Time variable gravity
observed by GPS derived orbit positions

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Work of Norbert Zehentner

Thesis will be finished end of this year

Norbert Zehentner, Dipl-Ing., Bakk.techn.

Kinematic orbit positioning applying the raw observation approach to observe time variable gravity

Doctoral Thesis

to achieve the University degree of

Doktor der technischen Wissenschaften

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Graz University of Technology

Supervisor

Univ.-Prof. Dr.-Ing. Torsten Mayer-Gürr

Institute of Geodesy

Working group Theoretical Geodesy and Satellite Geodesy

Graz, June 2016

Work of Norbert Zehentner

Thesis will b
of this year

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ORIGINAL ARTICLE

Precise orbit determination based on raw GPS measurements

Norbert Zehentner[1] · Torsten Mayer-Gürr[1]

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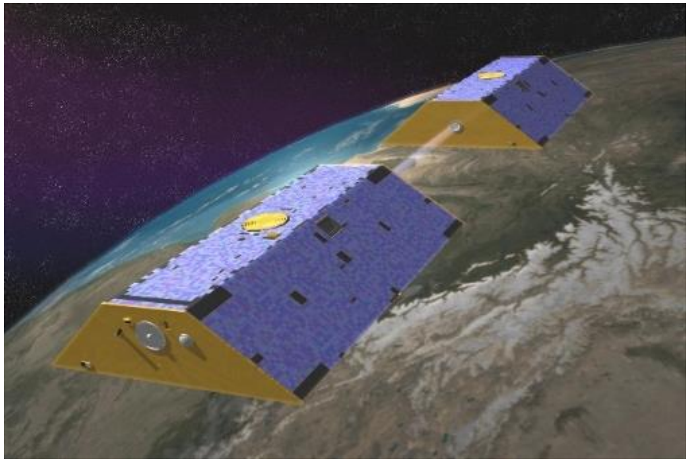
Abstract Precise orbit determination is an essential part of the most scientific satellite missions. Highly accurate knowledge of the satellite position is used to geolocate measurements of the onboard sensors. For applications in the field of gravity field research, the position itself can be used as observation. In this context, kinematic orbits of low earth orbiters (LEO) are widely used, because they do not include a priori information about the gravity field. The limiting factor for the achievable accuracy of the gravity field through LEO positions is the orbit accuracy. We make use of raw

Keywords Precise orbit determination · Low earth orbiter · Kinematic orbit · Raw GPS observations · Satellite-to-satellite tracking high-low · Time variable gravity

1 Introduction

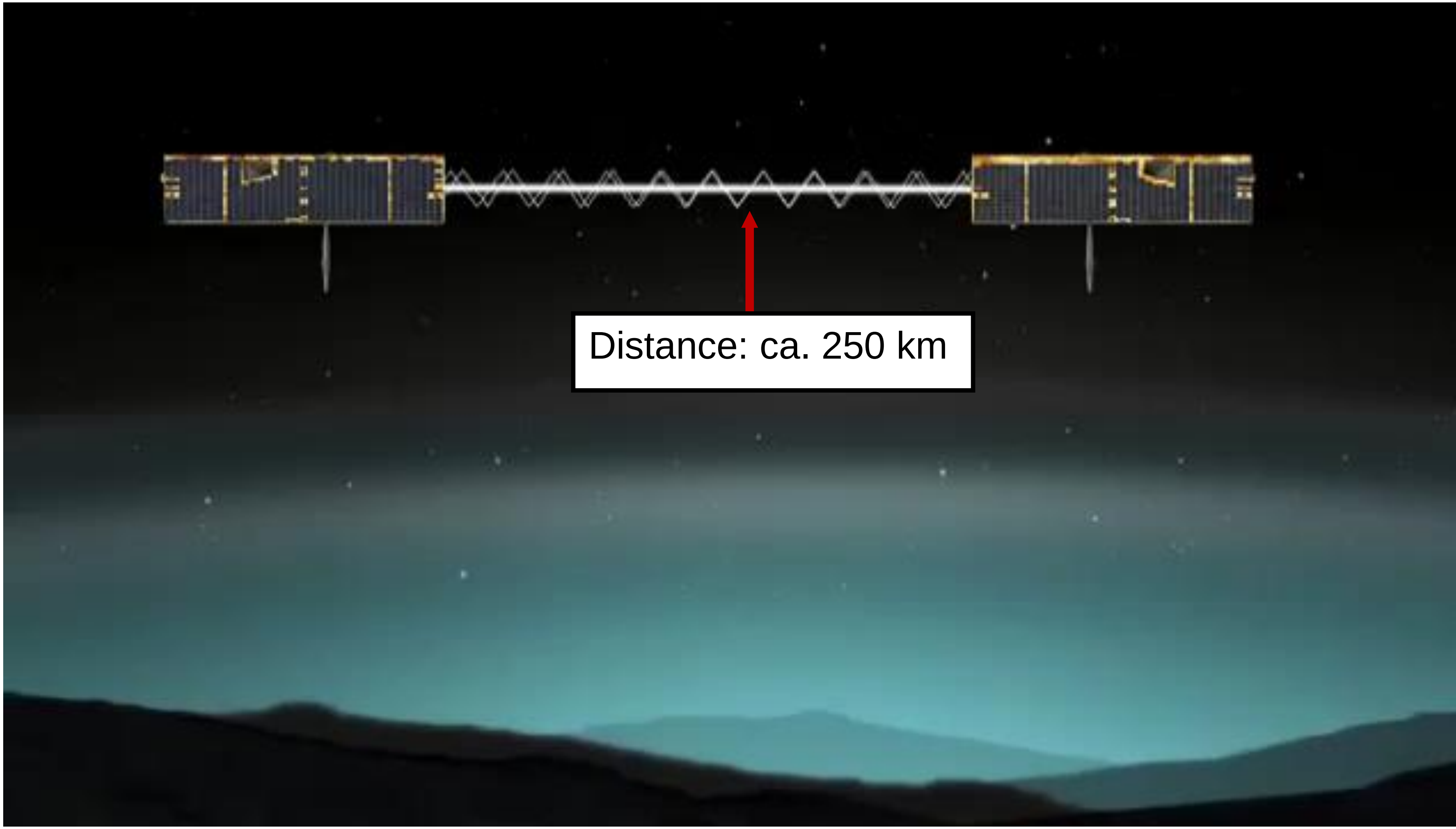
Kinematic orbit positions often serve as observations for gravity field estimation. Hence, their accuracy directly affects the quality of the gravity field estimates. We present a new

The reference of observing the time variable gravity field: The GRACE mission

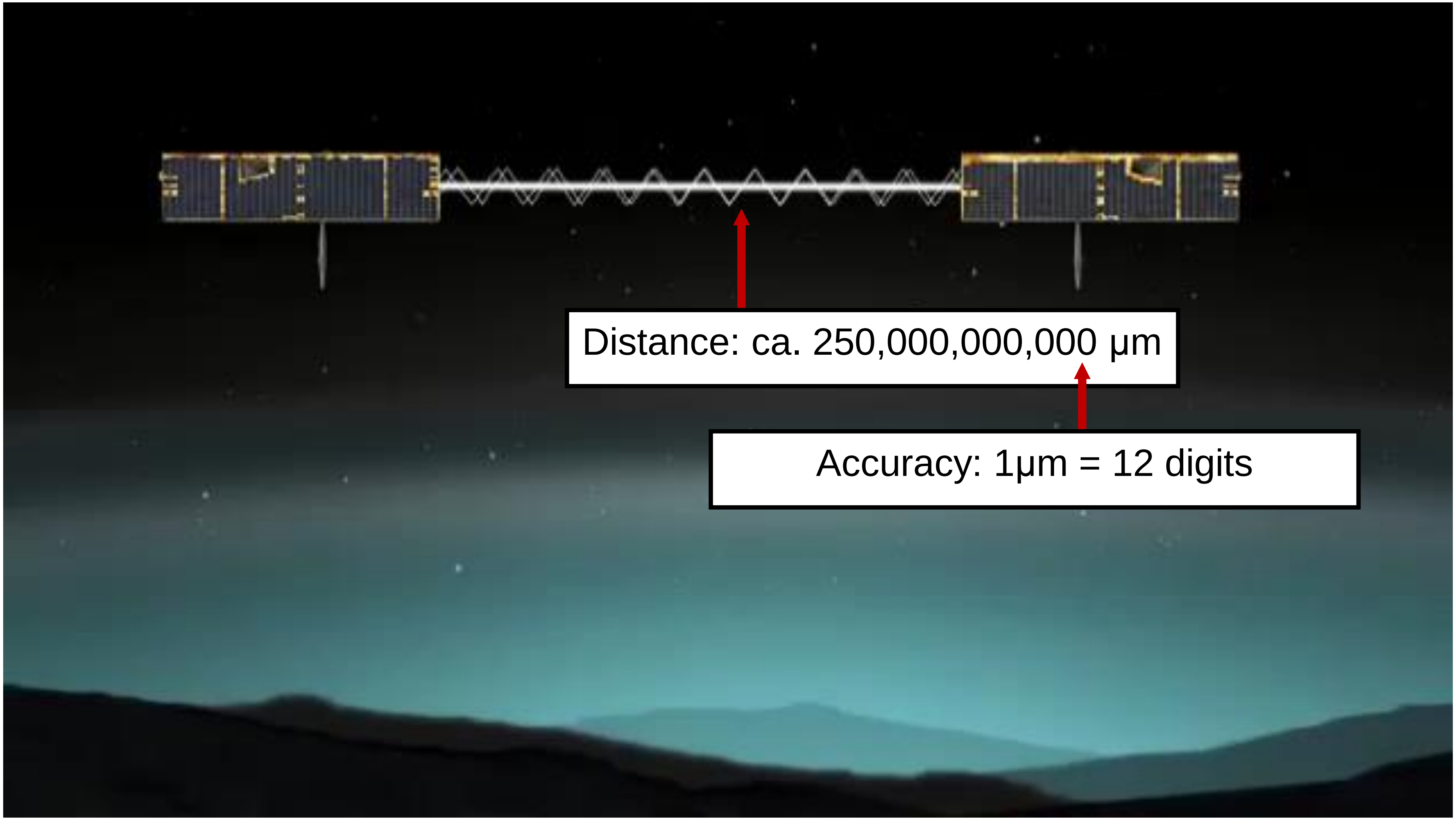


Gravity Recovery and Climate Experiment

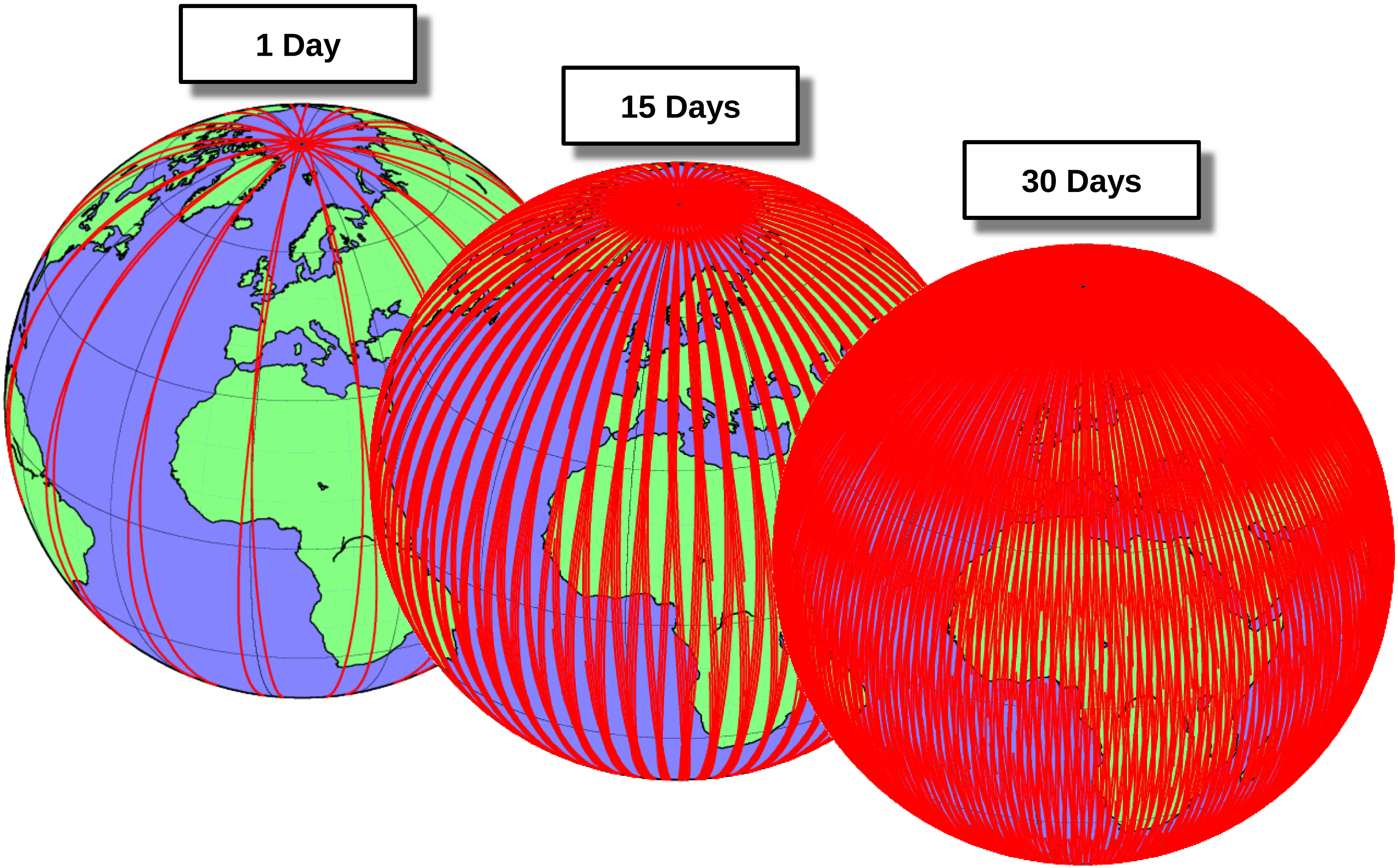
Gravity Recovery and Climate Experiment



Gravity Recovery and Climate Experiment



Groundtracks



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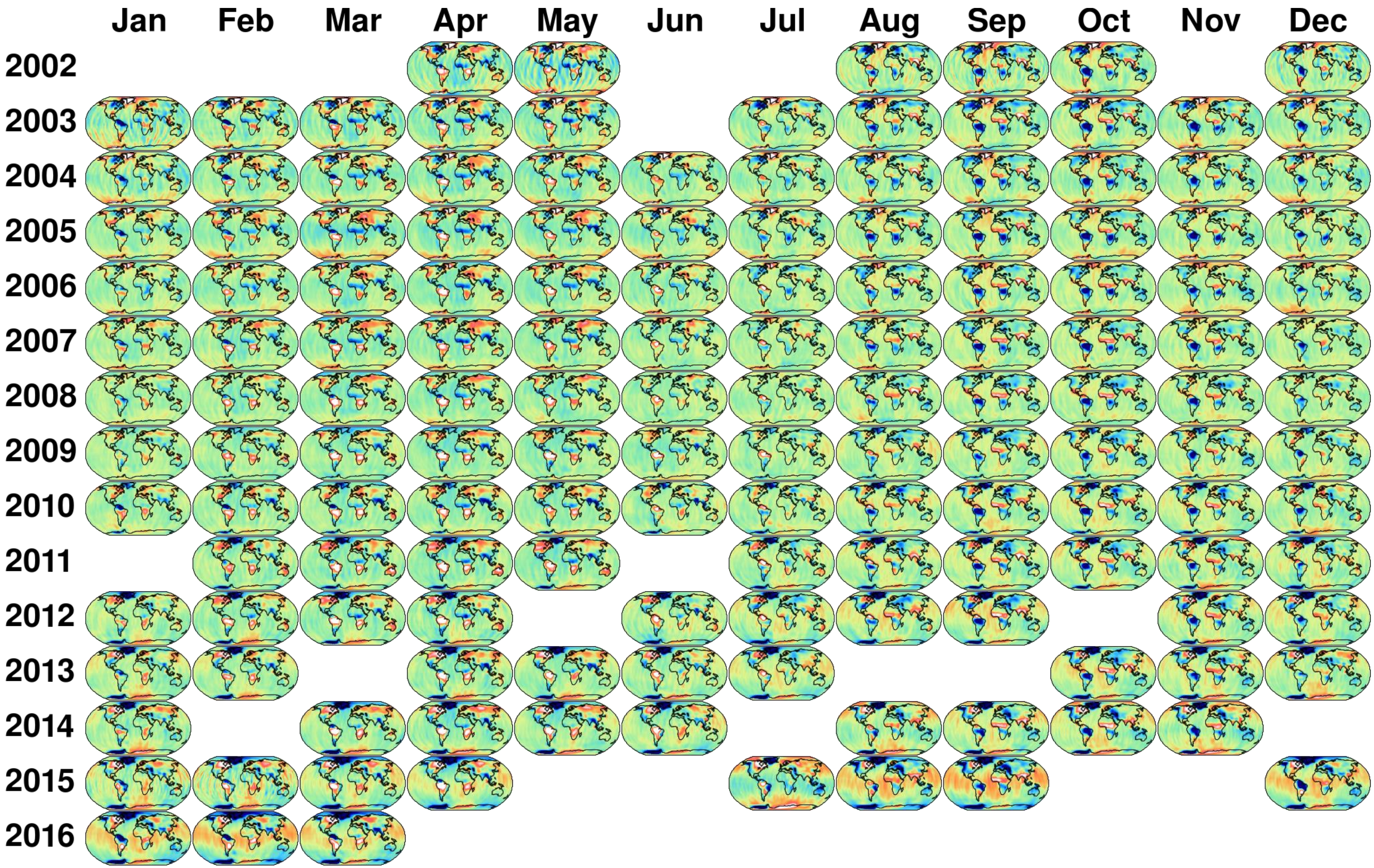


Gravity

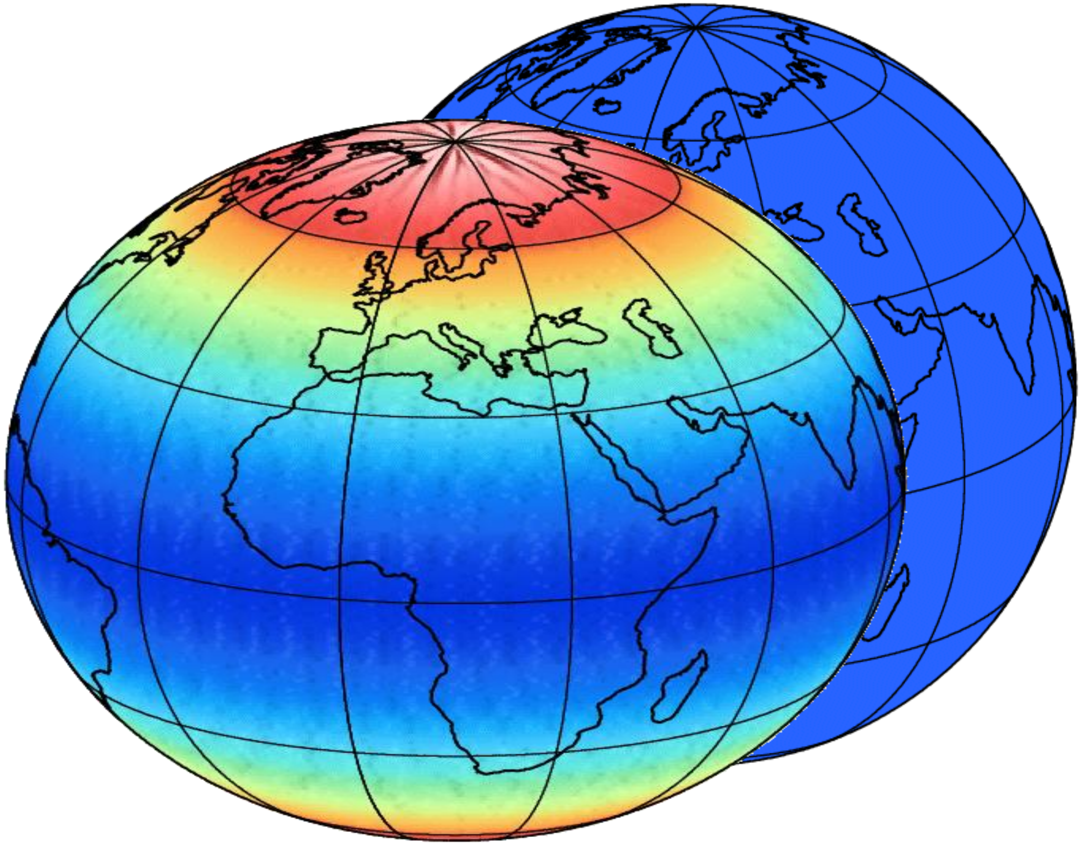
Gravity at Earth surface

$$g = 9{,}81 \frac{m}{s^2}$$

Gravity

Gravity at Earth surface

$$g = 9{,}78\frac{m}{s^2} \ldots 9{,}83\frac{m}{s^2}$$

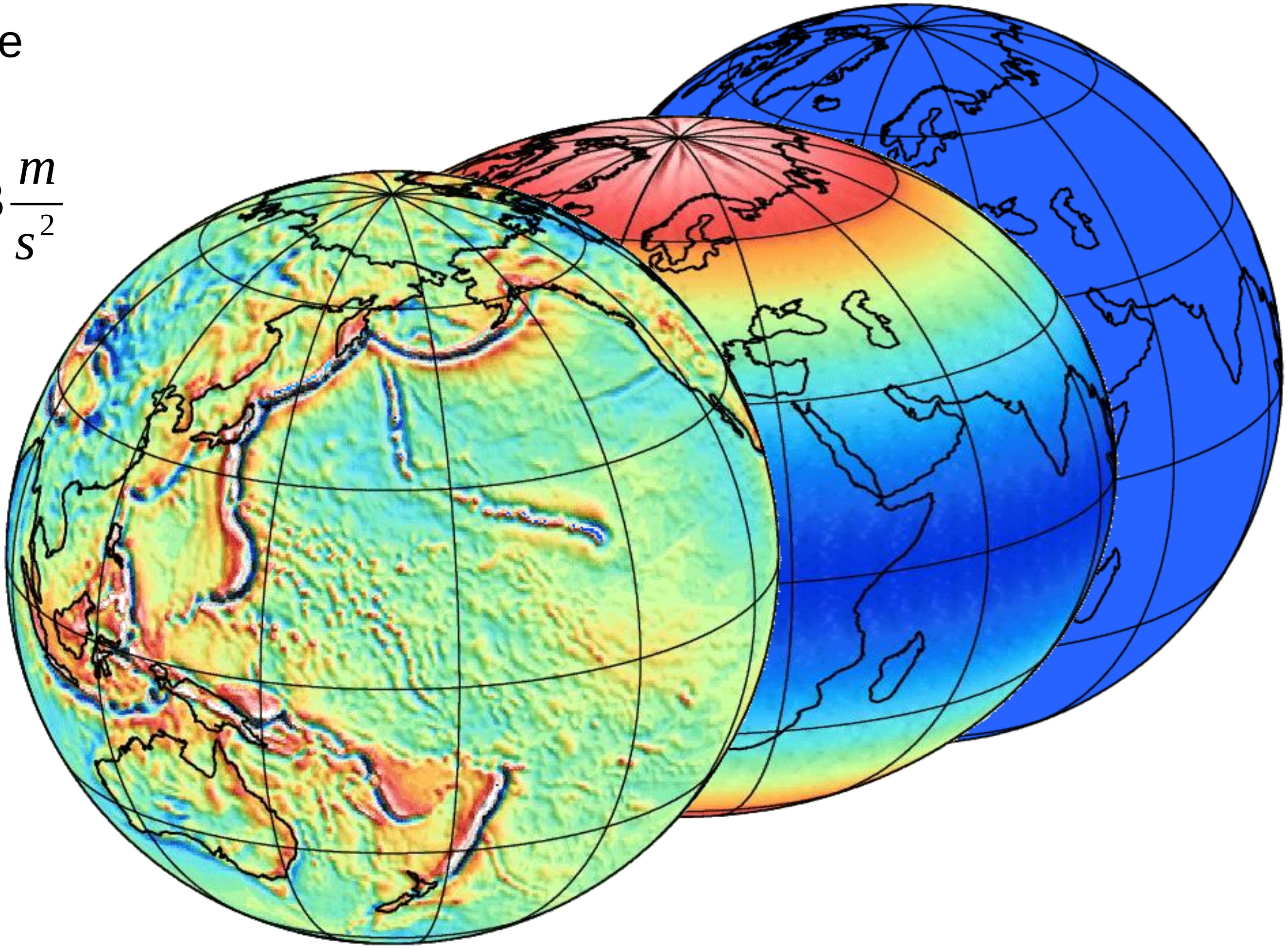


Gravity

Gravity at Earth surface

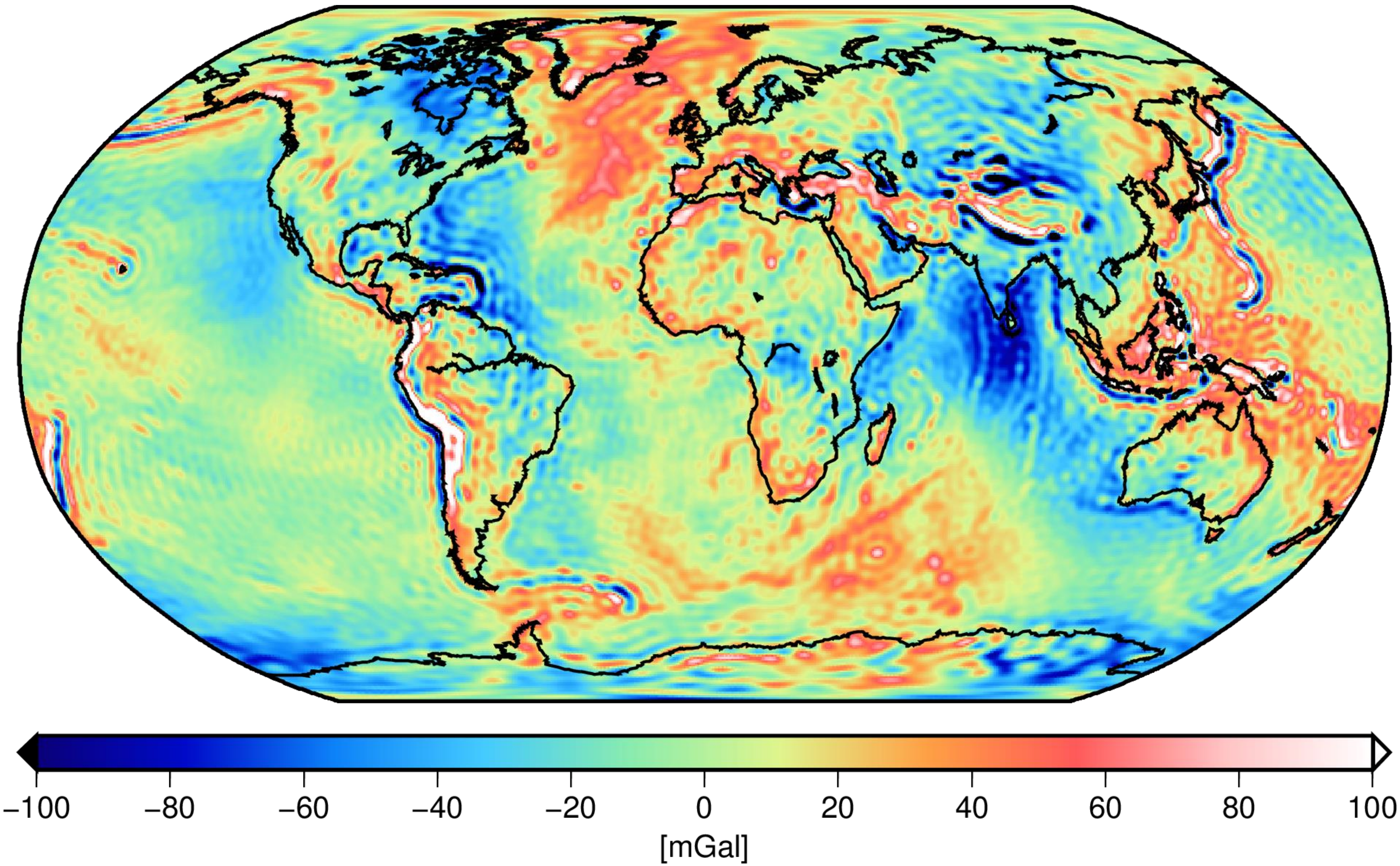
$$g = 9{,}78\frac{m}{s^2}\ldots 9{,}83\frac{m}{s^2}$$

