Generation and Comparison of Combined Global Gravity Field Models

Christoph Förste[1], Franz Barthelmes[1] and Richard Biancale[2]

[1]Deutsches GeoForschungsZentrum (GFZ)
Department 1 Geodesy and Remote Sensing
Telegrafenberg, D-14473 Potsdam, Germany

[2]Groupe de Recherche de Geodesie Spatiale
18, avenue Edouard Belin
F-31055 Toulouse, France

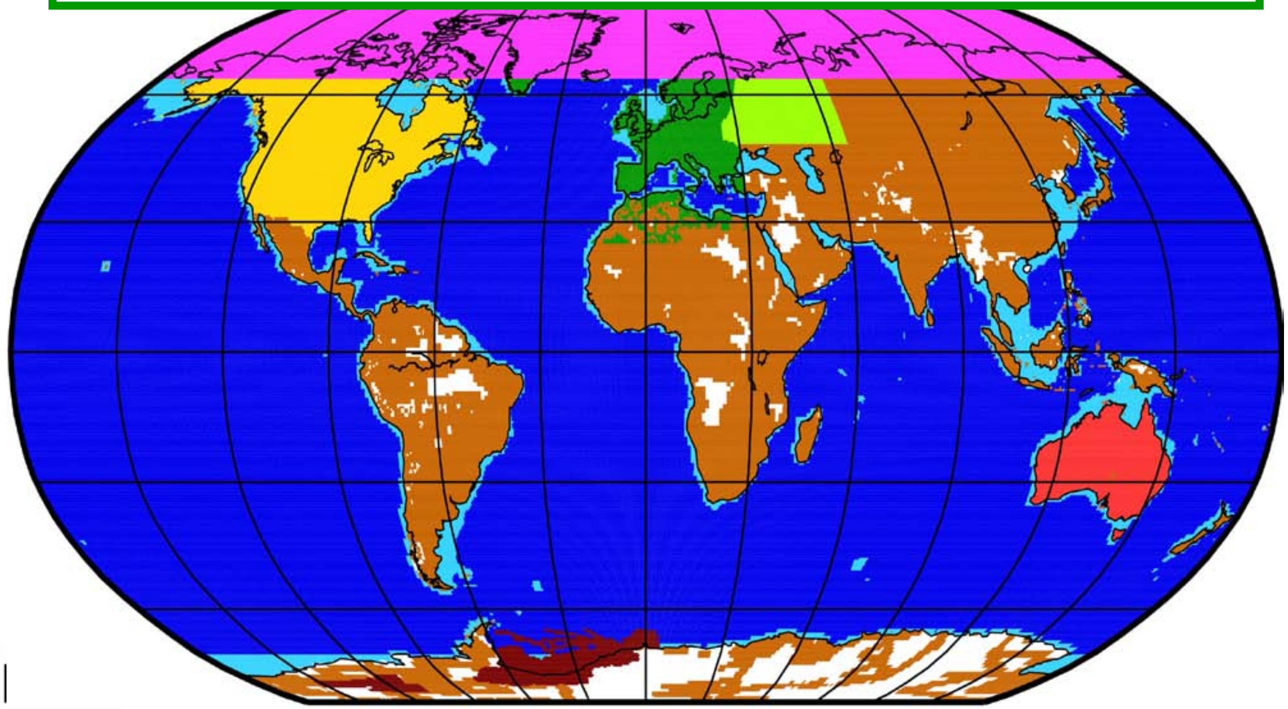
1. **Combination of terestrial and satellite data**
2. **Evaluation of combined gravity field models**
3. **Calibration aspects**
4. **Exchange data formats**

Computation of combined gravity field models

Global high-resolution gravity field models can be derived from the combination of satellite data and surface gravity data.
At GFZ Potsdam and GRGS Toulouse, such global gravity models are routinely produced in the framework of the EIGEN* processing activities. The combination of the different data sets is made on the basis of normal equations.

* EIGEN = European Improved Gravity model of the Earth by New techniques (i.e. since the launch of the CHAMP misson)

Patchwork of the presently at GFZ used ground data sets



Combined satellite data:

- GRACE
- LAGEOS
- CHAMP

- **In the future: GOCE**

Computation of combined gravity field models

Basic weighting principle:

The **relative weighting** for the combination of data from different satellites (for instance GRACE and LAGEOS) from different analysis centers (GFZ & GRGS) is done in accordance to their individually obtained variances and different data amounts.

The relative weighting for the combination of the different ground data sets among each others is done in accordance to the individually given standard deviations

The main questions concerning the accuracy of the combination of terrestrial and satellite data:

- The formal variances of the spherical harmonic coefficients from the satellite data are usually too optimistic → we don‘t apply a rigorous variance component estimation
- The errors of the different wavelenght components are degree-dependent

Combination scheme of EIGEN-5C

<u>contribution to the solution</u>, full normal matrix:

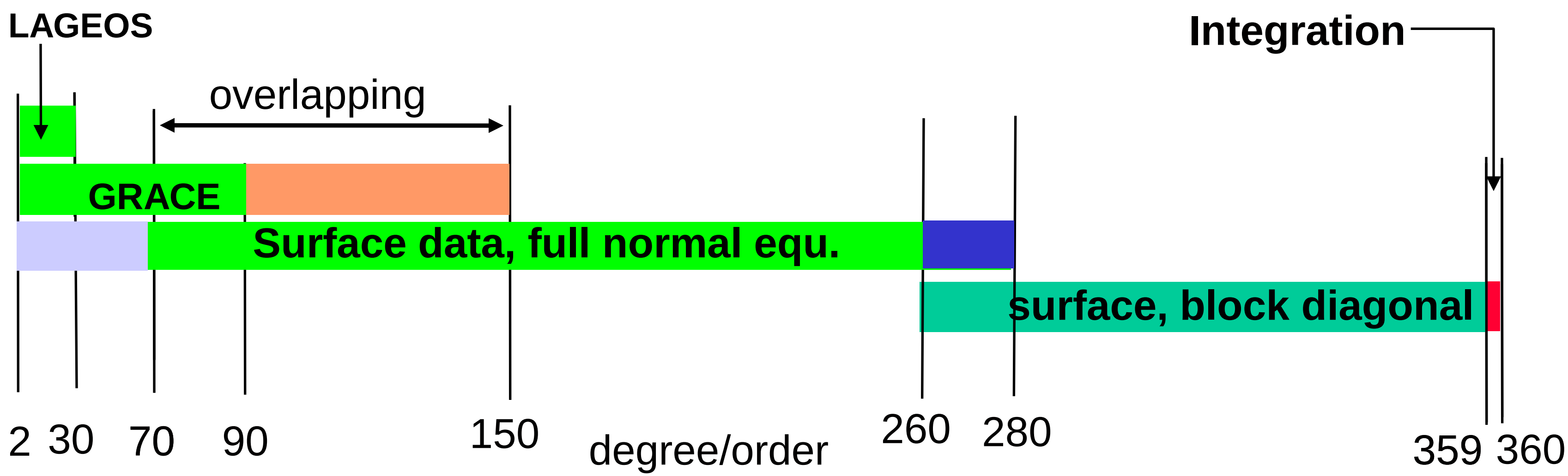
kept separately and bound together with the surface data using constraints):**

kept separately (reduced from the full normal matrix):

not used (low-pass filtered in order to avoid truncation errors) :

