EGSIEM

WP 400: Combination of monthly gravity models

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Horizon2020

Task 4.1-4.2

Design and concept

Presenter: Rolf Dach / Ulrich Meyer / Frank Flechtner

Affiliation: UBERN / UBERN /GFZ

Data Formats

Presenter: Rolf Dach

Affiliation: UBERN

SINEX

- SINEX: Solution INdependent EXchange Format
- widely used in the (geometry-related) space geodesy
- numerous parameter types are defined, among others gravity field parameters.
- two types of representation of a solution are possible:
  1. unconstrained normal equations
  2. solutions with full covariance information

Format description of SINEX

Since version 2.10:

- CN = Normalized spherical harmonic coefficient of the Earth's gravity field (cosine term)
- SN = Normalized spherical harmonic coefficient of the Earth's gravity field (sine term)

The degree and order of the spherical harmonic coefficients is stored in the columns 'Site Code' and 'Solution ID', respectively.

Format description of SINEX

SINEX with coordinates (as widely used):

```
+SOLUTION/ESTIMATE
*INDEX TYPE__ CODE PT SOLN _REF_EPOCH__ UNIT S __ESTIMATED VALUE____ _STD_DEV___
     1 STAX   GANP  A    1 10:207:43200 m    2 0.392918142065180E+07 .549572E-03
     2 STAY   GANP  A    1 10:207:43200 m    2 0.145523682233853E+07 .270852E-03
     3 STAZ   GANP  A    1 10:207:43200 m    2 0.479365395060395E+07 .654024E-03
...
```

SINEX for gravity field:

```
+SOLUTION/ESTIMATE
*INDEX TYPE__ CODE PT SOLN _REF_EPOCH__ UNIT S __ESTIMATED VALUE____ _STD_DEV___
...
   101 SN      100  A  100 10:207:43200      2 0.392918142065180E+07 .549572E-03
   102 CN      100  A  100 10:207:43200      2 0.145523682233853E+07 .270852E-03
   103 SN        1  A  101 10:207:43200      2 0.479365395060395E+07 .654024E-03
...
```

Format description of SINEX

SINEX with coordinates (as widely used):

```
+SOLUTION/ESTIMATE
*INDEX TYPE__ CODE PT SOLN _REF_EPOCH__ UNIT S __ESTIMATED VALUE____ _STD_DEV___
     1 STAX   GANP  A    1 10:207:43200 m    2 0.392918142065180E+07 .549572E-03
     2 STAY   GANP  A    1 10:207:43200 m    2 0.145523682233853E+07 .270852E-03
     3 STAZ   GANP  A    1 10:207:43200 m    2 0.479365395060395E+07 .654024E-03
...
```

Feature in column «S=Constraint Code» may also be applied for the gravity field determination:

- 0-fixed/tight constraints,
- 1-significant constraints,
- 2-unconstrained.

Sections in a SINEX-file:

- SOLUTION/STATISTICS
  - NUMBER OF OBSERVATIONS
  - NUMBER OF UNKNOWNS
  - SQUARE SUM OF RESIDUALS ($v^T P v$)
  - ...
- SOLUTION/EPOCHS
  - Parameter validity intervals (same for CN and SN):

```
+SOLUTION/EPOCHS
*CODE PT SOLN T _DATA_START_ __DATA_END__ _MEAN_EPOCH_
...
  100  A  100 P 10:207:00000 10:207:86370 10:207:43185
    1  A  101 P 10:207:00000 10:207:86370 10:207:43185
...
```

Sections in a SINEX-file:

- SOLUTION/ESTIMATE
  - estimated parameters
- SOLUTION/APRIORI
  - apriori information for estimated parameters
- SOLUTION/MATRIX_APRIORI
  - apriori constraint matrix (if there are any)

Sections in a SINEX-file:

Two representations of the solution:

- SOLUTION/NORMAL_EQUATION_VECTOR: A^TPl
  SOLUTION/NORMAL_EQUATION_MATRIX: A^TPA
  (in that case the SOLUTION/ESTIMATE block is informative)

- SOLUTION/MATRIX_ESTIMATE
  - variance-covariance matrix for the unknowns of this constrained normal equation system

Combination

Presenter: Ulrich Meyer

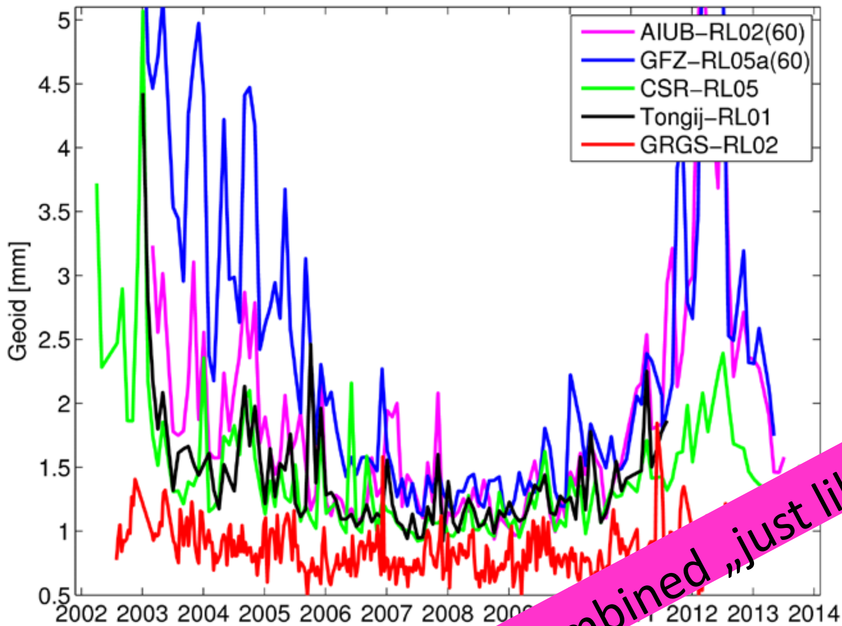
Affiliation: UBERN

Combination method

- On NEQ-level:
- On model level (SHC):
- On model level (Grids):

Noise assessment

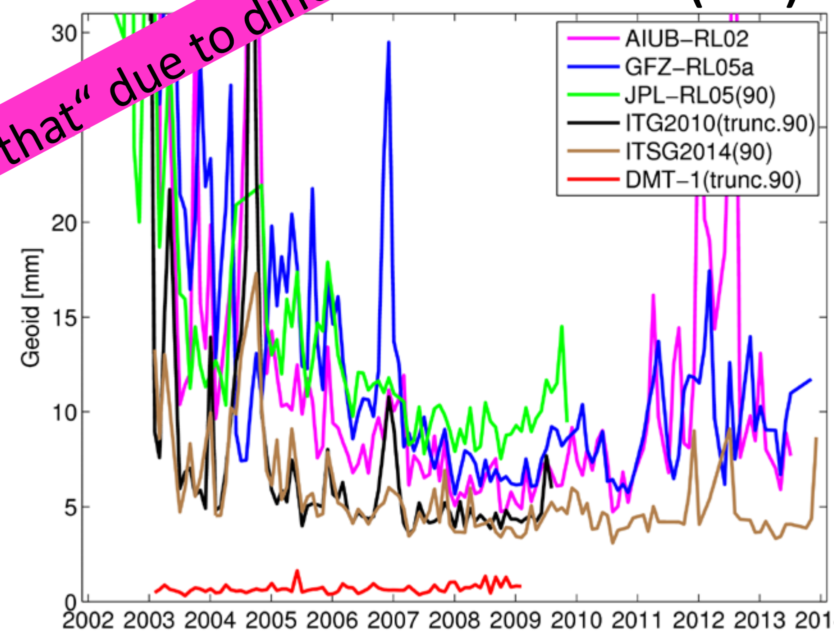
wSTD over oceans (60)



AIUB-RL02 (60[illegible] mm
GFZ-RL05a[illegible]): 1.8 mm
CSR-R[illegible] 1.3 mm
T[illegible]: 1.3 mm
GRGS-RL02 (50): 0.8 mm

