

NKG2026

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RI.
SE

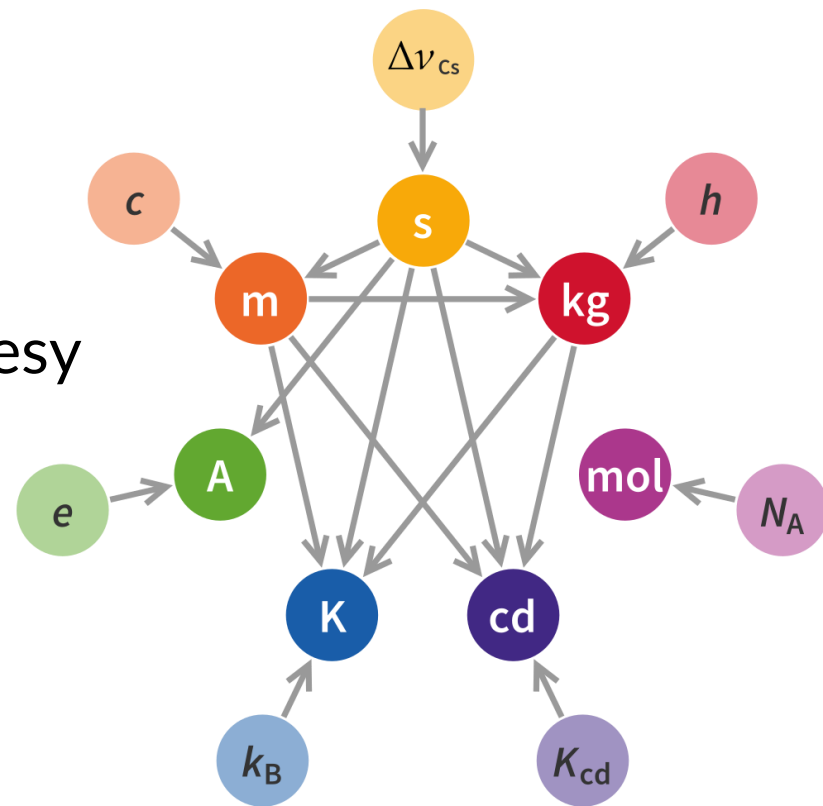
Time and Time Distribution

an overview

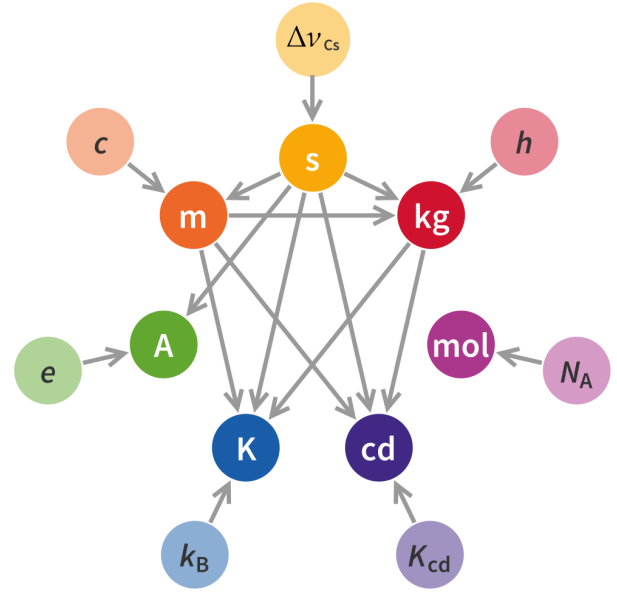
time@ri.se

Outline

- Metrology background on coordinate time scales and how it relates to geodesy
- Legacy GNSS, TWSTFT in a nutshell
- VGOS and Genesis
- Fiber based methods, WR/PTP optical frequency transfer and combs



Time and its coordinate



Time and the Meter System

Definitions of the second, as the SI unit of time interval

- Time was early on recognized as a corner stone for a coherent system of units
- Meter convention 1875 provides prototypes for the kilogram and the meter



Astronomy

- 1685: 1s $1/86400$ of a solar day of 24 hours of 60 minutes of 60 seconds
- 1956: $1/31556925.9747$ of the tropical year for 1900 January 0 at 12 hours ephemeris time

Metrology

- 1960 International System of Units/Quantities
 - 1960: IAU definition
 - 1967: The duration of 9192631770 periods of the radiation corresponding to the transition between the two hyperfine levels of the ground state of the caesium-133 atom
 - 2030: **redefinition based on transitions in the optical domain**

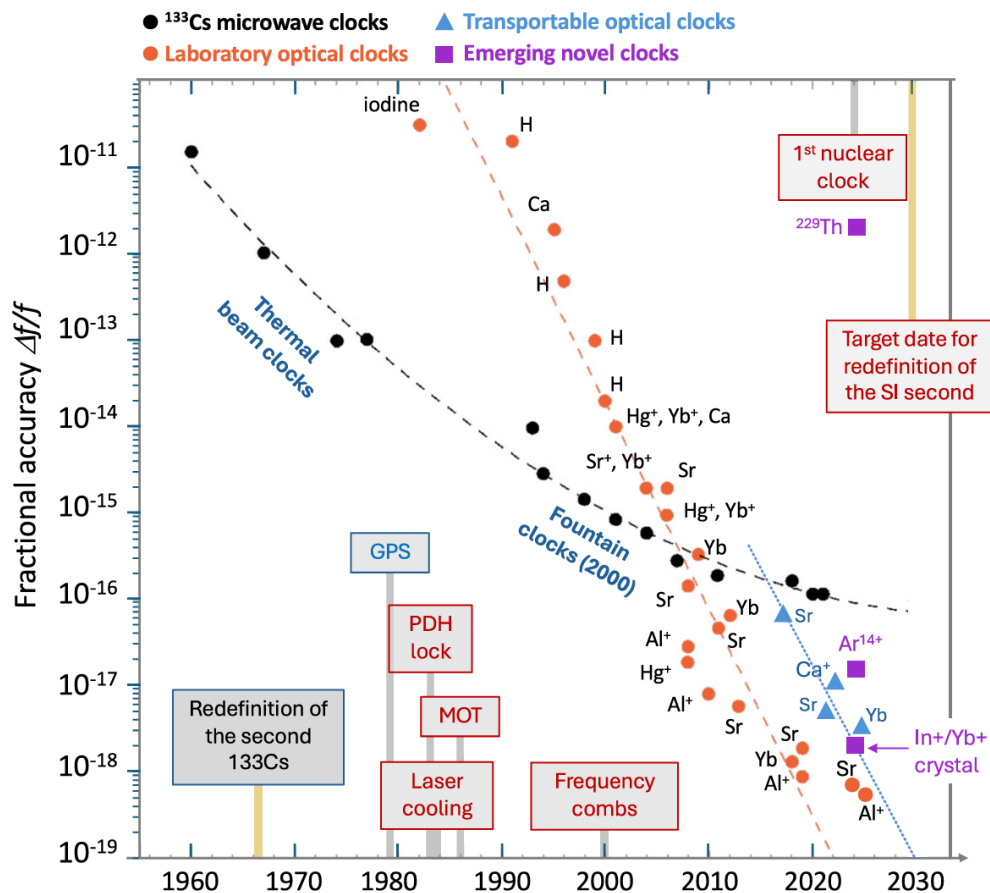
7 units are convenient
SI-base units

derived units

prefixes



Towards redefinition 2030



- Optical transition frequencies are inherently more accurate to measure than microwave frequencies
- Anticipated frequency inaccuracies below 1 part in 10^{20}

The optical analogues of the microwave clocks are based on nearly forbidden optical transitions in atoms or ions, where the optical frequency is close to 10^{15} Hz, and the transition natural linewidth is approximately 1 Hz or narrower.”

Tara M. Fortier, Andre N. Luiten, and Helen S. Margolis,
"Optical atomic clocks: defining the future of time and
frequency metrology," *Optica* 13, 143-163 (2026)

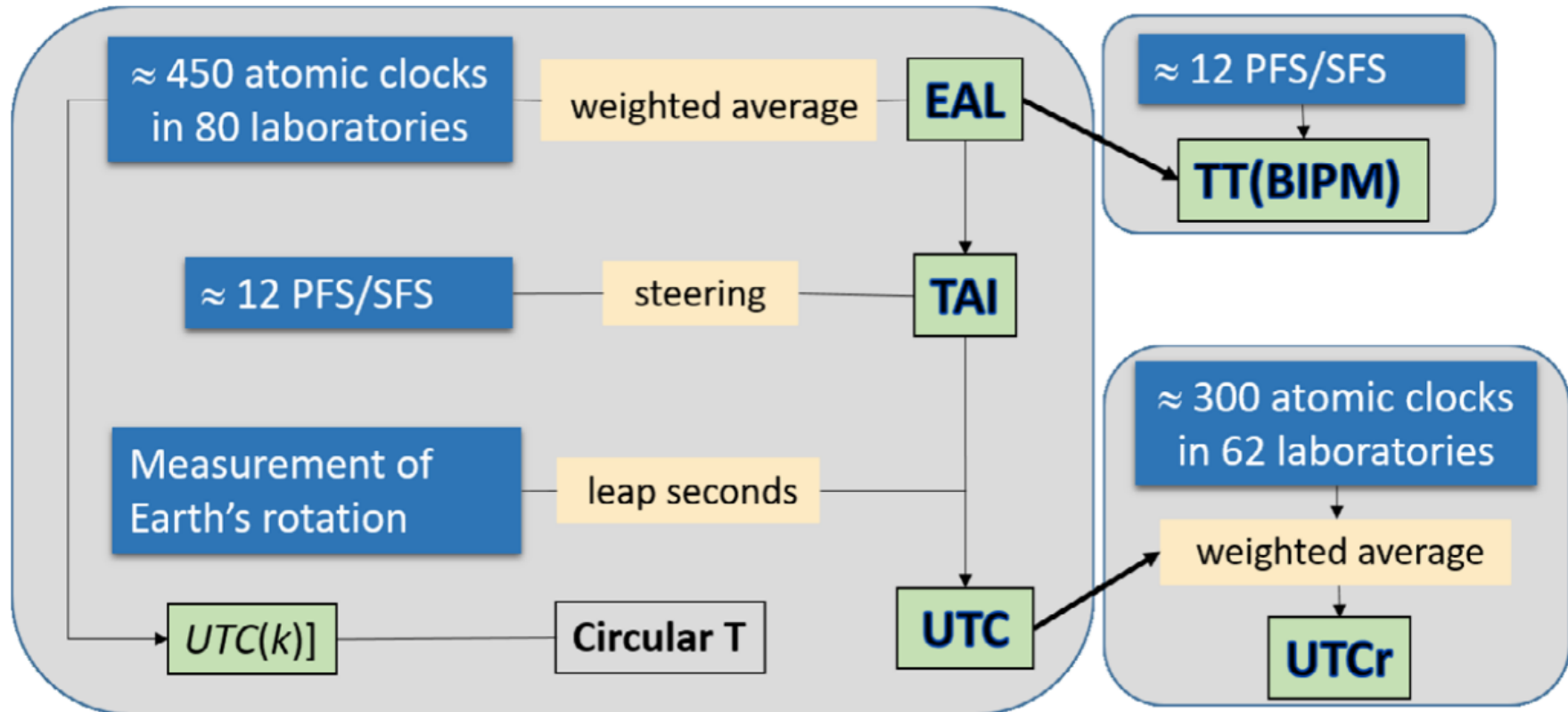
Local Time - GMT/UT - TAI - UTC/UTC(k)