<u>contribution to the solution</u>, block diagonal matrix:

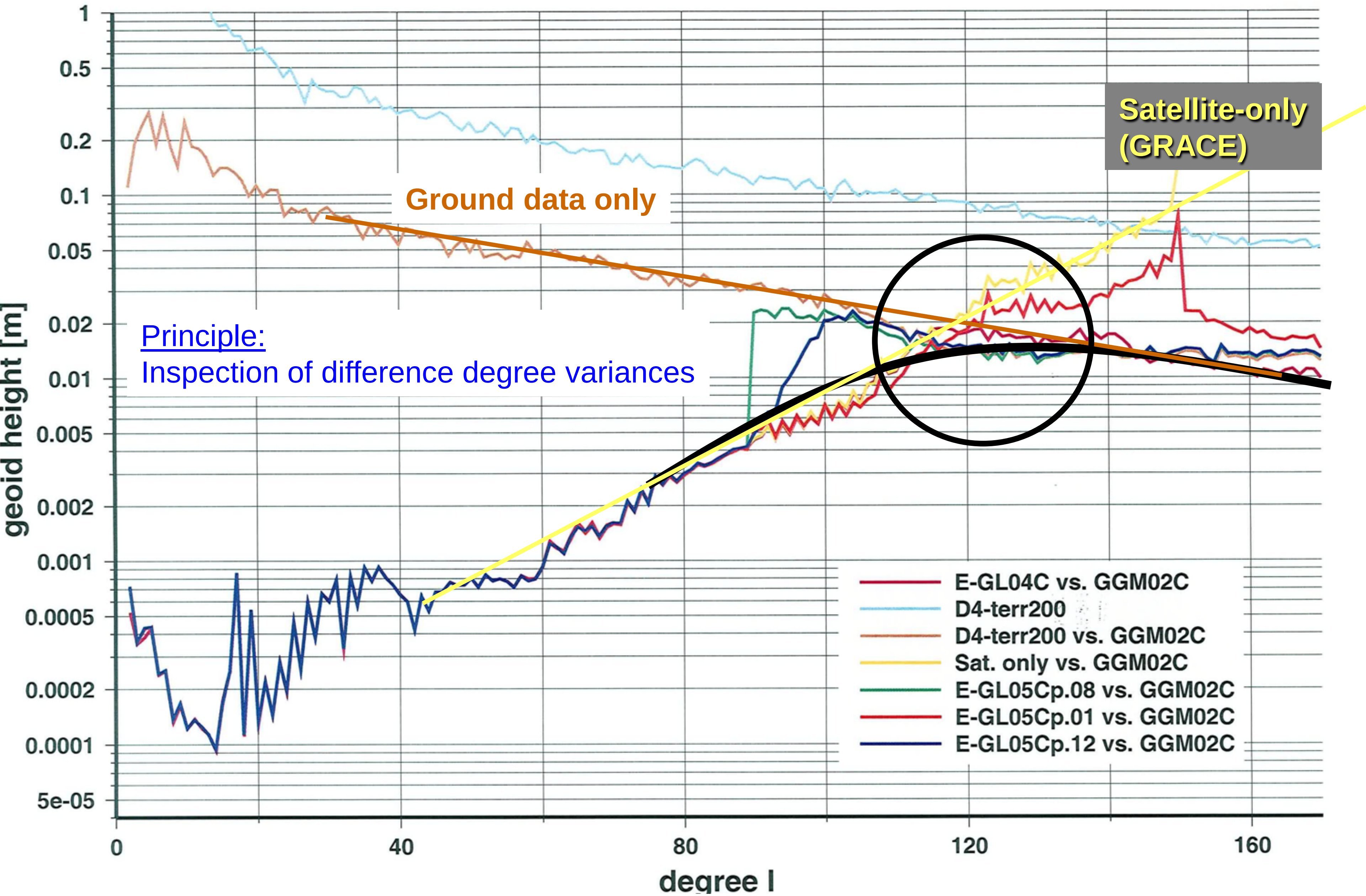
<u>contribution to the solution</u>, numerical integration:



**) constraints (pseudo observations), applied between degree 90 and 150:

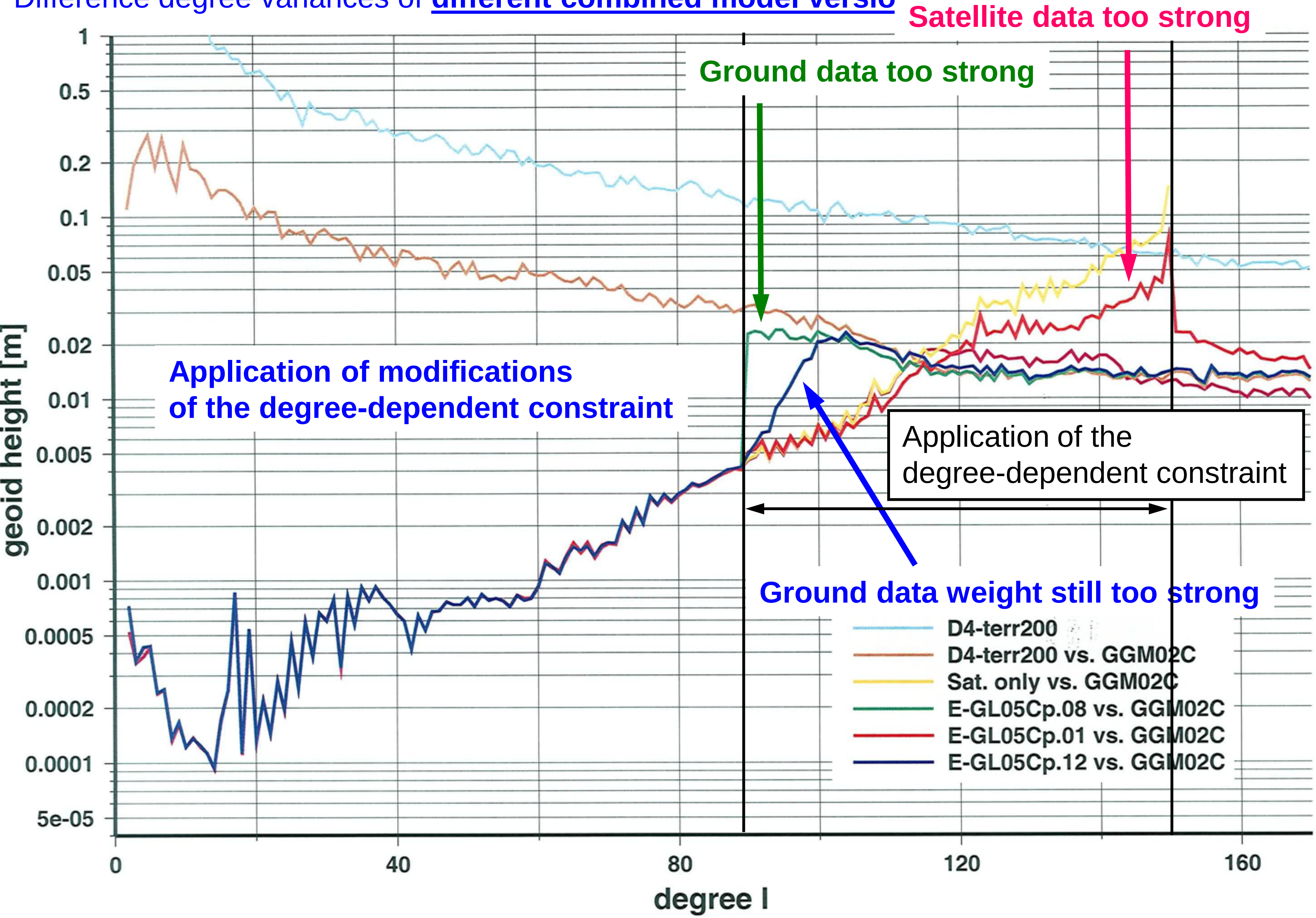
$$C/S_{n,m,\text{Surface}} - C/S_{n,m,\text{GRACE}} + \text{LAG.} = 0 \pm \sigma \qquad \sigma = 0.8696 \cdot 10^{-10} \cdot e^{\frac{l-90}{11.8}}$$

