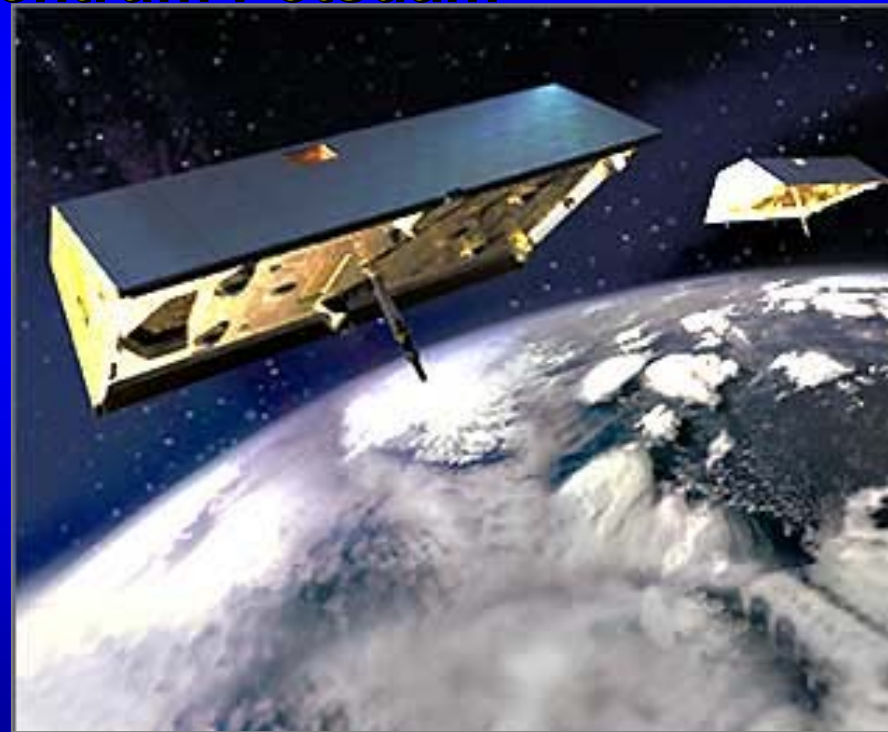
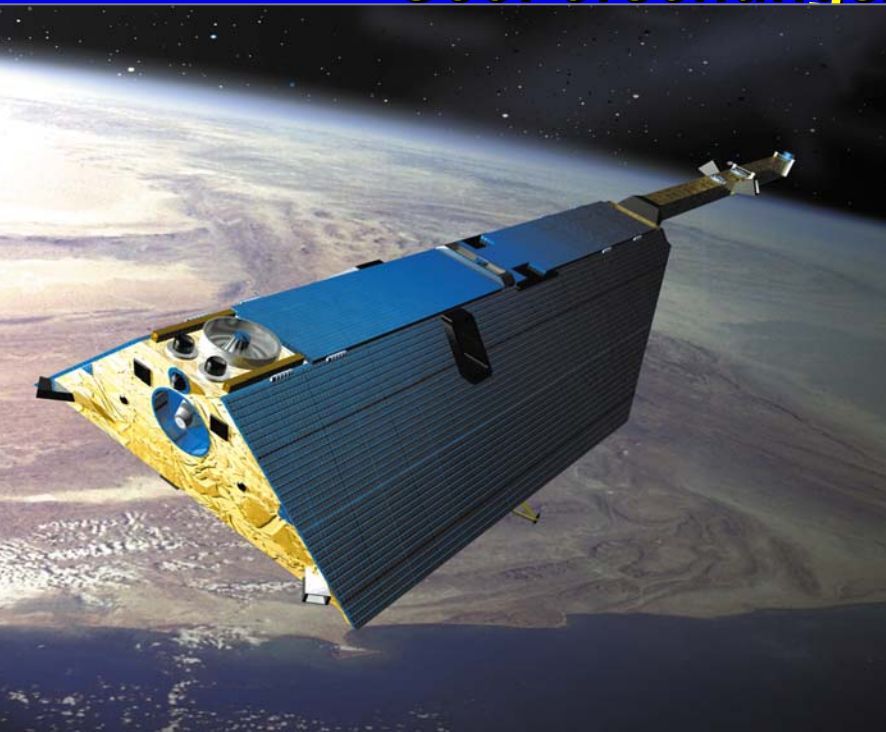
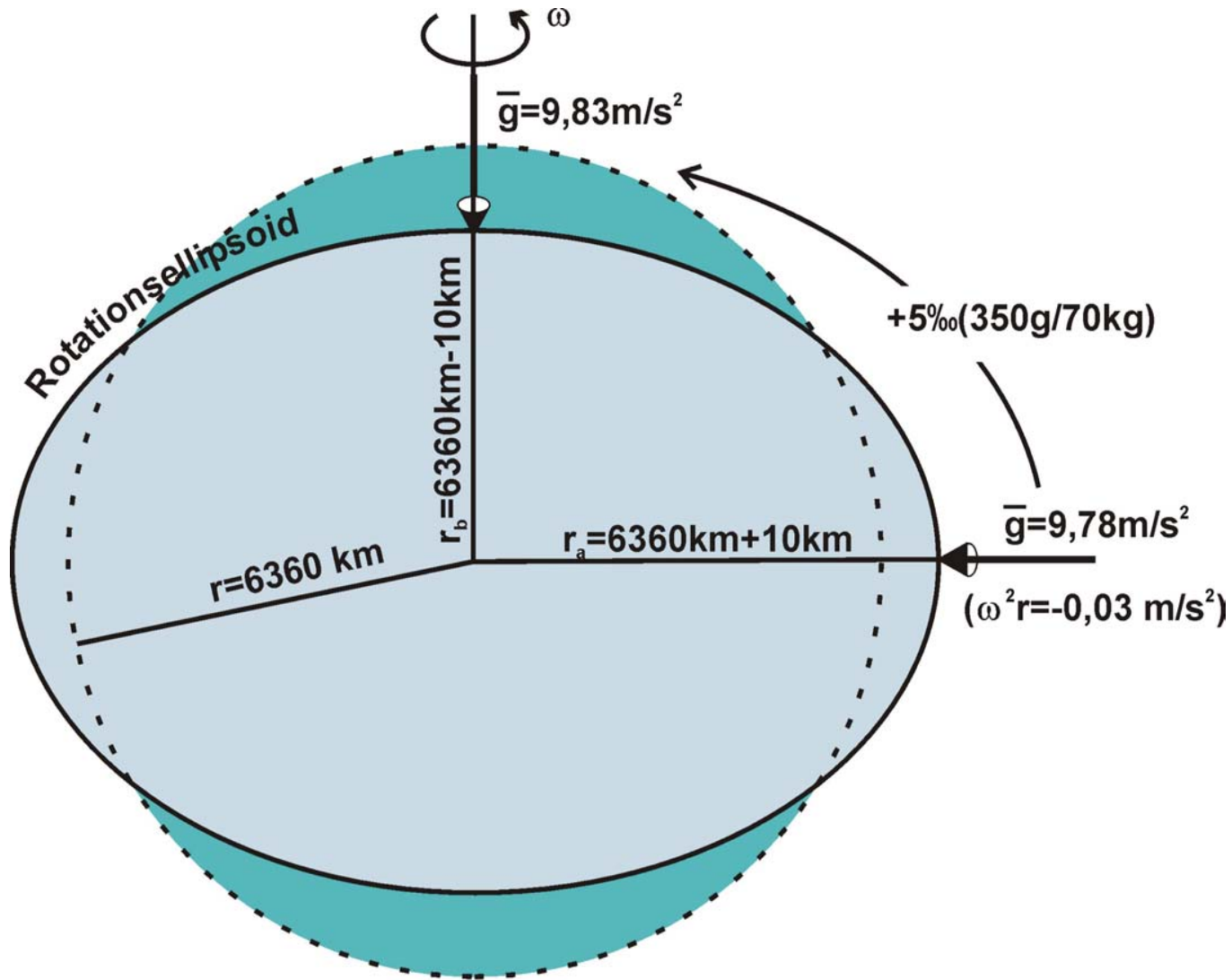


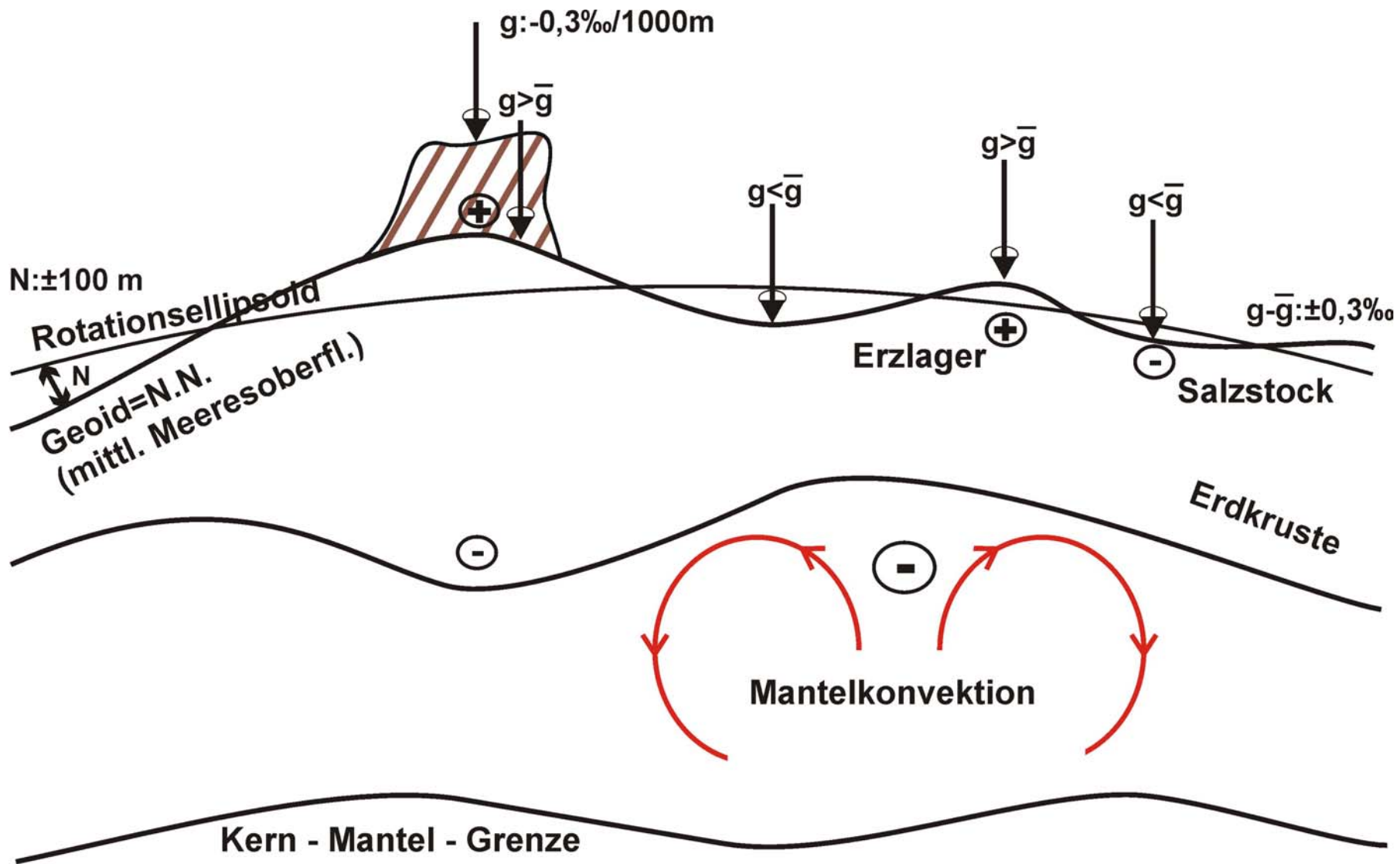
Das Schwerefeld der Erde: globale Erkundung mit Satelliten und geophysikalische Interpretation