- Solar time, local to municipalities
- Railroad traffic, fast transport
- Standard time and time zones
- International Meridian Conference 1884 recommended local time at the Royal Observatory in Greenwich GMT as base reference for universal time, aka UT
- Intercontinental radio time signals began in 1910 in France, Germany and USA,
- Need for coordination, IAU conceived Bureau International de l'Heure (the BIPM at present 1987-)
- Late 1950s atomic clocks to interpolate UT2
- Synchronization of time signals and its coordination start of UTC in 1964 with frequency and time offsets to BIH atomic time, aka **TAI 1972**

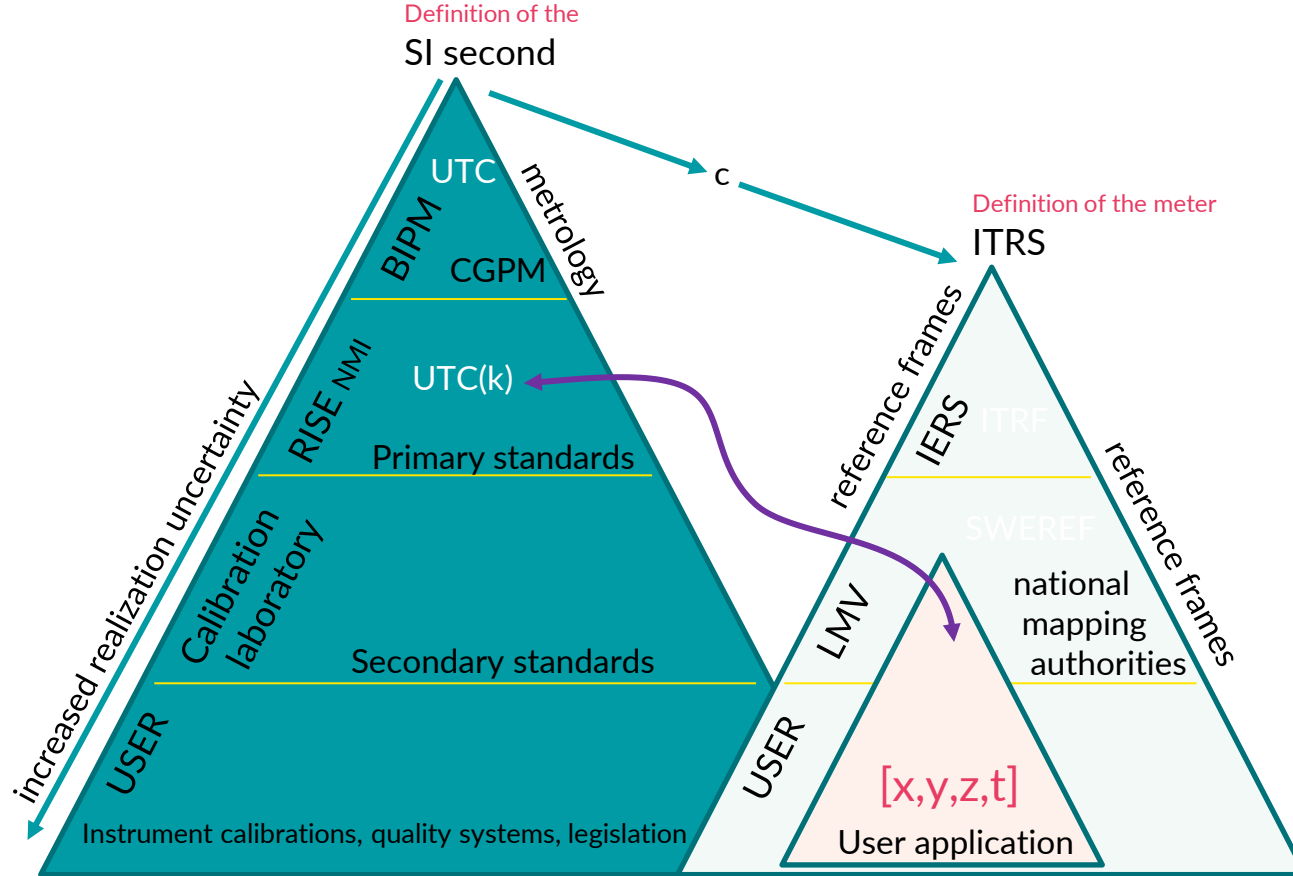


Local Time - GMT/UT - TAI - UTC/UTC(k)

Users required continuous frequency
— stepped atomic time
— leap second concept



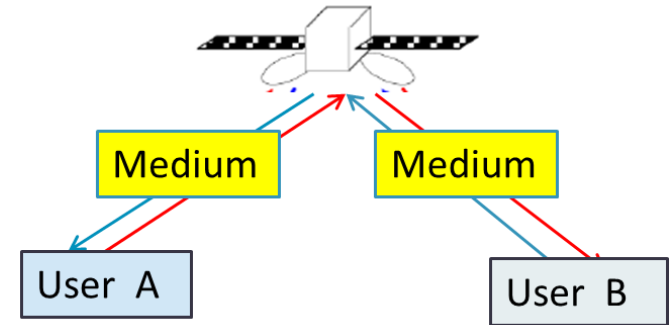
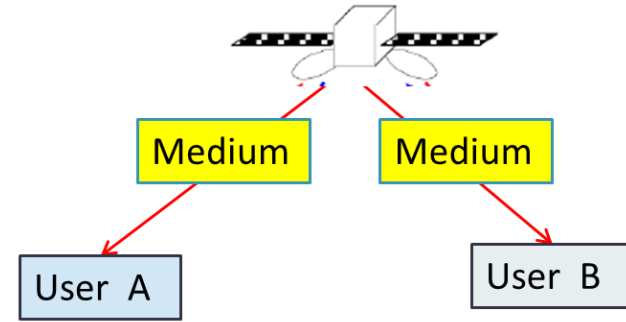
Traceability – Coordinates and a 4D World



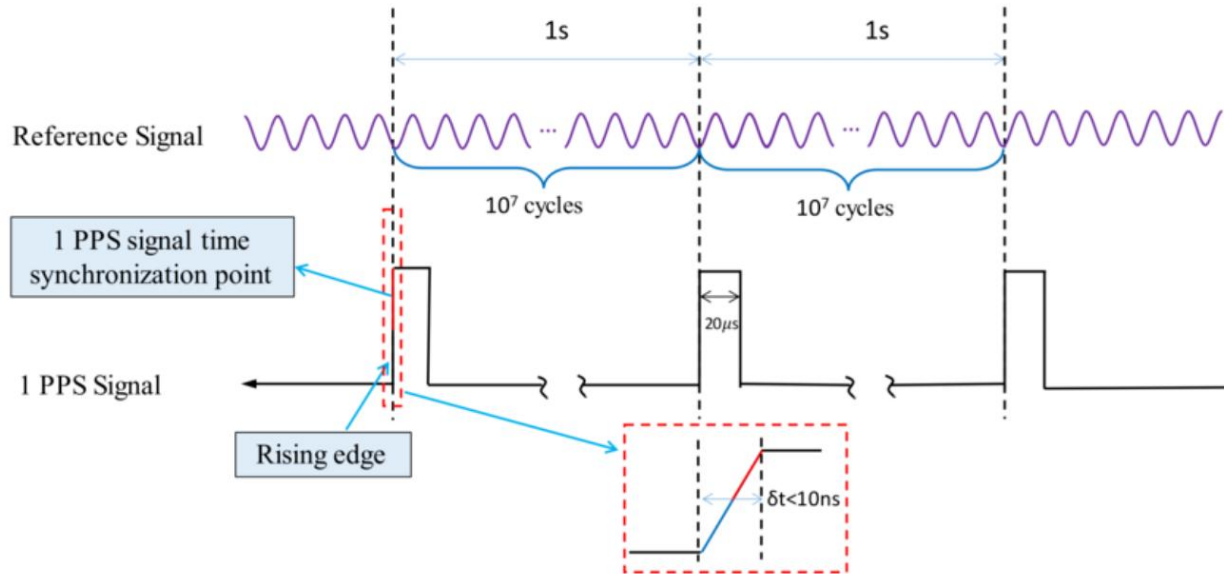
- SI system defines scales not coordinates
 “length of the second”
- Time metrology is concerned about coordinates – UTC ...
 “synchronization”
- Large scale 4D traceability and distribution

Calibration and documentation allows an unbroken chain from device to the definition

Time and how to measure it



Pulses in the Microwave Domain ...

