Projet ROYMAGE

hoRloge Optique à Ytterbium Mobile Appliquée à l'exploration GEodésique

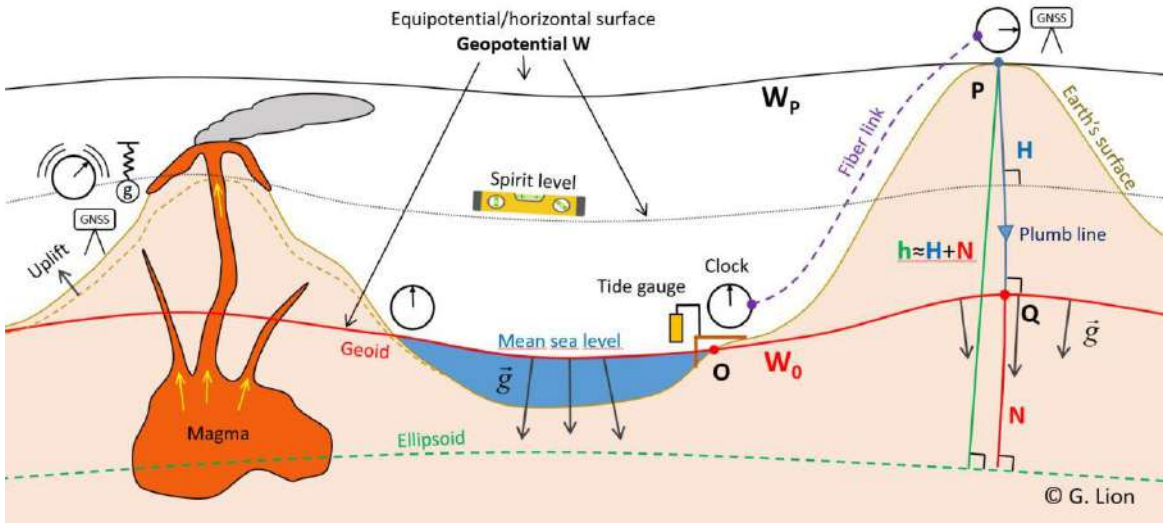
Rodolphe Le Targat (SYRTE), Guillaume Lion (IPGP), Olivier Jamet (IGN-IPGP), Marie-Françoise Lalancette (SHOM)

Motivation of the project

- At SYRTE, Observatoire de Paris, we start the design and the construction of transportable atomic clock based on neutral ytterbium
- Clocks experience the local gravitational potential, it is the **gravitational time dilation** predicted by Einstein:

$$\frac{\Delta\nu}{\nu} = \frac{W_A - W_B}{c^2} \approx \frac{g.\Delta z}{c^2}$$, e.g. 1 m difference turns into a 1×10^{-16} frequency change

- Therefore: a mobile clock can be used to map the gravitational potential of the Earth
- Complementary to traditional measurement means,
  - Computation of gravity potential values by the GNSS/geoid approach
  - Computation of gravity potential values by the geometric levelling approach
- resolution depends only on:
  - The availability of the link
  - The performance of the clock
- Only ground based direct measurement of the potential



Atomic clocks in a nutshell

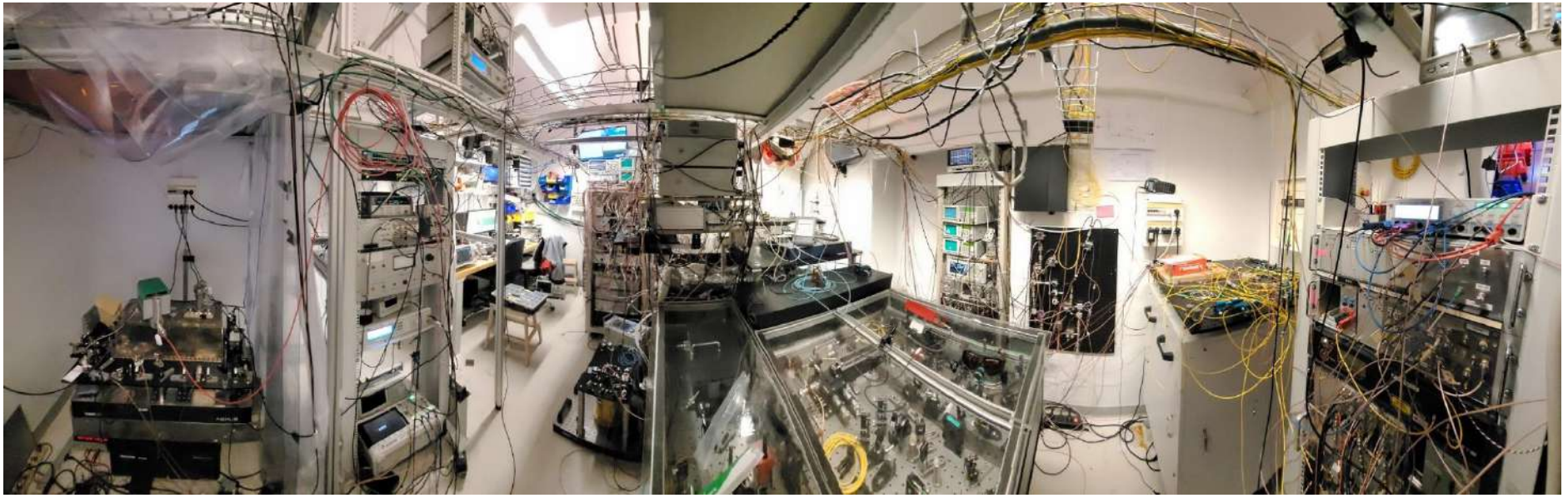
A few (nasty) details

New clock at LNE-SYRTE: a transportable optical lattice clock applied to Geodesy

The big picture: optical clocks network in Europe

The French atomic clocks

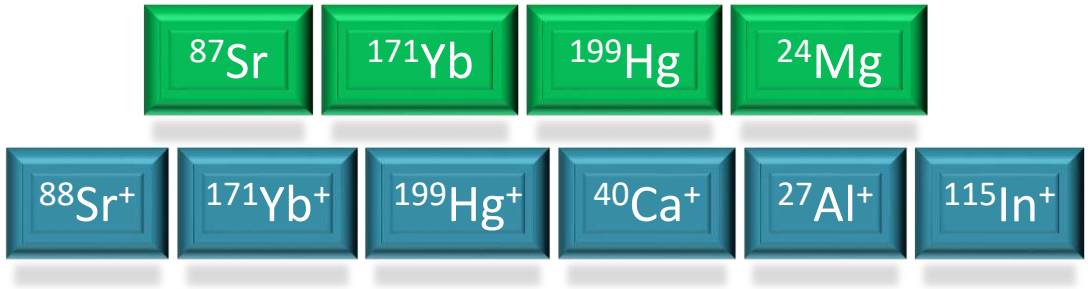
- LNE-SYRTE: National Metrology Institute for Time and Frequency
- Laboratory under the garden of the Paris Observatory
- 7 stationary state-of-the-art atomic clocks, built in 30 years
- Microwave atomic clocks based on Cs: definition of the second, control over 16 digits, SYRTE provides 40% of worldwide contributions to TAI (+Rb)
- New generation: optical clocks (2 x Sr, Hg, next = Yb), control at 17 digits, soon 18 digits



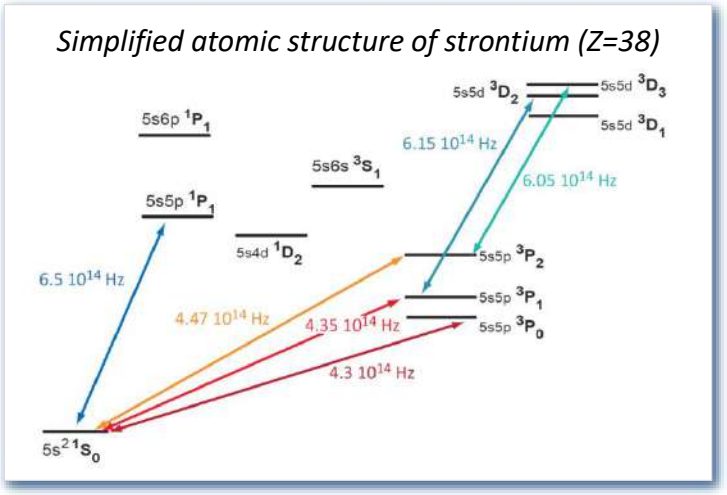
Why is an atomic clock so accurate?

