Gravity and Satellite Missions

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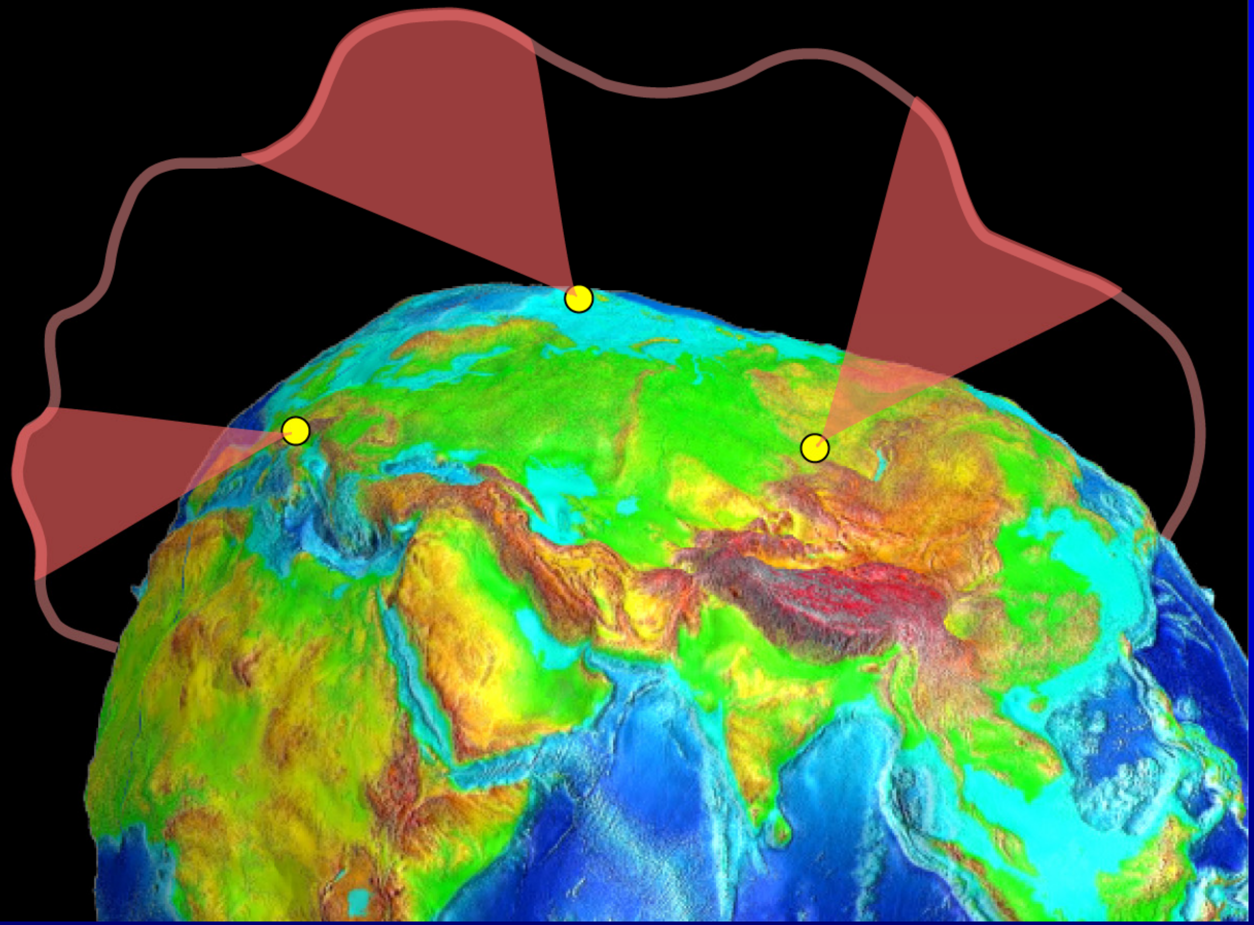
Typical Ground-Based Coverage

(before GPS Space Receiver became available)

- One dimension at a time
- Large coverage gaps
- Very critical for LEOs



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DOI Process for Gravity Field Recovery

$$\Delta r_i^T = [\Delta x_i, \Delta y_i, \Delta z_i] = f(\Delta C_{lm}, \Delta S_{lm})$$

Pseudo-observations

$$A = \left\{ \frac{\partial(\Delta x_i, \Delta y_i, \Delta z_i)}{\partial(\Delta C_{lm}, \Delta S_{lm})} \right\}$$

Design matrix from partials

$\{\Delta x_i, \Delta y_i, \Delta z_i\}$ → **LSA** → $\{\Delta \hat{C}_{lm}, \Delta \hat{S}_{lm}\}$

Observation residuals

Res. harmonic coeff.

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Gravity Field Representation & Functionals

$$T = \frac{GM}{R} \sum_{l=2}^{L} \sum_{m=0}^{l} \left(\frac{R}{r}\right)^{l+1} P_{lm}(\cos\vartheta) \left[\Delta\hat{C}_{lm} \cos m\lambda + \Delta\hat{S}_{lm} \sin m\lambda\right]$$

RESIDUAL GRAVITATIONAL POTENTIAL in m^2/s^2

RESOLUTION

100 km resolution requires L = 20000 km / 100 km = 200

$$N = R \sum_{l=2}^{L} \sum_{m=0}^{l} P_{lm}(\cos\vartheta) \left[\Delta\hat{C}_{lm} \cos m\lambda + \Delta\hat{S}_{lm} \sin m\lambda\right]$$

GEOID HEIGHTS in meter

$$\Delta g = \gamma \sum_{l=2}^{L} (l-1) \sum_{m=0}^{l} P_{lm}(\cos\vartheta) \left[\Delta\hat{C}_{lm} \cos m\lambda + \Delta\hat{S}_{lm} \sin m\lambda\right]$$

FREE AIR GRAVITY ANOMALIES in mgal (10^{-5} m/s^2)

$$c_l = \sum_{m=0}^{l} \left[C^2_{lm} + S^2_{lm}\right]$$

Power Spectral Density (PSD)
Average Signal Strength

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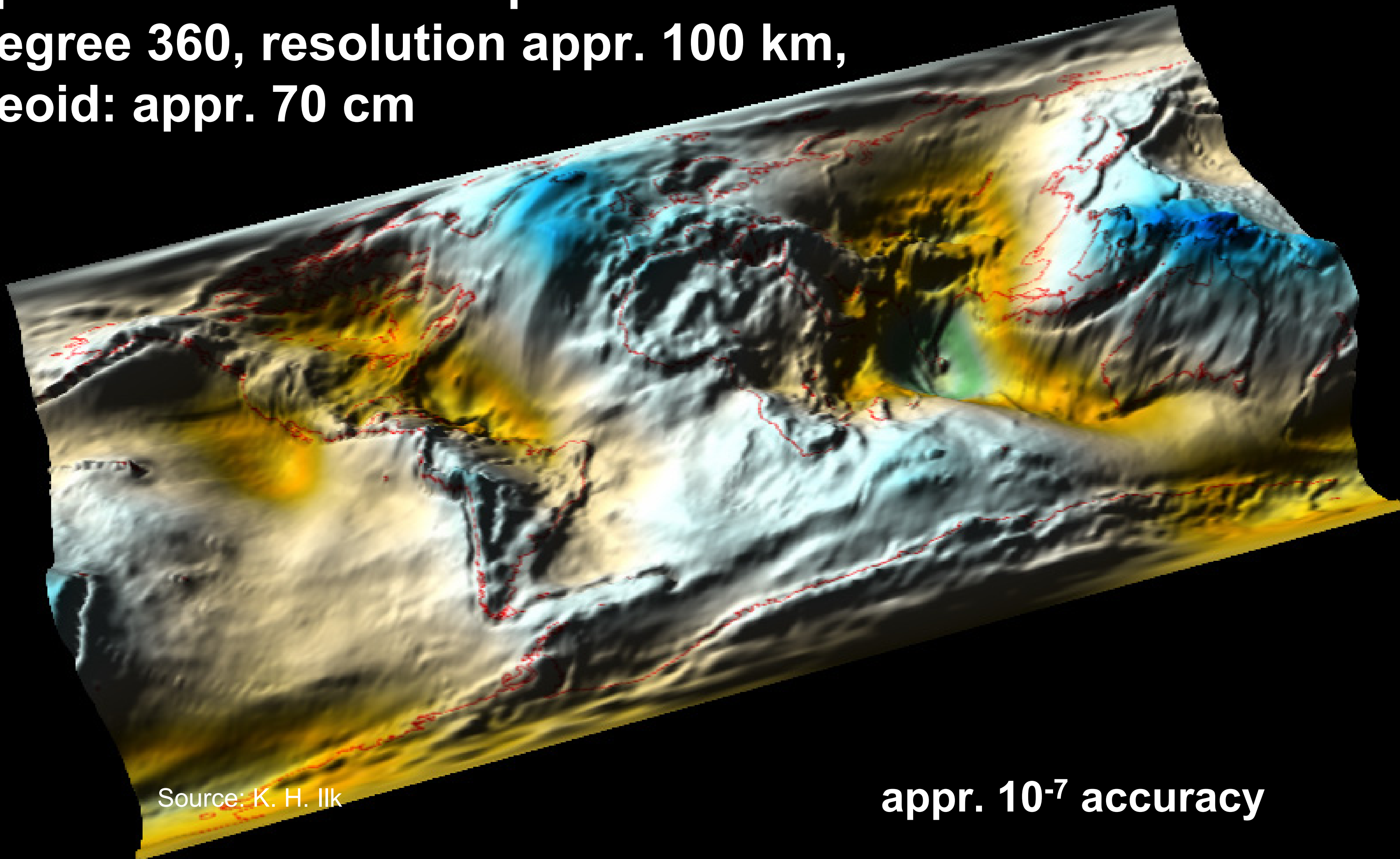
Earth Gravity Field in 2000

spherical harmonics up to degree 360, resolution appr. 100 km, geoid: appr. 70 cm



Source: K. H. Ilk

appr. 10^{-7} accuracy

Pre-CHAMP/GRACE Satellite Gravity Field Models

Model	Institution	Period
SE I-III	Smithonian Astrophysical Observatory	1966 - 1973
GEM 1-10/T1-3 *EGM 96*	Goddard Space Flight Center/ Ohio State University	1972 - 1998
GRIM 1-5	DGFI/GFZ Potsdam/GRGS Toulouse	1976 - 2000
TEG 1-4	CSR/UTEX Austin	1988 - 2001

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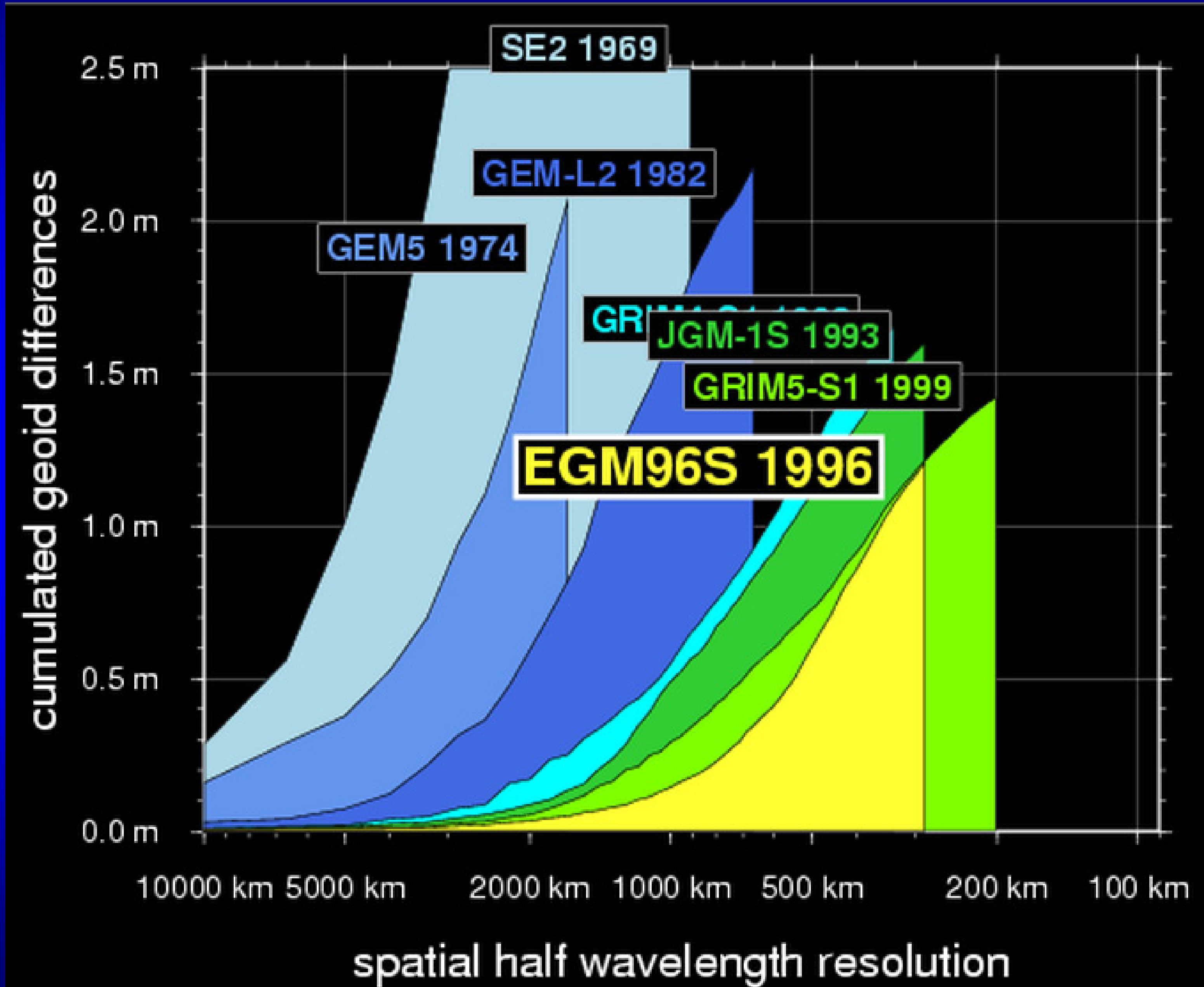
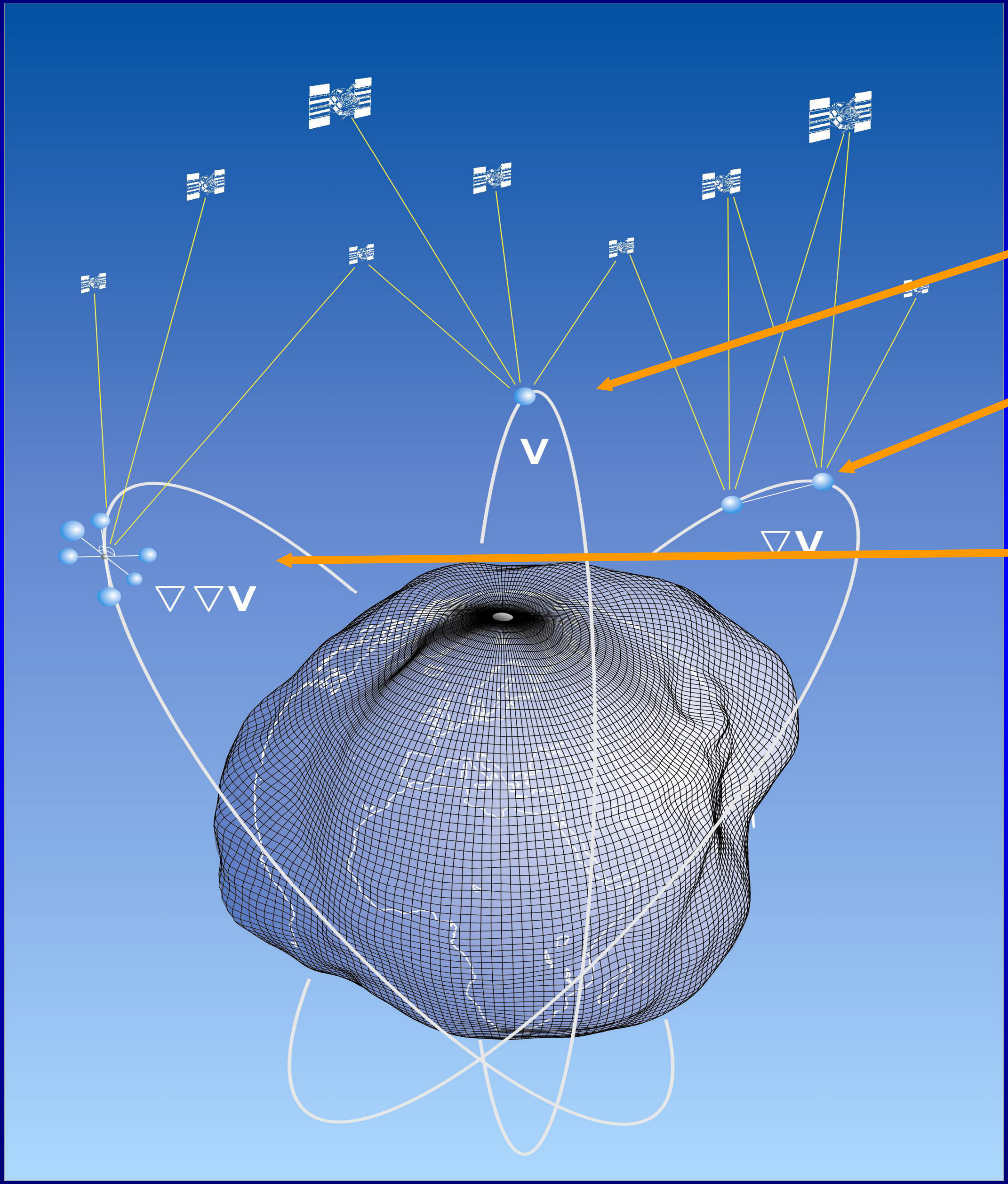
Pre-CHAMP/GRACE Satellite Gravity Field Models



