Fundamental physics and geodesy with atomic clocks

Pacôme DELVA

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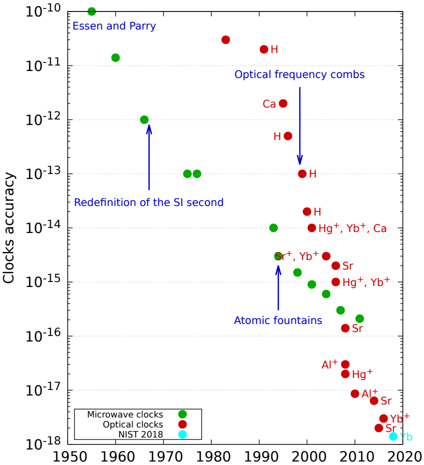
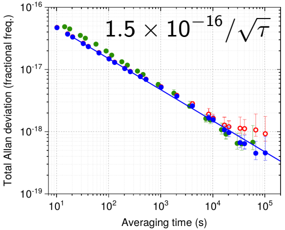
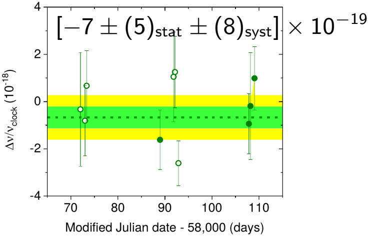
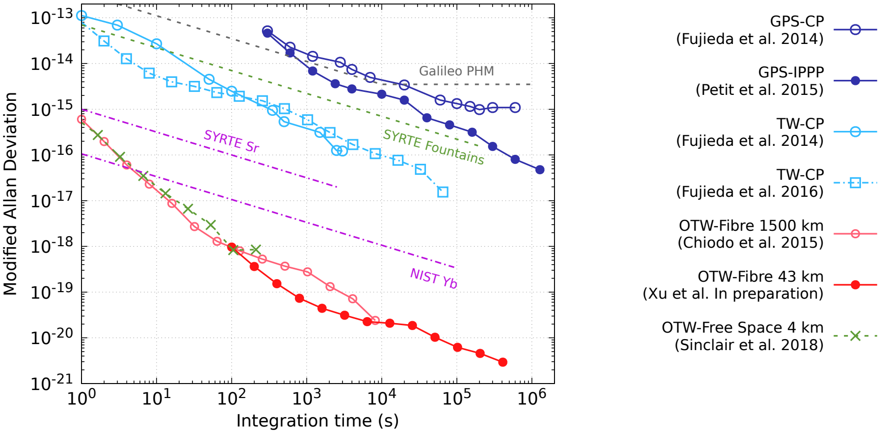
Séminaire du Département de Physique des Particules du CEA-Saclay
Paris-Saclay, 24 February 2020







- Microwave clocks accuracy $\sim 1 \times 10^{-16}$
- Optical clock: accuracy $= 1.4 \times 10^{-18}$, stability $= 4.5 \times 10^{-19}$ (McGrew et al. 2018, NIST)
- Very active, innovative and competitive field of physics



- Satellite (GNSS,TW): intercontinental but limited to $10^{-16} - 10^{-17}$, rather long integration time
- Fibre links: best stability 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

Outline

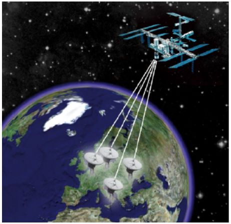
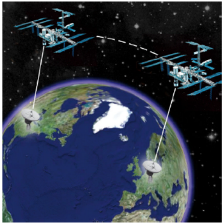
1. Gravitational redshift test with the future ACES mission
2. Gravitational Redshift test with Galileo eccentric satellites
3. Chronometric geodesy
4. Dark matter detection with atomic clocks

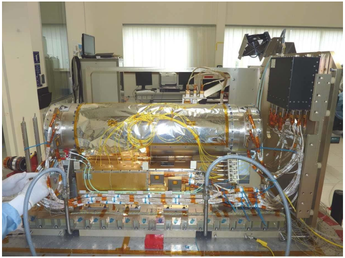
Outline

The ACES mission

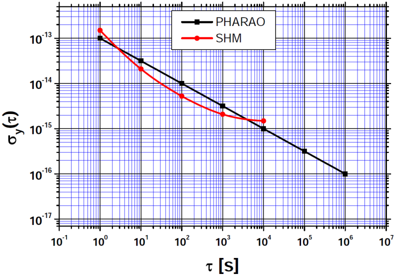
Goals

- Realize best timescale in orbit to date
- Allow time and frequency comparison between this timescale and the best ground clocks worldwide
- Use this data to perform fundamental physics tests
- Demonstrate possible applications in chronometric geodesy, inter-continental optical clocks comparisons, etc

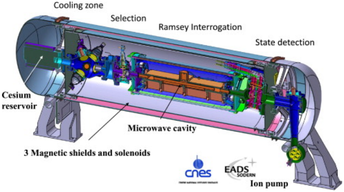





Pharao, Cs jet
(CNES, SODERN, SYRTE)



