Chronometric measurements in Geodesy and Geophysics

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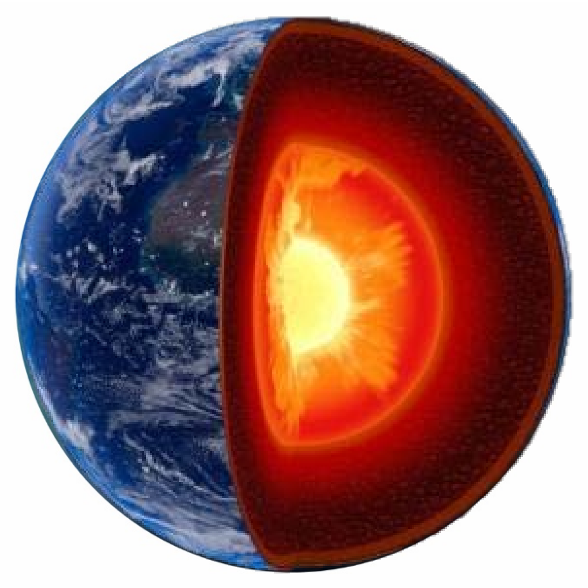

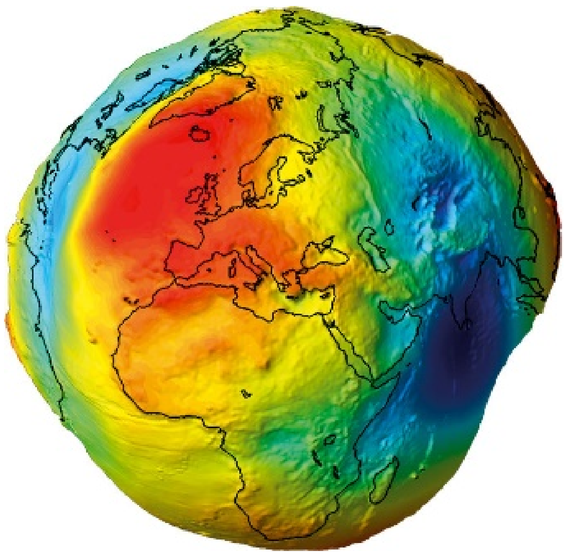

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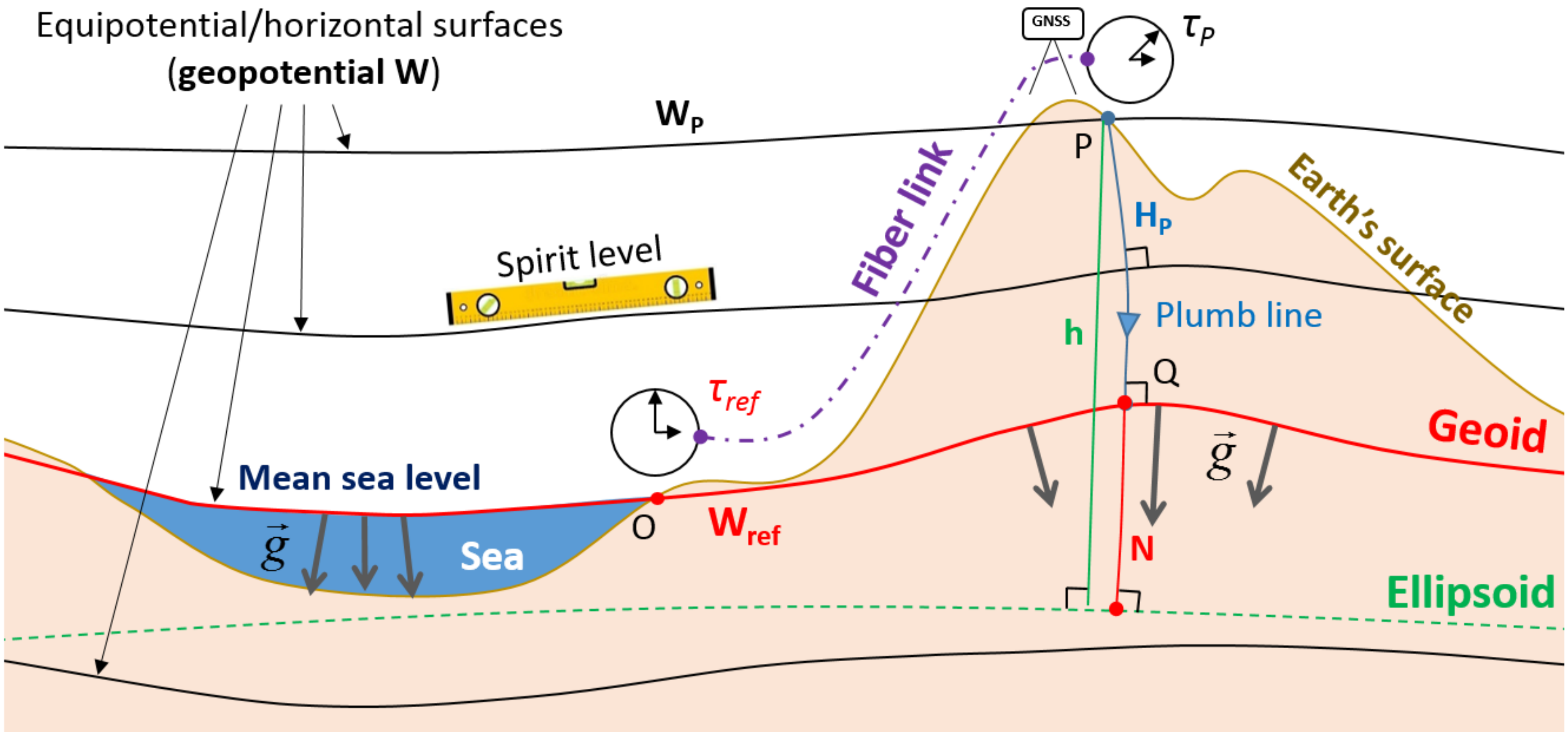
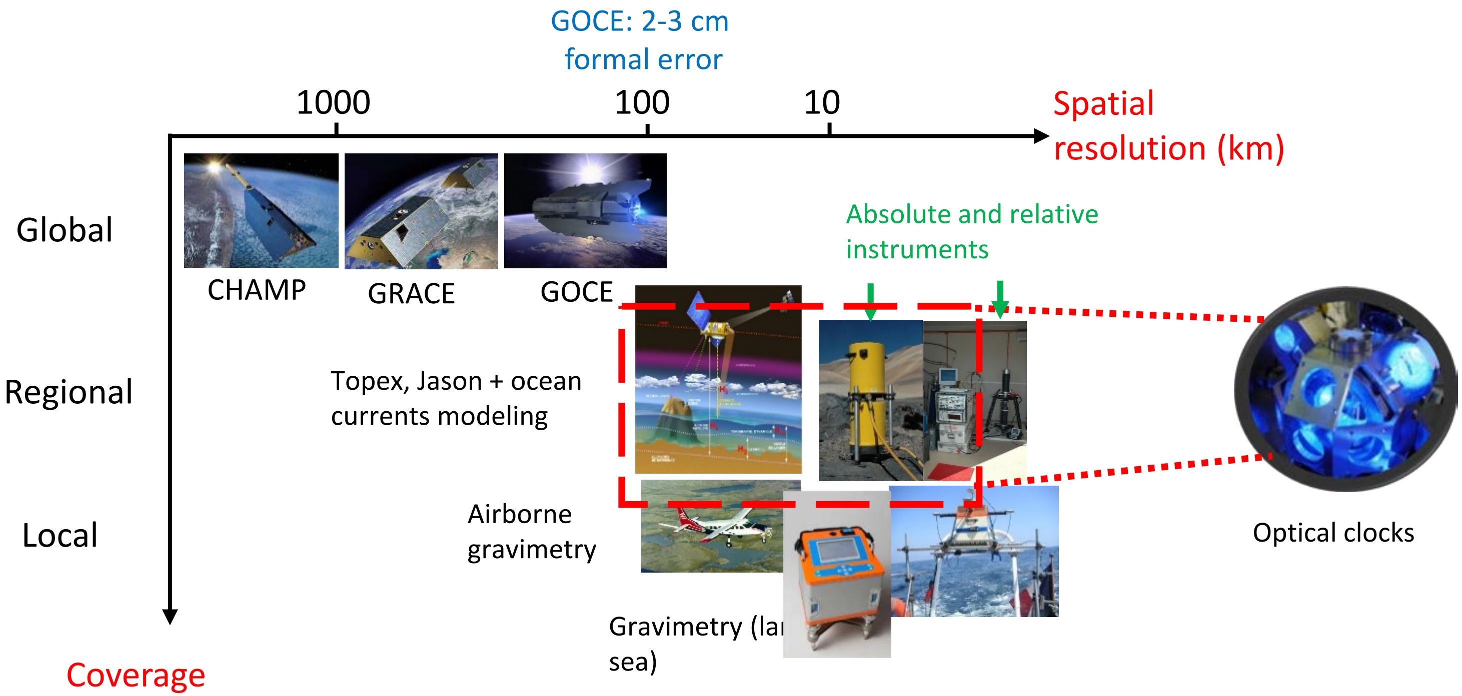
Principle of chronometric geodesy.



