Chronometric Geodesy and Navigation

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Theory Team

Contents

- Progress in time & frequency metrology
- Relativistic time & frequency transfer
- Chronometric geodesy
- On-going projects:
  - Relativistic GNSS
  - ACES
  - ITOC
- Some ideas for the future

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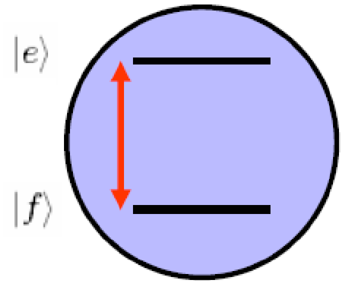
→ Deliver a signal with <u>stable</u> and <u>universal frequency</u>

$$\hbar\omega_{ef} = E_e - E_f$$



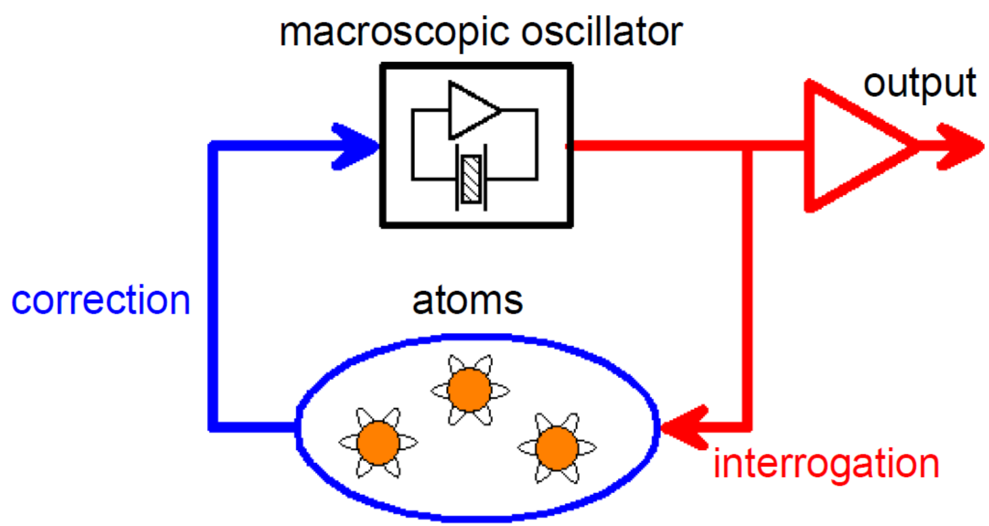
$$\omega(t) = \omega_{ef} \times (1 + \epsilon + y(t))$$

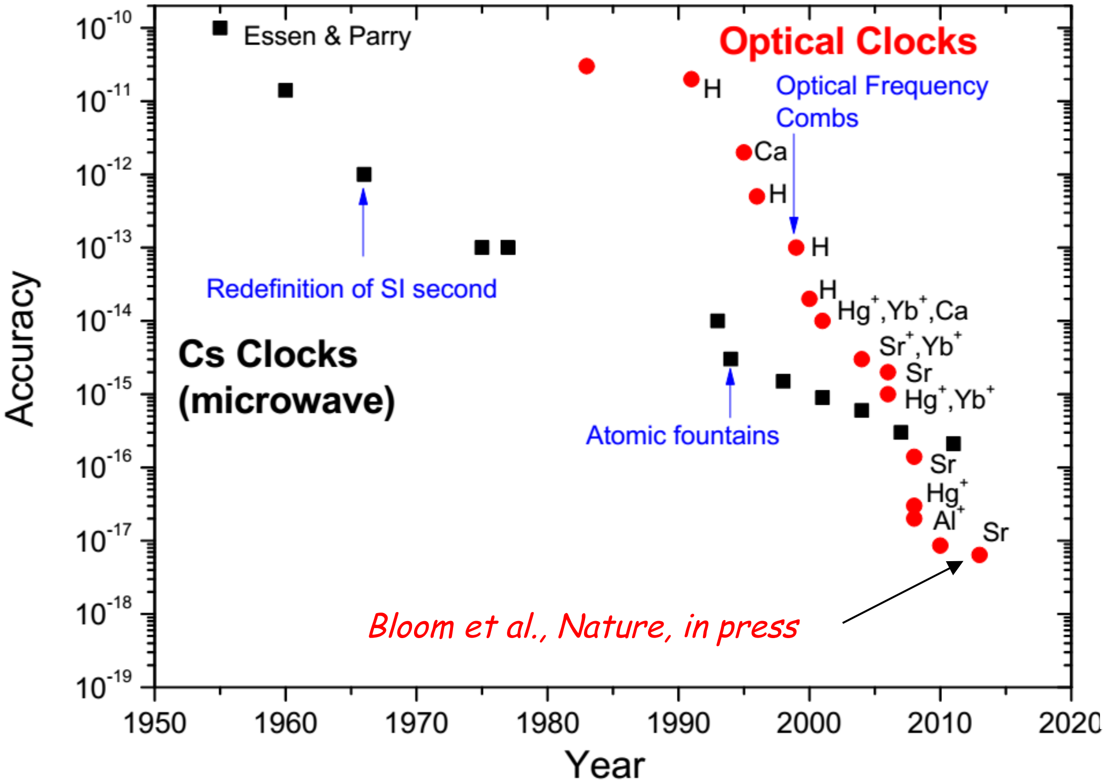
ε : fractional frequency offset

<u>Accuracy</u>: overall uncertainty on ε

y(t) : fractional frequency fluctuations

<u>Stability</u>: statistical properties of y(t), characterized by the Allan variance





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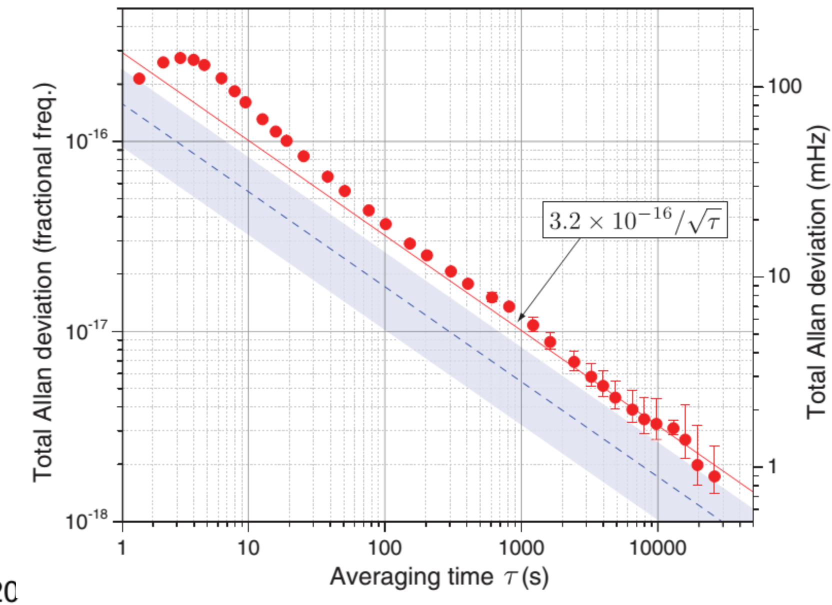
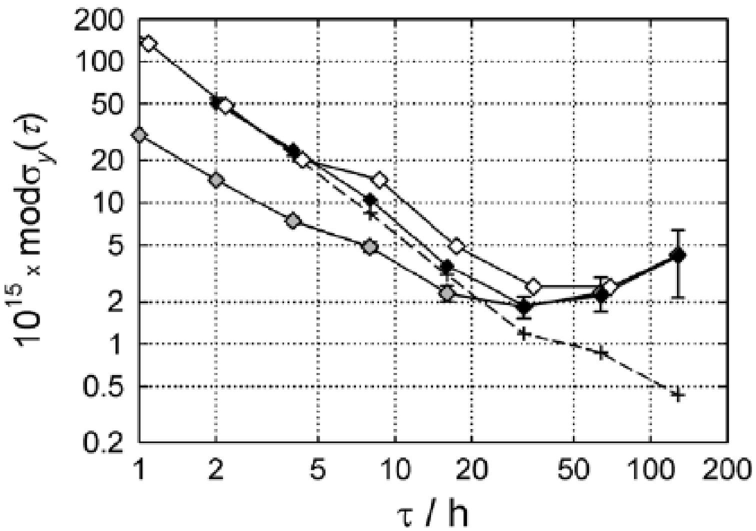


Hinkley et al., Science 341, 1215 (2013)

- Microwave clocks: 10^{-16} accuracy (Fountains)
- In space: microwave clocks with at best 10^{-14} stability at present (GNSS)
- Best performance of optical clocks to date:
  - Accuracy: Sr, 6.4×10^{-18} (JILA); Stability : Yb, 1.6×10^{-18} after 7 h averaging (NIST)
- Research in highly accurate clocks is an active, innovative and competitive field

- Best present satellite radio techniques (GNSS, TWSTFT) reach about 1×10^{-15} frequency stability after 1 day averaging ⇒ 3 years averaging required to reach 1×10^{-18} !!! – and that is being very optimistic.
- Best present optical satellite link (T2L2) reaches about 3×10^{-13} after 10 s averaging ⇒ 25 days averaging required to reach 1×10^{-18} !! – optimistic.
- ACES Microwave link is expected to reach 2×10^{-15} after 300 s averaging ⇒ 5 days to reach 1×10^{-18} – optimistic.

! 2-3 order of magnitudes improvement needed !

