Accurate Optical Time Transfer between a Clock on Ground and in Space

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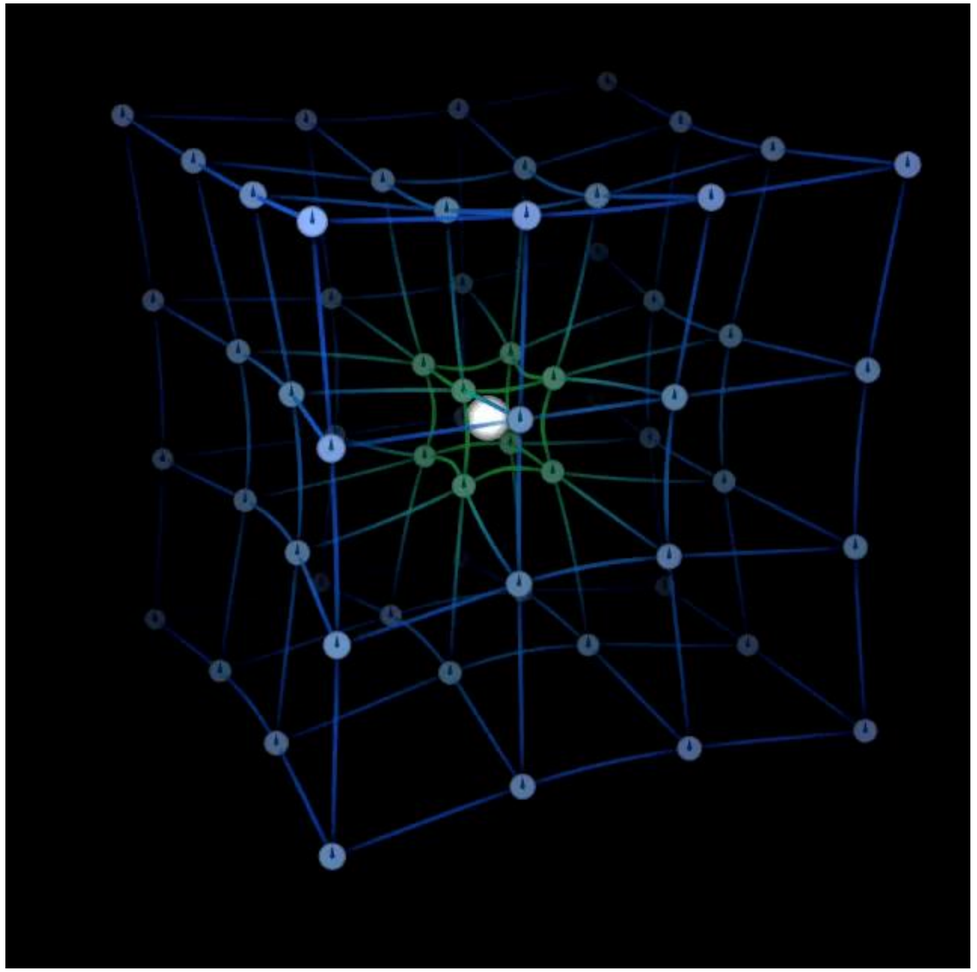
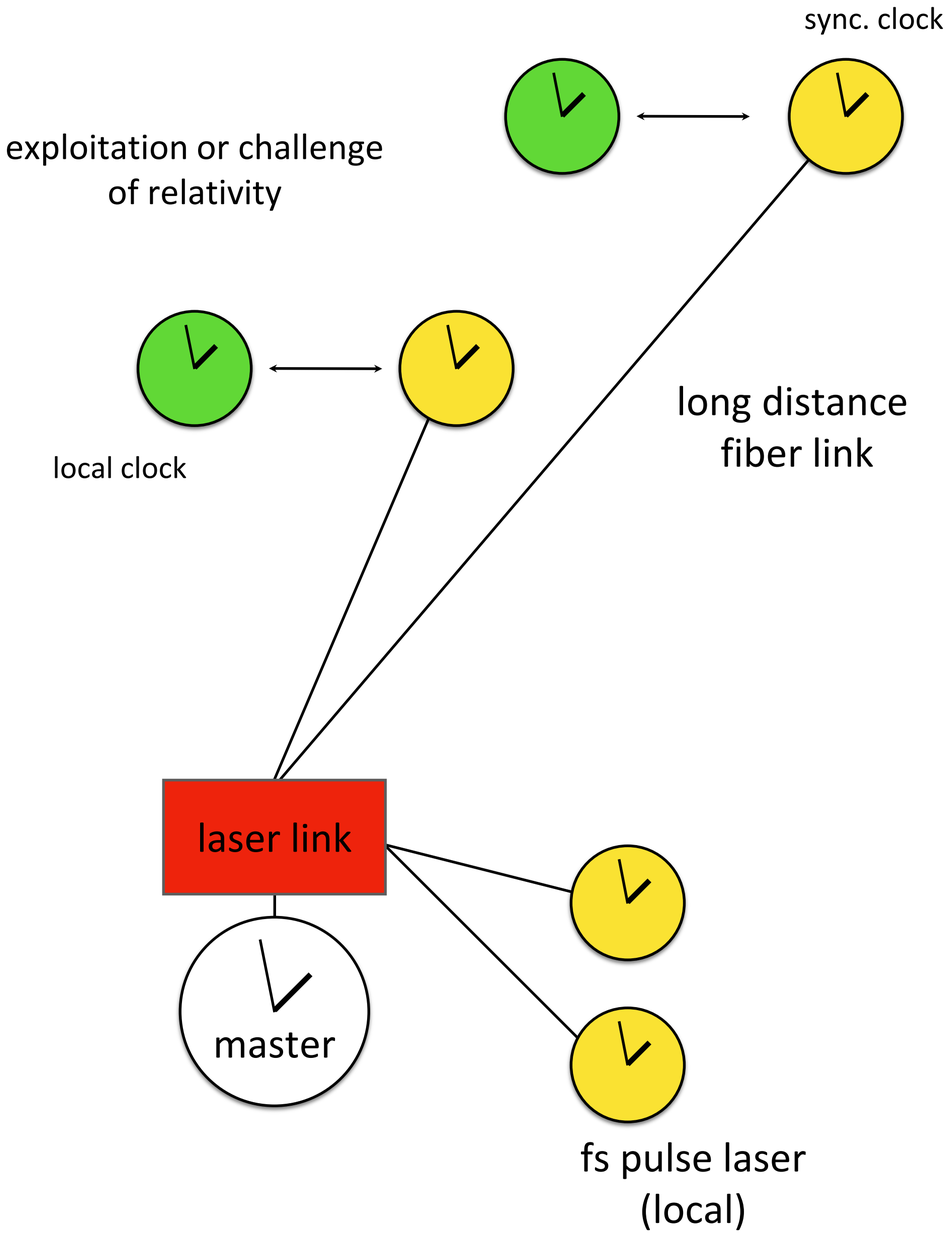
The Optical Time Transfer between a H-maser on the ground and the atomic clock ensemble in space (ACES) via the ELT interface, requires two concatenated highly stable two way laser links. While the use of satellite laser ranging provides both the range information and the reading (epoch) of the remote clock by a free space laser link relative to the geometrical reference points on the ground and the satellites, another actively stabilized fiber based ground link provides the accurate time reference between the H-maser on the ground and the ranging system. Once the local reference target at the ranging site is also equipped with similar two-way compensated timing reference, it is possible to identify and remove systematic errors to within 1 ps caused by otherwise not detectable system delays. We report on a lossless time and frequency distribution system that delivers this functionality.



