National Time and Time Services

Thomas Fordell, Thomas Lindvall, Kalle Hanhijärvi, Anders Wallin

National Metrology Institute VTT MIKES

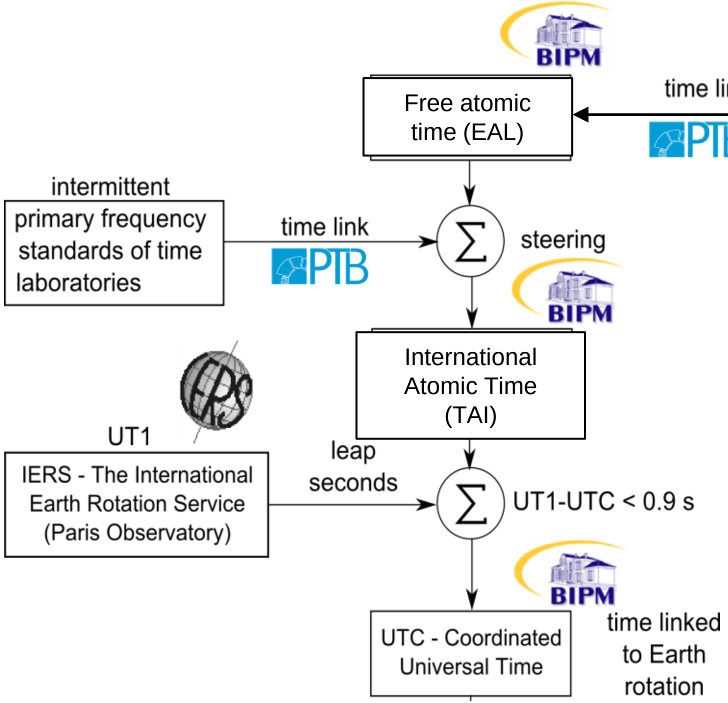
VTT

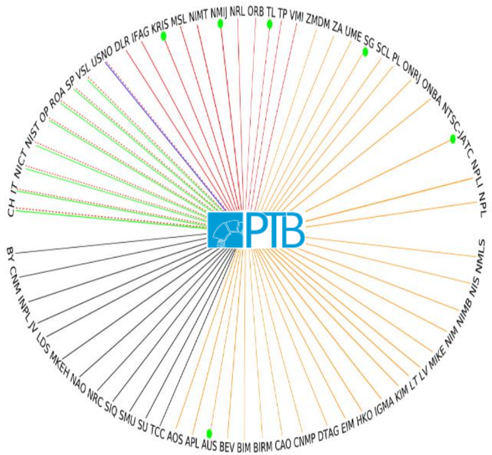
Outline

- Coordinated Universal Time
- VTT MIKES optical atomic clock
- Time Services

Coordinated Universal Time (UTC)

Cs fountain @ NPL





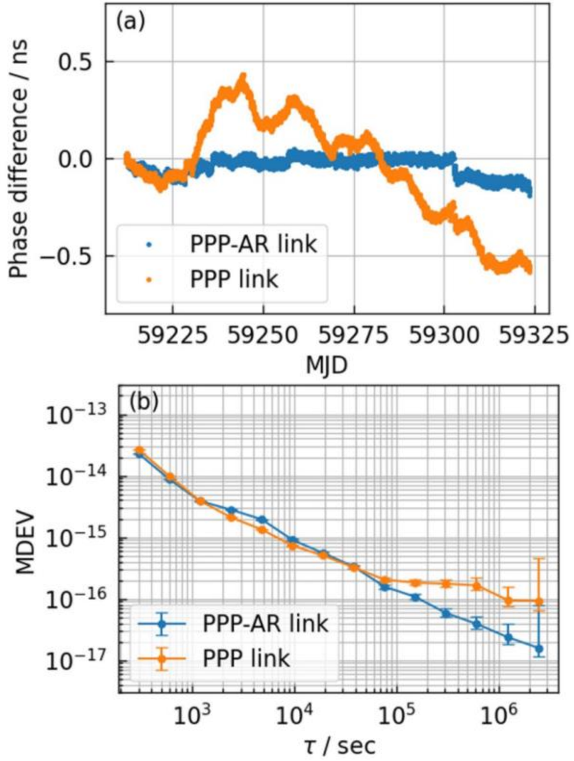
BIPM = International Bureau of Weights and Measures
PTB = Physikalisch-Technische Bundesanstalt, Germany

UTC Time Links: GNSS

- ❑ Geodetic multi-frequency GPS receivers
- ❑ Common-view used until 2006.
- ❑ In 2004 IGS introduces high-precision GPS clock products
  ➡ All-in view
- ❑ Precise Point Positioning (PPP) since 2009.
- ❑ Smallest statistical uncertainty 0.3 ns. Calibration 1.5 ns.
- ❑ PPP-AR in the near future?

Panfilo and Arias, Metrologia 56 042001 (2019)

Common clock, short baseline

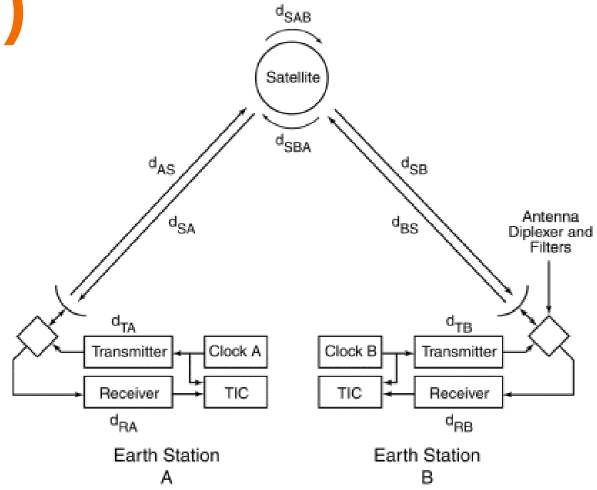


Jiang et al., Metrologia 60, 065002 (2023)

UTC Time Links: Two-Way Satellite Time and Frequency Transfer (TWSTFT)

- ❑ Introduced in 1999.
- ❑ Uses geostationary telecommunications satellite.
- ❑ Clocks compared simultaneously for two hours each day.
- ❑ Small number of links (12%) due to:
  - ❑ High cost (equipment and satellite service)
  - ❑ Operational complexity
- ❑ Statistical uncertainty < 1 ns. Calibration uncertainty 1 ns.