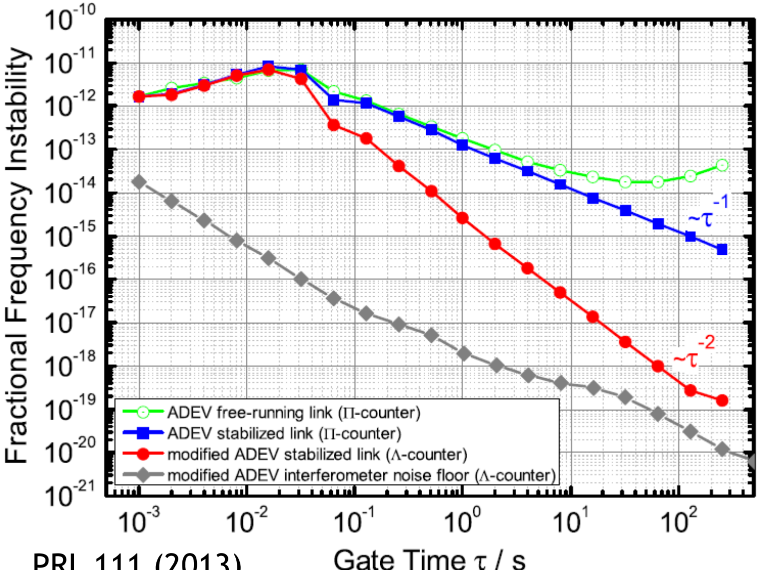


IEN-OP comparison with 3 techniques
(GPS code, GPS phase, TWSTFT)
(Bauch et al., Metrologia 2006)

refimeve.fr

- 100-2000 km phase coherent fibre links demonstrated
- Braunschweig-Munich: 1840 km → 4×10^{-19} (MDEV) in just 100s !!!
- Continental scales only
- Intensive development going on : (Western) Europe-wide network project Refimeve+
- Fibre costs : using existing fibres dedicated to research

- Free space coherent optical links through turbulent atmosphere are in their infancy, but show potential for similar performance as fibre links (SYRTE-OCA, NIST)
- Transportable optical clocks are being developed (back to the future ?)



Droste et al., PRL 111 (2013)

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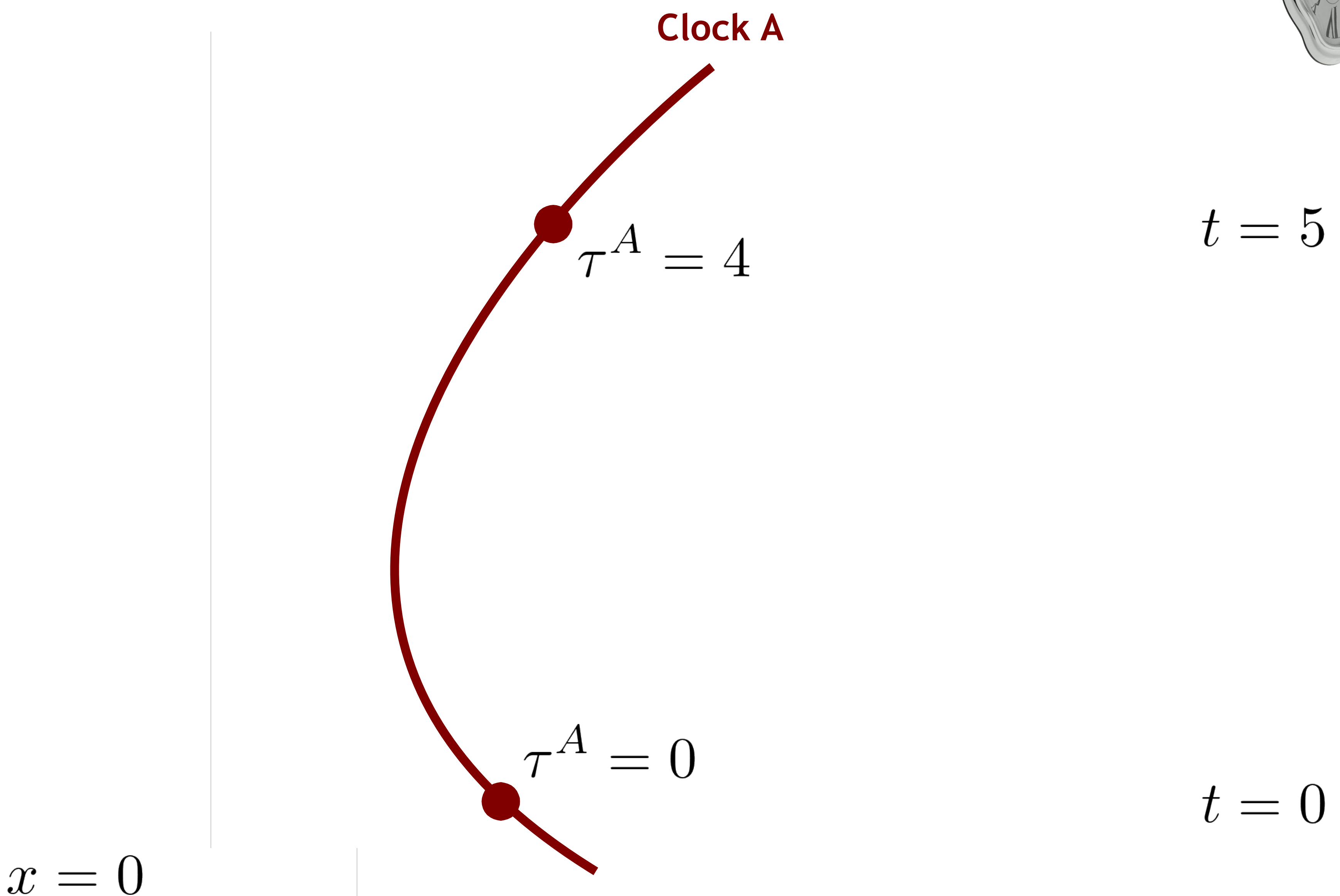
Proper time and coordinate time

- Proper time τ is the time given by an ideal clock: it is an **observable** → count of the number of ticks

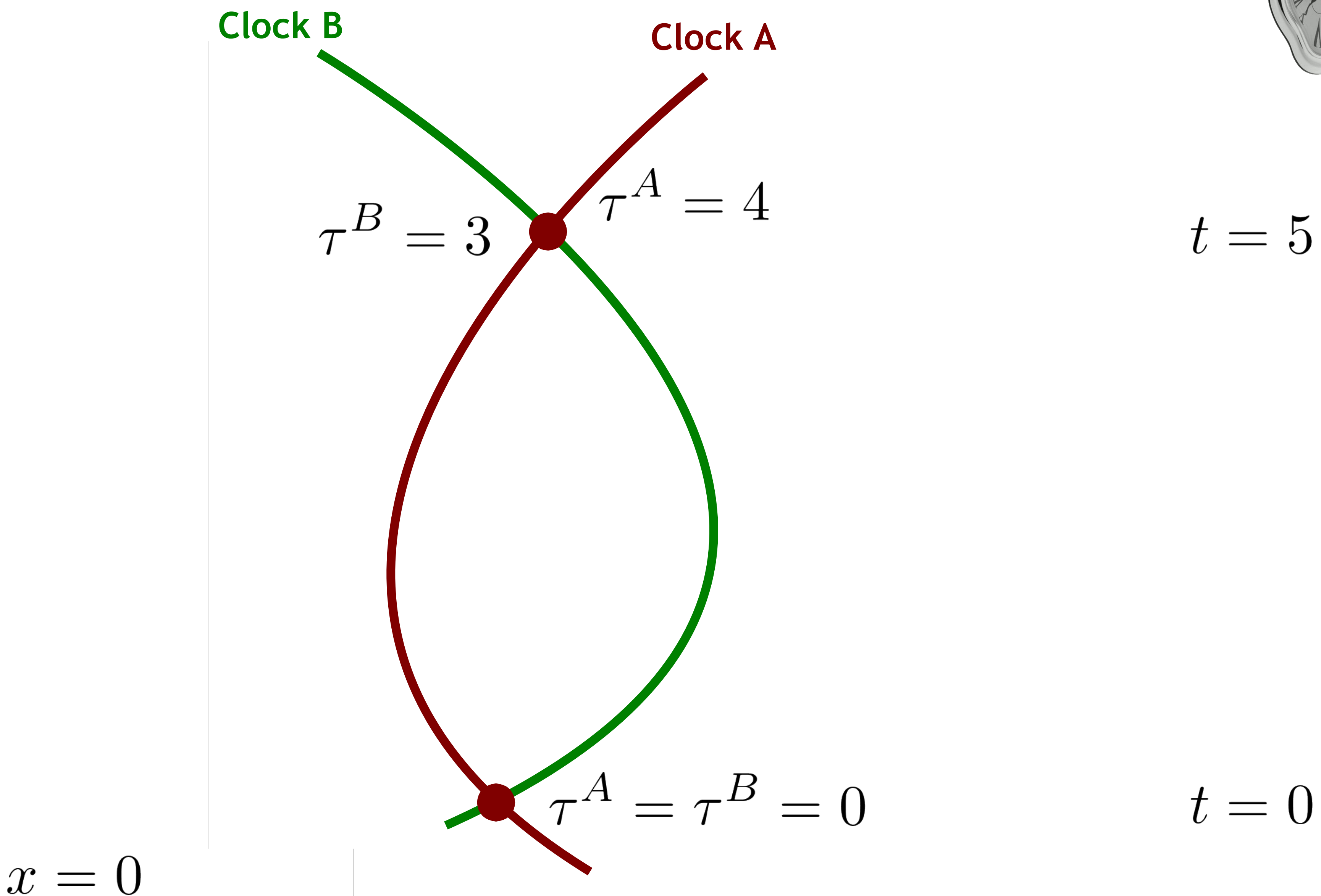
- Coordinate time t has no physical significance: it is a **convention** → a « grid »

