GRASP: Time/Frequency applications

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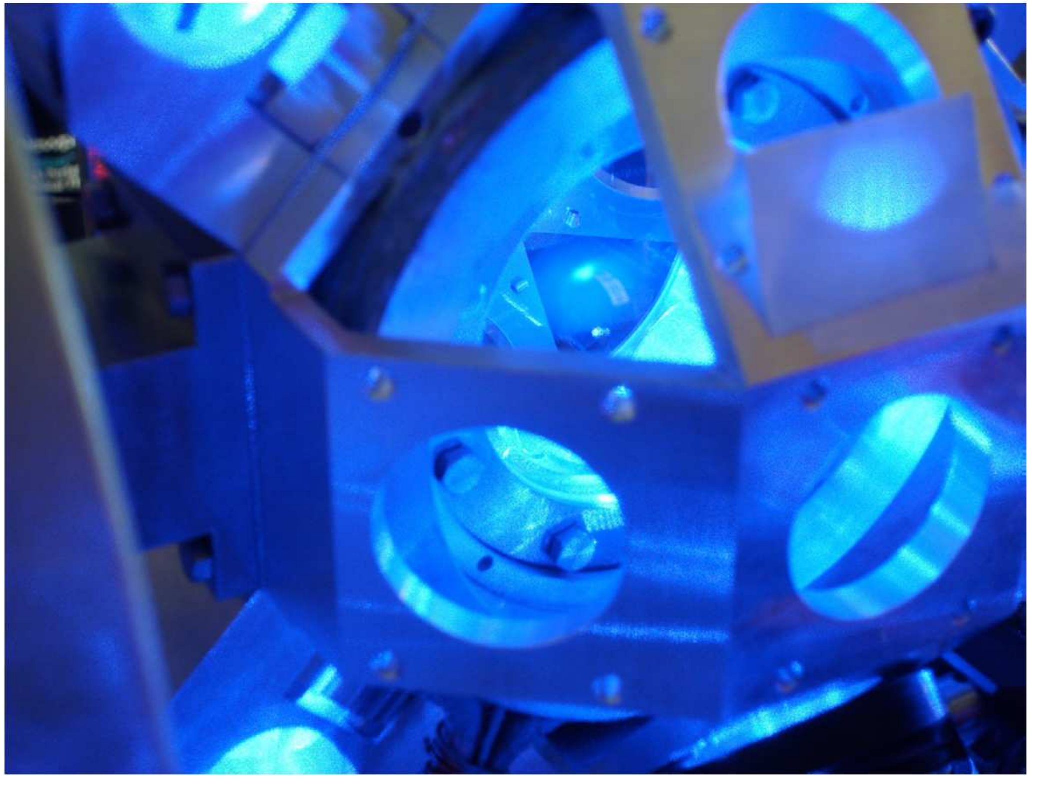
Atelier GRASP, CNES, 23 Octobre 2014