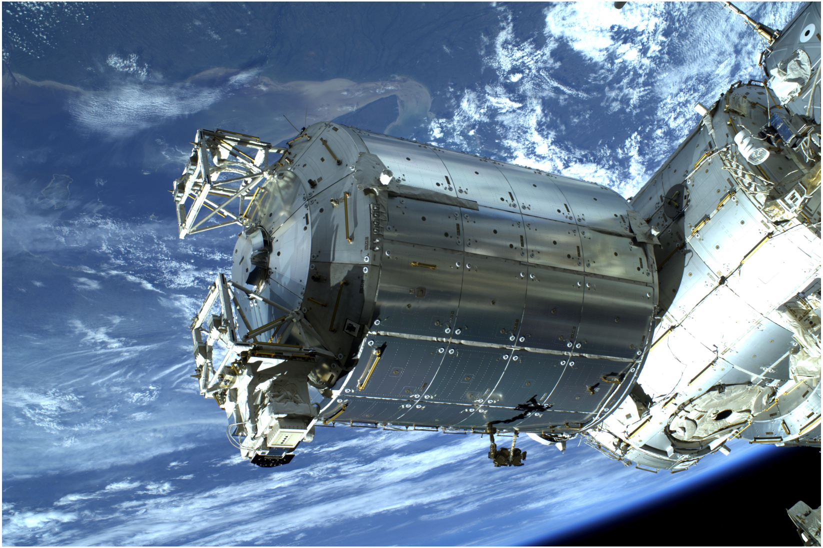
Pharao & SHM Allan Deviation



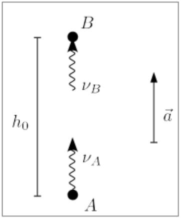
Pharao schema

ACES Payload

Expected launch date: 2021 (SpaceX, Columbus module)



Einstein effect is a gravitational redshift



- Consider two points A and B at rest in an accelerated frame with uniform acceleration $\mathbf{a}$
- Frame velocity increases by $\delta v = ah_0/c$ $(a = \sqrt{\mathbf{a} \cdot \mathbf{a}})$ between emission and reception

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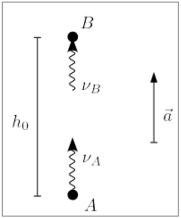

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$$\frac{\nu_B}{\nu_A} = 1 - \frac{\delta v}{c} = 1 - \frac{ah_0}{c^2}$$

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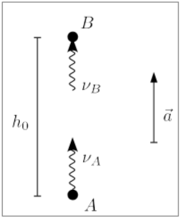

- Consider two points A and B at rest in an accelerated frame with uniform acceleration $\mathbf{a}$
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- Equivalence Principle postulates that $\mathbf{a} \Leftrightarrow -\mathbf{g}$ (locally)

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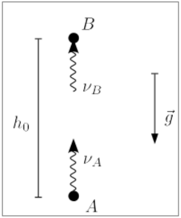

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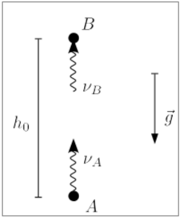

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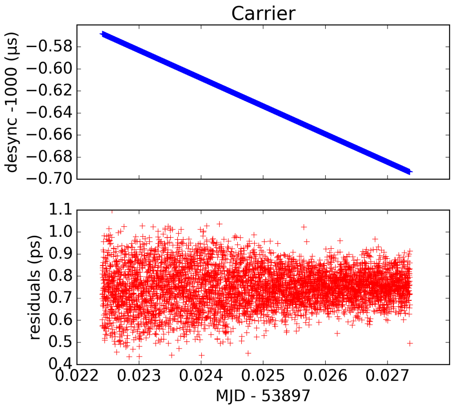
Total redshift between ACES (S) and a ground clock (G)

$$\frac{\delta f}{f} = \underbrace{\frac{GM}{c^2}\left(\frac{1}{r_G} - \frac{1}{r_S}\right)}_{4.1 \times 10^{-11}} + \underbrace{\frac{v_G^2 - v_S^2}{2c^2}}_{-3.3 \times 10^{-10}} \simeq -2.9 \times 10^{-10}$$



- Desynchronisation:
  - $\delta \sim 0.1\,\mu\text{s}$ for 1 pass
  - $\delta \sim 250\,\mu\text{s}$ for 10 days
- PHARAO accuracy $\sim 1 \times 10^{-16}$ (after 10d)

$$\frac{1 \times 10^{-16}}{4 \times 10^{-11}} \approx 2.5 \times 10^{-6}$$

elaborated simulations confirms this number (work by E. Savalle et al., arxiv 1907.12320)

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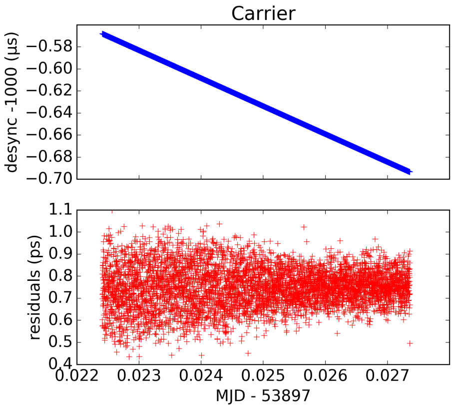