New Observation Techniques



Satellite-to-Satellite Tracking

- ♦ *high- low*

Wolff, 1969

- ♦ *low- low*

Satellite Gravity Gradiometry

Williamstown	*1969, NASA*
Elmau	*1979, ESA*
Erice	*1985, IAG*
Coolfont	*1991, NASA*

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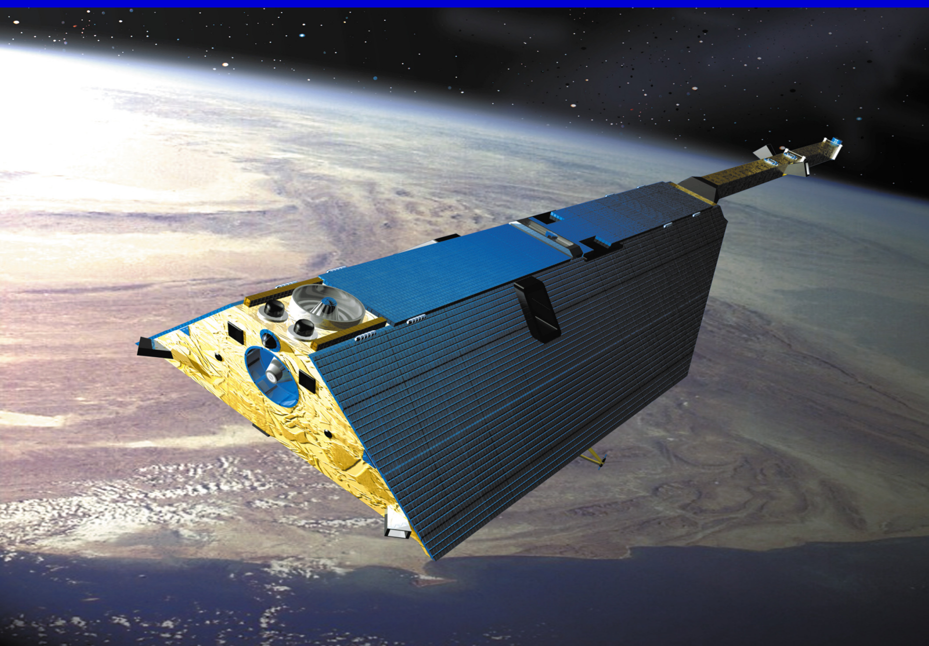
The Dawn of a New Age ....

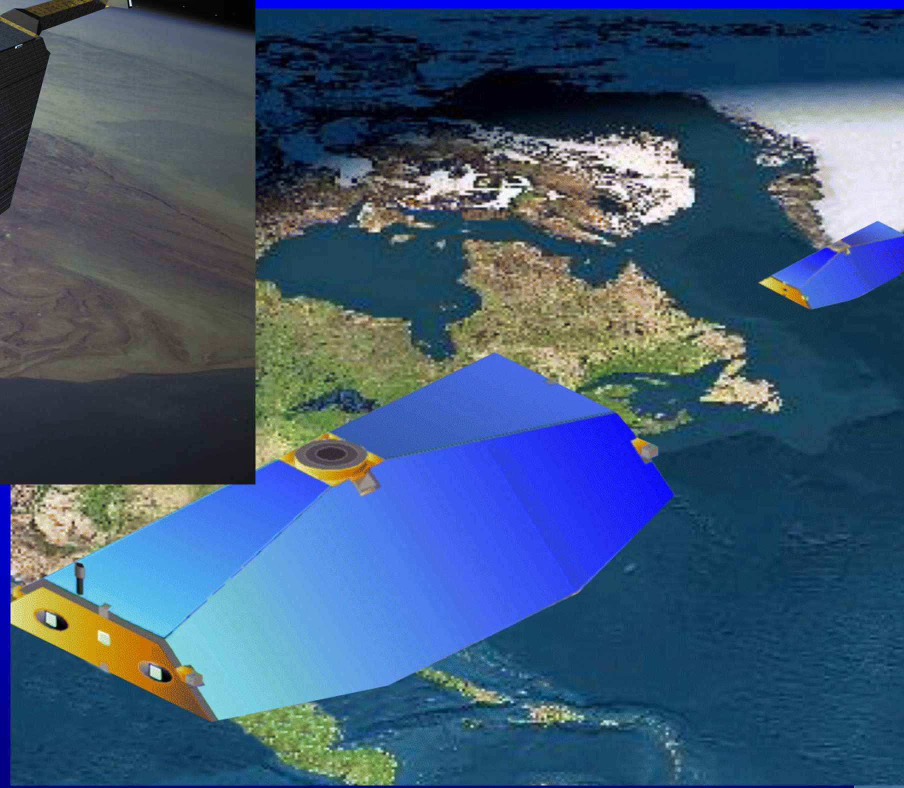
CHAMP (2000)

Germany



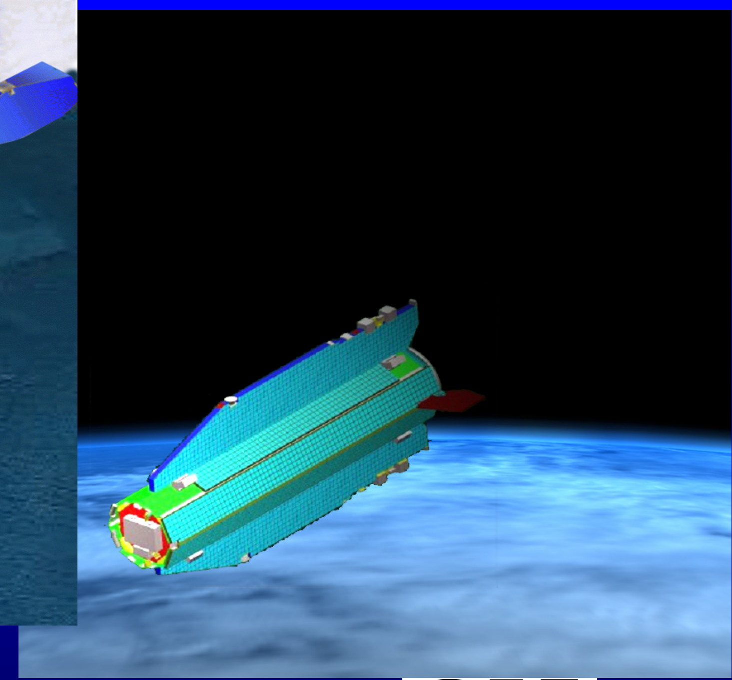
GRACE (2002)

USA-Germany



GOCE (2007)

European



CHAMP

Mission of GFZ Potsdam & DLR (Germany)
with contributions of NASA (USA), CNES (France) and AFRL (USA)

Launch: Juli 2000 **Mission duration:** 5 yrs
Orbit: nearly circular polar orbit (87°), 454 km altitude

Mission goals:

- **Gravity field mapping:** medium resolution static & time-variable components
- **Magnetic field mapping:** main & crustal field and time-variable components
- **Atmosphere & ionosphere sounding**

Payload:

- 3-D accelerometer (3x10^{-9} m/s^2).
- 16-channel GPS receiver (high-low SST)
- Laser-retro-reflector
- Magnetometer
- Ion drift meter
- Star sensors

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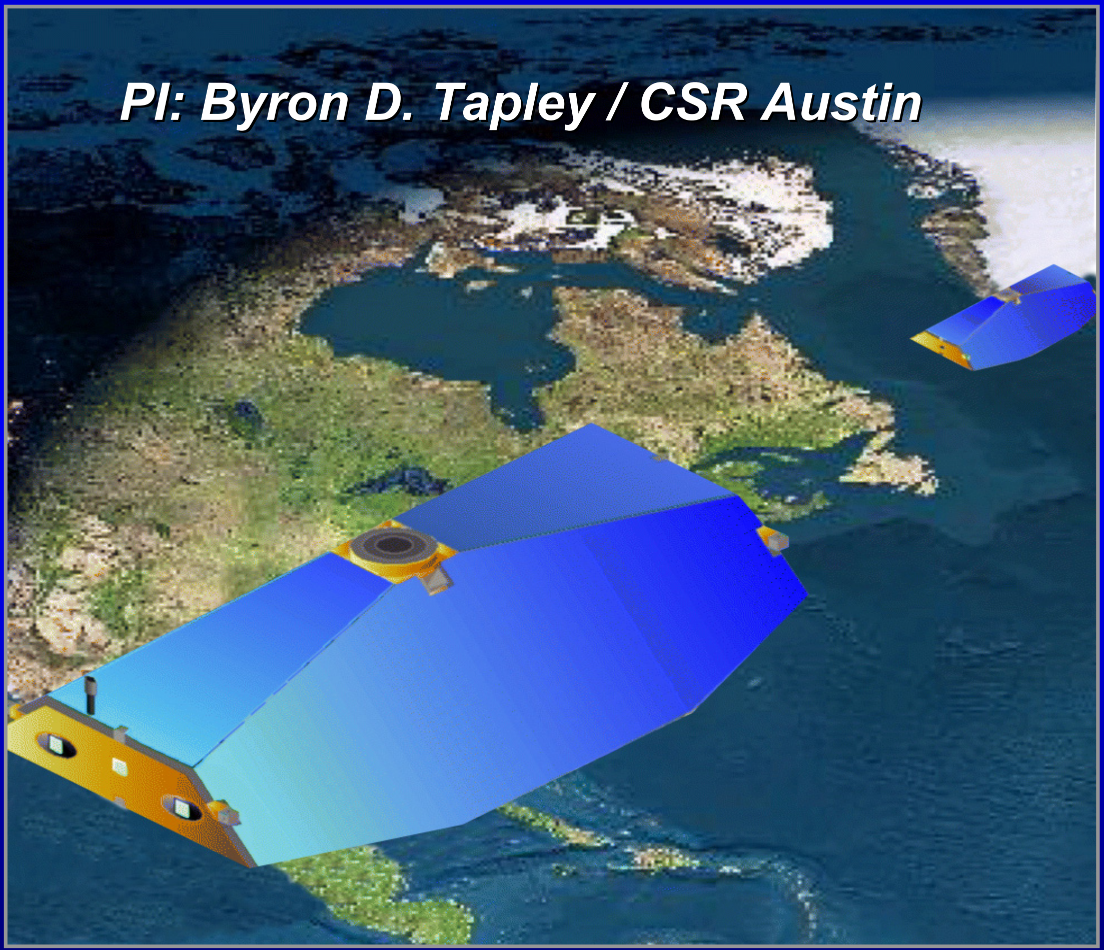
GRACE

Mission of NASA (USA), DLR (Germany), JPL(USA) , CSR/UTEX(USA) & GFZ Potsdam (Germany) within NASA´s ESSP Programme

Launch: Mar 2002 **Mission duration:** 5 yrs
Orbit: nearly circular polar orbit (89°), 500 km altitude



Mission goals:

- **High resolution, long- and medium-wave, mean & time- variable gravity field mapping**
- **Atmosphere sounding**

Payload:

- **Microwave distance ranging between the satellites (<5 μ), relative velocity (<0.5μ/s) (low-low SST)**
- **3-D accelerometer (10^{-10} m/s^2)**
- **24-channel GPS receiver (high-low SST)**
- **Laser-retro-reflector**
- **Star sensors**

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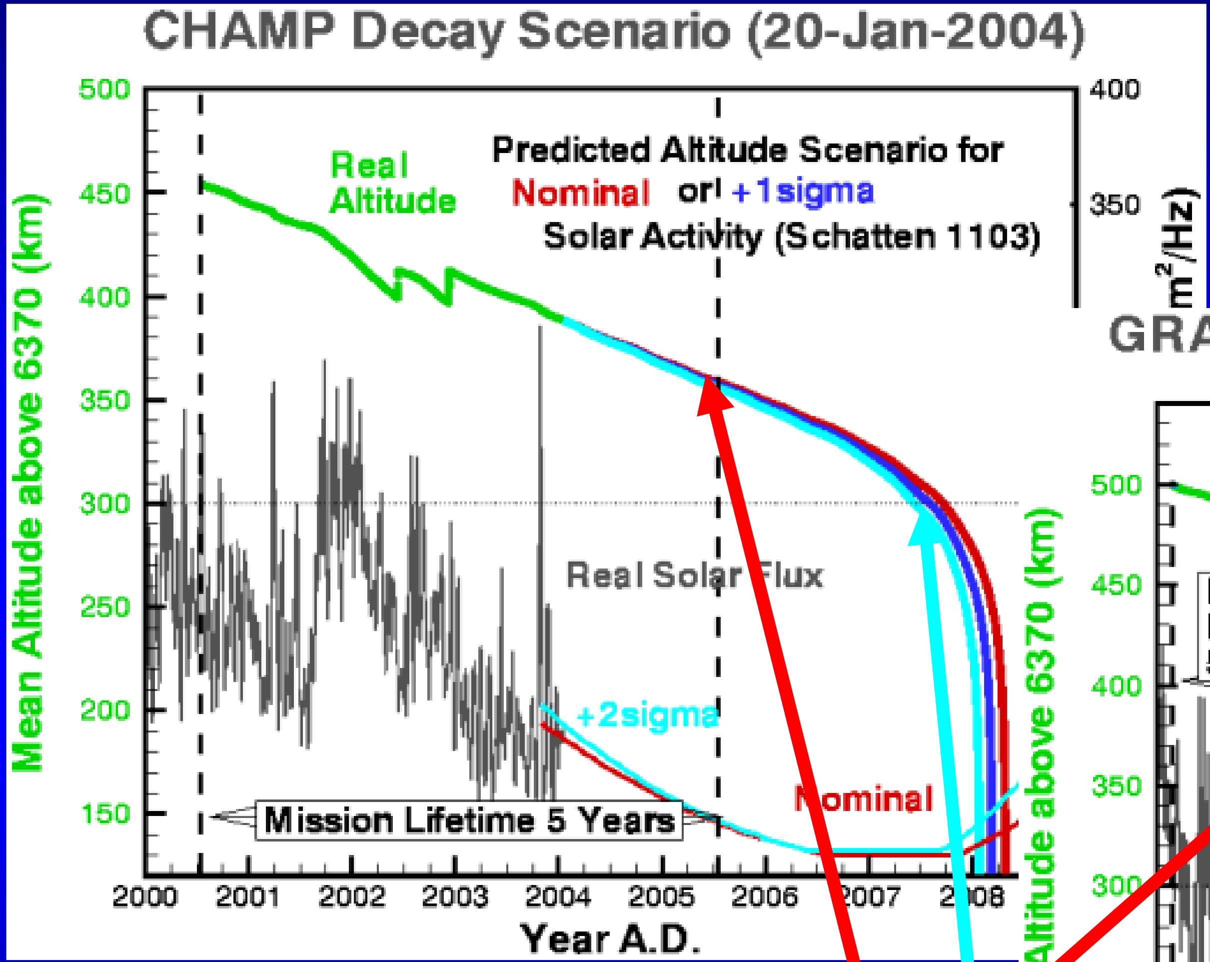
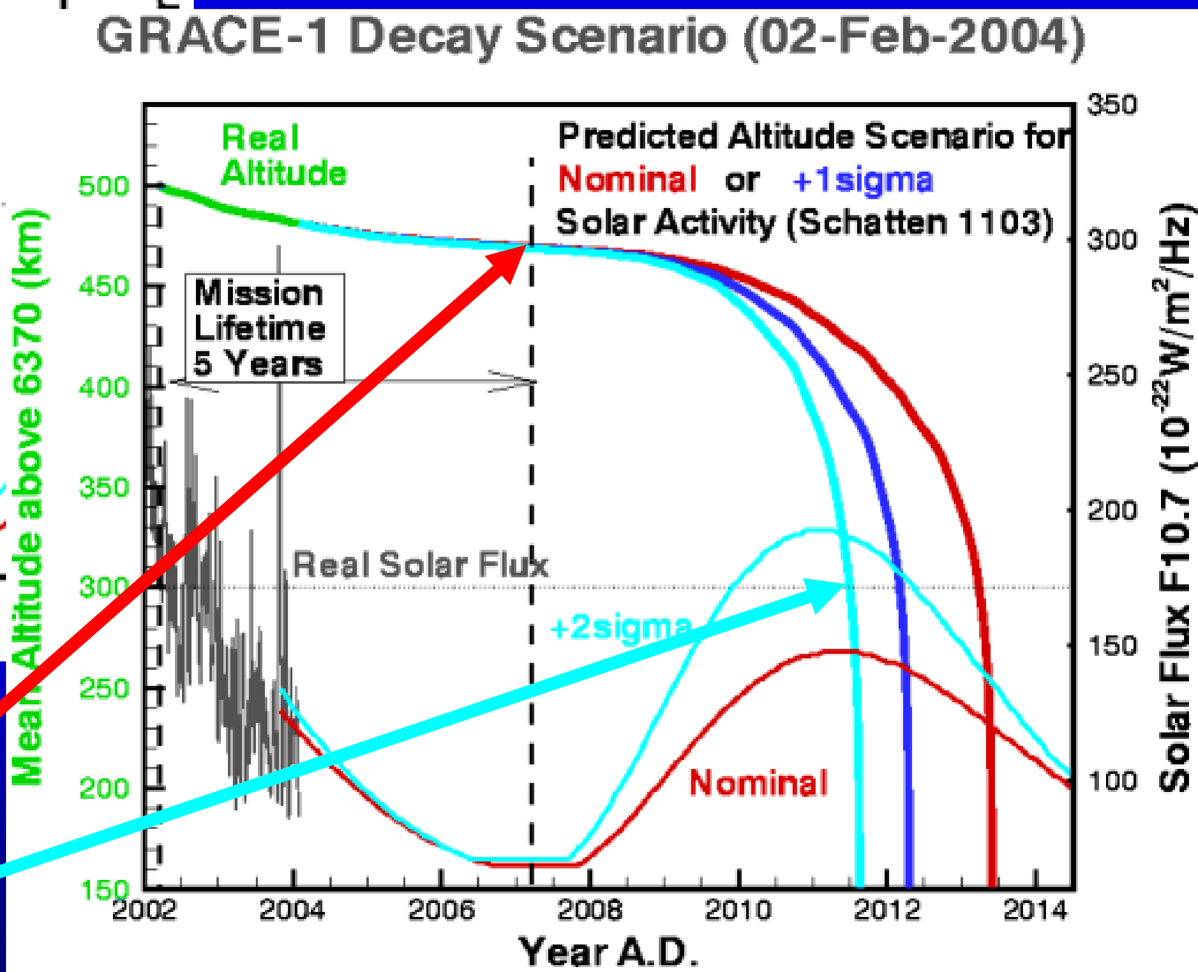
CHAMP & GRACE Orbit Altitude Evolution