Christoph Reigber, Peter Schwintzer
GeoForschungsZentrum Potsdam



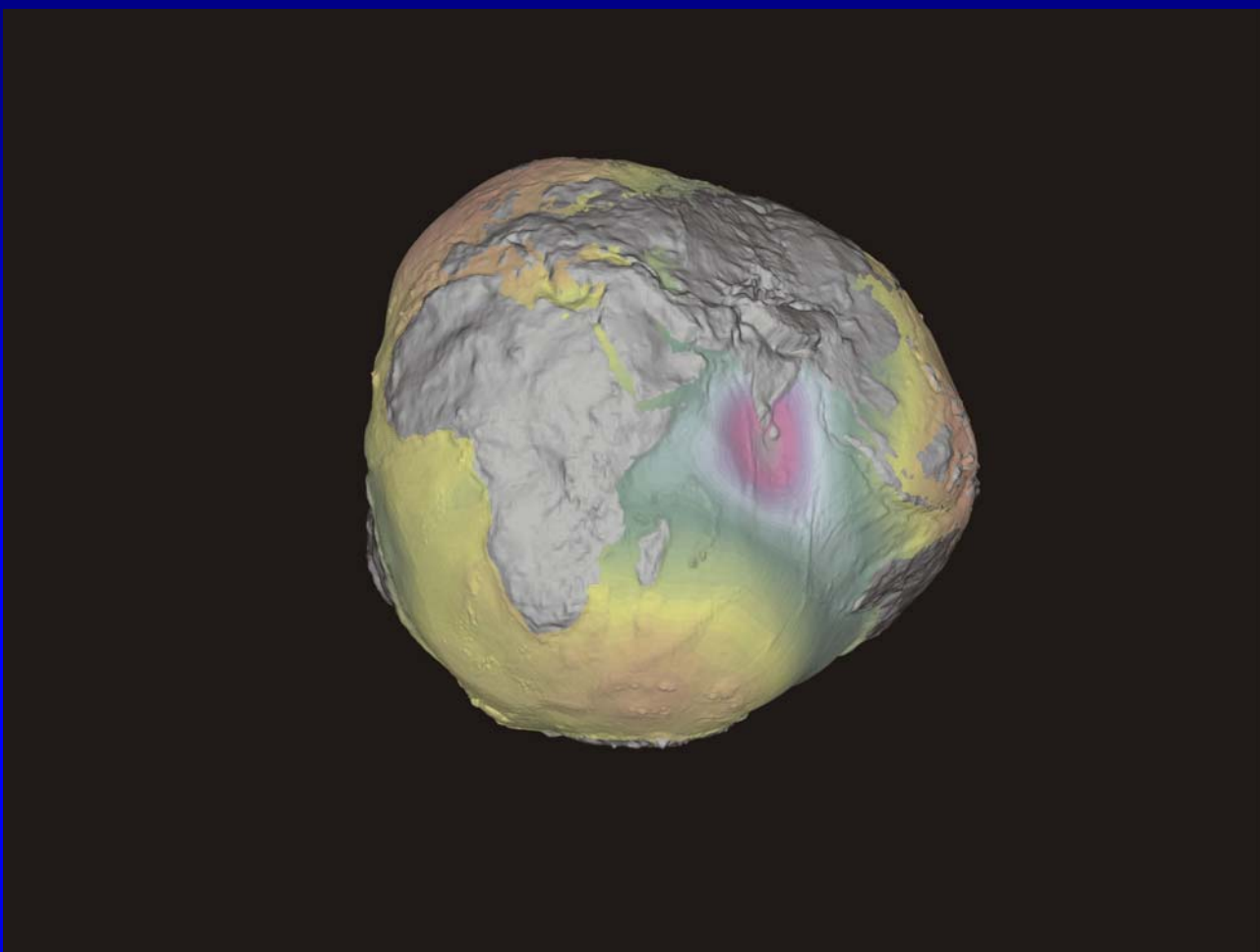


Erdfigur 1: Kugel → Ellipsoid

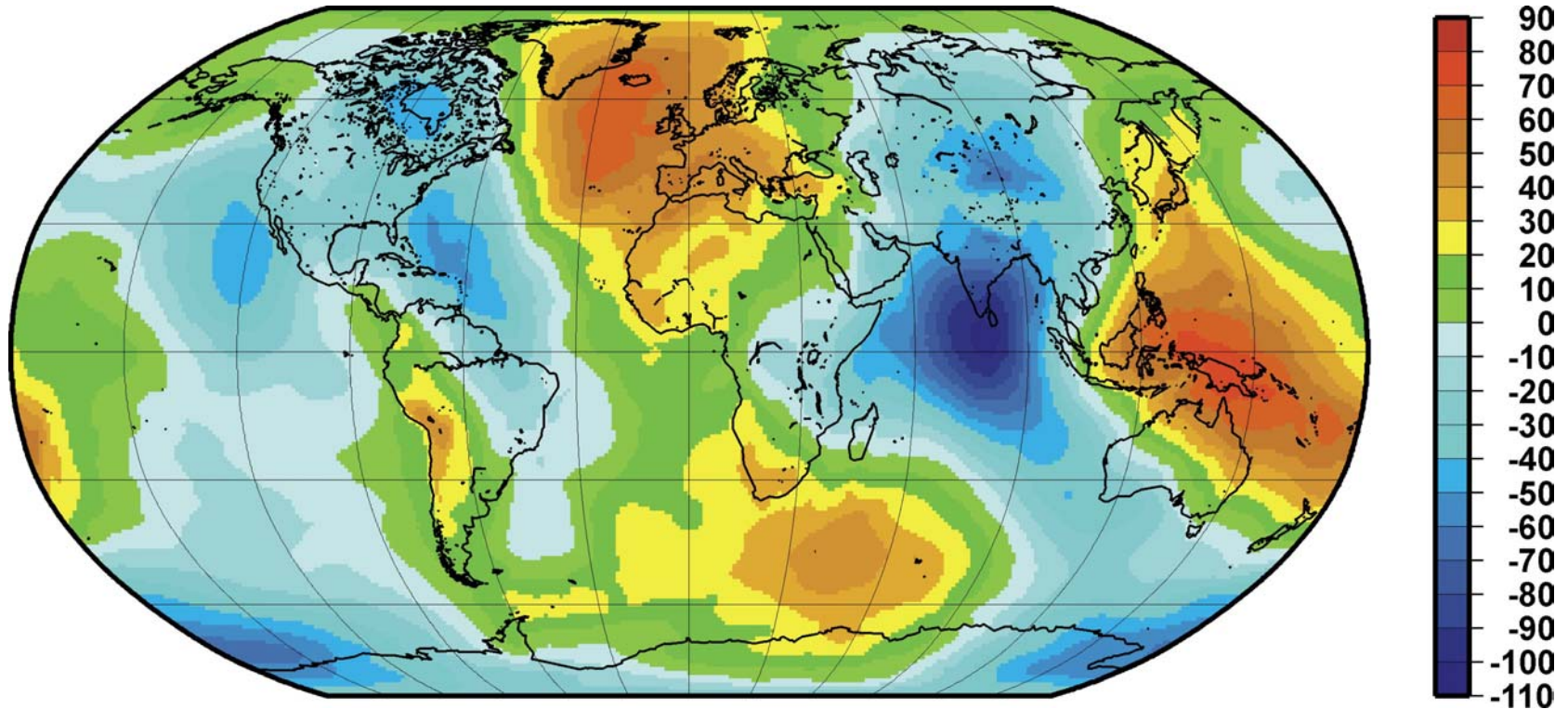


Erdfigur 2: Ellipsoid → Geoid

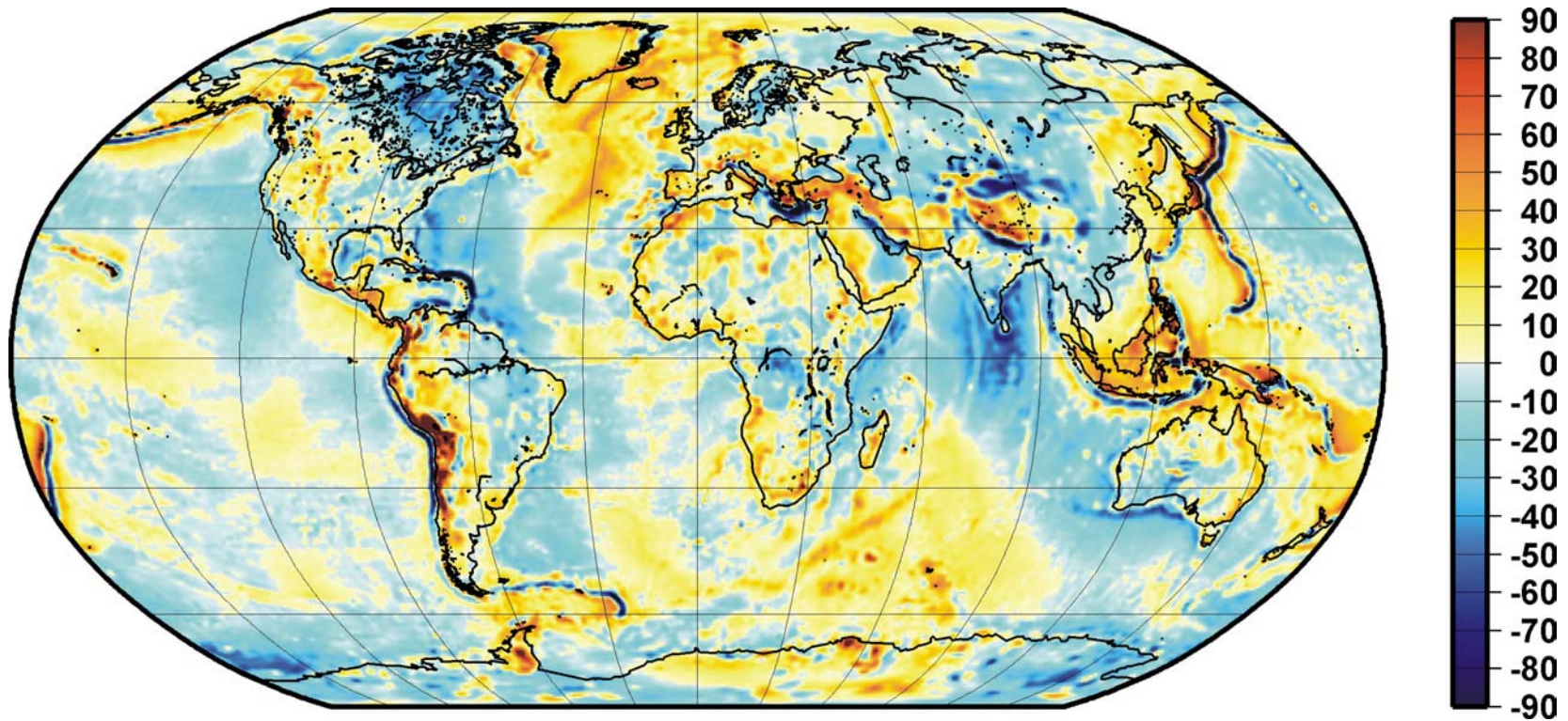




stark überhöhte Darstellung des Geoids (Fläche 'Normal Null'). Die Abweichungen des Geoids von einer regelmäßigen Ellipsoidoberfläche betragen nur maximal 100m. Die Oberfläche einer ganz mit Wasser bedeckten Erde würde unter dem Einfluss des Erdschwerefelds dem Geoid als Gleichgewichtsfläche entsprechen ('Potsdamer Kartoffel'). Über den Kontinenten ist das Geoid zur besseren Unterscheidung in Graustufen dargestellt



Die Differenzen zwischen Geoid und Bezugsellipsoid ('Beulen und Dellen') in ihrer geographischen Verteilung; von -110 m (dunkelblau) bis +90 m (dunkelrot).



Geographische Verteilung der Variationen in der Schwerebeschleunigung gegenüber der Schwere auf dem Bezugsellipsoid; von -90 (dunkelblau) bis $+90$ (dunkelrot) Millionstel der mittleren Schwerebeschleunigung auf der Erde. Einzelne Werte erreichen mehr als den dreifachen Betrag.

Kugelfunktionsentwicklung des Gravitationspotentials

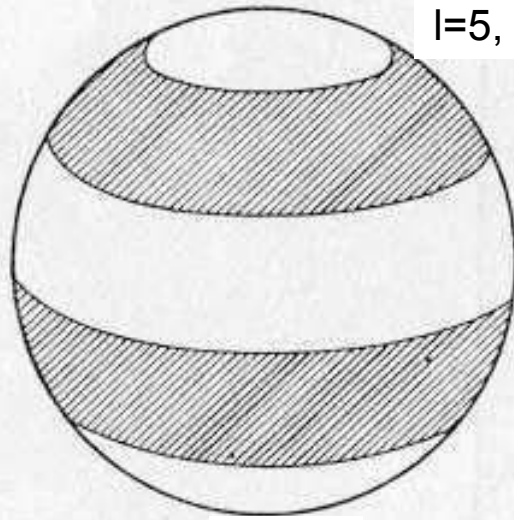
Die mathematische Darstellung des Gravitationspotentials U in Kugelfunktionen ist die fundamentale Ausgangsgleichung für die globale Betrachtungsweise in der Satellitengeodäsie lautet:

$$U(r, \varphi, \lambda) = \frac{GM}{r} \left[\bar{C}_{00} + \sum_{l=2}^{l_{\max}} \sum_{m=0}^l \left(\frac{R}{r} \right)^l \bar{P}_{lm}(\sin \varphi) (\bar{C}_{lm} \cos m\lambda + \bar{S}_{lm} \sin m\lambda) \right]$$

- mit r, φ, λ - sphärische geozentrische Koordinaten des Aufpunktes (Radius, Breite, Länge),
 R - Referenzlänge (mittlerer Äquatorradius)
 GM - Produkt aus Gravitationskonstante und Masse der Erde
 l, m - Grad, Ordnung der Entwicklung,
räumliche Auflösung: $\approx 40000\text{km}$ (für $r=R$)
 \bar{P}_{lm} - vollständig normierte Legendre-Funktionen
 $\bar{C}_{lm}, \bar{S}_{lm}$ - Stokes'sche Koeffizienten (vollständig normiert)

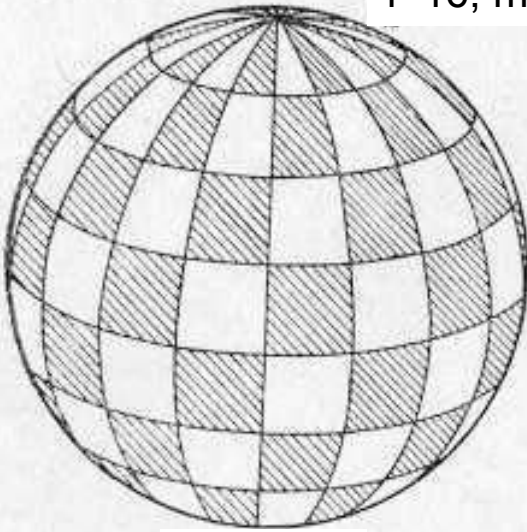
Wie sieht man von den niedriggradigen Koeffizienten der Ordnung Null die entsprechenden Stoke'schen Koeffizienten des ellipsoidischen Normalpotentials ($\bar{C}_{00}^{\text{ell}}, \bar{C}_{20}^{\text{ell}}, \dots, \bar{C}_{80}^{\text{ell}}$) so erhält man die Darstellung des Störpotentials in Kugelfunktionen.

$l=5, m=0$



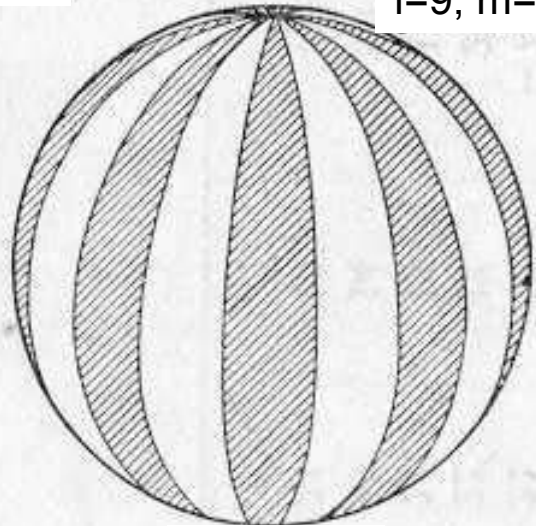
zonal

$l=16, m=9$

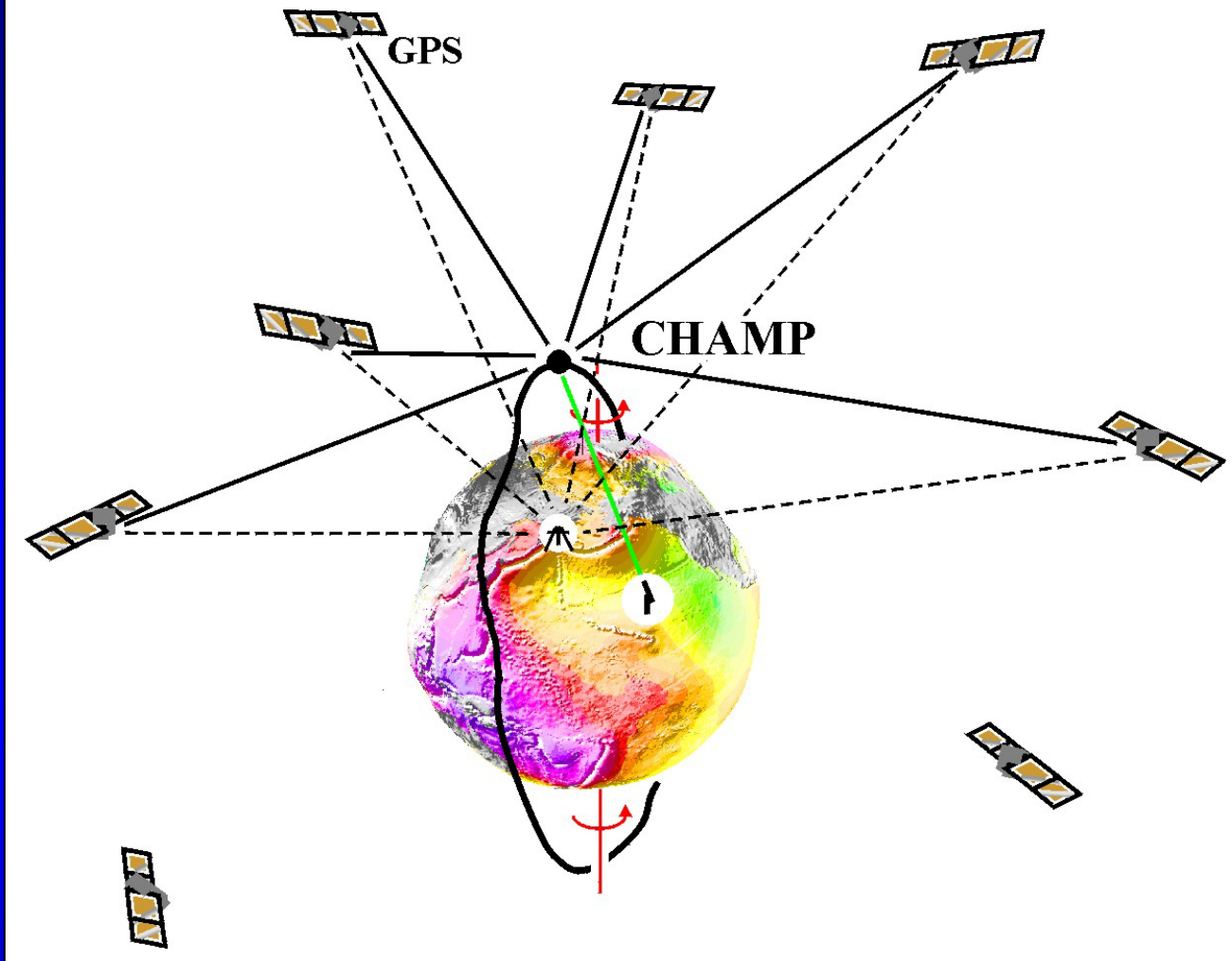


tesseral

$l=9, m=9$



sectorial



Prinzip der Satellitenbahnverfolgung am Beispiel des Satelliten CHAMP:
 Verbindungsmessungen von den hochfliegenden GPS-Satelliten bzw.
 Bodenstationen zu CHAMP. Aus den so beobachteten Bahnstörungen
 niedrigfliegender Satelliten werden die großräumigen Strukturen im Geoid
 und Erdschwerefeld abgeleitet.

Earth Gravity Field Recovery from Satellite Orbit Perturbations

Principle:

gravitational acceleration (+ non-gravitational forces, \longrightarrow satellite's equation of motion
air drag, solar and Earth radiation pressure
disturbing gravitational potential \longrightarrow satellite orbit perturbations
(w.r.t. spherical symmetric Earth) (w.r.t. Kepler orbit)

observe satellite trajectories with tracking devices from ground or space

olve inverse problem: observed orbit perturbations \longrightarrow anomalous geopotential
(global geoid, gravity anomalies)

rawback: attenuation of gravitational signal due to satellite's altitude, $\left(\frac{R}{R+h}\right)^{l+1}$,
presently restricts resolution to long-to mesoscale constituents ($\lambda > 800$ km, $l > 50$)

necessity: only way to determine global long-wave Earth gravity field accurately
and homogenously

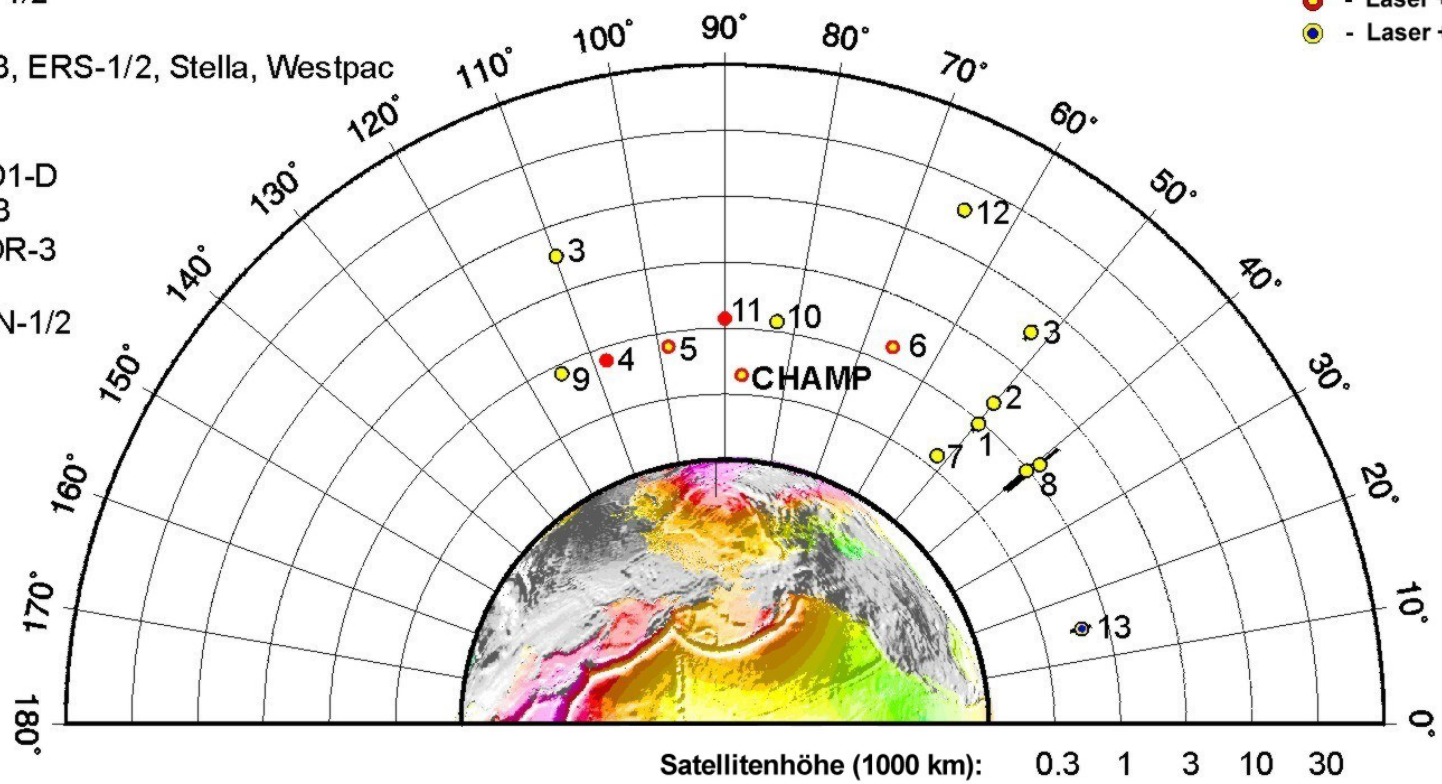
- The Satellite Itself Is Used As A Gravity Sensor -

Tracking Data Processing

- Numerical integration of satellite's equation of motion adopting an initial force field and reference frame (arc length 1 day ... 1 month)
 - Compute residuals to observed tracking observations and generate single-arc normal equations for a least squares adjustment ('best' fit of unknowns to observations)
 - Accumulate single arc normal equation systems for all arcs and satellites
-
- Solve resulting system by matrix inversion for
 - satellites, position and velocity at t_0 per arc
 - spherical harmonic coefficients of the gravitational geopotential including the time varying ocean tide potential
 - geocentric tracking station coordinates (reference frame)
 - other observation-type and arc-dependent parameters
-
- ➔ **EIGEN-2 CHAMP global gravity field solution:**
- 127 arcs of 1.5 d length
 - 5.6 million tracking observations (GPS-SST code and phase)
 - 16000 gravitational unknowns

