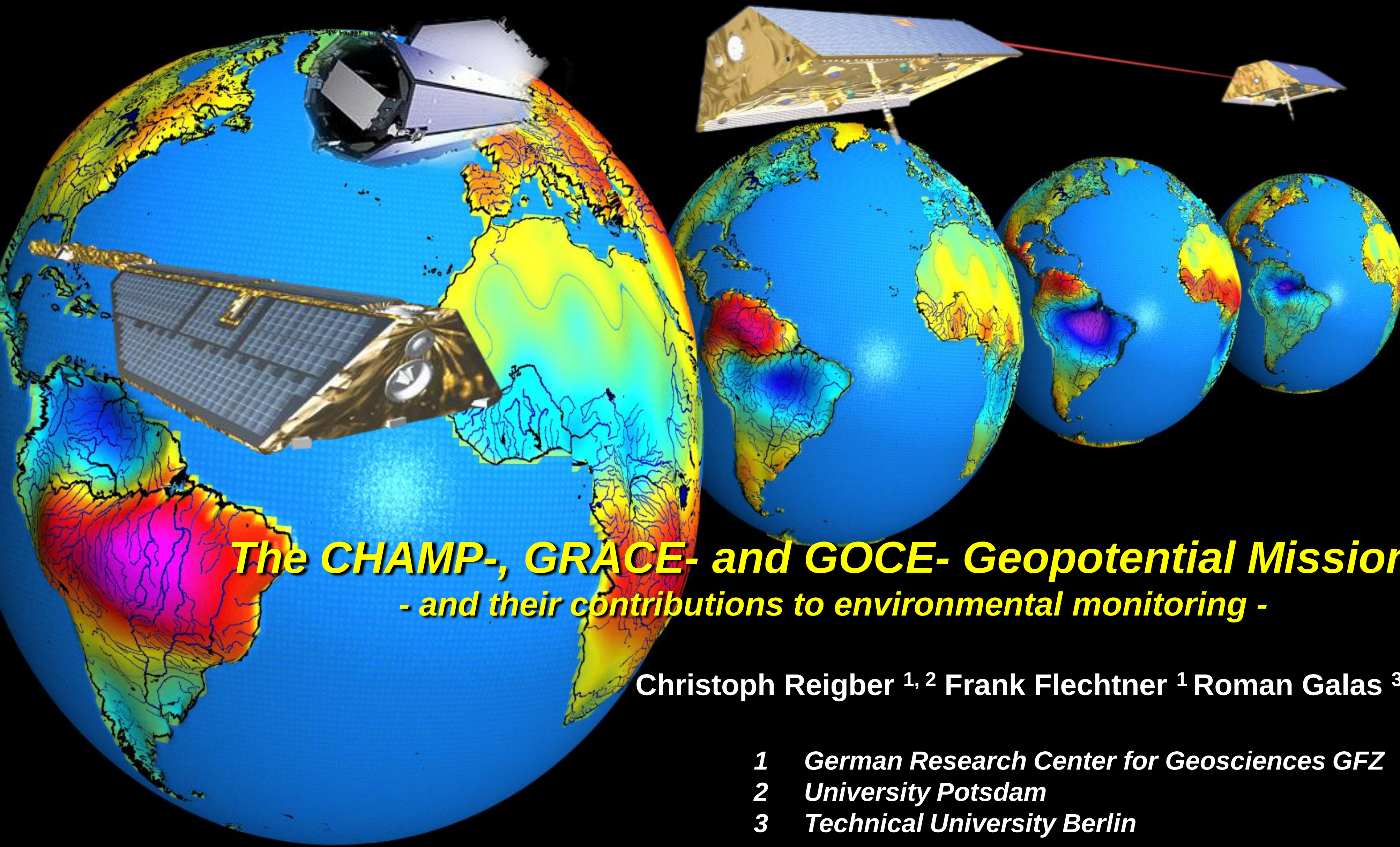


The CHAMP-, GRACE- and GOCE- Geopotential Missions

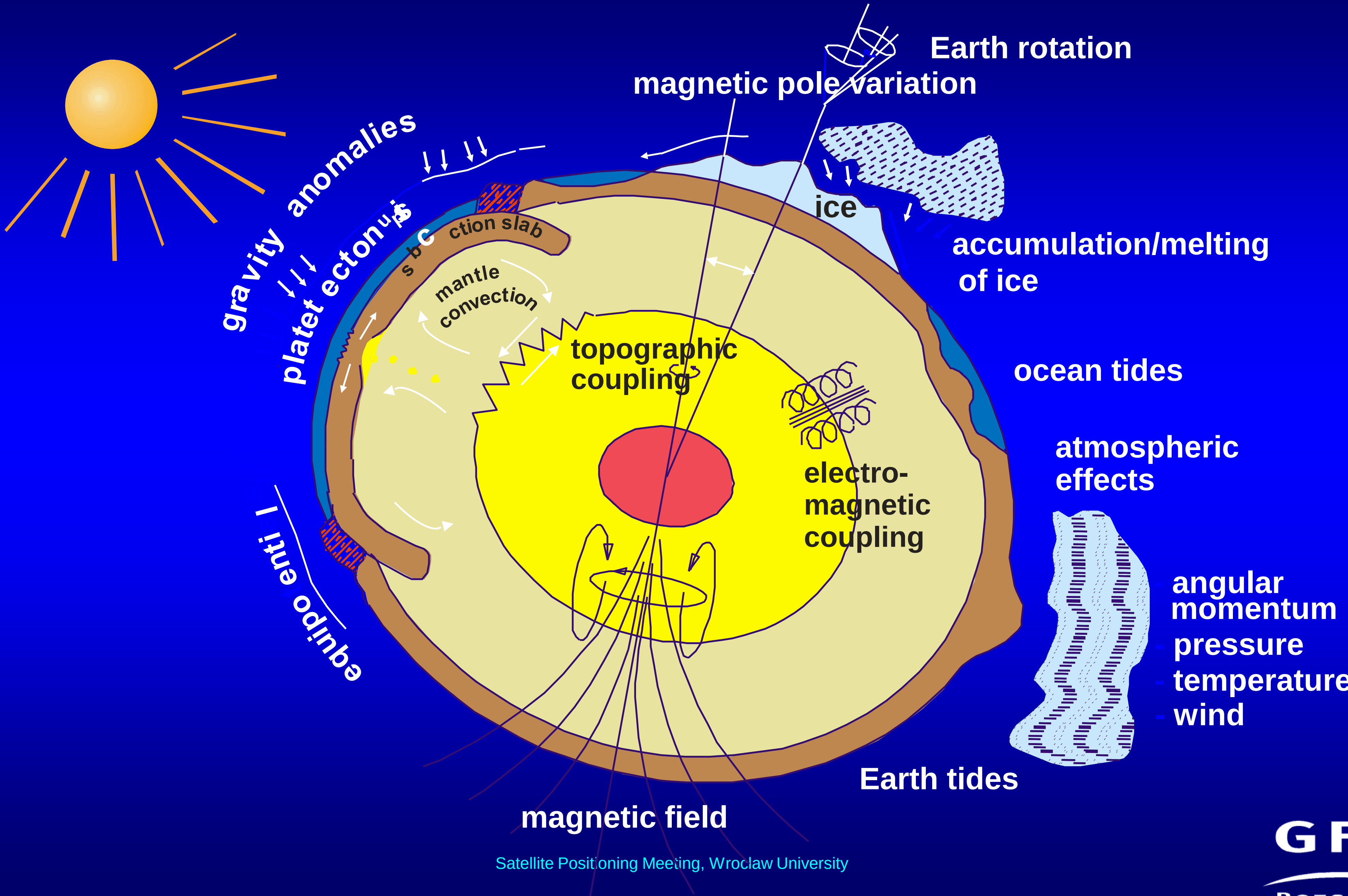
- and their contributions to environmental monitoring -

Christoph Reigber [1, 2] Frank Flechtner [1] Roman Galas [3]

