EGU General Assembly 2020

Validating future gravity missions via optical clock networks: Scientific Requirements

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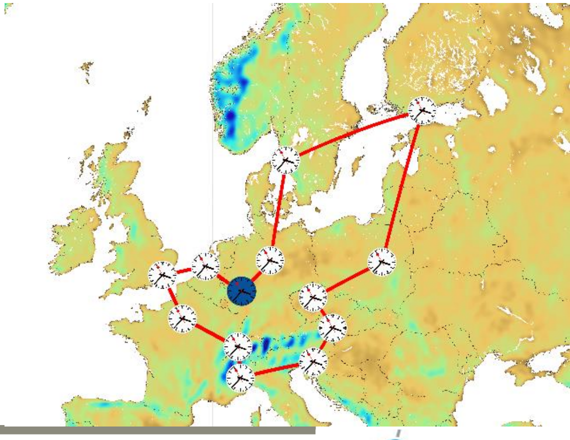

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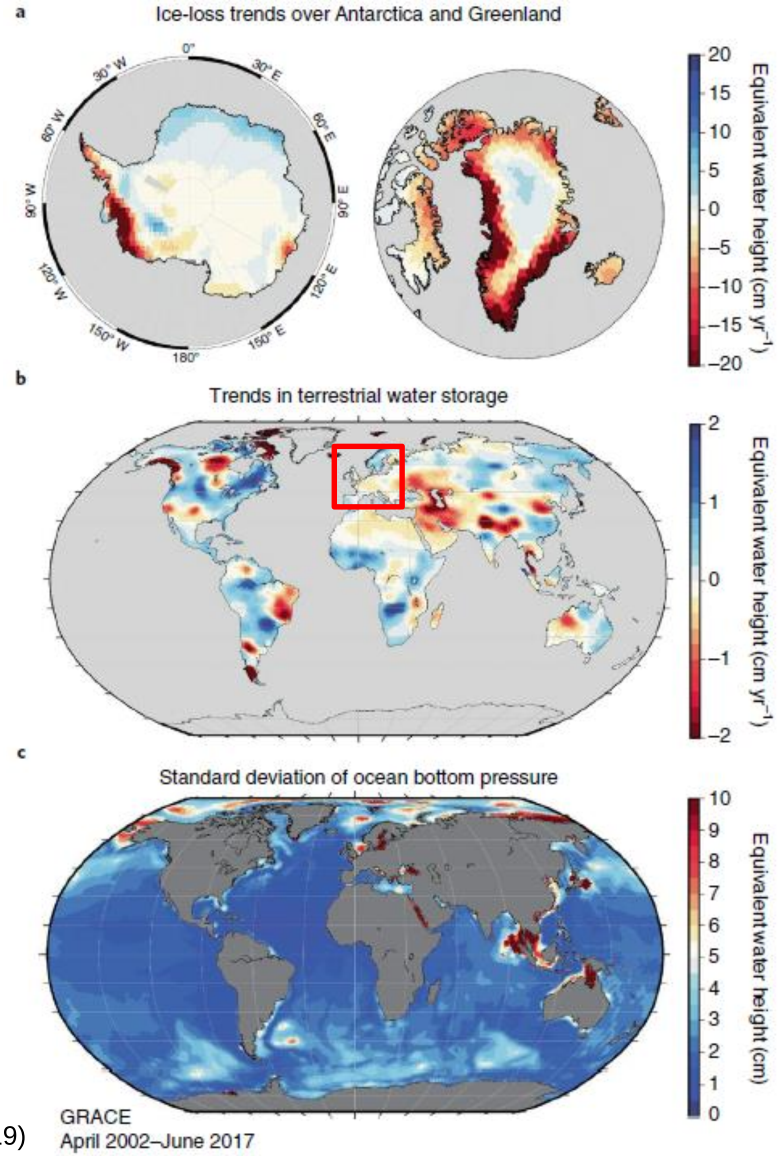
Session G4.2: Modern Concepts for Gravimetric Earth Observation

Thursday, 7 May 2020, 16:15-18:00

1 - Motivation

- Since 2002 GRACE observes the Earth’s gravity field variations with unprecedented accuracy
- Mission start of its successor GRACE Follow-On: 2018
- Further missions are suggested (e.g. Pail et al., 2015)

➢ However, it is difficult to validate GRACE results



Tapley et al. (2019)

WHY is validation of GRACE important?

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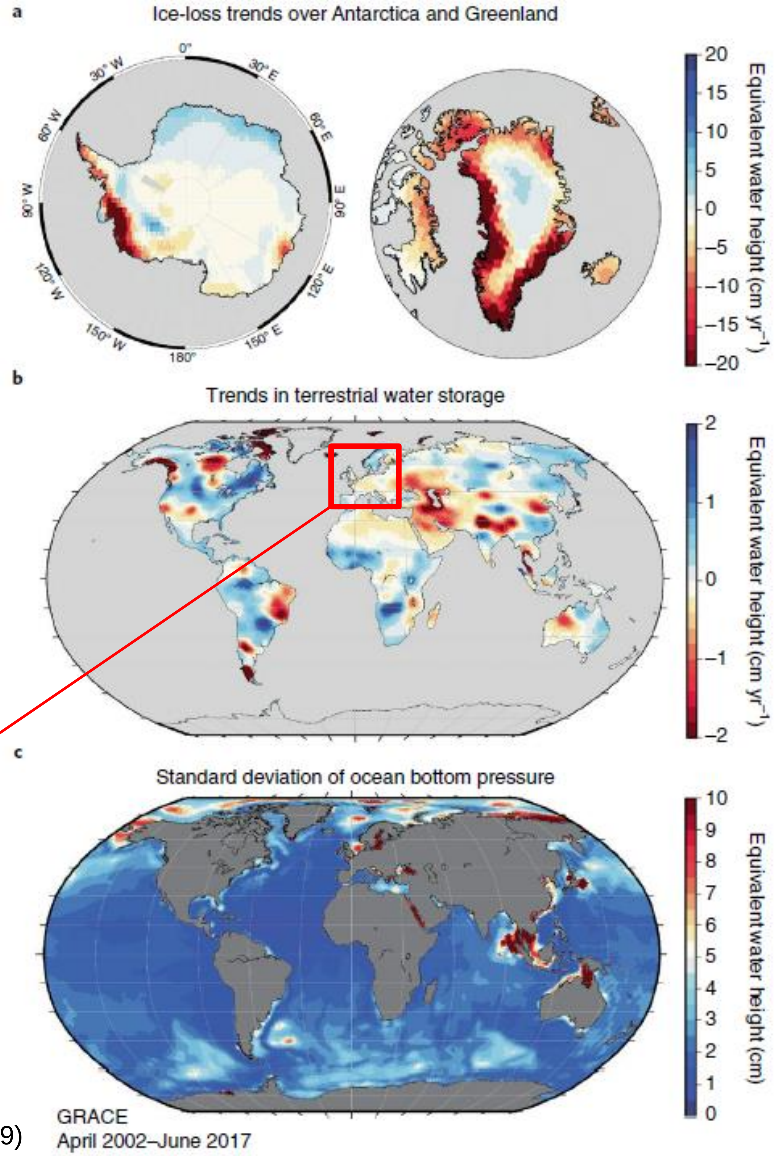
- required to identify/ understand **possible problems in sensor system and data analysis**
- required to better understand/quantify/calibrate GRACE **error estimates**
- helps to understand **resolution limits** of GRACE

➢ Especially important over Europe, where the signal is comparably small



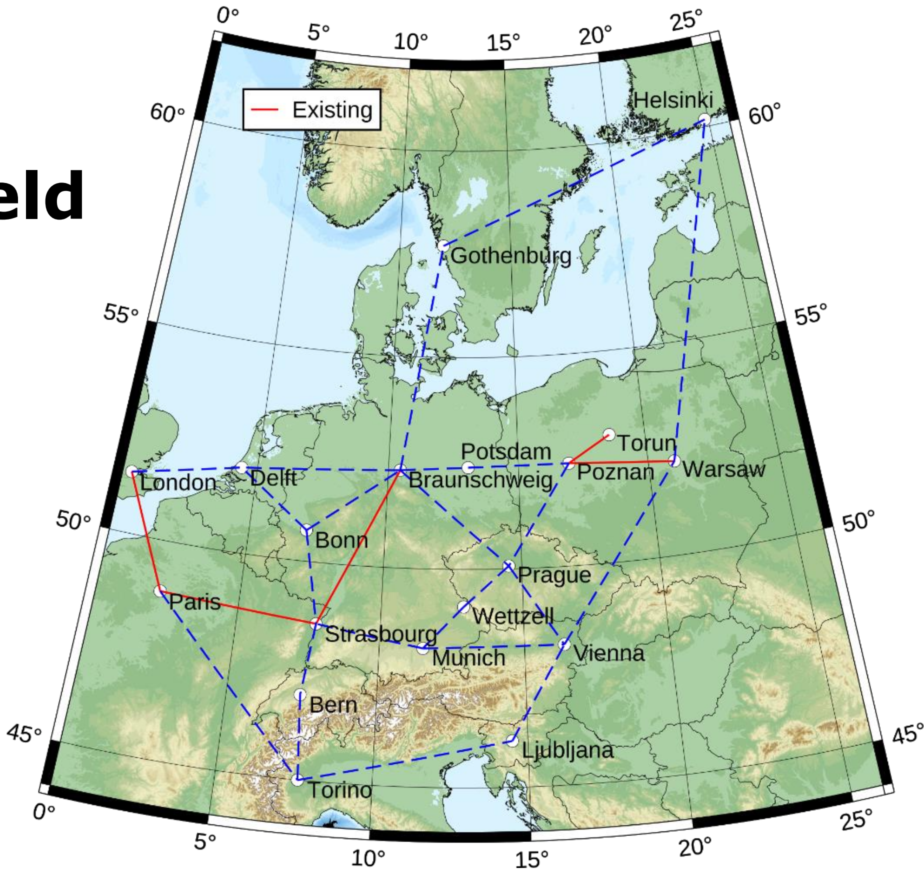
Tapley et al. (2019)

CLONETS

- The CLOck NETwork Services (CLONETS) project aims at developing an optical atomic clock network over Europe connected by fibre links

- How would it benefit **time-variable gravity field determination?**

- Which **accuracies** does it require to detect mass load variations?