Combination algorithm in the overlapping range – an example

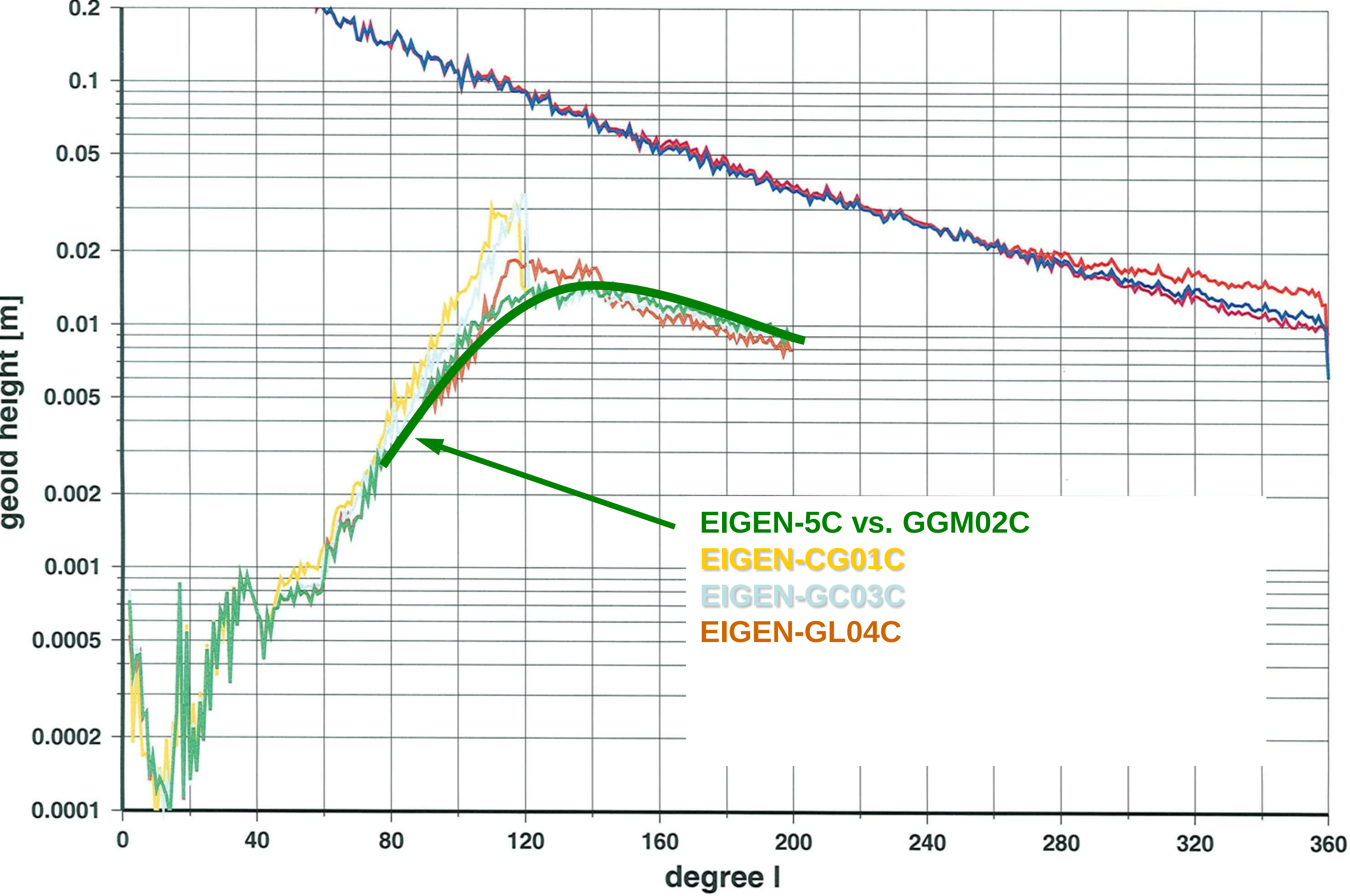


Difference degree variances of **satellite-only, terrestrial and combined models** with GGM02C

Difference degree variances of **different combined model versio**



Combination principle in the overlapping range – an example



Geoid Degree Amplitudes

Evaluation aspects

Evaluation – the proof for the quality of the combined models

Present evaluation methods at GFZ:

- Orbit fits with LEO satellites (which are sensitive till d/o 150): CHAMP,GRACE,GFZ-1
  technique:
  different max d/o, all other parameters fixed
  CHAMP/GRACE: fit to SLR data, which are not used for the orbit computation

- comparison with GPS/Leveling data sets

„Good“ combination → improved orbit fits (at least no degradation)
for the combined vs. the corresponding satellite-only models

Example: PGM2007A (= Beta-version of EGM2008)

