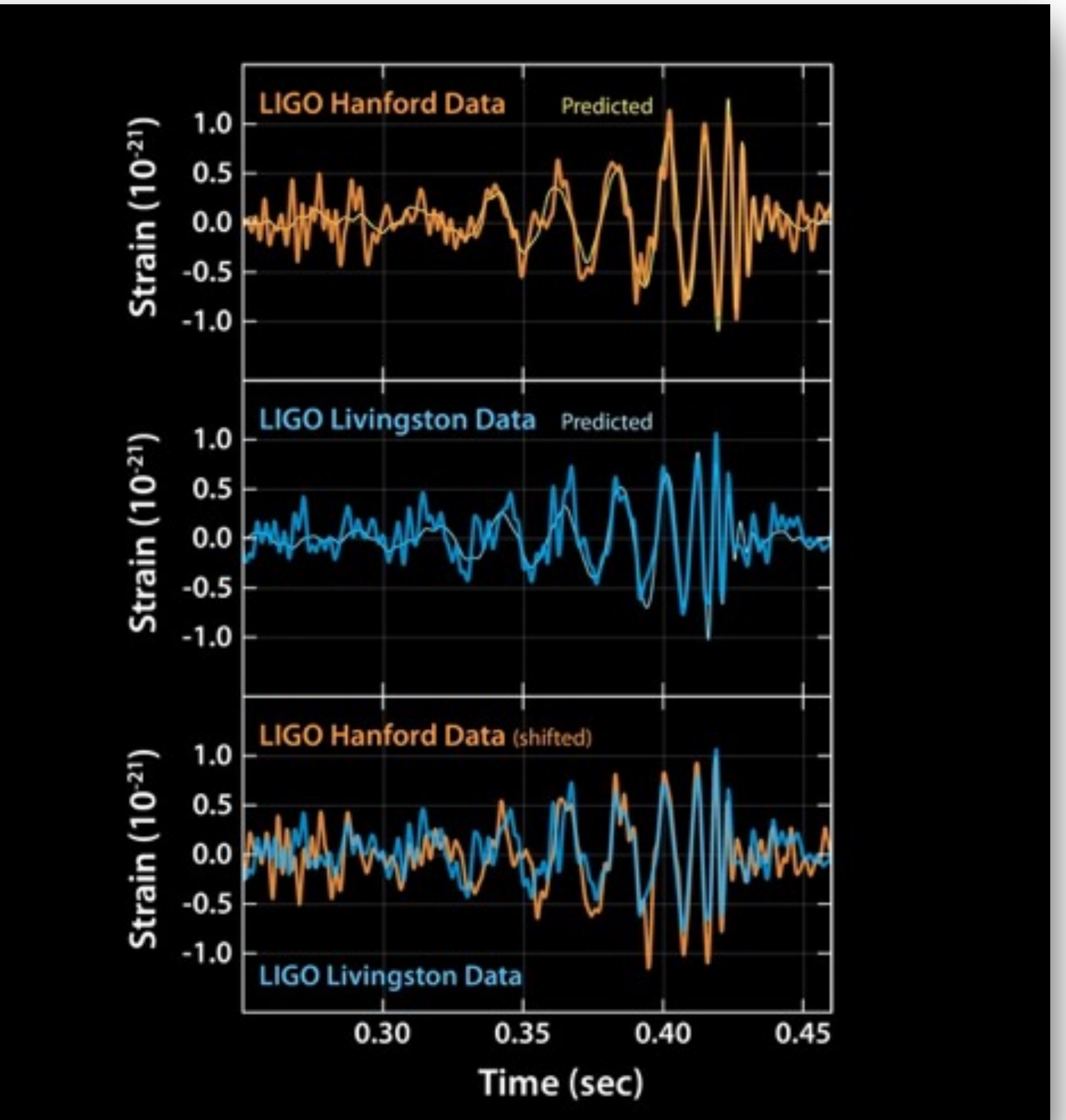
Optical metrology in space geodesy

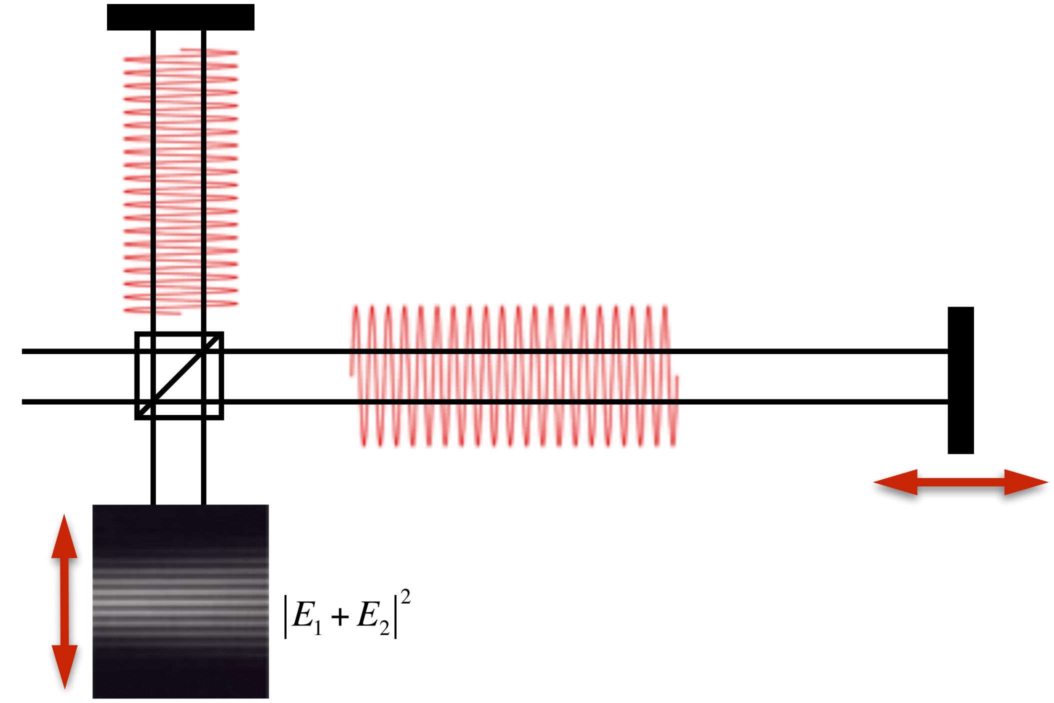
Ulrich Schreiber

Technical University of Munich, Geodetic Observatory Wettzell, Germany

With the first verified detections of gravitational waves the year 2016 has seen a major achievement for optical interferometry. Sagnac interferometry has also achieved a point of maturity where the measurement of LoD is a reasonable goal. Last but not least, optical atomic clocks become realistic candidates for a geodetic height system, including highly accurate long distance optical frequency comparisons. Against this background we find that optical frequency combs play a major roll in this enormous boost that the field of photonics has shown. On closer inspection it turns out that most of these very successful key technologies have a strong relationship with SLR. This talk provides some thoughts on how SLR fits into this rapidly developing field of photonics in order to stimulate discussions.



