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# Surface mass variation monitoring from SLR and orbit information of GPS-tracked low-Earth orbiters

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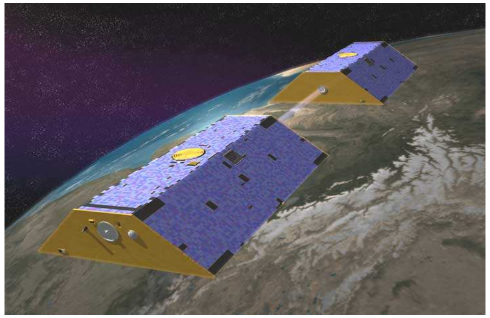
# Motivation

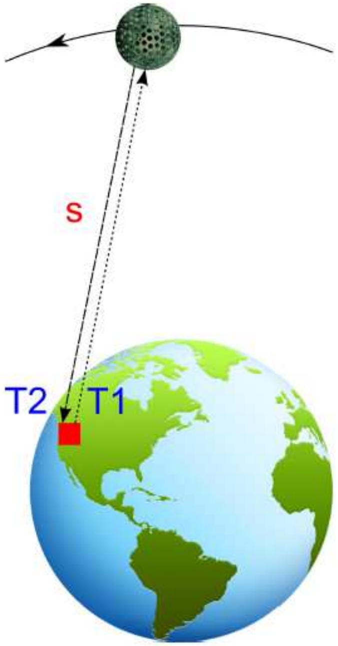
## GRACE – a story of success likely to be interrupted

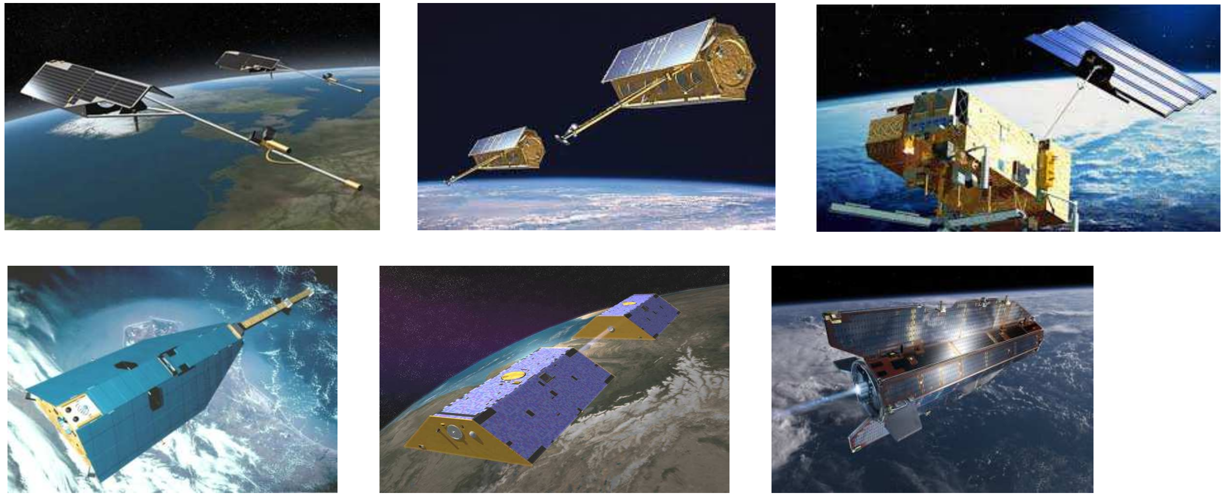


- Remaining mission lifetime unpredictable
- GRACE follow-on mission in late 2017 at the earliest
- Gap between GRACE and GRACE-FO very likely

Bridging candidates:

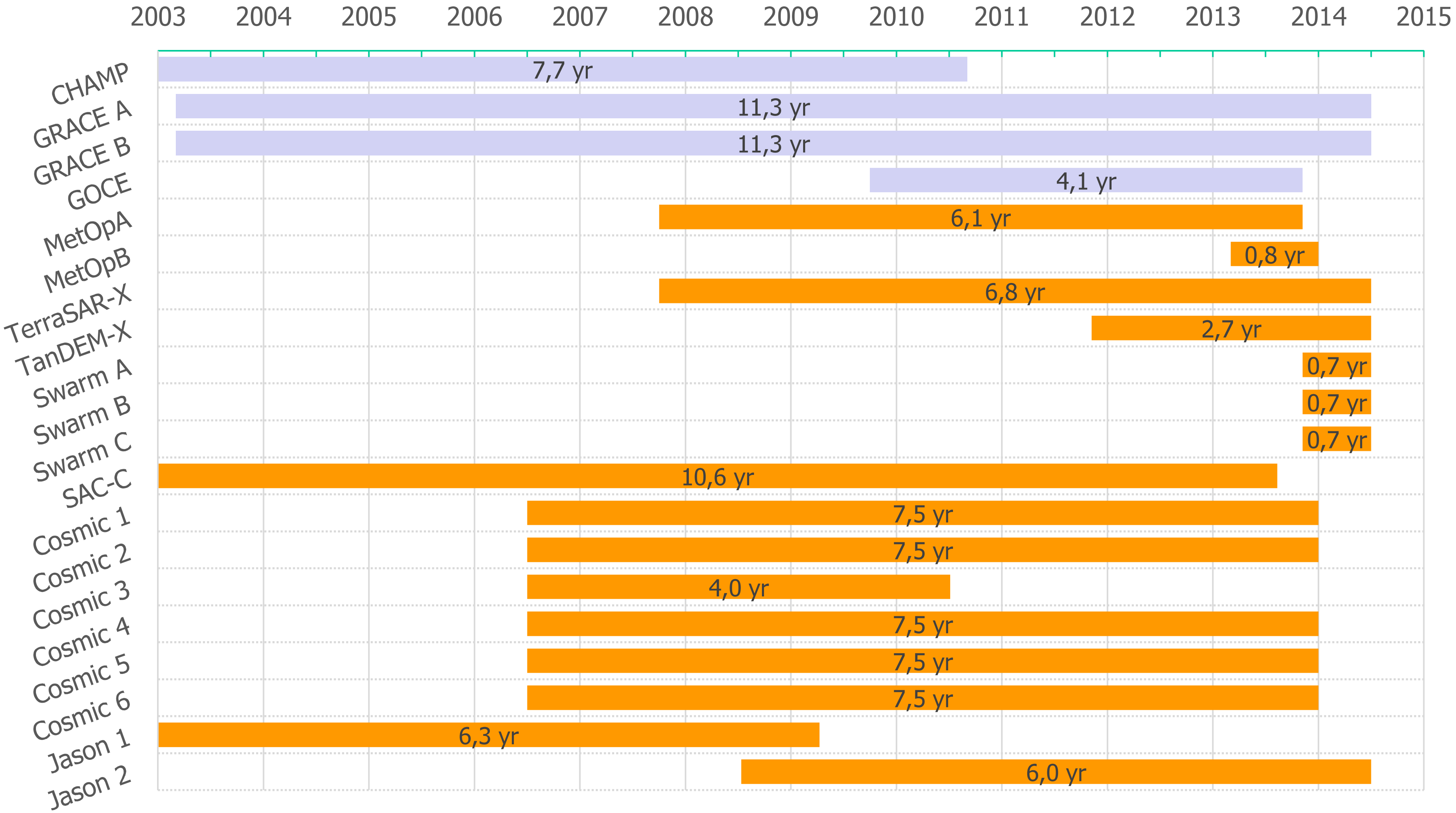
- Satellite Laser Ranging (SLR)
- GPS-tracked Low-Earth Orbiters (LEO-GPS) (non-dedicated, dedicated)