LNE
Le progrès, une passion à partager

cnrs
dépasser les frontières

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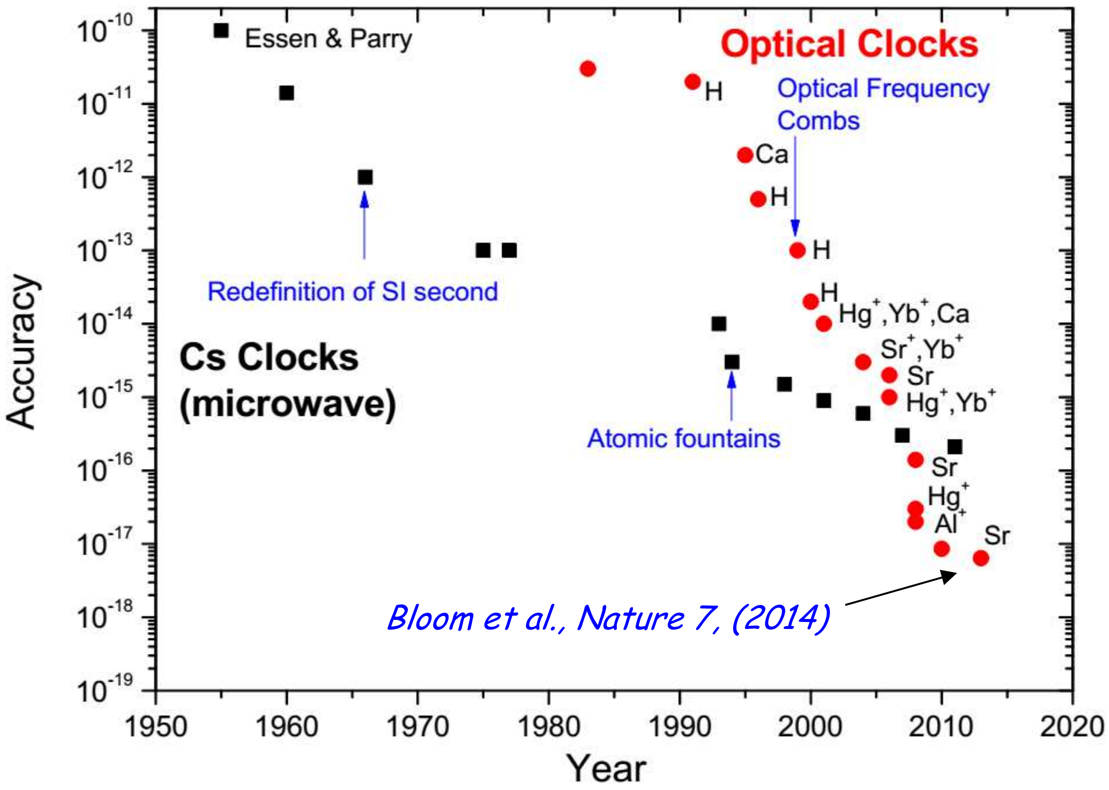
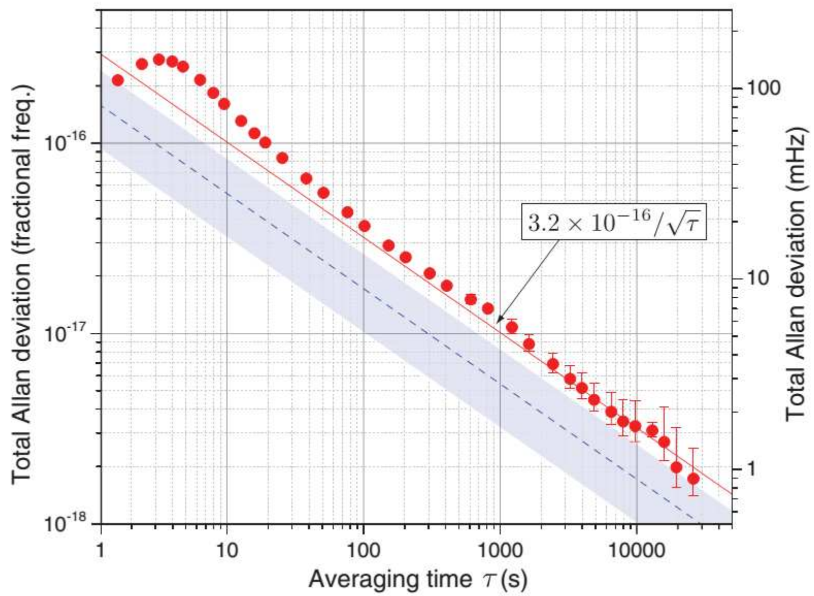
Progress in Time/Frequency Metrology



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



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

Nicholson et al., Phys. Rev. Lett. 109, 230801 (2012)

Hagemann et al., IEEE IM 62, 1556 (2013)

- Microwave clocks: 10^{-16} accuracy (Fountains)
- In space: Microwave clocks with about 10^{-14} stability @ 1 day
- 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