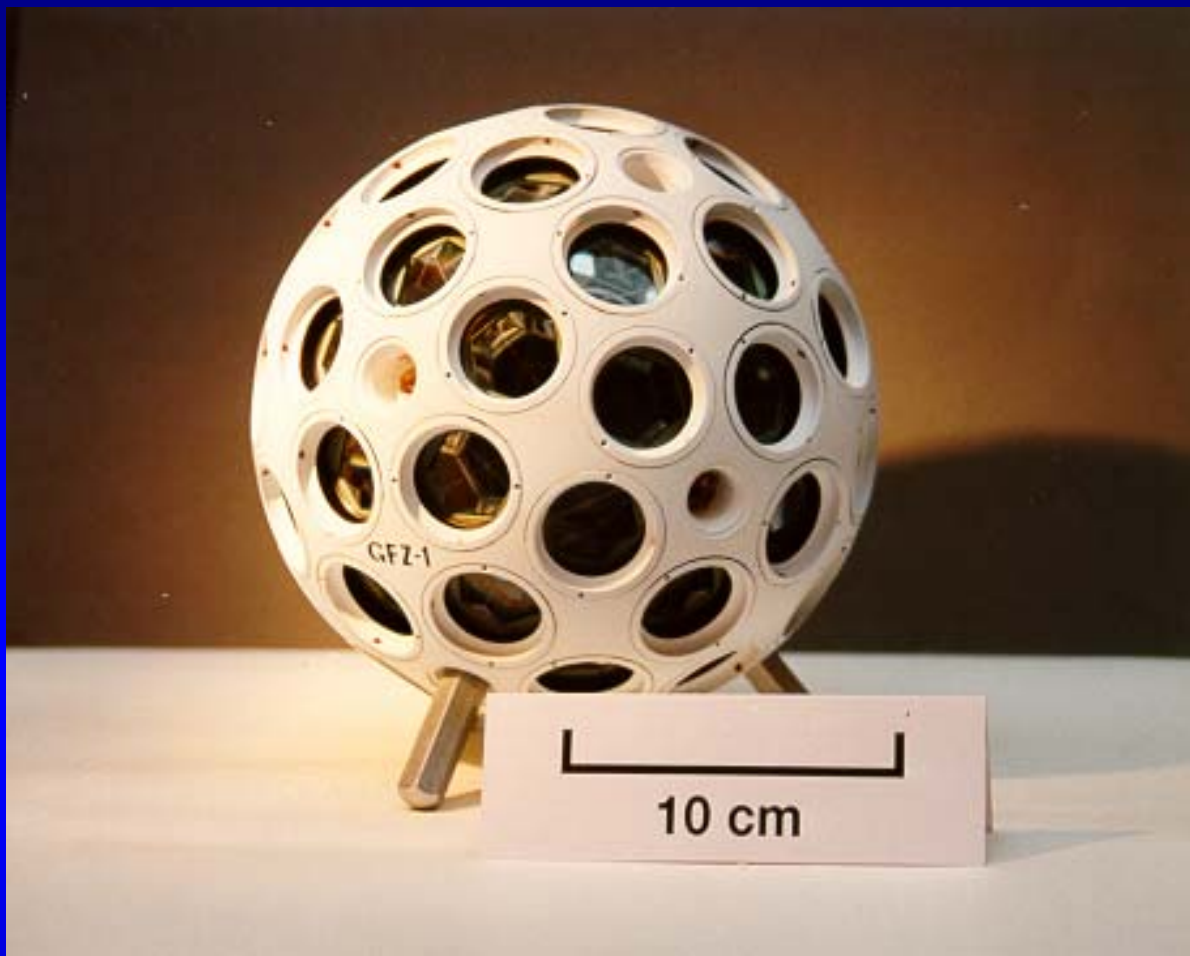
- 1 Starlette
- 2 Ajisai
- 3 Lageos 1/2
- 4 Geosat
- 5 Spot-2/3, ERS-1/2, Stella, Westpac
- 6 Topex
- 7 GFZ-1
- 8 D1-C, D1-D
- 9 GEOS-3
- 10 METEOR-3
- 11 NOVA3
- 12 ETALON-1/2
- 13 PEOPLE

- - Laser
- - Radiowellen
- - Laser + Radiowellen
- - Laser + Kamera

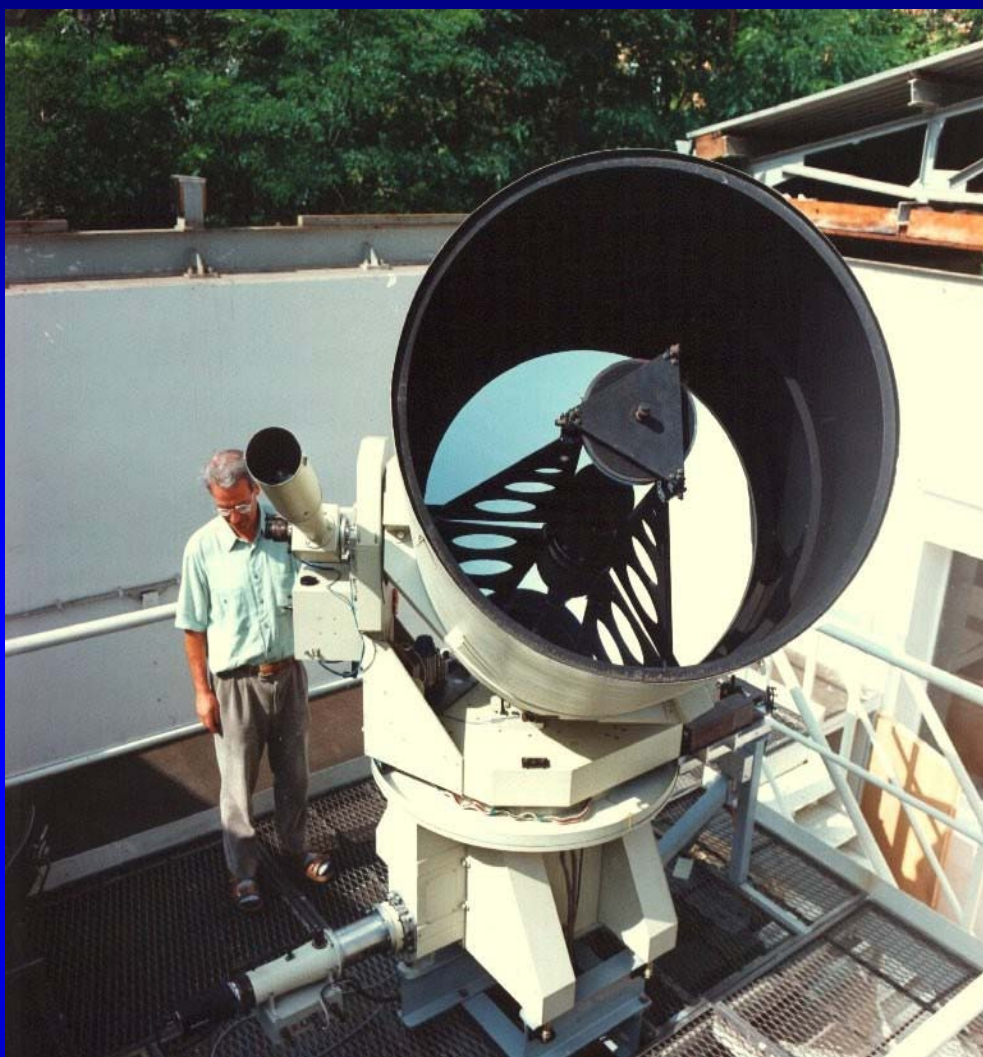


Verteilung der für eine neuere Geoid- und Schwerefeldlösung benutzten Satelliten in erdnahen Raum. Zu den Namen der Satelliten sind Flughöhe und Bahnneigung gegen die Äquatorebene eingezeichnet. Die Farben markieren die verwendeten Messsignaltechniken bei der Bahnverfolgung.

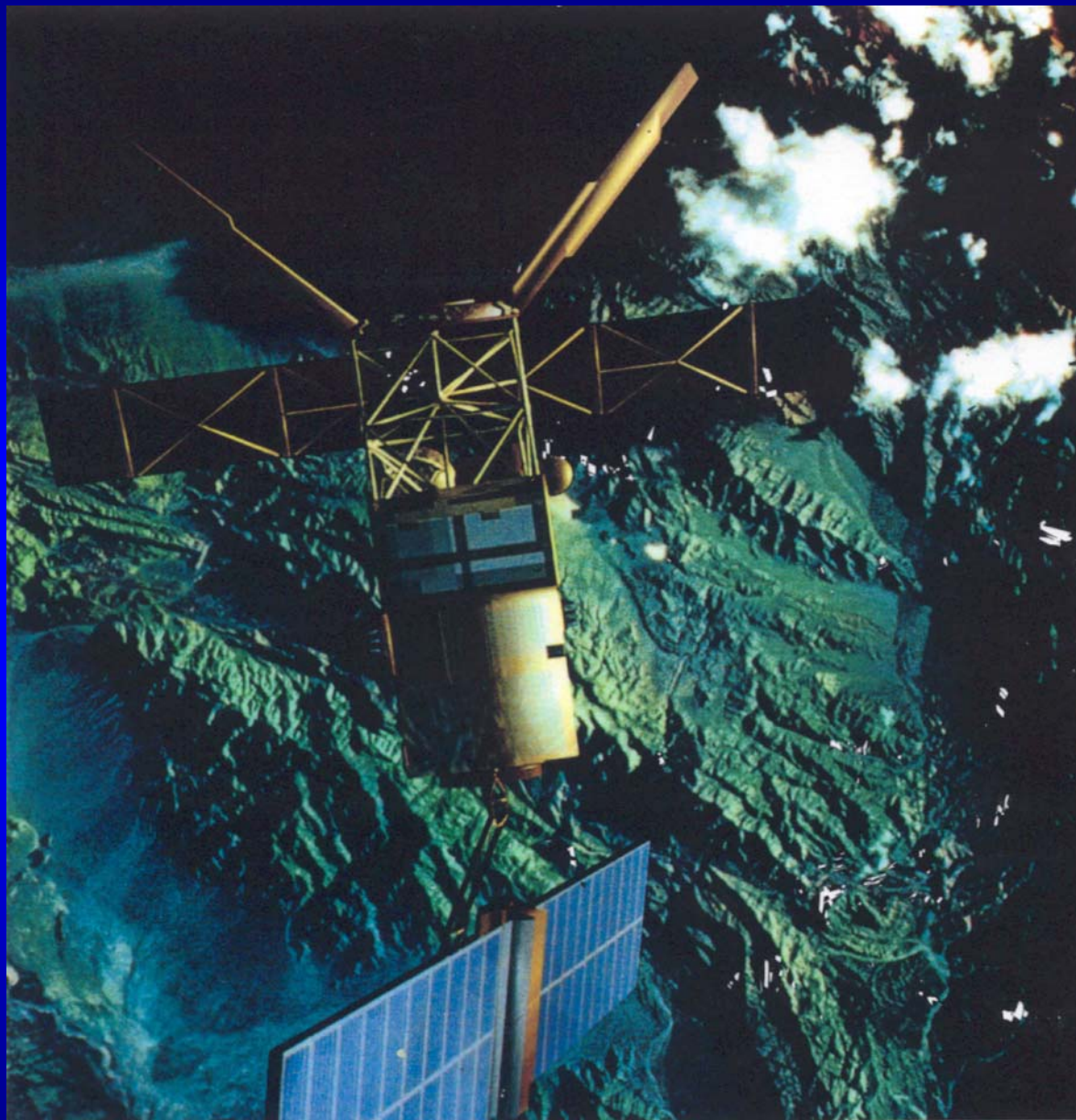




Der passive Kleinsatellit GFZ-1 umrundete die Erde von 1995-1999 in einer Höhe von anfänglich 390 km. Die Bahn des Satelliten wurde von weltweit verteilten Laserstationen über präzise Entfernungsmessungen verfolgt. Die im Bild erkennbaren Reflektoren am Satelliten haben die Funktion, auftreffende Laserimpulse zur Bodenstation zurückzulenken.

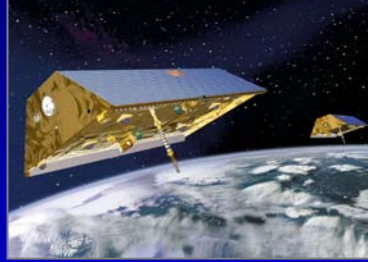
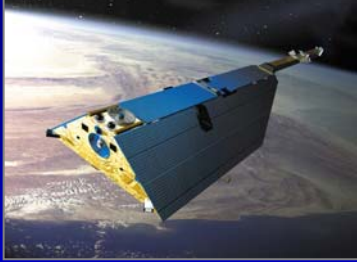


Laserteleskop des GFZ Potsdam zur Bahnverfolgung von Satelliten.
Gemessen werden – bei wolkenfreiem Himmel – die Entfernungen
zwischen Satellit und Bodenstation durch die Registrierung der Laufzeit
von ausgesandten und am Satelliten reflektierten Laserimpulsen.

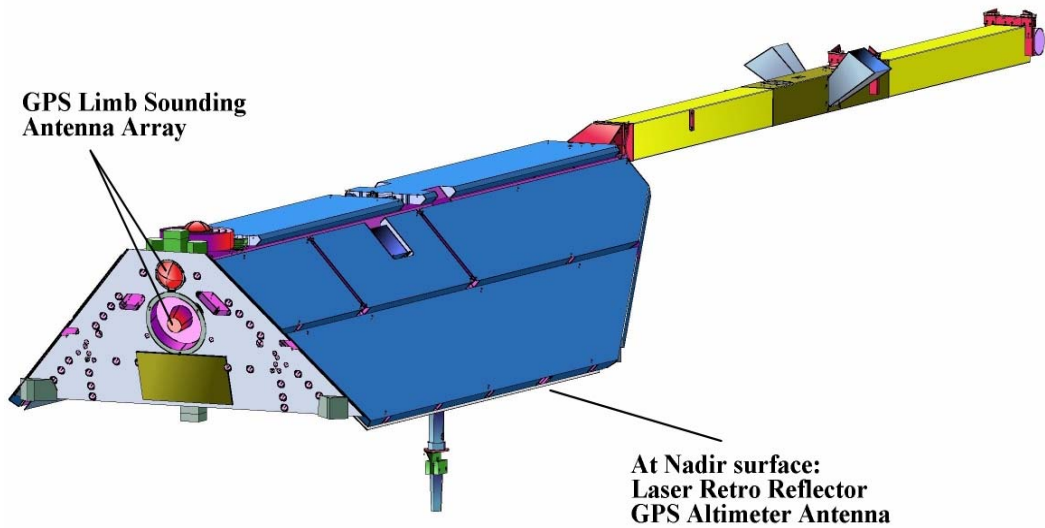
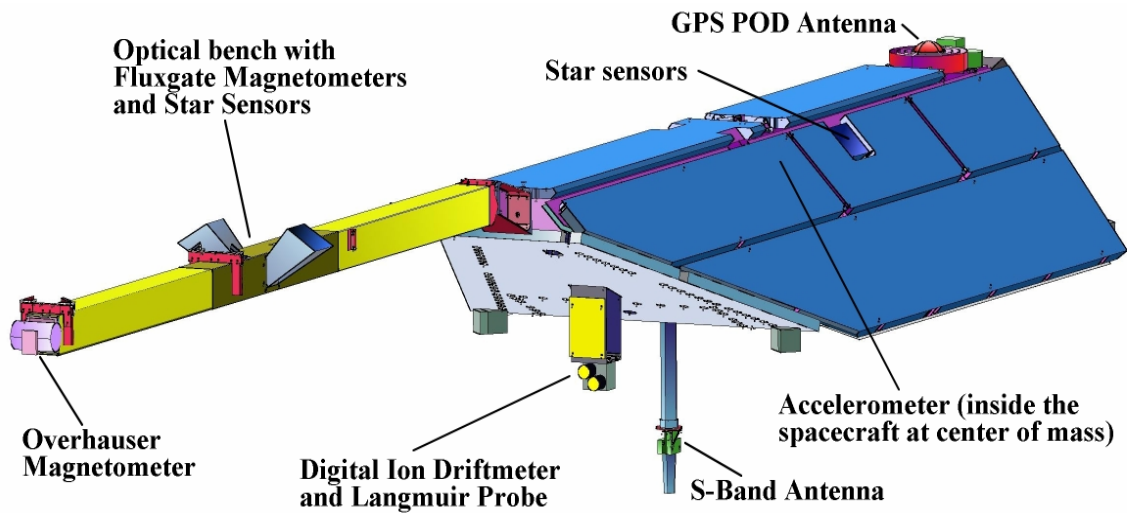




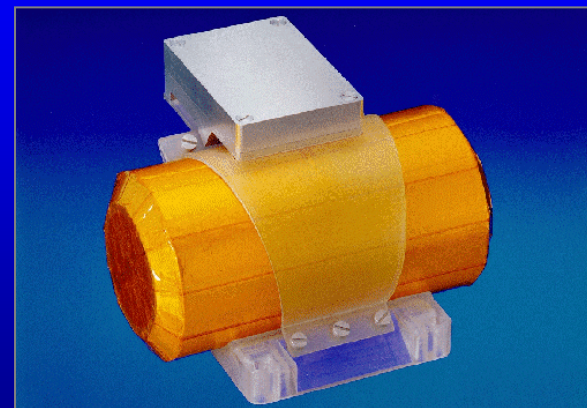
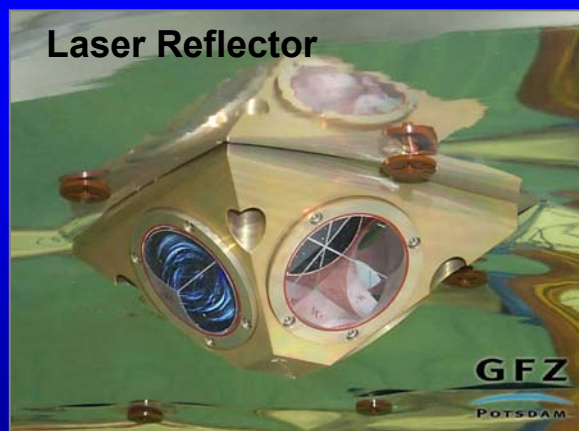
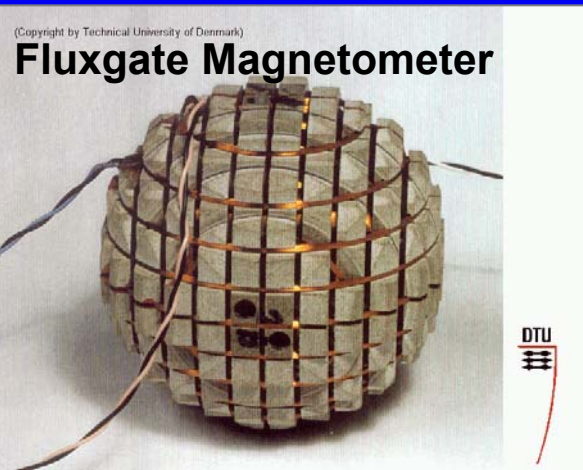
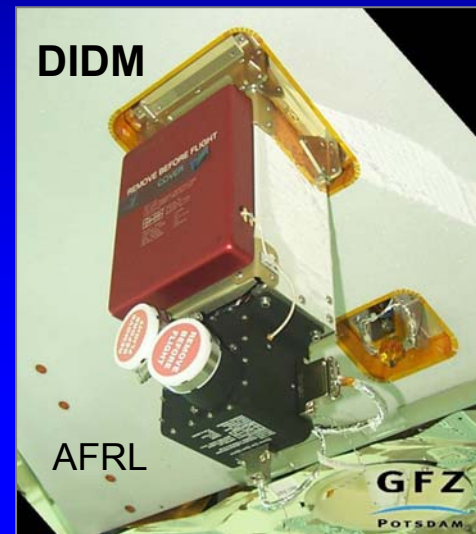
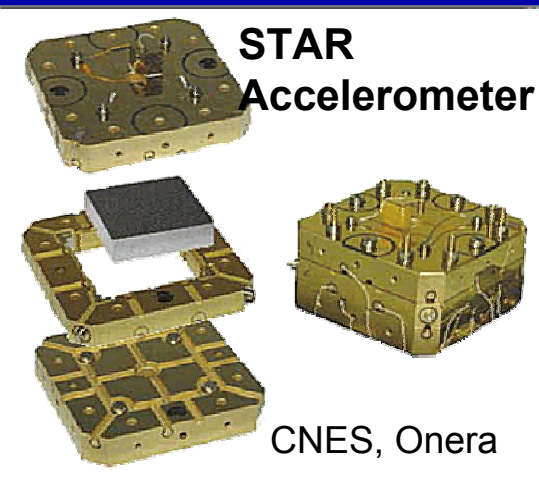
ine Bodenstation des mit Radiowellen – wetterunabhängig – arbeitenden Satellitenbahnverfolgungssystems PRARE. PRARE ist auf dem europäischen Erdkundungssatelliten ERS-2 seit 1995 im Einsatz. Aus der Signallaufzeit vom Satelliten zur Bodenstation und zurück werden die Entfernung und aus der Dopplerverschiebung zwischen ausgesandtem und empfangenem Signal die Geschwindigkeit des Satelliten relativ zur Bodenstation bestimmt. Die Daten mehrerer Überflüge werden im Satelliten gesammelt und über einer zentralen Empfangsstation abgestrahlt.



