Geodetic SAR for Sea Level and Height System Unification in the Baltic

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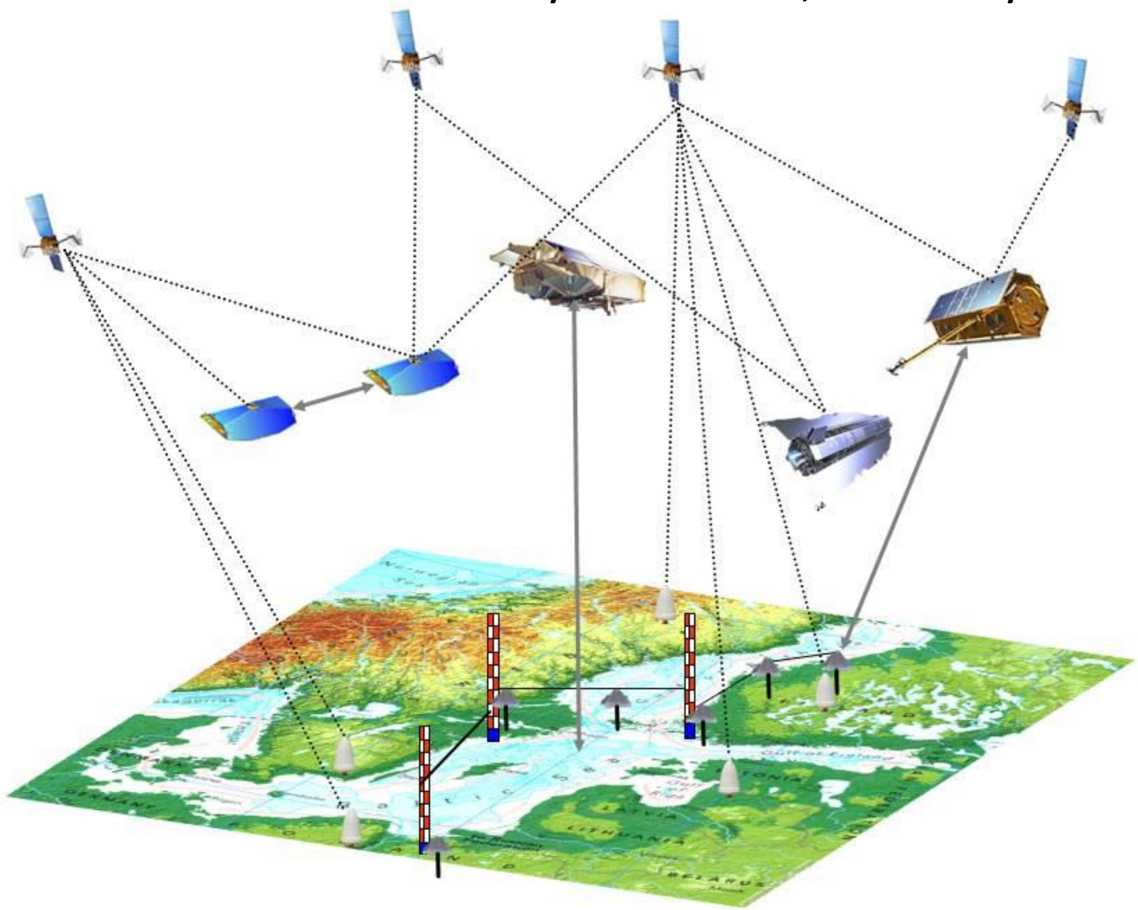
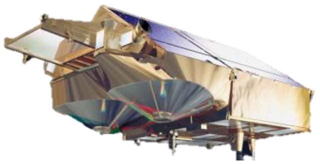


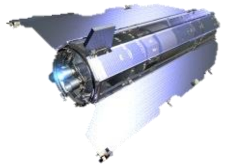
Outline

- Introduction Height Systems & Sea Level

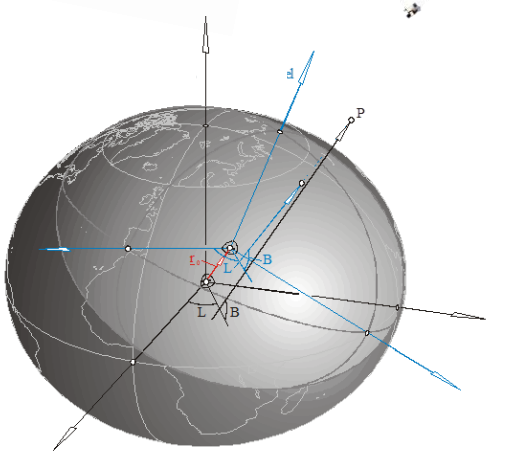
- Tide Gauges as Sea Level Sensor and Height Systems Reference