https://www.ligo.caltech.edu/image/ligo20160211a



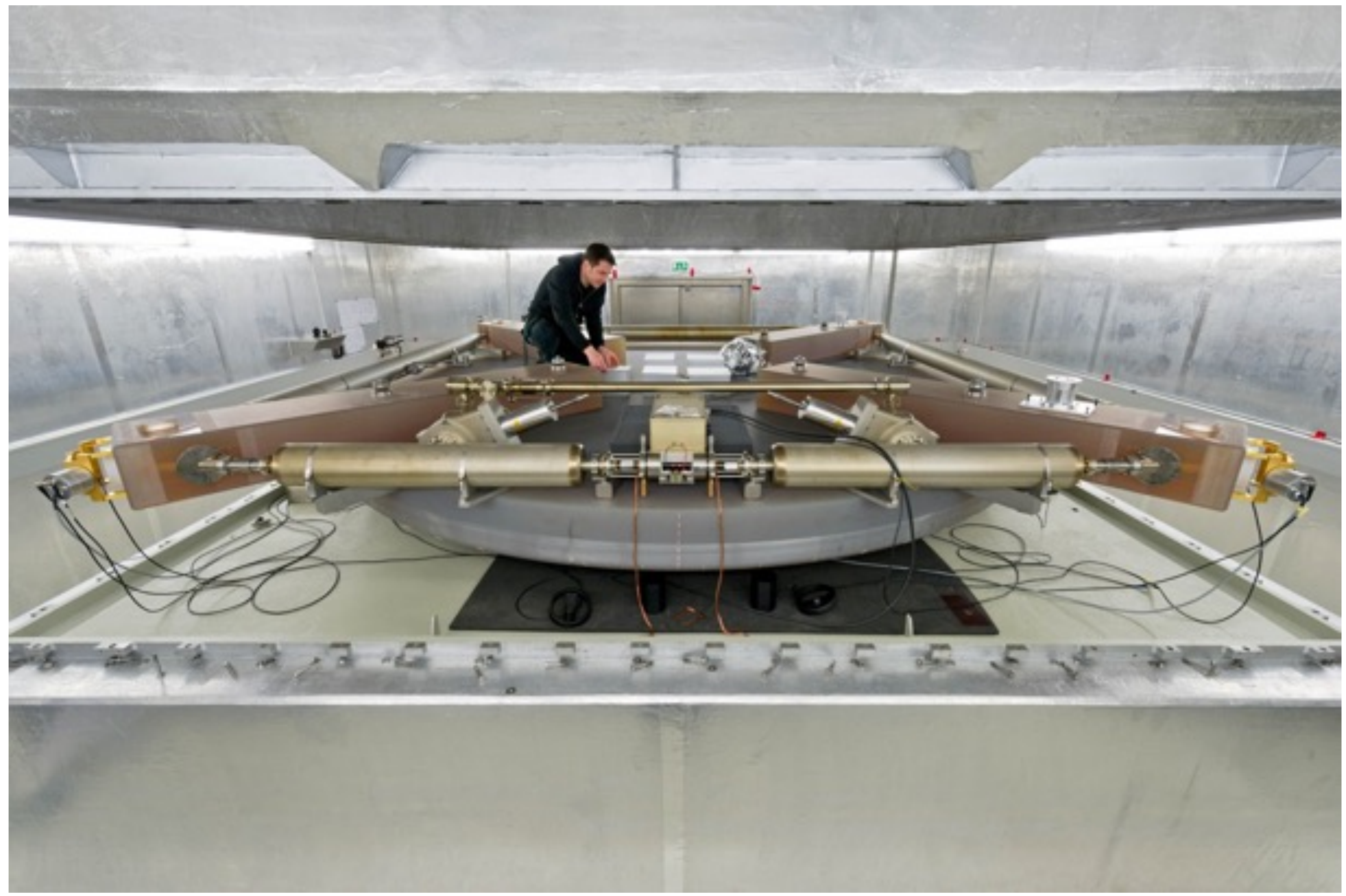
Interferometry with Light provides outstanding sensor resolution for the measurement of displacement...

...the latest example is the phenomenal achievement of detecting gravitational waves at strains of 10^{-21}.

How about applying the same concept for the measurement of rotation?

The 'G' - Ring is currently our best performing geodetic gyro

Since 2001 -



Perimeter: 16 m

Area: 16 m^2

FSR 18.75 MHz

$\Delta\nu_L \approx 274\ \mu$Hz

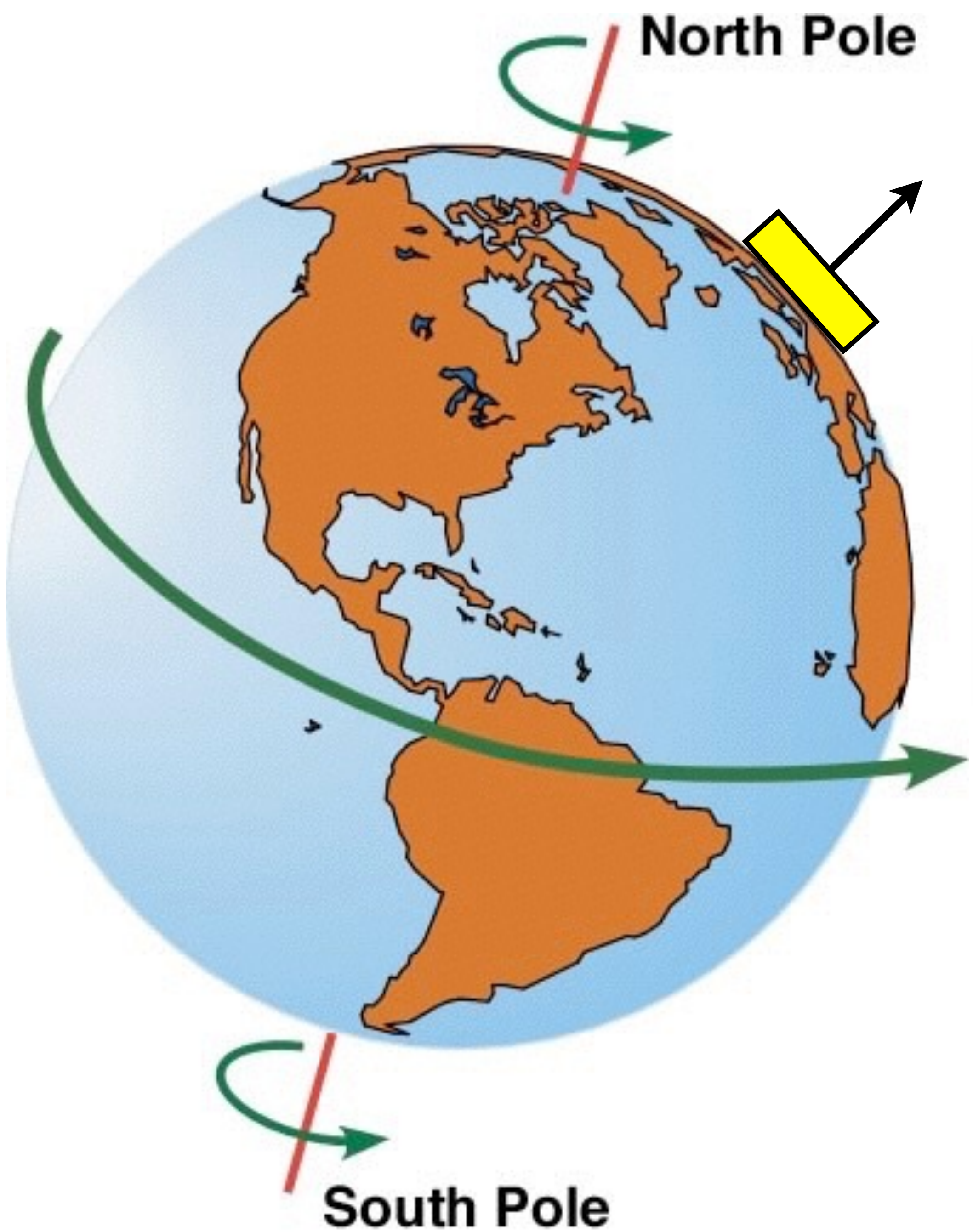
5 ppm loss / mirror

$Q = \omega\tau \approx 5\text{x}10^{12}$

10 mB gas pressure operated near laser threshold
Mode selection by gain starvation (self-locking)