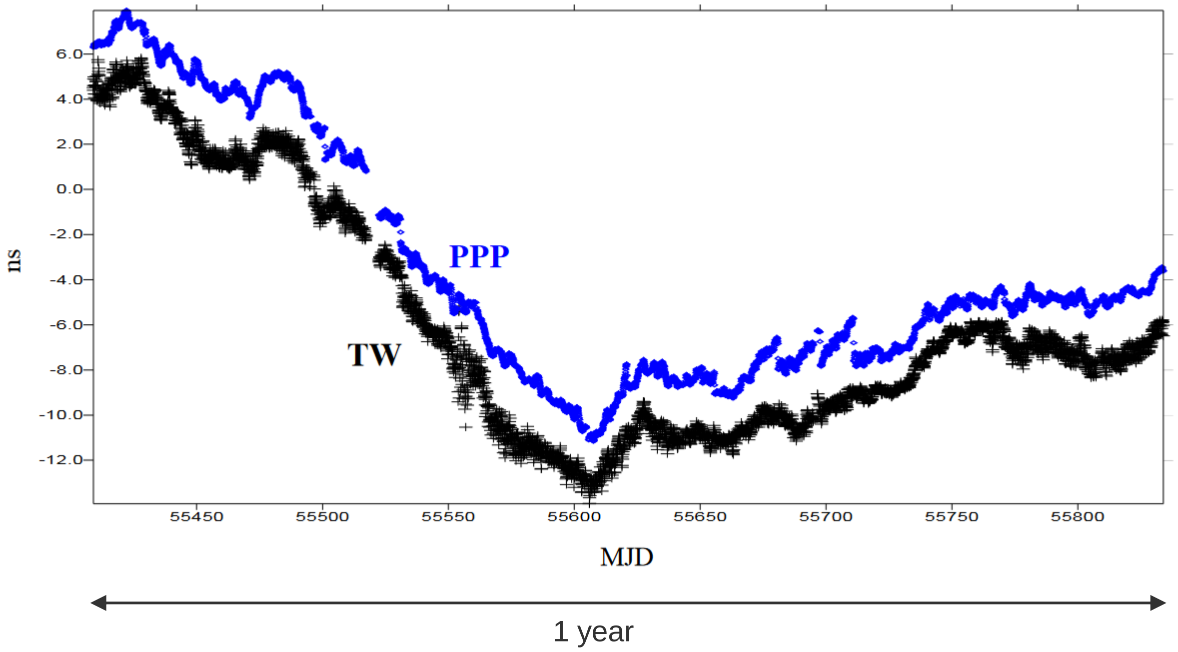
Panfilo and Arias, Metrologia 56 042001 (2019)]



LNE-SYRTE, Paris

UTC Time Links: Two-Way vs GPS PPP

NIST-PTB baseline

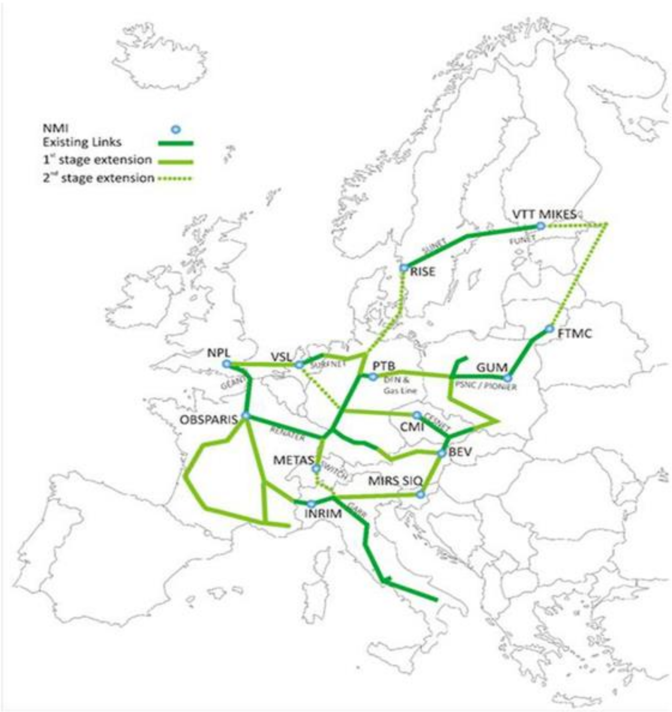


Jiang and Lewandowski, Rapport BIPM-2011/07

UTC Time Links: Fiber links

- <10^{-18} frequency uncertainty over continental distances
- Many different techniques
  - microwave (radio-over-fibre)
  - coherent optical
- Only two fibre links report data to BIPM (2019)

CLONETS



Circular-T

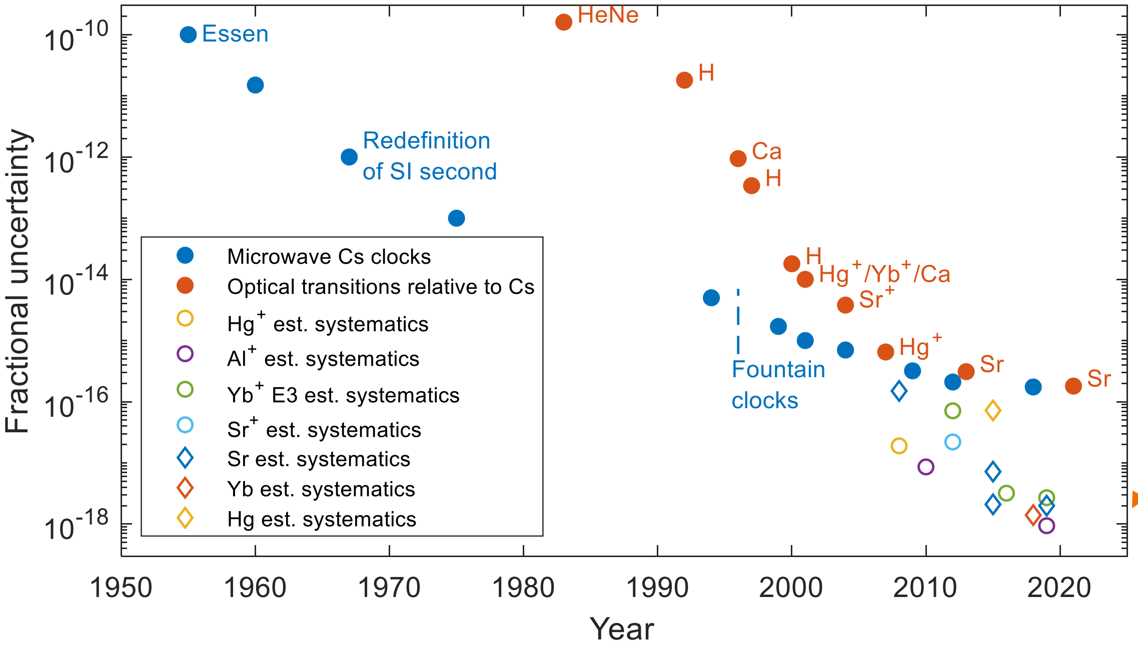
CIRCULAR T 357 ISSN 1143-1393
2017 OCTOBER 10, 13h UTC
BUREAU INTERNATIONAL DES POIDS ET MESURES
ORGANISATION INTERGOUVERNEMENTALE DE LA CONVENTION DU METRE
PAVILLON DE BRETEUIL F-92312 SEVRES CEDEX TEL. +33 1 45 07 70 70 FAX. +33 1 45 34 20 21 tai@bipm.org