- Geometric EO Sensors

- Gravimetric EO Sensors

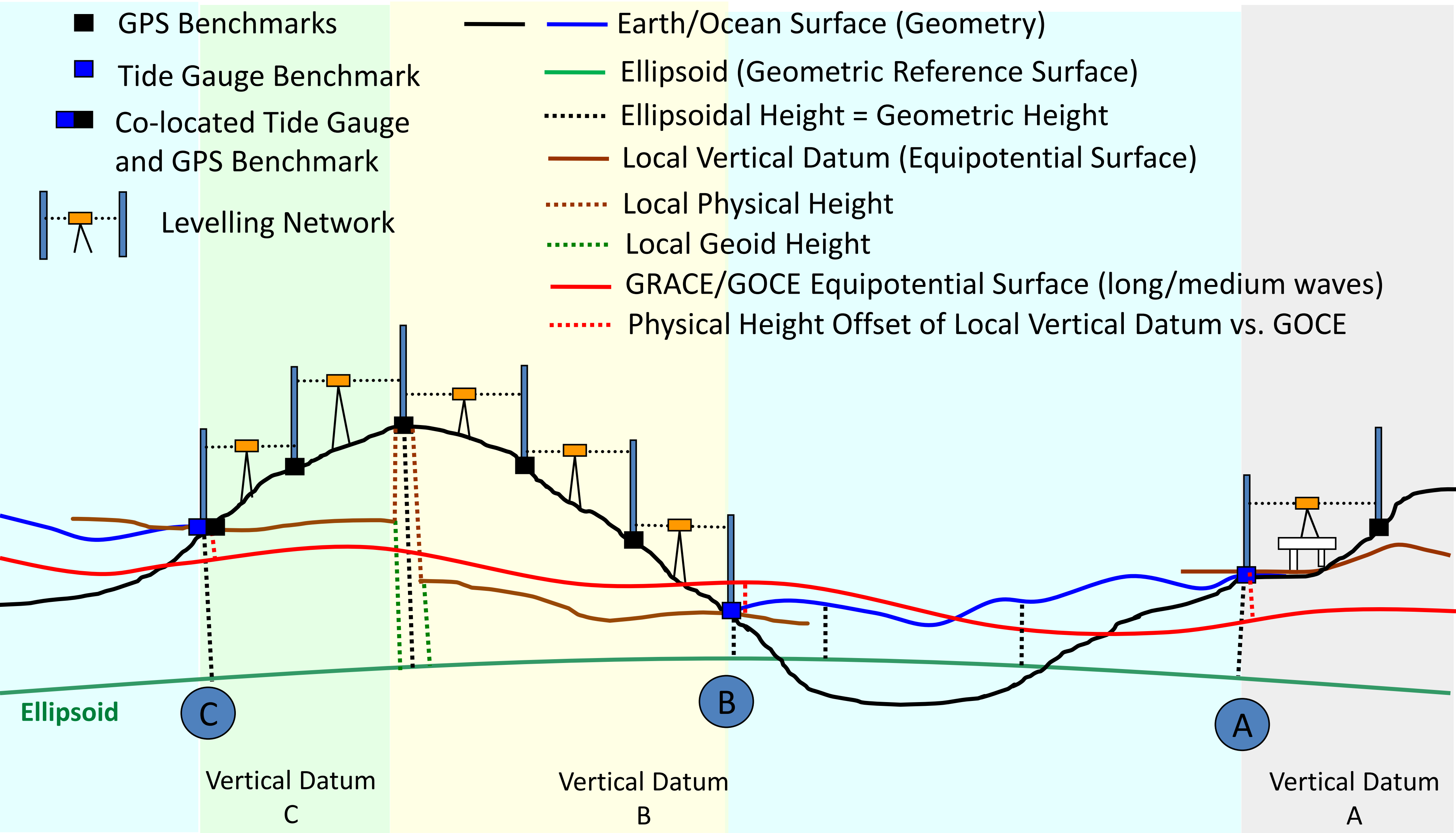


- Geometric & Gravimetric Reference Frames Consistency

- Summary & Conclusions

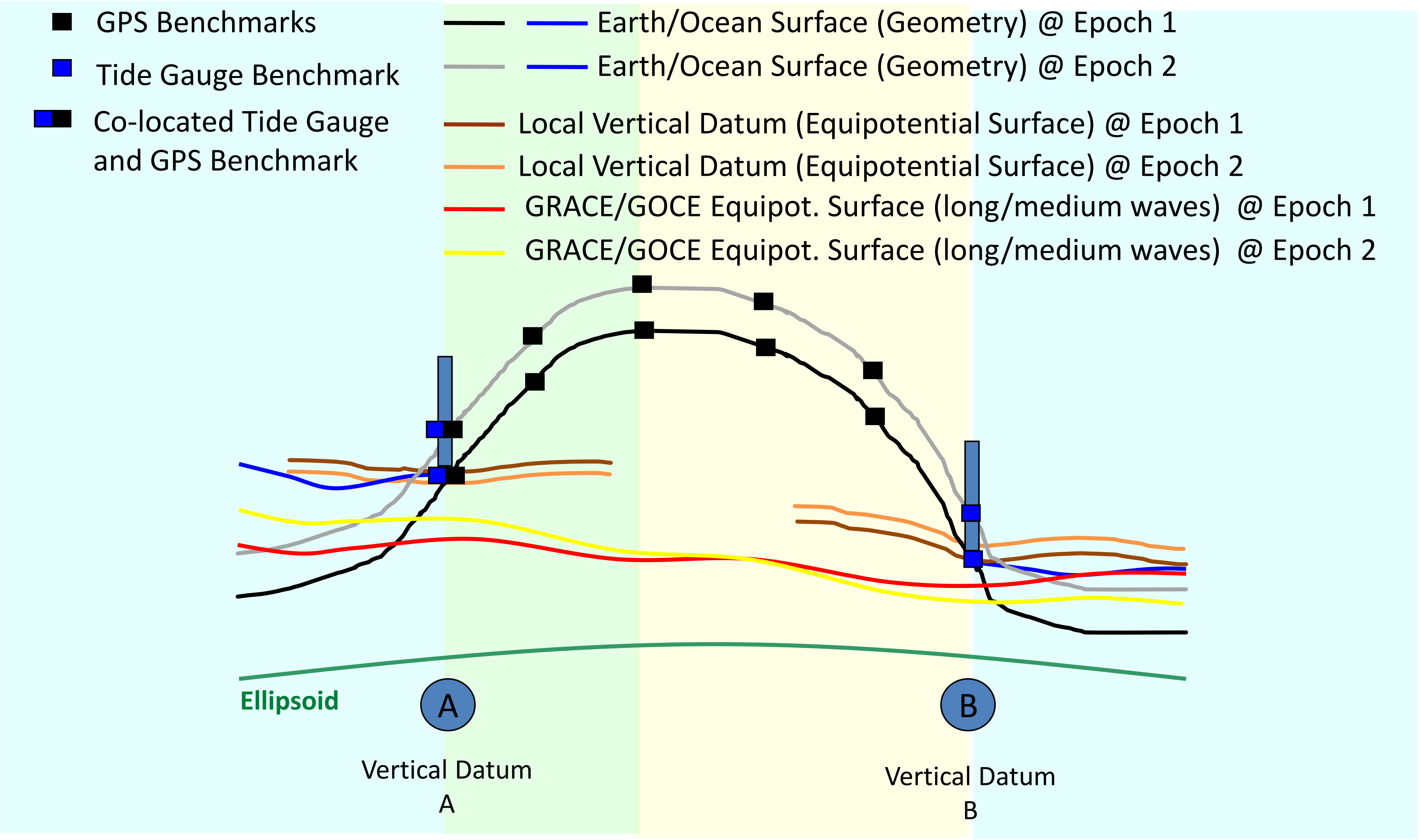
Introduction Height Systems & Sea Level

Geometrical and Physical Shape of the Earth – **Static Case**



Introduction Height Systems & Sea Level

Geometrical and Physical Shape of the Earth – **Dynamic Case**



Introduction Height Systems & Sea Level

Questions to be discussed

Absolute sea level observations, height system unification and GNSS-Levelling require the knowledge of the global static geoid.

- ➢ What is the role of the GOCE static geoid?

For GNSS-Levelling geometric and gravimetric reference frames need to be compatible.

- ➢ What is the impact of reference frame incompatibilities?

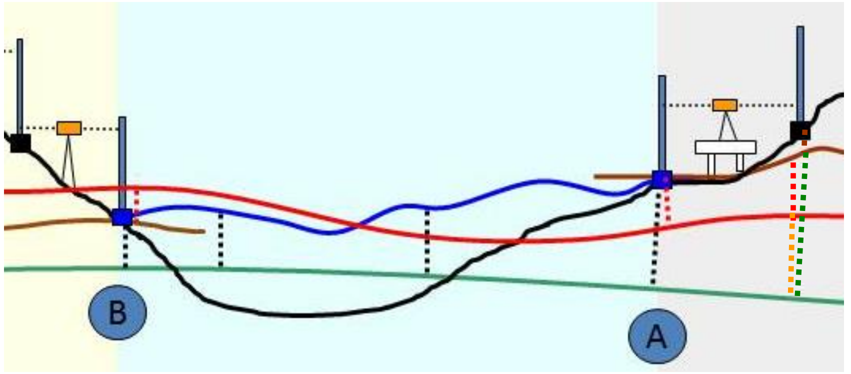
Sea level observations require knowledge about vertical changes of the geometric shape of the Earth.

- ➢ How can vertical changes of land be observed on a systematic base?

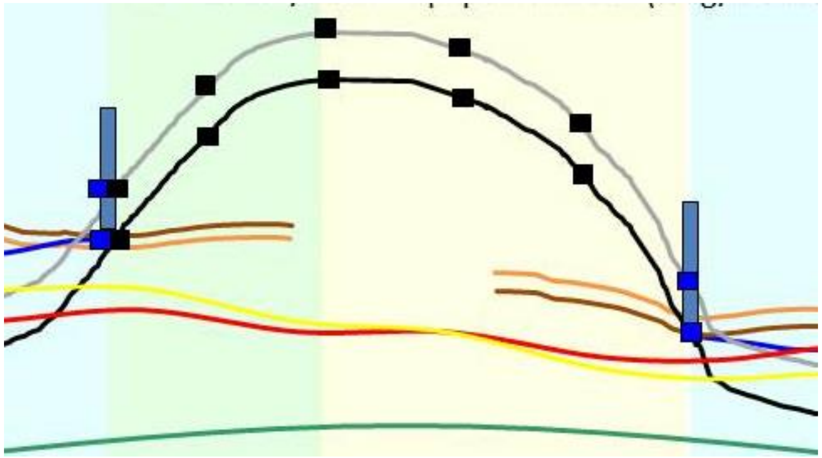
Mass variations cause variations of the reference equipotential surface. This has impact on absolute sea level observations, height systems and GNSS-Levelling.

- ➢ What is the impact of mass variations and how can it be observed?