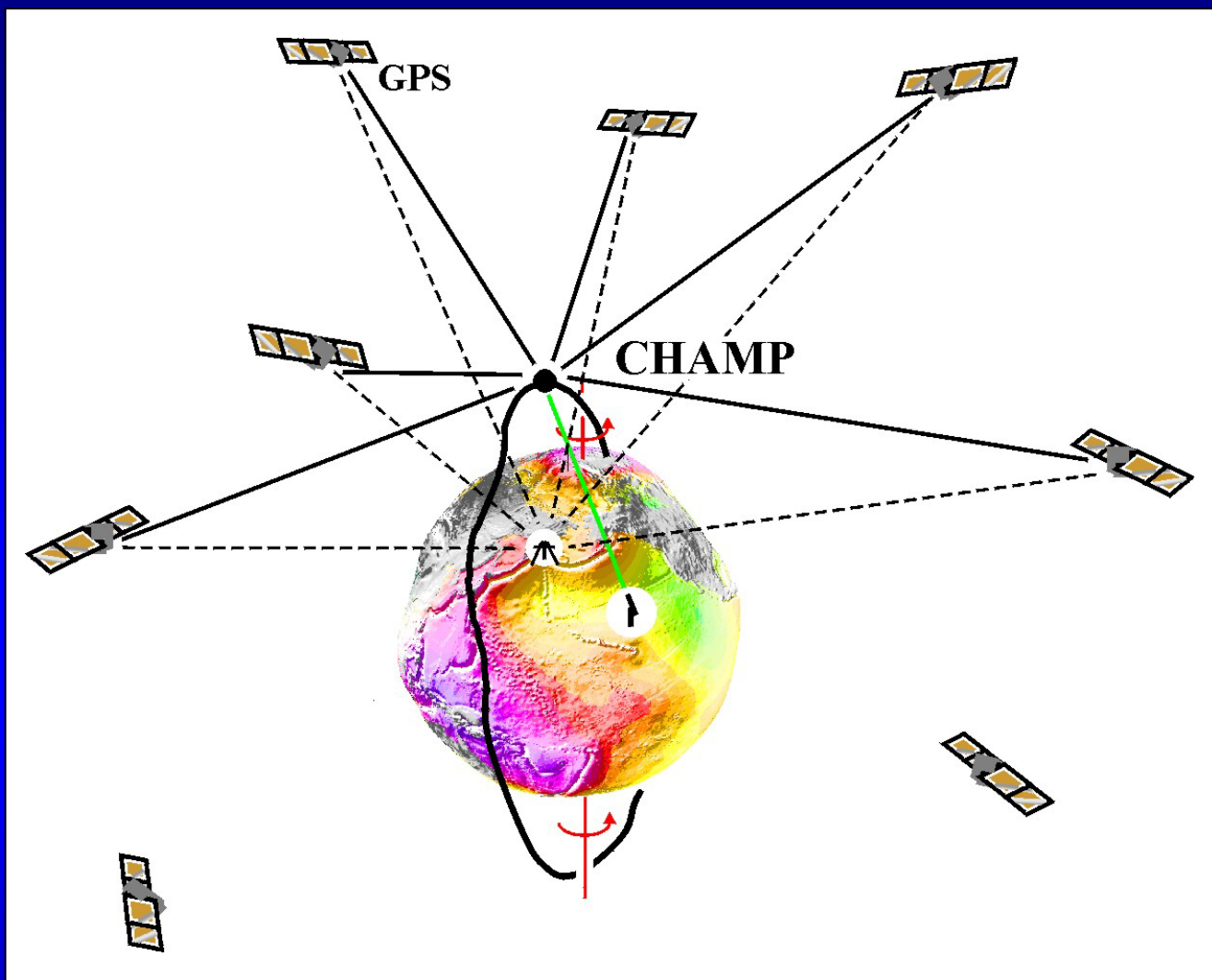
	CHAMP (launched July 2000)	GRACE -A, -B (launched March 2002)	GOCE (2006)
Orbit inclination	87°	89°	96.5°
Orbit altitude	454 ... 400 (2002) ... 300 km	500 ... 300 km	250 km
Mission lifetime	5 years	5 years	2 x 0.5 years
Surface force sensor	accelerometer	accelerometer	drag-free
Gravity sensor	GPS-CHAMP SST	GPS-GRACE SST, low-low KBR SST (220 km)	GPS-GOCE SST, Gradiometer
Gravity field recovery ($\lambda/2$)	achieved: 10 cm, 0.5 mgal @ 500 km goal: 1 mm @ 4000 km, 3 monthly	goal: 10 cm, 2 mgal @ 150 km 1 mm @ 500 km, monthly	goal: 1 cm, 1 mgal @ 100 km -



CHAMP Instruments

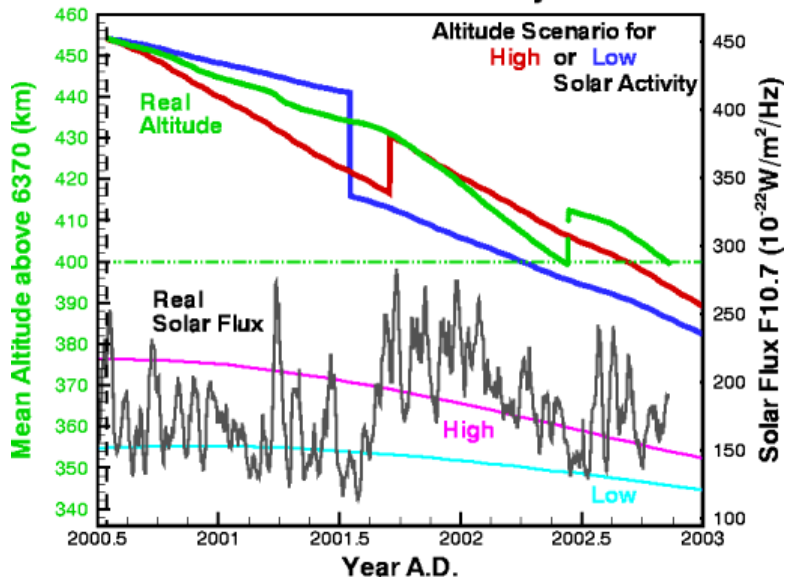


Overhauser
Magnetometer

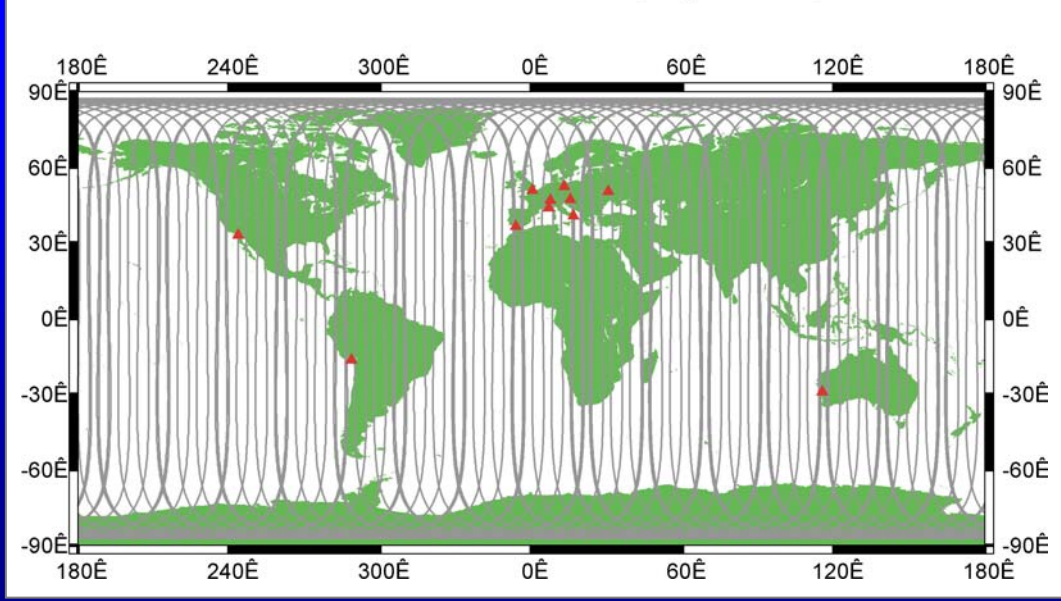


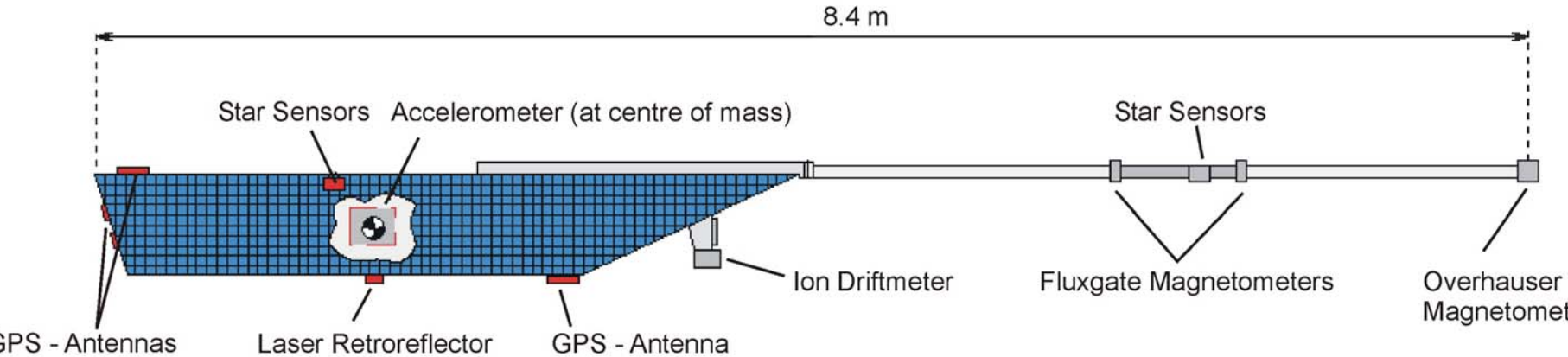
Prinzip der Satellitenbahnverfolgung am Beispiel des Satelliten CHAMP:
 Verbindungs- und Abstandsmessungen von den hochfliegenden GPS-Satelliten bzw.
 Bodenstationen zu CHAMP. Aus den so beobachteten Bahnstörungen
 niedrigfliegender Satelliten werden die großräumigen Strukturen im Geoid
 und Erdschwerefeld abgeleitet.

CHAMP Orbit Decay



CHAMP Ground Track and SLR Stations, Day 210 - 213, 2000





CHAMP mission benefits for a fundamental progress in gravity field recovery:

- near-polar orbit ($i=87^\circ$) for a complete coverage of the Earth
- continuous high-low GPS satellite-to-satellite tracking and a very low orbit (450 km, decaying to 300 km)
- on-board accelerometer for a direct measurement of hard-to-model non-gravitational surface forces, mainly air drag
- long mission lifetime (5 years) to resolve temporal gravity variations

CHAMP Gravity Field Data

(EIGEN – European Improved Gravity field of the Earth by New techniques)

Data Coverage: 180 days spread out over the periods
(for EIGEN-1S) 2000, Aug. – Dec. (88 days, 63 arcs) and
(for EIGEN-2p) 2001, Sept. – Dec. (92 days, 64 arcs)

Tracking Data: GPS Blackjack SST, 30s epochs (desampled from 10s)
1.1 mio. (2000) + 1.7 mio. (2001) code and phase observations,
resp. (max. 7 satellites per epoch in 2000, max. 8 in 2001)

Surface Force Accelerations: STAR three-axes accelerometer data

10s normal points from 1s values

S/C Orientation: ASC star camera quaternions (body-mounted heads),
10s epochs (desampled from 1s)

H/K Data: Thruster firing events (epoch and duration for 2 x 3
thruster pairs)

Gravity Field Solution Strategy (CHAMP-only)

- Two Step Approach:**
- (1) GPS satellite orbits and 30s clocks
(1.5 d arcs + 2 x 15 min overlap)
 - (2) CHAMP orbits (~1.5 d arcs) and normal equation system generation with GPS orbits and clocks fixed

Parametrization of CHAMP Normal Equation Systems:

CHAMP state vector per arc

CHAMP clock offsets (1 per 30s-epoch)

GPS-SST ambiguities (700 to 800 per 1.5 d arc)

accelerometer biases and scale factors per axis and day

1/rev empirical radial acceleration per arc (radial accel. channel corrected in 2001)

thruster mismatch linear accelerations

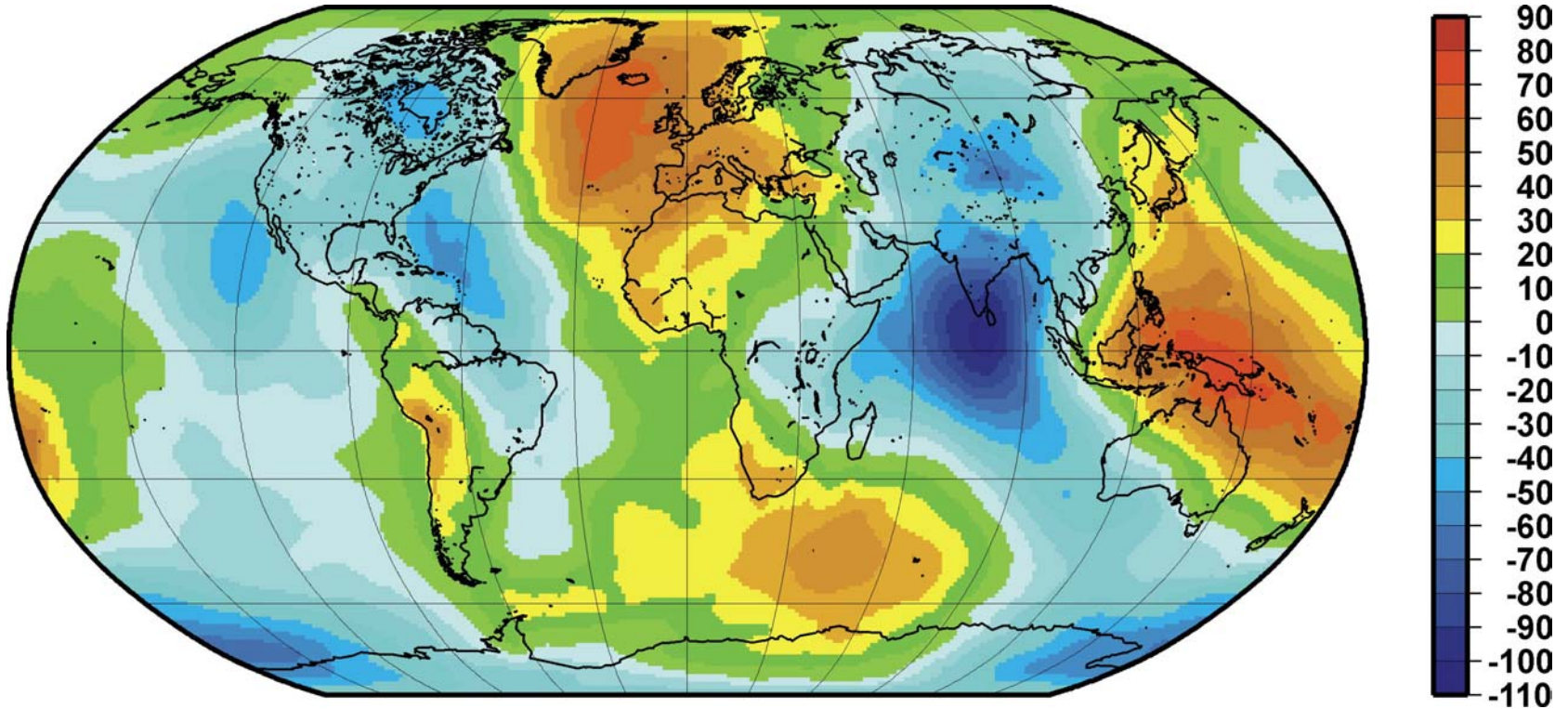
static gravitational geopotential: 15811 parameters (C_{lm} , S_{lm})
complete to degree/order 120

plus zonals, resonant (1st to 7th) and sectorial terms up to degree 140

ocean tide potential (diurnal, semi-diurnal) solved, long-period tides fixed
 C_{00} and temp. variations, not solved

Weighting: GPS code (50 cm), GPS phase (1 cm)

Solution of Accumulated Normal Equation System: with stabilization
(Kaula for terms $l > 29$)



Geoid aus 6 Monaten CHAMP-Daten

Die Signalamplitude σ_l pro Entwicklungsgrad wird aus den gelösten Stoke'schen Koeffizienten \overline{C}_{lm} und \overline{S}_{lm} des Grades l gemäß folgenden Formeln berechnet:

$$\sigma_l = \sqrt{\sum_{m=0}^l (\overline{C}_{lm}^2 + \overline{S}_{lm}^2)} \quad ; \quad \text{ohne physikalische Einheit}$$