GPS/Levelling test for recent global gravity field models

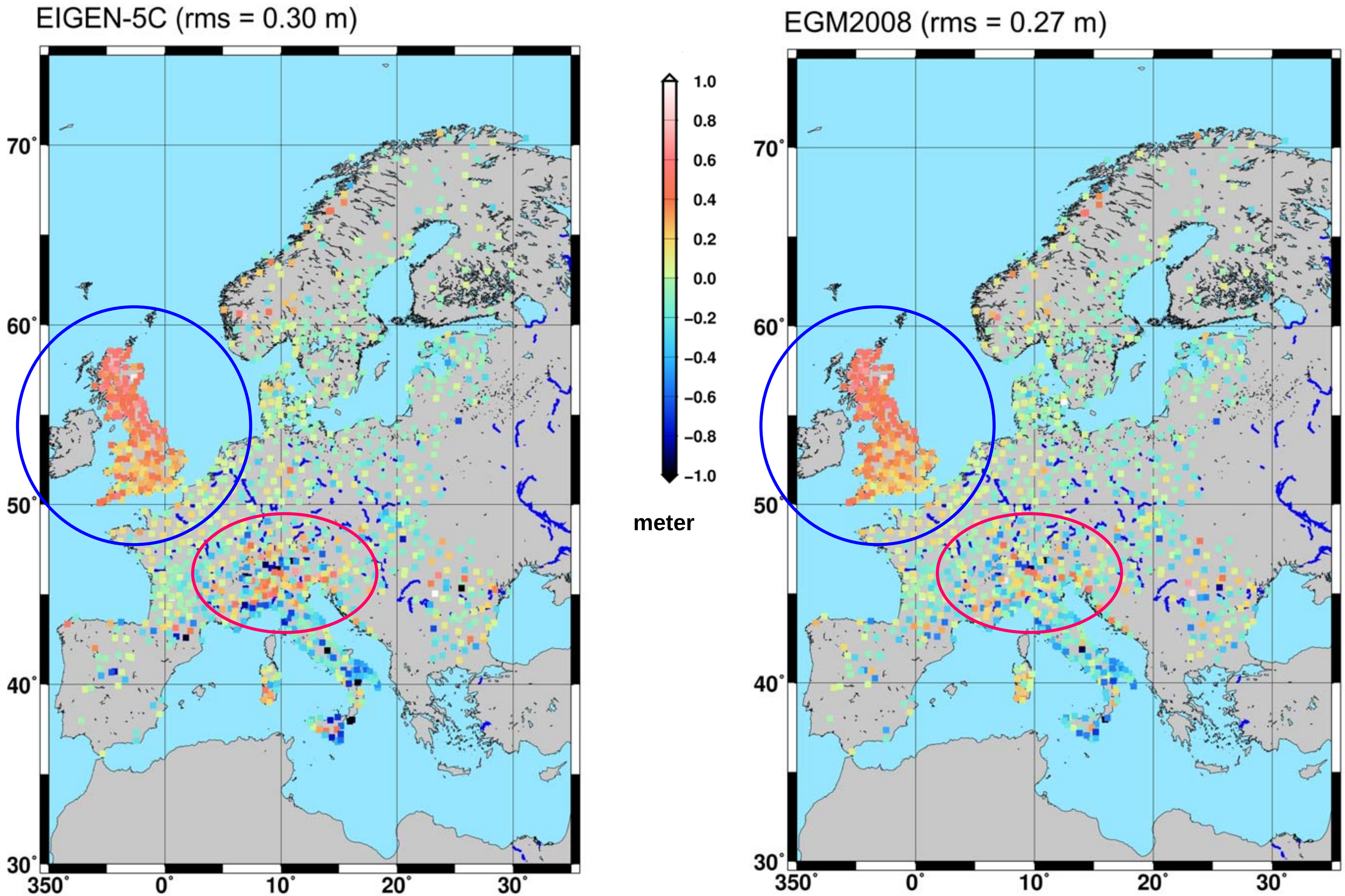
Comparison with geoid heights determined point-wise by GPS positioning and levelling:

- Root mean square (**cm**) about mean of GPS-Levelling minus model-derived geoid heights (number of points in brackets).

	GGM02C	GGM03C	EIGEN-5C	EIGEN-51p41	PGM2007A (till d/o 360)	EGM2008 (till d/o 360)
Europe (1234)	32.3	33.4	30.2	28.8	26.8	27.0
Germany (675)	16.5	19.0	15.2	14.8	14.3	14.3
Canada (1930)	25.9	27.6	25.1	24.4	23.3	23.0
USA (6169)	33.1	34.5	33.9	33.3	31.8	32.0
Australia (201)	24.8	25.8	24.3	23.3	23.7	23.7

EIGEN-51p41 = 6 years GRACE + 6 years CHAMP + DNSC08

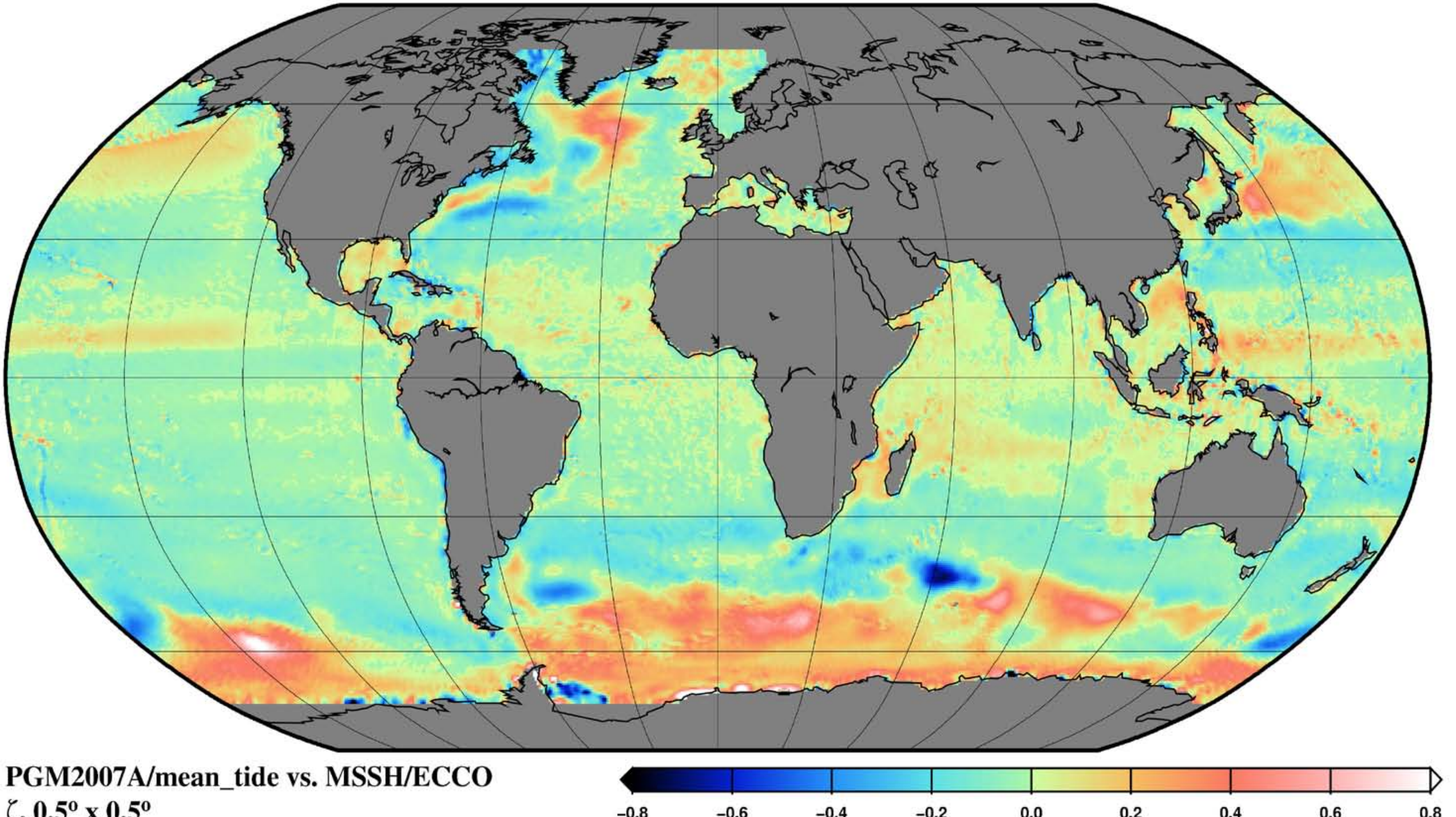
Example: GPS/Lev. vs. EIGEN-5C and EGM2008 resp. PGM2007A / Europa



