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INSTITUT NATIONAL
DE L'INFORMATION
GÉOGRAPHIQUE
ET FORESTIÈRE

Institut national de l'information géographique et forestière
EUREF 2026 - Tutorial

ATOMIC CLOCKS APPLICATION AT IGN FRANCE

EUREF 2026 Symposium
Paris

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Univ Gustave Eiffel, Géodata Paris, IGN France

*(**) IGN France, Service of Geodesy and Metrology*

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SUMMARY

Physical heights – a potential story

Why chronogeodesy ?

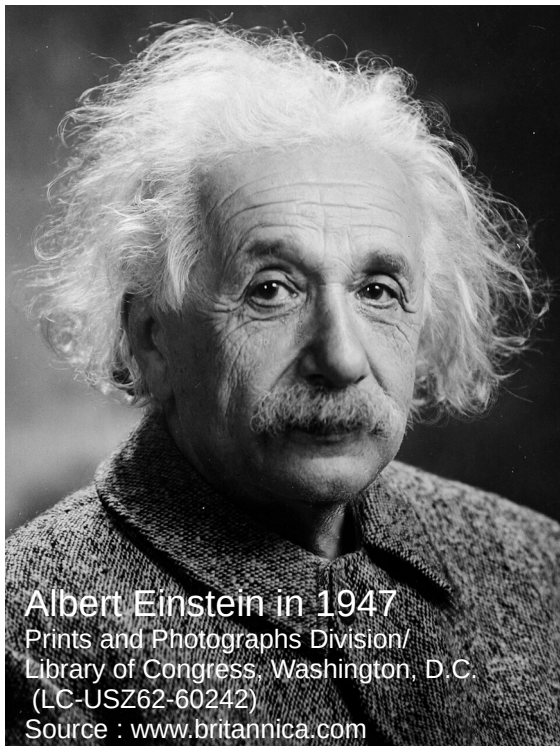
Application to levelling

Application to vertical reference surface modeling

Current work and perspectives at IGN France

Conclusion

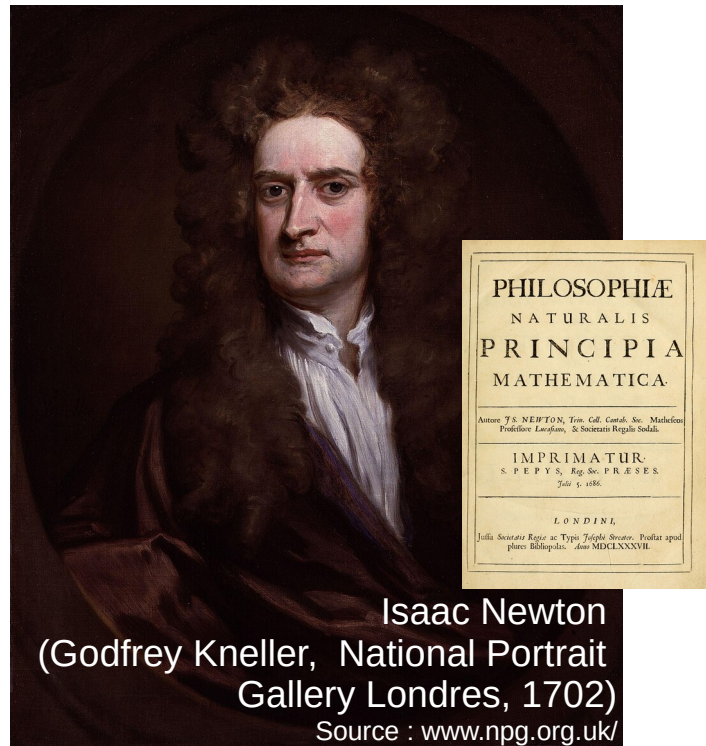
BACK TO NEWTON'S PHYSICS (1687)



Albert Einstein in 1947
Prints and Photographs Division/
Library of Congress, Washington, D.C.
(LC-USZ62-60242)
Source : www.britannica.com

Time:
Relative accuracy
 10^{-16} to 10^{-18}

Space:
Relative accuracy
 10^{-5} to 10^{-9}

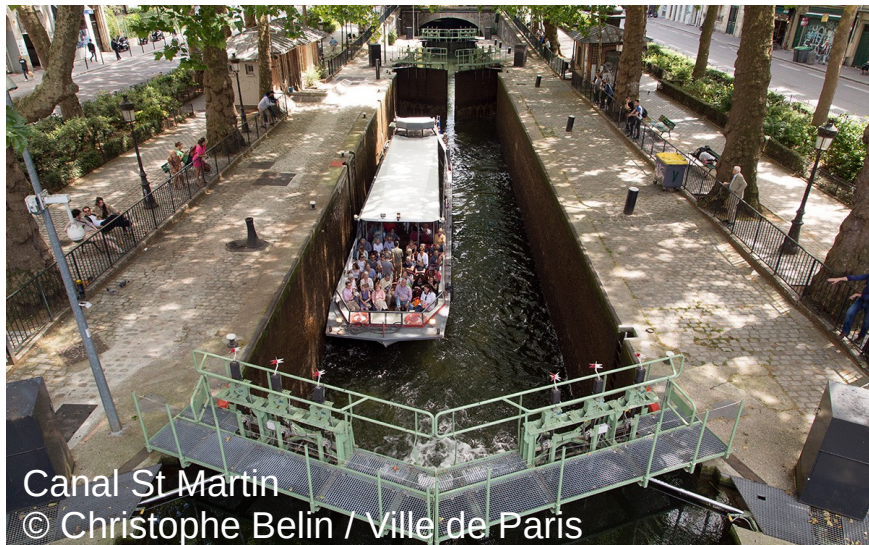


Isaac Newton
(Godfrey Kneller, National Portrait
Gallery Londres, 1702)
Source : www.npg.org.uk/