$$\Omega_E \pm 5 \cdot 10^{-9}$$

Requirements for Applications in Geodesy and Geophysics



Δ SKF $\leq 10^{-10}$

$\Delta\theta \leq 1$ n-rad

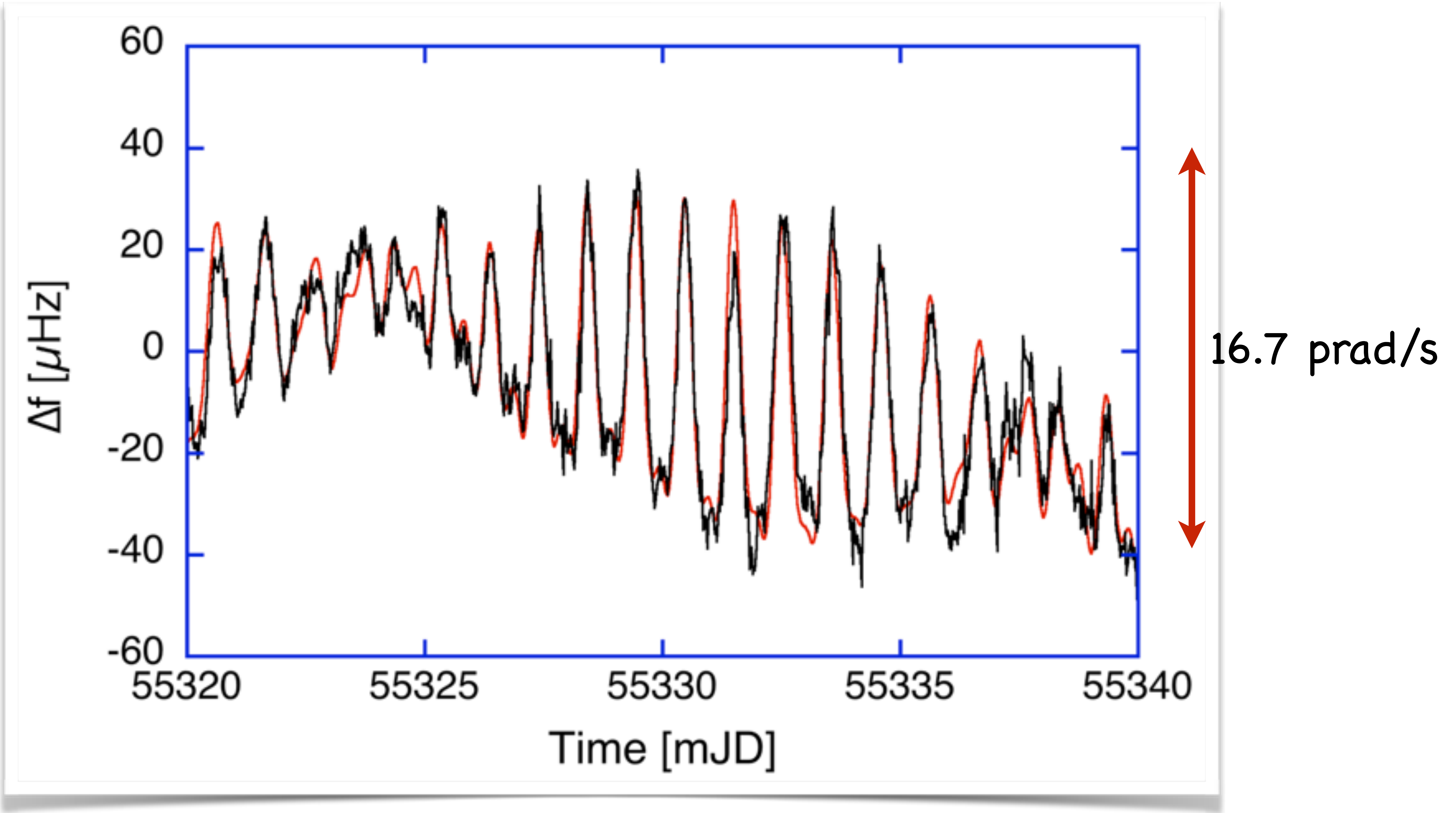
$$\delta f = \frac{4A}{\lambda P}\,\vec{n}\cdot\vec{\Omega} + f_{nr}$$