Static Case

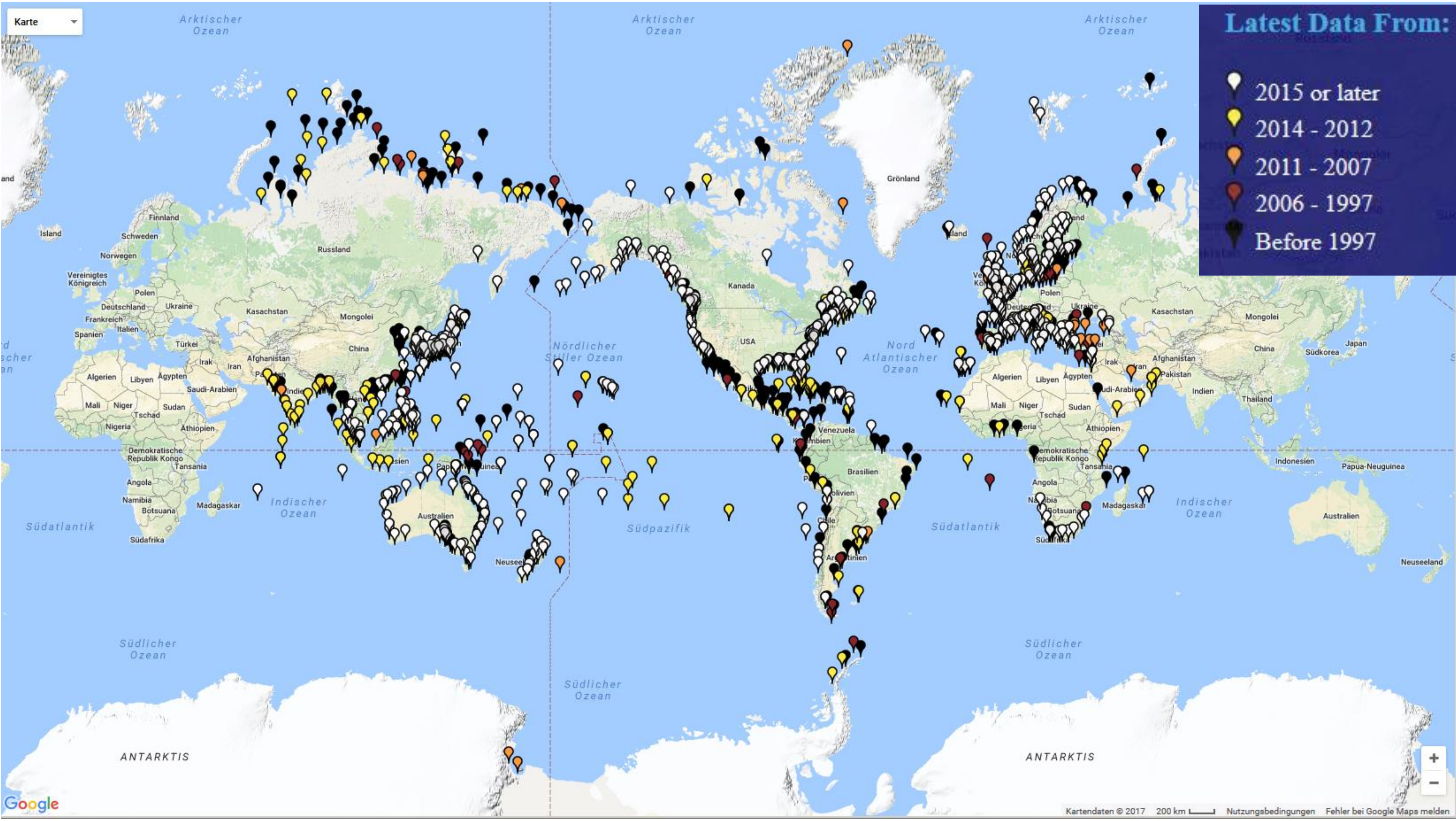


Dynamic Case



Tide Gauges

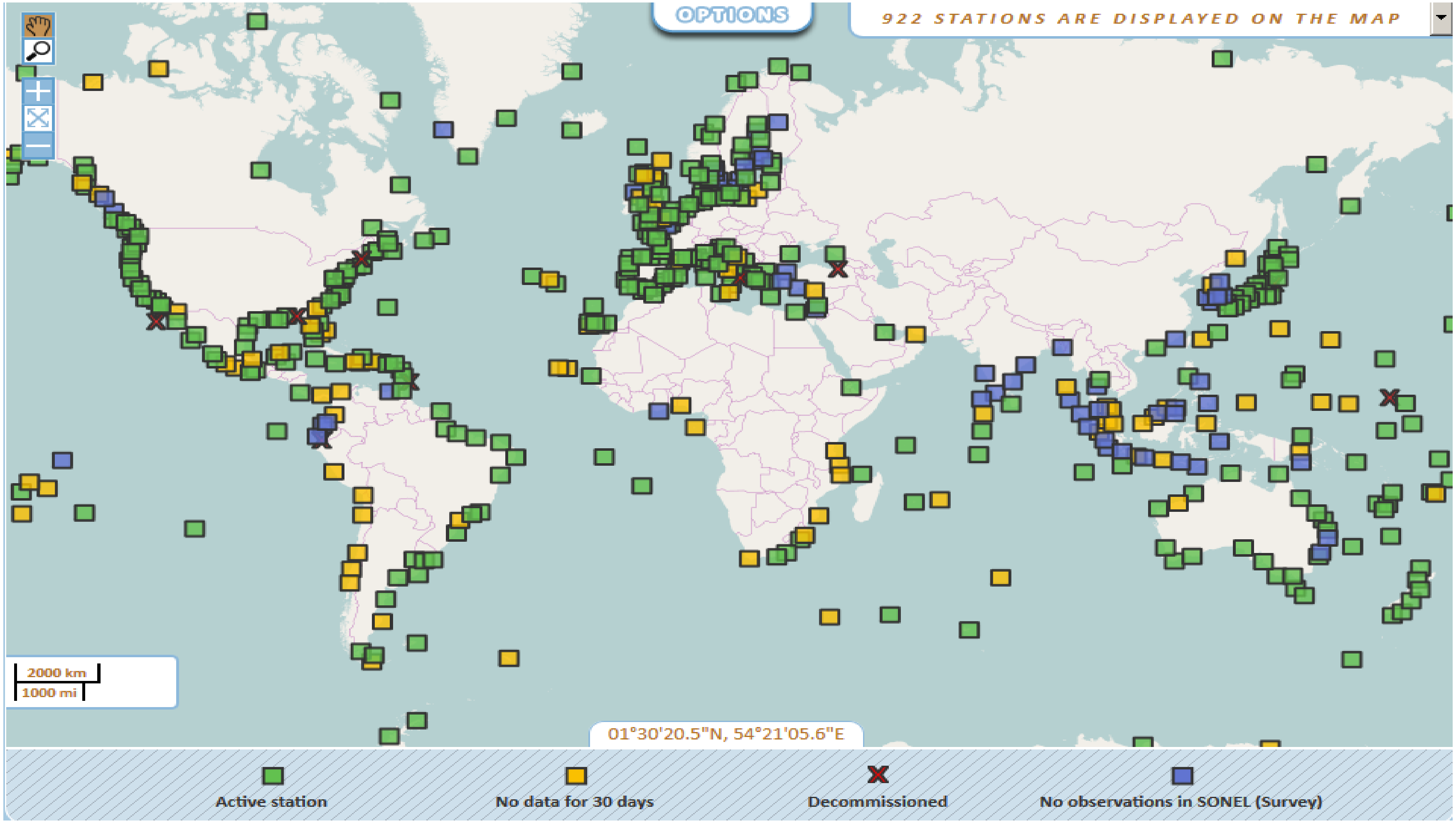
Permanent Service for Mean Sea Level (PSMSL) – Status Feb. 2017



Geometric EO Sensors - GNSS

How can vertical changes of land be observed on a systematic base?

Tide gauges co-located with permanent GPS stations within 10-15 km distance



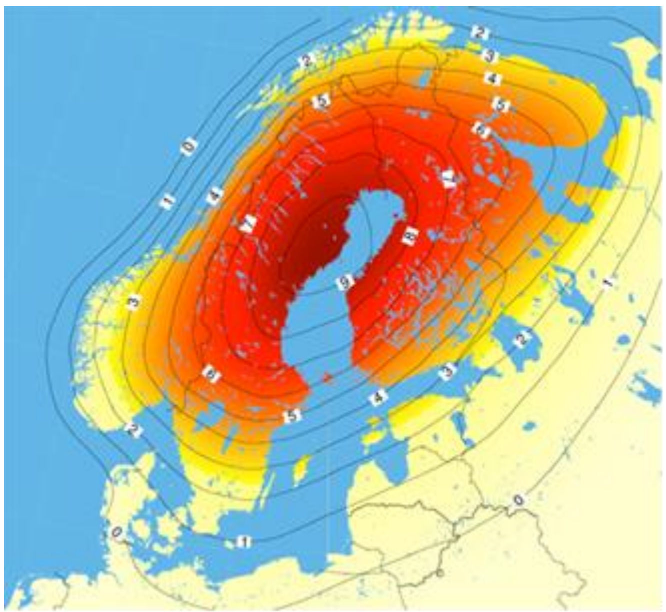
from SONEL http://www.sonel.org

Geometric EO Sensors - GNSS

How can vertical changes of land be observed on a systematic base?

Observation of vertical movement of tide gauge stations in the Baltic Sea by GPS

Baltic Sea is a very good test area due to post-glacial rebound signal.