Validating GRACE with GNSS

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- GRACE has been validated with **GNSS** measurements

- Main problems:
  - GNSS Comparison to GRACE requires an elastic loading model of the Earth
  - short wavelength signals like **local groundwater discharge and recharge** affects the GNSS but **does not follow elastic loading theory**, i.e. can not be detected with GRACE
  - Technique specific errors (e.g. Ray, 2006)

Validating GRACE with SG's

- If and how **Superconducting Gravimeters** (SG) can be used to validate GRACE, is disputed (see e.g. the discussion between Van Camp et al., 2014 and Crossley et al., 2014)

- Main problem:
  - Local hydrology and wet air mass affect the gravimeters, but not GRACE; they are hard to model

iGRAV043. Photo: Basem Elsaka, Uni Bonn

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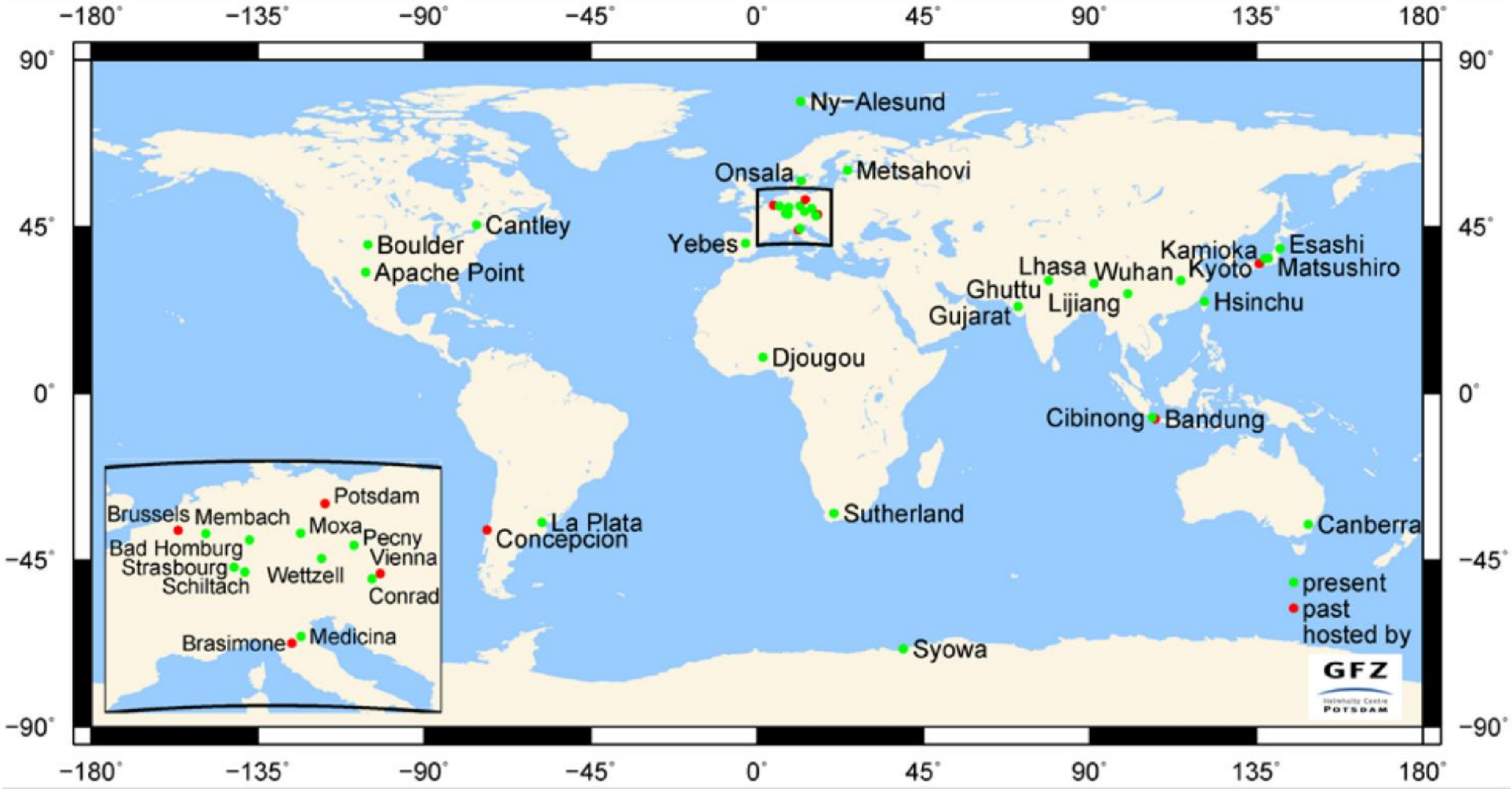
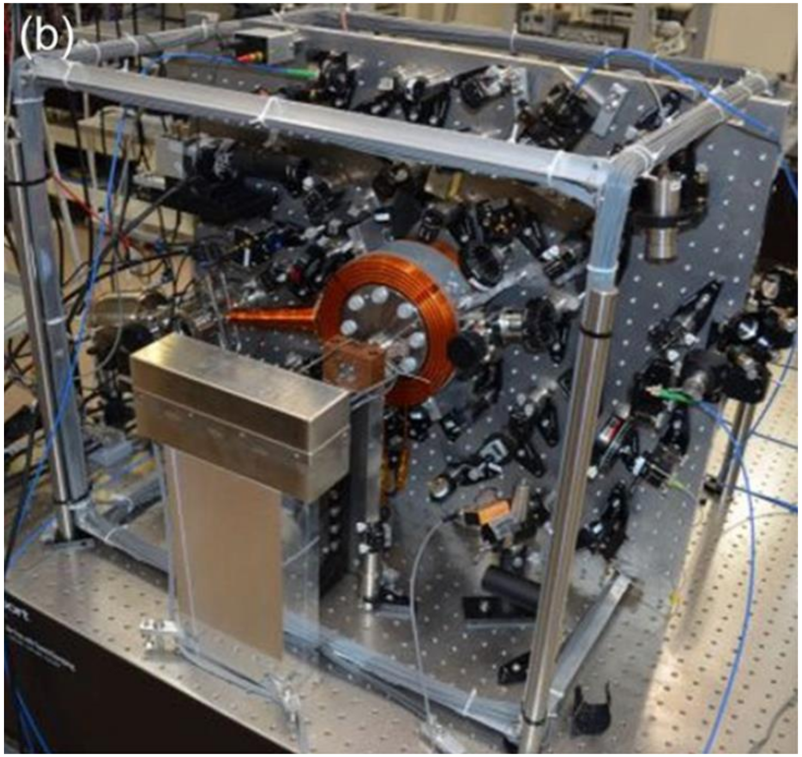
Another problem: heterogenous distribution of SG's



Voigt et al. (2016)