$$\pm 0{,}0004\frac{m}{s^2}$$

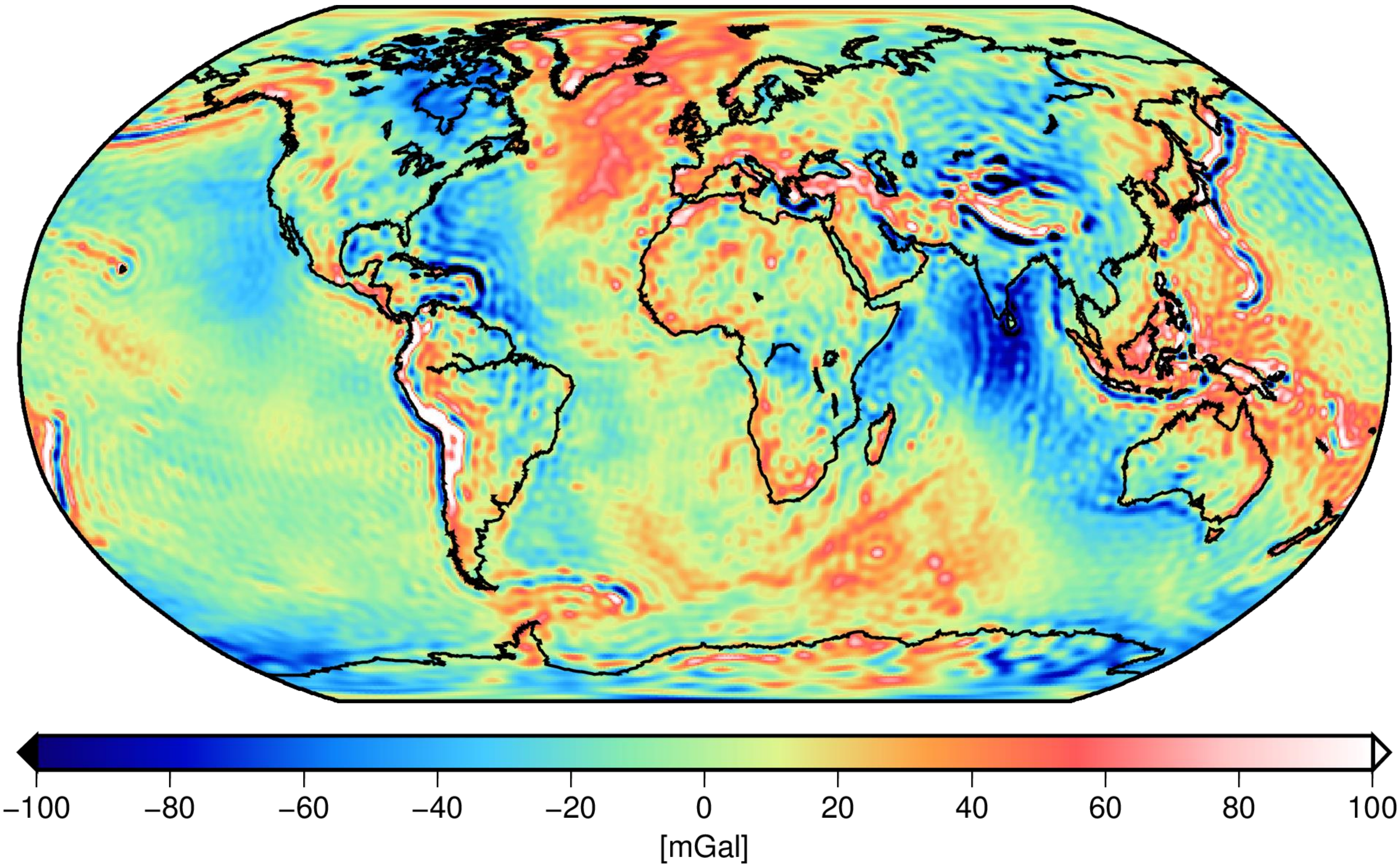


$$\left[1\mathrm{mGal} = 0{,}00001\frac{m}{s^2}\right]$$

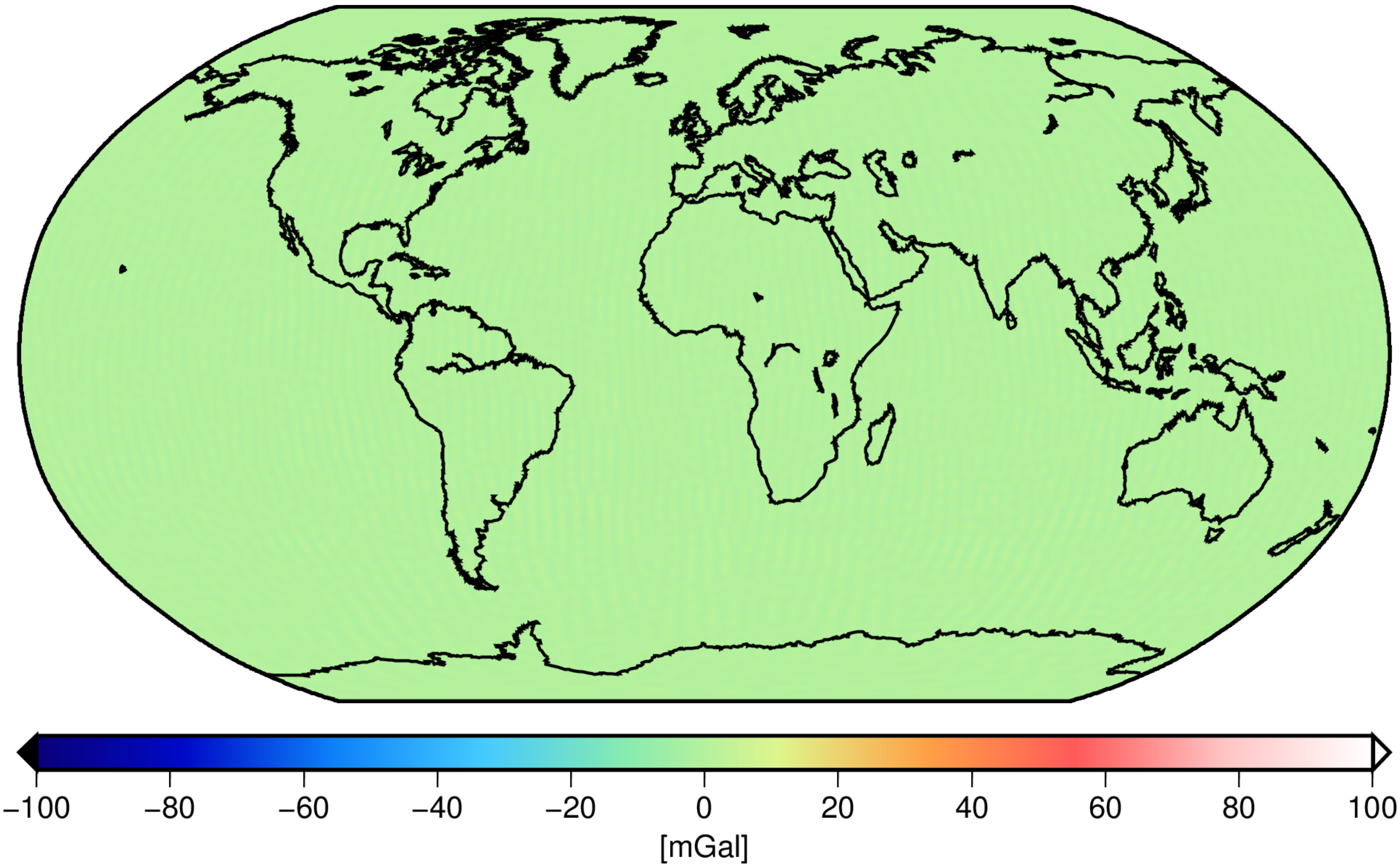
GRACE gravity field March 2008



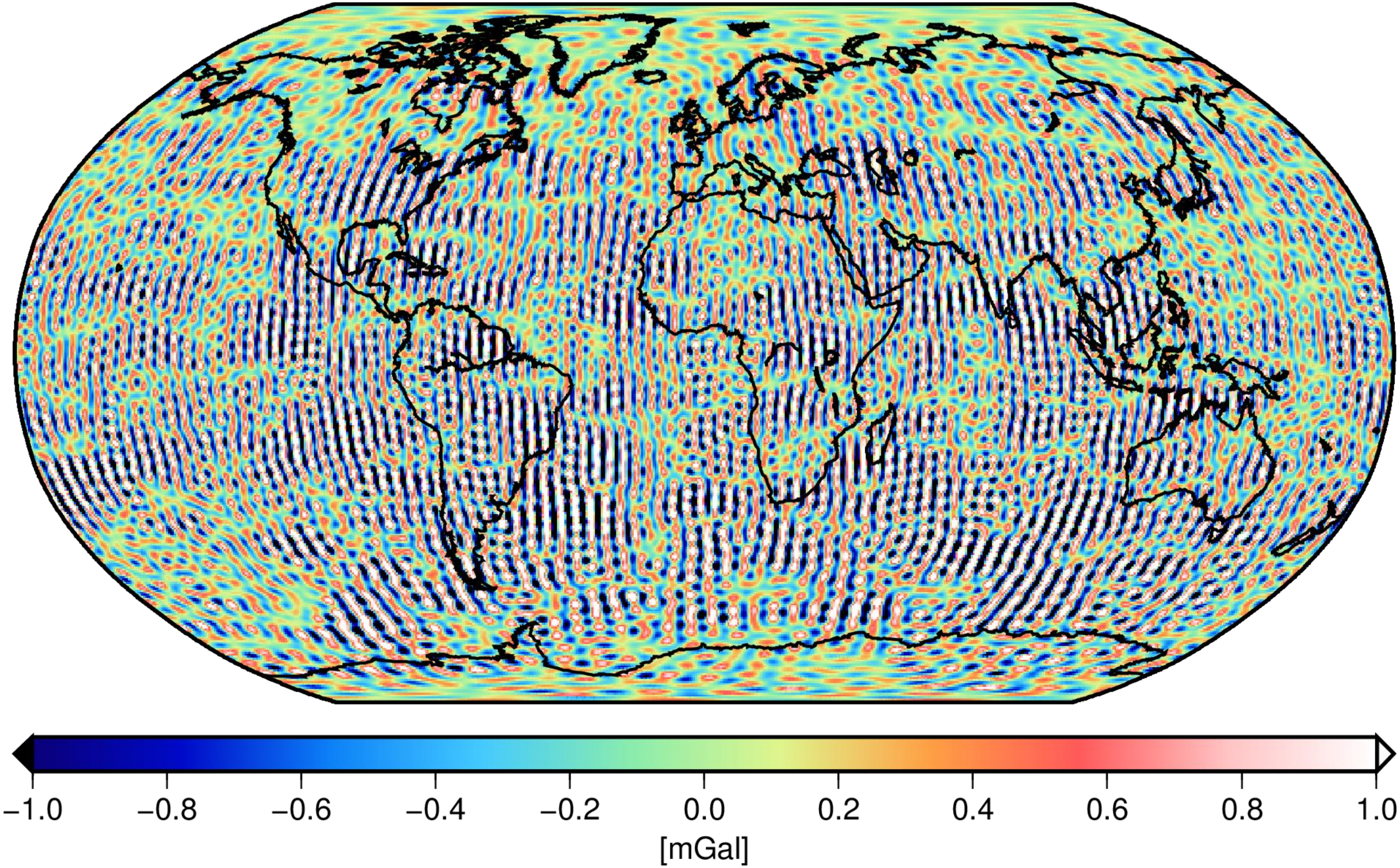
GRACE gravity field September 2008



September – March 2008



September – March 2008



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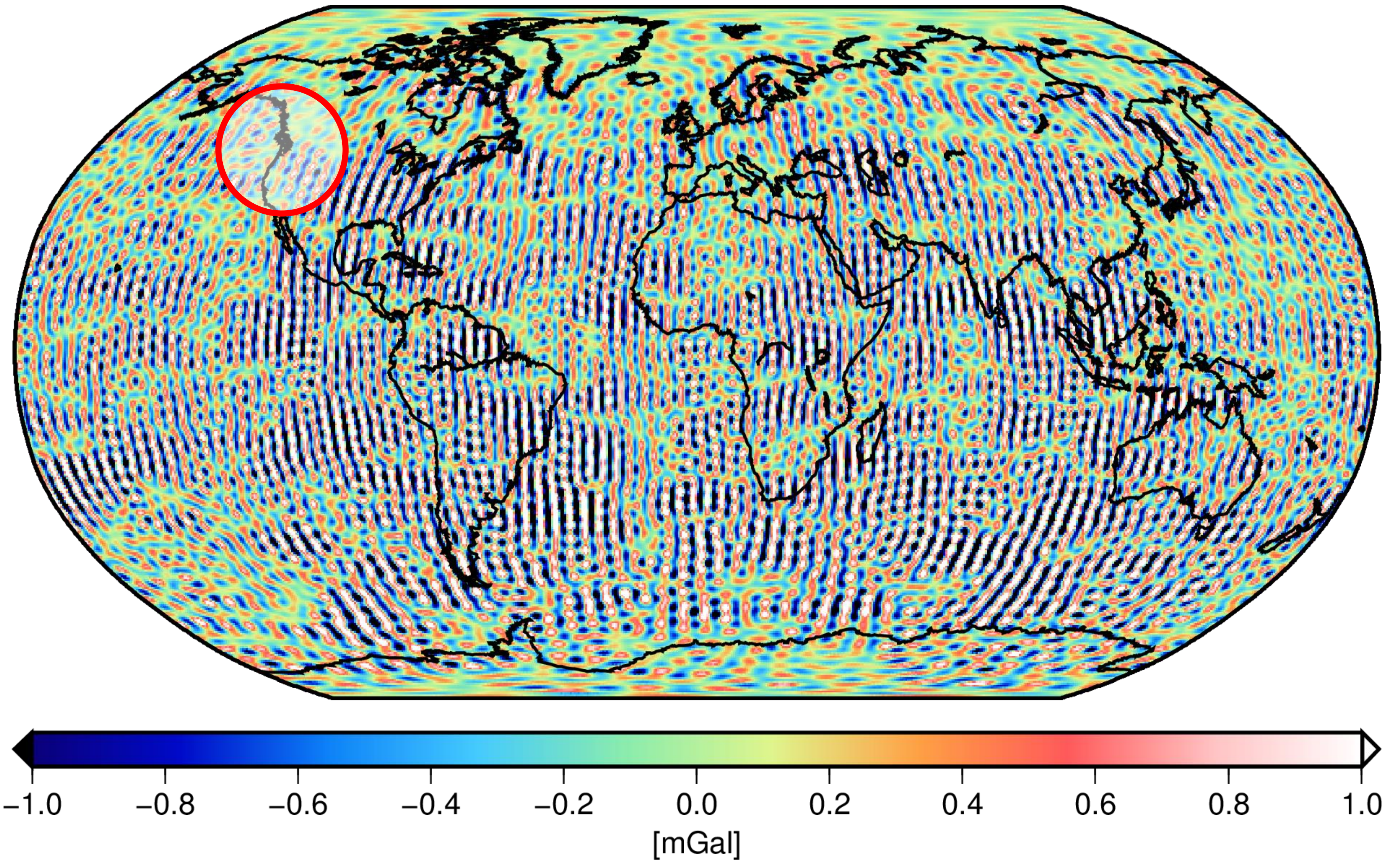

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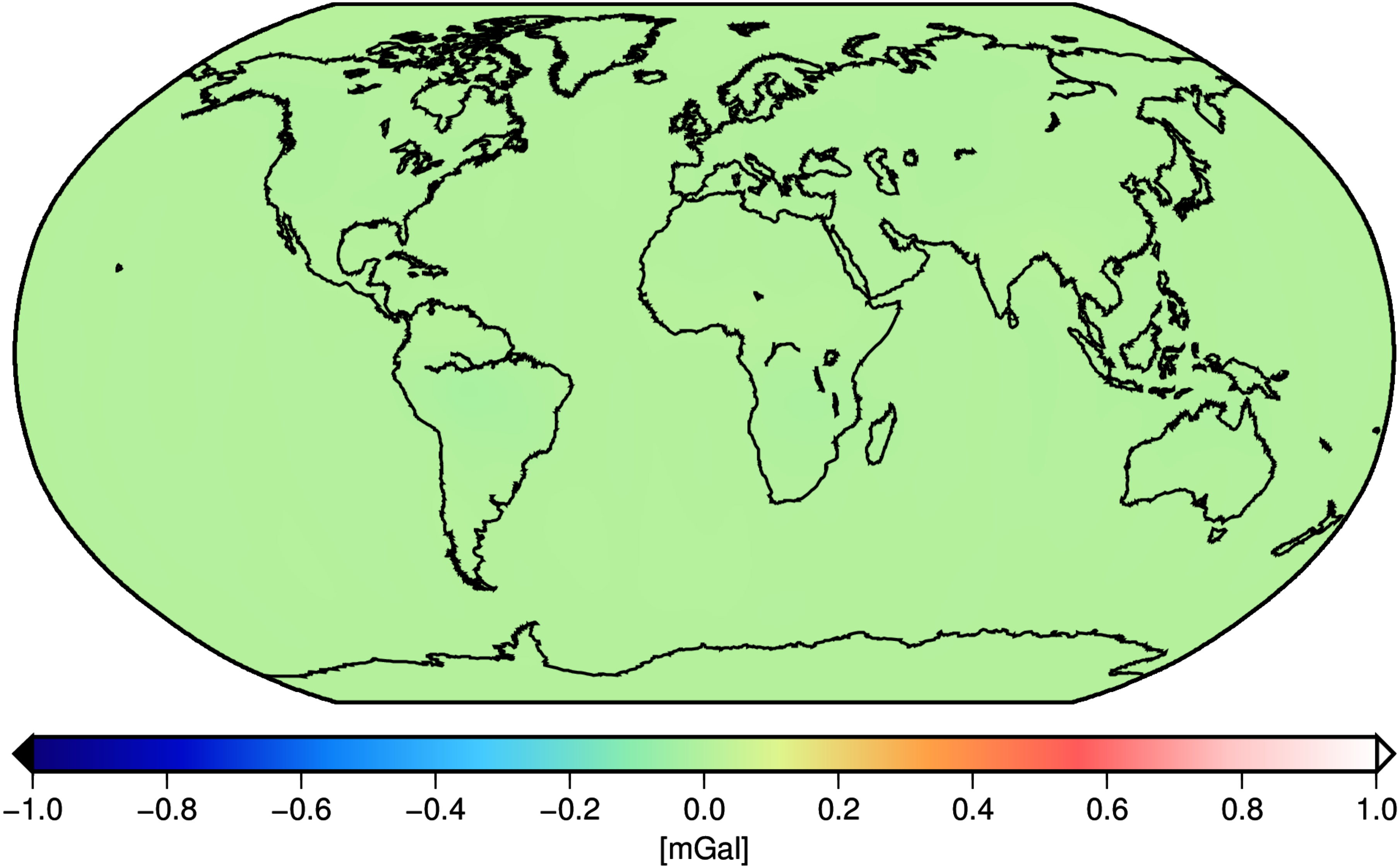
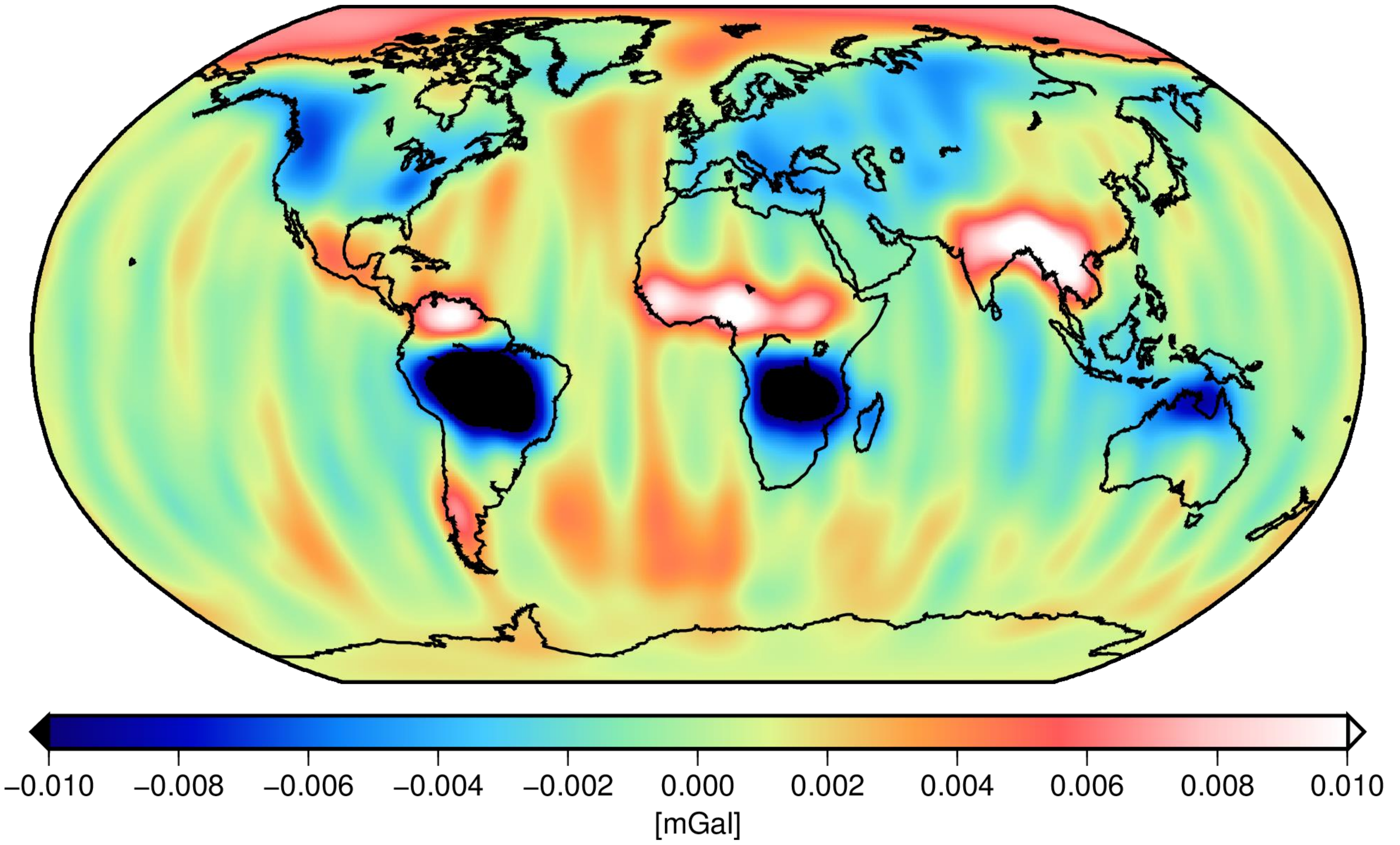
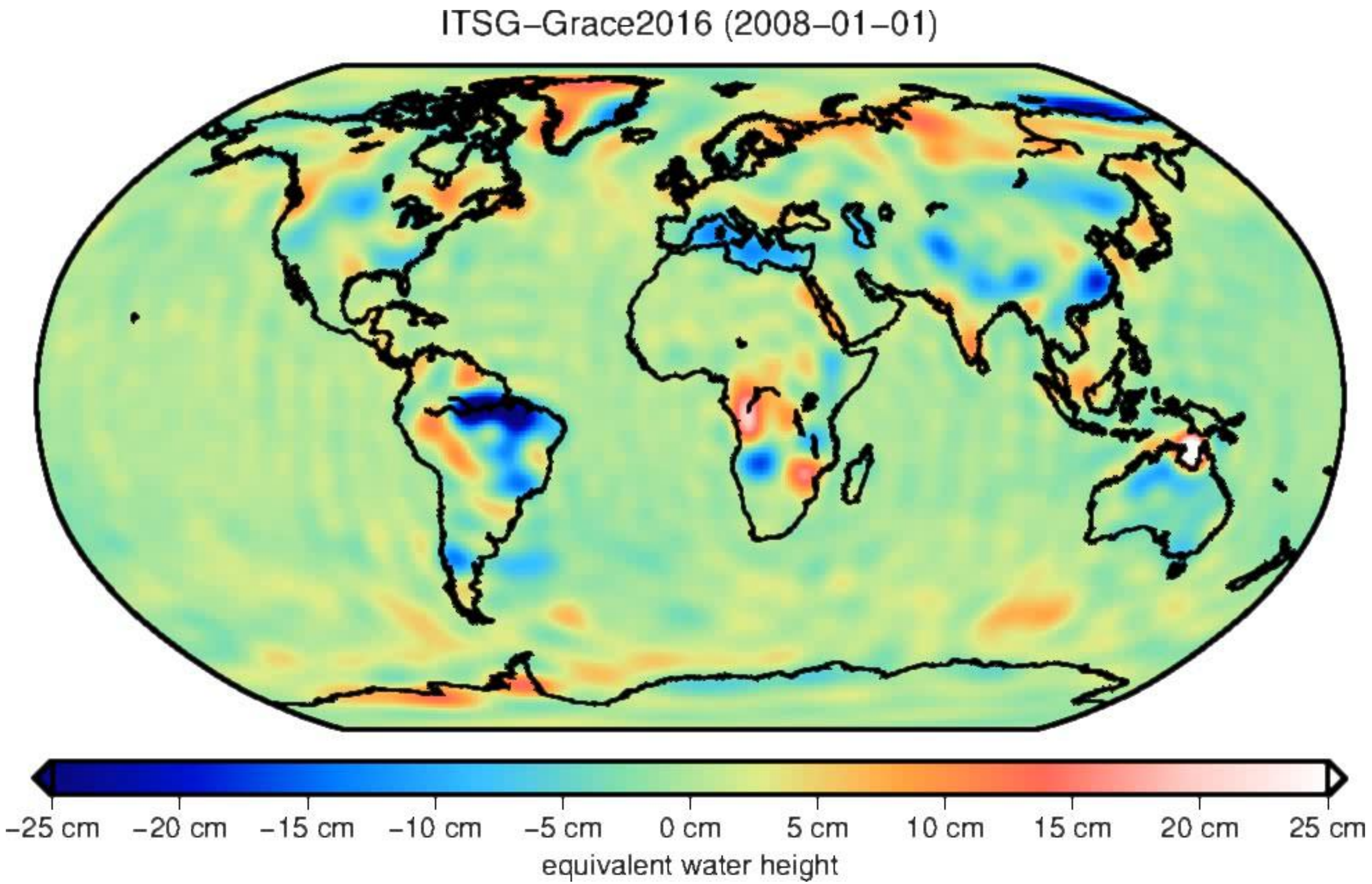


