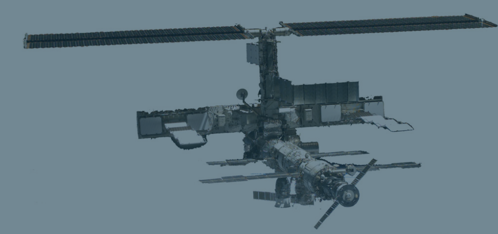
Atomic clocks : new prospects in Metrology and Geodesy



Workshop - Relativistic Positioning Systems and their Scientific Applications

Brdo near Kranj, Slovenia

September 2012, 19-21st

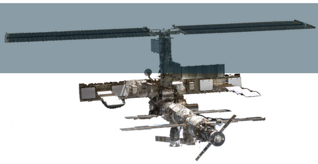
Pacôme DELVA

l'Observatoire de Paris — SYRTE — Systèmes de Référence Temps-Espace

CNRS — dépasser les frontières

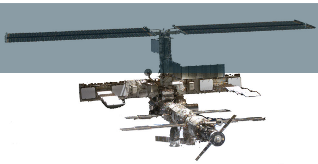
LNE — Sharing a passion for progress

UPMC — Sorbonne Universités



- Metrology
  - Toward a new definition of the second
  - Improving the timescale
  - Going in space

- Geodesy
  - Relativistic geodesy
  - Using clocks to measure the geopotential
  - The relativistic geoid

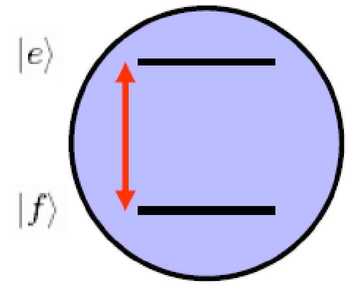


- Metrology
  - Toward a new definition of the second
  - Improving the timescale
  - Going in space

- Geodesy
  - Relativistic geodesy
  - Using clocks to measure the geopotential
  - The relativistic geoid

→ Deliver a signal with stable and universal frequency

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



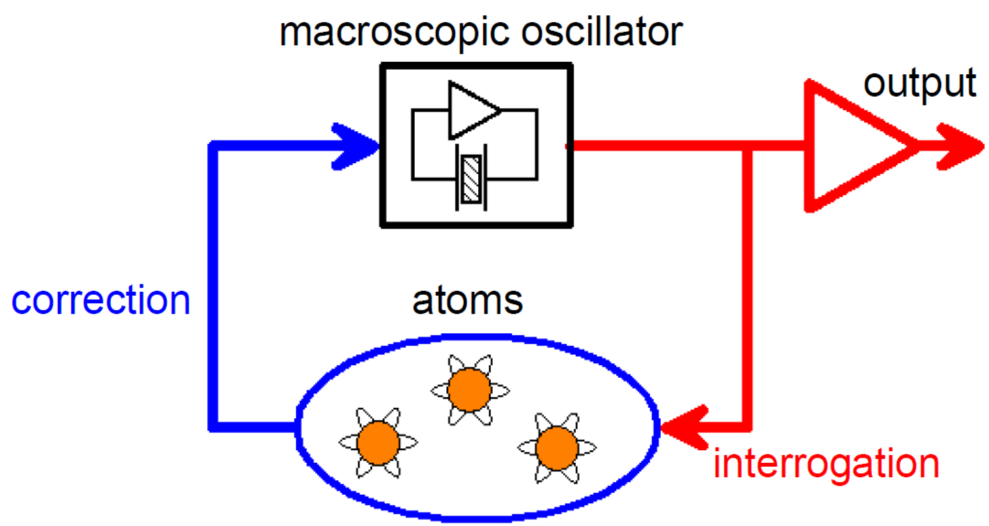
$$\omega(t) = \omega_{ef} \times (1 + \epsilon + y(t))$$

ε : fractional frequency offset

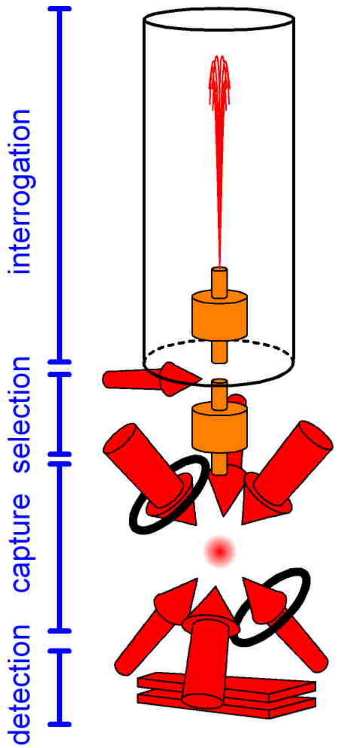
Accuracy: overall uncertainty on ε

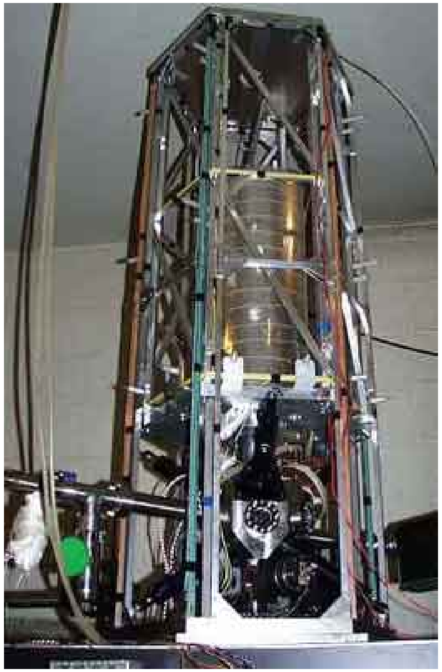
y(t) : fractional frequency fluctuations