- Realization of the second based on a microwave atomic transition = (almost) a physical constant (control over 16 digits)

- Optical atomic clocks are the **most accurate devices on Earth**: the frequency can be controlled over **18 digits**



- Example with the frequency of the strontium :



A 1 µW beam (on a 1 mm diameter) at 461 nm perturbs the 11th digit = AC Stark shift (=light shift)

Collisions between atoms perturb the 18th digit (or lower…) = Mean field effect

429 228 004 229 872.85x xxx xxx … Hz

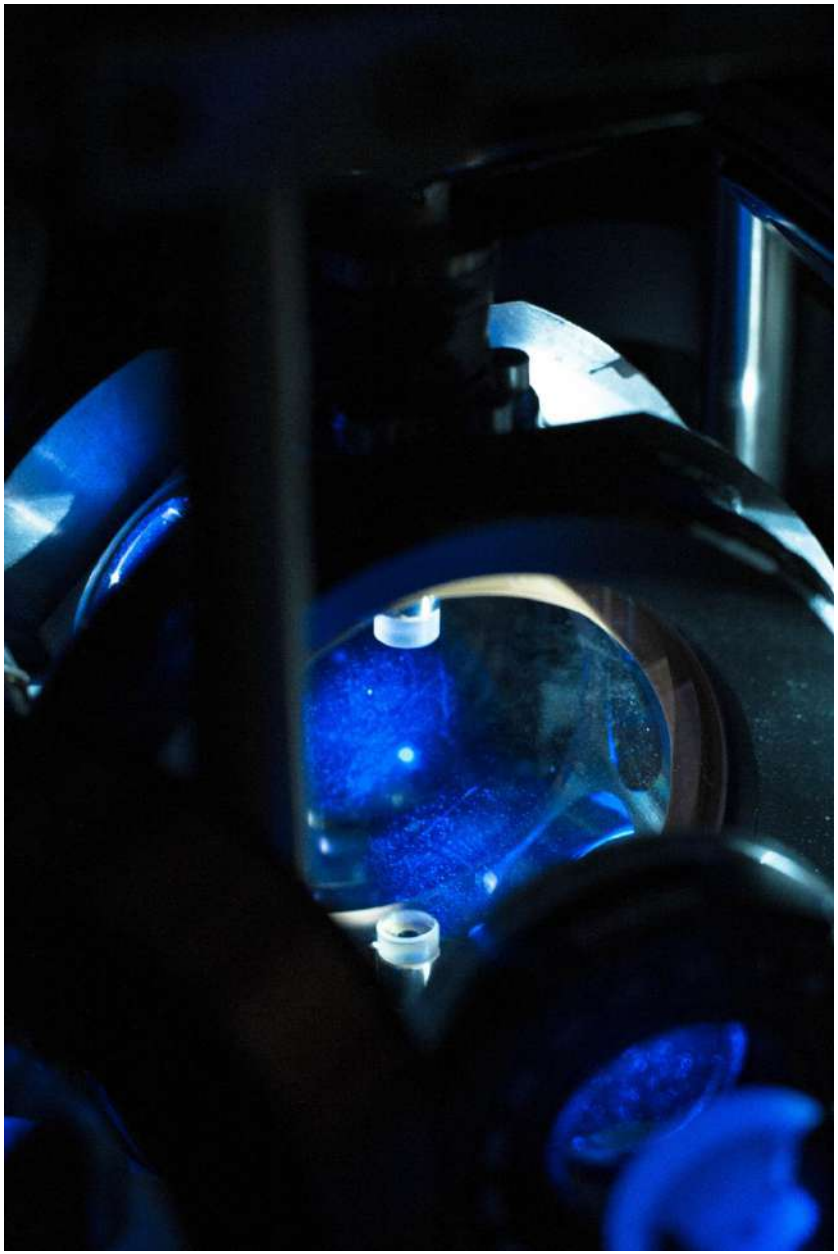
A magnetic field of 1 Gauss perturbs the 13th digit = ZEEMAN effect

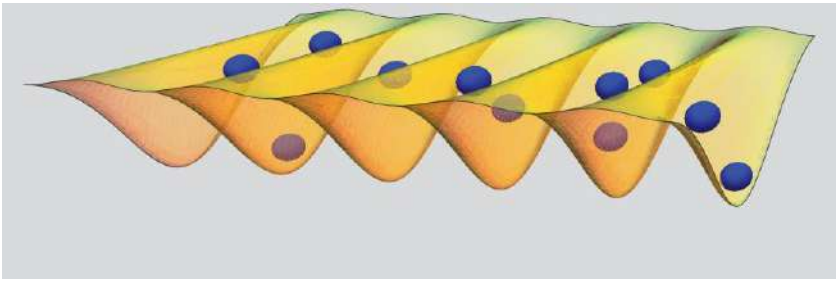
A temperature change of 1 K perturbs the 17th digit = Blackbody radiation shift

An electric field of 10 kV/m (thunderstorm !) perturbs the 14th digit = DC Stark shift

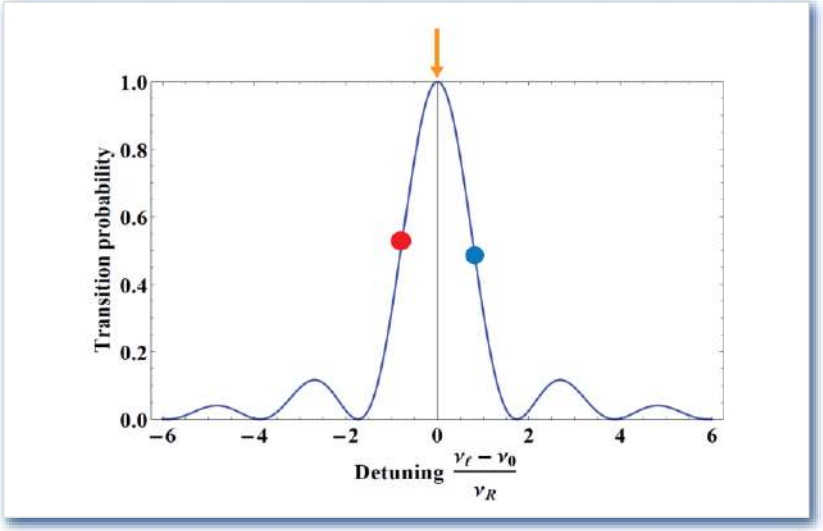
A height change of 1 m perturbs the 16th digit = gravitational time dilation