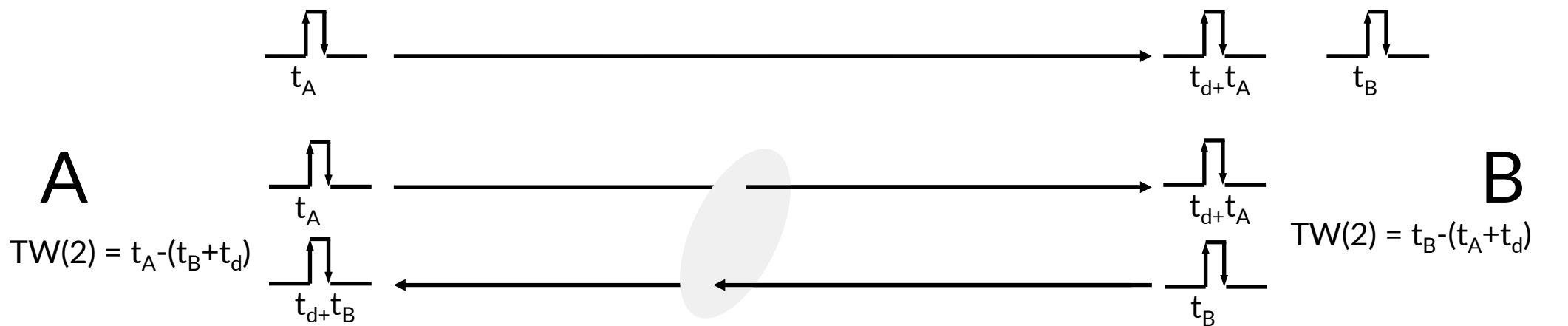


- Time interval using level triggered start/stop devices (TIC)
 - Frequency offset estimation based on time interval
- Beat note/frequency for frequency offset measurements using TIC

Time Transfer, Time Comparisons

Long distances

$$SW = t_B - (t_A + t_d)$$



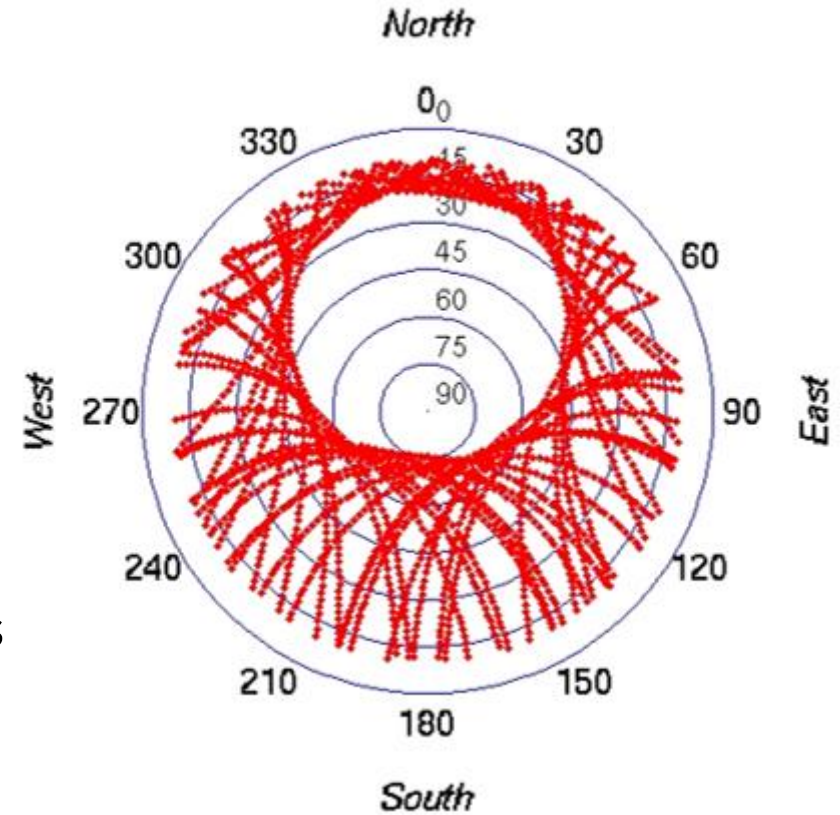
- One way, allows one to many distribution, estimation transmission delay of t_d
 - cables, fibers, long wave (DCF77 and friends), GNSS
- Two-way, active Tx at each and, peer relations, reciprocal path t_d is canceled
 - TWSTFT, network time (NTP, PTP, WR), optical

$$TW = t_B - t_A$$

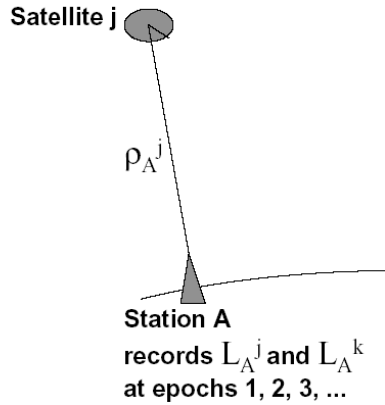
$$= \frac{TW(2) - TW(1)}{2}$$

GNSS, single positioning, differential

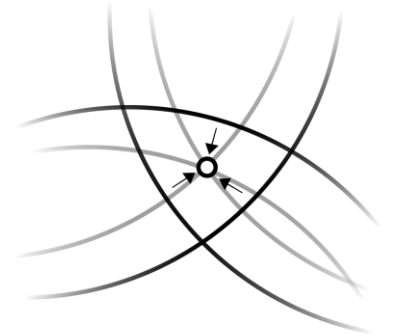
- Dominant technology, SPP (code range) disciplined oscillators (DO) for time and frequency applications, single/multi-frequency receivers, local antenna environment constrains time wander performance to 10-15 ns
- metrology uses code differential approaches on national baselines, reduces atmospheric errors
- iPPP for improved precision, $1\text{e-}16@1\text{d}$ ADEV
- Relative calibration with μp of about 3 ns



GNSS Single Point Position



- Undifferenced pseudo ranges
- Use navigation information for corrections
orbits, clocks, ionosphere
- real time, multi-lateration,
- meter accuracy, 10 ns in time

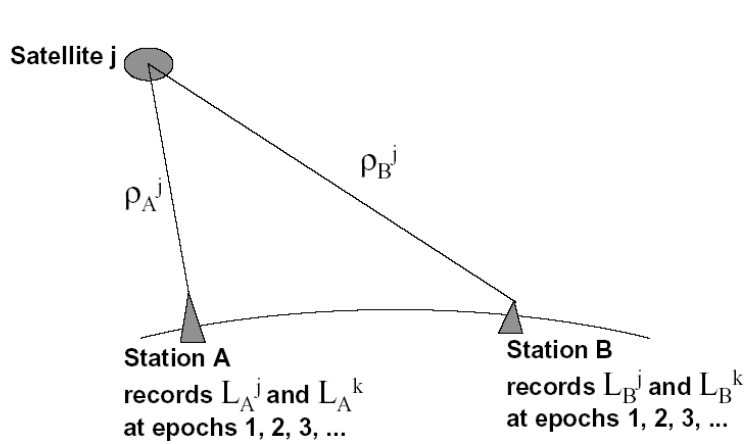


includes all clocks
Differential 'all in view
methods'

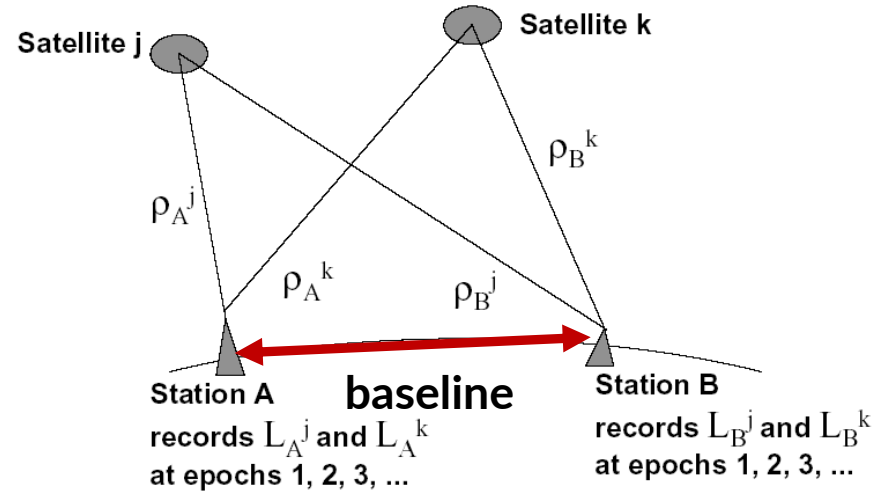
Timing and positioning user

- Precise Point Position, carrier phase
- High accuracy products, IGS
- Real time commercial products, sub –
nano seconds

GNSS differences, improve Single Point Position



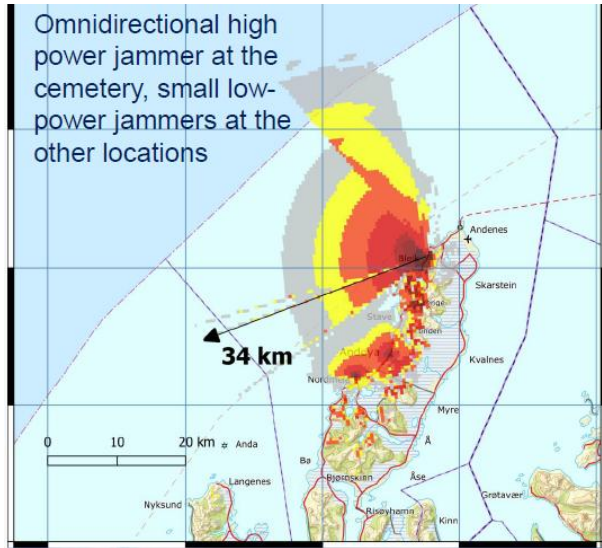
removes satellite clock
'Common view'
Timing user