Orbital altitude: 450 - 300 km

- Planned Mission duration: 5 years
- Expected Mission duration: 7- 8 years

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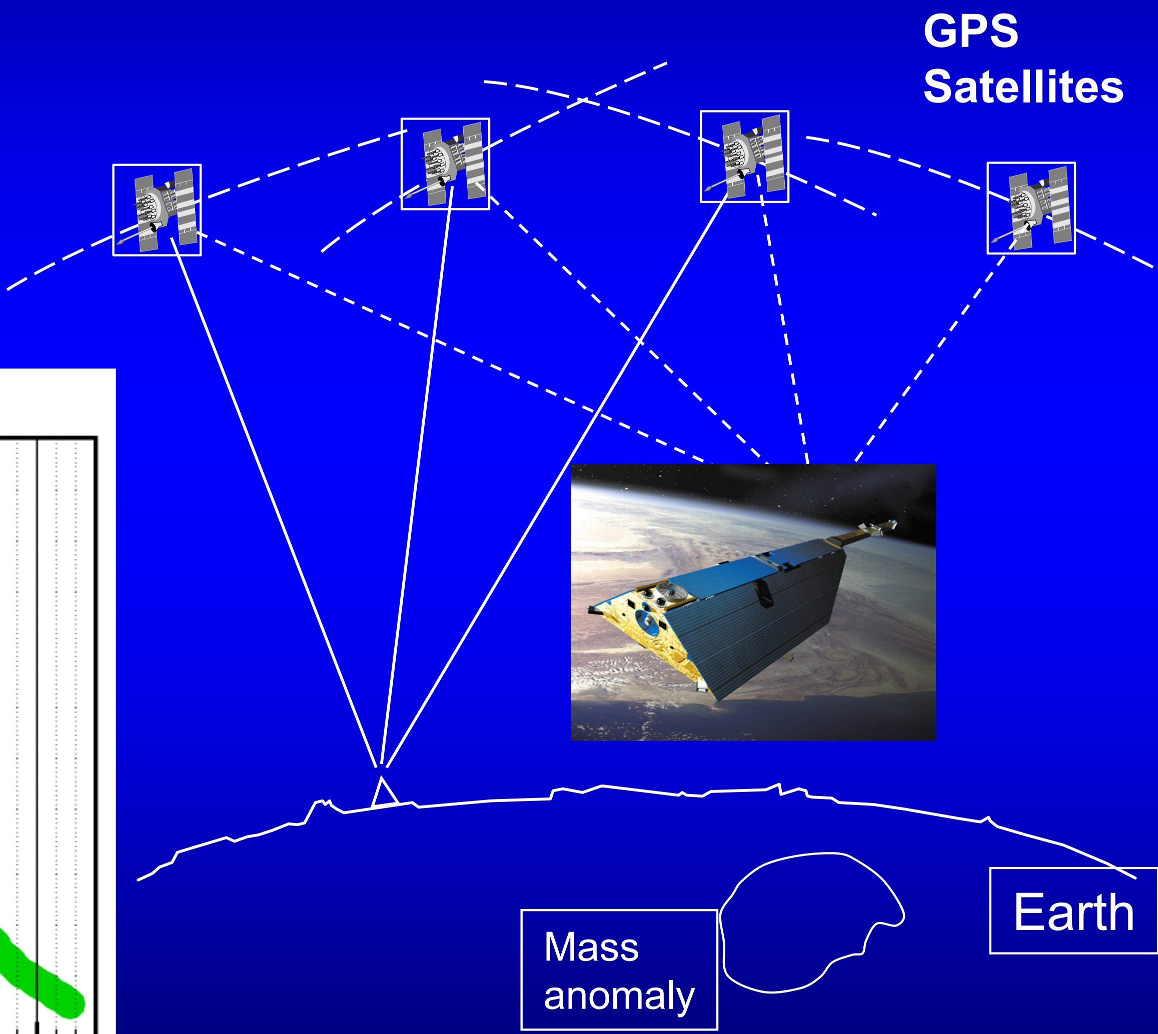
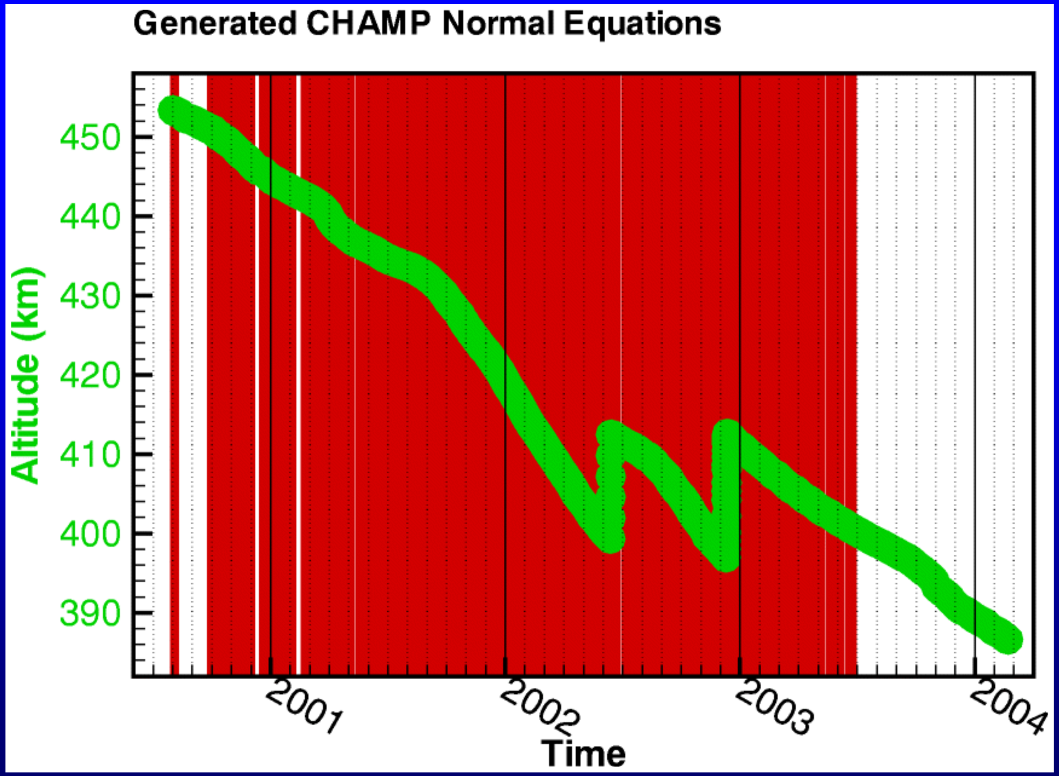
The CHAMP Mission - Gravity Recovery Part

Principle:

- GPS/CHAMP hl-SST-tracking
- 3D-measurement of surface forces
- Measurement of $\{x_i,\ \dot{x}_i\}$



Computed Normal Equations:



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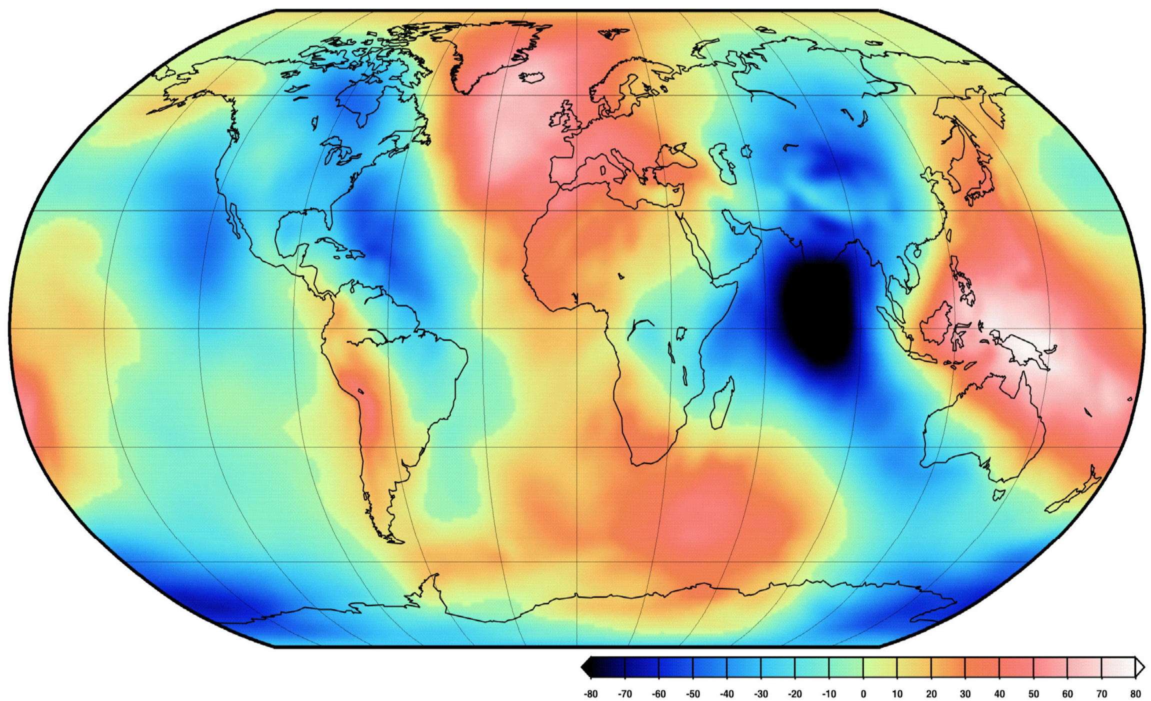
EIGEN –CHAMP03S GRAVITY MODEL

- **860 days of CHAMP data**
  (07/00-07/03) (570 1.5 day arcs)
  - 12 Mio GPS – SST code & phase observations
  - Attitude from star camera
  - Non-gravitational accelerations from Star accelerometer
- **Estimated parameters**
  - Initial conditions for 1.5 day arcs
  - Clock offsets
  - GPS-SST Ambiguities
  - Accelerometer bias and scale factors
- **Estimate 120x120 field using only data from CHAMP**



geoid [m] from 3 years of CHAMP data
(EIGEN-CHAMP03S), $\lambda/2$ = 2.5°

The geoid is the level (constant potential) surface that best coincides with mean sea level

The geoid height varies by ~200 m, but oceanographic applications need this to be determined to cm accuracy

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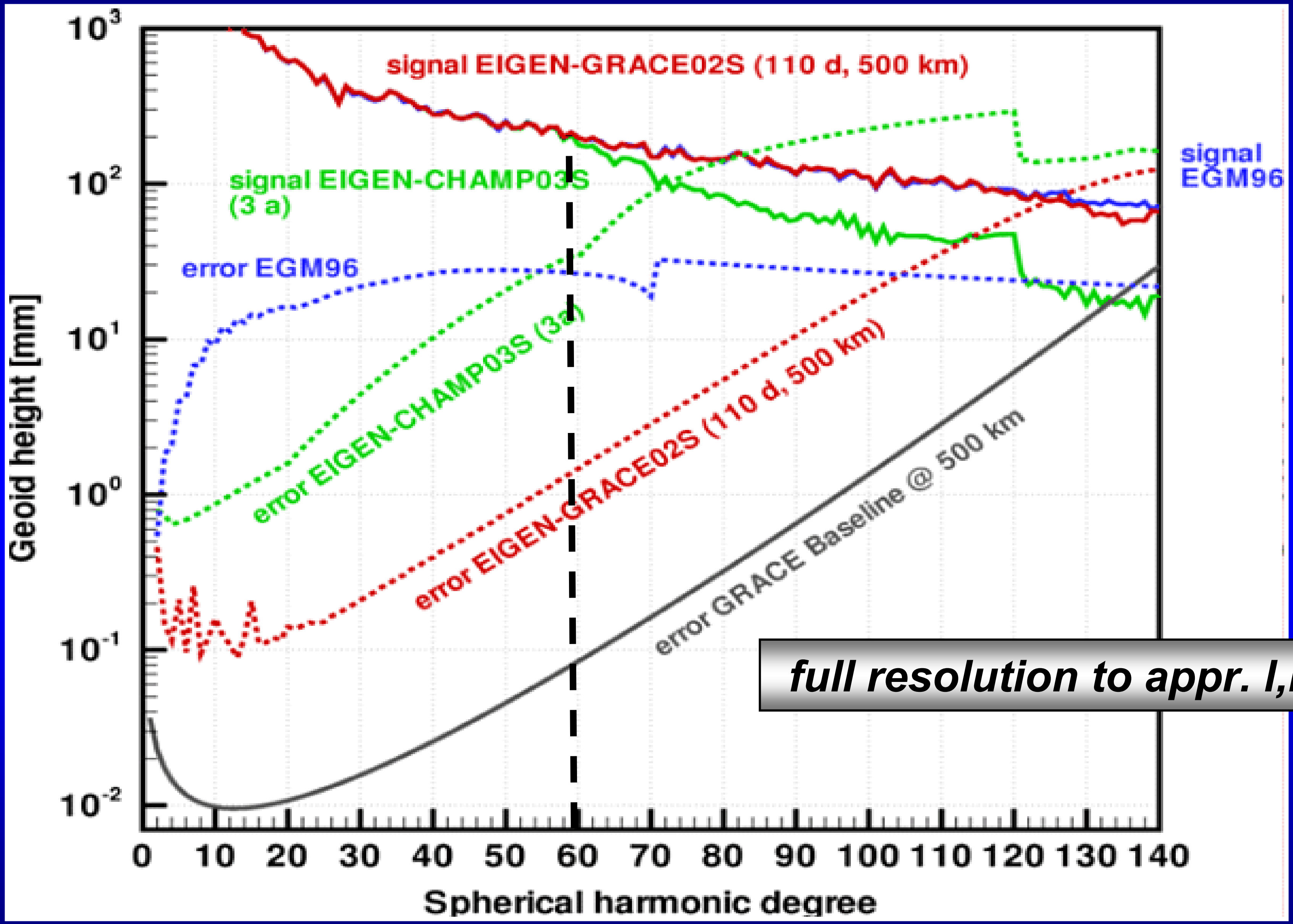
EIGEN-CHAMP03S Derived Geoid Signal & Error Spectrum



full resolution to appr. l,m = 60

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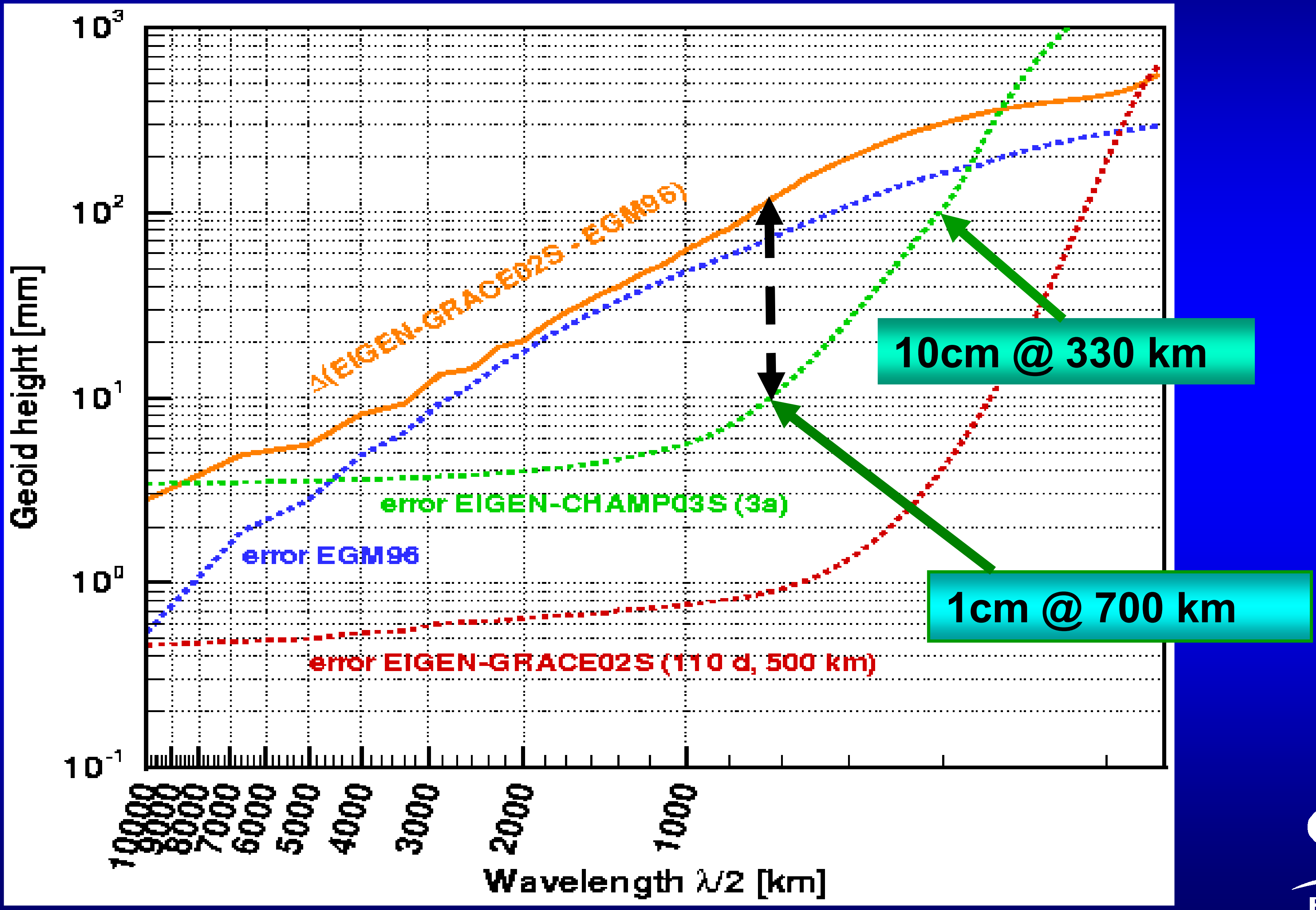
EIGEN – CHAMP03S Cummulated Geoid Error