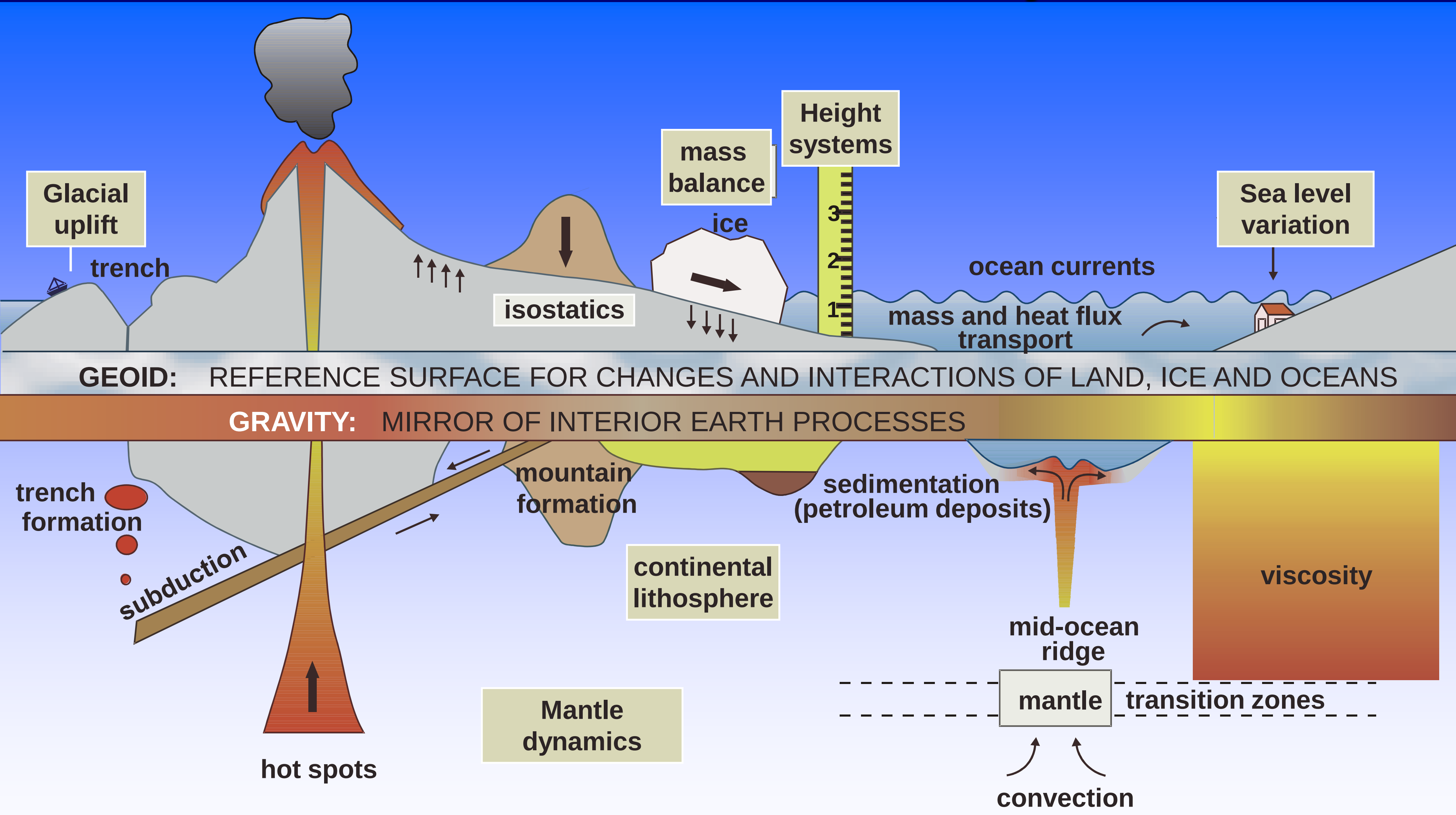
1 German Research Center for Geosciences GFZ
2 University Potsdam
3 Technical University Berlin

Satellite Positioning Methods in modern Geodesy & Navigation Meeting, Wroclaw June 02, 2011

Geosystem: The Changing Earth



Dual Role of Earth Gravity



Various forces effect mass redistributions. Gravity variations are correlated to these redistributions & are thus important impact factors.