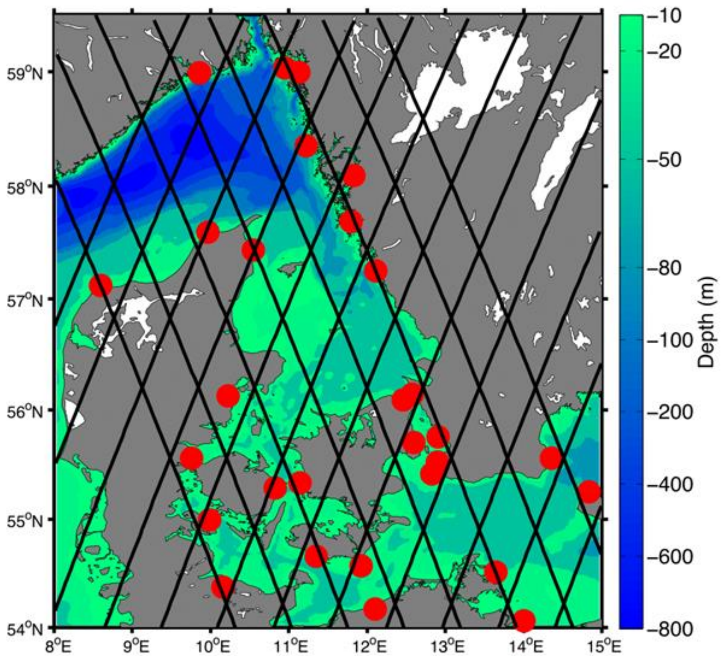


Postglacial land uplift in Scandinavia in [mm/yr]
[http://www.fgi.fi/fgi/themes/land-uplift]

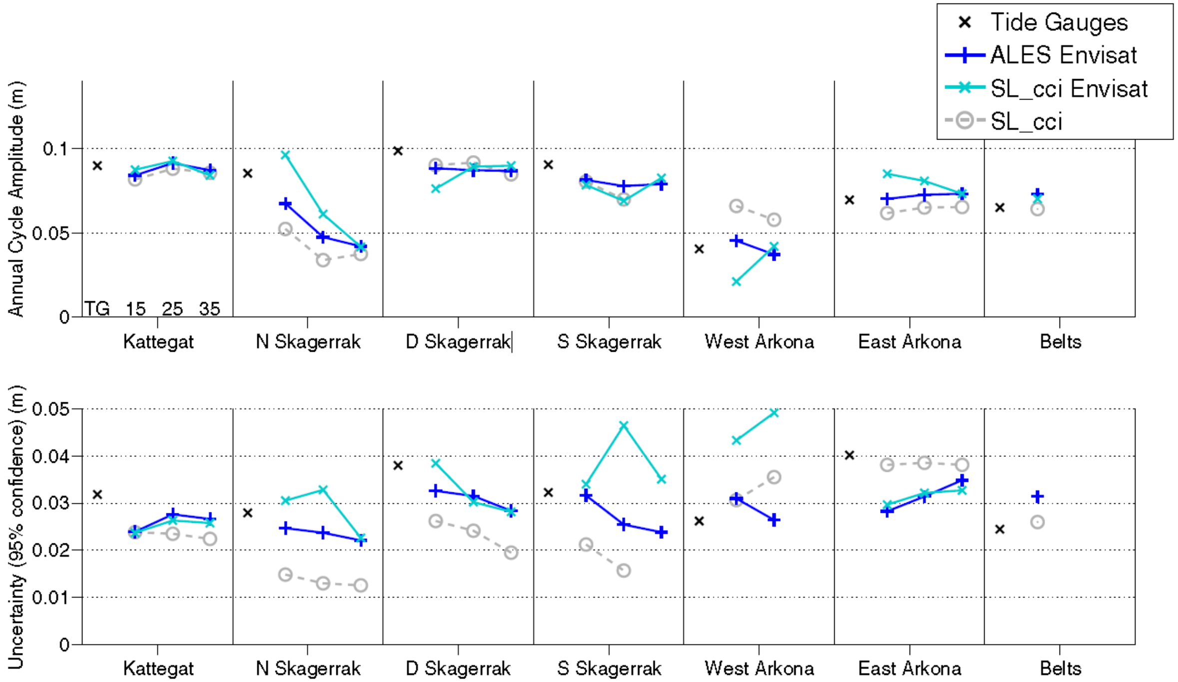
Geometric EO Sensors - Altimetry

How can vertical changes of land be observed on a systematic base?

Coastal altimetry can be a technique to link the geometric shape of the oceans with the geometric shape of land at tide gauges and ist temporal changes.



The red circles are the locations of the tide gauges and the black lines are Envisat track.



Estimates of the amplitude of the (top) annual cycle of the sea level and corresponding uncertainty at 95% level for each subbasin from TG data (black cross) and altimetry within 15 km of the coast, from 15 to 25 km and from 25 to 35 km (left to right in each subbasin box).

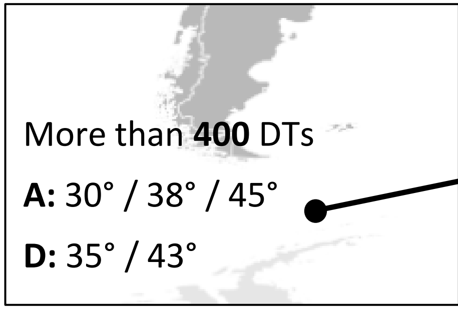
(both from Passaro, M., P. Cipollini, and J. Benveniste (2015), Annual sea level variability of the coastal ocean: The Baltic Sea-North Sea transition zone, J. Geophys. Res. Oceans, 120, doi:10.1002/2014JC010510.

Geometric EO Sensors - SAR

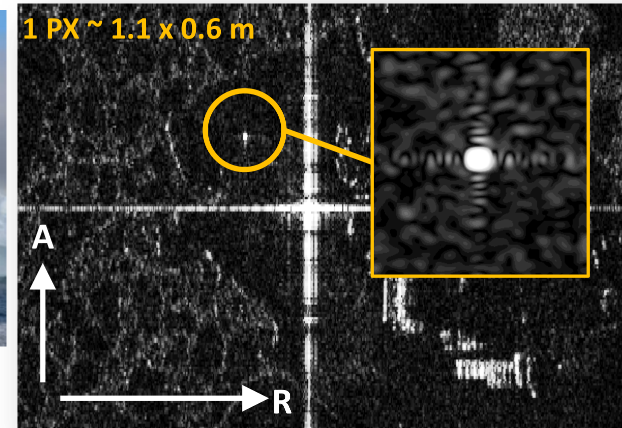
How can vertical changes of land be observed on a systematic base?

Absolute geodetic SAR positioning

TerraSAR-X data since 03/13



2 corner reflectors with known reference coordinates (< 5 mm)

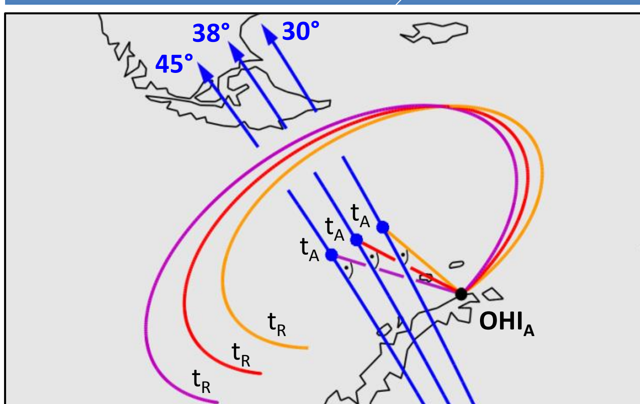


Radar Timings
- Range t_R
- Azimuth t_A

Corrections
- Atmosphere
- Geodynamics
- Calibration

3D Solution
- Corrected Observations
- Orbit

Results
- Coordinates
- Statistics



CR	Coordinates ΔN [cm]	Coordinates ΔE [cm]	Coordinates ΔU [cm]	Statistics (95%) s_N [±cm]	Statistics (95%) s_E [±cm]	Statistics (95%) s_U [±cm]
OHI_A	-1.5	-1.2	-0.5	1.1	1.9	1.6
OHI_D	-1.4	-1.5	0.3	2.1	4.2	3.7

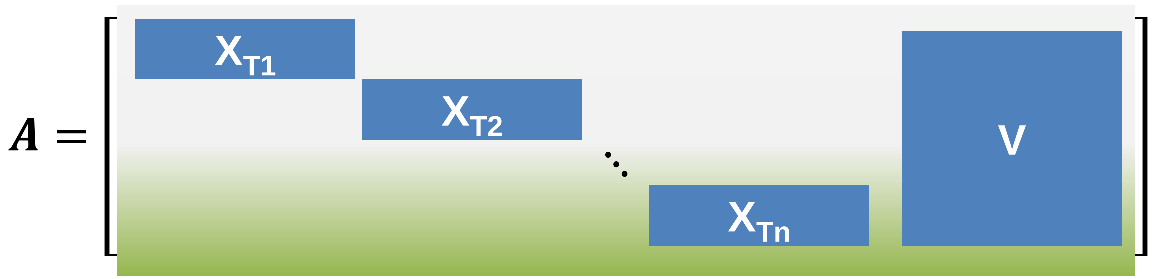
Geometric EO Sensors - SAR

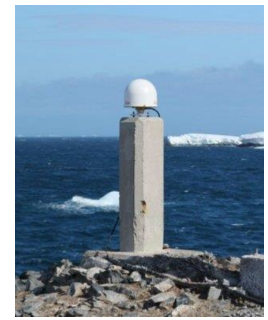
How can vertical changes of land be observed on a systematic base?