https://imgur.com/RaWqYkV

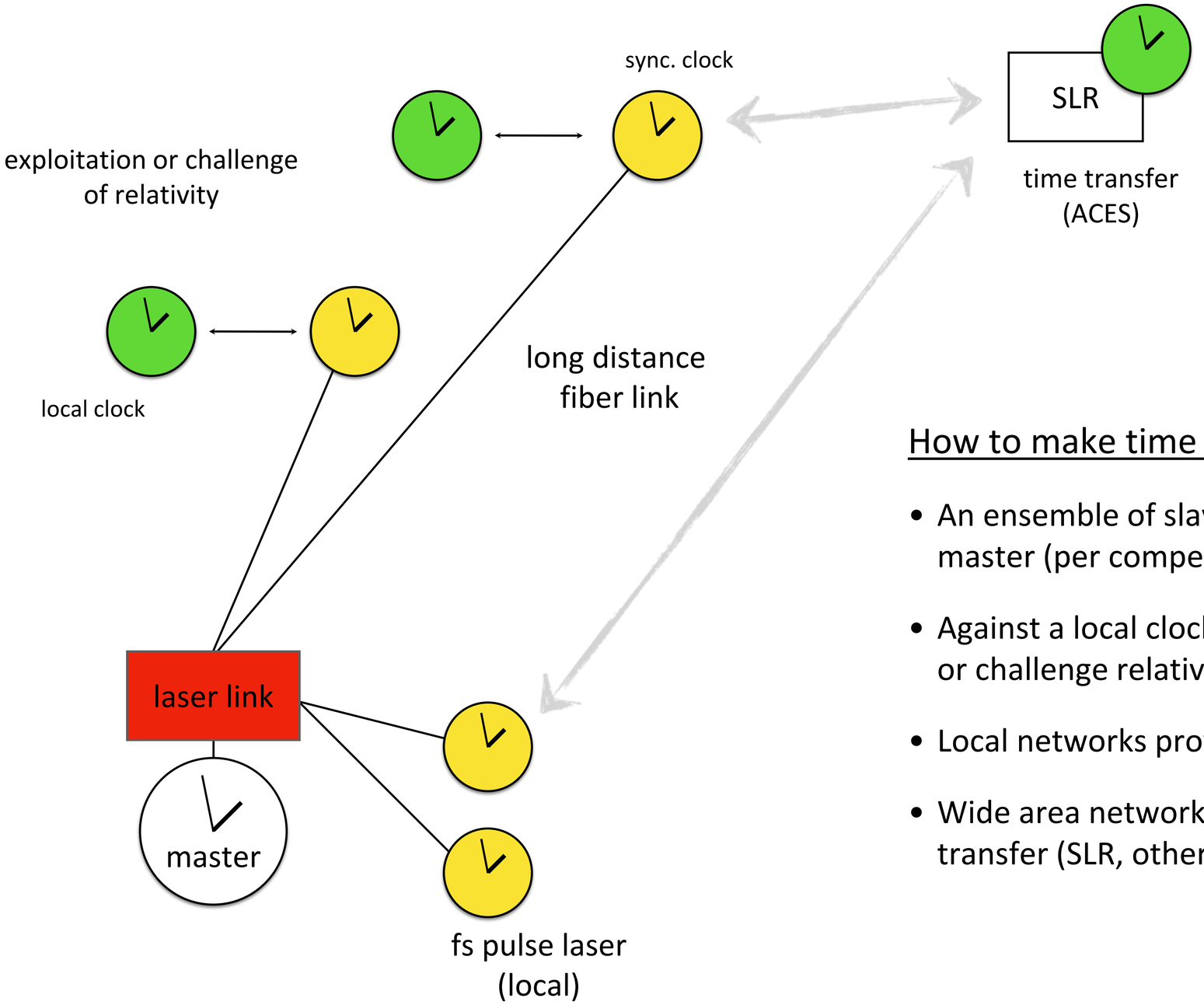
The value of optical time transfer

- Clocks probe the local physics (gravity and velocity)
- Clock oscillator performance demonstrated to 1 part in 10^{18}
- Frequency transfer over fiber links theoretically stable to 1 part 10^{19}
- Optical time transfer (ground to satellite on T2L2 ≈ 7 ps @ 30s)
- Coherent optical round trip time transfer (2 km free space on ground: 1 fs @ 1000 s)
- 2-way optical time transfer on a compensated fiber link (600 m) achieved stability of 1 ps over a week.



How to make time an observable

- An ensemble of slave clocks are sync'ed to a master (per compensated fiber link)
- Against a local clock this can be used to exploit or challenge relativity
- Local networks provide time and frequency



How to make time an observable

- An ensemble of slave clocks are sync'ed to a master (per compensated fiber link)
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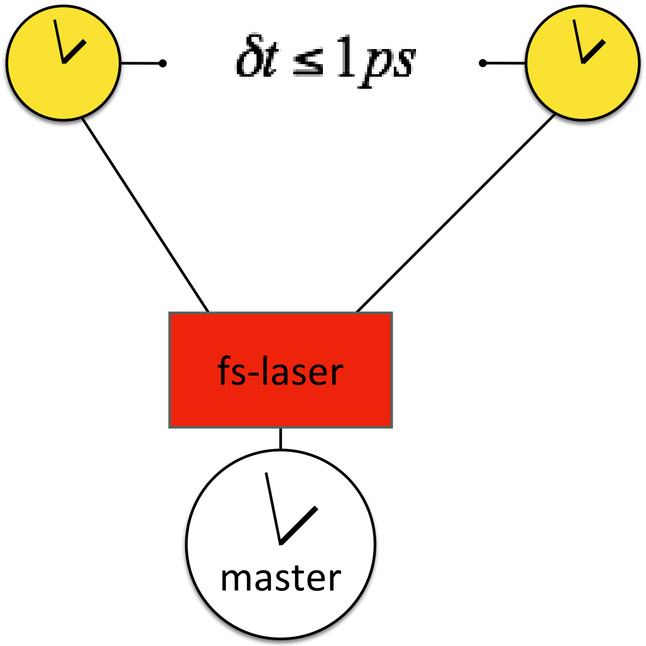
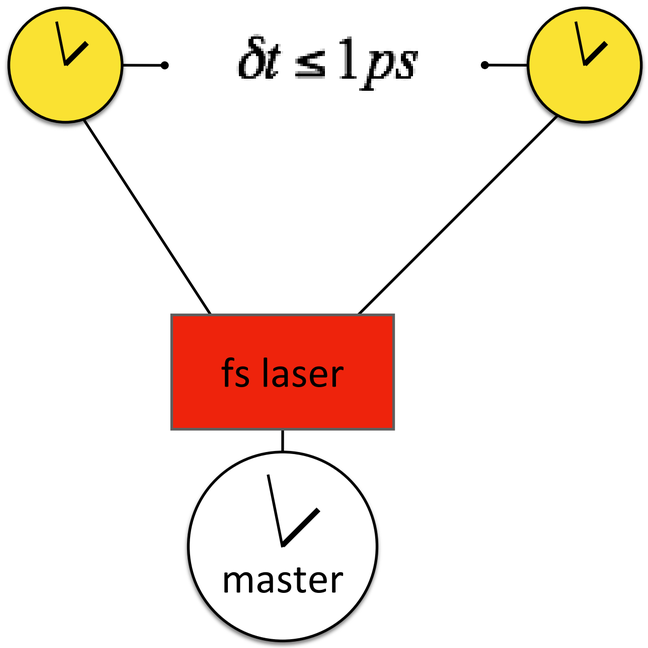
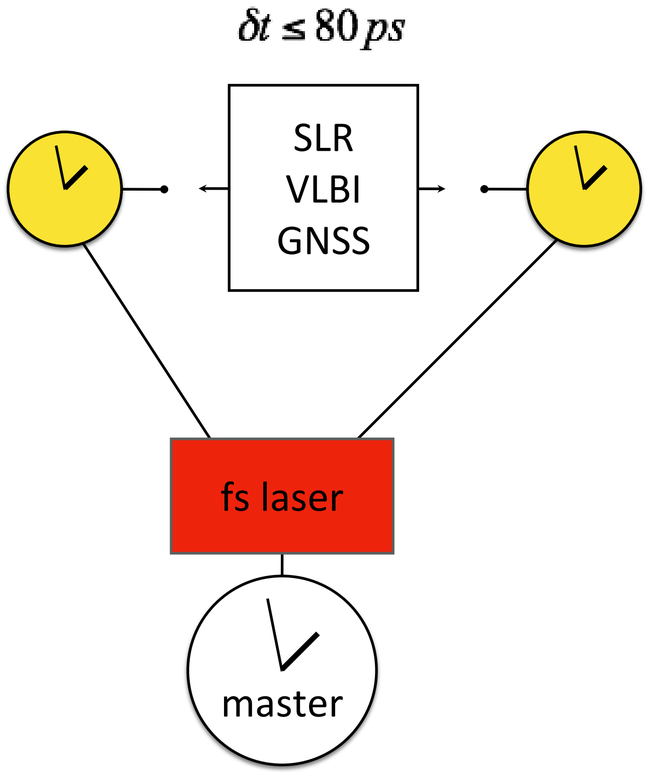
- Local networks provide time and frequency
- Wide area networks rely on optical time transfer (SLR, other?)