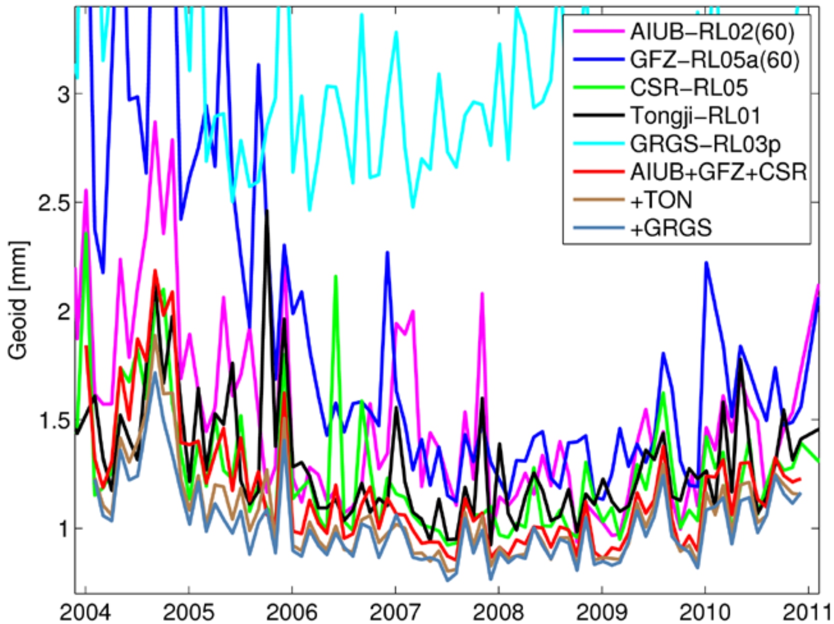
AIUB-RL02: 9.8 mm
GFZ-RL05a: 11.3 mm
JPL-RL05 (90): 11.9 mm
ITG2010 (trunc. 90): 6.[illegible]
ITSG2014 (90): [illegible] mm
DMT-1 (trunc[illegible] 0.7 mm

wSTD over oceans (90)



Solutions cannot be combined „just like that“ due to different solution strategies

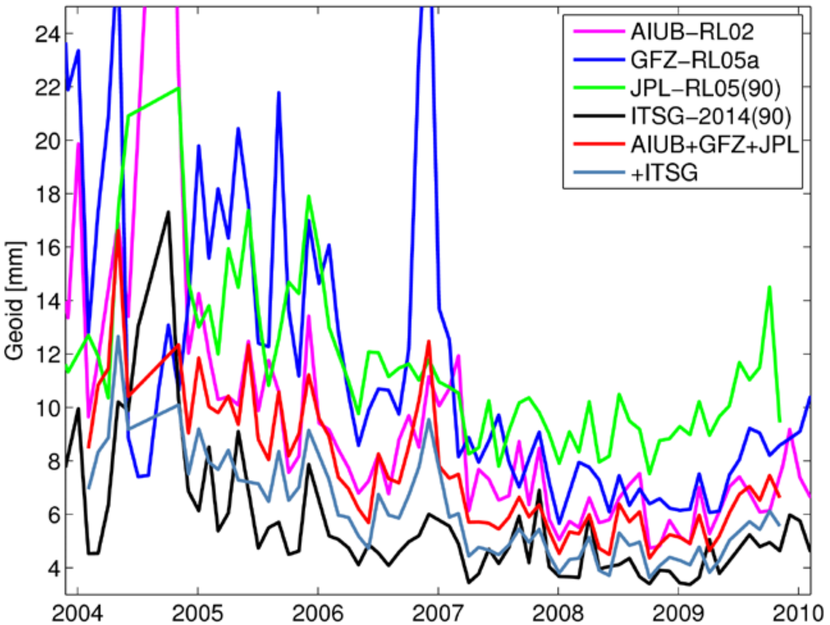
Averaged (free) monthly solutions



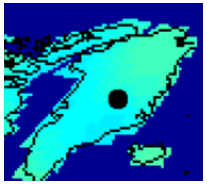
AIUB-RL02 (60):	1.5 mm
GFZ-RL05a (60):	1.8 mm
CSR-RL05:	1.3 mm
Tongji-RL01:	1.3 mm
GRGS-RL03p:	3.2 mm
Mean of 3:	1.2 mm
Mean of 4:	1.1 mm
Mean of 5:	1.0 mm

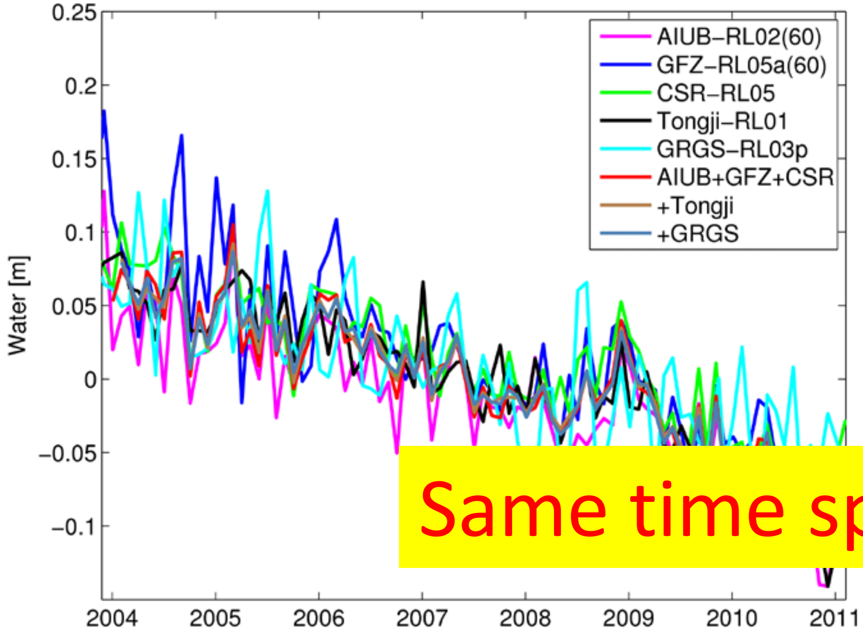
AIUB new (90):	9.8 mm
GFZ-RL05a (90):	11.3 mm
JPL-RL05 (90):	11.9 mm
ITSG-2014 (90):	5.3 mm
Mean of 3:	7.8 mm
Mean of 4:	6.4 mm

wSTD over oceans (90)



Averaged (free) monthly solutions

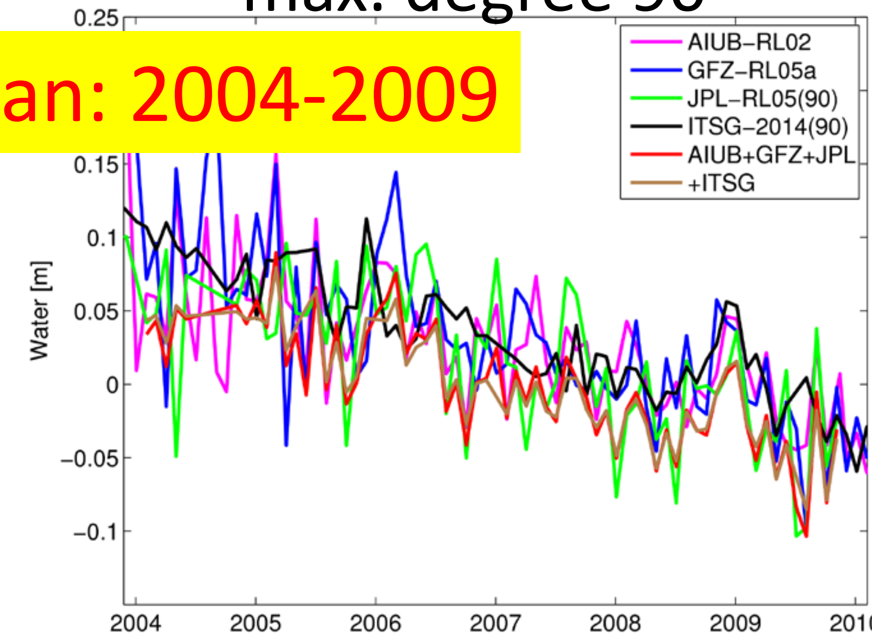




AIUB-RL02 (60): -15±1.7 mm/y
GFZ5-RL05a (60): -21±2.2 mm/y
CSR-RL05: -17±1.6 mm/y
TON-RL01: -20±1.4 mm/y
GRGS-RL03: -18±2.5 mm/y
Mean of 3: -20±1.2 mm/y
Mean of 4: -20±1.1 mm/y
Mean of 5: -20±1.0 mm/y