Observation of vertical movement by geodetic SAR positioning

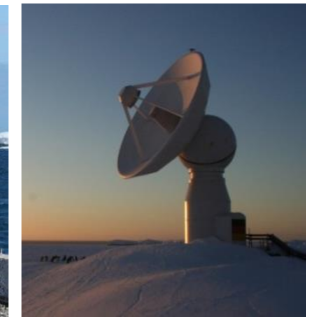
Joint velocity estimate with *n* radar reflectors:

$$\boldsymbol{X}_T(t) = \boldsymbol{X}_T(t_0) + \boldsymbol{v}_T \cdot \Delta t$$





GNSS

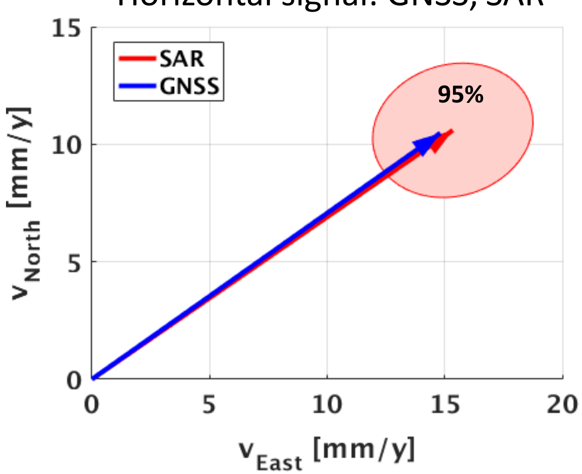


VLBI

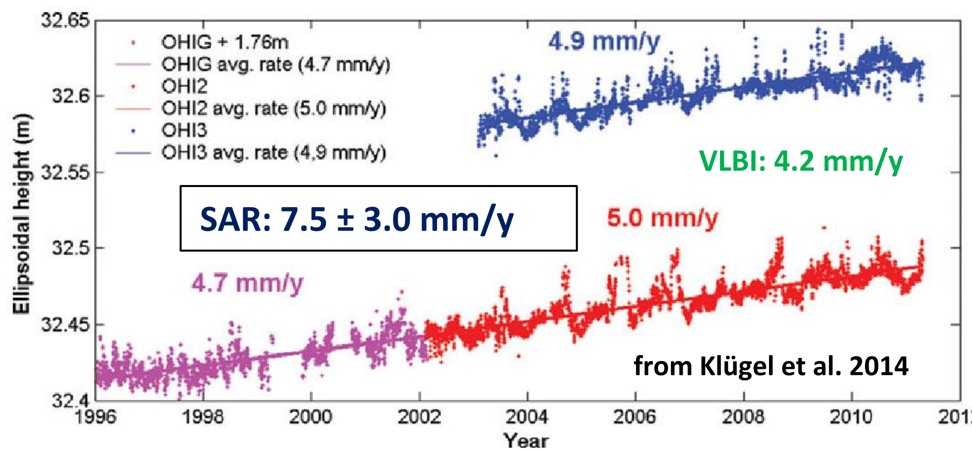
3.5 years of SAR data

	v_x [mm/y]	v_y [mm/y]	v_z [mm/y]
SAR	19.8 ± 3.6	-2.7 ± 3.0	-1.9 ± 2.4
GNSS	18.8 ± 0.1	-2.1 ± 0.2	-0.1 ± 0.3

Horizontal signal: GNSS, SAR



PGR uplift signal: GNSS, SAR, VLBI

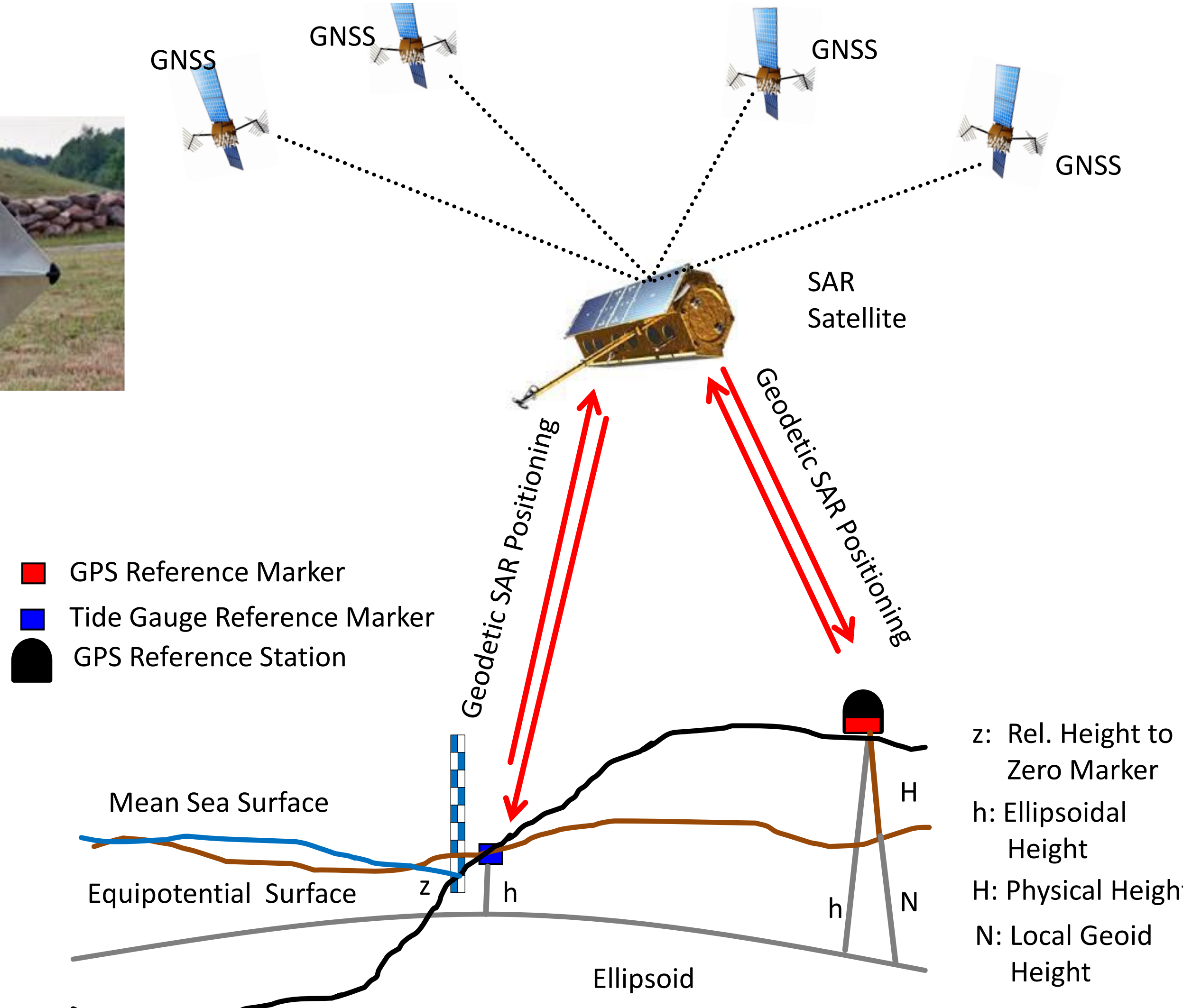


Geometric EO Sensors - SAR

How can vertical changes of land be observed on a systematic base?

Geodetic SAR positioning for height transfer (SAR-Levelling)