Probing System Performance utilizing Time



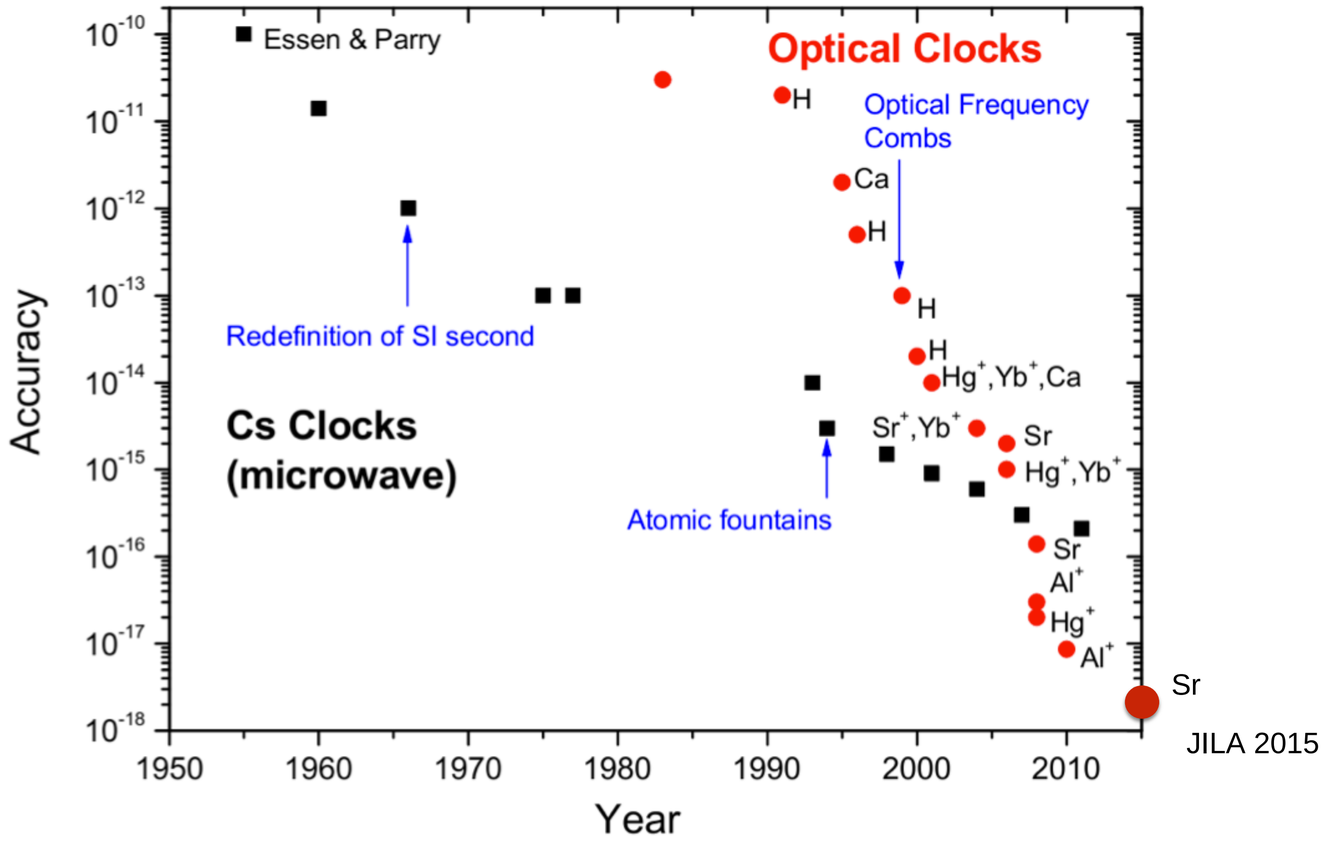
Probing System Performance utilizing Time





Building Block 1

Highly accurate clocks exploit frequency to utilize GR for a height system:

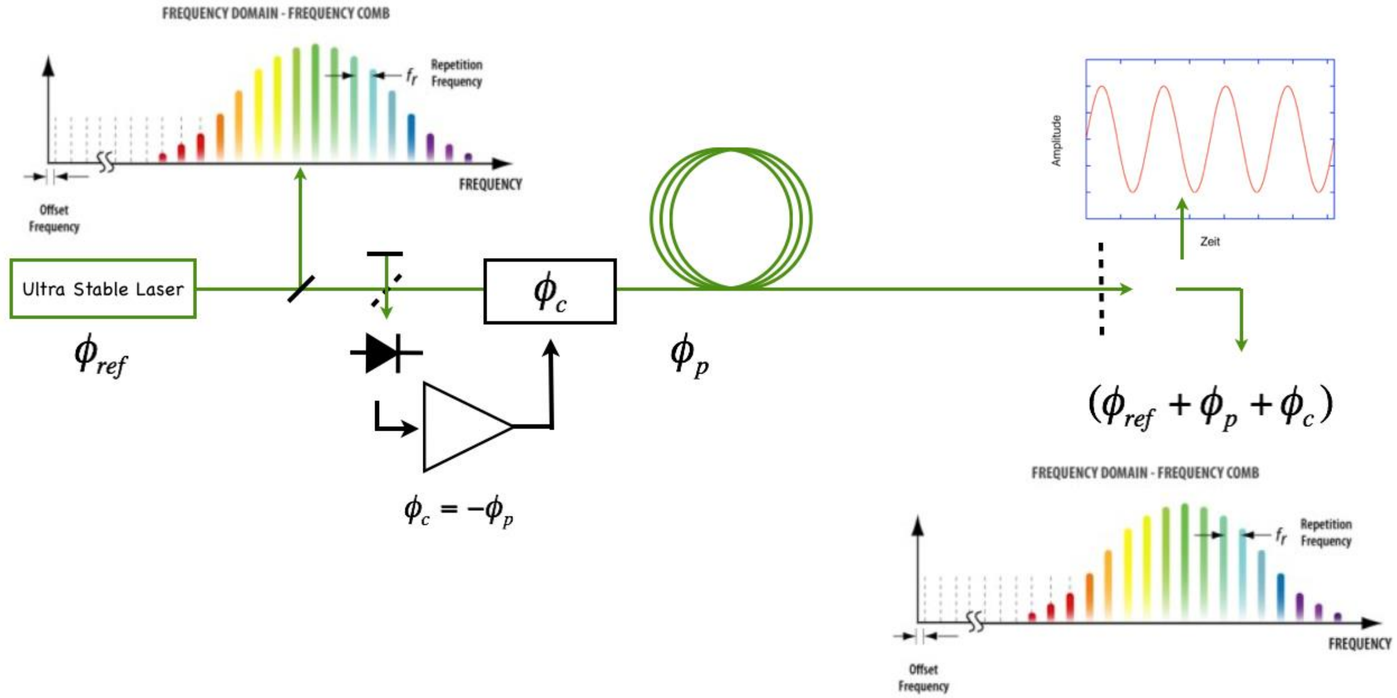


$$\Delta t' = (1 + \frac{g \cdot h}{c^2})\Delta t$$

“clock geodesy” -> Comparison with the PTB traveling Sr Clock and INRIM

Building Block 2

Accurate Comparison of remote optical oscillators by fiber link



Lossless Fiber Links for frequency transfer -> Clock comparison between NMI’s (PTB - Syrte - NPL)

How to compare two remote clocks… Einstein Synchronization!

3. Zur Elektrodynamik bewegter Körper; von A. Einstein.

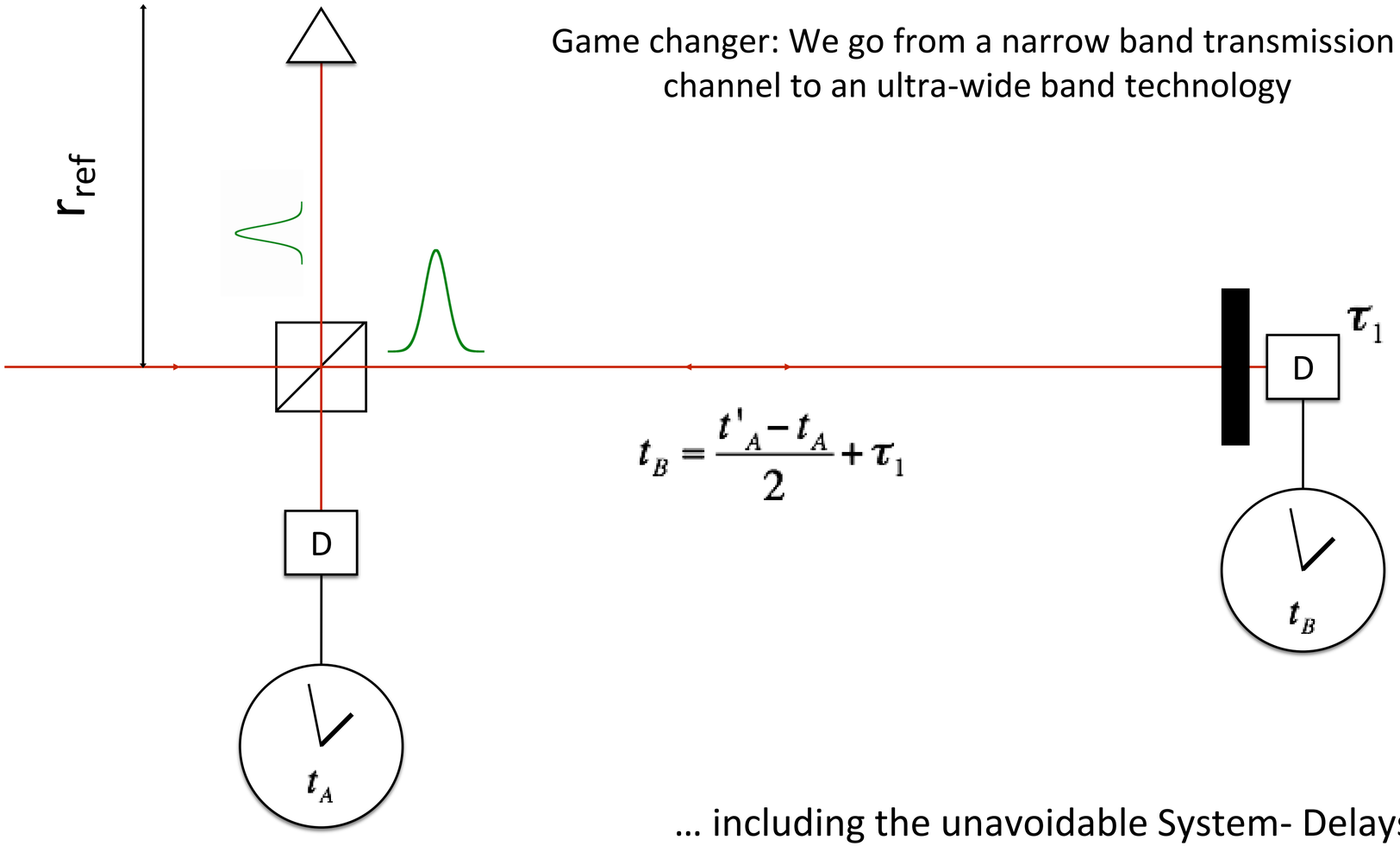
Die letztere Zeit kann nun definiert werden, indem man *durch Definition* festsetzt, daß die „Zeit“, welche das Licht braucht, um von A nach B zu gelangen, gleich ist der „Zeit“, welche es braucht, um von B nach A zu gelangen. Es gehe nämlich ein Lichtstrahl zur „A-Zeit“ t_A von A nach B ab, werde zur „B-Zeit“ t_B in B gegen A zu reflektiert und gelange zur „A-Zeit“ t'_A nach A zurück. Die beiden Uhren laufen definitionsgemäß synchron, wenn

$$t_B - t_A = t'_A - t_B.$$

Annalen der Physik. 17, 1905, S. 891–921

Isotropy of the speed of light!