source: ESA

GFZ POTSDAM

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

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

RESOLUTION

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

GEOID HEIGHTS in meter

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

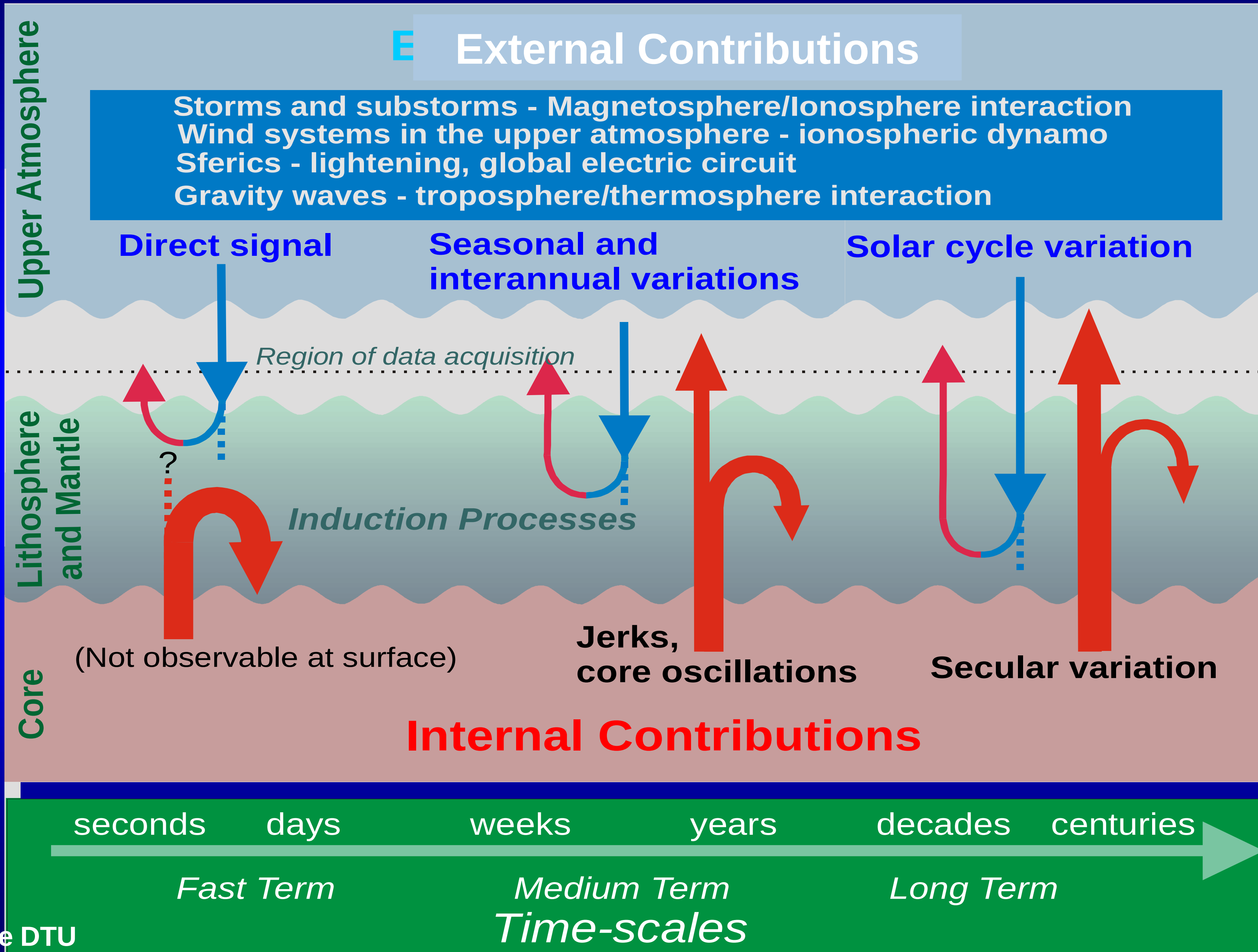
FREE AIR GRAVITY ANOMALIES in mgal (10^{-5} m/s^2)