AIUB-RL02: -15±2.4 mm/y
GFZ-RL05a: -23±2.8 mm/y
JPL-RL05(90): -19±3.0 mm/y
ITSG-2014 (90): -20±1.5 mm/y
Mean of 3: -19±2.0 mm/y
Mean of 4: -19±1.6 mm/y

max. degree 90



Same time span: 2004-2009

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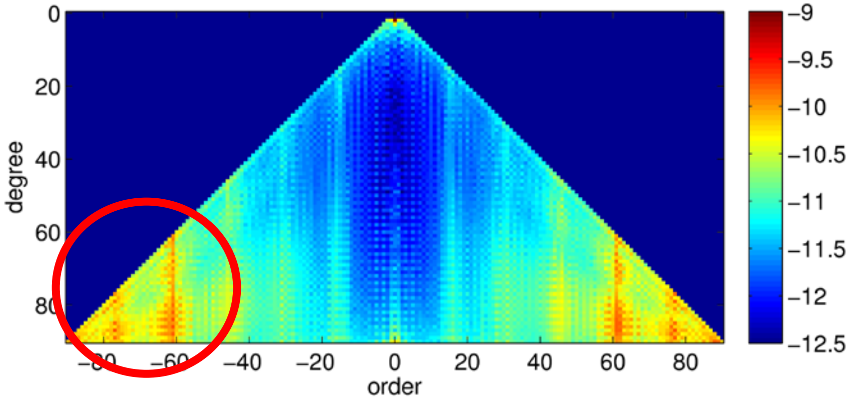
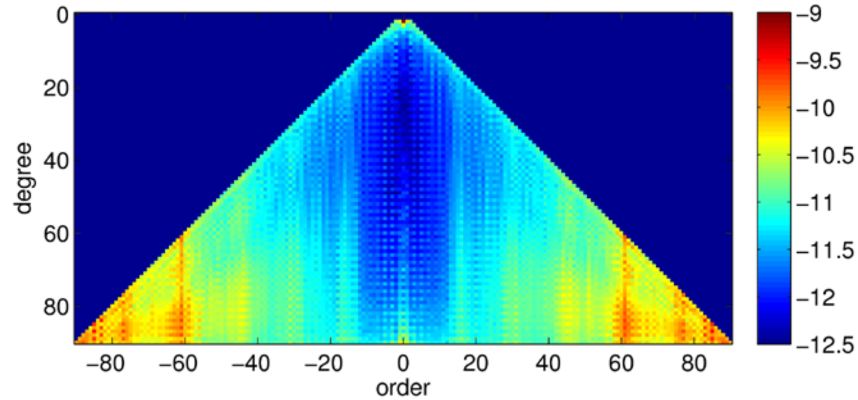
RMS of monthly differences per coefficient

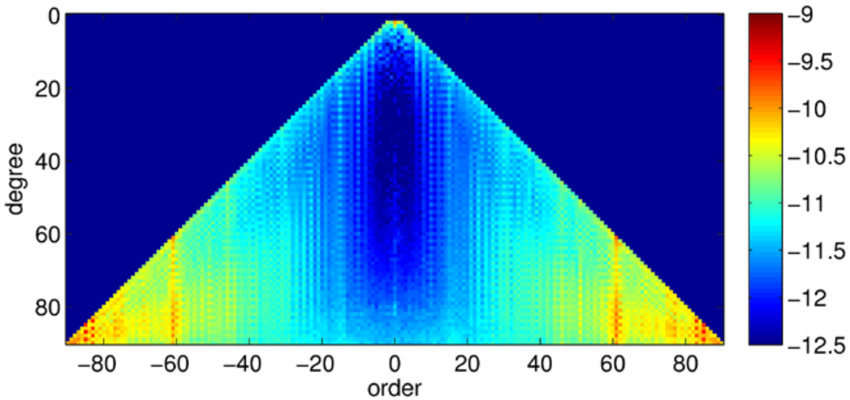
JPL-RL05 – AIUB-



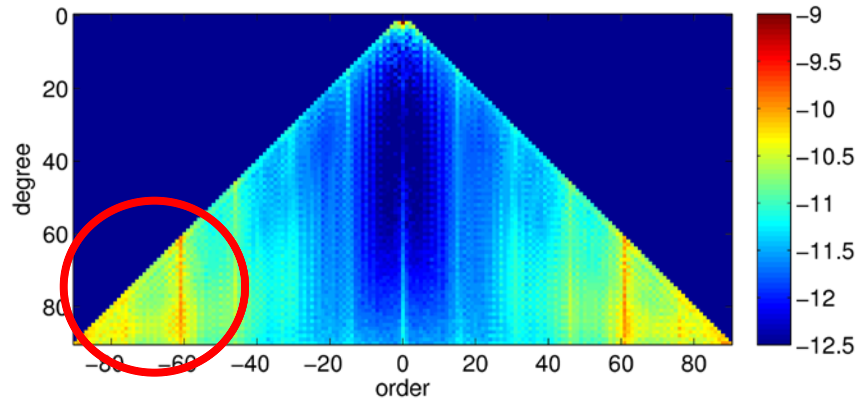
JPL-RL05 – GFZ-



GFZ-RL05a – AIUB-RL02

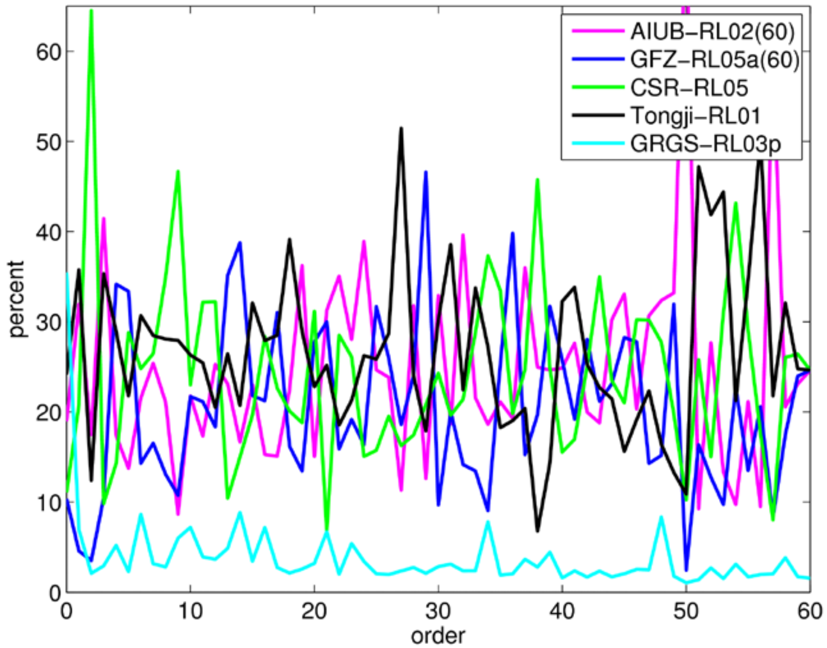


ITSG-2014 – AIUB-RL02



Monthly relative weights (example 03/2008)

Contribution per order



Mean:

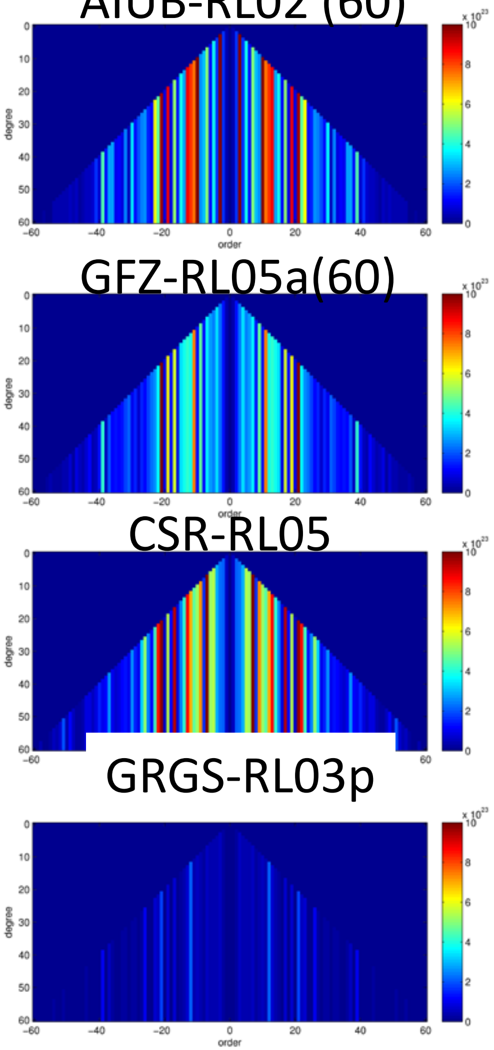
AIUB: 25 %

GFZ: 20 %

CSR: 24 %

TON: 27 %

GRGS: 4 %

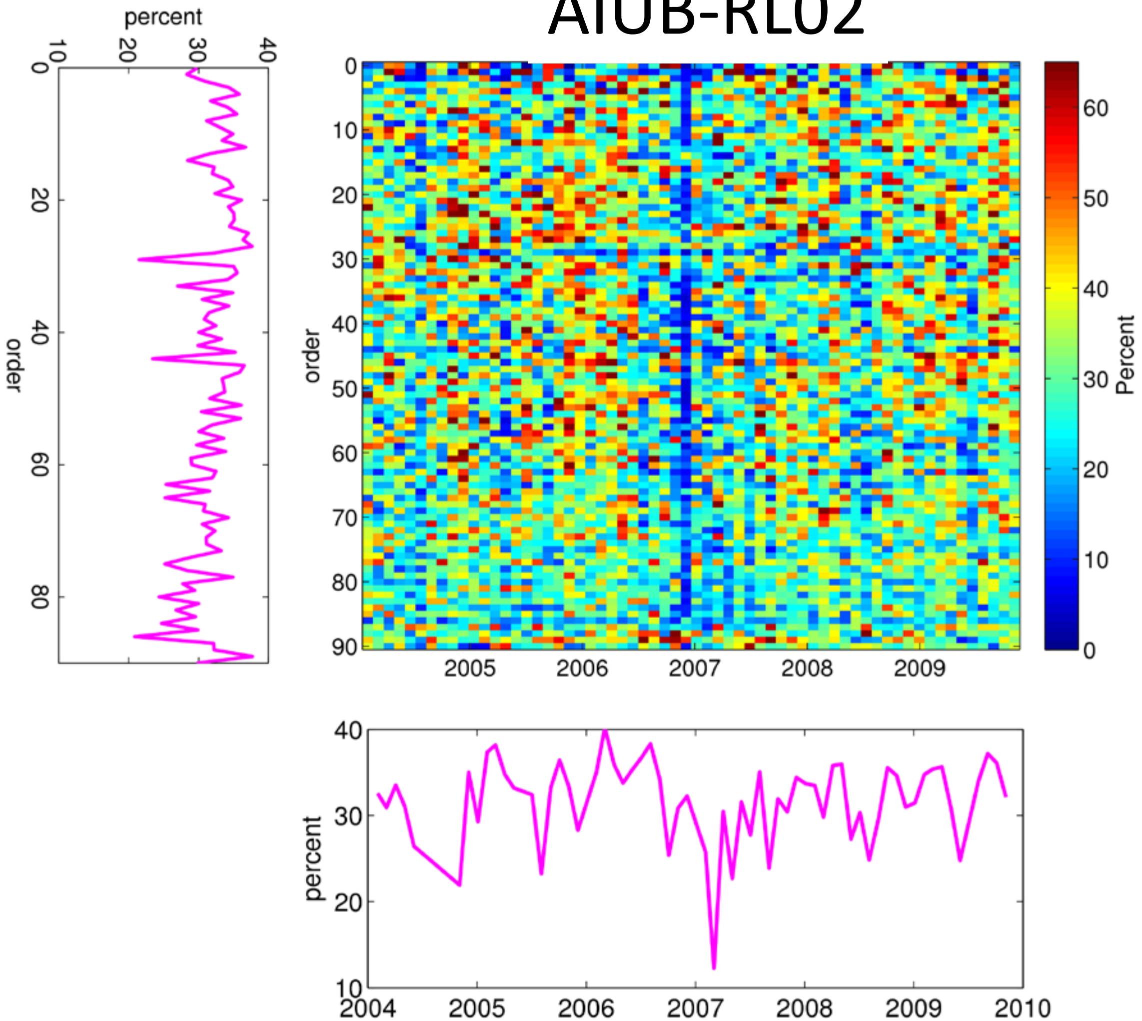


Percent: 100% * $w_i/(w_1+w_2+w_3)$

Weight matrix: $1/RMS^2$ per order

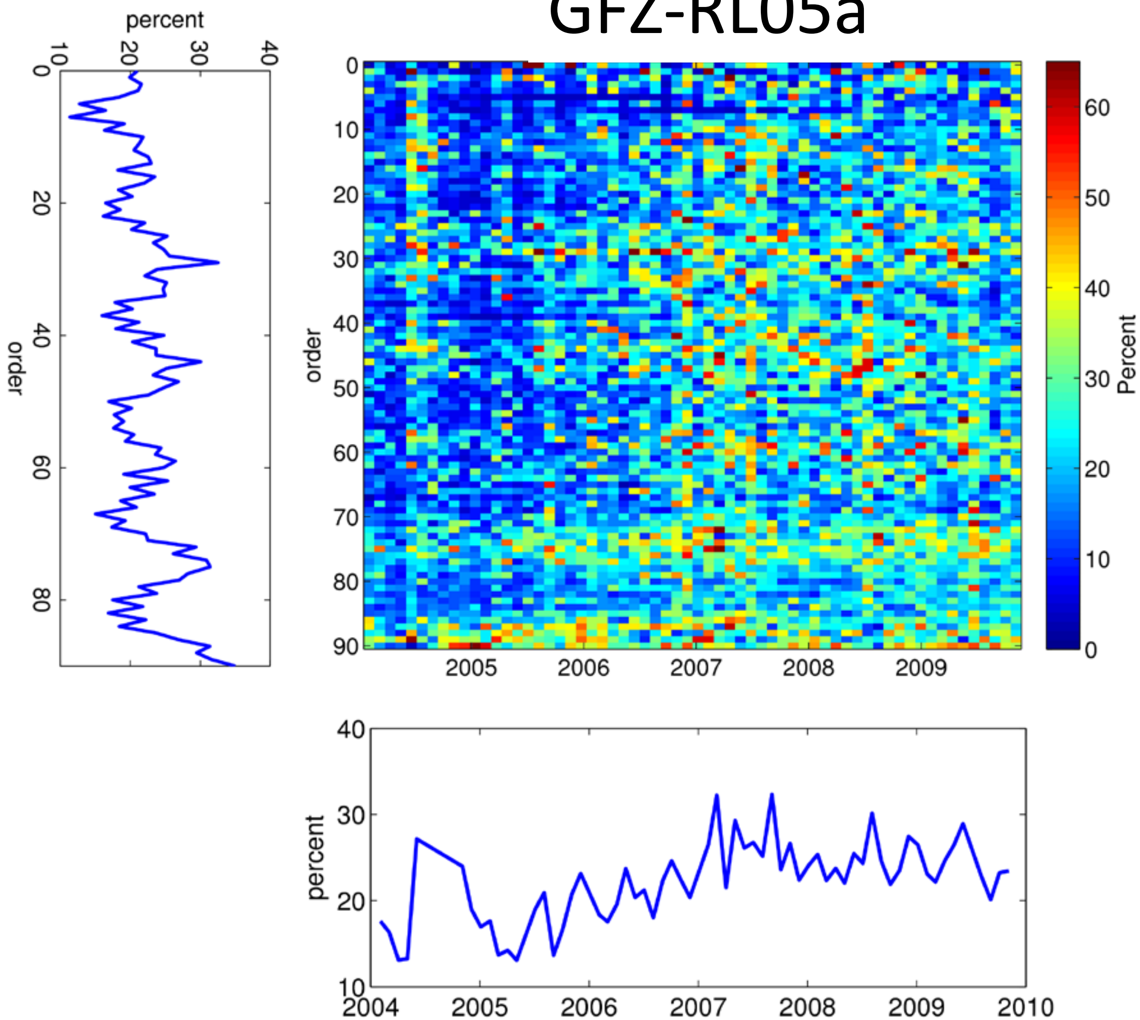
Monthly relative weights 90

AIUB-RL02



Monthly relative weights 90

GFZ-RL05a



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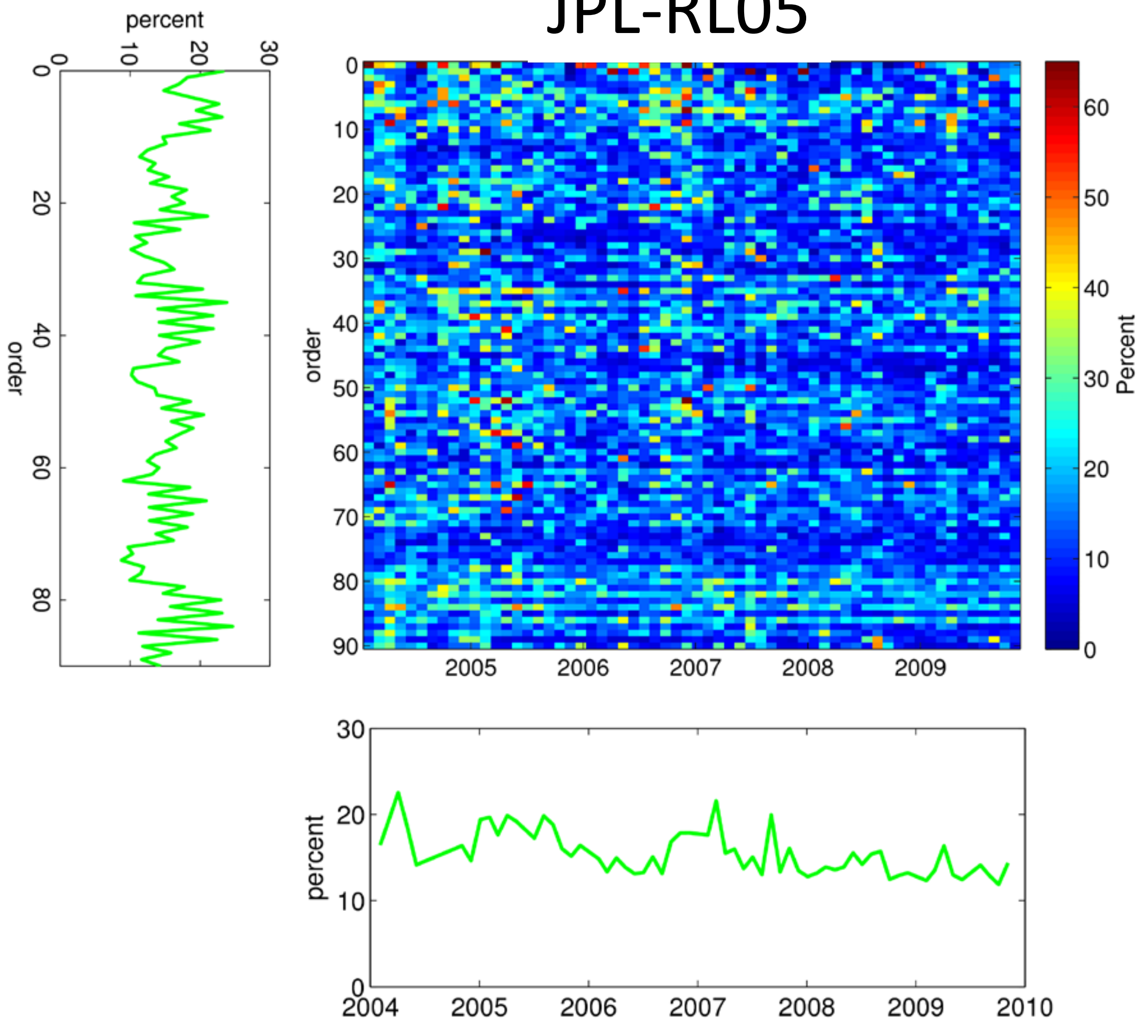