Our objectives

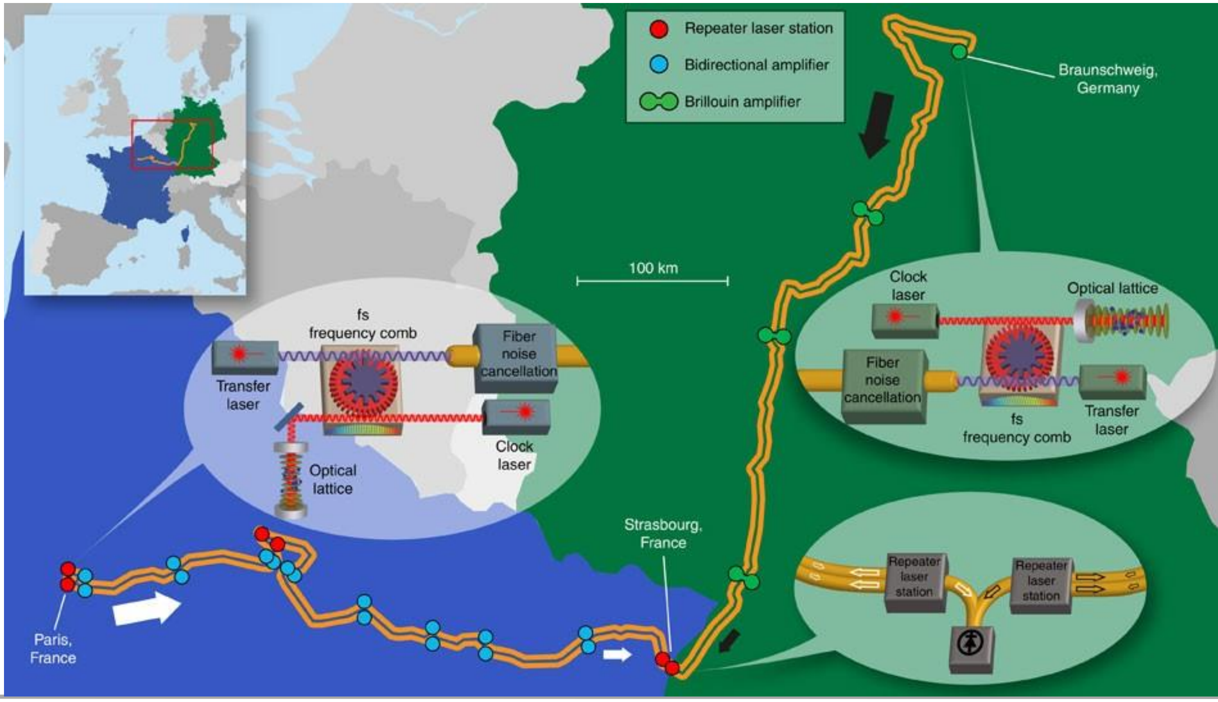
- Here, we suggest that **optical atomic clocks will soon be a third ground measurement tool for GRACE validation,** which is much less affected by local phenomena than GNSS and SG's
- In order to test this hypothesis, in this presentation we will **simulate atmospheric and hydrologic effects on gravity potential**



An optical atomic clock (Takamoto et al., 2015)

Our objectives

- Lisdat et al. (2016) observed gravitational redshift between Paris and Braunschweig due to **height** (and thus potential) **difference**
- We would like to take this one step further and investigate this relativistic effect due to **time-variable potential changes**



Lisdat et al. (2016)

Our objectives

	GRACE	Optical atomic clock network
Temporal resolution	1 month (daily/weekly solutions disregarded)	?
Spatial resolution	> 330 x 330 km $\triangleq l_{max} = 120$ This is rather an optimistic view considering that filters are used afterwards	?
Uncertainty	mm geoid height, averaged over 330 x 330 km	?

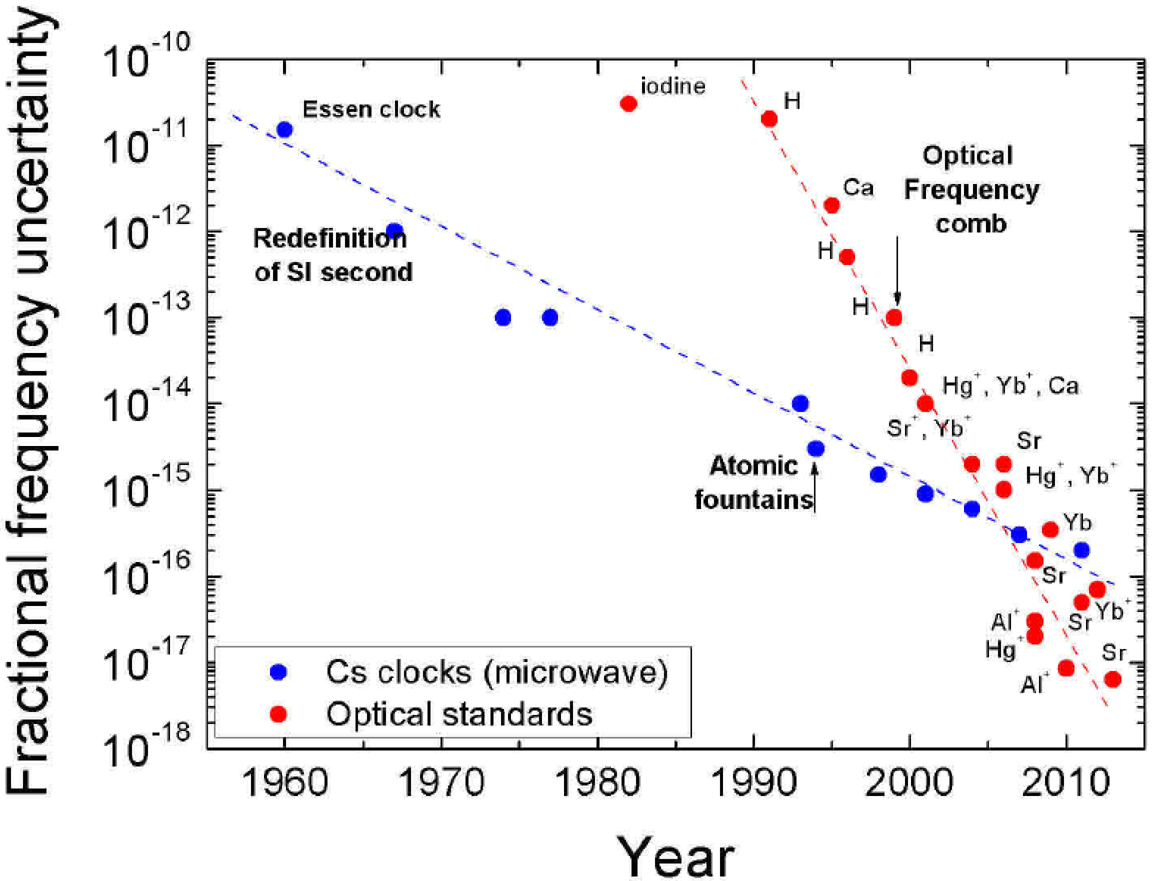
2 – Methods

$$\frac{\delta f}{f} = \frac{\delta U}{c^2} = \frac{\delta N - \delta h}{c^2}\frac{GM}{R^2}$$

- U … gravity potential
  N … geoid height
  h … vertical land motion
  $\frac{\delta f}{f}$ … relative frequency difference
- That means: **1cm** change in geoid height equals $\frac{\delta f}{f}$ of ~**1e-18**
- But: Vertical land motion acts similarly on potential

Optical atomic clock uncertainty

- Poli et al. (2014) show the rapid development of optical atomic clock uncertainty



Optical atomic clock uncertainty

- So, how good are the clocks now?
- Differentiate between a clock's **accuracy** and **stability**
- **Accuracy:** Common in geodesy; limited by systematic effects/drifts
- **Stability:** same as precision/repeatability; sometimes referred to as instability (because this term is proportional to the number)

Optical atomic clock uncertainty

- Case of Bothwell et al. (2019):
  Accuracy of 2.0e-18; this value is reached by the stability ($4.8e{-17}/\sqrt{\tau}$, τ are seconds) after <10 minutes of averaging

- Depending on how fast the accuracy value is reached by averaging, we could obtain **several values of potential difference per hour**

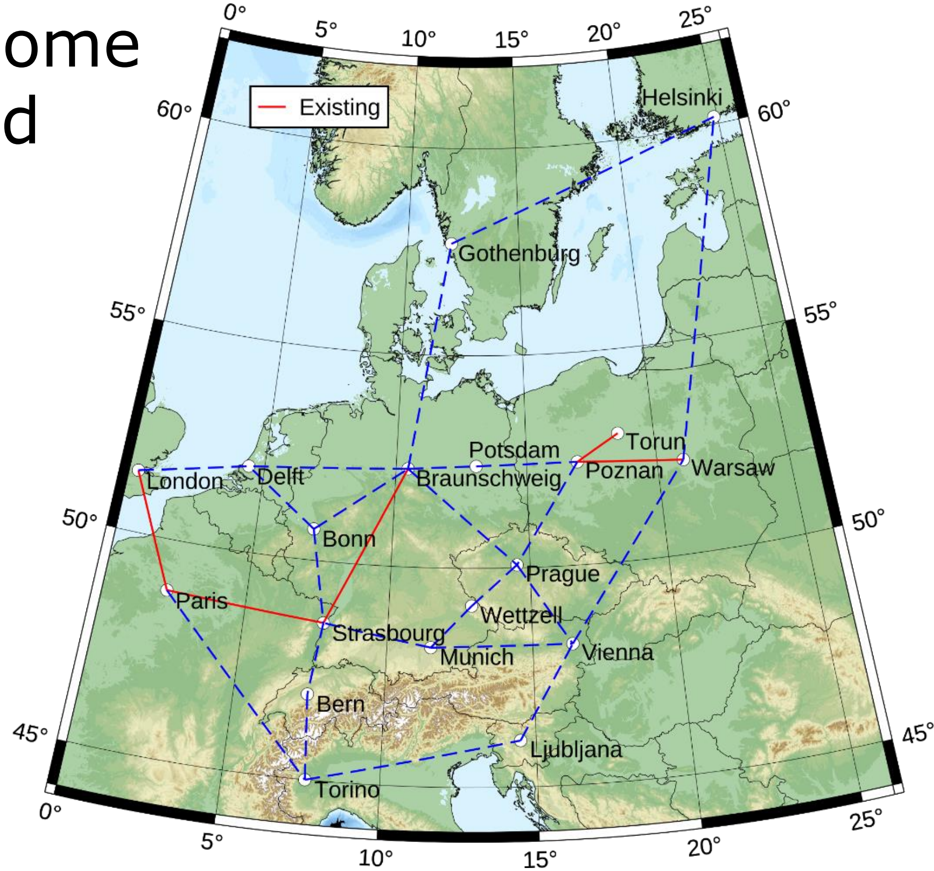
➢ Here, we will simulate **errors at 1e-18** (little bit better than state-of-the-art), **1e-19**, and 1e-20