The contents of the sections of BIPM Circular T are fully described in the document "Explanatory supplement to BIPM Circular T" available at ftp://ftp2.bipm.org/pub/tai/publication/notes/explanatory_supplement_v0.1.pdf

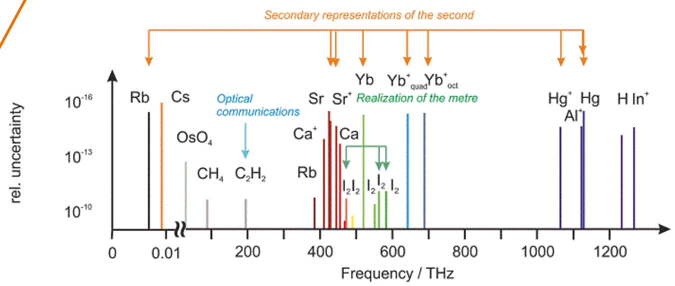
1 - Difference between UTC and its local realizations UTC(k) and corresponding uncertainties.
From 2017 January 1, 0h UTC, TAI-UTC = 37 s.

Date 2017 0h UTC	AUG 29	SEP 3	SEP 8	SEP 13	SEP 18	SEP 23	SEP 28	Uncertainty/ns			Notes
MJD	57994	57999	58004	58009	58014	58019	58024	uA	uB	u	
Laboratory k	[UTC-UTC(k)]/ns										
JV (Kjeller)	4.8	-6.2	-17.2	-16.6	-17.6	-19.0	-19.6	0.4	20.0	20.0	
KEBS (Nairobi)	-	-	-	-	-	-	-				
KIM (Serpong-Tangerang)	141.1	168.3	169.5	174.4	188.4	200.4	173.8	2.0	20.0	20.1	
KRIS (Daejeon)	35.5	40.3	44.3	47.7	50.6	52.2	52.9	0.4	11.1	11.1	
KZ (Astana)	-294.7	-322.8	-334.3	-331.1	-313.3	-298.9	-301.0	1.5	9.3	9.4	
LT (Vilnius)	158.7	144.0	145.4	157.0	152.5	168.8	181.8	2.0	11.3	11.4	
MASM (Bayanzurkh)	-411.6	-428.7	-451.6	-	-	-34.5	-60.0	0.7	20.0	20.1	
MBM (Podgorica)	51657.3	51989.6	52323.7	52643.4	52978.9	53335.9	53658.6	1.5	20.0	20.1	
MIKE (Espoo)	-0.4	-0.3	0.5	0.5	0.8	-0.2	-0.7	0.7	4.2	4.3	
MKEH (Budapest)	-65005.0	-65222.3	-65420.4	-65627.5	-65836.7	-66030.7	-66237.0	1.5	20.0	20.1	
MSL (Lower Hutt)	285.3	289.9	309.0	301.6	285.8	300.7	321.8	1.5	20.0	20.1	
MTC (Makkah)	1149.2	1164.1	1145.4	1170.6	1149.7	1204.2	1187.0	10.0	7.4	12.4	
NAO (Mizusawa)	99.4	86.1	93.0	95.8	97.0	89.5	75.7	2.0	20.0	20.1	
NICT (Tokyo)	-5.7	-5.8	-7.5	-6.9	-5.9	-4.2	-1.9	0.4	2.2	2.3	
NIM (Beijing)	5.2	4.5	3.8	3.3	3.9	3.7	2.9	0.7	1.9	2.0	
NIMB (Bucharest)	1813.1	1816.1	1803.5	1816.4	1818.9	1814.2	1808.5	0.4	7.2	7.2	
NIMT (Pathumthani)	203.3	208.9	214.5	217.7	219.5	218.6	221.5	1.0	20.0	20.1	
NIS (Cairo)	11.9	8.4	2.4	-19.9	-30.1	-48.5	-55.3	1.6	20.0	20.1	
NIST (Boulder)	0.5	0.6	1.1	1.7	2.2	2.2	1.4	0.4	4.9	4.9	

Historical evolution



- Time and frequency are the most accurately measurable quantities
- 10^{-18} uncertainty in f ↔ order of 1 s during the age of the universe!
- Many atoms/ions as SRS



1973 Optical single-ion frequency standards proposed by Dehmelt

1980s Experimental single-ion work (NBS/NIST, NRC, NPL,PTB)

2000 Optical frequency comb

2006- Optical transitions chosen as secondary representations of the second

2011- VTT MIKES ion-clock work

Optical atomic clocks

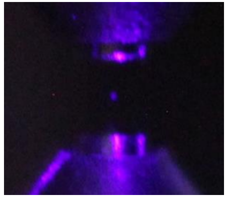
VTT

- Clock instability:
  - (quantum projection noise limited)

$$\sigma_y(\tau) \approx \frac{\Delta\nu}{\nu_0}\frac{1}{\sqrt{N}}\sqrt{\frac{T_c}{\tau}}$$

microwave vs optical
400 THz vs 9 GHz

- Two different kinds of atomic reference:
  - Single ion in radio-frequency trap:
    - ’ideal’ isolated quantum system
    - low SNR ($N = 1$)

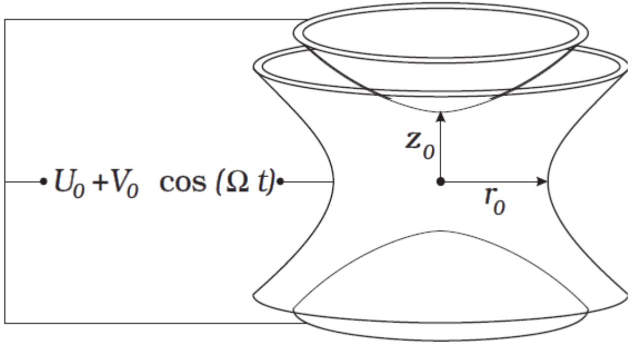


  - Neutral atoms in optical lattice:
    - interactions (atom-atom and atom-light) make analysis much more difficult
    - experimentally more involved (more and higher-power lasers, larger atom oven, water-cooled coils etc.)
    - better SNR ($N = 10^3 \ldots 10^4$)

$$\sigma_y(\tau) \approx \frac{\Delta\nu}{\nu_0}\frac{1}{\sqrt{N}}\sqrt{\frac{T_c}{\tau}}$$