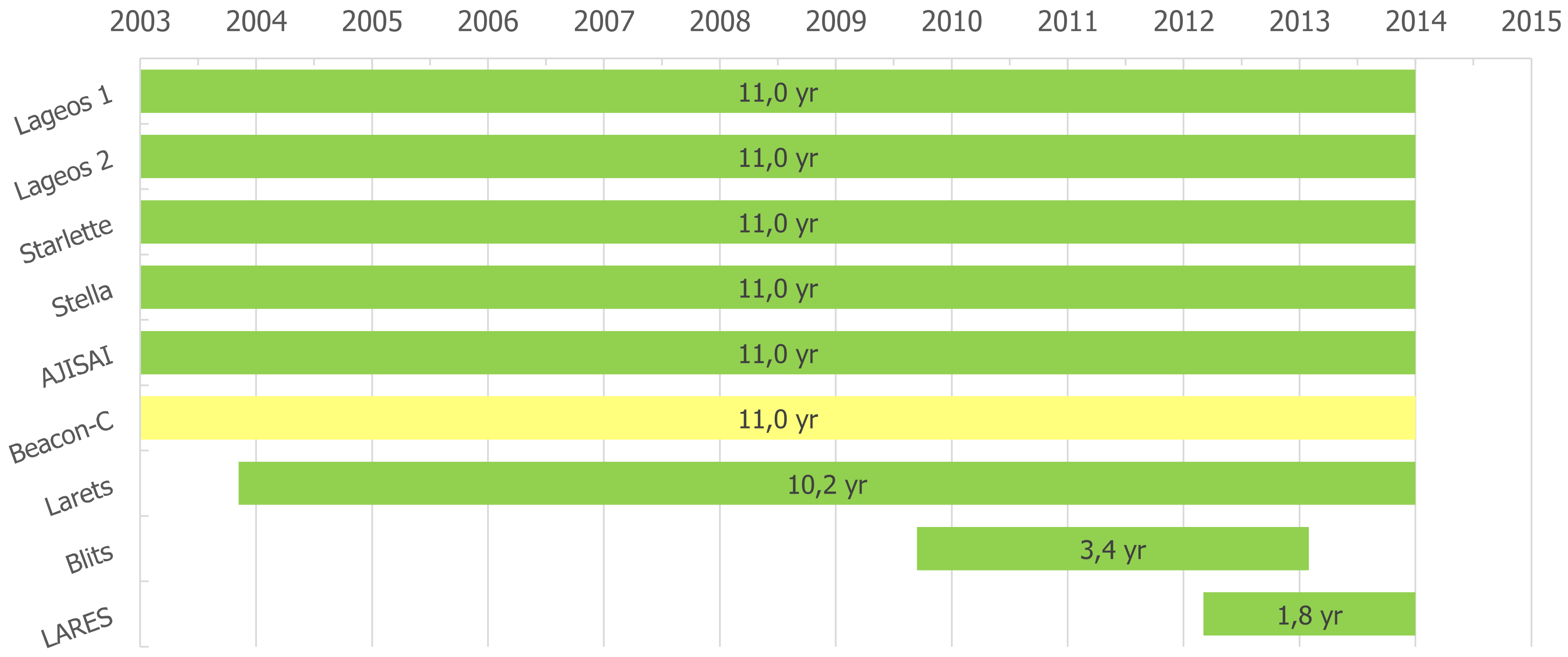
# Considered satellites

LEO-GPS: 20 satellites



# Considered satellites

SLR: 9 satellites



# Methods

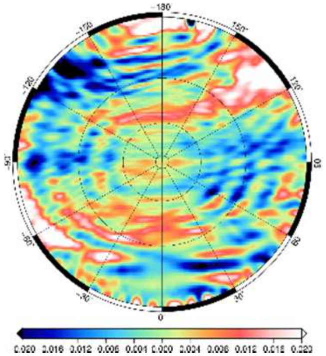
## Surface mass variation from LEO-GPS & SLR

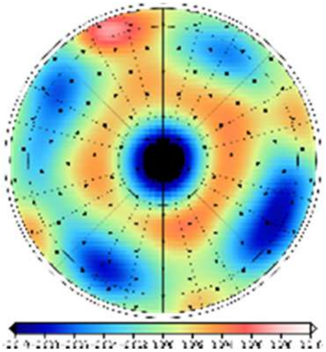
| | |
|---|---|
| Period | 01/2003-12/2013 |
| Precise orbit determination | based on GPS code and phase observations |
| LEO-GPS normal equations | kinematic orbit analysis from monthly data sets |
| SLR normal equations | orbital, geometrical, and force model parameters |
| Data combination | on the level of normal equations |
| “Manipulation” | |
| Degree-1 terms | replaced, cf. Swenson et al. (2008) |
| Post-processing | |
| Band-pass filtering | cf. Weigelt et al. (2013) |
| Spatial averaging | Gaussian smoothing with a radius of 750 km |
| Inference of mass variation | |
| Surface mass densities | according to Wahr et al. (1998) |
| Leakage consideration | according to Baur et al. (2009) |
| Time series fit | regression line, together with four sinusoids |

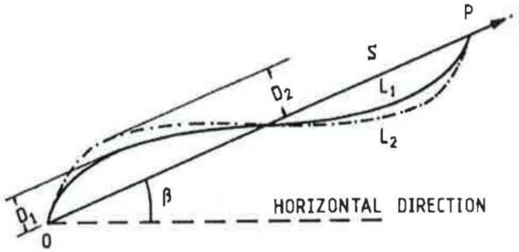
# Methods

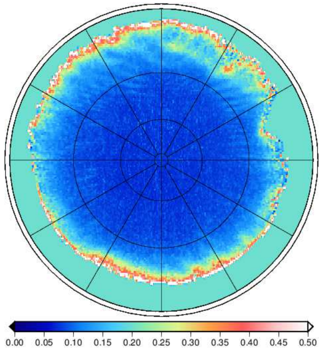
## Precise orbit determination

- Code and phase observations on L1 and L2
  - Directly used in least-squares adjustment
  - Precise point positioning (PPP) approach
- Antenna center variations for code/phase observations
  - Azimuth- and elevation-dependent for receiver and transmitter
- Ionospheric correction including 2nd, 3rd order terms and bending correction
- Azimuth- and elevation-dependent observation weighting