- Relation between both is **local**


Clock A
$\tau^A = 4$
$t = 5$
$\tau^A = 0$
$t = 0$
$x = 0$

- The flow of time, or the rate of the clock when compare to coordinate time, depends on the **coordinate velocity** of the clock and on the **gravitational field** (that depends on the mass distribution)

$$\left.\frac{\mathrm{d}\tau}{\mathrm{d}t}\right|_A = \sqrt{-\left(g_{00} + 2g_{0i}\frac{v^i}{c} + g_{ij}\frac{v^i v^j}{c^2}\right)}\Bigg|_A \, , \quad v^i = \frac{\mathrm{d}x^i}{\mathrm{d}t}$$


Clock B
Clock A
$\tau^B = 3$
$\tau^A = 4$
$t = 5$
$\tau^A = \tau^B = 0$
$t = 0$
$x = 0$

Buisson et al., *Initial results of the NAVSTAR GPS NTS-2 satellite*, PTTI proceedings

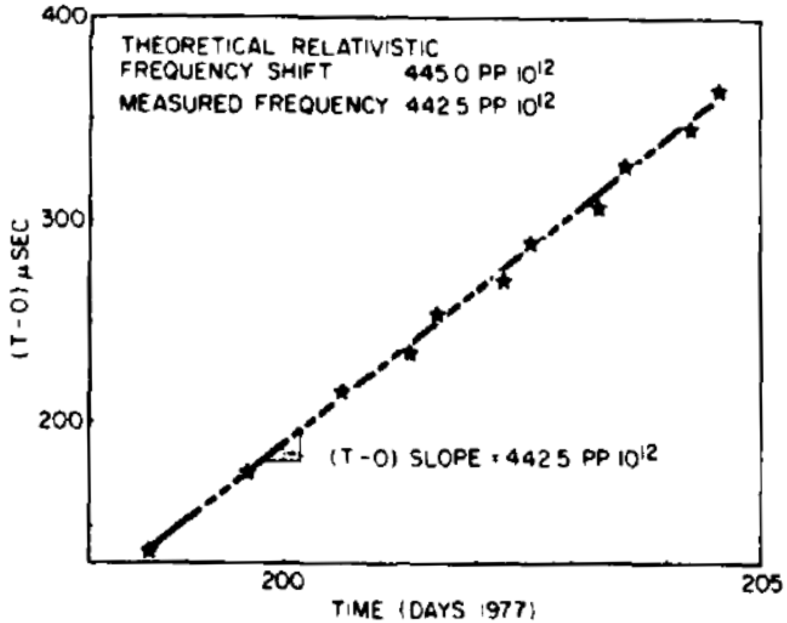


Fig. 20 - Cesium frequency via (T-O) slope

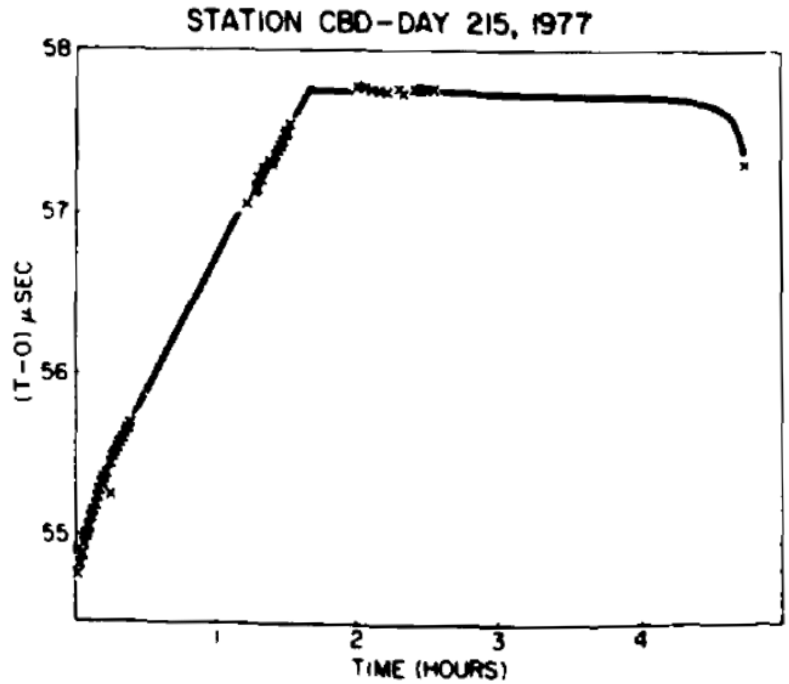
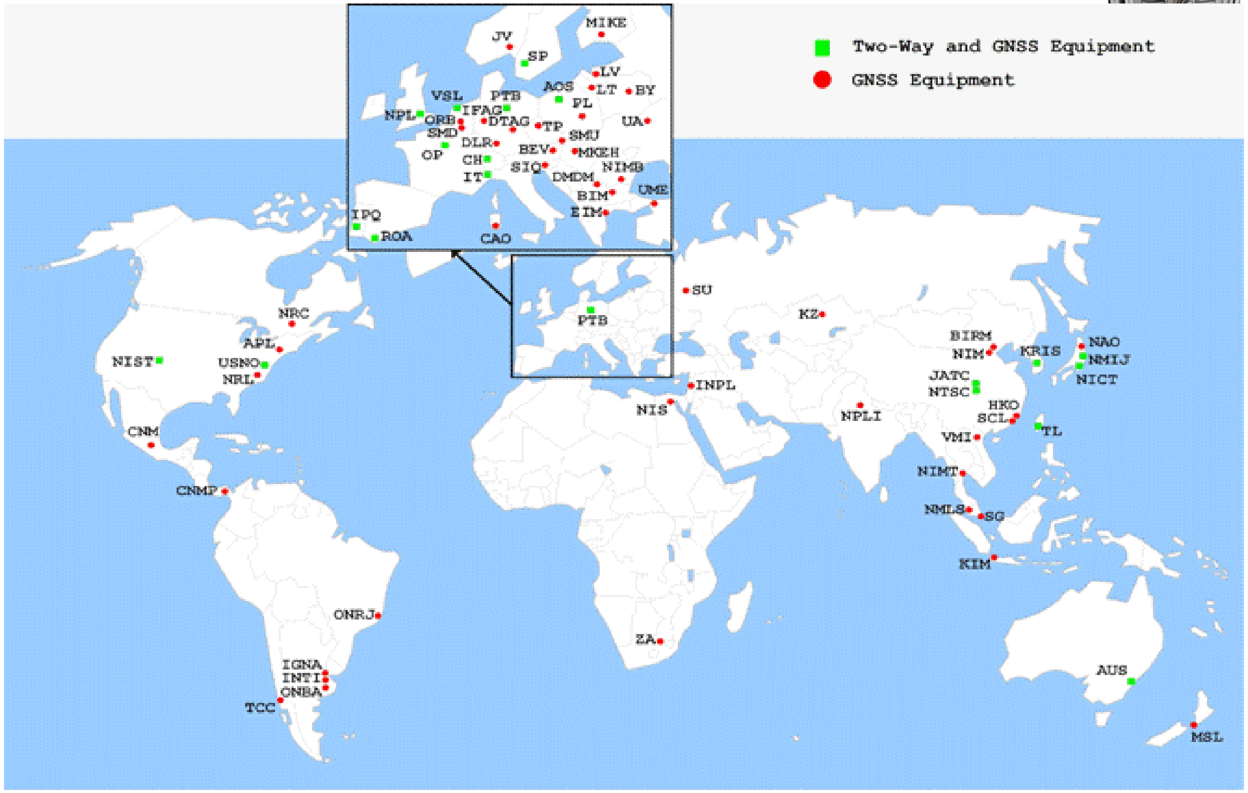


Fig. 21 - Effect of relativity correction

Effet relativiste = **décalage gravitationel** (« redshift ») + **effet Doppler du second ordre** = 38,5 µs @ 1d = 11,6 km @ 1d (~445x10^{-12})

- "TAI is a **coordinate time scale** defined in a geocentric reference frame with the **SI second as realized on the rotating geoid** as the scale unit" (CCDS 1980)
- (free-running) reference : timescale calculated by BIPM using ~400 clocks in more than 70 labs worldwide



- TAI unit (the second) is corrected by steering the frequency to the one of Caesium fountains (Primary Frequency Standards) → **correction of relativistic effect**
- TAI is independent from Earth rotation : UTC = TAI – 34 secondes (leap second)
- Clocks participating to TAI are compared with **satellite time transfer** (GNSS and TWSTFT)