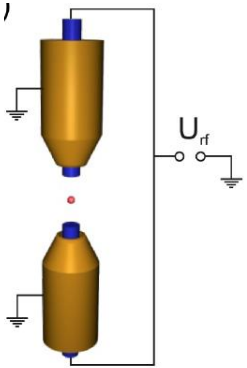
- $^{88}Sr^+$ was chosen for its ’simplicity’

Radio-frequency ion traps



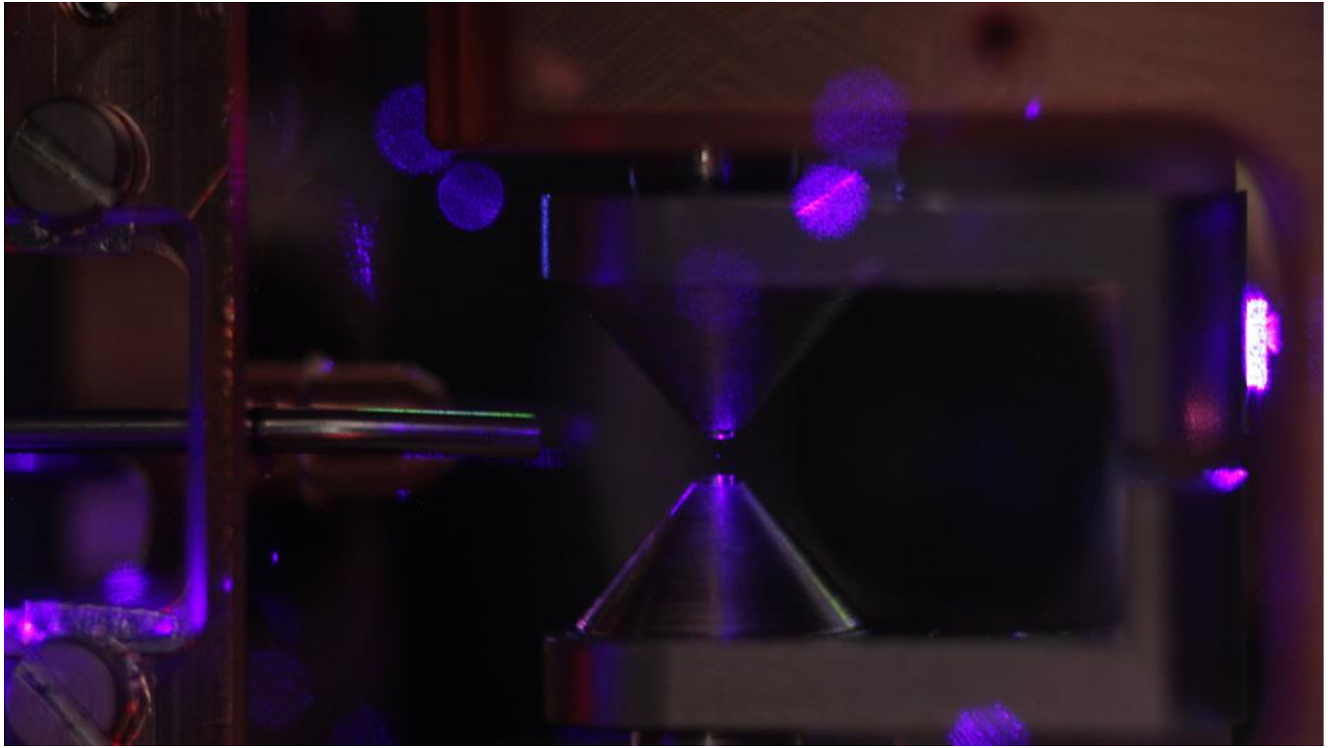
Hyperbolic Paul trap (1953): ’infinite’ electrodes
=> ideal quadrupole potential

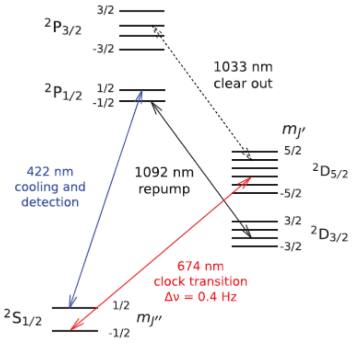
Ring trap for improved
optical access (PTB)

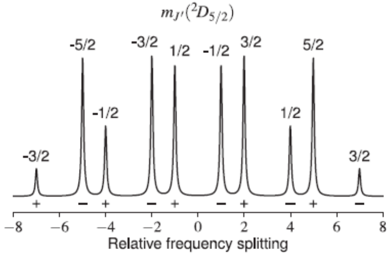


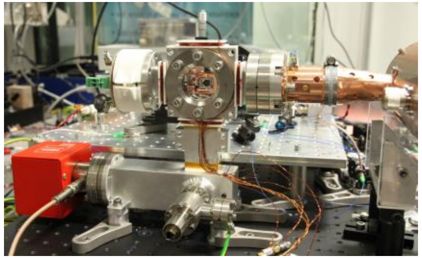
Endcap trap: even better
optical access

Sr⁺ single-ion “clock”









Preliminary uncertainty budget: October 2023

VTT

Source	Shift (1e-18)	Unc. (1e-18)
Blackbody radiation E1 shift	513.11	
BBR field		0.38
differential polarizability		0.76
dynamic correction		0.07
Blackbody radiation M1 shift	-0.0101	0.0002
Collisional shift	0	0.22
Thermal motion	-1.58	0.63
Electric quadrupole shift	0	0.069
Excess micromotion	0	0.003
Tensor Stark shift	0	0.001
1092-nm ac Stark shift	-0.40	0.40
674-nm E1 ac Stark shift	0.01	0.01
674-nm E2 ac Stark shift	0	0.06
Quadratic Zeeman shift, applied B	0.1632	0.0032
Quadratic Zeeman shift, rf B	0	0.000 01
AOM chirp	-0.2	0.1
First-order Doppler shift	0	0.3
Servo errors	0	0.1
TOTAL:	**511.1**	**1.2**