SLR is the practical Realization of the Einstein Synchronization…



Game changer: We go from a narrow band transmission channel to an ultra-wide band technology

$$t_B = \frac{t'_A - t_A}{2} + \tau_1$$

… including the unavoidable System- Delays

Building Block 3

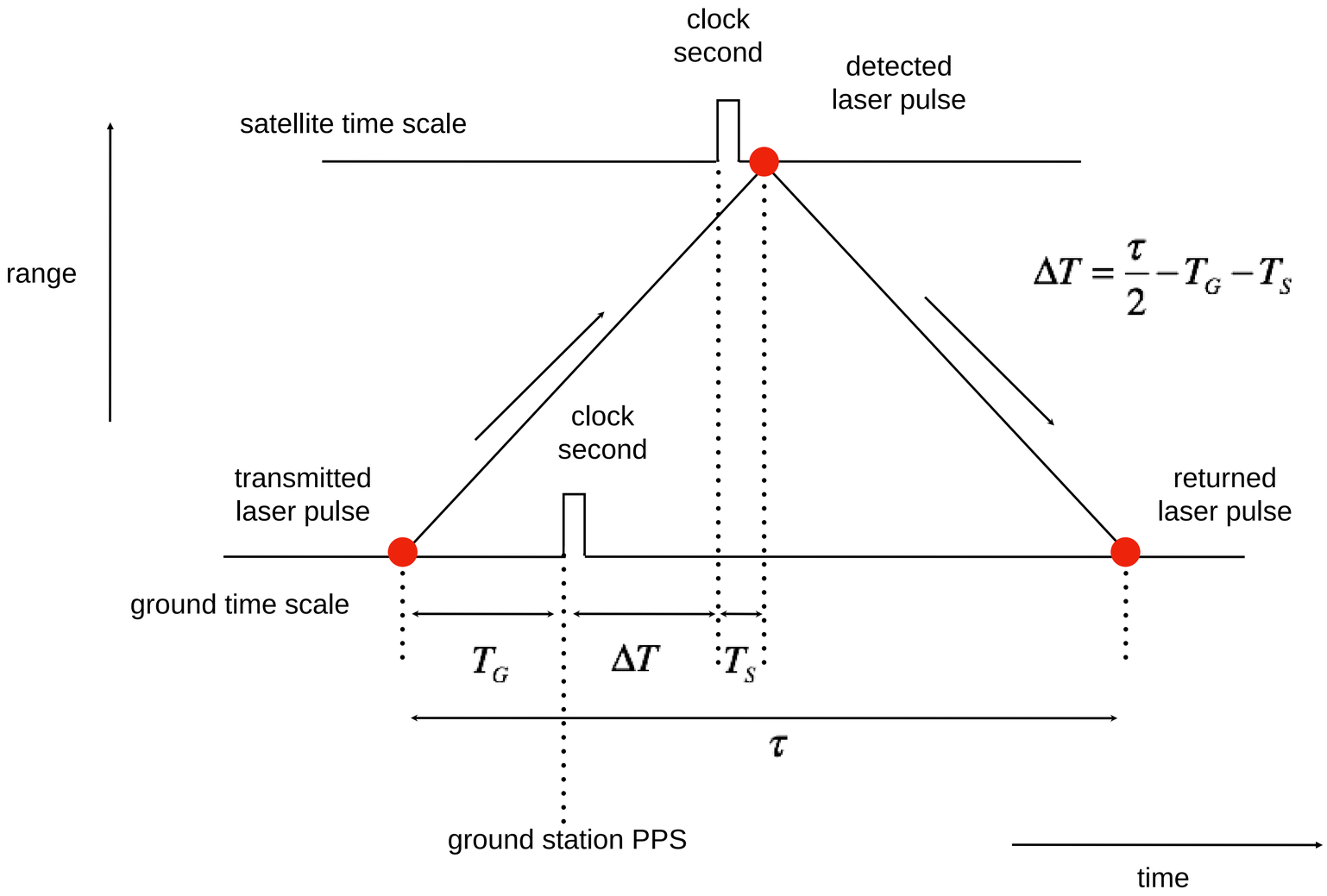
Accurate distribution of time (Einstein Synchronization)

satellite clock
(interpolator)

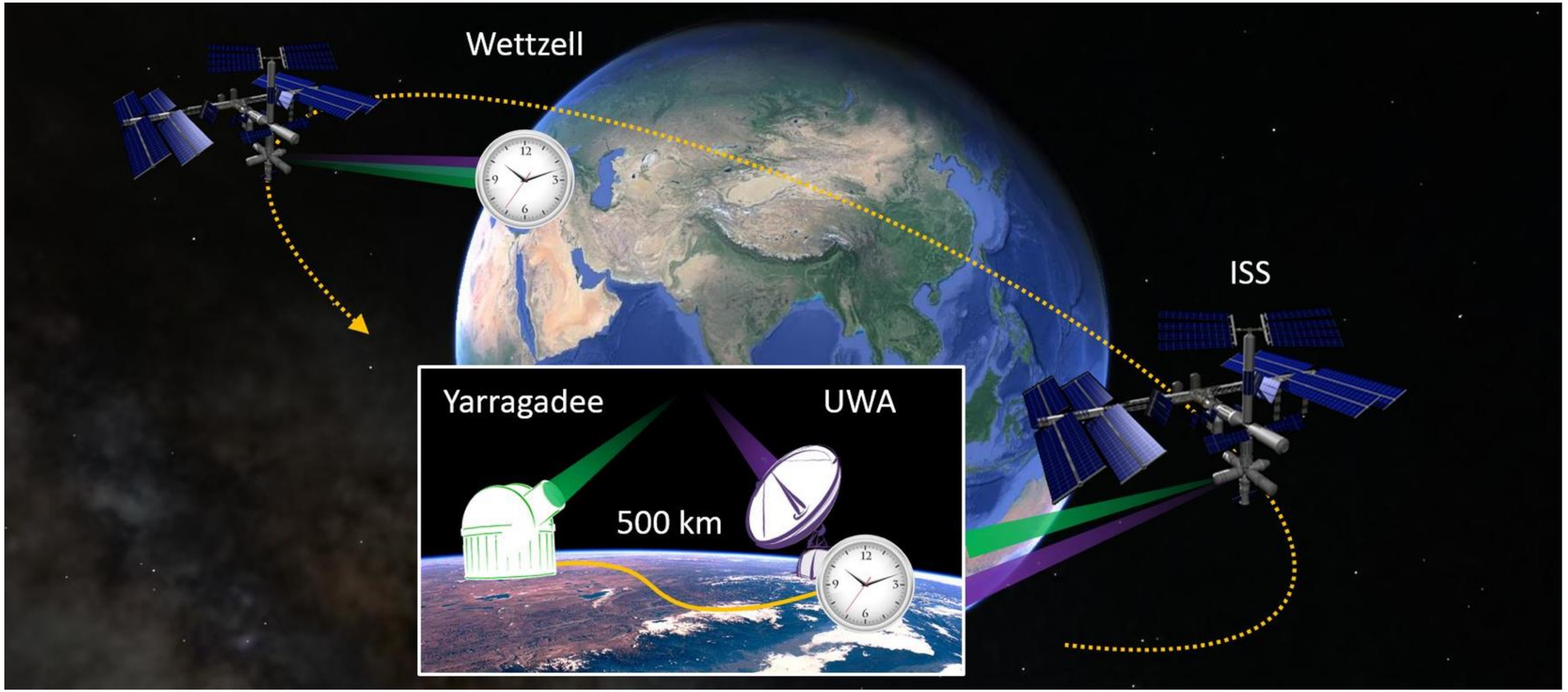
geodetic
reference point
(space time)

- Time is associated with a well defined geodetic coordinate
- The satellite is in fast motion and under changing gravity
- In order to preserve time, the orbit must be known
- Internal delays have to be knocked down

