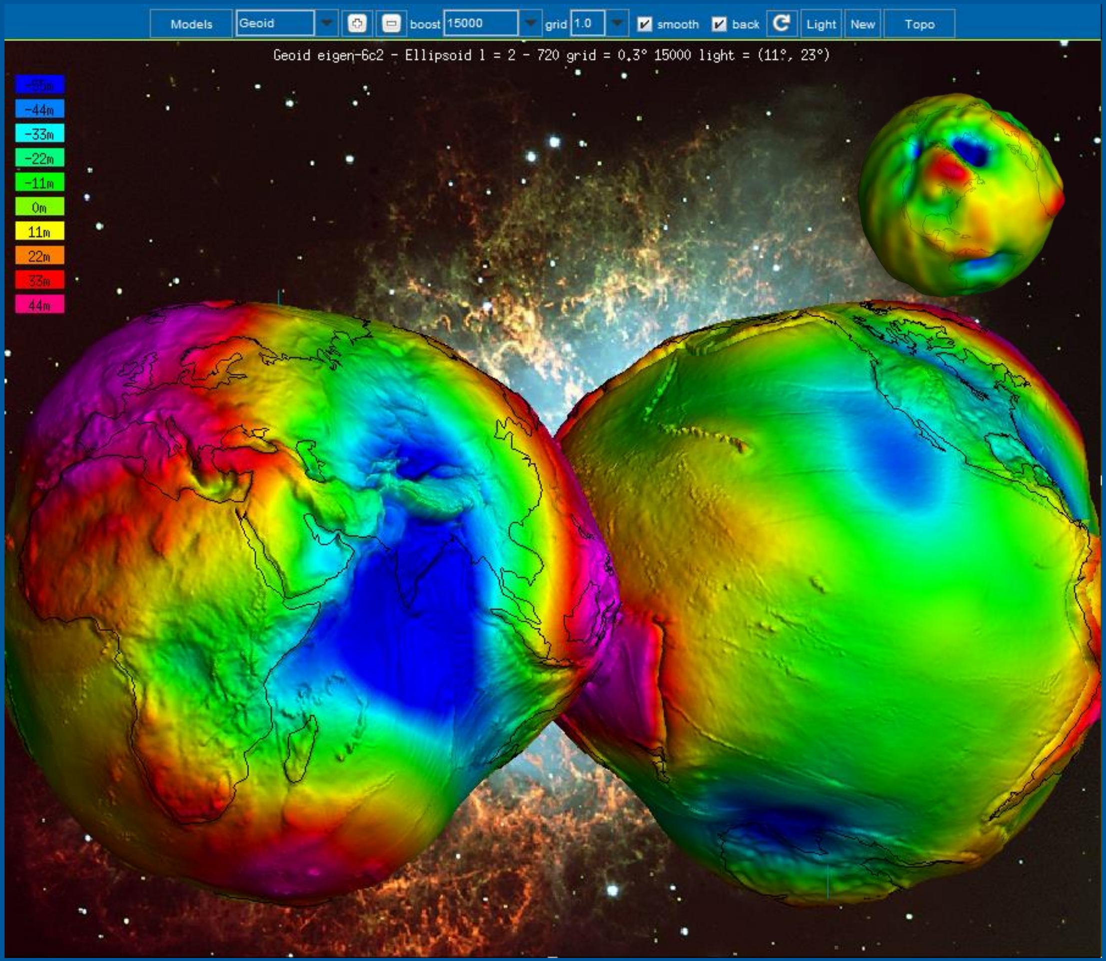
ICGEM

Global Gravity Field Models and the IAG Service ICGEM

(International Centre for Global Earth Models)



Franz Barthelmes

Wolfgang Köhler

GFZ German Research Centre
for Geosciences
Telegrafenberg
14473 Potsdam
Section 1.2

GFZ
Helmholtz Centre
Potsdam

HELMHOLTZ
ASSOCIATION

Global Gravity Field Models

Where are they come from?

Satellites + satellite altimetry + terrestrial gravimetry

Satellites → Gravity Field: What can we measure?

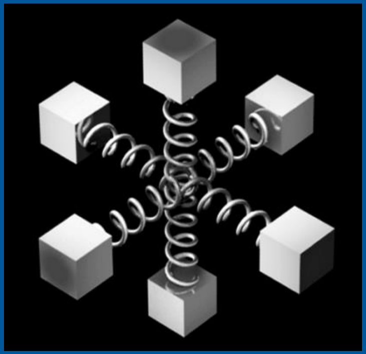
Global Gravity Field Models

Where are they come from?

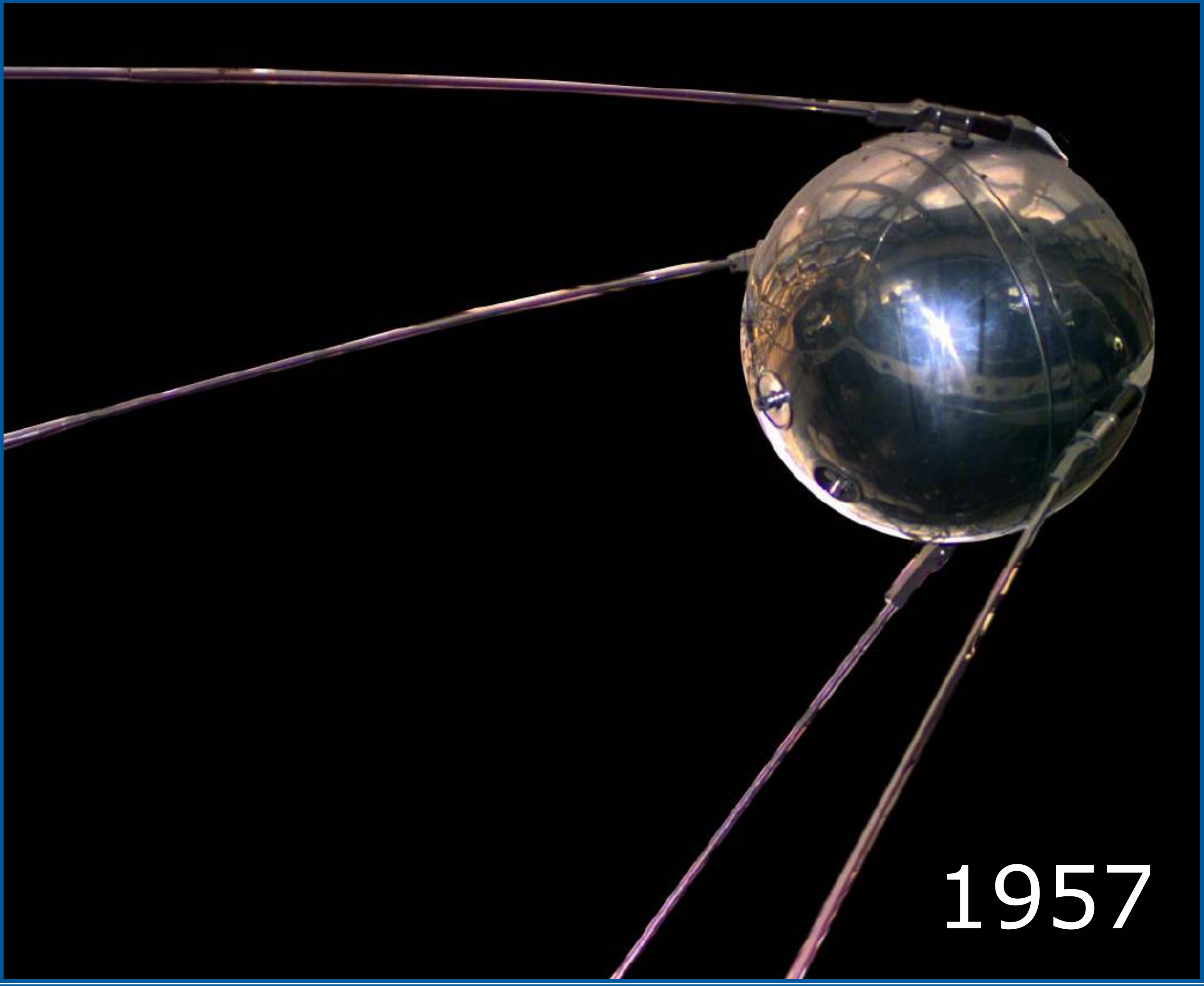
Satellites + satellite altimetry + terrestrial gravimetry

Satellites → Gravity Field: What can we measure?

acceleration differences inside the satellite
→ Gradiometry



The Beginning: Sputnik 1



The first Measurements

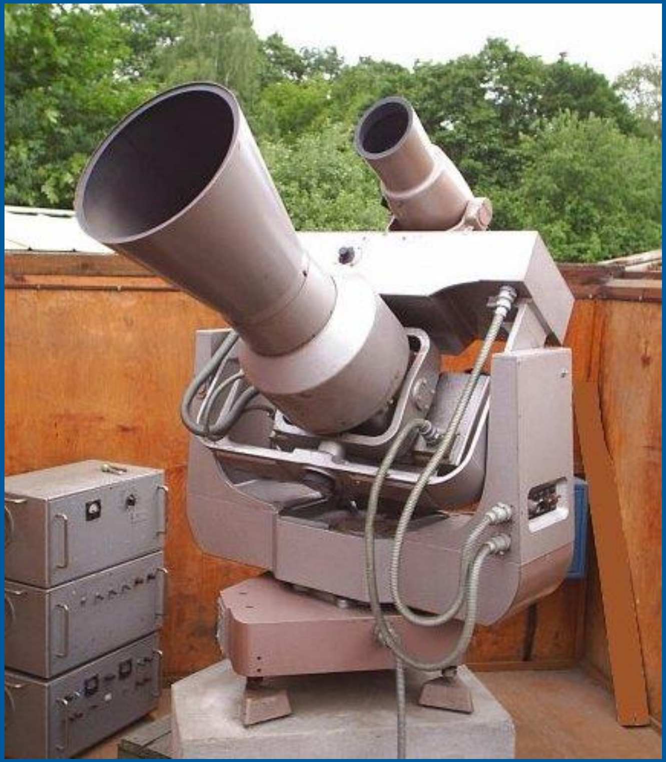
optical observation

Sputnik-observations in Potsdam

1957: Sputnik 2
→ oblateness
(Coefficient $C_{2,0}$
of sph. harm.)

Optical Satellite Tracking

Baker Nunn
(USA 1957)



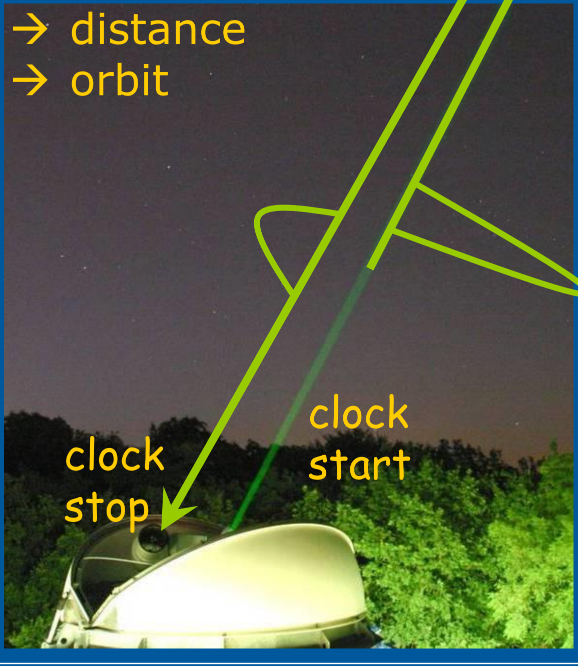
AFU-75
(USSR/Latvia 1967)

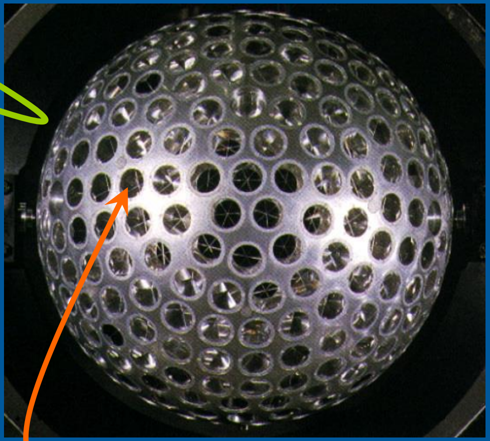
SBG
(Germany/Jena 1966)

Laser Ranging

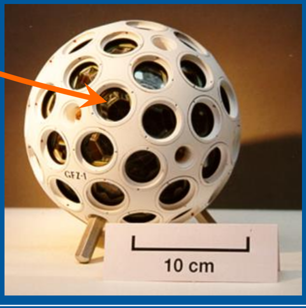
1975: Lageos-1
1975: Starlette
1995: Lageos-2
1995: GFZ-1

pulsed laser
photon detector
time measurement
→ distance
→ orbit

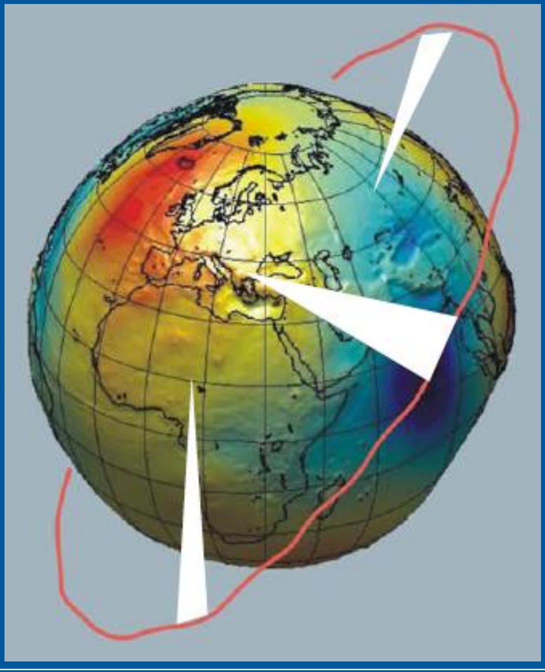




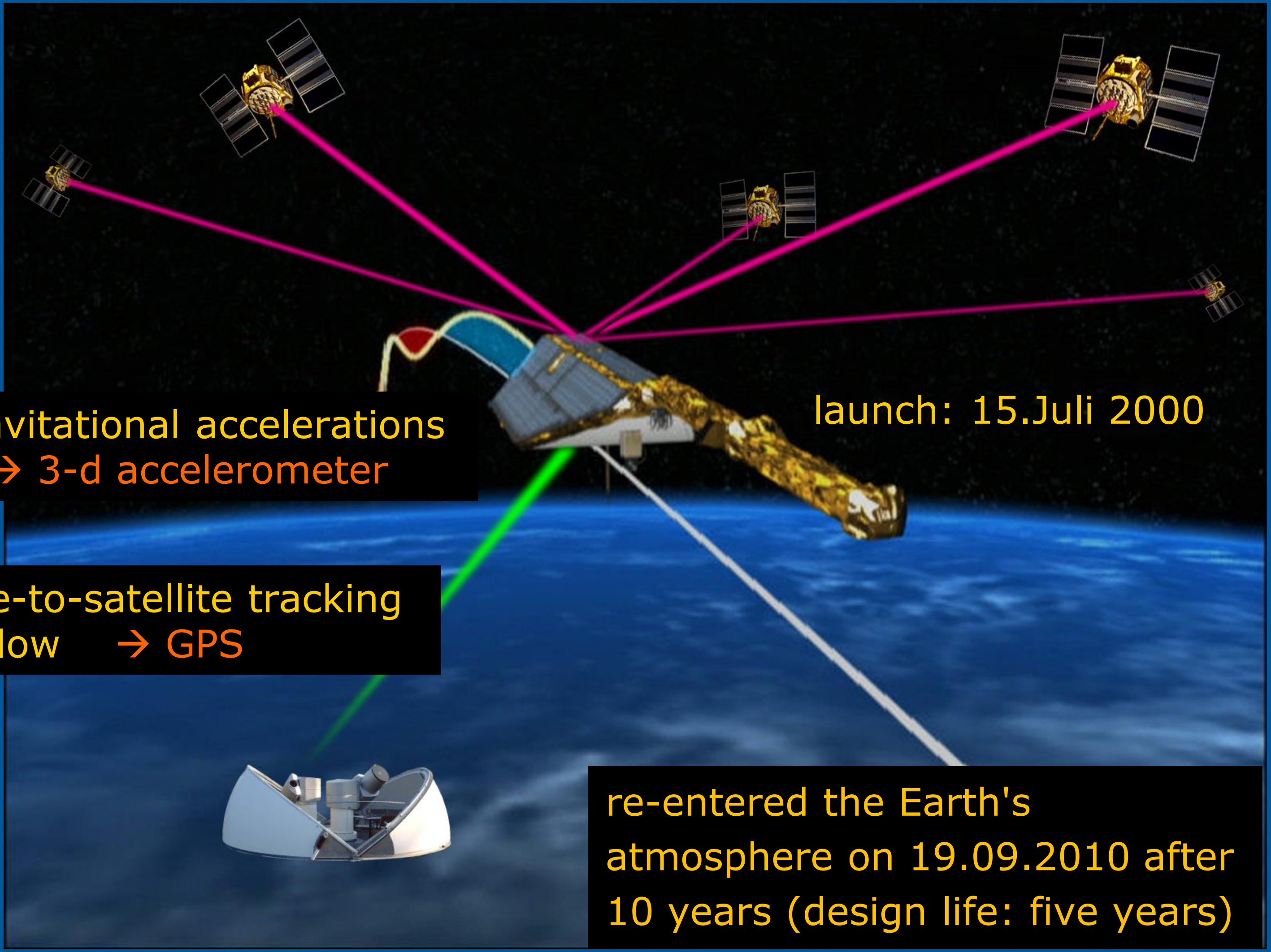
triple prism



parts of orbits



High–Low with GPS → CHAMP



non-gravitational accelerations
→ 3-d accelerometer

launch: 15.Juli 2000

satellite-to-satellite tracking
high – low → GPS

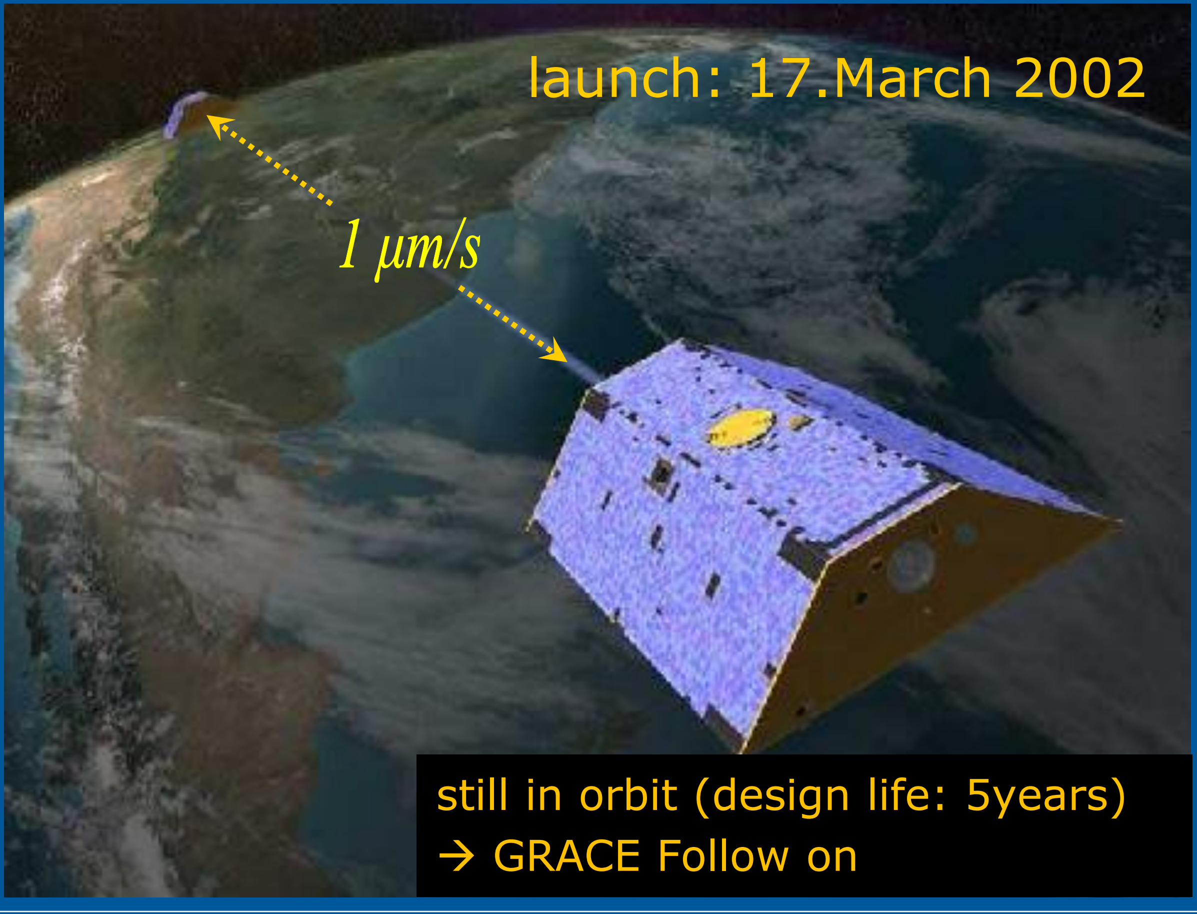
re-entered the Earth's atmosphere on 19.09.2010 after 10 years (design life: five years)