➢ We will simulate only **one data point per day** here

3 - Results

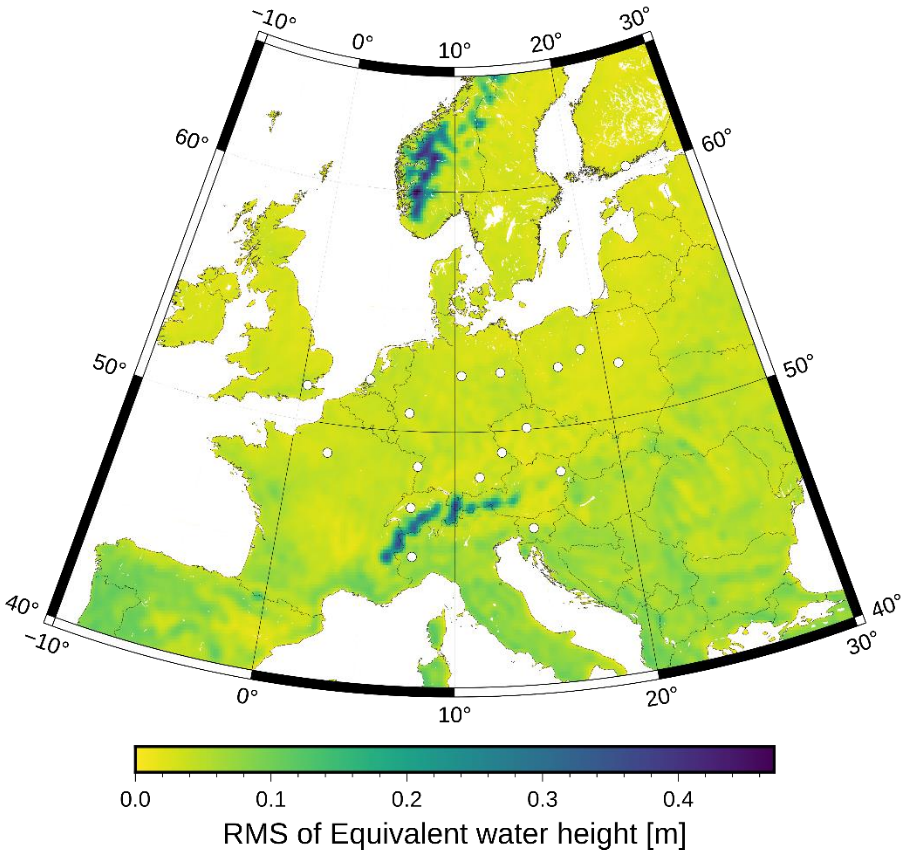
- Optical fibre links are already established between some European National Metrology institutes (NMI) and other (possible) optical clock locations
- We show simulations for some of the existing and planned clocks and links

Location	Institution	Abbr.	Country
Vienna	Federal Office of Metrology and Surveying	**BEV**	Austria
Prague	Association of legal entities	CESNET	Czech Republic
Helsinki	National Metrology Institute of Finland	**MIKES**	Finland
Paris	Time Space Reference Systems, Paris Observatory	**SYRTE**	France
Strasbourg	University	US	France
Braunschweig	Physikalisch-Technische Bundesanstalt	**PTB**	Germany
Bonn	University	UB	Germany
Munich	Technical University	TUM	Germany
Potsdam	GeoForschungsZentrum	GFZ	Germany
Wettzell	Geodetic Observatory	GOW	Germany
Torino	Italian National Metrology Institute	**INRiM**	Italy
Delft	Dutch Metrology Institute	**VSL**	Netherlands
Poznan	Supercomputing and Networking Center	PSNC	Poland
Torun	University	UT	Poland
Warsaw	Central Office of Measures	**GUM**	Poland
Ljubljana	Slovenian Institute of Quality and Metrology	**SIQ**	Slowenia
Gothenburg	National Laboratory for Length and Dimensional Metrology, Research Institutes of Sweden	**RISE**	Sweden
Bern	Federal Institute of Metrology	**METAS**	Switzerland
London	National Physical Laboratory	**NPL**	United Kingdom

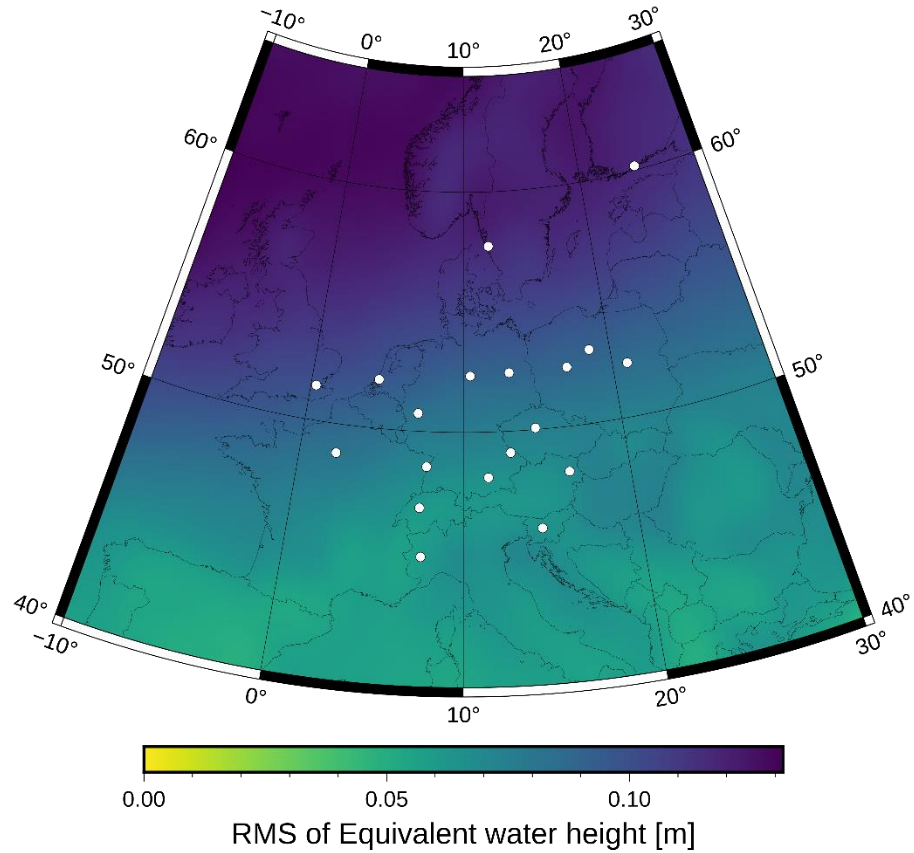


RMS of considered mass variations

- We focus on **hydrology** and **atmosphere**



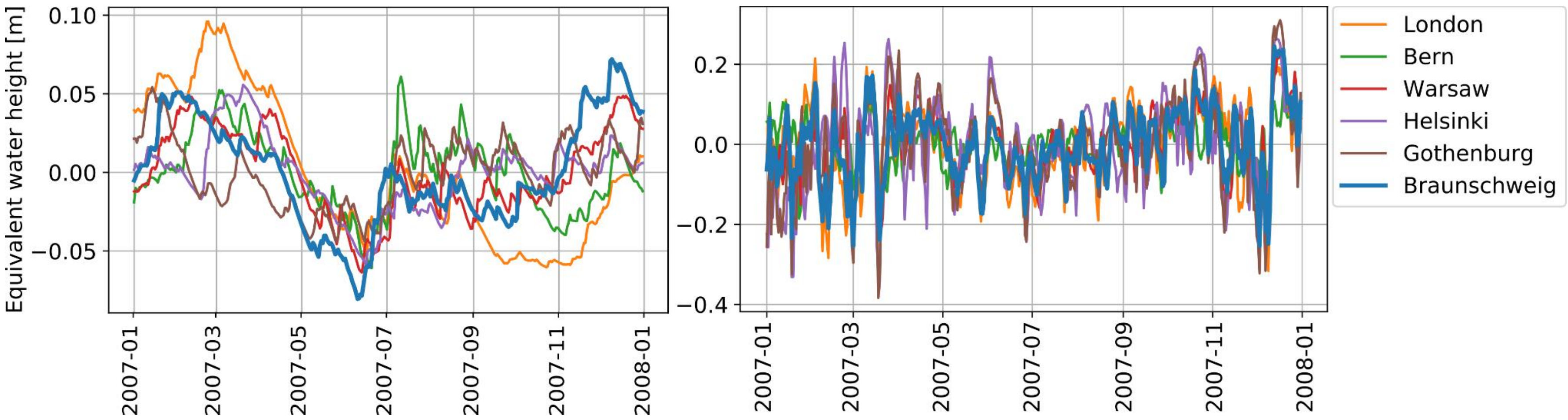
Community Land Model (CLM) Total water storage variability in 2007, expanded to spherical harmonics (l_{max}=720), RMS computed from daily values



Atmospheric mass variability computed after Forootan et al. (2013), from ERA-5 data, expanded to spherical harmonics (l_{max}=180); we consider the elastic loading of the Earth‘s crust via the LLN approach; RMS computed from daily values; dry+wet air

Time series of considered mass variations

- Let’s take a look at some time series at certain clock locations
- Atmospheric part is much **more variable at shorter time scales** and has **higher overall magnitude**
- So what does this mean for fractional frequency measurements?