UNIVERSAL GRAVITATION governs our daily life



UNIVERSAL GRAVITATION governs our daily life



90°



60°N

PHYSICAL HORIZONTAL SURFACE can be observed from space

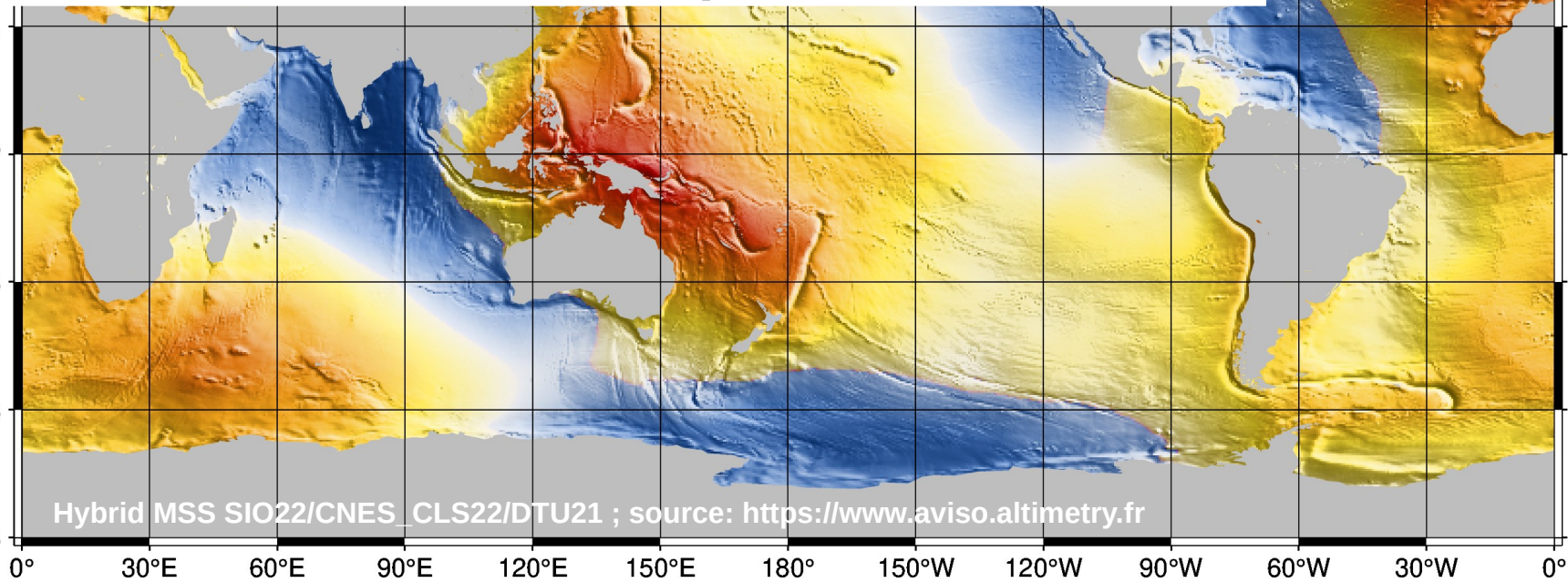
30°N

0°

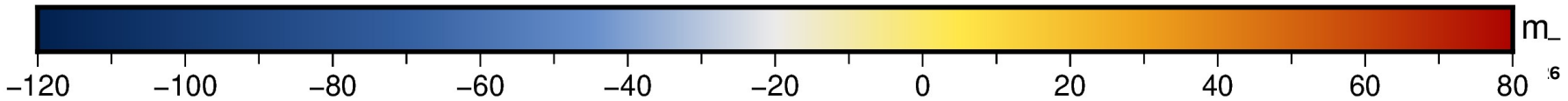
30°S

60°S

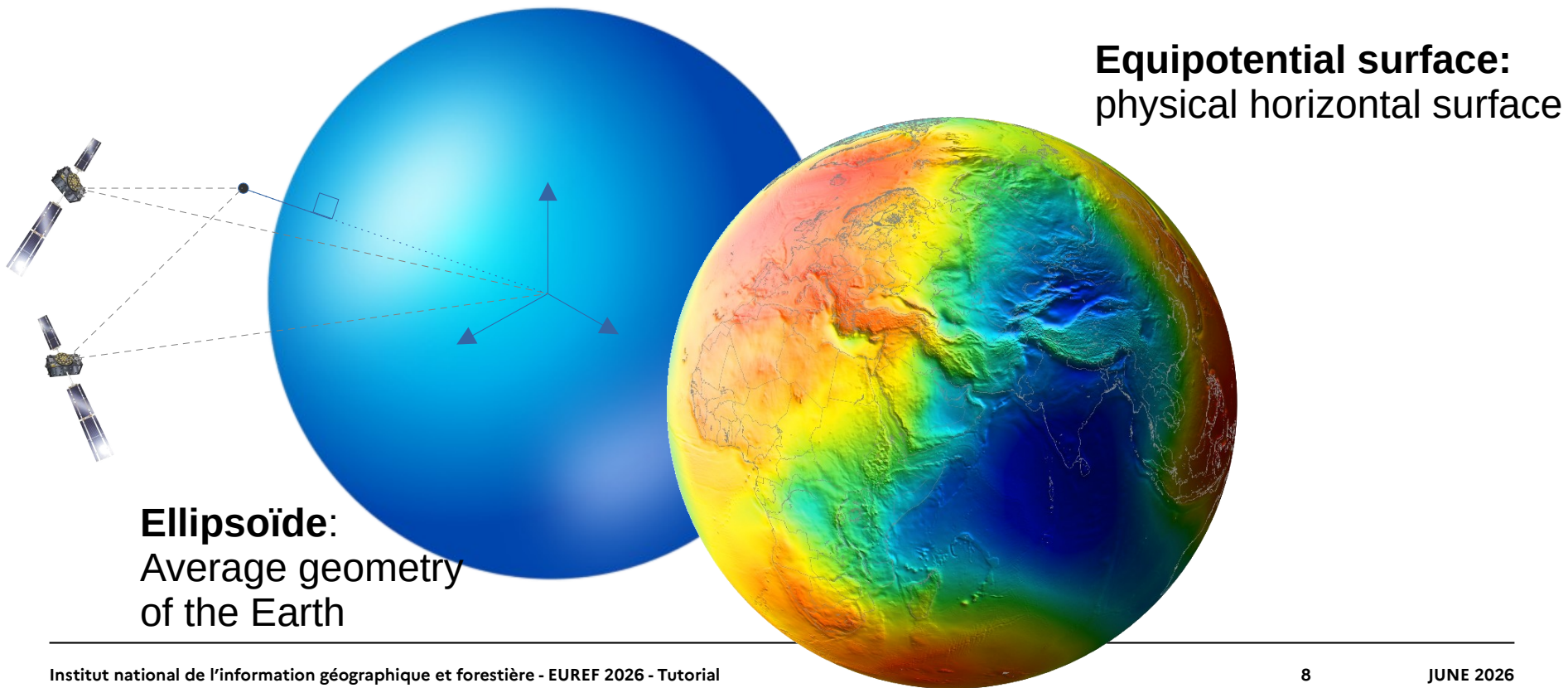
90°S



Hybrid MSS SIO22/CNES_CLS22/DTU21 ; source: <https://www.aviso.altimetry.fr>

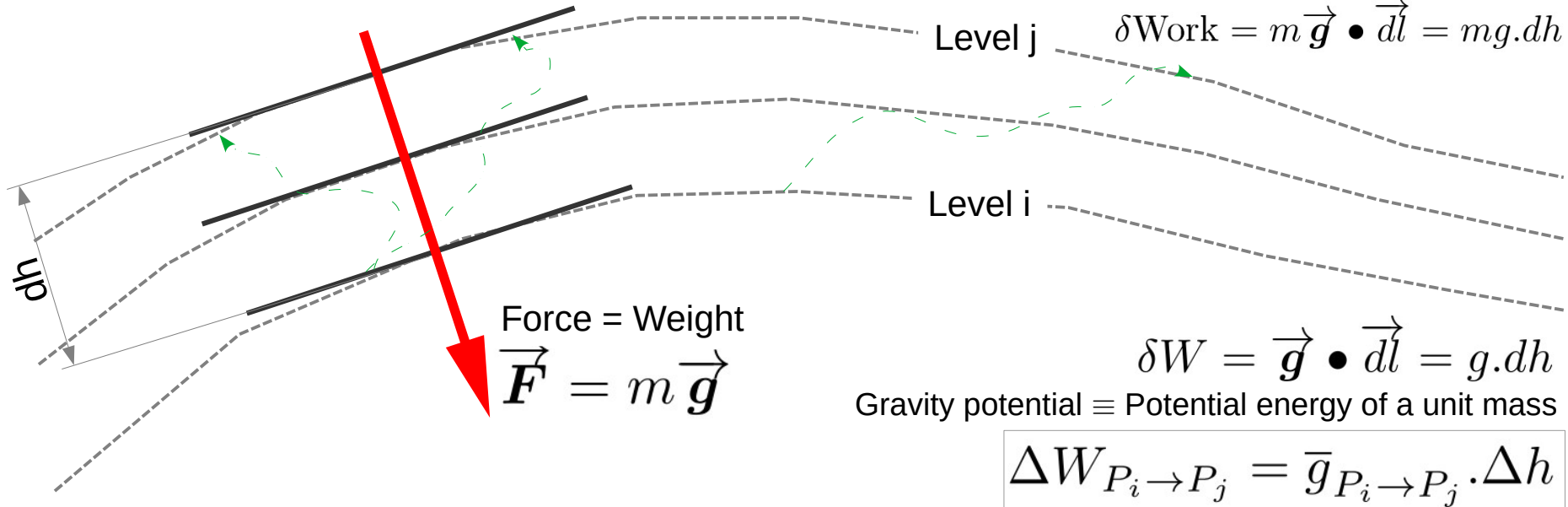


GEOMETRIC HEIGHTS vs PHYSICAL HEIGHTS

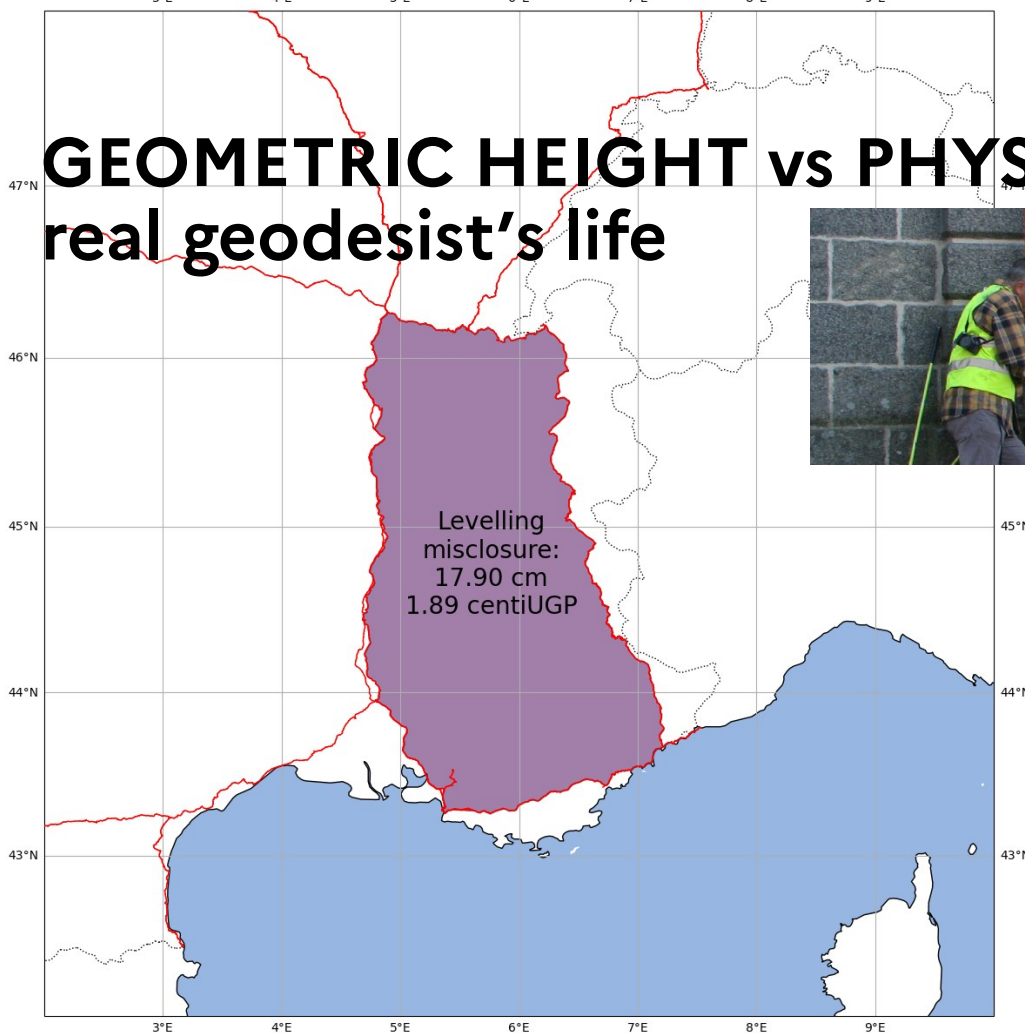


HORIZONTAL SURFACES of the gravity field

Let's drop a piece of physics into it



GEOMETRIC HEIGHT vs PHYSICAL HEIGHT in the real geodesist's life



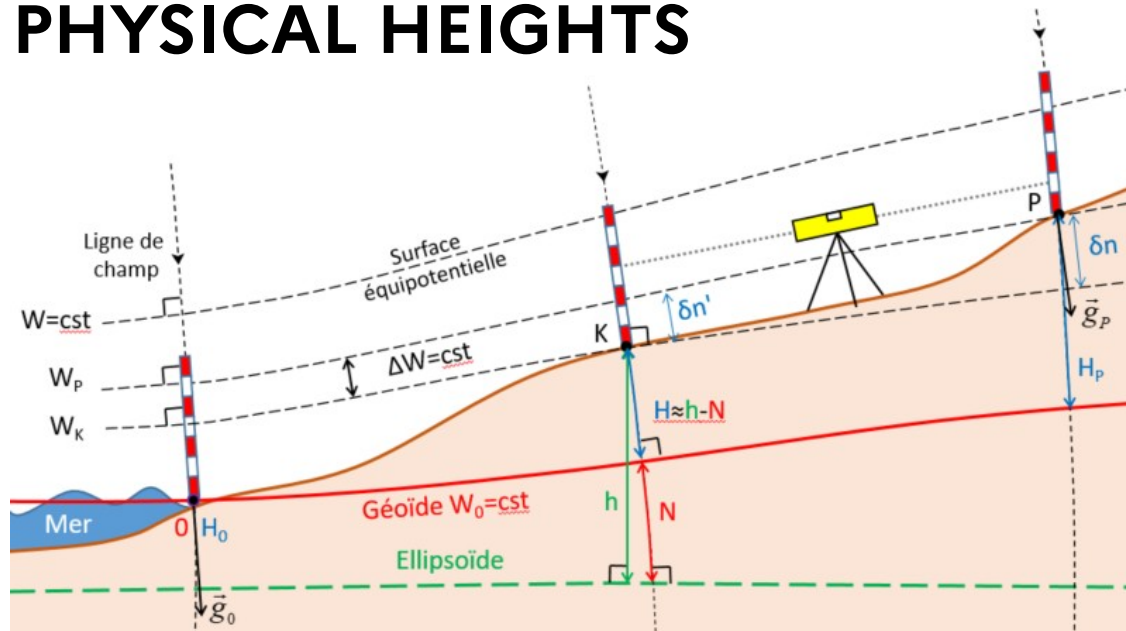
Source : <https://geodesie.ign.fr>, © SGM

Loop length: ~ 1200 km

Geometric misclosure: 17.9 cm

ΔW misclosure: $0.189 \text{ m}^2\text{s}^{-2}$
(~ 1.8 cm)

PHYSICAL HEIGHTS



h: ellipsoïdal height (GNSS)
N: géoïd (equipotential surface)
H: conventional physical height

$$\Delta W = g \cdot \Delta h$$

$$H_P = \frac{W_P - \underbrace{W_0}_{\text{Origin}}}{\underbrace{\bar{\gamma}}_{\text{Average gravity}}}$$