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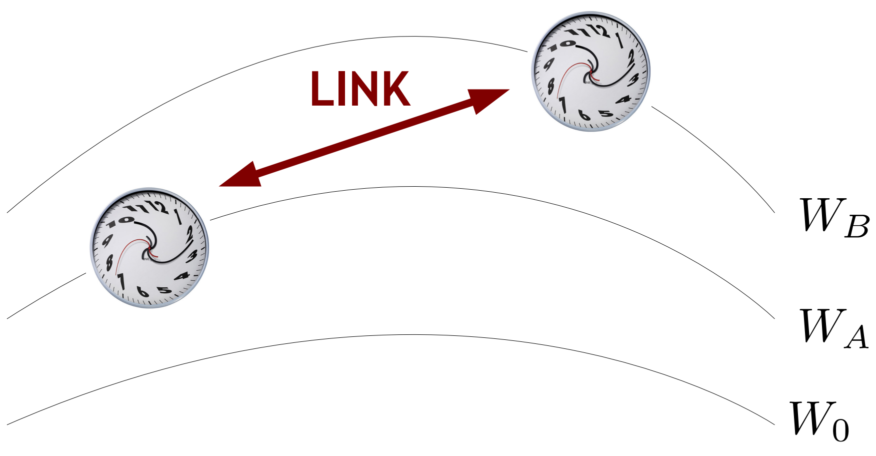
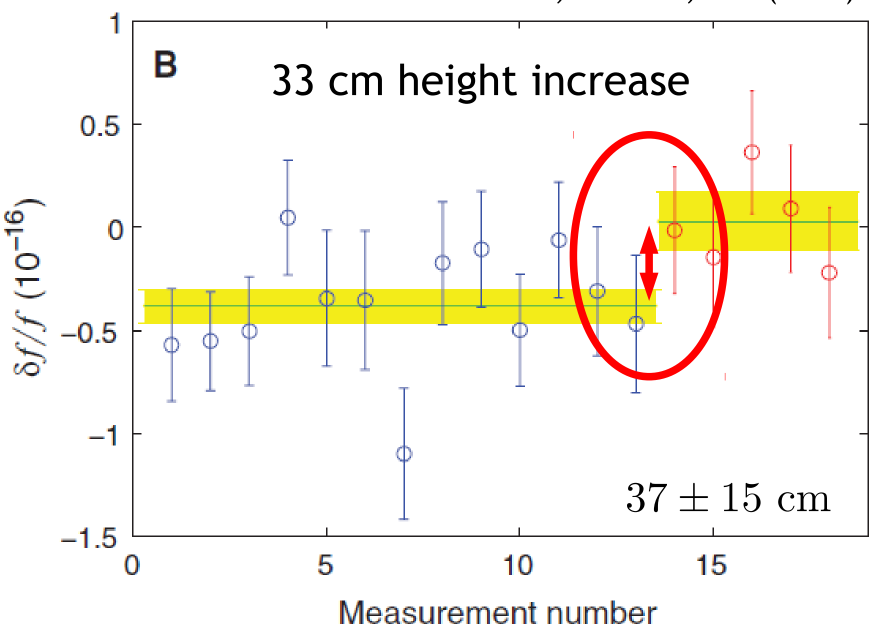
- Clock frequency comparison → measure directly gravity potential differences

$$\frac{\Delta f}{f} = \frac{W_B - W_A}{c^2} + O(c^{-4}) \ , \ W = U + \frac{v^2}{2}$$

$$10^{-18} \leftrightarrow 0.1 \ \mathrm{m}^2.\mathrm{s}^{-2} \leftrightarrow 1 \ \mathrm{cm}$$



Chou et al, Science, 329 (2010)



- An **isochronometric surface** is a surface where all clocks beat at the same rate.
- They are almost equivalent to **equipotential surfaces of the gravity field** (differences of the order of 2 mm)
- Geopotential is known with an accuracy < 10 cm on the surface, on a grid of ~ 10 km x 10 km

$$\left.\frac{\mathrm{d}\tau}{\mathrm{d}t}\right|_S = \mathrm{cst}$$

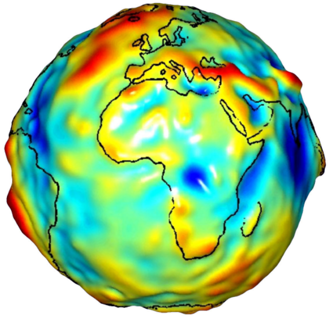
- Let t be the time given by a clock at infinity and at rest in the GCRS. Then the reference isochronometric surface (TT) defined by IAU is:

$$\frac{\mathrm{d}\tau}{\mathrm{d}t} = \mathrm{cst} = 1 - L_G$$

where $L_G = 6.969290134 \times 10^{-10}$ is a **defining constant** (IAU resolution B1.9, 2000)

- From this definition we get a reference equipotential

$$W_0 \equiv U + \frac{v^2}{2} = c^2 L_G + O(c^{-2})$$



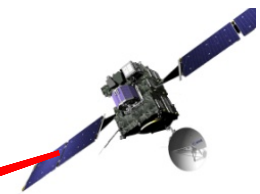
EGM2008 includes satellite data + gravimetric (ground) data
→ decomposition in spherical harmonics (up to degree 2100)

- As a proof-of-principle, one can determine (roughly) J_2 with two clocks:

$$\frac{\Delta f}{f} = \frac{W_B - W_A}{c^2} + O(c^{-4}) \ , \ W = U + \frac{v^2}{2}$$

$$U = \frac{GM_E}{r}\left[1 + \frac{J_2 R_E^2}{2r^2}\left(1 - 3\sin(\phi)^2\right)\right]$$

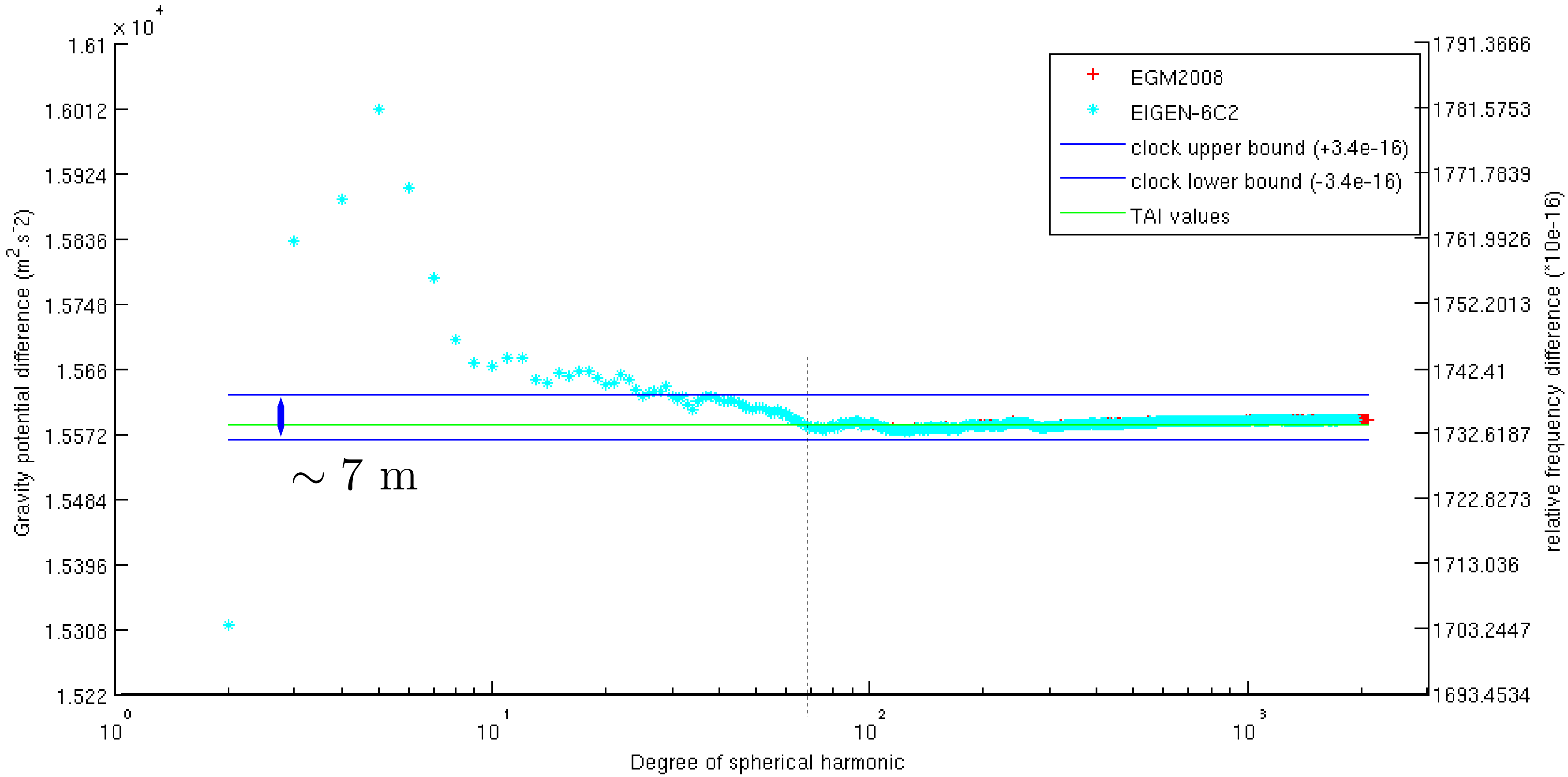
A: INRIM CsF1 (Turin, Italy)
B: SYRTE FO2 (Paris, France)