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

Power Spectral Density (PSD)
Average Signal Strength

GFZ POTSDAM

Dual Role of Magnetic Field



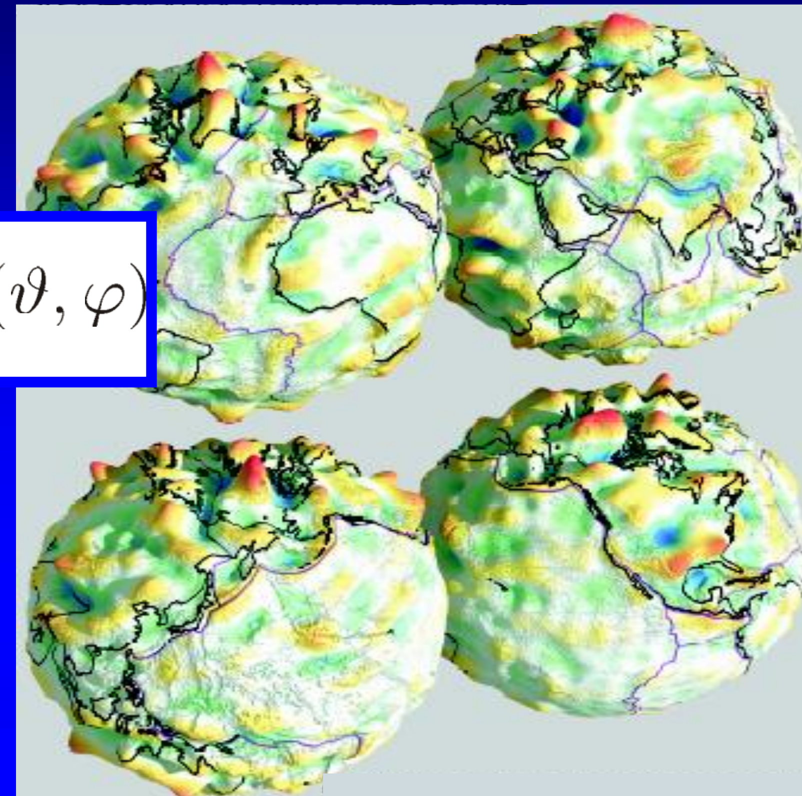
Source DTU

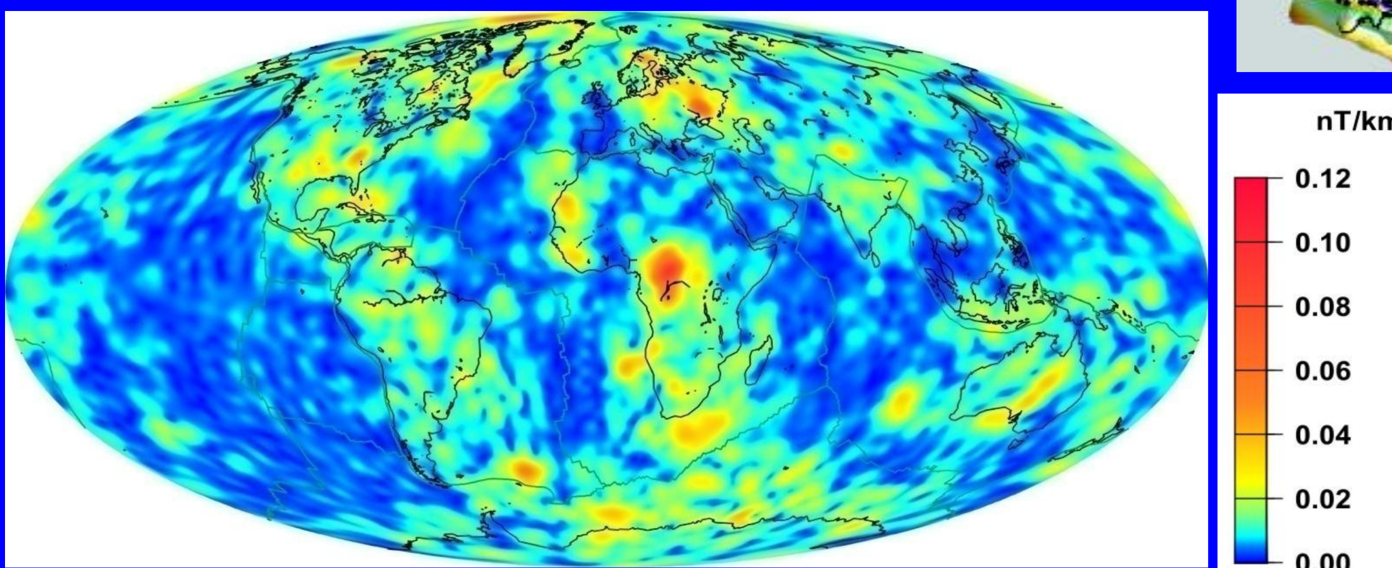
Magnetics Represented by Crustal Magnetic Anomalies

$$\Psi(r,\vartheta,\varphi) = a \sum_{\ell=1}^{\infty} \sum_{m=-\ell}^{\ell} \left[g_\ell^m \left(\frac{a}{r}\right)^{\ell+1} + k_\ell^m \left(\frac{r}{a}\right)^{\ell} \right] Y_\ell^m(\vartheta,\varphi)$$