Chronometric observables: interests?

- New type of geodetic observable: geopotential differences directly observed
- Mass sensitivity: complementary to gravity and gravity gradients
- Spatial resolution beyond that of satellite techniques
- Reduction of heterogeneities in coverage of ground measurements
- Comparisons over long distance

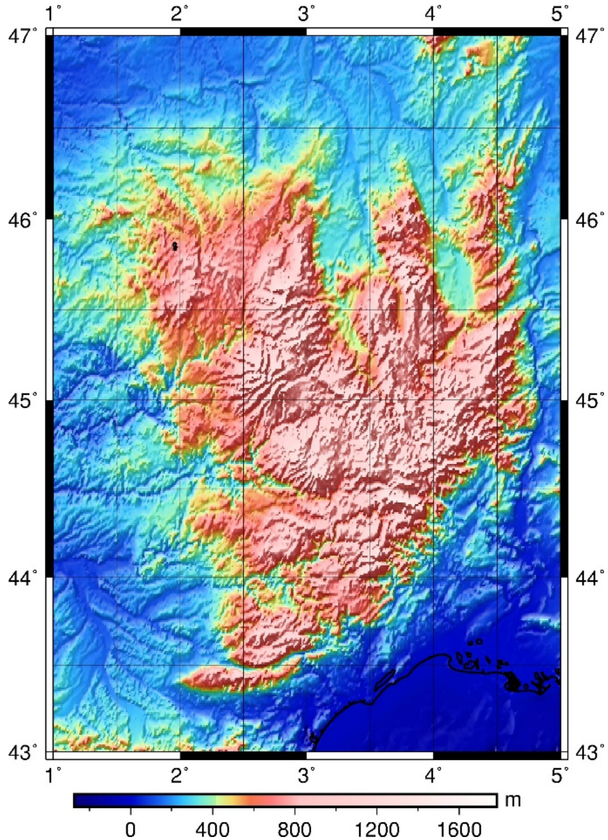


Clocks to improve the determination of the geopotential

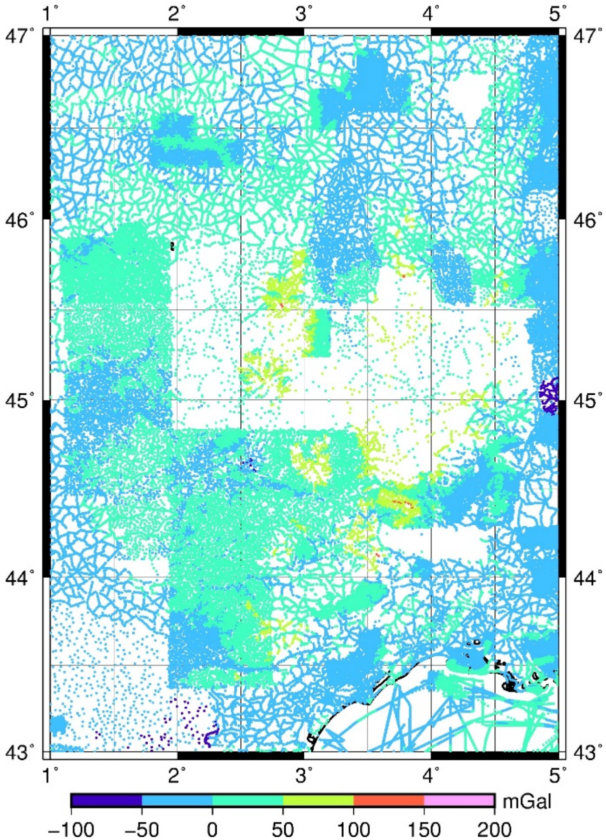
An example in France

Massif central

- Moderately mountainous terrain
- Intermediate gravity data coverage: 149522 data (BGI)



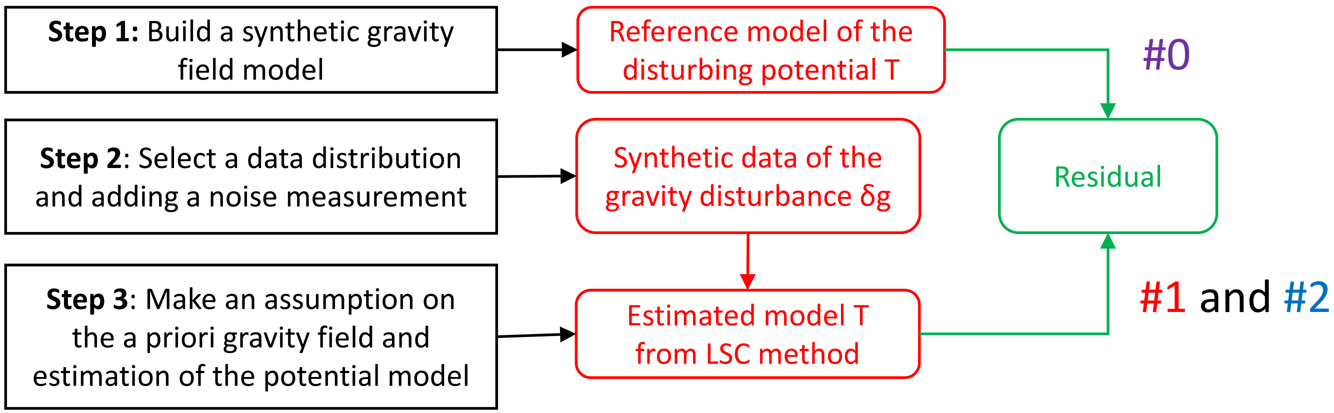
Topography



Terrestrial and marine free-air gravity anomalies

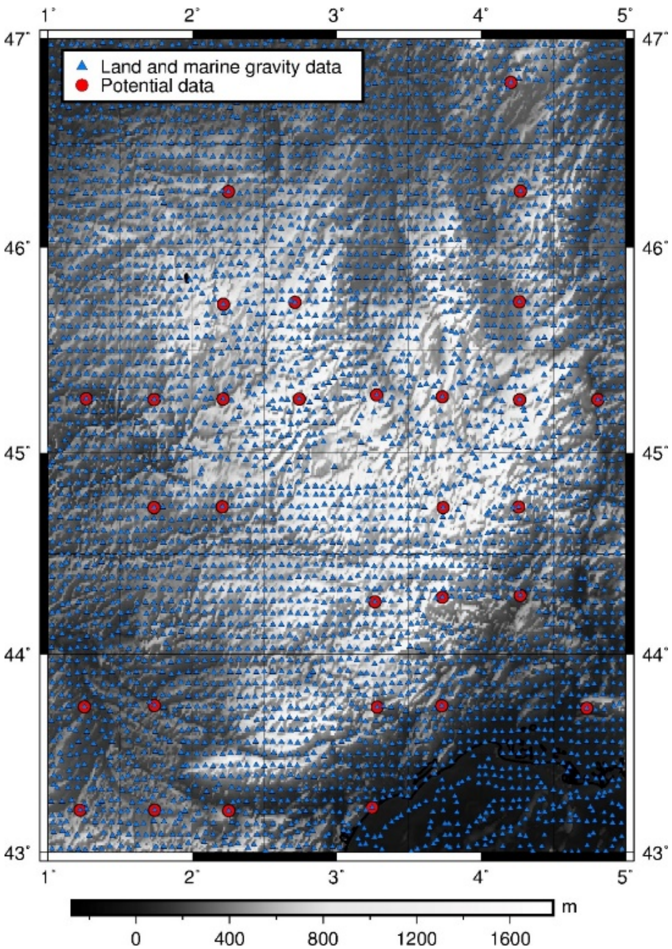
Methodology

Tools: Generation, analysis and estimation of a gravity field model



- Evaluation of the contribution of clock measurements by comparing the solutions #1 and #2 wrt a reference solution #0
  - #1: only from gravity data
  - #2: from gravity and potential data

- T is estimated on a regular grid interval of 10 km using the Least Squares Collocation method (LSC) [Moritz, 1980]



- 4374 reduced gravity data δg
  → noise = 1mGal
- 33 potential data T
  → noise = 0.1 m^2/s^2

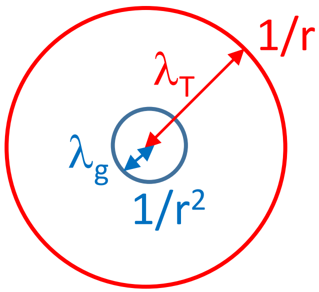
How to select the gravi points ?