Stability: statistical properties of y(t), characterized by the Allan variance

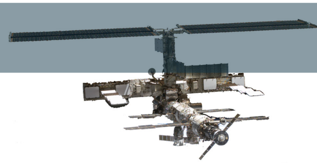


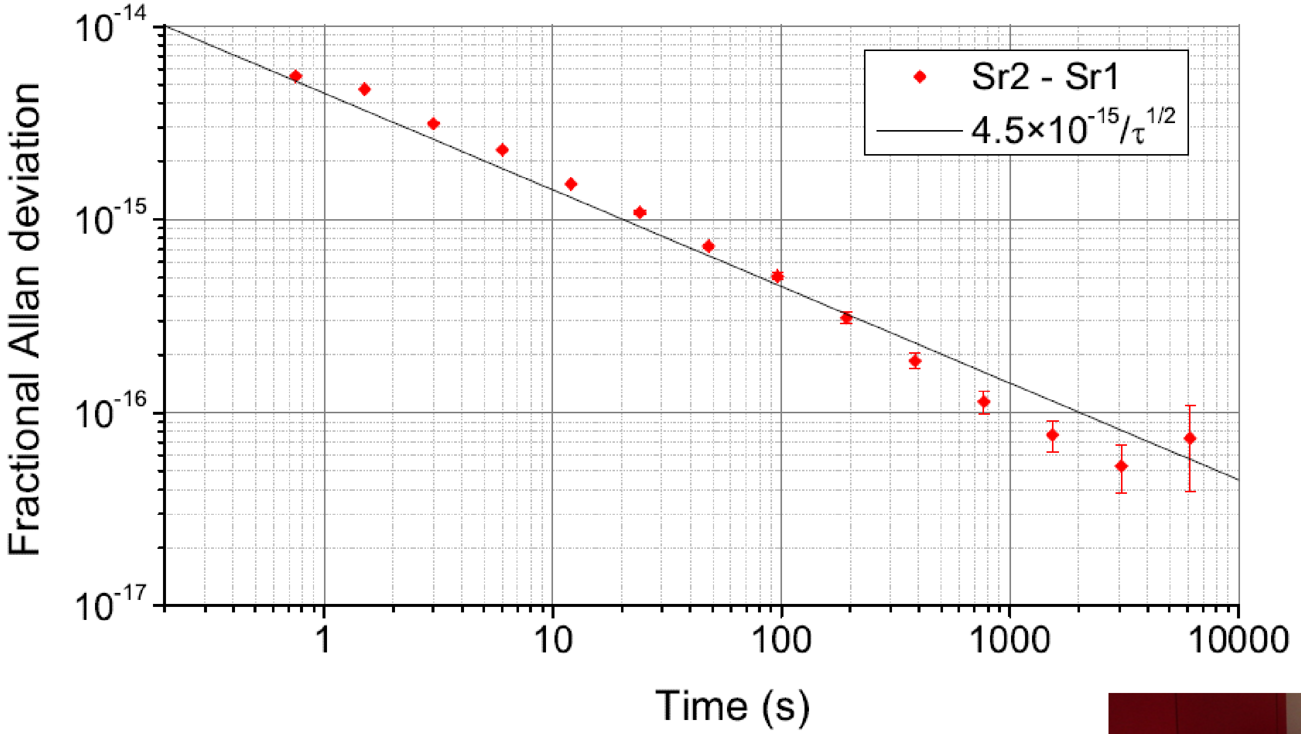
- CGPM 1967 : « the second is the duration of 9192631770 periods of the radiation corresponding to the transition between two hyperfine levels of the ground state of the caesium 133 »
- Cs fountains :
  - Primary Frequency Standards (PSF), only a few worldwide
  - Accuracy (relative frequency error) : 2-3 * 10^{-16}
  - Stability : few $10^{-14}/\sqrt{\tau}$, i.e. around 10^{-16} @ 1d
  - Local frequency comparisons effectively achieve such noise levels

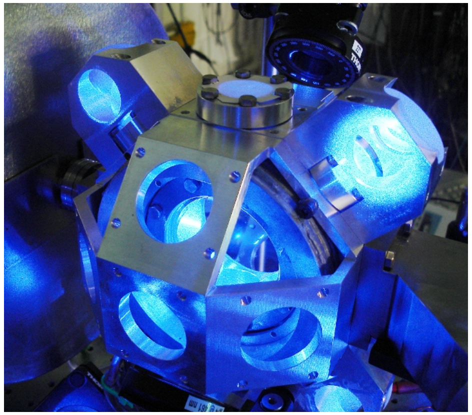


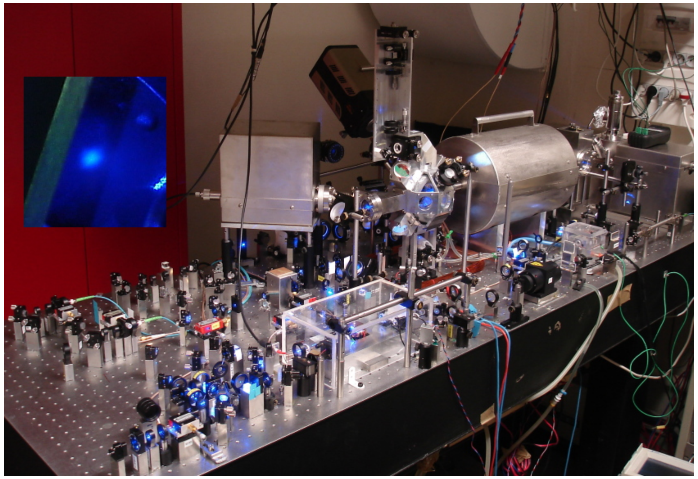


SYRTE Rb/Cs dual fountain FO2



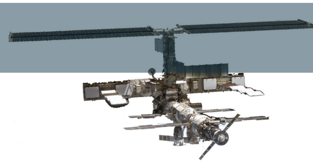




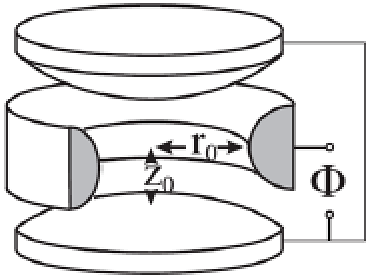


- $4.5 * 10^{-15}/\sqrt{\tau}$
- Goes below 10^{-16} after 1000 s

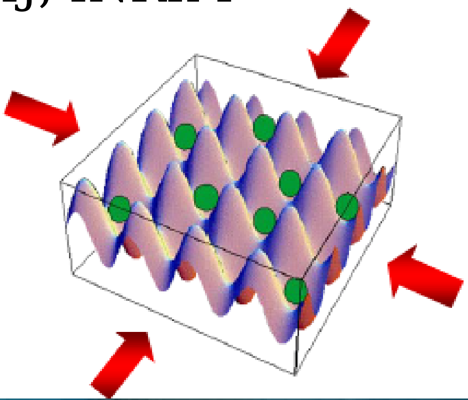
  (J. Lodewyck et al.)