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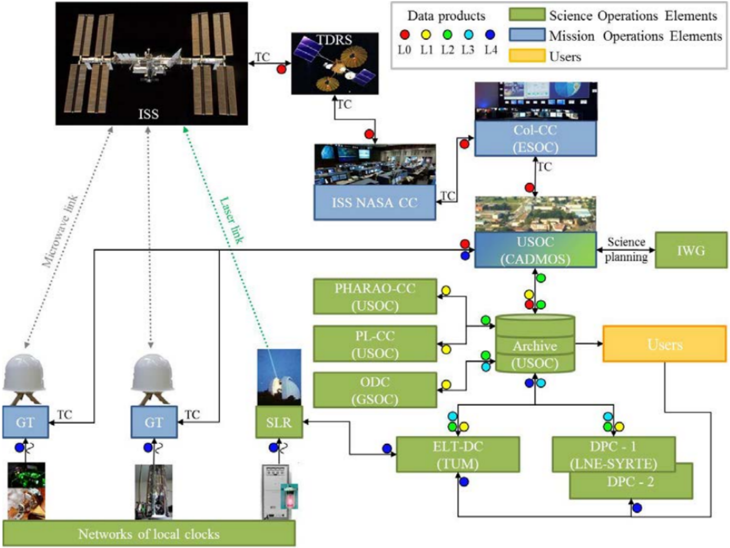
ACES Ground segment



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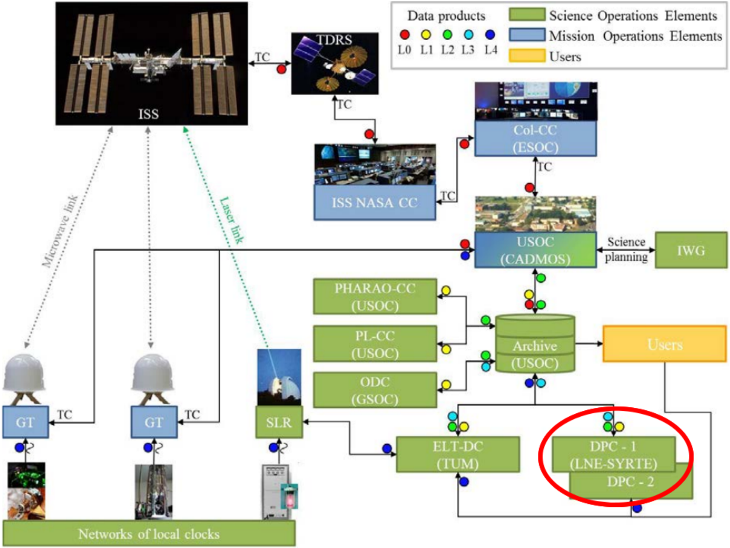
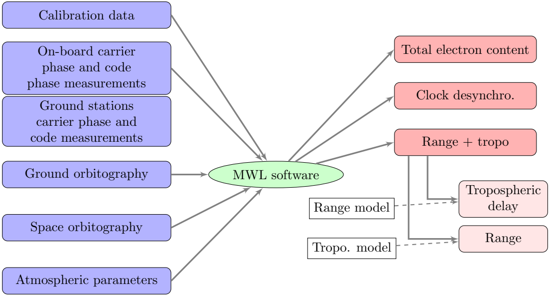


After 6 years, many TimeTech and ADS (Airbus Defence and Space) documents, countless meetings and a few headaches. . .

- Simulation software: 1500 lines of Matlab, highly flexible, produces input (blue) and output (red)
- Processing software: 6300 lines of Python, designed for operation, takes input (blue) and produces output (red)



Meynadier et al. 2018 (*Class. Quantum Grav.*)

Gravitational redshift test with the future ACES mission

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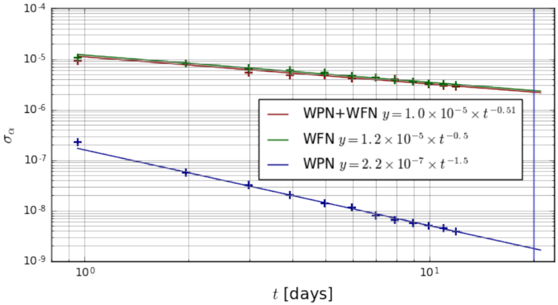
[2]Laboratoire Kastler Brossel, ENS-Université PSL, CNRS, Sorbonne Université, Collège de France, 24 rue Lhomond, 75005 Paris, France
[3]Bureau International des Poids et Mesures, Pavillon de Breteuil, 92312 Sèvres Cedex, France

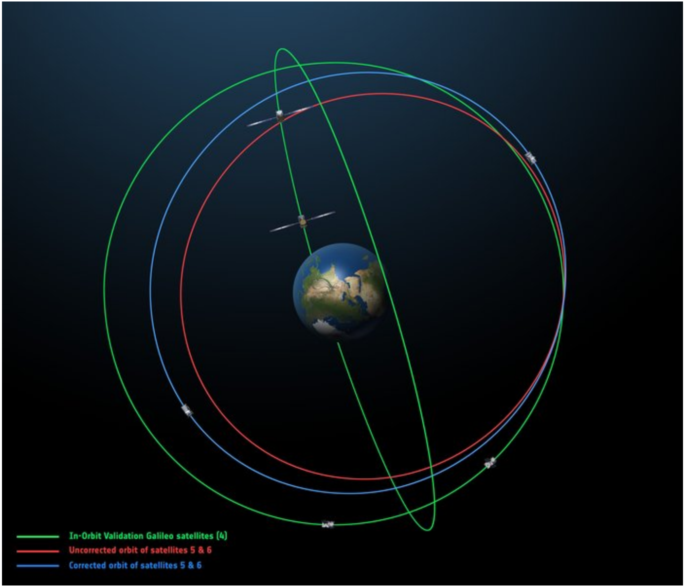
Classical and Quantum Gravity 36(24), 2019



Uncertainty of the gravitational redshift test as a function of the experiment duration (blue vertical line at 20 days), considering realistic noise (White Phase Noise + White Frequency Noise).