Principle of an optical lattice clock

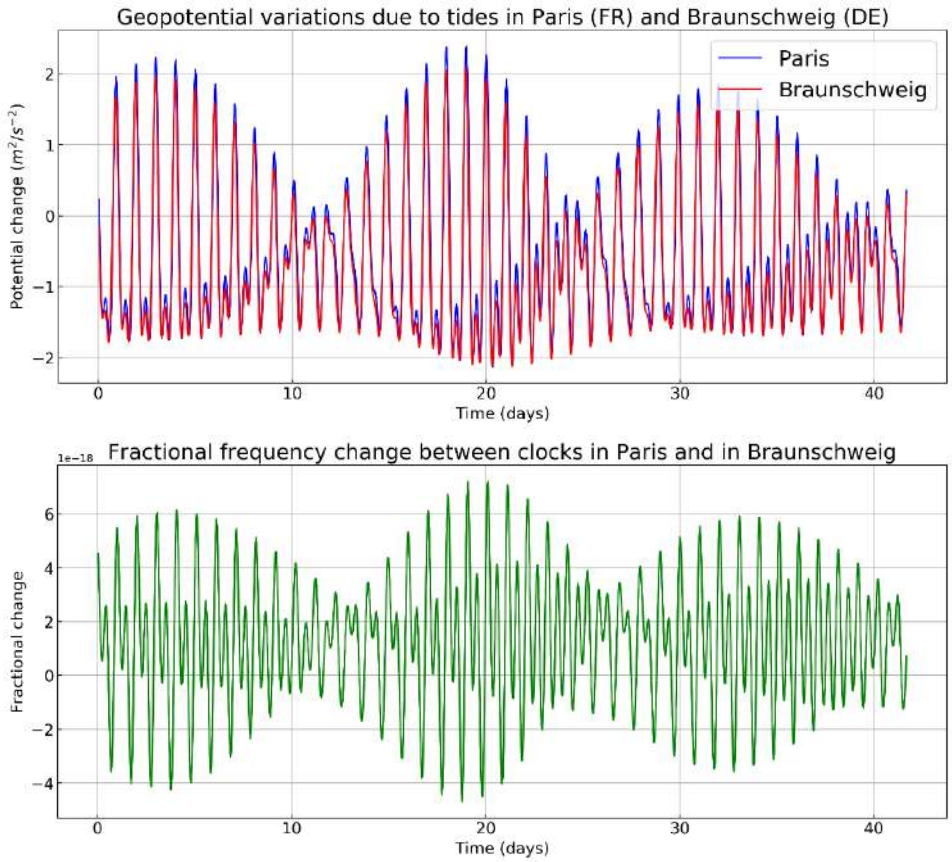


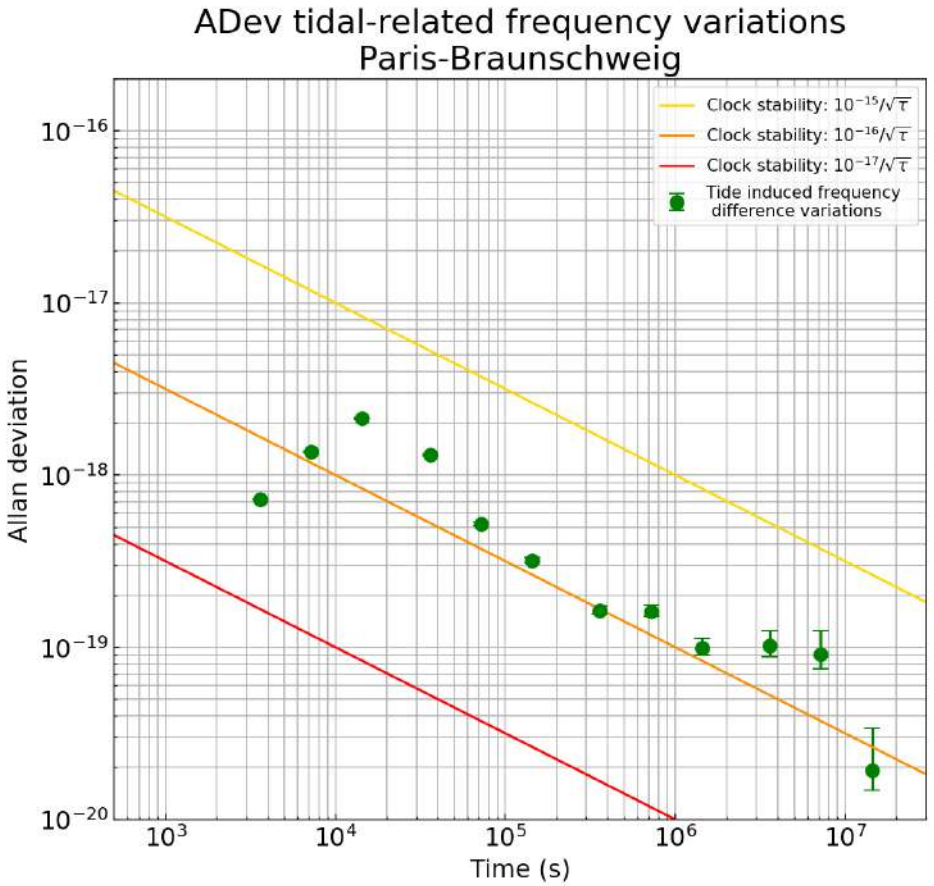


- ⇨ many neutral atoms probed at the same time, resolution scaling as $1/\sqrt{N}$
- ⇨ Resolution of >15 digits in a single shot, scaling as $1/\sqrt{\text{integration time}}$



Exploiting the stability: Example of Earth tides





- ⇨ Prediction of Earth tides: differential effect, turning into a frequency difference variation
- ⇨ This can be detected provided the resolution is good enough
- ⇨ Prerequisite to a new definition of the second

Clocks and gravitational potential

- 2017: Levelling of the German transportable clock at SYRTE
- 2021: New levelling in the framework of ROYMAGE

- European levelling in 2013
- First International clock comparison in 2015

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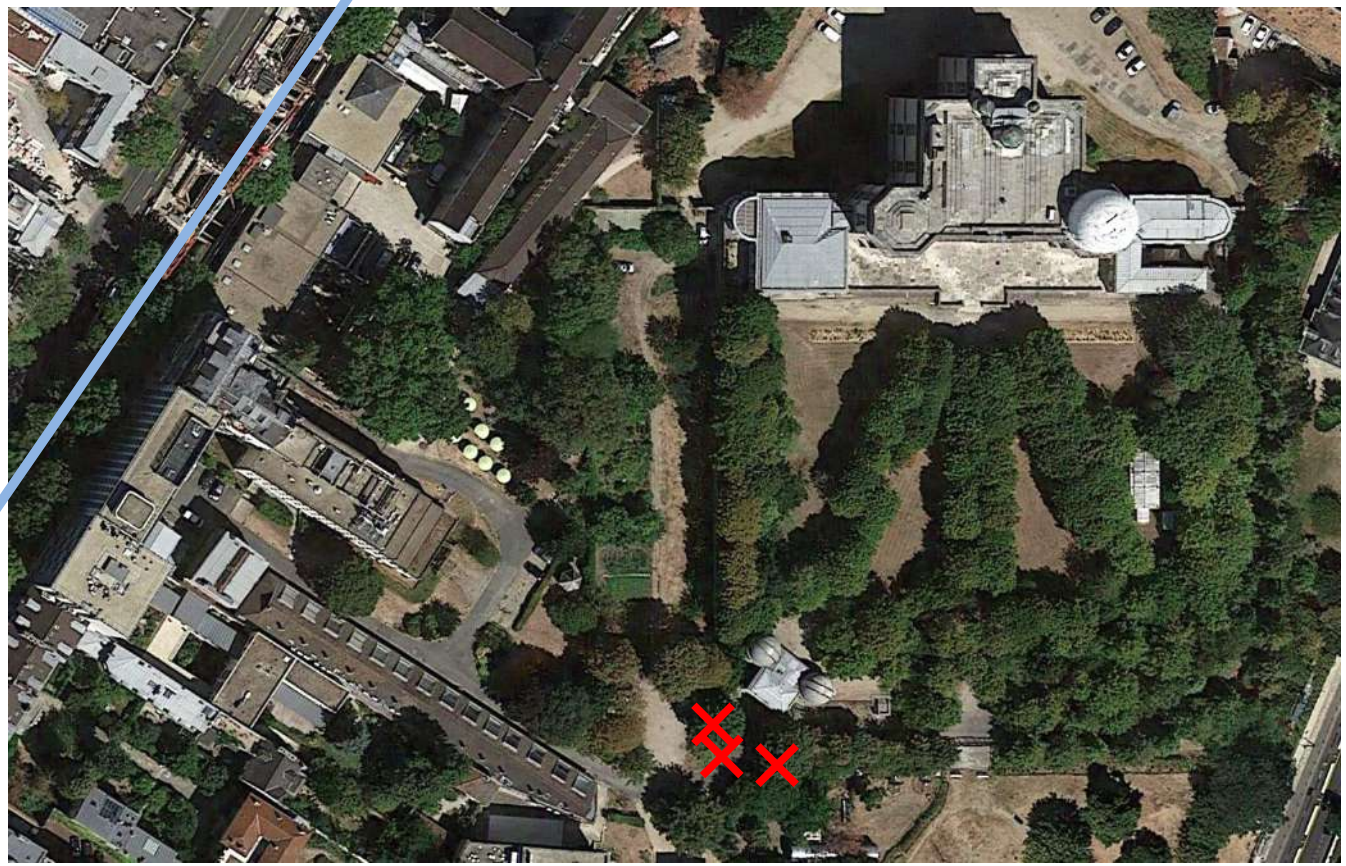
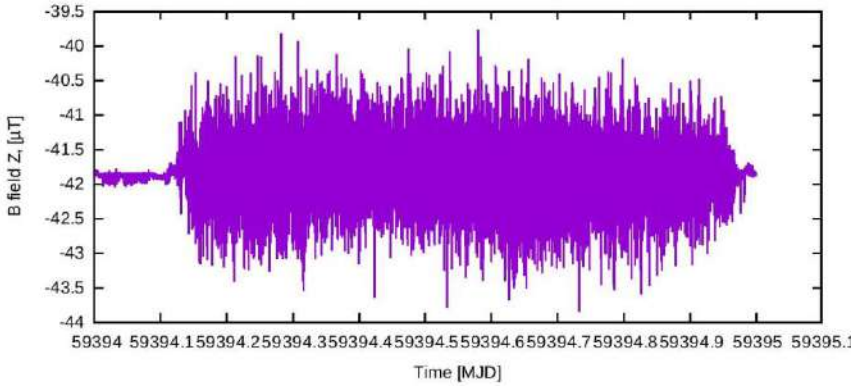
The big picture: optical clocks network in Europe