Also removes receiver clock
'RTK'
Surveyor, navigator

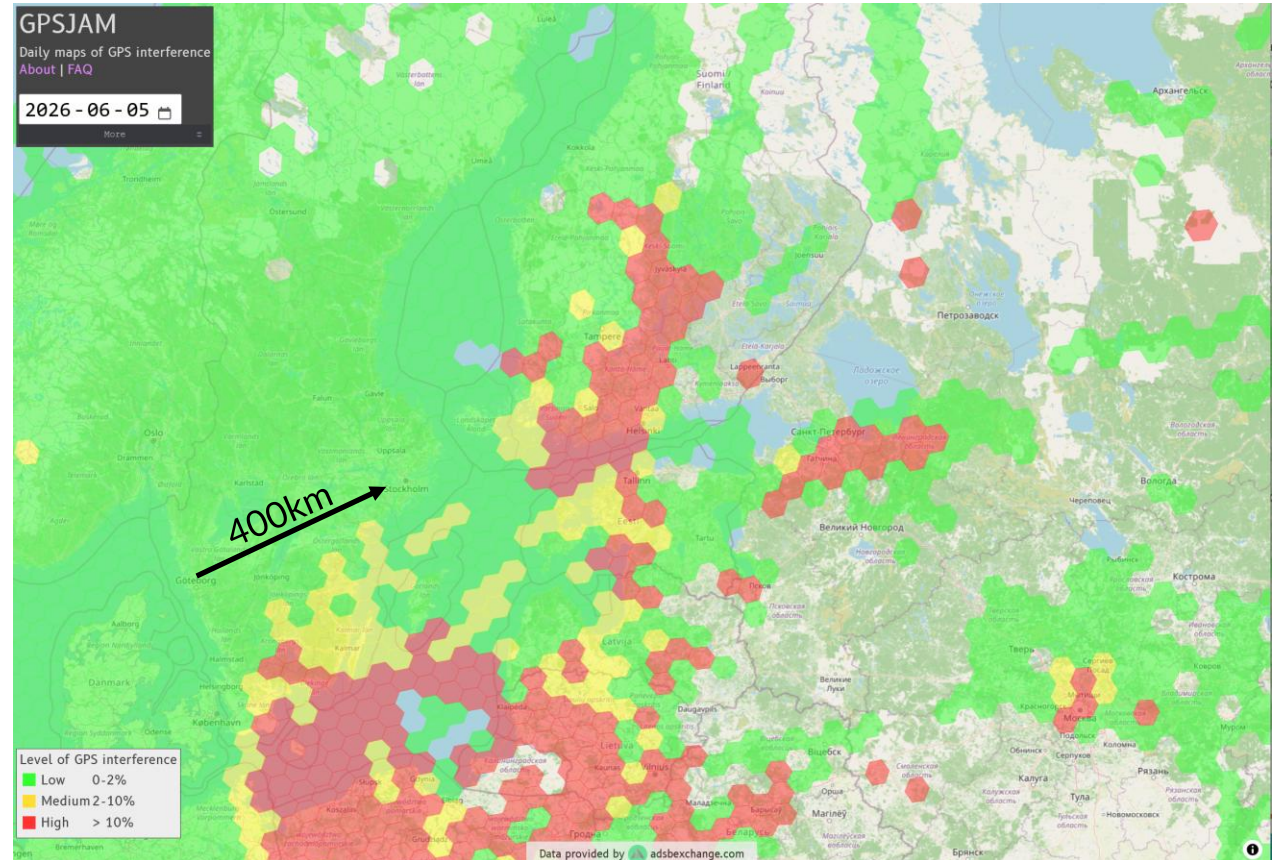
GNSS vulnerabilities

- ground based
- airborne/space based
- NMA
- Signal authentication



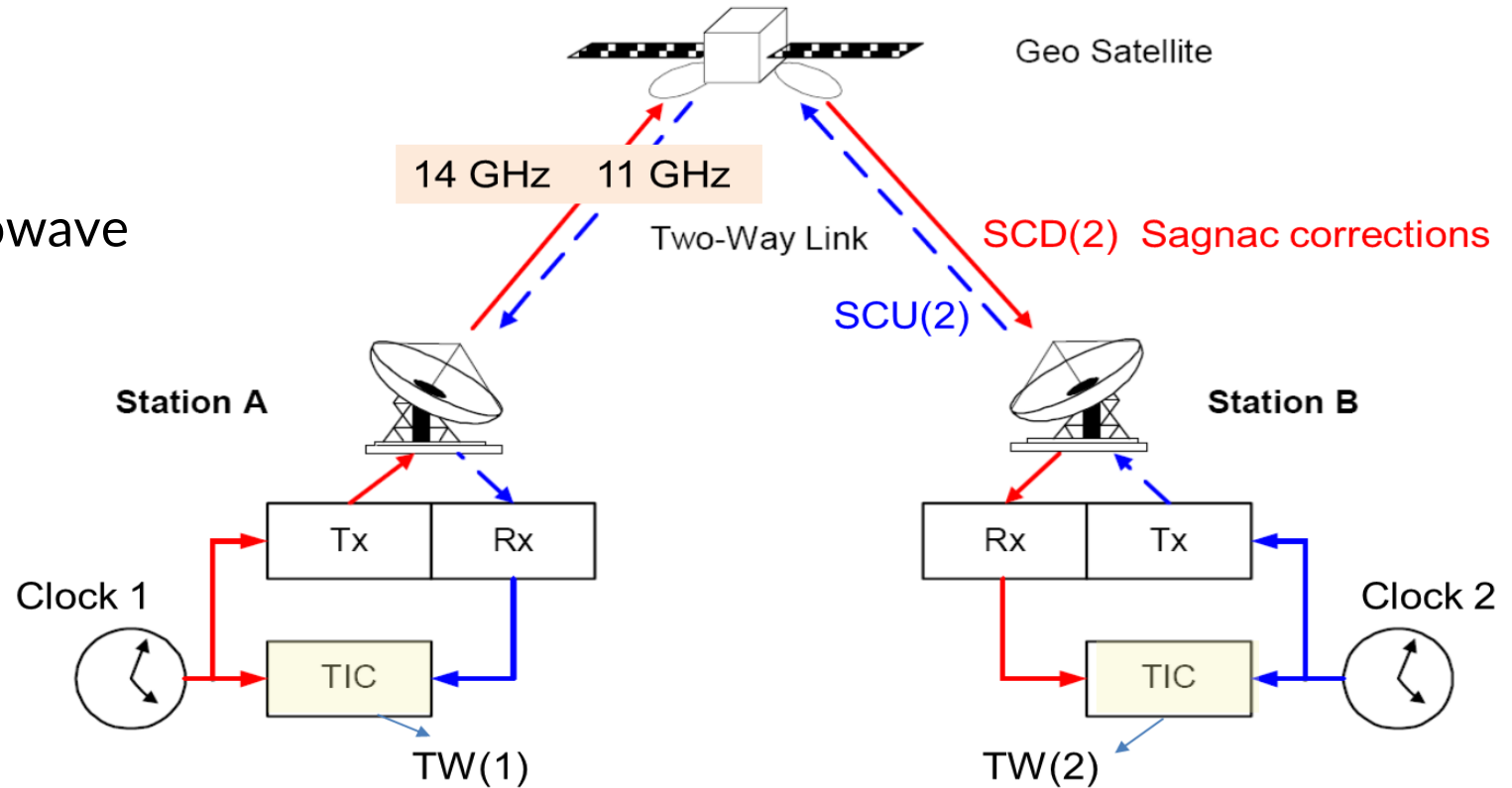
Jammertest 2026

GPSJAM GPS/GNSS Interference Map



TWSTFT

- Most accurate microwave method, $u_B < 1\text{ns}$
- Majority of clocks in TAI/UTC are linked using TW
- 1.8 m parabola directive, Ku band
- Active transmissions
- Passive - single way use as GNSS timing complement



Basic equations:

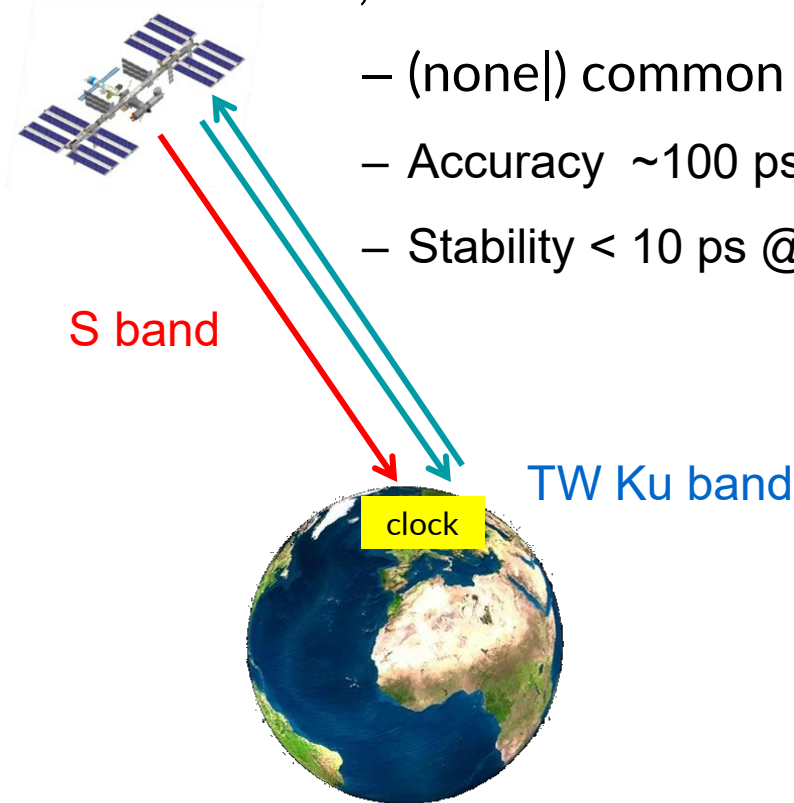
$$TW(1) = CL(1) - CL(2) + TX(2) + SP(2) + RX(1) + SCU(2) + SCD(1)$$