Heigh–Low + Low–Low → GRACE

GRACE: Gravity Recovery And Climate Experiment

satellite-to-satellite tracking
high – low → GPS
low – low → microwaves
K-band (1.13-1.67cm)

non-gravitational accelerations
→ 3-d accelerometer

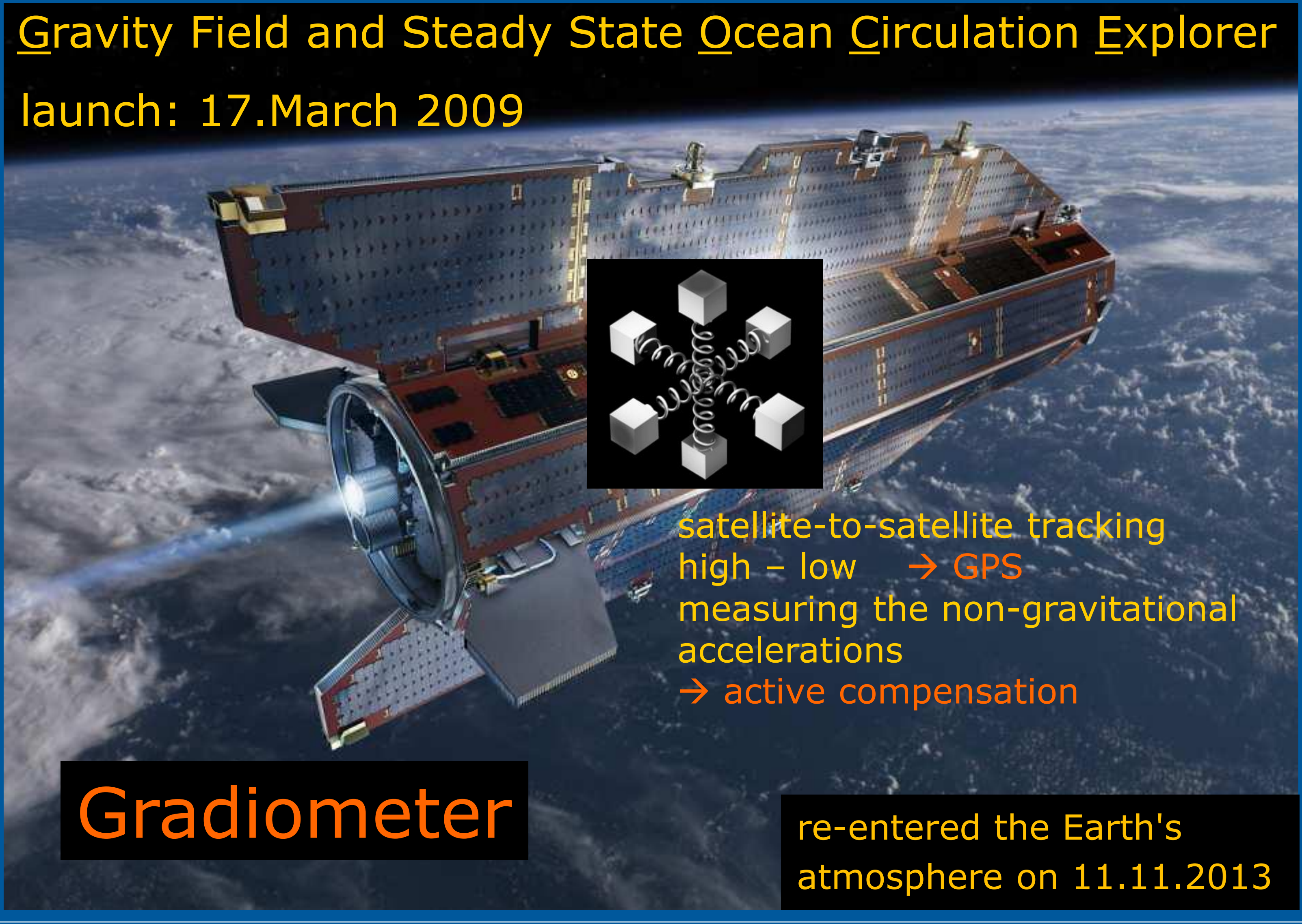


still in orbit (design life: 5years)
→ GRACE Follow on

GOCE

Gravity Field and Steady State Ocean Circulation Explorer

launch: 17.March 2009



satellite-to-satellite tracking
high – low → GPS
measuring the non-gravitational accelerations
→ active compensation

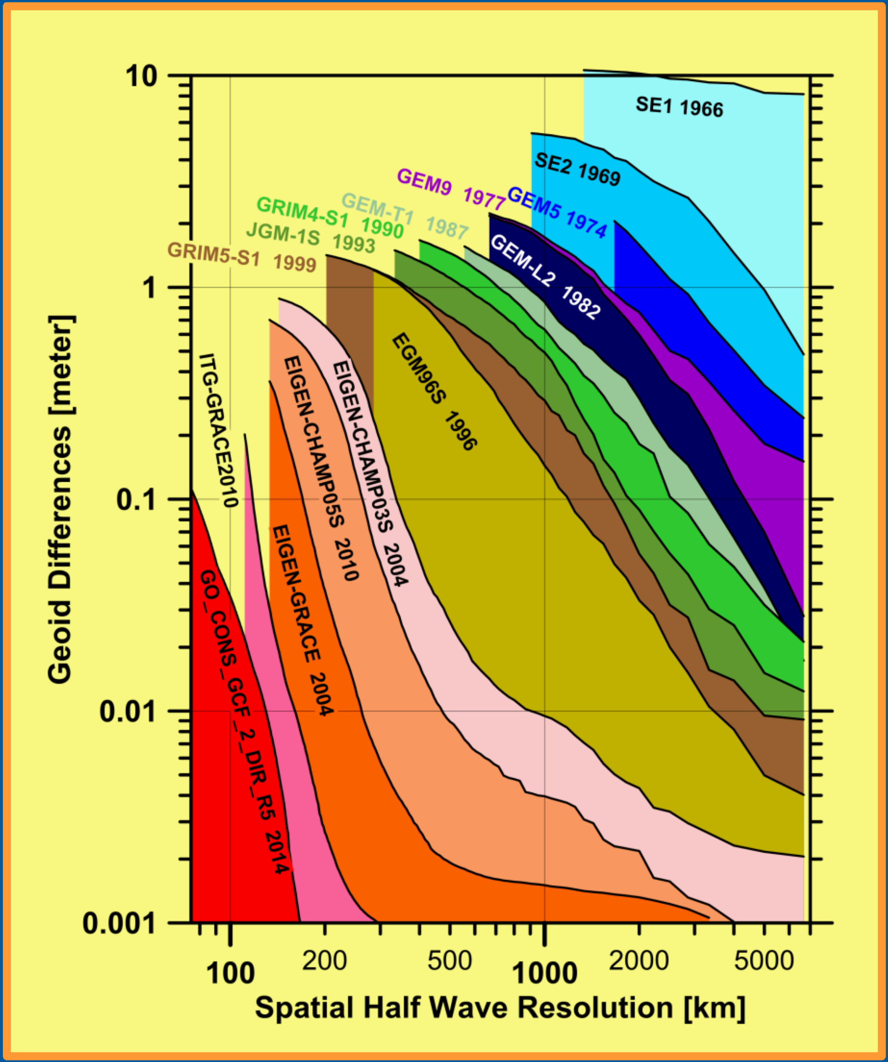
Gradiometer

re-entered the Earth's atmosphere on 11.11.2013

Global Models – Improvement in History

Geoid differences of satellite-only models of the past to recent ("best") combination solution as a function of spatial resolution

→ **differences to EIGEN-6C4**



Mathematical Representation

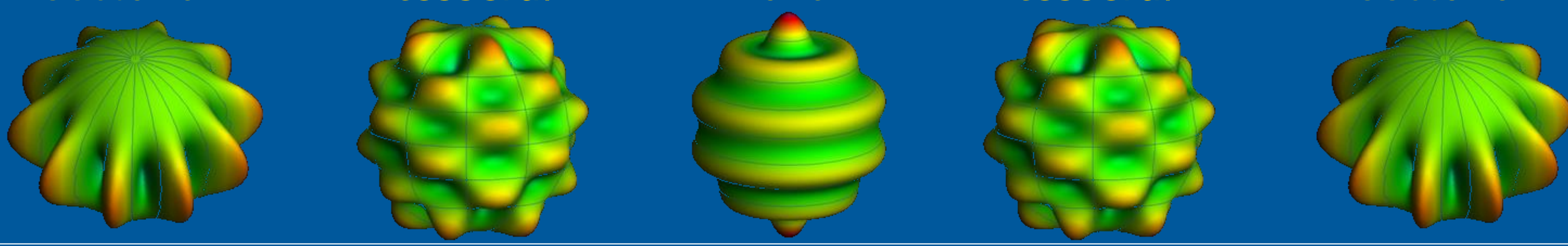
$$W_a(r,\lambda,\varphi) = \frac{GM}{r} \sum_{\ell=0}^{\infty} \left(\frac{R}{r}\right)^{\ell} \sum_{m=0}^{\ell} \left[C_{\ell m} Y^c_{\ell m}(\lambda,\varphi) + S_{\ell m} Y^s_{\ell m}(\lambda,\varphi) \right]$$

$$Y^s_{\ell m}(\lambda,\varphi) = P_{\ell m}(\sin\varphi) \sin m\lambda$$

$$Y^c_{\ell m}(\lambda,\varphi) = P_{\ell m}(\sin\varphi) \cos m\lambda$$

					C_{00}					
				S_{11}	C_{10}	C_{11}				
			S_{22}	S_{21}	C_{20}	C_{21}	C_{22}			
		S_{33}	S_{32}	S_{31}	C_{30}	C_{31}	C_{32}	C_{33}		
	S_{44}	S_{43}	S_{42}	S_{41}	C_{40}	C_{41}	C_{42}	C_{43}	C_{44}	
S_{55}	S_{54}	S_{53}	S_{52}	S_{51}	C_{50}	C_{51}	C_{52}	C_{53}	C_{54}	C_{55}

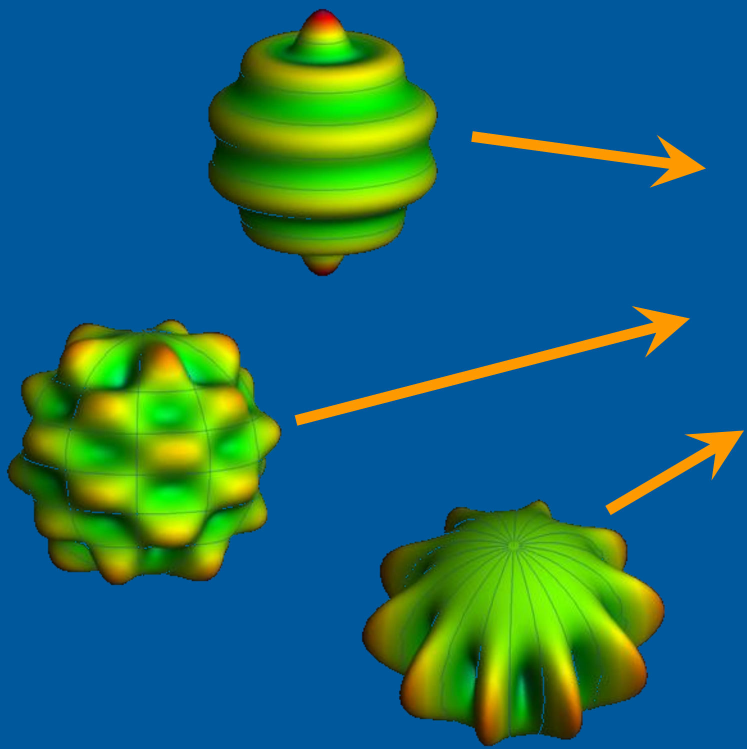
sectorial tesseral zonal tesseral sectorial

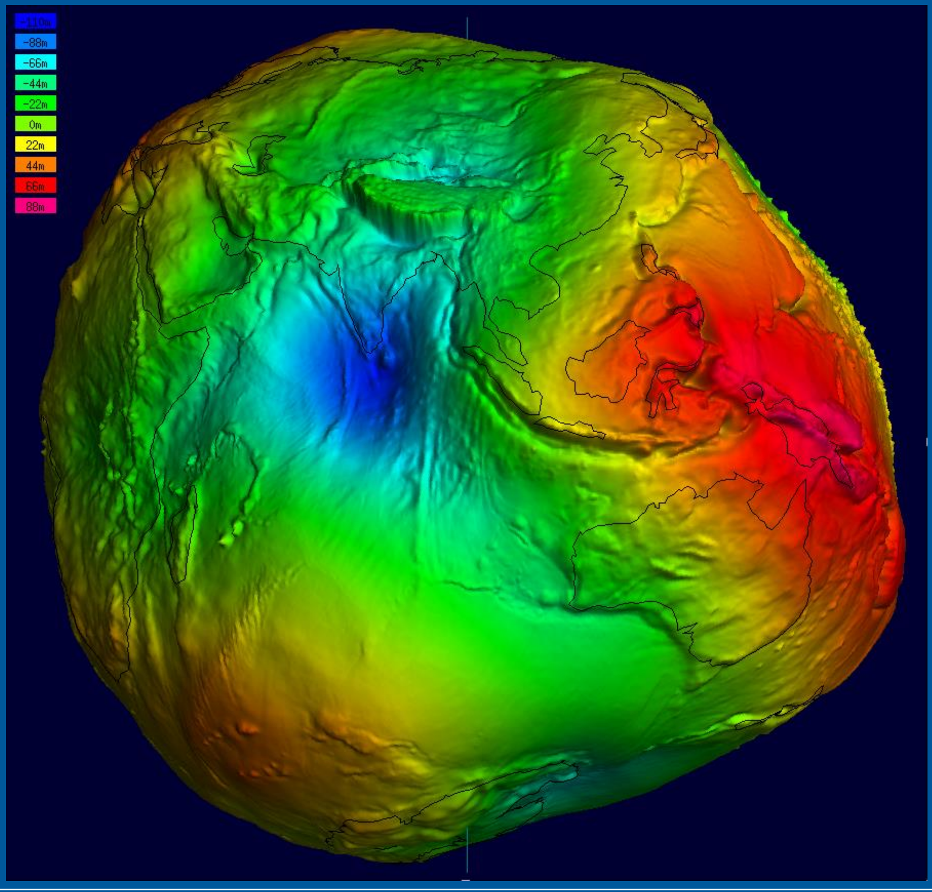


Mathematical Representation

$$W_a(r,\lambda,\varphi) \approxeq \frac{GM}{r} \overset{\ell_{max}}{\sum_{\ell=0}^{\infty}} \left(\frac{R}{r}\right)^{\ell} \sum_{m=0}^{\ell} \left[C_{\ell m} Y^{c}_{\ell m}(\lambda,\varphi) + S_{\ell m} Y^{s}_{\ell m}(\lambda,\varphi)\right]$$

spherical frequency domain





Resolution of Spherical Harmonics

Maximum Degree	Number of Coefficients	Resolution ψ_{min}			
		$\psi_{min}(\ell_{max}) \approx \frac{\pi R}{\ell_{max}}$		$\psi_{min}(\ell_{max}) = 4 \arcsin\left(\frac{1}{\ell_{max}+1}\right)$	
ℓ_{max}	N	[degree]	[km]	[degree]	[km]
2	9	90.0	10000.000	77.885	8653.876
5	36	36.000	4000.000	38.376	4264.030
10	121	18.000	2000.000	20.864	2318.182
15	256	12.000	1333.333	14.333	1592.587
30	961	6.000	666.667	7.394	821.587
36	1369	5.000	555.556	6.195	688.321
40	1681	4.500	500.000	5.590	621.154
45	2116	4.000	444.444	4.983	553.626
50	2601	3.600	400.000	4.494	499.342
75	5776	2.400	266.667	3.016	335.073
180	32761	1.000	111.111	1.266	140.690
360	130321	0.500	55.556	0.635	70.540
500	251001	0.360	40.000	0.457	50.828
1000	1002001	0.180	20.000	0.229	25.439
2000	4004001	0.090	10.000	0.115	12.726
2190	4800481	0.082	9.132	0.105	11.622