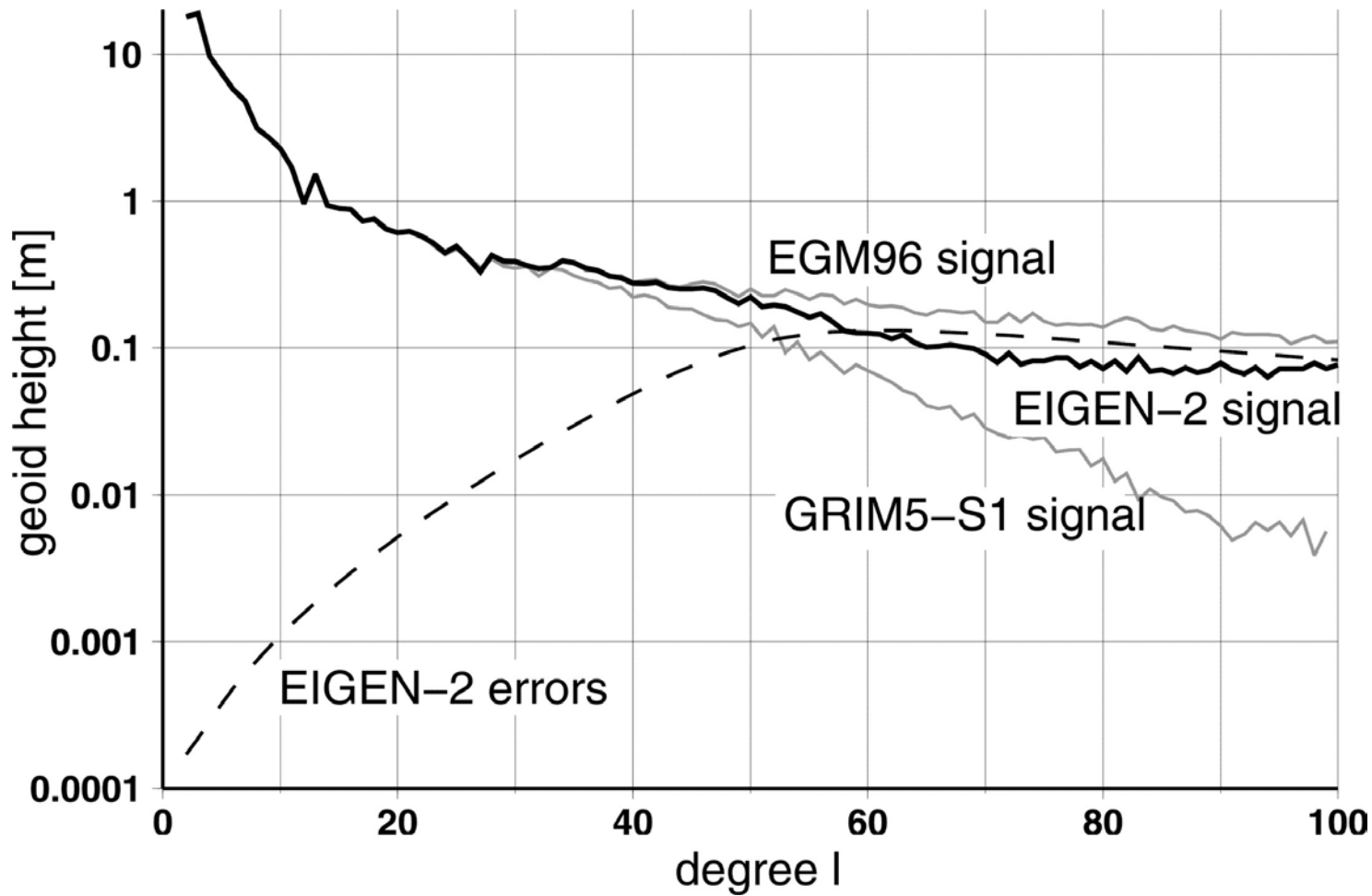
$$\sigma_l \text{ (Geoid)} = R \cdot \sigma_l \quad ; \quad \text{in Geoeinheiten (metrisch)}$$

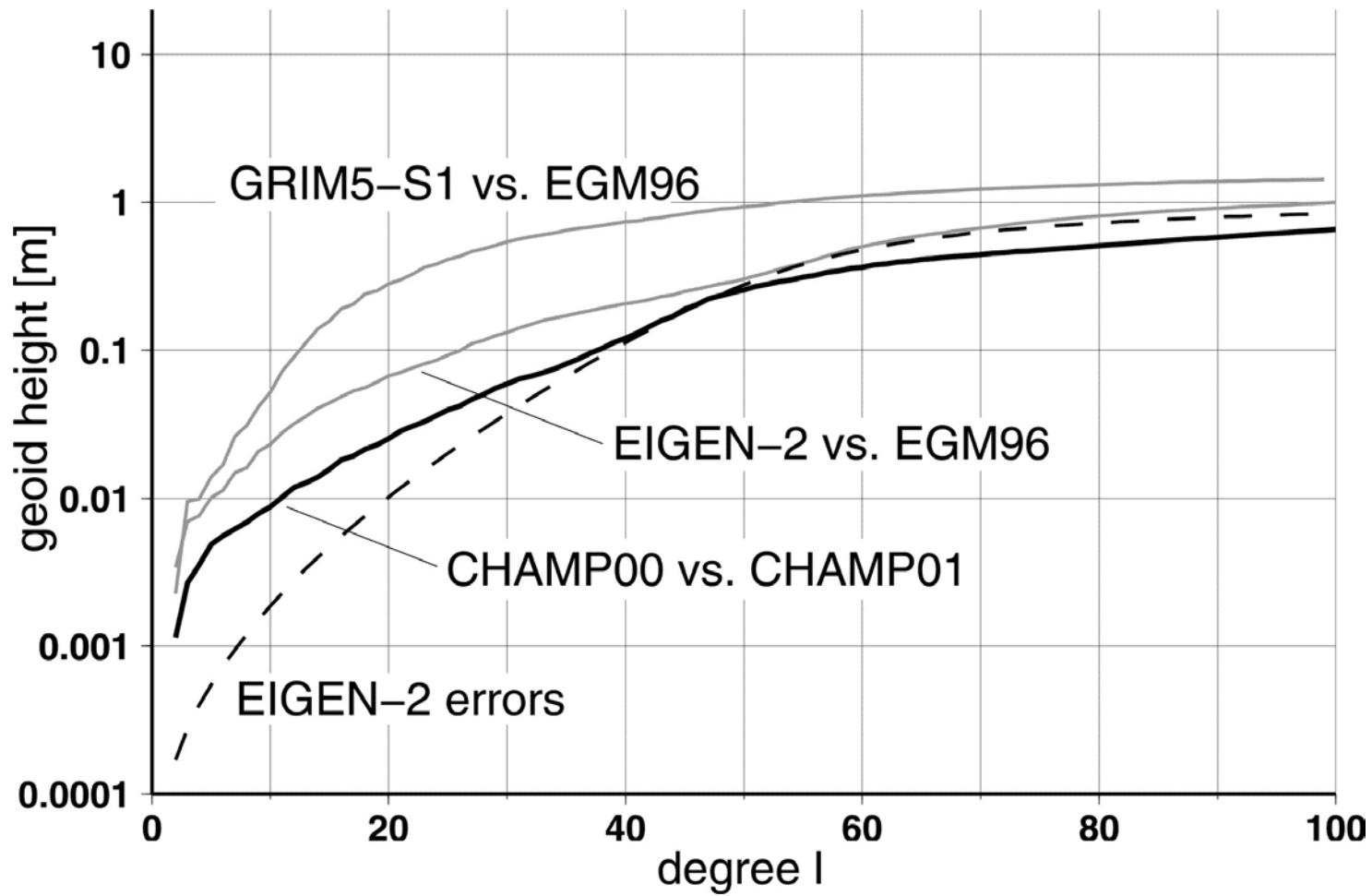
mit R – Erdradius (6378 km) und

$$\sigma_l \text{ (Schwere)} = \overline{g} \cdot (l-1) \sigma_l \quad ; \quad \text{in Schwereeinheiten (Beschleunigung)}$$

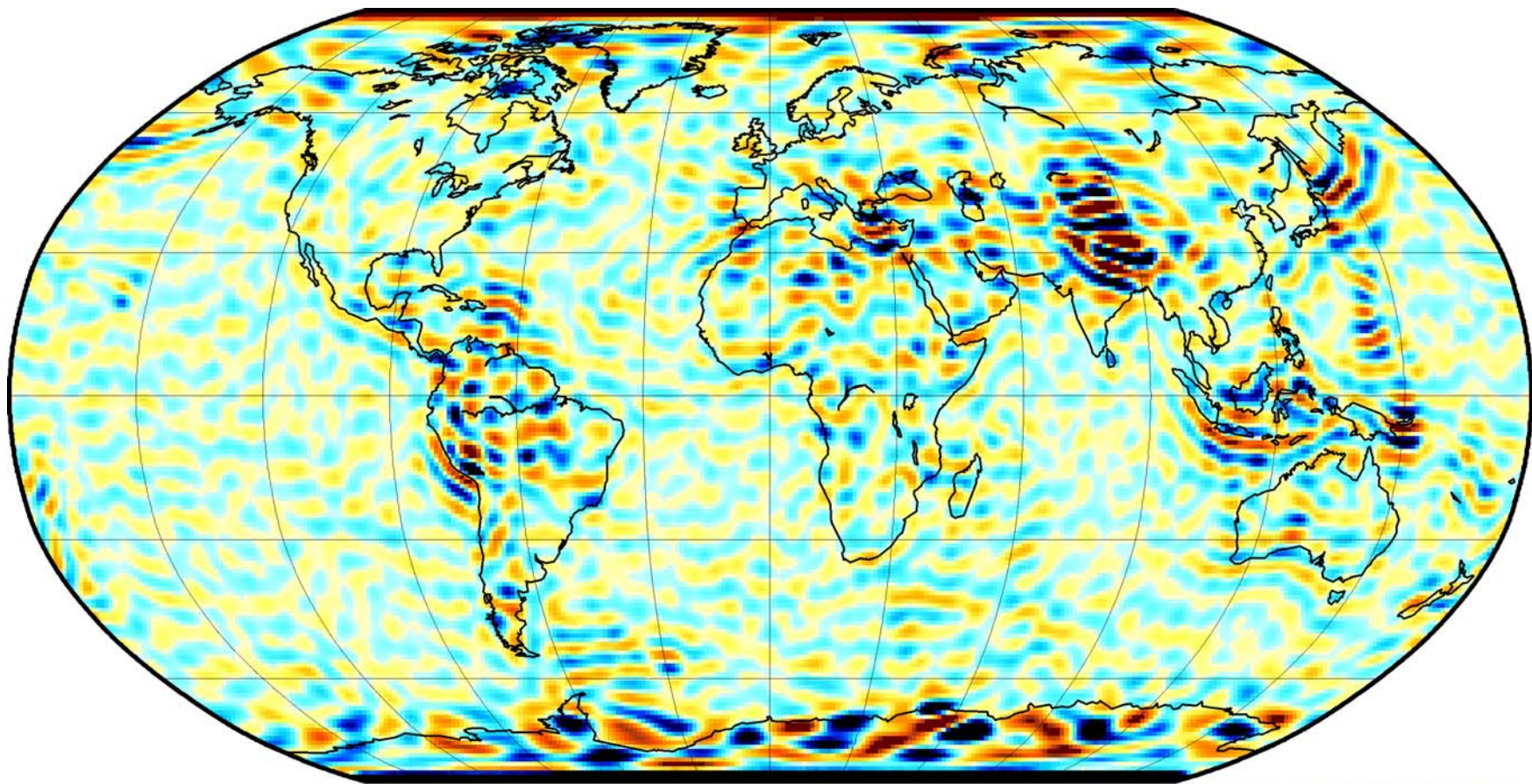
mit \overline{g} - mittlere Gravitationsbeschleunigung (9,78 m/s²).

Die \overline{C}_{l0} - Terme werden vor der Anwendung von (2) vom Beitrag des Potentials des Referenzellipsoids befreit, um das Mittel (\overline{C}_{00}) und den betragsmäßig großen Anteil der Erdabplattung, der sich hauptsächlich in \overline{C}_{20} - Term widerspiegelt, herauszurechnen.





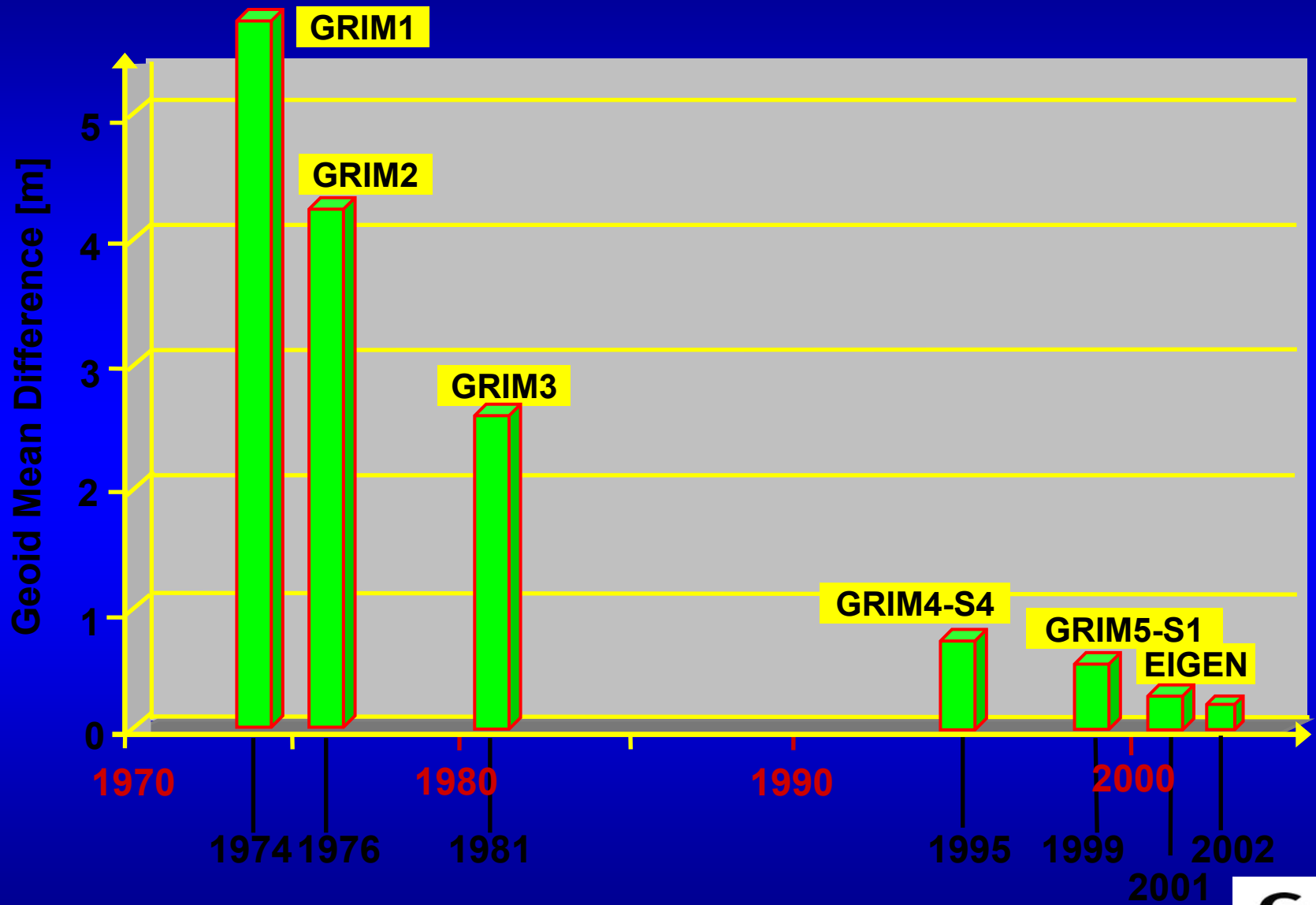
CHAMP Gravity Anomaly Differences to EGM96



half filterlength: 5° , wrms about mean = 1.46 mgal



Geoid Differences to Altimetry 5° x 5° Blocks



GRACE Mission



Science Goals

High resolution, mean & time variable gravity field mapping for Earth System Science applications.

Mission Systems

Instruments

- K-Band Ranging (JPL/SSL)
- Accelerometer (ONERA)
- Star Cameras (DTU)
- GPS Receiver (JPL)

Satellite (JPL/Astrium)

Launcher (DLR/Eurockot)

Operations (DLR/GSOC)

Science (CSR/JPL/GFZ)