$10^{-9}\Omega_E \approx 0.07$ prad/s

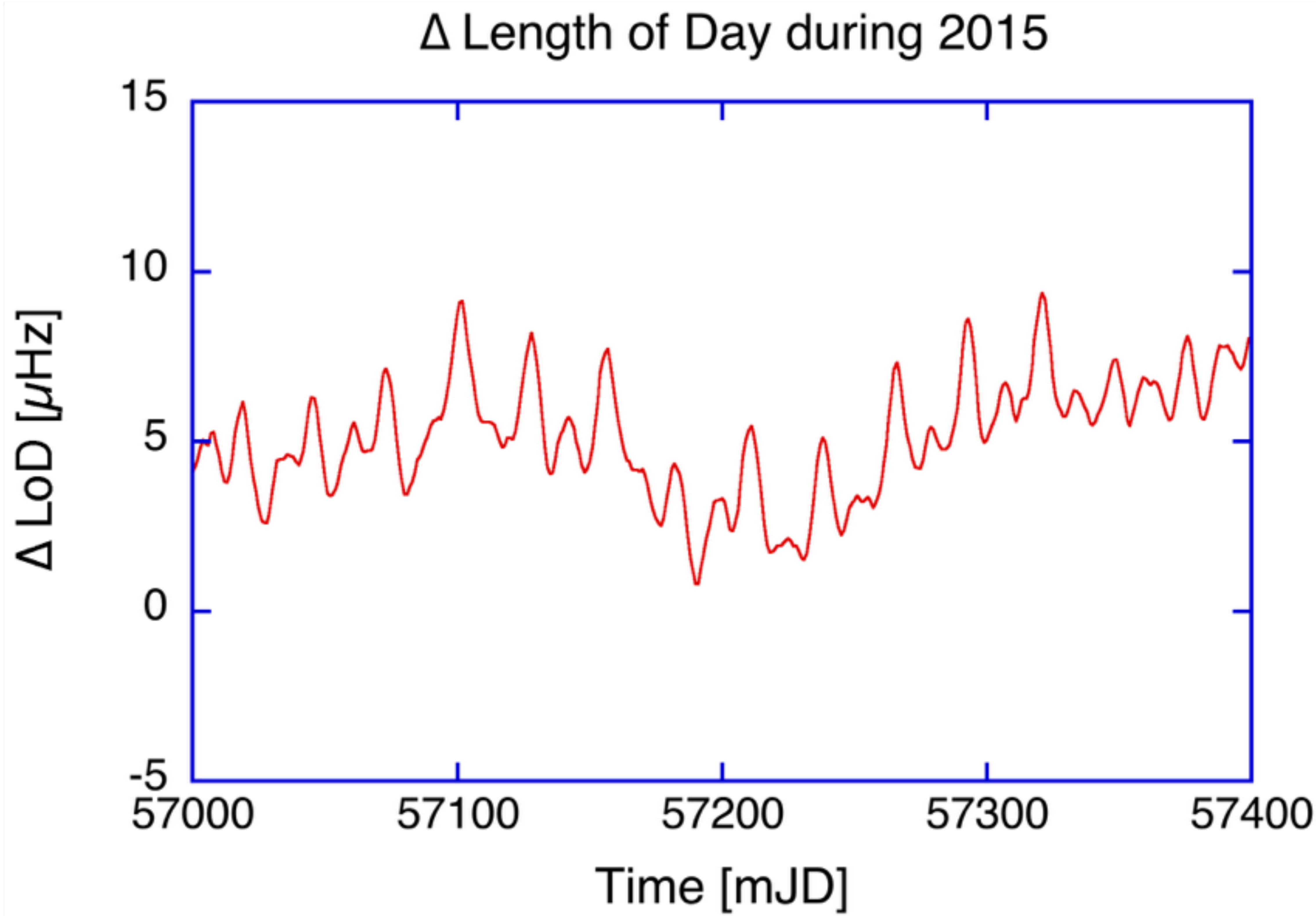
$\Delta f_{nr} < 0.3\ \mu$Hz

www.uni-muenster.de/imperia/md/content/physik_ap/nlol/physika1213/

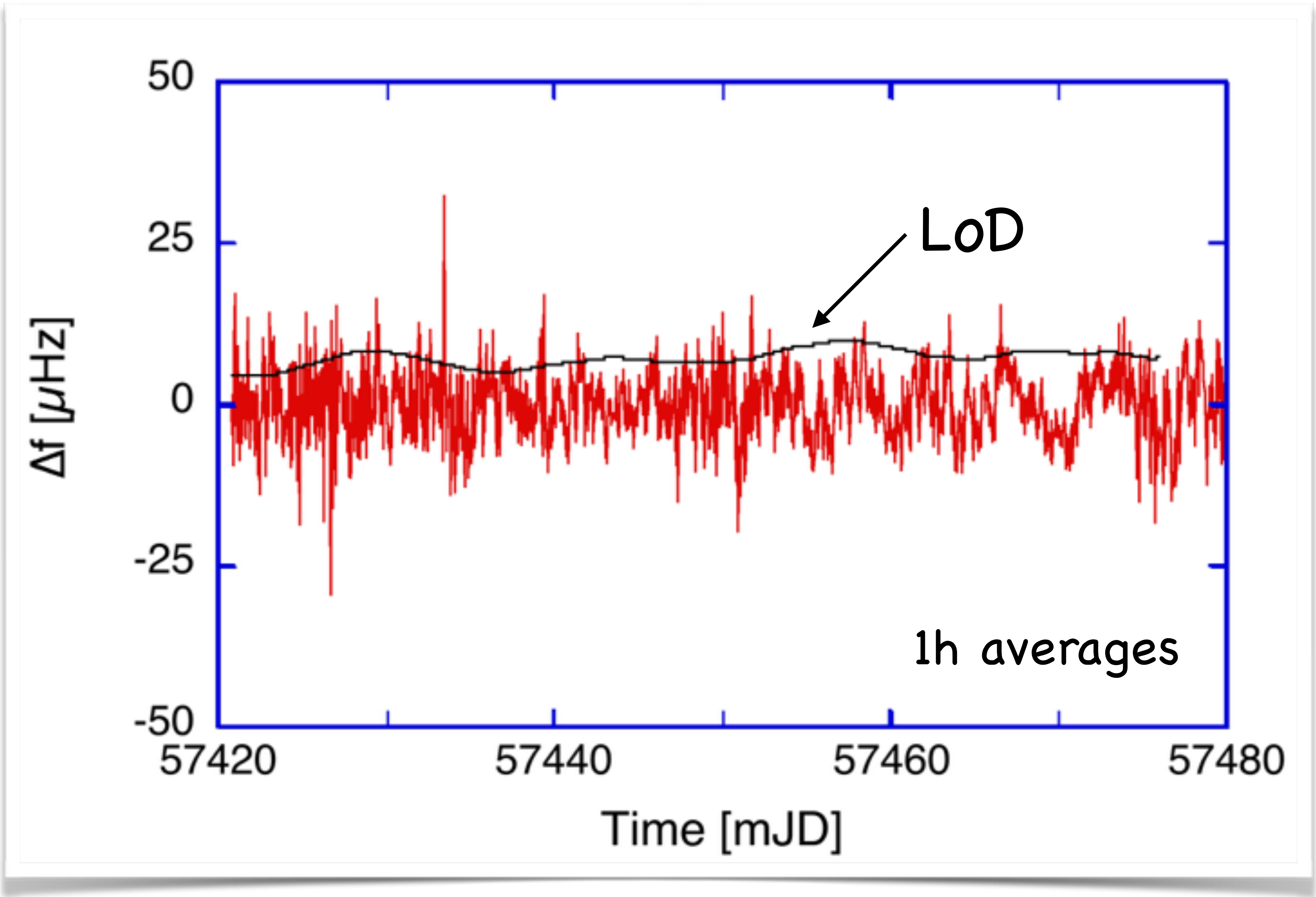
Comparison of G tied to the Earth crust against the (known) geophysical signals due to orientation variation



Earth rotation causes a beat note of 348.517 Hz. Tilt induced geophysical signals show signatures in the range of ±50 μHz


Δ Length of Day during 2015
15
10
5
0
-5
Δ LoD [μHz]
57000
57100
57200
57300
57400
Time [mJD]