GFZ
Helmholtz Centre
POTSDAM

Testing for meridional stripes

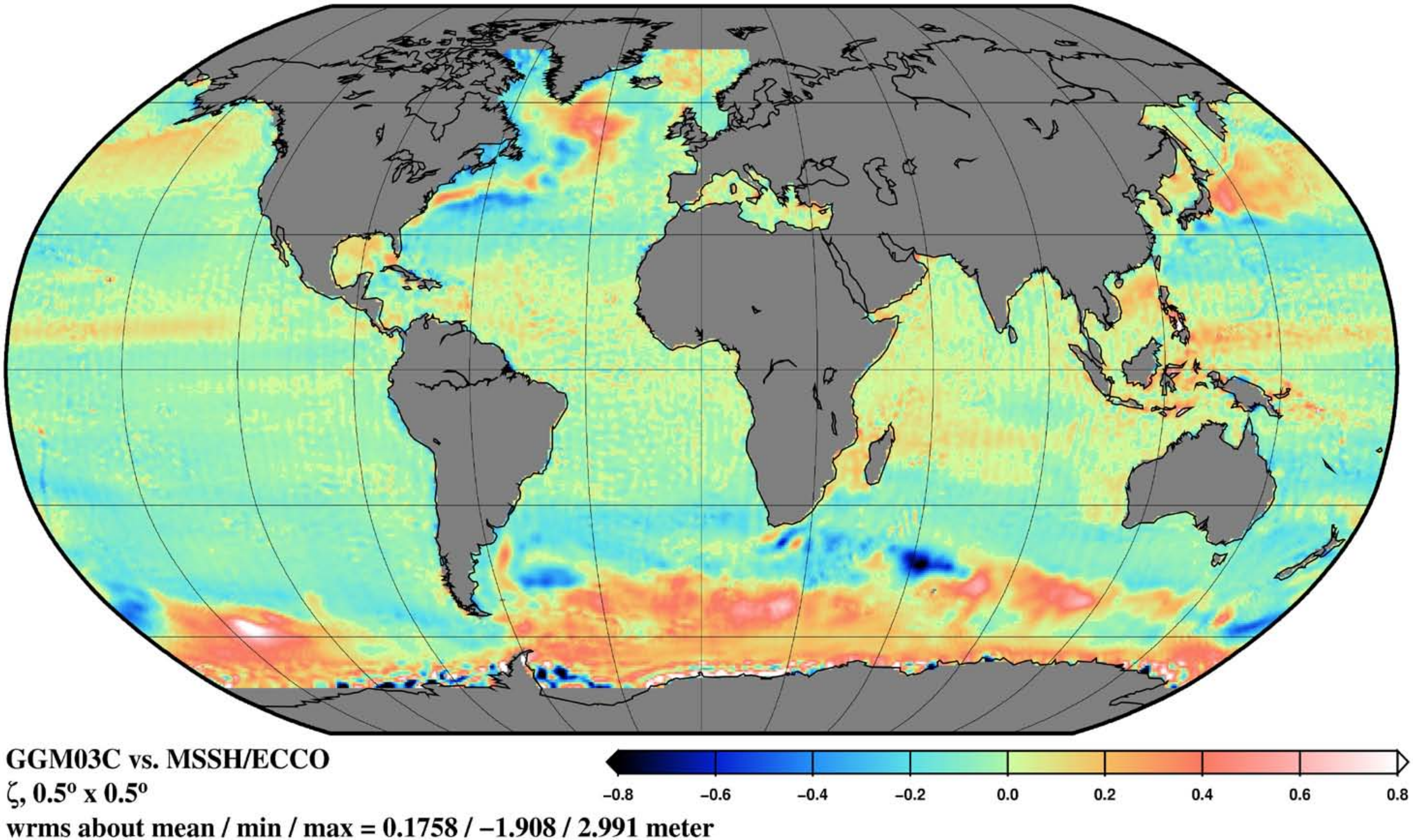
PGM2007A – (MSSH(GFZ) - DOT (ECCO))



PGM2007A/mean_tide vs. MSSH/ECCO
ζ, 0.5° x 0.5°
wrms about mean / min / max = 0.1787 / –2.186 / 3.79 meter

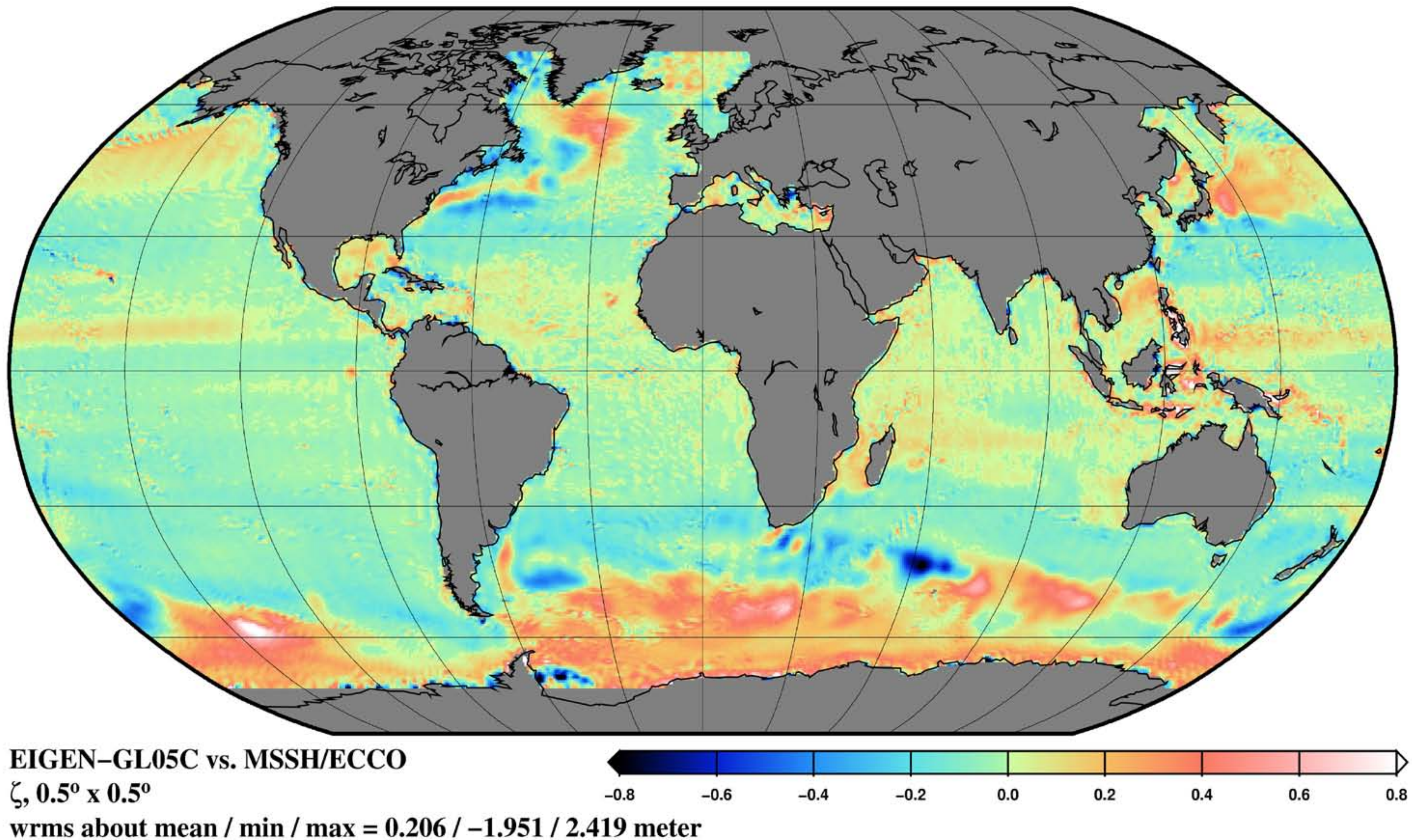
Testing for meridional stripes

GGM03C – (MSSH(GFZ) - DOT (ECCO))