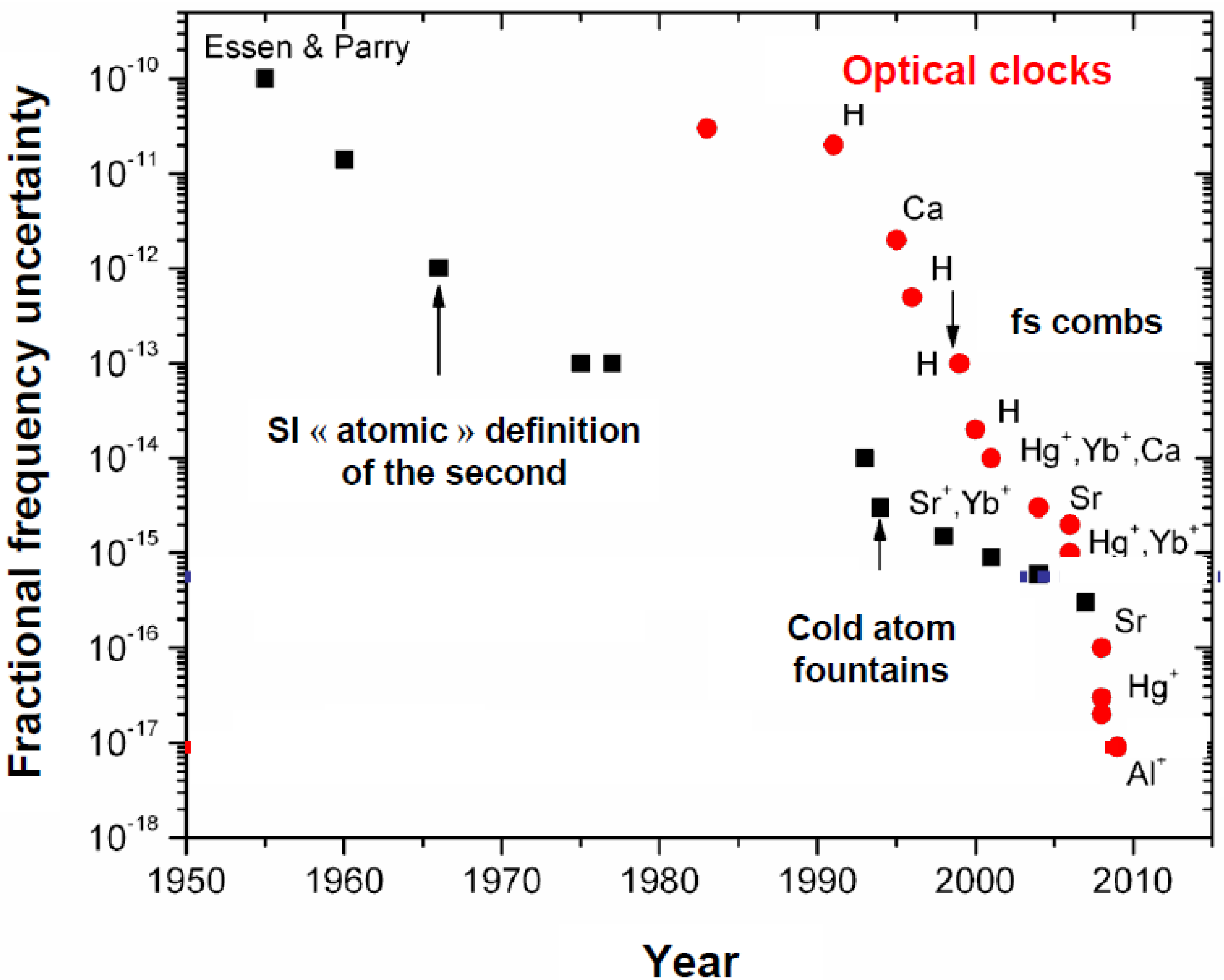


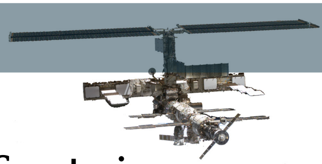
- Single ion clock :
  - Very few interaction with the trap → good accuracy
  - Al+ NIST : $9 * 10^{-18}$
  - Stability ($\sim 3*10^{-15}/\sqrt{\tau}$) limited by the shot noise (only one ion)
- Developments
  - NIST : Al+, Al+, Hg+
  - Europe : PTB, NPL, …
  - France : Provence University (Ca+)



- Neutral atoms
  - Intense trap but controlled
  - Accuracy ~ $2 * 10^{-16}$ but in constant improvement
  - High number of atoms (10^4) → good ultimate stability (actually $\sim 2*10^{-15}/\sqrt{\tau}$)
- Developments
  - Sr : Tokyo, JILA, SYRTE, PTB
  - Yb : NIST, NMIJ, INRIM
  - Hg : SYRTE



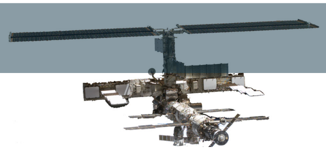

Essen & Parry
Optical clocks
H
Ca
H
fs combs
H
H
SI « atomic » definition of the second
Hg+,Yb+,Ca
Sr+,Yb+
Sr
Hg+,Yb+
Cold atom fountains
Sr
Hg+
Al+
Fractional frequency uncertainty
Year
10-10
10-11
10-12
10-13
10-14
10-15
10-16
10-17
10-18
1950
1960
1970
1980
1990
2000
2010