→ Data reduction from the ~150000 locations
→ Distance between each point ~6.5 km
→ Each point is weighted (number of real points in the vicinity)

How to select the clock points ?

→ T more sensitive to medium wavelengths λ than δg

→ The location of the clock points is chosen to better complete the gravity network



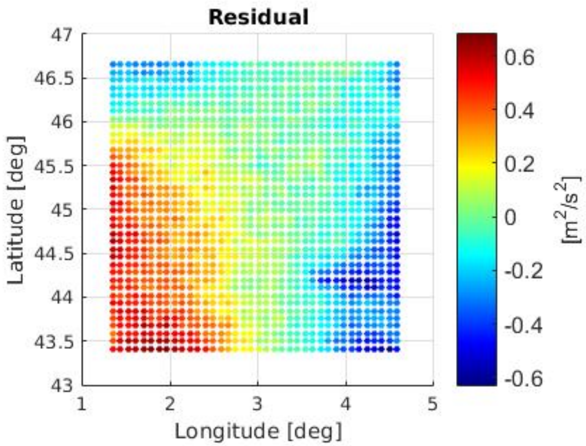
→T at same location as δg

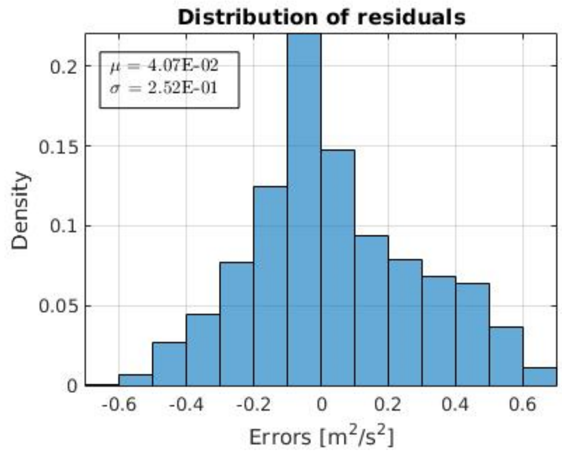
→ Red points are an example of "handmade coverage" (not optimized)

White noise is added to the perfect synthetic data

Reconstruction of T from δg data only

Results from *Lion et al. (2017)*

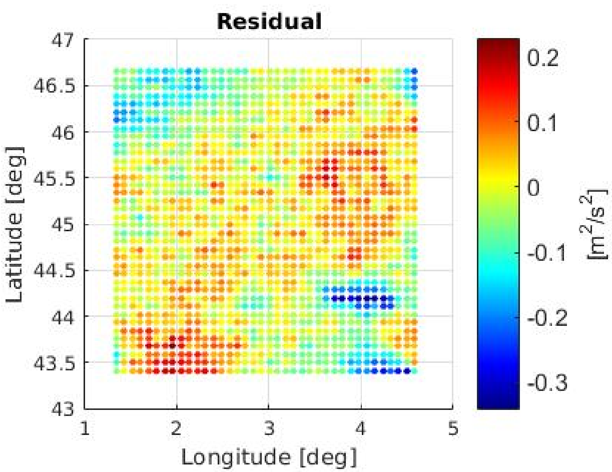


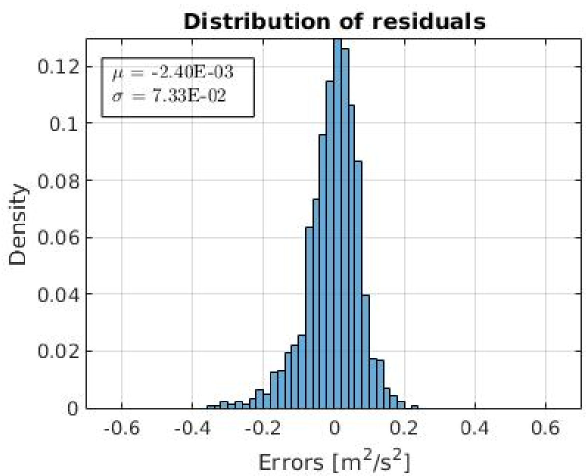


Bias: -0.04 m^2/s^2
→ 4mm

RMS: 0.3 m^2/s^2
→ 3cm

Reconstruction of T from data on both δg and T





Bias: -0.002 m^2/s^2
→ 0.2mm

RMS: 0.1 m^2/s^2
→ 1cm

→ Allow to reduce the bias and improve the accuracy
→ Fix medium wavelenght of the gravity field recovery
→ Complement existing surface information on the gravity field

- Solving complex optimization problems by simulating the process of biological evolution
- Genetic Algorithm: ε-MOEA (Multi-Objective Evolutionary Algorithm)
- The user can define: objectives, constraints, ε-dominance (tolerance on the value of the objectives)
- The method provides a set of Pareto optimal solutions

Objectives

→ Minimize the reconstruction residual on T (bias μ and RMS σ)