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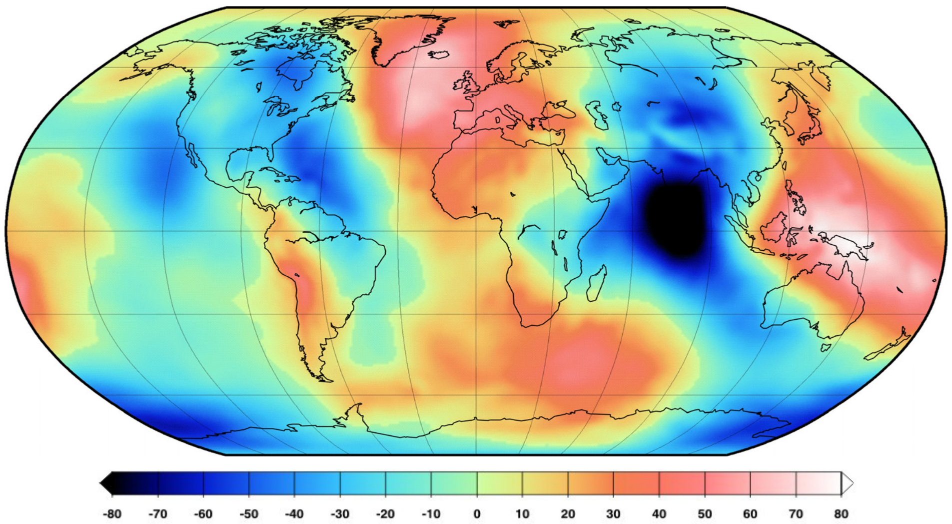
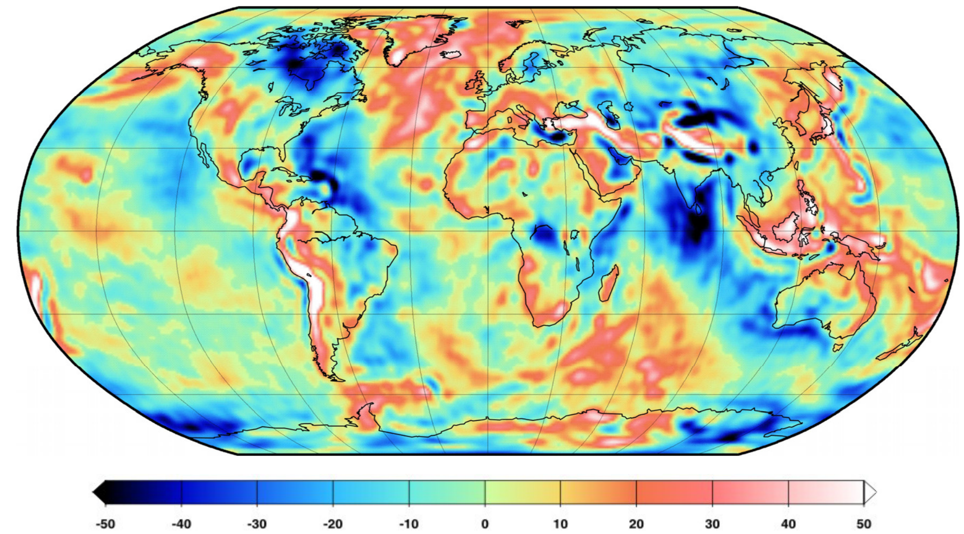
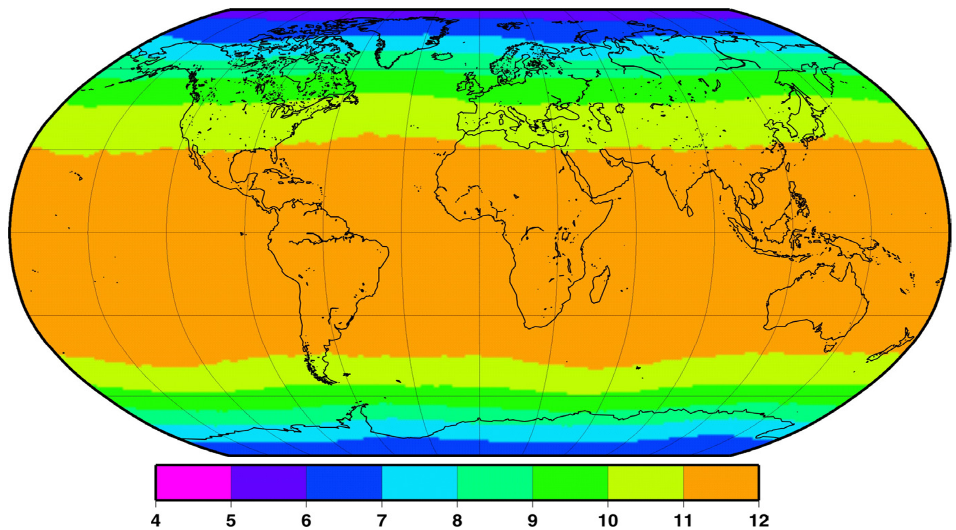
EIGEN-CHAMP03S Global Gravity Model



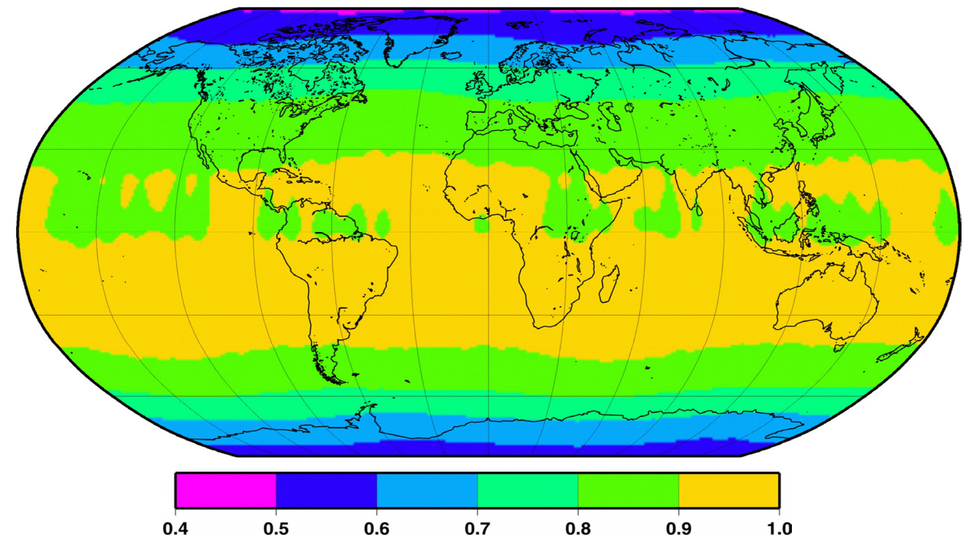
EIGEN-CHAMP03S geoid from 29 months CHAMP data, 2.5x2.5



EIGEN-CHAMP03S gravity anomalies from 29 moths CHAMP data, 2.5x2.5 deg (mgal)



EIGEN-CHAMP03S calibr. geoid standard deviations (cm), wrms = 10.7 cm, l_{max} = 60

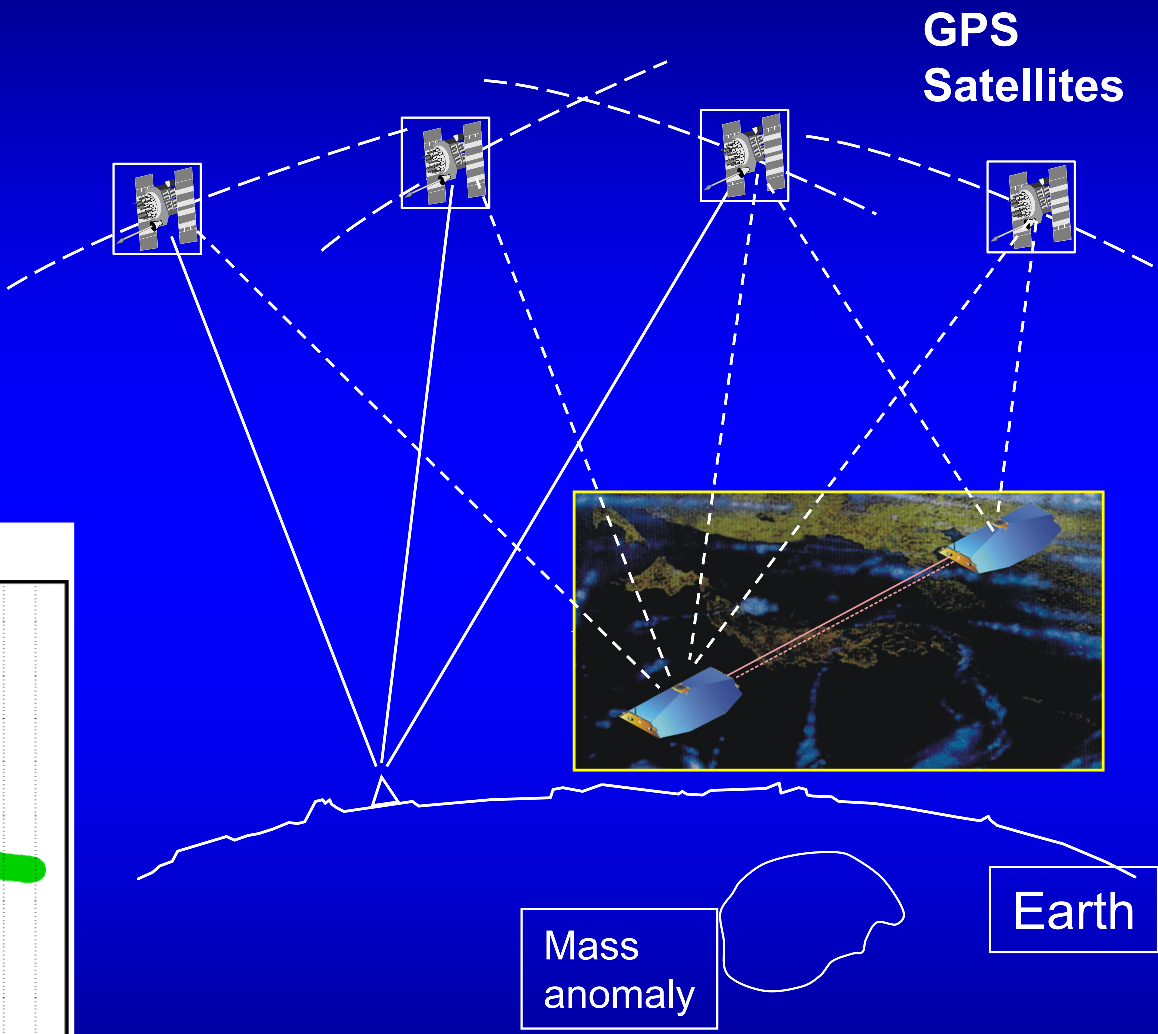


EIGEN-CHAMP03S calibr. Δg standard deviations (mgal), wrms = 0. 86 mgal, l_{max} = 60

GRACE Mission - Gravity Recovery Part

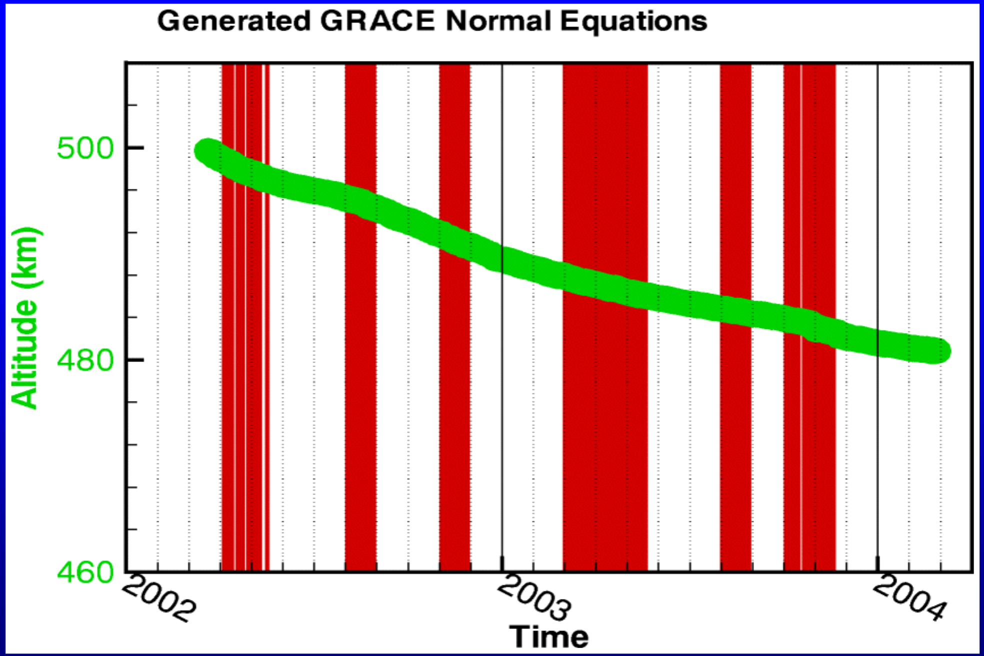
Principle:

- GPS/GRACE hl-SST-tracking
- GRACE A/B ll-SST-tracking
- 3D-measurement of surface forces
- Measurement of $\{x_i, \dot{x}_i\}$
- Measurement of $\{\rho_i, \dot{\rho}_i\}$