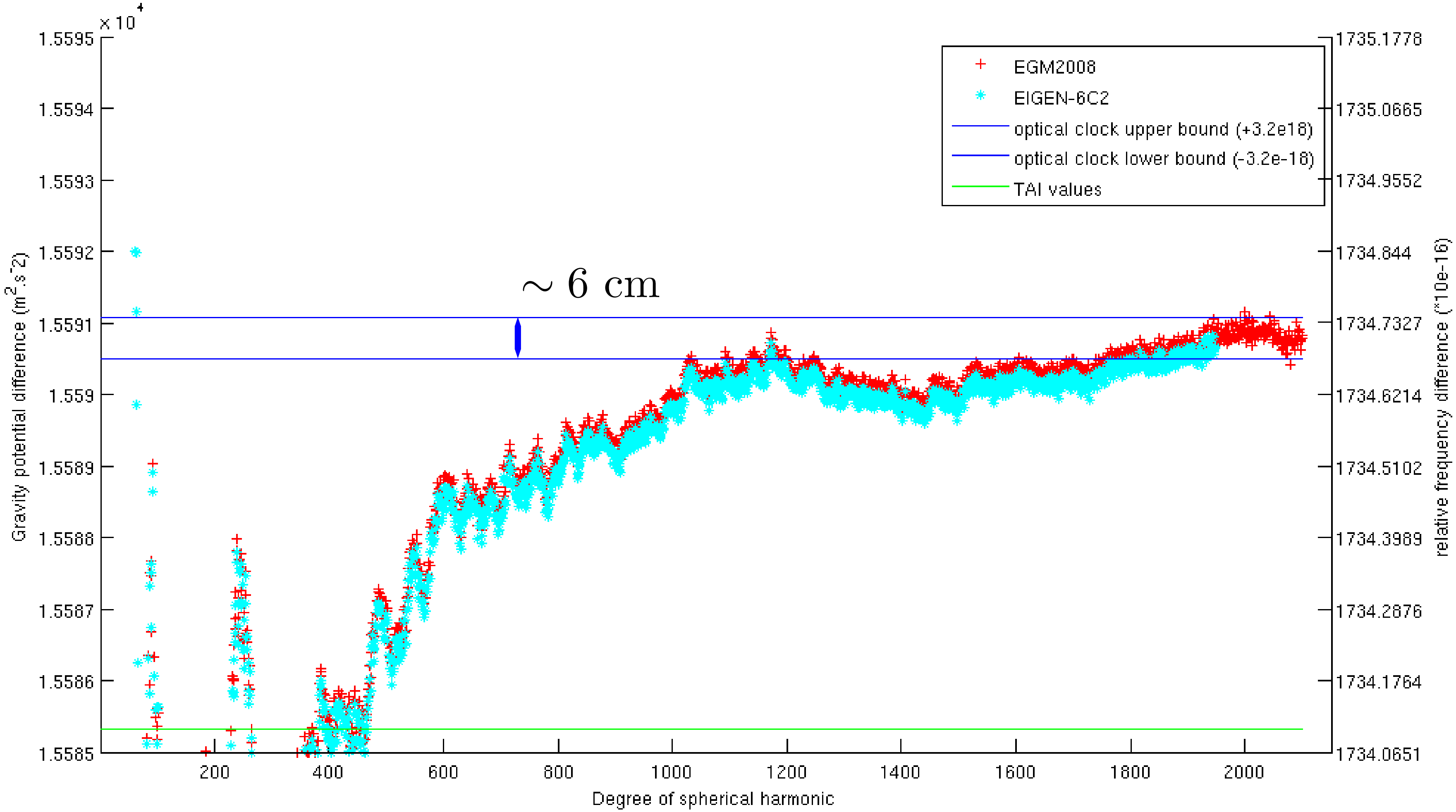
$$J_2 = (1.097 \pm 0.016) \times 10^{-3}$$

- Error of ~1.4% compare to best known value
- However, ground clocks are sensitive to higher order multipoles

- Comparison between SYRTE-FO2 (Paris, France) and NIST-F1 (Boulder, Colorado, U.S.)



- Imaginary comparison between 2 (best) optical clocks in (Paris, France) and (Boulder, Colorado, U.S.)



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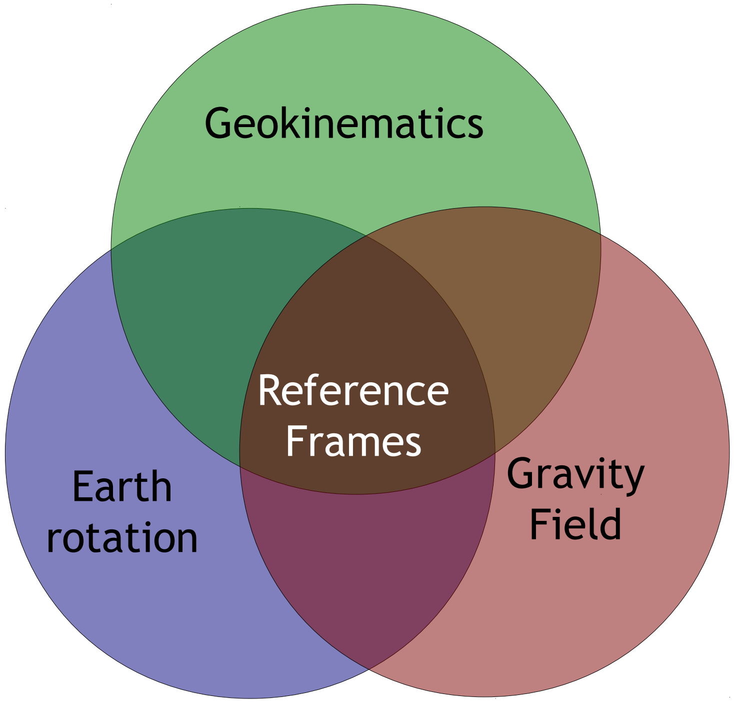
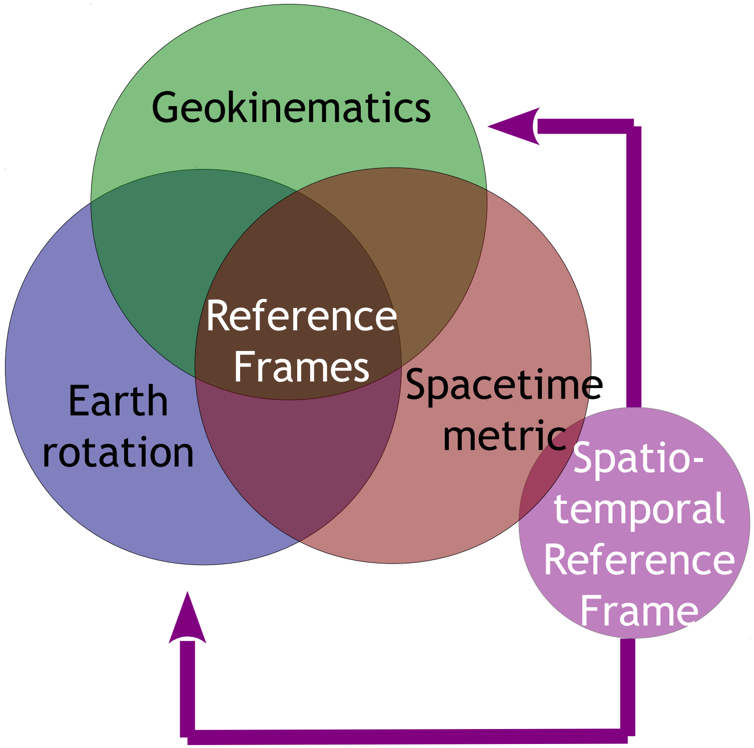


the « three pillars » of Global Geodetic Observing System

- **Non relativistic** framework
- **High intricacy** of problems
  - parameters degeneracy
  - Huge variety of observation types makes difficult a common framework model
  - Coherency of multi-technique schemes ?
- Heavy and **dedicated infrastructure** (VLBI, tracking stations, satellites, gravimeters…)
- **Earth gravity will limit clocks** on ground (to ~10^{-17})

Question: how can we solve these problems ? → ABC reference system

- Use **Inter-Satellite Links (ISL)** to track the satellites
- Use **satellite orbits as clocks** with long-term stability to correct for satellite clocks



- Its realization **does not rely on observations from Earth**
  - No entanglement with Earth internal dynamics
  - No Earth stations for maintaining of the reference frame
- **Stability and accuracy**
  - Based on well-known satellite dynamics
  - Satellite orbits are very stable in time, and can be accurately described
- **Positioning system**: observation of the signals sent by 4 satellites allows anyone to know its coordinates
- **Relativistic framework**:
  - Time is just the fourth coordinate → realization of a 4D spatio-temporal reference frame
  - Deep understanding of localization in spacetime
- Several **scientific applications**

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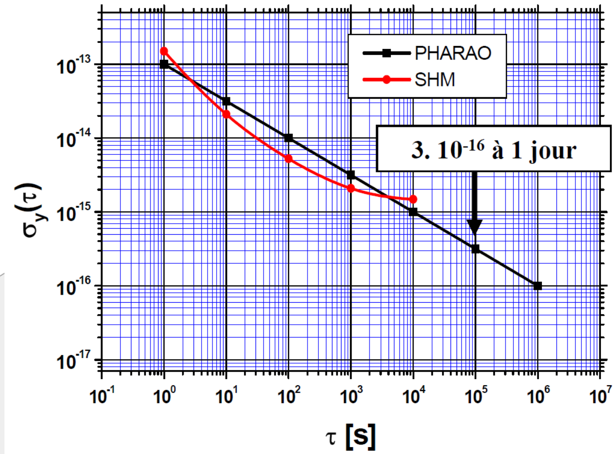
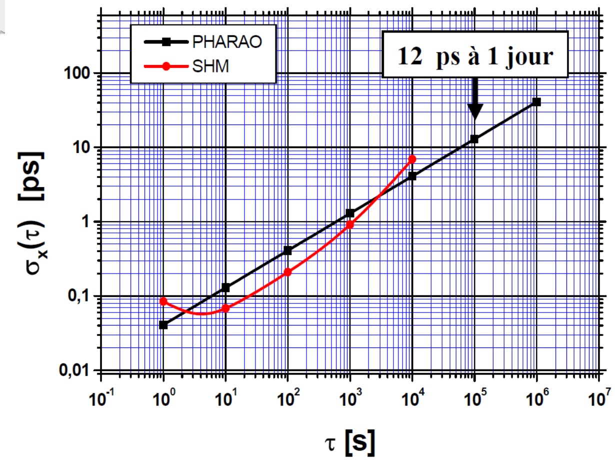
- A time scale in space of **high stability**…
  - better than $\sigma_y = 10^{-13} \cdot \tau^{-1/2}$ (in frequency)
  - better than $\sigma_x = 2.1 \cdot 10^{-14} \cdot \tau^{+1/2}$ (in time)
- …and **accuracy** ~ 10^{-16}
- **International cooperation** of more than 150 people
  - Science: LKB/ENS, SYRTE, PTB, Neuchâtel, UWA, …
  - Space agencies: ESA, CNES
  - Industrial: EADS/Astrium, EADS/Sodern, TimeTech, …
- Main **scientific objectives**
  - Atomic clock and microwave link performances in a space environment
  - Distant clock comparisons
  - Equivalence principle tests
  - Chronometric geodesy





