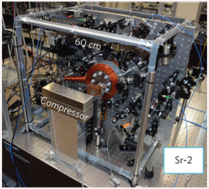
An Optical Clock Network for New Physics

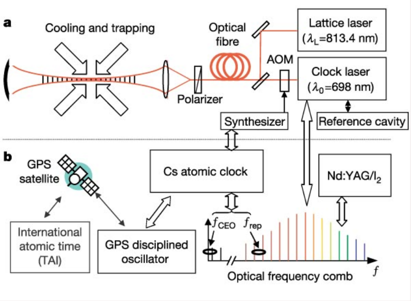
An optical clock network has the potential to open new avenues to experiments:

- The search for dark matter
- The Einstein equivalence principle
- Very long baseline interferometry
- Building a new geodetic reference frame on relativistic geodesy

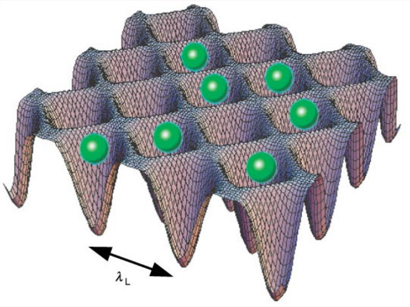
Strontium Optical Lattice Clocks

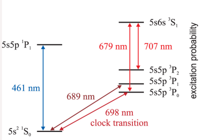
Sr Clock Schematic

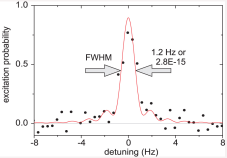




Sr Clock Lattice and Transitions

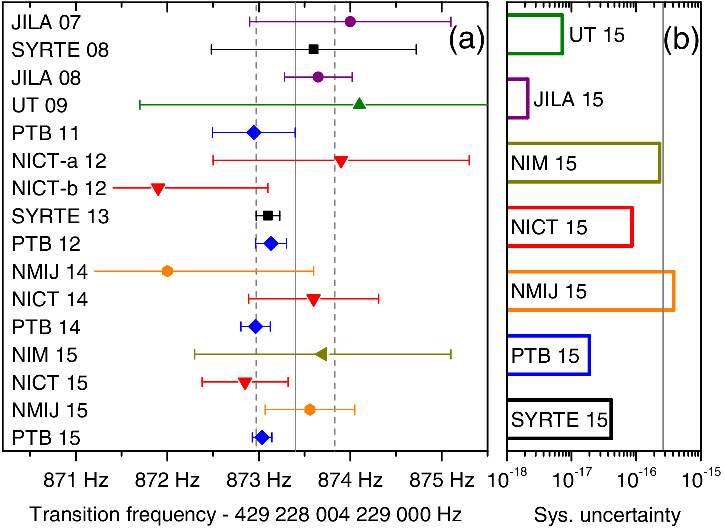






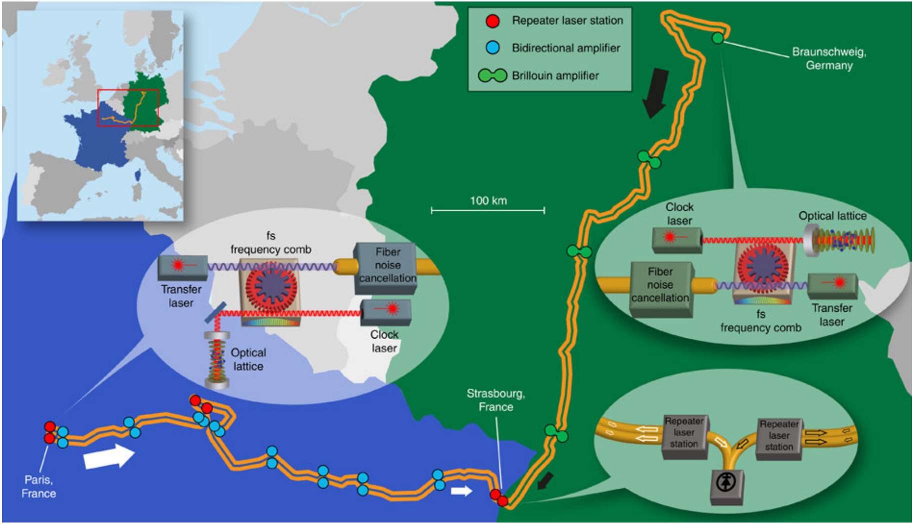
Falke et al. [2014], Ushijima et al. [2015], Takamoto et al. [2005]