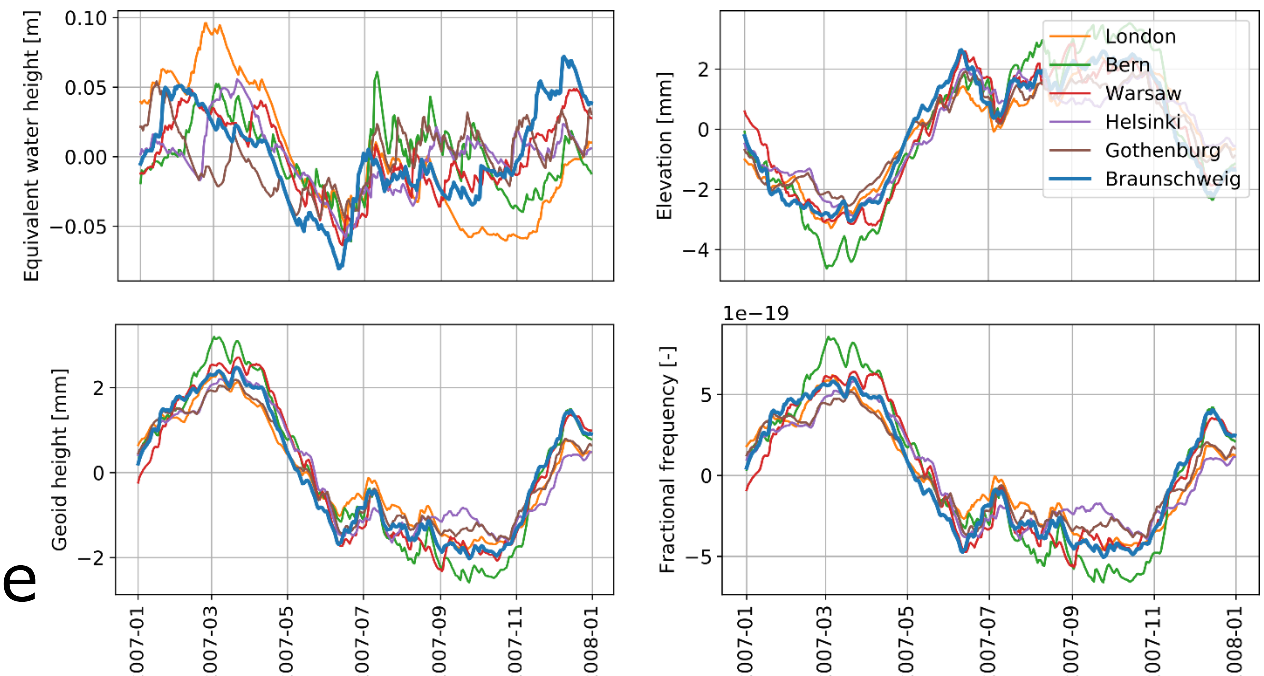
Geoid height and vertical land motion

- **Hydrologic** EWH change + resulting elevation, geoid, and $\frac{\delta f}{f}$

$$\frac{\delta f}{f} = \frac{\delta U}{c^2} = \frac{\delta N - \delta h}{c^2} \frac{GM}{R^2}$$

- Clear annual signal; geoid change and elevation go in opposite directions, but their effect on potential goes in the same direction

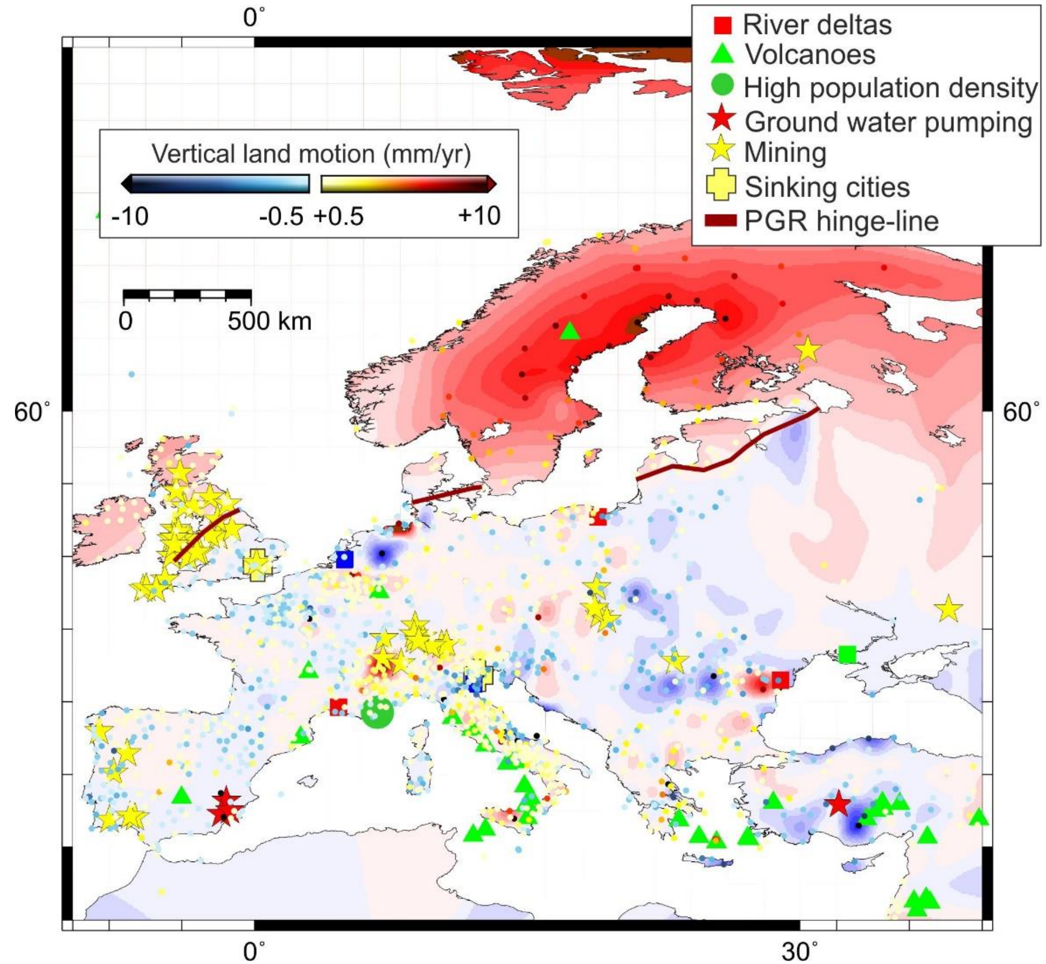
➢ To infer geoid change from $\frac{\delta f}{f}$, we have to correct for land elevation change



GNSS required

- Effects like local groundwater changes do not follow elastic loading theory:
- Vertical land motion that is not associated with much geoid change

➢ **GNSS as correction for the resulting potential change is inevitable**



Effects on vertical land motion apart from elastic loading.
Source: Anna Klos, NEROGRAV project presentation (2019).