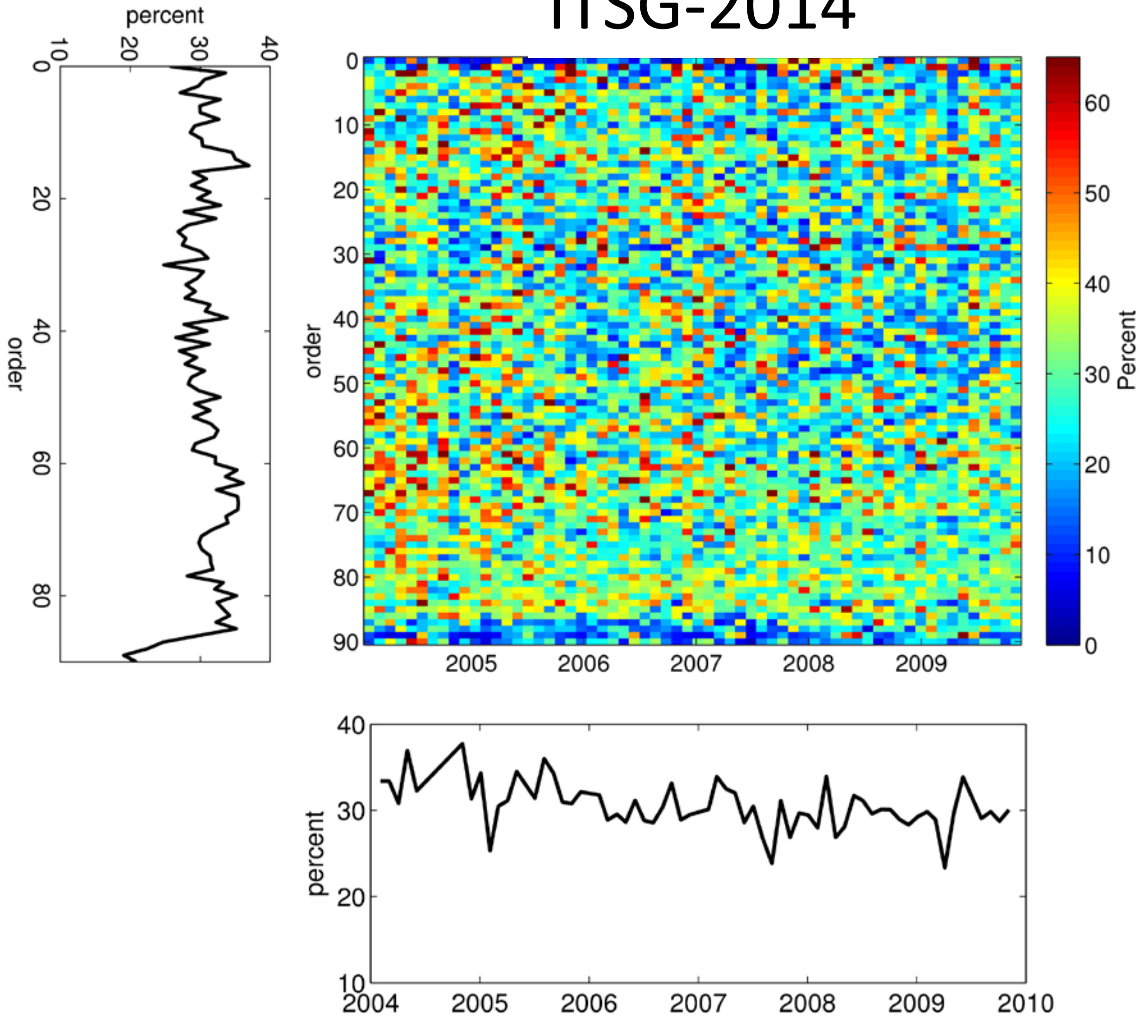
Monthly relative weights 90

JPL-RL05



Monthly relative weights 90

ITSG-2014



Outlook

- Evaluation of un-biasedness of solutions
  - Regional signal comparisons (riverbasins, Greenland)
  - Correlation analysis (with/without seasonal signal)
  - Noise comparisons (oceans, deserts)
- Evaluation/Combination of gridded models?
- Evaluation/Combination of filtered models?
- Combination on normal equation level!