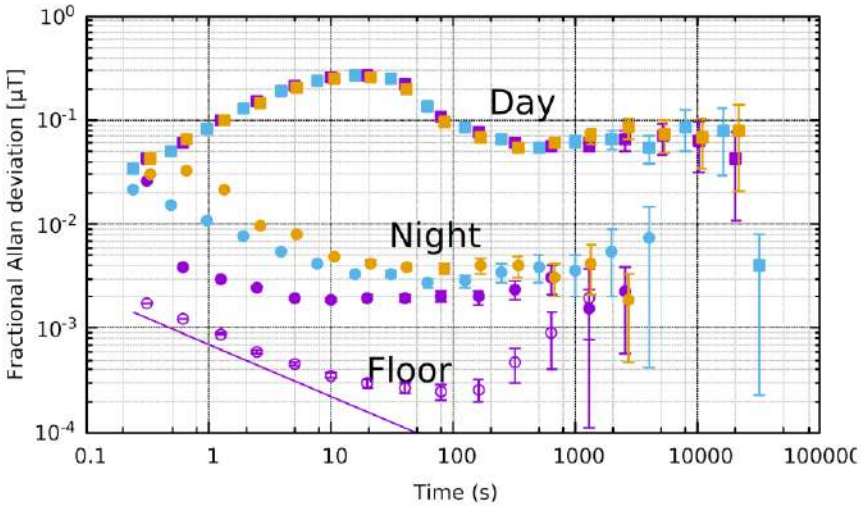
Example of perturbation: B-field of the Métro



⇨ Drastic change night/day



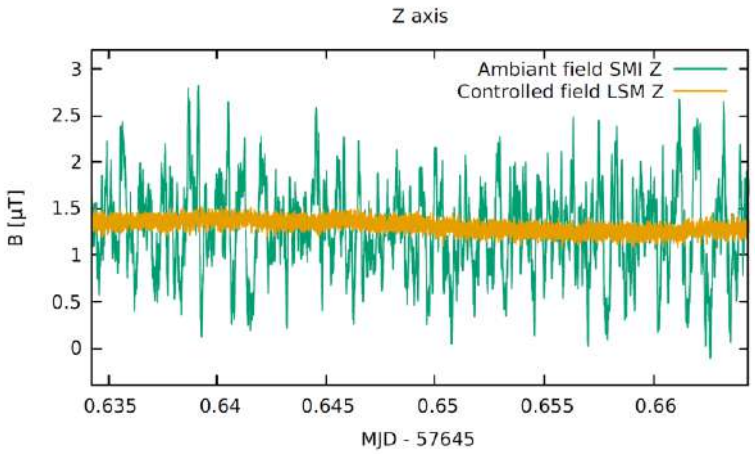
Example of perturbation: B-field of the Métro

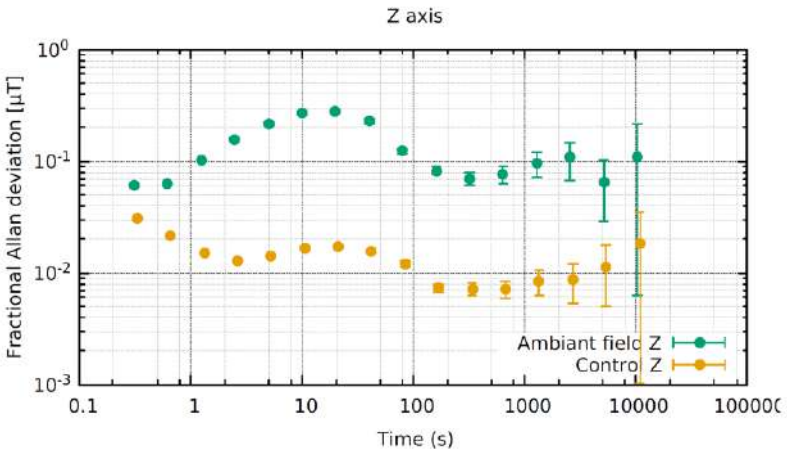


⇨ The frequency of the clock depends on the B-field!

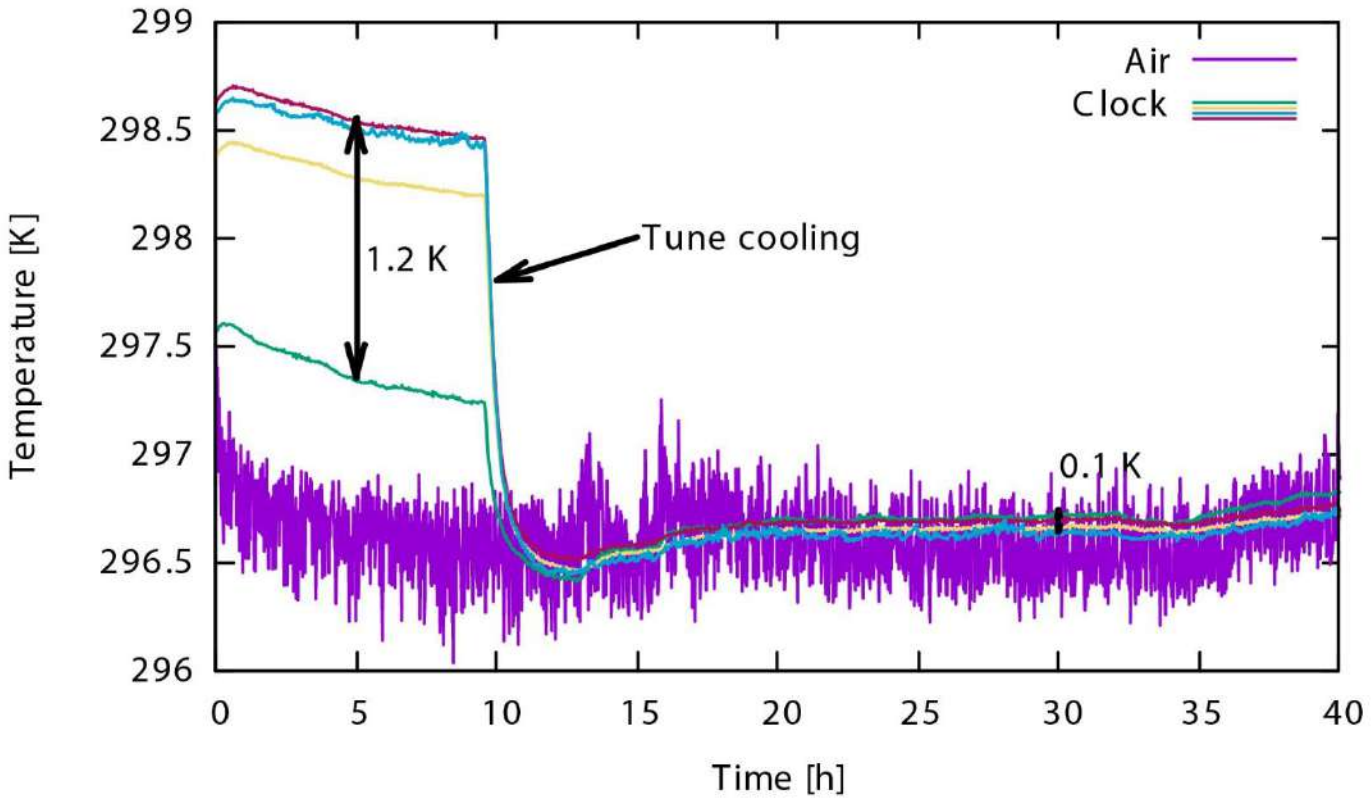
$$\nu = \nu_0 + \frac{\mu_B g_F m_F}{h} \boldsymbol{B} + \gamma \boldsymbol{B^2}$$