Outline

Galileo satellites 201&202 orbit



Galileo sats 201&202 launched in 08/22/2014 on the wrong orbit due to a technical problem ⇒ GRedshift test (GREAT Study)

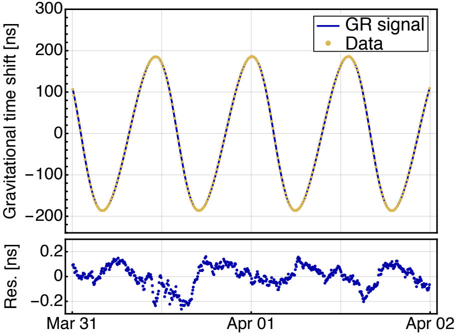
esa

GALILEO

Why Galileo 201 & 202 are perfect candidates?

- An elliptic orbit induces a periodic modulation of the clock proper time at orbital frequency

$$\tau(t) = \left(1 - \frac{3Gm}{2ac^2}\right) t - \frac{2\sqrt{Gma}}{c^2} e \sin E(t) + \mathrm{Cste}$$

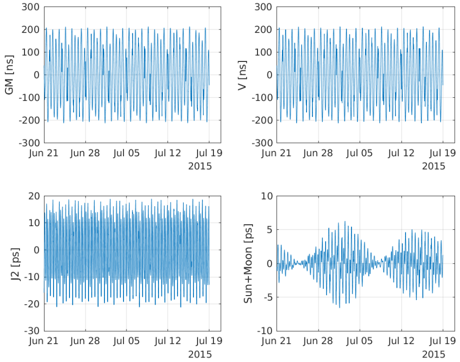


(Delva et al. 2018)

- Very good stability of the on-board atomic clocks → test of the variation of the redshift
- Satellite life-time → accumulate the relativistic effect on the long term
- Visibility → the satellite are permanently monitored by several ground receivers

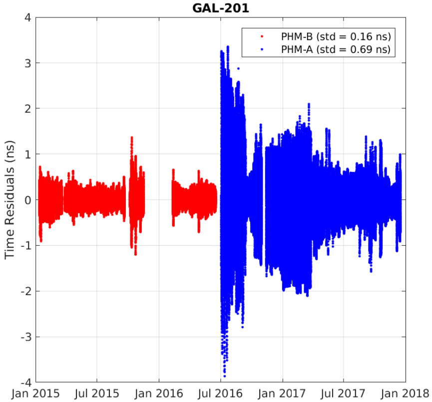
- Orbit and clock solutions: ESA/ESOC
- Transformation of orbits into GCRS with SOFA routines
- Theoretical relativistic shift and LPI violation

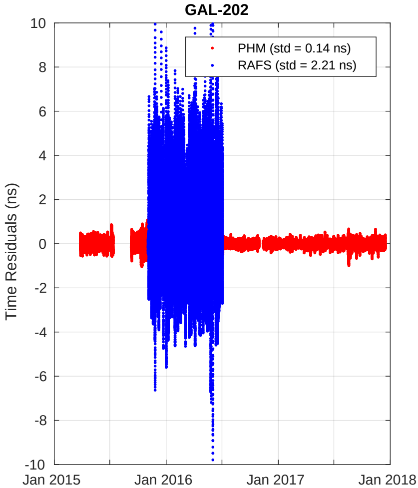
$$x_{\mathrm{redshift}} = \int \left[1 - \frac{v^2}{2c^2} - \frac{U_E + U_T}{c^2}\right] dt \; ; \; x_{\mathrm{LPI}} = -\alpha \times \int \frac{U_E + U_T}{c^2} dt$$



Peak-to-peak effect $\sim 400\,\mathrm{ns}$: model and systematic effects at orbital period should be controlled down to 4 ps in order to have $\delta\alpha \sim 1 \times 10^{-5}$

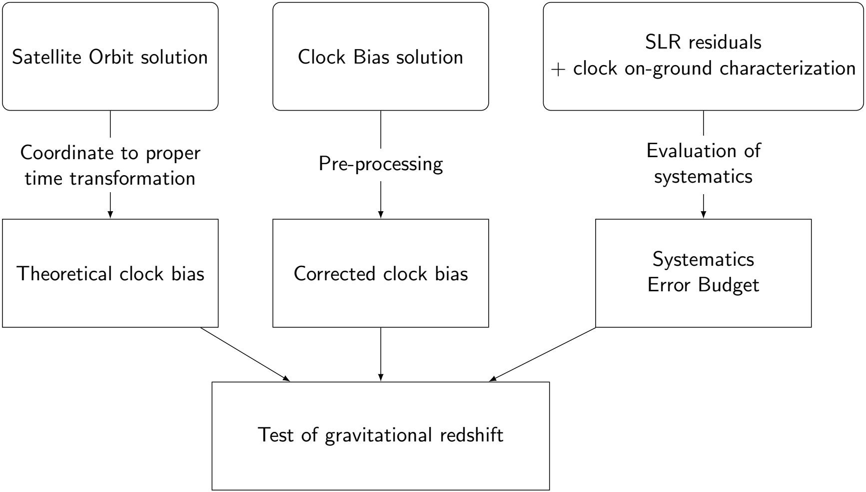
Choice of clock





- GAL-201: only PHM-B (PHM-A is removed) → 359 days of data
- GAL-202: only PHM (RAFS is removed) → 649 days of data