$$TW(2) = CL(2) - CL(1) + TX(1) + SP(1) + RX(2) + SCU(1) + SCD(2)$$

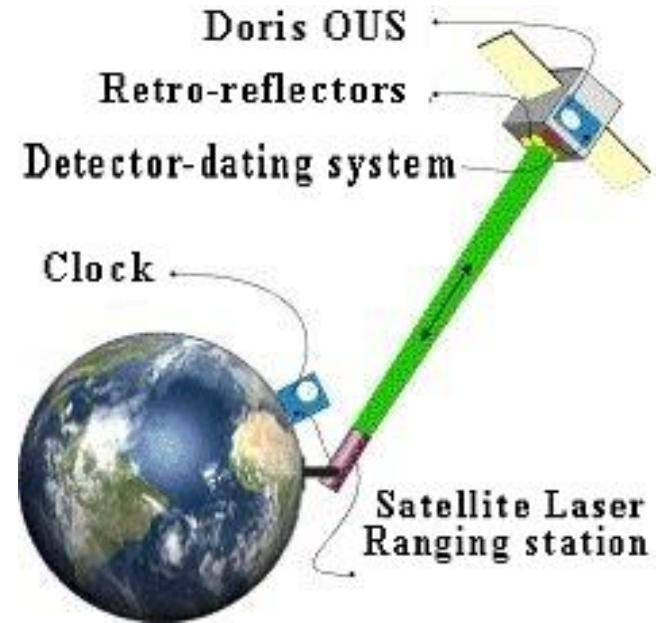
ACES, T2L2 and friends

- Atomic Clock Ensemble in Space
ACES, advanced microwave link

- (none|) common view
- Accuracy ~100 ps
- Stability < 10 ps @ 1 day



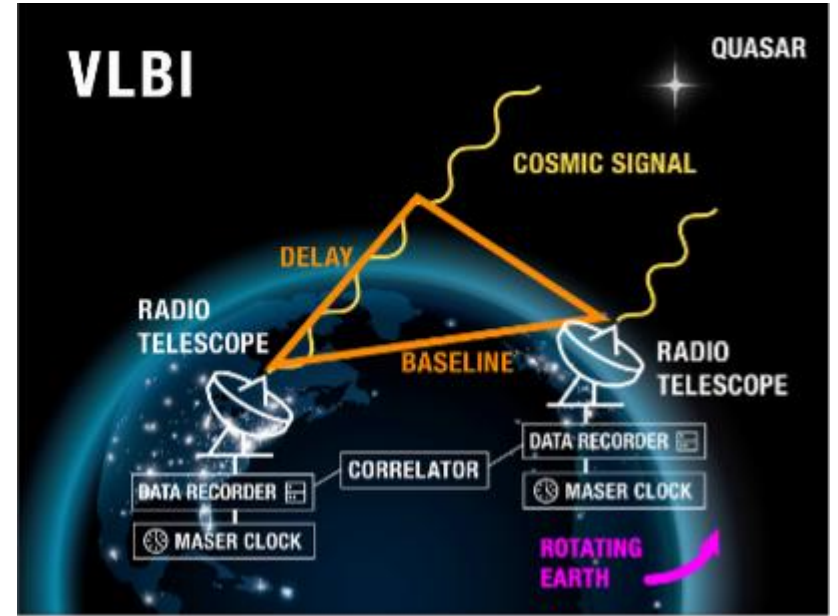
Measures light reception time



Measures the time of light departure and photon back reception

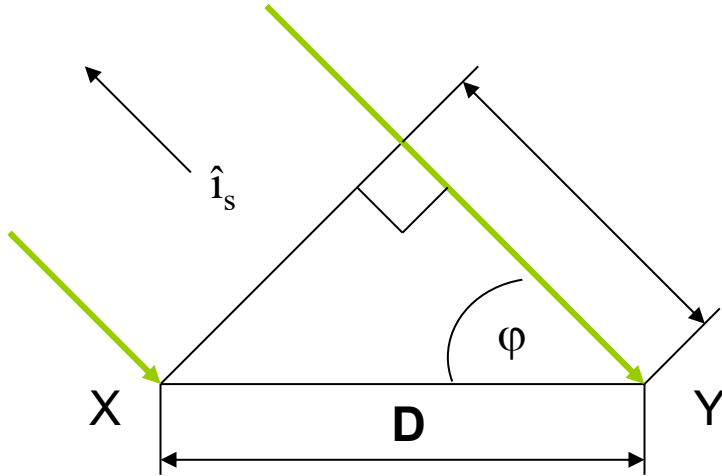
- Time Transfer by Laser Link
- Stability of the ground to ground time transfer of 3×10^{-15} over 10 days

VGOS and ESA Genesis

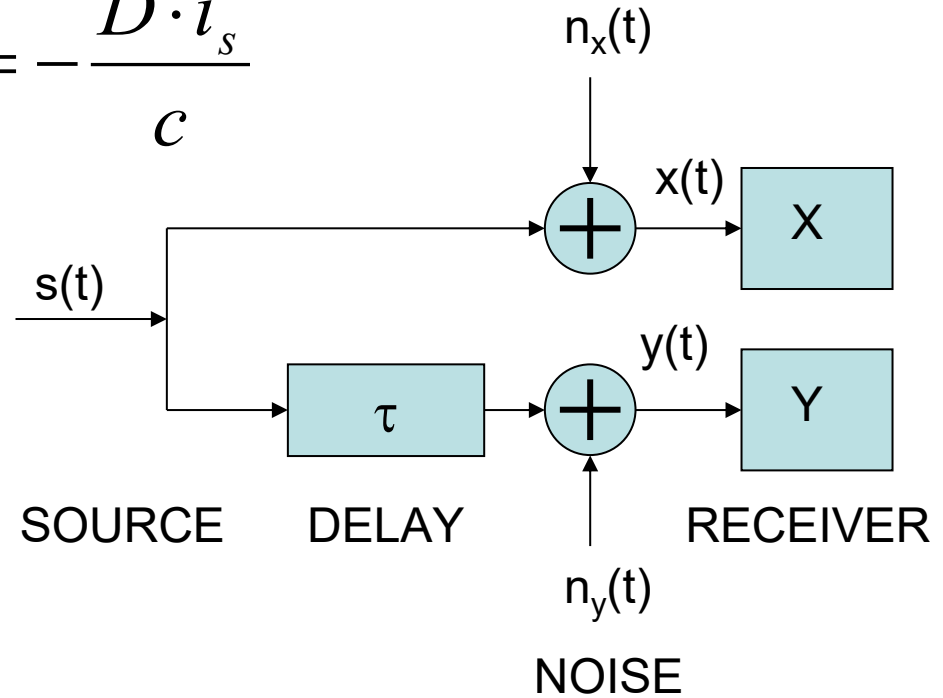


Classical VLBI

Signal model



$$\tau_g = -\frac{D \cdot \hat{l}_s}{c}$$

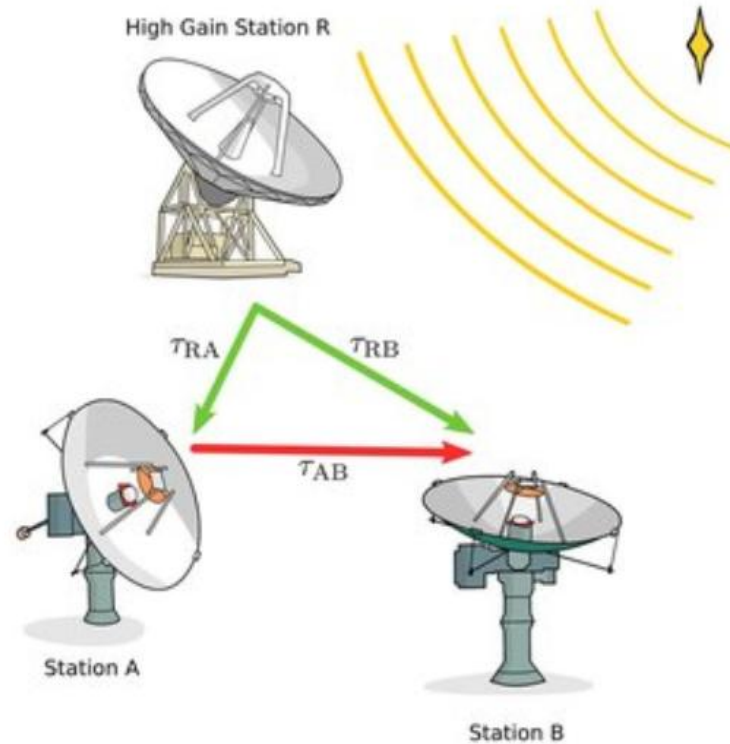


$$\sigma_\tau \approx \frac{1}{2\pi \cdot SNR \cdot B^*} \approx 10 ps$$

$$SNR \approx \sqrt{\frac{A_1 \cdot A_2}{T_{s1} \cdot T_{s2}} \cdot 2 \cdot B \cdot t \cdot \frac{F}{2k}}$$

Celestial Radio Sources as common “clocks”

- Node-hub style observations with small broadband VLBI stations
- small VLBI stations A and B can be used for intercontinental baseline by using a Node-hub style VLBI scheme with the station R
- Delay data of AB baseline is computed by linear combination of delay data on RA and RB baselines



ESA Genesis

Greek Γένεσις, **Génesis** aka 'Origin' or 'in the beginning'

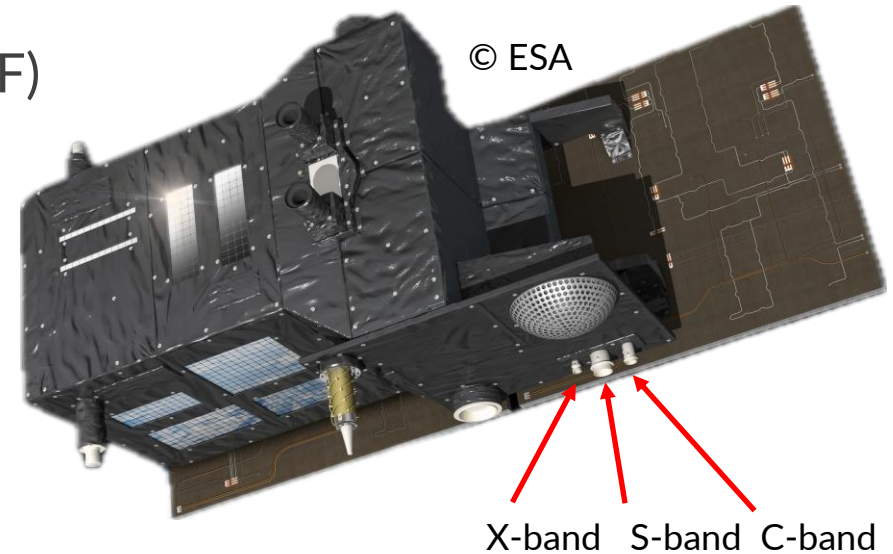
Genesis is a mission of the FutureNAV programme, to fly 2028

Genesis' goal is to contribute to improving the accuracy and stability of the International Terrestrial Reference Frame (ITRF)

- navigation applications
- refine models used for climate and environmental monitoring

co-locating the four geodetic techniques (GNSS, **VLBI**, SLR, DORIS), calibrated

synchronized by an ultra-stable oscillator



[2] https://www.esa.int/Applications/Satellite_navigation/Genesis.