BBR shift updated dynamically

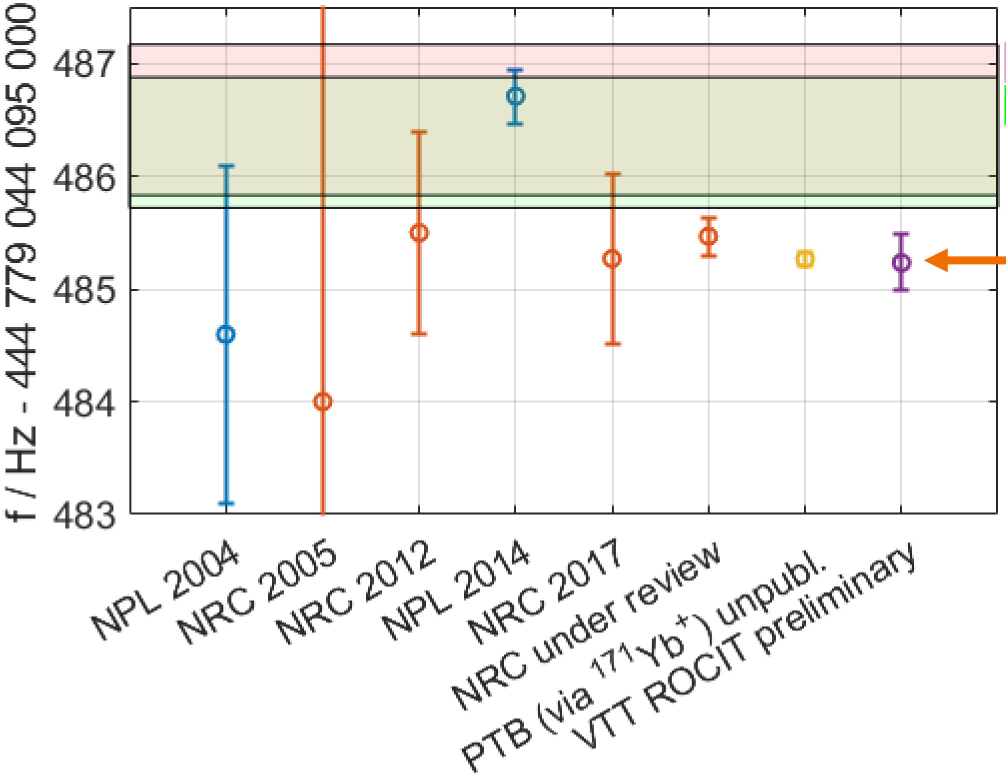
efficient cancellation schemes

will be reduced by MEMS switch

$^{88}Sr^{+}$ has extremely low sensitivity

$^{88}Sr^{+}$ has great potential with BBR under control!

Absolute frequency measurement against TAI during March 2022 campaign



CIPM 2017: … … 486.5 Hz (u=1.5e-15)

CIPM 2021: … … 486.3 Hz (u=1.3e-15)

Our preliminary value in excellent agreement with recent unpublished values from NRC and PTB

- Recommended $^{88}Sr^{+}$ SRS frequency strongly dominated by lowest-uncertainty published value.
- Recent unpublished NRC, PTB, and VTT values **disagree with CIPM 2021**.

Applications
-new physics

LETTER 204 | NATURE | VOL 567 | 14 MARCH 2019
https://doi.org/10.1038/s41586-019-0972-2

Optical clock comparison for Lorentz symmetry testing

Christian Sanner[1,5*], Nils Huntemann[1], Richard Lange[1], Christian Tamm[1], Ekkehard Peik[1], Marianna S. Safronova[2,3] & Sergey G. Porsev[2,4]

Selected for a Viewpoint in *Physics*
PRL **113,** 210802 (2014) PHYSICAL REVIEW LETTERS week ending 21 NOVEMBER 2014

Improved Limit on a Temporal Variation of m_p/m_e from Comparisons of Yb^+ and Cs Atomic Clocks

N. Huntemann, B. Lipphardt, Chr. Tamm, V. Gerginov, S. Weyers, and E. Peik*

Selected for a Viewpoint in *Physics*
PRL **113,** 210801 (2014) PHYSICAL REVIEW LETTERS week ending 21 NOVEMBER 2014

Frequency Ratio of Two Optical Clock Transitions in $^{171}Yb^+$ and Constraints on the Time Variation of Fundamental Constants

R. M. Godun,[1,*] P. B. R. Nisbet-Jones,[1] J. M. Jones,[1,2] S. A. King,[1] L. A. M. Johnson,[1] H. S. Margolis,[1] K. Szymaniec,[1] S. N. Lea,[1] K. Bongs,[2] and P. Gill[1]