Reference surface

$$N = H_P - h_P$$

Physical heights
Physical reference surface } $\propto \Delta W$

WHY CHRONOGEODESY ?

LET'S RETURN TO EINSTEIN'S PHYSICS (1915)

What about clocks ?

Physical heights $\propto \Delta W$

First post-newtonian approximation (*)

$$\frac{\Delta f}{f_0} = \frac{f_0 - f_P}{f_0} = \frac{\Delta W}{c^2} = \frac{W_0 - W_P}{c^2} + o(c^{-4})$$

Gravity potential

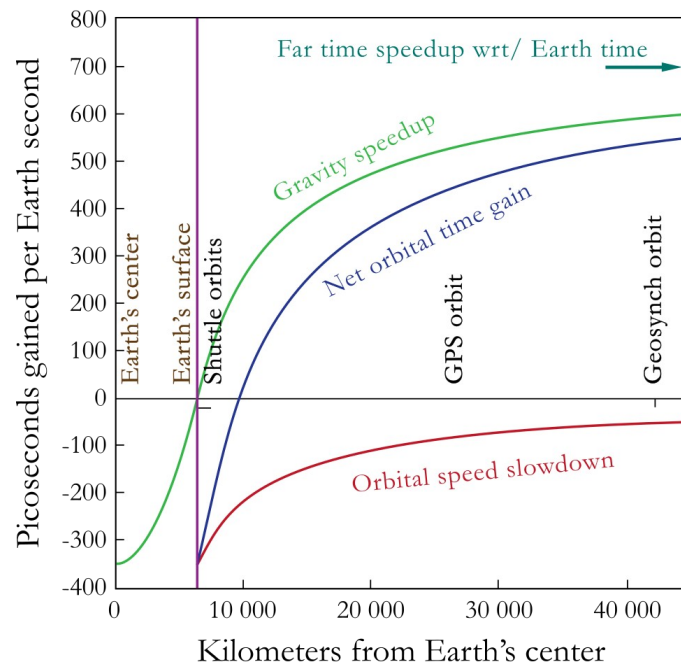
Clock frequency

(*) See Denker et al. (2017)

Doi:10.1007/s00190-017-1075-1

$$\begin{array}{lcl} 0.1 \text{ m}^2\text{s}^{-2} & \approx & 10^{-18} \\ 1 \text{ cm} & \approx & \end{array}$$

Time Dilation Effects on Earth



© P. Fraundorf, source wikimedia commun

RETURN TO EINSTEIN'S PHYSICS (1915)

What about clocks ?

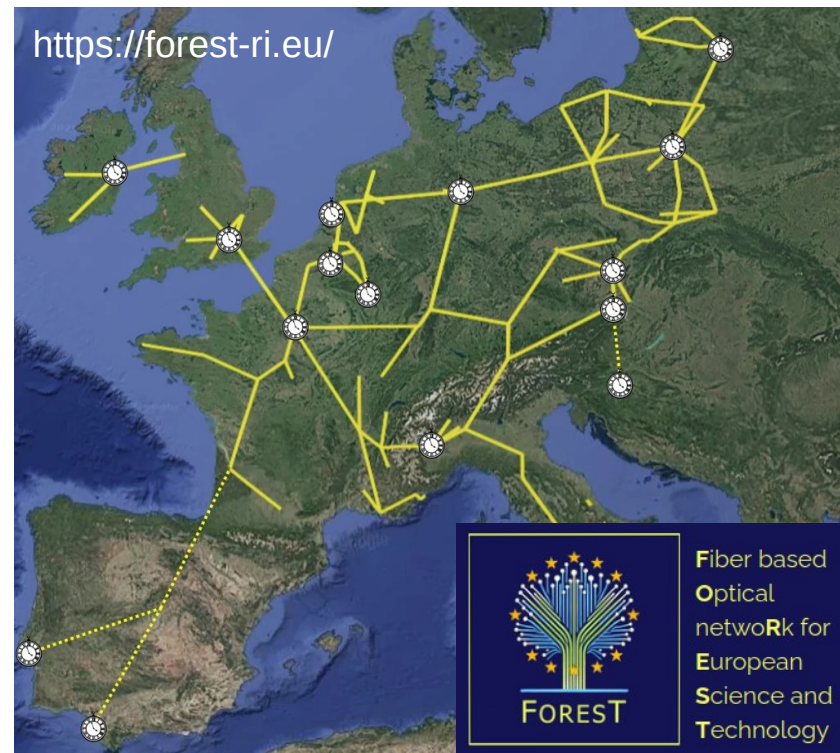
Physical heights $\propto \Delta W$

First post-newtonian
approximation (*)

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Doi:10.1007/s00190-017-1075-1



RETURN TO EINSTEIN'S PHYSICS (1915)

What about clocks ?

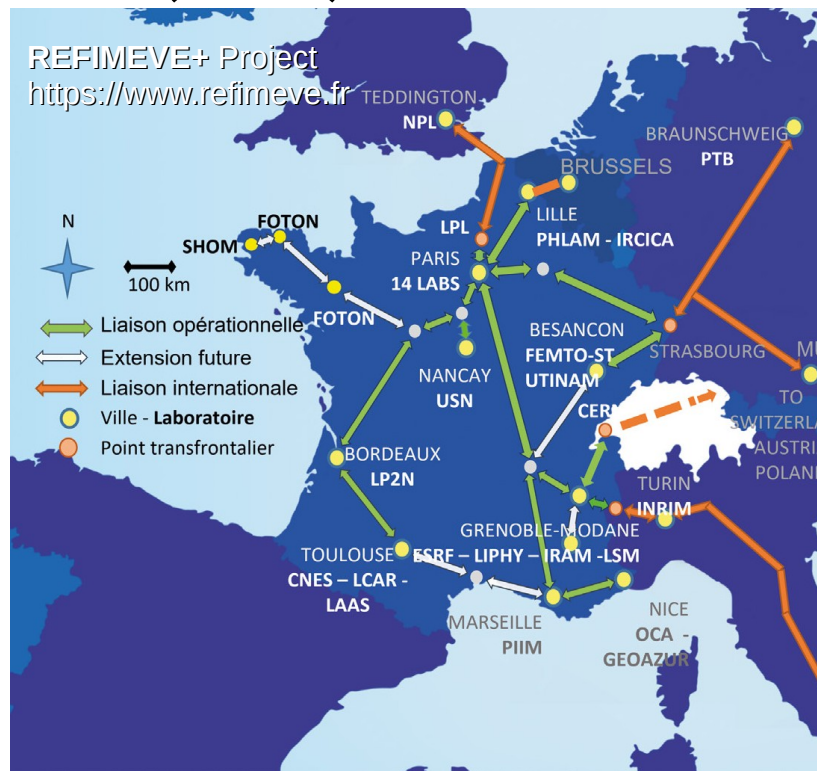
Physical heights $\propto \Delta W$

First post-newtonian
approximation (*)