# Methods

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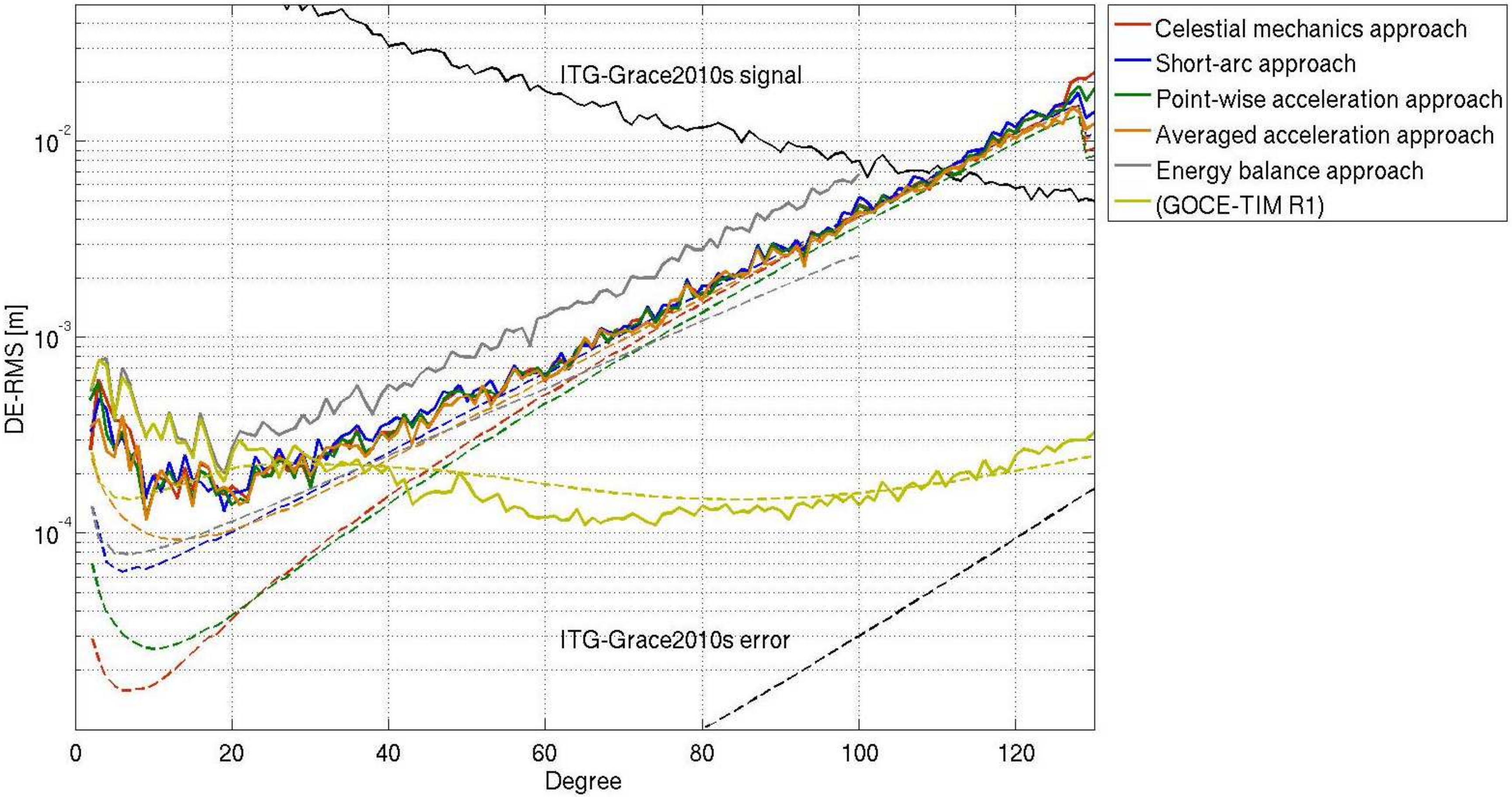
# Methods

## LEO-GPS normal equations



Baur O, Bock H, Höck E, Jäggi A, Krauss S, Mayer-Gürr T, Reubelt T, Siemes C, Zehentner N
*Comparison of GOCE-GPS gravity fields derived by different approaches*, J. Geod. 88, 959-973, 2014

# Methods

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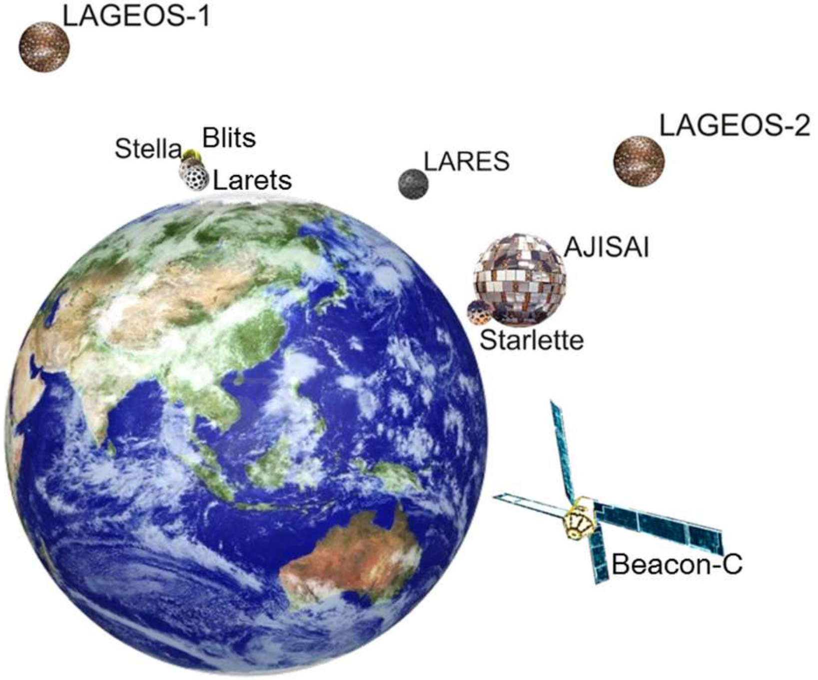
# Methods

## SLR normal equations

| Estimated parameters | | SLR solutions |
|---|---|---|
| | | LAGEOS-1/2, Starlette, Stella, AJISAI, LARES, Blits, Larets, Beacon-C |
| Orbits | Osculating elements | $a, e, i, \Omega, \omega, u_0$<br>(LAGEOS: 1 set per 10 days, LEO: 1 set per 1 day) |
| | Dynamical parameters | LAGEOS-1/2 : $S_0$, $S_S$, $S_C$ (1 set per 10 days)<br>Sta/Ste/AJI : $C_D$, $S_C$, $S_S$, $W_C$, $W_S$ (1 set per day) |
| | Pseudo-stochastic pulses | LAGEOS-1/2 : no pulses<br>Sta/Ste/AJI : once-per-revolution in along-track only |
| Earth rotation parameters | | $X_P$, $Y_P$, UT1-UTC (piecewise linear, 1 set per day) |
| Geocenter coordinates | | 1 set per 30 days |
| Earth gravity field | | **Full up to d/o 10** (1 set per 30 days) |
| Station coordinates | | 1 set per 30 days |
| Other parameters | | Range biases for all stations (LEO) and for selected stations (LAGEOS) |



- Up to 9 satellites (different altitudes and inclinations)
- Weighting of observations: from 8 mm (LAGEOS-1/2) to 50 mm (Beacon-C)

# Methods

## Surface mass variation from LEO-GPS & SLR

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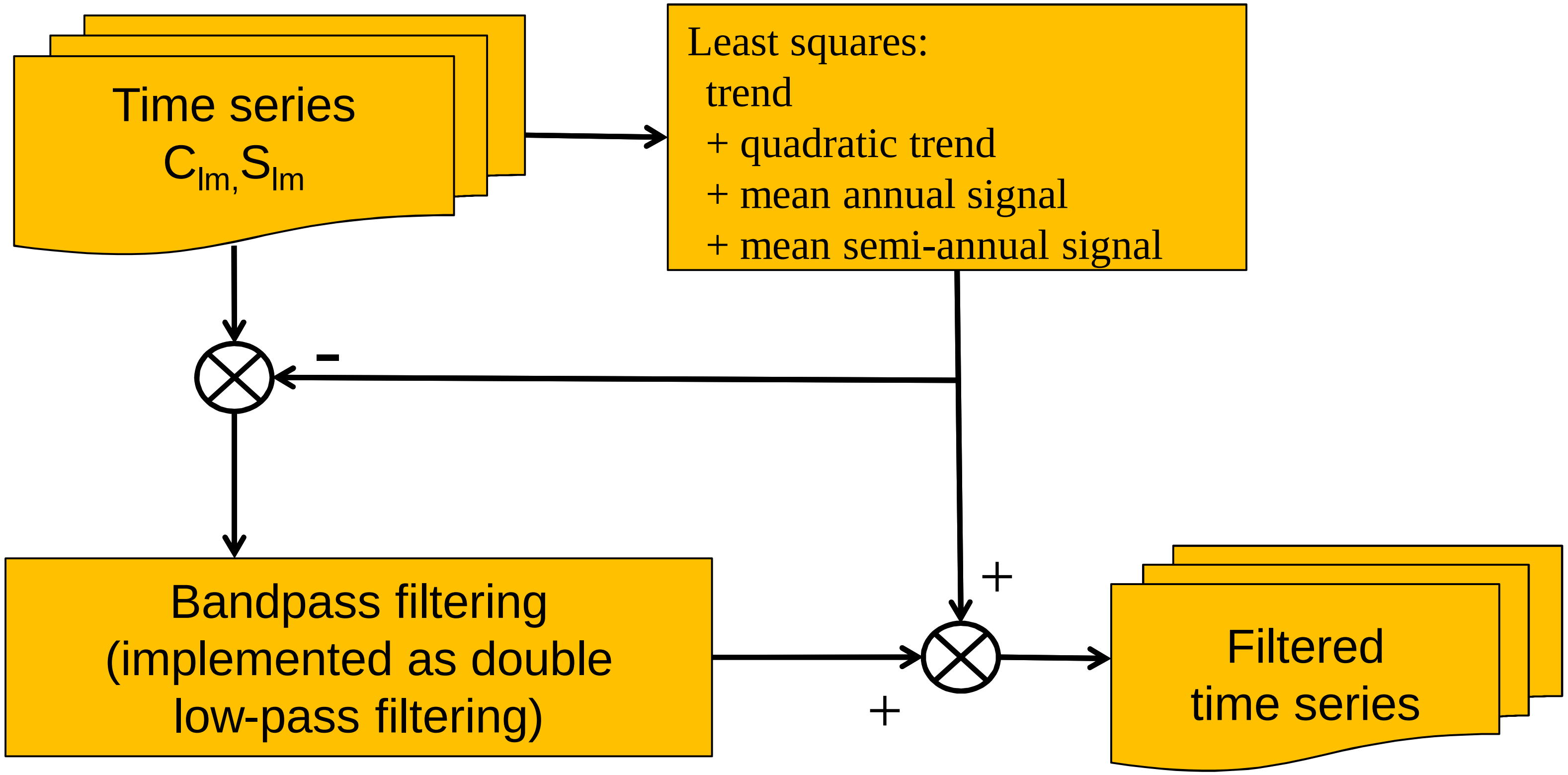
# Methods