→ Minimize, fixe or set free the number of clock data N

Constrains on a clock point and the area

→ At the same place as a gravity point

→ In an area poorly covered by gravity

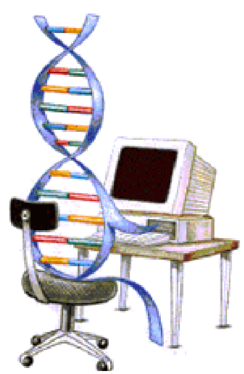
→ On land

→ Minimum distance between 2 clock points

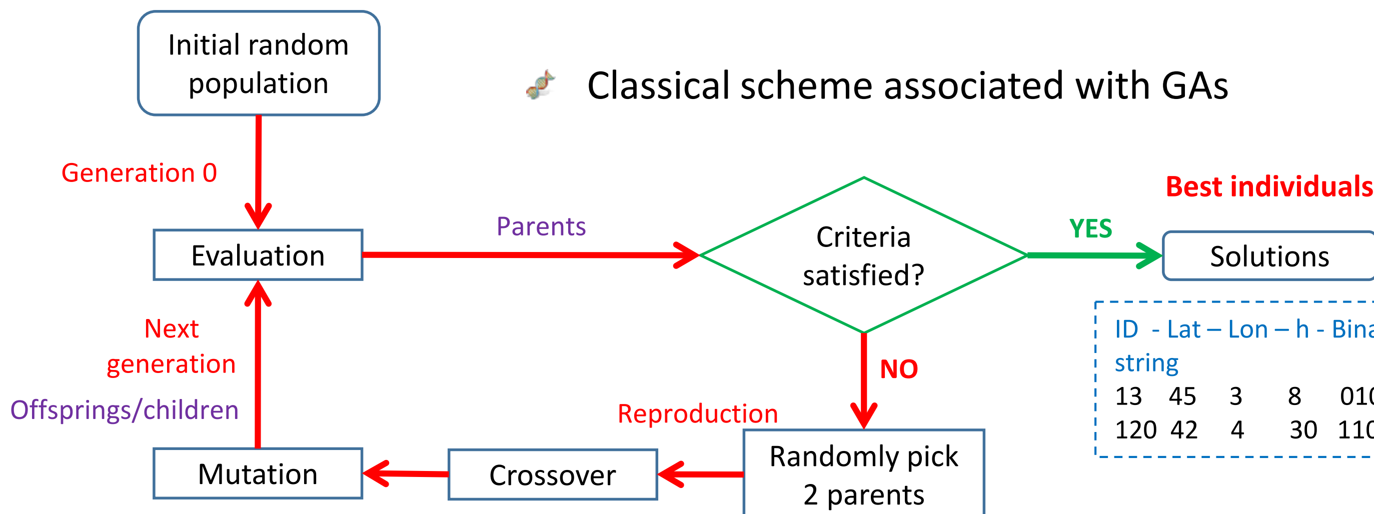
→ Regional area is subdivided

ID - Lat – Lon – h - Binary string

53	45	4	10	0101011
149	46	3	15	1101110
…				
577	44	1	3	0100011



- Classical scheme associated with GAs



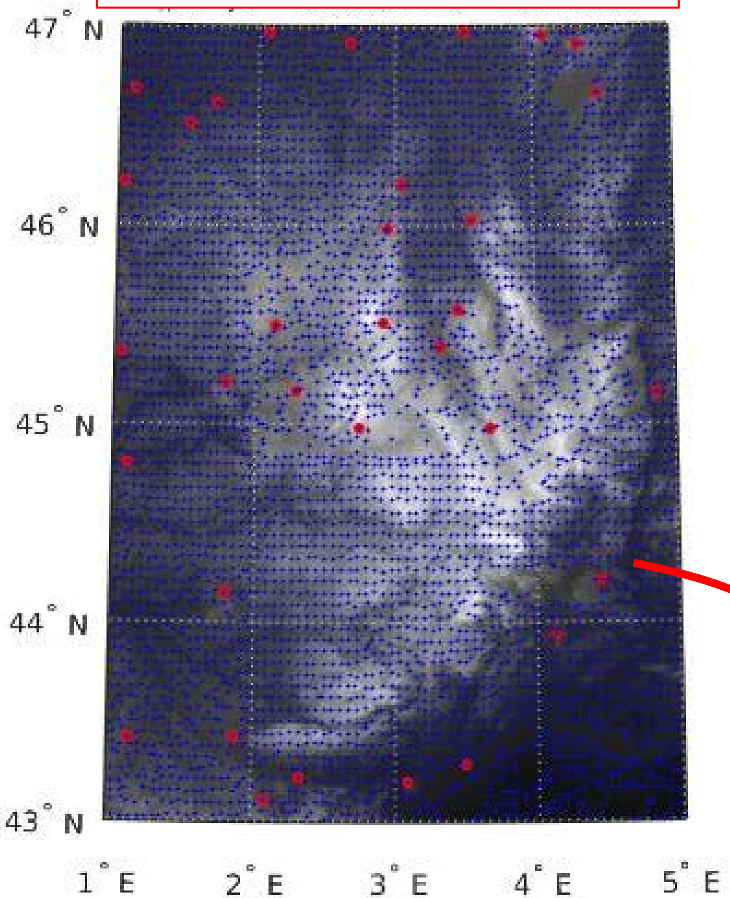
ID - Lat – Lon – h - Binary string

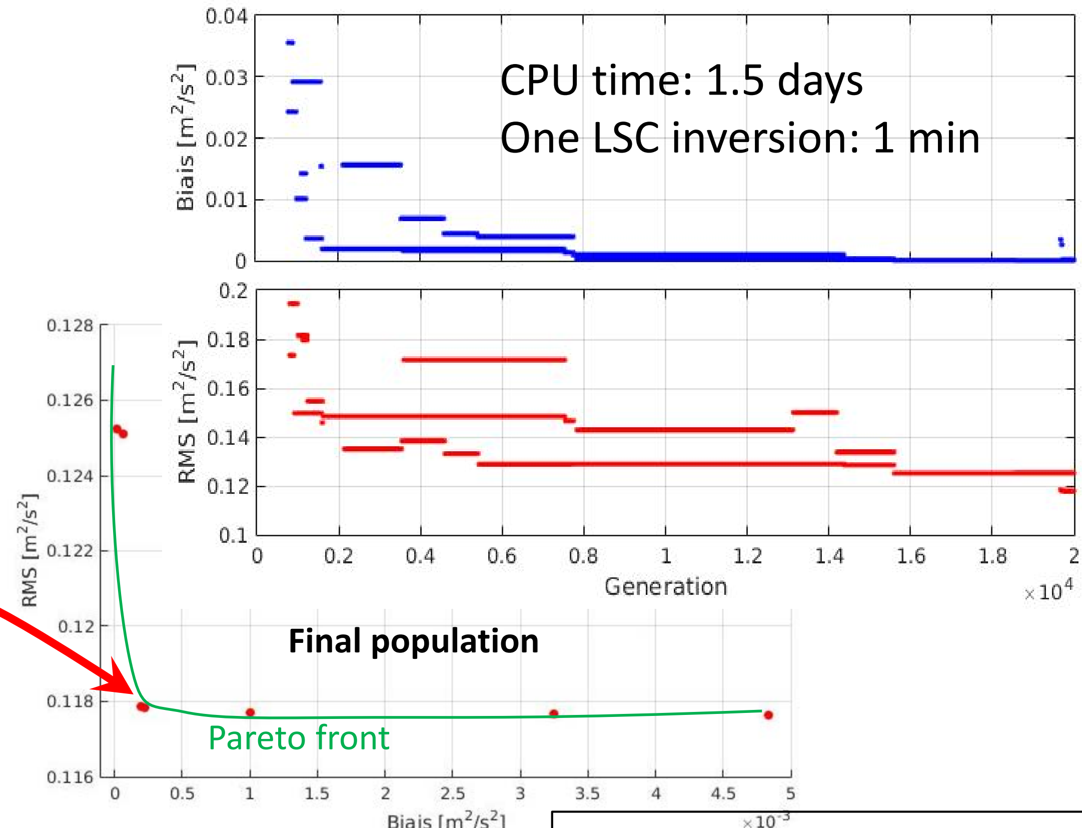
13	45	3	8	0101101
120	42	4	30	1101000

- N=33 clock data from a set of 2154 distinct gravity location points

N=33; μ=0.02 mm; σ=1 cm

→ 8.94E+72 combinations!





Initial random population: 400
20000 generations
Resolution: ε_μ=1.E-6 ; ε_σ=1.E-3

→ GA can find good clock data distributions

→ For the same number of clock data, GA offers different solutions with a strong bias (RMS) and good RMS (bias), or a trade-off

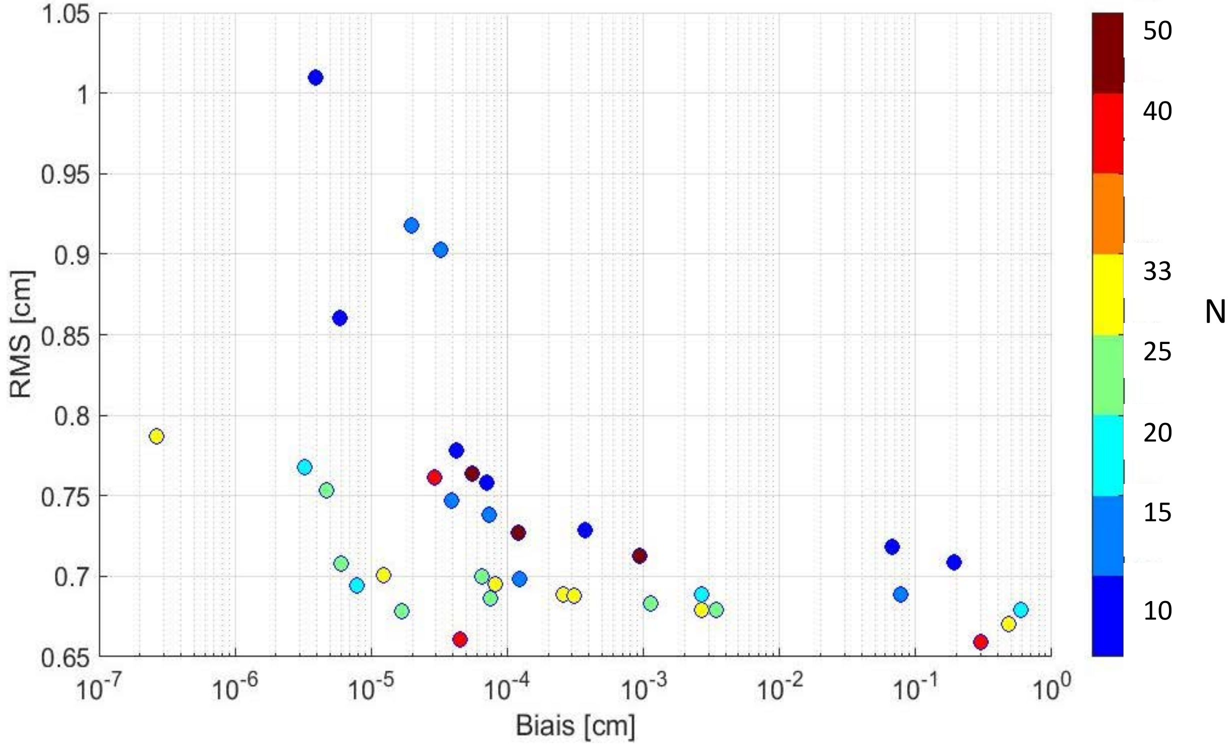
Geopotential determination with genetic algorithms