Atmosphere for comparison

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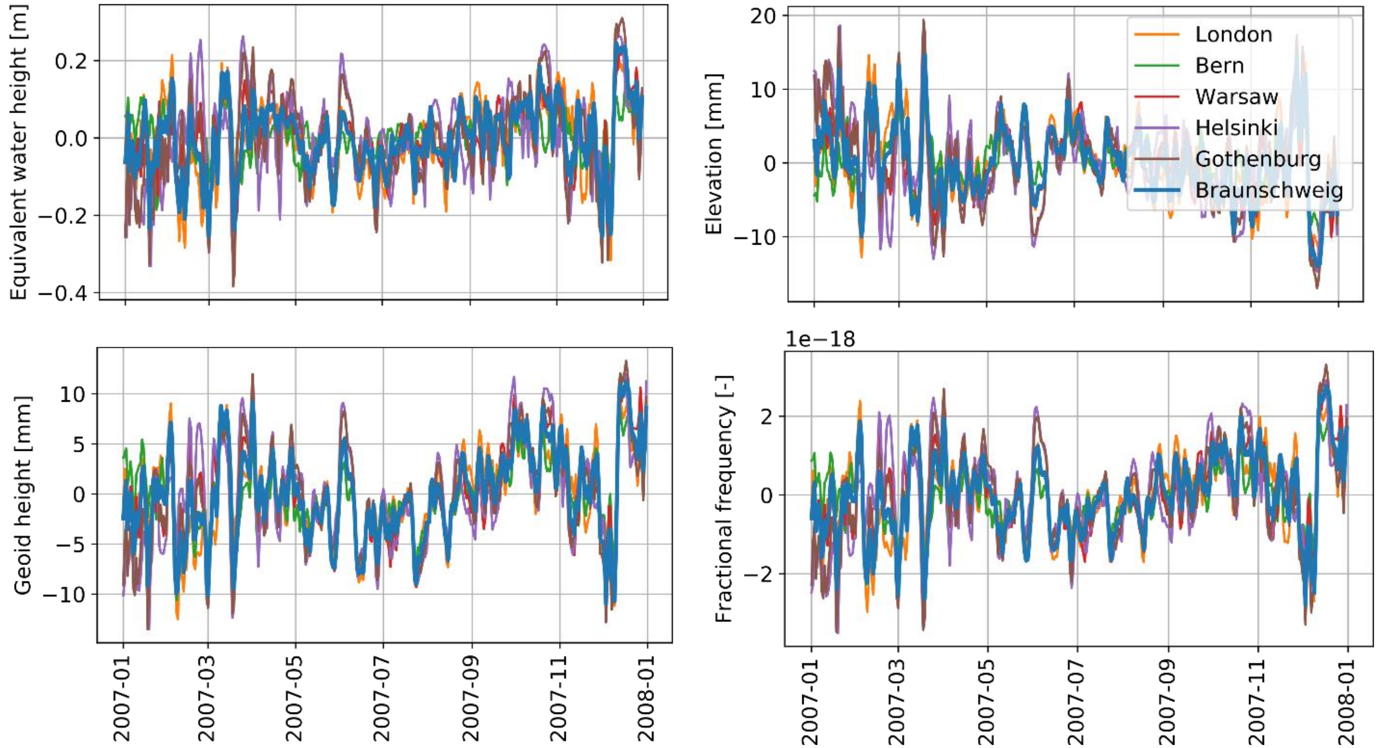
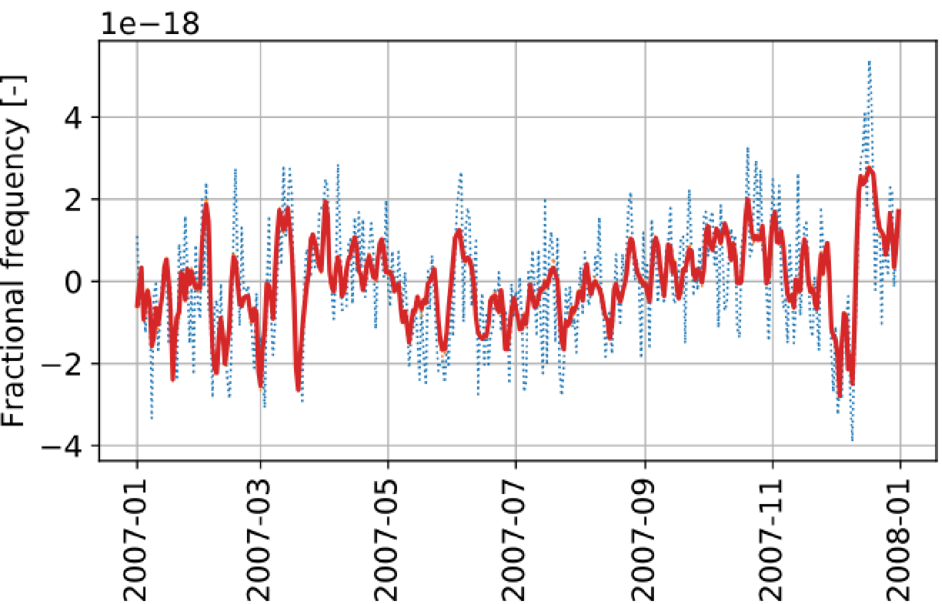
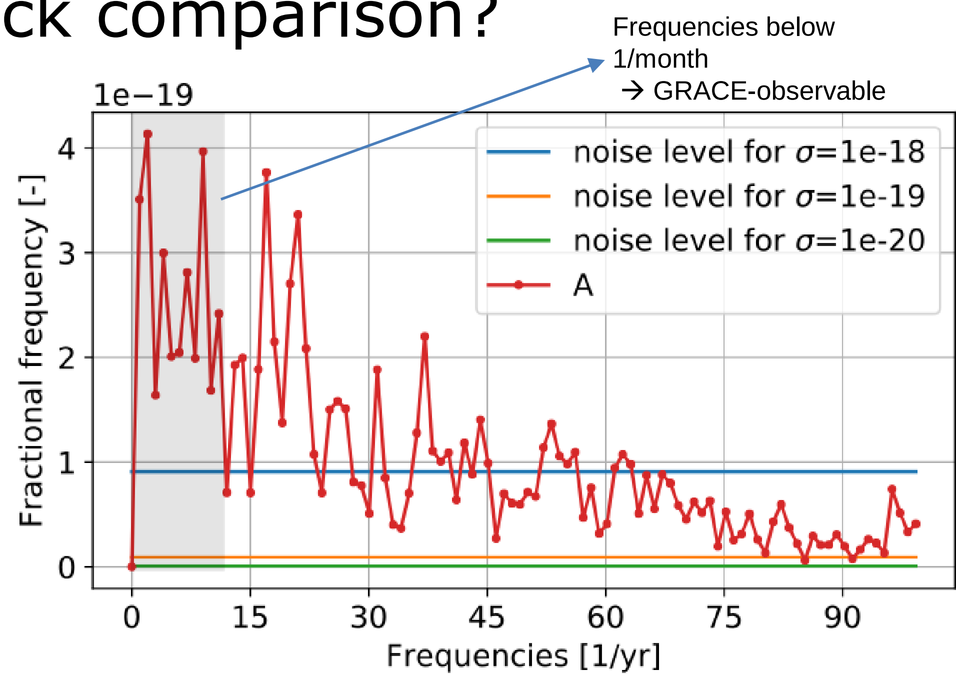
- 3-4 times higher effect on $\frac{\delta f}{f}$
- Let's take one time series and make some **assumptions for errors**



PTB Braunschweig

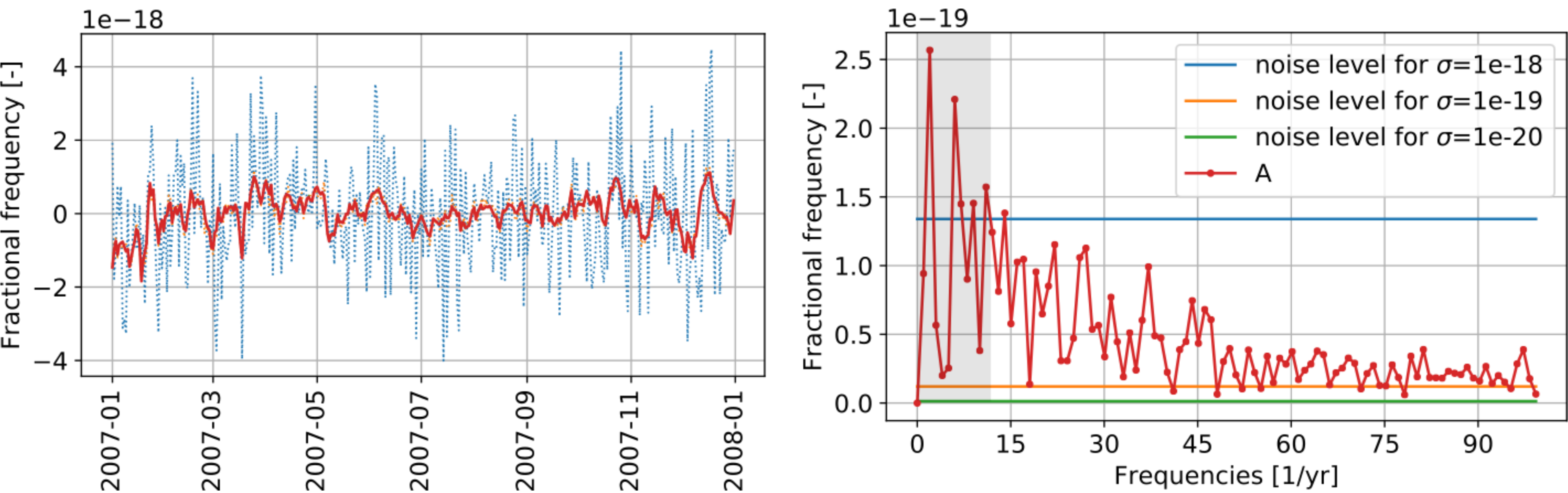
- Braunschweig (Physikalisch-Technische Bundesanstalt) – time series and amplitude spectrum
- Modelled **white noise with** $\boldsymbol{\sigma = 1e - 18\ (19,\ 20)}$
- Signal larger than noise
- But: We are only observing a single clock … How does it look for a clock comparison?