Passive Reflectors
Active Transponder

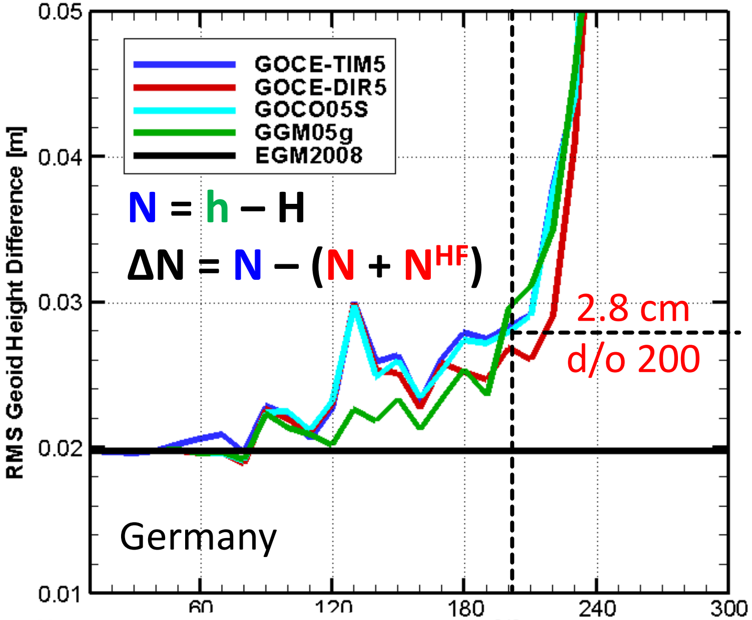


Gravimetric EO Sensors - GOCE

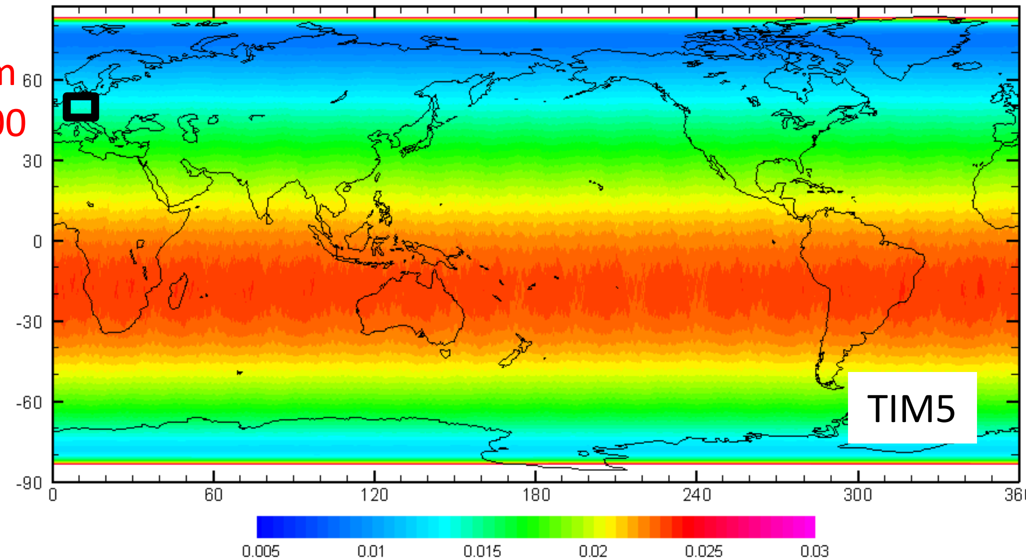
What is the role of the GOCE static geoid?

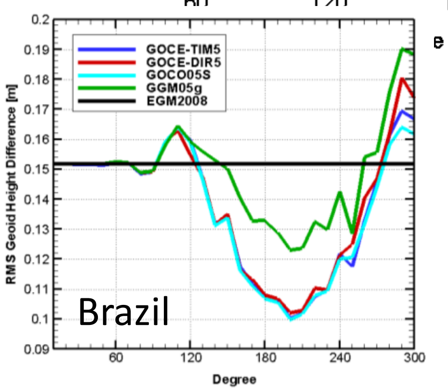
GOCE geoid error at 100 km spatial resolution (d/o 200)

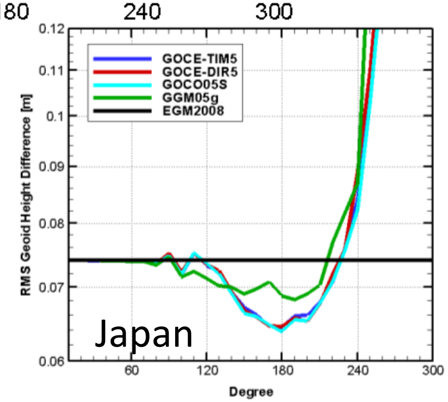
External Validation with GNSS-Levelling



Error Propagation full VCM to Geoid Map (d/o 200)







GNSS-Levelling error is composed by:

- GPS height error **h**: ≈ 1.5 cm
- Normal height error **H** ≈ 1.5 cm
- Error of EGM2008 N^{HF} ≈ 1.0 cm
- Total after error propagation: 2.4 cm

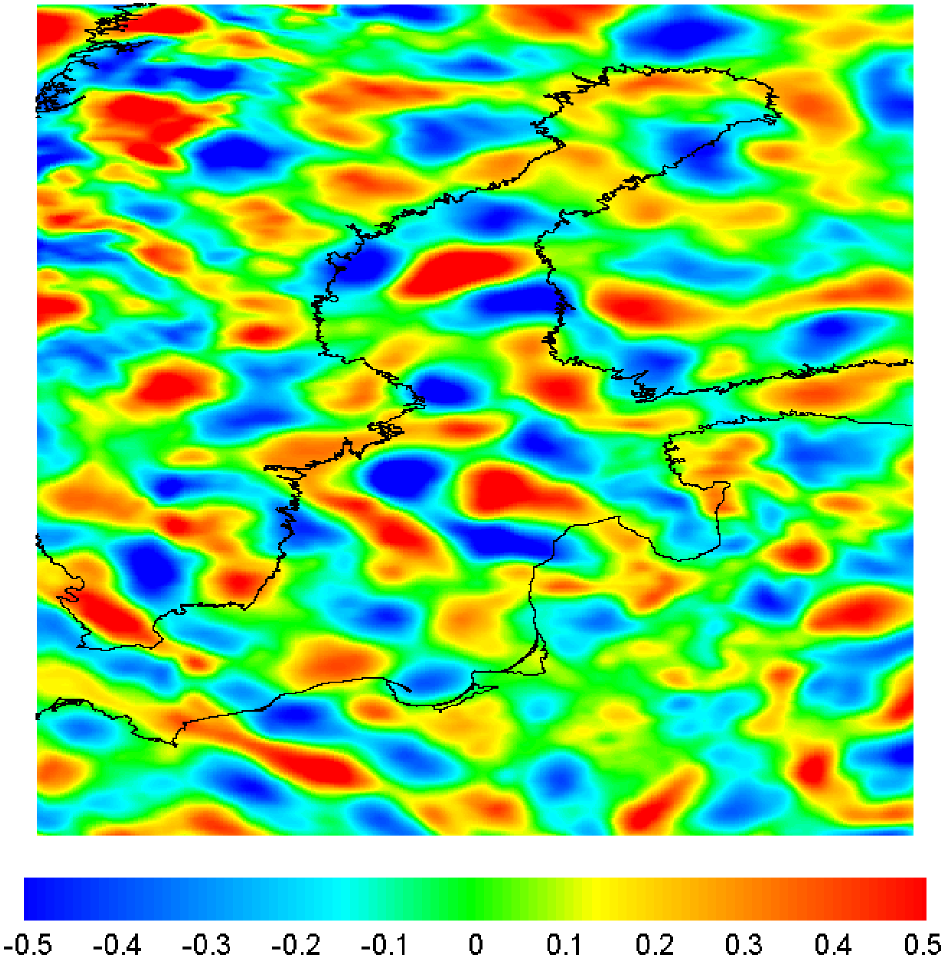
GOCE geoid **N** error (reverse propagation)

- 1.4 to 1.5 cm
- Consistent to geoid error map

Gravimetric EO Sensors - GOCE

What is the role of the GOCE static geoid?

Geoid signal beyond the GOCE resolution in the Baltic Sea (Omission error from EGM2008) [m]



- The GOCE geoid represents a global reference for height systems and absolute sea level observations.
- The GOCE geoid accuracy at 100 km spatial resolution is between 1 and 2 cm quasi globally (within GOCE orbit coverage).
- The omission error needs to be estimated or computed from observations.
  - For height reference stations / tide gauges a local high quality geoid based on the GOCE geoid shall be computed based on gravity observations and terrain model (with data of at least 100 km around the point of interest).
  - In sparsely surveyed areas the GOCE geoid in many cases represents the best possible reference surface.

Gravimetric EO Sensors - GOCE

What is the role of the GOCE static geoid?

Example for sparsley surveyed areas – Height of Mount Everest

GOCE-TIM5 to d/o 280 at height 0

EGM2008 to d/o 2190 at height 0

GOCE-TIM5 d/o 200 & EGM2008 d/o 201-2190 at height 0

EGM/Rapp: EGM2008 to d/o 2190 solved at height H and correction term applied

$$H = h - N \text{ or } H = h - N$$

	GNSS Height	Geoid	Height above Sea Level
Mount Everest	**h = 8821.47 m** Average from GPS and classical techniques for snow surface [1]	$N_{GOCE-TIM5}$ = -26.58 m $N_{EGM2008}$ = -22.90 m $N_{GOCE/EGM}$ = -22.19 m $N_{EGM/Rapp}$ [2] = -28.50 m $N_{local\ geoid}$ [1] = -26.46 m	$H_{GOCE-TIM5}$ = 8848.05 m $H_{EGM2008}$ = 8844.37 m $H_{GOCE/EGM}$ = 8843.66 m $H_{EGM/Rapp}$ = 8849.97 m $H_{local\ geoid}$ = 8847.93 m