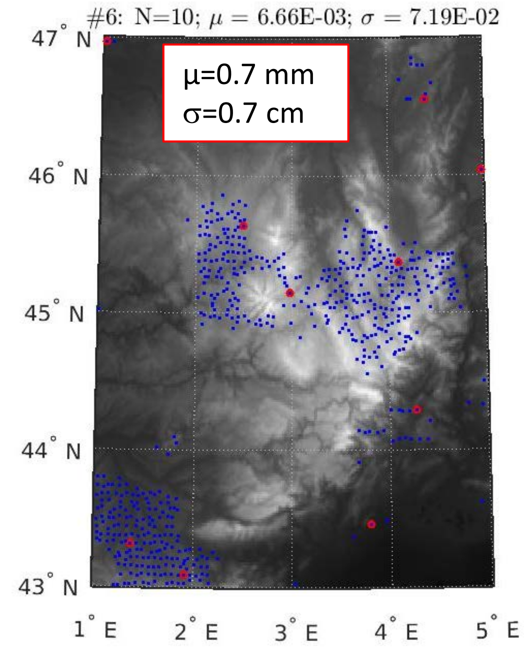
- Fixed N clock data from a set of 577 points

→ Better solutions are found when the design space exploration is better pre-selected

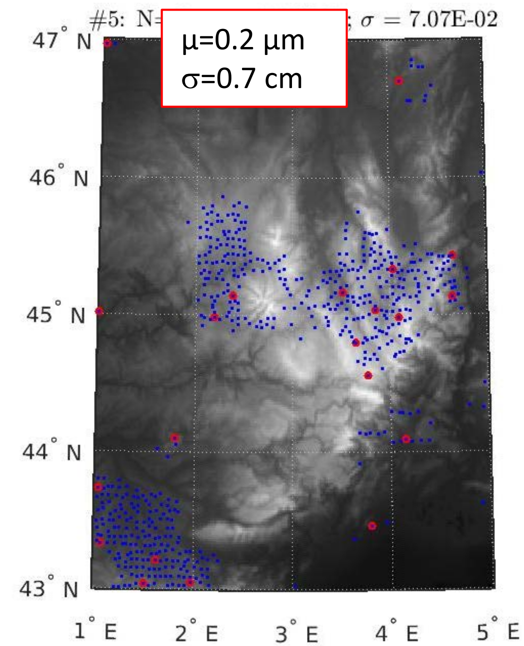
→ Similar residuals are found with different clock data network

Lion et al. (in preparation)





N_{Tf} = 10



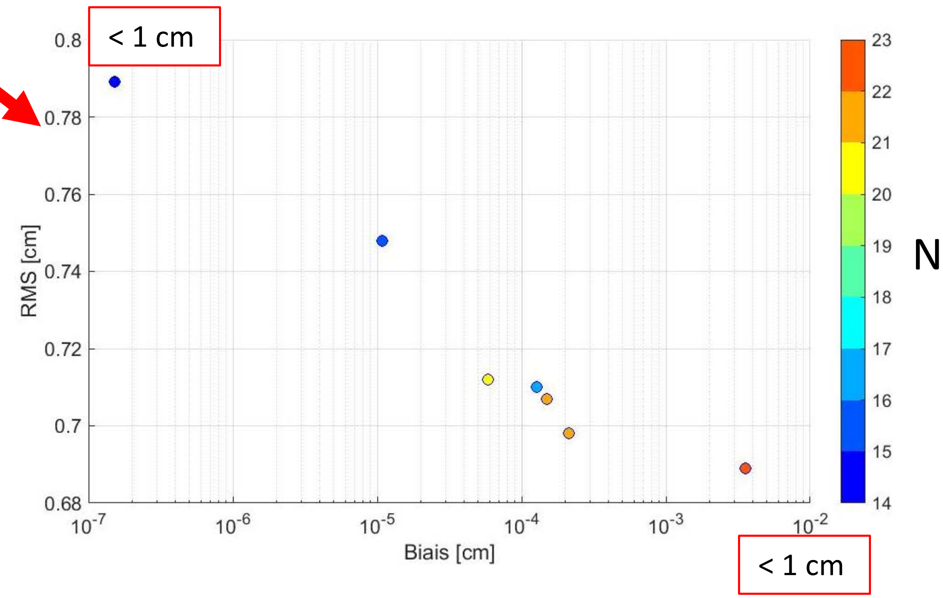
N_{Tv} = 21

Distribution with variable N $\in [5; 50]$

	N free – [m²/s²]			N minimized – [m²/s²]		
N cells	Nb clocks	Bias	RMS	Nb clocks	Bias	RMS
1	14	1.52×10^{-8}	7.89×10^{-2}	8	1.56×10^{-6}	1.58×10^{-1}
	15	1.08×10^{-6}	7.48×10^{-2}	8	1.65×10^{-6}	9.90×10^{-2}
	20	5.89×10^{-6}	7.12×10^{-2}	9	1.85×10^{-6}	8.16×10^{-2}
	16	1.28×10^{-5}	7.10×10^{-2}	9	6.52×10^{-6}	7.98×10^{-2}
	21	1.50×10^{-5}	7.07×10^{-2}	12	1.67×10^{-4}	7.88×10^{-2}
	21	2.13×10^{-5}	6.98×10^{-2}	13	2.64×10^{-4}	7.61×10^{-2}
	23	3.58×10^{-4}	6.89×10^{-2}	14	4.97×10^{-4}	7.44×10^{-2}
				13	1.93×10^{-3}	7.41×10^{-2}
4	19	2.05×10^{-4}	8.88×10^{-2}			
	26	1.53×10^{-4}	8.29×10^{-2}			
	30	6.72×10^{-5}	6.93×10^{-2}			
	30	2.21×10^{-4}	6.89×10^{-2}			
	25	1.76×10^{-4}	6.81×10^{-2}			
9	19	4.08×10^{-4}	8.06×10^{-2}			
	26	1.19×10^{-3}	7.12×10^{-2}			
	30	2.30×10^{-4}	6.39×10^{-2}			
	30	4.52×10^{-4}	6.38×10^{-2}			
	25	2.75×10^{-4}	6.28×10^{-2}			
16	23	4.93×10^{-4}	6.09×10^{-2}			
	22	1.50×10^{-3}	6.00×10^{-2}			
	28	2.54×10^{-3}	5.99×10^{-2}			

Global area (N cells = 1); Regionalized area (N cells = 4, 9, 16)

- Regionalization is a strong constrain
- GA can find the optimal number of clock data of the problem



Lion et al. (in preparation)