Testing for meridional stripes

EIGEN-5C – (MSSH(GFZ) - DOT (ECCO))



Orbit adjustment tests: CHAMP and GRACE

SLR residuals (cm) after an orbit determination based on GPS (CHAMP, GRACE) and K-Band Range-Rate (GRACE) data
The SLR data were not included for the orbit adjustment!
Data: **three 1.5 day arcs** per satellite,
Included SLR normal points: GRACE: **592** CHAMP: **358**

Satellite	truncation	GGM02C	EIGEN-GL04C	EIGEN-GL05S	EIGEN-GL05Cp.24	PGM2007A	JEM1-RL03B	ITG-GRACE03S
CHAMP	120 x 120	5.32	5.44	5.47	5.48	8.05	5.35	5.38
	150 x 150	5.19	5.41	5.42	5.39	7.85	------	5.30
GRACE	120 x 120	5.50	5.25	5.14	5.11	6.21	5.55	5.39
	150 x 150	5.54	5.24	5.18	5.10	6.22	-----	5.38

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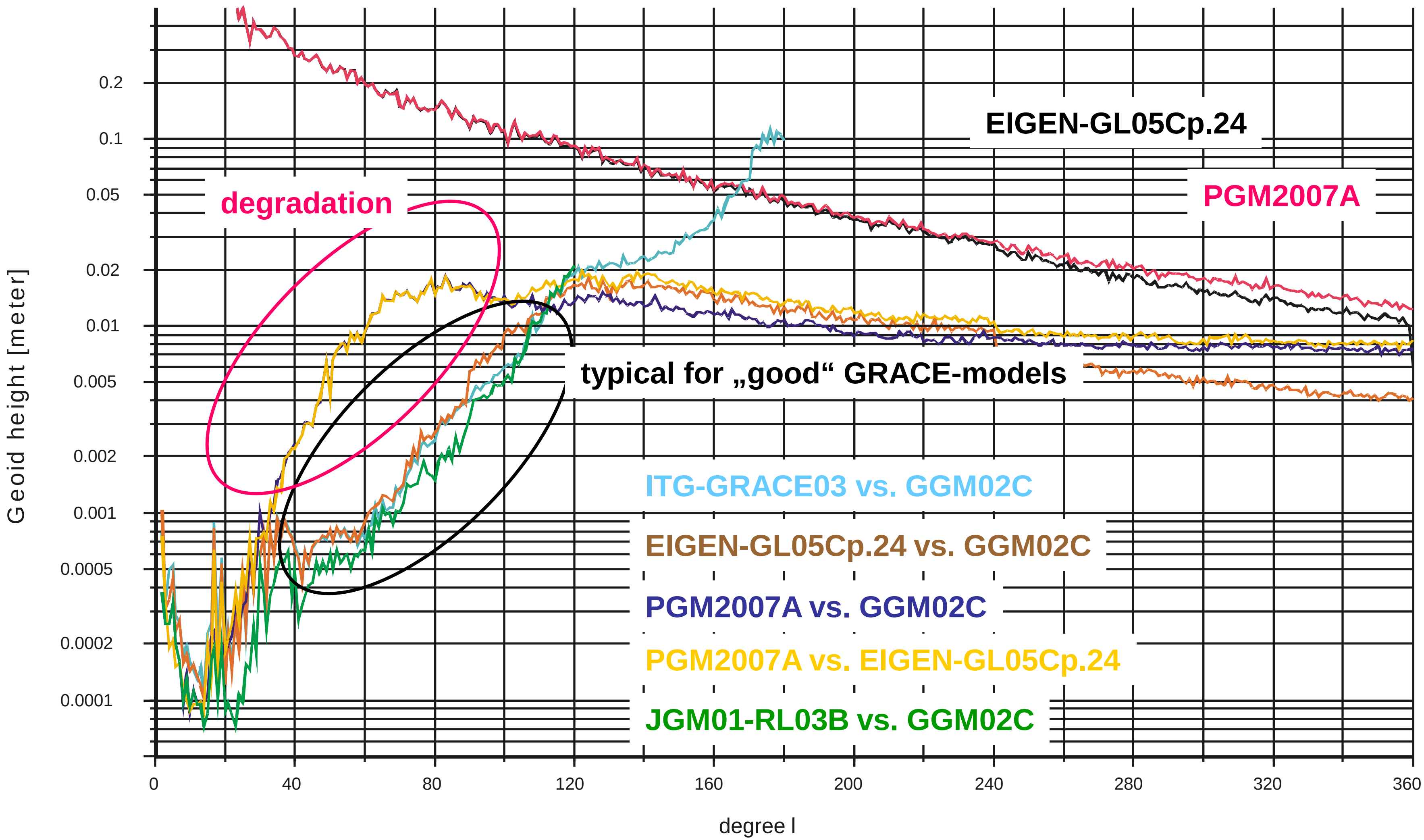
Comparison: PGM2007A and other Gravity Field models

Comparison of degree variances



Orbit adjustment tests: CHAMP and GRACE

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Data: **three 1.5 day arcs** per satellite,
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Satellite	max. degree used	GGM02C	GGM03S	JEM1-RL03B	EIGEN-GL04C	EIGEN-5S	EIGEN-5C	ITG-GRACE03S	EGM2008
CHAMP	70	17.62	16.71	19.66	17.94	17.68	17.86	15.97	16.74
	80	9.39	9.51	9.48	9.50	9.66	9.69	8.69	9.34
	90	6.12	6.10	6.15	6.12	6.14	6.14	5.96	6.02
	100	5.89	5.96	5.95	5.97	6.01	6.03	5.58	5.97
	110	5.48	5.53	5.51	5.61	5.60	5.59	5.39	5.57
	120	5.32	5.45	5.35	5.44	5.55	5.51	5.38	5.51
	150	5.19	5.44	--	5.41	5.56	5.49	5.30	5.46
GRACE	70	14.11	15.00	14.03	14.93	14.92	14.93	16.06	15.49
	80	7.39	6.54	7.35	6.51	6.43	6.44	8.24	7.27
	90	5.76	5.05	5.75	5.03	4.92	4.93	6.30	5.57
	100	5.40	5.20	5.41	5.20	5.09	5.09	6.12	5.54
	110	5.61	5.31	5.64	5.31	5.20	5.19	5.84	5.45
	120	5.50	5.28	5.55	5.25	5.17	5.15	5.39	5.46
	150	5.54	5.27	--	5.24	5.19	5.14	5.38	5.43