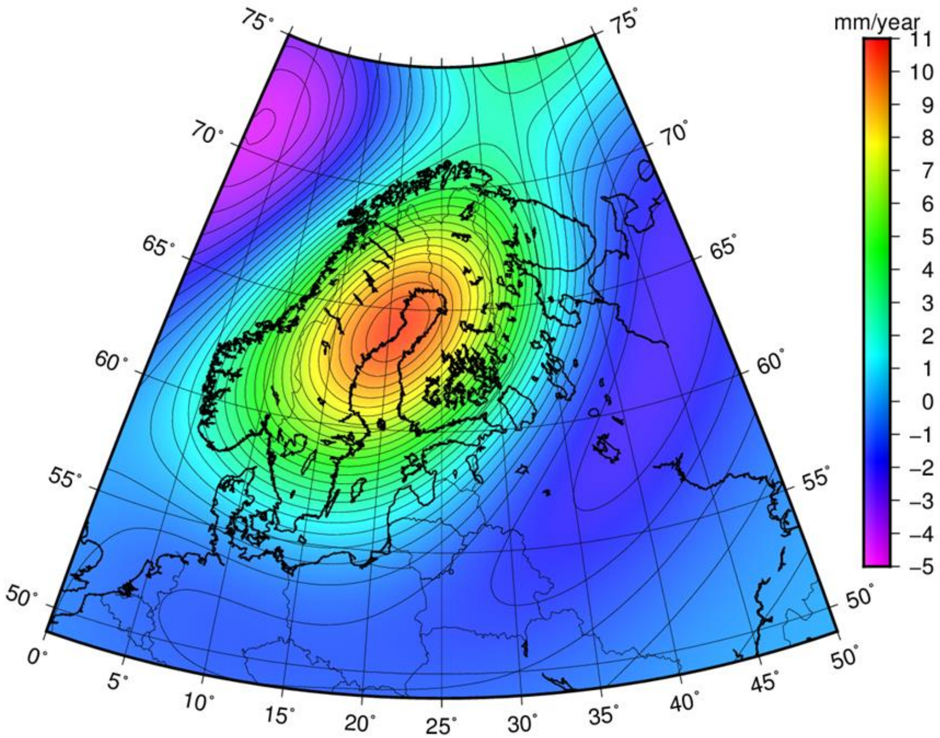
[1] Chen, J. et al, 2006, Science in China; doi: 10.1007/s11430-006-0531-1

[2] Rapp, 1997, Journal of Geodesy, Vol. 71, p. 282-289

Gravimetric EO Sensors - GRACE

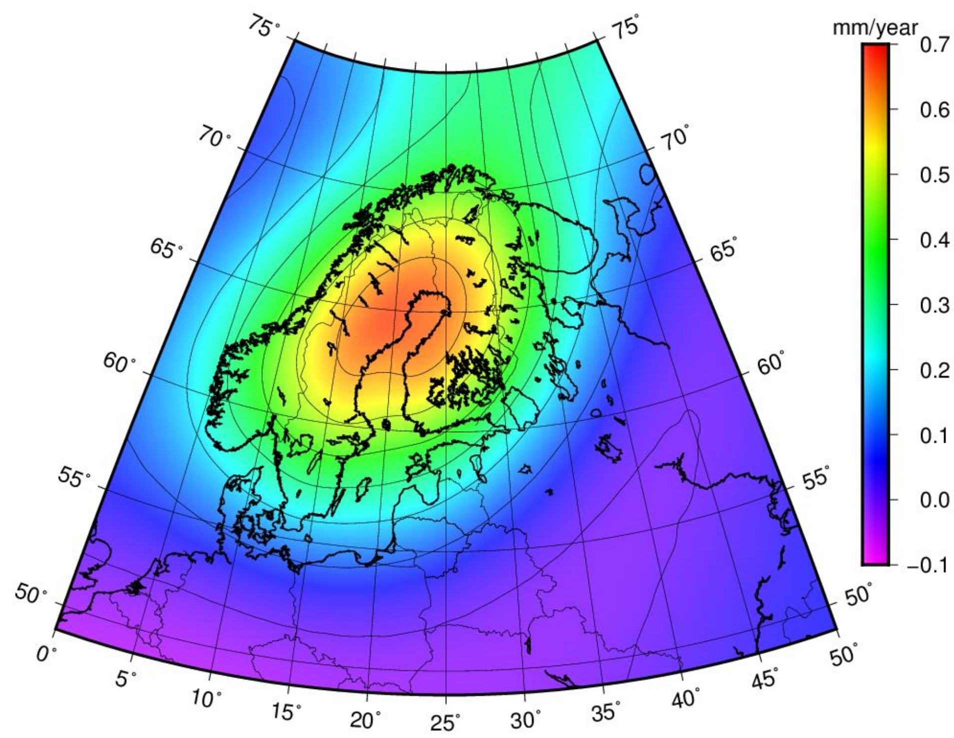
What is the impact of mass variations and how can it be observed?

NKG2016GIA_prel0306 – vertical land uplift



Gridded vertical displacement rate
(Steffen & Ågren, pers. comm.)

NKG2016GIA_prel0306 – Geoid rise

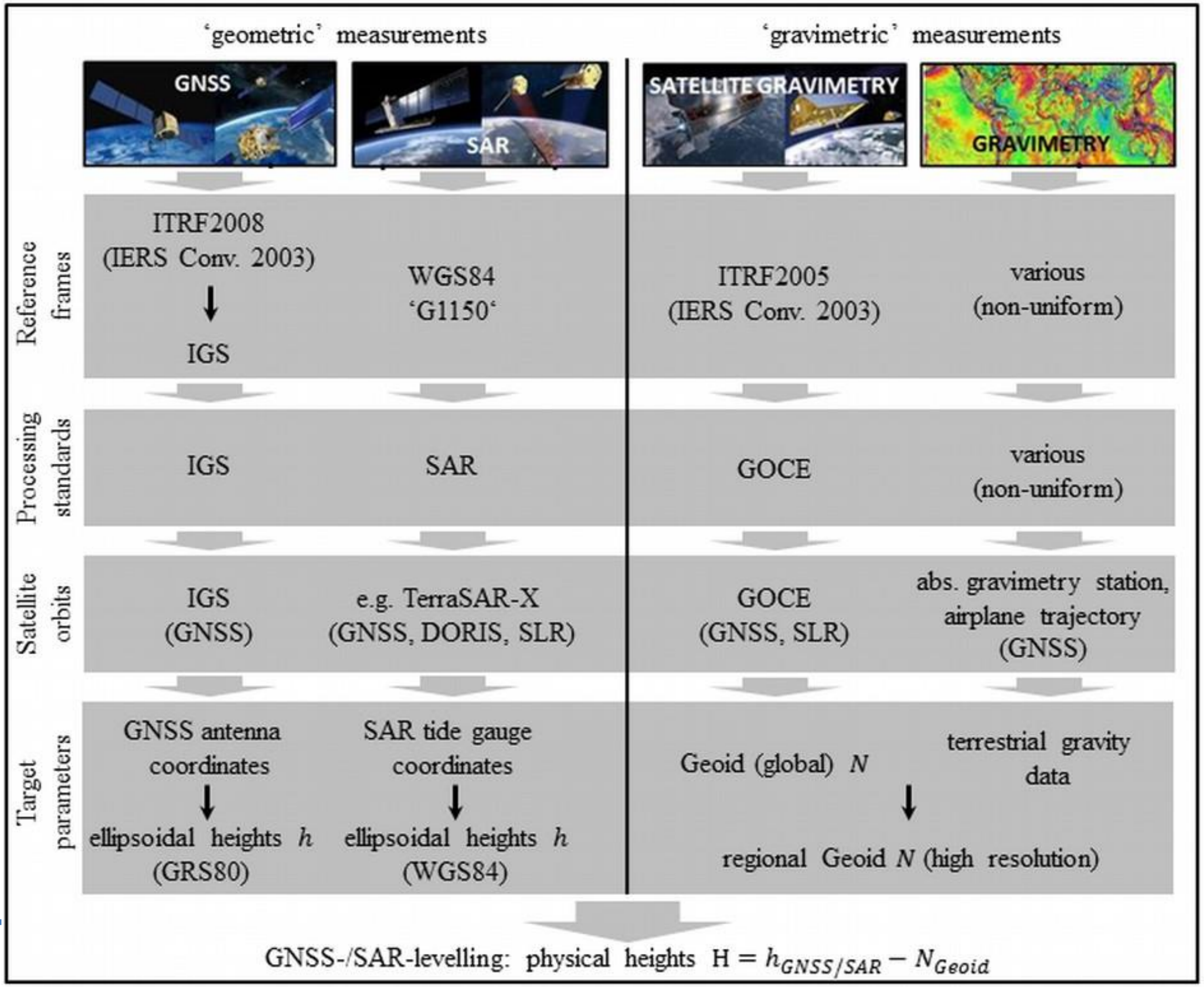


Gridded geoid change rate
(Steffen & Ågren, pers. comm.)

Reference Frame Consistency

What is the impact of reference frame incompatibilities?