Orbit

Launch: 17th March 2002

Altitude: 500 km

Inclination: 89 deg

Eccentricity: ~0.001

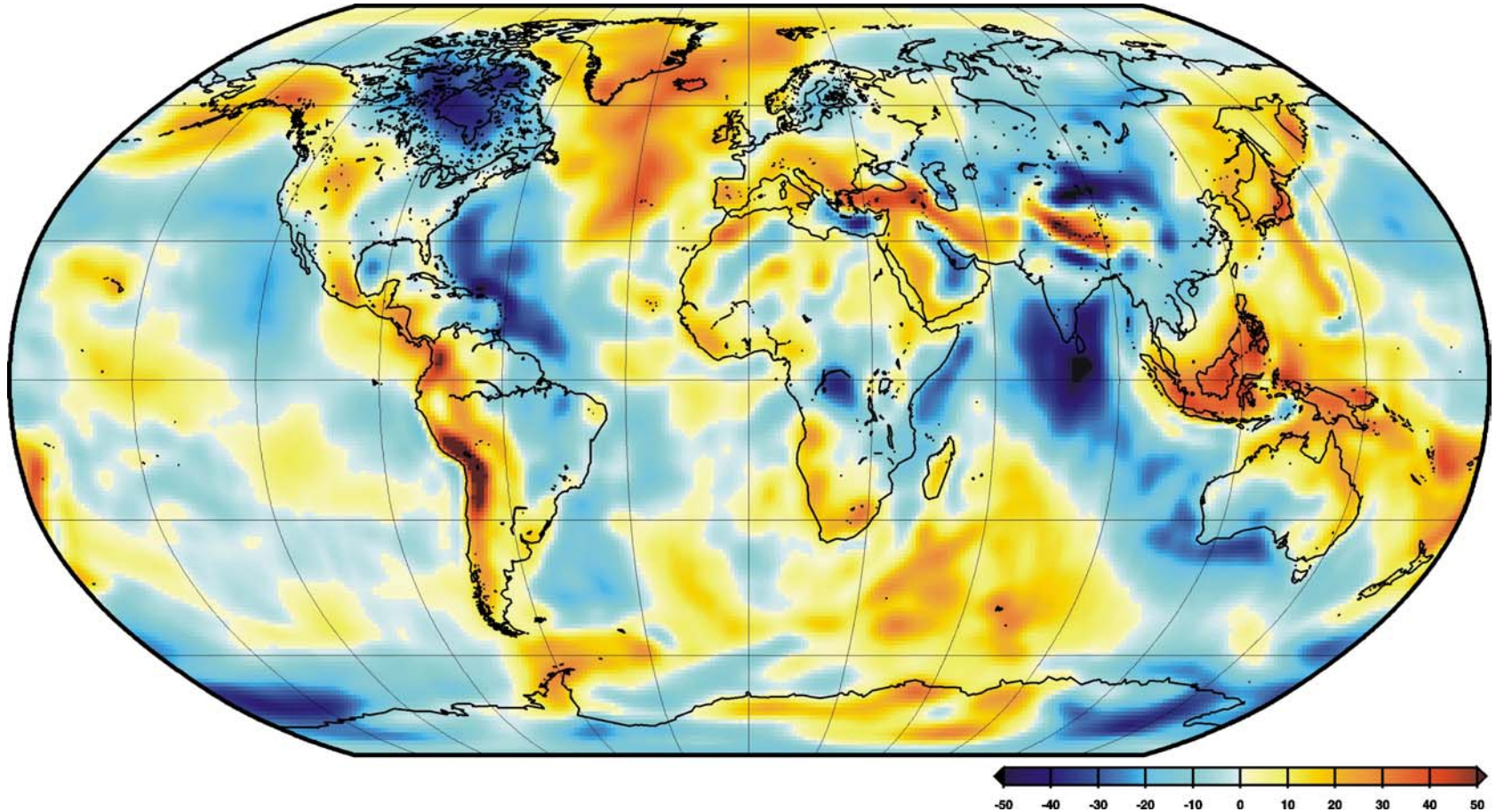
Lifetime: 5 years

Non-Repeat Ground Track

Earth Pointed,

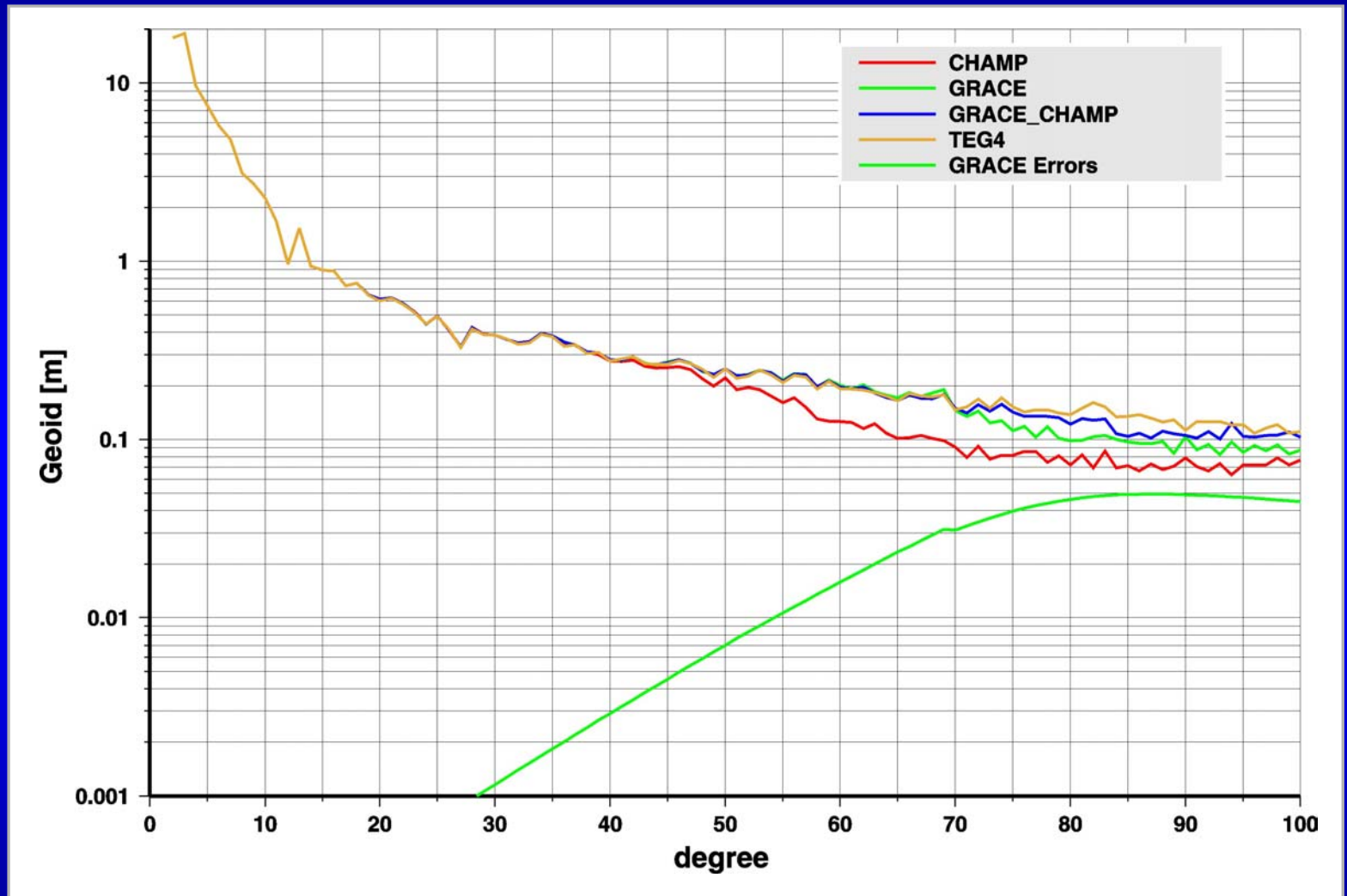
3-Axis Stable

GFZ

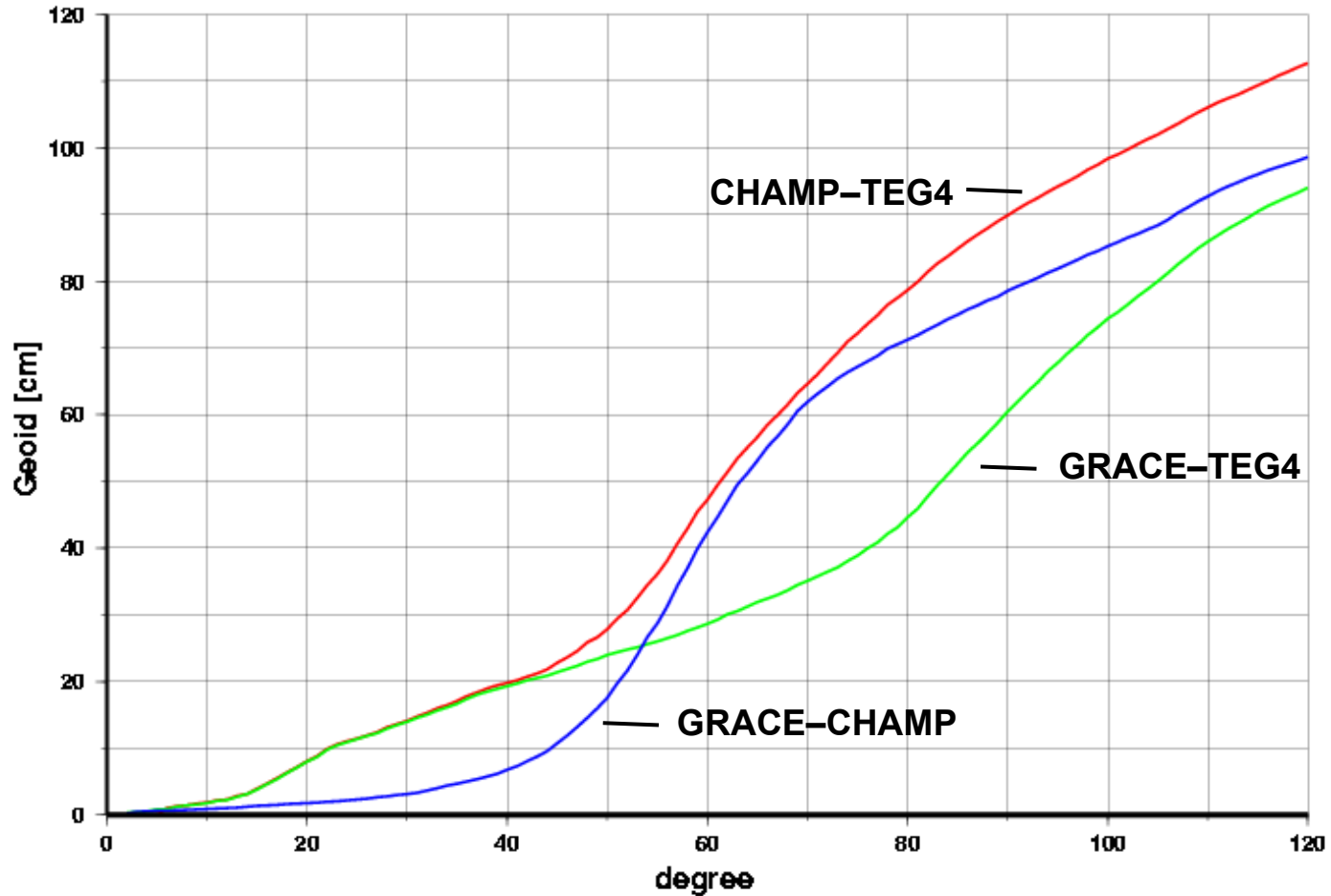


Gravity anomalies [mgal] from 10 days of GRACE data

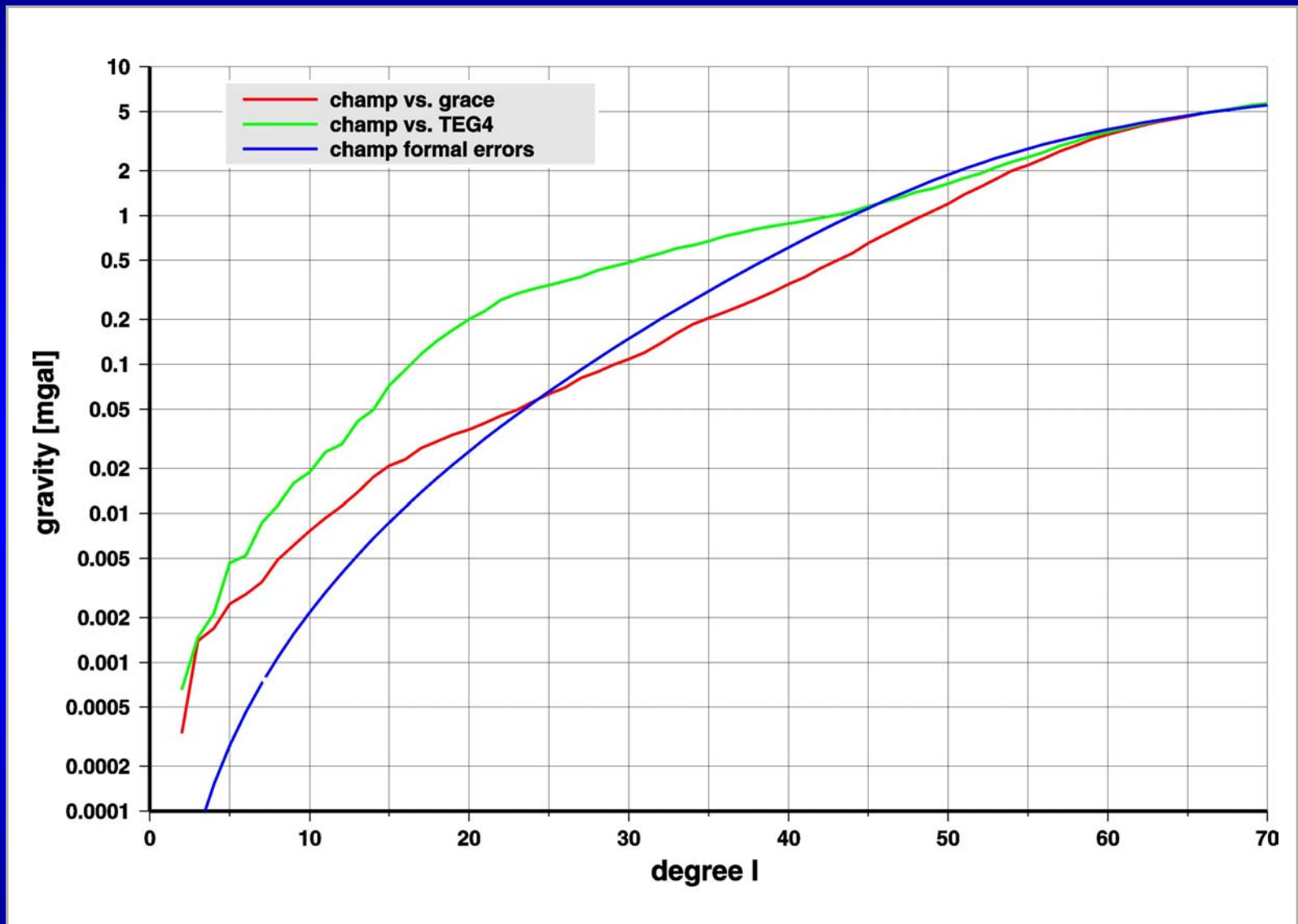
Signal / Error Degree Amplitudes



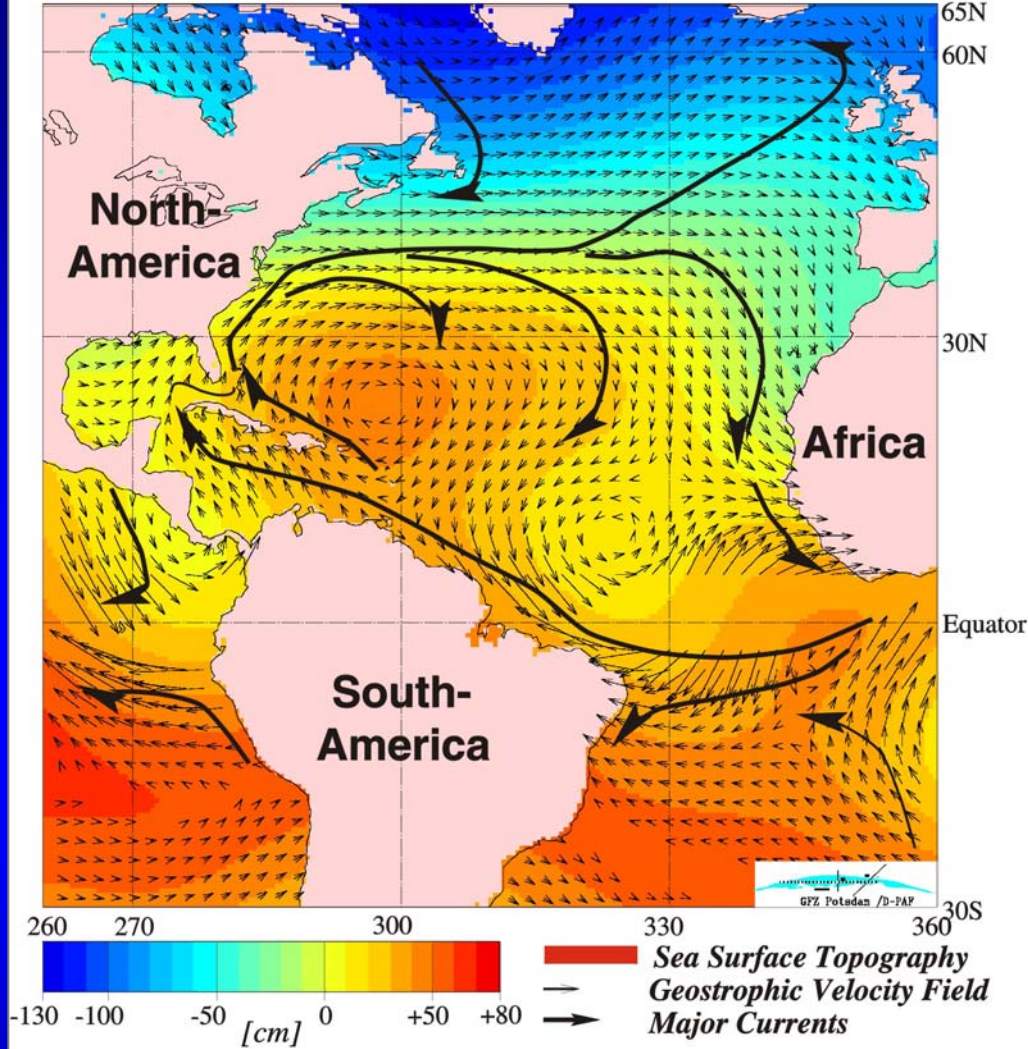
Difference Amplitudes as a Function of Maximum Degree



Difference Amplitudes as a Function of Maximum Degree



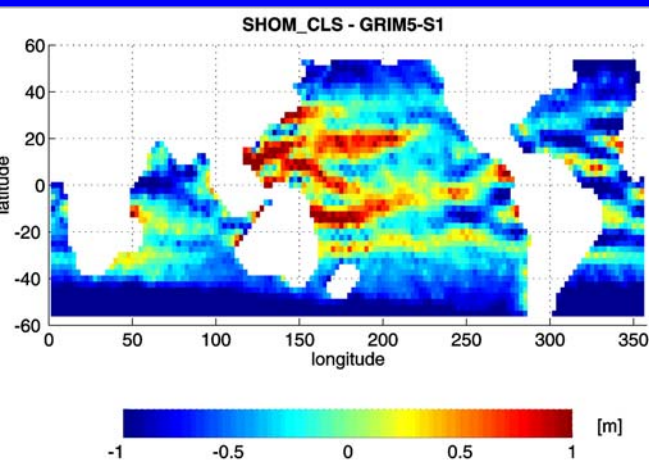
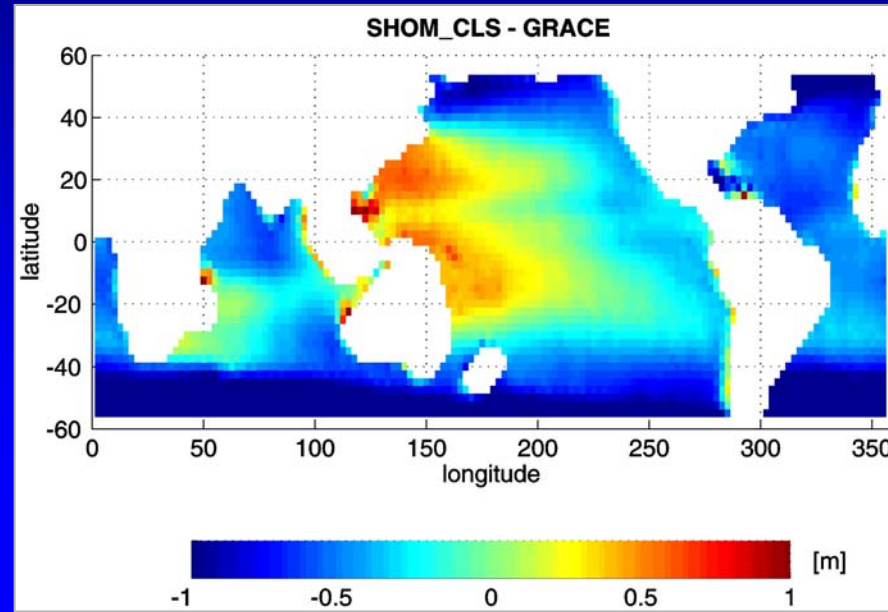
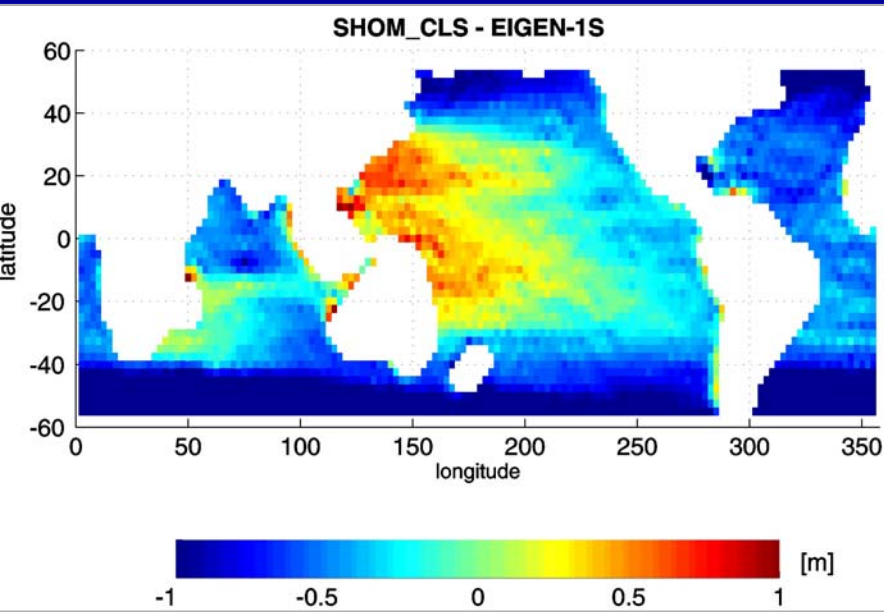
GRAVITY MODEL	Altimetry		GPS - Leveling	
	MSS99 minus POCM 5°/2.5° geoid	NIMA96 5°/2.5° Δg	USA / Canada 6611 points	Europe 186 points
satellite-only:				
CHAMP-only (7 months)	0.16/0.38m	0.78/4.4mgal	1.0m	1.6m
GRACE-only (11 days)	0.15/0.32m	0.47/3.9mgal	1.1m	1.3m
CHAMP+GRACE	0.14/0.33m	0.40/4.4mgal	1.1m	1.4m
pre-CHAMP satellite-only:				
GRIM5-S1	0.41/0.69m	2.0/5.4mgal	1.1m	1.6m
EGM96S	0.35/0.64m	1.8/5.4mgal	1.1m	1.8m
high-resolution combined:				
EGM96 ($l_{\max}=360$)	0.14/0.18m	0.24/1.2mgal	0.44m	0.45m
TEG4 ($l_{\max}=200$, 80d CHAMP)	0.14/0.18m	0.29/0.9mgal	0.52m	0.60m



CHAMP provides with the geoid a most accurate reference surface, allowing an enhanced evaluation of satellite ocean monitoring data to recover the broad pattern of the climatically important **global ocean circulation**.