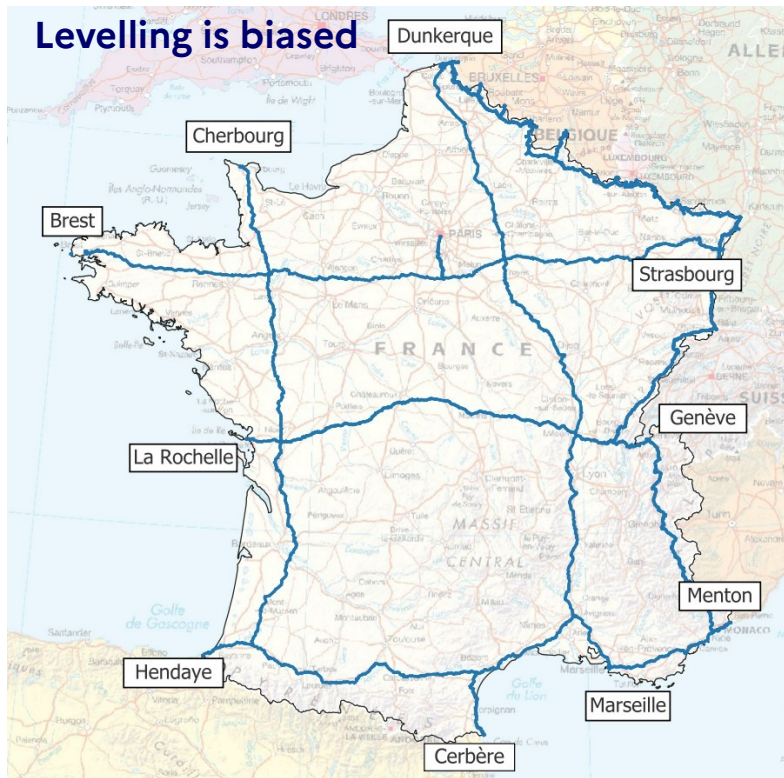
$$\frac{\Delta f}{f_0} = \frac{f_0 - f_P}{f_0} = \frac{\Delta W}{c^2} = \frac{W_0 - W_P}{c^2} + o(c^{-4})$$

(*) See Denker et al. (2017)

Doi:10.1007/s00190-017-1075-1



APPLICATION TO LEVELLING



NIREF: *Nivellement de référence*
(reference levelling –
part of the French contribution to EULN/EVRF)

Cautious measurement protocol

Precision $0.8 \text{ mm} / \sqrt{\text{km}}$

Cf. Conferences by
T. Bauer or J. Schwabe
on wed. PM



© SGM

APPLICATION TO LEVELLING

Levelling is biased

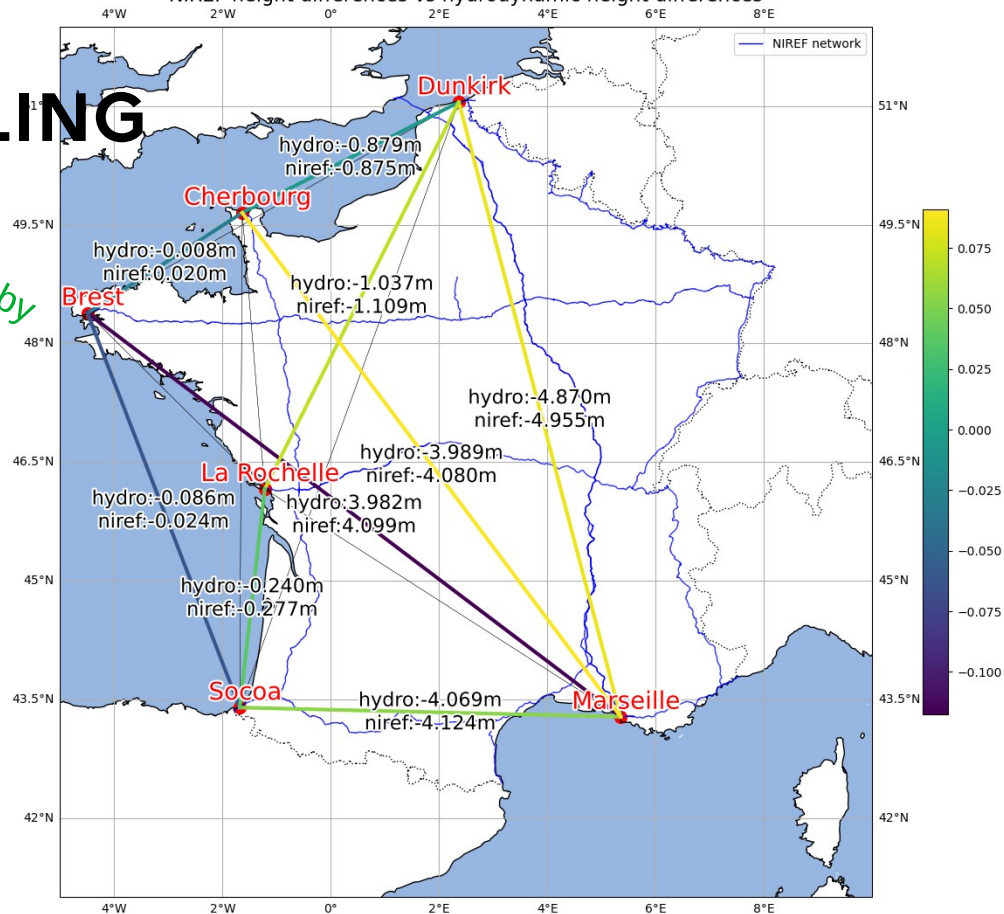
ΔH (Physical heights)
comparison:

- NIREF adjusted network
- VS.
- Hydrodynamic heights differences (HHD)

*Cf. Conferences by
J. Chenal
on thurs. PM*

Baseline	NIREF	HHD	Discrepancy
Dunkirk - Cherbourg	87.5 cm	87.9 cm	0.4 cm
Brest - Cherbourg	2.0 cm	-0.8 cm	2.8 cm
Socoa - Brest	2.4 cm	8.6 cm	6.2 cm
Dunkirk - La Rochelle	110.9 cm	103.7 cm	7.2 cm
Socoa - La Rochelle	27.7 cm	24.0 cm	3.7 cm

NIREF height differences vs hydrodynamic height differences



APPLICATION TO LEVELLING

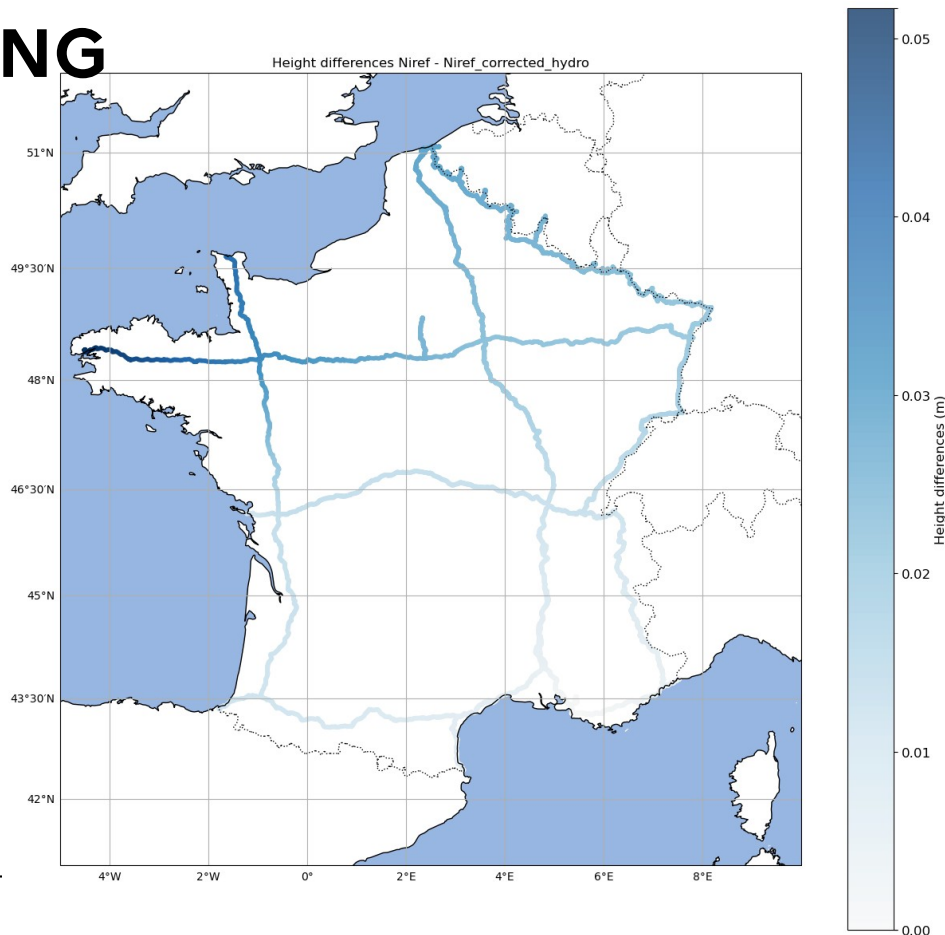
Effect of long range measurements on levelling

Experiment:

NIREF network adjustment

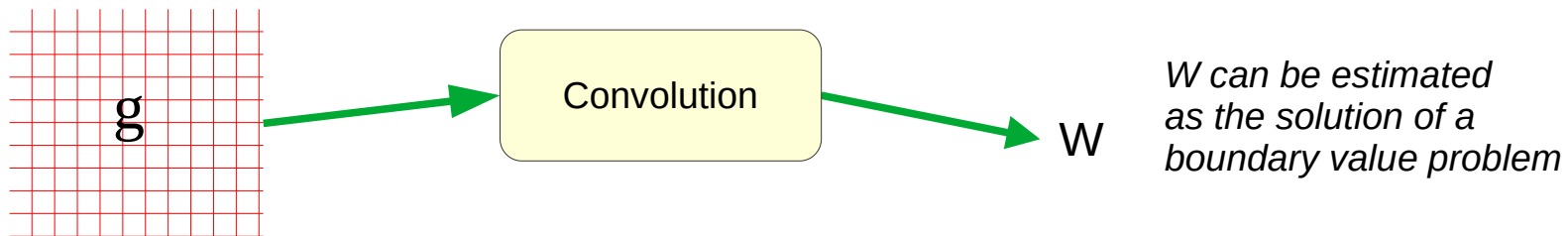
VS.