Source: NASA

Data used so far



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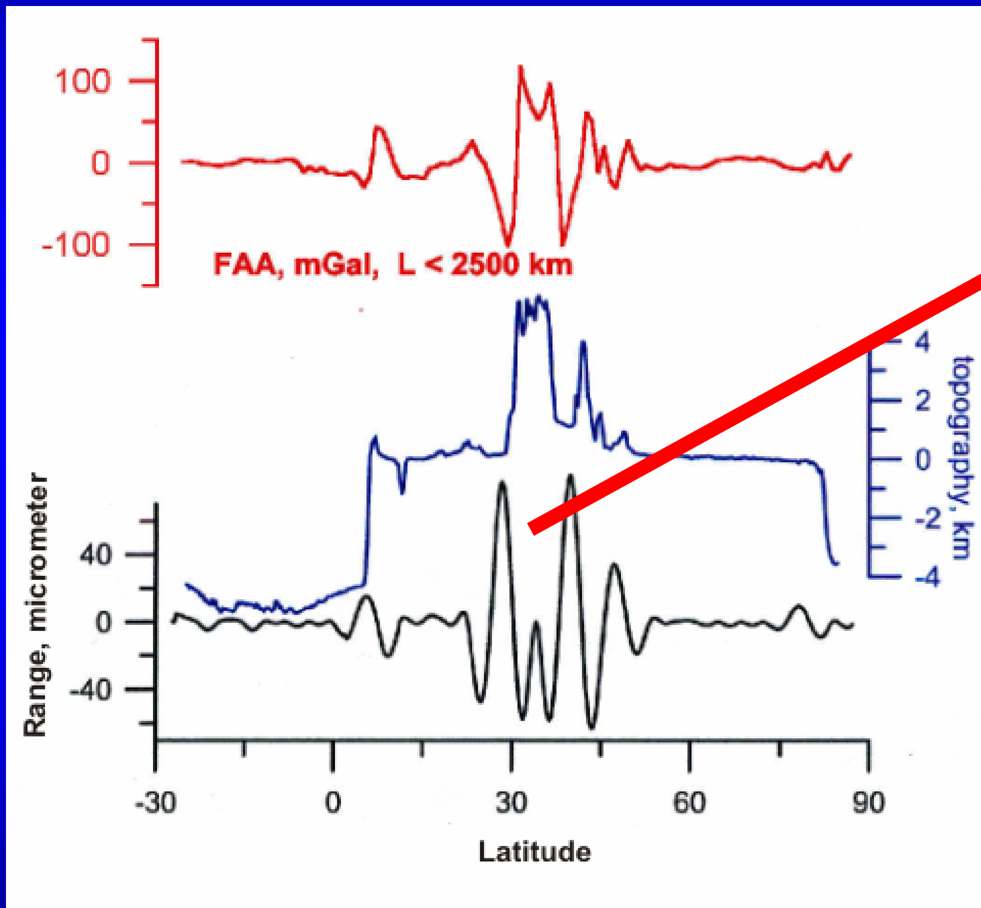
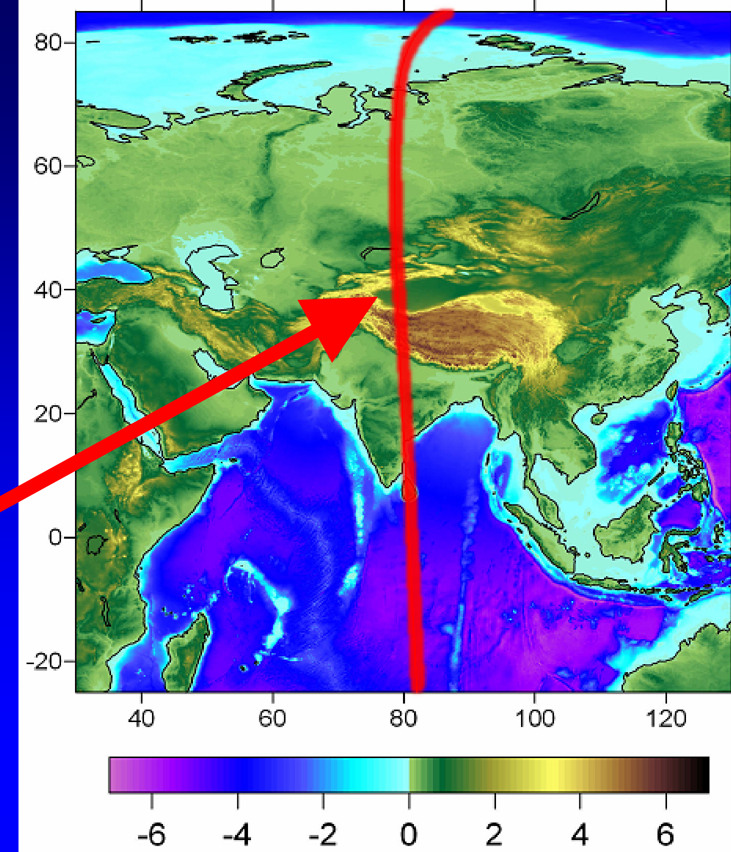
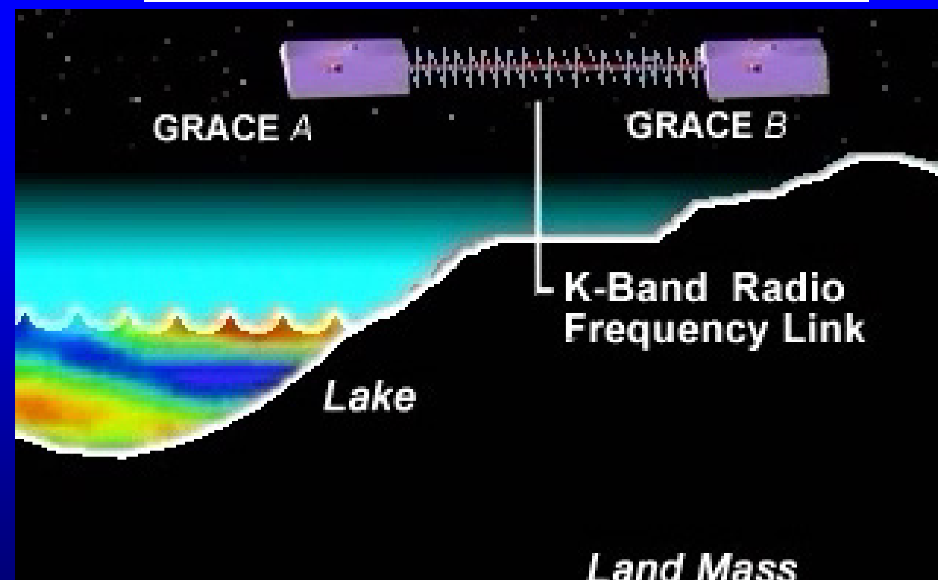
GRACE Inter-Satellite Ranging

May 3, 2003

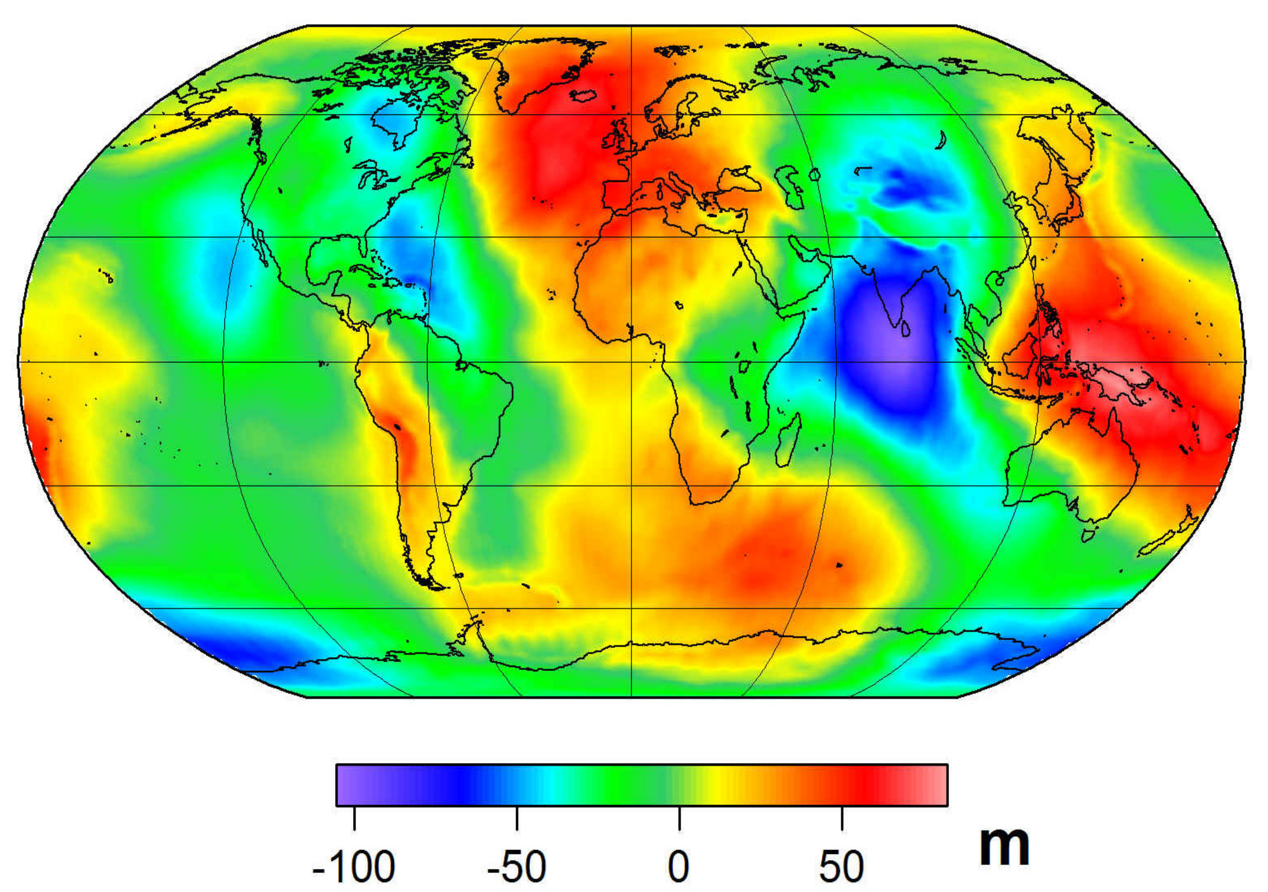






EIGEN -GRACE GRAVITY MODEL 02

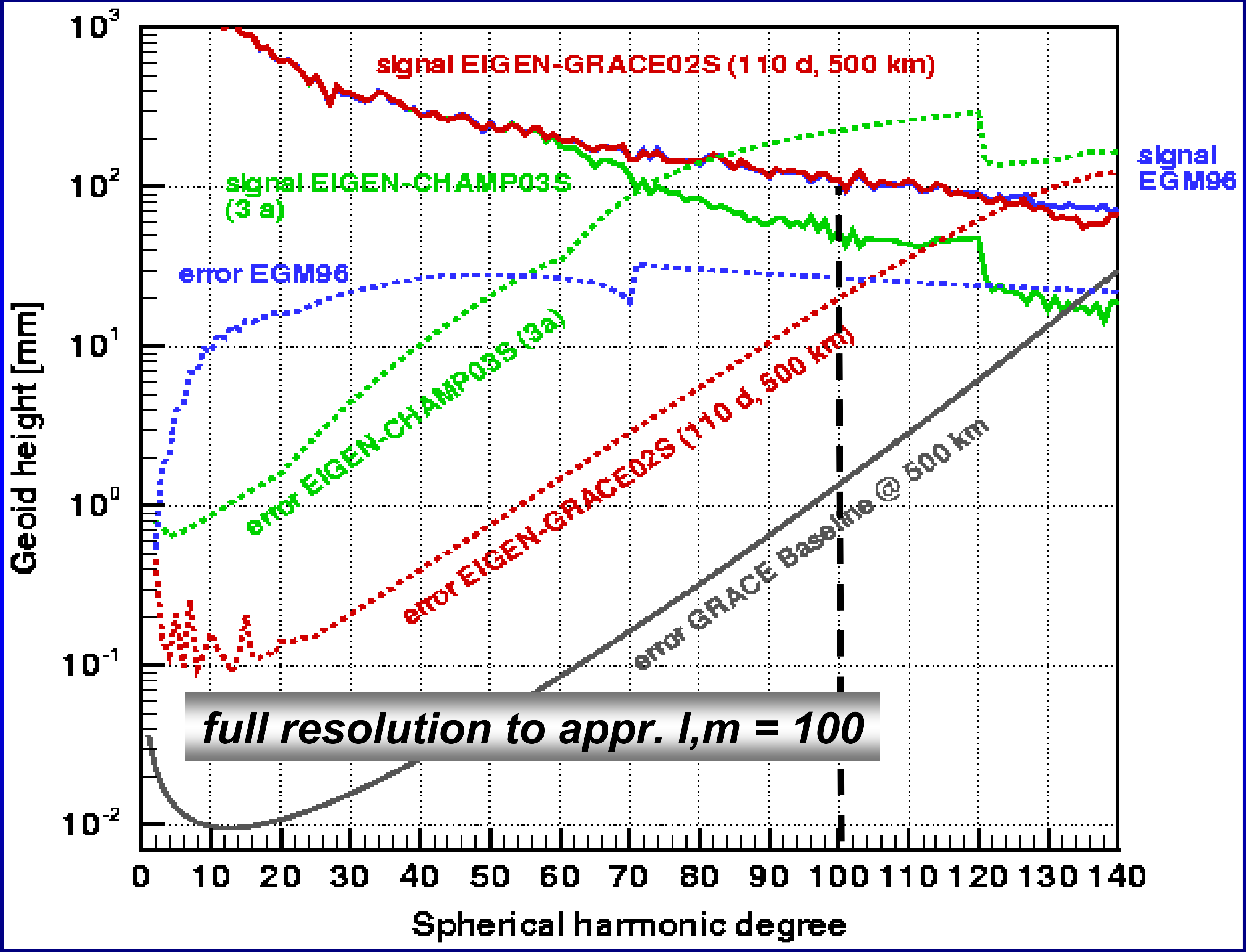
- **109 days of GRACE data**
  (08/02-04/03)
  - KBR range-rate and GPS phase data
  - Attitude from star camera
  - Non-gravitational accelerations from SuperStar accelerometer
- **Estimated parameters**
  - Initial conditions for daily arcs
  - Accelerometer bias and scale factors
  - KBR biases
- **Estimate 150x150 using only data from GRACE**



The geoid is the level (constant potential) surface that best coincides with mean sea level

The geoid height varies by ~200 m, but oceanographic applications need this to be determined to cm accuracy

EIGEN-GRACE02S Derived Geoid Signal & Error Spectrum



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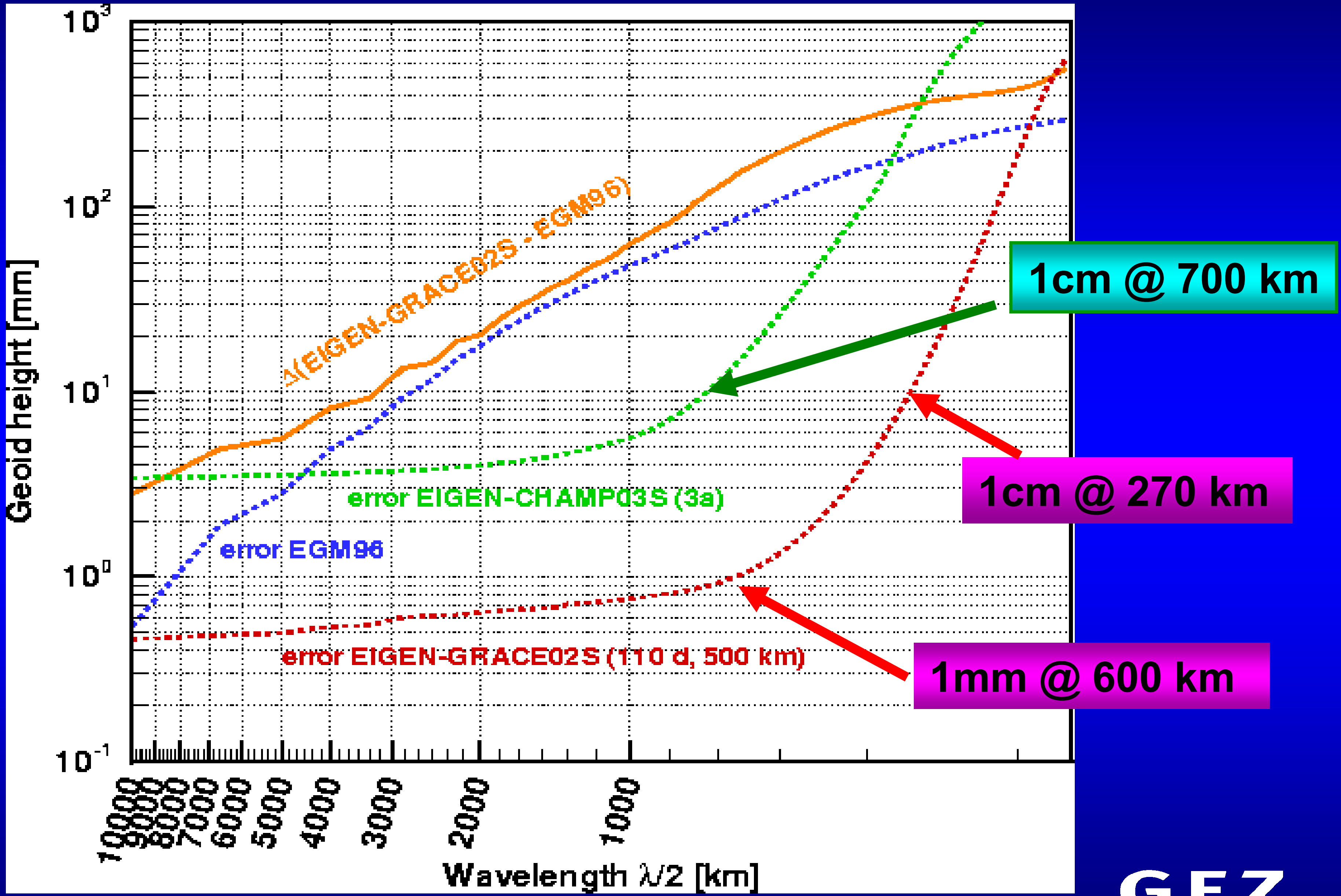
EIGEN – GRACE02S Cummulated Geoid Error