Common view

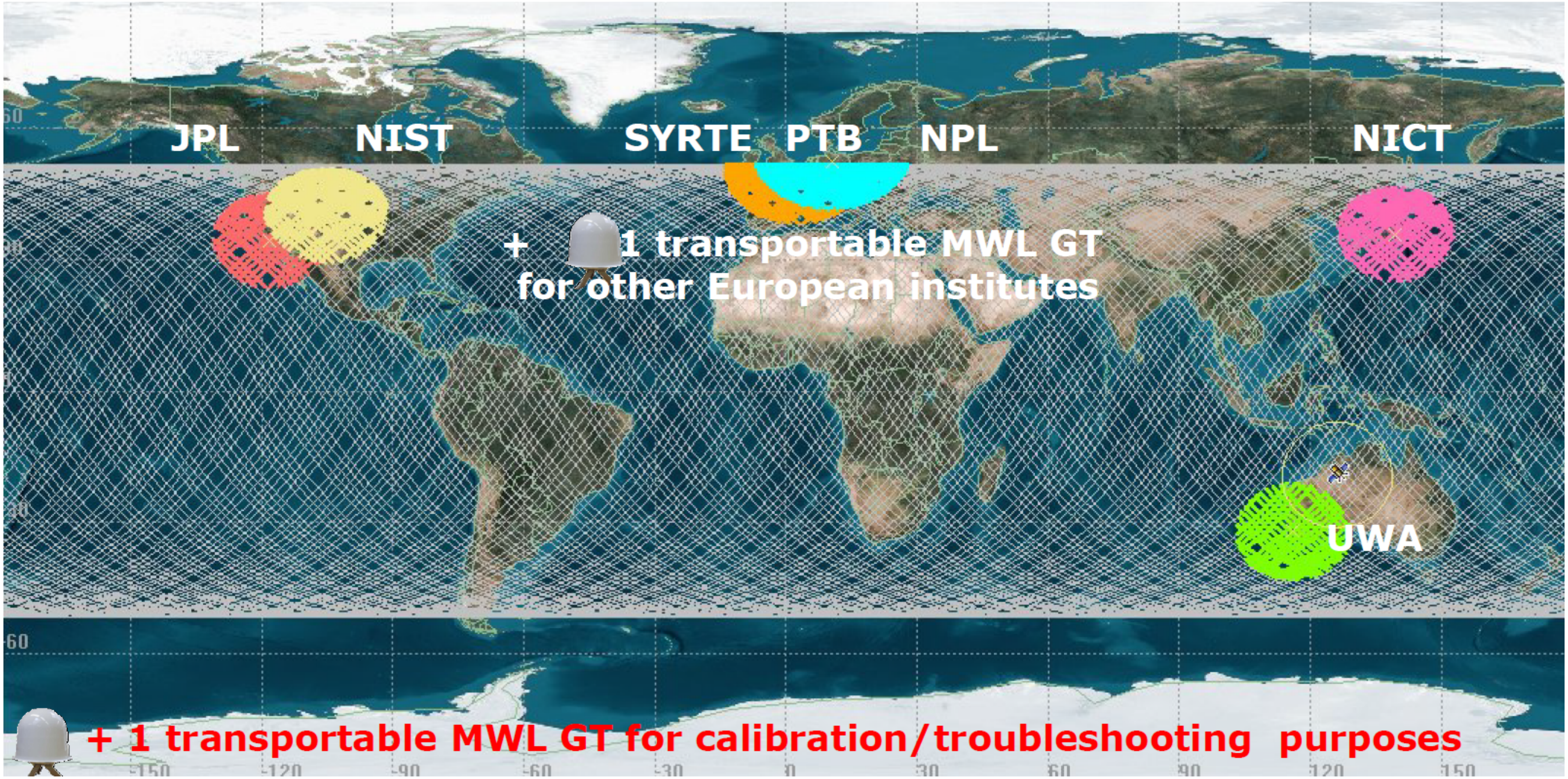
Stability ~ 0.3 ps @ 300 s.

Non common view

Stability ~ 7 ps @ 1 day

Chronometric geodesy with ACES

- Measure **"absolute" altitude of clocks** (referenced to the space clock)
- Measure **ground-to-ground gravitational potential differences** up to 1 $m^2.s^{-2}$ accuracy (10 cm, 10^{-17} relative frequency shift)



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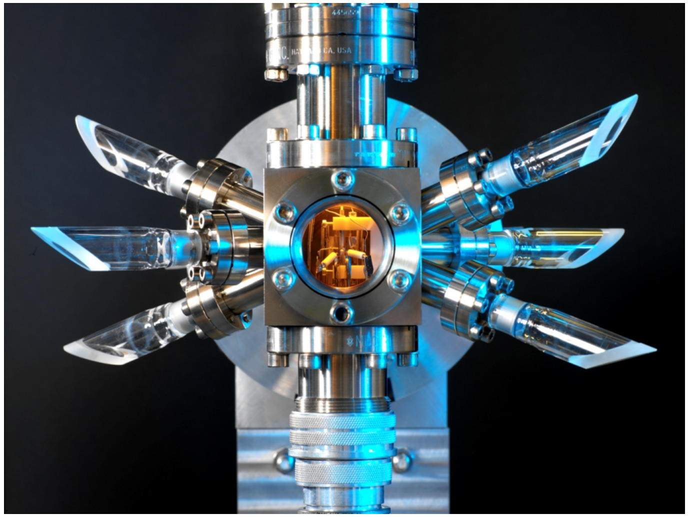
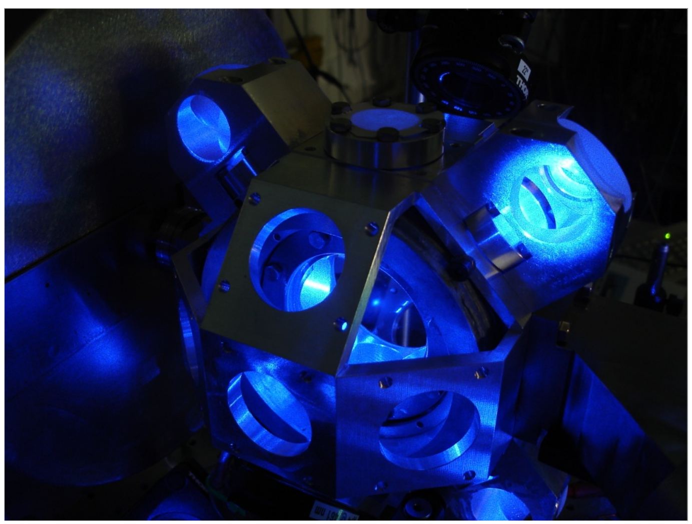
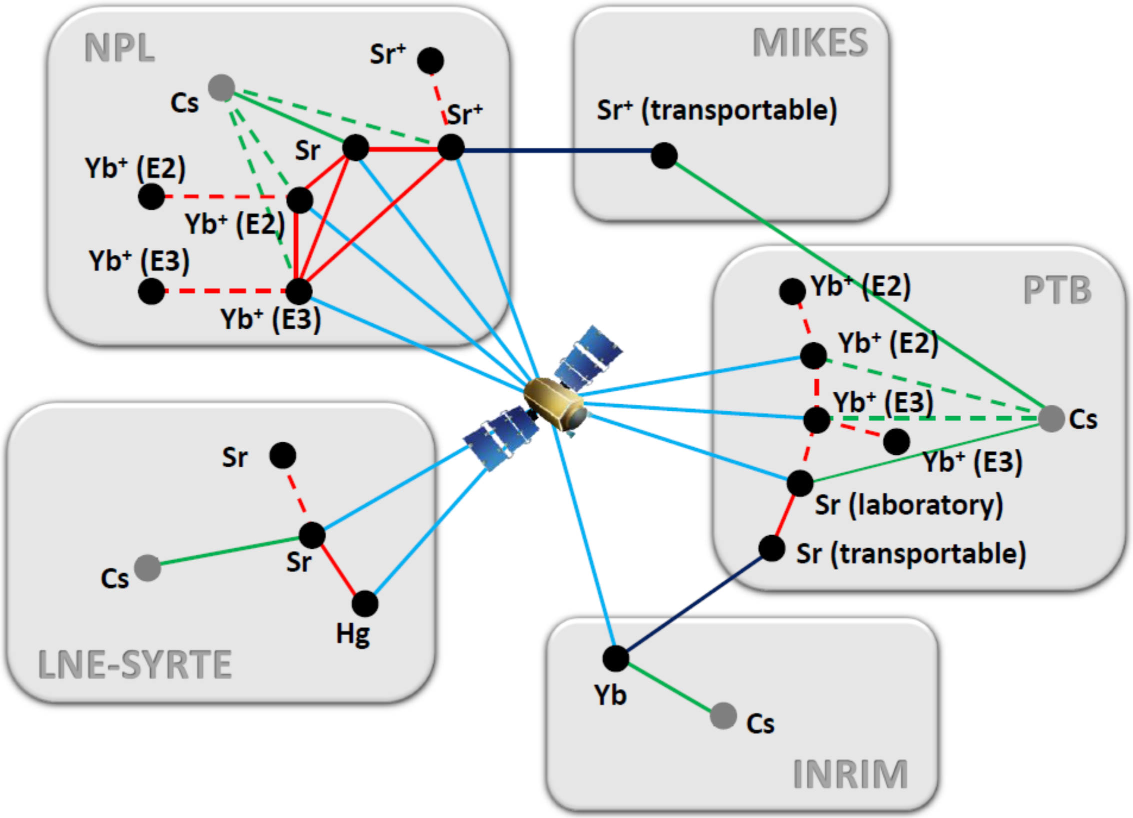