Data analysis flowchart



Galileo final result

	LPI violat [$\times 10^{-5}$]	Tot unc [$\times 10^{-5}$]	Stat unc [$\times 10^{-5}$]	Orbit unc [$\times 10^{-5}$]	Temp unc [$\times 10^{-5}$]	MF unc [$\times 10^{-5}$]
GAL-201	-0.77	2.73	1.48	1.09	0.59	1.93
GAL-202	6.75	5.62	1.41	5.09	0.13	1.92
Combined	0.19	2.48	1.32	0.70	0.55	1.91

- Local Position Invariance is confirmed down to 2.5×10^{-5} uncertainty
- more than 5 times improvements with respect to Gravity Probe A measurement (1976)
- PRL cover: Delva et al. PRL 121.23 (2018) and Herrmann et al., PRL 121.23 (2018)
- Nice outreach video by Derek Muller on Veritasium (youtube channel `www.youtube.com/watch?v=aKwJayXTZUs`)

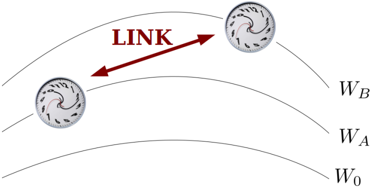
Outline

Basic principle of chronometric geodesy

The flow of time, or the rate of a clock when compared to coordinate time, depends on the velocity of the clock and on the space-time metric (which depends on the mass/energy distribution).

In the weak-field approximation:

$$\frac{\Delta\tau}{\tau} = \frac{\Delta f}{f} = \frac{U_B - U_A}{c^2} + \frac{v_B^2 - v_A^2}{2c^2} + O(c^{-4})$$
$$= \frac{W_B - W_A}{c^2} + O(c^{-4}) \quad (1)$$



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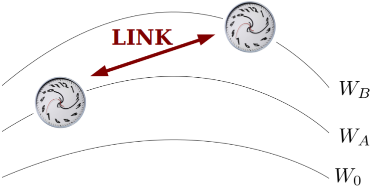

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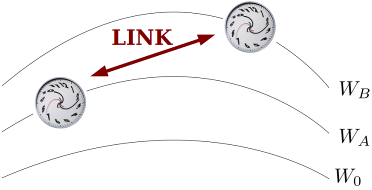

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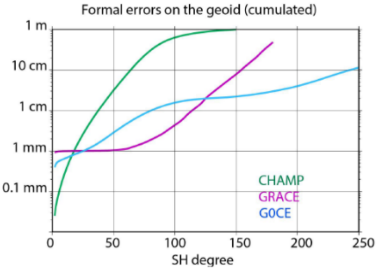
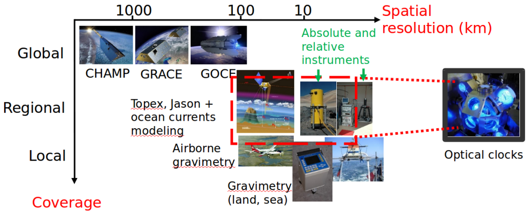
Chronometric observables in geodesy

- Chronometric observables are a completely new type of observable in geodesy: gravity potential differences are directly observed
- Accuracy of optical clocks starts to be competitive with classical methods





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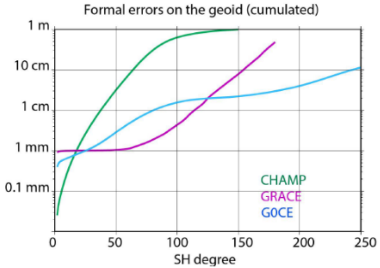

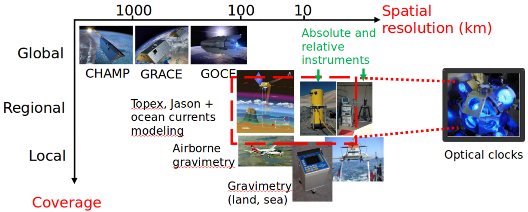

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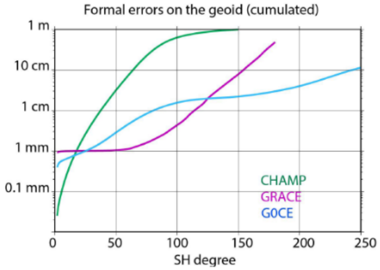
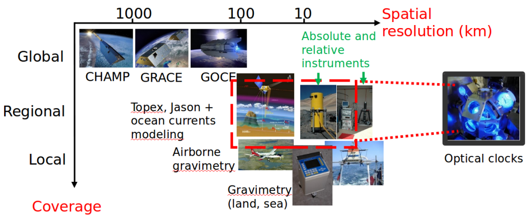
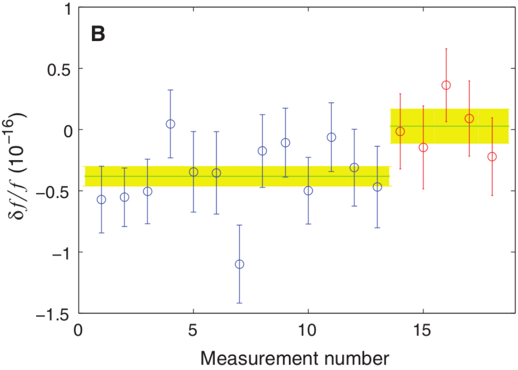




A local comparison

Experimental demonstration of the dependency of clock frequency with local heigth with two Al^+ optical clocks (Chou et al. 2010)

Starting at data point 14, one of the clock is elevated by 33 cm. The net relative shift is measured to be $(41 \pm 16) \times 10^{-18}$.