## Post-processing



Time series

$C_{lm,}S_{lm}$

Least squares:

trend

+ quadratic trend

+ mean annual signal

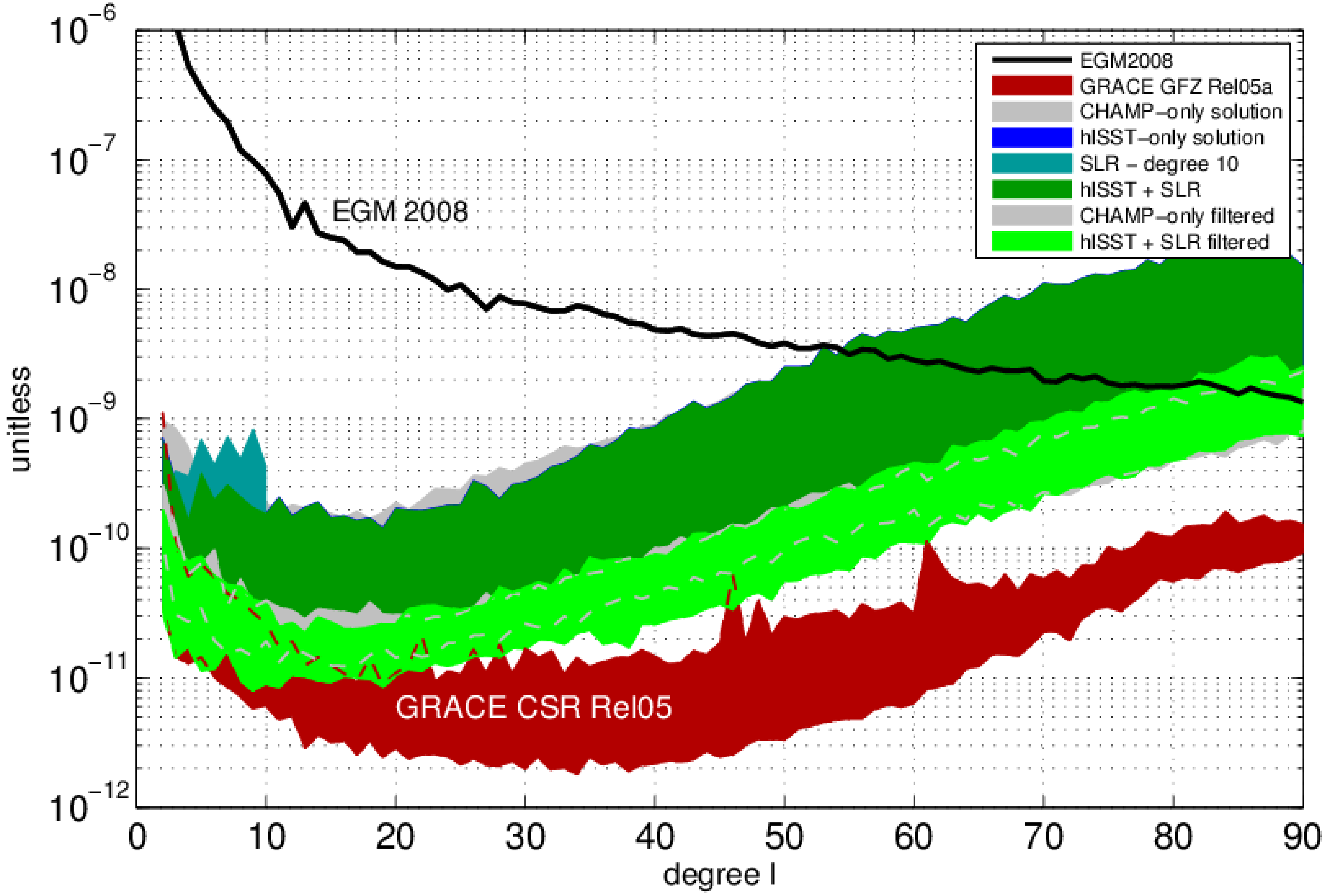
+ mean semi-annual signal

Bandpass filtering
(implemented as double
low-pass filtering)

Filtered
time series

# Methods

## Post-processing



# Methods

## Surface mass variation from LEO-GPS & SLR

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| Data combination | on the level of normal equations |
| “Manipulation” | |
| Degree-1 terms | replaced, cf. Swenson et al. (2008) |
| Post-processing | |
| Band-pass filtering | cf. Weigelt et al. (2013) |
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# Methods