September – March 2008

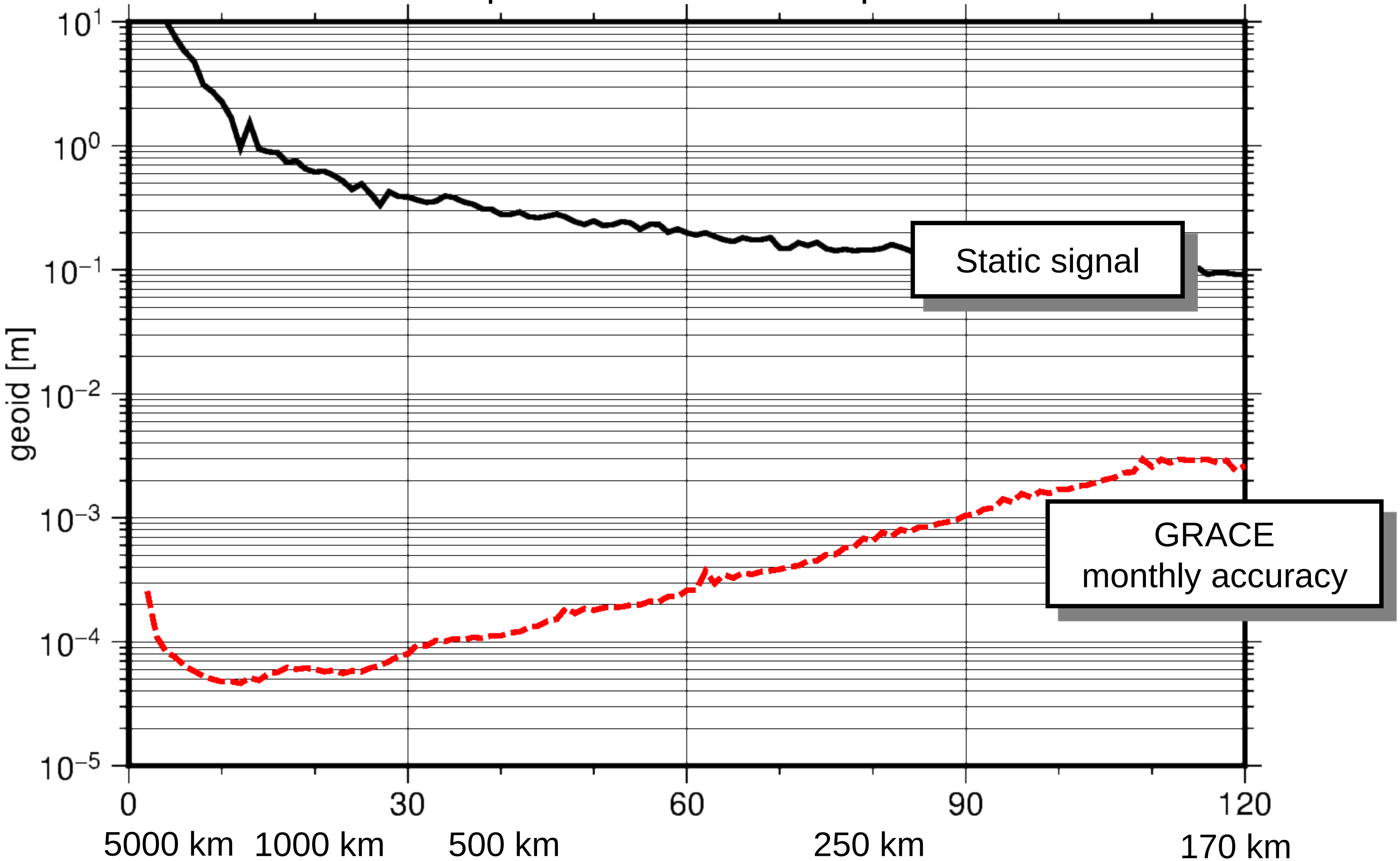


ITSG-Grace2016 Daily Kalman solutions



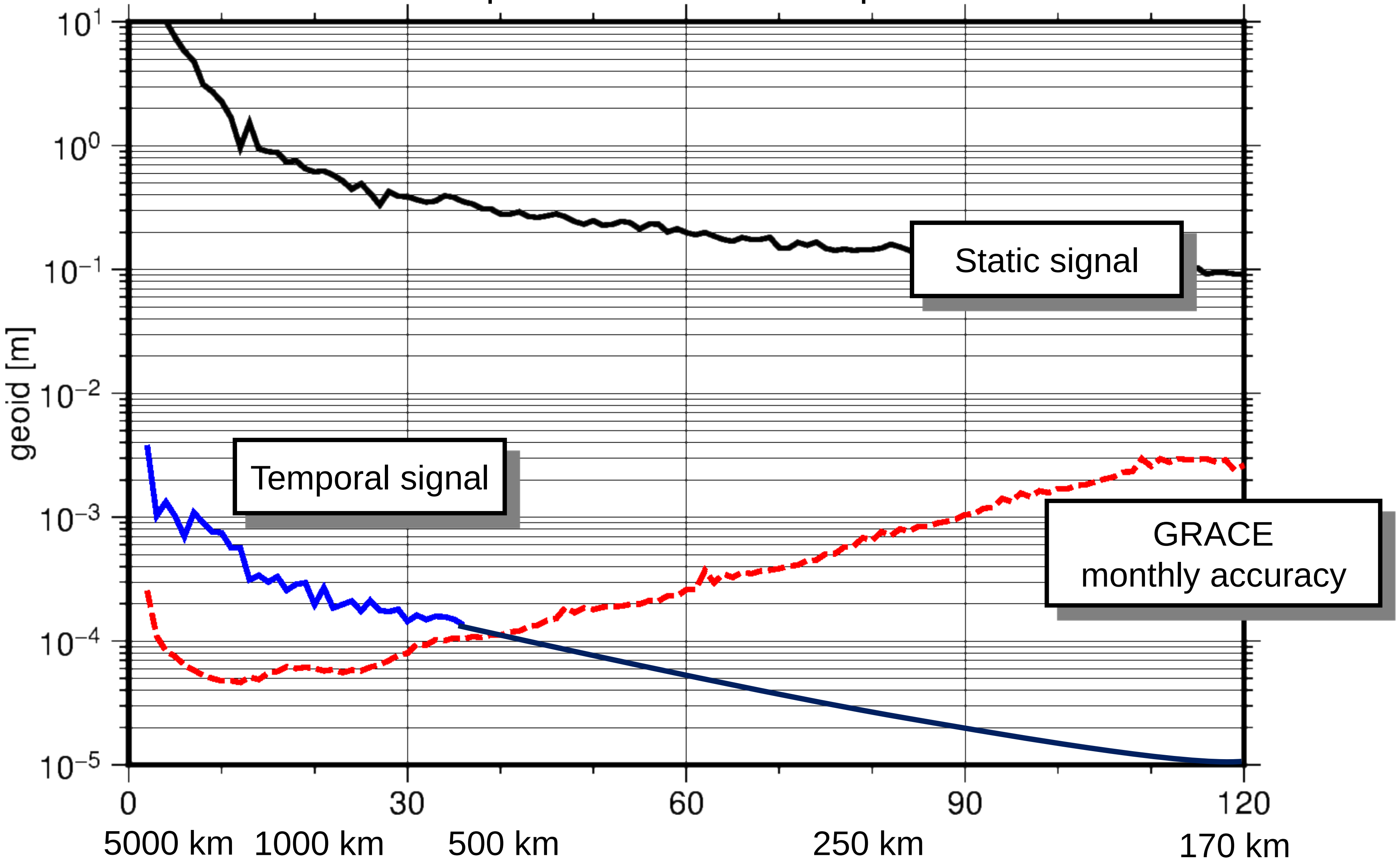
Degree amplitudes

of the spherical harmonics expansion



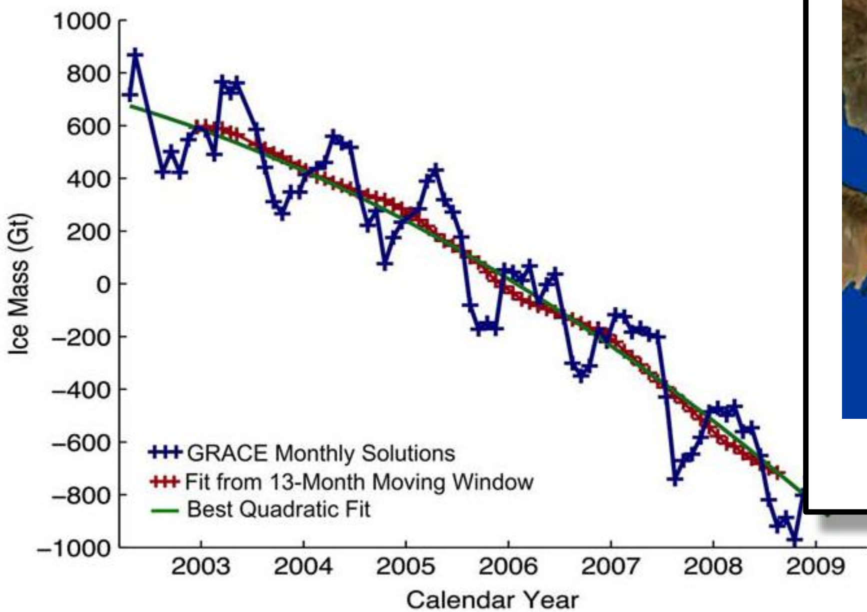
Degree amplitudes

of the spherical harmonics expansion



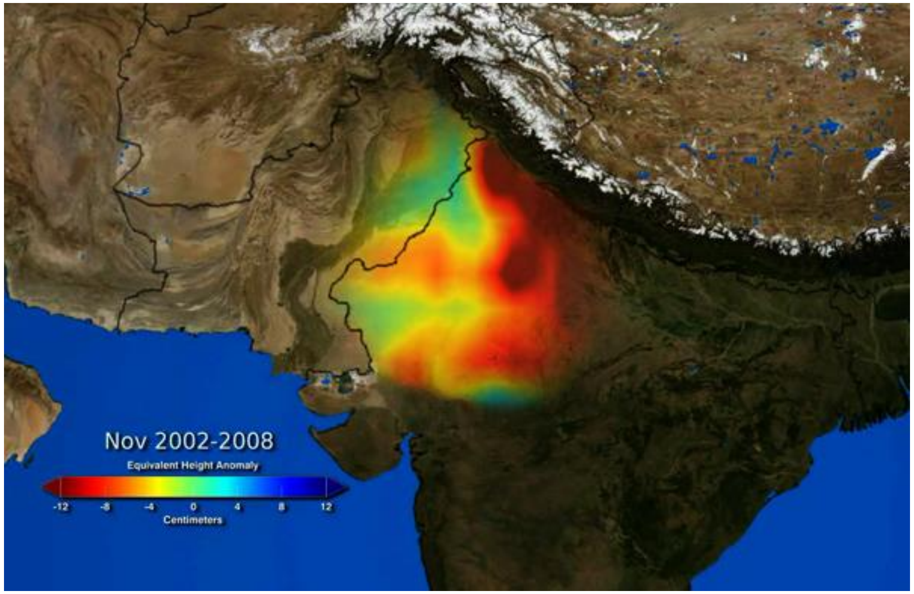
Gl

Ice mass variations in Greenland

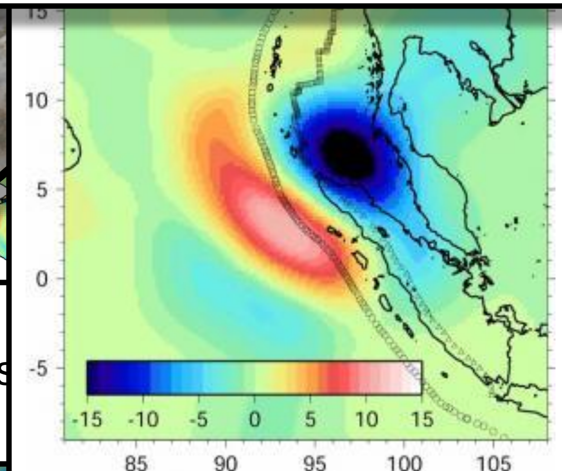


Velicogna, 2009, Geophys. Res. Lett.

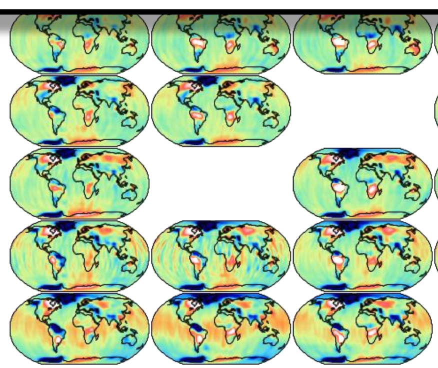
Groundwater depletion in North India



Rodell et al., 2009, Nature



Han et al., 2006, Science

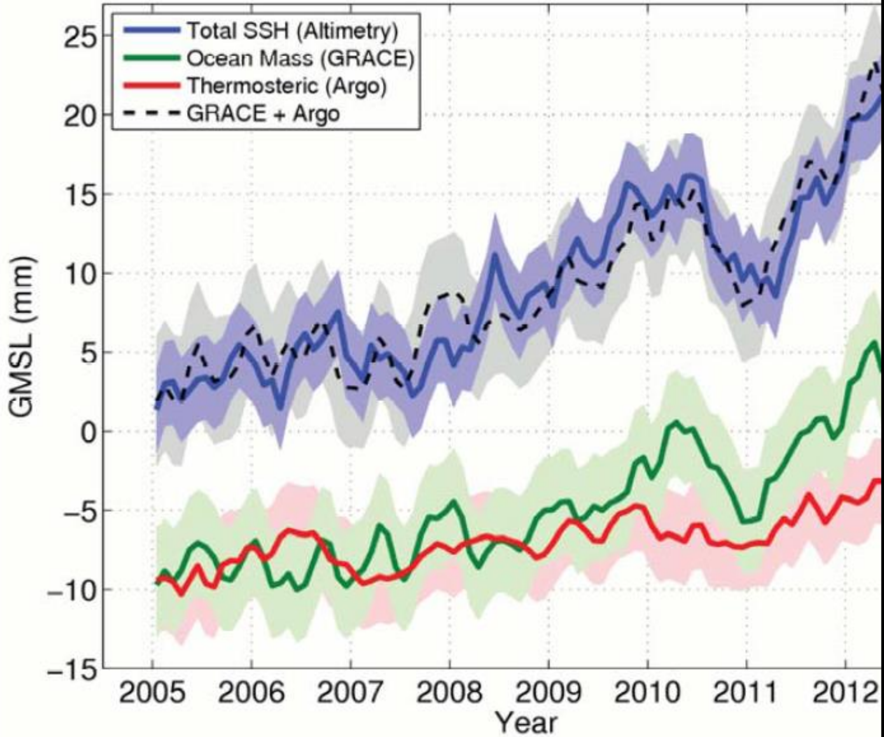


> 3.000 Publications
(GRACE Tellus, grace.jpl.nas

Gl

Ice mass variations in Greenland

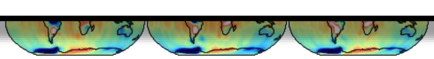
Global Sea level change



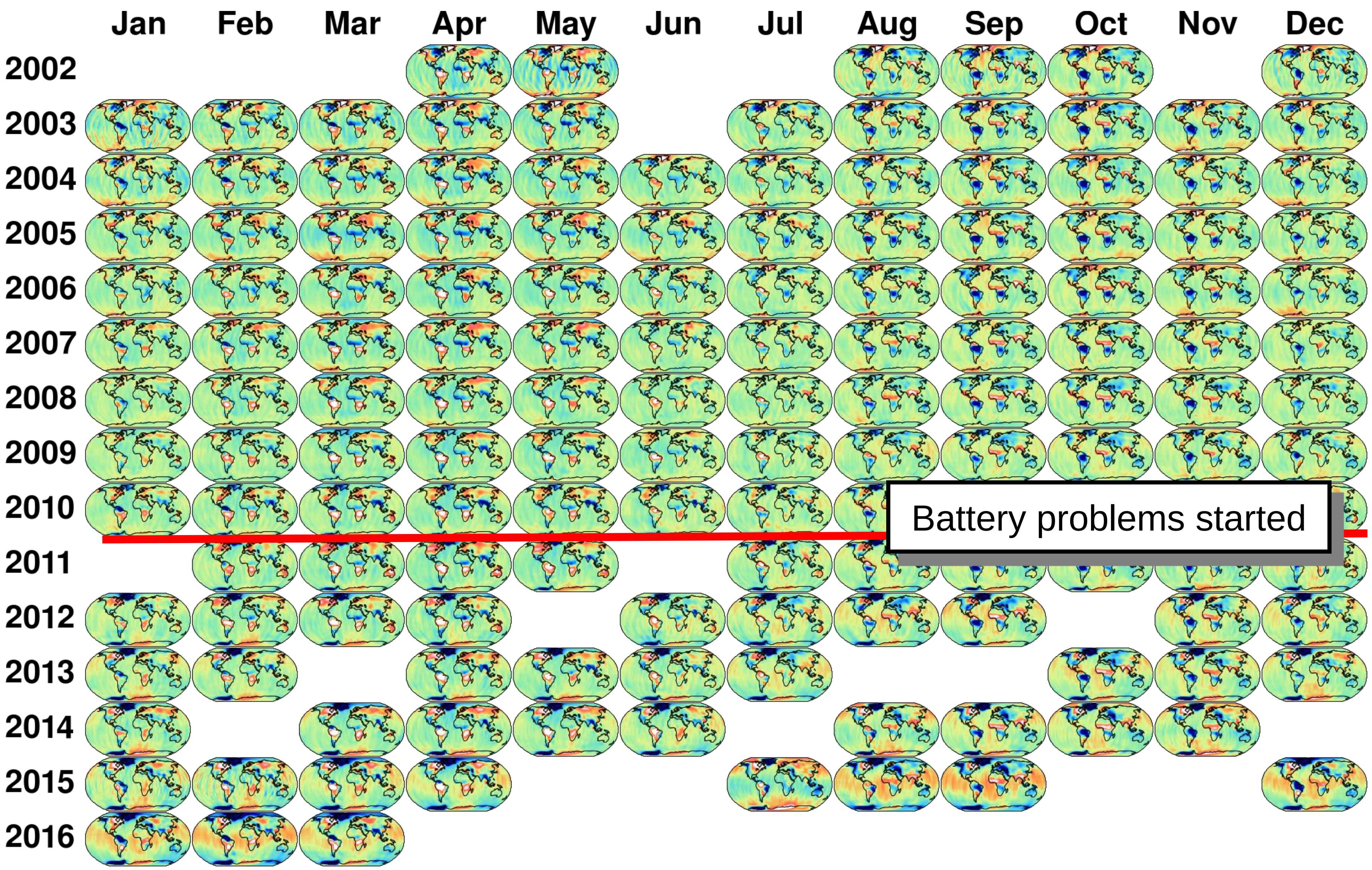
IPCC WGI Fifth Assessment Report, 2

Groundwater depletion in North India

20
20
20
20
2010

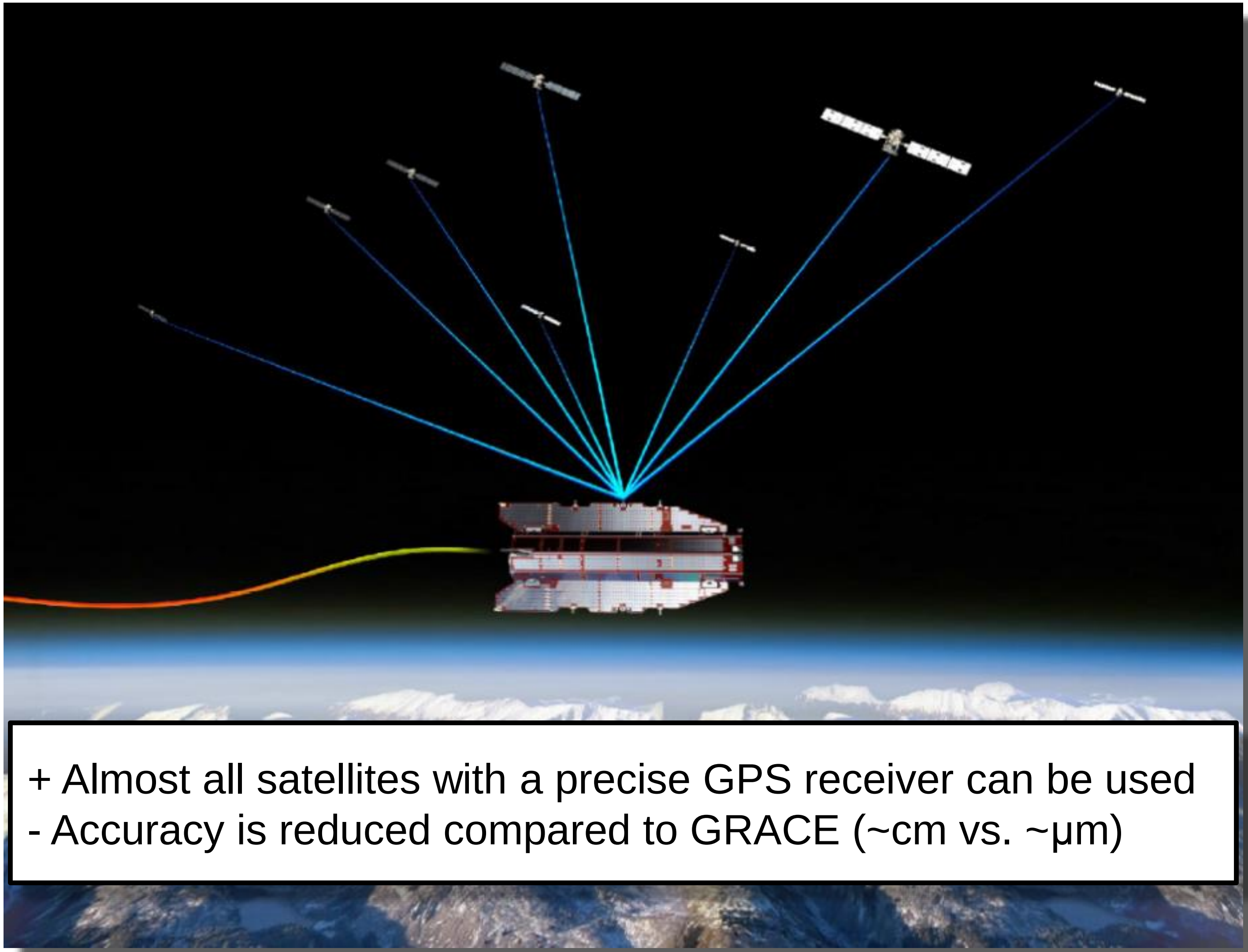


ITSG-Grace2016 Monthly solutions



Alternatives?

High-Low Satellite-to-Satellite Tracking (hlSST)



+ Almost all satellites with a precise GPS receiver can be used
- Accuracy is reduced compared to GRACE (~cm vs. ~µm)

Satellite missions

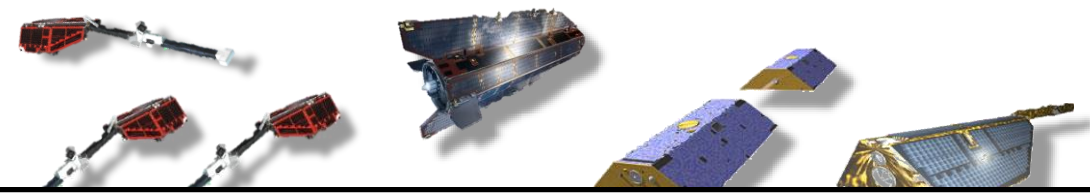
- CHAMP
- GRACE
- GOCE

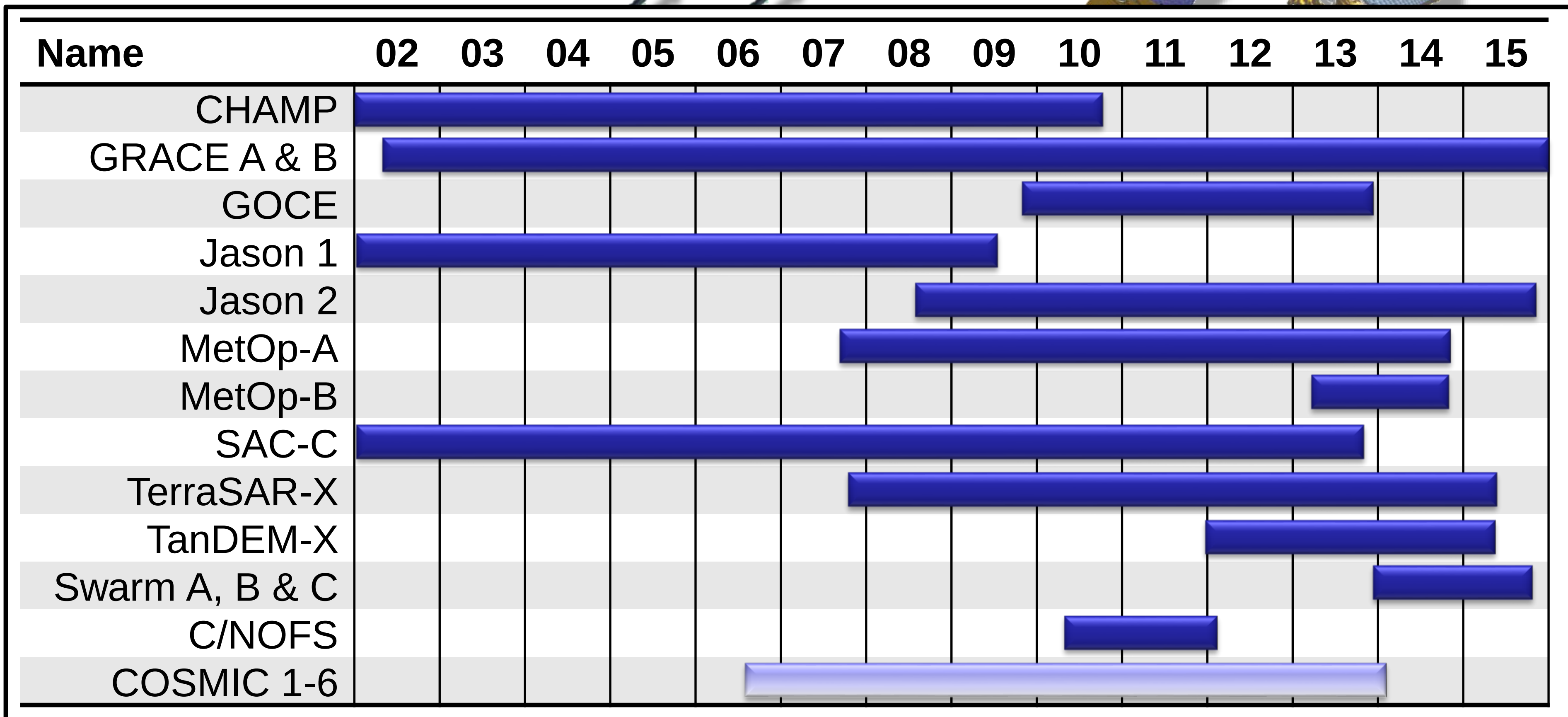
- Swarm A, B & C
- MetOp A & B
- TerraSAR-X & TanDEM-X
- FORMOSAT-3/COSMIC
- SAC-C
- Jason 1 & 2
- C/NOFS

Total 21 satellites

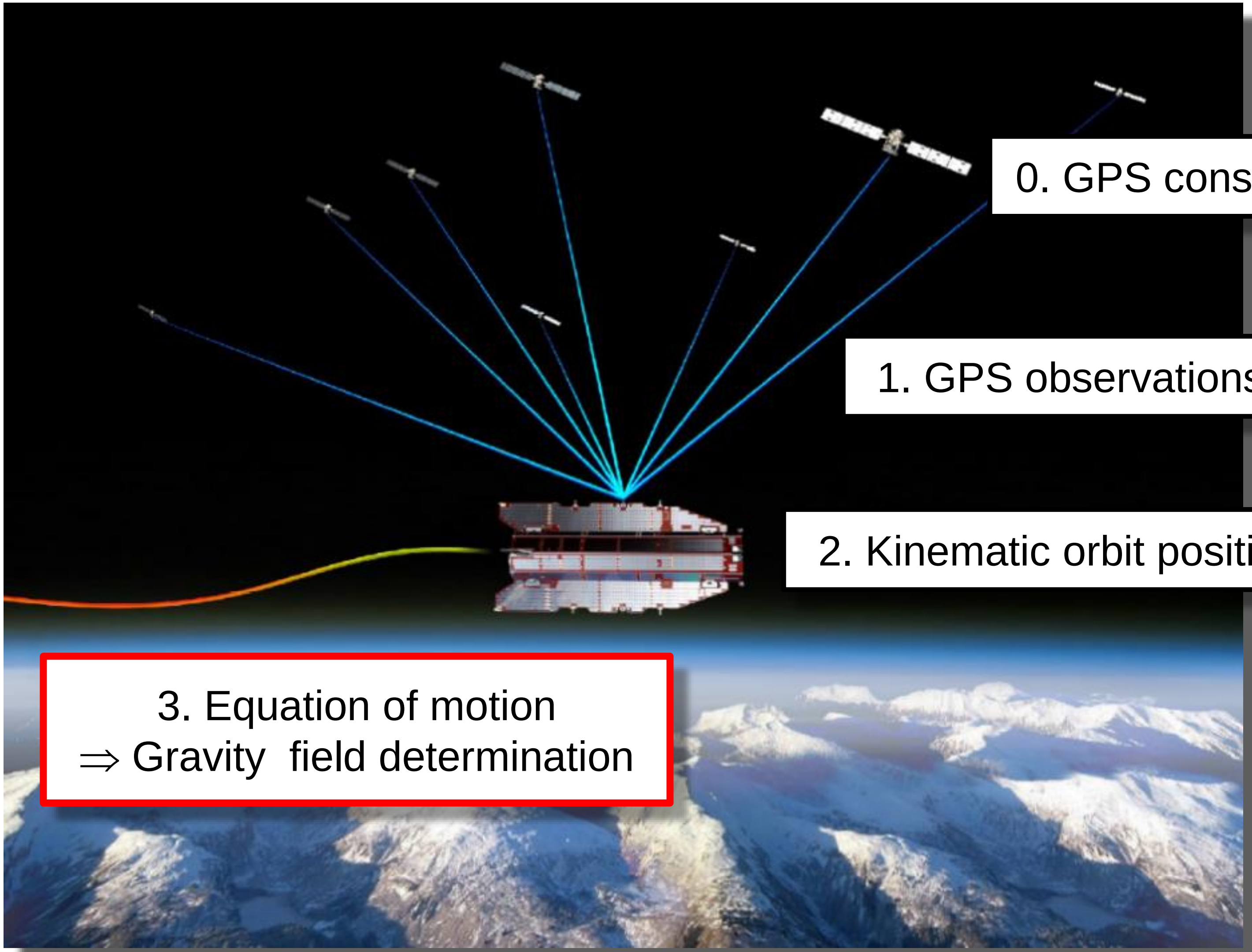
Satellite missions

- CHAMP
- GRACE

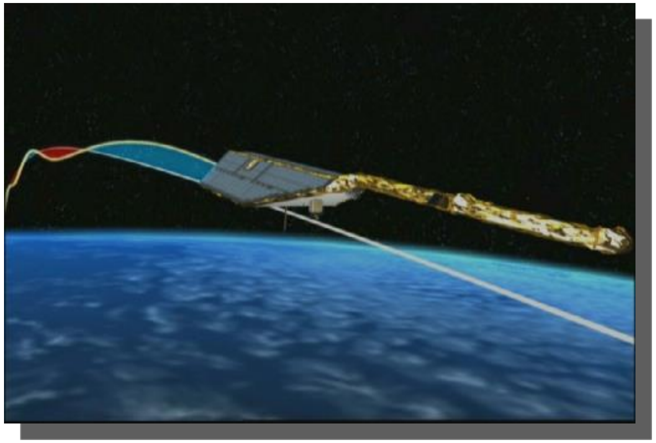




High-Low Satellite-to-Satellite Tracking (hlSST)



Physical model: Orbit dynamics



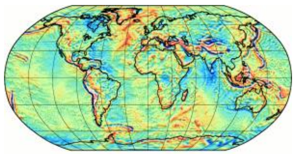
Equation of motion

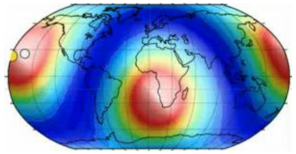
$$m\ddot{\mathbf{r}}(t) = \mathbf{F}(t, \mathbf{r}, \ldots)$$

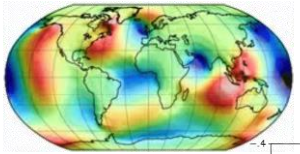
$\Rightarrow$ Numerical orbit integration

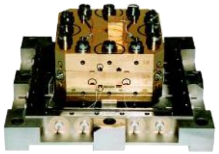
Forces:

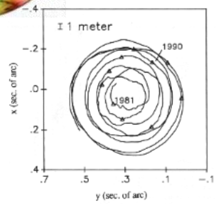
- Static gravity field:	GOCO05s
- Direct tides (Sun, moon, planets):	JPL DE421
- Solid Earth tides:	IERS 2010
- Ocean tides:	EOT11a
- Pole tides:	IERS 2010
- Ocean pole tides:	Desai 2004
- Atmosperic tides (S1, S2)	Bode-Biancale 2003
- Dealiasing (atmos, ocean):	AOD1B RL05
- Non conservative forces:	Not modelled
- Relativistic effects	IERS 2010





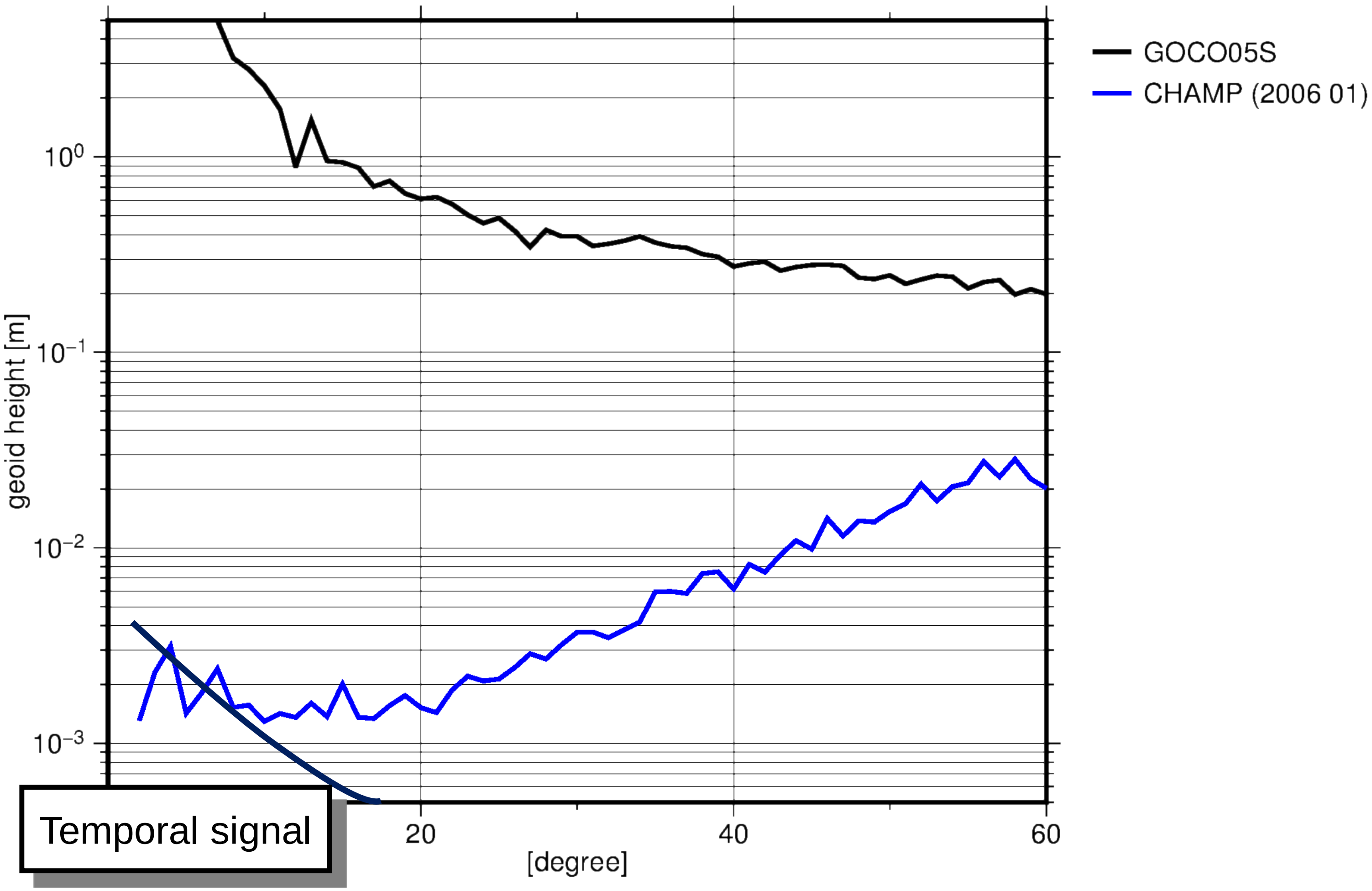






Degree amplitudes

(Monthly solutions)