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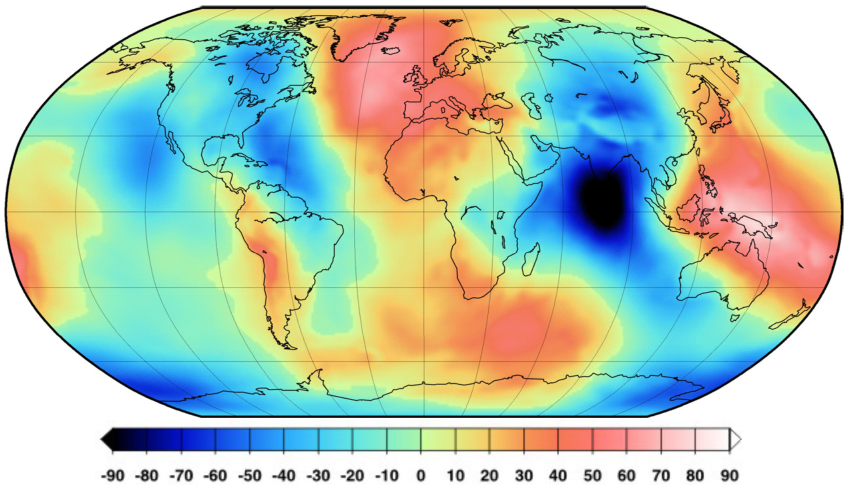
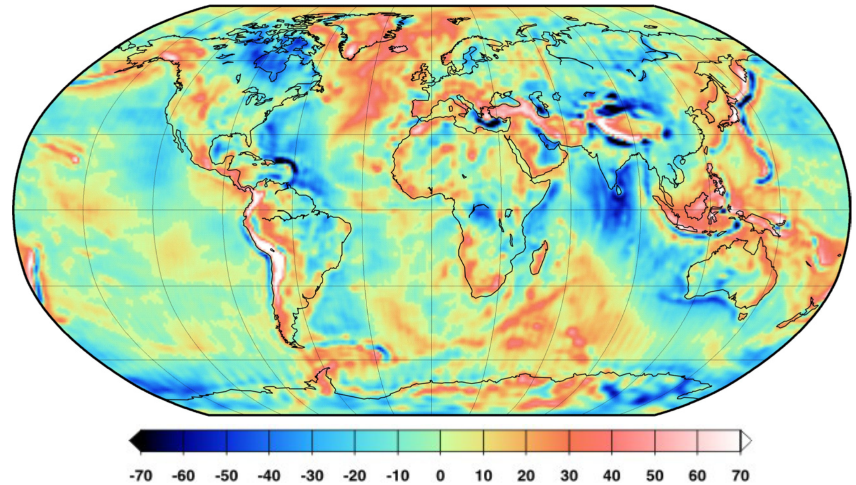
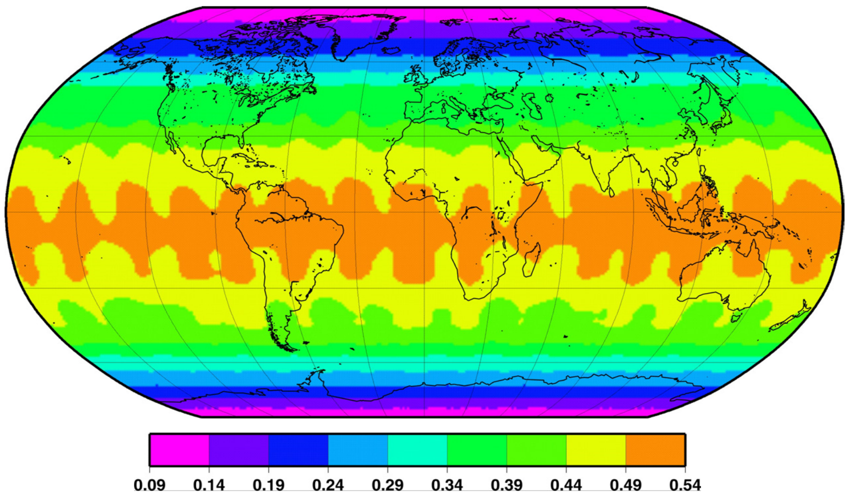
EIGEN-GRACE02S Global Gravity Model



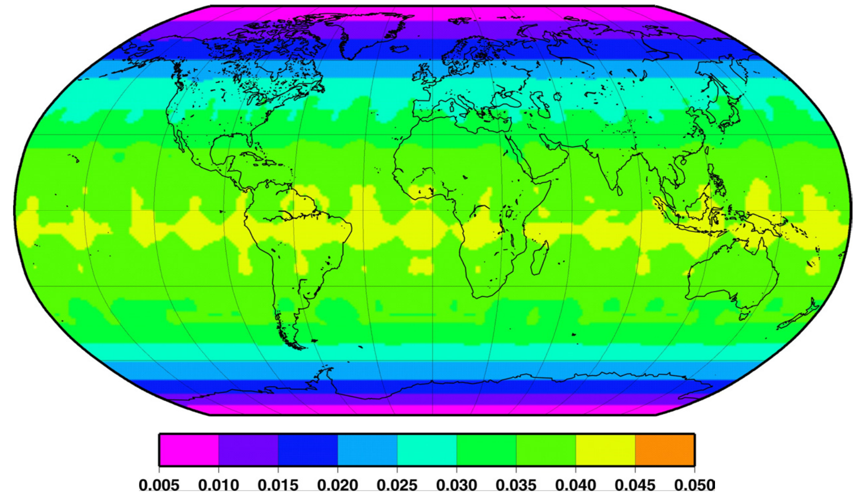
EIGEN-GRACE02S geoid from 39 days GRACE data, 1.5x1.5 deg (m)



EIGEN-GRACE02S gravity anomalies from 39 days GRACE data, 1.5x1.5 deg (mgal)



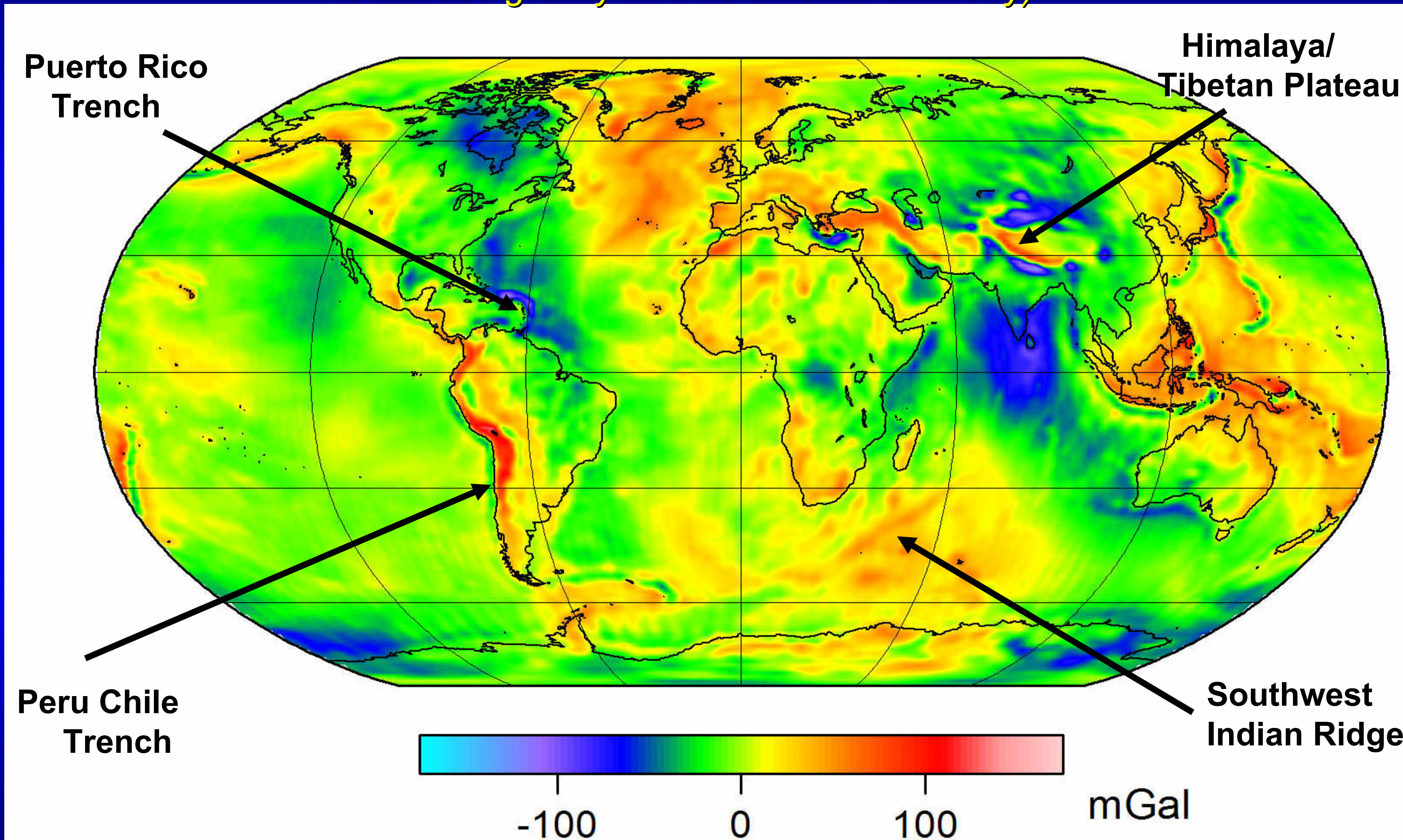
EIGEN-GRACE02S calibr. geoid standard deviations (cm), wrms = 0.42 cm, l_{max} = 60



EIGEN-GRACE02S calibr. Δg standard deviations (mgal), wrms = 0.034 mgal, l_{max} = 60

Gravity Field as Seen from Space by GRACE

(only 109 days from first science data set used, no surface gravity and no satellite altimetry)



Orbital Fit Results for Various Geodetic Satellites

SLR resp. GPS Phase/SLR RMS (CHAMP, GRACE)

Gravity Model	Starlette [cm]	Stella [cm]	Lageos-1/2 [cm]	GFZ-1 [cm]	Ajis [cm]	ERS-2 [cm]	ENVI [cm]	CHAMP [cm]	GRACE [cm]
MultiSatComb									
GRIM5-C1	2.7	3.1	1.11/1.06	14.7	3.3	5.5	4.5	10.4/62	36.4/217
EGM96	3.2	6.7	1.15/1.15	24.7	4.0	9.2	7.1	10.2/81	19.1/70
TEG4*)	3.7	3.4	1.11/1.09	20.5	3.5	5.7	5.3	1.4/14	5.1/28
CHAMP-only									
EIGEN-3	3.4	6.8	1.15/1.08	13.6	3.4	7.3	15.2	0.6/5.7	2.2/10.1
GRACE-only									
GGM01S-CSR	2.5	3.6	1.13/1.05	14.5	3.3	5.9	6.3	0.6/6.7	1.4/6.7
GRACE01S	2.7	3.4	1.11/1.05	13.5	3.5	6.0	4.8	0.6/6.0	1.3/7.5
GRACE01Sup	2.5	3.5	1.11/1.05	14.5	3.1	5.7	5.2	0.6/6.9	1.2/6.0
GRACE02S	2.7	3.2	1.13/1.07	14.3	3.2	5.5	4.5	0.5/5.8	1.1/5.6

All arcs are not included in gravity modelling

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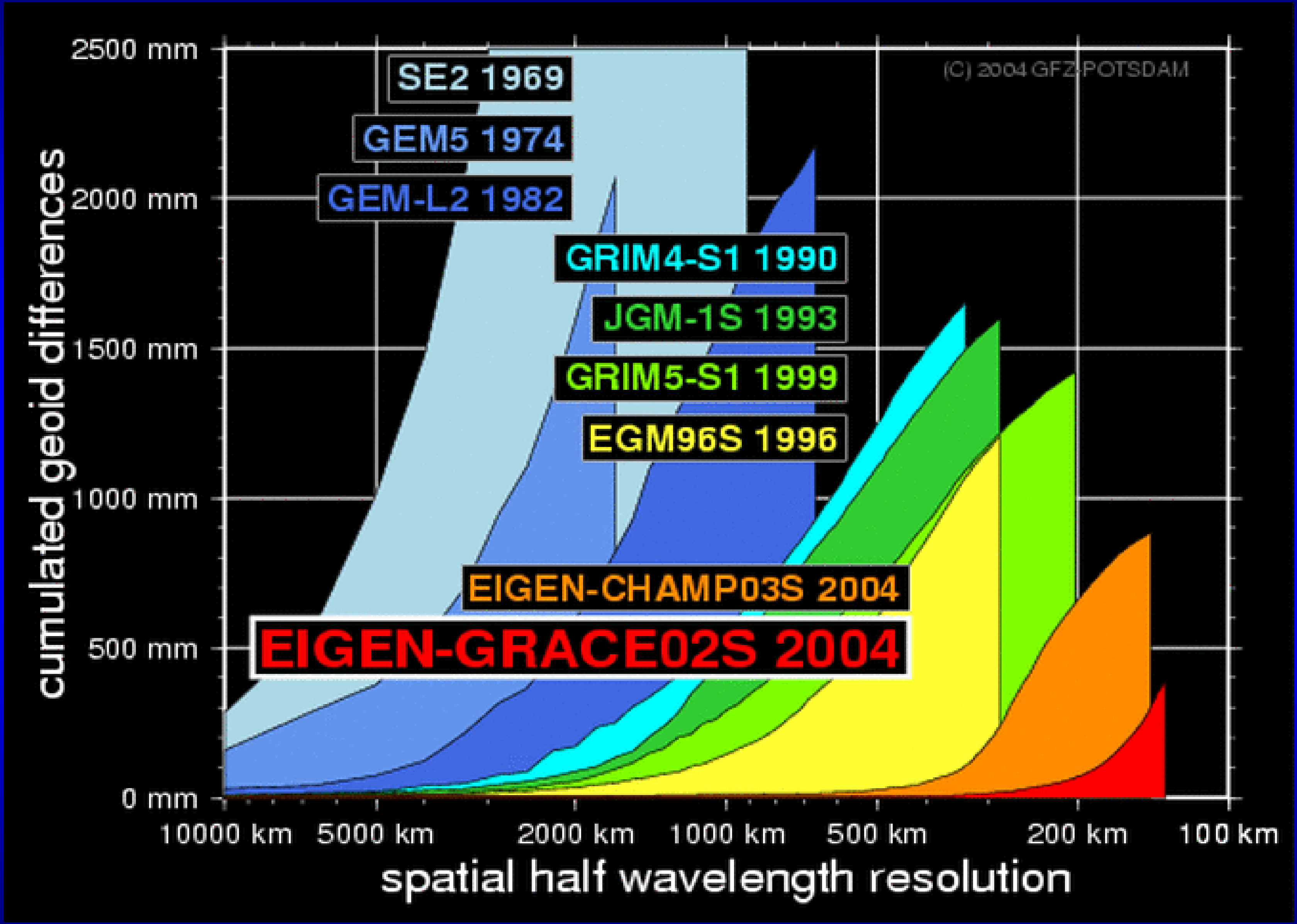
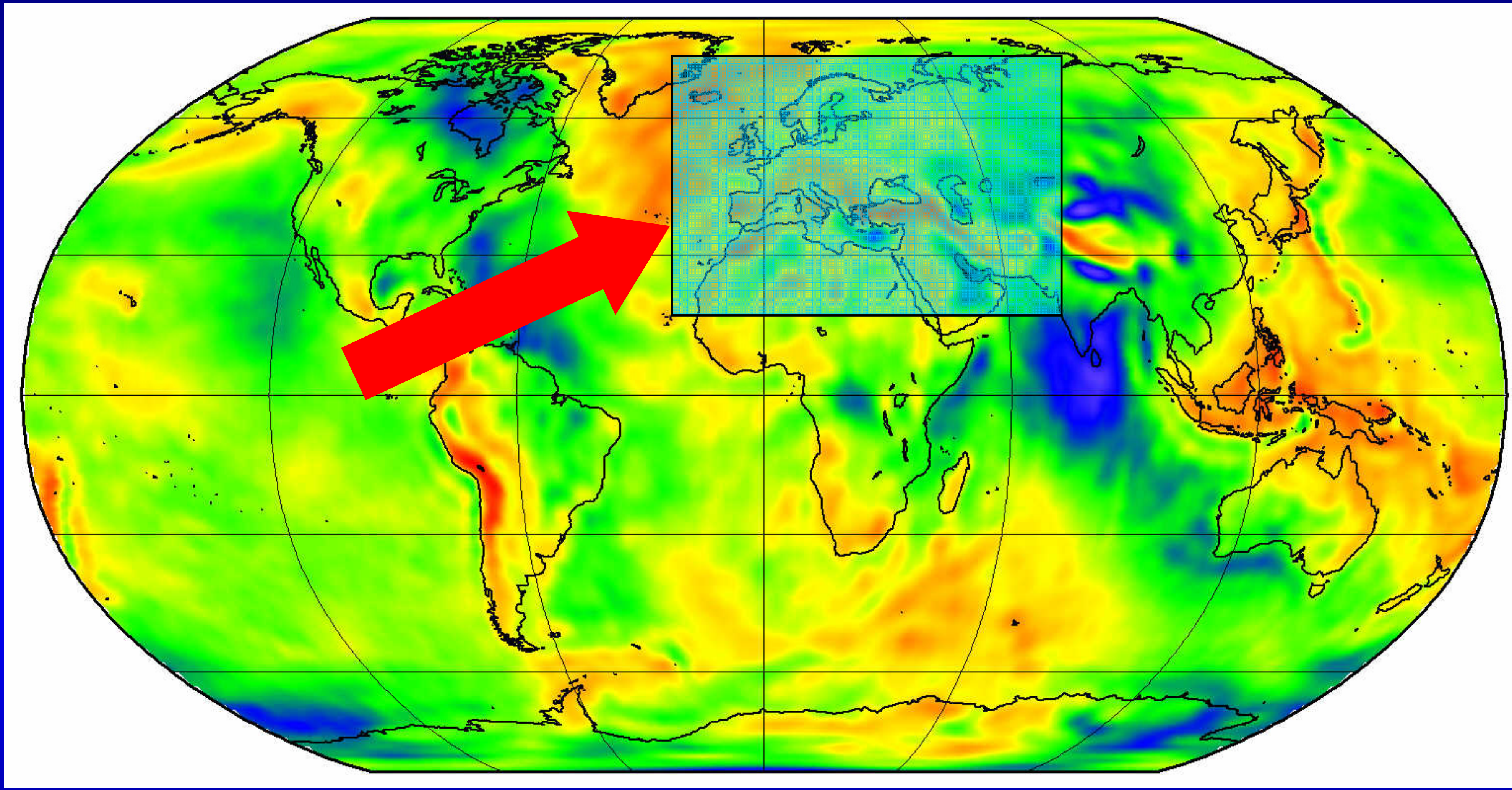
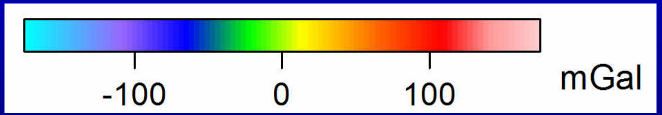
Geoid Differences to GRACE Combined Solution