Level-3 Products

Presenter: Frank Flechtner

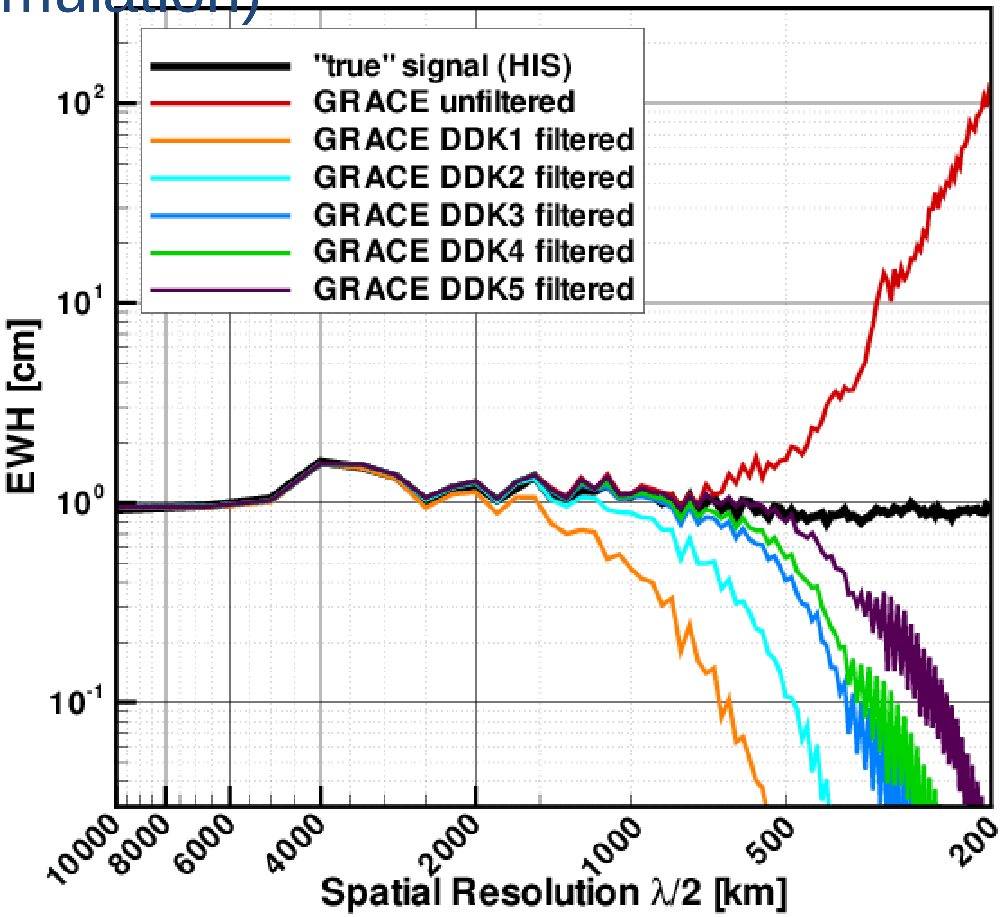
Affiliation: GFZ

Level-3 Products: General

- The observed GRACE monthly changes in gravity (spherical harmonics) are caused by monthly changes in mass. The mass changes can be thought of as concentrated in a very thin layer of water thickness changes near the Earth's surface.
- Level-2 dimensionless GRACE spherical harmonics cannot be used by hydrologists „as is“
- Need postprocessing (filtering) to reduce large errors of mid to high degrees due to aliasing.

Level-3 Products: Filtering of Level-2 Products

Noise reduction vs. signal dampening (Example from simulation)



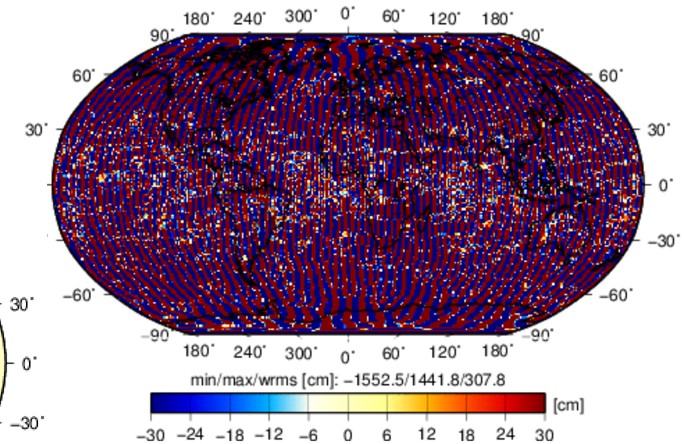
Unfiltered GRACE solution shows increased noise in mid to low frequencies

True signal

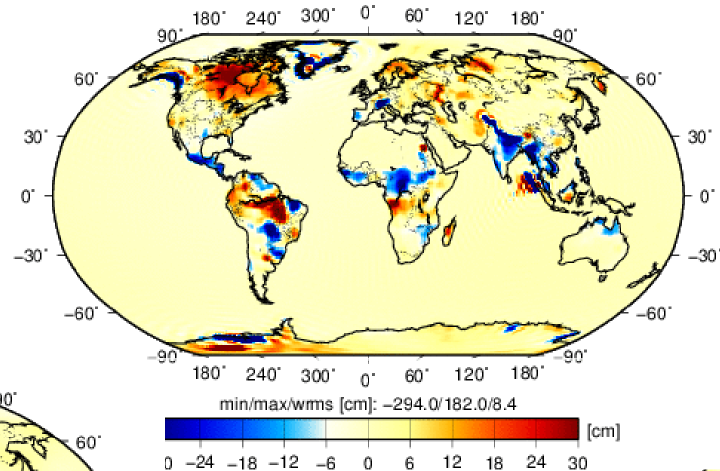
(DDK) filtered results also show signal damping starting earlier than filter length

Level-3 Products: Filtering of Level-2 Products

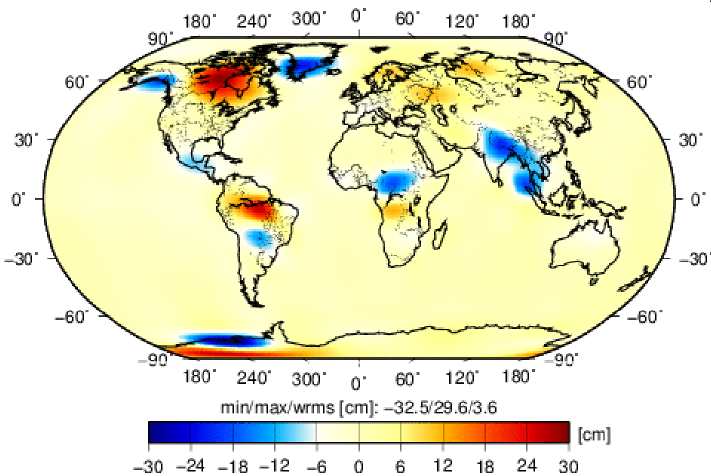
Noise reduction vs. signal dampening (Example from simulation)



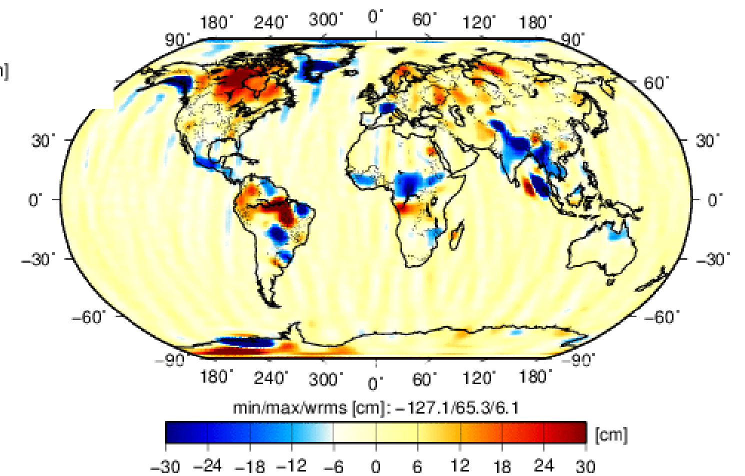
unfiltered



truth



DDK1



DDK5

Level-3 Products: General

- Dimensionless coefficients have to be converted to Equivalent Water Height (EWH)

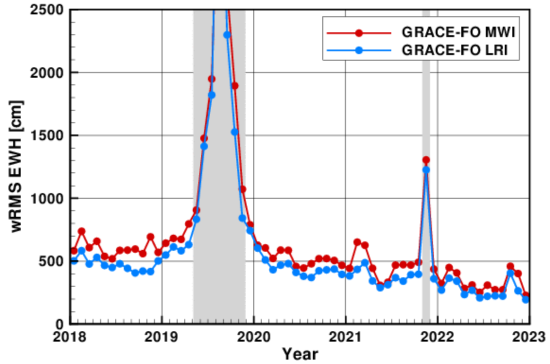
$$\Delta\sigma(\phi,\lambda) = a_e\rho_w \sum_{l=0}^{\infty}\sum_{m=0}^{l} \bar{P}_{lm}(cos\phi)(\Delta\hat{C}_{lm}cos(m\lambda) + \Delta\hat{S}_{lm}sin(m\lambda)) \quad (1)$$