Geopotential determination

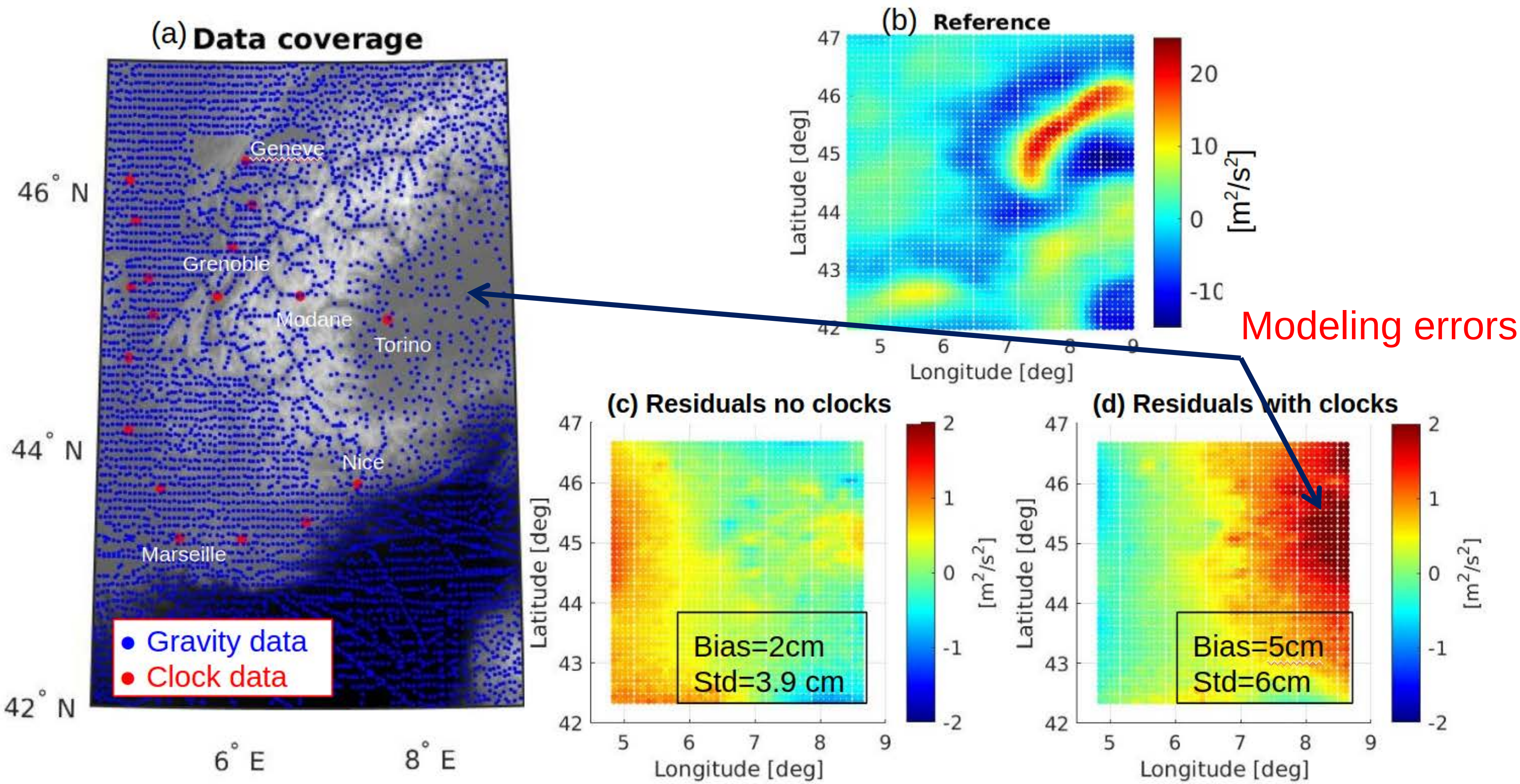
Koller et al. (2017)

Where to measure the potential?

Refimeve+

Alps – REFIMEVE

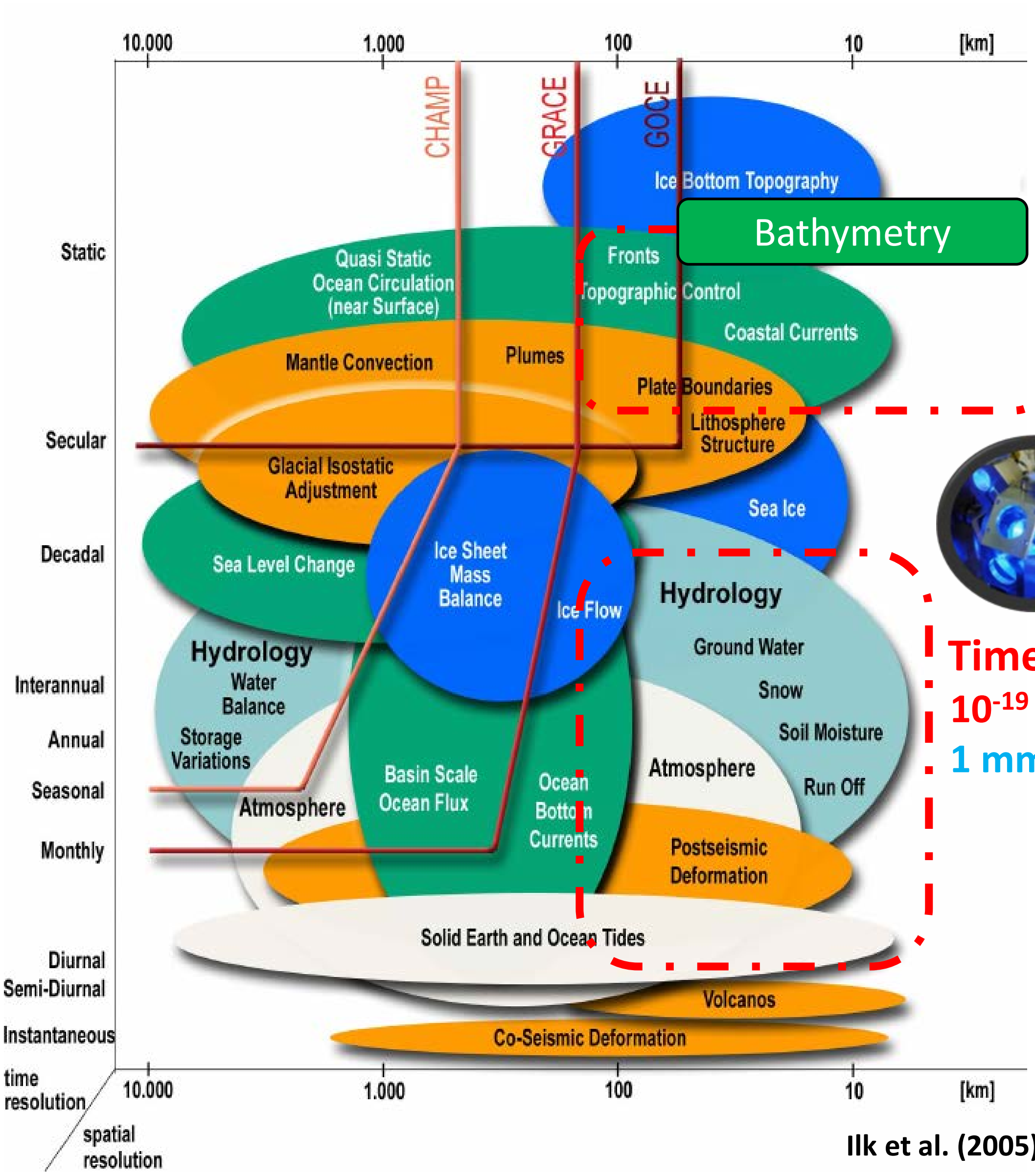
Preliminary results - work in progress - *Lion et al.*



➔ Local improvement in areas where we put clock data along the fiber network

➔ Need a homogenous coverage to eliminate the trend on the global region

Clocks for monitoring mass transporting geodynamic processes?