Strontium Clocks Frequency Comparison



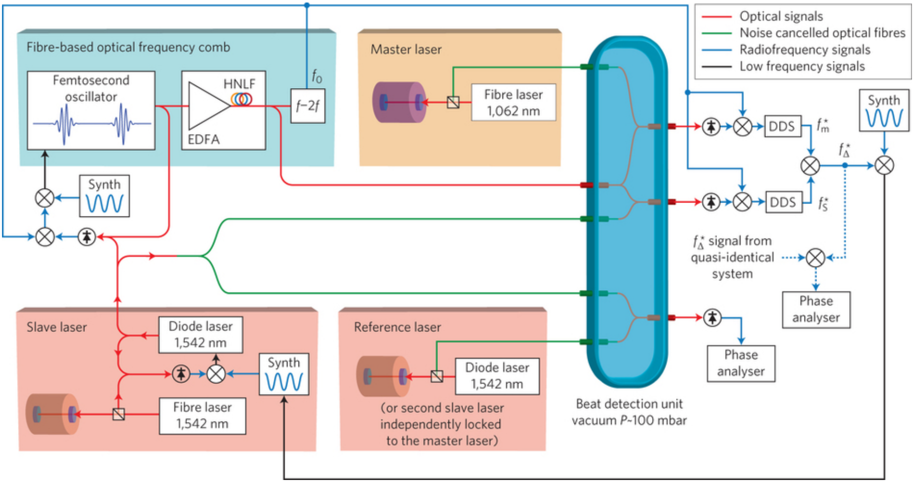
Grebing et al. [2016]

Schematic of Clock Comparison



Lisdat et al. [2016]

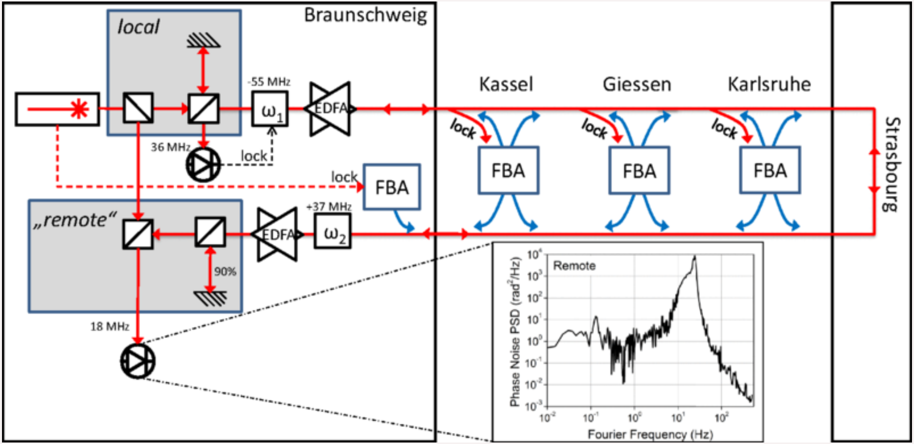
Schematic of Transfer Laser System



Nicolodi et al. [2014]

Braunschweig to Strasbourg Uplink

Fiber Brillouin Amplification Schematic

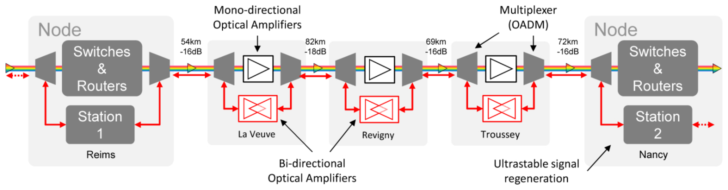


Raupach et al. [2015]

Paris to Strasbourg Uplink

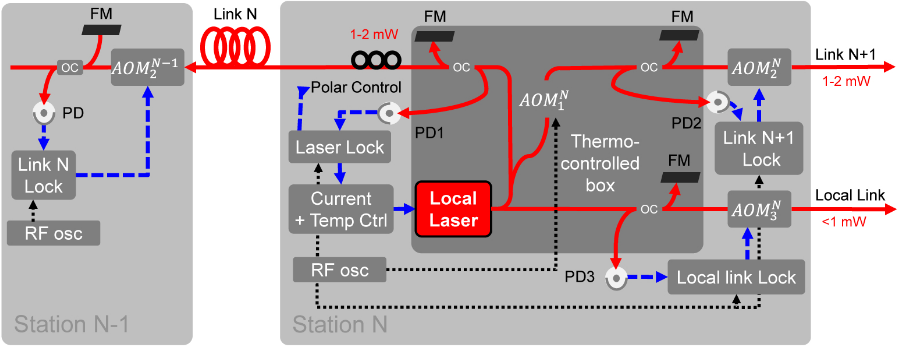
Uplink Map

Schematic of Cascaded Optical Fiber Link



Chiodo et al. [2015]