Main present limitation

- Best present satellite radio techniques (GNSS, TWSTFT) reach about 1×10^{-15} frequency stability after 1 day averaging $\Rightarrow$ 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 $\Rightarrow$ 25 days averaging required to reach 1×10^{-18} !! – optimistic.
- ACES Microwave link is expected to reach 2×10^{-15} after 300 s averaging $\Rightarrow$ 5 days to reach 1×10^{-18} – optimistic.
- Phase coherent fibre links have been demonstrated to reach < 1×10^{-18} after 1000 s averaging – OK but limited to continental scales.
- Free space coherent optical links through turbulent atmosphere are in their infancy, but show potential for similar performance as fibre links (SYRTE-OCA, NIST).

920 km fibre link [Predehl 2012]

But many applications require long distance (intercontinental) clock comparisons on ground and/or in space.

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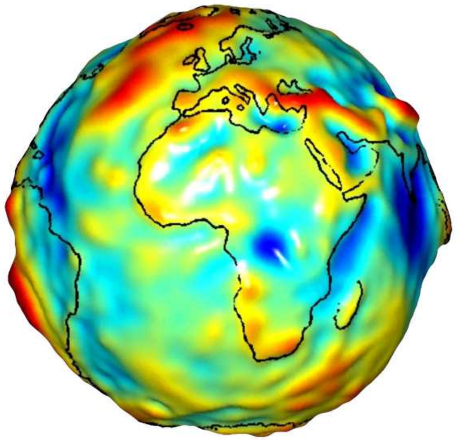
Clock based Geodesy

- An **isochronometric surface** is a surface where all clocks beat at the same rate with respect to coordinate time.

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

- They are almost equivalent to **equipotential surfaces of the Newtonian gravitational field** (differences of the order of 2 mm which can be modelled)
- Geopotential is known with an accuracy ~ 10 cm on the surface, on a grid of ~ 10 km x 10 km



e.g. EGM2008 includes satellite data + gravimetric (ground) data

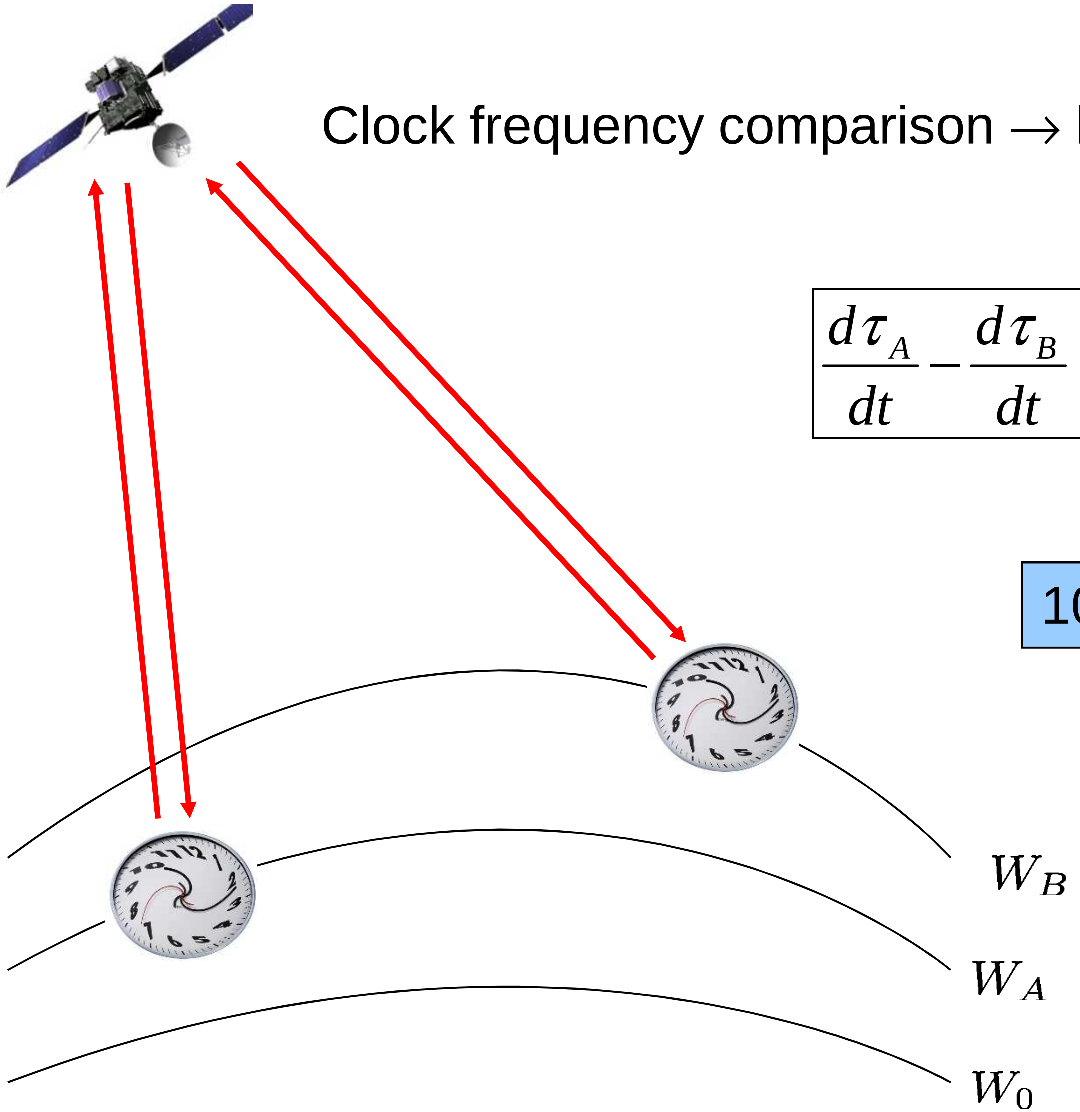
→ decomposition in spherical harmonics (up to degree 2100)