Simplified scheme for the determination of ellipsoidal heights from the geodetic SAR technique and GNSS (left) and the determination of physical heights referring to a common physical reference surface based on GOCE and terrestrial/airborne data (right).

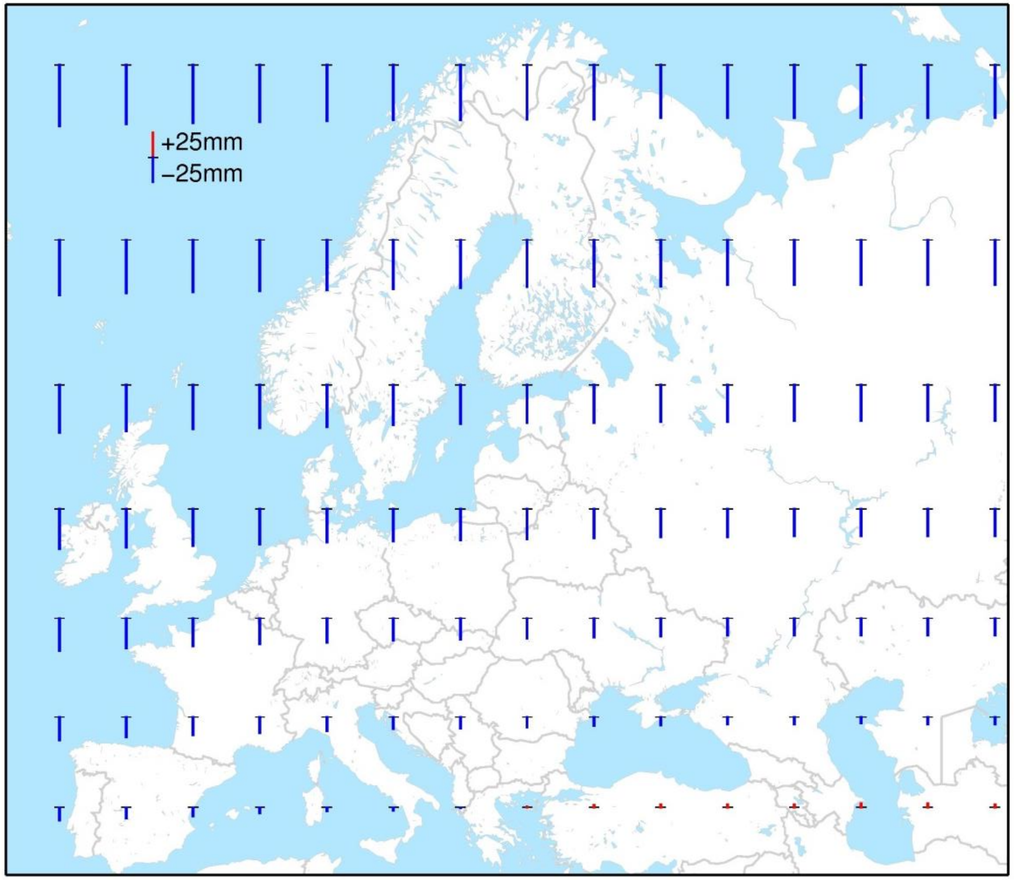


Reference Frame Consistency

What is the impact of reference frame incompatibilities?

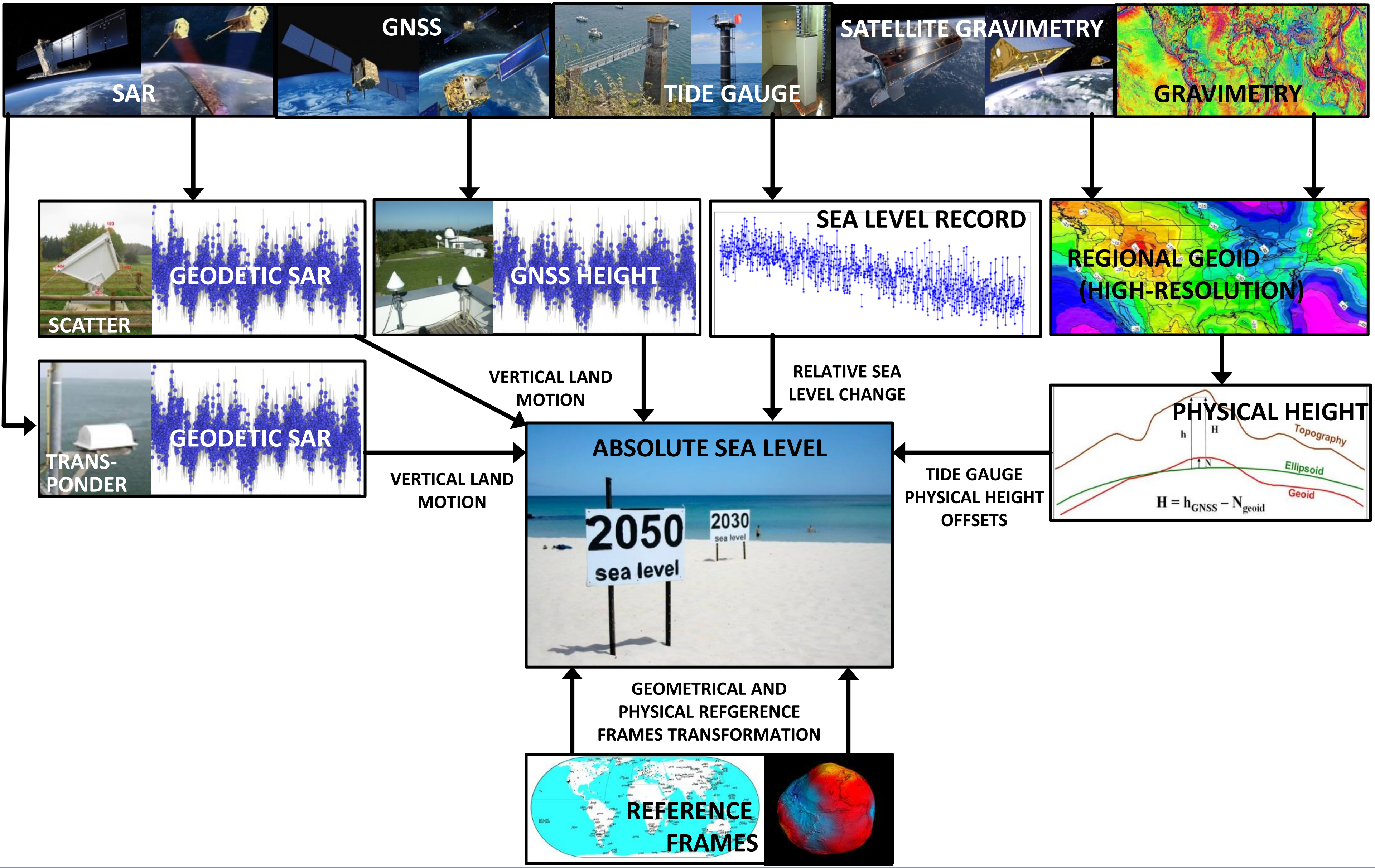
Impact of Coordinate Frame Transformations on GNSS Heights
(Study performed by G. Liebsch, BKG)

ITRF1989 – ITRF2008



- GNSS and geoid heights need to be in a consistent frame (reference ellipsoid).
- GOCE geoid heights refer to CoM.
- GNSS ellipsoidal heights refer to an ITRFxxxx with a center of origin which is not CoM.
- ITRF2008 is known to be close to CoM.
- ITRF1989 (ETRF1989) to ITRF2008 offset is (x,y,z): 2.8 - 3.9 - 10.1 cm
- 7 parameter Helmert transformation result in height change of up to 7 cm in Europe (see figure).
- For any combined use of geometric and physical heights this needs to be taken into account.

Summary & Conclusions



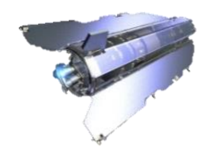
Summary & Conclusions

Tige Gauges

- Should be kept operational worldwide.

Geometric EO Sensors (GNSS, Altimetry, SAR)

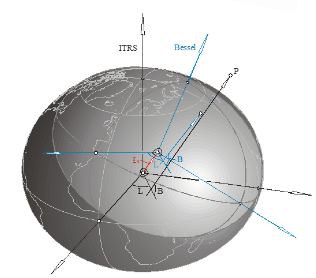
- Sustained observations available from Sentinel missions & others.
- Ground processing to be further developed (e.g. SAR positioning, coastal altimetry).



Gravimetric Space Sensors

- Spatial resolution of static global gravity field to be improved with new observation technologies (e.g. cold atom gradiometry on satellite).

- Sustained observation of temporal variations of gravity field with improved spatial & temporal resolution (e.g. double-pair concepts).



Reference Frames Consistency

- Joint systematic observation of geometric & physical reference frames (e.g. CoM versus Center of Figure)