internal sources

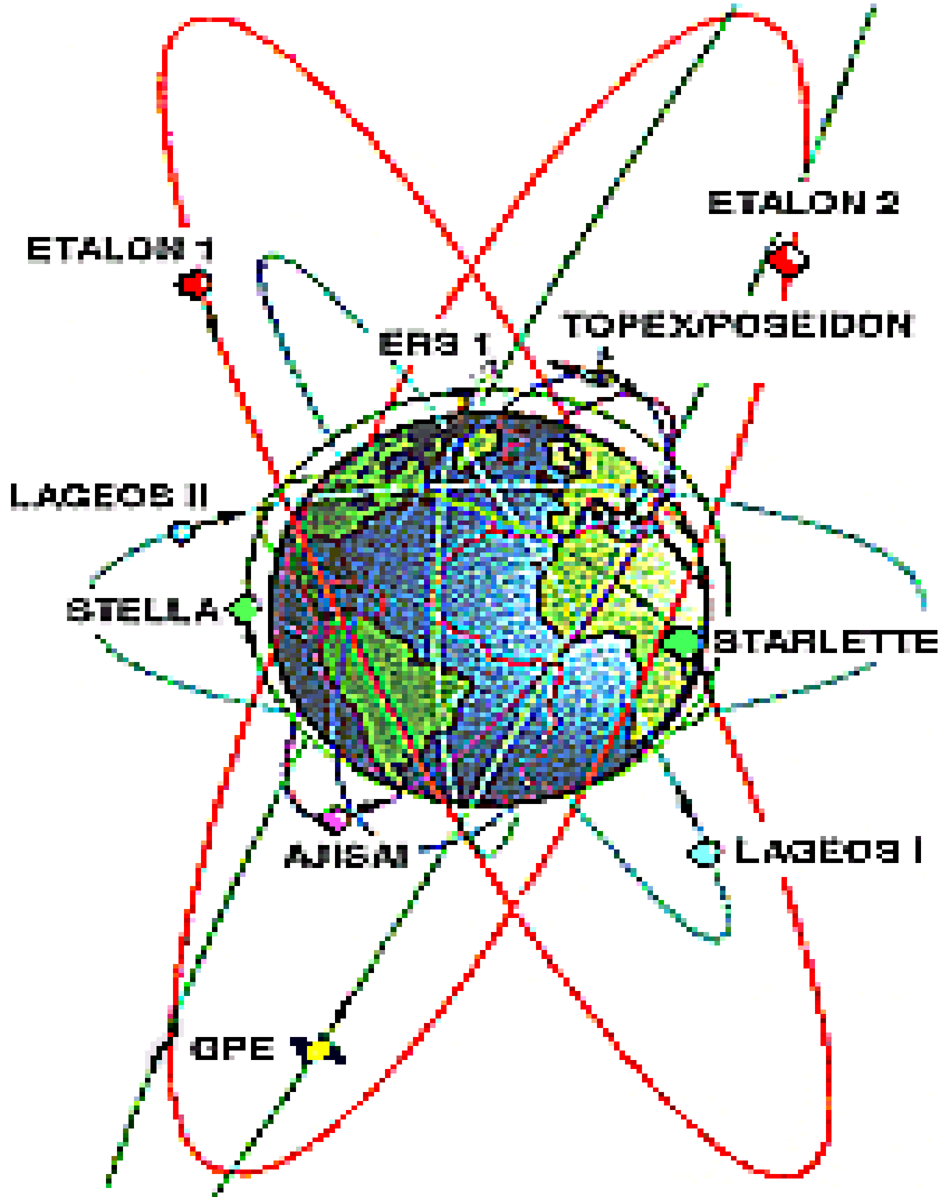
external sources





GFZ POTSDAM

Gravity Field Determination through Analysis of Satellite Orbit Perturbations



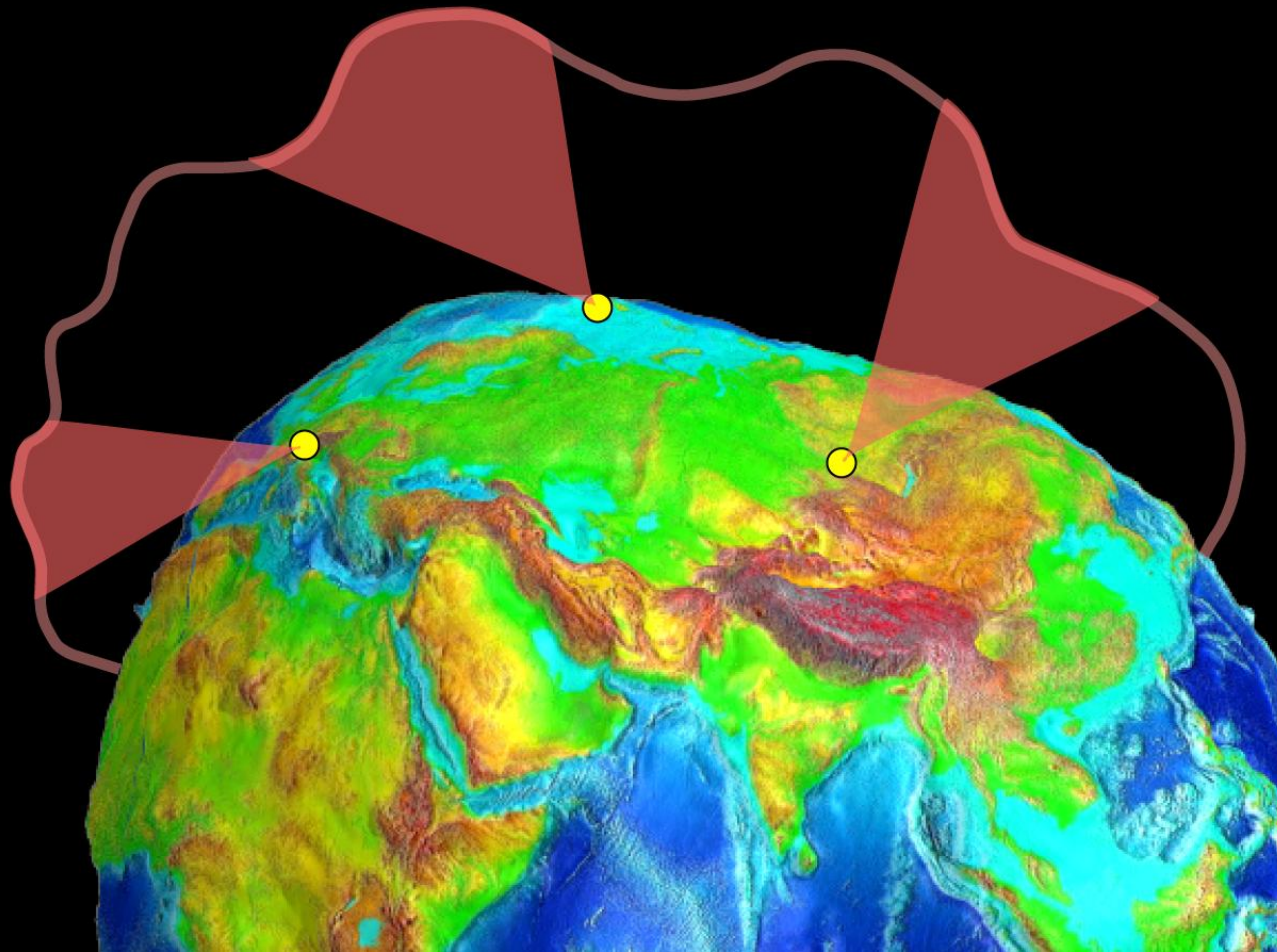
Classical Approach:

- **Ground tracking of orbital segments of various near Earth satellites over many years**
- **Solution of motion equations for all these objects and common adjustment of orbit residuals**
- **Modelling of surface forces, such as air drag, solar radiation pressure etc.**

Typical Ground-Based Coverage

(before GPS Space Receiver became available)

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



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** → $\{\Delta \hat{C}_{lm}, \Delta \hat{S}_{lm}\}$

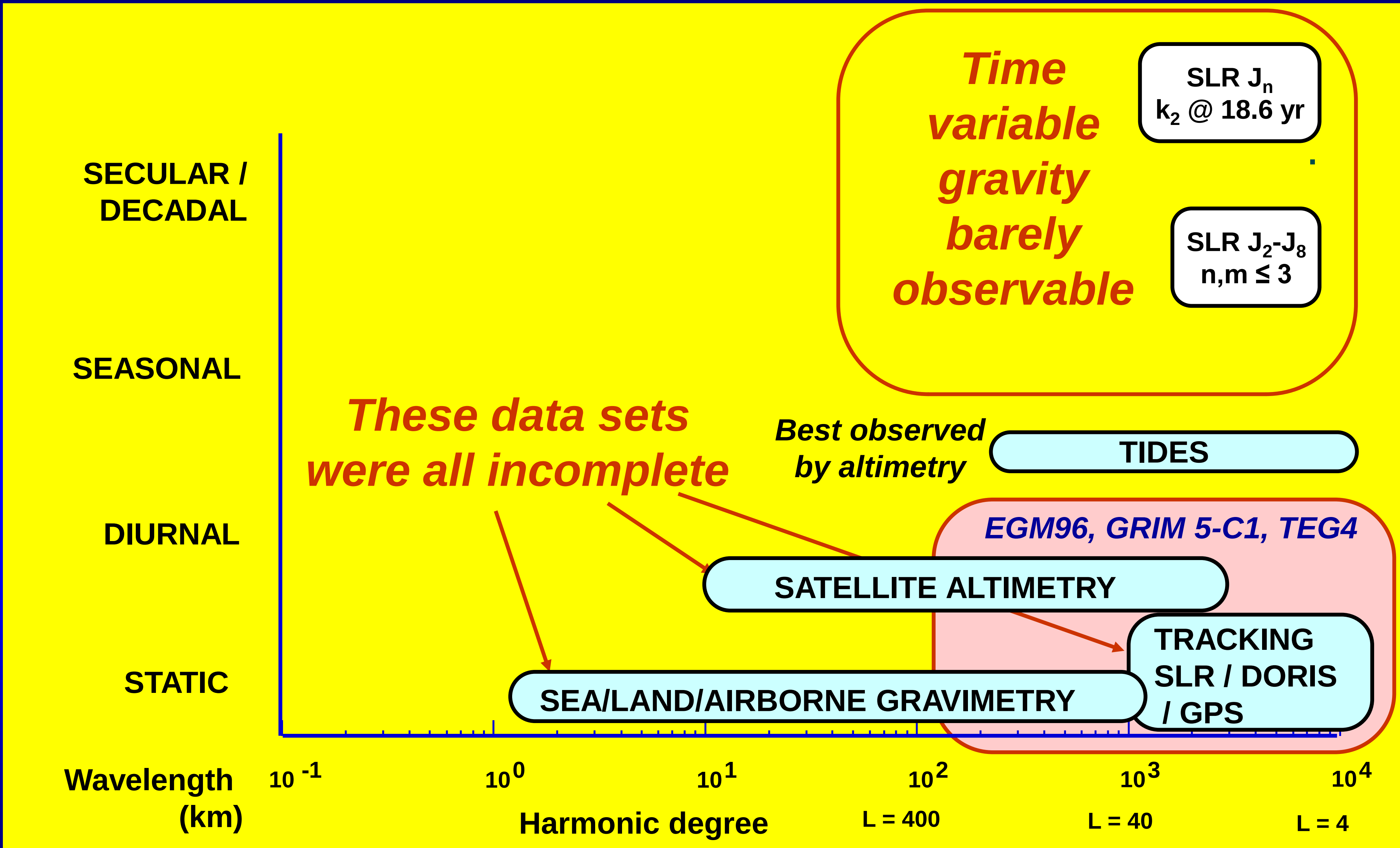
Observation residuals

Res. harmonic coeff.