Degree amplitudes

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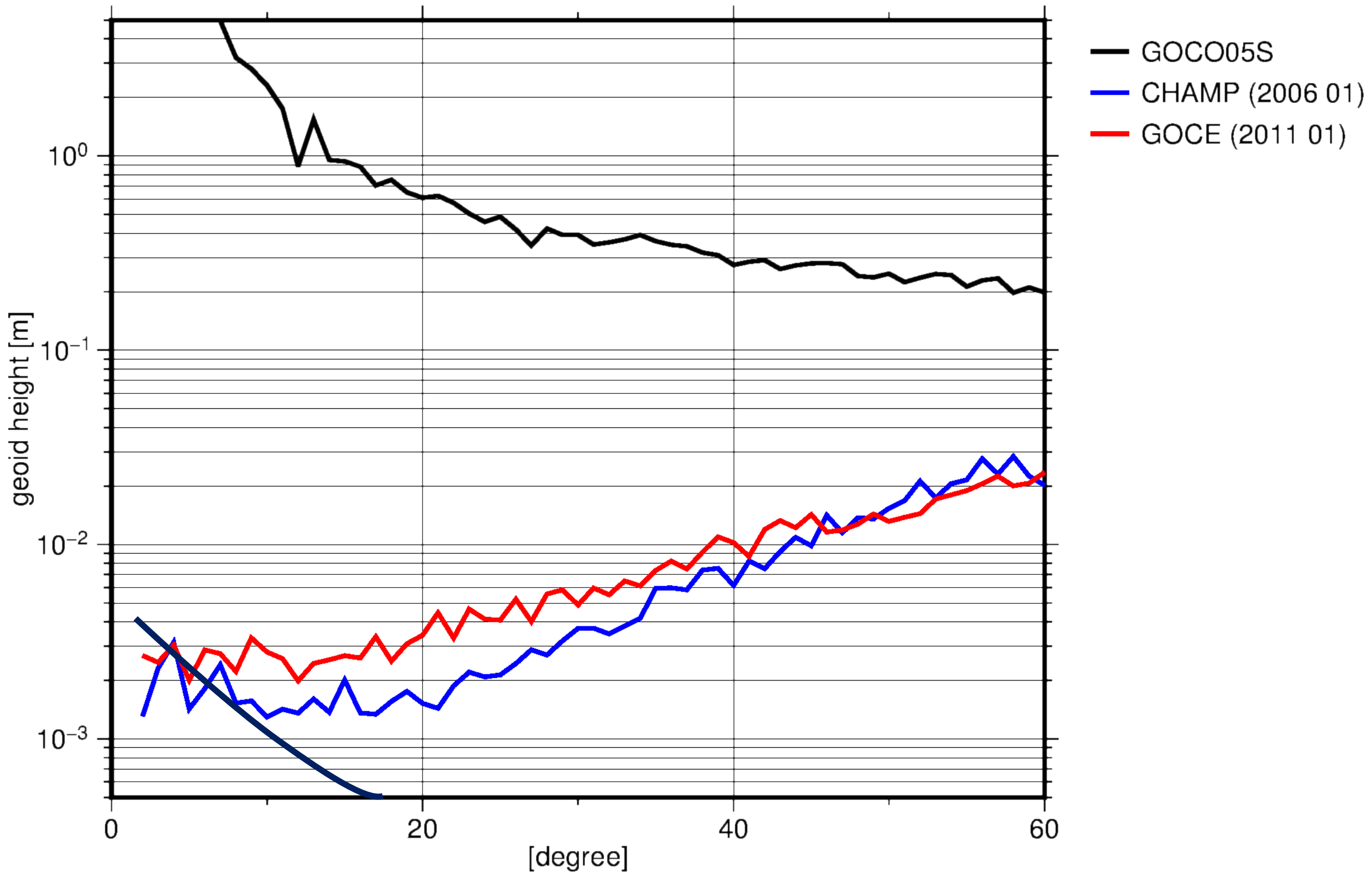

Degree amplitudes

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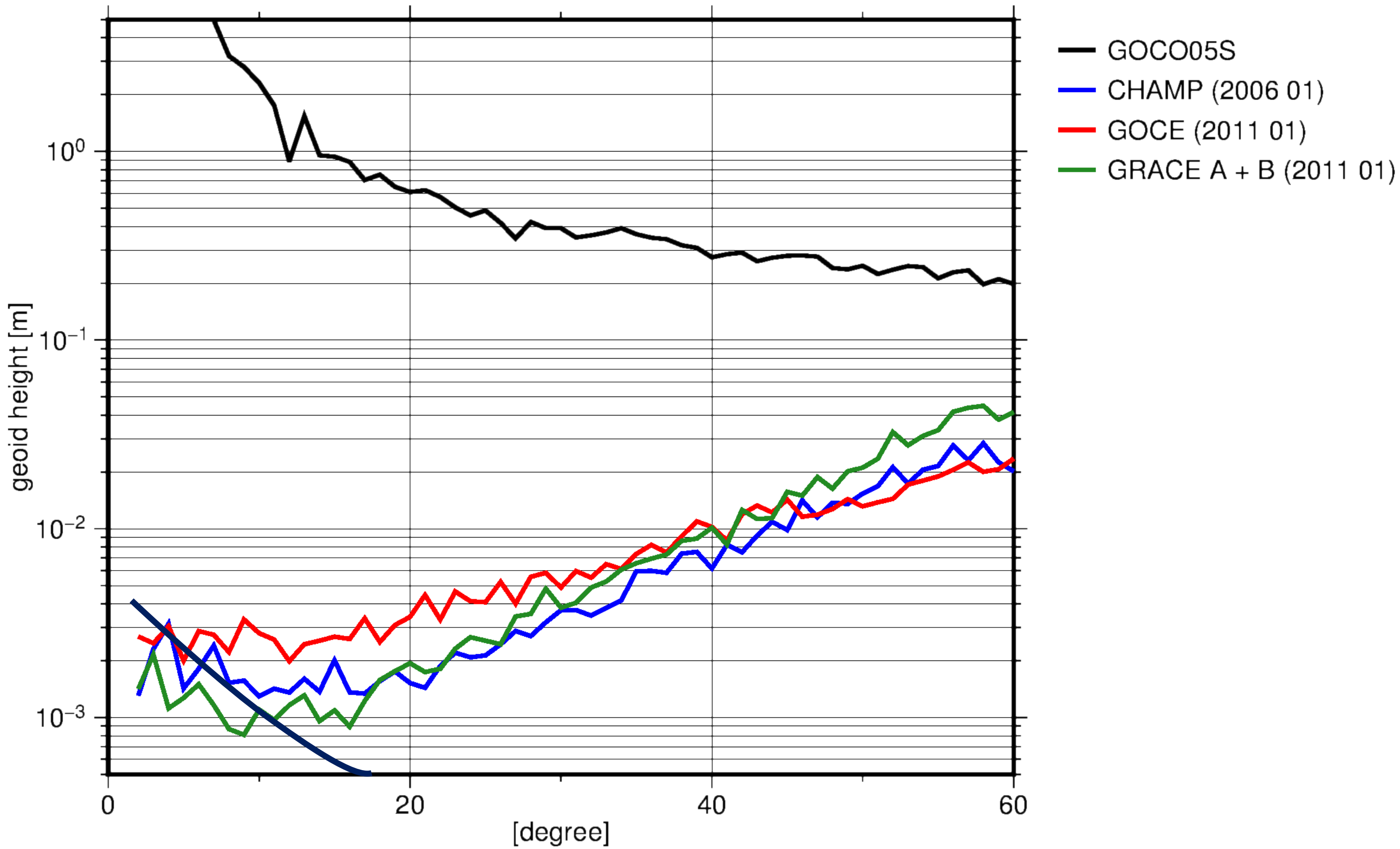

Degree amplitudes

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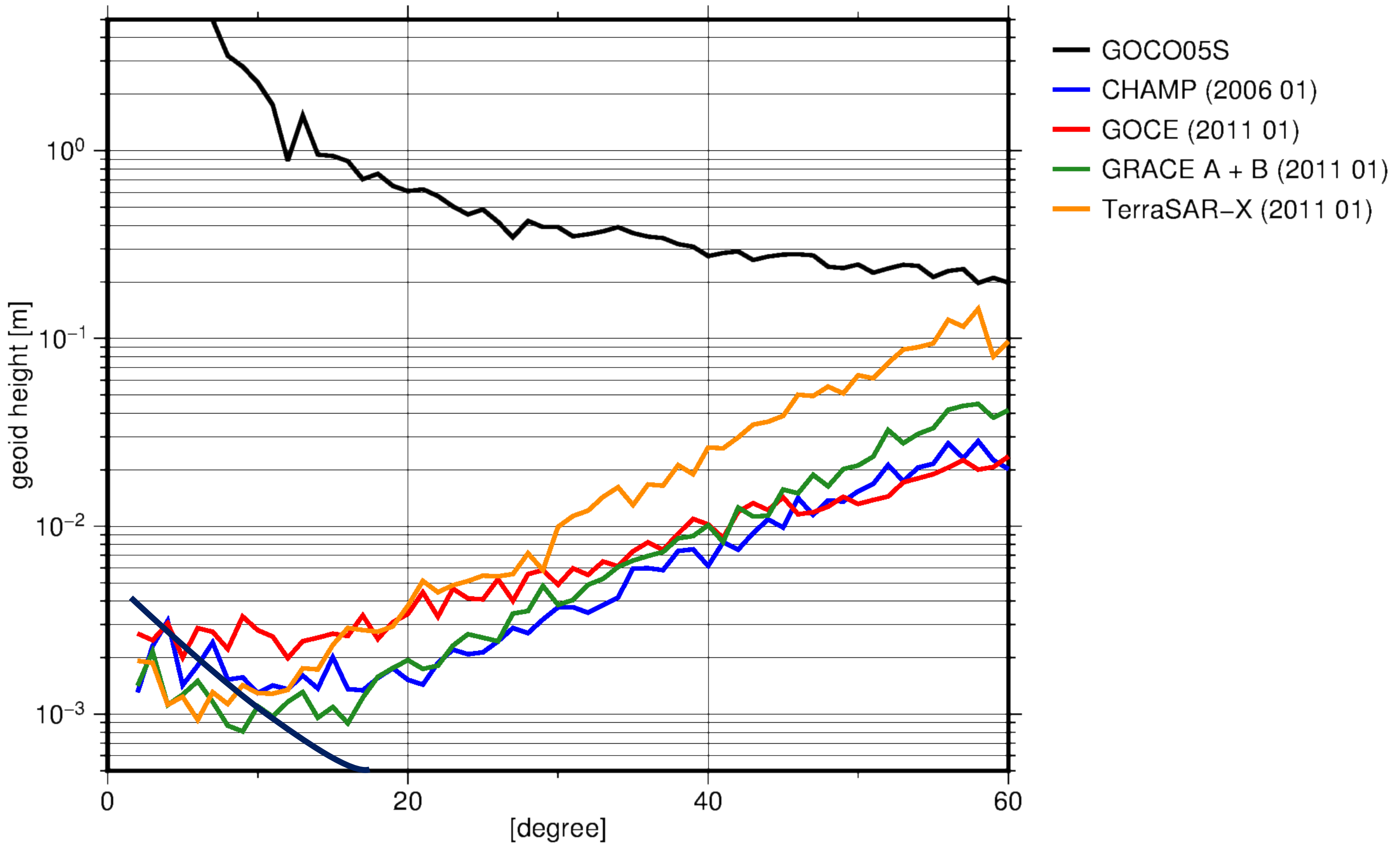

Degree amplitudes

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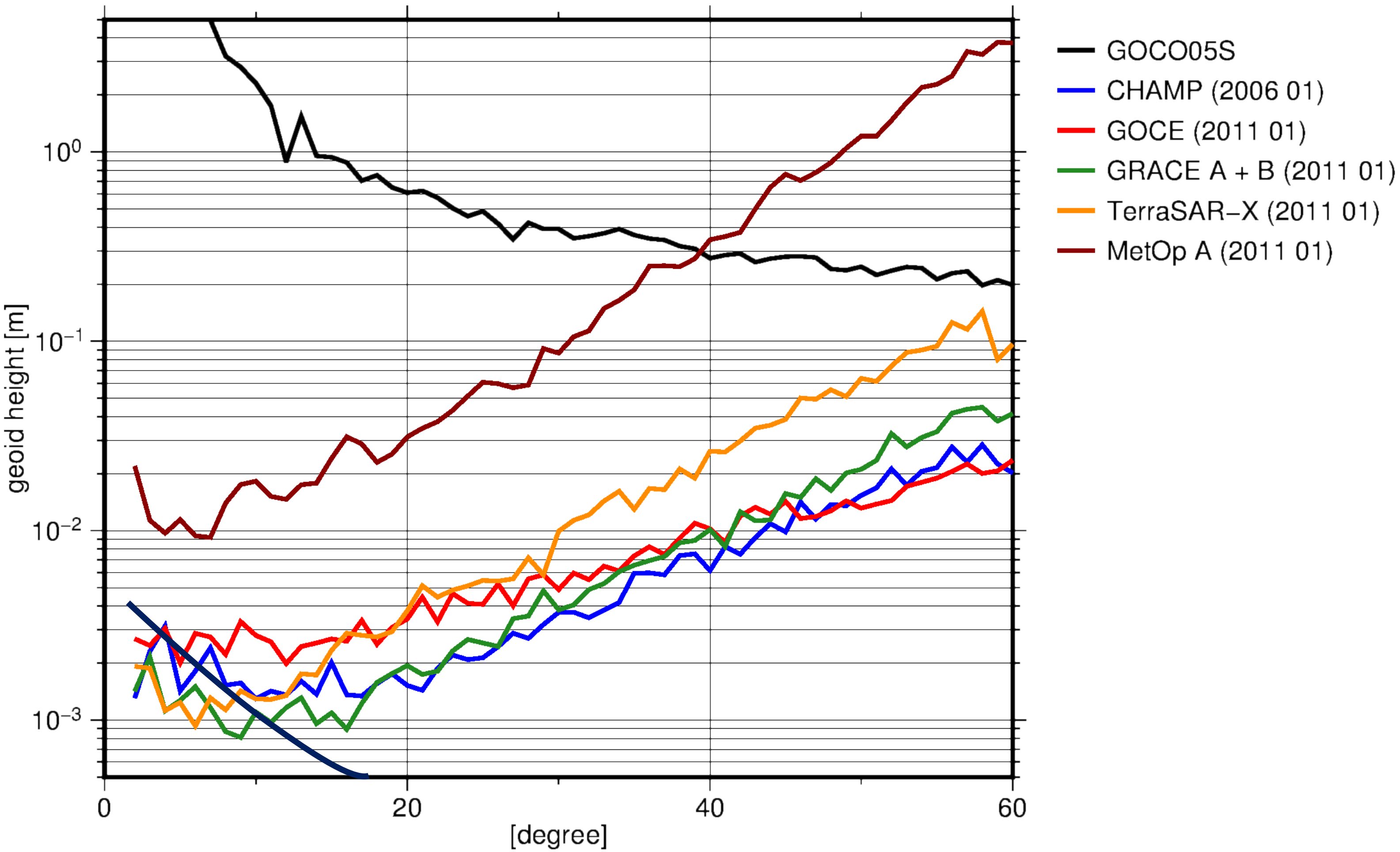

Degree amplitudes

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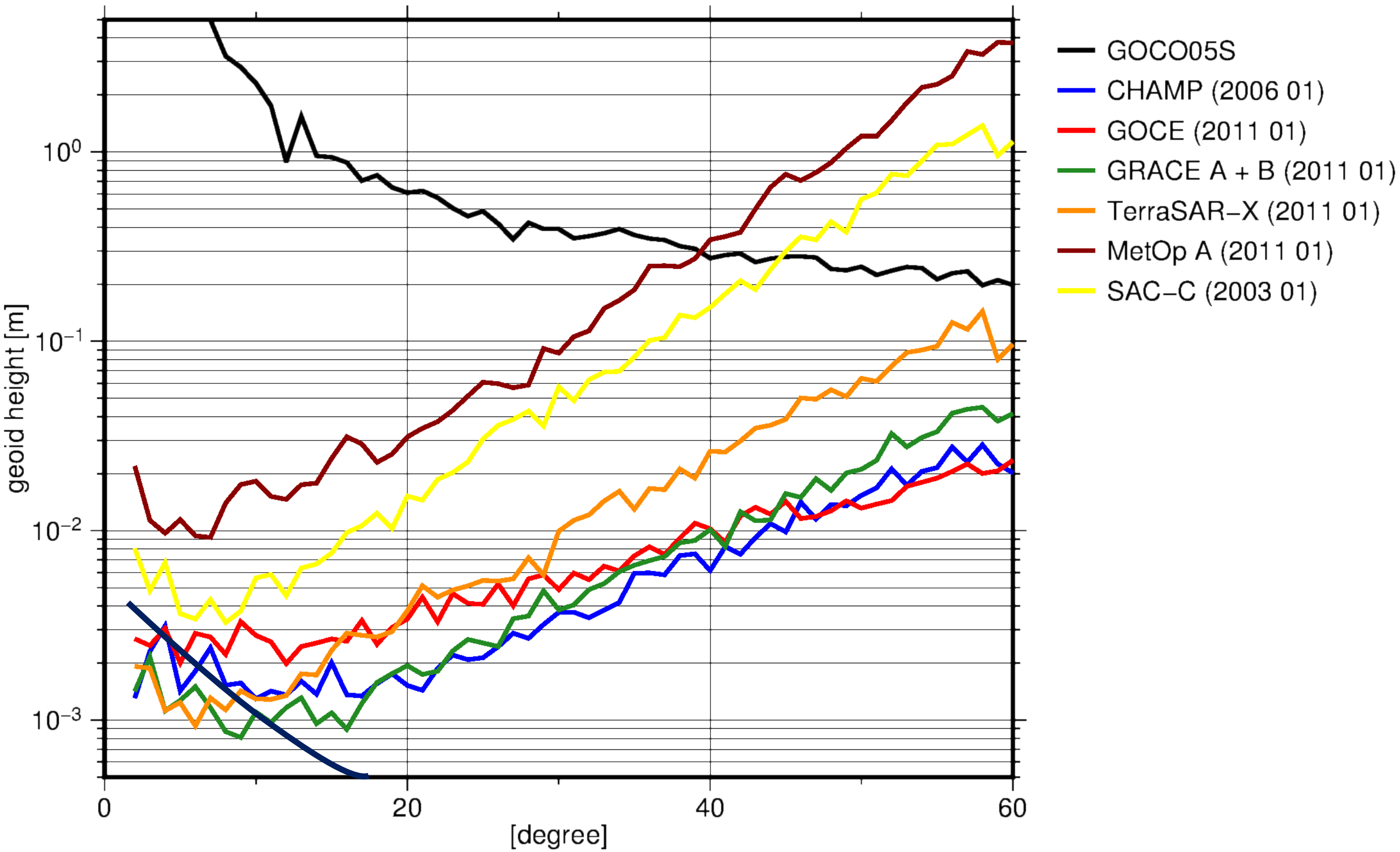
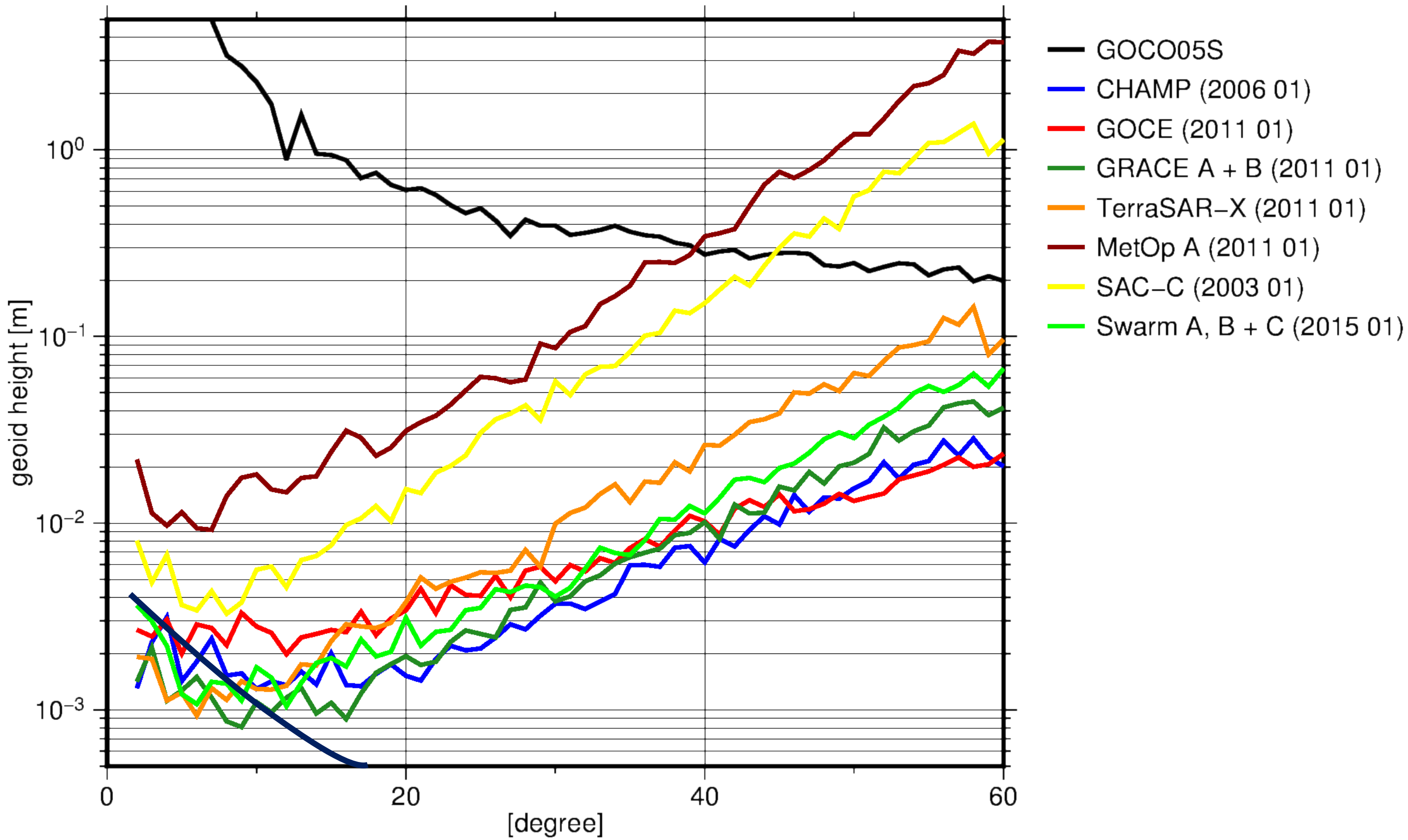


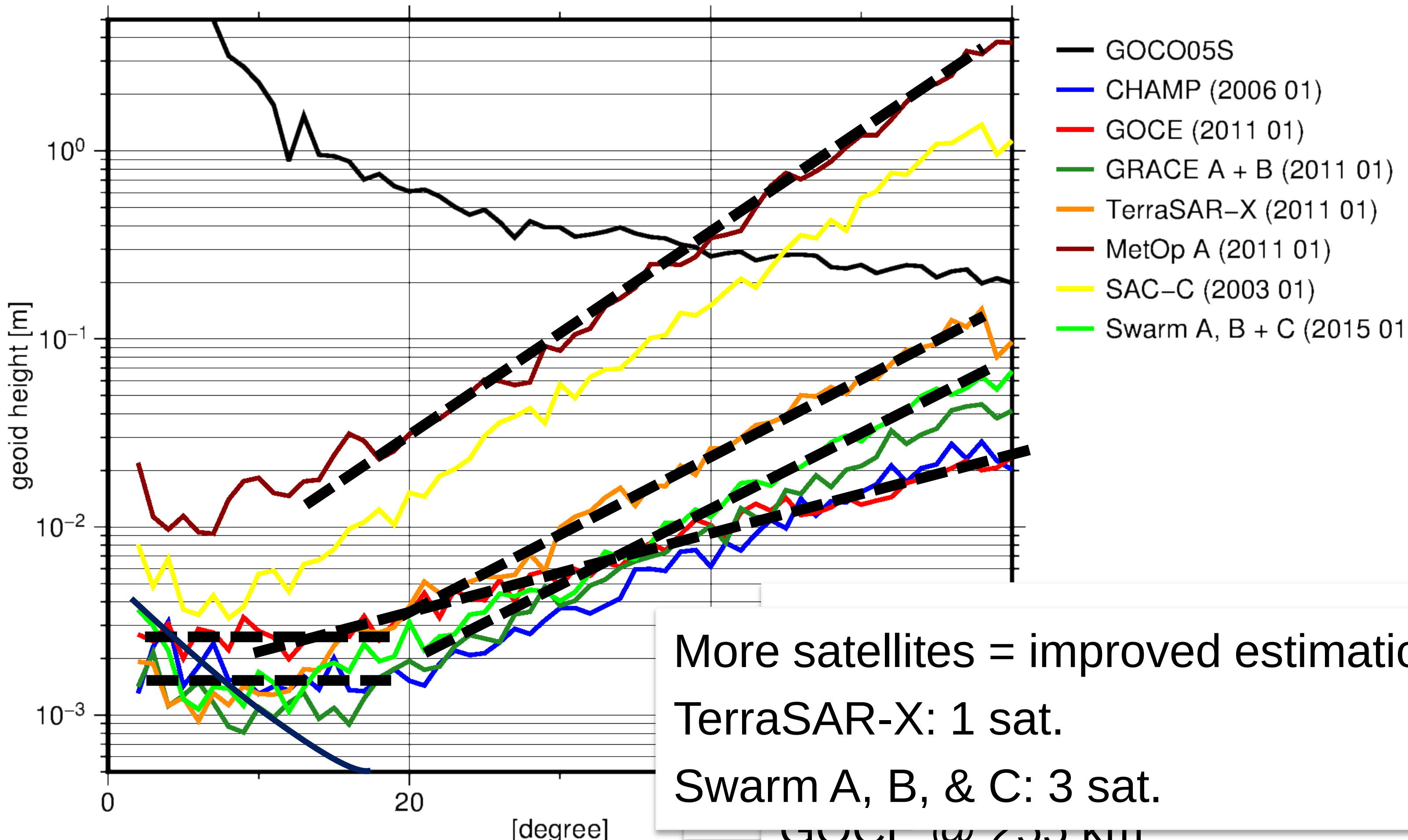
Degree amplitudes

(Monthly solutions)



Degree amplitudes

(Monthly solutions)

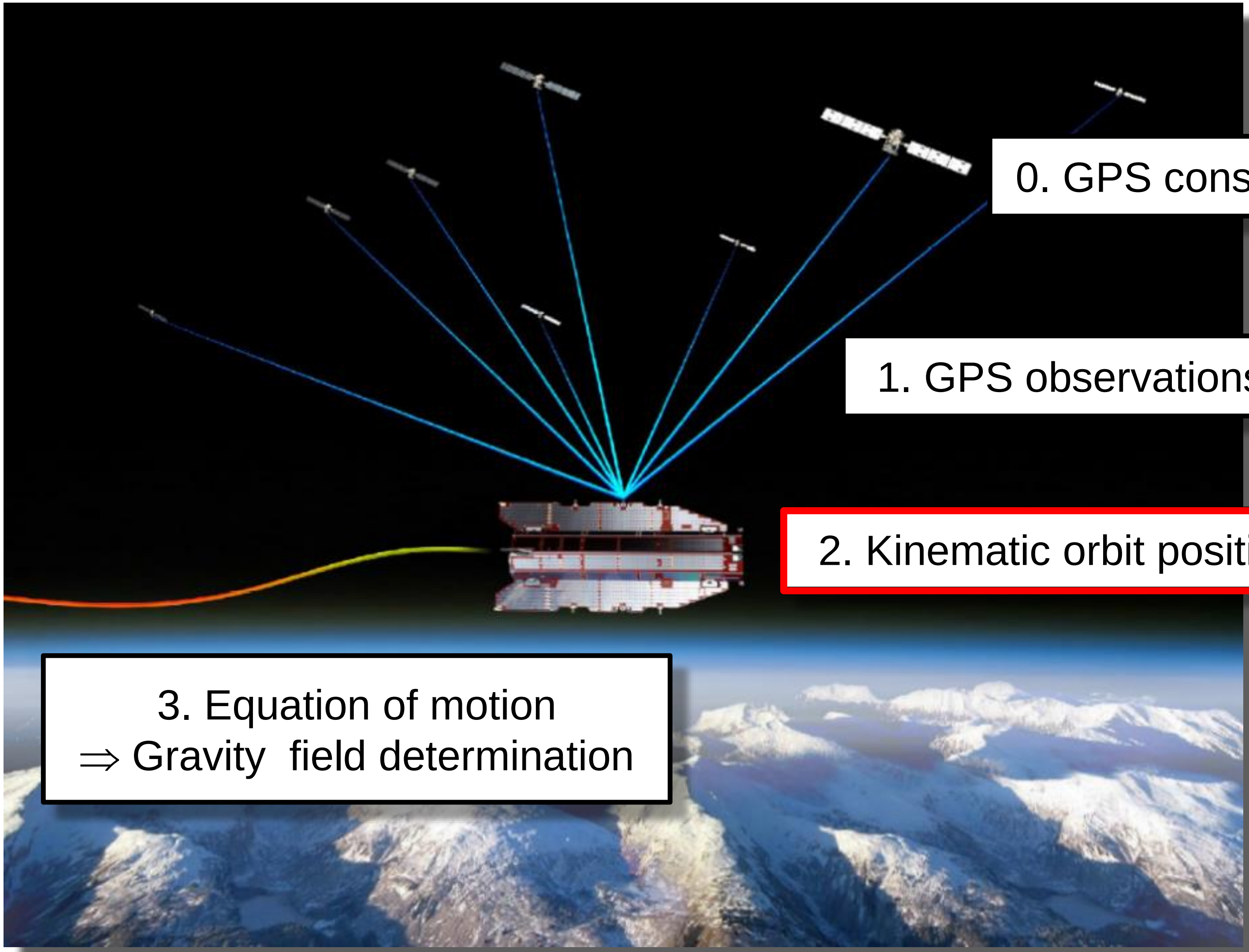


More satellites = improved estimation

TerraSAR-X: 1 sat.