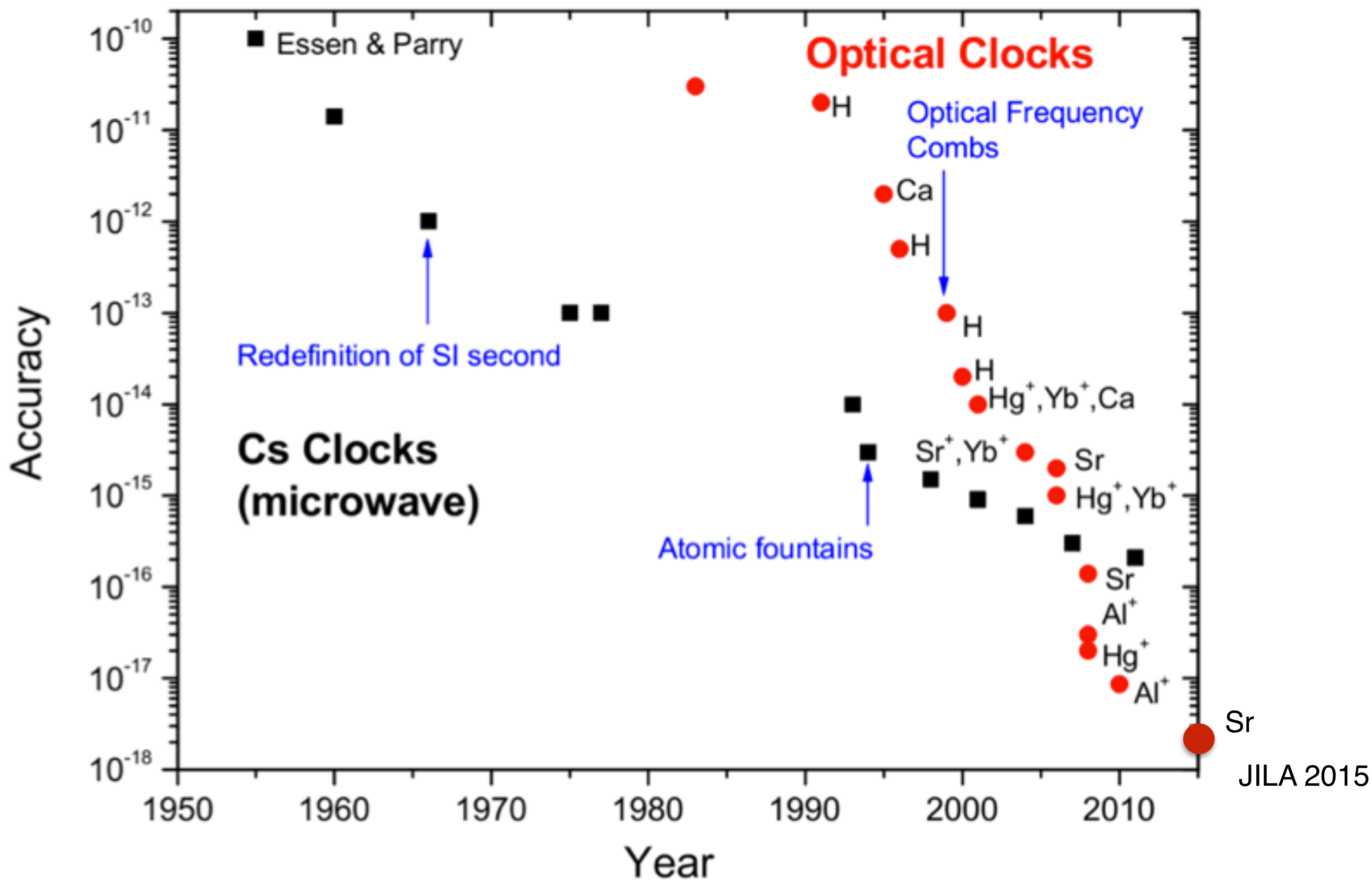
Given that minor gain variations are no longer a concern...



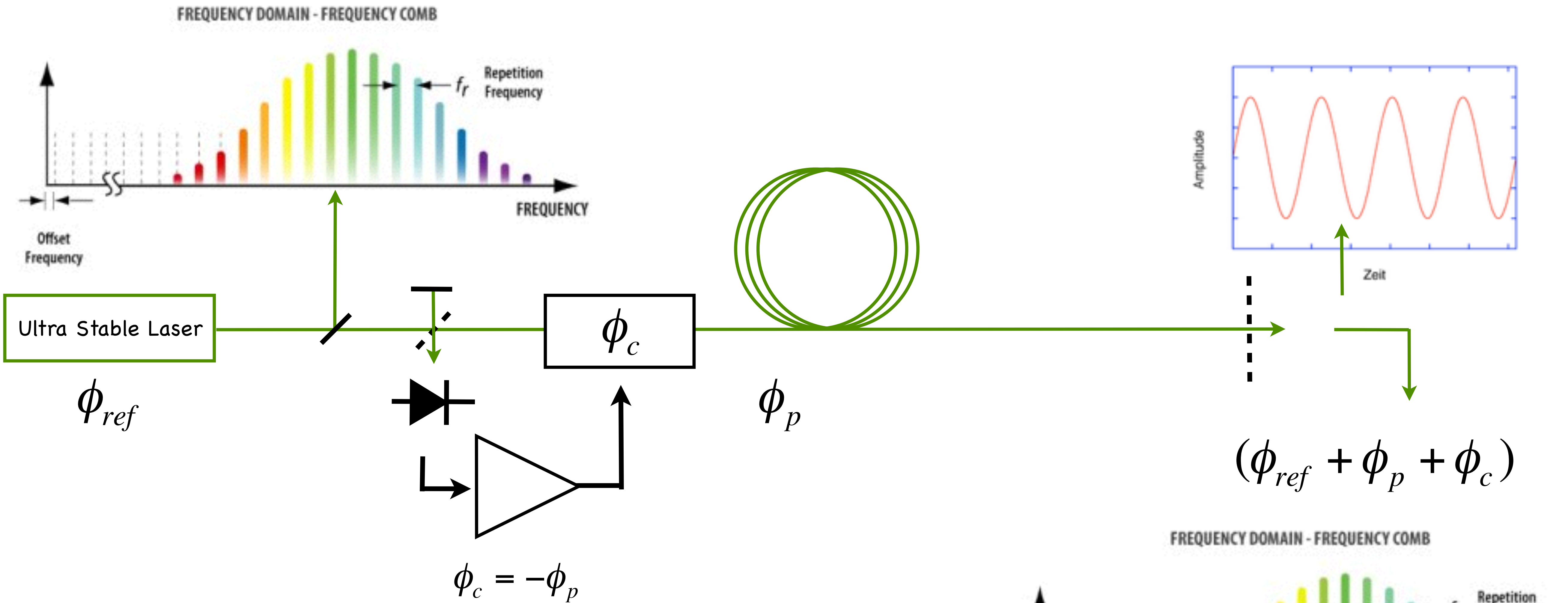
...we are very close to our dream: obtain LoD straight from the RLG.

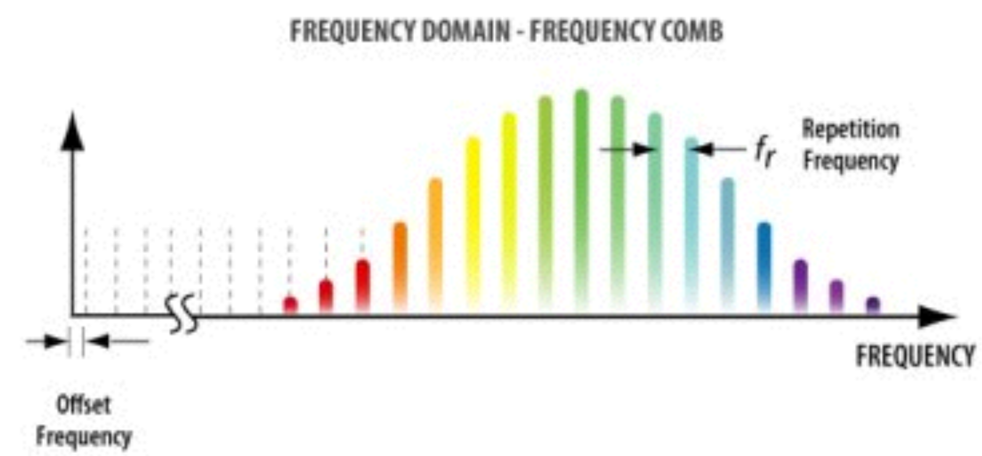
Highly accurate clocks allow to exploit GR for a height system:

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



How to compare two remote optical oscillators?