Calibration aspects

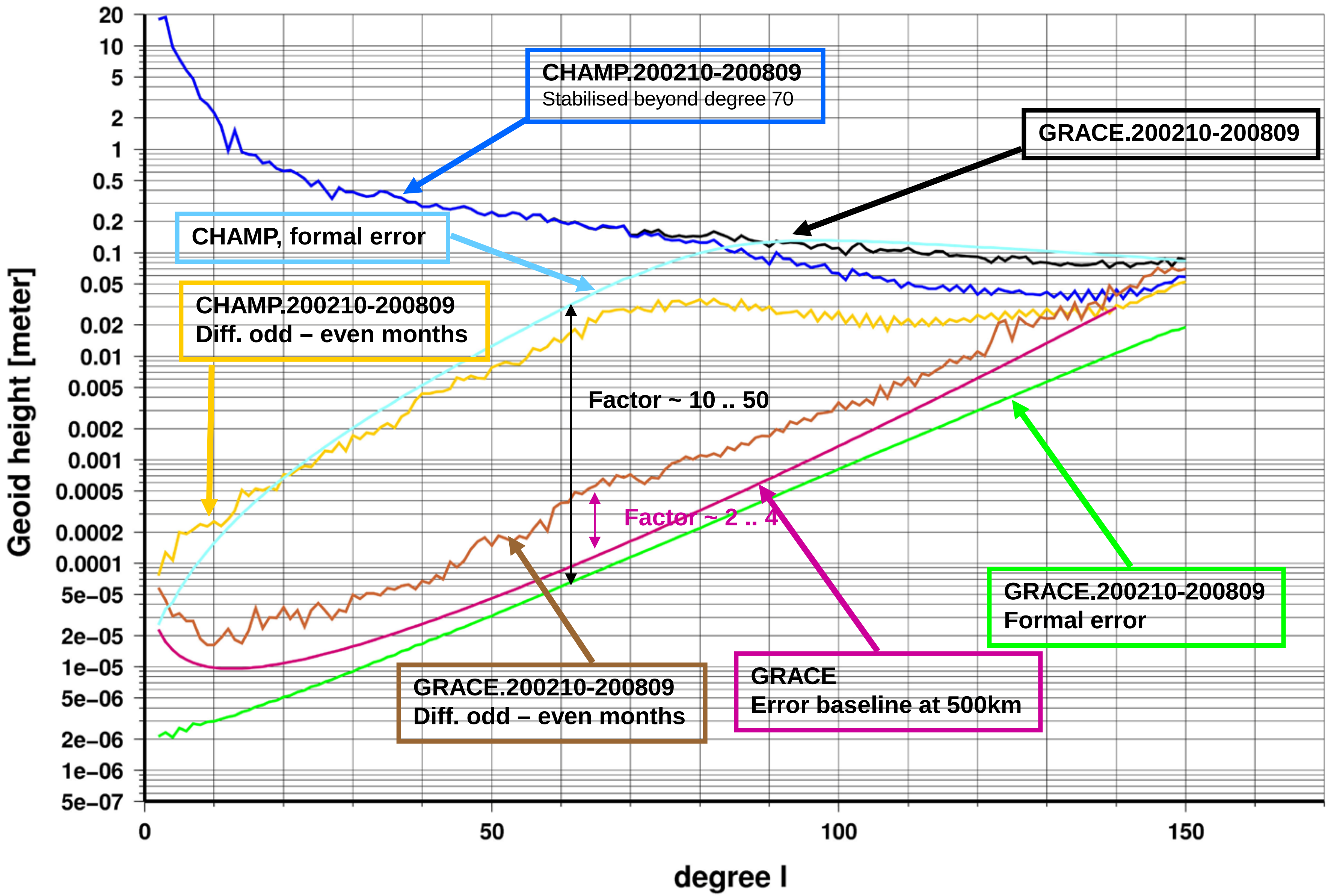
<u>Calibration of the standard deviations:</u>
- the formal errors are usually too optimistic and must be scaled to be physically realistic

The present main calibration method at GFZ:
- Intercomparison of partial solutions

- Example: CHAMP & GRACE – 6 years – odd minus even months

<u>Other calibration methods (presently not used at GFZ):</u>
Comparison of the predicted radial orbit error (from the var/cov matrix) with altimetry crossover errors (Rosborough 1986 & Klokocnic et al. 1990)

Spectral behaviour of the 200210-200809 accumulated solutions for CHAMP and GRACE



Exchange data formats:

1. TOTSOL-format for normal equations

2. ICGEM-format for global gravity field models

3. VCM-format for variance/covariance matrices
   of global gravity field models

Exchance data formats: 1) Normal equation exchange format (TOTSOL-format)

ASCII, fixed format

☛ Standard exchange format i.e. between GFZ and GRGS/Toulouse

☛ This format is not restricted on gravity field models

- Header:
  general and statistical information
  signaletic elemenents
  apriori values of the solve-for parameters
- Body: lower triangel of the A^{T}pA-matrix & right hand side

```
HEADER
COMMNT - rhubarb, rhubarb
CODE  FORMATTED
EARTHC 0.39860044150000E+15 0.63781364600000E+07 0.29825765000001E+03 0.72921150000000E-04
STATIG    460355     26233       372 0.10889065226105D+07

STATIS 0201201 GRA1      KBRRATE  090131 090201    16253 24115 0.2500000000E-06 0.10000000000000E+01 0.41032594652823E+05
NORMAL
     26233
GCN   0   0 20000101 GRA1GCN   1  0 20000101 GRA1GCN   2  0 2000(      4  0 20000101 GRA1
………..
OCN +255.555   5  1 LAG1OSN +2          +255.555   6  1 LAG1OSN +255.555   6  1 LAG1OCN +255.555   2  2 LAG1
OSN +255.555   2  2 LAG1OCN +2          +255.555   3  2 LAG1OCN +255.555   4  2 LAG1OSN +255.555   4  2 LAG1
…………
PX V     1999120212     PY V     1999120212     PDLV     19              )312     PY V     1999120312
PY V     1999120512     PDLV     1999120512 LAG1SXB                           99 SZB                     99
……..
SXC                    99 SXS                     99                          99 SZC                     99
SZ V7839340211001S00299DSX V7811380212205S00199              311380212205S00199DSX V1868590112341S00199D

0.10000000000000D+010.00000000000000D+00-.48416527400000D-030.95718563400000D-060.53997339500000D-060.68683616000000D-07
-.14995366200000D-060.90516280100000D-070.49483336000000D-070.28014158500000D-070.53327772400000D-07-.50770187500000D-07
……………
0.61183942817560D+21
0.14491432988796D+210.20654021228129D+21
0.53549149141957D+20-.23482996319949D+200.33835346572466D+22
-.77694265314778D+200.13760171083179D+20-.60196659762333D+210.50578695403614D+22
-.98442184925948D+20-.31944258721490D+200.76806293391813D+21-.30587959643722D+210.78816286934427D+21
0.17827034532001D+200.34028346817761D+19-.46547972256512D+210.19816775410155D+22-.28867558785194D+210.17468394847378D+22
-.33998872112611D+20-.61009282565431D+19-.10830108637616D+210.13534834802850D+210.11581968556411D+210.53905106650948D+20
0.10731459615498D+21
0.13256737235151D+200.30314234243475D+180.38504664038918D+19-.56673628070411D+21-.13172297504363D+200.48716639336816D+20
-.16332687036501D+200.14032930082926D+21
```