Swarm A, B, & C: 3 sat.

High-Low Satellite-to-Satellite Tracking (hlSST)



Kinematic orbit determination

Raw Observation Approach:

- Use all available observations in a least squares adjustment
- No linear combinations / no differences (single/double difference)
- Known influences are corrected
- Remaining influences are estimated as parameters

Observation equations

Phase
$$\varphi_i^k - \varphi_{i,0}^k = \rho_i^k + c\Delta t_i + Iono_{i,L1/l2}^k + ACV_{i,\varphi} + ACV_{\varphi}^k + n\lambda_{i,L1/l2}^k + \varepsilon$$

Range (Code)
$$R_i^k - R_{i,0}^k = \rho_i^k + c\Delta t_i + Iono_{i,L1L2}^k + ACV_{i,R} + ACV_R^k + \varepsilon$$

Observations (R_i^k)

Corrections ($R_{i,0}^k$)
- Center of mass
- Phase windup
- Relativistic time corr.
- Space-time curvature
- Biases
- …

Geometrical distance (ρ_i^k)
$$\sqrt{(x^k - x_i)^2 + (y^k - y_i)^2 + (z^k - z_i)^2}$$

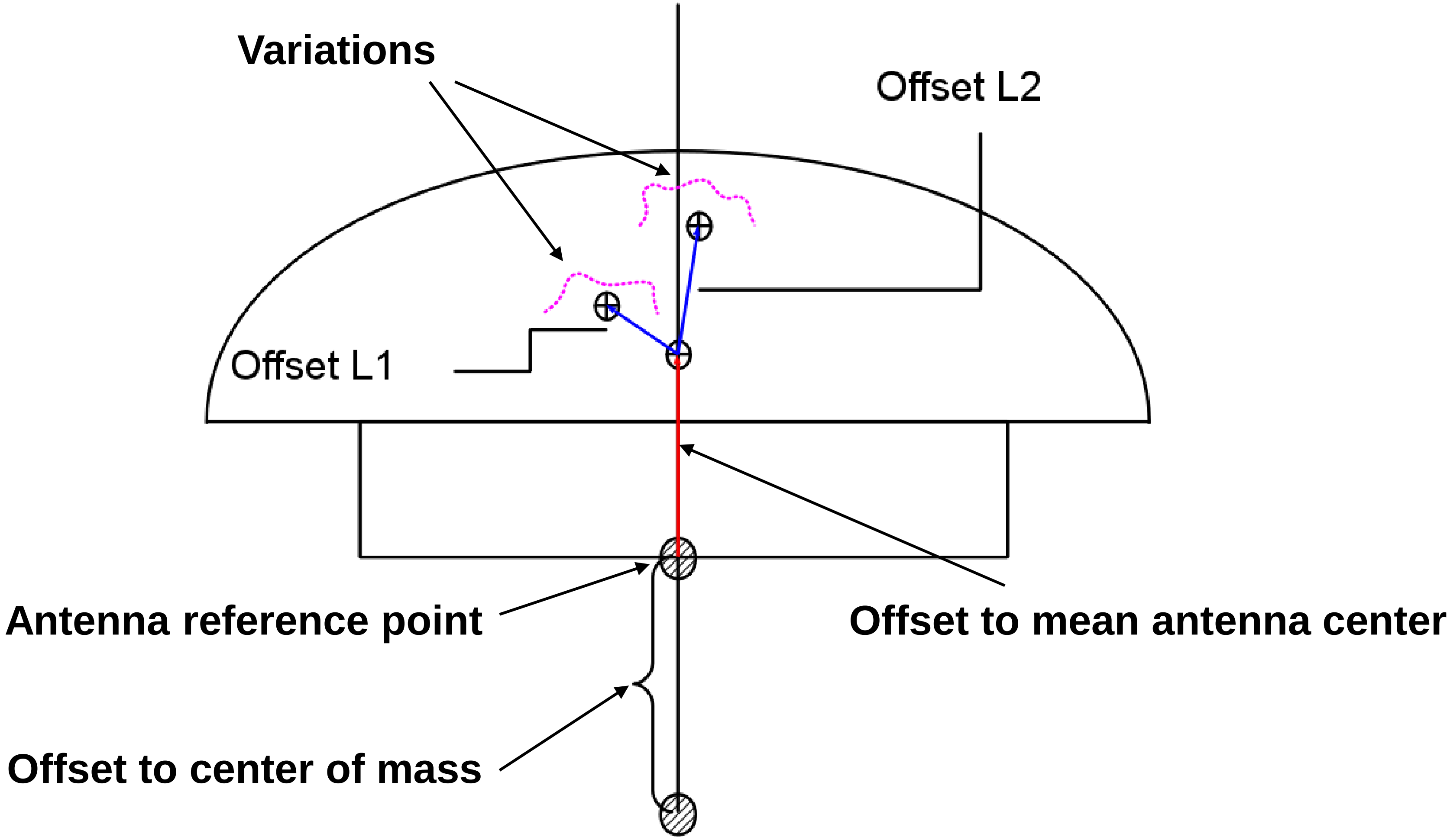
Receiver clock error ($c\Delta t_i$)

Ionospheric effects ($Iono_{i,L1L2}^k$)

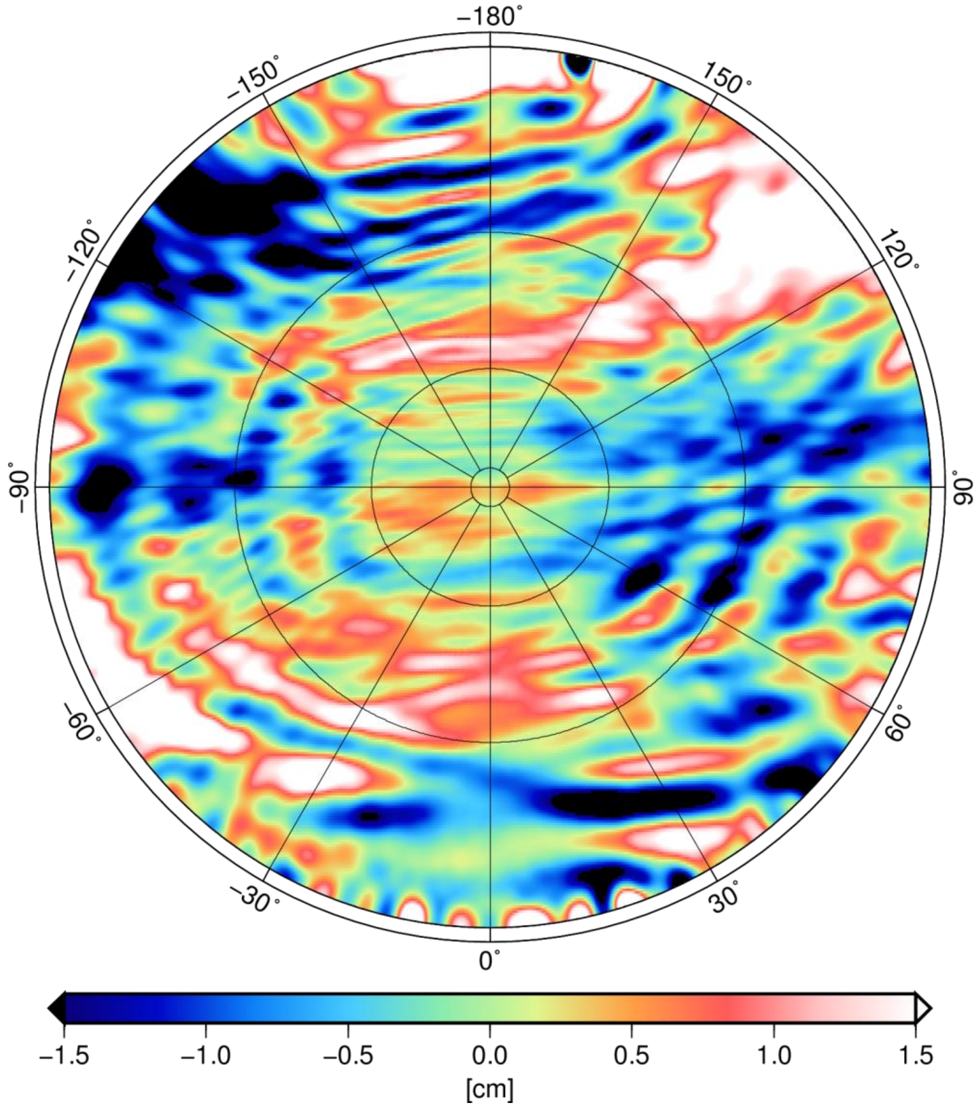
Antenna Center Variations ($ACV_{i,R}$, ACV_R^k)
- Receiver
- Transmitter

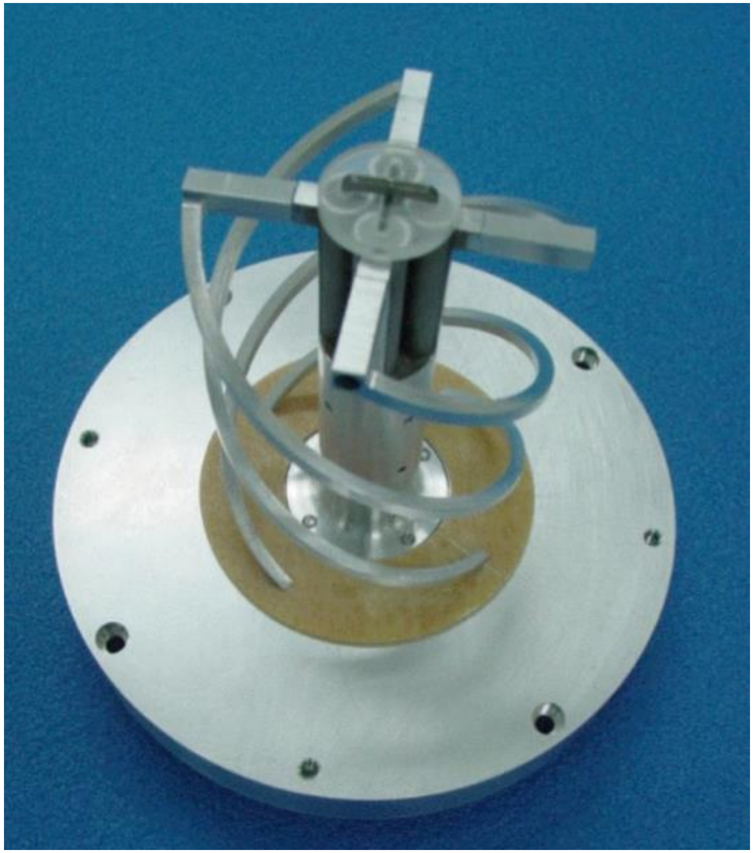
Ambiguity ($n\lambda_{i,L1/l2}^k$)

Antenna Center Variations

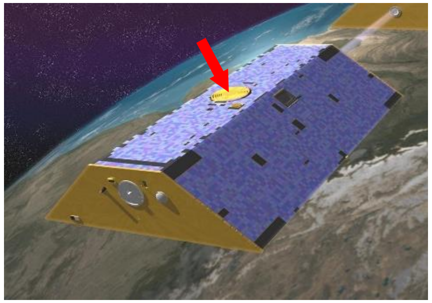


Antenna Center Variations - GOCE



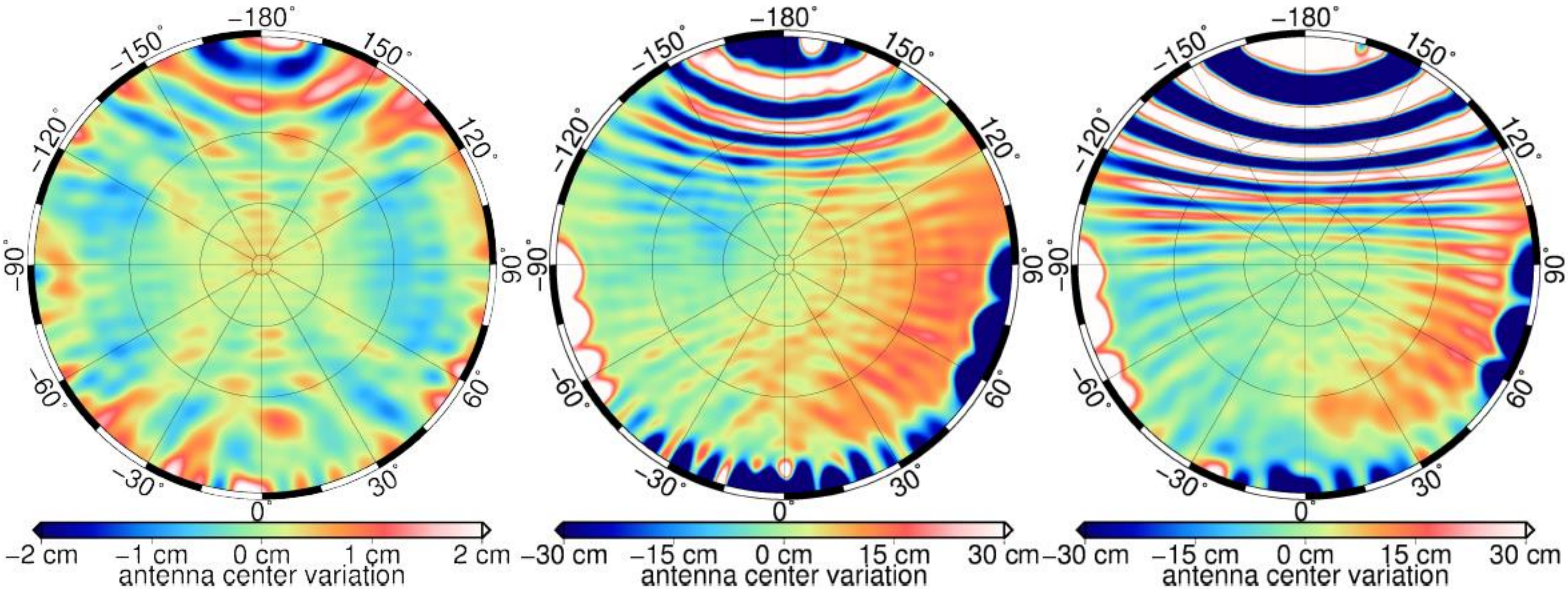


Antenna Center Variations – GRACE A

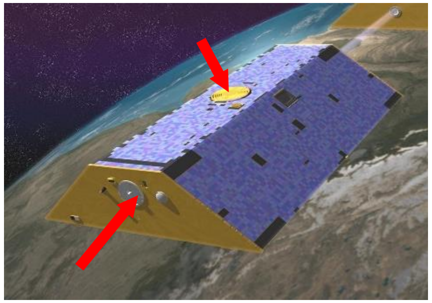


- Depend on observation type and frequency

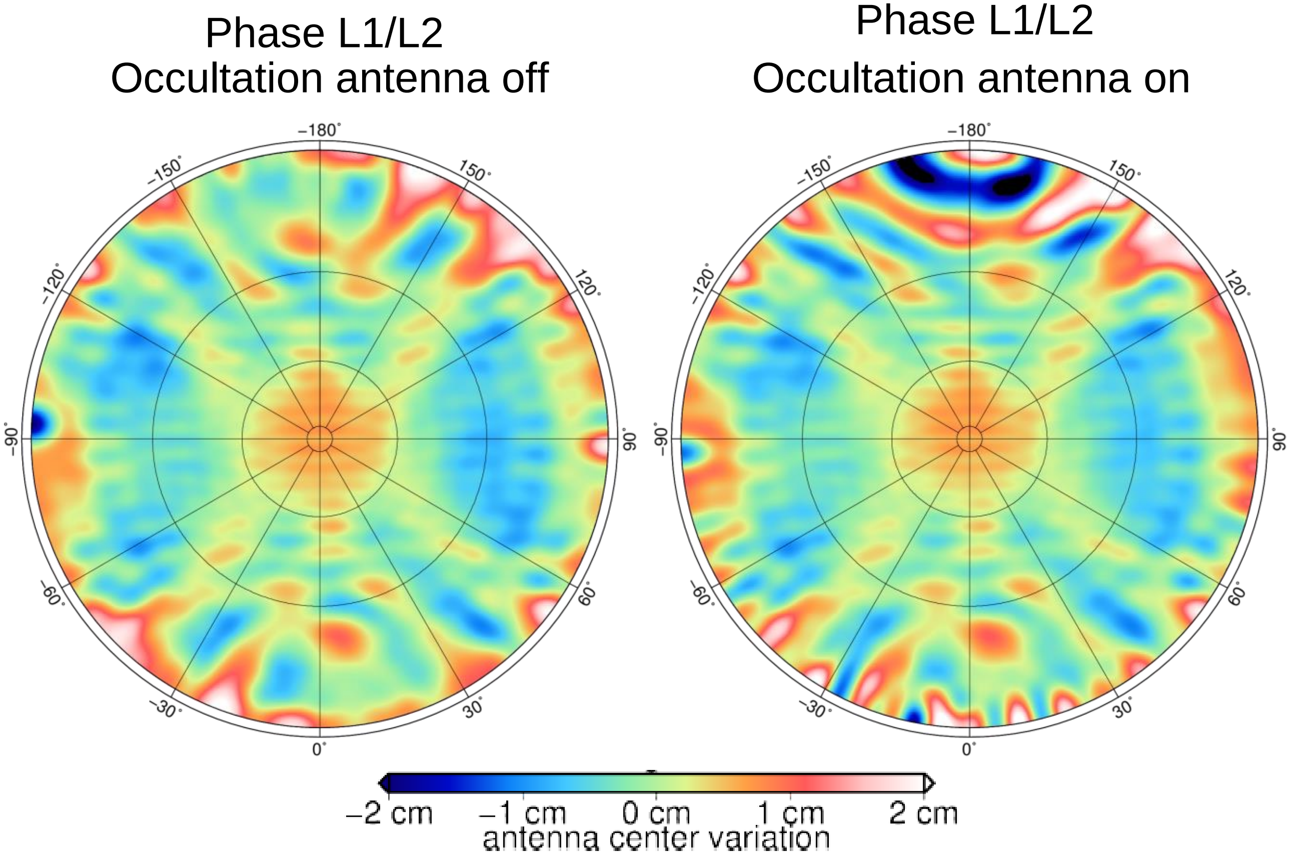
Phase L1/L2 | Code P1 | Code P2



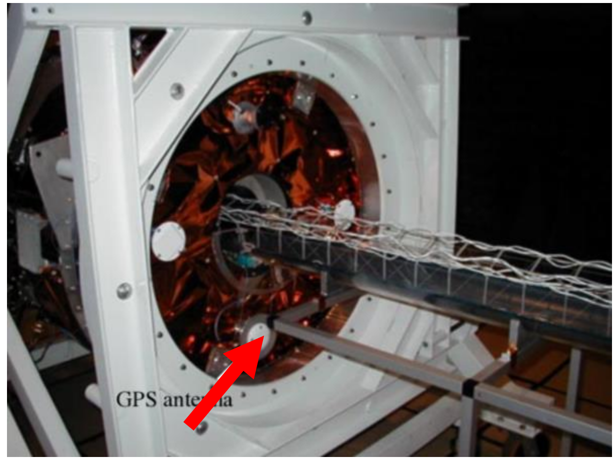
Antenna Center Variations – GRACE A

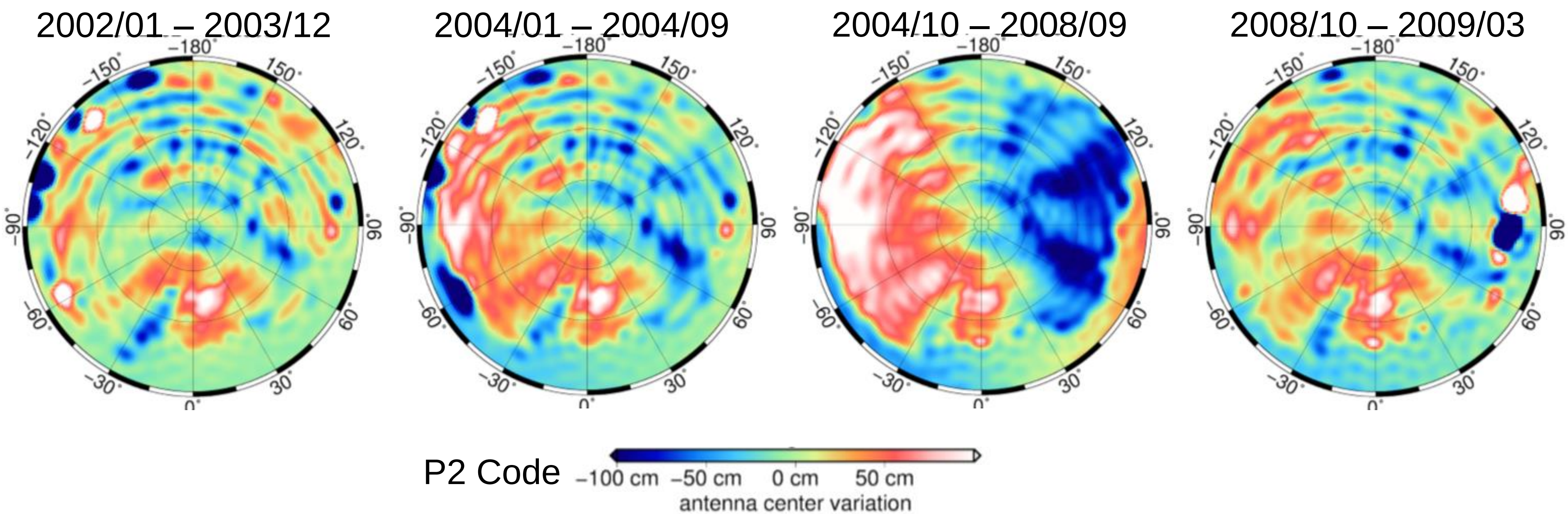


- Depend on observation type and frequency
- Depend on other instruments / satellite status
- Can change with software updates

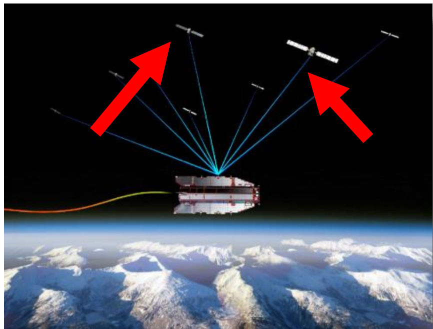


Antenna Center Variations – SAC-C





GPS Antenna Center Variations additional to IGS



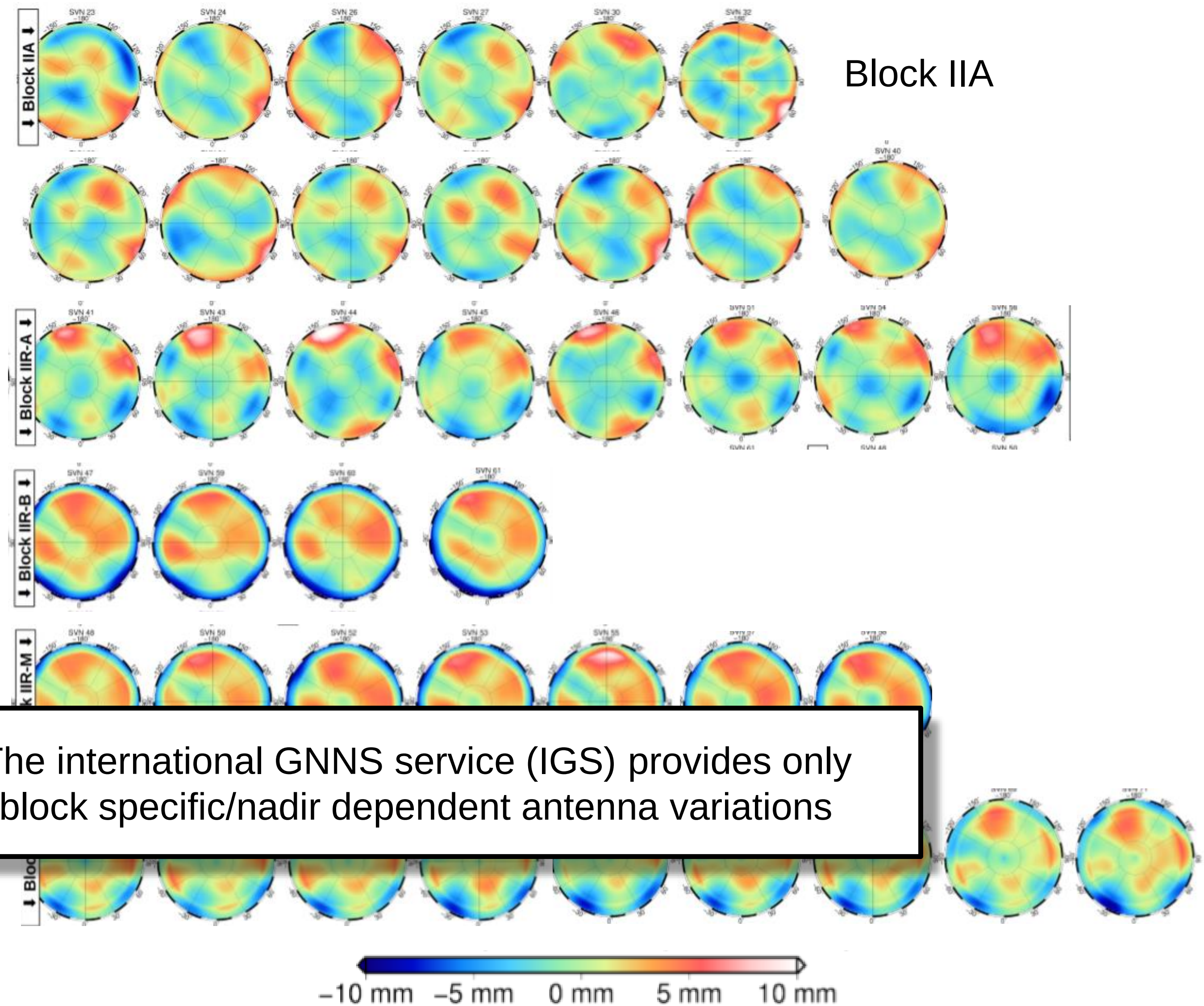
Block IIA

Block IIR-A

Block IIR-B

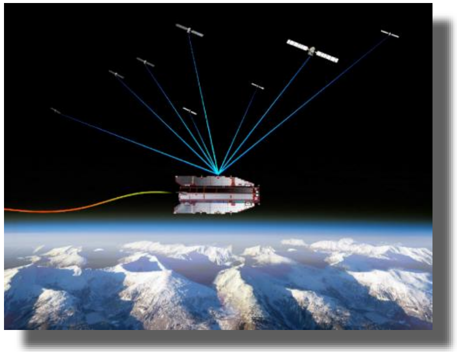
Block IIR-M

Block IIR-F



The international GNNS service (IGS) provides only block specific/nadir dependent antenna variations