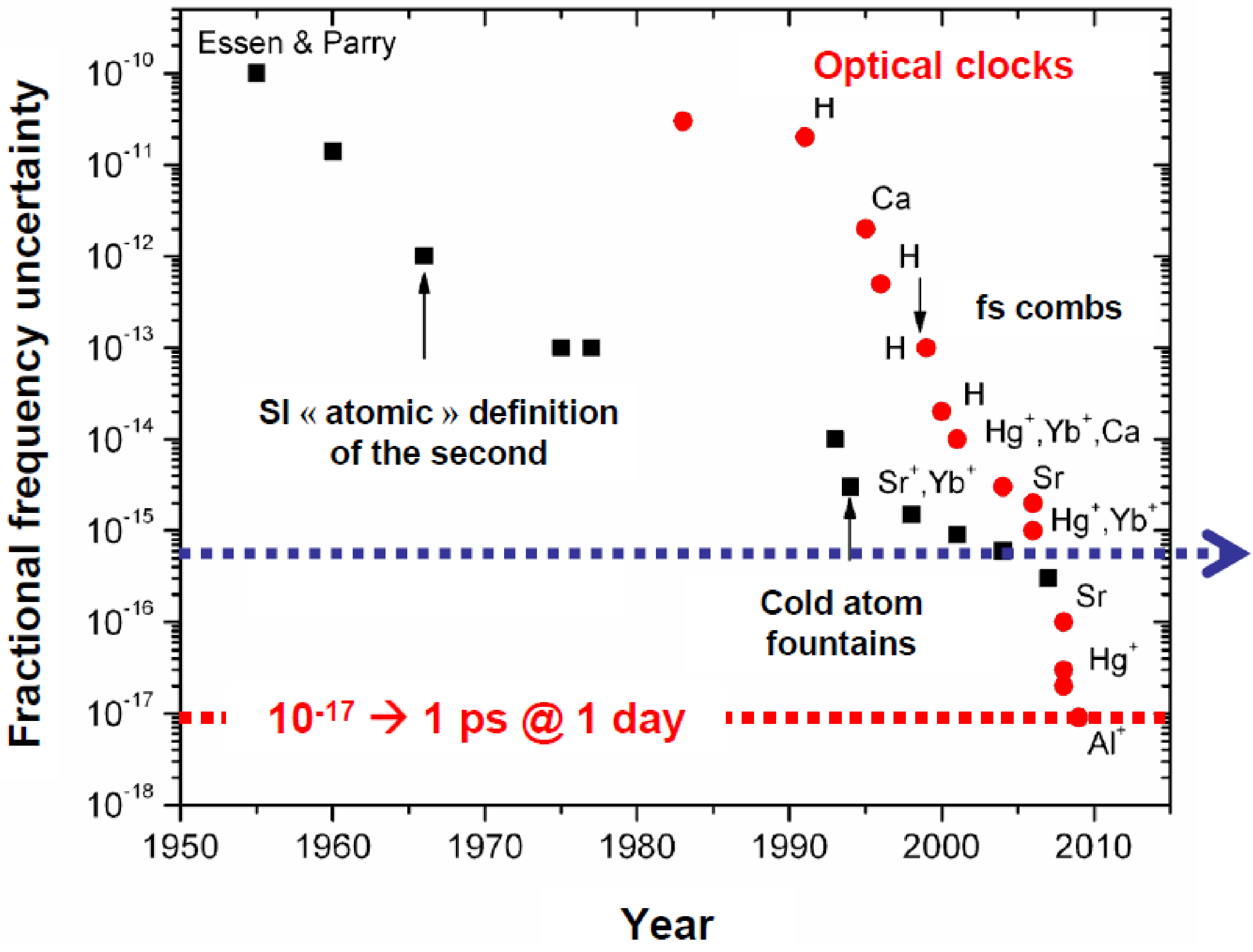


- Optical clocks have reached an accuracy better than the Cs fontain clocks
- They could be used as secondary representations of the second, to help characterizing the Primary Frequency Standards
- Their uncertainty cannot be better than the one of Cs fountains
- Possible future redefinition of the second

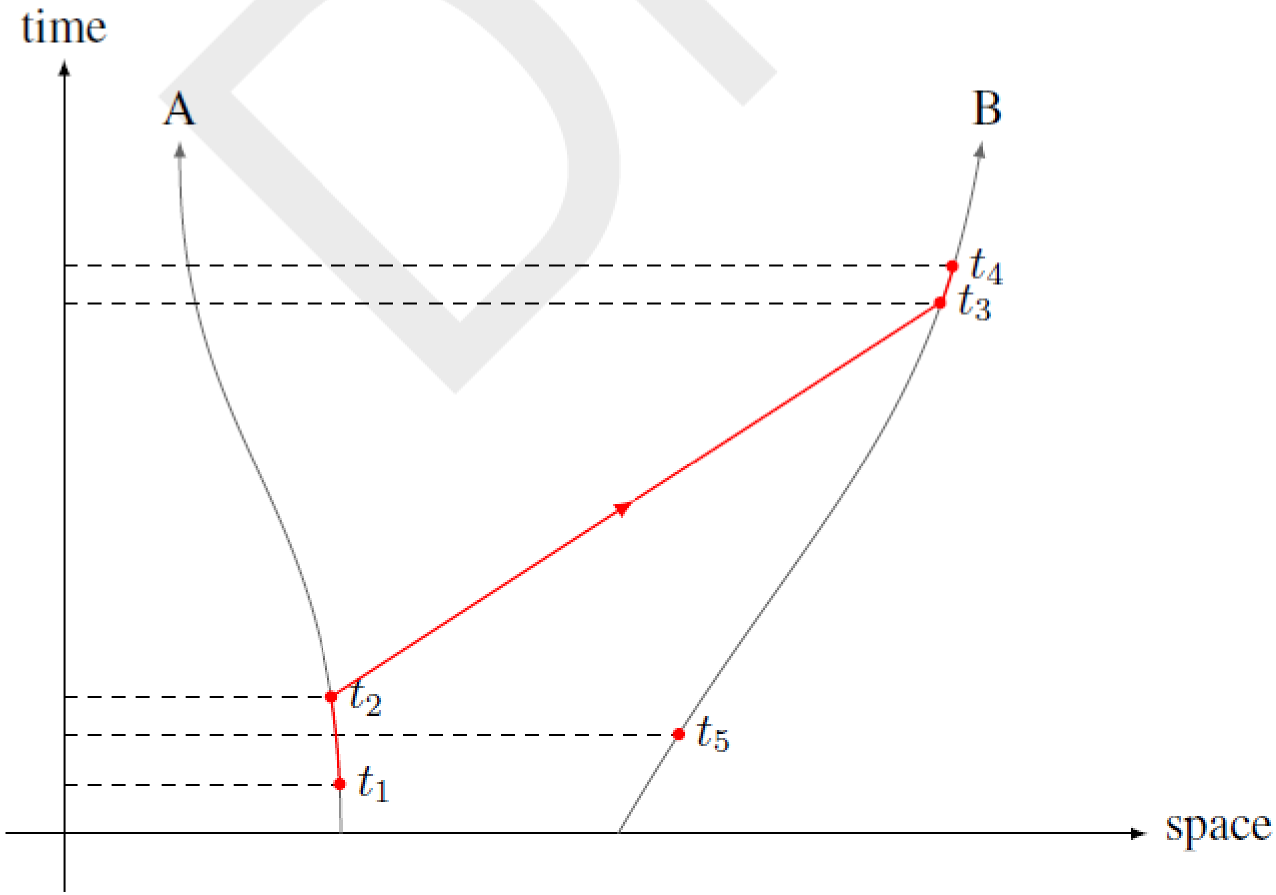
→ Period of preparation and study of different standards

→ Need to compare these secondary representations of the second at a challenging level





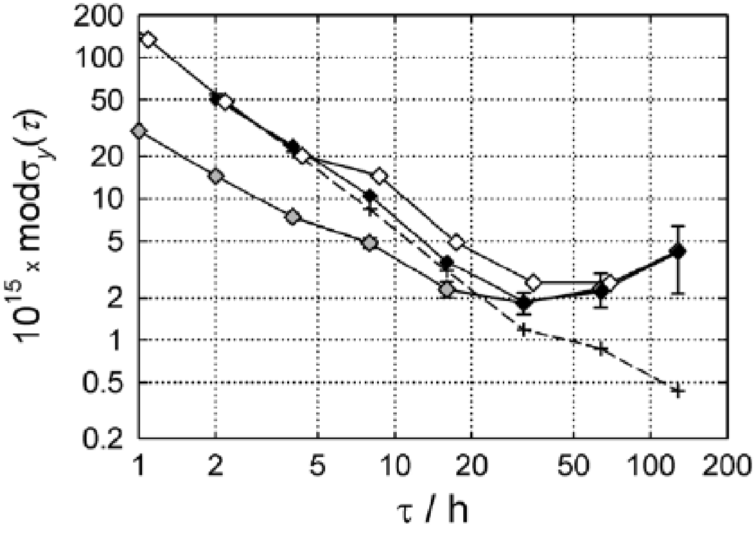
Current performance (@ 1day) of « operational » systems (GNSS, TWSTFT code)



$$\begin{aligned}\Delta\tau^B\left(\tau^B(t_4)\right) &= \tau^B(t_5) - \tau^B(t_4)\\ &= \tau^A(t_1) - \tau^B(t_4)\end{aligned}$$

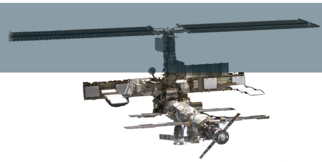
- Current long distance global comparison methods
  - GNSS-based techniques
  - TWSTFT (using telecomms satellites)
- Performances
  - Frequency comparison stability : $< 10^{-15}$ @ 1 day
  - Proportional to $1/\tau$
  - → ~ 10 days to compare 2 fountains

! 2-3 order of magnitudes improvement needed !