Laser ~~Time~~ Frequency Transfer

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

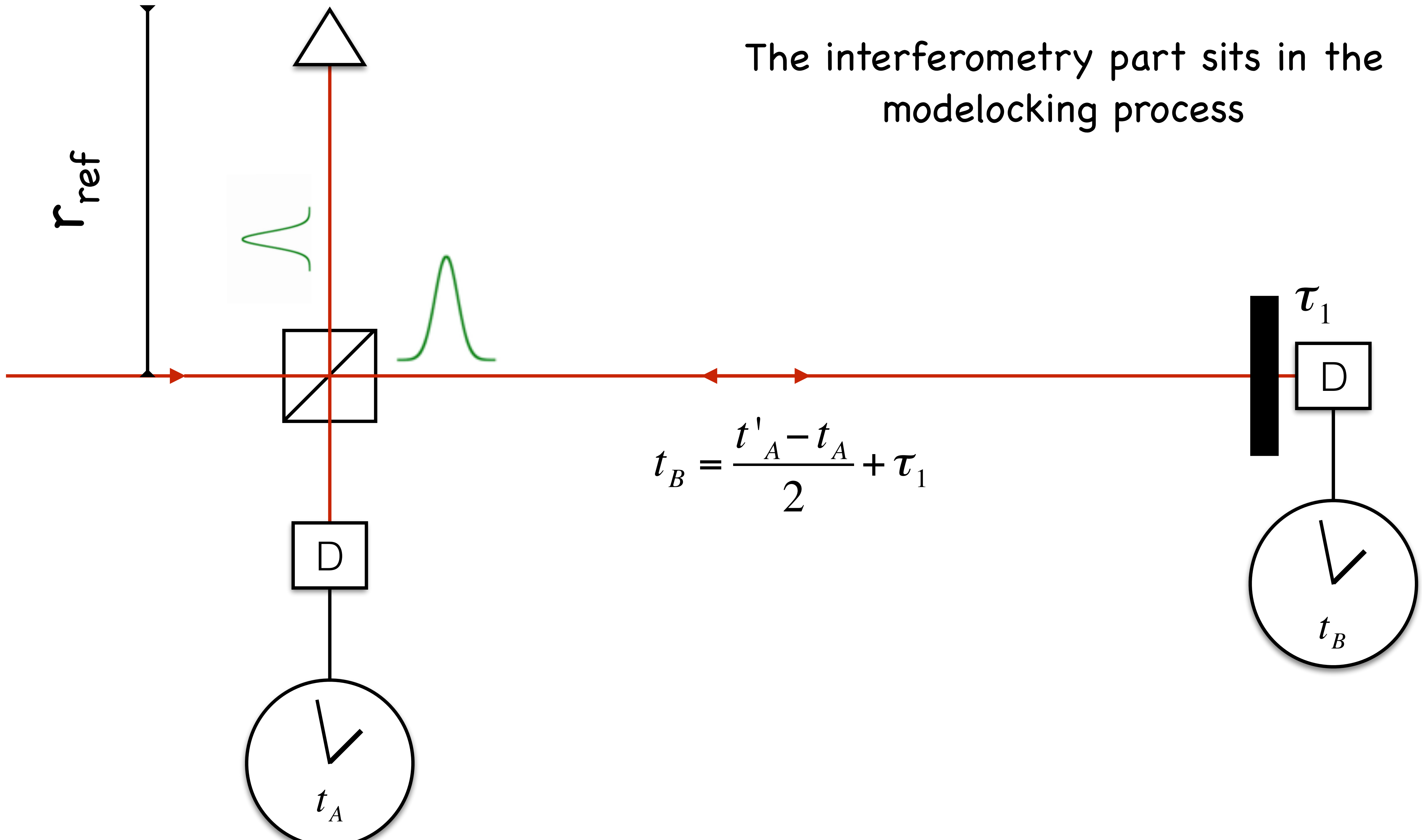
$$t_B - t_A = t'_A - t_B.$$

Isotropy of the speed of light!

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

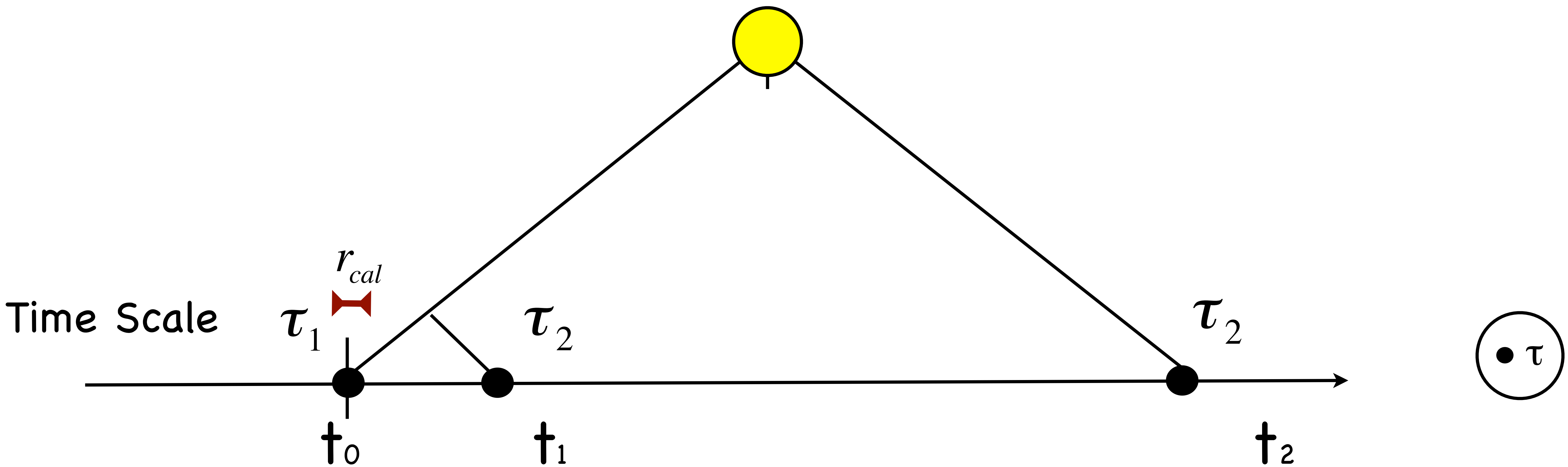
SLR is the practical Realization of the Einstein Synchronization…