Detailed View of Gravity over Europe





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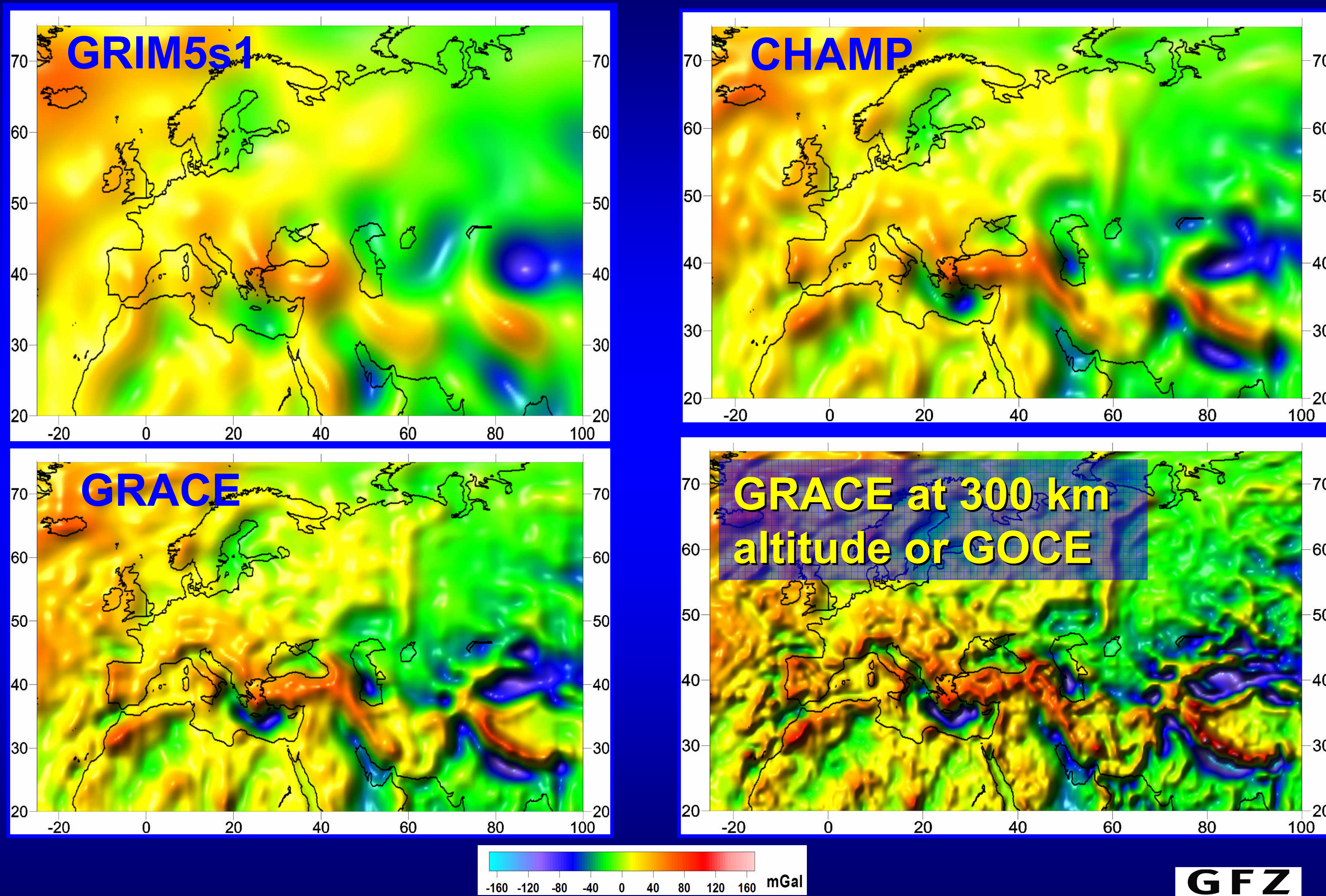
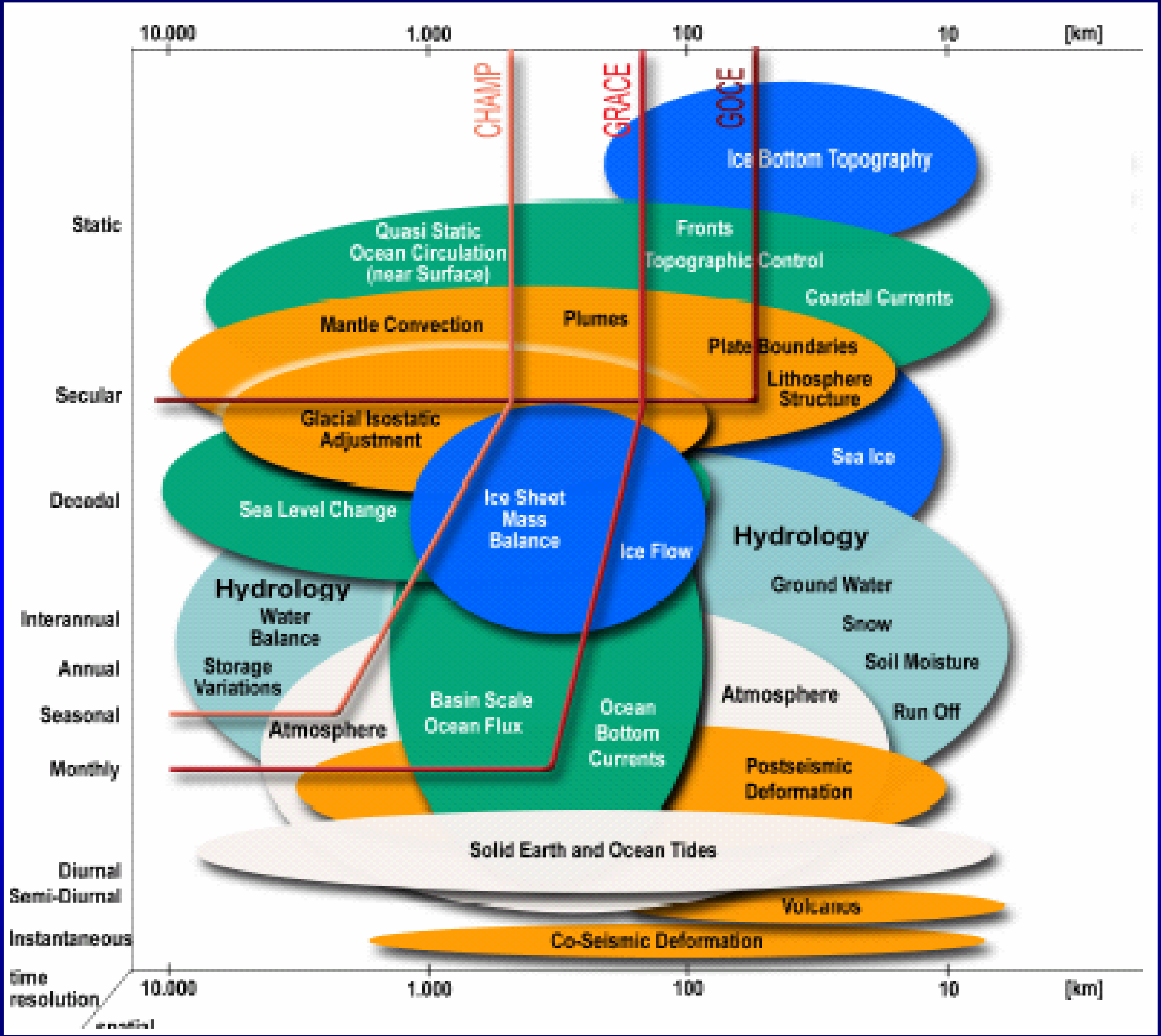
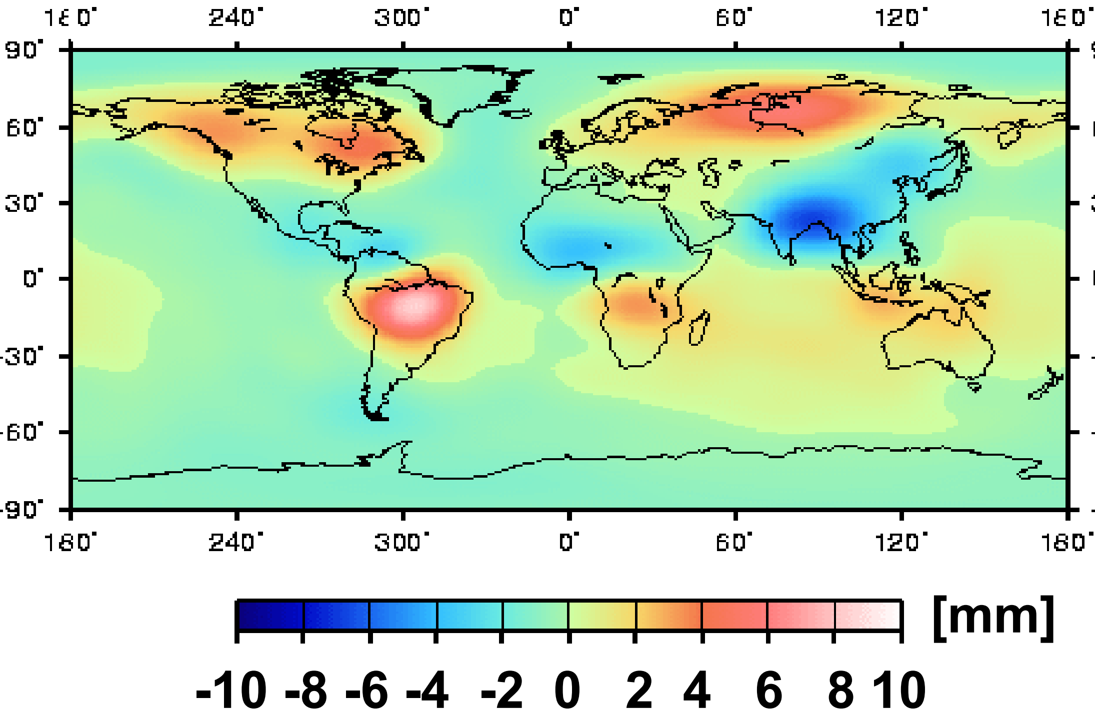
Gravity over Europe as Seen by Different Missions



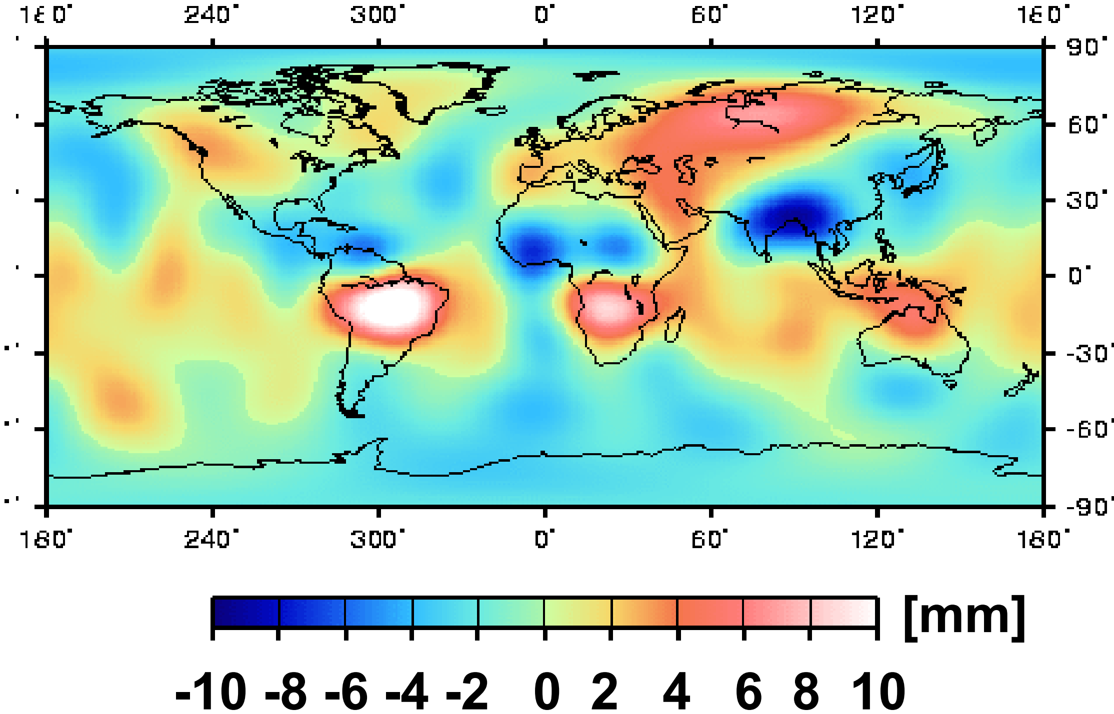

10.000
1.000
100
10
[km]
CHAMP
GRACE
GOCE
Ice Bottom Topography
Static
Quasi Static
Ocean Circulation
(near Surface)
Fronts
Topographic Control
Coastal Currents
Mantle Convection
Plumes
Plate Boundaries
Lithosphere
Structure
Secular
Glacial Isostatic
Adjustment
Sea Ice
Decadal
Sea Level Change
Ice Sheet
Mass
Balance
Ice Flow
Hydrology
Ground Water
Snow
Soil Moisture
Run Off
Atmosphere
Interannual
Annual
Seasonal
Monthly
Hydrology
Water
Balance
Storage
Variations
Atmosphere
Basin Scale
Ocean Flux
Ocean
Bottom
Currents
Postseismic
Deformation
Solid Earth and Ocean Tides
Diurnal
Semi-Diurnal
Volcanos
Instantaneous
Co-Seismic Deformation
time
resolution
10.000
1.000
100
10
[km]

MAI03 - AUG03 (Nmax = 13)

Hydrologie - WGHM



GRACE



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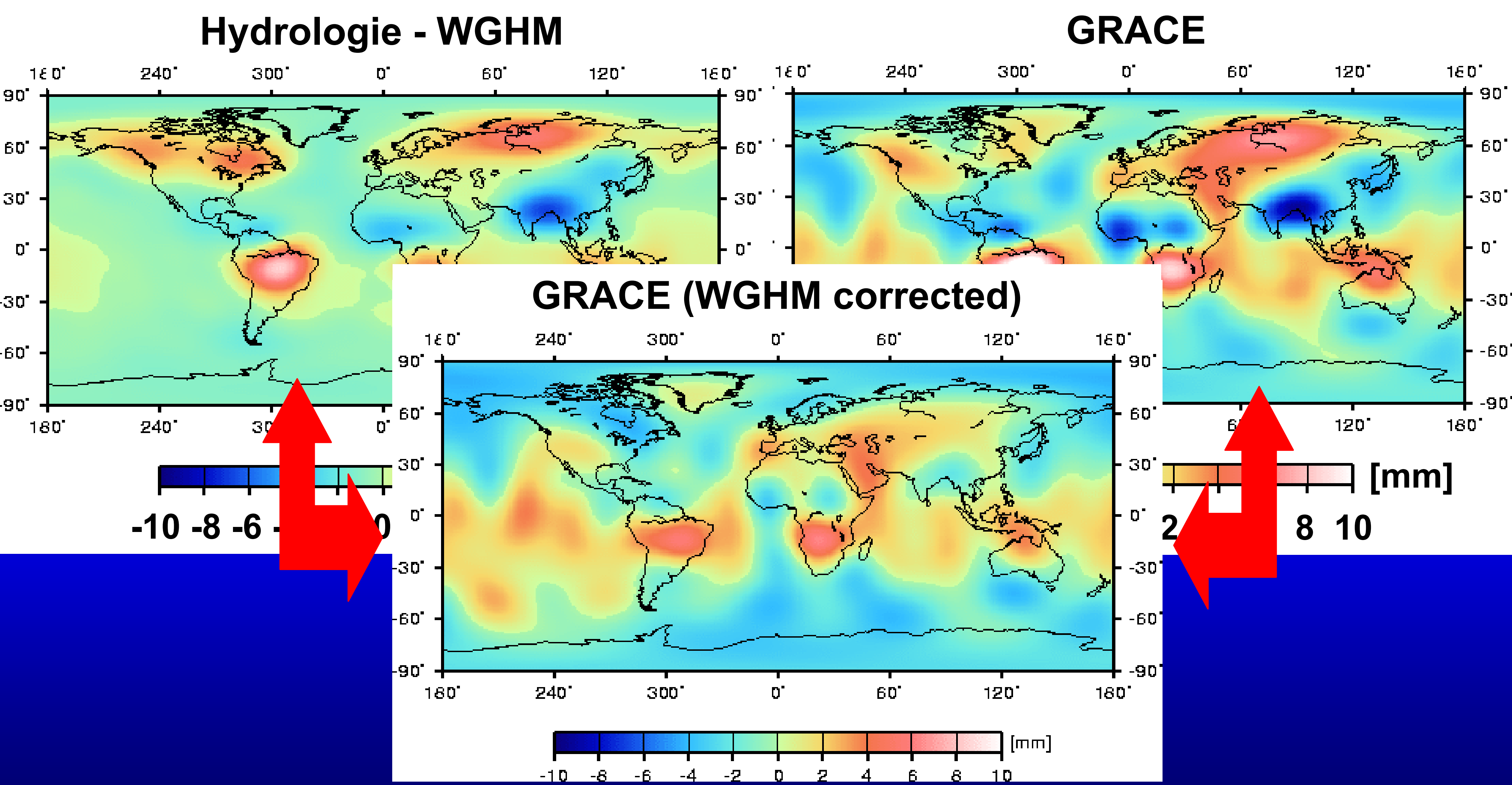
MAI03 - AUG03 (Nmax = 13)