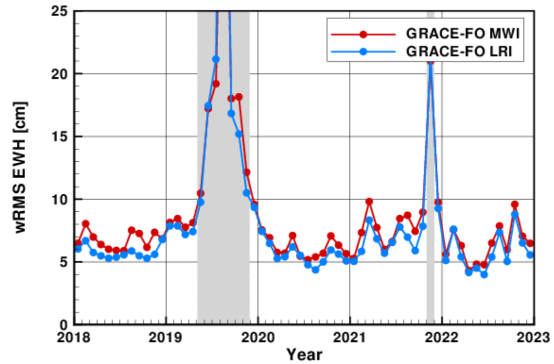
$$\Delta\hat{C}_{lm} = \frac{\rho_{ave}}{3\rho_w}\frac{2l+1}{1+k_l}\Delta C_{lm}$$
$$\Delta\hat{S}_{lm} = \frac{\rho_{ave}}{3\rho_w}\frac{2l+1}{1+k_l}\Delta S_{lm} \quad (2)$$

- Resulting global filtered EWH grids are Level-3 products
- Open Issues:
  - not 100% clear which filter is „the best“ (see GRACE-FO E2E simulation results next page). Needs further investigation!
  - Others: C20 substitution, GIA effect, Degree 1 coefficients (see below)

GFZ GRACE-FO Simulation Study Result

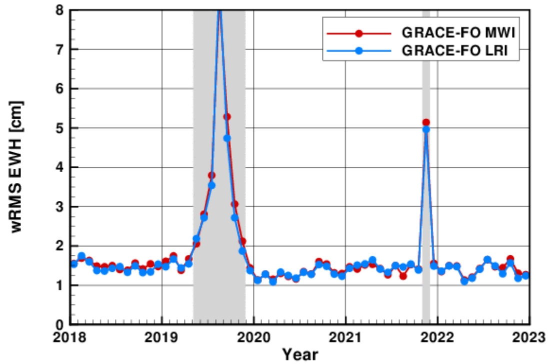
unfiltered

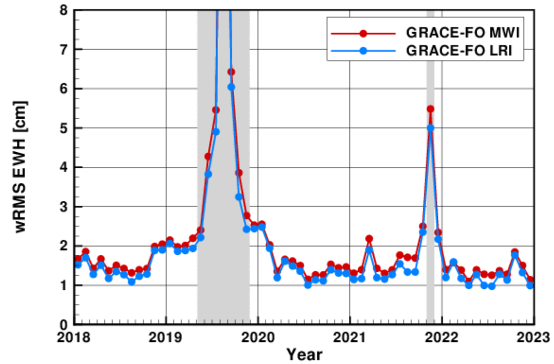




Gauss 250km

DDK4



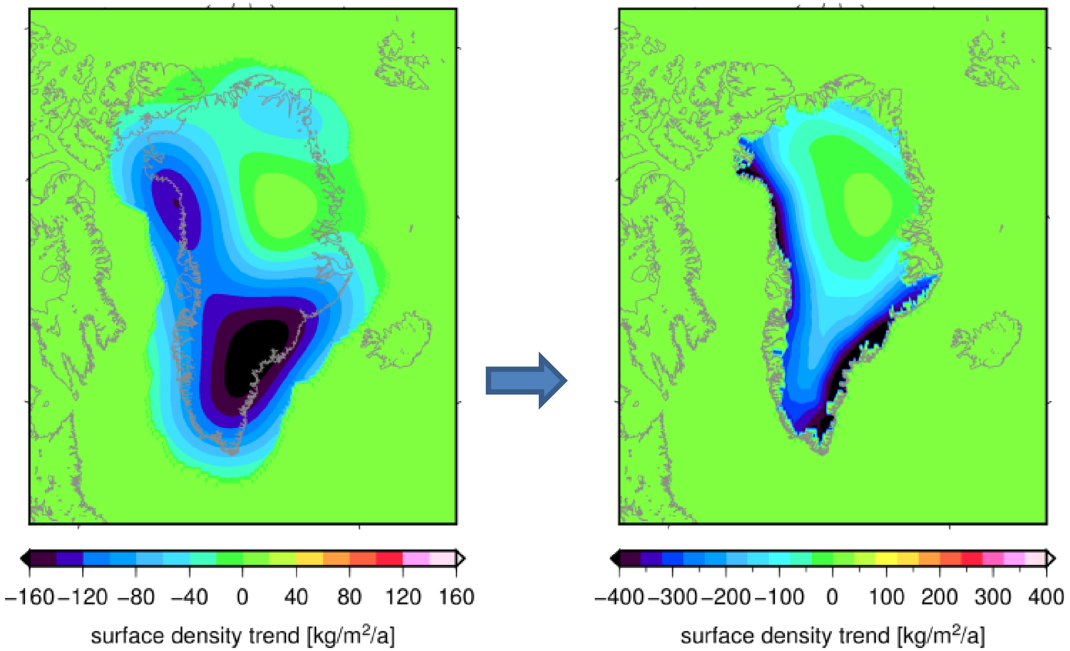


Swensson Destriping & Gauss 250km

Unfiltered (top left), 250 km Gauss filtered (top right), DDK4 filtered (bottom left) and destriped & 250 km Gauss filtered (bottom right) monthly differences between recovered and simulated gravity fields in terms of wRMS of EWH for the five years simulation period using simulated GRACE-FO MWI (red) and LRI (blue) data. Periods with imperfect ground track pattern have been marked grey.

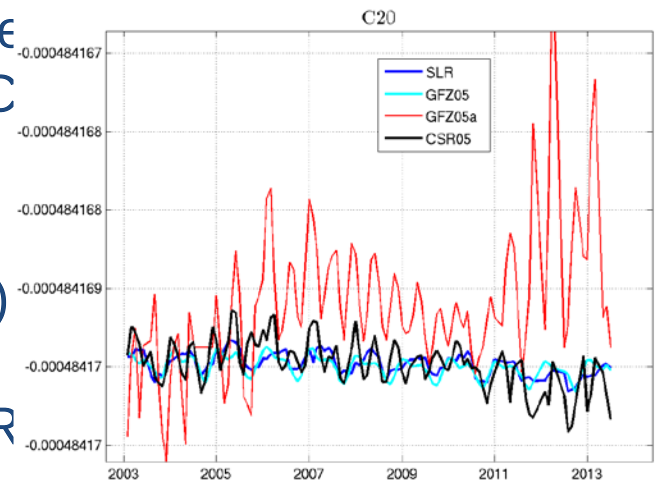
Level-3 Products: Leakage

- Leakage:
  - Caused by limitations in spatial resolution and post-filtering
  - Rescaling: estimation of scaling factors using geophysical models (e.g. for continental hydrology: WGHM)
  - Restoration of mass signals leaked between subsystems (e.g. land – ocean)



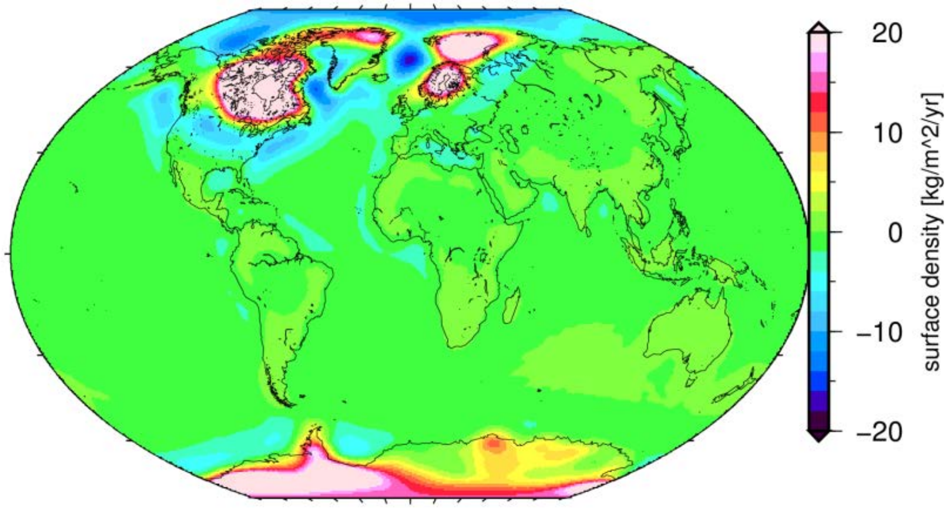
Level-3 Products: Low Degrees

- Degree 1:
  - Variations in degree 1 (geocenter motion) are not observed by GRACE
  - Need to be applied e.g. when comparing GRACE with GNSS or OBP
  - Provided from regularly updated external data, e.g.
    - SLR data (Cheng et al. 2010),
    - Joint inversion GPS, OBP and GRACE (Rietbroeck et al. 2012), or
    - Using global eustatic sea-leve … tion of geocenter motion from GRAC
- C_{20}:
  - GRACE observed variations in coefficient C_{20} (Earth oblateness) are noisy
  - Suggestion: Replacement by SLR derived values (GRACE TN07)