Ilk et al. (2005)

Static

10^{-17} @ 1s – 10^{-18} @ 1h

10 - 1 cm

Time variable

10^{-19} @ 1j - 10^{-20} @ >1j

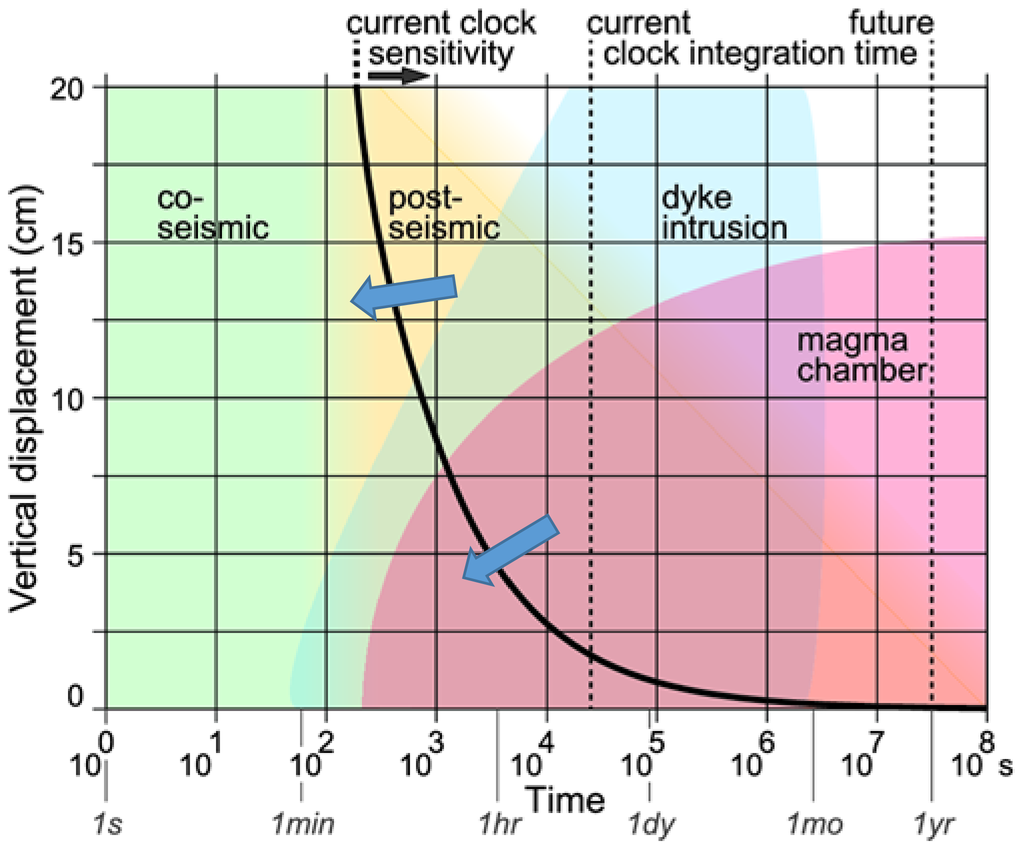
1 mm and below

Temporal and spatial scales of geoid signals associated to…

- **solid Earth**
- **Ocean**
- **Ice**
- **Continental**

… processes

Characterizing geological processes: magmatic or tectonic deformation



Bondarescu et al. (2015)

Phenomena that could be monitored with optical clock networks, supposing that

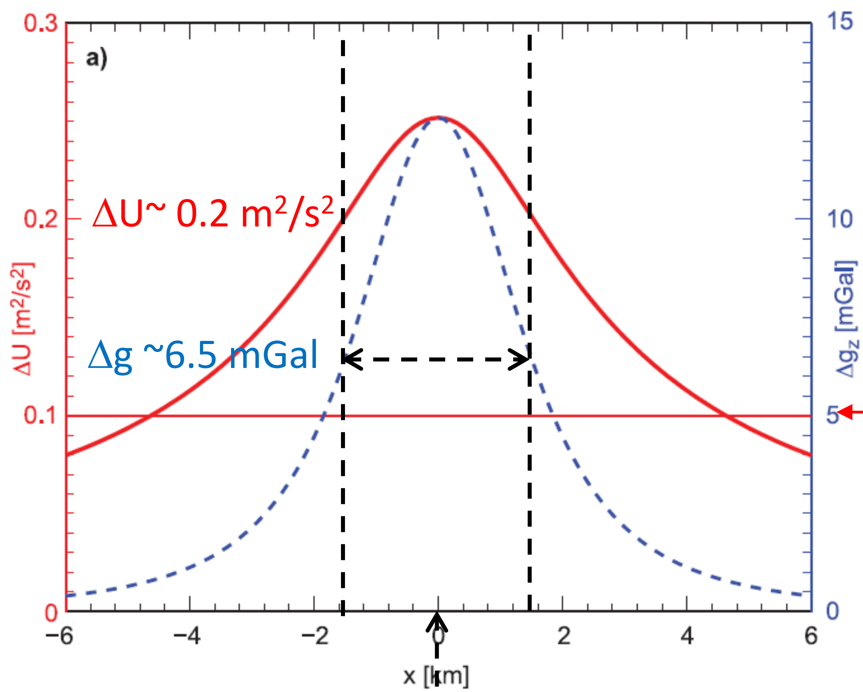
$$\Delta f \,/\, f \approx 3\times10^{-16} \,/\, \sqrt{\tau \,/\, \mathrm{sec}}$$

eg. Etna volcano: clocks "today" could see the uplift (8 cm) and mass redistribution caused by an inflating magma chamber (if integrated for about ten days, 1yr, resp.)

→ But the authors considered only white frequency noise for the clock

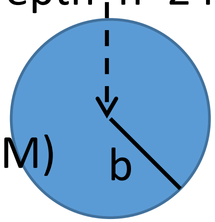
Gravity and geopotential signal

Geopotential anomaly ΔU and gravity anomaly Δg of a buried sphere
→Bondarescu et al. (2012)

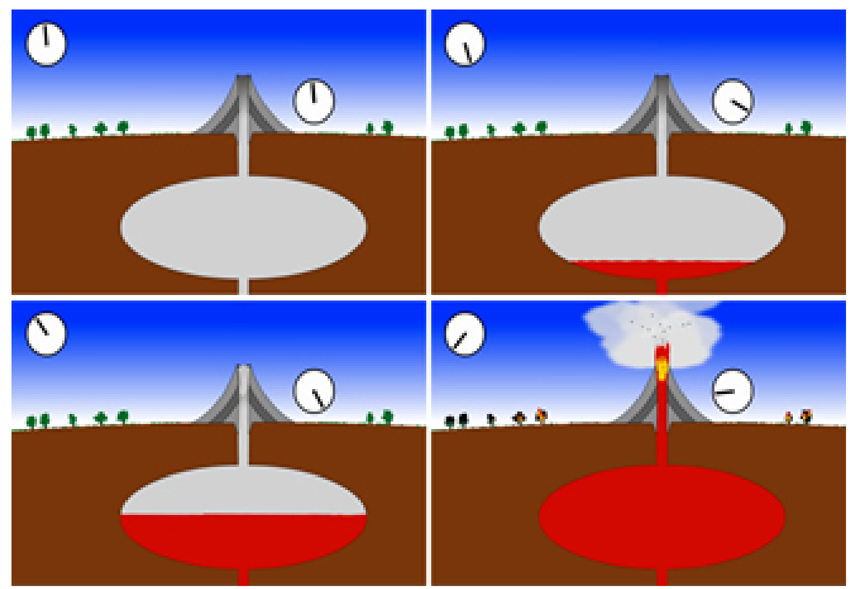


Detection threshold of a clock (1 cm)

Depth h=2 km

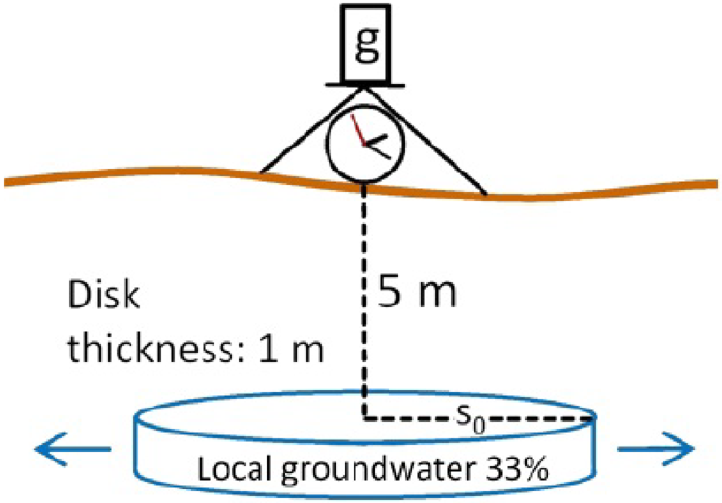


Buried sphere (mass M)
Radius b =1.5 km
Density contrast: $\Delta\rho/\rho$=20 %



Groundwater storage

→ monitoring and quantifying water mass changes
→ Approximation planar disk



Mehlstaubler et al. (2018)

Radius S_0	Δg [µGal]	ΔN [mm]
10m	7,71	0,0001
100m	13,15	0,0014
1km	13,77	0,0141
10km	13,83	0,1400
100km	13,83	1,3650
1000km	13,83	10,7170