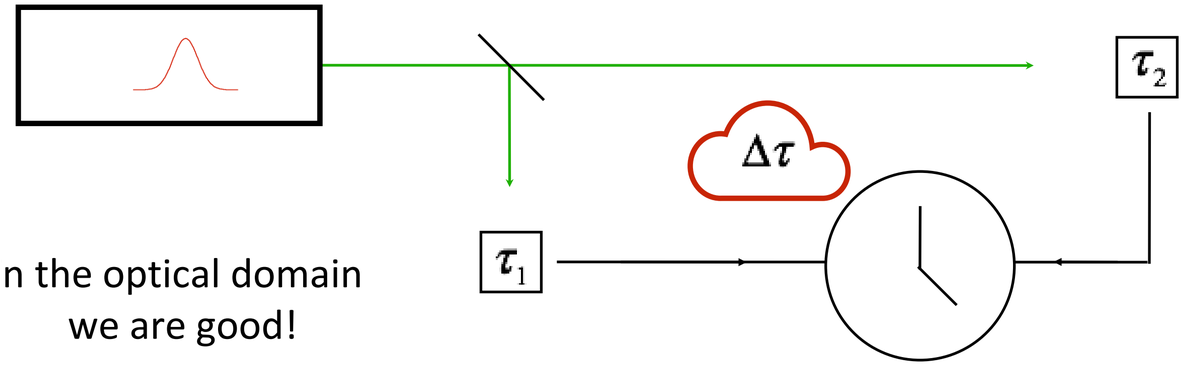
Connecting a “local clock” to the world - The ACES mission



Inter Continental Time Transfer via ACES

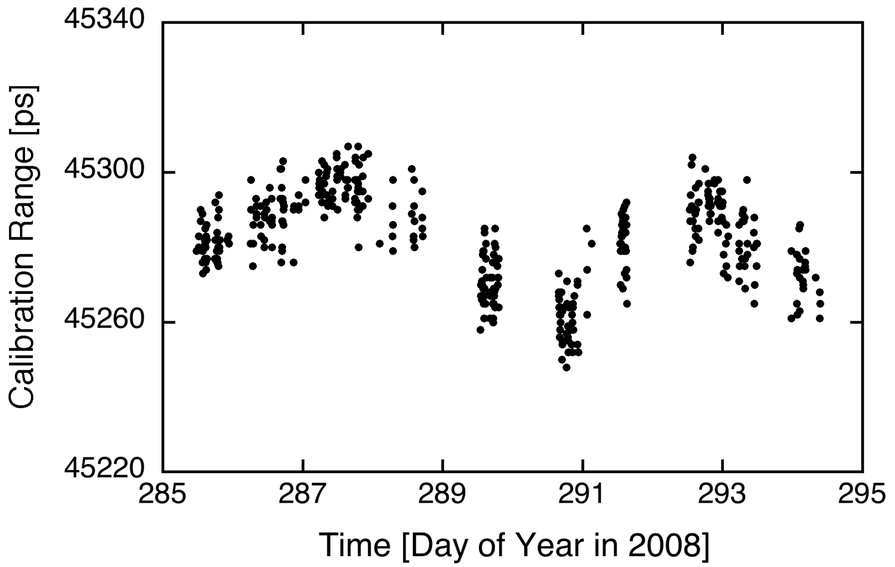


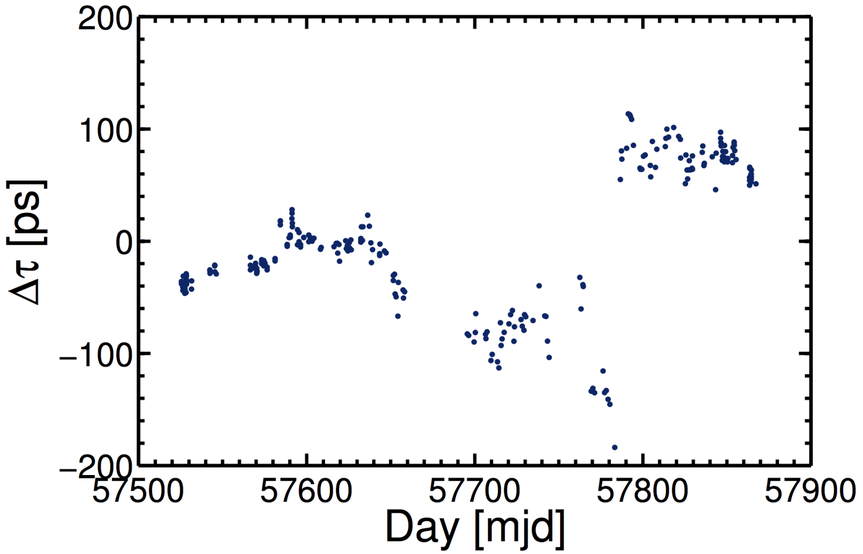
Observation: Variable delays due to electronics

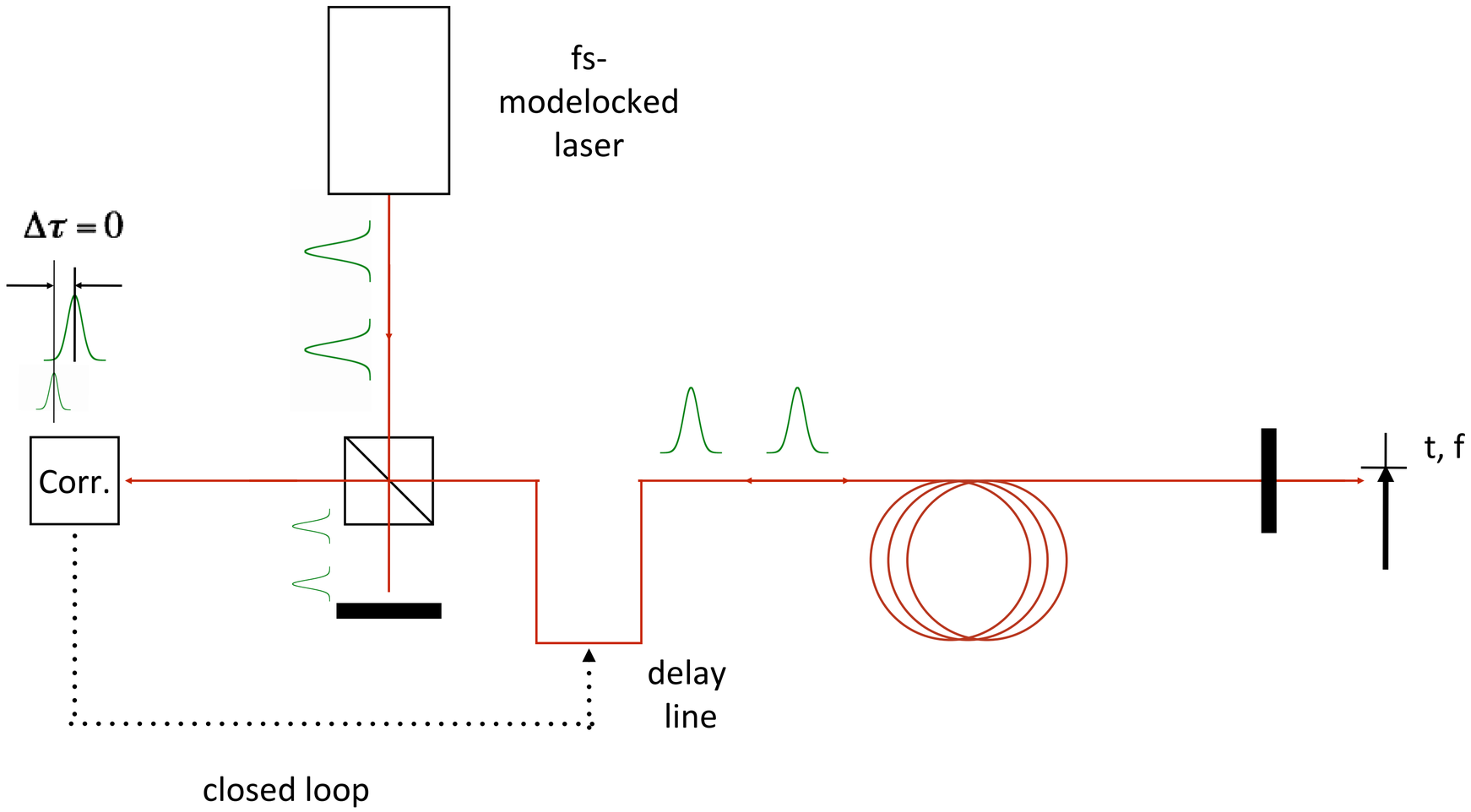


in the optical domain
we are good!

asymmetry of
clock channels







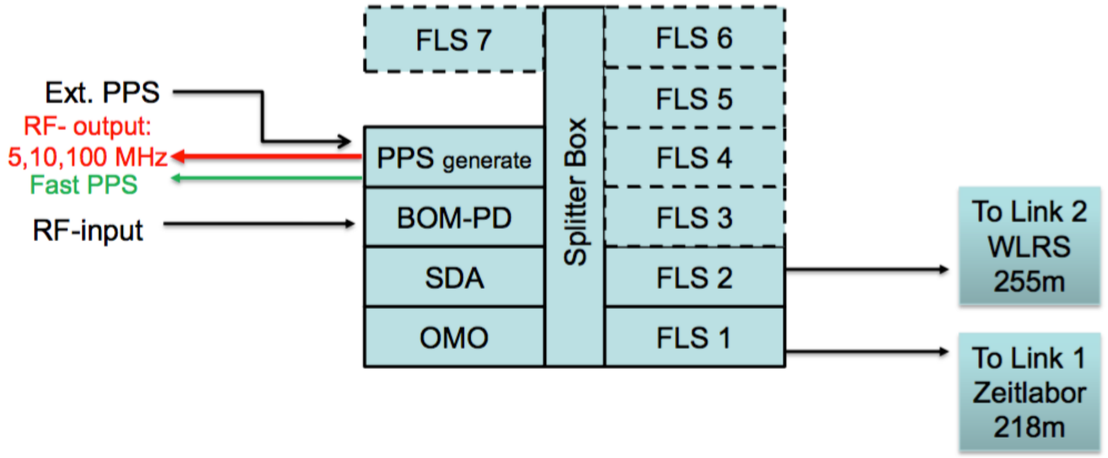
Schreiber et al.: Space Science Reviews, **214 (**1), p. 1371, (2017)