number of coefficients

$$(\ell_{max}+1)^2$$

divide the sphere into equareal pieces of size: A_{min}

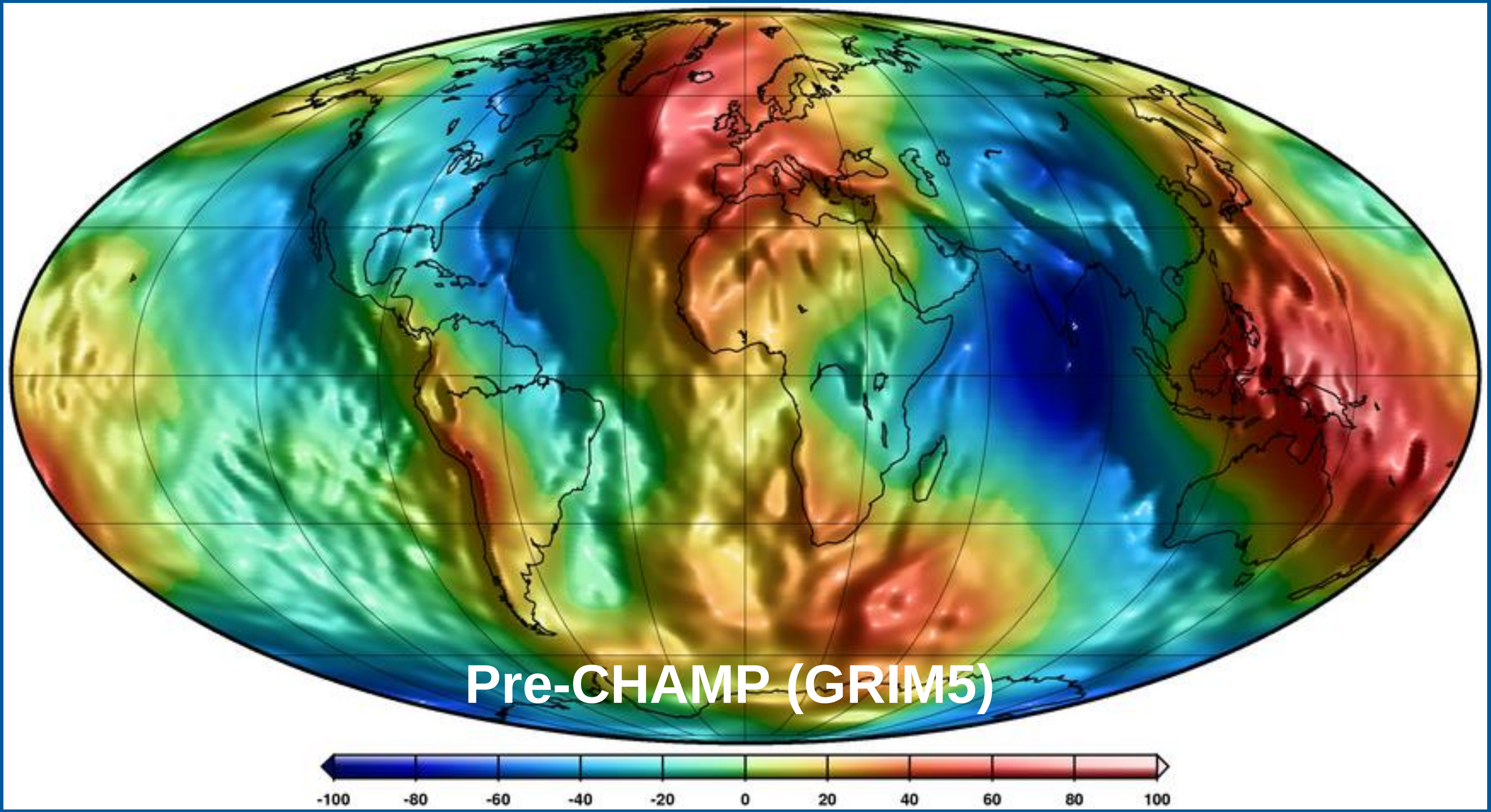
$$A_{min}(\ell_{max}) = \frac{4\pi R^2}{(\ell_{max}+1)^2}$$

diameter [degree] of spherical cap with A_{min}

$$4 \arcsin\left(\frac{1}{\ell_{max}+1}\right)$$

Improvement of the Global Models

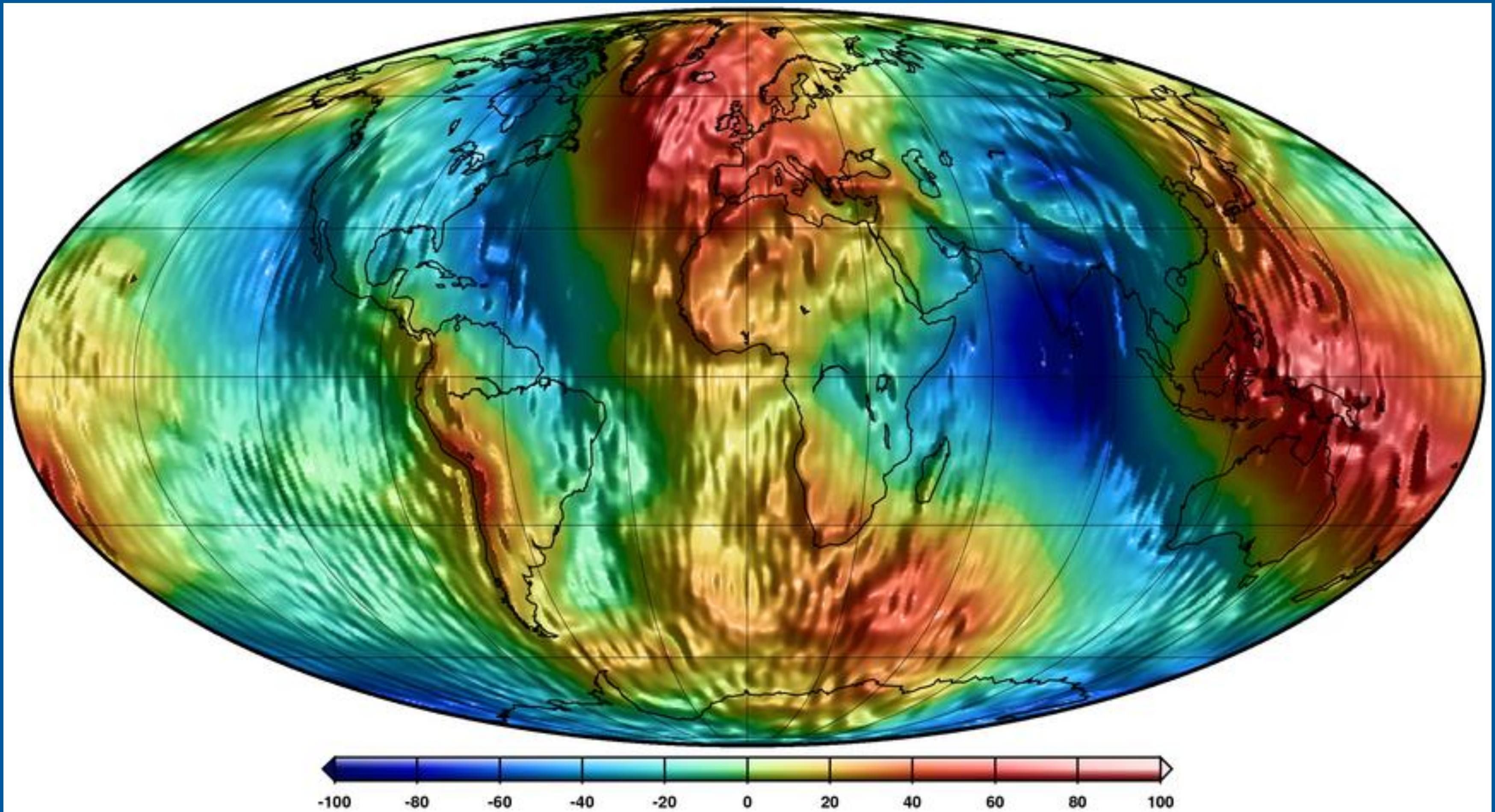
Geoid [m]



Improvement of the Global Models

Geoid [m]

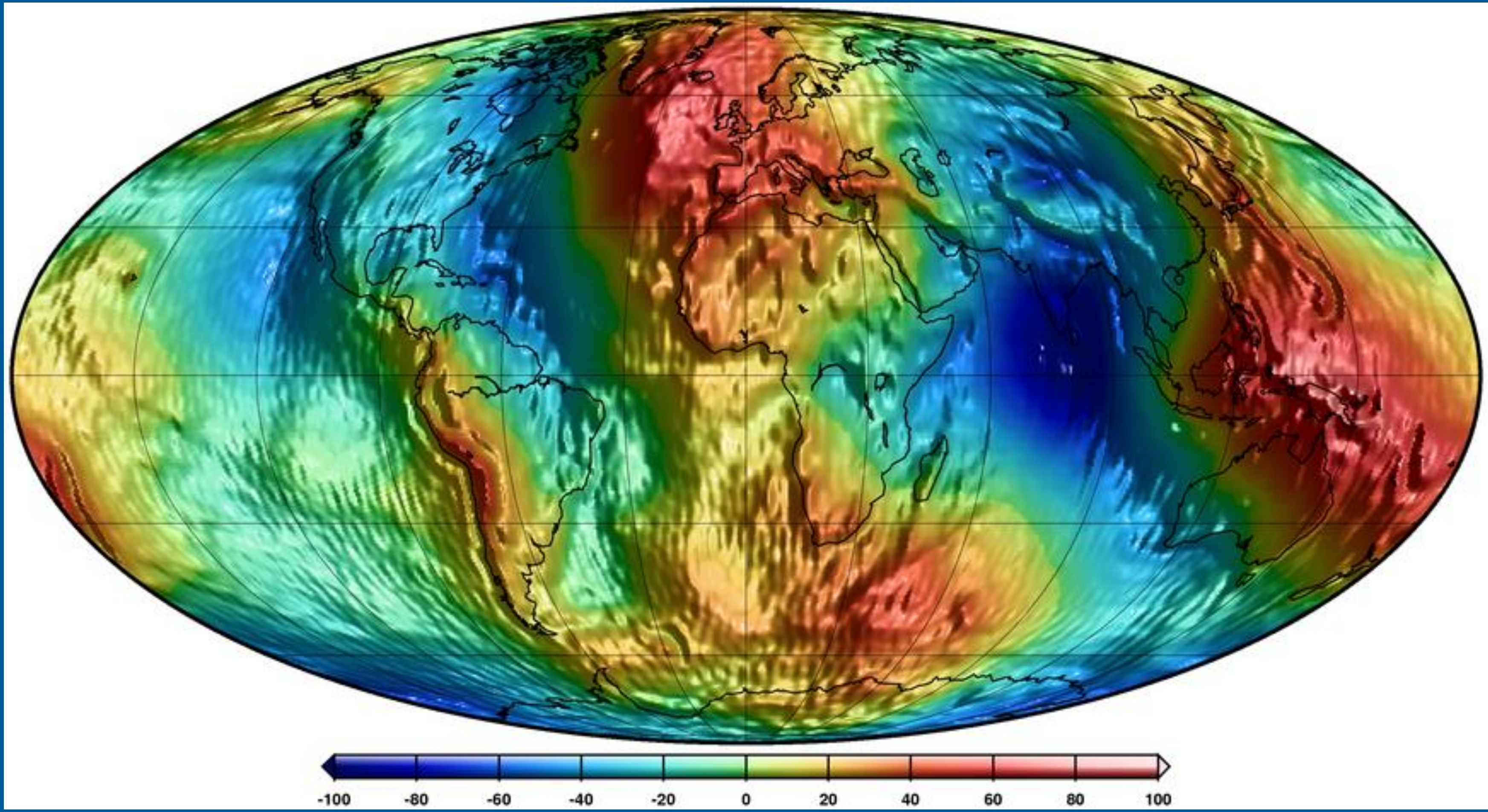
CHAMP 2004



Improvement of the Global Models

Geoid [m]

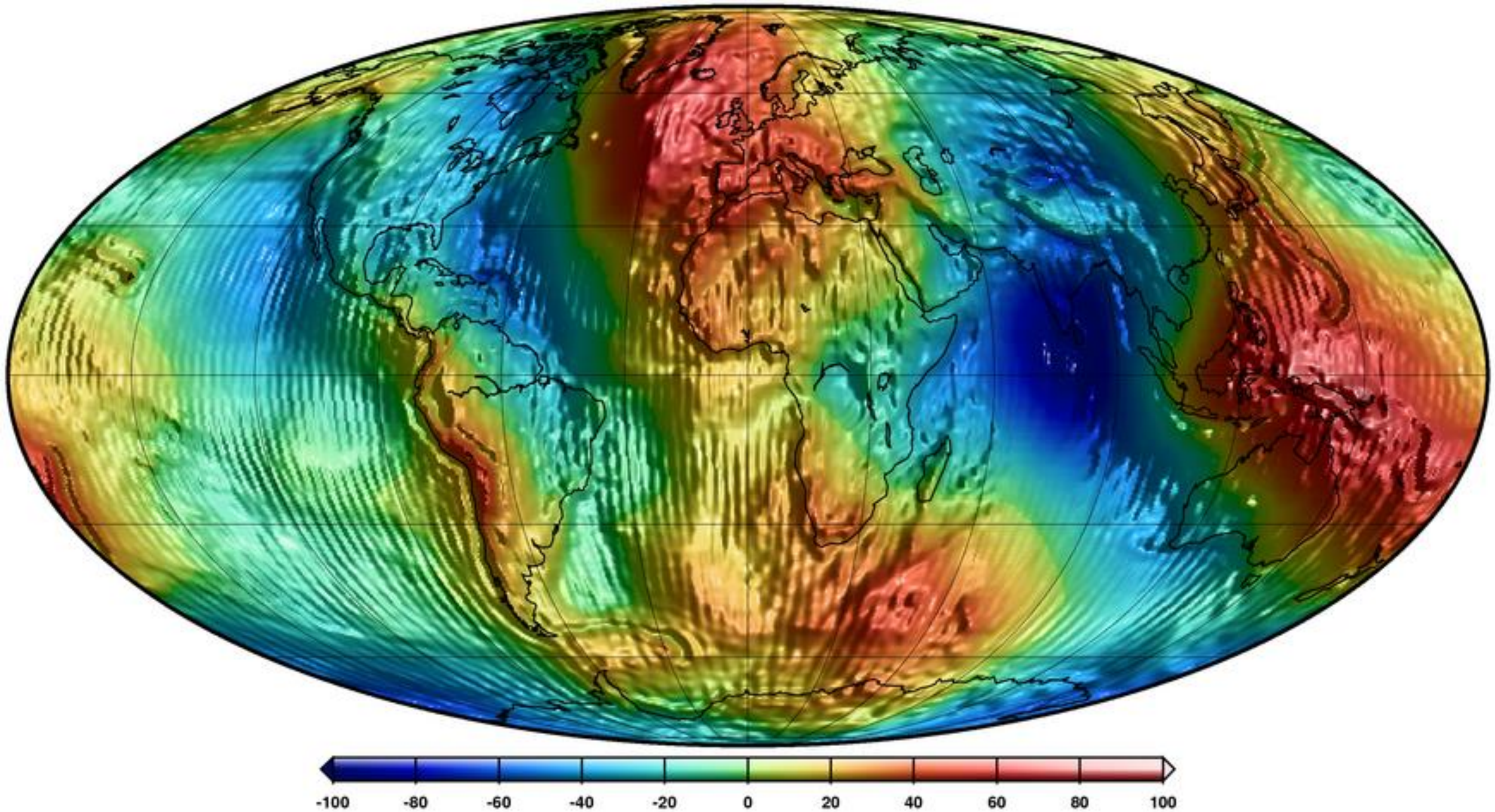
CHAMP 2010



Improvement of the Global Models

Geoid [m]

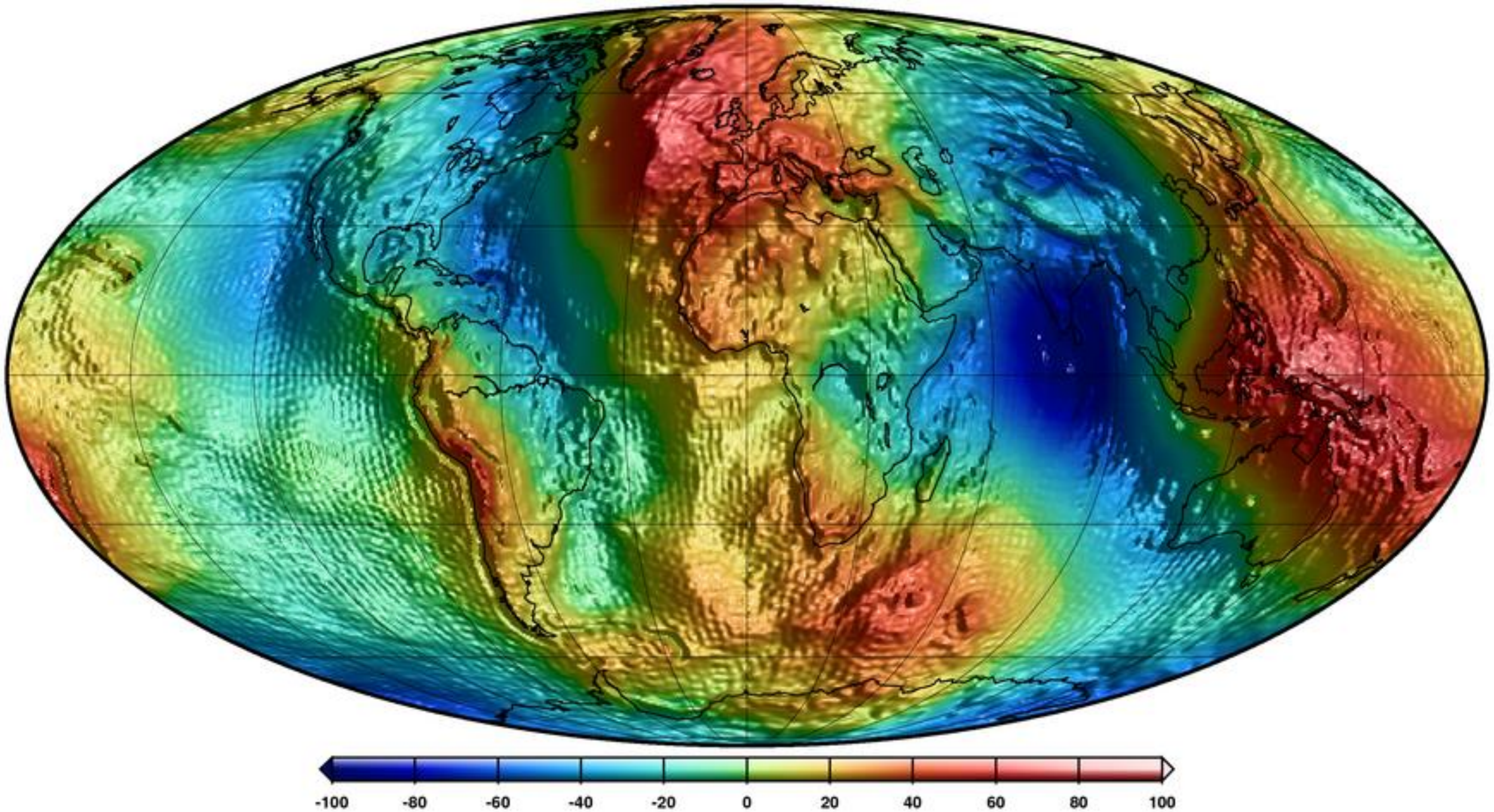
GRACE 2004



Improvement of the Global Models

Geoid [m]

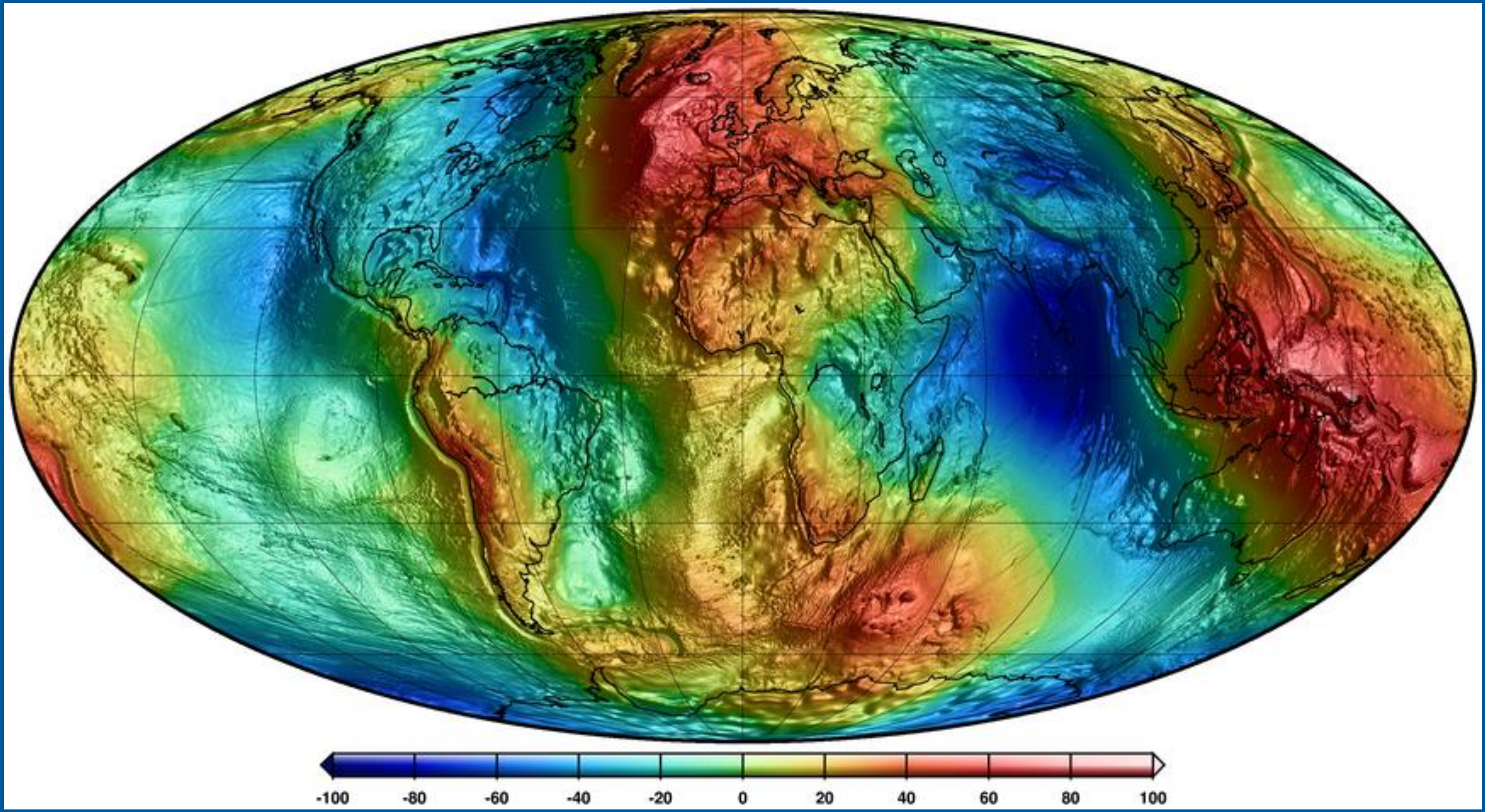
GRACE 2010



Improvement of the Global Models

Geoid [m]