4

geodetic instruments

1

mm accuracy

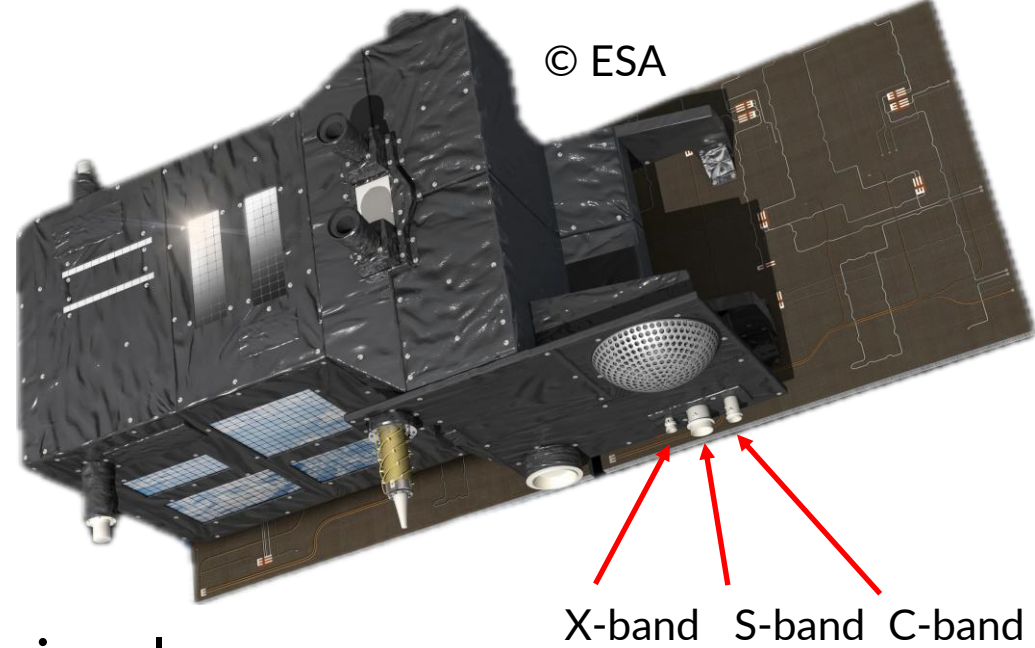
0.1

mm/year stability

RI
SE

Genesis VLBI transmitter

- Orbit: $h=6000$ km, $i=95.5^\circ$
- ITU bands and bandwidth
- S-, C-, X-band antennas for VLBI signal
 - 3100–3300 MHz, 5250–5570 MHz, 8000–8400 MHz, 9300–9800 MHz
- Goal: 10 Jy on earth surface in nadir direction
- USO stability < $1e-10@1d$
short term $5e-13@1-100s$



VLBI with Genesis



Distant quasar  $\leq$ position (i.e. "phase center") accuracy ca. $30 \mu\text{as}$
 $\leq$ no "transmit antenna gain" variation

$\leq$ plane wave front

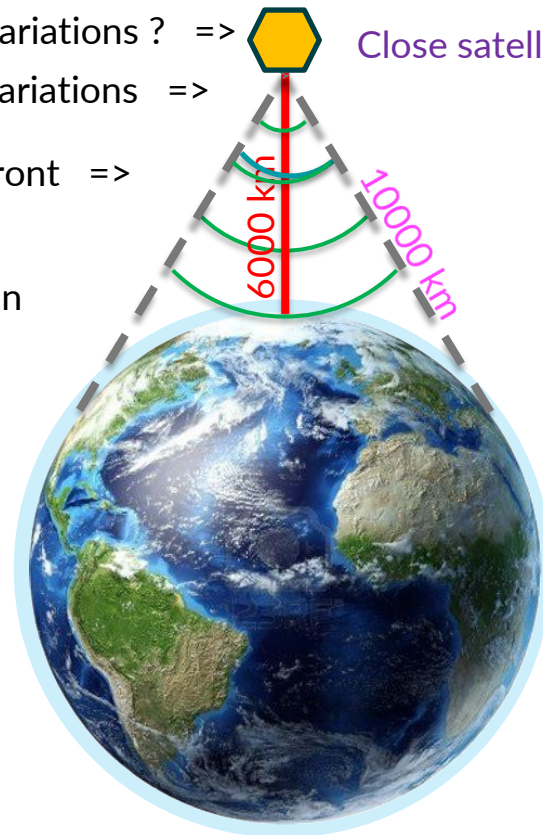
$\leq$ distance
source – station
is "infinite"



three transmit antennas, phase center offsets $\Rightarrow$
phase center variations ? $\Rightarrow$  Close satellite
antenna gain variations $\Rightarrow$

curved wave front $\Rightarrow$

distance
source – station
varies $\Rightarrow$



The important differences are:

- 1) Source position and attitude
- 2) High rotational speed
- 3) Antenna characteristics
- 4) Wavefront
- 5) Distance source – station
- 6) Non-sidereal tracking needed

Objectives – VLBI stations and Genesis for time and frequency

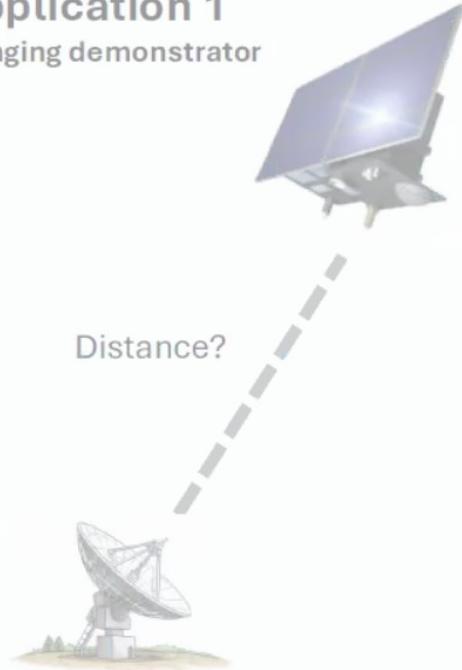
- VLBI has good timing infrastructure, some are UTC(k) or close to a UTC(k)
 - Connection to TAI and international time keeping
 - Intercontinental
- Legacy methods GNSS and TWSTFT are not sufficient to support optical frequency standard comparisons
- Non-interferometric time via Genesis could improve robustness of VLBI analysis (requirements on the clocks residuals is in single millimeters, 10 ps)
- Resolving satellite attitude with single band range analysis

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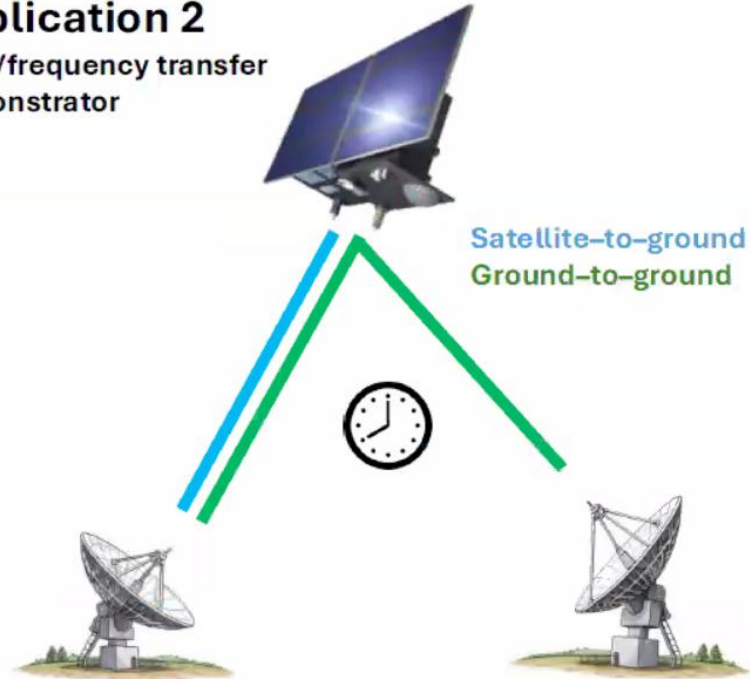
Application 1

Ranging demonstrator



Application 2

Time/frequency transfer demonstrator



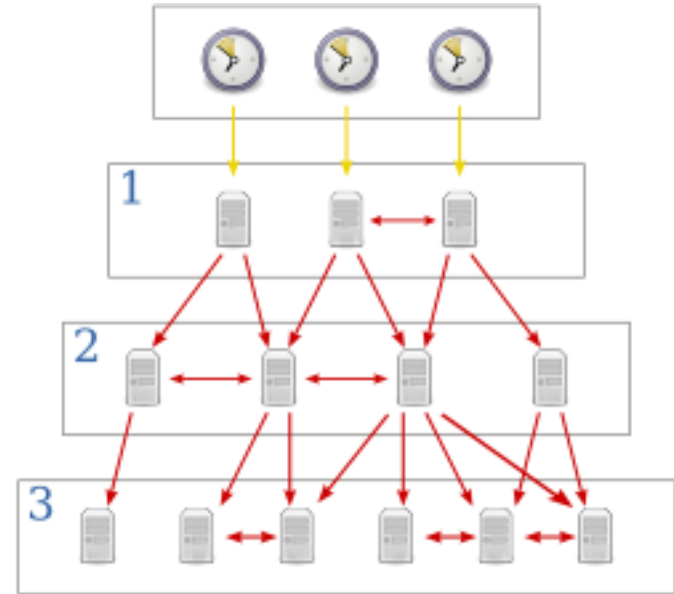
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Ground Based - Fibers