**NIREF + Hydrodynamic heights
network adjustment**



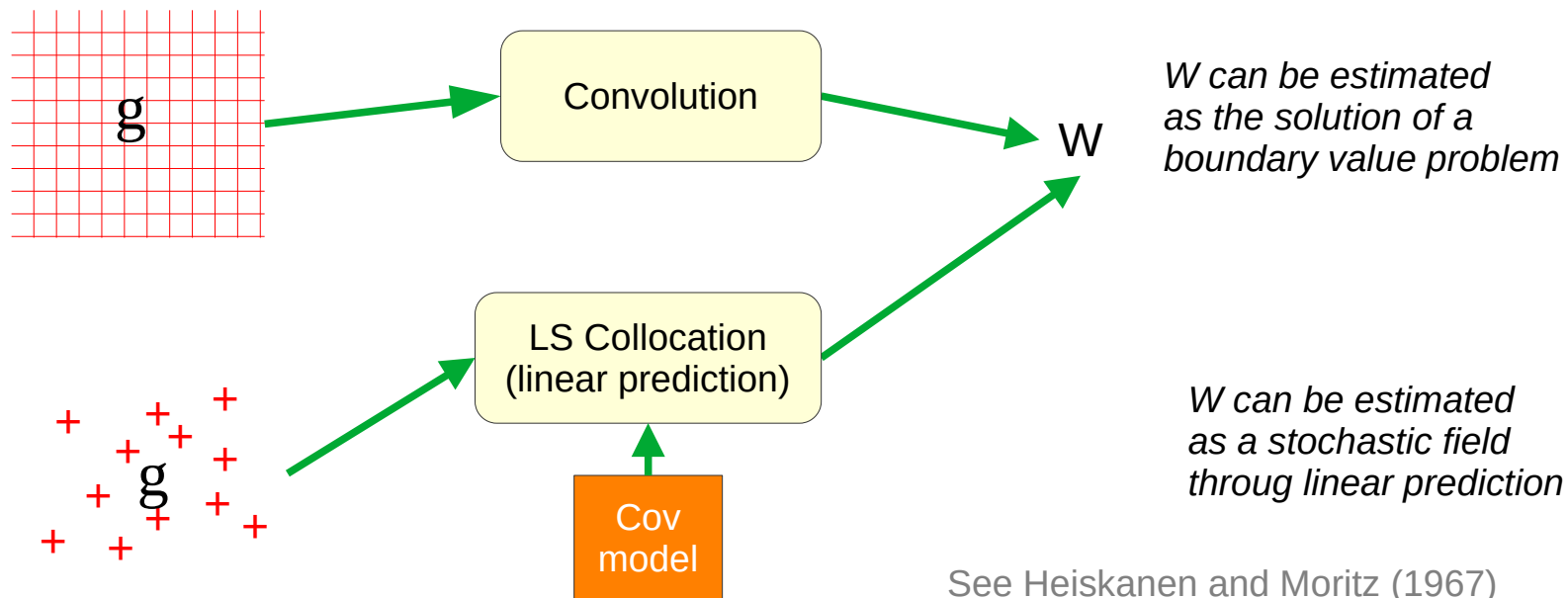
APPLICATION TO REFERENCE SURFACE COMPUTATION

Background: W is a 3D scalar field obeying Laplace equation outside the sources $\Delta W = 0$



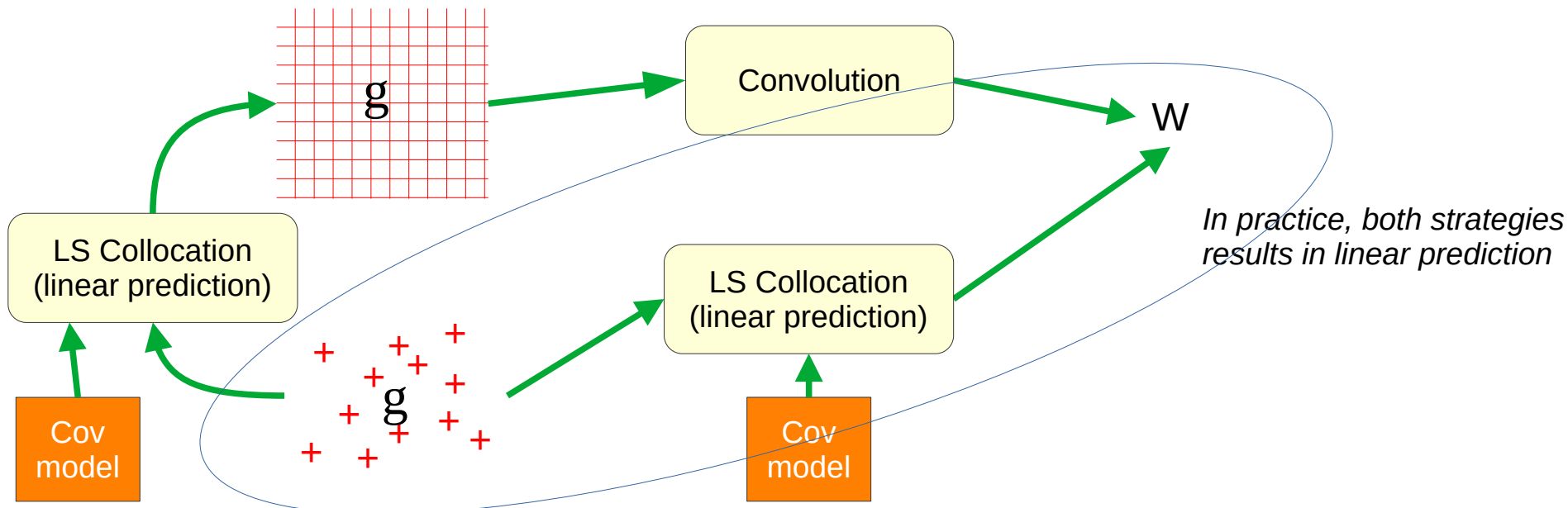
APPLICATION TO REFERENCE SURFACE COMPUTATION

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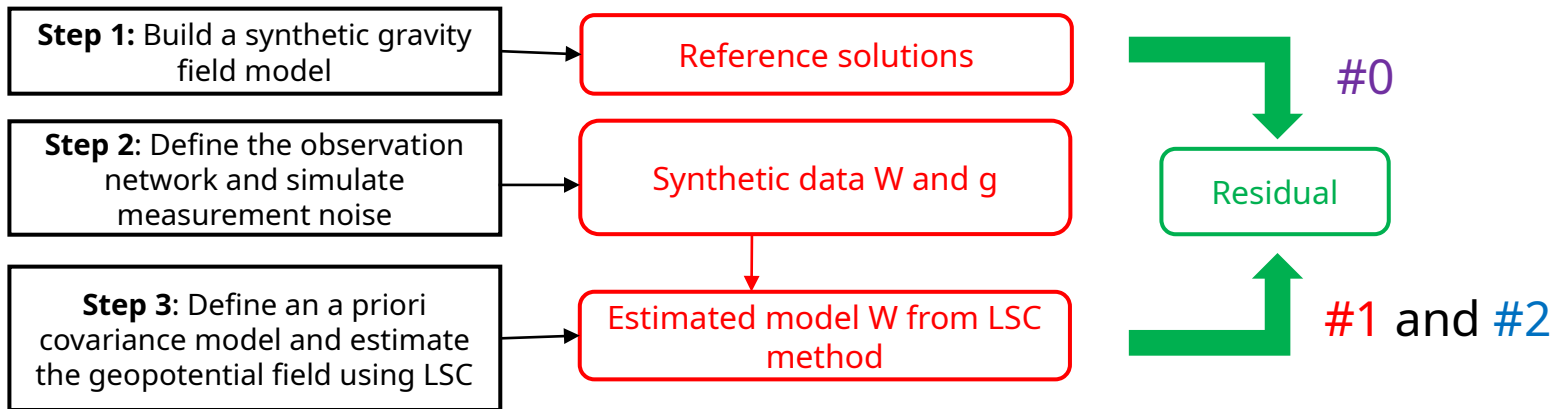
APPLICATION TO REFERENCE SURFACE COMPUTATION

Background: W is a 3D scalar field obeying Laplace equation outside the sources $\Delta W = 0$



APPLICATION TO REFERENCE SURFACE COMPUTATION

Testing conditions



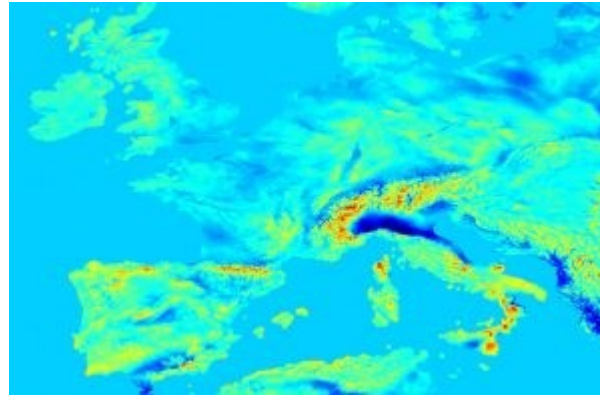
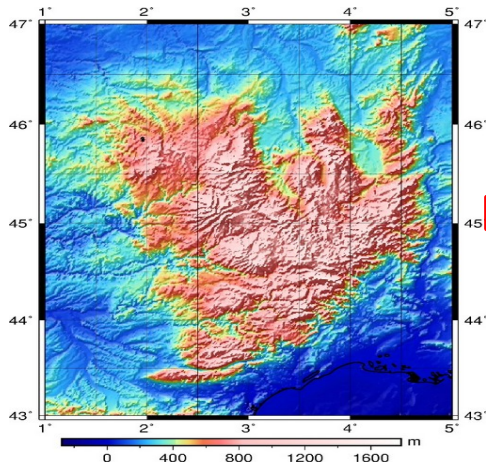
Assess the contribution of clock observations by comparing solutions #1 and #2 wrt a reference solution #0