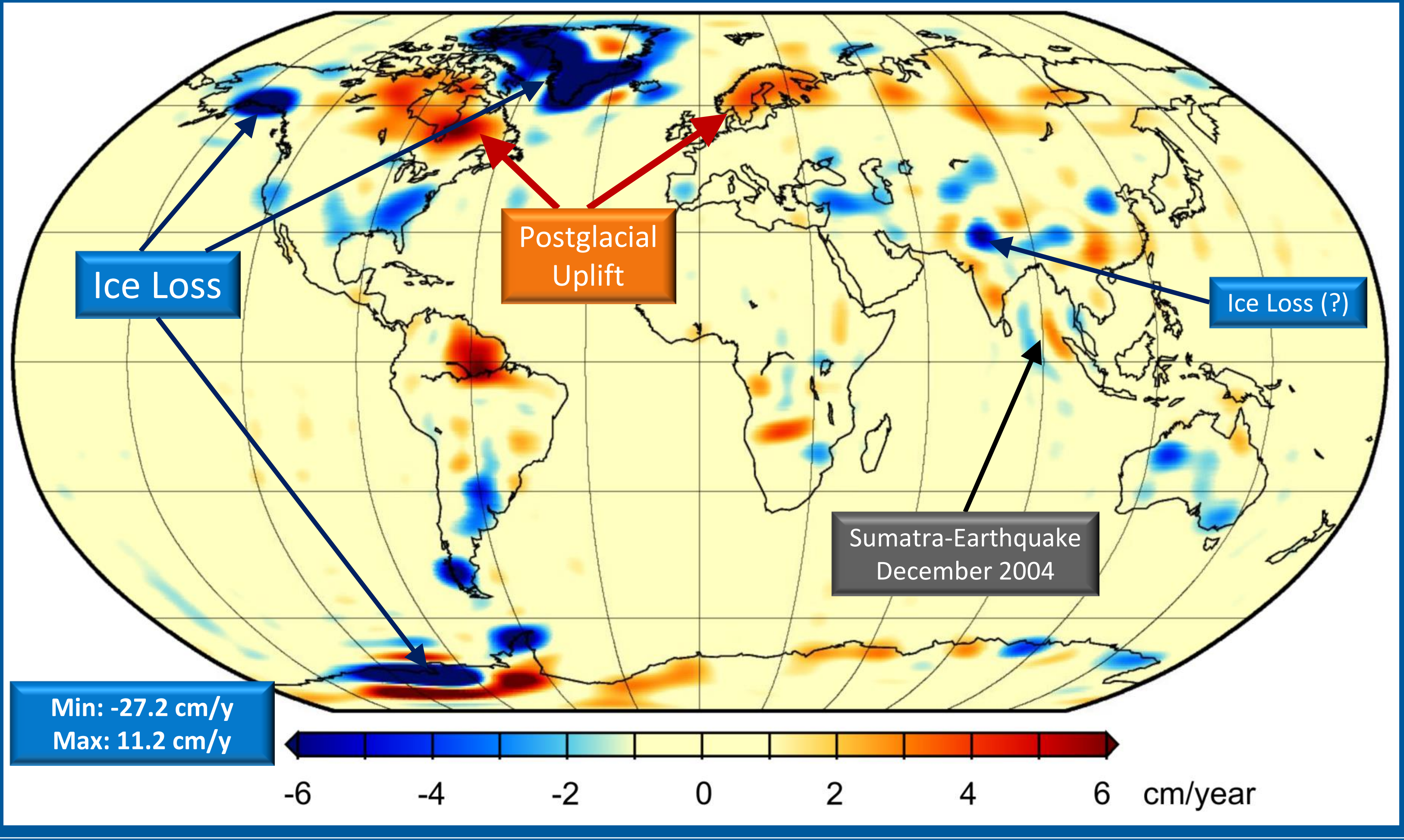
GRACE + GOCE + surface data



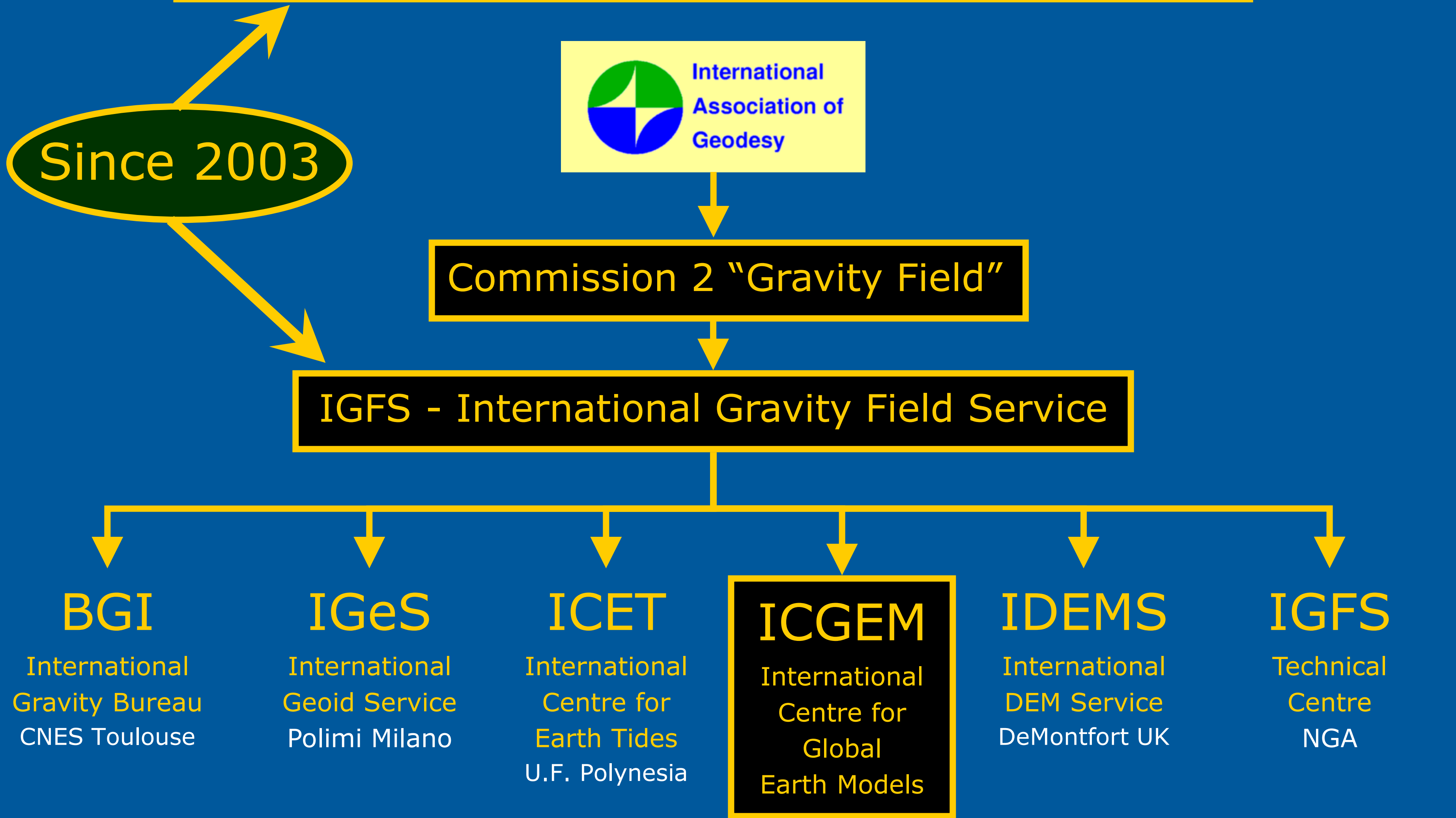
Change in Gravity Field from GRACE

Linear Trend from the model EIGEN-6 (time span: 1 Jan 2003 till 30 June 2009)

Geoid → Equivalent Water Height (cm/year)



ICGEM – A Service of the IAG



Objectives / Status of ICGEM

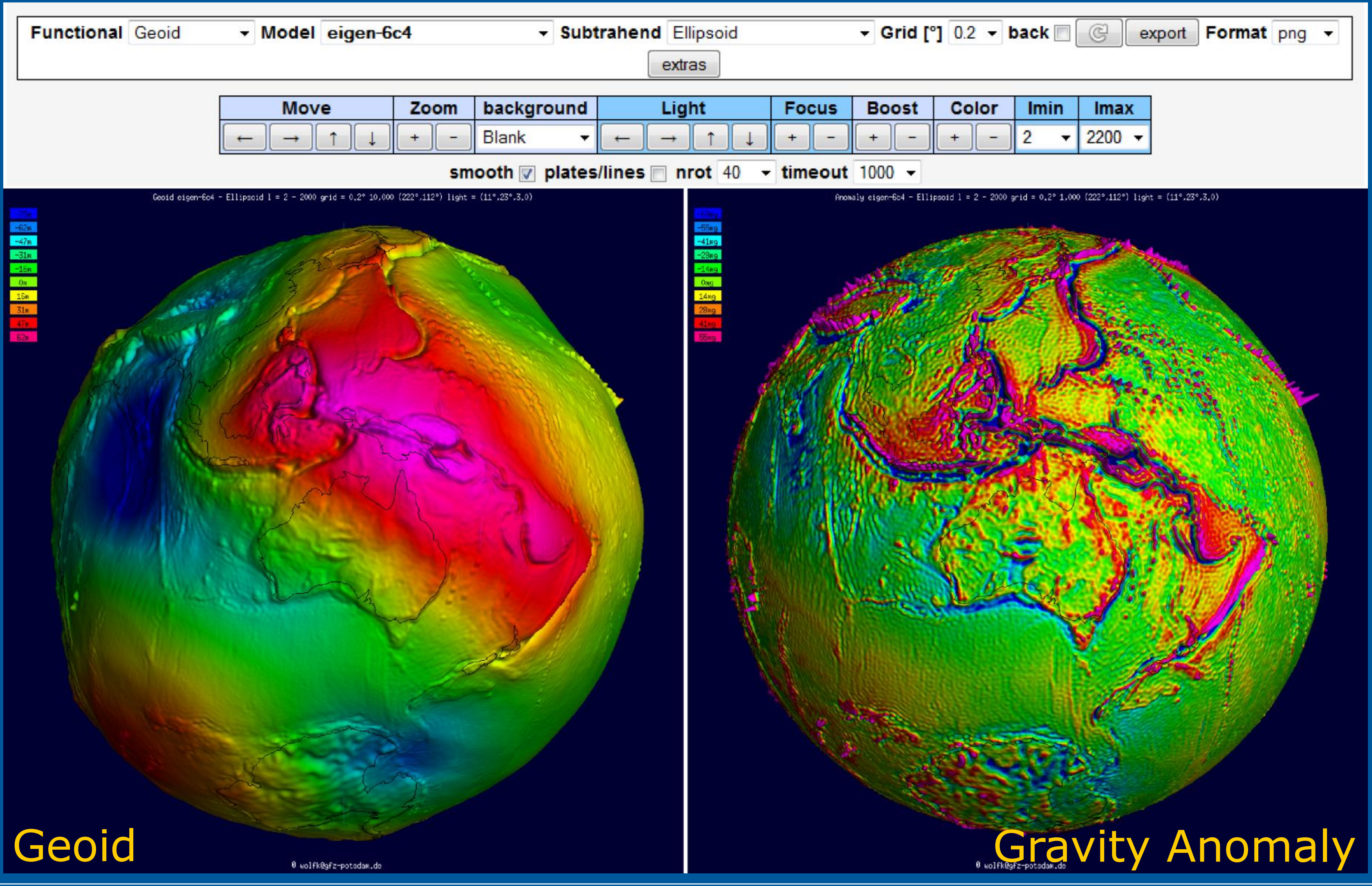
- collecting and archiving of all existing global gravity field models
- making them available on the web
- use of standardised format (self-explanatory) (→ accepted for GOCE / ESA)
- interactive visualisation of the models, their differences, and their time variation
- web-interface to calculate different gravity field functionals from the spherical harmonic models on freely selectable grids (filtering included)

- evaluation of the models (→ differences in the frequency domain, comparison with GPS/levelling)
- answering of questions (online discussion forum / guest book)

Table of available Models

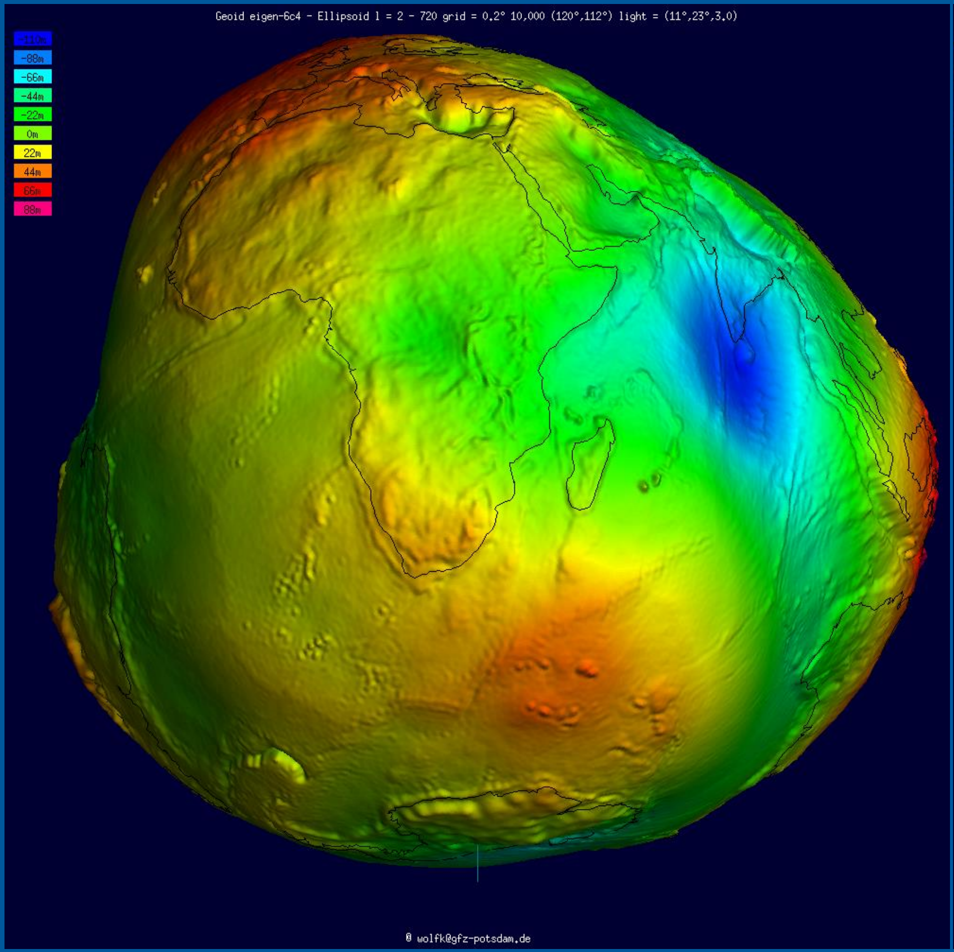
Nr ▲	Model ⇅	Year ⇅	Degree ⇅	Data ⇅	Reference ⇅	download	calculate	show
150	GOCO05s	2015	280	S(see model)	Mayer-Gürr, et al. 2015	gfc zip	calculate	show
149	GO_CONS_GCF_2_SPW_R4	2014	280	S(Goce)	Gatti et al, 2014	gfc zip	calculate	show
148	EIGEN-6C4	2014	2190	S(Goce,Grace,Lageos),G,A	Förste et al, 2014	gfc zip	calculate	show
147	ITSG-Grace2014s	2014	200	S(Grace)	Mayer-Gürr et al, 2014	gfc zip	calculate	show
146	ITSG-Grace2014k	2014	200	S(Grace)	Mayer-Gürr et al, 2014	gfc zip	calculate	show
145	GO_CONS_GCF_2_TIM_R5	2014	280	S(Goce)	Brockmann et al, 2014	gfc zip	calculate	show
144	GO_CONS_GCF_2_DIR_R5	2014	300	S(Goce,Grace,Lageos)	Bruinsma et al, 2013	gfc zip	calculate	show
143	JYY_GOCE04S	2014	230	S(Goce)	Yi et al, 2013	gfc zip	calculate	show
142	GOGRA04S	2014	230	S(Goce,Grace)	Yi et al, 2013	gfc zip	calculate	show
141	EIGEN-6S2	2014	260	S(Goce,Grace,Lageos)	Rudenko et al. 2014	gfc zip	calculate	show
140	GGM05S	2014	180	S(Grace)	Tapley et al, 2013	gfc zip	calculate	show
8	GEM2	1972	16	S,G	Lerch et al, 1972a	gfc	calculate	show
7	GEM1	1972	12	S	Lerch et al, 1972a	gfc	calculate	show
6	KOCH71	1971	11	S,G	Koch and Witte, 1971	gfc	calculate	show
5	KOCH70	1970	8	S,G	Koch and Morrison, 1970	gfc	calculate	show
4	SE2	1969	22	S,G	Gaposchkin and Lambeck, 1970	gfc	calculate	show
3	OSU68	1968	14	S,G	Rapp, 1968	gfc	calculate	show
2	WGS66	1966	24	G	WGS Committee, 1966	gfc	calculate	show
1	SE1	1966	15	S	Lundquist and Veis, 1966	gfc	calculate	show