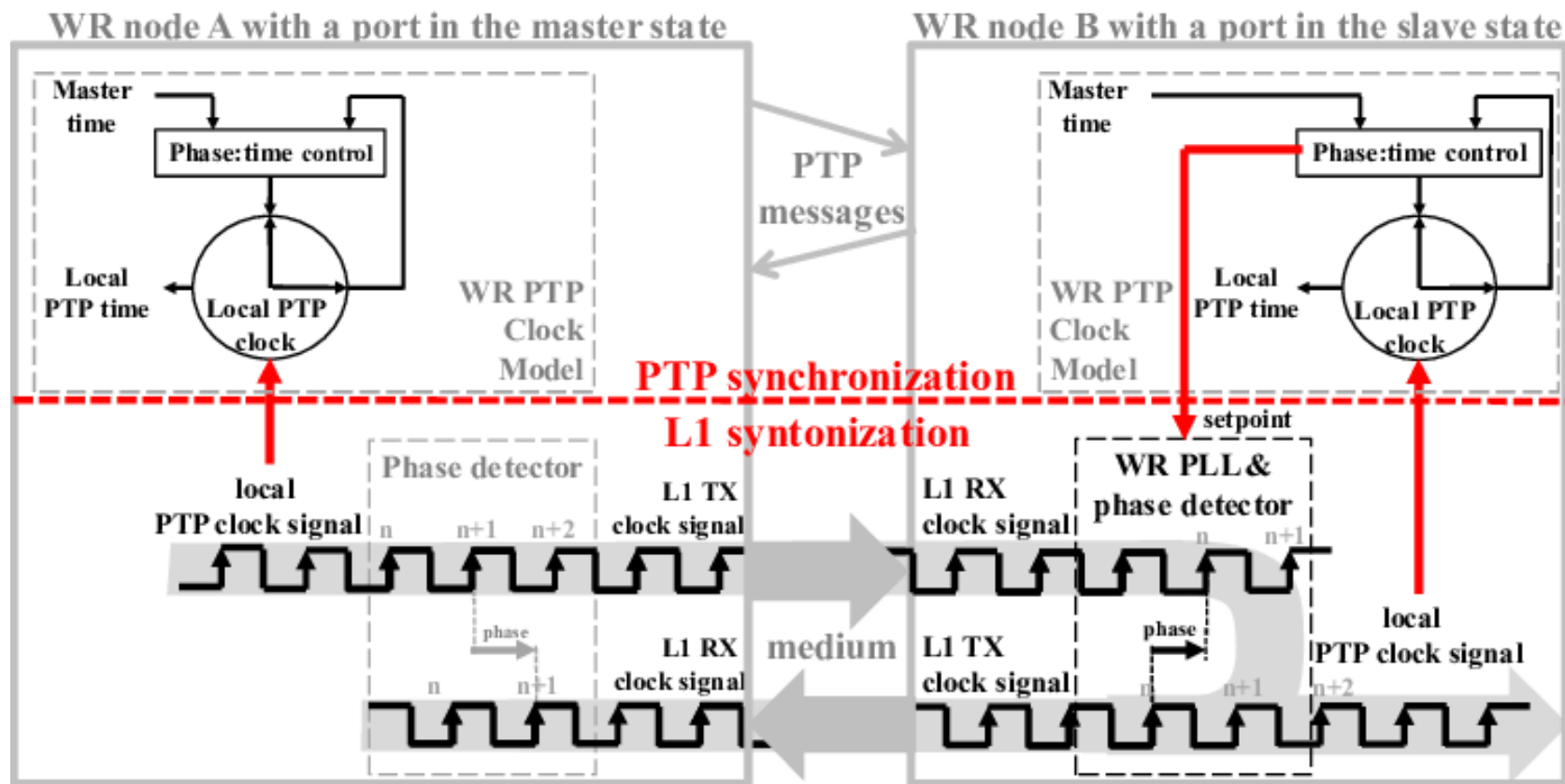


Network Time – Two-Way principles

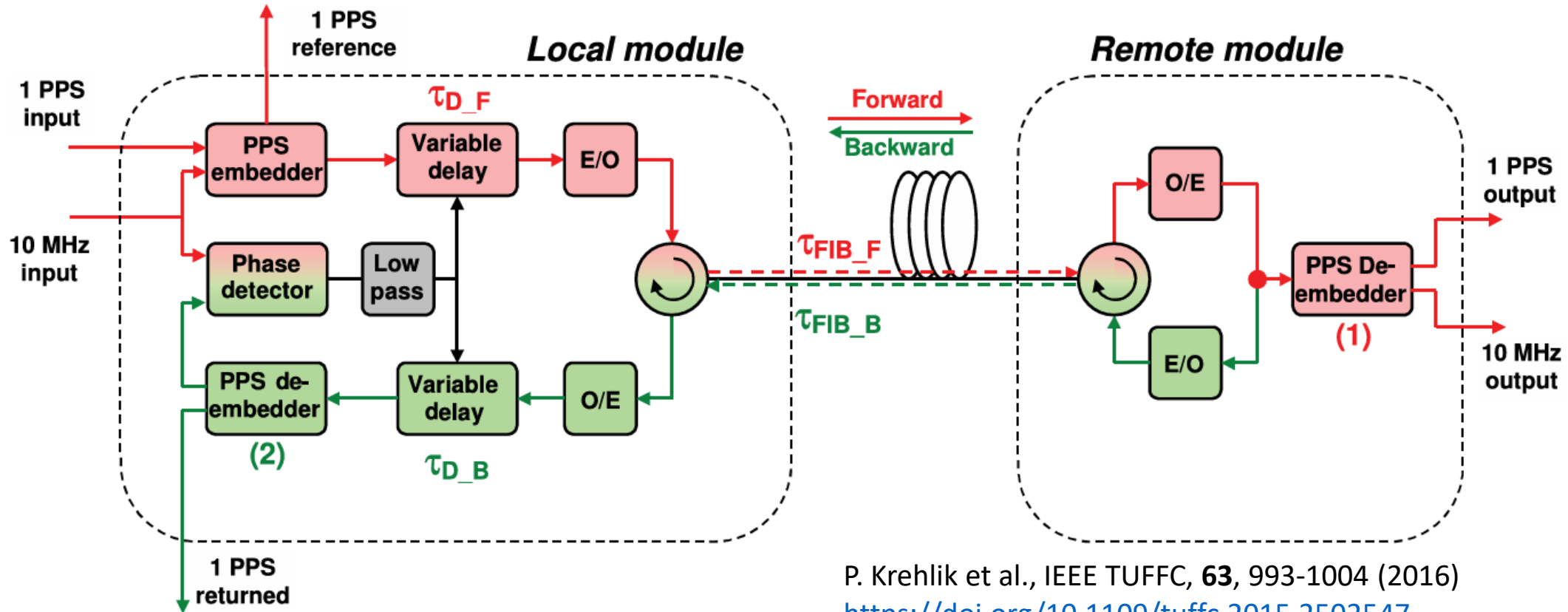
- Protocol based – routed Internet
 - Introduces asymmetric and variable delays
 - NTP, PTP improves in LAN architecture
- Minimize errors by assuring reciprocal paths
- Bidirectional approach using wavelength or polarization multiplexing
 - typical communication networks do not support this,
“timing channels” bypass asynchronous network



White Rabbit / IEEE1588 HA



ELSTAB - electronically stabilized fiber-optic time and frequency distribution



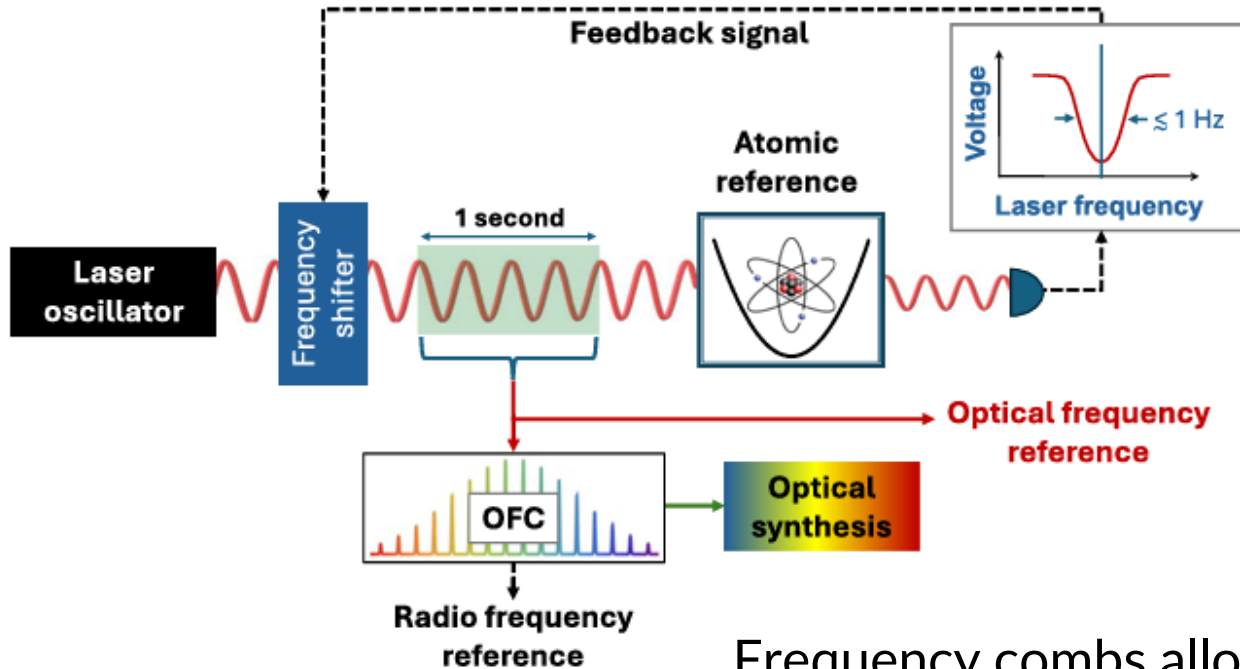
P. Krehlik et al., IEEE TUFFC, **63**, 993-1004 (2016)

<https://doi.org/10.1109/tuffc.2015.2502547>

Optical Frequency and Combs



Clocks – Higher Frequencies are better

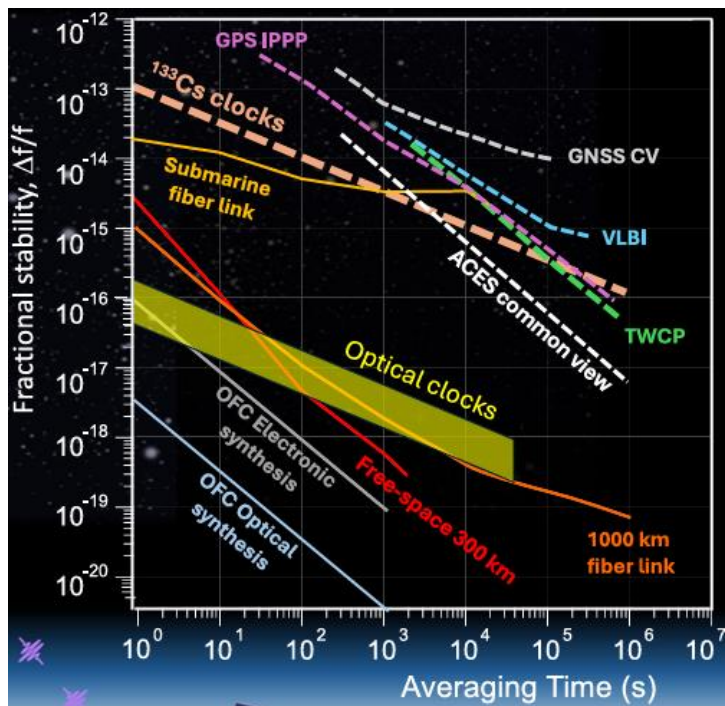


- Vapor cells
- Single ion
- Lattice clocks
- Nuclear clocks

$$\sigma_y(\tau) = \frac{1}{2\pi \nu_0 \sqrt{N_a T_m \tau}}.$$

Frequency combs allow direct measurements between microwave and optical domains

Time Transfer – Free Space



"Over 300 km between mountaintops in Hawaii with launched powers as low as 40 μW, distant timescales are synchronized to 320 attoseconds. "