Bern – Braunschweig clock comparison

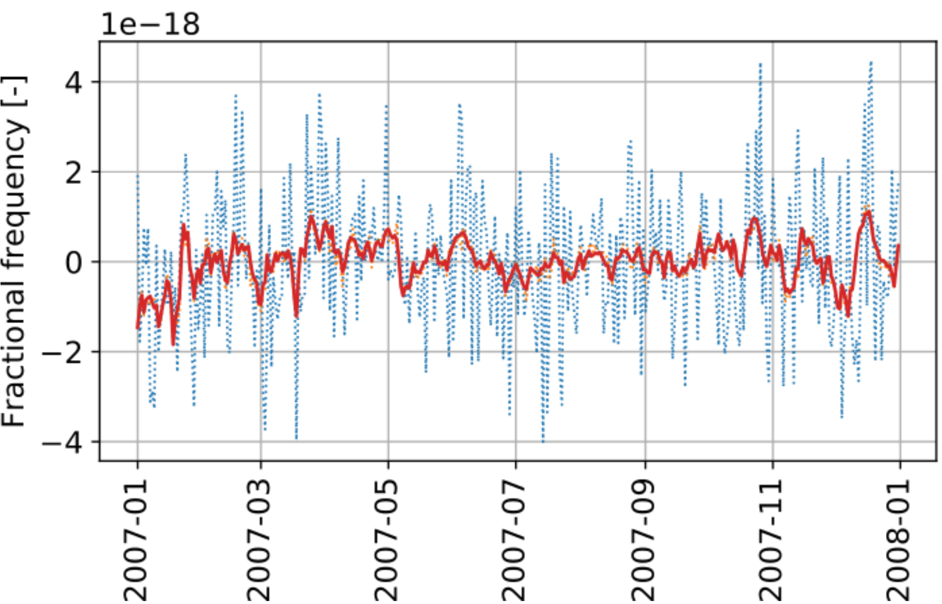
- White **noise is now larger** ($\sigma = \sqrt{2}e - 18\ \ (19,\ 20)$)
- **Signal is smaller** because large scale/low degree signals vanish
- Only a few frequencies of the amplitude spectrum visible for clock uncertainty of 1e-18 $\frac{\delta f}{f}$

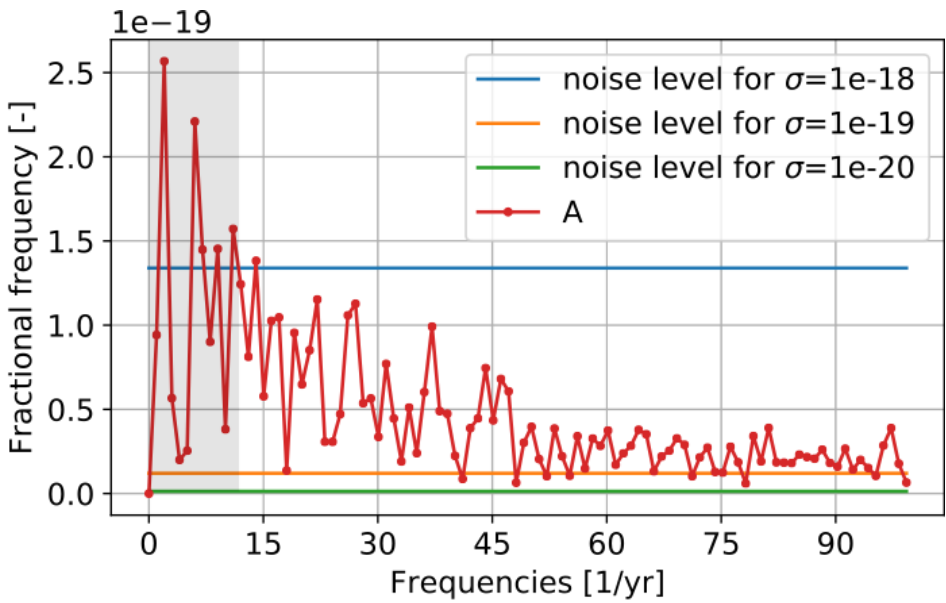


Bern – Braunschweig clock comparison

- **An optical clock network at NMI locations with clock uncertainty of 1e-18 is not able to detect time-variable gravity over Europe**

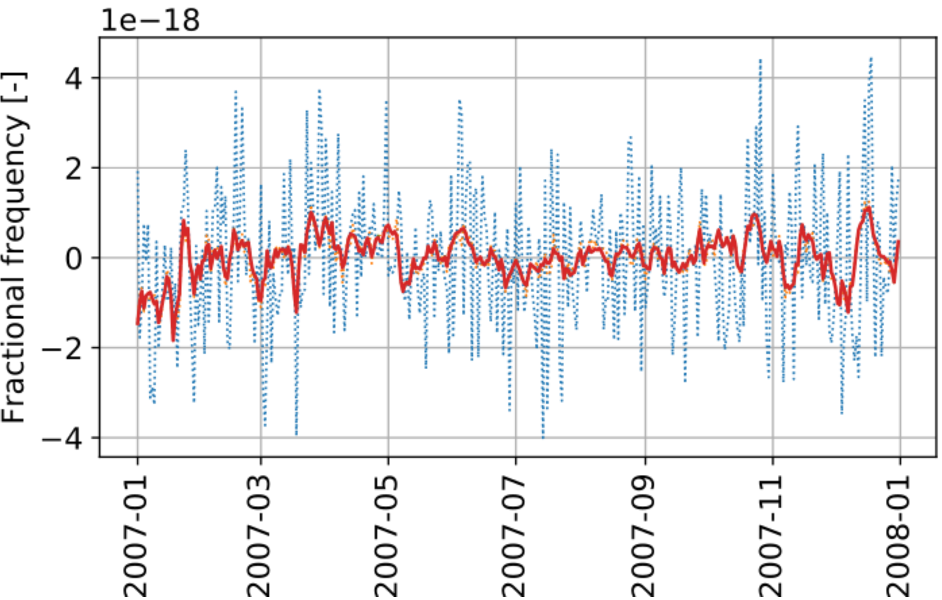
- Let's go down one magnitude

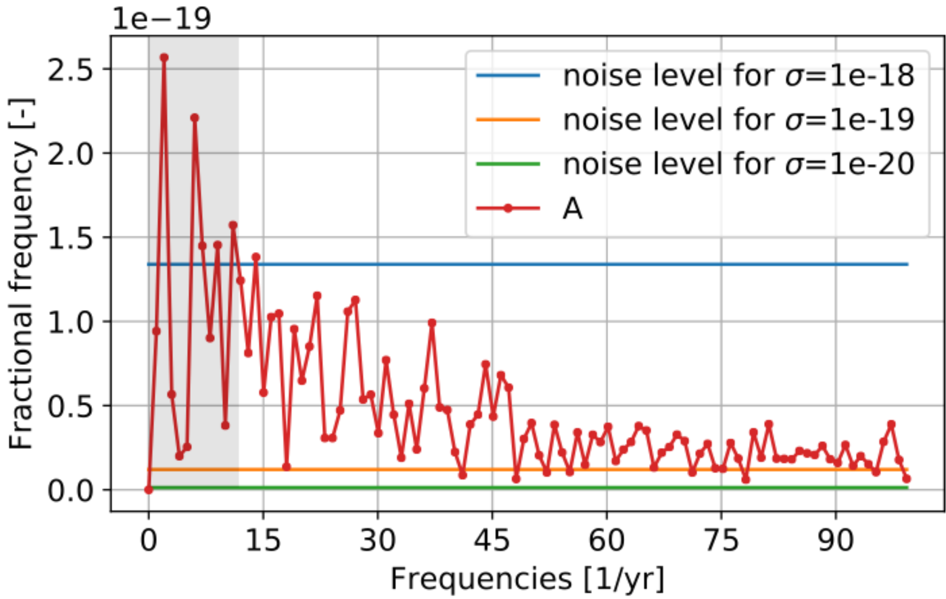




Bern – Braunschweig clock comparison

- The √2e-19 noise in orange can hardly be seen on the time series
- It's also way below almost all frequencies in the amplitude spectrum
- ➢ **Clocks with uncertainty of 1e-19 could very well detect atmospheric changes over Europe**