The interferometry part sits in the modelocking process



… including the unavoidable System- Delays

Two-Way ranging technique: SLR

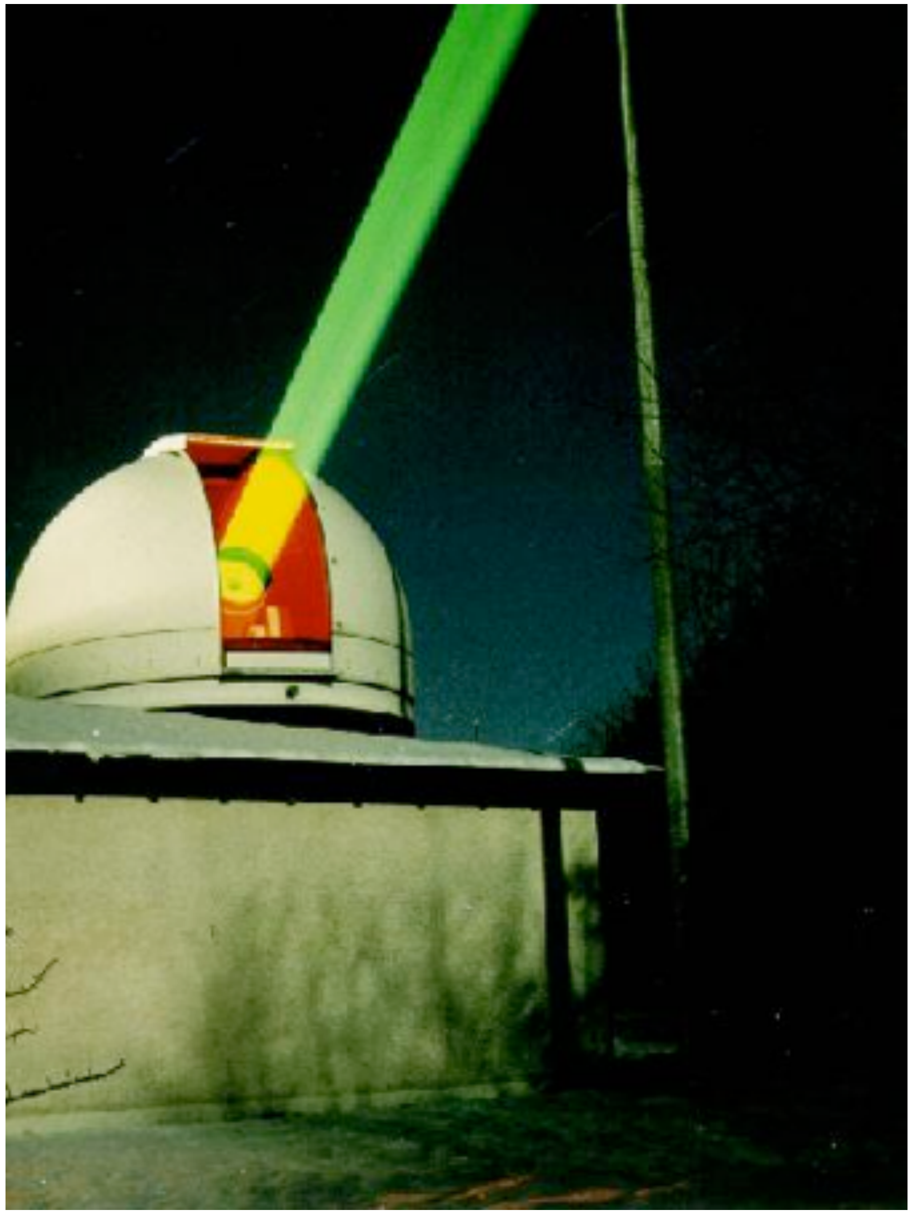


$$r(t_0) = \frac{c((t_2+\tau_2)-(t_0+\tau_1))}{2} = \frac{c}{2}(t_2 - t_0 + \Delta\tau)$$

$$r_{cal}(t_0) = \frac{c((t_1+\tau_2)-(t_0+\tau_1))}{2} = \frac{c}{2}(t_1 - t_0 + \Delta\tau)$$

$$r(t_0) = r_{cal}(t_0) + \frac{c}{2}(t_2 - t_1)$$

Two-Way ranging technique: SLR

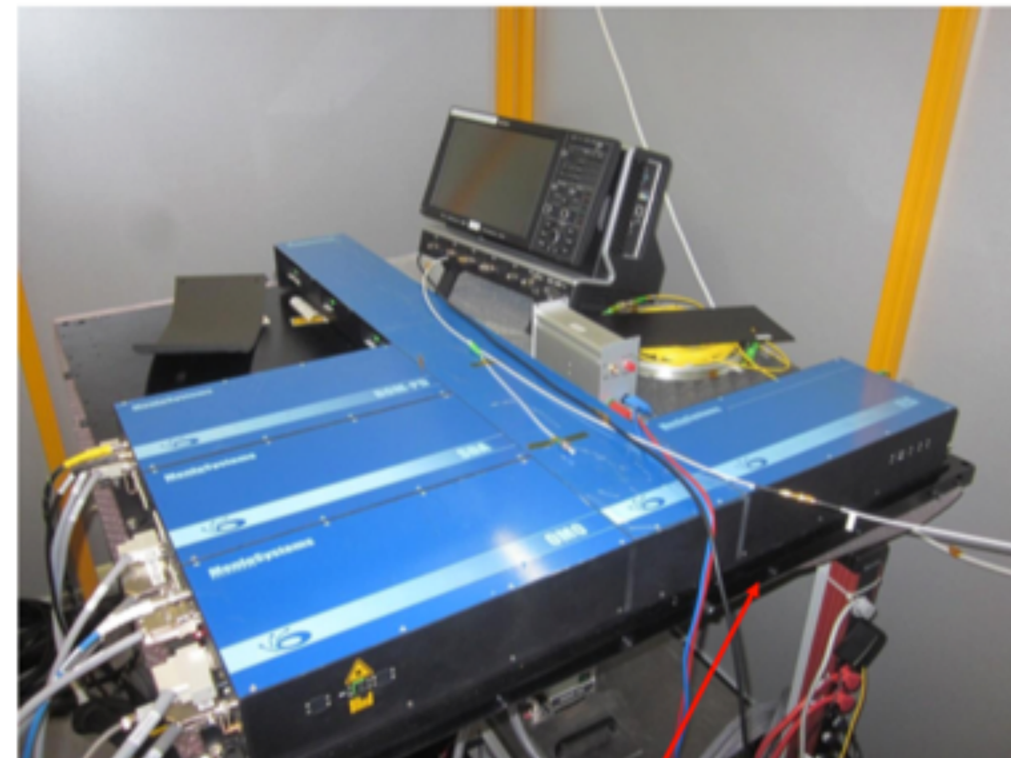


$$\Delta t = \frac{2}{c}(\rho_{range} + \delta\rho_{atm.} + \delta\rho_{rel.}) + \frac{1}{c}\delta\rho_{sys} + \varepsilon$$

- Δt measured on the ground clock only
- requires precision not accuracy from clock
- atmosphere is "better behaved" in the optical regime (troposphere and ionosphere do not matter)
- Time (epoch) is required to point at the satellite and for the orbit (1 μs ≈ 1 cm)
- For time transfer high accuracy is required for both epoch and Δt.