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

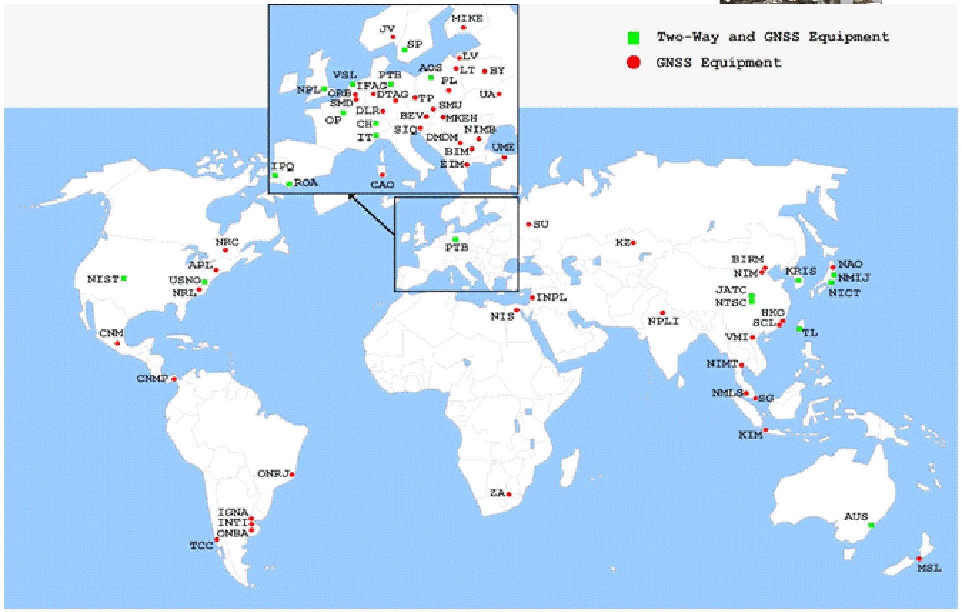
- 100-1000 km links demonstrated, e.g. Braunschweig-Munich 900 km
- ~ 10^{-19} stability @ 1 day
- Continental scales only
- Intensive development going on
- Europe-wide network project NEAT-TF
- Fibre costs : using existing fibres dedicated to research



- T2L2 : Time Transfer by Laser Link
  - Launched on Jason-2 in 2008
  - Results consistent with objective of < 10^{-16} @ 1 day
- ACES mission – Atomic Clock Ensemble in Space (2015)
  - Micro Wave Link (MWL)
  - Expected stability ~ 10^{-16} @ 1 day and < 10^{-16} @ 10 day
  - Always visible
- STE-QUEST mission – Space-Time Explorer and QUantum Equivalence principle teST (2022)
  - Coherent laser link
- Galileo Evolution : GNSS+ & ADVISE
  - See talk by F. Amarillo Fernandez tomorrow
  - Inter-satellite links in Galileo aiming at 1 cm accuracy on orbit determination and < ns accuracy on synchronization
  - Implication on ground clock frequency comparison ???

TAI : Temps Atomique International

- Useful timescale (coordinate timescale) :
  - Realize the unit (=second)
  - Continuous time reference
- Reference : Temps Atomique International (TAI) : timescale calculated by BIPM using ~250 clocks in more than 50 countries → frequency stability, robustness, accuracy, ...



- TAI unit (the second) is corrected by steering the frequency to the one of Caesium fountains (Primary Frequency Standards)
- TAI is independant from Earth rotation : UTC = TAI – 34 secondes
- Clocks participating to TAI are compared with satellite time transfer

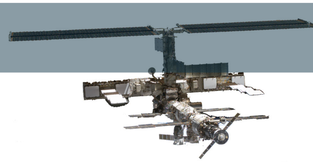


Table 1. Effects on syntonization with respect to TCG of clocks on the Earth's surface; Orders of magnitude and uncertainties of the corrections

Effect	Order of magnitude	Uncertainty
Earth's gravitational potential	7×10^{-10}	10^{-17}
Centrifugal potential ($v^2/2/c^2$)	1×10^{-12}	$< 10^{-18}$
Volcanic and coseismic (highly localised)	$< 10^{-16}$	?
External masses (Moon, Sun)	10^{-17}	$< 10^{-18}$
Solid Earth tides	10^{-17}	$< 10^{-18}$
Ocean tides	10^{-17}	$< 10^{-18}$

P. Wolf and G. Petit, A&A (1995)

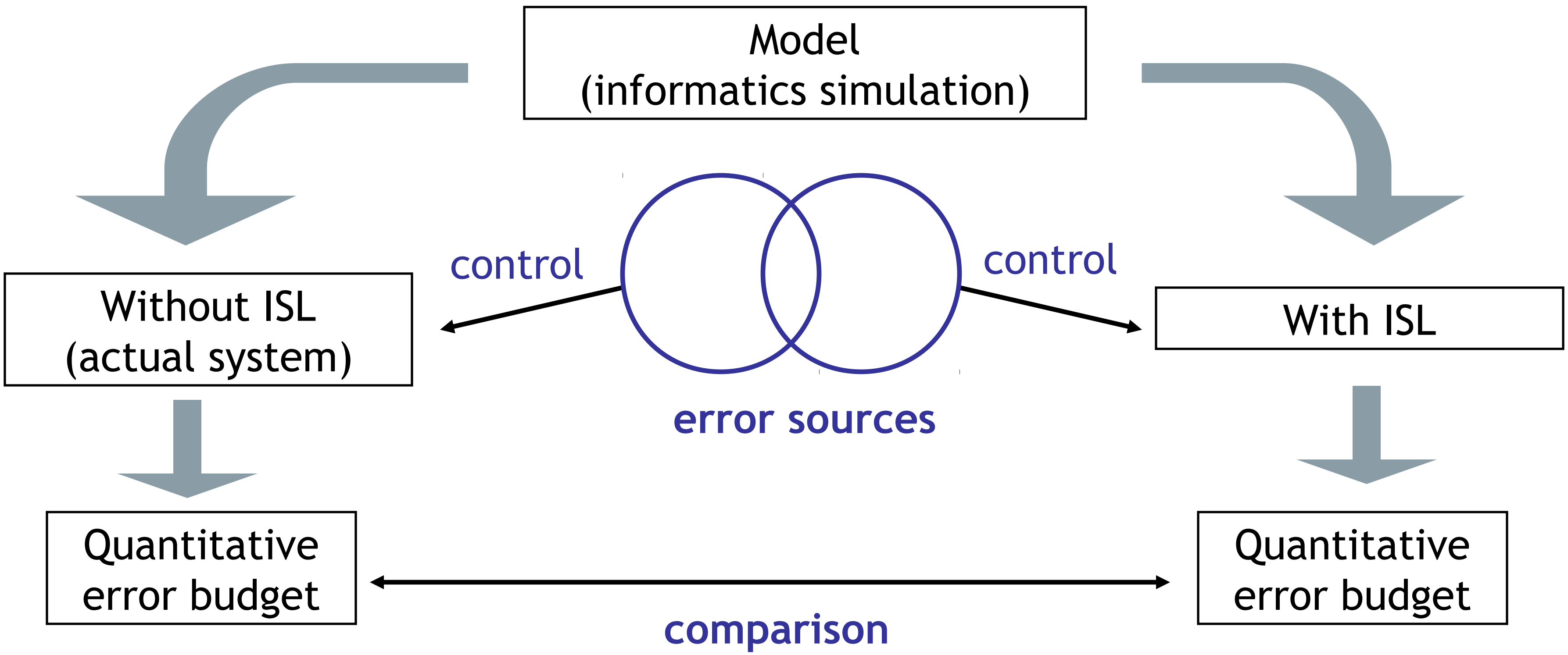
→ Realize a timescale in space ???