- Develop **improved methods for comparing optical clocks** developed in different laboratories;
- Carry out a **coordinated programme of clock comparisons** to build confidence in the performance of the optical clocks, to anchor their frequencies to the current definition of the second, and to establish the leading contenders for a redefinition;
- **Evaluate relativistic effects** influencing comparisons between clocks at an improved level of accuracy, including the gravitational redshift of the clock transition frequency;
- Establish a framework and procedures for the optical clocks to be **integrated into international timescales**.



Local optical frequency comparisons using femtosecond combs

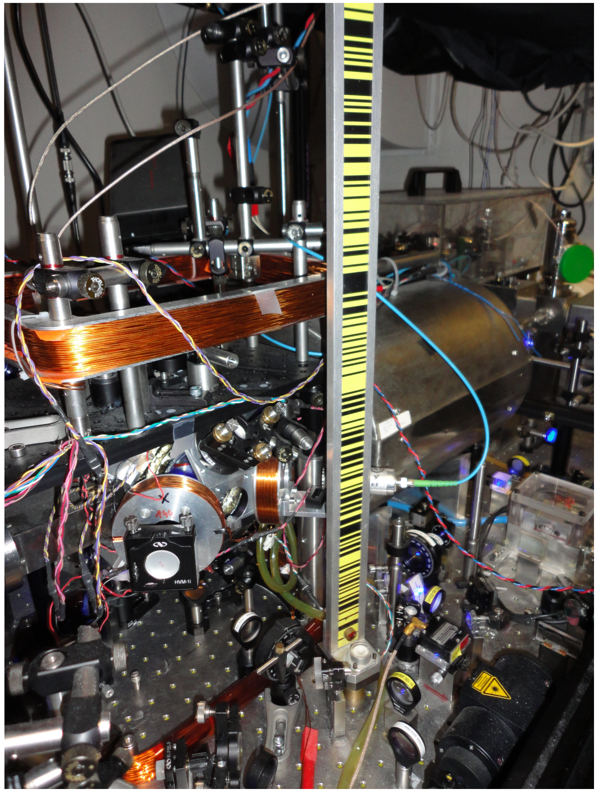
Frequency comparisons using transportable optical clocks

Optical frequency comparisons using broad bandwidth TWSTFT

Absolute frequency measurements

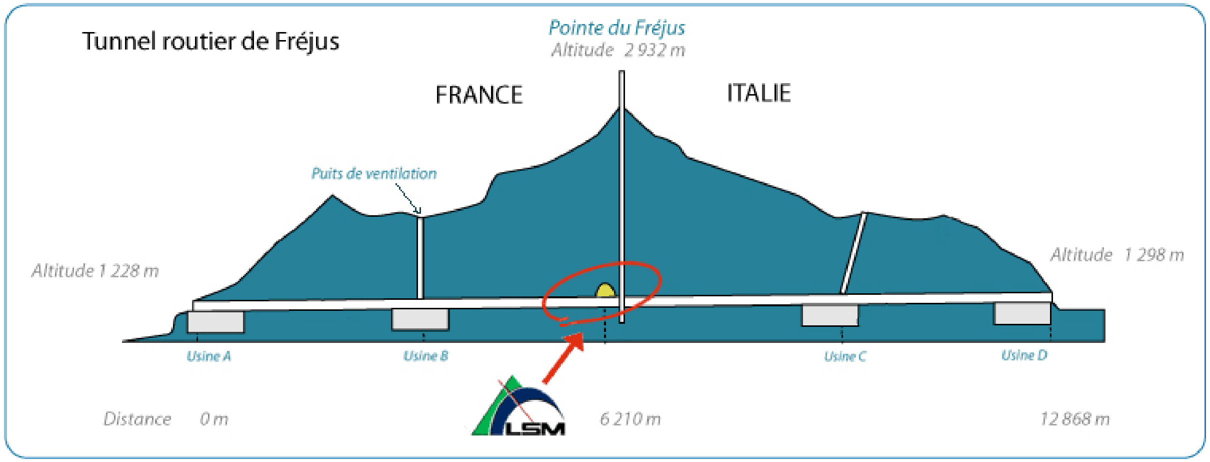
- Design of setups to **determine the static gravity potential at all clock locations** (potential differences for clock comparisons, absolute potential values for timescales);
- Development of a **refined European geoid model** including new gravity observations around all relevant clock sites;
- Investigation of **time-variable components of the gravity potential**, e.g. due to tides.

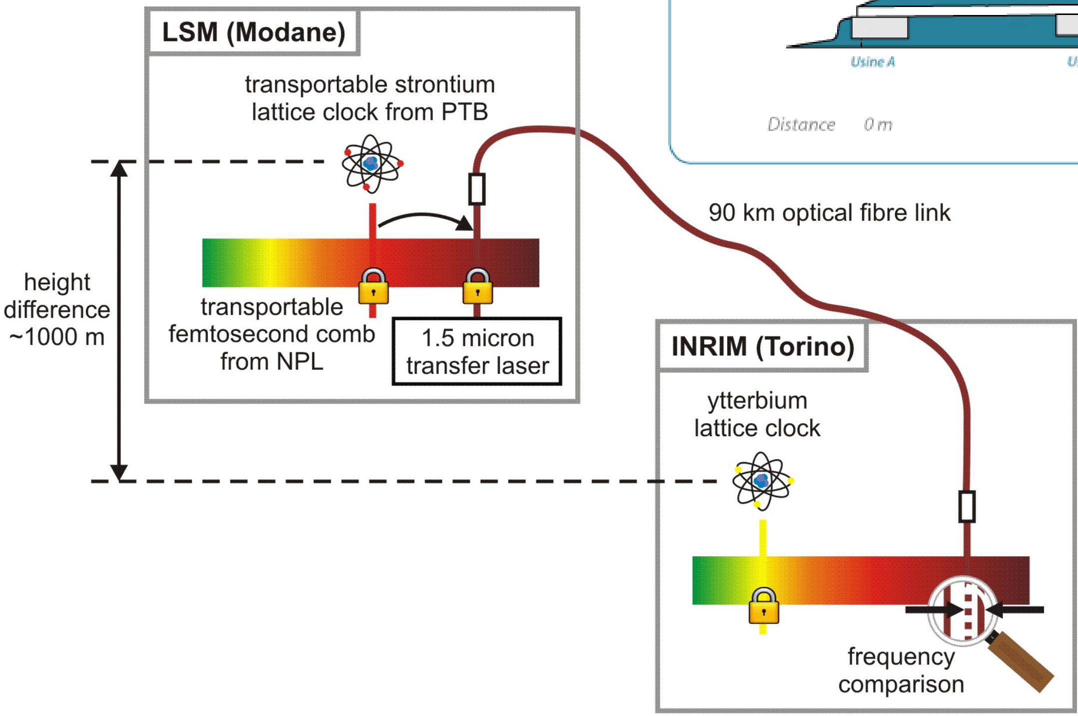
SYRTE clocks leveling campaign (IGN SGN Travaux Spéciaux)



Proof-of-principle clock-based geodesy experiment

- **Aim**: to demonstrate that optical clocks can be used to **measure gravity potential differences** over medium-long baselines with **high temporal resolution**.