⇨ Flux gate magnetometer





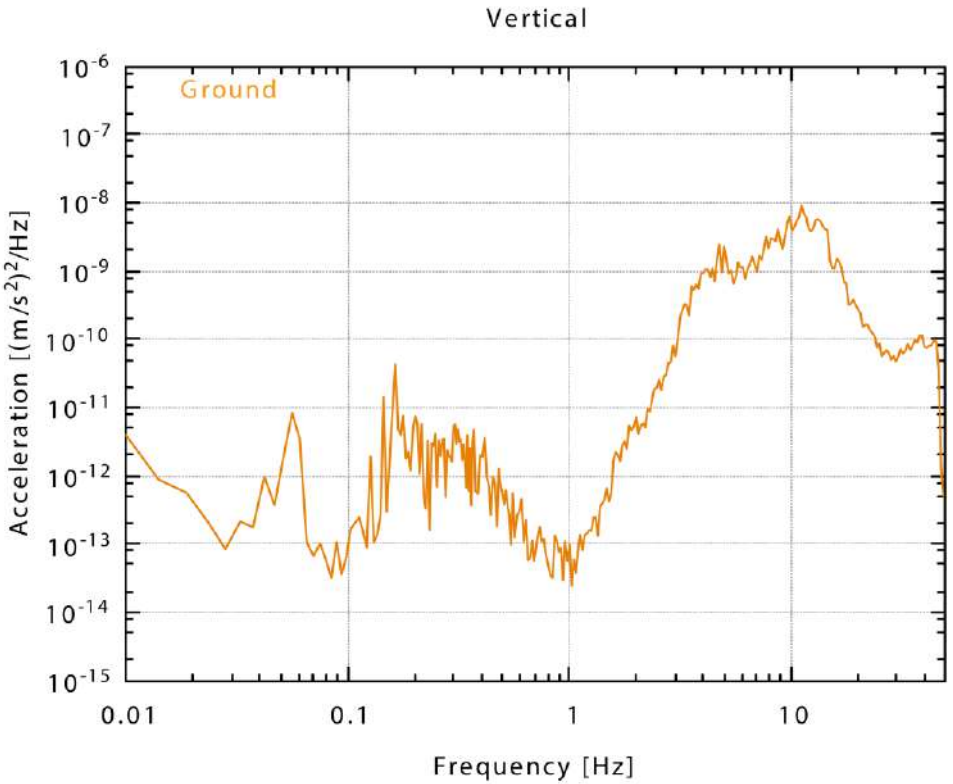
Effective temperature experienced by the atoms?

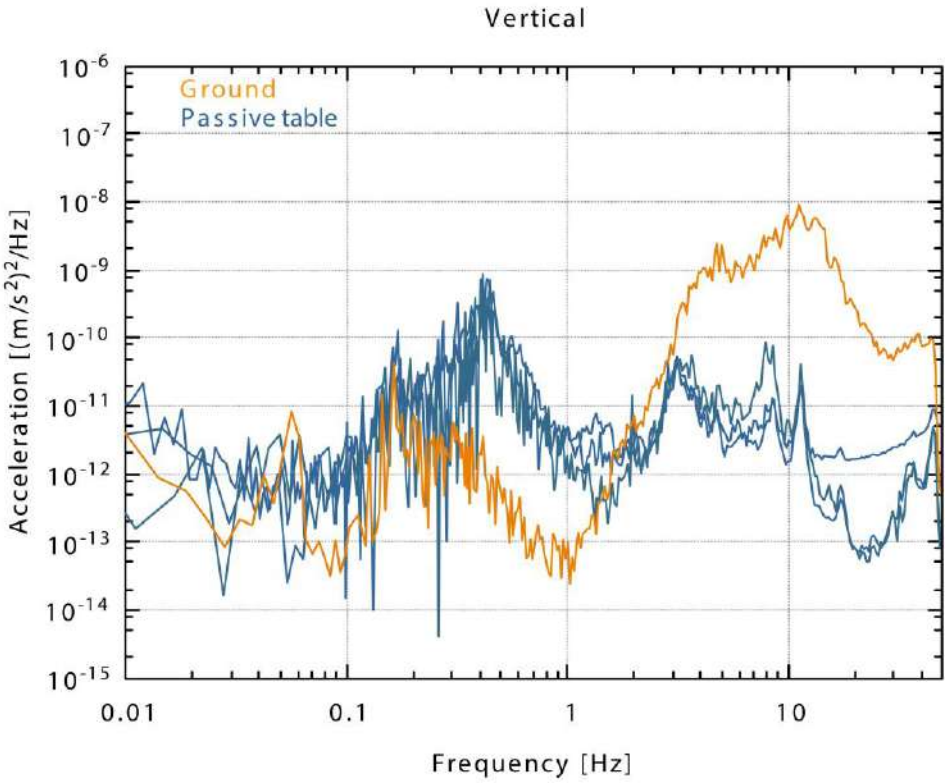


- Black body radiation shift: $\nu = \nu_0 + \sigma T^4$
- Necessity to either control or measure the temperature

More nasty details

- Vibrations of ground are perturbing the low frequency noise of the lasers
- Only solution: put the lasers on antivibration platforms