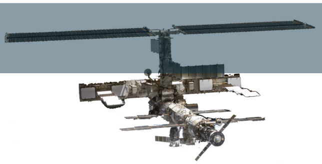
- Useful if you can achieve high accuracy : gravimetry
  - Use interconnected clocks (eg in GNSS) and correct them with a priori knowledge on their dynamics → ABC system
  - Put optical clocks in space

Quantitative study of spatio-temporal positioning

- Real time positioning
- High precision positioning
- Temporal positioning

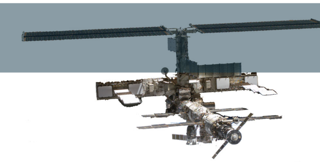
- Earth-based user (stationary or moving)
- Space-based user (LEO satellite)



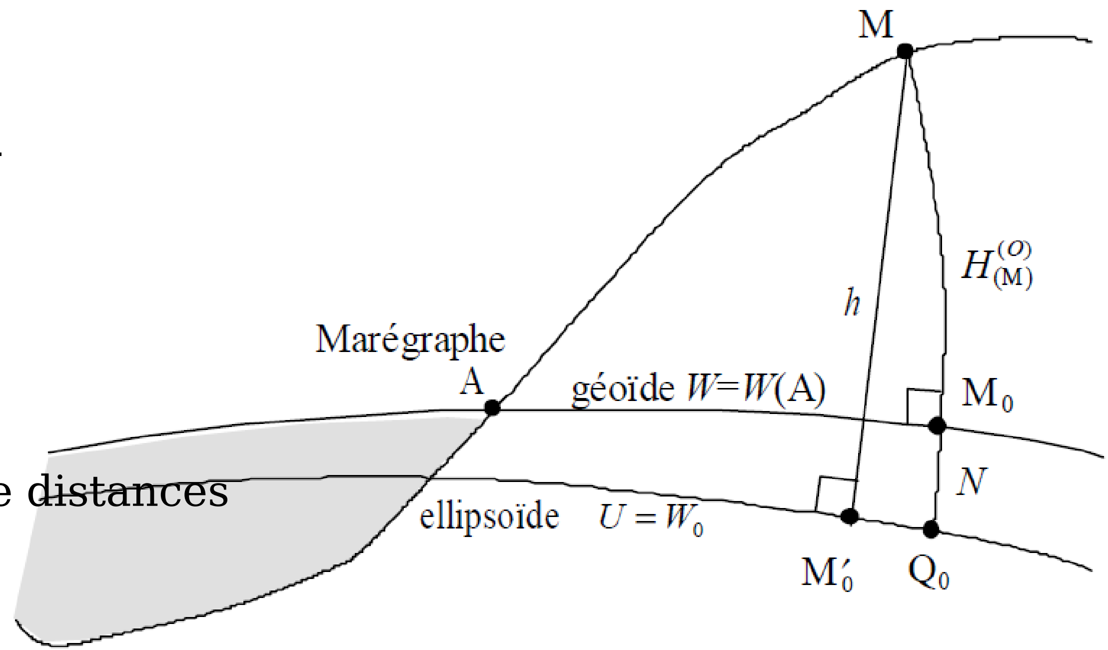


- Metrology
  - Toward a new definition of the second
  - Improving the timescale
  - Going in space

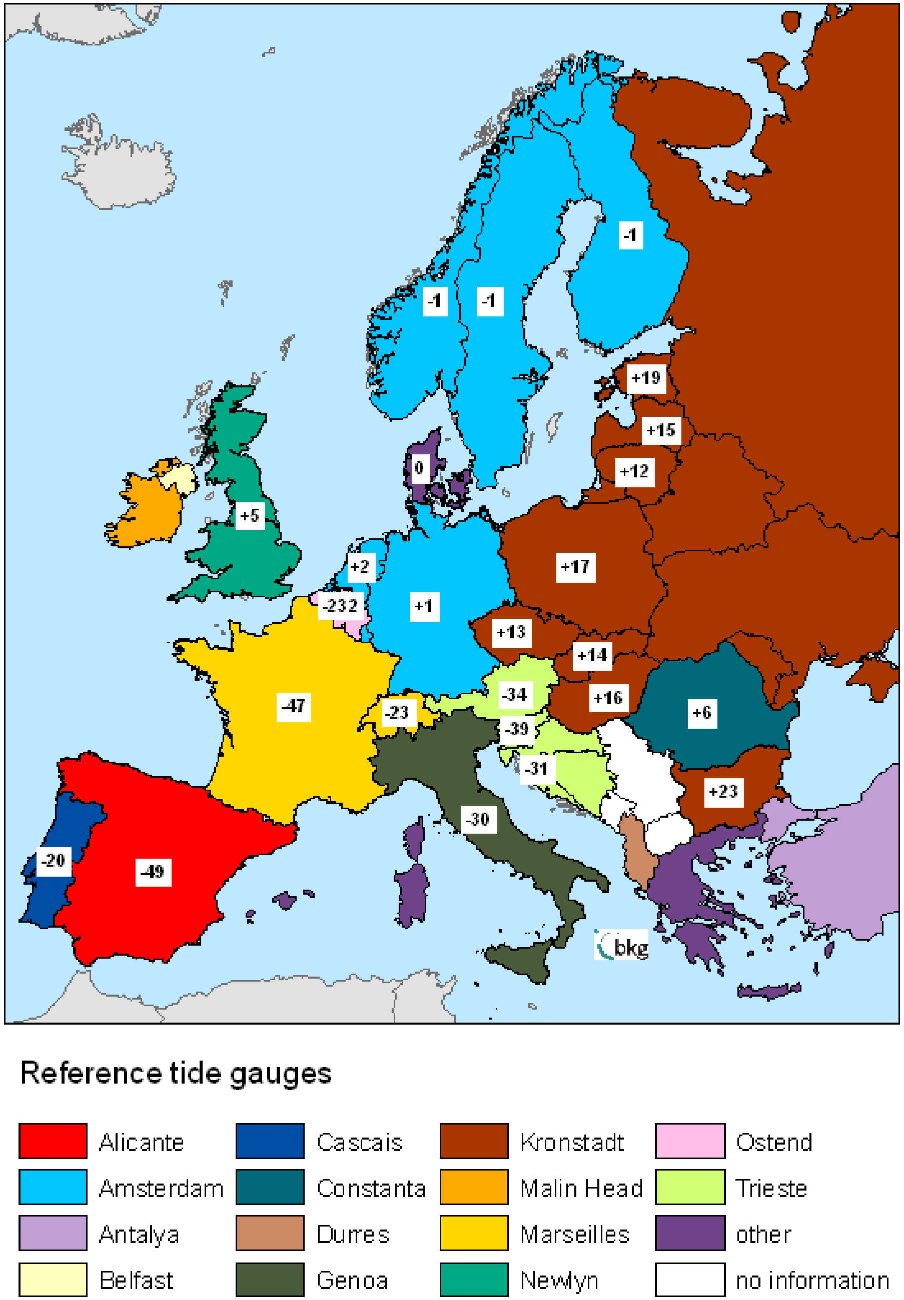
- Geodesy
  - Relativistic geodesy
  - Using clocks to measure the geopotential
  - The relativistic geoid