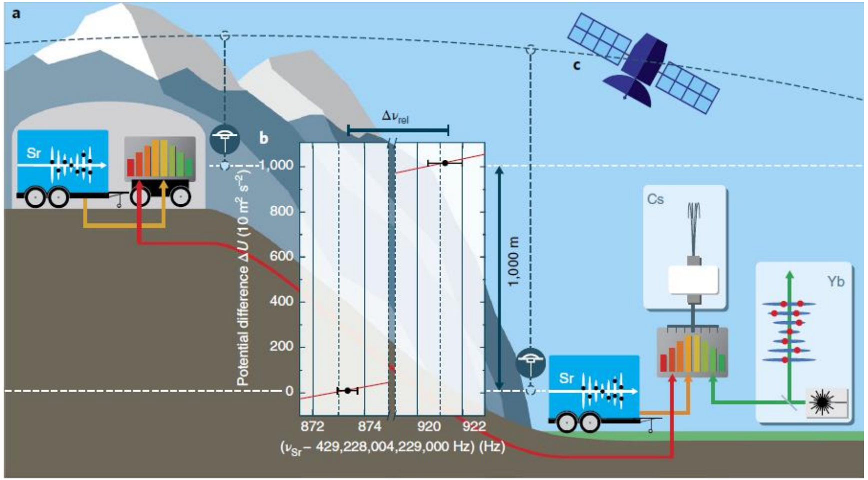
Applications
-Relativistic geodesy

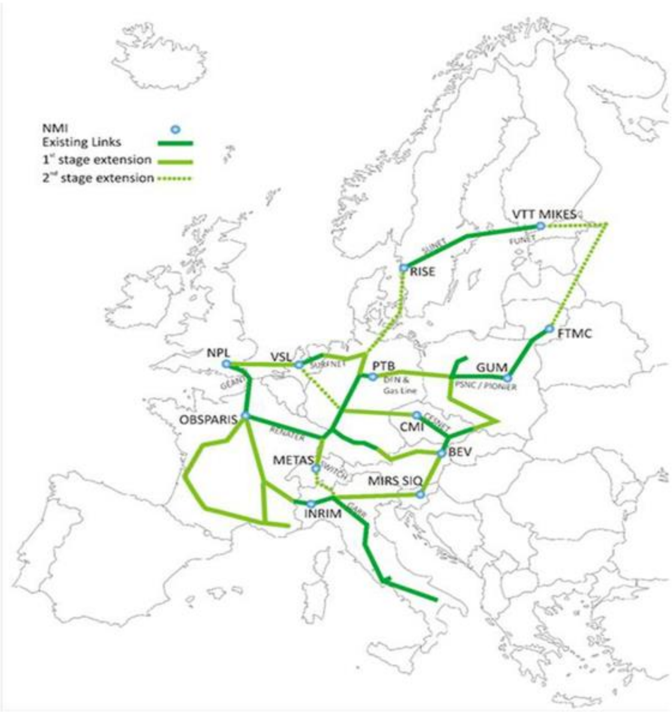
CLONETS

Geodesy and metrology with a transportable optical clock

NATURE PHYSICS | VOL 14 | MAY 2018 | 437–441 |

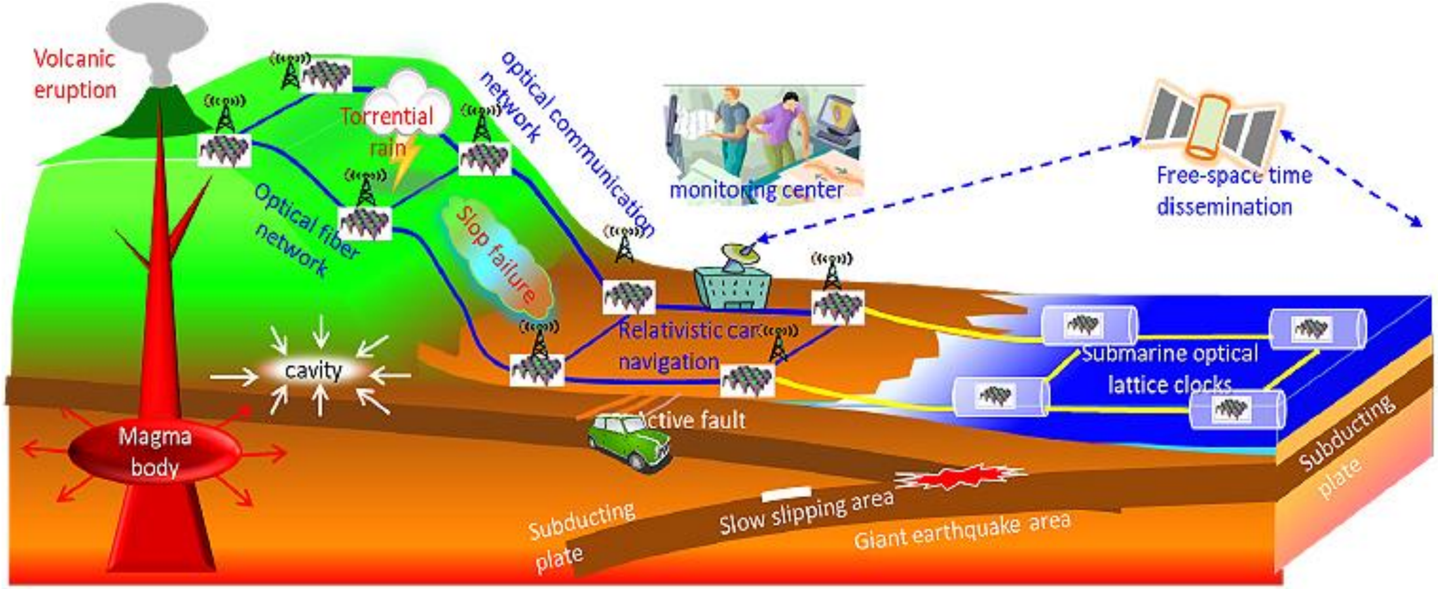
Jacopo Grotti[1], Silvio Koller[1], Stefan Vogt[1], Sebastian Häfner[1], Uwe Sterr[1], Christian Lisdat[1*], Heiner Denker[2], Christian Voigt[2,3], Ludger Timmen[2], Antoine Rolland[4], Fred N. Baynes[4], Helen S. Margolis[4], Michel Zampaolo[5], Pierre Thoumany[6], Marco Pizzocaro[6], Benjamin Rauf[6,7], Filippo Bregolin[6,7], Anna Tampellini[6,7], Piero Barbieri[6,7], Massimo Zucco[6], Giovanni A. Costanzo[6,7], Cecilia Clivati[6], Filippo Levi[6] and Davide Calonico[6]