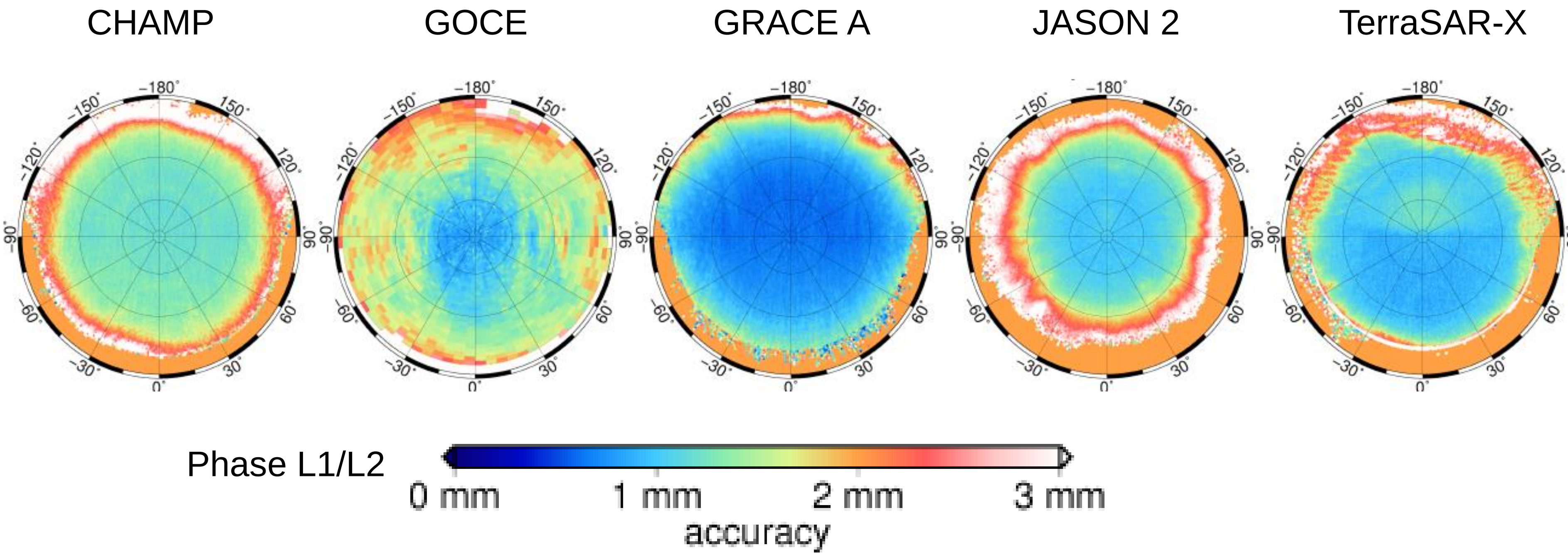
Accuracy of the observations



Accuracy of the observations depends on

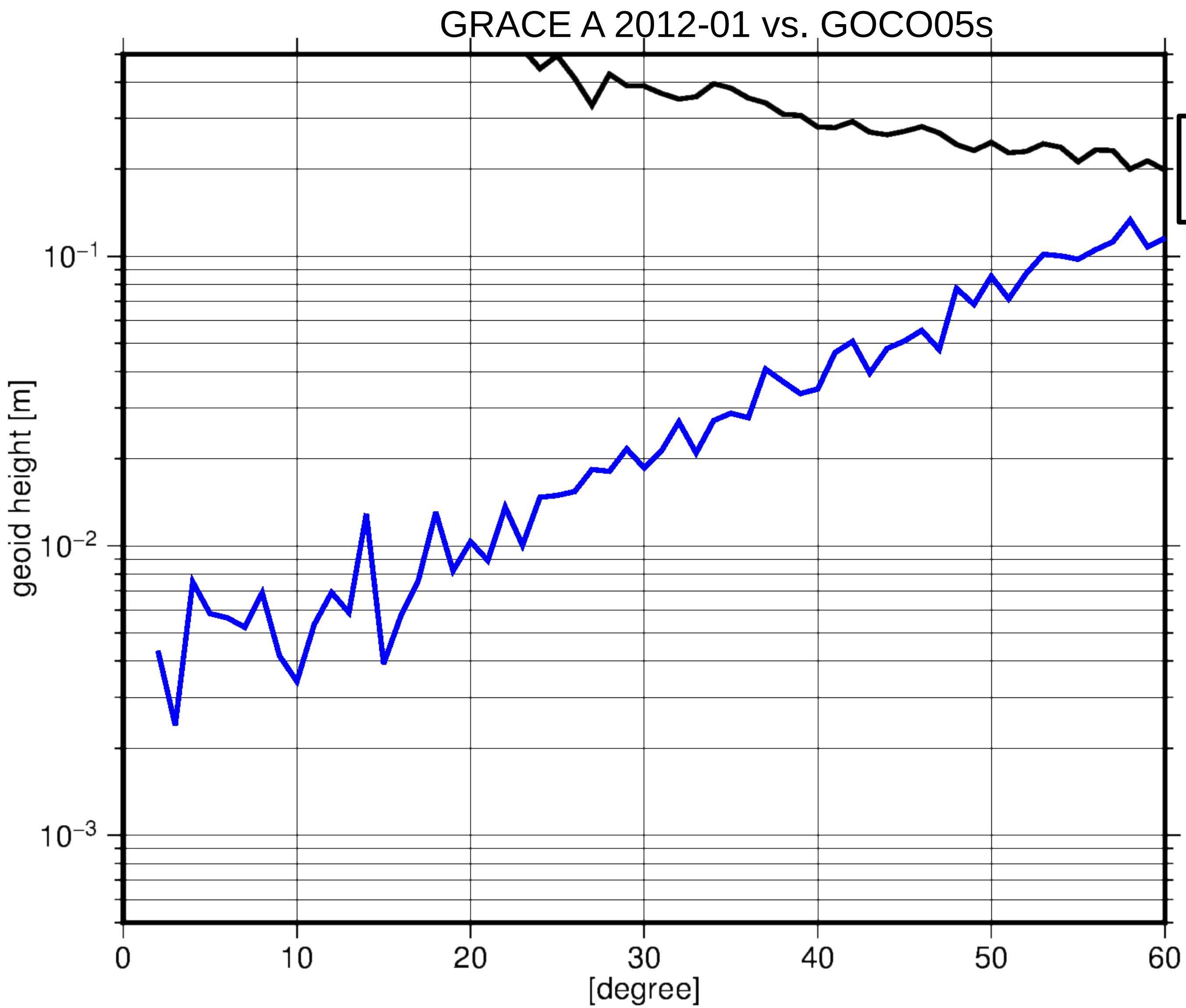
- the type and frequency
- elevation and azimut

⇒ Analyizing the residuals to generate accuracy maps



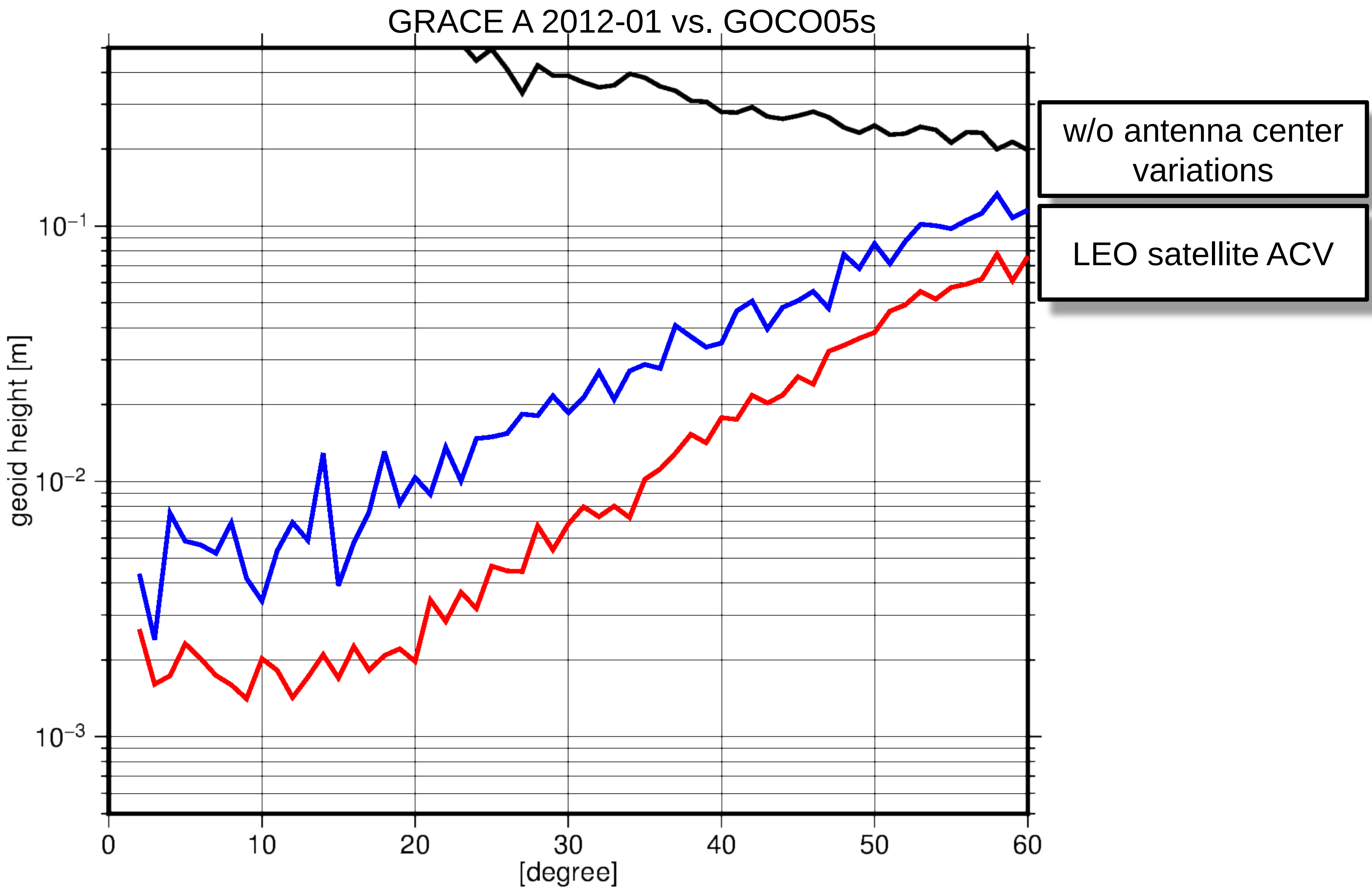
Contribution to the gravity field estimation?

Degree amplitudes

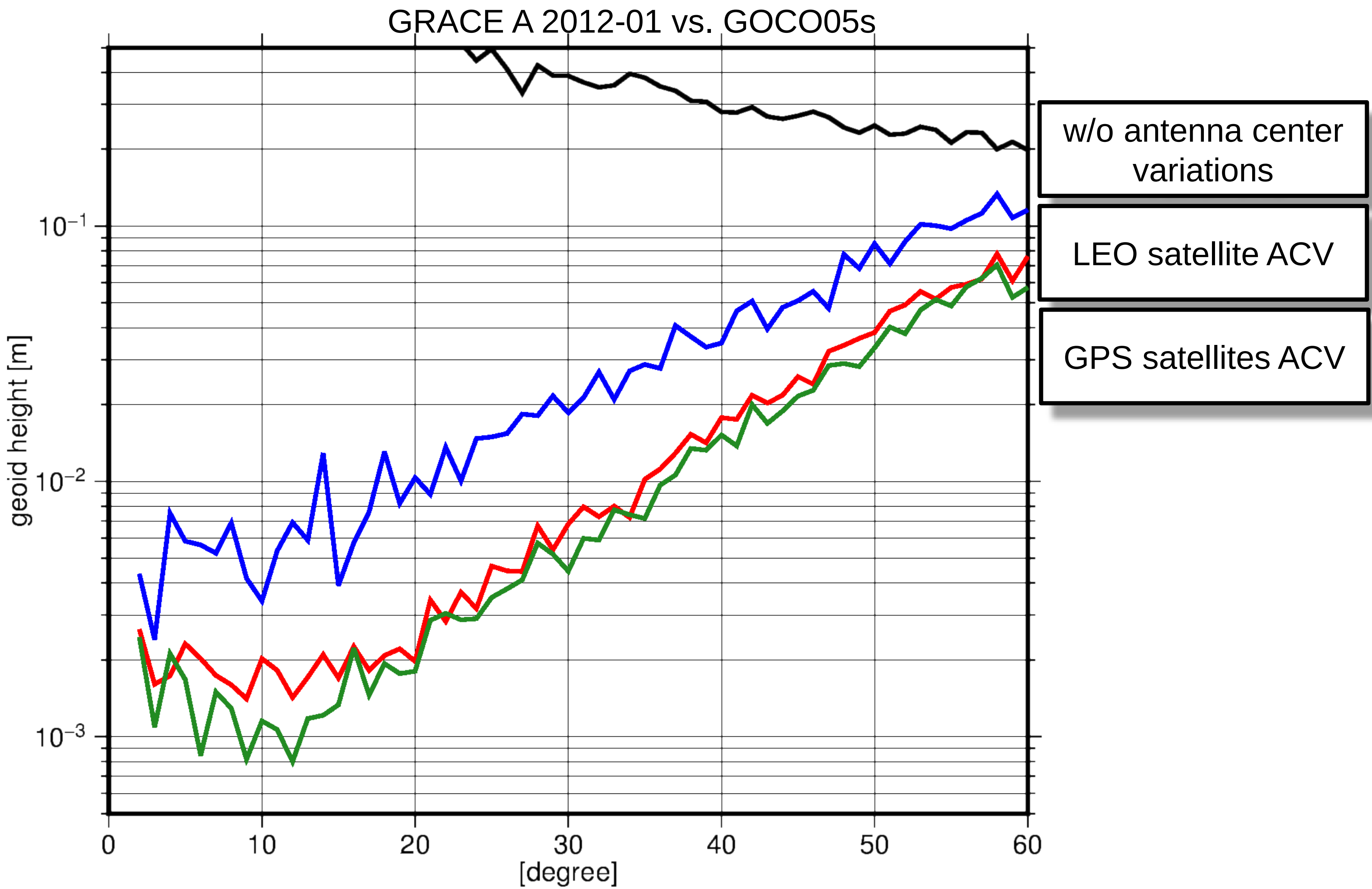


w/o antenna center variations

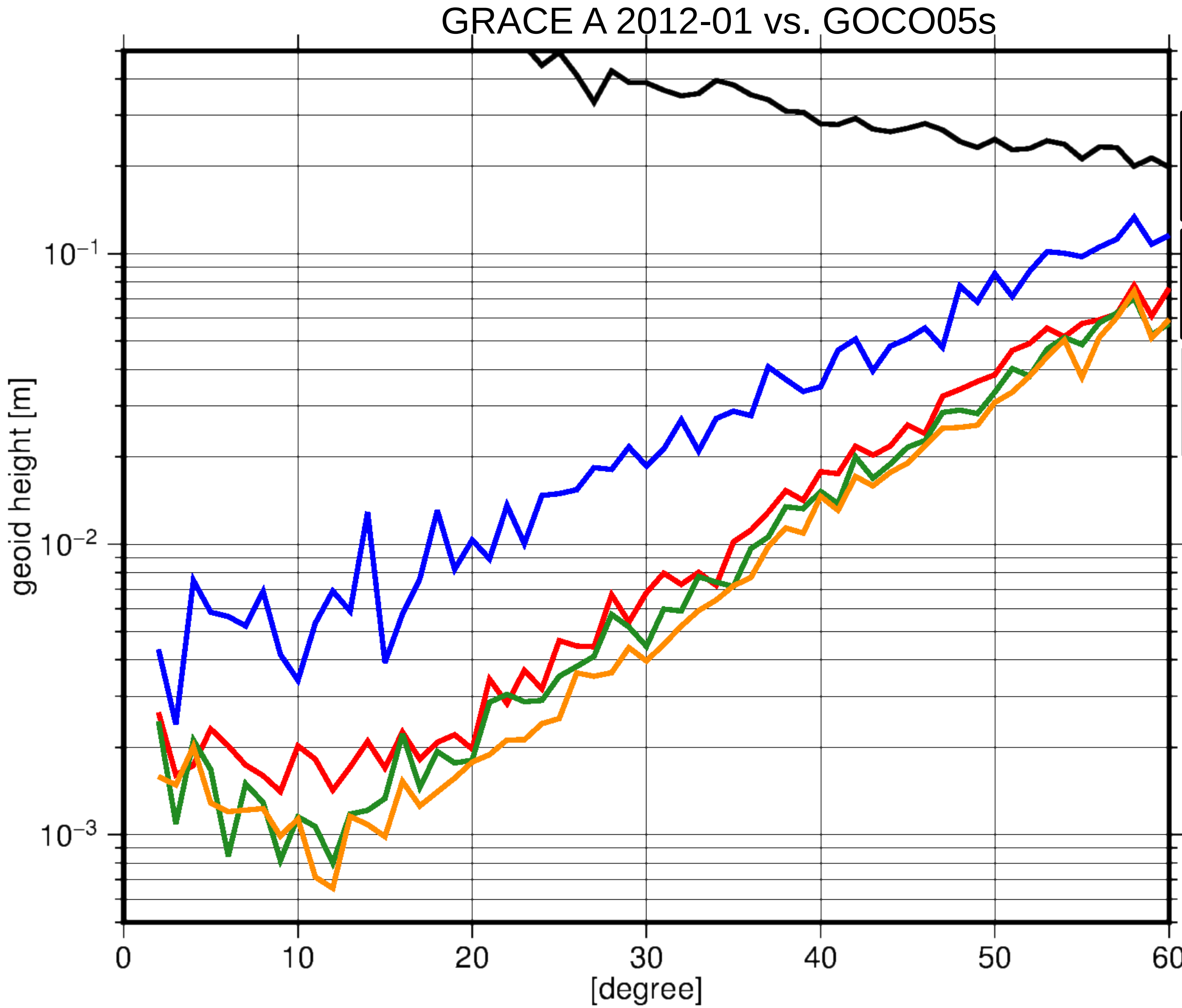
Degree amplitudes



Degree amplitudes



Degree amplitudes



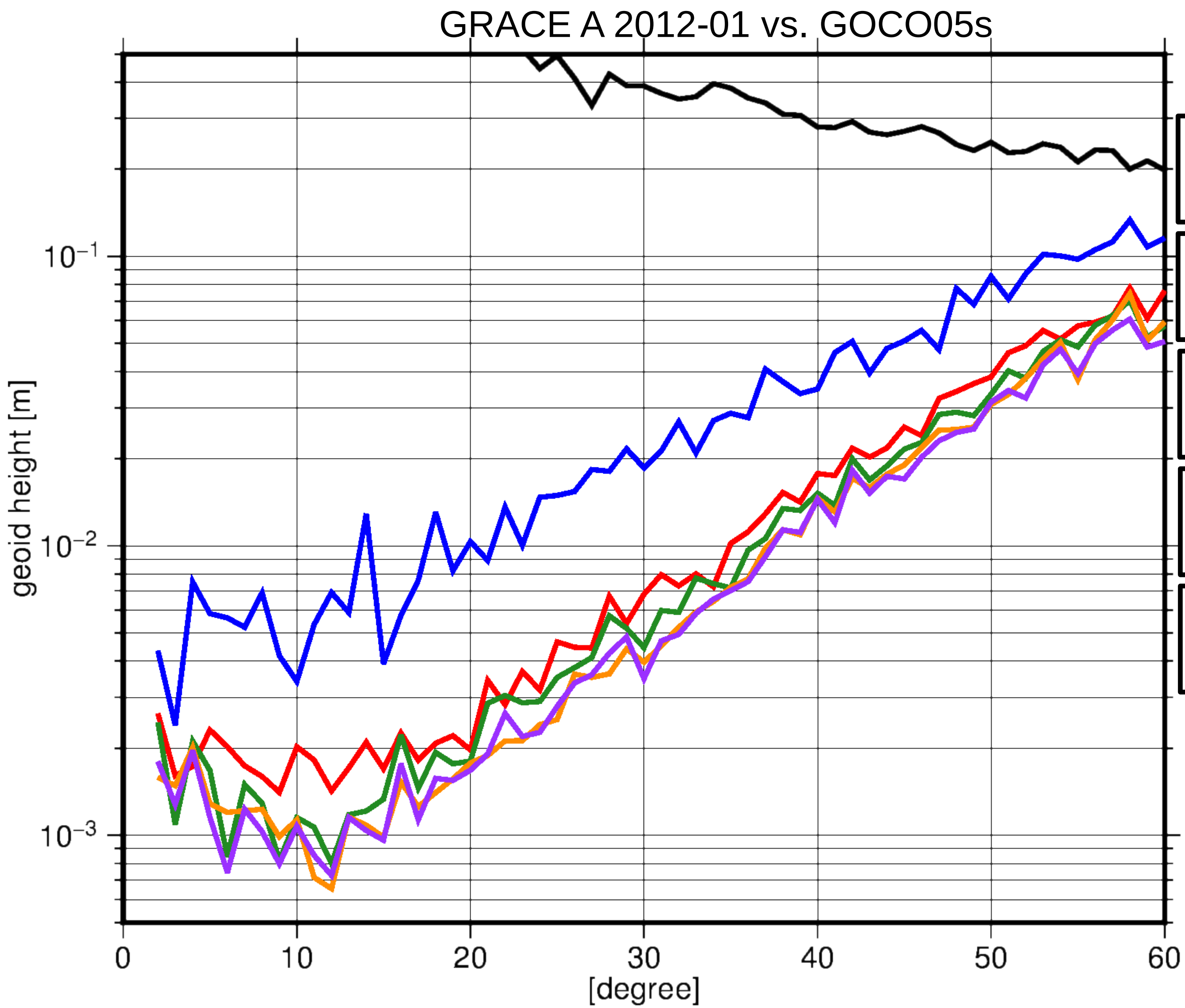
w/o antenna center variations

LEO satellite ACV

GPS satellites ACV

Elevation dependent weights

Degree amplitudes



w/o antenna center variations

LEO satellite ACV

GPS satellites ACV

Elevation dependent weights

Accuracy maps

Kinematic orbit determination

Raw Observation Approach:

- Use all available observations in a least squares adjustment
- No linear combinations / no differences (single/double difference)
- Known influences are corrected
- Remaining influences are estimated as parameters

Observation equations

Phase $$\varphi_i^k - \varphi_{i,0}^k = \rho_i^k + c\Delta t_i + Iono_{i,L1/l2}^k + ACV_{i,\varphi} + ACV_\varphi^k + n\lambda_{i,L1/l2}^k + \varepsilon$$

Range (Code) $$R_i^k - R_{i,0}^k = \rho_i^k + c\Delta t_i + Iono_{i,L1L2}^k + ACV_{i,R} + ACV_R^k + \varepsilon$$

Observations

Corrections
- Center of mass
- Phase windup
- Relativistic time corr.
- Space-time curvature
- Biases
- …

Receiver clock error

Ionospheric effects

Ambiguity

Geometrical distance
$$\sqrt{(x^k - x_i)^2 + (y^k - y_i)^2 + (z^k - z_i)^2}$$

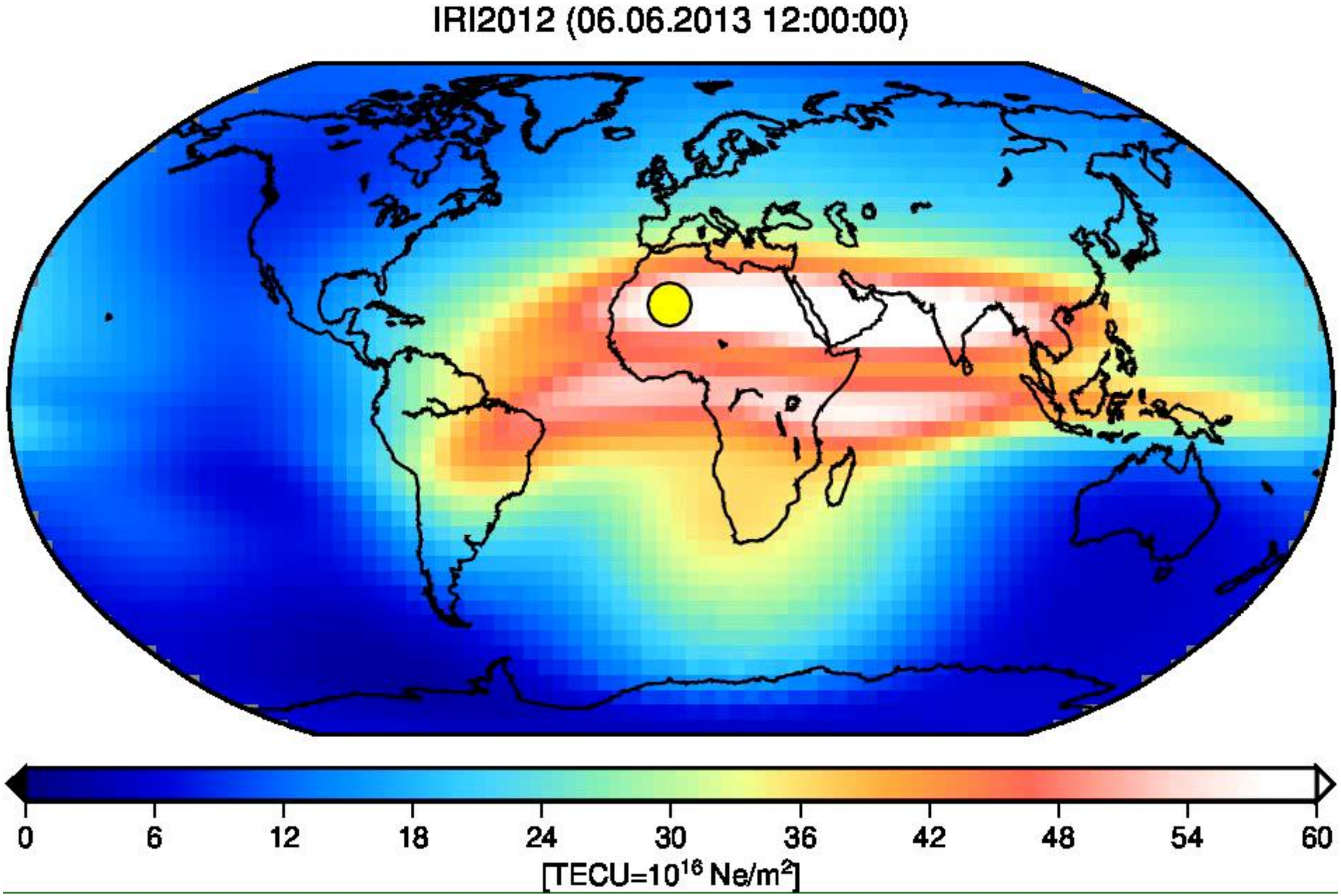
Antenna Center Variations

Receiver

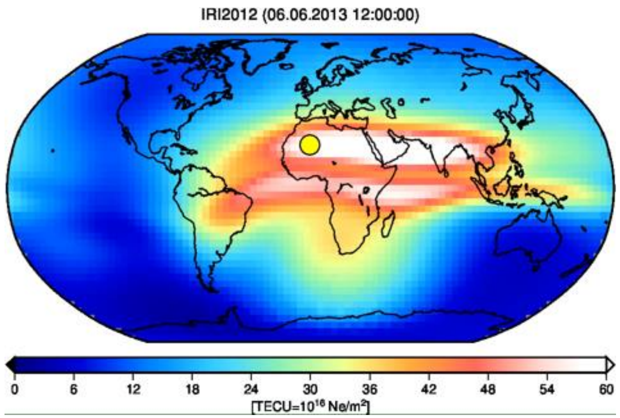
Transmitter

Ionospheric influence

Ionosphere, vertical total electron content (VTEC)



Ionospheric influence



Phase $$\Delta_{ph} = \frac{q}{f_i^2}$$

Range (Code) $$\Delta_{gr} = -\frac{q}{f_i^2}$$

with $q = 40.3 \int N\, ds$ (slant) total electron content along path

$\Rightarrow$ Can be estimated with two frequency observations (99% is eliminated)

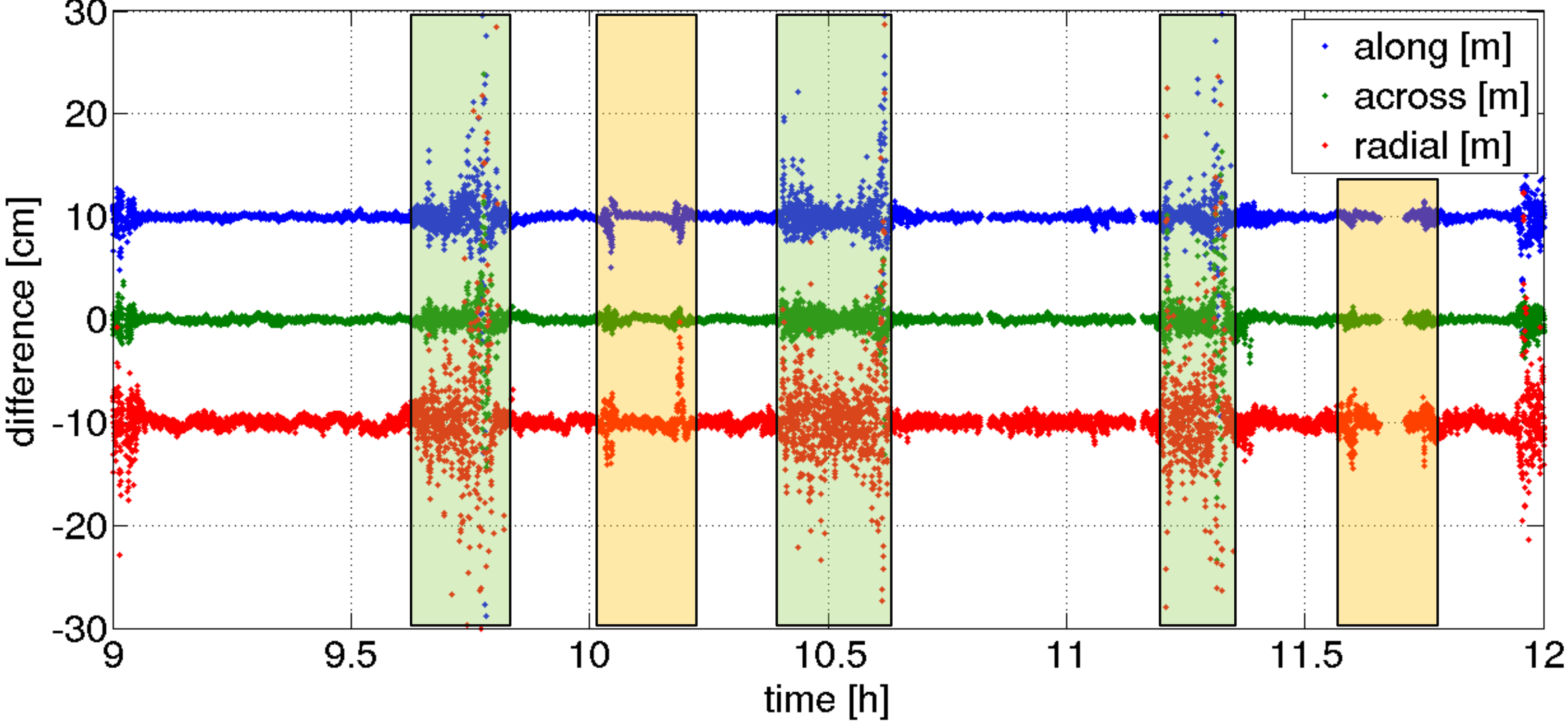
Kinematic orbit

Kinematic vs. reduced-dynamic

Magnetic pole crossings

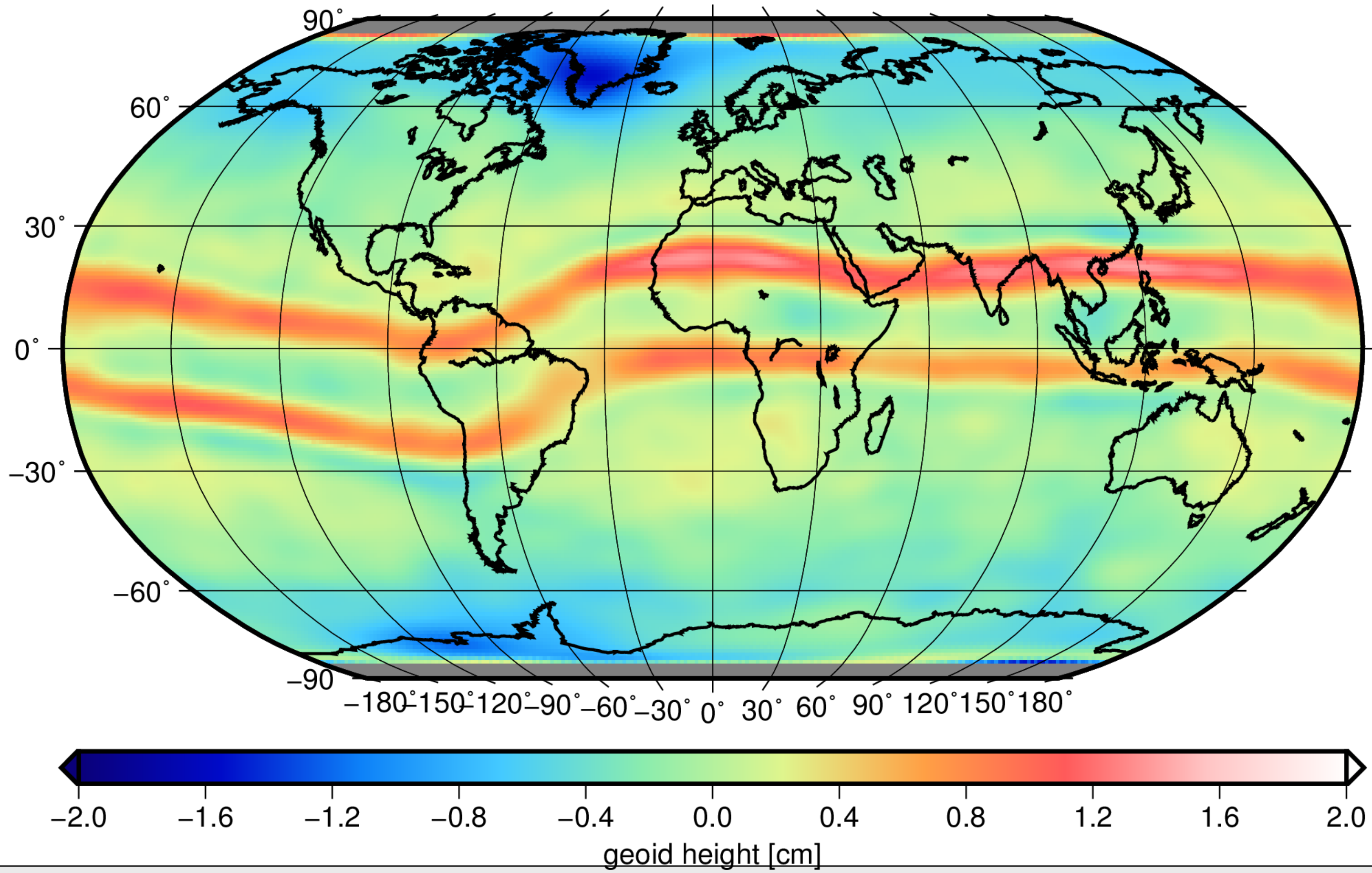
Magnetic equator crossings

01.08.2014 Swarm A



Influence on gravity field solution

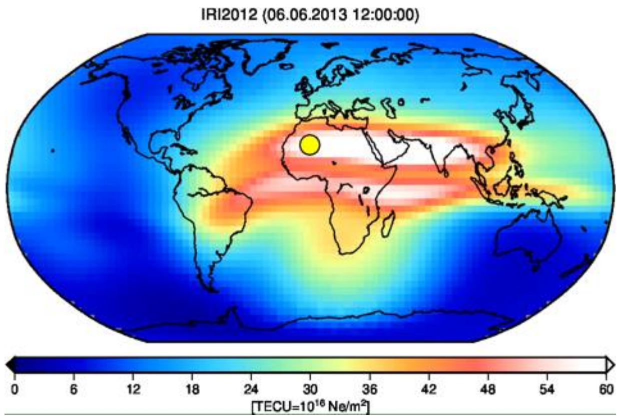
Long term GOCE SST-hl gravity field
vs. GOCO05s
Gaussian filter 500 km applied