Clock based Geodesy

Clock frequency comparison → knowledge of the gravity field

$$\frac{d\tau_A}{dt} - \frac{d\tau_B}{dt} = \frac{W_B - W_A}{c^2} + O(c^{-4})$$

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



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Space projects: How GRASP fits in (1)

- T2L2 on JASON2: since 2008
  - demonstrated 2×10^{-17} @ 10 d, on 30 m baseline
  - 100 ps accuracy on European baselines
  - limited to continental scales, “patchy” temporal coverage

- ACES-MWL on ISS: 2016 – 2019
  - expect similar, or slightly better, performance than T2L2
  - common views limited to continental scales, good temporal coverage
  - factor 10 (at least) degradation on intercontinental

- ACES-ELT on ISS: 2016 - 2019
  - expect similar, or slightly worse, performance than T2L2
  - common views limited to continental scales, “patchy” temporal coverage
  - factor 10 (at least) degradation on intercontinental

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Space projects: How GRASP fits in (2)

- T2L2 (MWL?) on GRASP: 2019 - 2022
  - Similar performance to JASON (ACES)
  - Extension to intercontinental common views
  - Temporal extension, e.g. better ground clocks available and operational
  - Better on board clock and higher orbit (fund. phys.)

- NG MWL on STE-QUEST: 2025 - 2029
  - Higher frequencies (2.2 $\rightarrow$ 8.6 GHz, 14.7 $\rightarrow$ 25.7 GHz)
  - improved performance (< 10^{-18} @ 2 d)
  - intercontinental common views > 1/day, all weather
  - ACES MWL heritage

STE-QUEST M4

Space Time Explorer and QUantum Equivalence principle Space Test

- Preselected with 4 other candidates in 2010 for 2022/23 Cosmic Vision M3 launch
- Extensive assessment study for missions and instruments (2011 – 2013)
- Not selected in 2014 (PLATO)

Re-proposed in ongoing M4 call (DL Jan 16, 2015):

- Combined fundamental physics + geodesy mission
  - NG MWL (8.5 and 25.7 GHz downlinks, 23.0 GHz up). VLBI?
  - Onboard accelerometers (2×10^{-11} m/s^2/√Hz @ 5×10^{-5} – 0.05 Hz)
  - SLR
  - GNSS receiver
  - orbit 5000 km, 74.5°, or elliptic 800x5000 km
- Geodesy group being set up:

  R. Biancale, J. Johansson, M. Rotacher, H-G. Scherneck, D. Svehla

  + …..