$\Delta f/f = 10^{-18}$ ⟷ $\Delta h = 1$ cm

Applications
-Relativistic geodesy

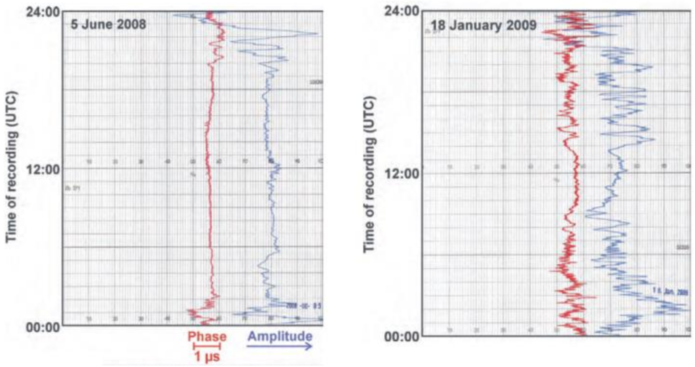


H. Katori et al., Space-time information platform with a cloud of optical lattice clocks (Japan)

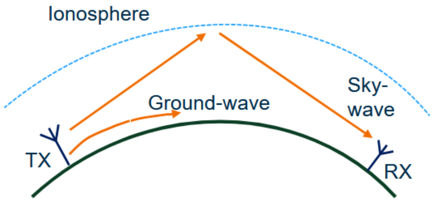
$\Delta f/f=10^{-18}$ ⟷ $\Delta h=1$ cm

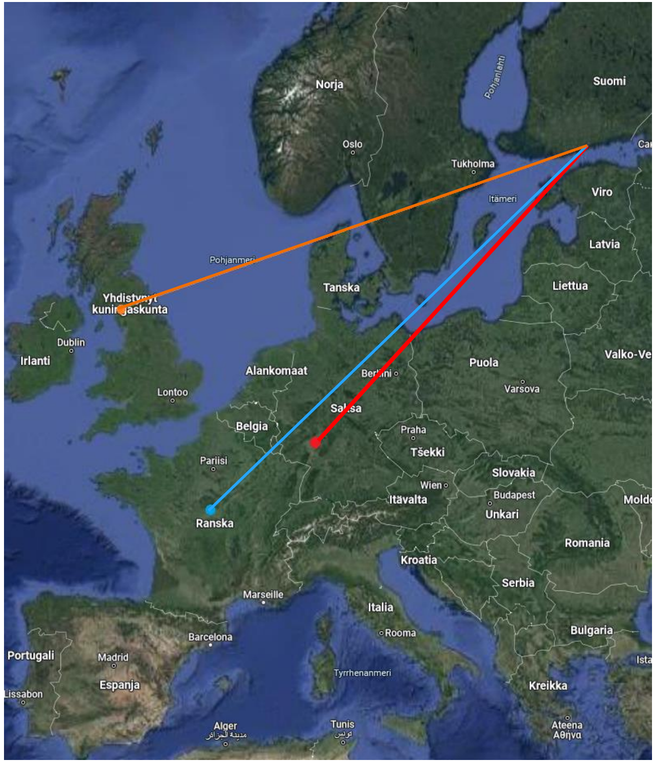
Time Services:
Low-Frequency Time Transfer

- DCF77 started in 1959.
  - 77kHz, AM and PM



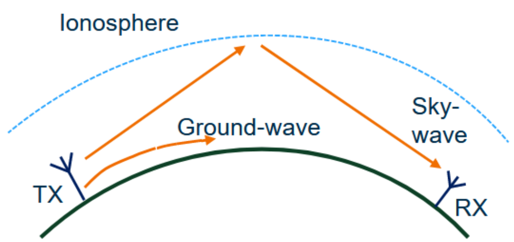
Bauch et al., PTB Mitteilungen 119, 3 (2009)



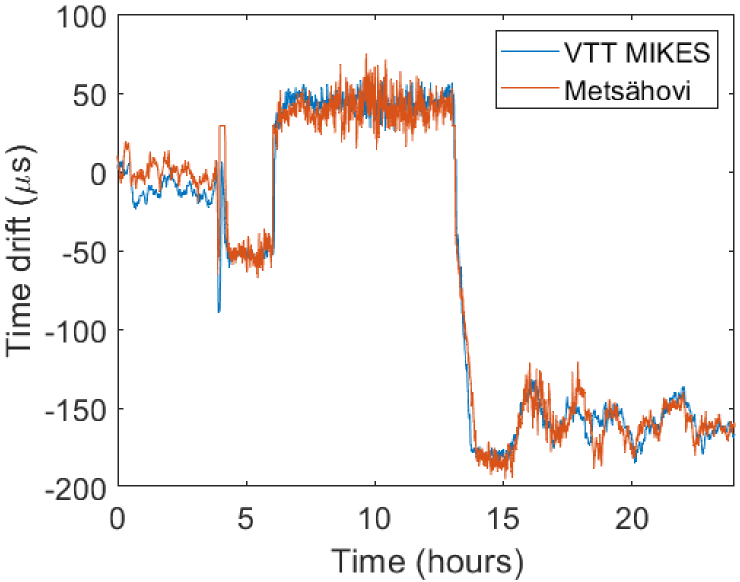


- DCF77, Germany ~1500 km, 77.5 kHz
- MSF, UK, ~1800 km, 60 kHz
- TDF, France, ~2000 km, 162 kHz

Low-Frequency Time Transfer



- DCF77 @ VTT MIKES vs Metsähovi



=> With augmentation a backup for GNSS ?

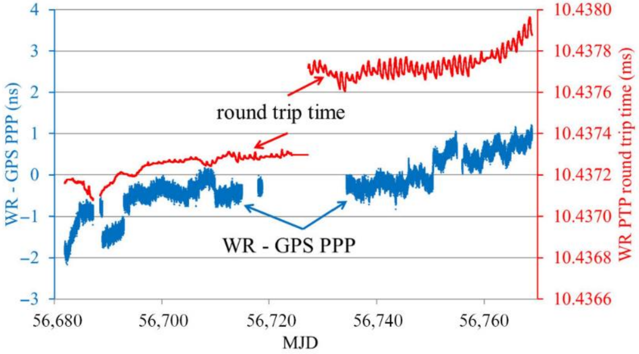
Fiber-Optic Time Services

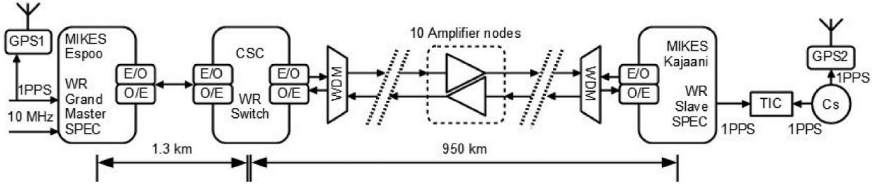
NTP: milliseconds
(software time-stamping)

PTP: microseconds
(hardware time-stamping)

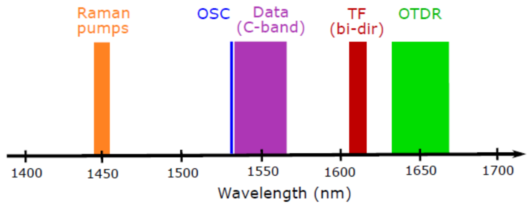
PTP White Rabbit: < nanoseconds
(hardware time-stamping enhanced
by precise phase-measurement)

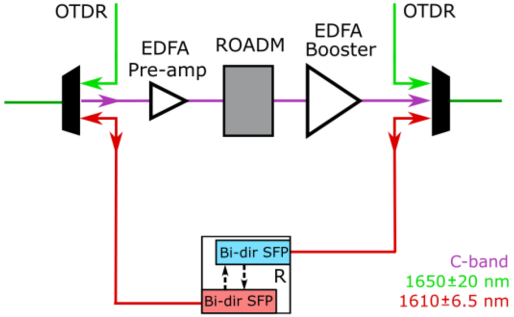
Specialized solutions: ps (…fs…as).