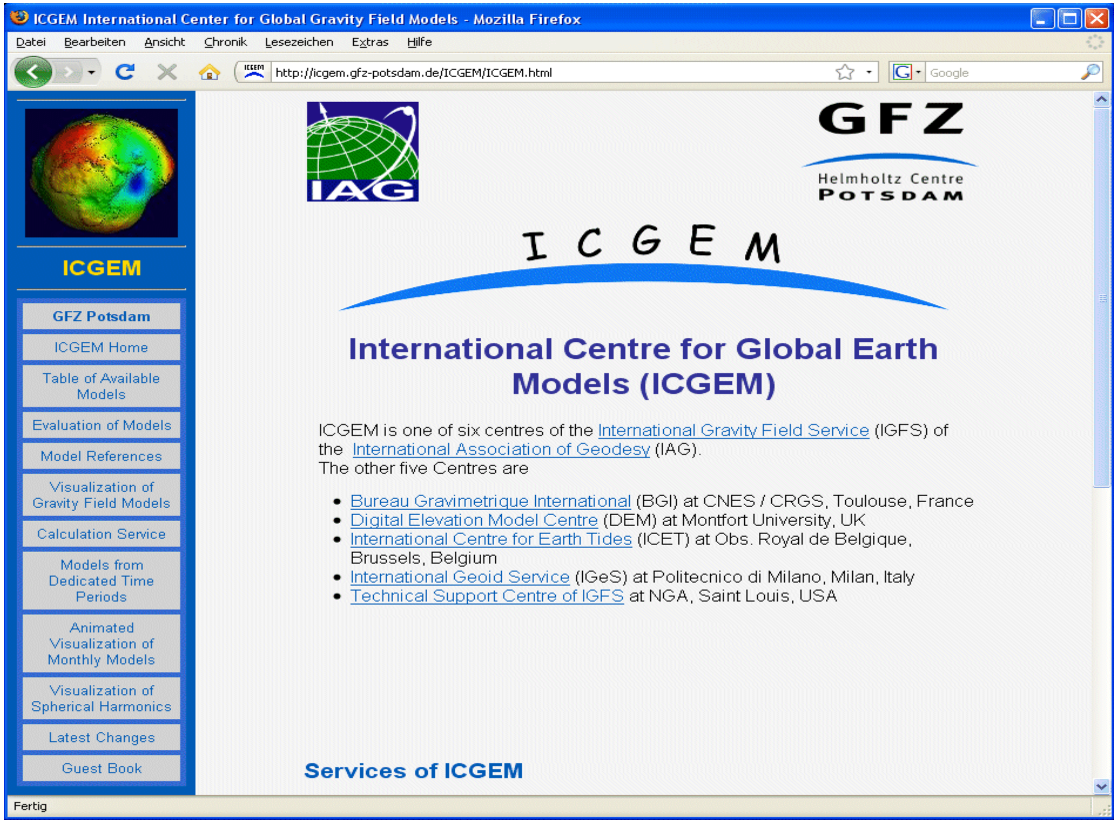
Level-3 Products: GIA

- Modelled and unmodelled mass changes
  - reduction of mass signals superimposed to those of primary interest (such as hydrology) using appropriate model predictions (e.g. AOD, ocean tides etc.)
  - A-posteriori correction of unmodelled signals such as glacial isostatic adjustment in presently or formerly glaciated regions (global model: ICE5G(VM2))



Level-3 Products Dissemination

- Level-2 Products from WP2, 4 and 5 can be disseminated via GFZ´s ICGEM
- Level-3 Product I/F needs to be developed, e.g. via GFZ´s ISDC



Task 4.3
External Validation

Presenter: Matthias Weigelt / Frank Flechtner
Affiliation: UBERN

External solutions (level 2 comparison)

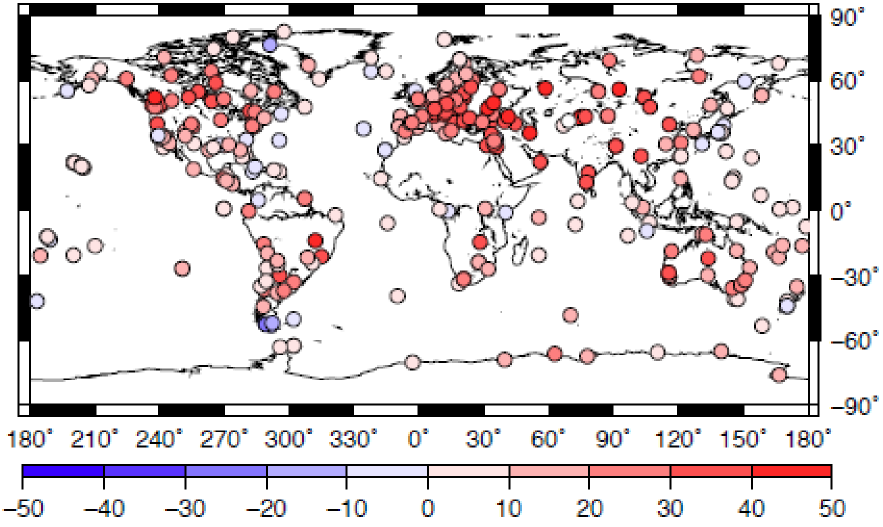
- Comparison with independent solutions (global and regional)
- Standard tools:

Class	Measure
Orbit	Orbit residuals
Spectral	Degree RMS (including spread of solution)
	Cumulative geoid errors
	Signal-to-noise ratio
Spatial	Global and basin RMS
	Latitude and longitude dependent RMS
Time series	Equivalent water height
	Total water storage change
	Gravity-based loading

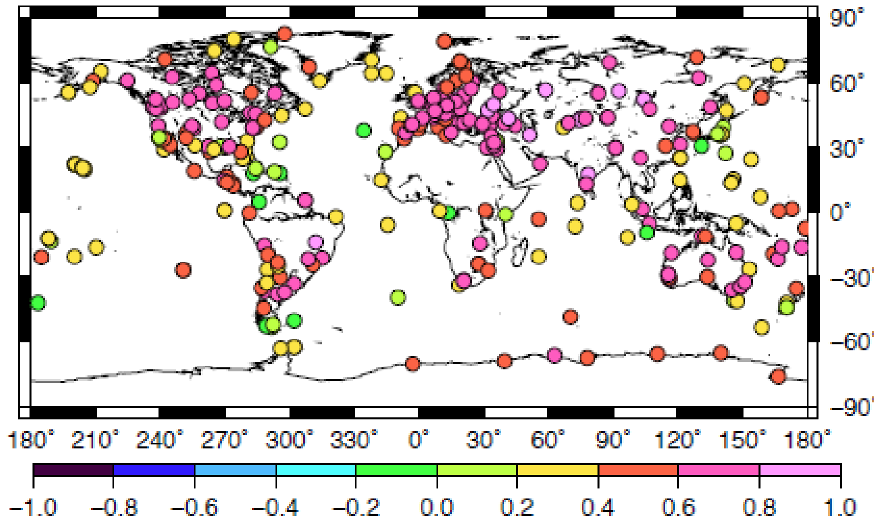
GNSS loading (level 2 comparison)

- GPS displacements for 250 stations from T3.3
  + other data sources (IGS, UNR, ...)
- Pre-processing (e.g. AOD product, averaging, filtering, leakage correction, detrending ...)
- Conversion SH to displacements (Kusche and Schrama, 2005)

Reduction in %



Correlation



Hydrological models (level 3 comparison)

- Comparison with existing and upcoming hydrological models
- Pre-processing and filtering of models to ensure (spectral) comparability
- Data sources (excerpt):
  - GLDAS
  - WGHM
  - NCEP
  - MERRA
- Possibly extension (at a later stage) to hydro-meteorological comparisons using moisture flux divergences: SLA with GI Stuttgart and KIT ?

Error budgeting

- What is error budgeting?
  1. attempt to assign errors to sources
  2. initialization of a (simple) indicator for quality
- How to do #2?
  - usage of all comparison results
  - normalization (best and worst solution form limits)
  - weighted mean (possibly application dependent)
- Challenge:
  no experience on method and acceptance