Over continents, the geoid is the basis for **elevation models** on all scales and modern height measurements

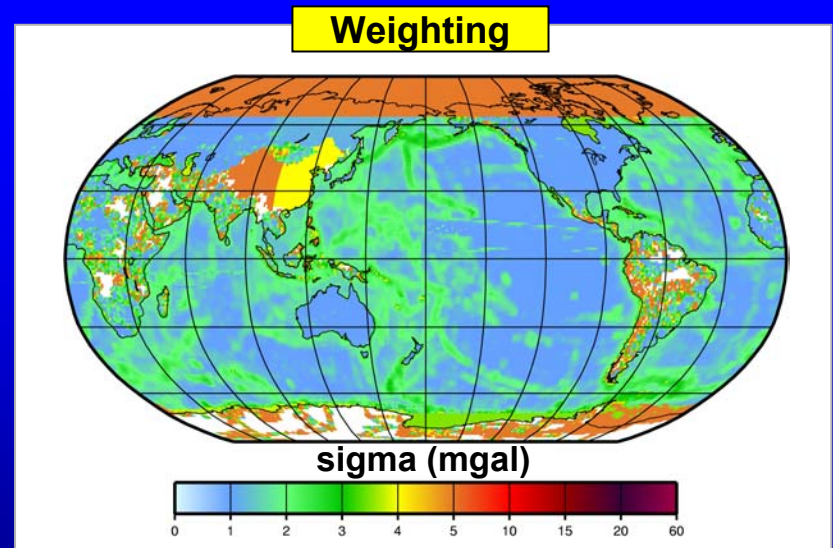
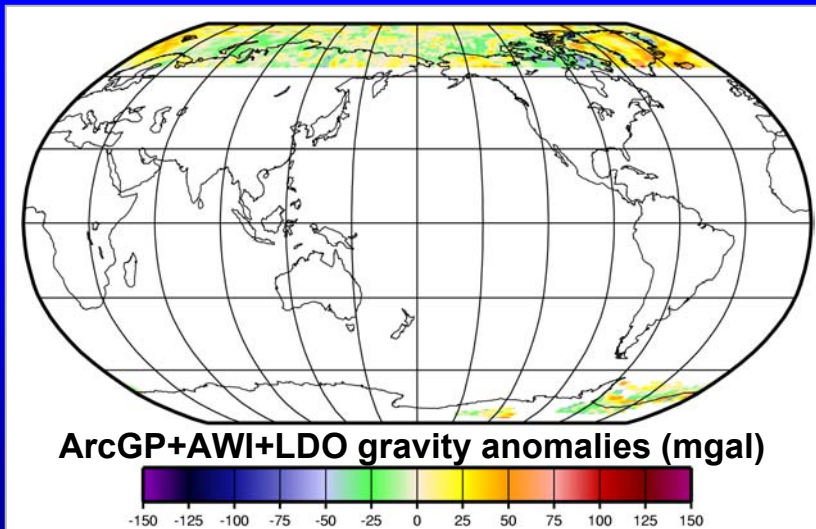
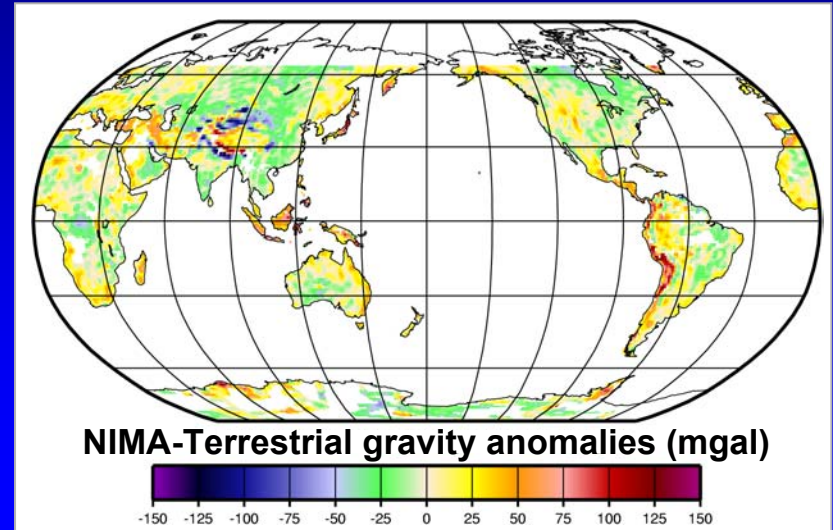
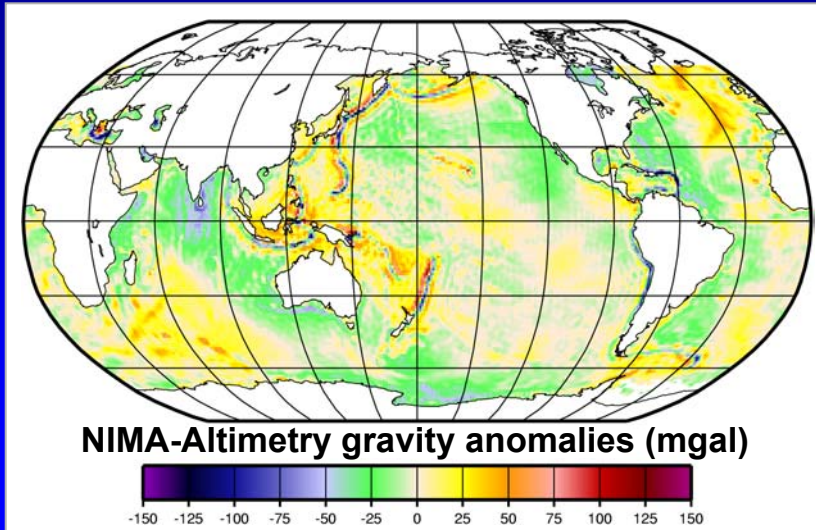
Sea Surface Topography



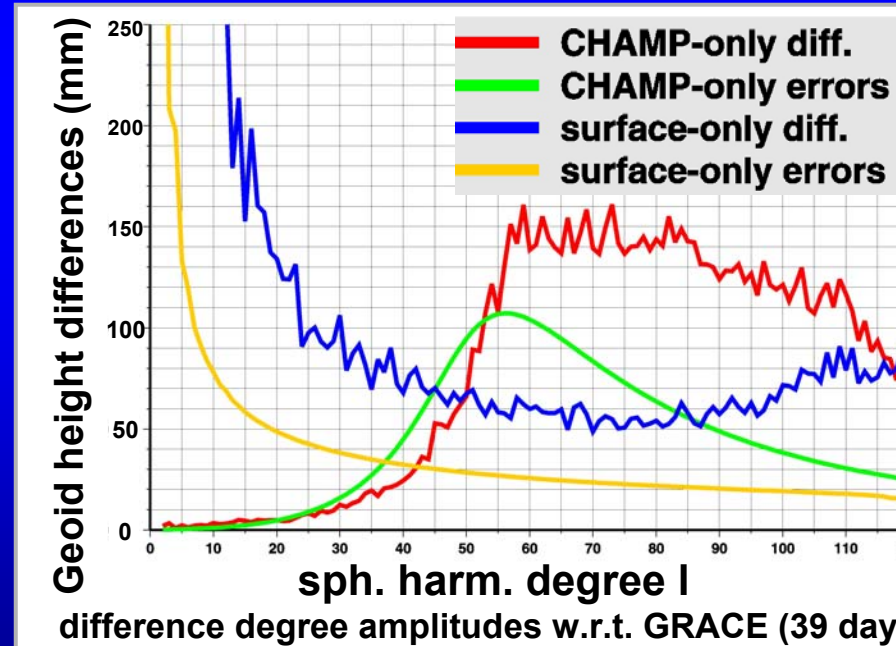
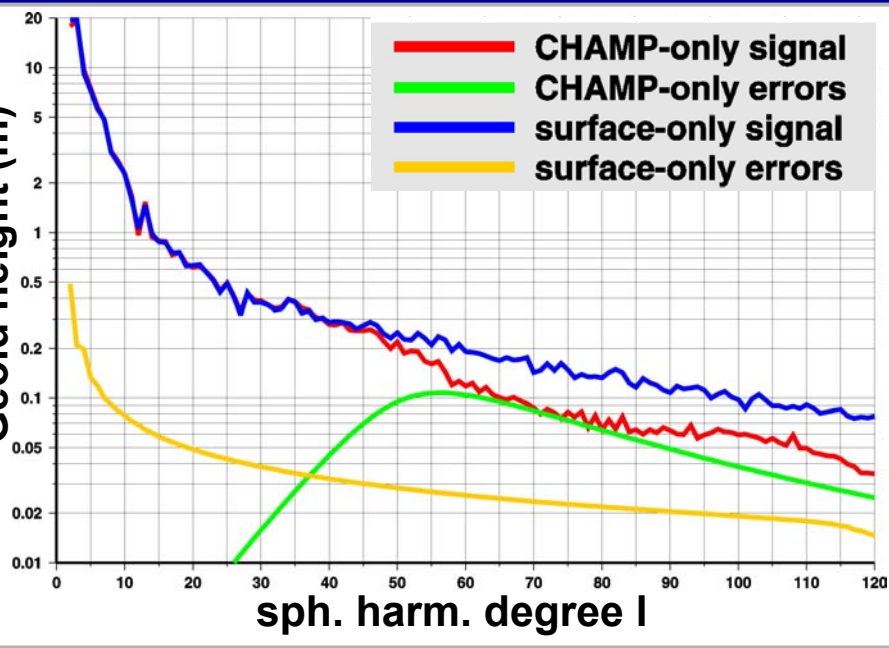
SSTop (Hanning filter, $r = 350$ km)

Schröter, Seufer (AWI 11/0)

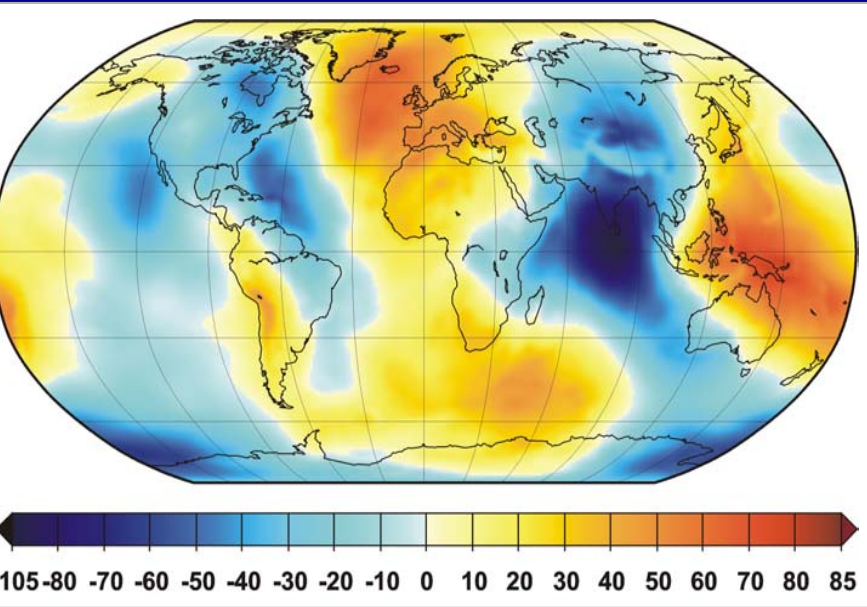
Input Surface Data and Weighting



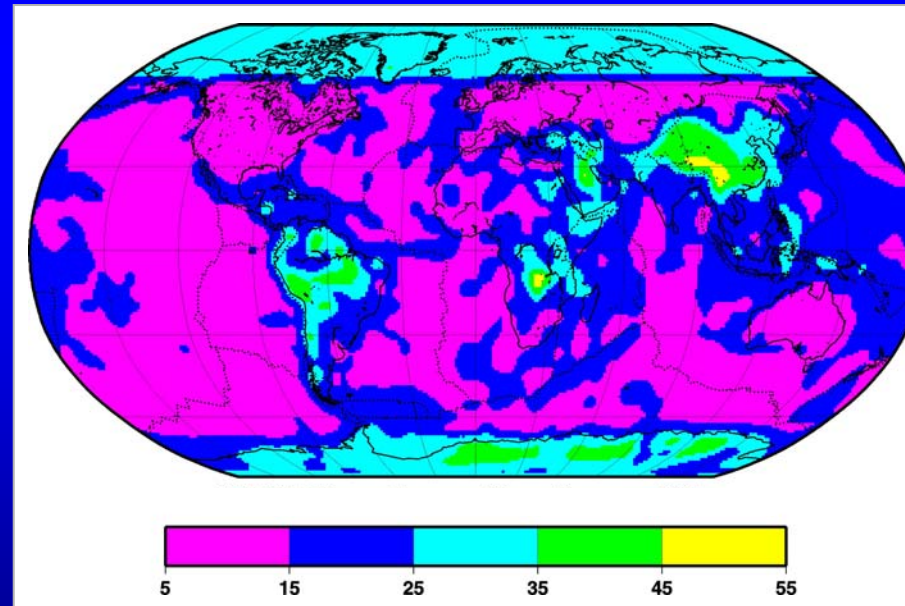
Geoid Signal / Difference Degree Amplitudes



EIGEN-2Cp Geoid

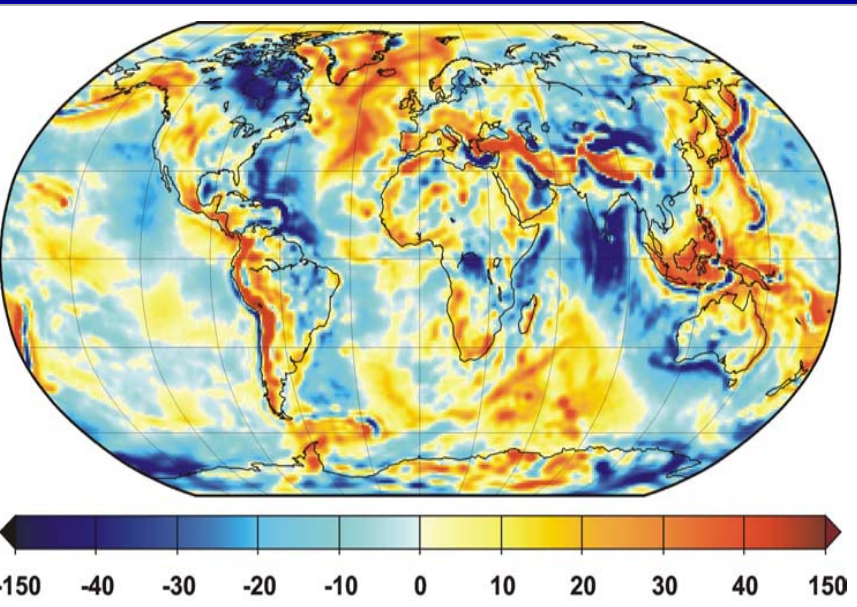


Geoid [m]

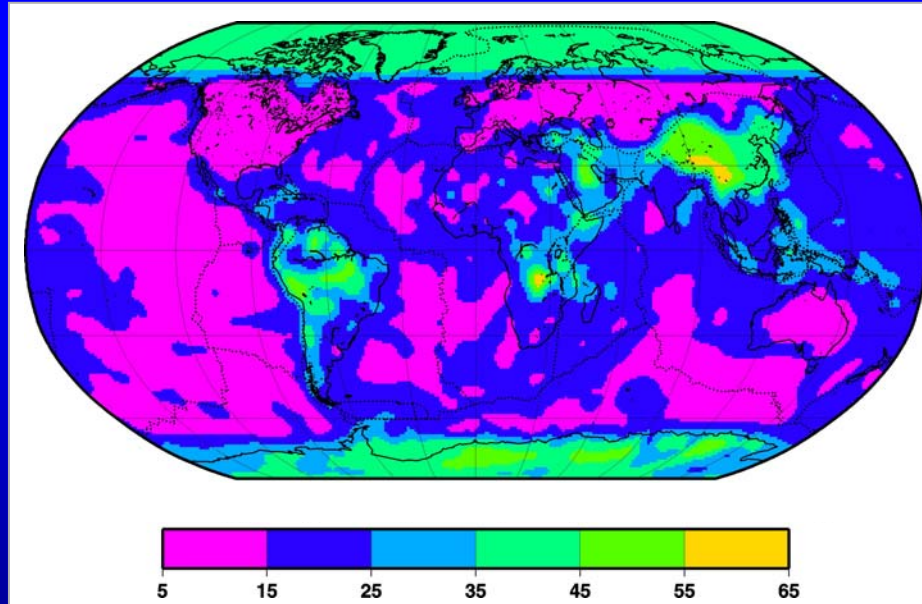


**EIGEN-2Cp geoid errors (formal)
wrms: 19.0 cm**

EIGEN-2Cp Gravity Anomaly Field



Δg [mgal]