Interactive Visualisation Service

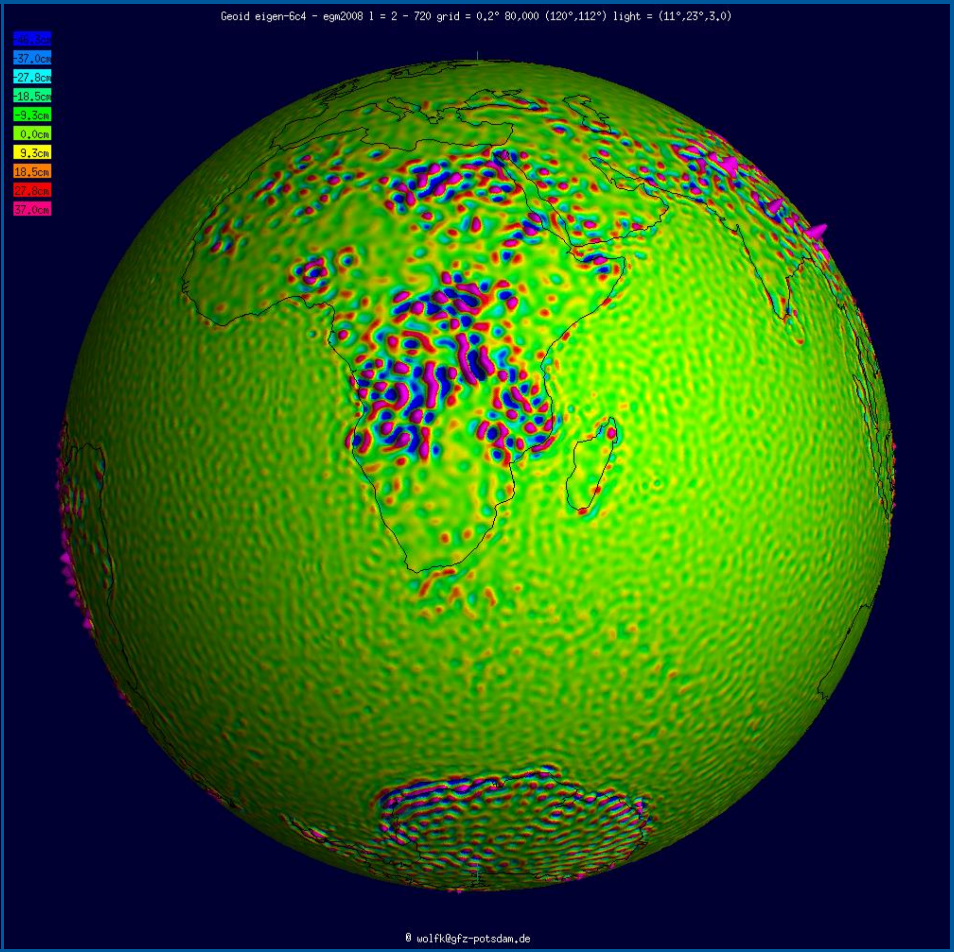


Interactive Visualisation Service

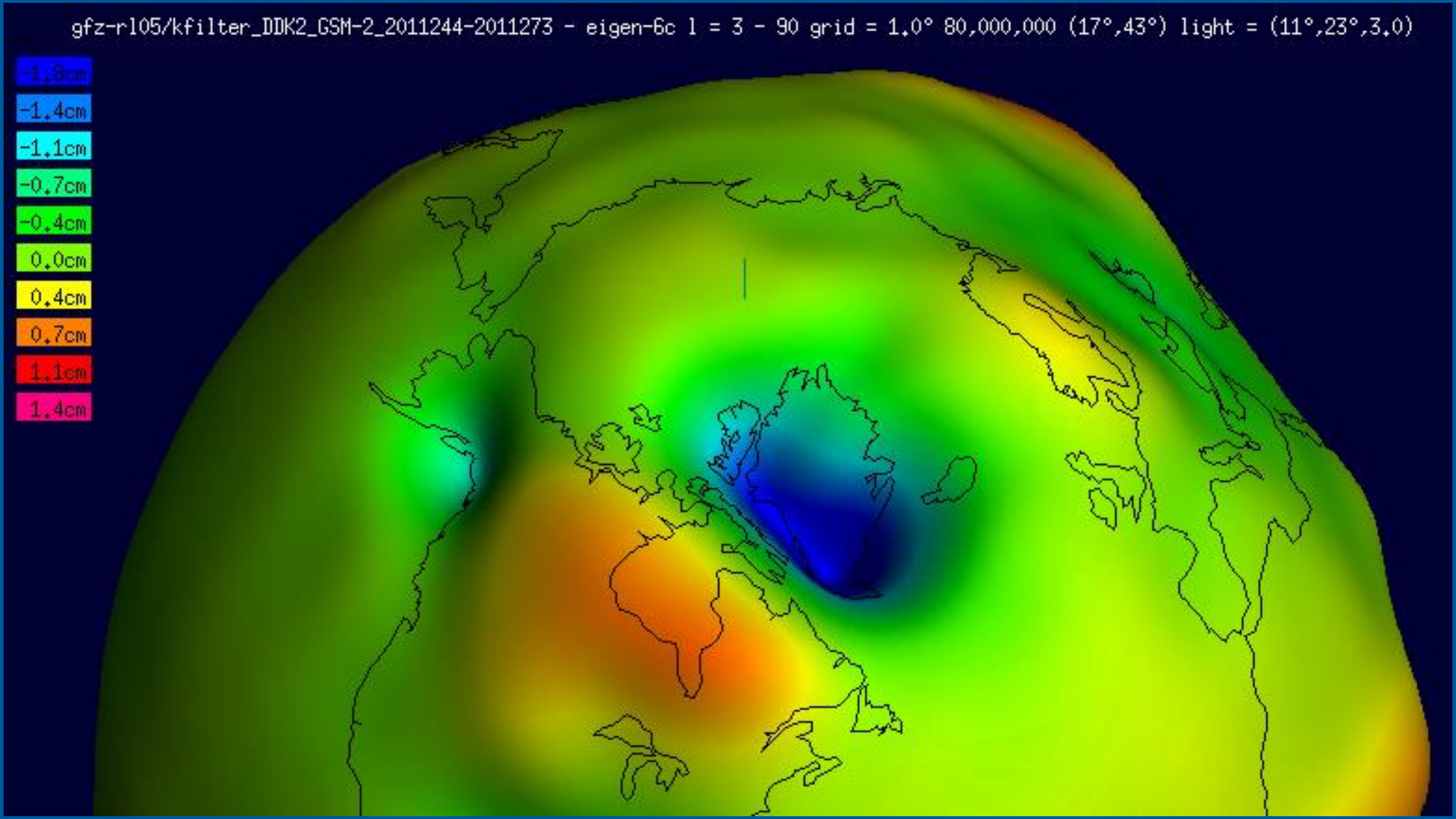
Geoid



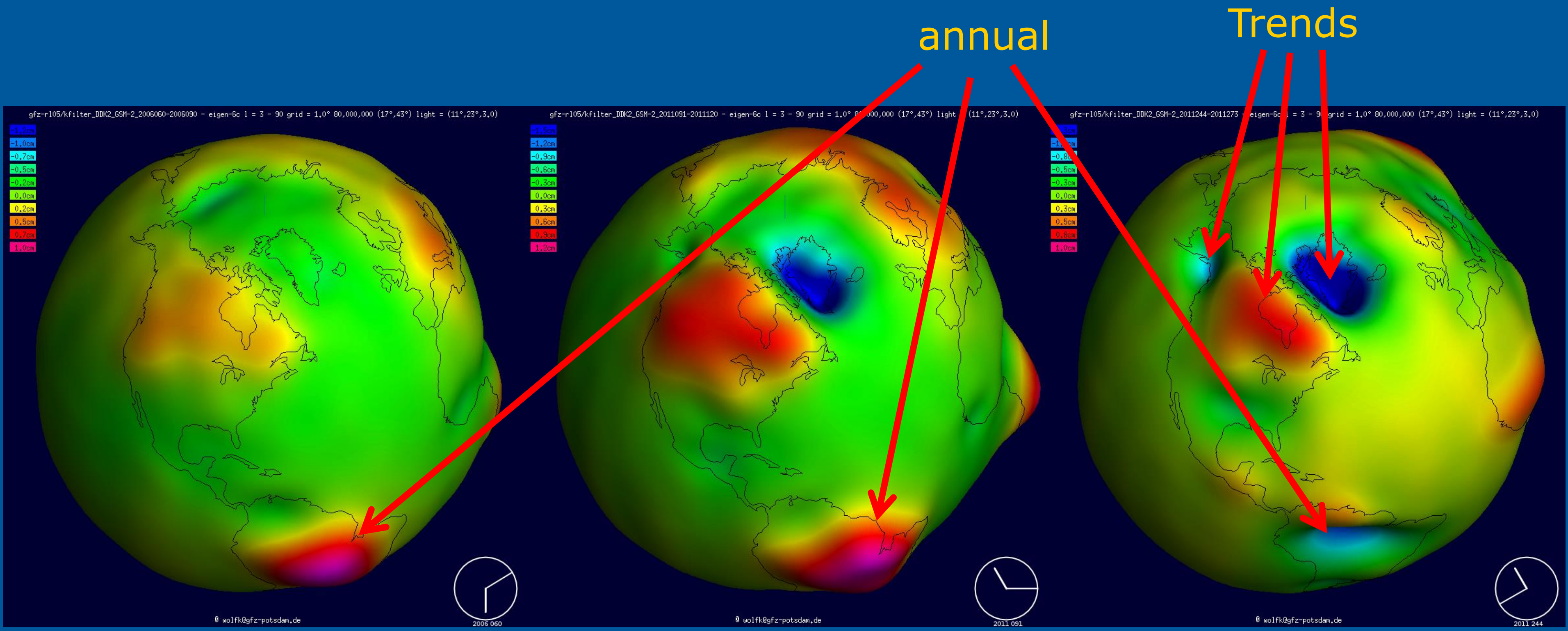
Differences of 2 Models



Visualisation of Monthly Solutions



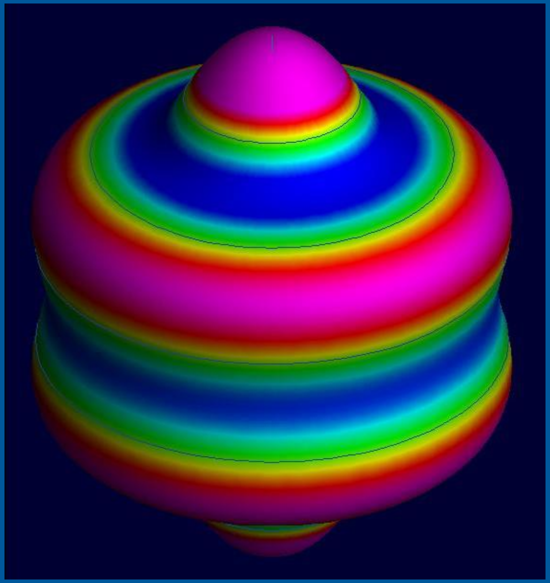
Visualisation of Monthly Solutions



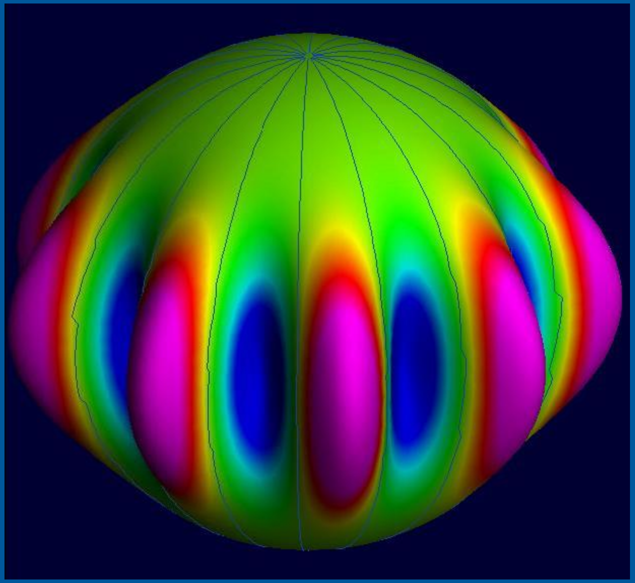
March 2006 March 2011 July 2011

Interactive Visualisation Service

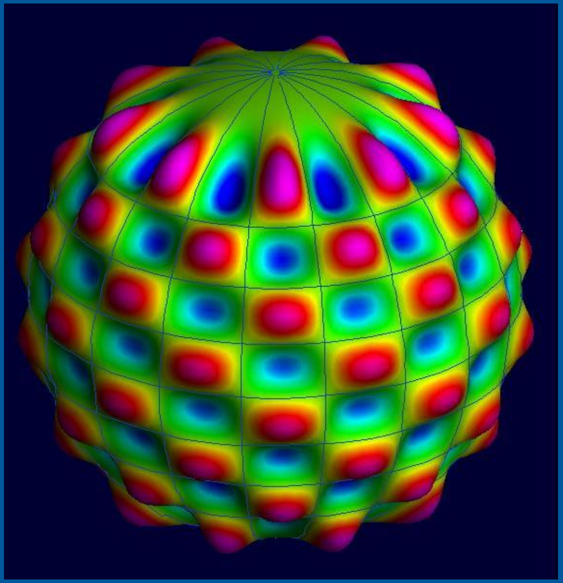
Spherical Harmonics as Tutorial



zonal: $\ell = 6$, $m = 0$

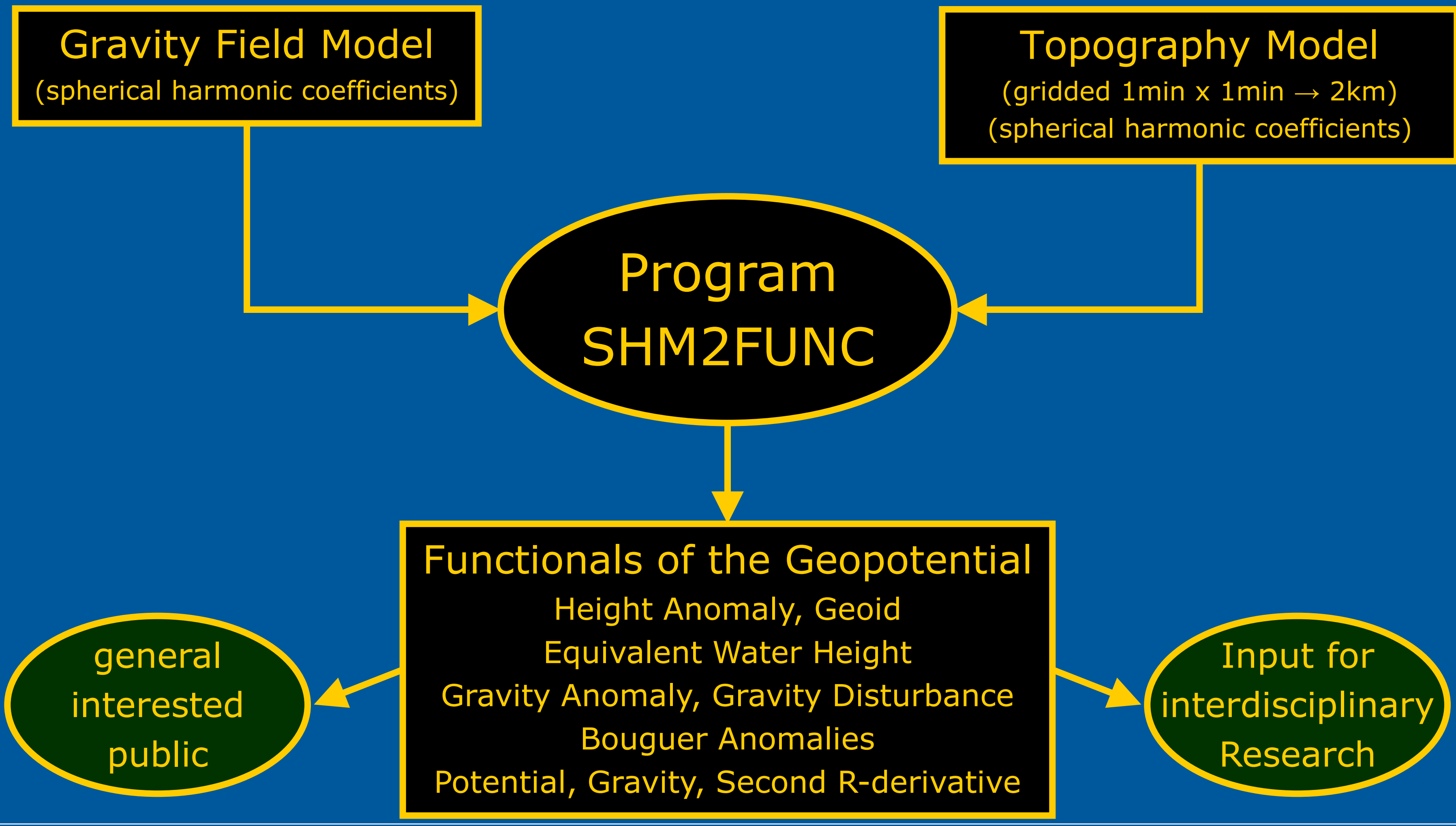


sectorial: $\ell = 9$, $m = 9$

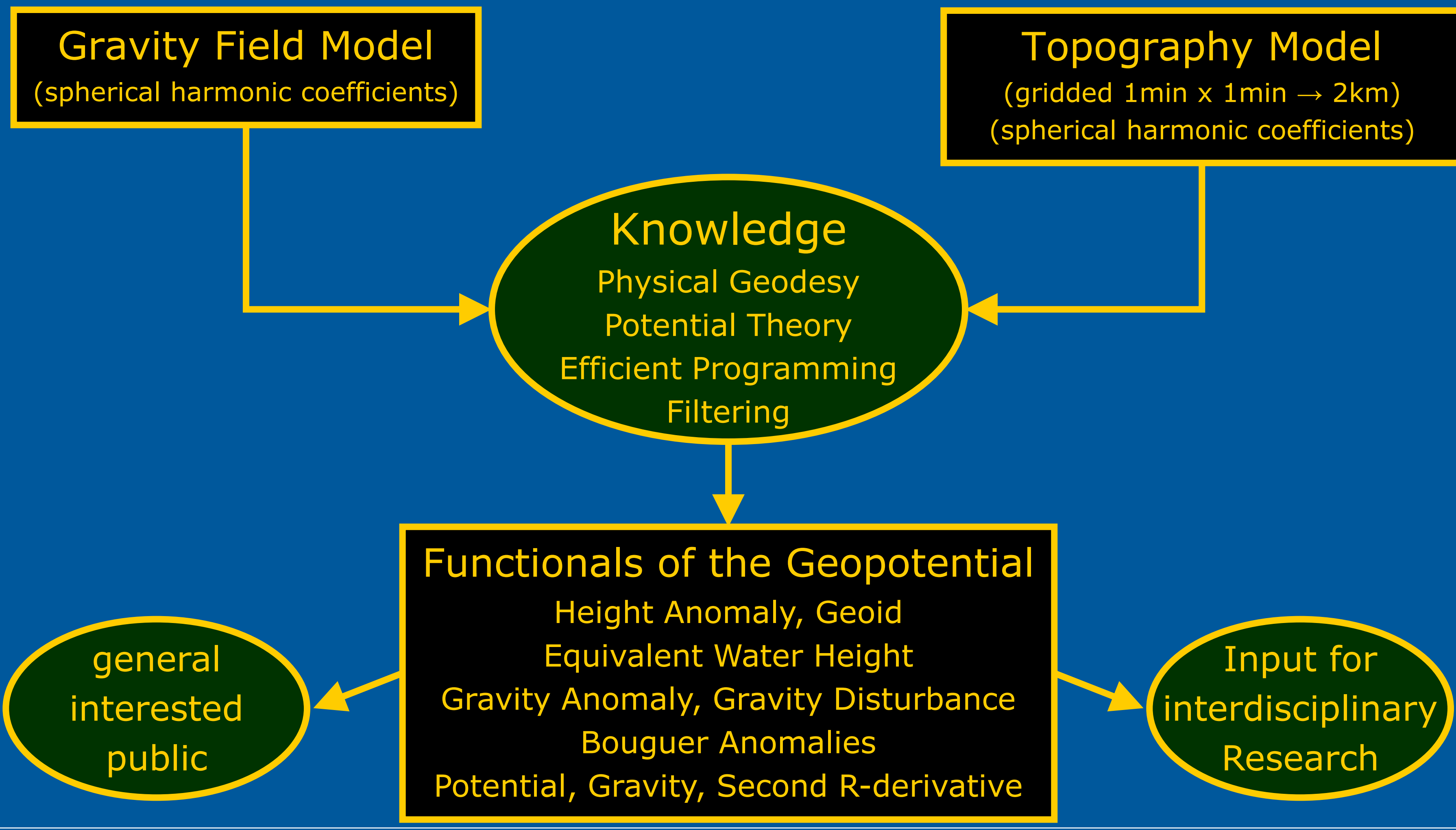


tesseral: $\ell = 16$, $m = 9$

Calculation Service

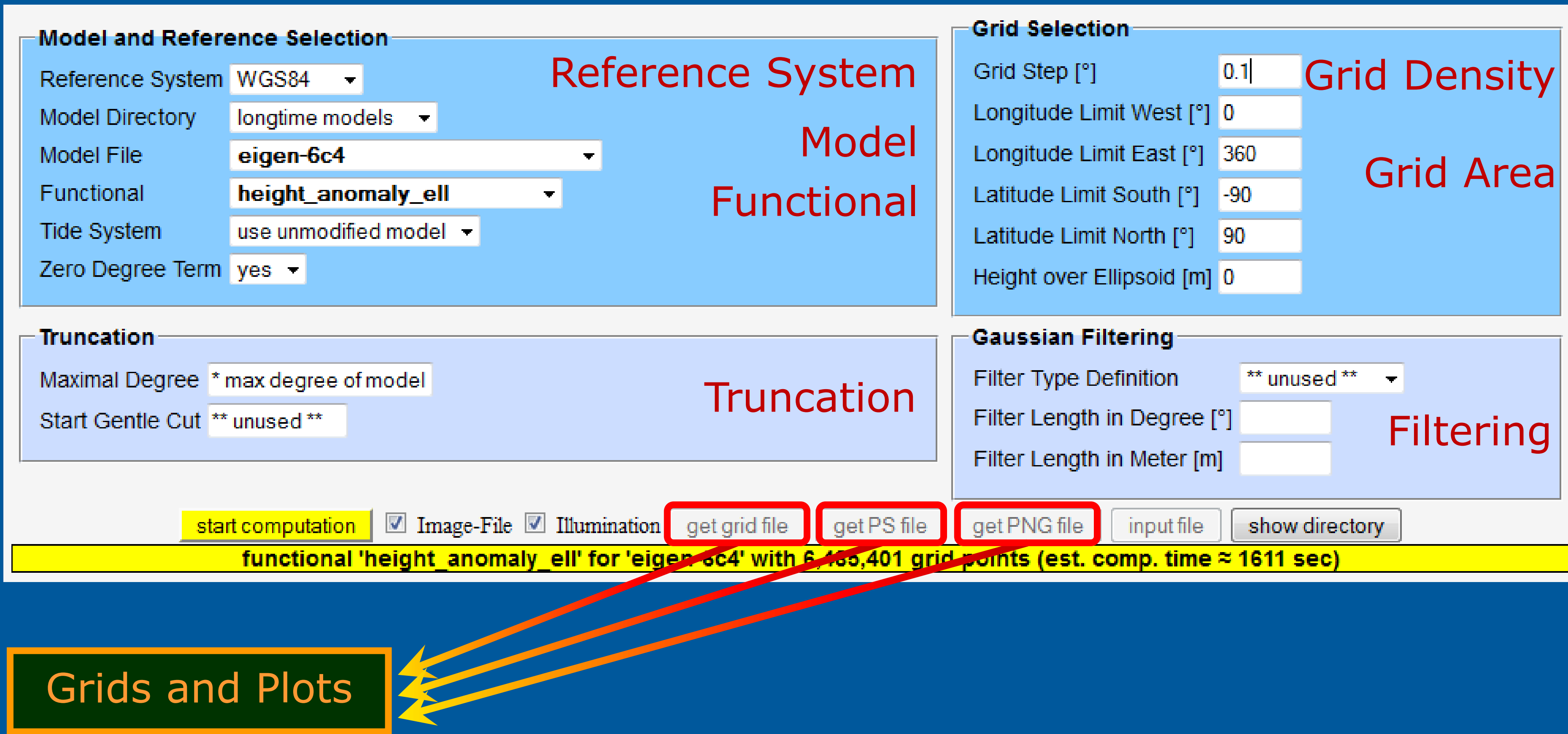


Calculation Service



Calculation Service

Web-Interface



Calculation Service

available functionals

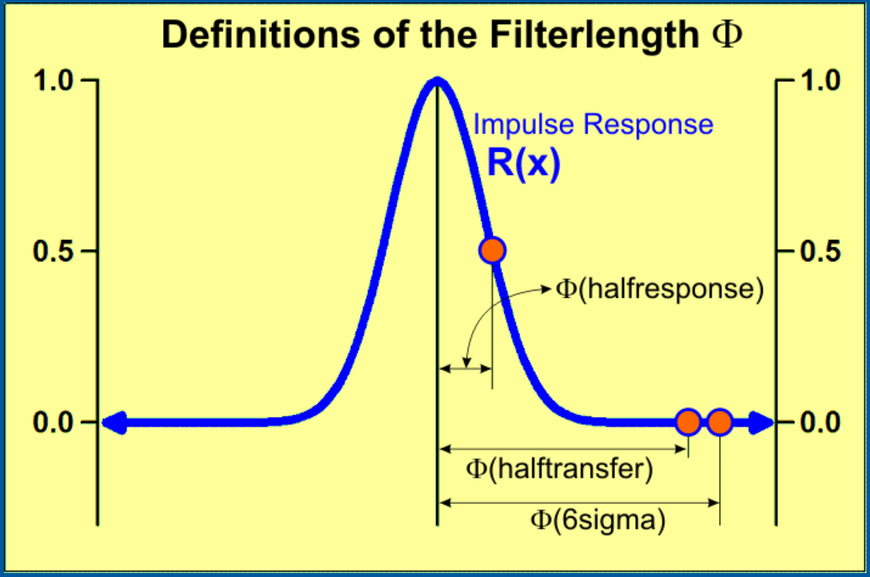
- height anomaly (on the Earth’s surface, on the ellipsoid)
- geoid undulation
- gravity anomaly (Molodensky, classical ≈ free air, spherical approximation, Bouguer)
- gravity disturbance (on the Earth’ surface, spherical approximation)
- gravity (on the Earth’ surface, on or above the ellipsoid)
- gravitation (on or above the ellipsoid)
- second radial derivative (on or above the ellipsoid)
- equivalent water height (including elastic deformation)
- potential (on or above the ellipsoid)

Calculation Service

Explanation of the Functionals

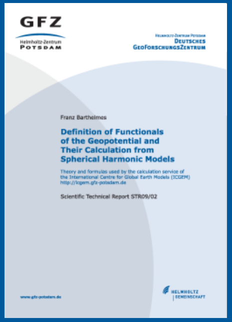
keyword	explanation
height_anomaly	The so called "height anomaly" is an approximation of the geoid according to Molodensky's theory. It is equal to the geoid over sea. Here it will be calculated, as defined, on the Earth's surface approximated by Bruns' formula on the ellipsoid plus a first order correction (eqs. 81 and 119 of STR09/02).