## Surface mass variation from GRACE-KBR

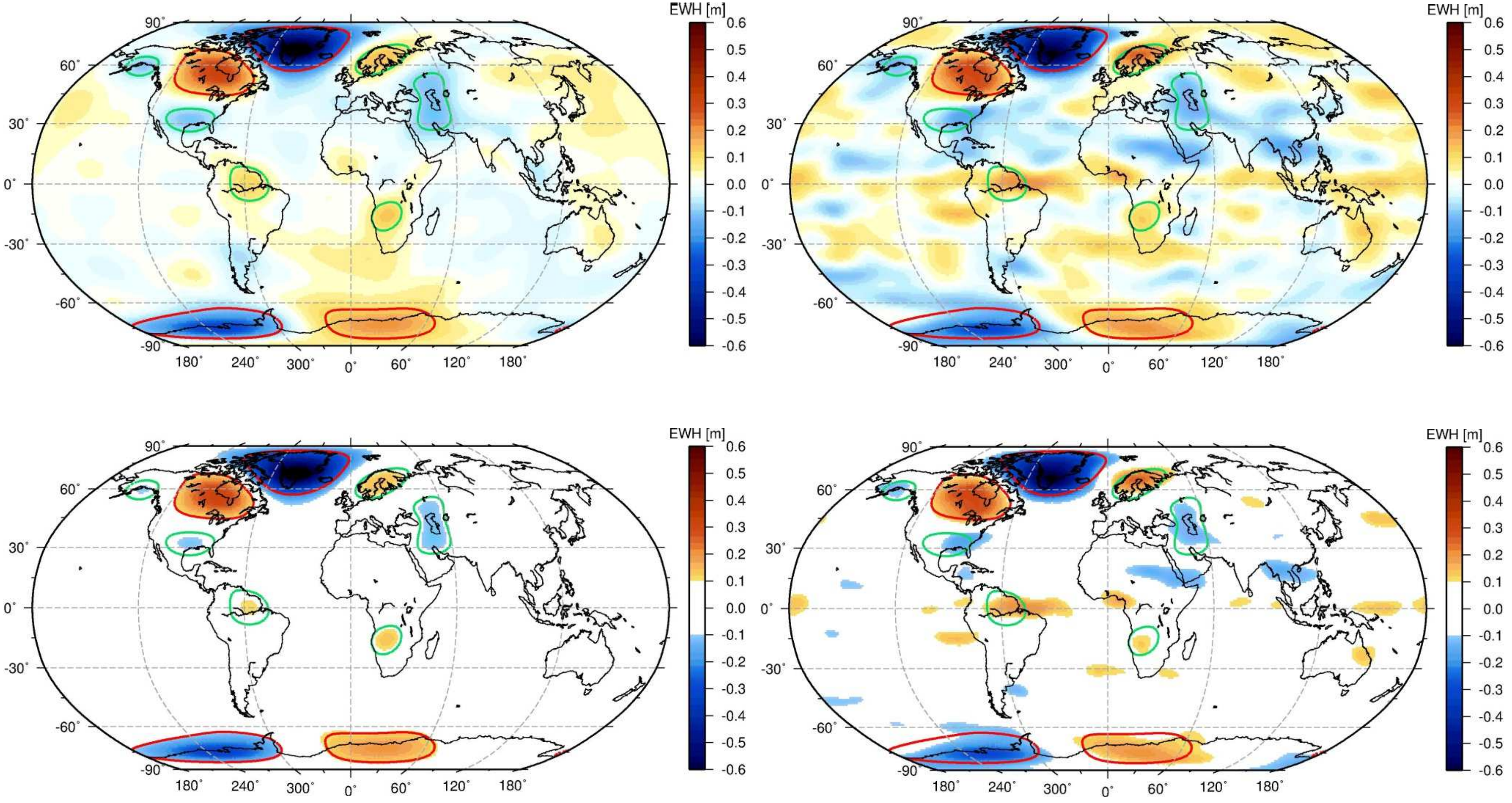
| | |
|---|---|
| Period | 01/2003-12/2013 |
| Gravity fields | CSR, release 05 |
| “Manipulation” | |
| Degree-1 terms | replaced, cf. Swenson et al. (2008) |
| $c_{20}$ coefficients | replaced by values from SLR, cf. Maier et al. (2014) |
| Post-processing | |
| De-correlation | according to Swenson and Wahr (2006) |
| Spatial averaging | Gaussian smoothing with a radius of 750 km |
| Inference of mass variation | |
| Surface mass densities | according to Wahr et al. (1998) |
| Leakage consideration | according to Baur et al. (2009) |
| Time series fit | regression line, together with four sinusoids |