G = Spher. harm. coefficients

O = Ocean tides

P = Polar coordinates

S = Station parameters

Exchance data formats: 2) ICGEM format for spher. harm. coefficients data set

ASCII, free format, self-explanatory simple structure:
- header & body
- keyword + information

Standard format i.e. for
- ICGEM (IGFS)
- ESA-standard for GOCE products

comments

```
Reference:
The GGM03 Mean Earth Gravity Model from GRACEB. Tapley, J. Ries, S. Bettadpur, D. Chambers,
M. Cheng, F. Condi, S. PooleEos Trans. AGU 88(52), Fall Meet. Suppl., Abstract G42A-03,
2007.GGM03C is a combination of GRACE gravity information (from GGM03S) with landand ocean
gravity information, complete to degree and order 360. GGM03S wasdetermined from 47 months
of GRACE K-band intersatellite range-rate data, GPS tracking and GRACE accelerometer data
spanning the period from January 2003 through December 2006 (January 2004 excluded). The
terrestrial gravity informationwas a combination of the NIMA surface gravity anomalies, the
CSR mean sea surface (MSS95), and the Arctic Gravity Project (ArcGP) gravity anomalies.
GGM03Swas used to fill where no terrestrial gravity information was available.
```

header records

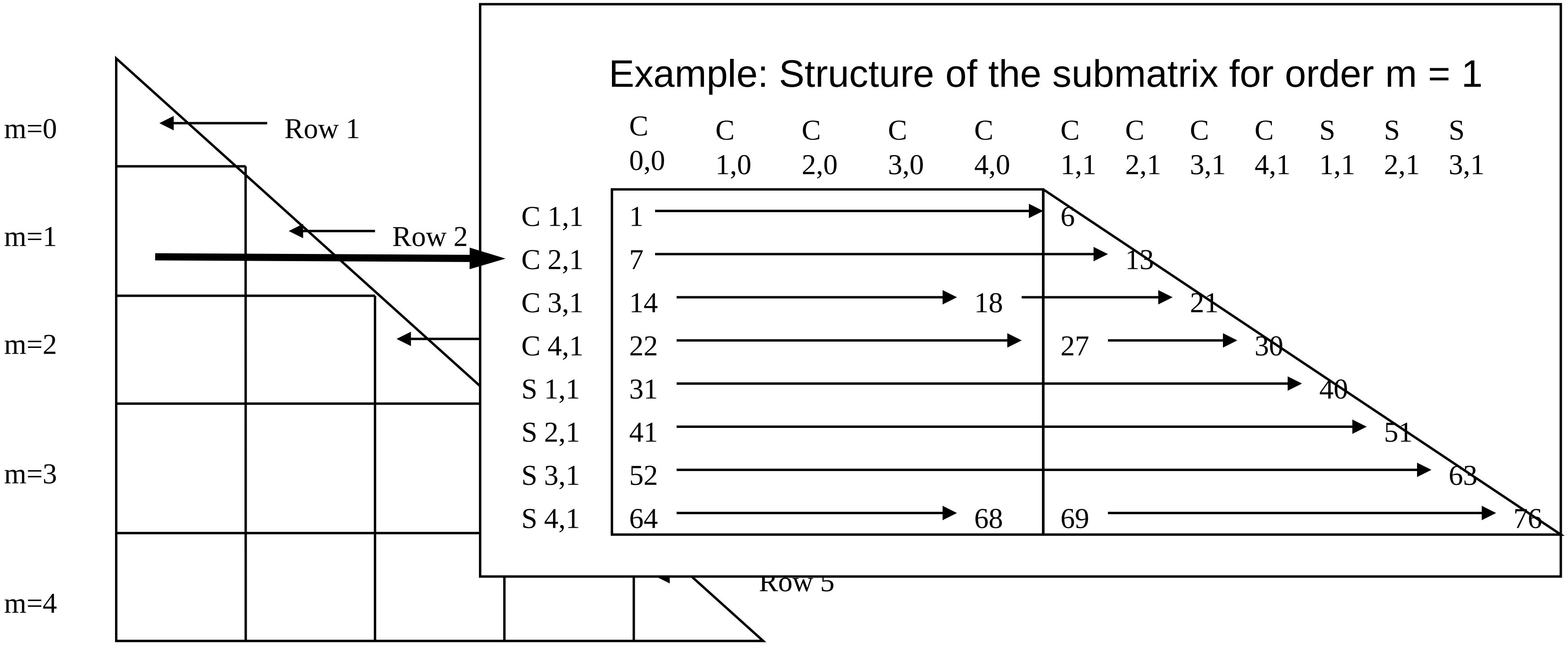
```
product_type                  gravity_field
modelname                     GGM03C
earth_gravity_constant        0.3986004415E+15
radius                        0.6378136300E+07
max_degree                    360
errors                        calibrated
norm                          fully_normalized
tide_system                   zero_tide
```

data records

```
key     L    M          C                   S                  sigma C      sigma S
end_of_head ==========================================================================
gfc     0    0  1.000000000000D+00  0.000000000000D+00  0.00000D+00  0.00000D+00
gfc     1    0  0.000000000000D+00  0.000000000000D+00  0.00000D+00  0.00000D+00
gfc     1    1  0.000000000000D+00  0.000000000000D+00  0.00000D+00  0.00000D+00
gfc     2    0 -4.841693259705D-04  0.000000000000D+00  4.68460D-11  0.00000D+00
gfc     2    1 -2.189810040712D-10  1.467451636117D-09  7.75160D-12  7.81670D-12
gfc     2    2  2.439349093502D-06 -1.400284857733D-06  7.80670D-12  7.80760D-12
```

Exchance data formats: 1) The VCM exchange format for spher. harm. coefficients

- ASCII, developed for large var/cov matrices (till d/o 250 or more)
- Storage of the lower triangle, distributed among several submatrices
- The spher. harm. coefficients are sorted by order
- One submatrix per order incl. one master meta file



ESA standard format for GOCE VCM products

Exchance data formats: 1) The VCM exchange format for spher. harm. Coefficients (2)

```
product_type                  variance-covariance matrix
modelname                     EXAMPLE-MODEL
earth_gravity_constant        0.3986004415E+15
radius                        0.6378136460E+07
max_degree                    4
errors                        formal
covariance_matrix_type        full
sequence_number_entries                   25
                                      C_000_000
                                                                C_001_000
                                                                C_002_000
                                                                C_003_000
                                                                C_004_000
                                                                C_001_001
                                                                C_002_001
                                                                C_003_001
                                                                C_004_001
                                      S_001_001
                                                                S_002_001
                                                                S_003_001
                                                                S_004_001
                                                                C_002_002
                                                                C_003_002
                                                                C_004_002
                                                                S_002_002
                                                                S_003_002
                                                                S_004_002
                                                                C_003_003
                                                                C_004_003
                                                                S_003_003
                                                                S_004_003
                                                                C_004_004
                                                                S_004_004
sequence_number_files         5
                                                                data_file_000
                                                                data_file_001
                                                                data_file_002
                                                                data_file_003
                                                                data_file_004
```

Master meta file:

- the included parameters
- names of the submatrix file

```
meta_data_file_name           main_file
order                         1
number_entries                76
begin_data
-0.7657887654320E-09
…
…
…
…
…
…
+1.0567758766890E-14
end_data
```

Submatrix file

Thank you for your attention!