The shape of the Earth

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

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

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

- using INRIM CsF1 vs. SYRTE FO2 comparison we find:

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

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- However, ground clocks are sensitive to higher order multipoles of the grav. potential

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- using INRIM CsF1 vs. SYRTE FO2 comparison we find:

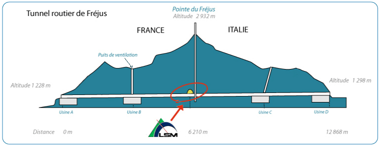
$$J_2 = (1.097 \pm 0.016) \times 10^{-3}$$

- Error of $\sim 1.4\%$ compare to best known value
- However, ground clocks are sensitive to higher order multipoles of the grav. potential

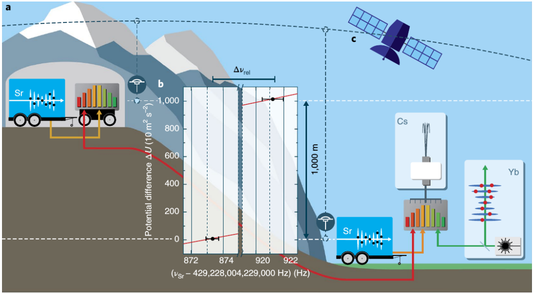
Large-scale demonstration of chronometric geodesy

International Timescales with Optical Clocks (ITOC): Demonstrate that optical clocks can be used to measure gravity potential differences over medium-long baselines with high temporal resolution

Height difference ~ 1 km $\Rightarrow$ Gravitational redshift $\sim 10^{-13}$



J. Grotti et al., Nature Physics 14(5), 2018



Chronometric geodesy for high resolution geopotential

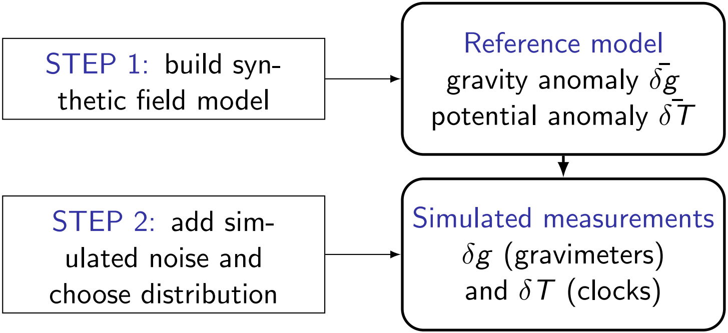
- Collaboration between SYRTE/Obs.Paris, LAREG/IGN and LKB, with the support of GRAM, First-TF and ERC grants
- Goals
  - evaluating the contribution of optical clocks for the determination of the geopotential at high spatial resolution
  - Find the best locations to put optical clocks to improve the determination of the geopotential
- Lion, G., Panet, I., Wolf, P., Guerlin, C., Bize, S., Delva, P., 2017. *Determination of a high spatial resolution geopotential model using atomic clock comparisons.* **J Geod** 115.

Global methodology

STEP 1: build synthetic field model → Reference model

Reference model
gravity anomaly $\bar{\delta g}$
potential anomaly $\bar{\delta T}$

Global methodology



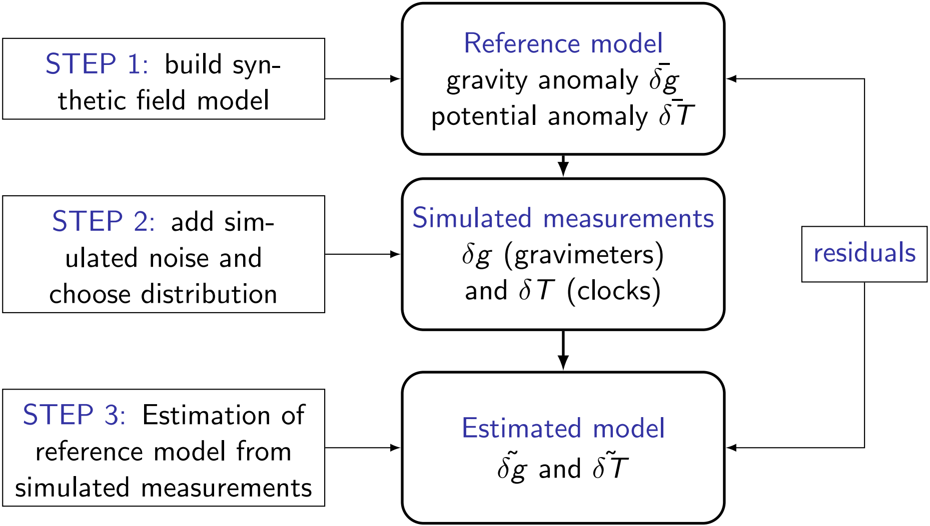
Global methodology

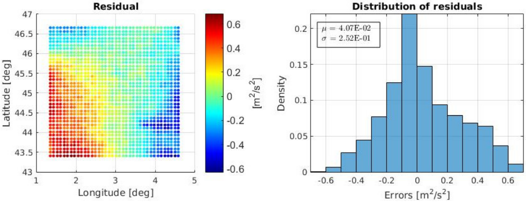
STEP 1: build synthetic field model → **Reference model**
gravity anomaly $\delta\bar{g}$
potential anomaly $\delta\bar{T}$

STEP 2: add simulated noise and choose distribution → **Simulated measurements**
δg (gravimeters)
and δT (clocks)