height_anomaly_ell	The height anomaly can be generalised to a 3-d function, (sometimes called "generalised pseudo-height-anomaly"). Here it can be calculated on (h=0) or above (h>0) the ellipsoid, approximated by Bruns' formula (eqs. 78 and 118 of STR09/02).
geoid	The Geoid is one particular equipotential surface of the gravity potential of the Earth. Among all equipotential surfaces, the geoid is those which is equal to the undisturbed sea surface and its continuation below the continents. Here it will be approximated by the height anomaly plus a topography dependent correction term (eqs. 71 and 117 of STR09/02).
gravity_disturbance	The gravity disturbance is defined as the magnitude of the gradient of the potential at a given point minus the magnitude of the gradient of the normal potential at the same point. Here it will be calculated on the Earth's surface (eqs. 87 and 121 – 124 of STR09/02).
gravity_disturbance_sa	The gravity disturbance calculated by spherical approximation (eqs. 92 and 125 of STR09/02) on (h=0) or above (h>0) the ellipsoid.
gravity_anomaly	The gravity anomaly (according to Molodensky's theory) is defined as the magnitude of the gradient of the potential on the Earth's surface minus the magnitude of the gradient of the normal potential on the Telluroid (Earth's surface minus height anomaly) (eqs. 101 and 121 – 124 of STR09/02).
gravity_anomaly_cl	The classical gravity anomaly is defined as the magnitude of the gradient of the downward continued potential on the geoid minus the magnitude of the gradient

Explanation of the Filtering



Theory and Formulas

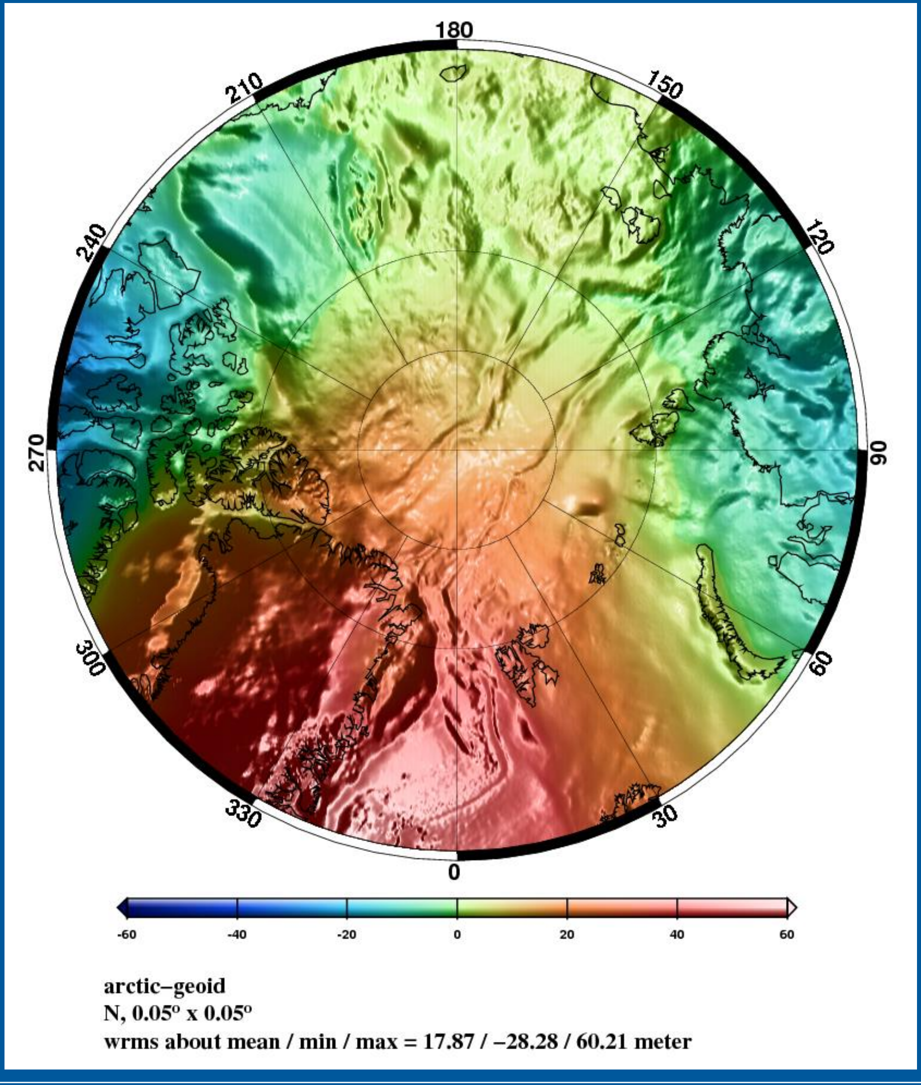
➔ Link to: Report STR09/02



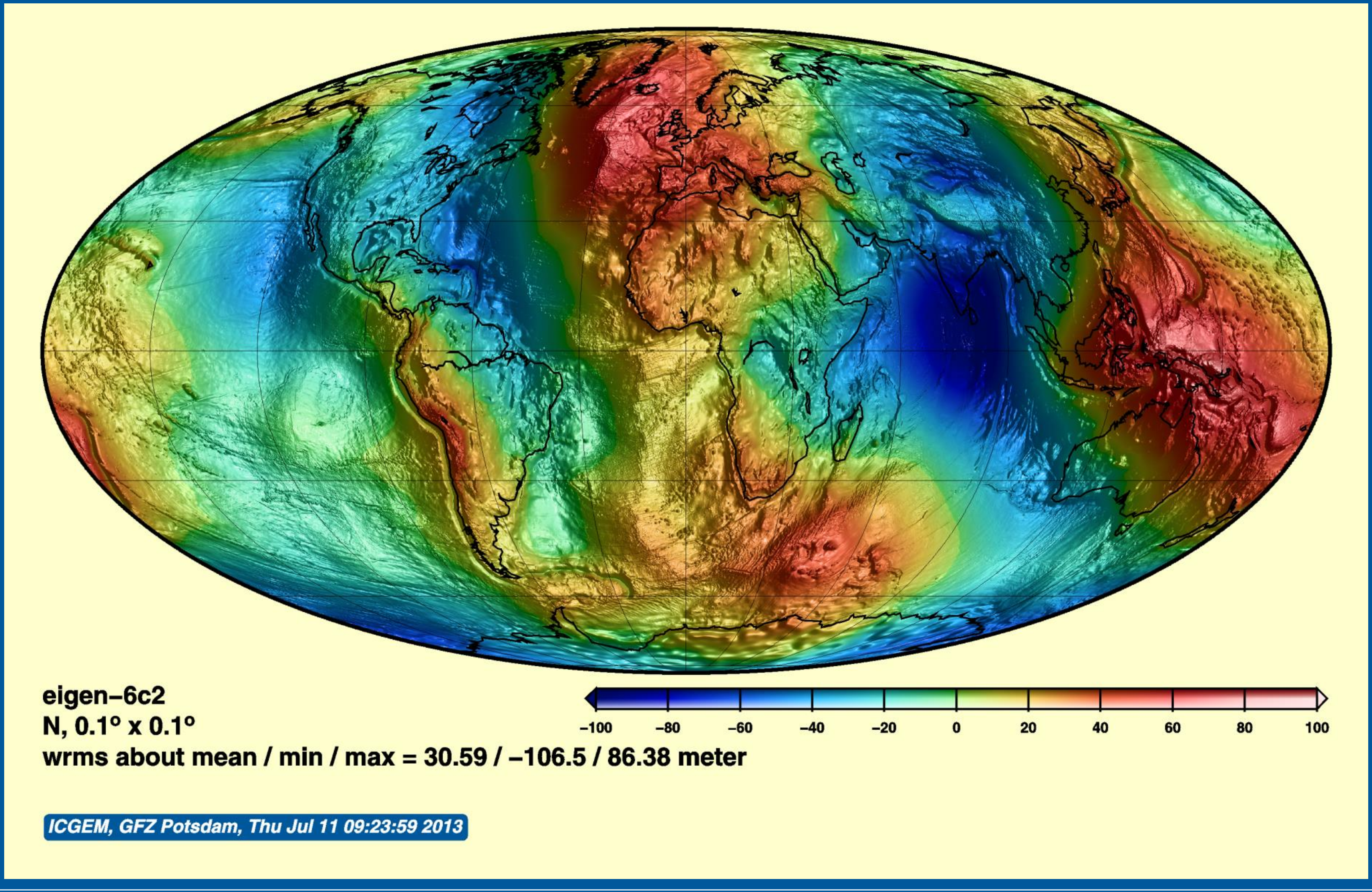
Calculation Service

Calculation of downloadable Grids

- freely selectable grid areas
- automatic generation of plots

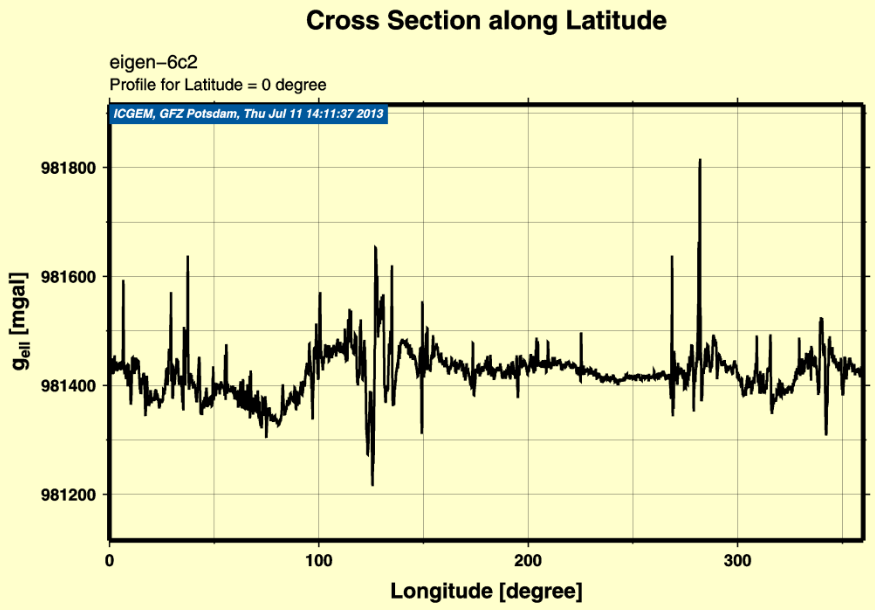


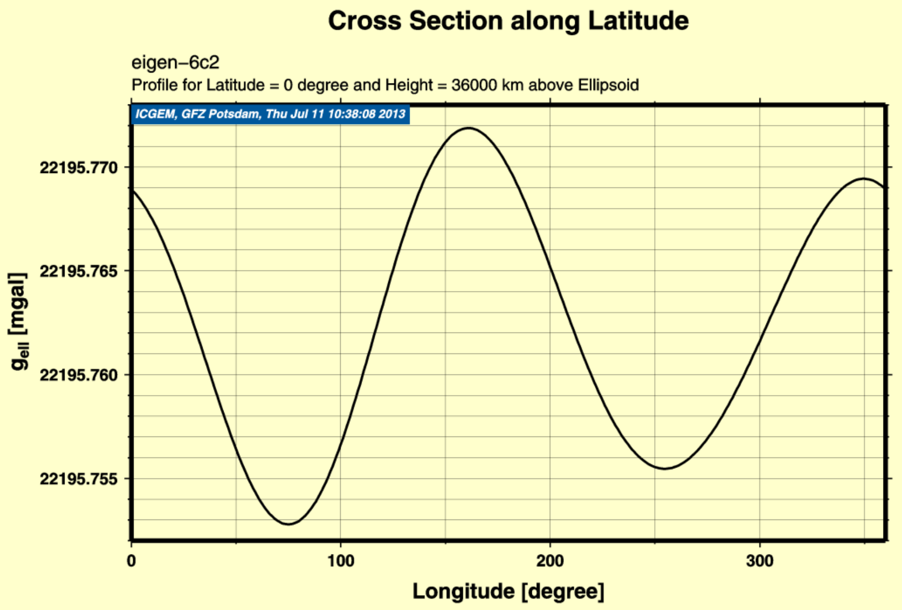
Calculation Service



Calculation Service

Cross Sections
(here: gravitation on and above the ellipsoid)