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Correlation GRACE - Hydrology

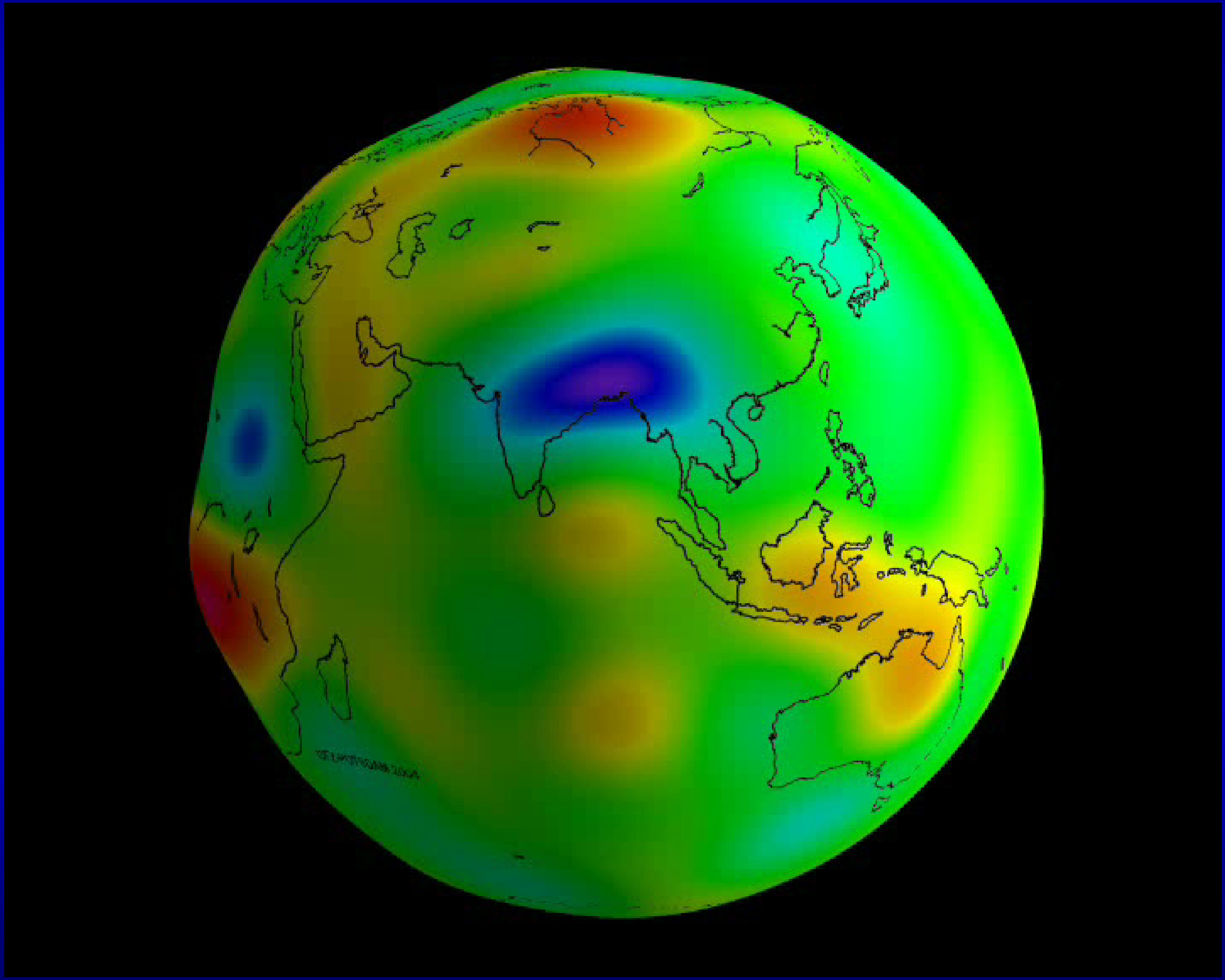
Difference	Δt	WGHM	Milly	Yun-Fan
APR02 - MAY02	1 M	0.47	0.52	0.60
MAY02 - AUG02	3 M	0.76	0.77	0.63
AUG02 - NOV02	3 M	0.47	0.25	0.56
NOV02 - MAR03	4 M	0.84	0.90	0.80
MAR03 - APR03	1 M	0.28	-0.14	0.19
APR03 - MAY03	1 M	0.66	0.51	0.38
MAY03 - AUG03	3 M	0.82	-	0.89

Correlation Geoid Height Variation from GRACE and Hydrology Models on 1x1 grid over land

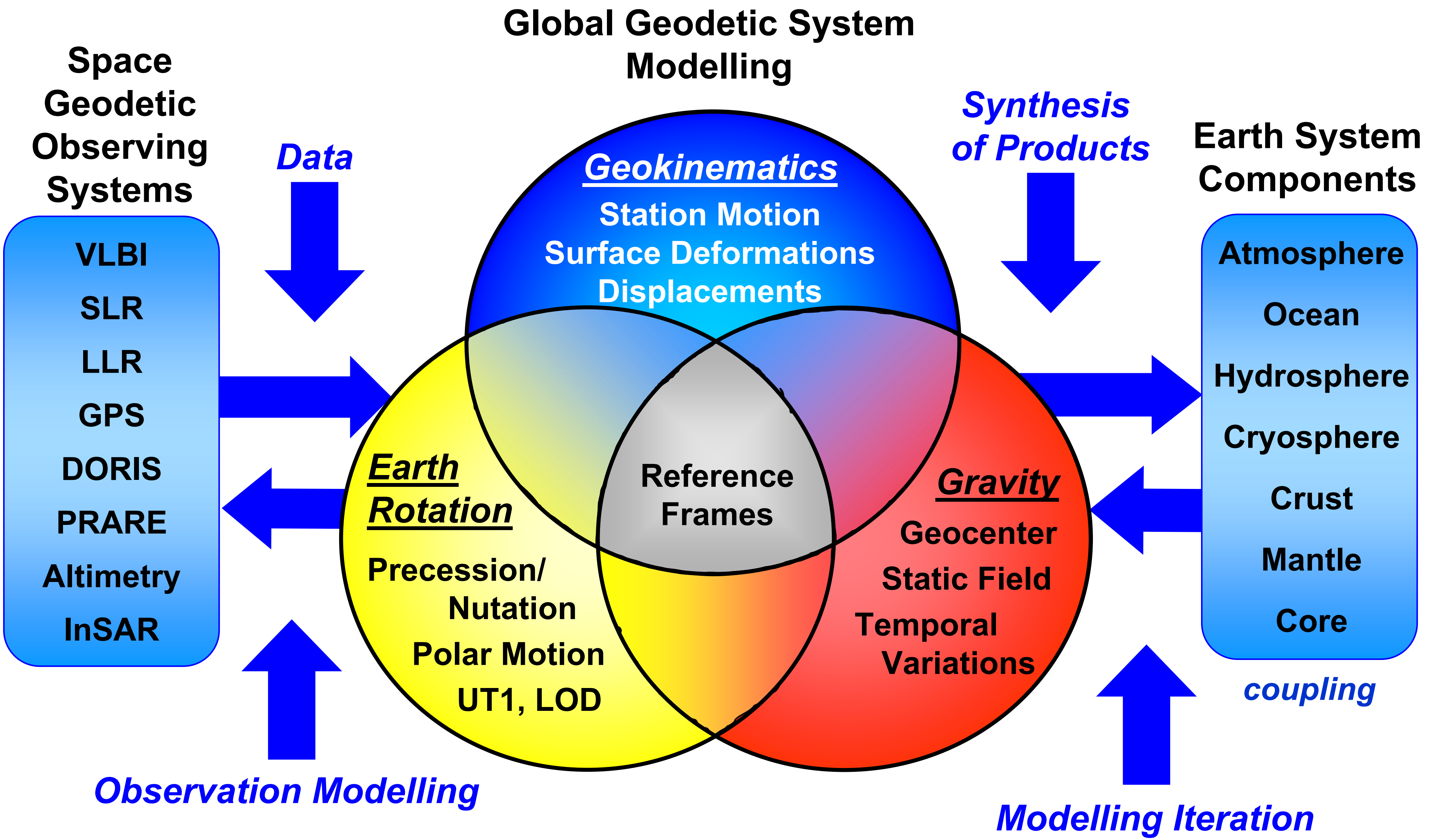
Variation in Continental Water Storage

from GRACE monthly gravity solutions (nmax=13)

(here April 03 – August 02)



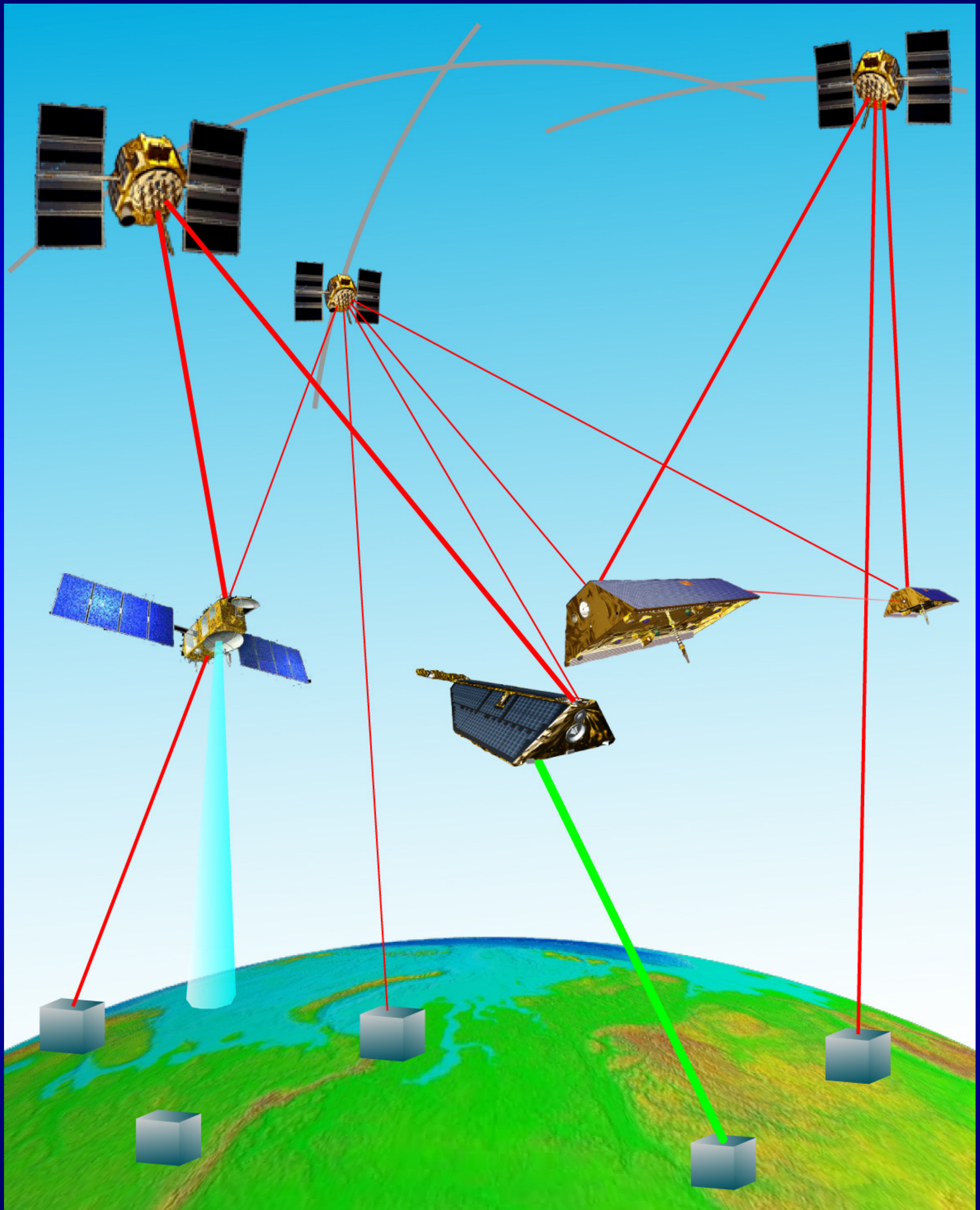
Observing and Modelling the Earth System



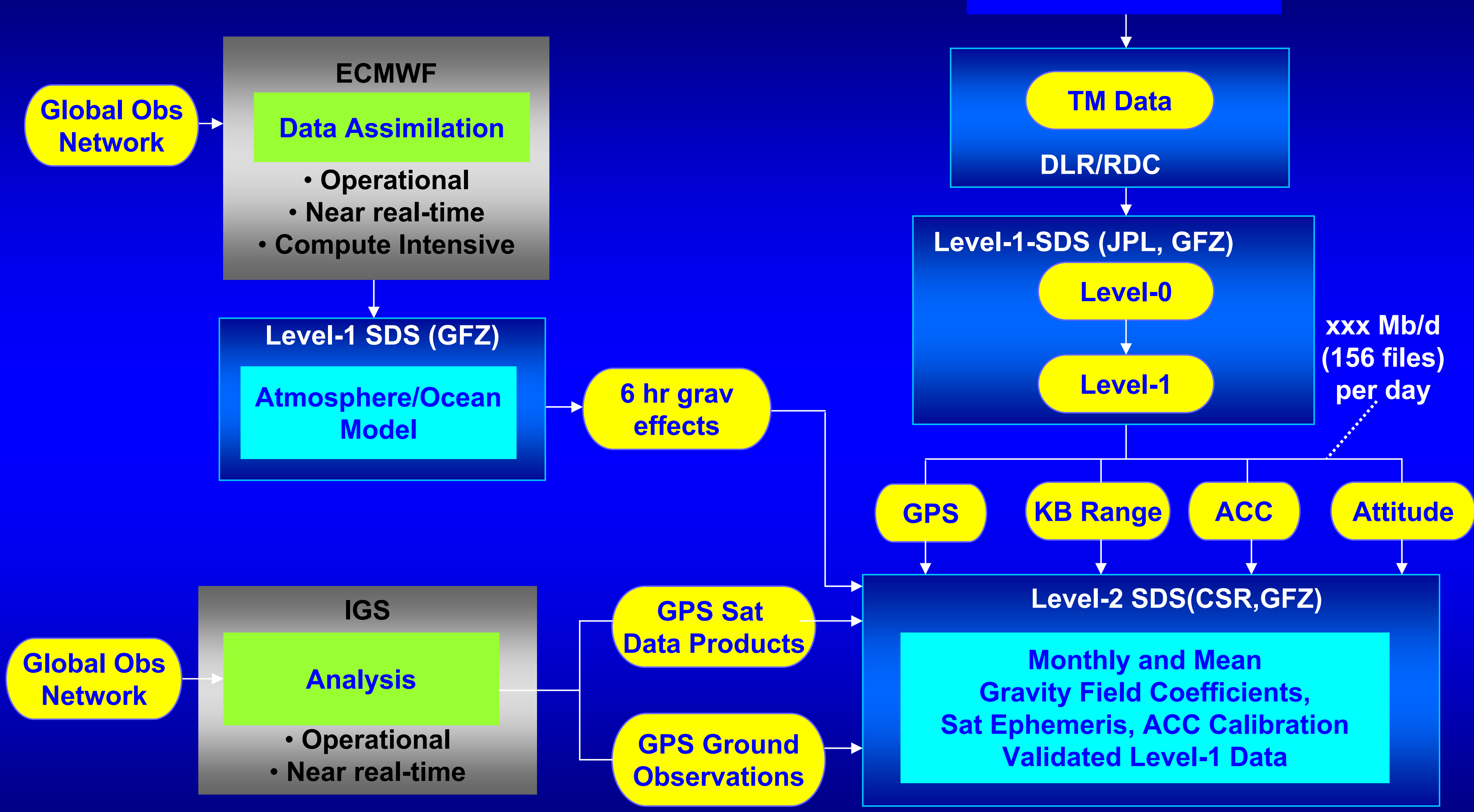
Layer 3

Layer 2

Layer 1



GRACE Mission Data Flow



GRACE Mission Data Flow

GRACE Satellites

ECMWF

Data Assimilation

- Operational
- Near real-time
- Compute Intensive

Global Obs Network

Level-1 SDS (GFZ)

Atmosphere/Ocean Model

Thank You IGS Community for the Great Support of both the CHAMP and the GRACE Mission

IGS

Analysis

- Operational
- Near real-time

Global Obs Network

GPS Sat Data Products

GPS Ground Observations

Level-2 SDS(CSR,GFZ)

Monthly and Mean
Gravity Field Coefficients,
Sat Ephemeris, ACC Calibration
Validated Level-1 Data