Ionospheric influence

Phase $$\Delta_{ph} = \frac{q}{f_i^2} + \frac{t}{f_i^3} + \frac{r}{f_i^4}$$

Range (Code) $$\Delta_{gr} = -\frac{q}{f_i^2} - \frac{t}{2 f_i^3} - \frac{r}{3 f_i^4}$$



with $q = 40.3 \int N\, ds$ (slant) total electron content along path

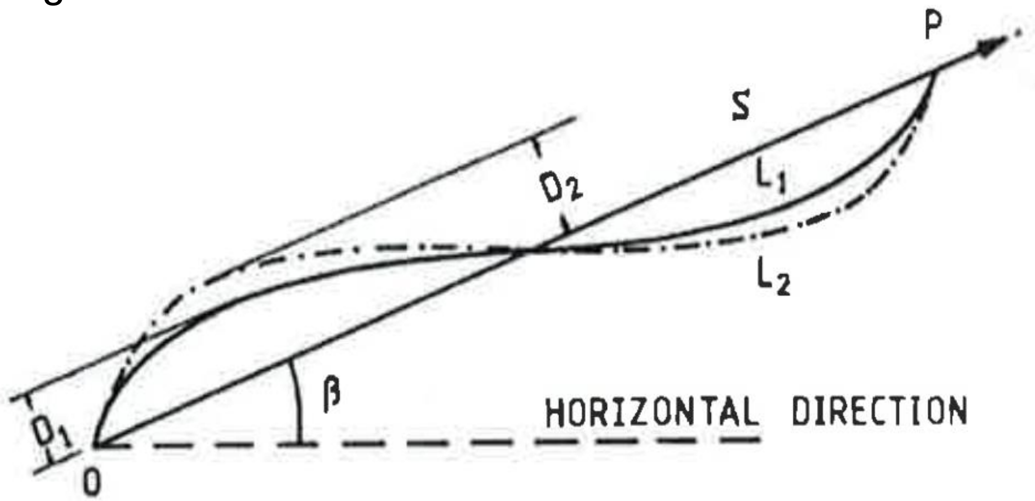
$t = 7527 c \int N\, \mathbf{B}\, ds$ with **B** magnetic field vector

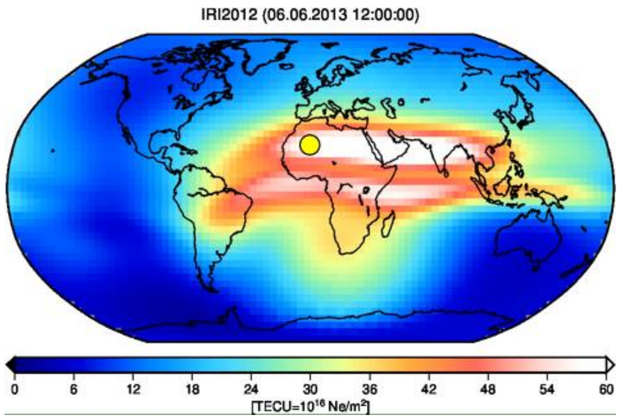
$r = 2437 \int N^2\, ds + \cdots$

$\Rightarrow$ Higer order corrections (Fritsche et.al., 2005)

Ionospheric influence

Signals are also bended





⇒ Different path lengths for each frequency

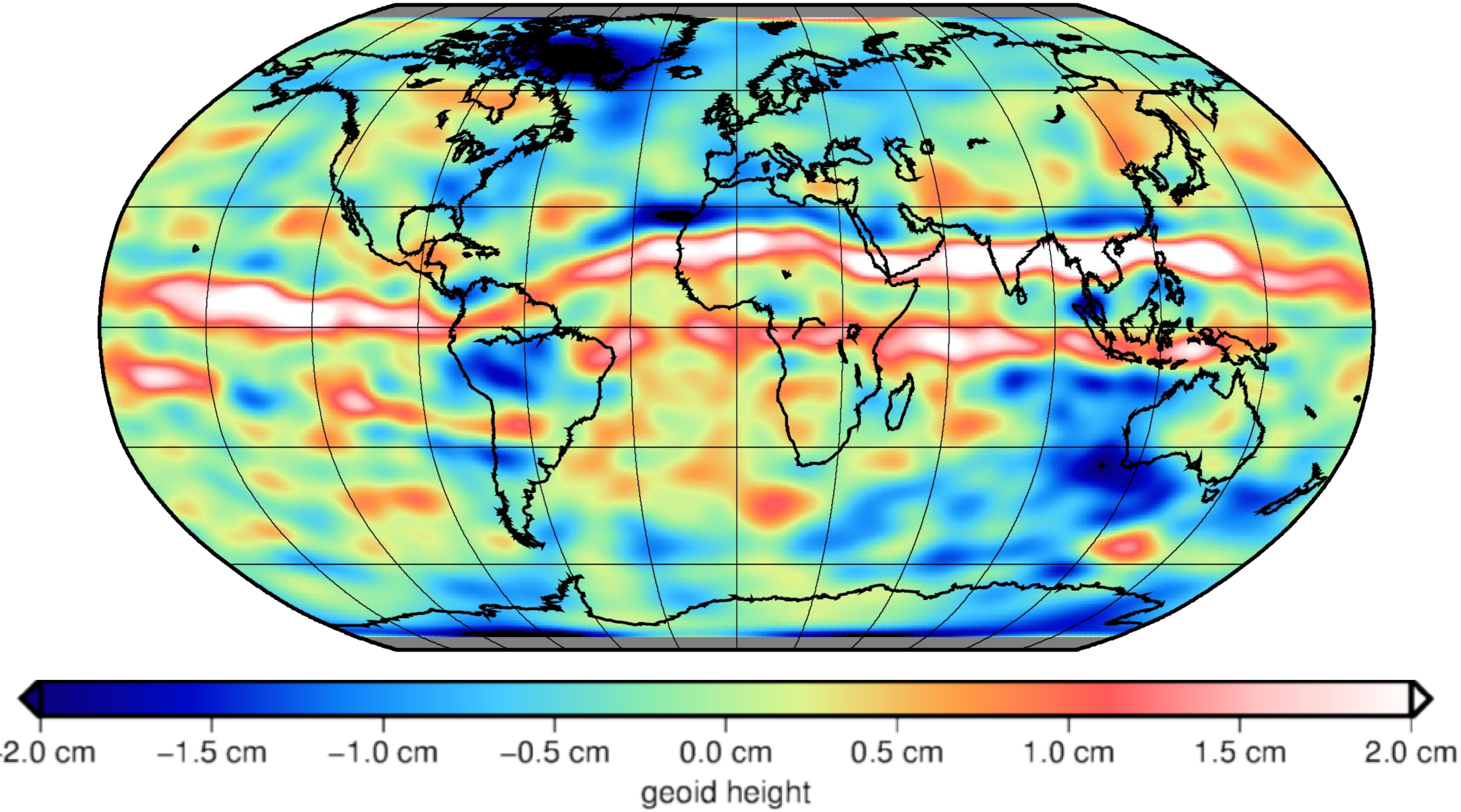
⇒ Different TEC along different paths

Empirical correction formulas are used according to Petrie et. al. 2010

What are the benefits?

No high order, no bending

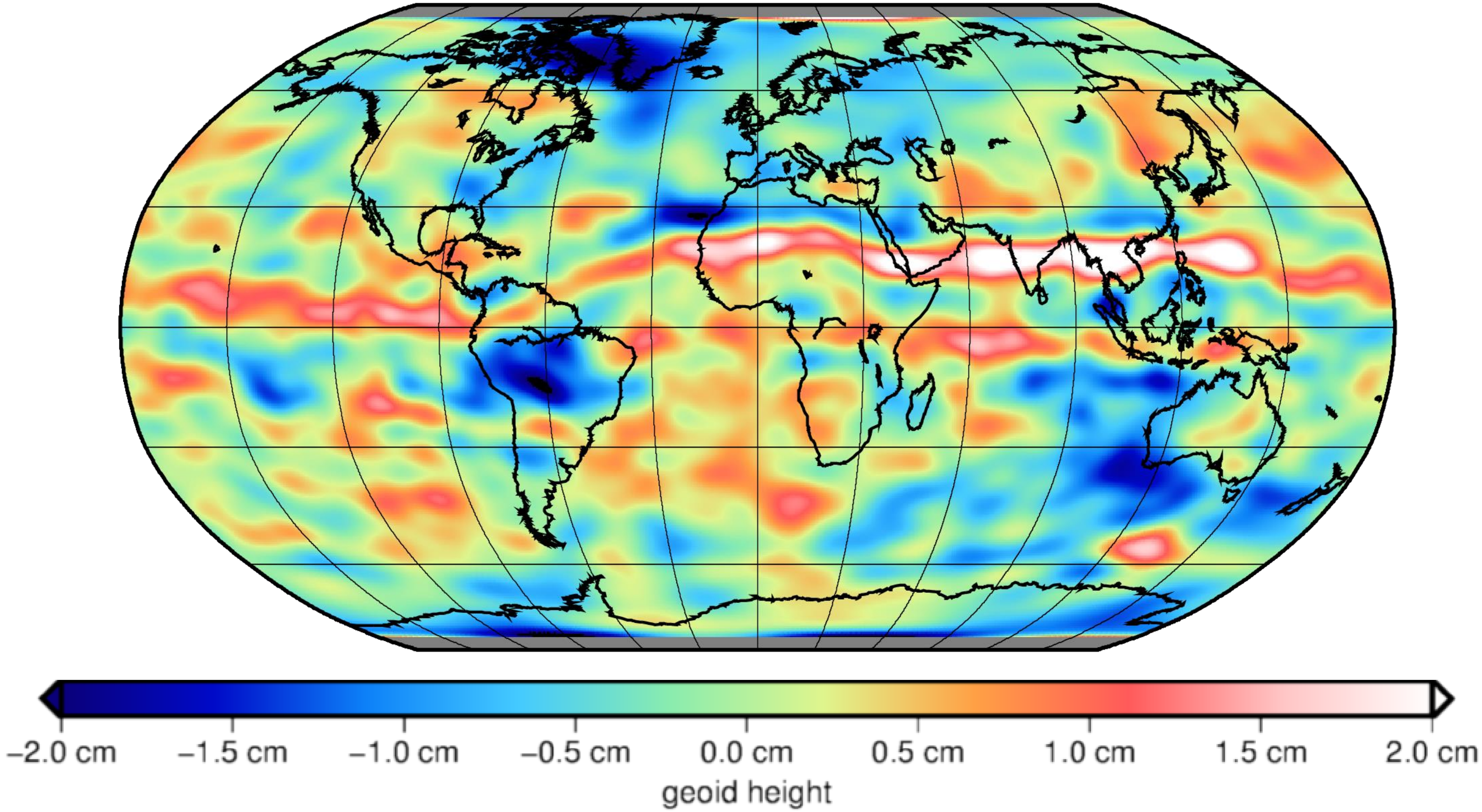
Monthly GOCE SST-hl (2010-10) vs. GOCO05s
Gaussian filter 500 km applied



What are the benefits?

high order corrections, bending correction

Monthly GOCE SST-hl (2010-10) vs. GOCO05s
Gaussian filter 500 km applied



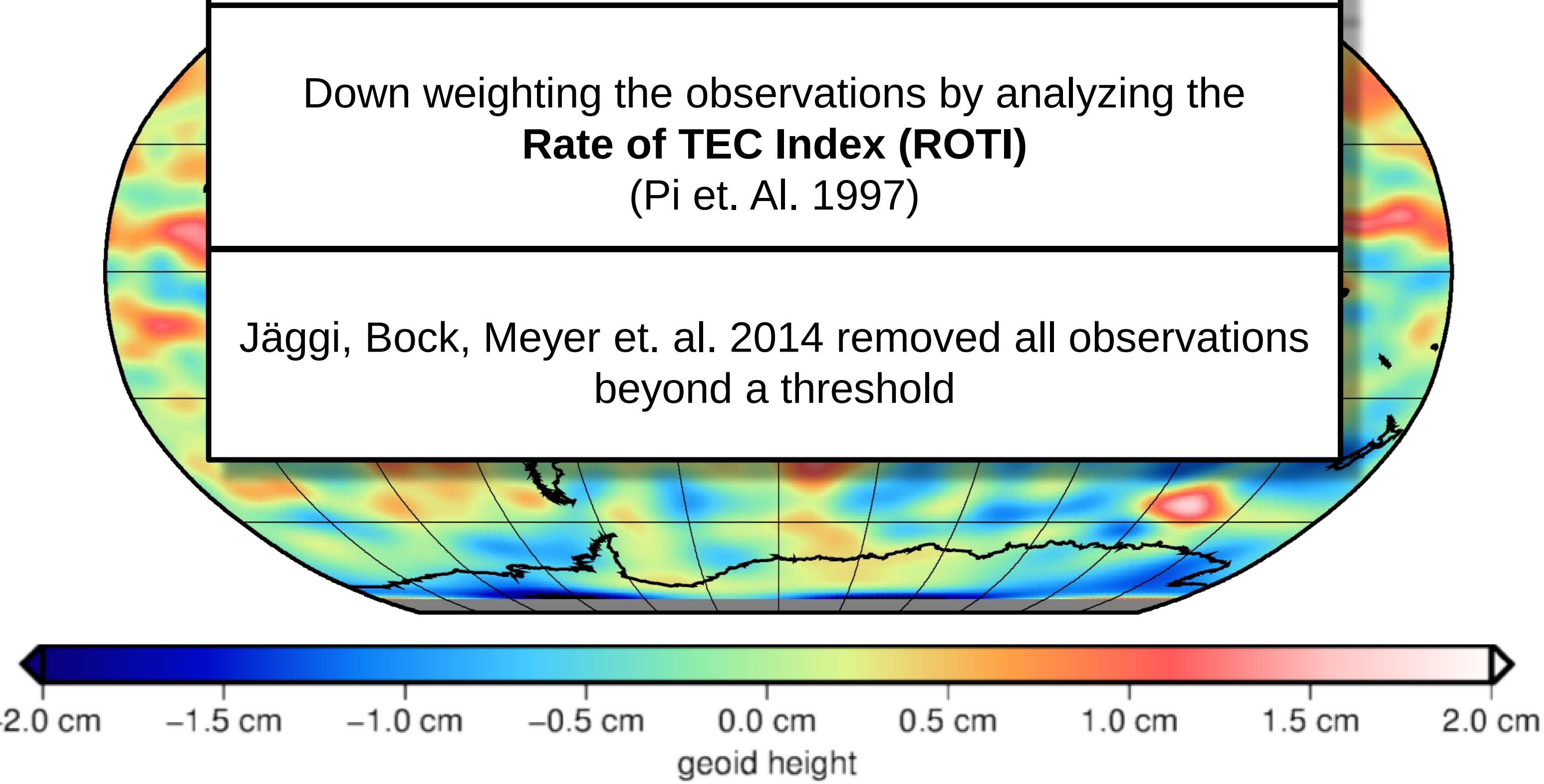
What are the benefits?

high order corrections, bending correction

Only small improvement,
problem still remain

Down weighting the observations by analyzing the
Rate of TEC Index (ROTI)
(Pi et. Al. 1997)

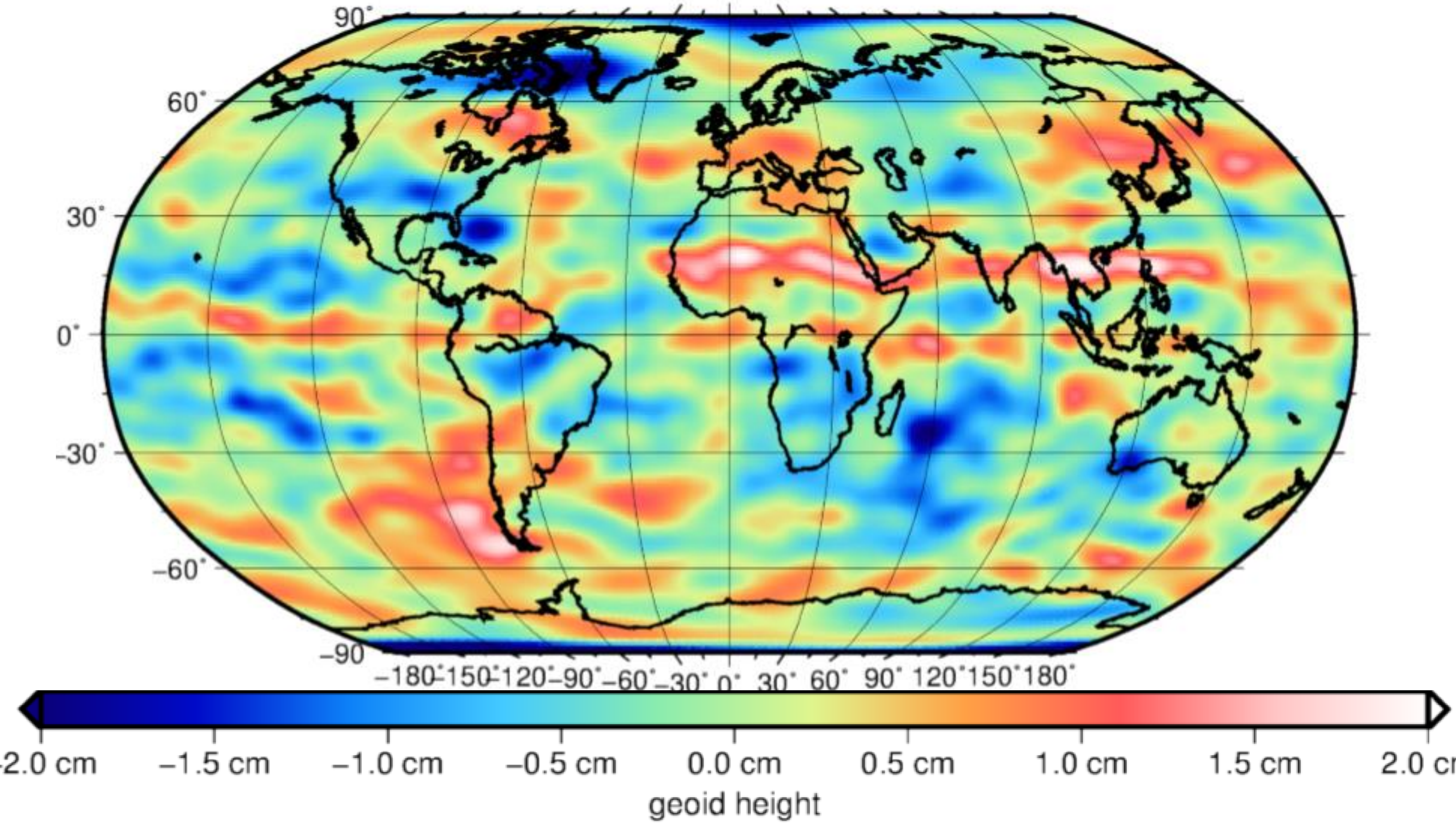
Jäggi, Bock, Meyer et. al. 2014 removed all observations
beyond a threshold



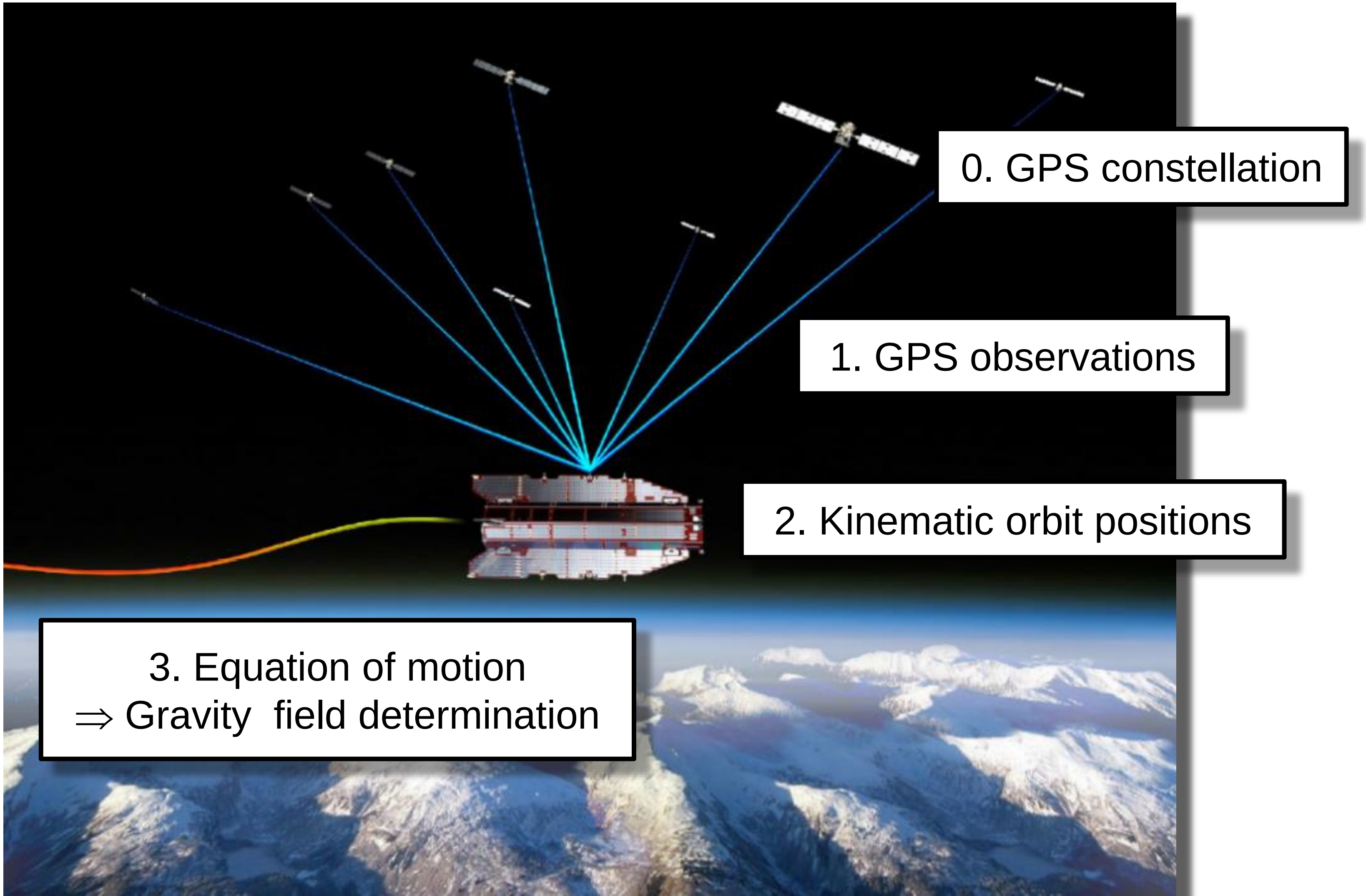
What are the benefits?

high order corrections, bending correction, ROTI weighting

Monthly GOCE SST-hl (2010-10) vs. GOCO05s
Gaussian filter 500 km applied



High-Low Satellite-to-Satellite Tracking (hlSST)



Satellite missions

- CHAMP
- GRACE
- GOCE

- Swarm A, B & C
- MetOp A & B
- TerraSAR-X & TanDEM-X
- FORMOSAT-3/COSMIC
- SAC-C
- Jason 1 & 2
- C/NOFS