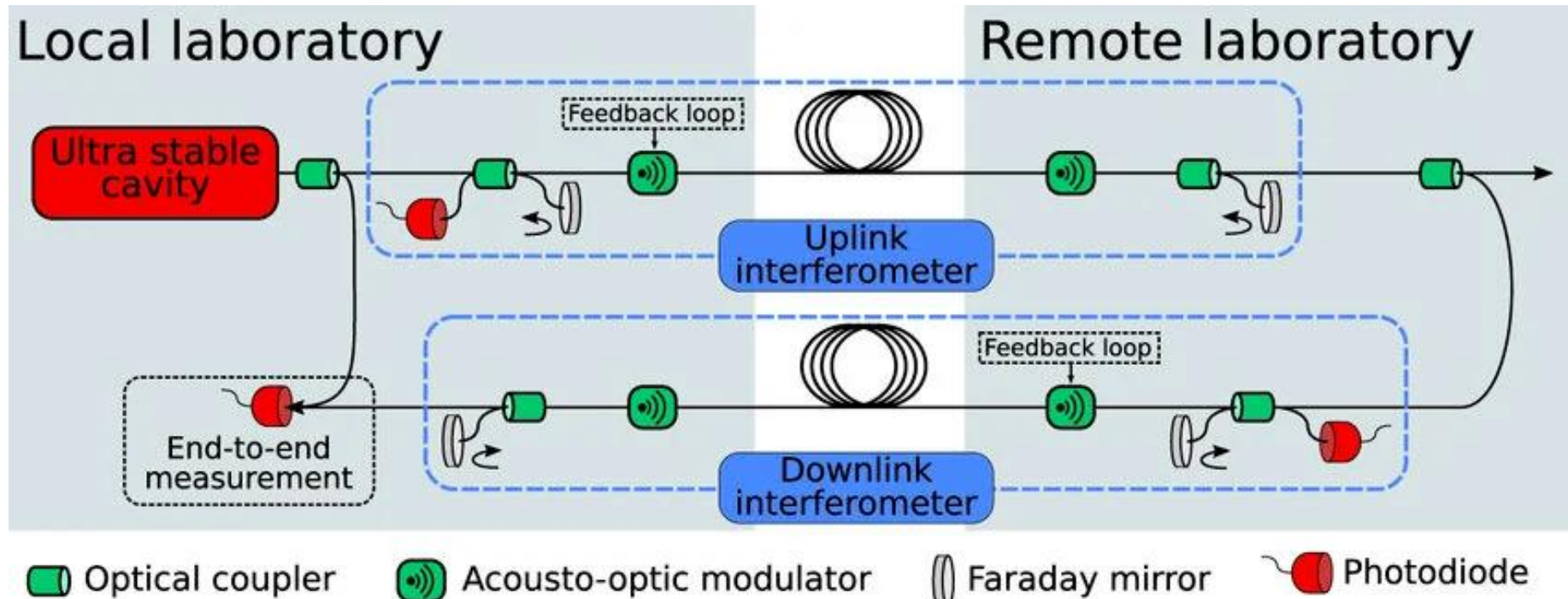
$$\frac{\Delta f_{GR}}{f} = -\frac{\Delta W}{c^2}$$

Caldwell, Emily D., et al. "Quantum-limited optical time transfer for future geosynchronous links." *Nature* 618 (2023)

Tara M. Fortier, Andre N. Luiten, and Helen S. Margolis,
"Optical atomic clocks: defining the future of time and
frequency metrology," *Optica* 13, 143-163 (2026)

Frequency Transfer – in fibers

- Active noise delay compensation for real time, transmission
- Two-way scheme for measuring two lasers

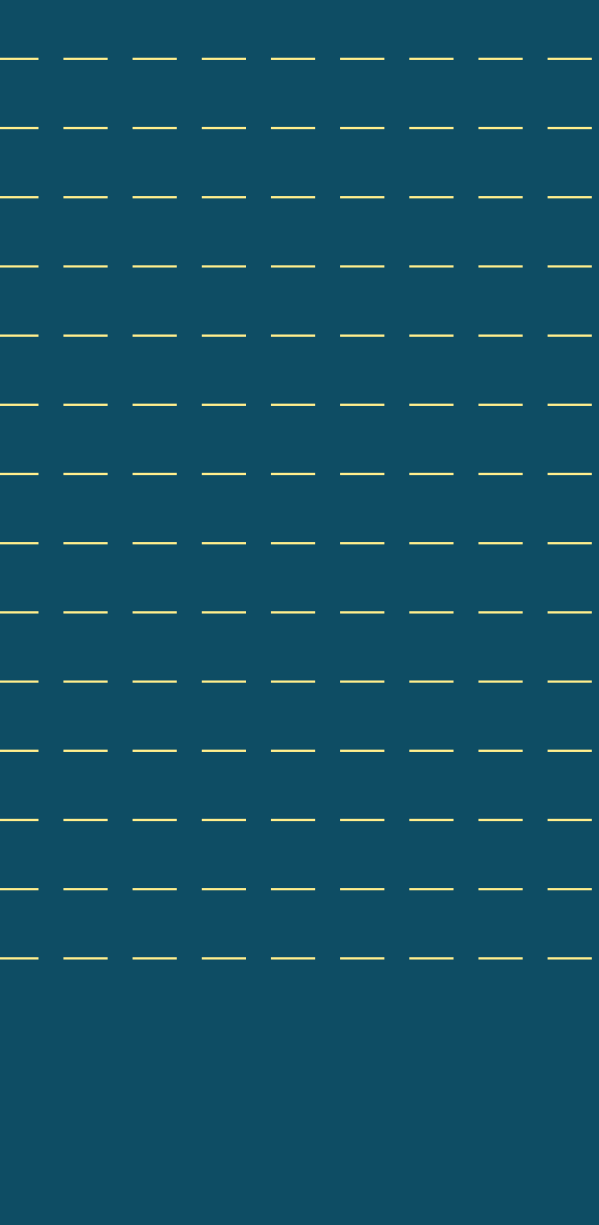


Wrap up



Conclusion

- Legacy time and frequency methods GNSS and TWSTFT dominate time and frequency metrology
- GNSS is vulnerable, TW is not scalable
- Fiber methods cannot (yet) span trans-continental distances, but ...
- ... optical domain is the future both in clocks and comparison methods
- Redefinition of the SI-second with optical frequencies is limited by current comparison methods
- Space geodetic methods will continue to play important roll for the near future – distribution and measurement of time and frequency

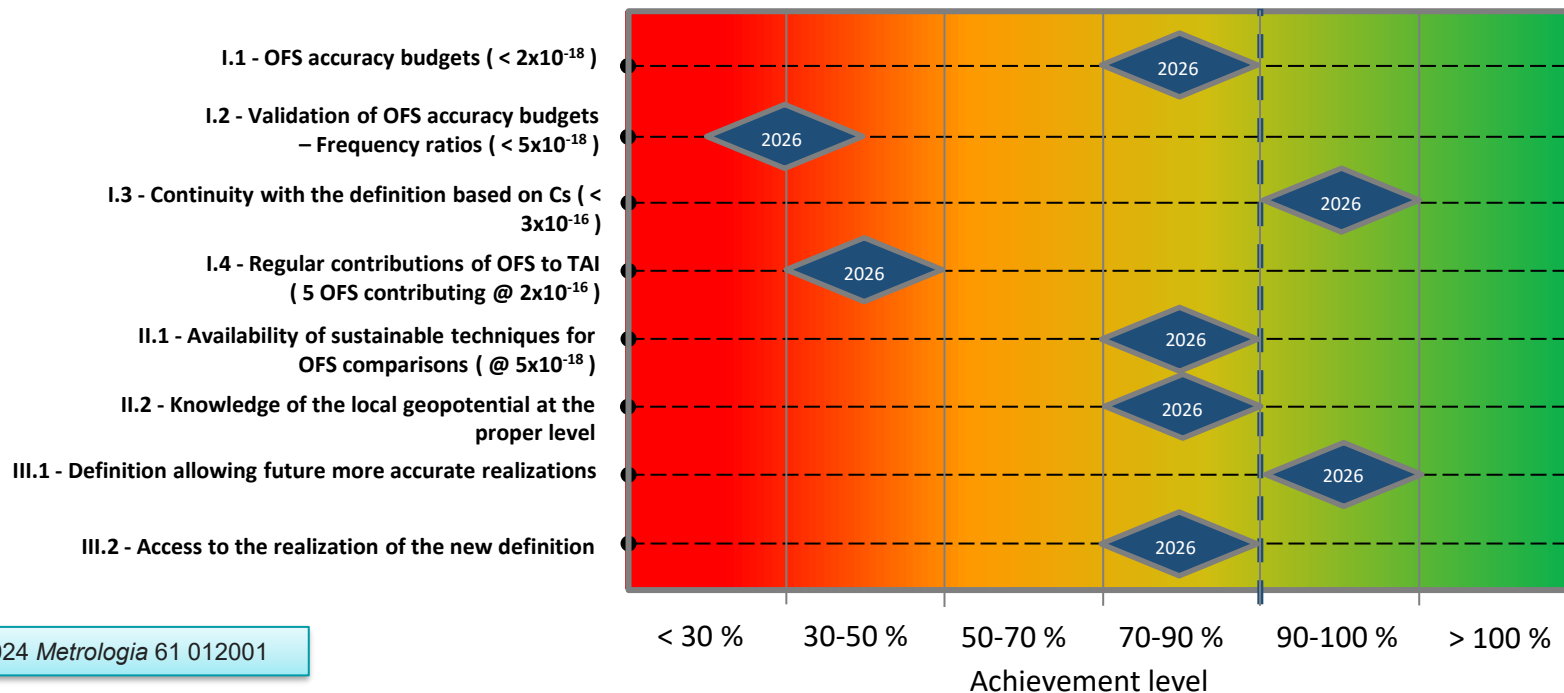


Thank you for your attention

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Mandatory requirements for the redefinition of the SI-second

Mandatory criteria



N Dimarcq et al 2024 *Metrologia* 61 012001