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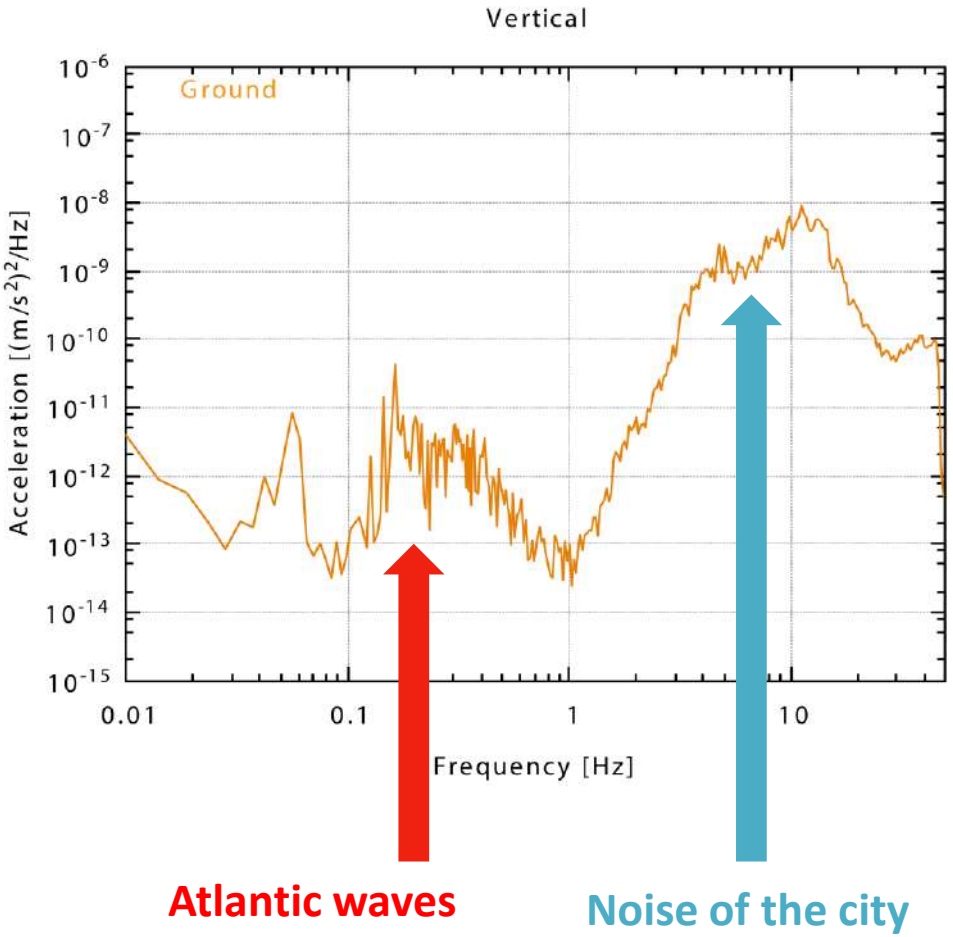
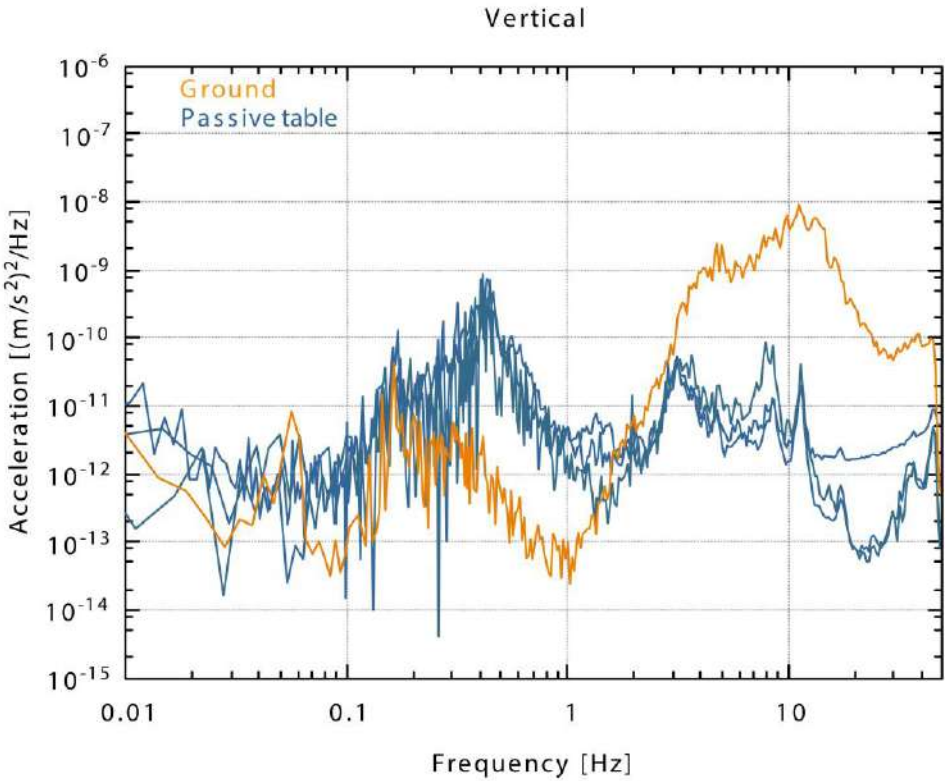
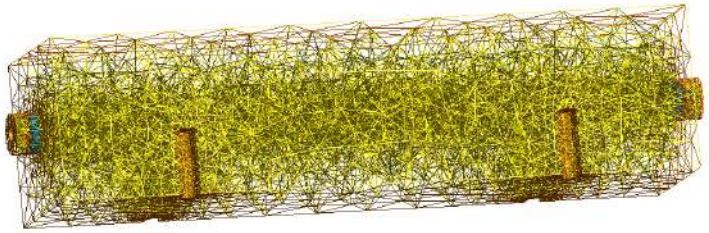
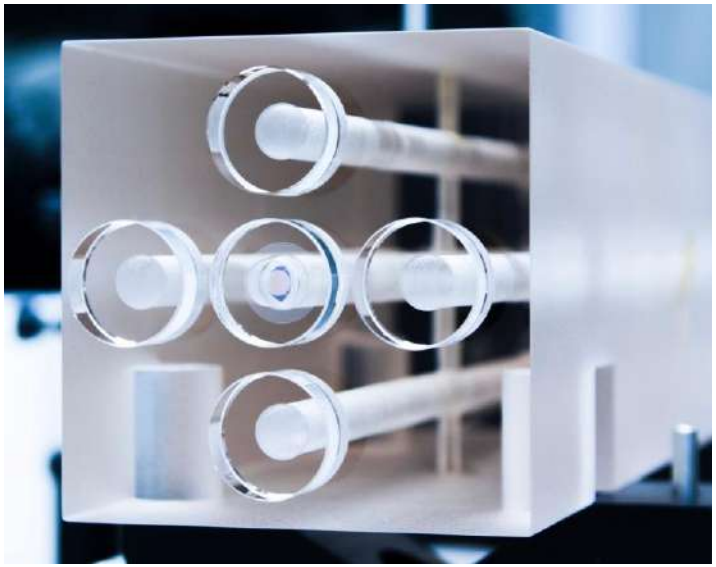




New technological development in ultrastable lasers



- Spectrally ultrapure lasers are required to perform the spectroscopy of the clock transition
- Best lasers in the world : linewidth of 10 mHz (@ 1542 nm)
- At SYRTE : development of a long cavity (40 cm long) @ 1542 nm, based on a new generation of coatings
- Stabilization assisted by seismometers



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The big picture: optical clocks network in Europe

Overview of ANR ROYMAGE (CES Technos Quantiques, 2021-2025)

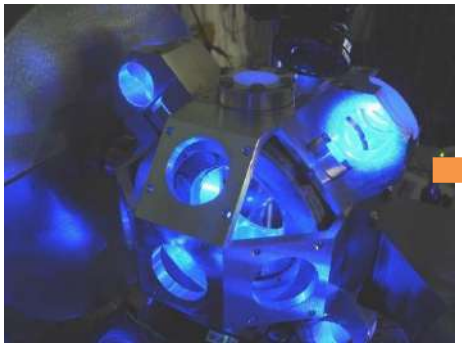
Consortium to apply
Optical atomic clocks to Earth Sciences

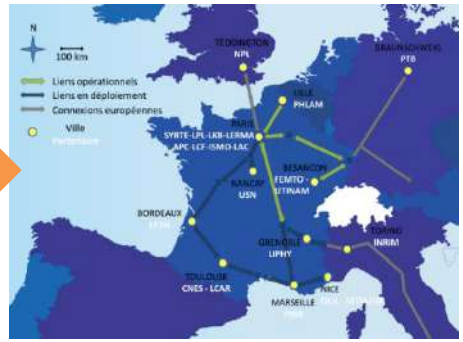
LNE-SYRTE
atomic clocks and international frequency dissemination by fiber networks

IPGP
geodetic reference frames, Earth gravity potential determination and geodynamics

SHOM
predicts evolution of the **physical marine environment**, disseminate the information

IGN/SGM
operational unit in charge of the realization, dissemination and maintaining of the **French geodetic reference**





Goals

Build a **transportable optical lattice clock** based on the $^1S_0$-$^3P_0$ transition of neutral Ytterbium 171

Connect it to the **REFIMEVE+ network** (~60 possible outputs over the French territory) and compare it to the ~12 European stationary optical clocks