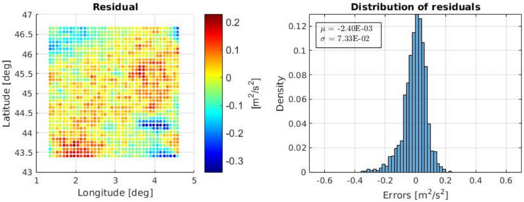
STEP 3: Estimation of reference model from simulated measurements → **Estimated model**
$\delta\tilde{g}$ and $\delta\tilde{T}$

Global methodology





- Estimation of potential from gravimetric data
  - Standard deviation $\sigma = 0.25$ m^2.s^{-2}
  - Mean $\mu = -0.04$ m^2.s^{-2}
  - Trend from West to East of the residuals

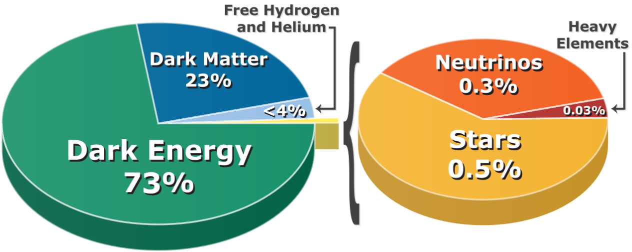


Lion et al. 2017 (*J Geod*)

- Estimation of potential from gravimetric and clock data ($\sim$ 30)
  - Standard deviation $\sigma = 0.07$ m^2.s^{-2}
  - Mean $\mu = -0.002$ m^2.s^{-2}
  - The residual trend disappeared

Outline

Content of the Universe

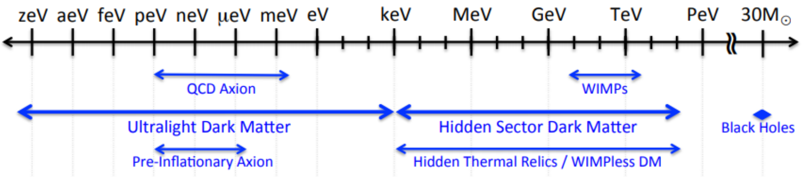


Ben Finney (CC-BY-3.0)

"Mostly it's coffee, which is dark energy, then there's a fair amount of cream, which is dark matter and then there's a tiny bit of sugar – this is the ordinary matter, and this is what science has been all about for thousands of years – until now." (Ulf Danielsson)

Dark Matter: What is it?

- Possible mass range: $\sim$ 90 orders-of-magnitude
- In our study we concentrate on low masses ($<$ 1 eV), where standard collisional detection techniques fail



US Cosmic Visions report, arXiv:1707.04591

(context: $m_{\mathrm{Earth}} \sim 10^{60}$ eV $\quad m_{\mathrm{electron}} \sim 10^{6}$ eV)

$\Longrightarrow$ Wide range of possibilities: requires large range of searches

Variations of fundamental constants: atomic clocks tests

When dark matter fields couple to standard matter violation of local position invariance occurs, and thus of Einstein equivalence principle, through the variation of fundamental constants:

- linear temporal drift (Rosenband et al. 2008; Guéna et al. 2012; Leefer et al. 2013; Godun et al. 2014; Huntemann et al. 2014)
- harmonic temporal variation (Van Tilburg et al. 2015; Hees et al. 2016; Geraci et al. 2018)
- spatial variation w.r.t. the Sun gravitational potential (Ashby et al. 2007; Guéna et al. 2012; Leefer et al. 2013; Peil et al. 2013)
- Transients (Flambaum and Dzuba 2009; Derevianko and Pospelov 2014; Wcisło, Morzyński, et al. 2016; Roberts et al. 2017; Wcisło, Ablewski, et al. 2018) $\Longrightarrow$ transient shifts in energy levels $\Longrightarrow$ shifts in clock frequencies

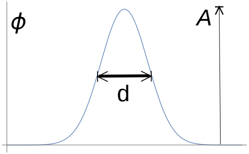
$$\frac{\delta\nu_0}{\nu_{AB}} = K_{AB}\frac{\delta\alpha_0}{\alpha} = K_{AB}\frac{\phi_0^2}{\Lambda_\alpha^2}$$

Topological Defect DM

- Ultralight ($m_\phi \ll eV$) $\implies$ high occupation number

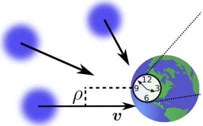
Topological Defects

- monopoles, strings, walls,
- Defect width: $d \sim 1/m_\phi$
- Earth-scale object $\sim 10^{-14}$ eV



Dark matter: Gas of defects

- DM: galactic speeds: $v_g \sim 10^{-3}c$
- ϕ_0^2, d, $\mathcal{T}_{\mathrm{b/w\,collisions}} \implies \rho_{\mathrm{DM}}$



$$\phi_0^2 = \rho_{\mathrm{DM}}\, v_g\, d\, \mathcal{T},$$

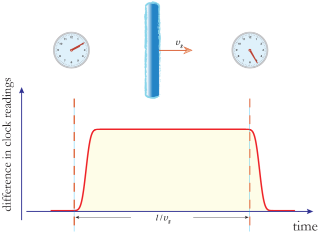
- Vilekin '85, Coleman '85, Lee '89, Kibble '80, ...