Repeater Station



Chiodo et al. [2015]

Experimental Uncertainties

Table 1 | Uncertainty budget.

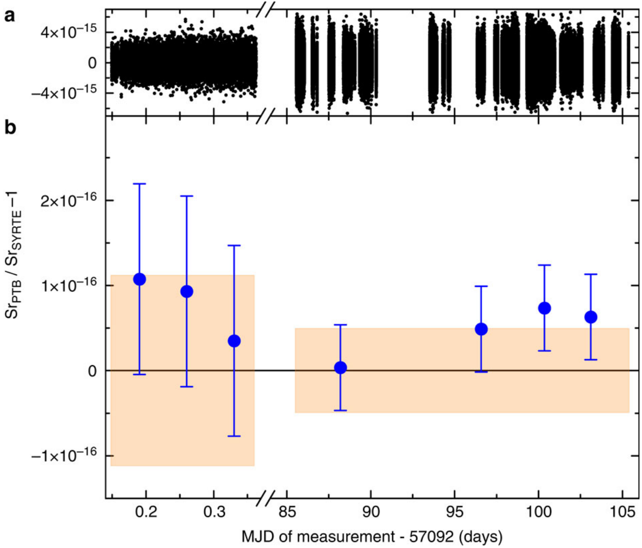
Clock uncertainty	Sr lattice clock Paris		Sr lattice clock Braunschweig	
	Corr. (10^{-17})	Unc. (10^{-17})	Corr. (10^{-17})	Unc. (10^{-17})
First and higher-order lattice LS	0	2.5	−1.1	1.0
Black-body radiation	515.5	1.8	492.9	1.3
Black-body radiation oven	0	1.0	0.9	0.9
Density shift	0	0.8	0	0.1
Quadratic Zeeman shift	134.8	1.2	3.6	0.15
Line pulling	0	2.0	0	$\ll 0.1$
Total clocks	**650.3**	**4.1**	**496.3**	**1.9**

Ratio Sr_{PTB}/Sr_{SYRTE}	Campaign I Unc. (10^{-17})	Campaign II Unc. (10^{-17})
Systematics Sr_{SYRTE}	4.1	4.1
Systematics Sr_{PTB}	2.1	1.9
Statistical uncertainty	2	2
fs combs	0.1	0.1
Link uncertainty	<0.1	0.03
Counter synchronization*	10	<0.01
Gravity potential correction†	0.4	0.4
Total clock comparison	**11.2**	**5.0**

Corr., fractional correction; LS, light shift; Unc., fractional uncertainty.
The numbers vary slightly over the course of the measurement. All uncertainties are 1σ.
*Frequency counters have been synchronized in the second campaign.
†The applied gravity potential correction is -247.2×10^{-17}, see text.
Bold entries represent the sum of all the individual contributions listed before rather than another contribution.

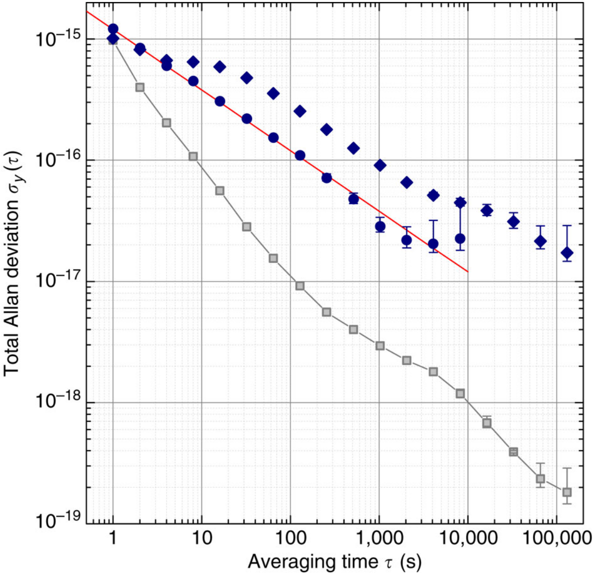
Lisdat et al. [2016]