Campus Distribution for accurate Time

Menlo Systems | Syncronization ASOPS Systems

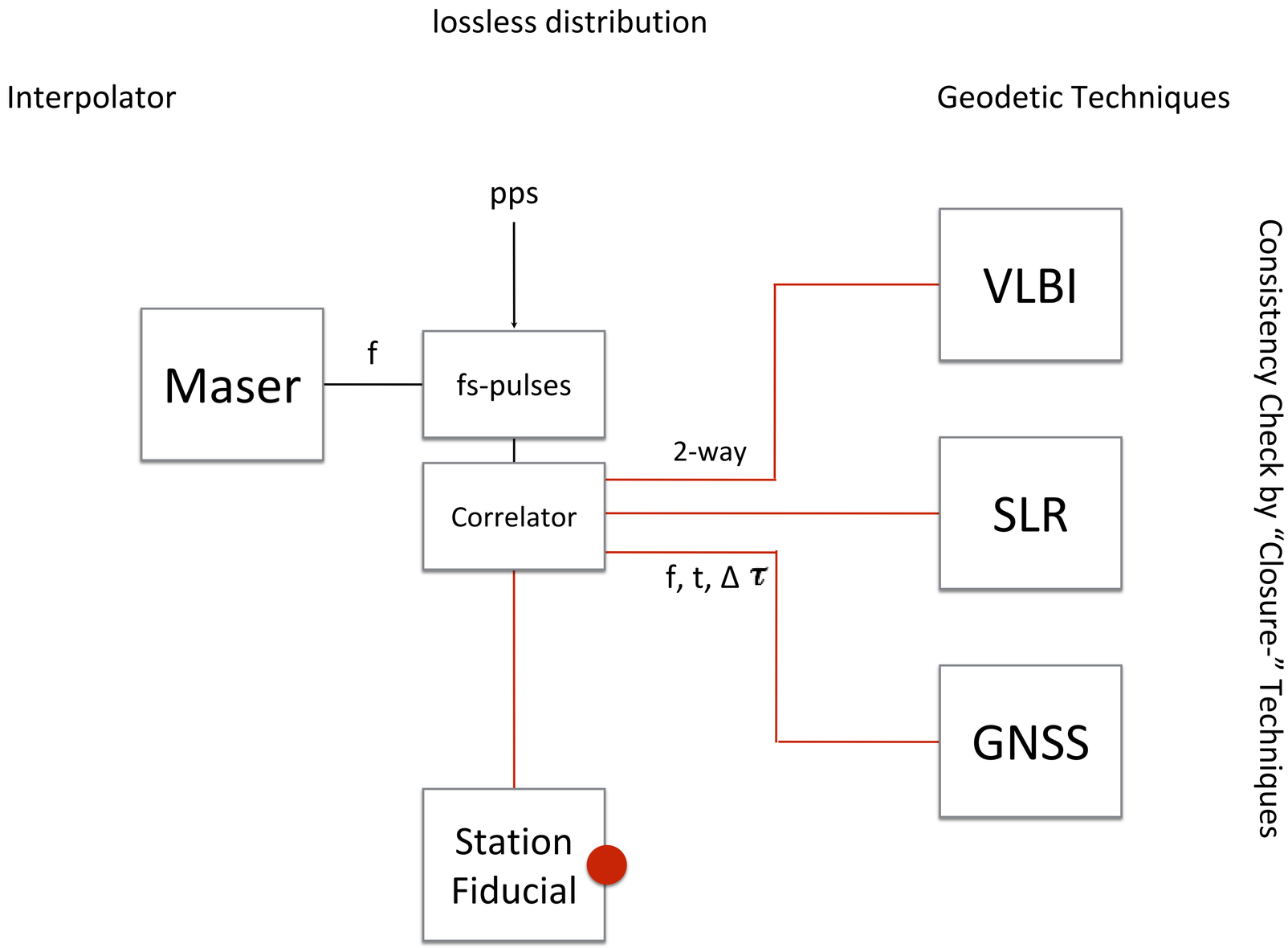
Timing Distribution System (TDS): **Final setup**

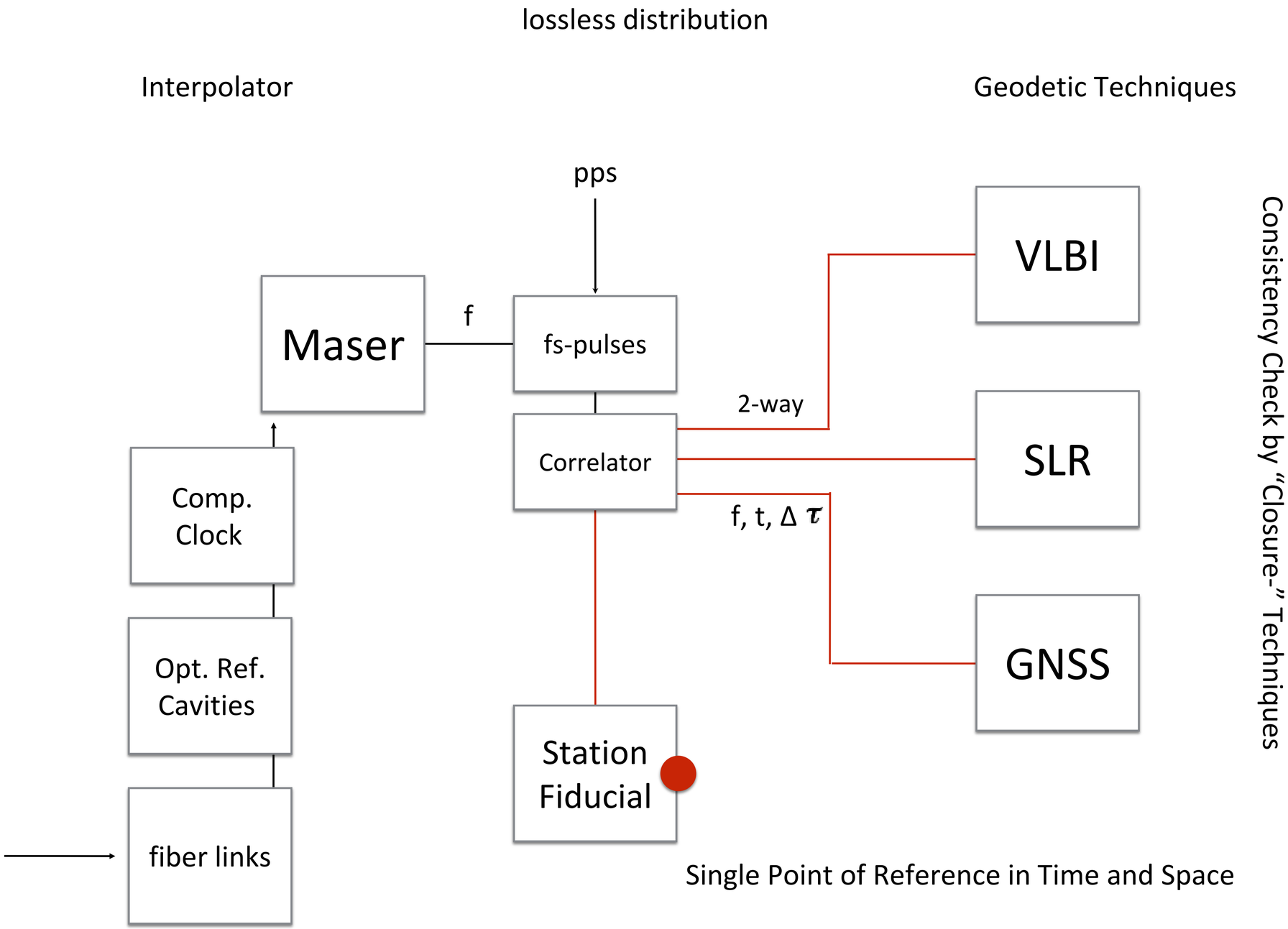
Mechanical devices



Timing Distribution System (TDS) (Wettzell)