Total 21 satellites

Time variable gravity fields

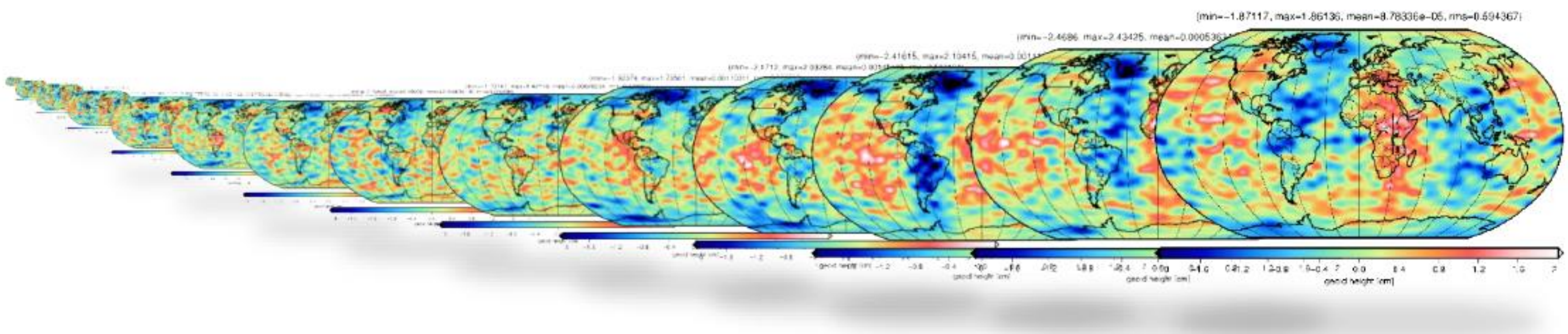
Time variable gravity fields

1. Kinematic orbits from 21 satellites

2. Monthly gravity fields for each satellite (Normal equations)

3. Combined monthly gravity fields

4. Trend and seasonal estimation from the monthly time series

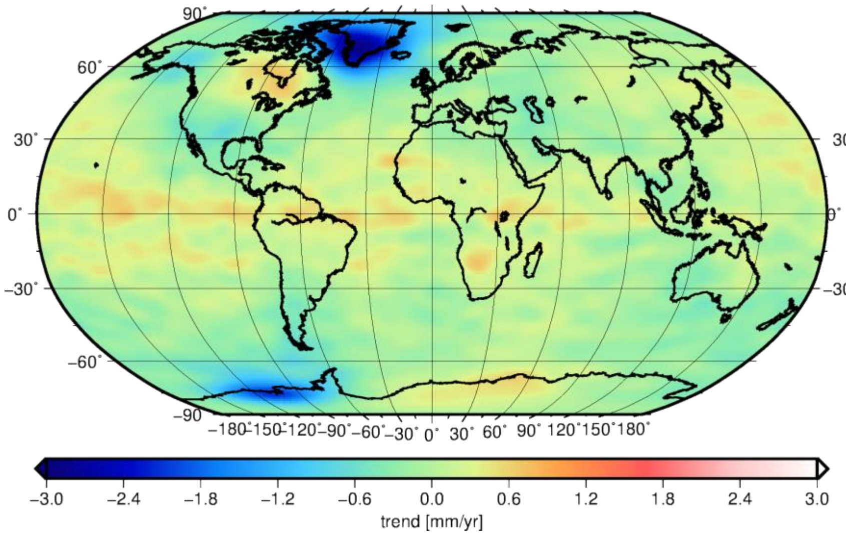


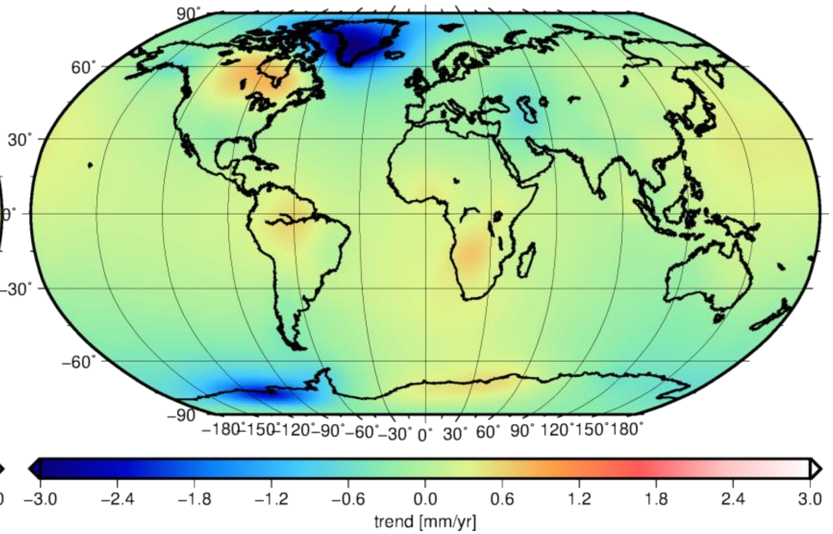
Gravity field variations

IfG SST-hl

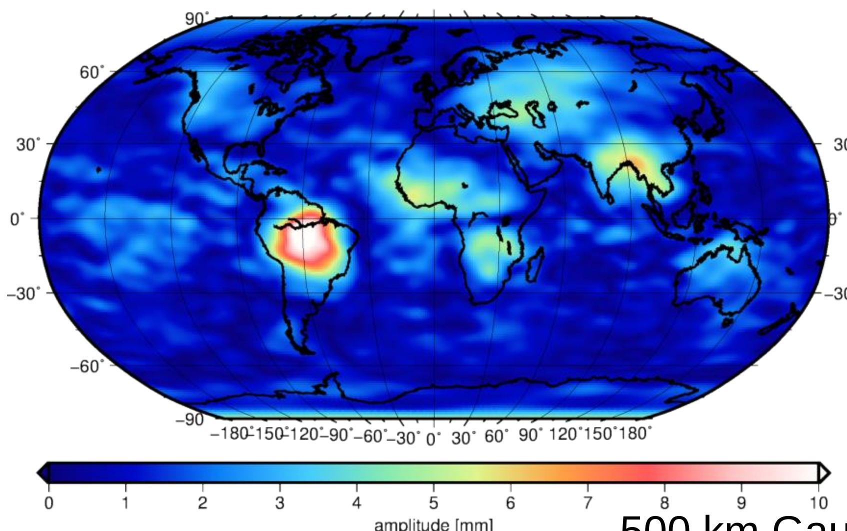
ITSG-Grace2014

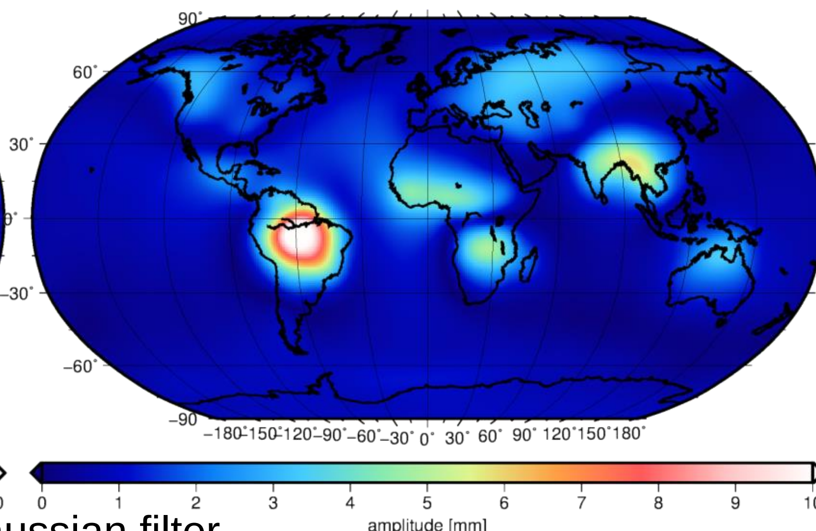
Trend





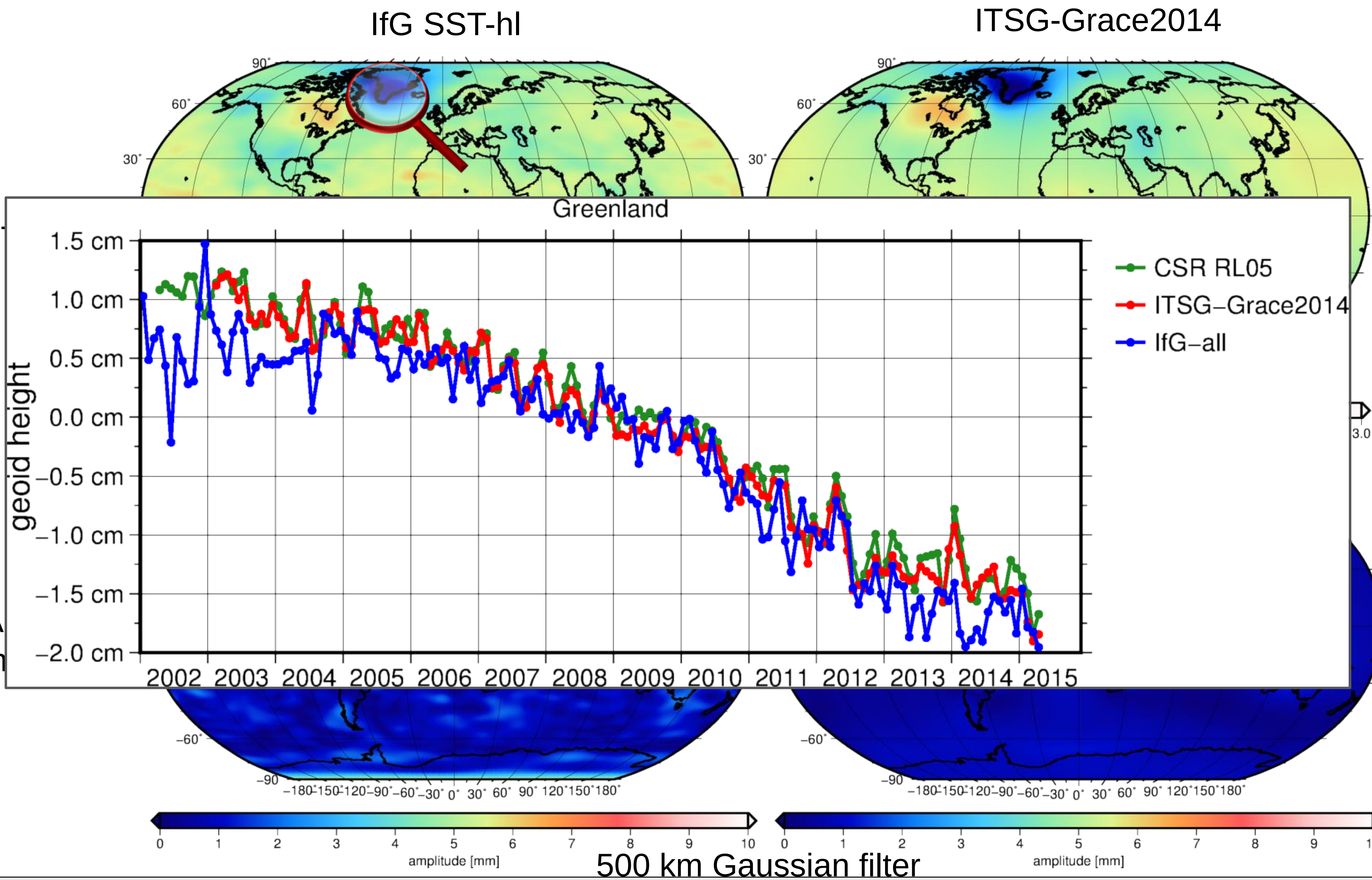
Annual amplitude





500 km Gaussian filter

Gravity field variations



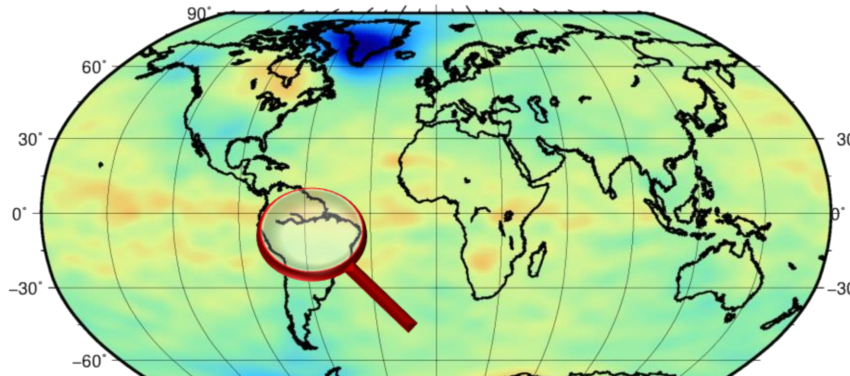
A
am

500 km Gaussian filter

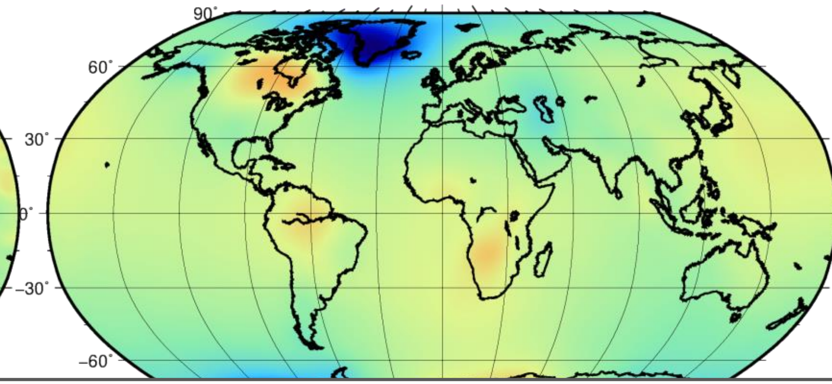
Gravity field variations

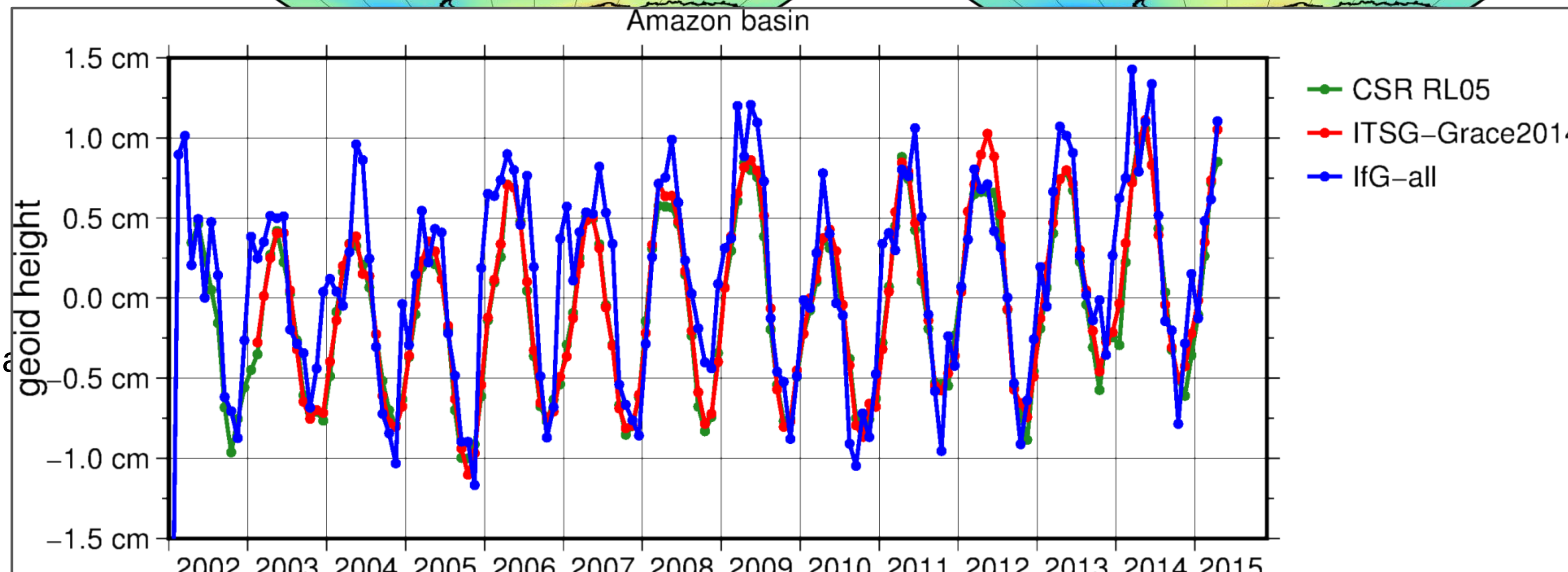
Trend

IfG SST-hl



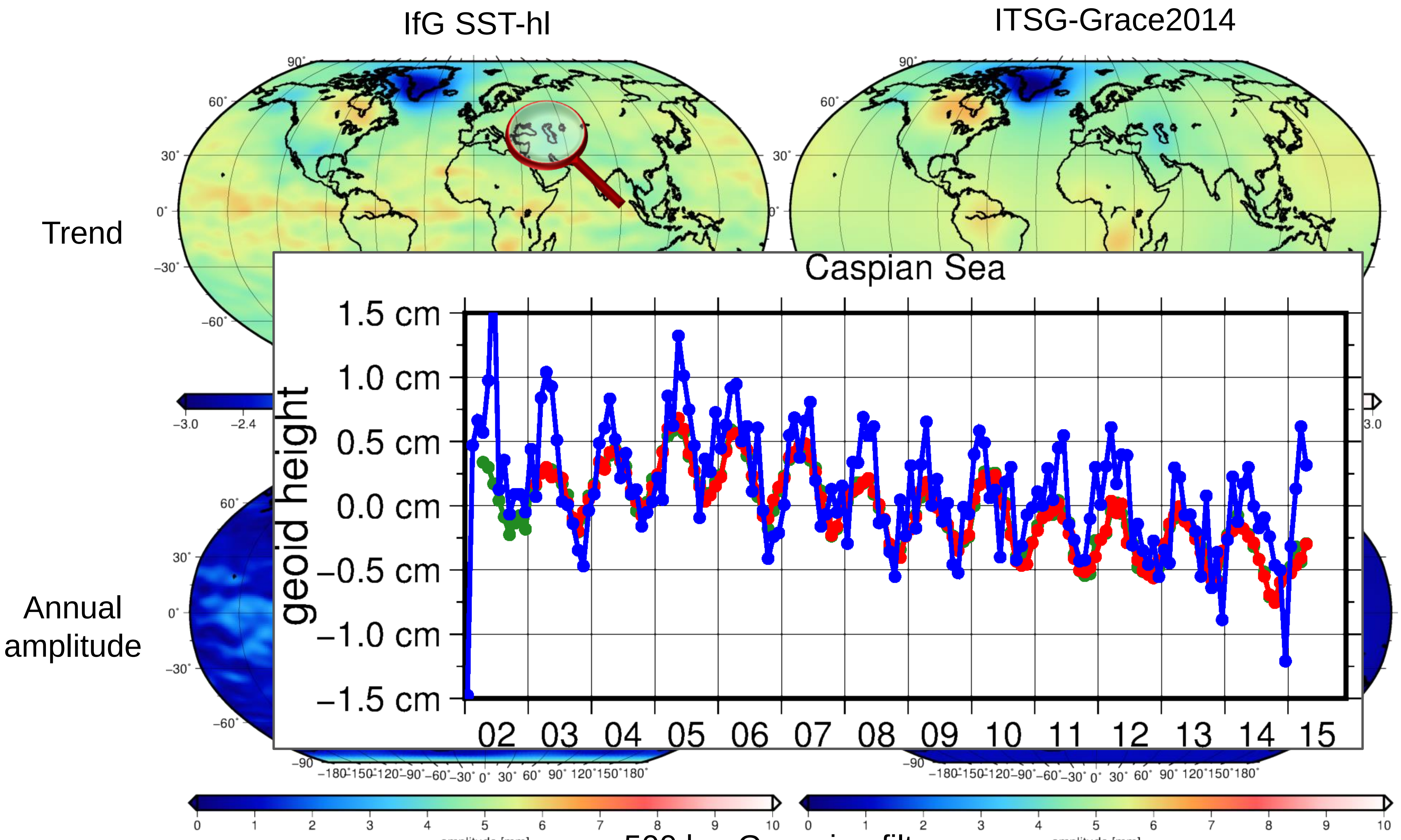
ITSG-Grace2014





500 km Gaussian filter

Gravity field variations

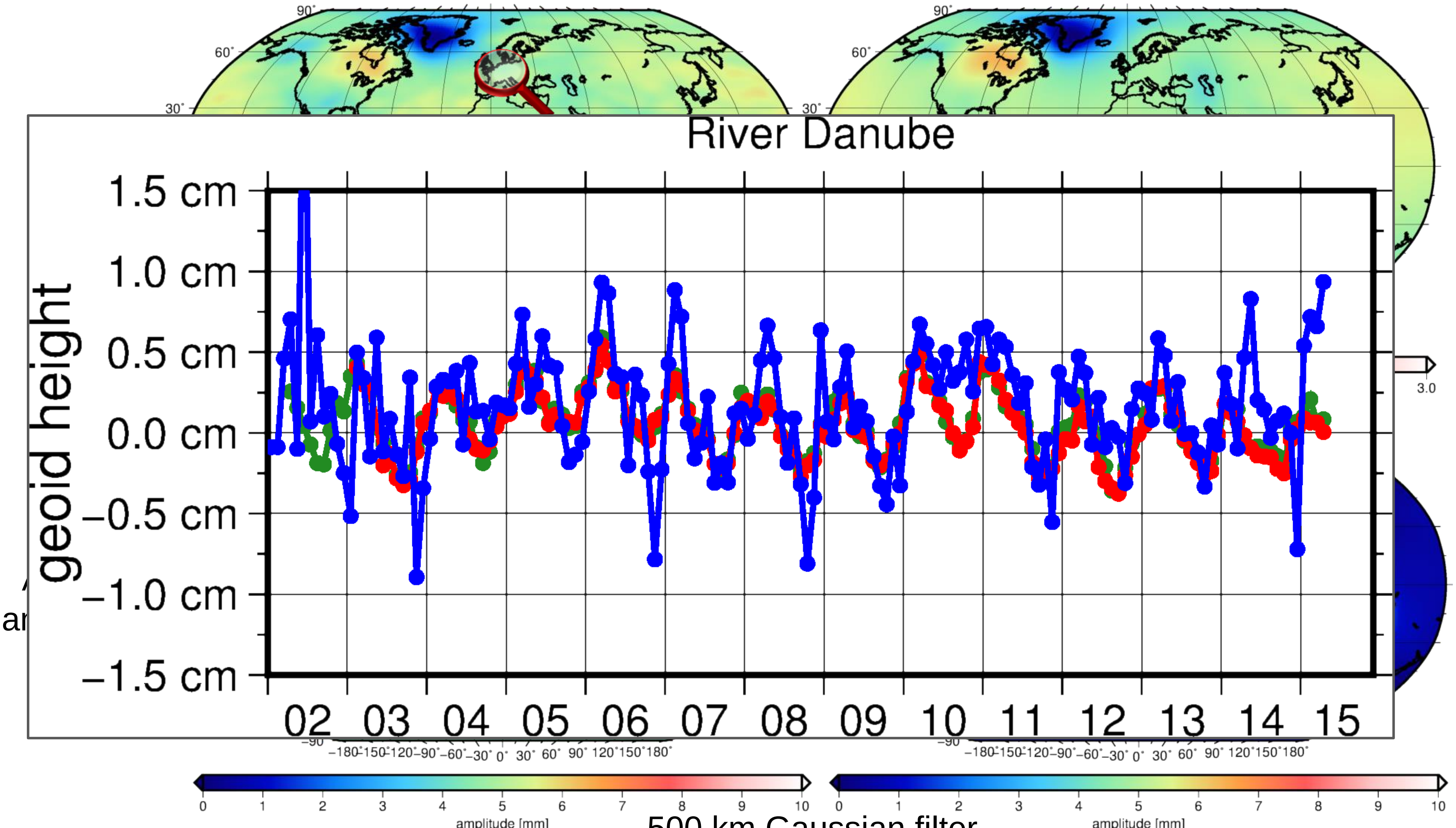


500 km Gaussian filter

Gravity field variations

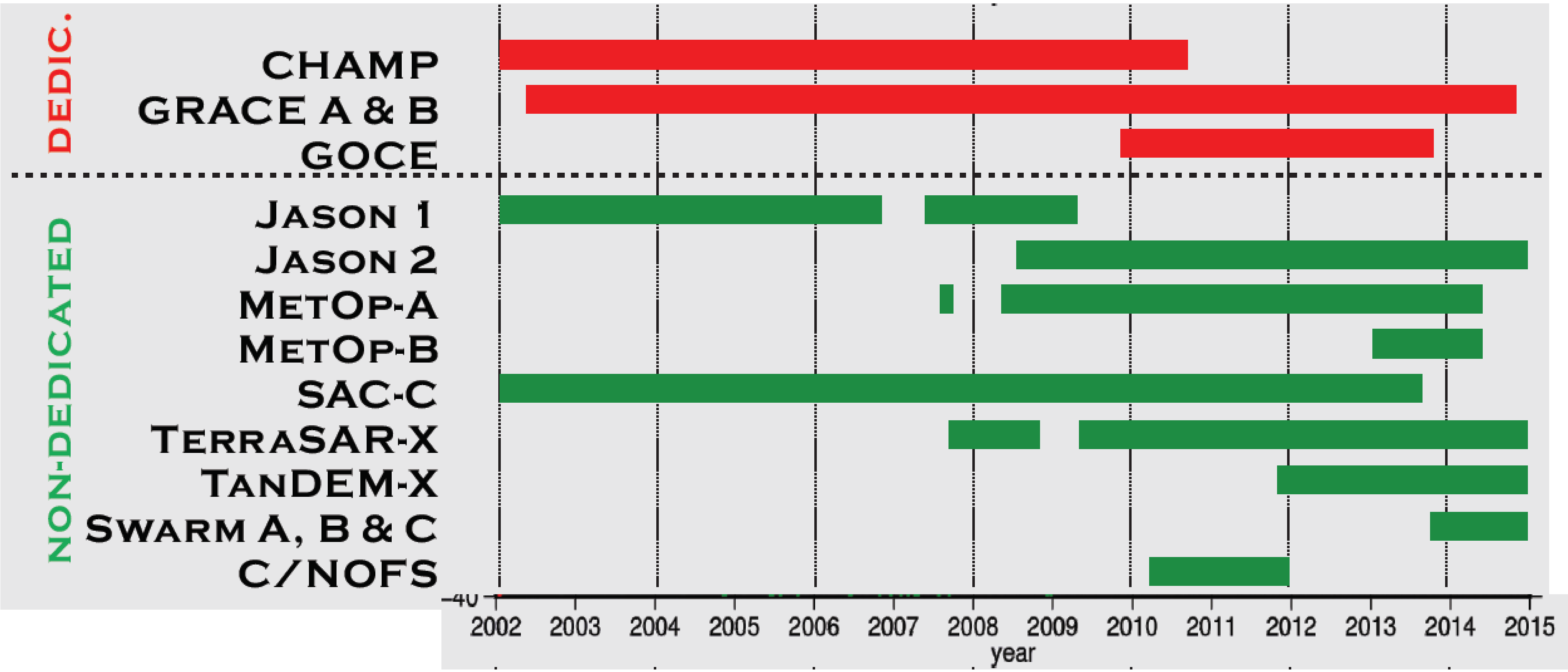
IfG SST-hl

ITSG-Grace2014



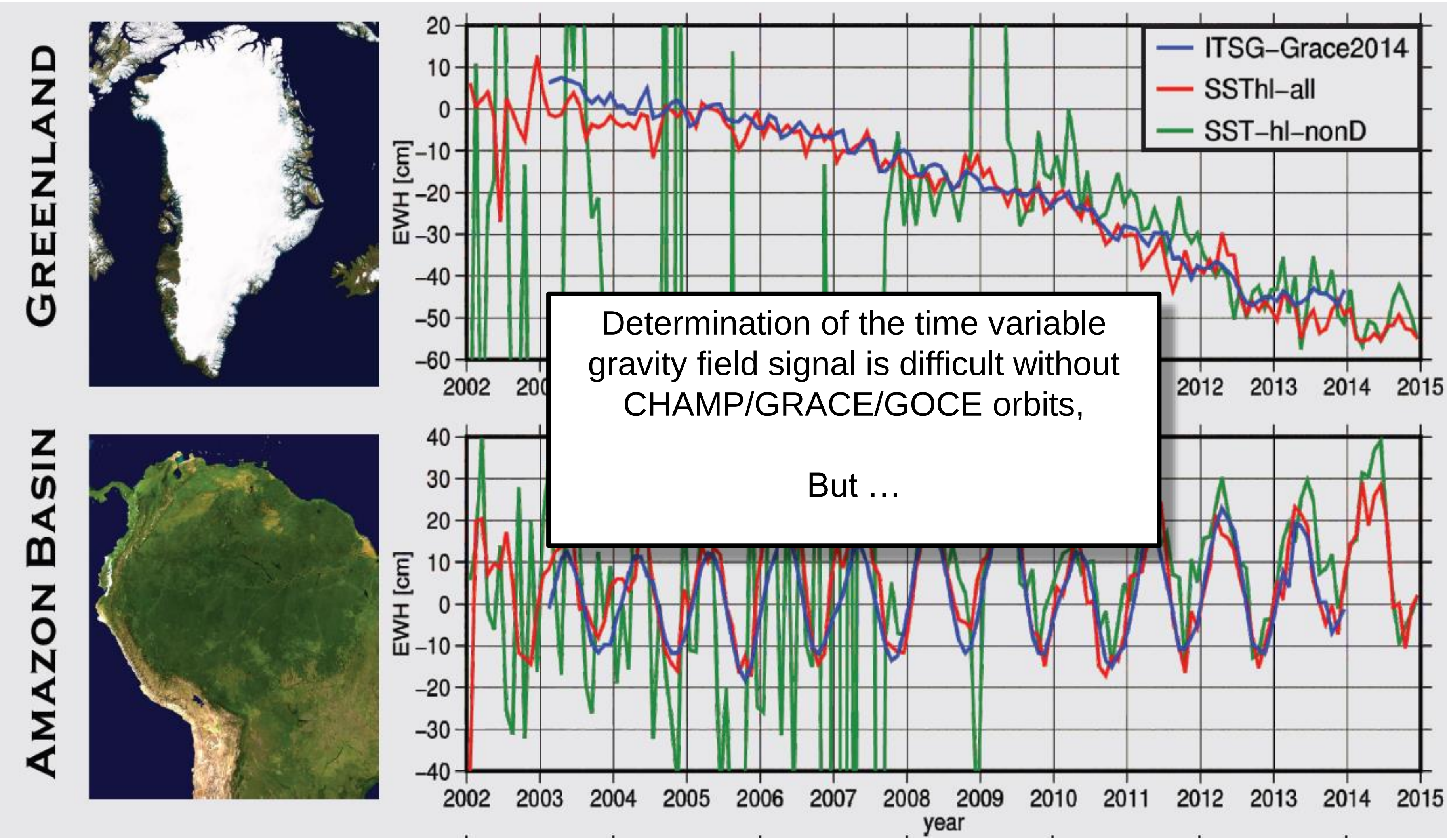
500 km Gaussian filter

Dedicated / Non-dedicated missions



What if CHAMP/GRACE/GOCE would not be available?

Time variable signal



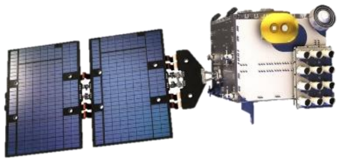
Determination of the time variable gravity field signal is difficult without CHAMP/GRACE/GOCE orbits,

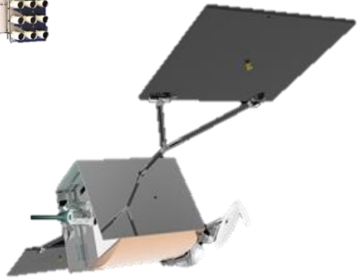
But …

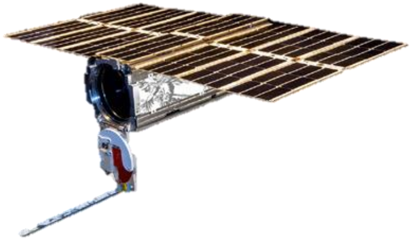
750 km Gaussian filter

Exciting times are ahead

- Upcoming missions
  - Increasing number of scientific satellites (Sentinels, COSMIC 2, …)
  - Commercial micro-satellite constellations:
    - OneWeb: communication (~648 sat)
    - BlackSky Global: Earth imagery (~60 sat)
    - Planet Labs: Earth imagery (>100 sat)
    - UrtheCast: optical and SAR (16 sat)
    - Iridium: communication (~66 sat)
    - …





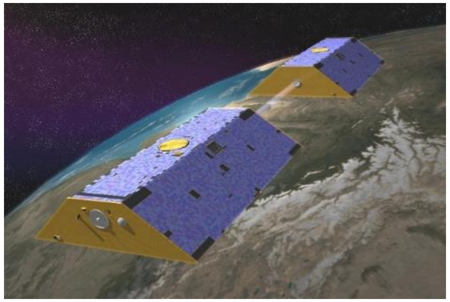


Data

All data are public available: **ifg.tugraz.at**

1. Kinematic orbits:
   CHAMP, GRACE, GOCE, SWARM, TerraSAR-X, …

2. Combined hl-SST monthly gravity fields



3. ITSG-Grace2016s
   - Monthly/Daily gravity fields
   - Full variance/covariance information