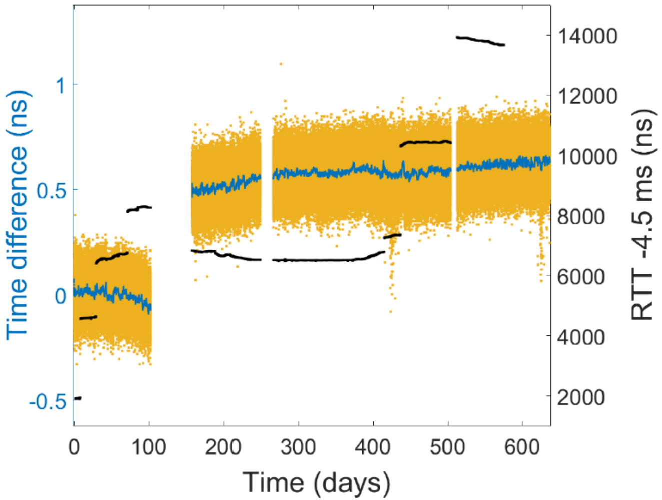


WR PTP Kajaani-Oulu





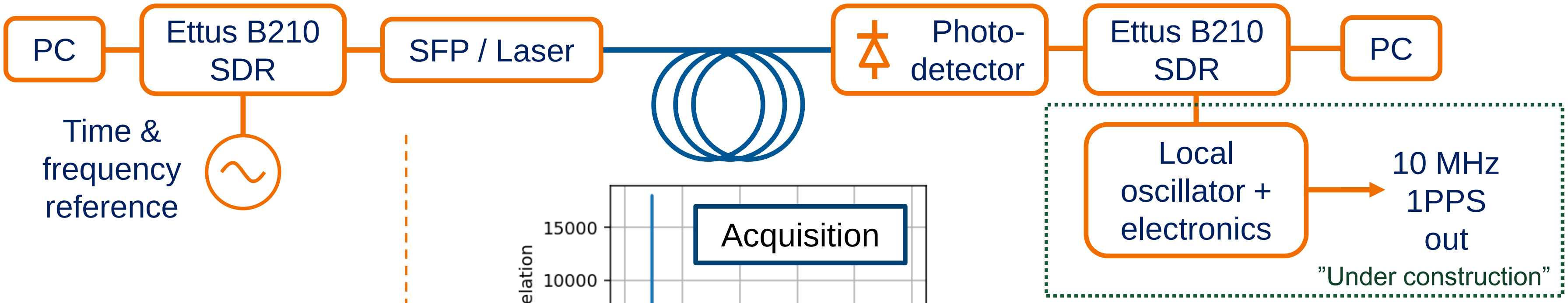
Kajaani-Oulu-Kajaani 2x228km



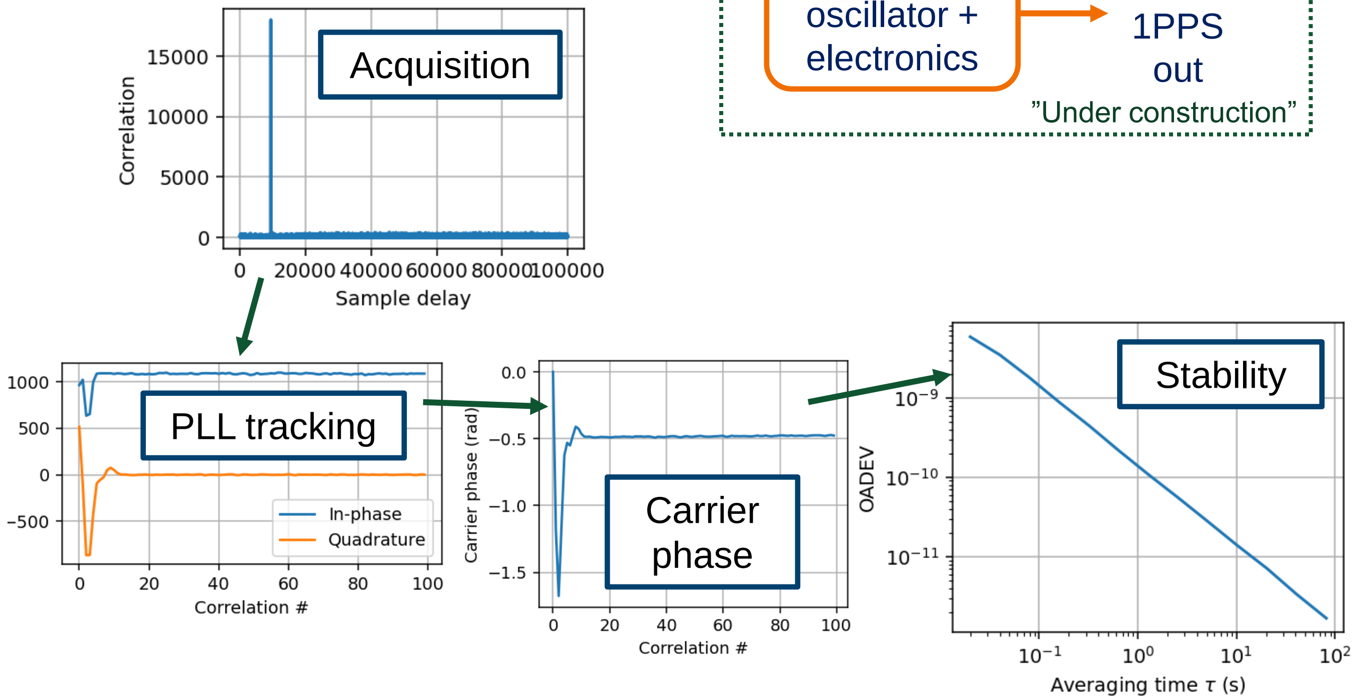
Optical-Electrical-Optical amplification
+ High-gain (>30 dB)
+ Signal reshaping
- Wavelength drift => symmetric repeater

Fordell et al., IEEE Trans. Ultrason. Ferroelectr. Freq. Control (2023)

GNSS-style fiber-optic time transfer



- Long-distance time transfer over fiber using GPS L1 -style spread spectrum signal
- Signal is BPSK-modulated with pseudorandom bit sequence of desired length
- Planned to work with low signal strengths, beyond the normal range of fiber-optic transceivers
- Max. sample rate and attenuation ultimately limit performance (to be characterized)



Conclusions

- Lots of activity in developing optical frequency standards
  - Fundamental science
    - New physics (dark matter, temporal variation of physical constants, symmetry violations,…)
    - Relativistic geodesy
    - Low-frequency gravitational wave observatories
  - Time keeping
    - Only a few report regularly to BIPM

- Fibre-optic time and frequency transfer
  - Continental distances
  - Best performance with symmetric, single-fibre, out-of-band solutions
  - Loss-tolerant ”GNSS-type” solutions needed for wider availability?

- Augmented low-frequency time signals as backup for GNSS