Water cooled base plate


lossless distribution
Interpolator
Geodetic Techniques
pps
Maser
f
fs-pulses
2-way
Correlator
f, t, Δ τ
Station
Fiducial
VLBI
SLR
GNSS
Consistency Check by "Closure-" Techniques
Single Point of Reference in Time and Space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Opt. Ref. Cavities
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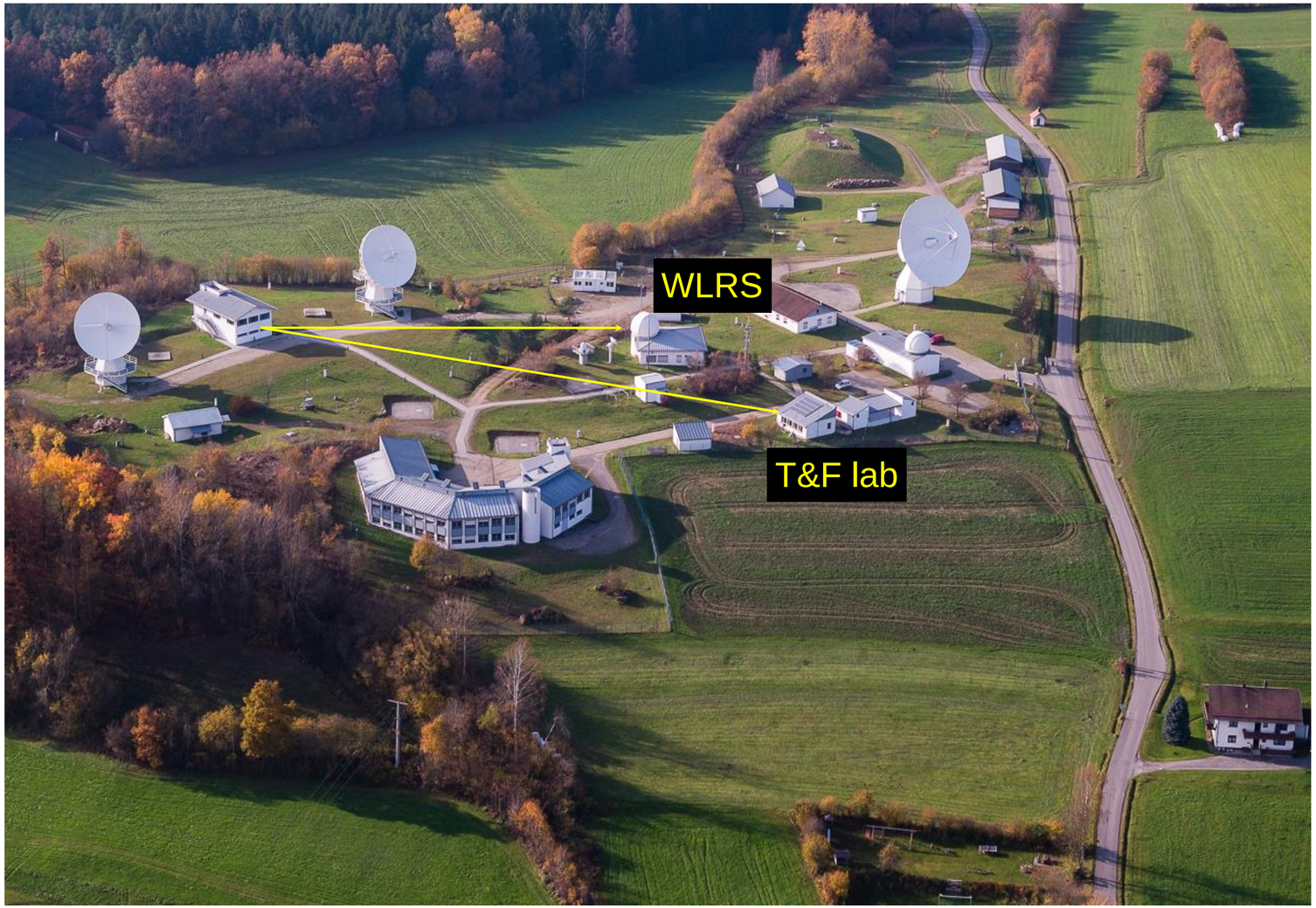
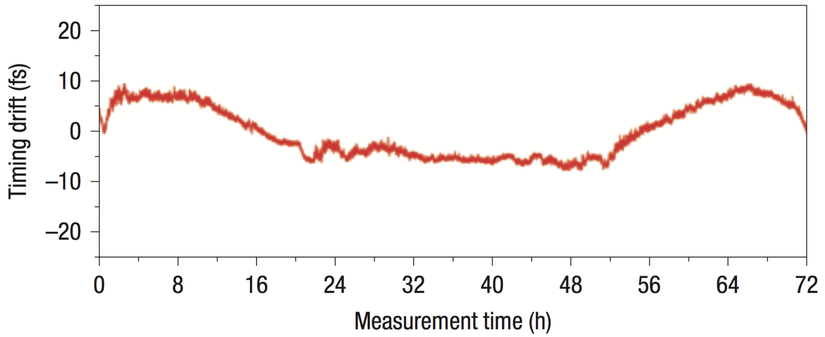
Link Verification



Common Clock for Space Geodetic Techniques

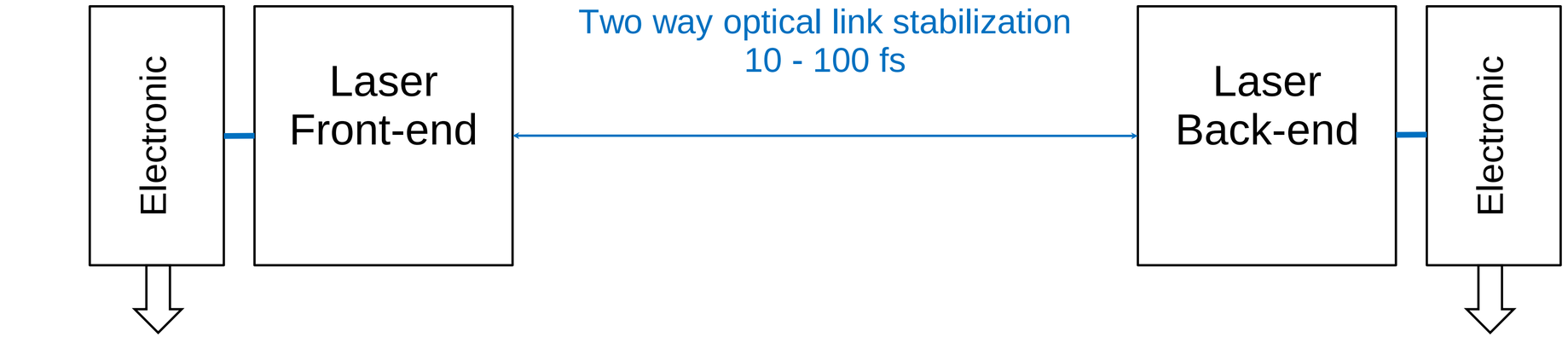
optical cross- correlation of
2 fiber lines (300 m)



6.4 fs r.m.s.

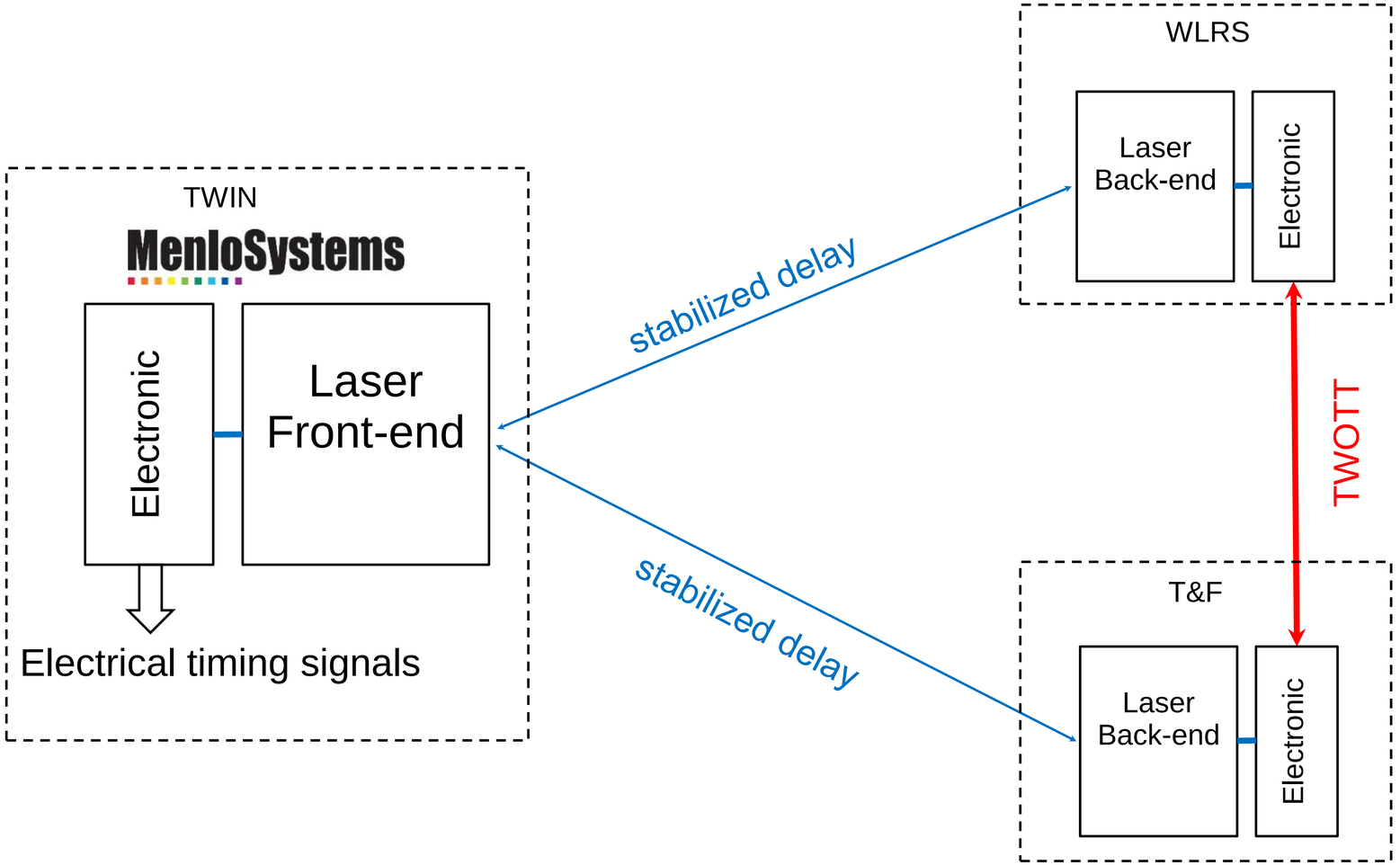
Kim et al. Nature Photon, **2(**12), 733–736, (2008)