# Results

## Total secular variation

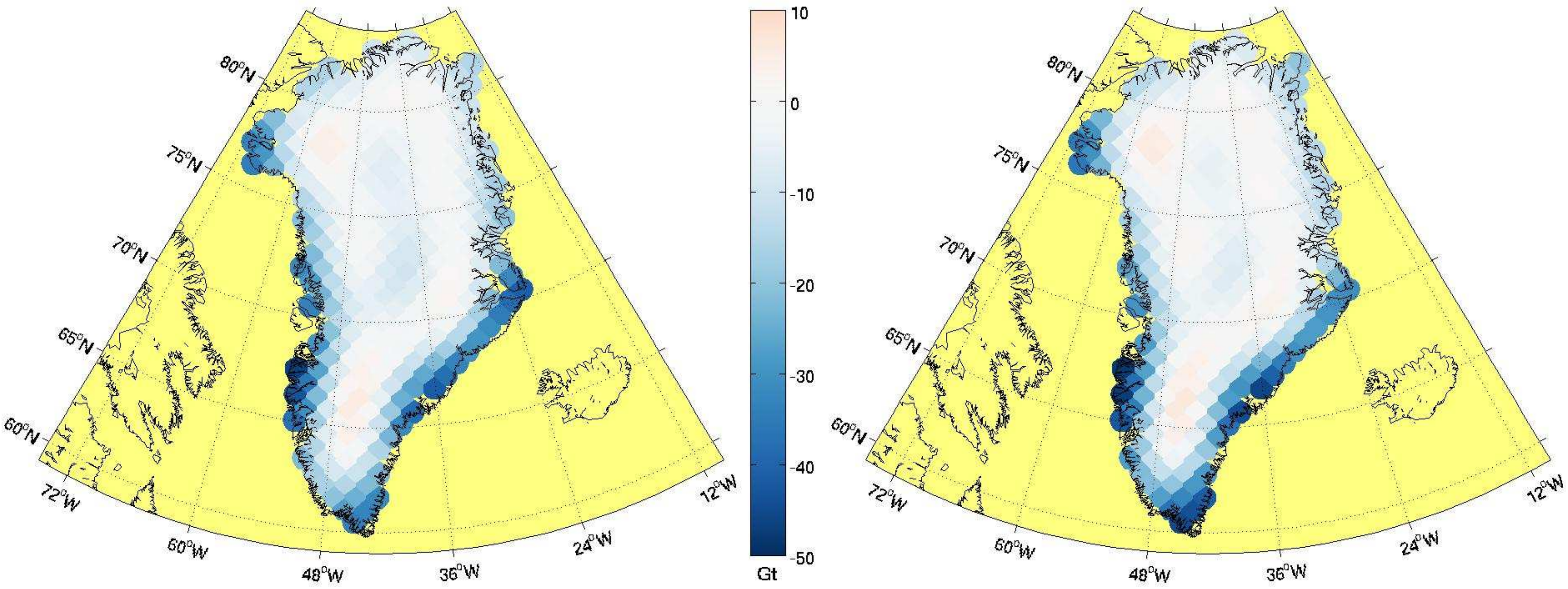
GRACE-KBR

LEO-GPS & SLR



# Results

## Total secular variation

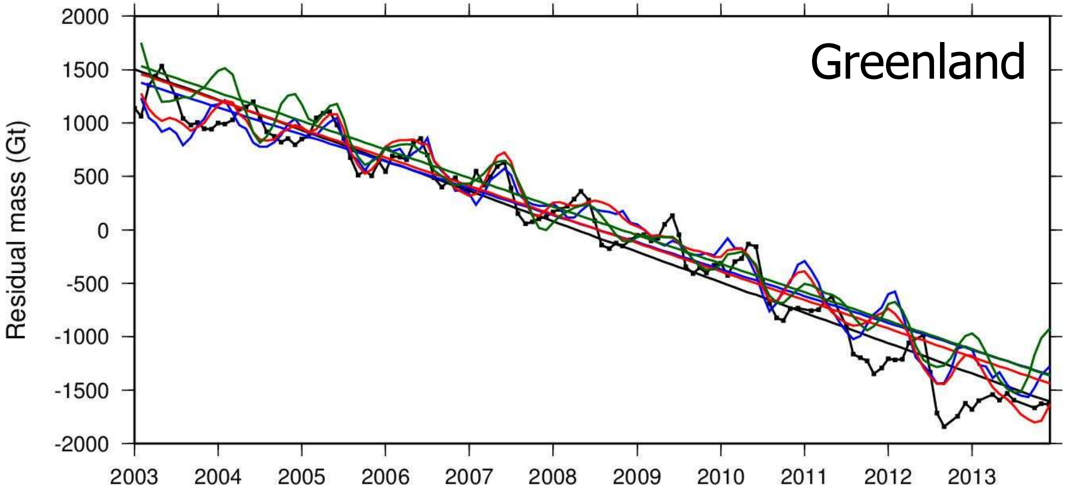


GRACE-KBR

LEO-GPS & SLR

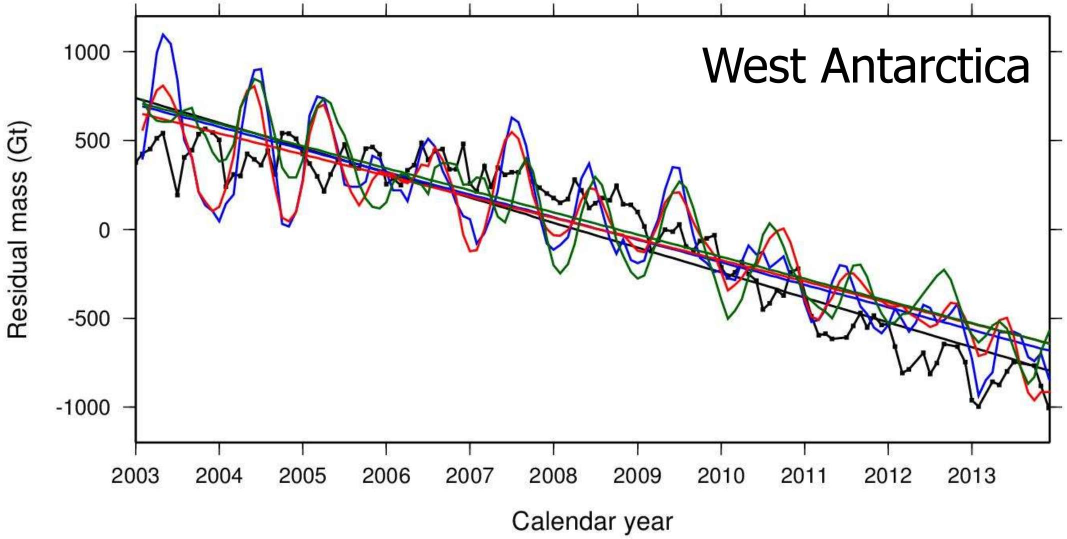
# Results

## Linear trend



Mass trend (Gt/yr)

| | | |
|---|---|---|
| GRACE-KBR | -285 ± 10 | |
| LEO-GPS11 | -252 ± 10 | (12%) |
| LEO-GPS11 & SLR | -267 ± 12 | (6%) |
| LEO-GPS20 & SLR | -267 ± 8 | (6%) |

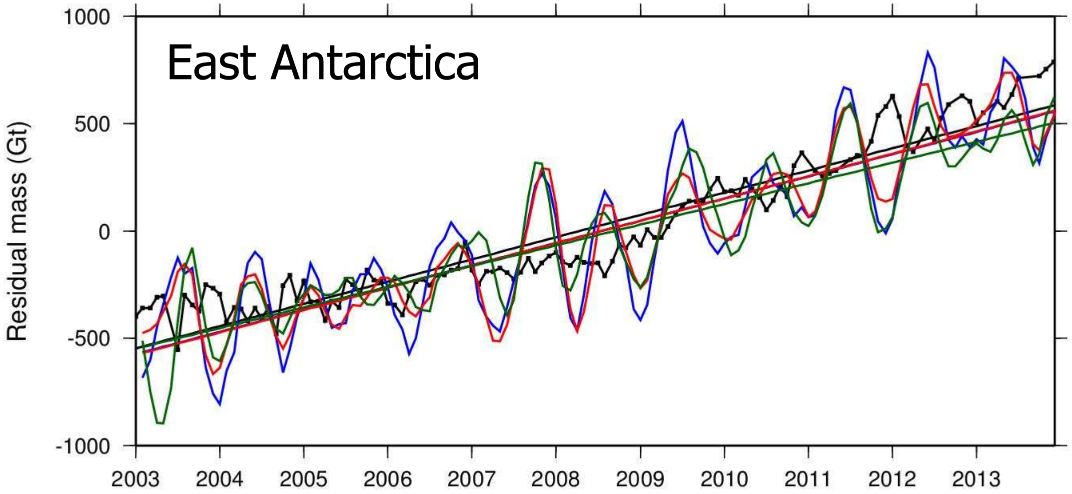


Mass trend (Gt/yr)

| | | |
|---|---|---|
| GRACE-KBR | -140 ± 10 | |
| LEO-GPS11 | -127 ± 10 | (10%) |
| LEO-GPS11 & SLR | -119 ± 10 | (15%) |
| LEO-GPS20 & SLR | -124 ± 8 | (11%) |

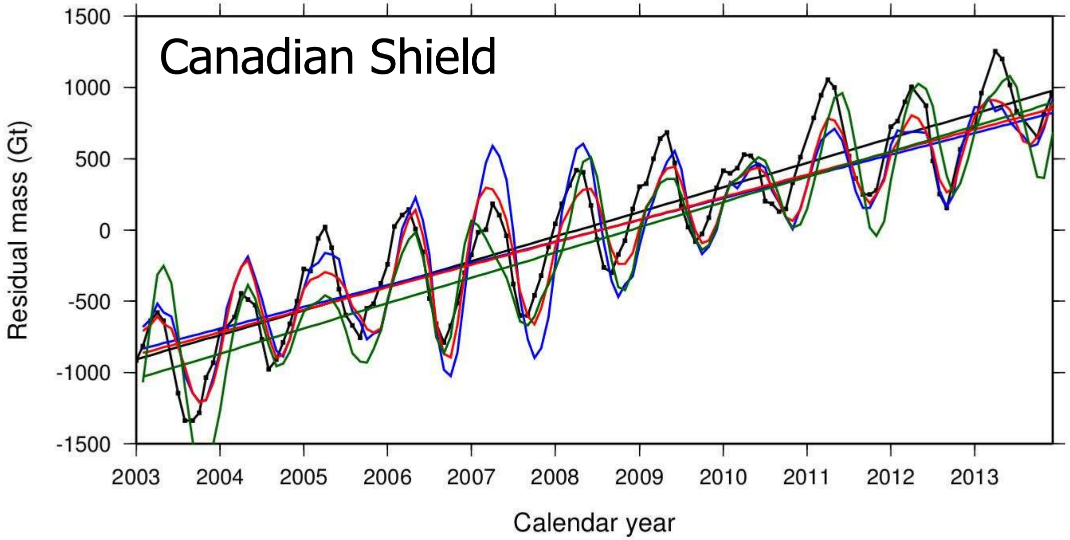
# Results

## Linear trend



Mass trend (Gt/yr)

| | |
|---|---|
| GRACE-KBR | 104 ± 6 |
| LEO-GPS11 | 103 ± 10 (1%) |
| LEO-GPS11 & SLR | 104 ± 10 (0%) |
| LEO-GPS20 & SLR | 96 ± 9 (7%) |



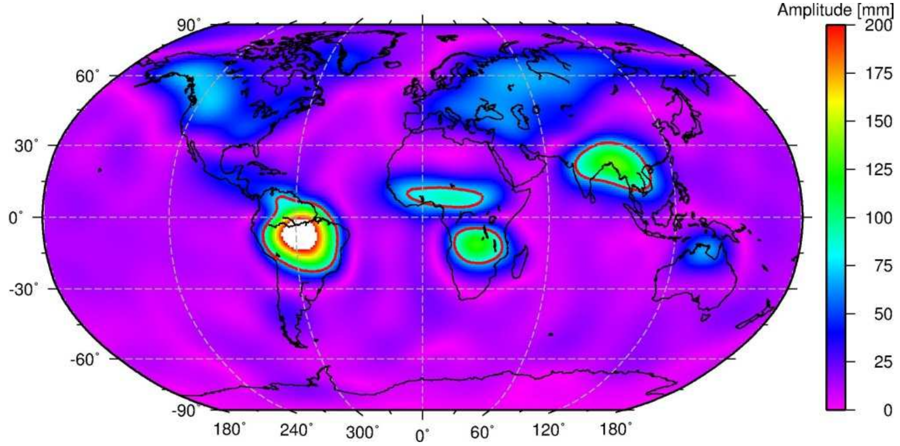
Mass trend (Gt/yr)

| | |
|---|---|
| GRACE-KBR | 172 ± 6 |
| LEO-GPS11 | 152 ± 10 (12%) |
| LEO-GPS11 & SLR | 158 ± 6 (8%) |
| LEO-GPS20 & SLR | 177 ± 10 (3%) |