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Two possible payload elements: T2L2, MWL

- T2L2 – presentation by P. Exertier

- ACES MWL:

Mass (incl. antenna):	16.5 kg
Power :	51.3 W
TRL (now):	7
TRL (post 2017):	9

all weather, low elev (< 5°) operation

frequencies: 2.24 and 14.7 GHz (down), 13.48 GHz (up)

ground stations may be available from ACES heritage

Radiations ??

built by TimeTech(D) and ADS(D) under ESA contract

Price: (< 10 M€)

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Conclusion

• Clocks are reaching uncertainties of 10^{-18} in fractional frequency
• Intercontinental (and mobile) T/F comparison techniques at that level are lacking, but essential to many applications.
• T2L2 on JASON2, and ACES MWL are providing sub 10^{-16} performance on short baseline (continental).

• GRACE could extend that to intercontinental baselines in intermediate time-frame (early 2020s), with applications in fund. physics and geodesy.

• In the longer term (> 2025) STE-QUEST would provide 10^{-18} performance on intercontinental scales, with similar geodesy objectives.

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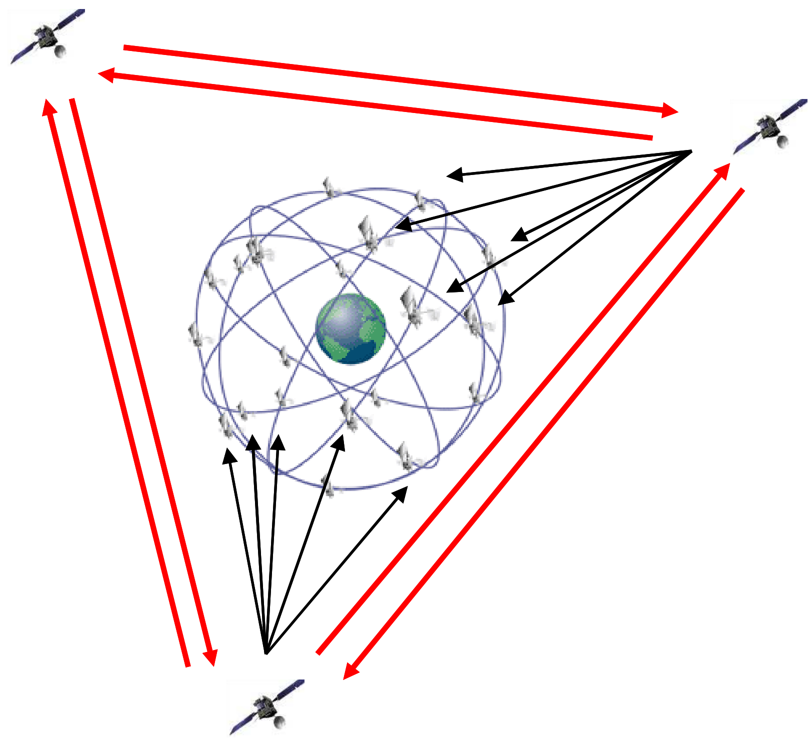
Navigation and Reference Systems

- *Realize the primary reference frame in space*

- Time and frequency metrology
  - Better time unit (s)
  - Synchronization over large distances
  - Precise frequency dissemination
- Navigation
  - Ultra precise tracking of spacecraft
  - Formation flying
  - Improved Global Navigation Systems
- Geodesy
  - Earth's gravitational potential determination
- Fundamental physics
  - Tests of general relativity



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