EIGEN-2Cp gravity anomaly errors
(formal), wrms: 2.2 mgal

Processes

above

atmosphere

on

**Oceans, ice,
continental water**

within

solid Earth

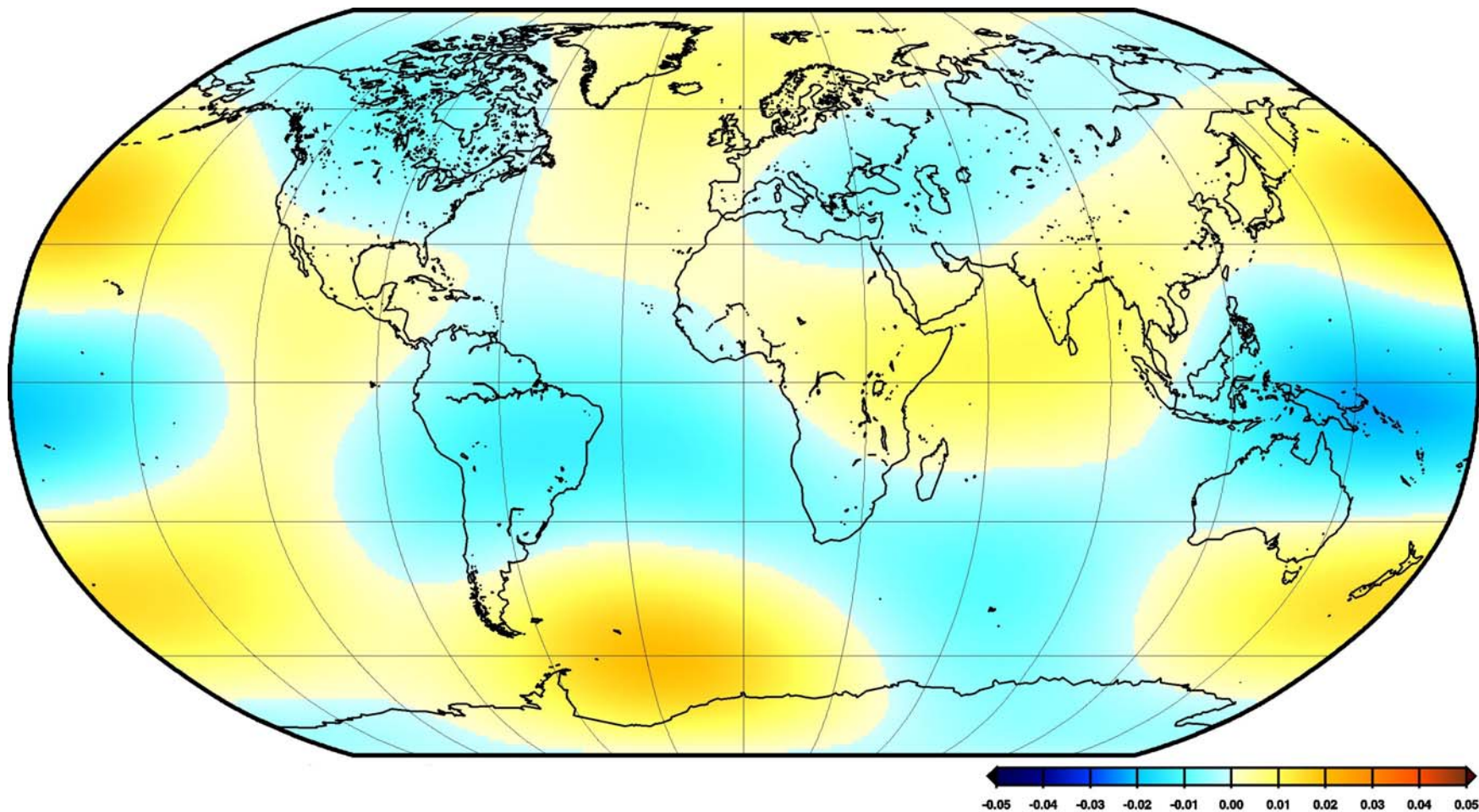
the Earth

global change
and
mass redistribution



gravity signal

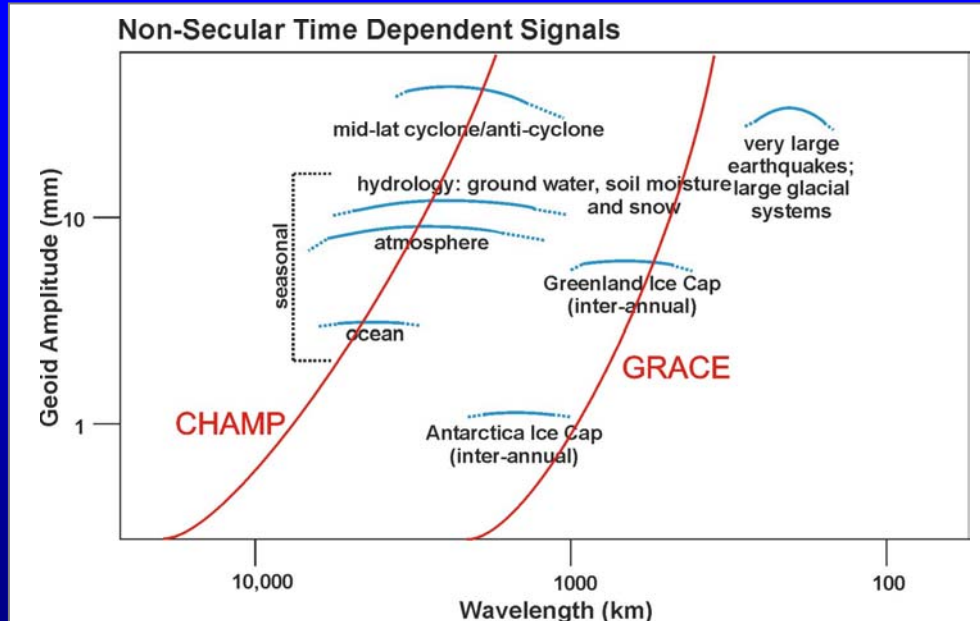
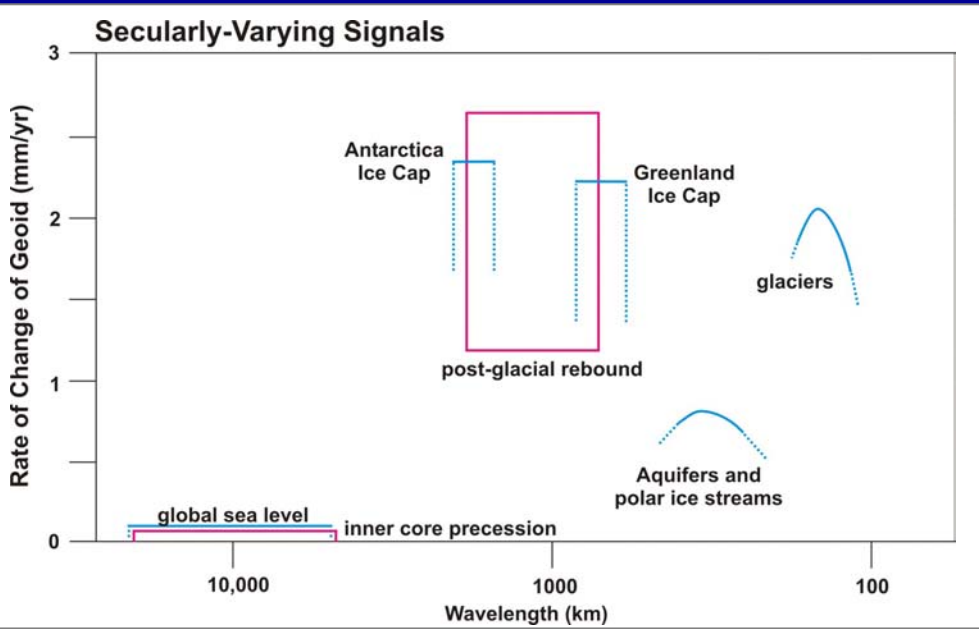
Global change and temporal gravity variations



CHAMP Geoid Sept/Oct 01 vs. Nov/Dec 01, $I_{\max} = 5$
unit: meter, wrms about mean: 0.006 m

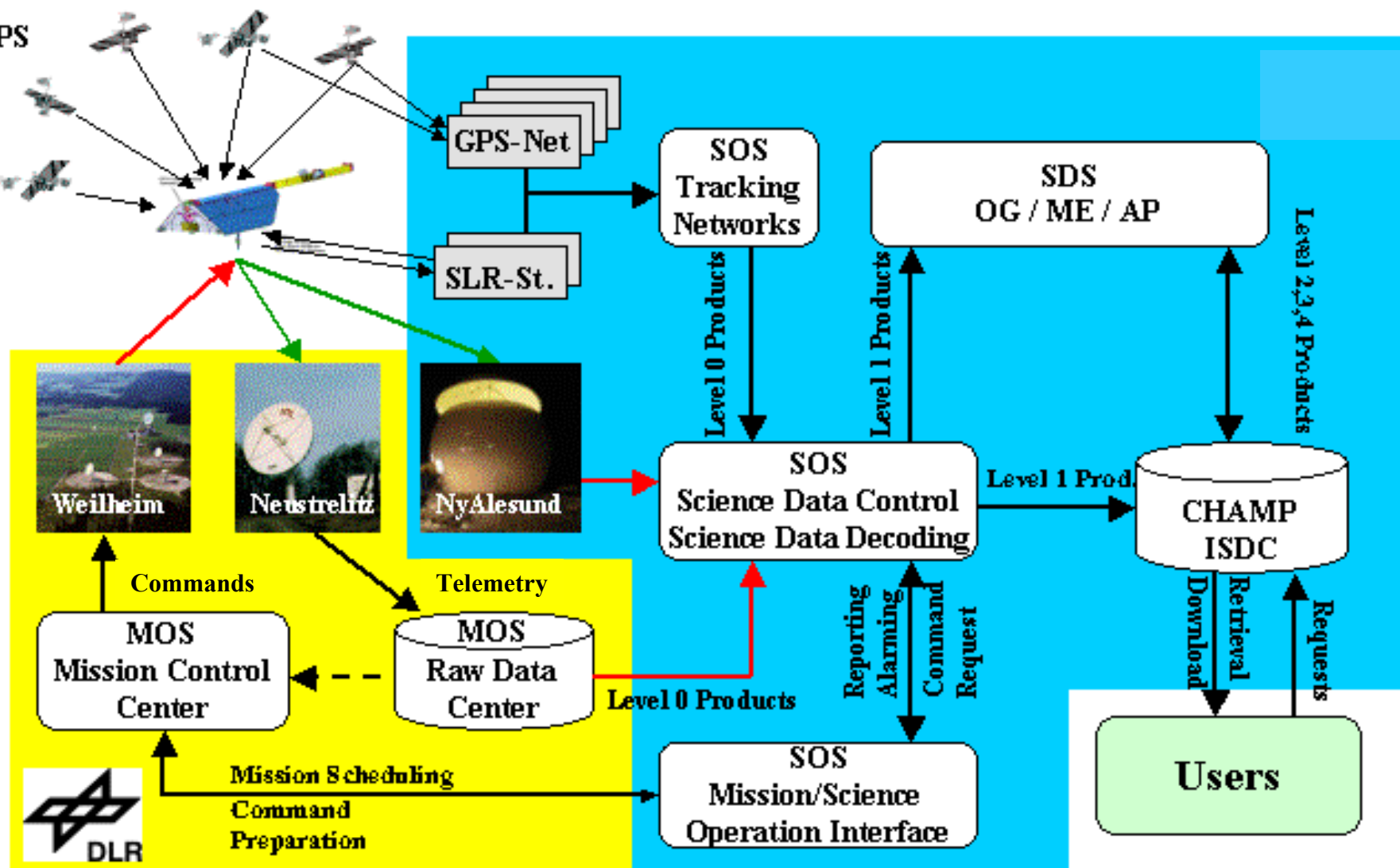
Temporal Gravitational Changes (Non-Tidal)

(from NRC-Report 1997)



CHAMP System Components

GPS



MOS Mission Operation System
 SDS Science Data System
 SOS Science Operation System

Mission Support
 by Astrium

OG Orbit Gravity Processor
 ME Magnetic/Electric Field Processor
 AP Atmosphere Processor

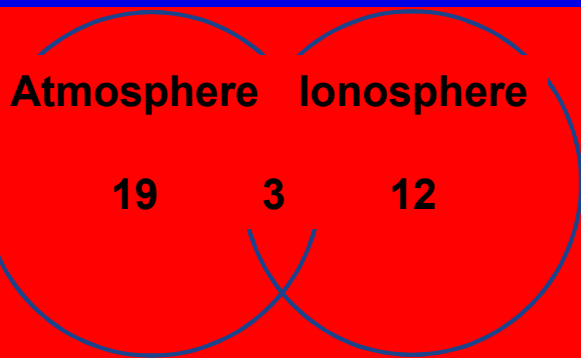


CHAMP Announcement of Opportunity

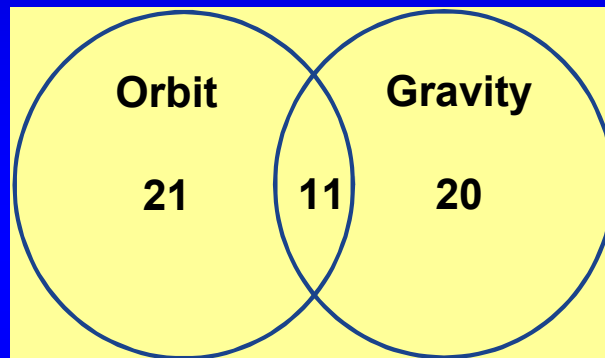
Received and Accepted Proposals

- Total Number: 113 groups, 150 individuals
- Research / Application Area:

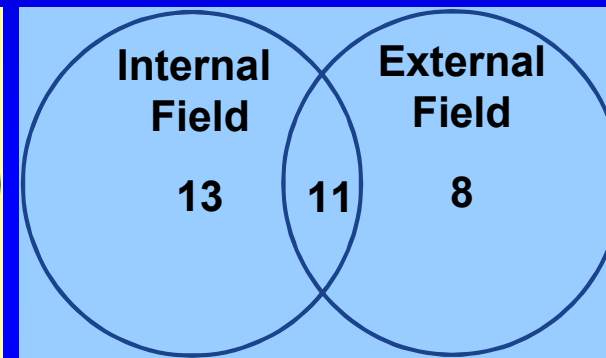
GPS Radio Occultation (34)



Orbit and Gravity Field (52)



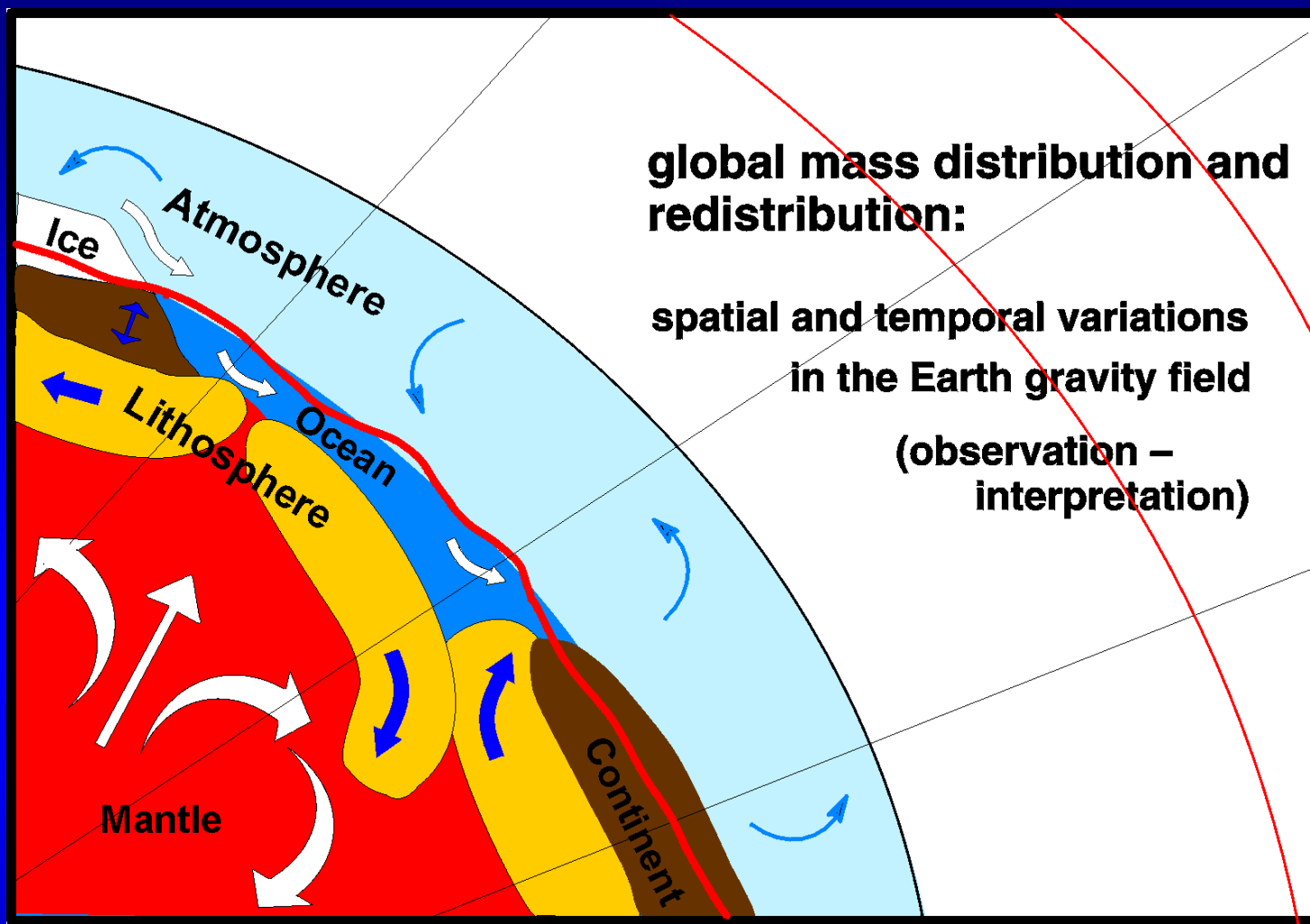
Magnetic and Electric Field (2)



Countries:

Lead-Coinvestigators (Co-investigators)

Austria	2	Finland	2	Korea	(1)	Sweden	1
Australia	2	France	9 (2)	Netherlands	4 (2)	Turkey	1 (1)
Canada	1 (2)	Germany	28 (5)	Russia	2 (2)	Taiwan	1 (1)
China	4 (1)	Greece	1 (1)	South Africa	2	United Kingdom	5
Columbia	(1)	Italy	5 (3)	Spain	1 (1)	USA	29 (9)
Denmark	8 (4)	Japan	4	Switzerland	1	Venezuela	(1)



The improved knowledge of the gravity field variations with CHAMP constrains **geophysical models** of e.g. mantle convection, which is the driving force for plate tectonics, volcanism and earthquakes, and 'global change' theories, when analyzing long-term mass redistributions associated with post-glacial rebound and sea level variations due to changes in the polar ice mass balance.