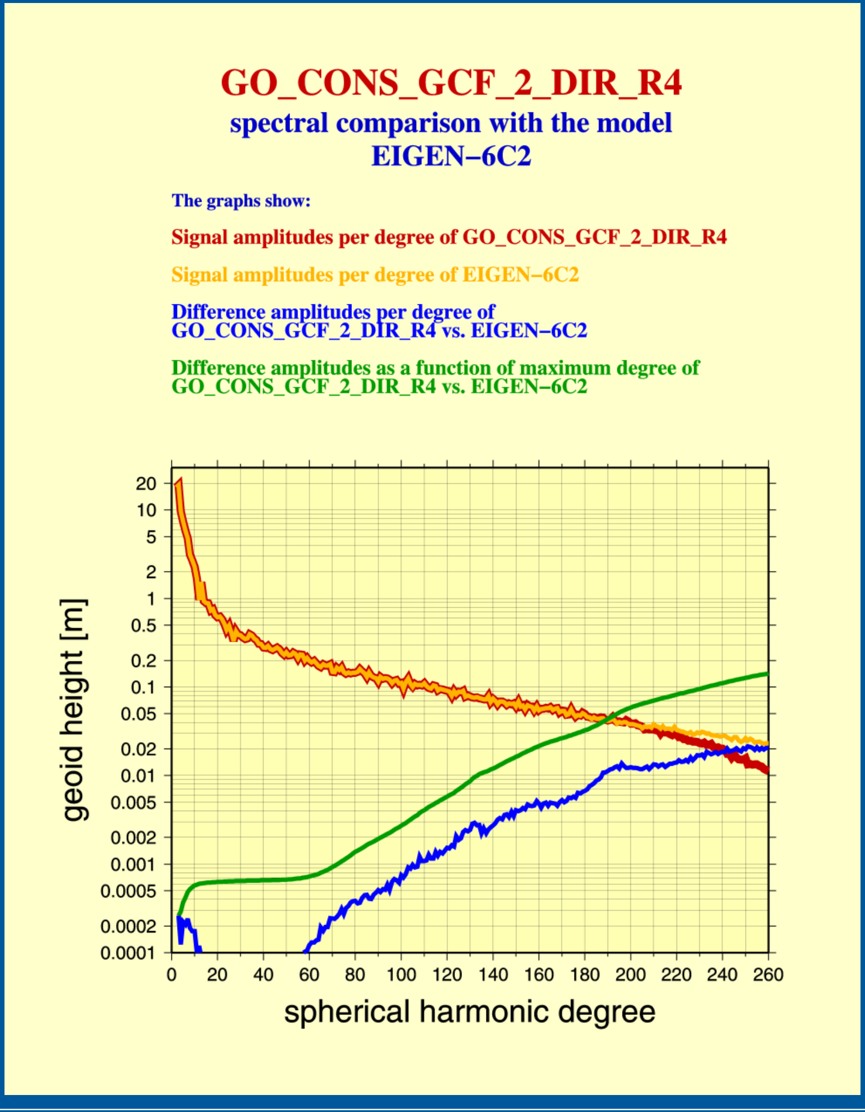




Evaluation of the Models

Comparisons in the spectral domain

→ plot for each model



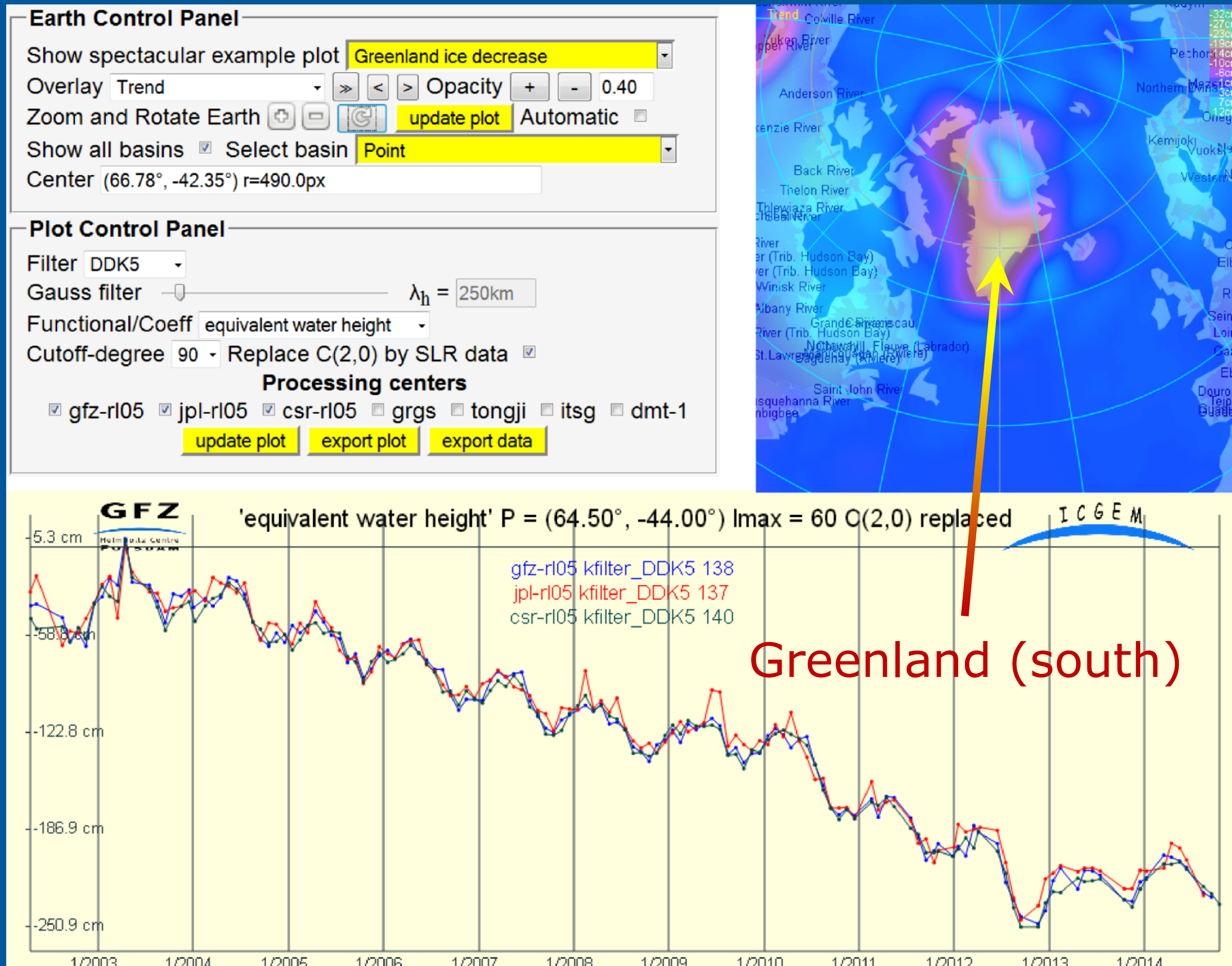
Evaluation of the Models

Comparisons with GPS-levelling data

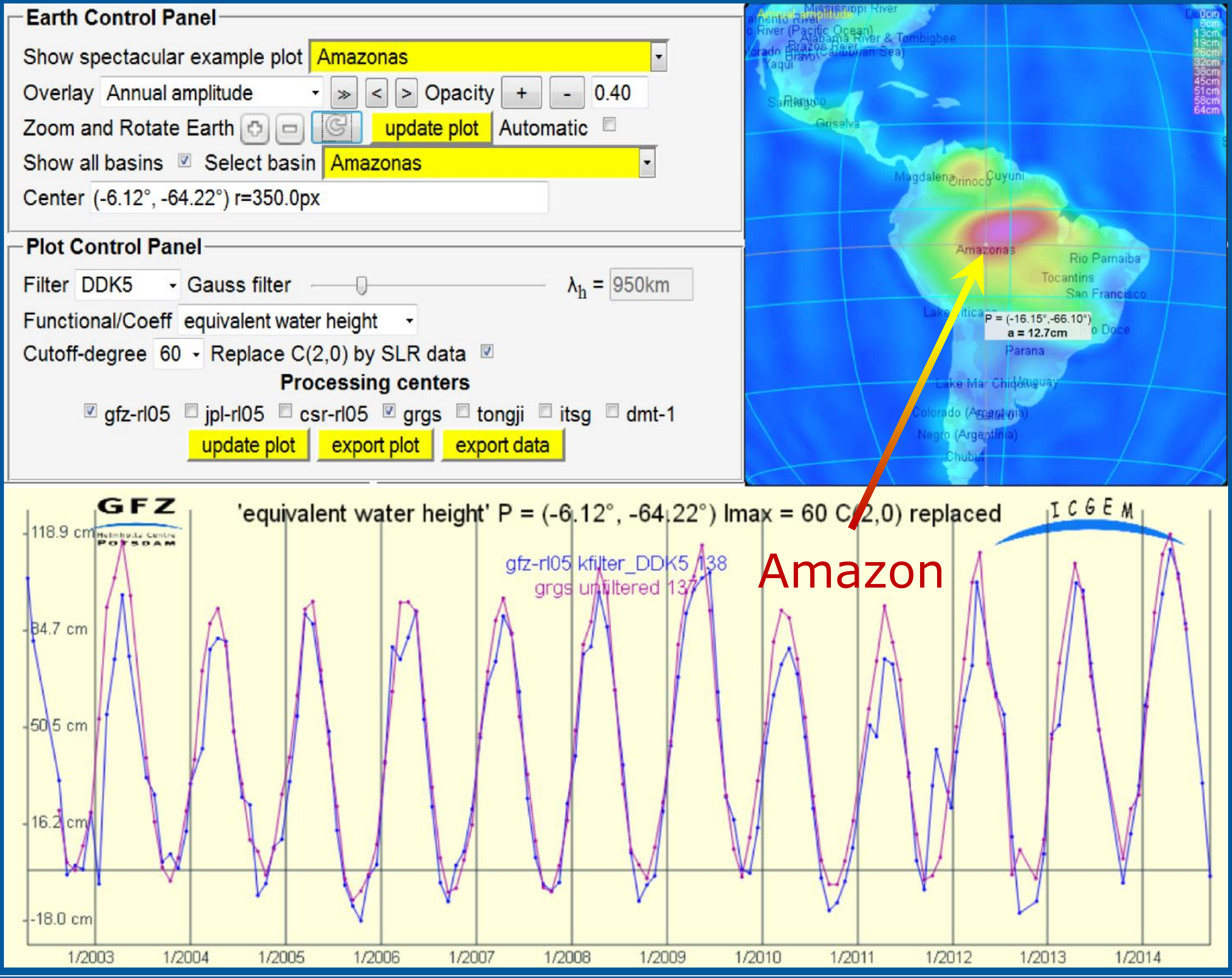
The table is interactively re-sortable for all columns by clicking in the header cells.

Nr▲	Model ⇅	Nmax ⇅	USA ⇅ 6169 points	Canada ⇅ 2691 points	Europe ⇅ 1235 points	Australia ⇅ 201 points	Japan ⇅ 816 points	Brazil ⇅ 1112 points	All ⇅ 12224 points
136	**GOCO05S**	280	0.399 m	0.308 m	0.372 m	0.335 m	0.450 m	0.505 m	0.3921 m
135	**GO_CONS_GCF_2_SPW_R4**	280	0.406 m	0.330 m	0.394 m	0.322 m	0.473 m	0.508 m	0.4037 m
134	**EIGEN-6C4**	2190	0.247 m	0.126 m	0.210 m	0.212 m	0.079 m	0.446 m	0.2408 m
133	**ITSG-GRACE2014S**	200	1.095 m	0.871 m	1.015 m	1.175 m	0.932 m	1.273 m	1.0508 m
132	**ITSG-GRACE2014K**	200	0.542 m	0.419 m	0.580 m	0.433 m	0.651 m	0.611 m	0.5350 m
131	**GO_CONS_GCF_2_TIM_R5**	280	0.398 m	0.310 m	0.371 m	0.336 m	0.450 m	0.505 m	0.3919 m
130	**GO_CONS_GCF_2_DIR_R5**	300	0.405 m	0.299 m	0.373 m	0.327 m	0.447 m	0.507 m	0.3937 m
129	**JYY_GOCE04S**	230	0.422 m	0.359 m	0.416 m	0.342 m	0.506 m	0.511 m	0.4225 m
128	**GOGRA04S**	230	0.421 m	0.359 m	0.415 m	0.342 m	0.507 m	0.511 m	0.4220 m
127	**EIGEN-6S2**	260	0.405 m	0.322 m	0.393 m	0.337 m	0.476 m	0.512 m	0.4025 m
126	**GGM05S-UPTO150**	150	0.640 m	0.606 m	0.699 m	0.478 m	0.876 m	0.668 m	0.6576 m
125	**EIGEN-6C3STAT**	1949	0.247 m	0.129 m	0.212 m	0.213 m	0.078 m	0.447 m	0.2415 m
124	**TONGJI-GRACE01**	160	0.596 m	0.595 m	0.694 m	0.495 m	0.835 m	0.682 m	0.6314 m
123	**JYY_GOCE02S**	230	0.422 m	0.386 m	0.423 m	0.344 m	0.516 m	0.522 m	0.4304 m
11	**WGS72**	28	2.971 m	2.248 m	3.529 m	2.984 m	7.610 m	3.721 m	3.4777 m
10	**GEM4**	16	3.467 m	3.145 m	2.880 m	3.314 m	5.647 m	3.058 m	3.4987 m
9	**GEM3**	12	5.225 m	4.954 m	3.336 m	3.954 m	4.322 m	4.655 m	4.8767 m
8	**GEM2**	22	2.910 m	3.359 m	3.720 m	3.003 m	4.080 m	3.677 m	3.2625 m
7	**GEM1**	22	4.180 m	5.075 m	3.164 m	3.449 m	4.847 m	2.713 m	4.2348 m
6	**KOCH71**	11	17.179 m	10.880 m	12.101 m	11.823 m	6.075 m	21.583 m	15.3930 m
5	**KOCH70**	8	15.783 m	12.300 m	10.683 m	13.334 m	2.854 m	10.538 m	13.5699 m
4	**SE2**	22	3.897 m	4.777 m	4.434 m	3.325 m	4.924 m	3.719 m	4.2110 m
3	**OSU68**	14	4.261 m	8.921 m	3.654 m	5.097 m	4.013 m	3.690 m	5.5474 m
2	**WGS66**	24	3.206 m	5.307 m	3.360 m	3.982 m	5.853 m	4.680 m	4.1311 m
1	**SE1**	15	3.895 m	5.071 m	8.339 m	3.826 m	5.003 m	6.003 m	5.0527 m

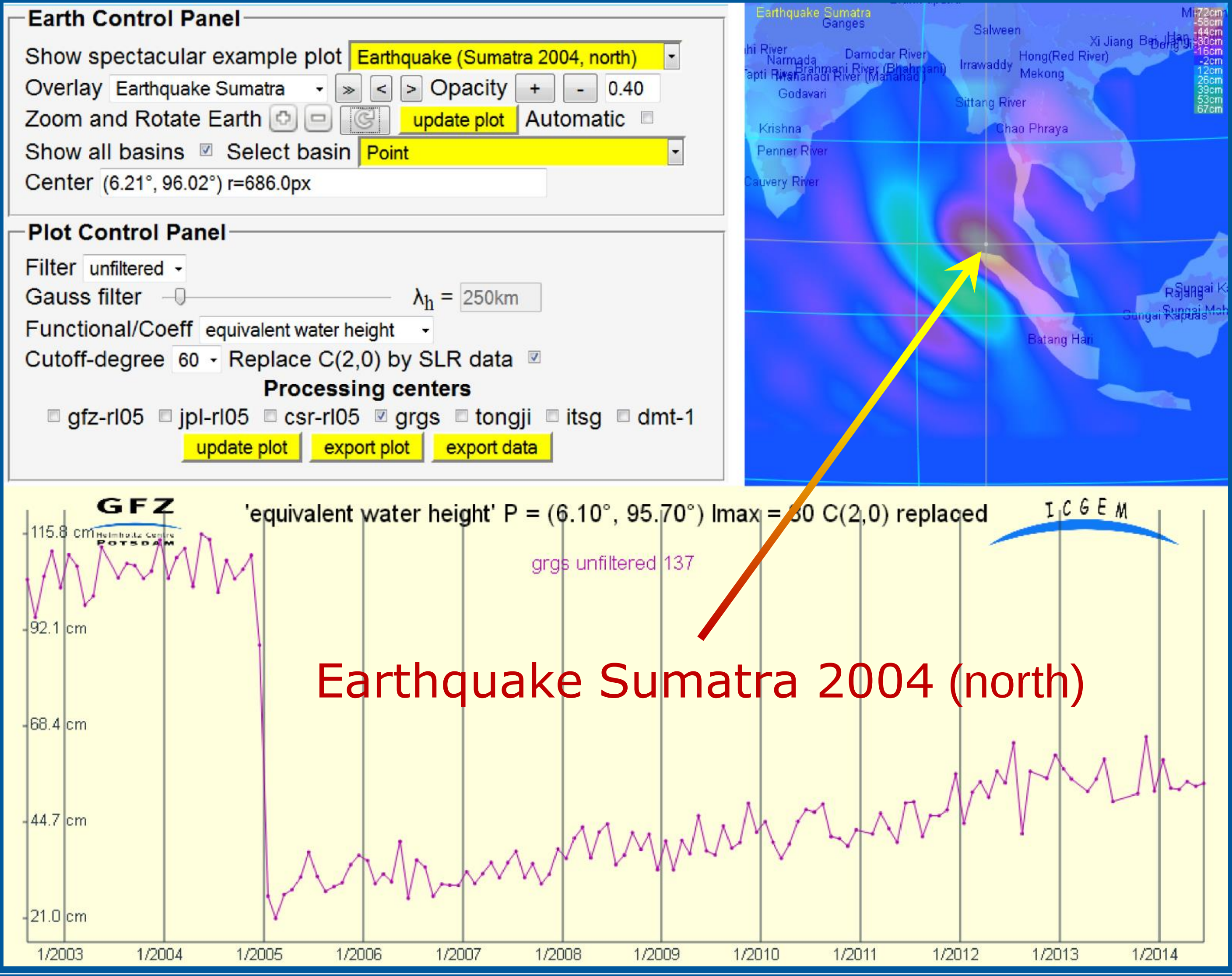
The G^3-Browser (GFZ Grace Gravity Browser)



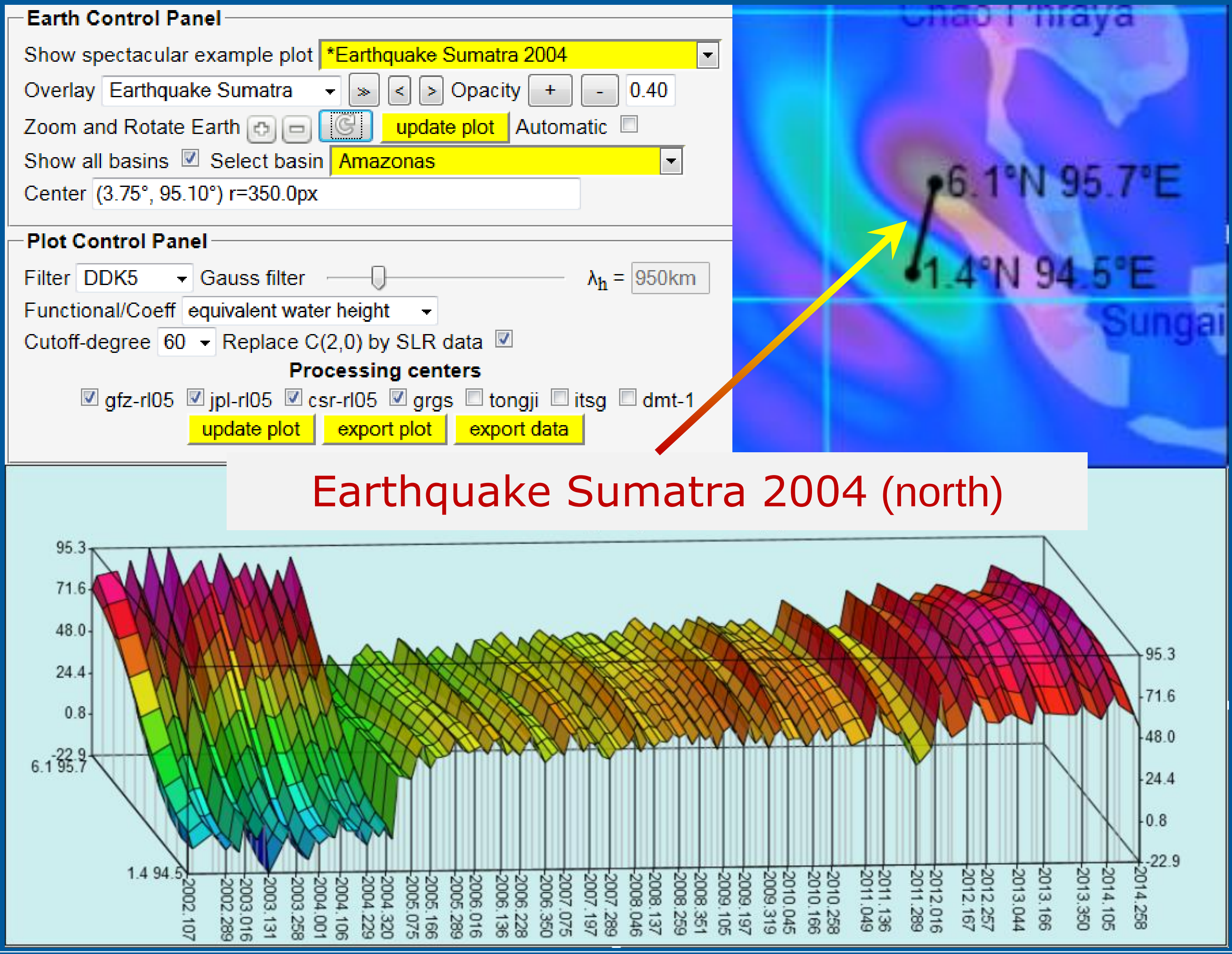
The G³-Browser (GFZ Grace Gravity Browser)