Apply the measurements to assist **geoid determination** with atomic clocks data

Objectives of the Project

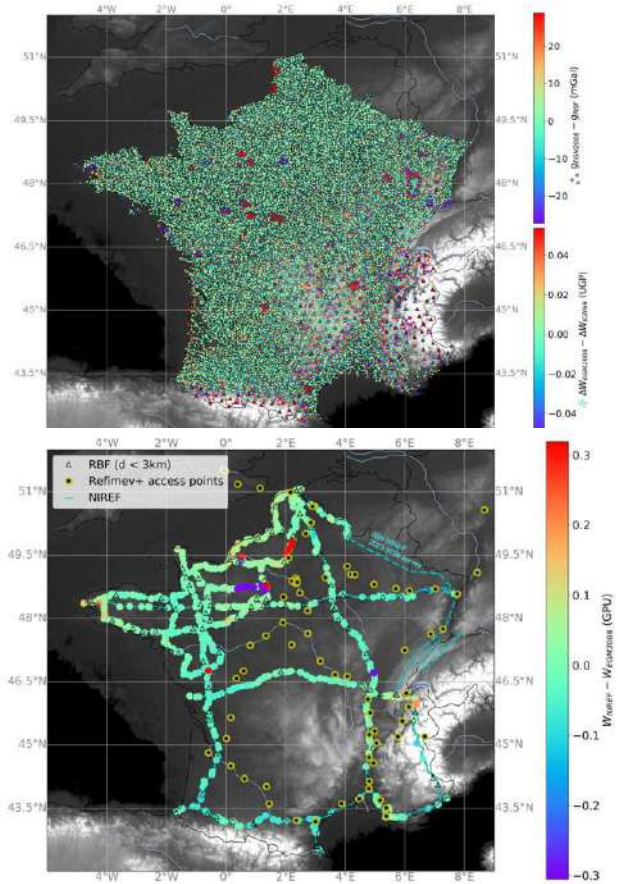
Objectives

Vertical Reference Frames

Geodynamic processes

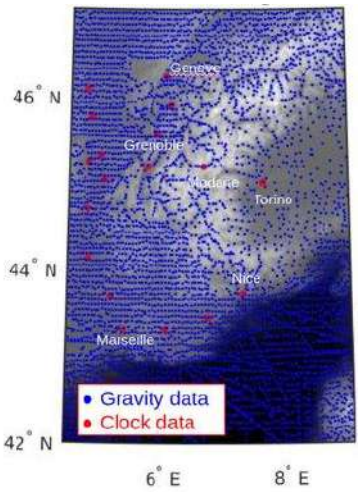
Geoid models in coastal areas

Towards the next definition of the second



- ⇨ Assess the quality of the French reference levelling network NIREF
  - ⇨ **Full scale test between SYRTE (Paris, F) and PTB (Braunschweig, D) +additional GPS surveys to densify links between satellites and ground measurements**
  - ⇨ **Medium resolution regional gravity modelling as complementary investigation tool (error modelling, synthetic experiments…)**
  - ⇨ **NIREF error model assessment**
- ⇨ Assess the future benefits from chronometric geodesy: cost benefit of clock measurements, synthetic and real data experiments

Other available data:
g @ ~ 1 000 locations
dN @ ~ 13 000 locations
- **Additional measurements:**
- GPS @ ~600 NIREF points
- High accuracy levelling tie between SYRTE and NIREF



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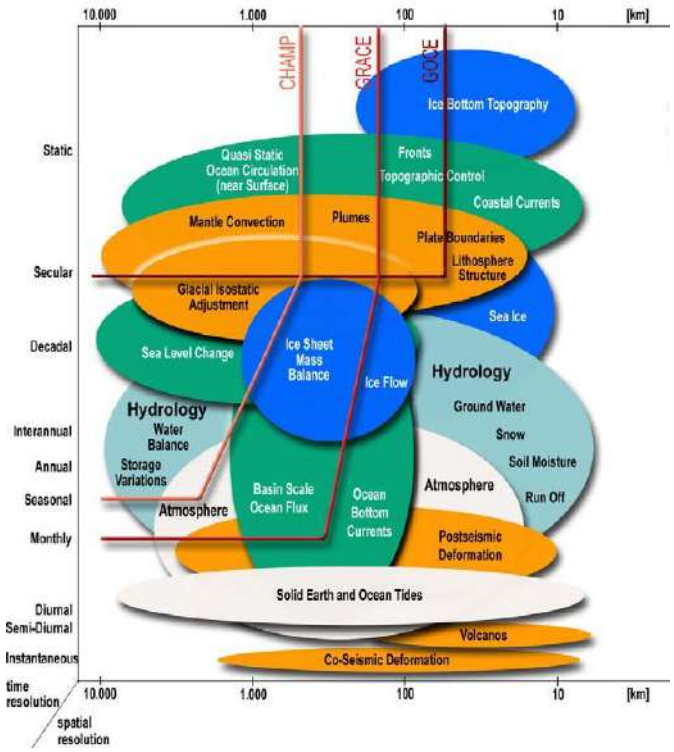
Vertical Reference Frames | **Geodynamic processes** | Geoid models in coastal areas | Towards the next definition of the second

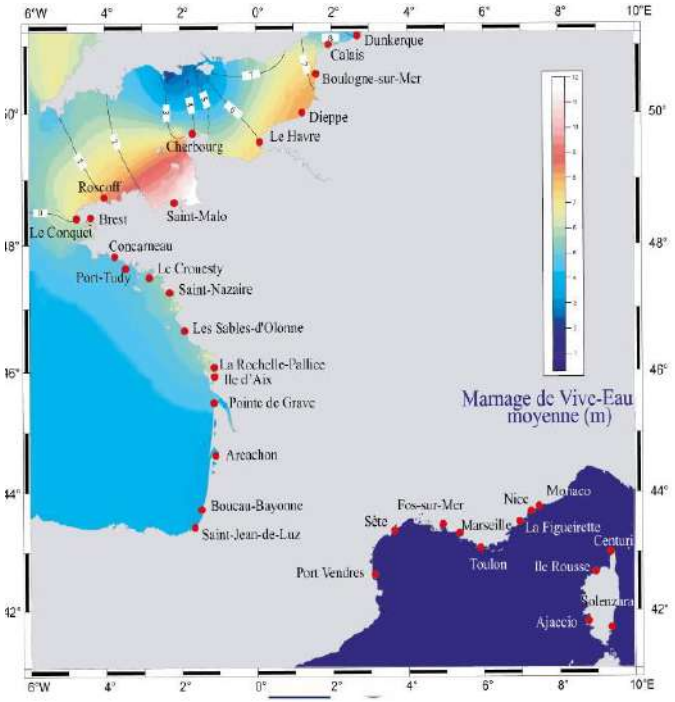


- ⇨ Assess the contribution of clock measurements for sensing large-scale temporal geopotential changes
- ⇨ Identify and model geodynamic signals for which clock data are interesting
- ⇨ Leads to explore: rise of the sea level, early signs of brutal events (earthquakes, tsunamis)