- Height difference ~ 1000 m → Gravitational redshift ~ 10^{-13}
- Target → resolution of tens of cm in a few hours

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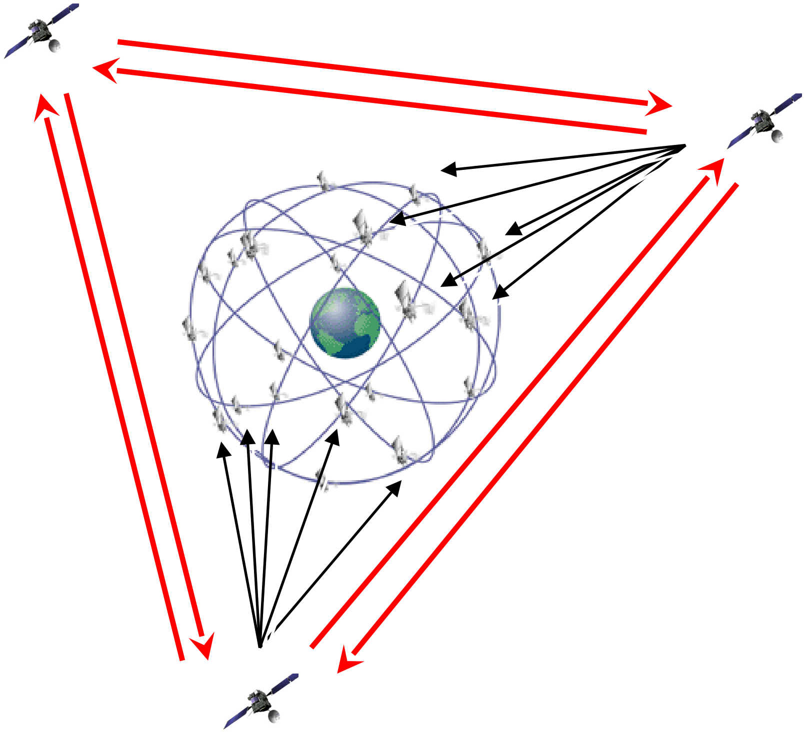
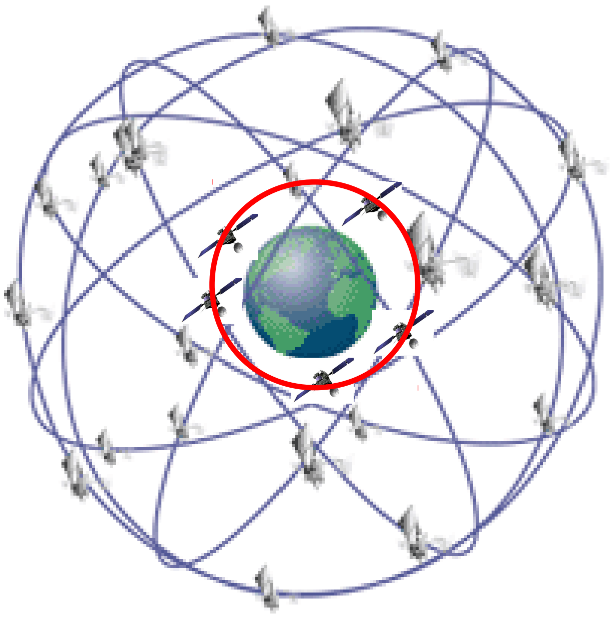
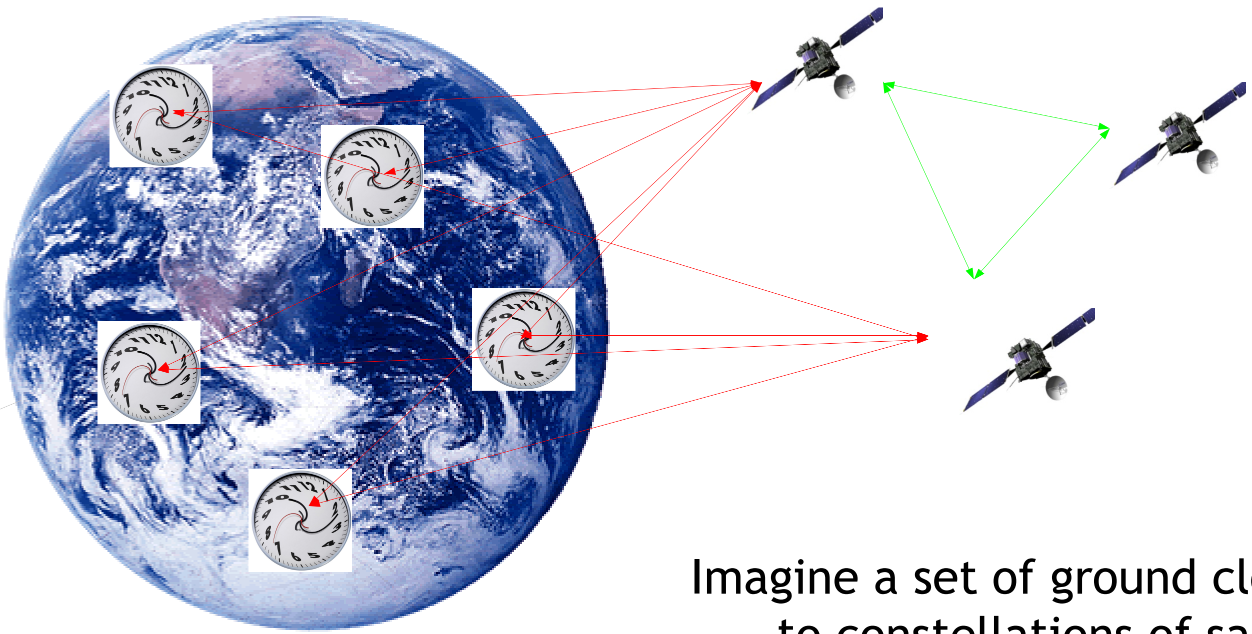


Geostationnary constellation for high accuracy time dissemination

LEO constellation for Earth gravitational field determination



A worldwide clock network

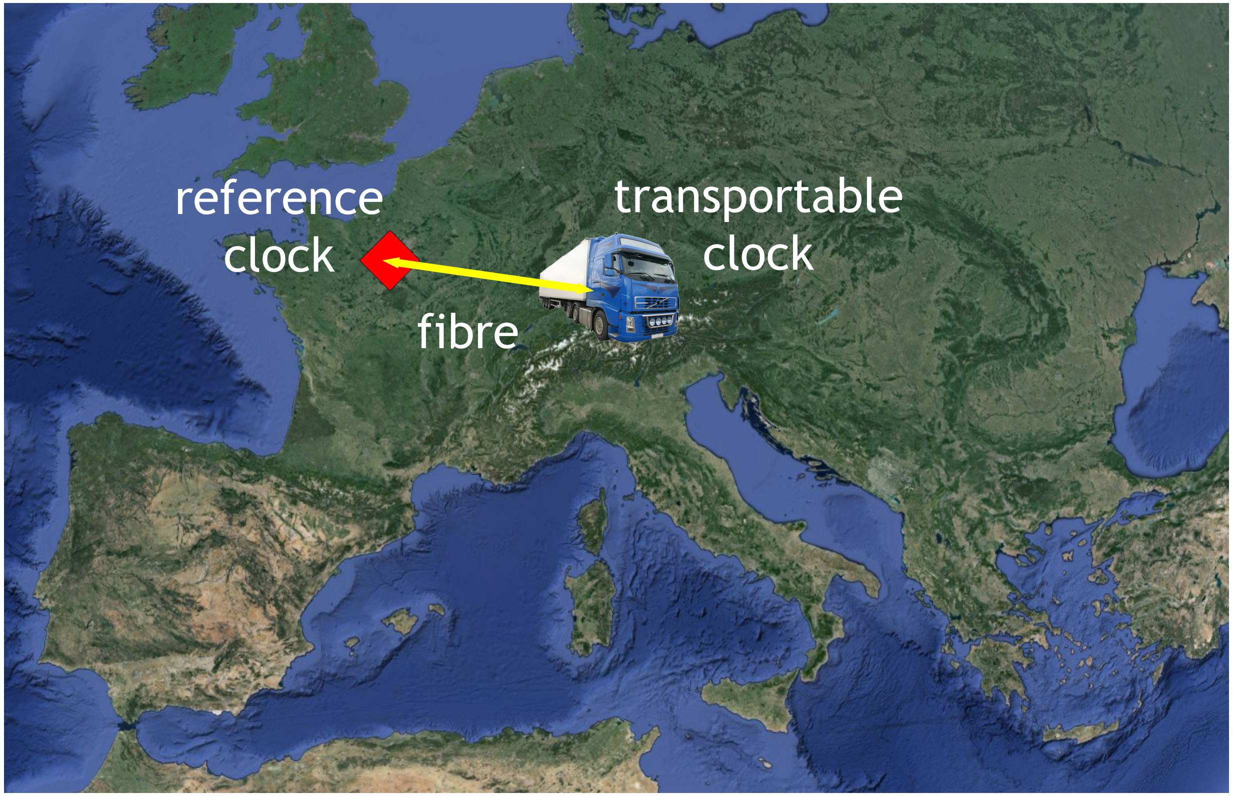


Imagine a set of ground clocks linked
to constellations of satellites

- Realisation of a isochronometric surface (where clocks beat at the same rate) → < 10 cm accuracy with optical clocks
- Measurement of static and time-varying gravitational field by comparing clocks at different locations
- First large-scale demonstrations of chronometric geodesy: ACES and ITOC

Chronometric leveling

- Imagine a transportable optical clock compared to a reference clock
  - long distance **leveling with few centimeters accuracy**
  - On **continental distance** along the existing fibre network
  - Intercontinental → need to develop new satellite T&F transfer techniques



Several transportable OCs are under development (U.S., Germany, Finland, ...)

Conclusion

- Atomic clocks are **rapidly improving** in accuracy and stability
- By comparing clocks, it is possible to **measure directly gravitational potential differences** (~ 0.6 $m^2.s^{-2}$, ~ 6 cm); and **variations** of gravitational potential differences (~0.1 $m^2.s^{-2}$ @ 7h, ~ 1 cm @ 7h)
- **Relativistic GNSS**: ISLs on 2nd generation Galileo will allow the realization of a quasi-inertial dynamical **4D reference frame in space**
- **ACES**: beginning of 2016 → **chronometric geodesy to ~10cm accuracy** (one day of integration time, few month of observations); few points on the Earth
- **ITOC**: European programme of OC comparison; new model of geoid; **proof-of-principle chronometric geodesy** (~50cm accuracy over 1km after 7h of integration time)
- **Applications to geophysics** (Isabelle Panet, Gwendoline Métivier, Laurent Métivier, Guillaume Lyon) → study temporal variations of the potential associated with geodynamic processes