Bern – Braunschweig clock comparison

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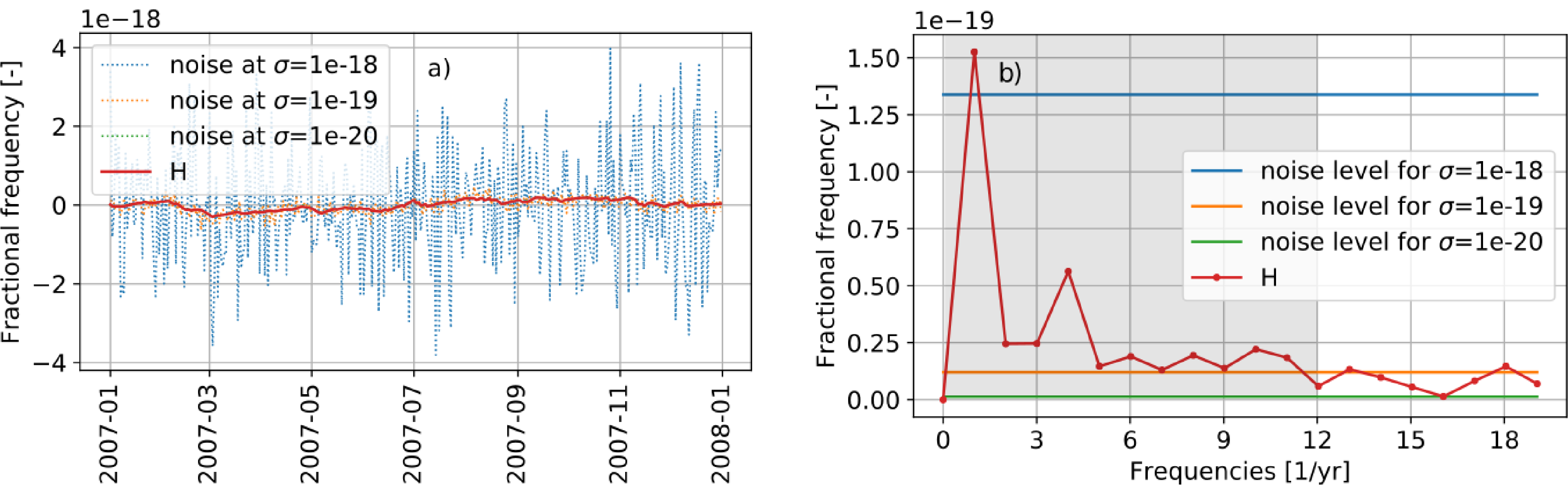
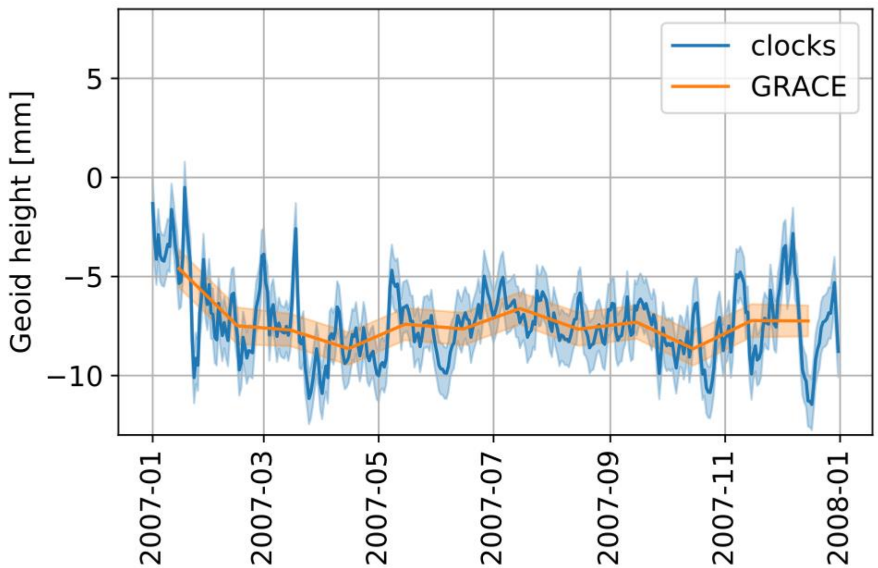
- For **hydrology** the noise of 1e-19 becomes critical as the variations in $\frac{\delta f}{f}$ are at ± 2e-19

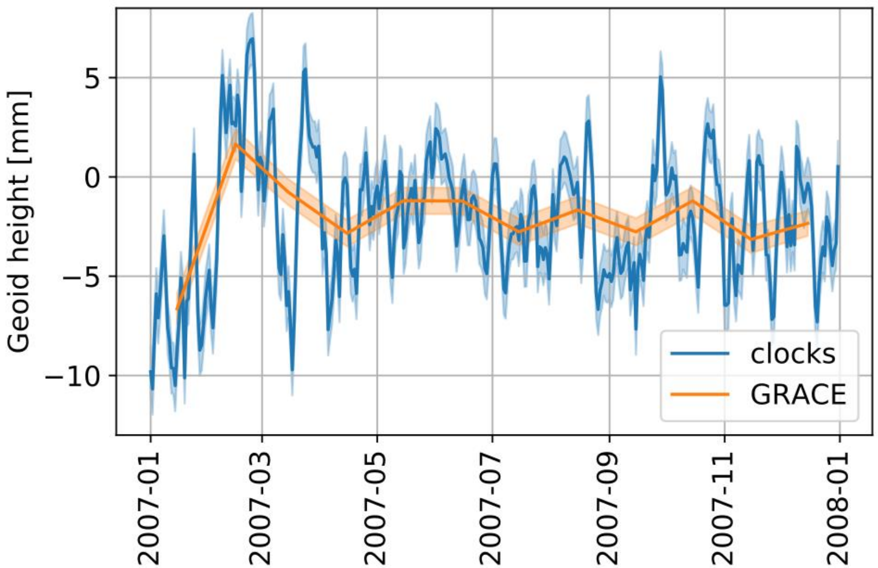
- Clocks with an uncertainty of 1e-19 would be just about able to detect **hydrologic changes over Europe;** which is small compared to other continents



Comparison of optical atomic clock network and GRACE

- Compare that to GRACE: simulate GRACE measurements + errors at clock locations
- We assumed to be able to correct for land elevation change below the mm-level





4 - Summary

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- Which accuracies do we need for proper validation?
  - **largest time-variable signals detectable at 1e-18** (~1cm geoid height) accuracy of clocks
  - To actually use an optical atomic clock network to validate GRACE or next generation gravity missions (NGGM) we need to go below that level: **At 1e-19** (~1mm) **we reach a point where only short time hydrological variations pose a problem.**
    Here, the correction factor GNSS reaches its limits as well

Resolution and Uncertainty

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	GRACE	Optical atomic clock network
Temporal resolution	1 month (daily/weekly solutions disregarded)	At least daily, maybe even < 1 hour
Spatial resolution	> 330 x 330 km $\triangleq l_{max} = 120$ This is rather an optimistic view considering that filters are used afterwards	< 3000 km (depending on extent of the network) $\triangleq l_{min} = 13$ > 100 km (depending on clock distribution) $\triangleq l_{max} = 400$
Uncertainty	mm geoid height, averaged over 330 x 330 km	Right now: Few cm geoid height (but rapidly improving, possibly at 1mm in the next decade), point-wise

Validation tools

<table>
<tr><th>SG</th><th>GNSS</th><th>Optical atomic clock network</th></tr>
<tr><td>Measures gravity variations

Often highly affected by direct gravitational effect of local hydrologic changes</td><td>Measures (vertical) land motion

Good distribution of stations with free available data

Affected by local land motion that is not aligned with elastic loading</td><td>Measures geopotential differences

Rapidly improving technology

Clocks sitting on the surface measure the vertical land motion induced potential change</td></tr>
<tr><td></td><td colspan="2">Combination allows for direct estimation of geoid height variations</td></tr>
<tr><td colspan="3">Combination might be interesting e.g. for a better SG signal separation</td></tr>
</table>

Thank you

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Paper in preparation:
Schröder et al.

Thank you for taking the time to go through our slides!

We are looking forward to the online discussions before, after, and during the actual **session at May 7th**

You can also write me an Email:
schroeder@geod.uni-bonn.de

References

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- *Bothwell et al. (2019): JILA SrI optical lattice clock with uncertainty of 2.0 x 10^{-18}.* https://doi.org/10.1088/1681-7575/ab4089
- *Crossley et al. (2014): Comment on: 'The quest for a consistent signal in ground and GRACE gravity time-series', by Michel Van Camp, Olivier de Viron, Laurent Metivier, Bruno Meurers and Olivier Francis.* https://doi.org/10.1093/gji/ggu259
- *Forootan et al. (2013): Comparisons of atmospheric data and reduction methods for the analysis of satellite gravimetry observations.* https://doi.org/10.1002/jgrb.50160
- *Lisdat et al. (2016): A clock network for geodesy and fundamental science*. https://doi.org/10.1038/ncomms12443
- *Ludlow et al. (2015): Optical atomic clocks.* https://doi.org/10.1103/RevModPhys.87.637
- *Pail et al. (2015): Science and User Needs for Observing Global Mass Transport to Understand Global Change and to Benefit Society*. https://doi.org/10.1007/s10712-015-9348-9
- *Poli et al. (2014): Optical atomic clocks.* https://doi.org/10.1393/ncr/i2013-10095-x
- Ray (2006): *Systematic errors in GPS position estimates. paper presented at IGS Workshop 2006.* Available at acc.igs.org/trf/igs06-errors.ppt
- *Takamoto et al. (2015): Frequency ration of Sr, Yb, and Hg based optical lattice clocks and their applications .* https://doi.org/10.1016/j.crhy.2015.04.003
- *Van Camp et al. (2014): The quest for a consistent signal in ground and GRACE gravity time-series.* https://doi.org/10.1093/gji/ggt524
- *Voigt et al. (2016): Report on the Data Base of the International Geodynamics and Earth Tide Service (IGETS).* https://doi.org/10.2312/GFZ.b103-16087