- #1: only from gravity data
- #2: from gravity and potential data

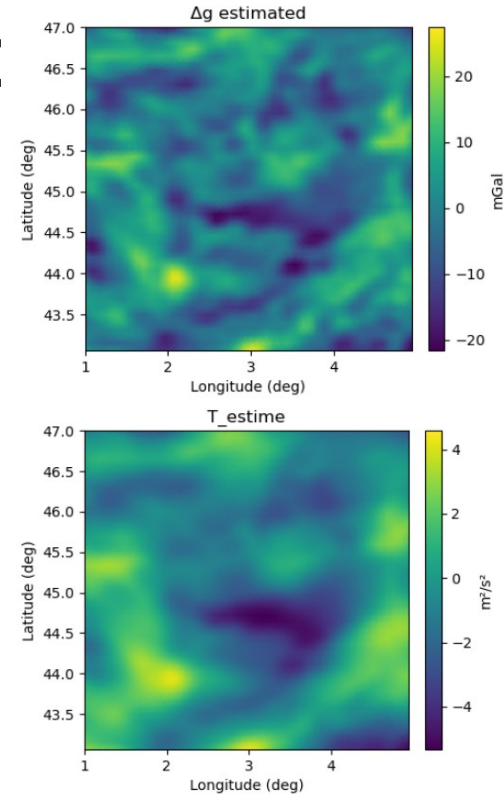
See Lion et al. (2017)
Doi: 10.1007/s00190-016-0986-6

APPLICATION TO REFERENCE SURFACE COMPUTATION

Synthetic data



Global gravity model

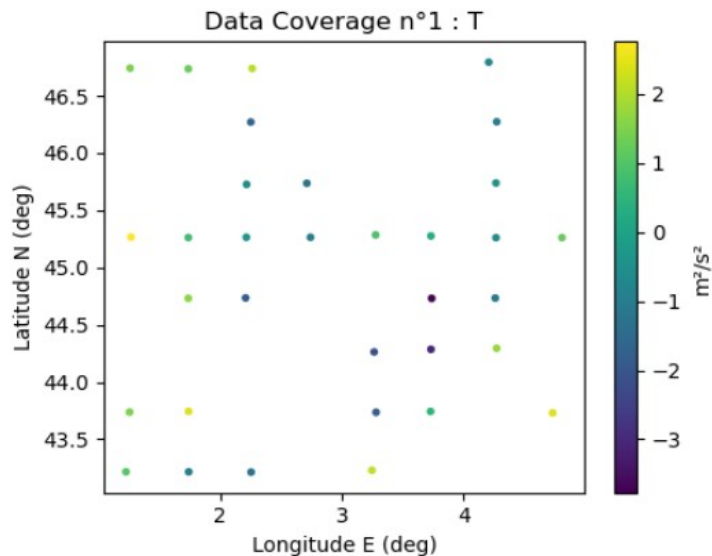


See Lion et al. (2017)

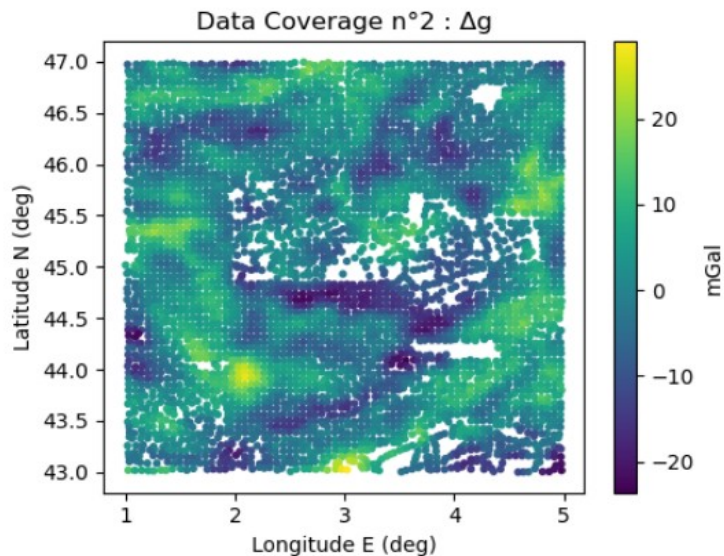
Doi: 10.1007/s00190-016-0986-6

APPLICATION TO REFERENCE SURFACE COMPUTATION

Synthetic measurement coverage



W

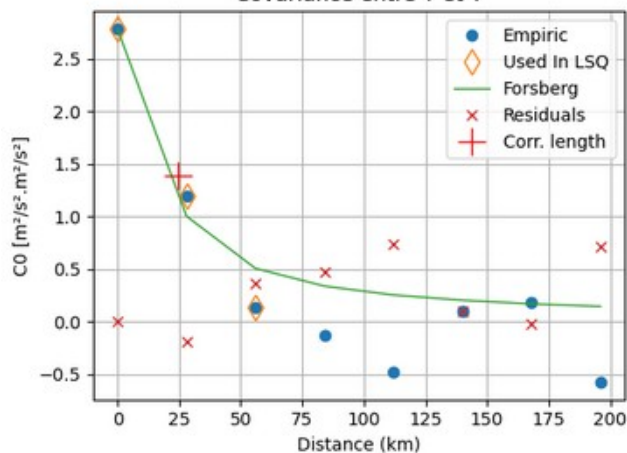


See Lion et al. (2017)
Doi: 10.1007/s00190-016-0986-6

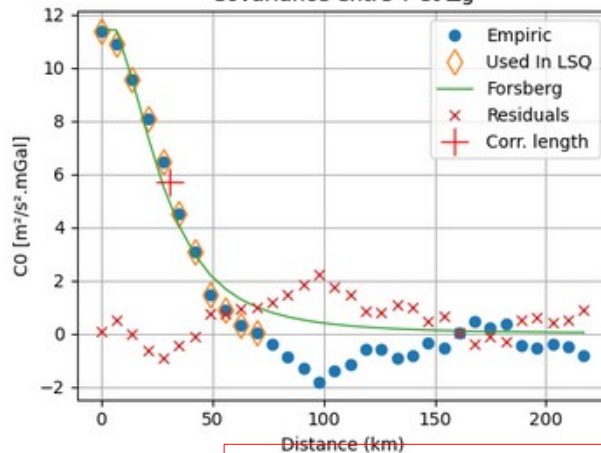
APPLICATION TO REFERENCE SURFACE COMPUTATION

Covariance model adjustment

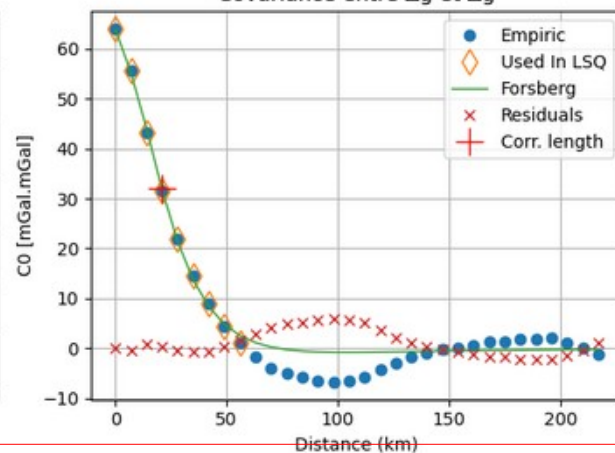
Covariance entre T et T



Covariance entre T et Δg



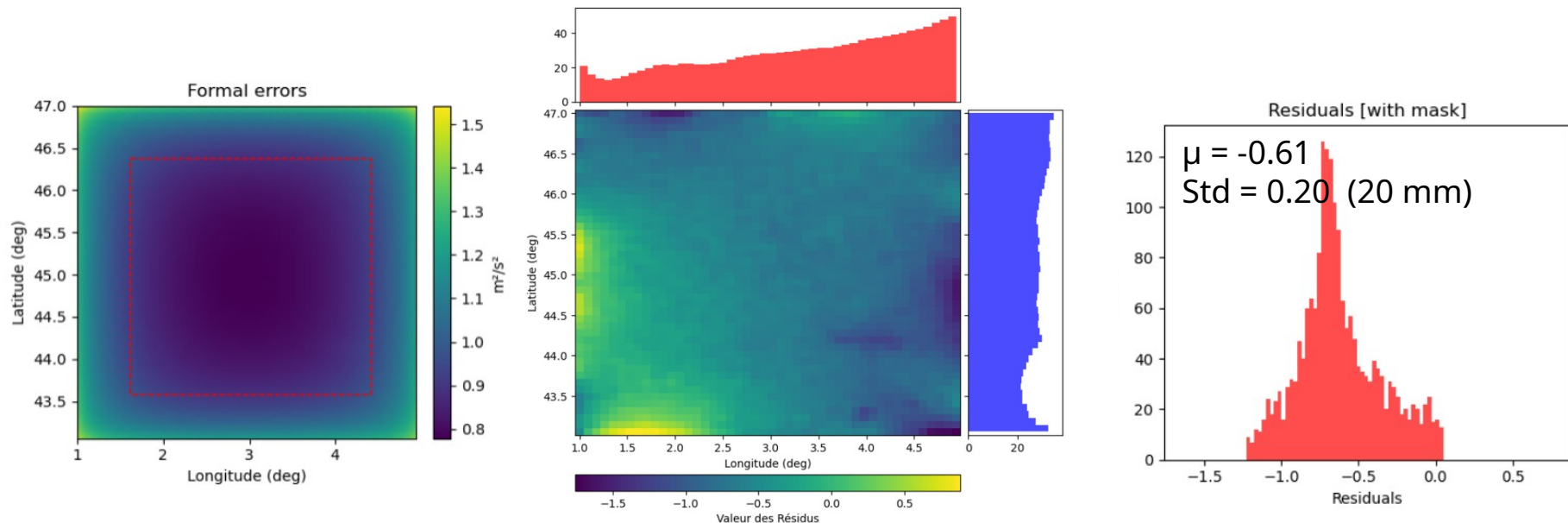
Covariance entre Δg et Δg



Consistent covariance parameters are obtained from T, Δg , and cross-covariance analyses.