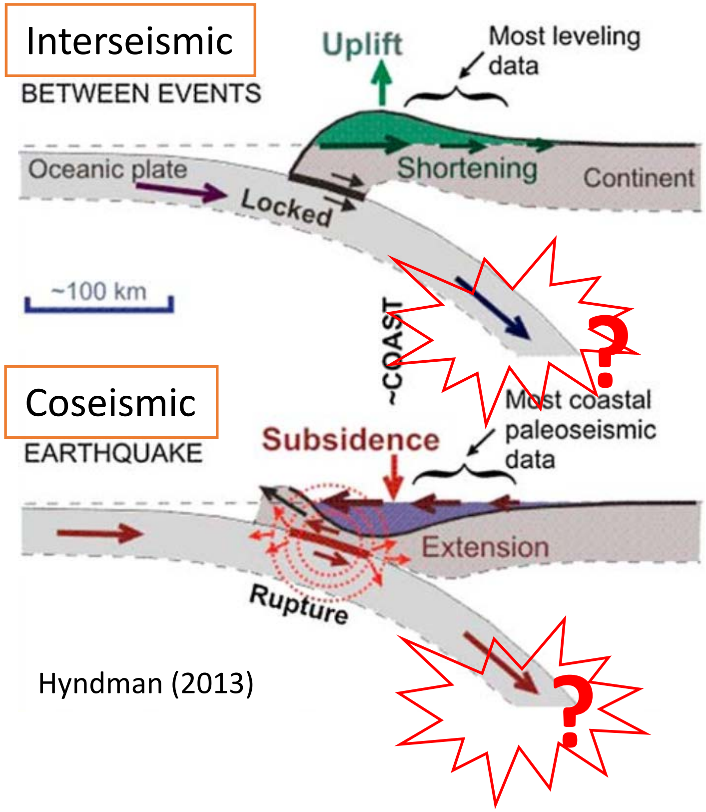
Detection threshold of a clock (1 cm)

Hard to quantify changes at greater depths

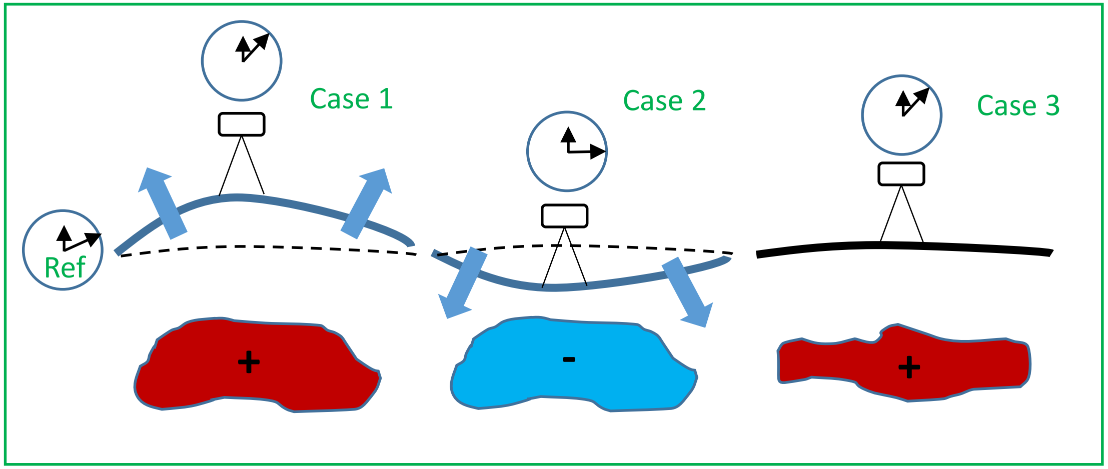
→ Clocks sensitive to mass redistributions at depth

Subduction zone

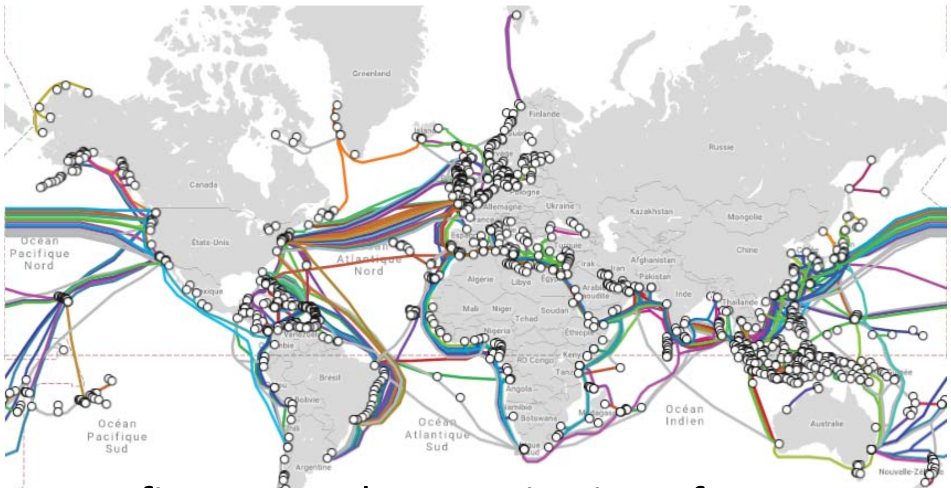
- Deeper pre-seismic signal
- Large scale deformation



Hyndman (2013)



→ Fiber networks below the oceans



→ first optical frequency transfer experiment + first noise characterization of submarine fiberlinks for frequency metrology [Clivati et al., 2018]

→ stability of 10^{-16} could still be achieved over thousands of kilometers

Quantum metrology and relativistic geodesy provide novel methods for geodesy and Earth observation !

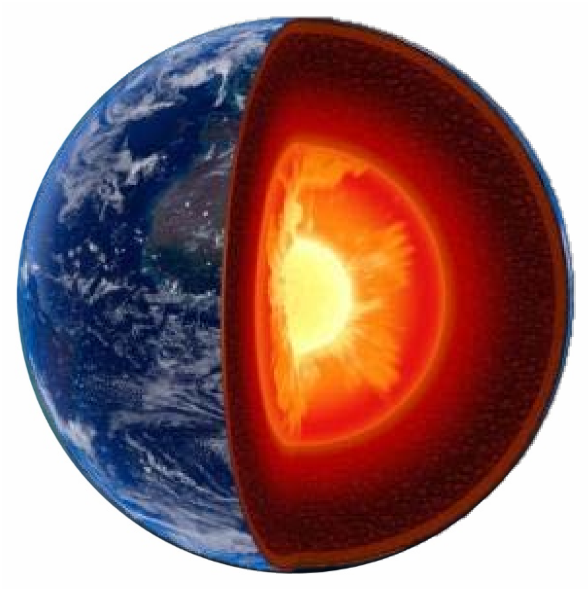
Optical atomic clocks….

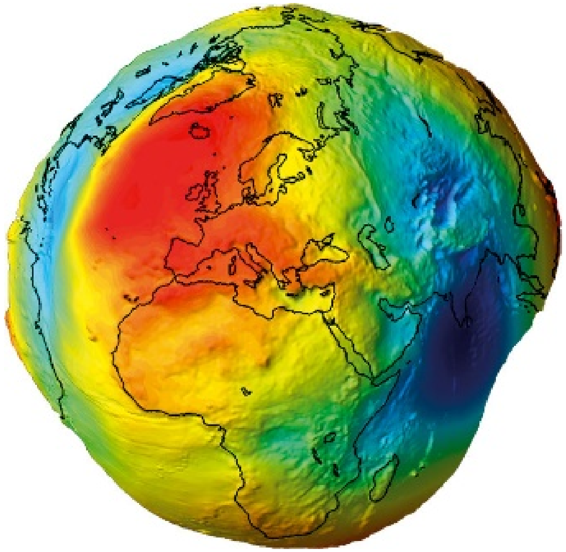
- ✓ provide complementary information to surface and satellite data, particularly in areas poorly covered by gravity data
- ✓ can improve the geopotential reconstruction: bias (by a factor 3) and accuracy (more than 2 orders of magnitude)
- ✓ can connect distant area: coherent fibre links

- ➢ could resolve discrepancies in classical realizations of height systems and geoid solutions (using GNSS, levelling and gravimetric data)
- ➢ could compare different national height systems with different datum
- ➢ could monitoring mass redistribution and geophysical processes

future work !

Thank you for your attention!





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