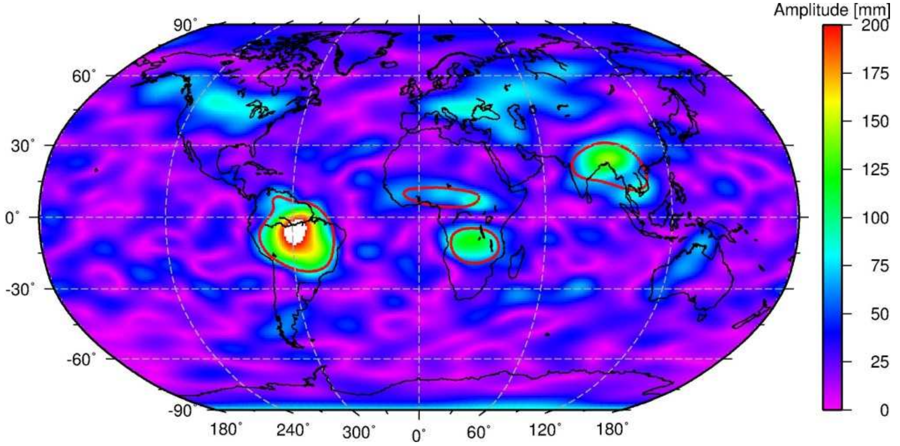
# Results

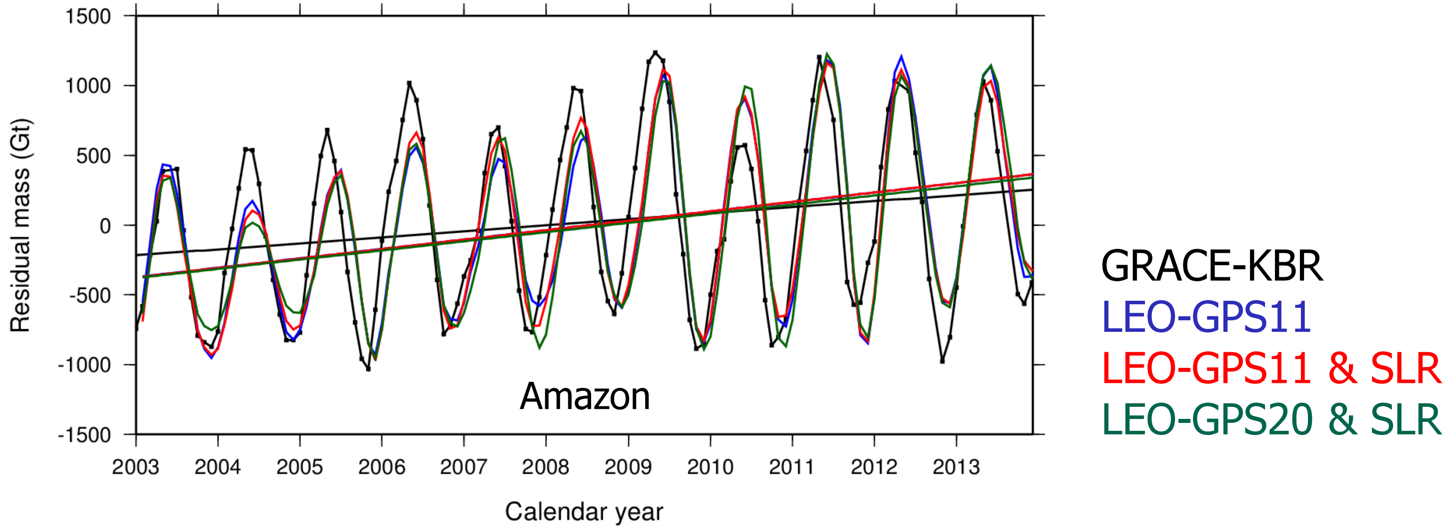
## Annual amplitude

GRACE-KBR



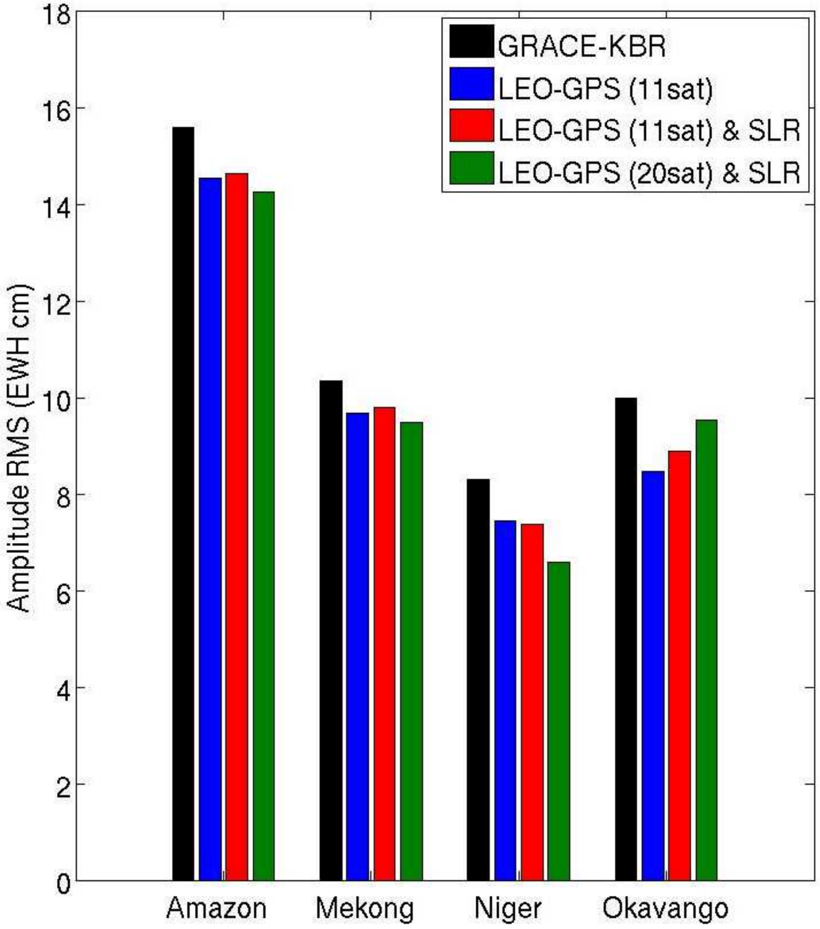
LEO-GPS & SLR

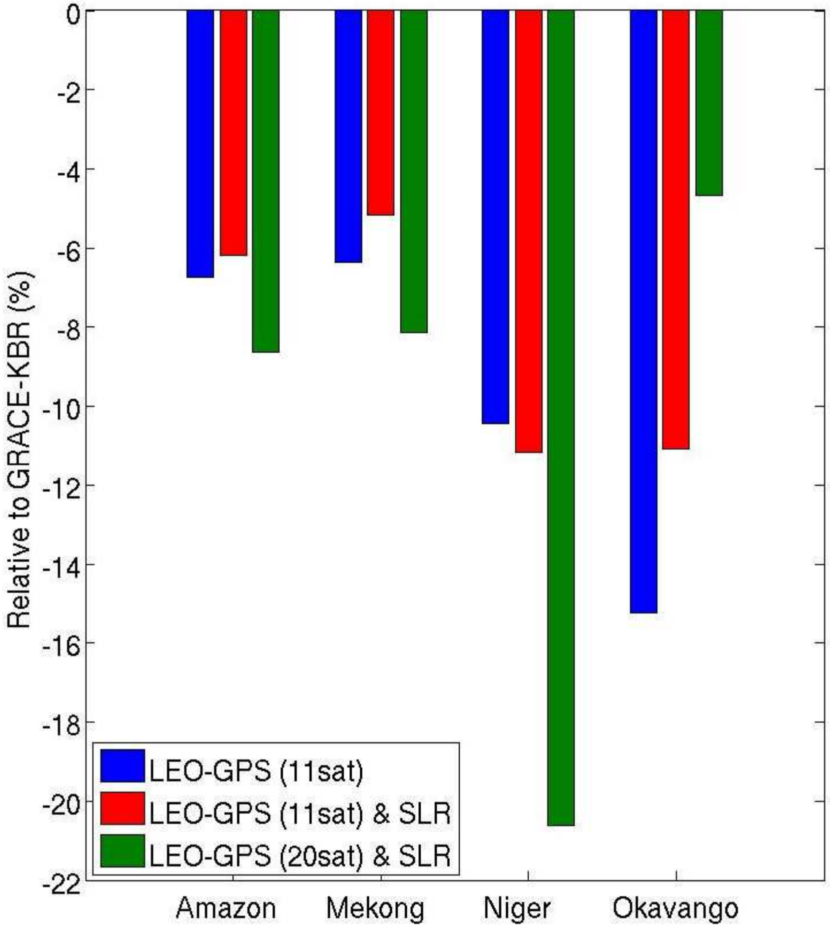




# Results

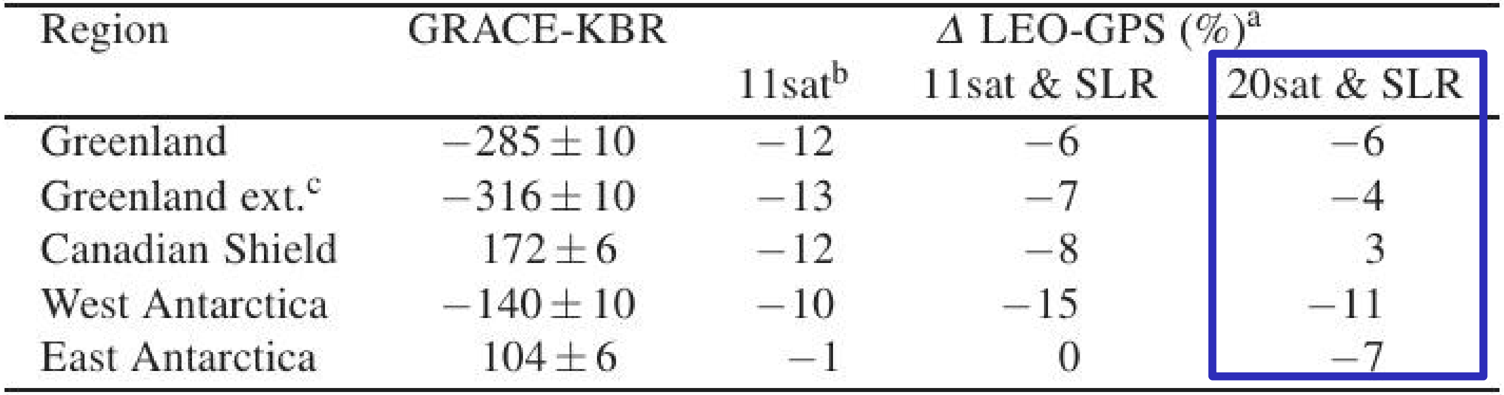
## Annual amplitude





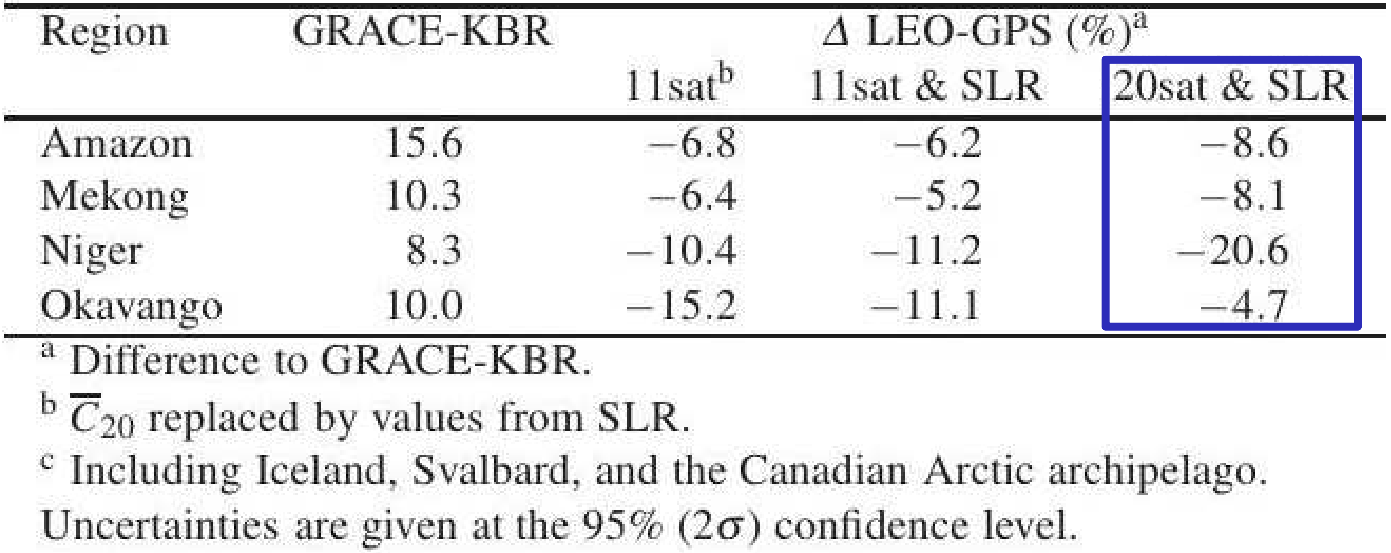
# Summary

## Trend (Gt/yr)



| Region | GRACE-KBR | Δ LEO-GPS (%)[a] | | |
|---|---|---|---|---|
| | | 11sat[b] | 11sat & SLR | 20sat & SLR |
| Greenland | −285 ± 10 | −12 | −6 | −6 |
| Greenland ext.[c] | −316 ± 10 | −13 | −7 | −4 |
| Canadian Shield | 172 ± 6 | −12 | −8 | 3 |
| West Antarctica | −140 ± 10 | −10 | −15 | −11 |
| East Antarctica | 104 ± 6 | −1 | 0 | −7 |

## Amplitude RMS (EWH cm)



| Region | GRACE-KBR | Δ LEO-GPS (%)[a] | | |
|---|---|---|---|---|
| | | 11sat[b] | 11sat & SLR | 20sat & SLR |
| Amazon | 15.6 | −6.8 | −6.2 | −8.6 |
| Mekong | 10.3 | −6.4 | −5.2 | −8.1 |
| Niger | 8.3 | −10.4 | −11.2 | −20.6 |
| Okavango | 10.0 | −15.2 | −11.1 | −4.7 |

[a] Difference to GRACE-KBR.

[b] $\overline{C}_{20}$ replaced by values from SLR.

[c] Including Iceland, Svalbard, and the Canadian Arctic archipelago.

Uncertainties are given at the 95% ($2\sigma$) confidence level.

# Conclusions

## Good news

- GNSS tracking of (non-dedicated) satellites allows large-scale surface mass variation detection
- Additional benefit by the incorporation of SLR to geodetic satellites
- Mass change rates agree up to 97% with GRACE K-band ranging results
- Annual amplitudes agree up to 95% with GRACE K-band ranging results; inter-annual variations are detectable
- LEO-GPS & SLR is an option to bridge from GRACE to GRACE-FO

## (Present) limitations

- Level of agreement correlates with signal magnitude
- Spatial resolution (precision of GNSS and SLR observations)
- Results from orbit analysis tend to underestimate signal magnitudes (related to post-processing filtering)
- Any “bridging option” is inferior to the GRACE-KBR performance