MenloSystems



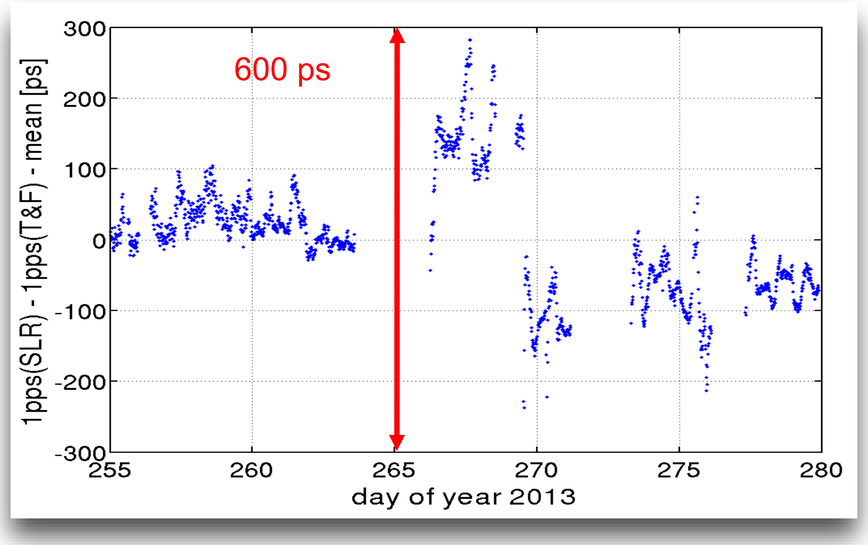
“electrical” Timing stability ~1ps

Common Clock for Space Geodetic Techniques

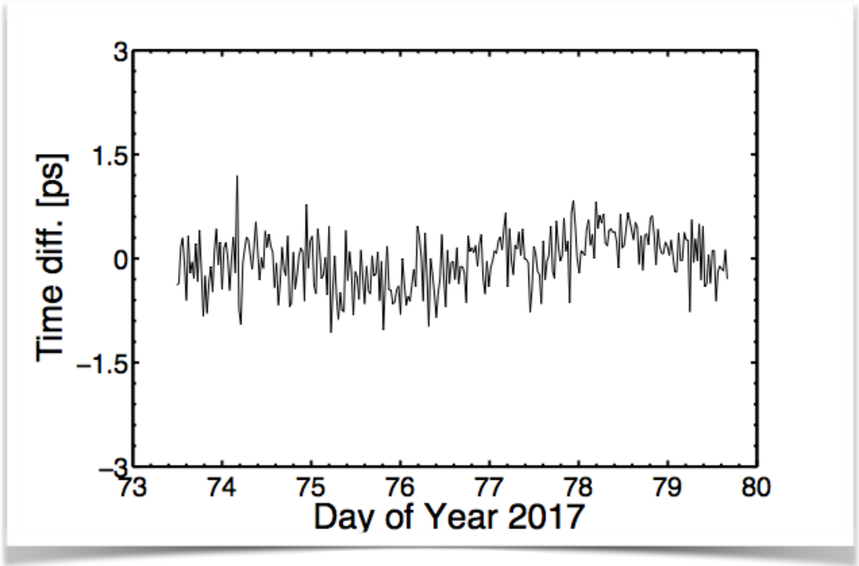


The distribution of the broadband PPS time signal over cable and electronic devices shows variability at the level of several hundred ps - and next to none over a compensated fiber link

cable based



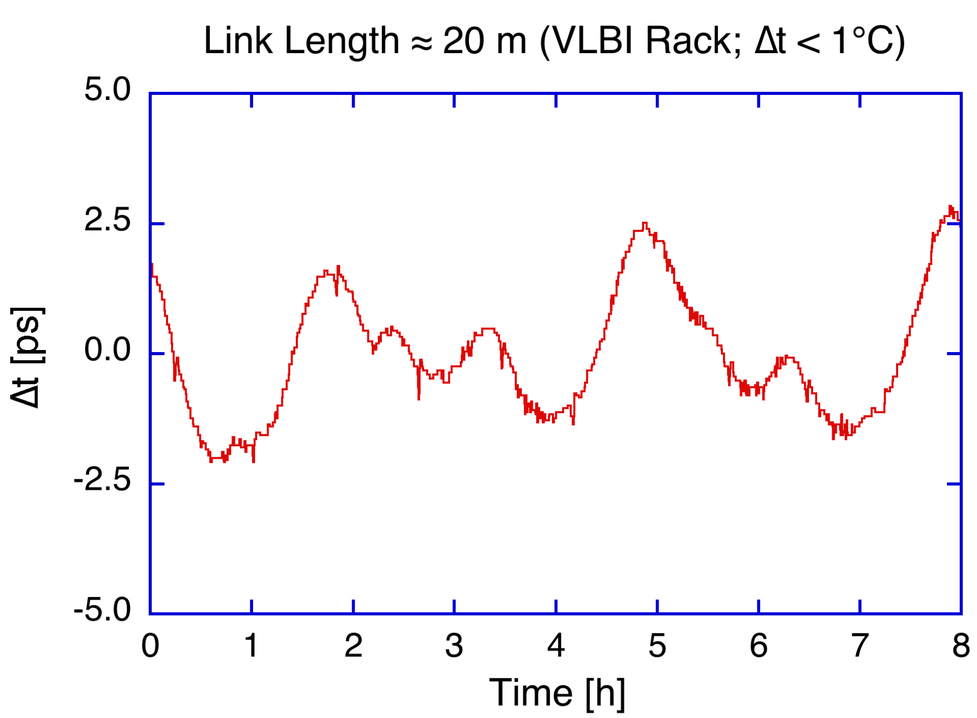
fiber based

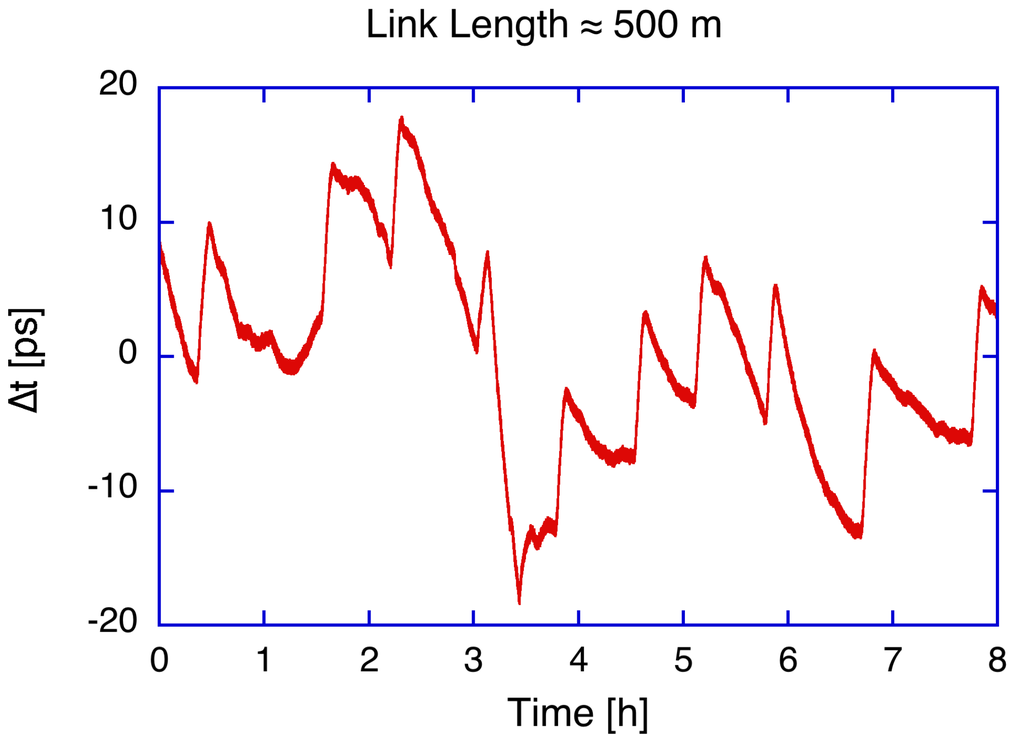


… over a longer period: $\Delta t \leq 5$ ns

?

Error Signal for the closed loop fiber stretcher





Most of the excursions appear to be caused by the air conditioning

Error Signal for the closed loop fiber stretcher