Frequency Ratio Between PTB and SYRTE



Lisdat et al. [2016]

Allen Deviation Plots



Lisdat et al. [2016]

Conclusions

- Researchers measured a fractional offset between the two clocks as $(4.7 \pm 5.0) \times 10^{-17}$.
- After less than an hour of averaging they reached a statistical uncertainty of 2×10^{-17}. This marks an order of magnitude improvement on all previous long distance frequency comparisons with a four order of magnitude reduction in measurement time.
- The foundations are set for an optical clock network across the continent of Europe.

Further Reading

N. Chiodo, N. Quintin, F. Stefani, F. Wiotte, E. Camisard, C. Chardonnet, G. Santarelli, A. Amy-Klein, P.-E. Pottie, and O. Lopez. Cascaded optical fiber link using the internet network for remote clocks comparison. *Optics express*, 23(26): 33927–37, 2015. ISSN 1094-4087. doi: 10.1364/OE.23.033927. URL http://arxiv.org/abs/1509.05885.

S. Falke, N. Lemke, C. Grebing, B. Lipphardt, S. Weyers, V. Gerginov, N. Huntemann, C. Hagemann, A. Al-Masoudi, S. Häfner, S. Vogt, U. Sterr, and C. Lisdat. A strontium lattice clock with $3 \times 10 - 17$ inaccuracy and its frequency. *New Journal of Physics*, 16:0–18, 2014. ISSN 13672630. doi: 10.1088/1367-2630/16/7/073023.

C. Grebing, A. Al-Masoudi, S. Dörscher, S. Häfner, V. Gerginov, S. Weyers, B. Lipphardt, F. Riehle, U. Sterr, and C. Lisdat. Realization of a timescale with an accurate optical lattice clock. *Optica*, 3(6):563, jun 2016. ISSN 2334-2536. doi: 10.1364/OPTICA.3.000563. URL http://arxiv.org/abs/1511.03888https://www.osapublishing.org/abstract.cfm?URI=optica-3-6-563.

C. Lisdat, G. Grosche, N. Quintin, C. Shi, S. Raupach, C. Grebing, D. Nicolodi, F. Stefani, A. Al-Masoudi, S. Dörscher, S. Häfner, J.-L. Robyr, N. Chiodo, S. Bilicki, E. Bookjans, A. Koczwara, S. Koke, A. Kuhl, F. Wiotte, F. Meynadier, E. Camisard, M. Abgrall, M. Lours, T. Legero, H. Schnatz, U. Sterr, H. Denker, C. Chardonnet, Y. Le Coq, G. Santarelli, A. Amy-Klein, R. Le Targat, J. Lodewyck, O. Lopez, and P.-E. Pottie. A clock network for geodesy and fundamental science. *Nature Communications*, 7:12443, aug 2016. ISSN 2041-1723. doi: 10.1038/ncomms12443. URL http://arxiv.org/abs/1511.07735http://www.nature.com/doifinder/10.1038/ncomms12443.

D. Nicolodi, B. Argence, W. Zhang, R. Le Targat, G. Santarelli, and Y. Le Coq. Spectral purity transfer between optical wavelengths at the 10-18 level. *CPEM Digest (Conference on Precision Electromagnetic Measurements)*, 8(January):64–65, 2014. ISSN 05891485. doi: 10.1109/CPEM.2014.6898260.

S. M. F. Raupach, A. Koczwara, and G. Grosche. Brillouin amplification supports 110-20 uncertainty in optical frequency transfer over 1400 km of underground fiber. *Physical Review A - Atomic, Molecular, and Optical Physics*, 92(2):1–5, 2015. ISSN 10941622. doi: 10.1103/PhysRevA.92.021801.

M. Takamoto, F.-L. Hong, R. Higashi, and H. Katori. An optical lattice clock. *Nature*, 435(7040):321–324, 2005. ISSN 0028-0836. doi: 10.1038/nature03541.

I. Ushijima, M. Takamoto, M. Das, T. Ohkubo, and H. Katori. Cryogenic optical lattice clocks. *Nature Photonics*, 9(February): 1–5, 2015. ISSN 1749-4885. doi: 10.1038/nphoton.2015.5. URL http://www.nature.com/doifinder/10.1038/nphoton.2015.5.