- Ellipsoid : terrestrial reference surface, purely geometrical
- Geoid : equipotential surface « nearest » to the mean sea level
- N < 100 m
- Geopotential number : $C_M = W_0 - W_M = -\int_P^M dW = \int_P^M g\,dn$
  - Gravimeter, geometrical nivelling
- Height : dynamic quantity that reflect the distance from the geoid (realized with tide gauges)
  - $$H^{(*)}_{(M)} = \frac{W(A) - W(M)}{\gamma^{(*)}(M)}$$
  - Normal height
  - Orthometric height
  - Dynamic height
  - Errors accumulate on large distances



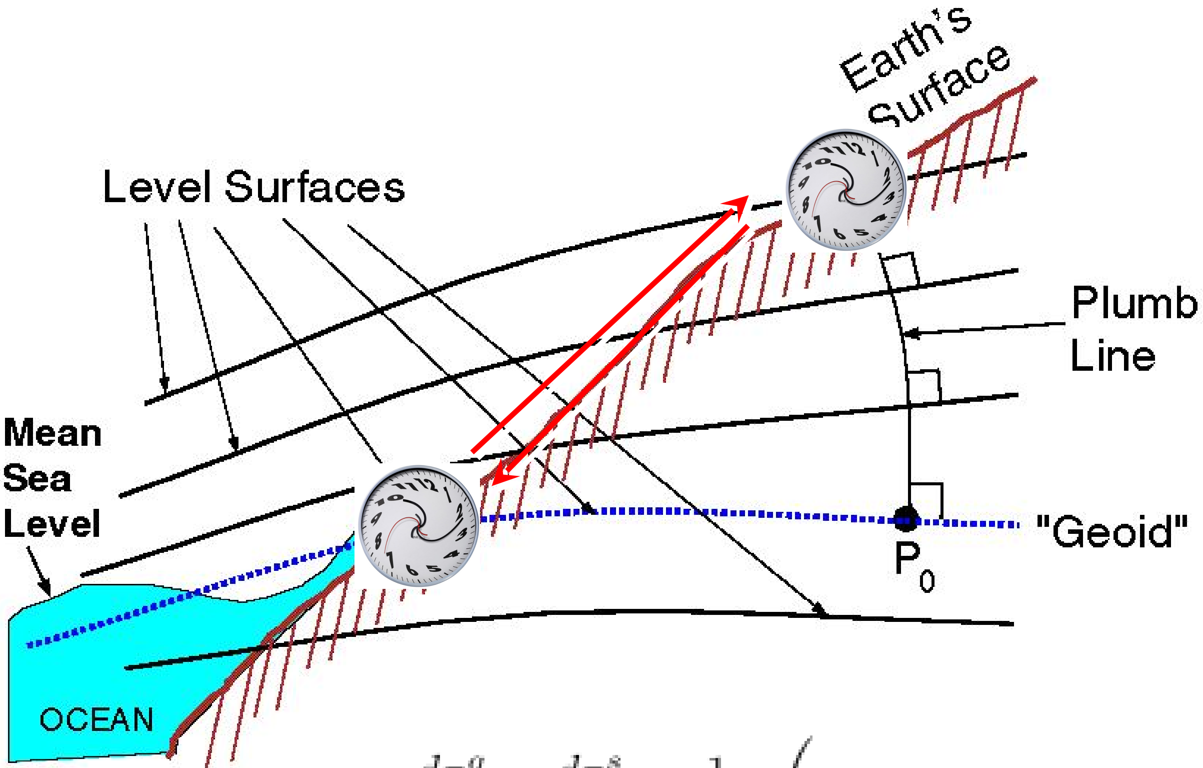
D. Bouteloup lecture (IGN, 2002)