The G³-Browser (GFZ Grace Gravity Browser)



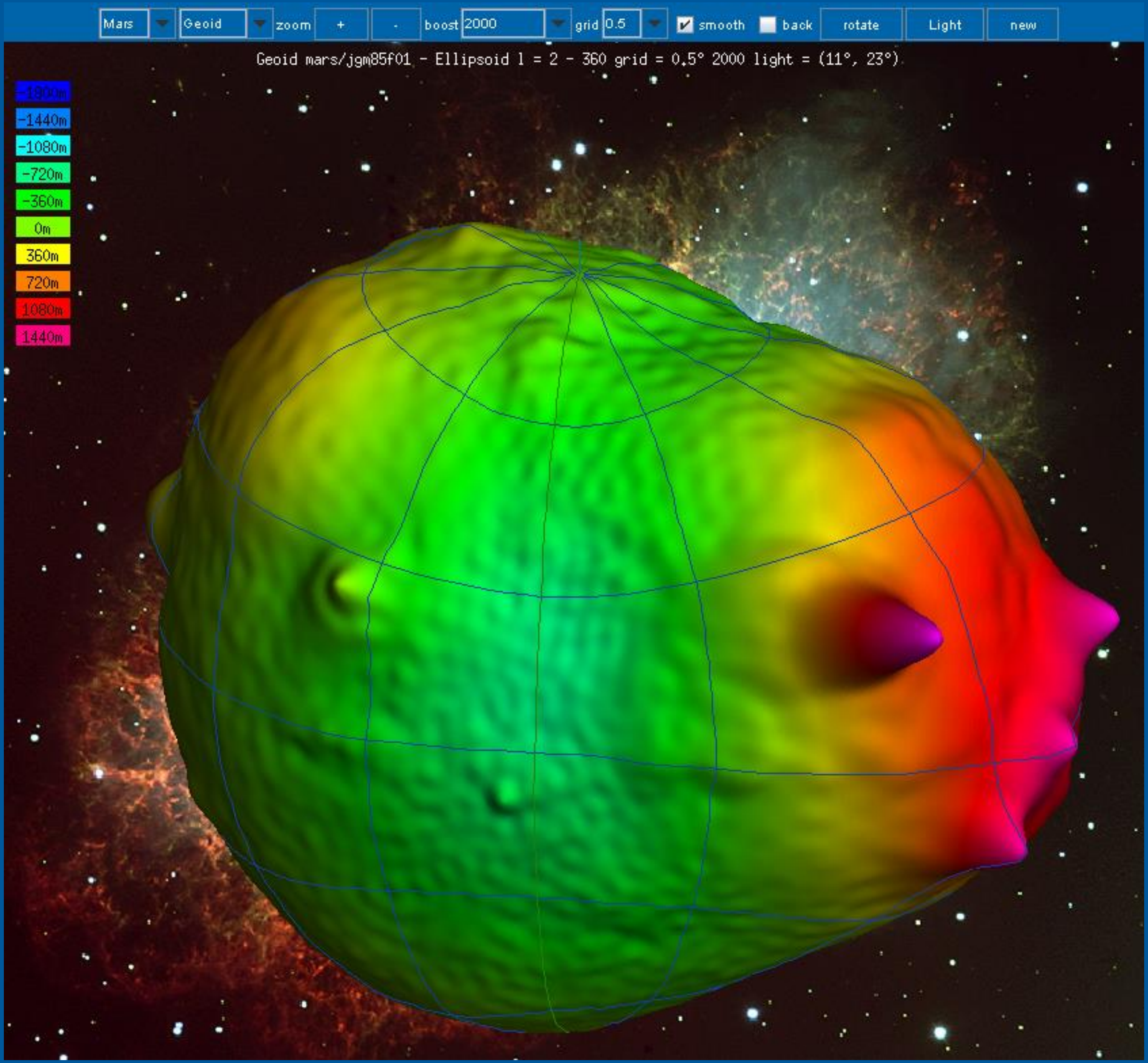
The G³-Browser (GFZ Grace Gravity Browser)



Latest Changes (and history)

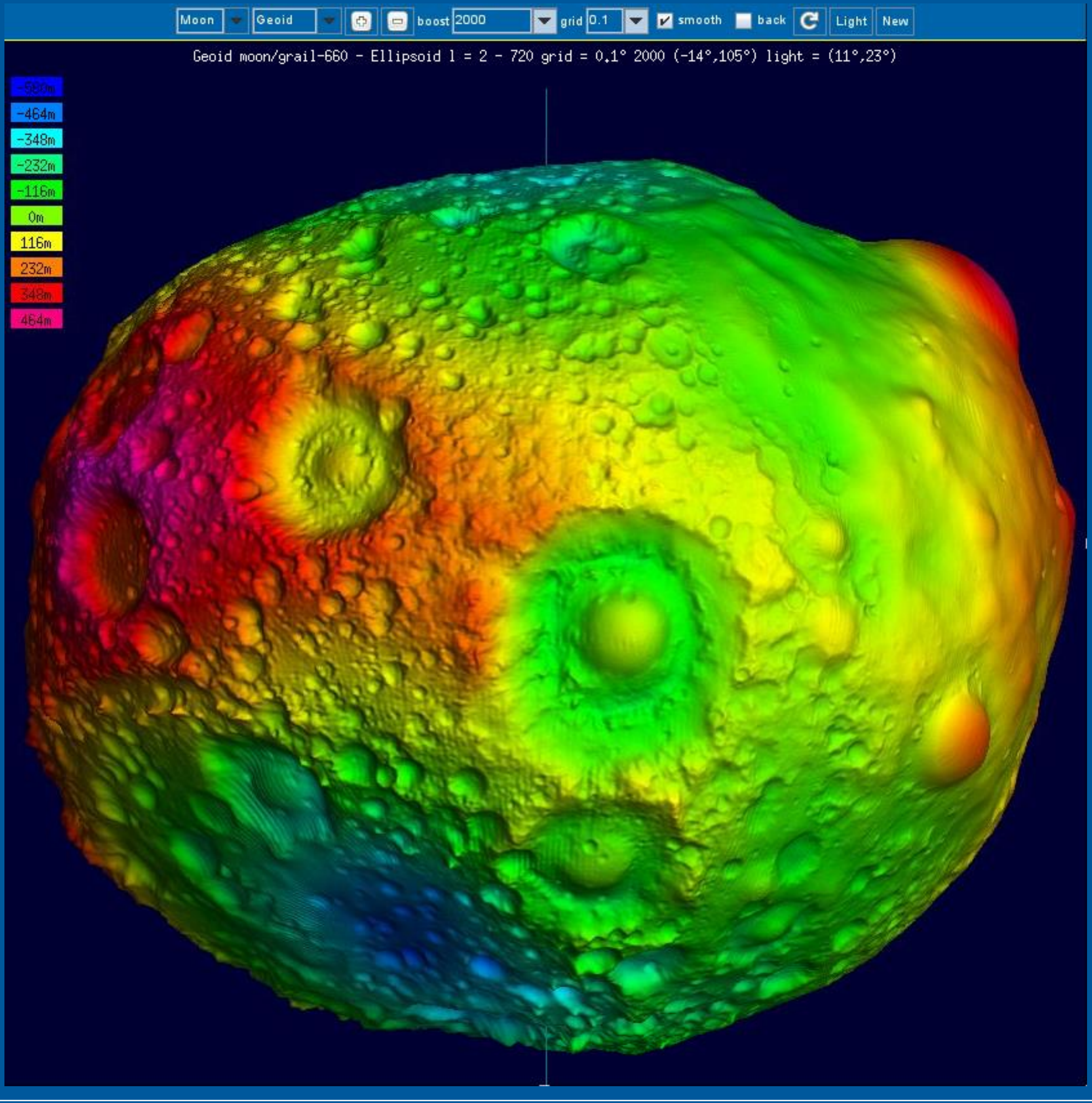
- **15. May 2015:**
  Bugfix for the Visualizations Services: The computed grids for very small values of lmax (*lmax ≤ 5*) contained extremely large numbers. Unfortunately, this error could have quite drastic consequences for the user: Since the Java-server-thread did not finish rendering, the limitation of access numbers could inhibit further connections for this client.
- **27. April 2015:**
  The "G³ Browser" has the new feature to display 3D-grid-plots for cross-sections (a line defined by two end-points). Example plots for the two major Earthquakes and polar regions have been added.
- **16. April 2015:**
  For the Visualization Services now also the functional Water column can be displayed (for static fields and monthly models of the Earth).
- **31. March 2015:**
  New model **GOCO05s** included.
- **27. March 2015:**
  The last two pages that contained Java applets ("Visualization of Monthly Models", "Calculation Service for Celestial Bodies") have been replaced with JavaScript versions. Our ICGEM-service is from now completely free of Java Applets!
- **25. March 2015:**
  The server-program for visualizations ("potato-server.C") now enables computations for higher orders (lmax > 360) by an improved routine for Legendre polynoms.
- **9. March 2015:**
  The Visualization Services (Potato.html, Tutorial.html, PotatoBodies.html) are now implemented completely in JavaScript (**no Java Applets**) to avoid Oracle's restrictions. It should now work for all operating systems and browsers. The ICGEM-service is now nearly **Java-free** (on the client-side).
  Additionally, users have now the option to download generated images as files, and in the page "Table of Models" the visualization of gravity models is now possible with a simple mouse click on the button 'show' (analogous to 'calculate').
- **30. January 2015:**
  The table of models on the page Evaluation of Models is now also interactively sortable, allowing a direct ranking of the models for different regions (and complete GPS/levelling data set).
- **26. January 2015:**
  - The Calculation Service is now implemented completely in JavaScript (**without Java Applets**) to avoid the access restrictions introduced by Oracle.
    It should now work for all operating systems and browsers without trouble.
    Additionally, users have now the option to download generated images as PNG file.
  - The Table of Models is now sortable (for 'Model','Year', 'Degree', 'Data' and 'References').
    The buttons calculate in the last column of the table now offer a direct link to the Calculation Service for the selcted model.

Byproducts: Models of Moon, Mars and Venus



Mars

Byproducts: Models of Moon, Mars and Venus

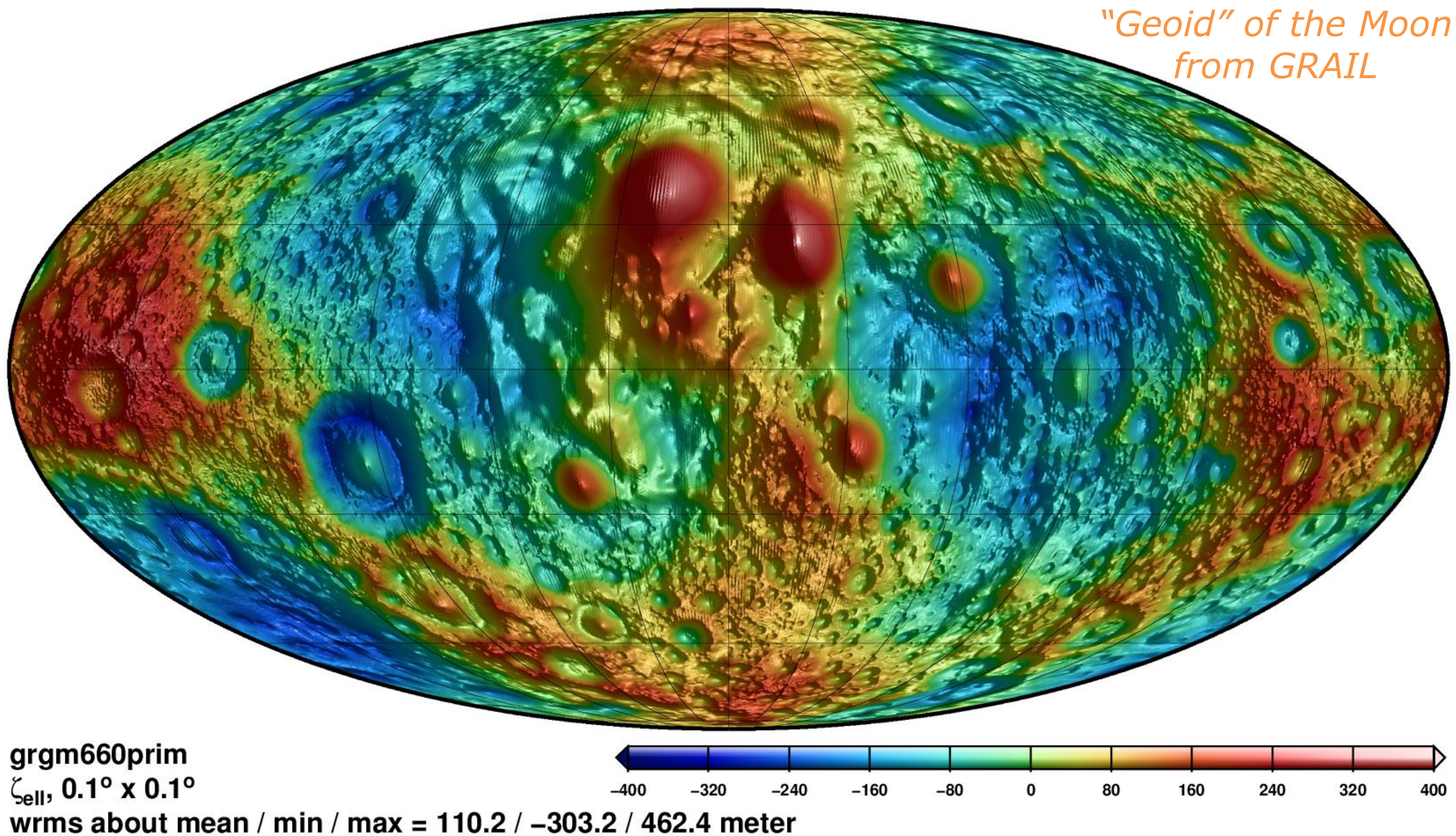


Moon

(GRAIL-mission)

Byproducts: Models of Moon, Mars and Venus

"Geoid" of the Moon from GRAIL

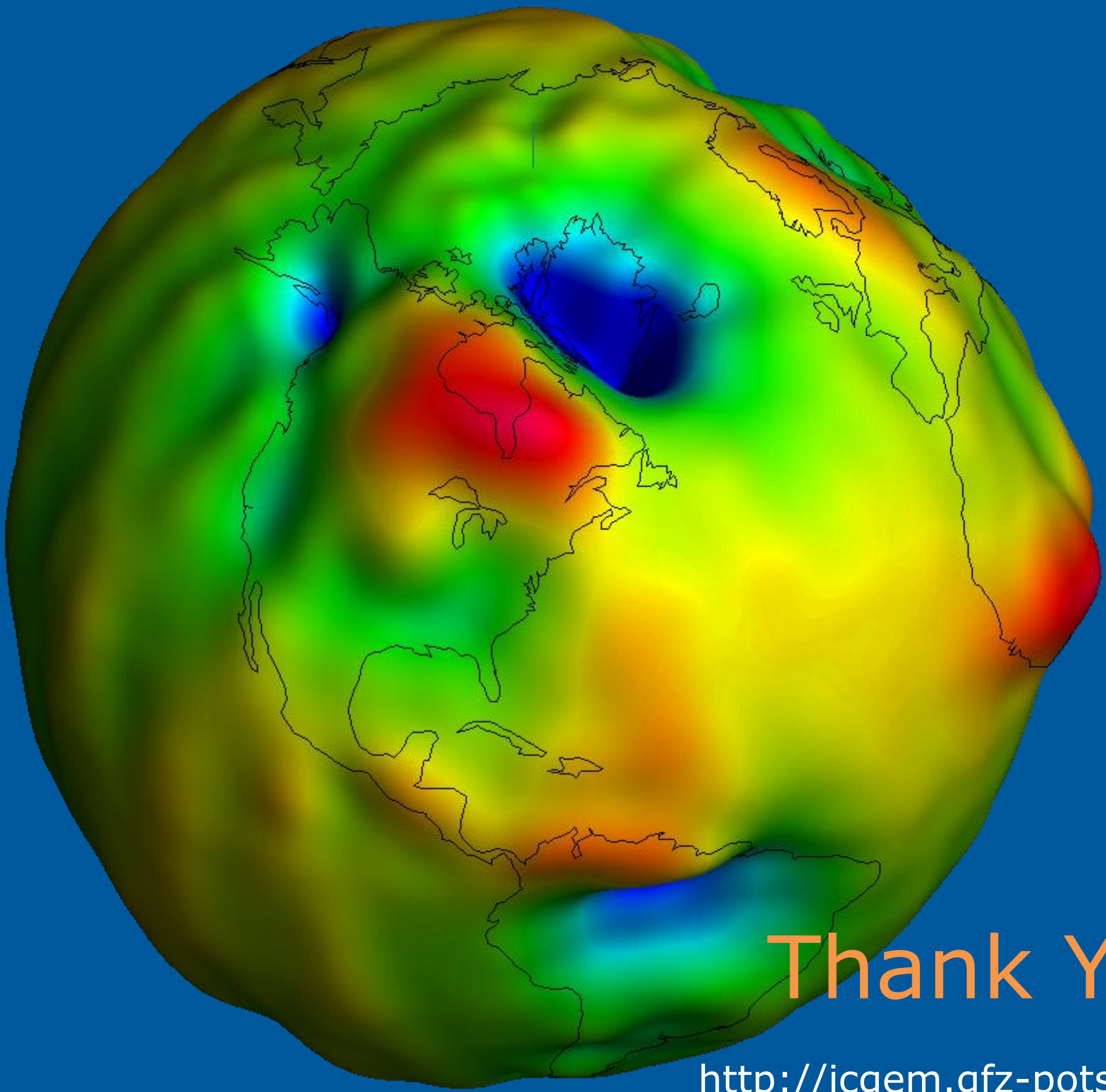


Conclusion

ICGEM do NOT offer:
research at the push of a button

But (hopefully) ICGEM:

- is useful for educational purposes
- helps to overcome obstacles in using the global gravity field models
- enables and stimulates research



Thank You

http://icgem.gfz-potsdam.de/ICGEM/