Objectives of the Project

Objectives

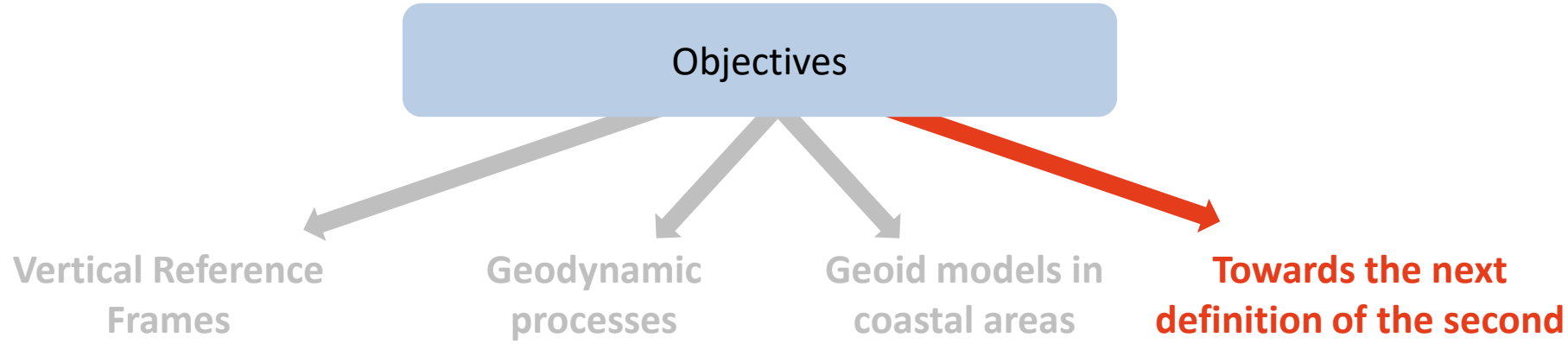
Vertical Reference Frames | Geodynamic processes | **Geoid models in coastal areas** | Towards the next definition of the second



- ⇨ Existing network of tide gauges to measure the height of the tides
- ⇨ But: loading effects have been shown to lead to periodic height variations of almost 20 cm at high tides in Brest
- ⇨ quantum measurements close to the coasts, to study and better connect terrestrial and marine vertical references: measuring geopotential variations in the vicinity of tide gauges will allow to disentangle motion of the gauges and sea level rise.

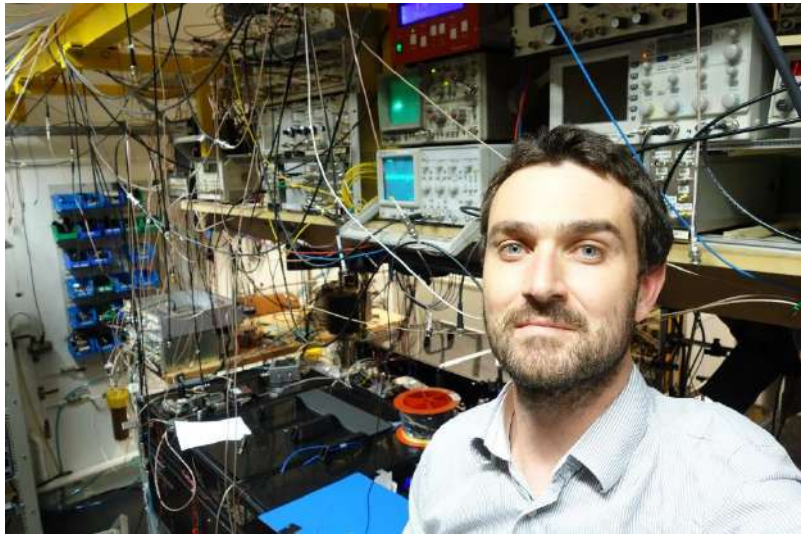
Gravimetric control (gravimeters) + potential measurements (clock)

Objectives of the Project



- Test of Fundamental Physics (Lorentz invariance, drift of fundamental constants, search for Dark matter …)
- Accurate geoid determination: prerequisite to a new definition of the second
- Participate to the frequent European campaigns to assess the reliability of the next possible primary and secondary representations of the second (Sr, Hg, Yb, Yb+, Al+ …)

The ROYMAGEs



PI @ SYRTE:
Rodolphe Le Targat

Scientific responsible @ IPGP:
Guillaume Lion

Scientific responsible @ SHOM:
Marie-Françoise Lalancette

Scientific responsible @ IGN:
Olivier Jamet

The SYRTE Team

The Ytterbium Team, left to right: Angélique Lartaux, William Moreno, Fatima Rahmouni, Jérôme Lodewyck, Jesús Romero González, Benjamin Pointard, Rodolphe Le Targat

Theory @ SYRTE: Pacôme Delva and colleagues

Liens optiques fibrés @ SYRTE: Paul-Eric Pottie and colleagues

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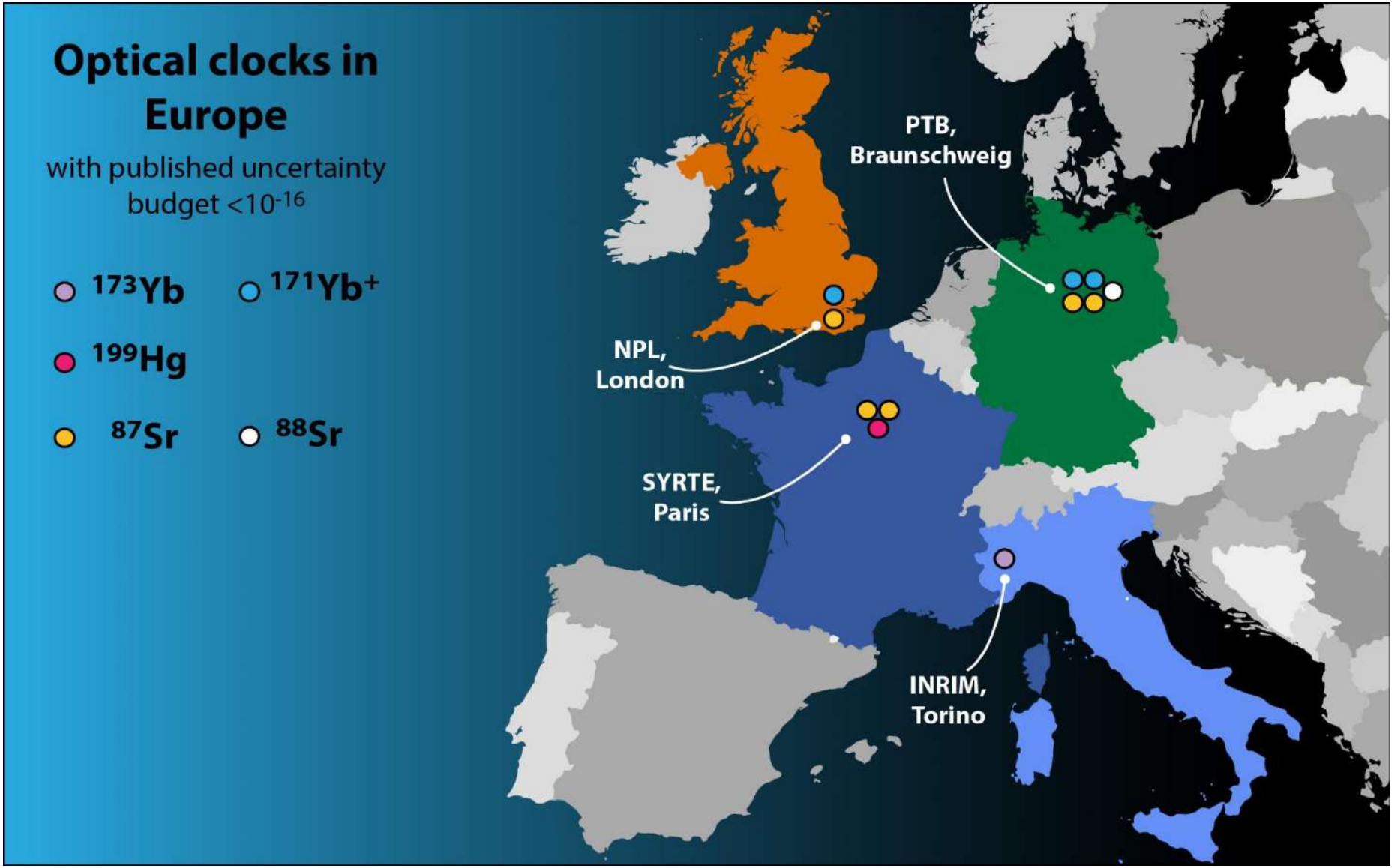
Optical clocks in Europe
with published uncertainty budget <10-16
173Yb
171Yb+
199Hg
87Sr
88Sr
PTB, Braunschweig
NPL, London
SYRTE, Paris
INRIM, Torino

The keystone: the REFIMEVE+ network (Equipex, PIA)