Another possibility is an oscillating classical field

Shift in atomic clock frequencies

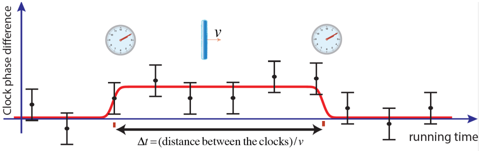
Monitor Atomic Clocks

- Temporary frequency shift → bias (phase) build-up
- Initially synchronised clocks become desynchronised



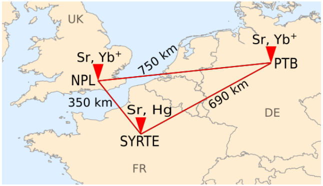
Signal vs. noise?

- Transient signal:
  looks essentially like any outlier
- i.e. what is the specific DM signature?



Derevianko, Pospelov, Nat. Phys. 10, 933

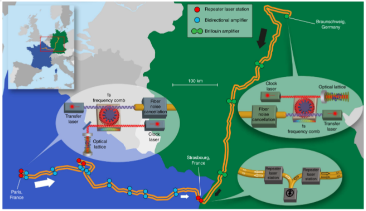
European fibre-linked optical clock network



Fibre network

- High-accuracy long-distance clock-clock (atom-atom) comparisons
- Different clocks: $Hg/Sr/Yb^+$
- $\sim$ Days – weeks synchronous running

- Sensitivity: ✓ $(\delta\alpha, \Lambda)$
  limited only by clocks:
  Sr-Sr: $\delta\omega/\omega \sim 3 \times 10^{-17}$ at 1000s
- Long observation time: ✓ $(\mathcal{T})$
- Long-term stability: ✓ (d)

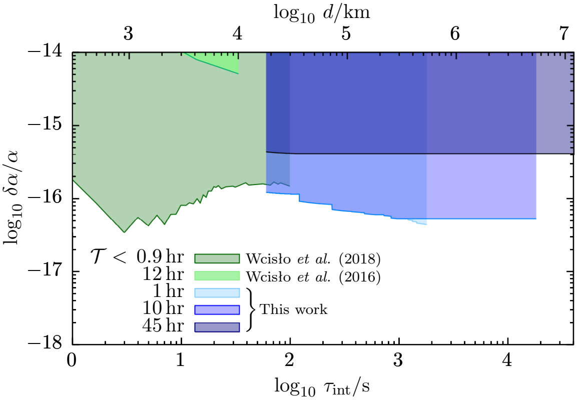


- Lisdat *et al.* (PTB, LNE-SYRTE), Nature Commun. **7**, 12443 (2016).
- Delva *et al.* (PTB, SYRTE, NPL, ..), Phys. Rev. Lett. **118**, 221102 (2017).

Transient variation of fine-structure constant

Orders-of-magnitude improvement: especially for large objects (τ)

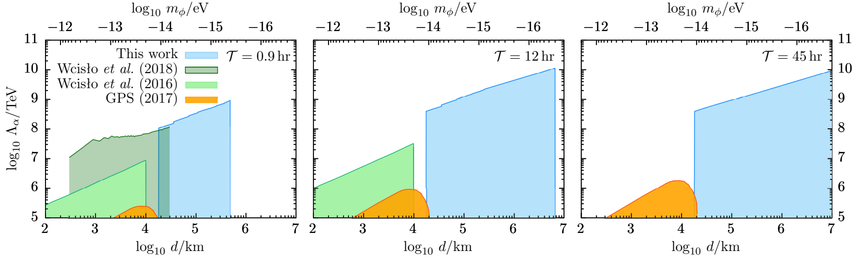
- $\delta\alpha(\tau)/\alpha \lesssim 5 \times 10^{-17}$ @ $\tau = 10^3$ s, & $\mathcal{T} = 1$ hr
- $\delta\alpha(\tau)/\alpha \lesssim 4 \times 10^{-15}$ @ $\tau = 10^4$ s, & $\mathcal{T} = 45$ hr



Topological defect dark matter

Assume DM is made from Topological Defects:

$$\phi_0^2 = \hbar c \, \rho_{\rm DM} v_g \, \mathcal{T} d \ , \qquad \mathcal{T} = \frac{\rho_{\rm inside}}{\rho_{\rm DM}} \frac{d}{v_g}$$



- nb: GPS results (orange): go up to $\mathcal{T} \sim 10\,\mathrm{yrs} \sim 10^5$ hrs

$$\Longrightarrow \ \Lambda_\alpha^2(\mathcal{T}, d) > \frac{\hbar c \alpha \rho_{\rm DM} v_g \mathcal{T} d}{|\delta\alpha_0(\mathcal{T}, \tau_{\rm int})|} .$$

arXiv:1907.02661

Search for transient variations of the fine structure constant and dark matter using fiber-linked optical atomic clocks

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(Dated: July 10, 2019)

Systèmes de Référence Temps-Espace

Fundamental physics

- ACES SYRTE DAC is ready $\rightarrow$ ACES to be launched in 2020, targeting 2×10^{-6} gravitational redshift test
- Gravitational redshift test with eccentric Galileo to 2.5×10^{-5} accuracy $\rightarrow$ $5.6\times$ improvement with respect to GP-A (1976)
- Time dilation (SR) test with optical clocks at the level the best Ives-Stilwell type experiments ($\sim 10^{-8}$)
- Search for Dark Matter with networks of optical clocks $\rightarrow$ bounds on model parameters

Chromometric geodesy

- Best determination of redshift correction within ITOC for a set of European optical clocks and fountains
- Possible improvement of regional geoid models with a few tens of comparisons

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