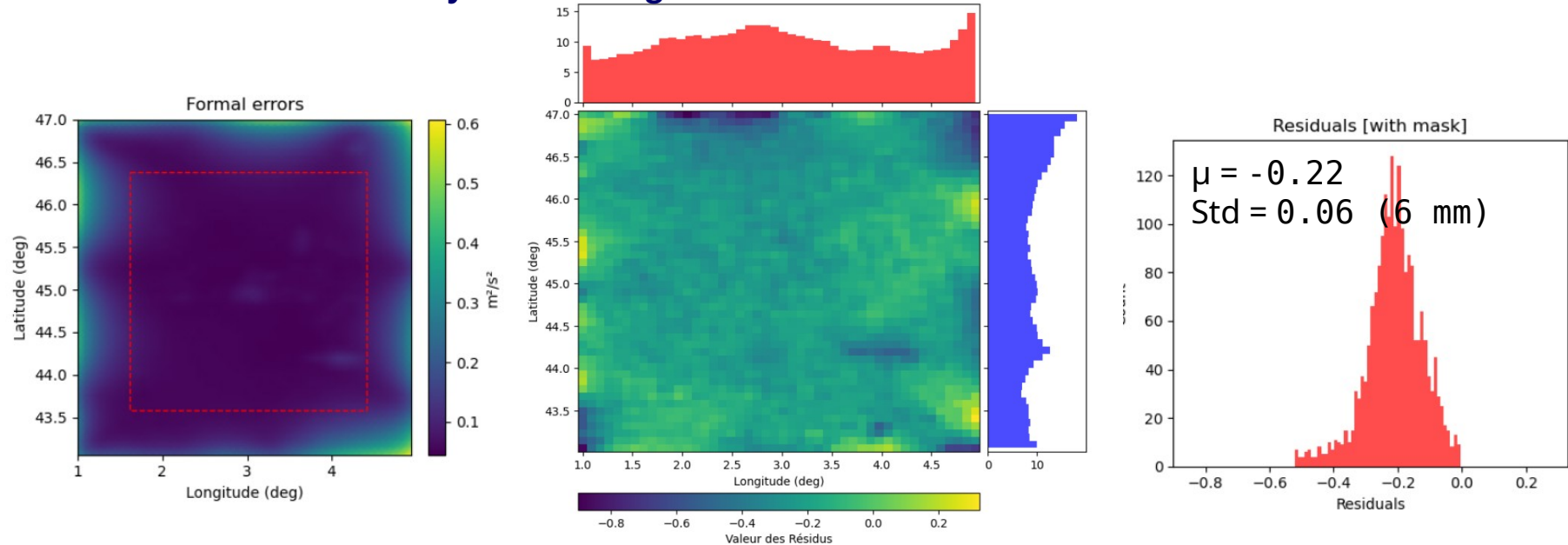
APPLICATION TO REFERENCE SURFACE COMPUTATION

Collocation results: recovery of W from g



APPLICATION TO REFERENCE SURFACE COMPUTATION

Collocation results: recovery of W from g



WORK IN PROGRESS AT IGN

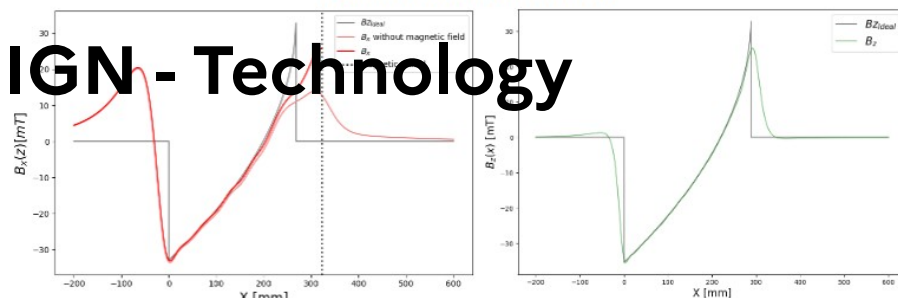
WORK IN PROGRESS AT IGN - Technology

Prepare the future

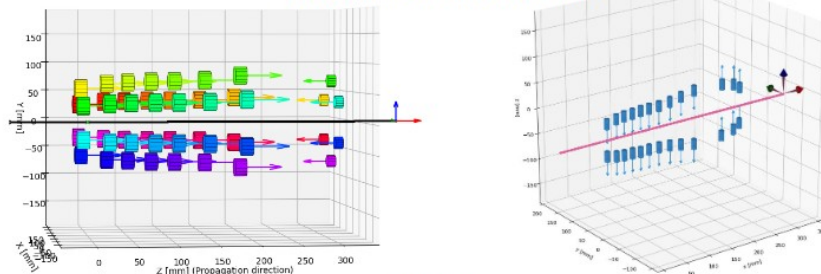
2021 - 2026:
ROYMAGE Project:
contribution as final user

Zeeman slower with permanent magnet
Source: Romero González et al. (2023)
<https://hal.science/hal-04139115v1>

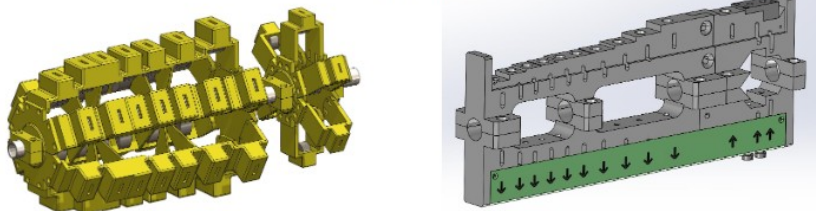
Magnetic field along Zeeman axis



Arrangement of permanent magnets



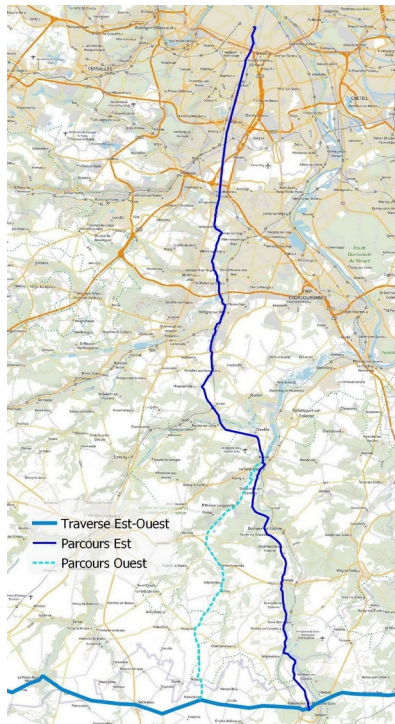
Structure



WORK IN PROGRESS AT IGN - Infrastructure

Prepare the future

2022: Tying the Paris
Observatory clock to the
French reference
levelling network NIREF

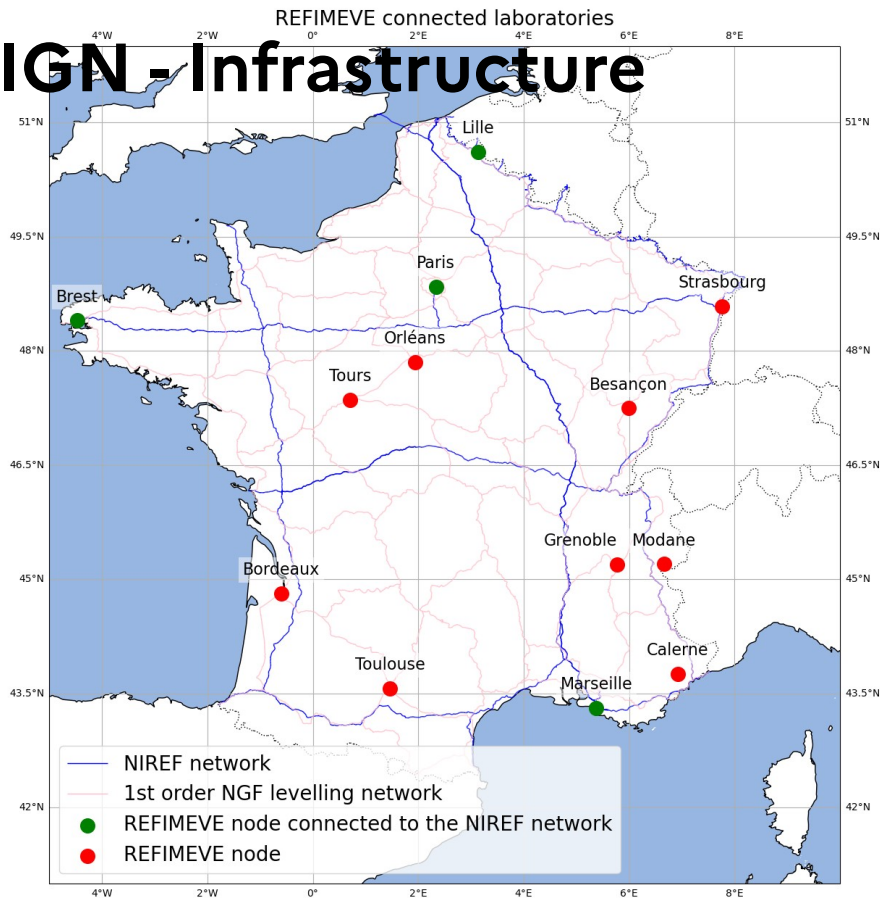


WORK IN PROGRESS AT IGN - Infrastructure

Prepare the future

Work in progress:

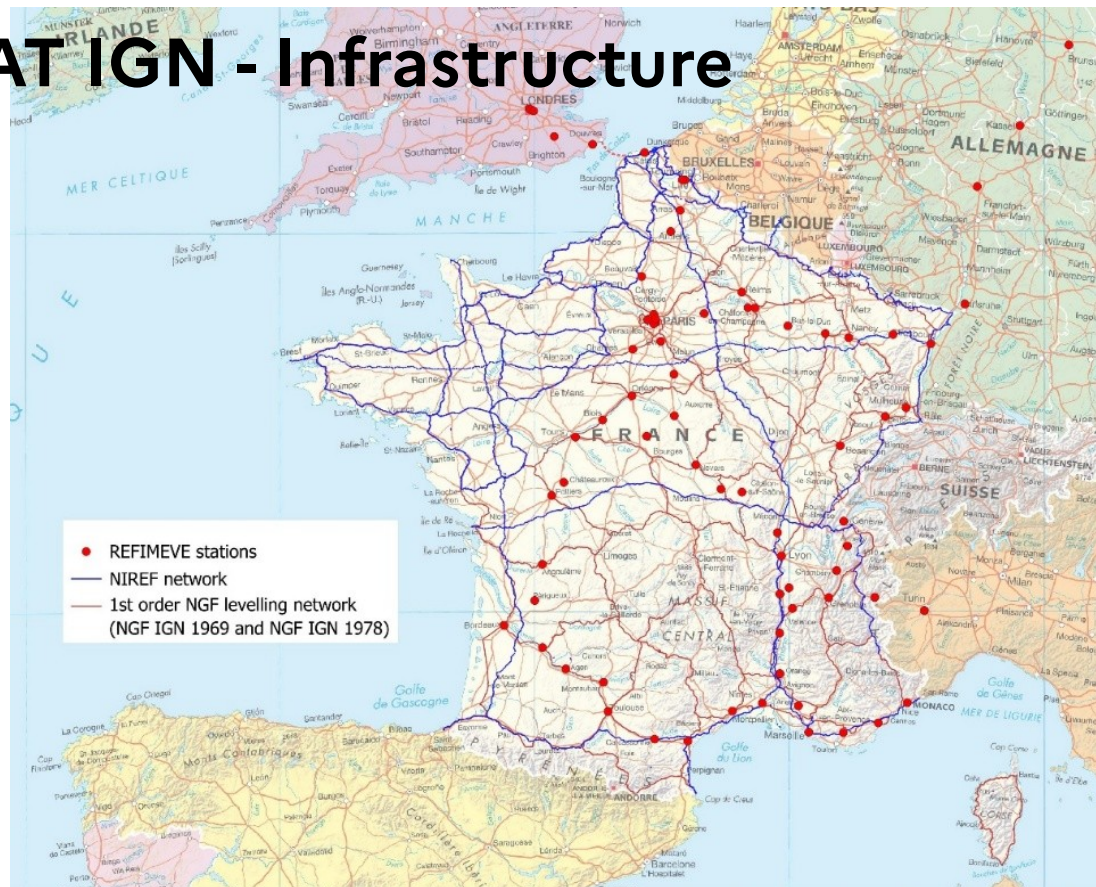
Tying the REFIMEVE nodes to the NIREF + 1st order network



WORK IN PROGRESS AT IGN - Infrastructure

Prepare the future

Work in progress:
Assessing the benefit for
connecting more REFIMEVE
stations



WORK IN PROGRESS AT IGN – Other studies

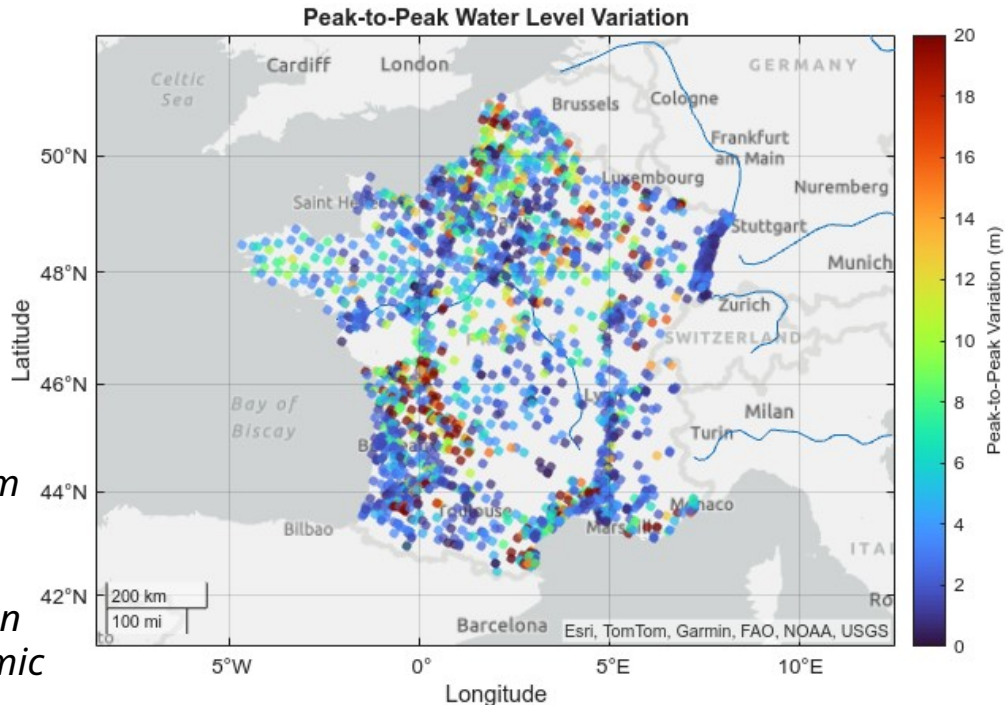
Monitoring applications

Example:

Sensitivity of W to aquifer status in France

Some French aquifers exhibit peak-to-peak groundwater-level variations exceeding 20 m over the 2019–2026 period.

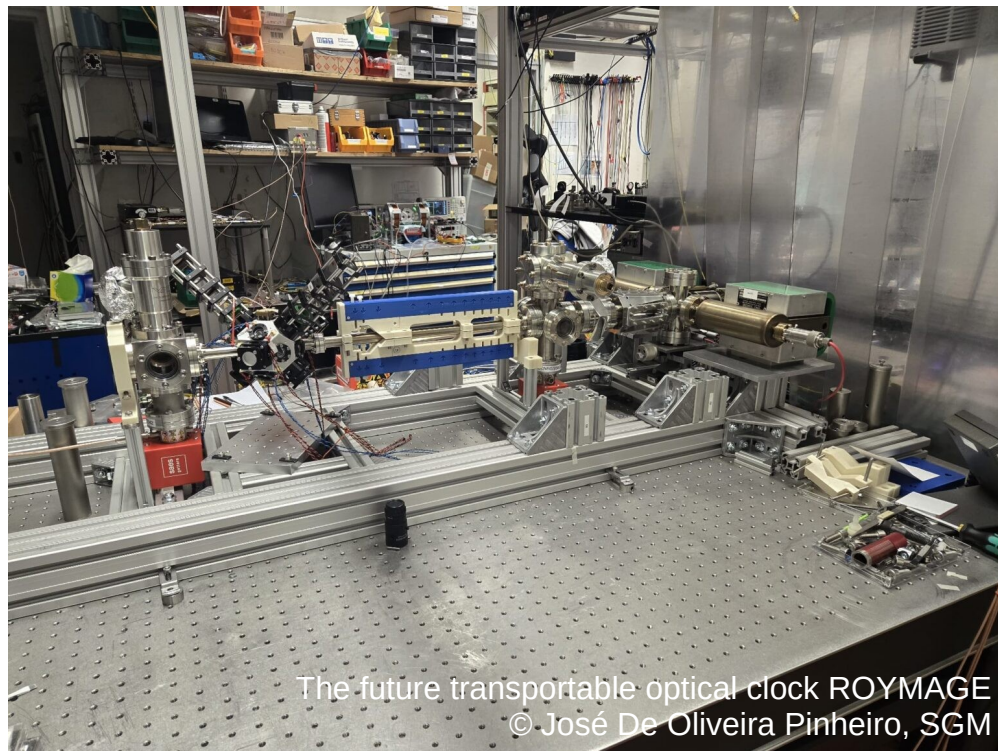
Groundwater-level changes of about 3 m can occur within only 3 weeks in the most dynamic aquifers.



FINAL (OPTIMISTIC) WORD

The future vertical reference frame

- Optical clocks reach the centimeter sensitivity
- cm transportable clocks will show up within 5 to 10 years
- They will allow the setting up of a consistent unbiased vertical reference frame over continental Europe along the FOREST network



The future transportable optical clock ROYMAGE
© José De Oliveira Pinheiro, SGM

THANK YOU FOR YOUR ATTENTION