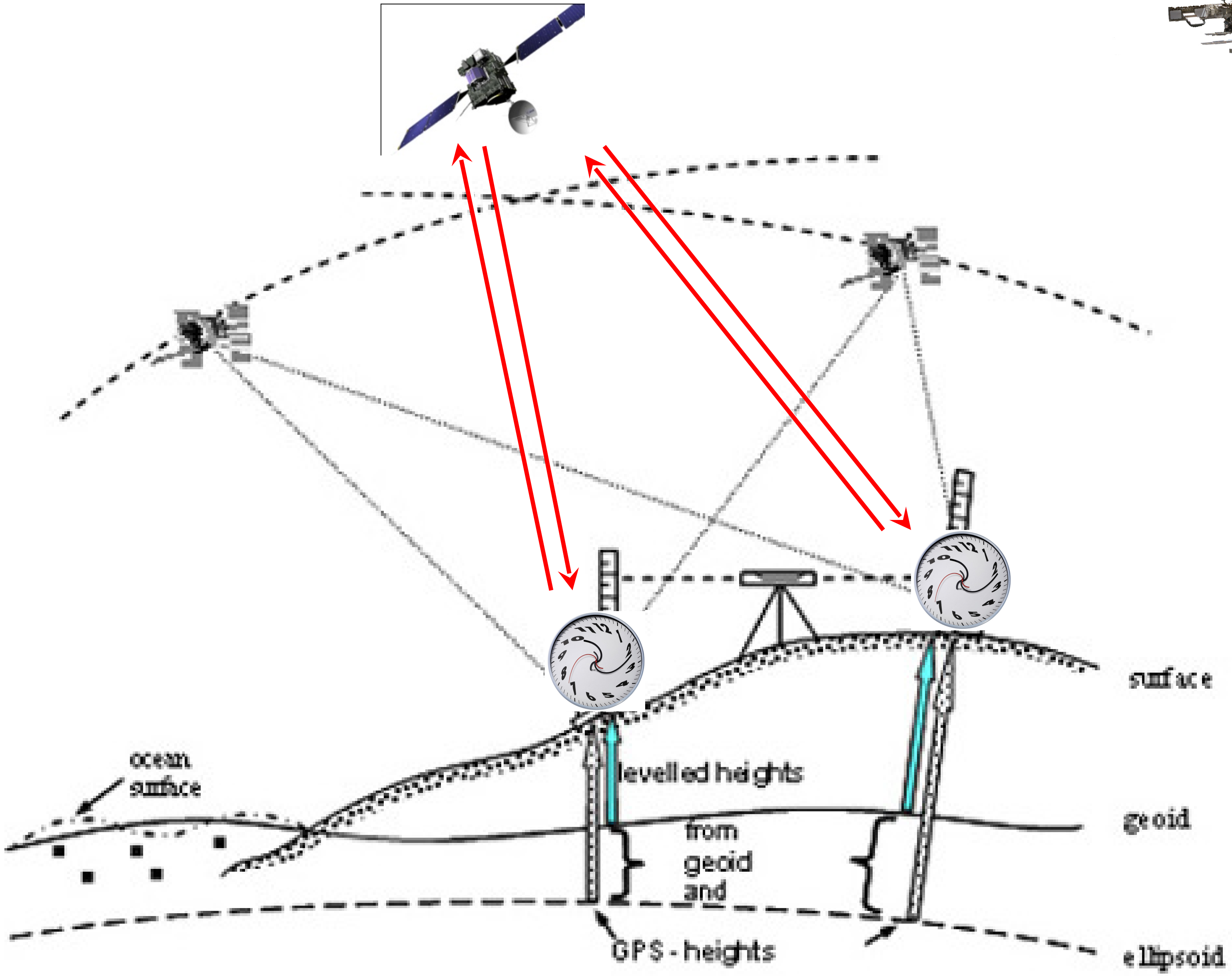
« The national height reference systems of the European countries are tied to different reference points (tide gauges). Due to this fact and also as a result of the differences in the theoretical definition of heights, the reference heights may differ from each other by several dm, in maximum even up to 2 m. »

(BKG website)

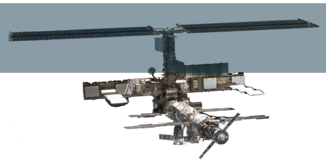
- One way out : global geoid model (satellite + ground gravimetry) + GPS measurements (~ 10 cm accuracy)



$$\frac{d\tau^g}{dt} - \frac{d\tau^s}{dt} = \frac{1}{c^2} \cdot \left(U(t, \vec{x_s}) - U(t, \vec{x_g}) + \frac{v_s^2(t)}{2} - \frac{v_g^2(t)}{2} \right) + O(c^{-4})$$



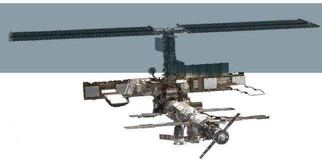
ocean
surface
levelled heights
from
geoid
and
GPS - heights
surface
geoid
ellipsoid



International timescales with optical clocks

- To make a complete evaluation of all relativistic effects influencing time and frequency comparisons at the 10^{-18} level of accuracy.
- To establish a connection to geodetic models in order to describe the variation of the clocks due to changes in the gravity potential, e.g. related to tidal effects
- To investigate the possibility of using continuously operated transportable optical clocks for the comparison of remote clocks
- To carry out a proof-of-principle experiment using optical clocks to measure gravity potential differences
- To perform an analysis of the complete frequency ratio measurement matrix derived from the optical clock comparison programme
- To consider how the output from this analysis could be used to derive steering corrections to UTC(k) timescales

Relativistic geodesy



- Reference in space : syntonization to Terrestrial Time
  - Ground clocks measure the « global » potential

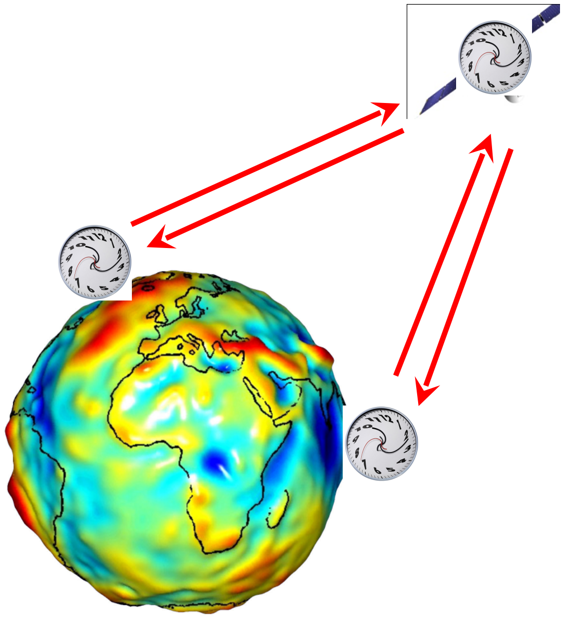


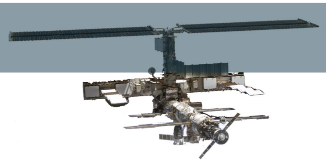
Table 2. Effects on syntonization with respect to TCG of clocks on board terrestrial satellites; Orders of magnitude and uncertainties of the corrections where h represents the altitude of the satellite

Effect	Order of magnitude	Uncertainty
Earth's gravitational potential	$< 6 \times 10^{-10}$	Few 10^{-18} (GEM-T3) $< 10^{-18}$ at $h > 4000$ km Few 10^{-18} (5 cm orbit uncertainty) $< 10^{-18}$ at $h > 10\,000$ km
2nd order Doppler ($v^2/2/c^2$)	$< 3 \times 10^{-10}$	$< 10^{-18}$ at $h > 10\,000$ km
External masses : (at $h = 300\,000$ km) Moon	4×10^{-13}	$< 10^{-18}$
Sun	4×10^{-14}	
Venus	6×10^{-18}	
Solid Earth tides Ocean tides Polar motion Atmospheric pressure	10^{-18} (at low altitudes)	$< 10^{-18}$

- Relativistic geoid : surfaces of constant clock rates

$$W_g = W_E + \frac{1}{2}V^2 - \frac{W_E^2}{2c^2} - \frac{4W_E^b V^b}{c^2} + \frac{3W_E V^2}{2c^2} + \frac{V^4}{8c^2}$$

J. Muller et al, J. Geod. 82 (2008)



Realize the primary reference frame in space

- Time and frequency metrology
  - Better time unit (s)
  - Desynchronisation over large distance
  - Precise frequency dissemination
- Navigation
  - Ultra precise tracking of spacecrafts
  - Improve satellite navigation systems
- Geodesy
  - Earth's gravitational potential determination
- Fundamental physics
  - Test of general relativity
  - Link to the ICRF