Campus Distribution for accurate Time

Timing Distribution System (TDS) (Wettzell)



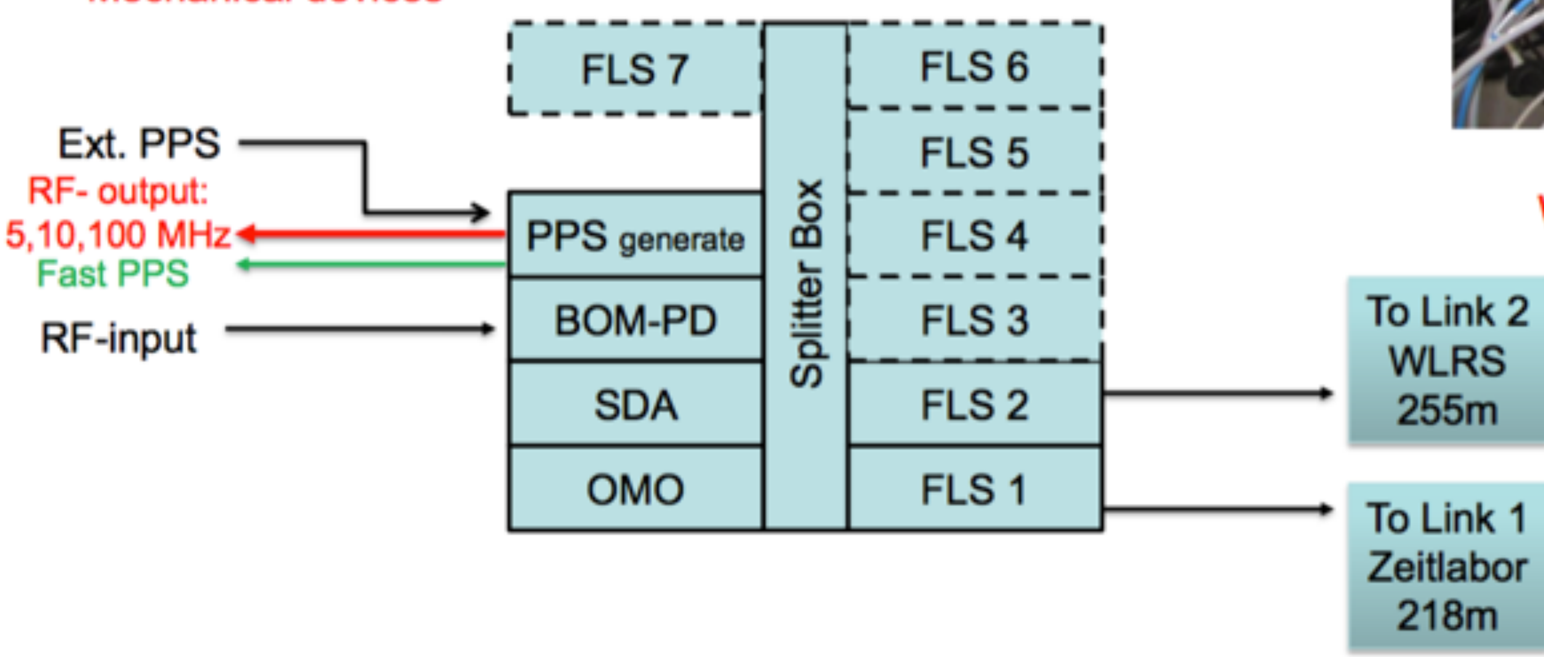
Water cooled base plate

Menlo Systems

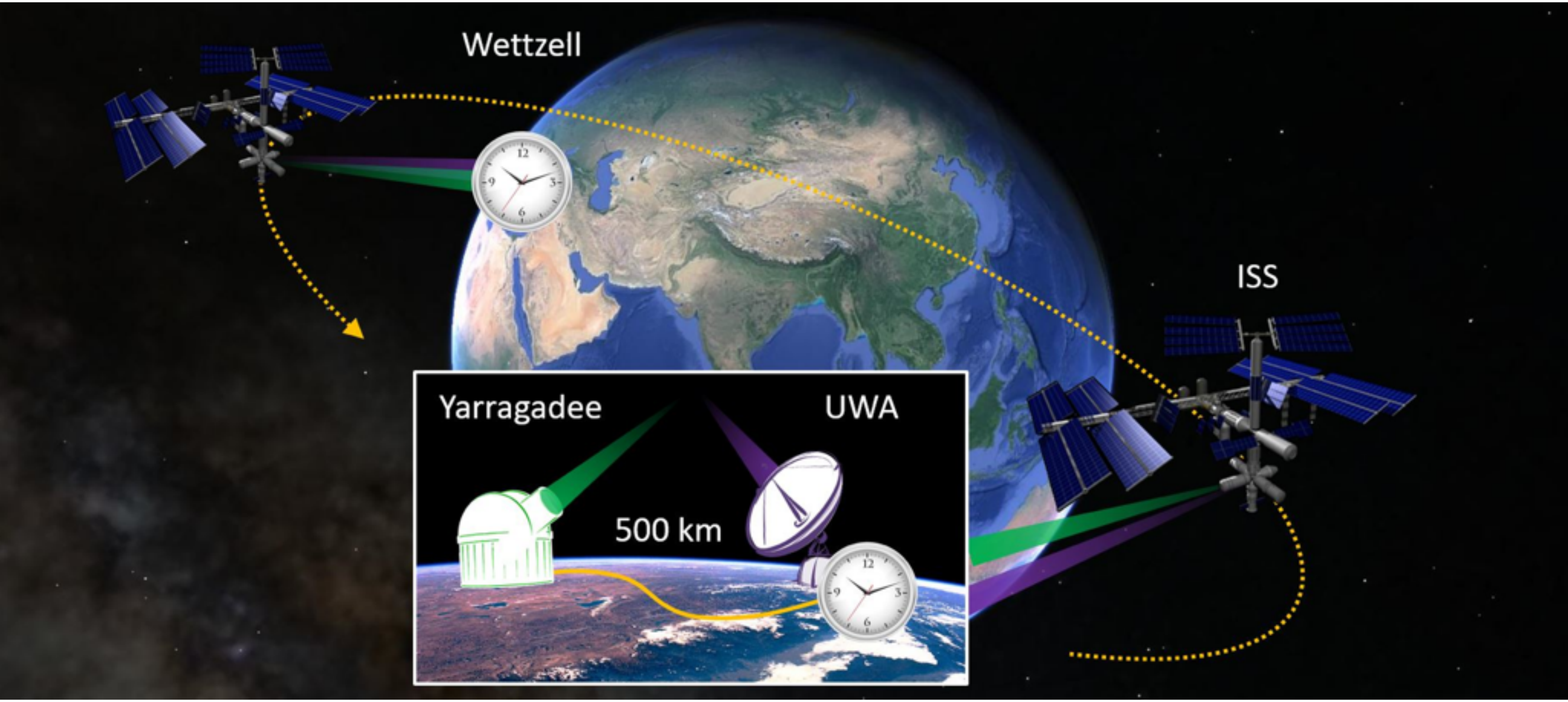
Syncronization ASOPS Systems

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

Mechanical devices



Inter Continental Time Transfer via ACES



Proposed Fibre Infrastructure

Western Australia Space Centre (WASC)