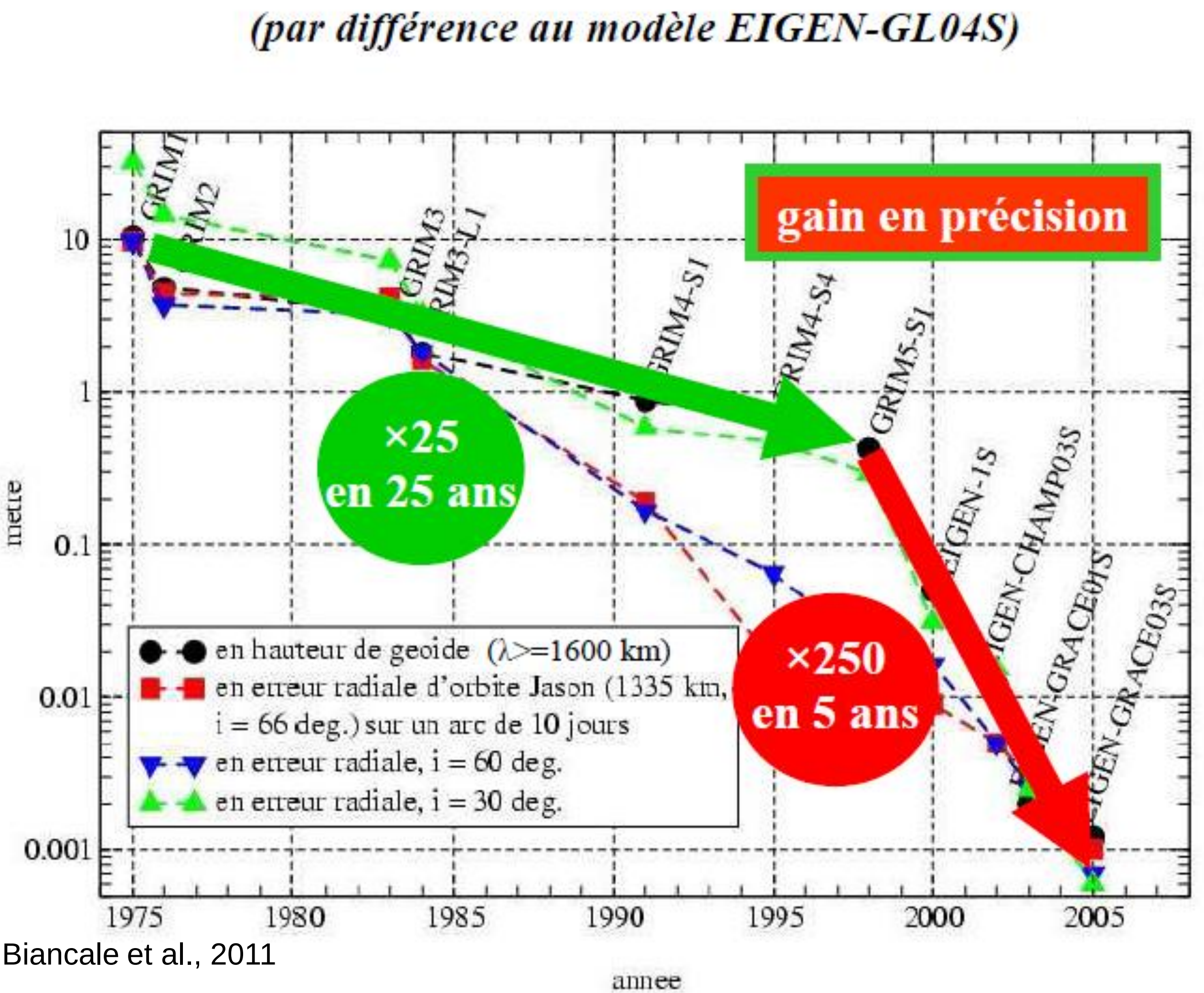
History of Satellite Gravity Field Modelling

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 - 1996
GRIM 1-5	DGFI/GFZ Potsdam/GRGS Toulouse	1976 - 1998
TEG 1-4	CSR /UTEX Austin	1988 - 1999

Situation Gravity Field Determination in 2000



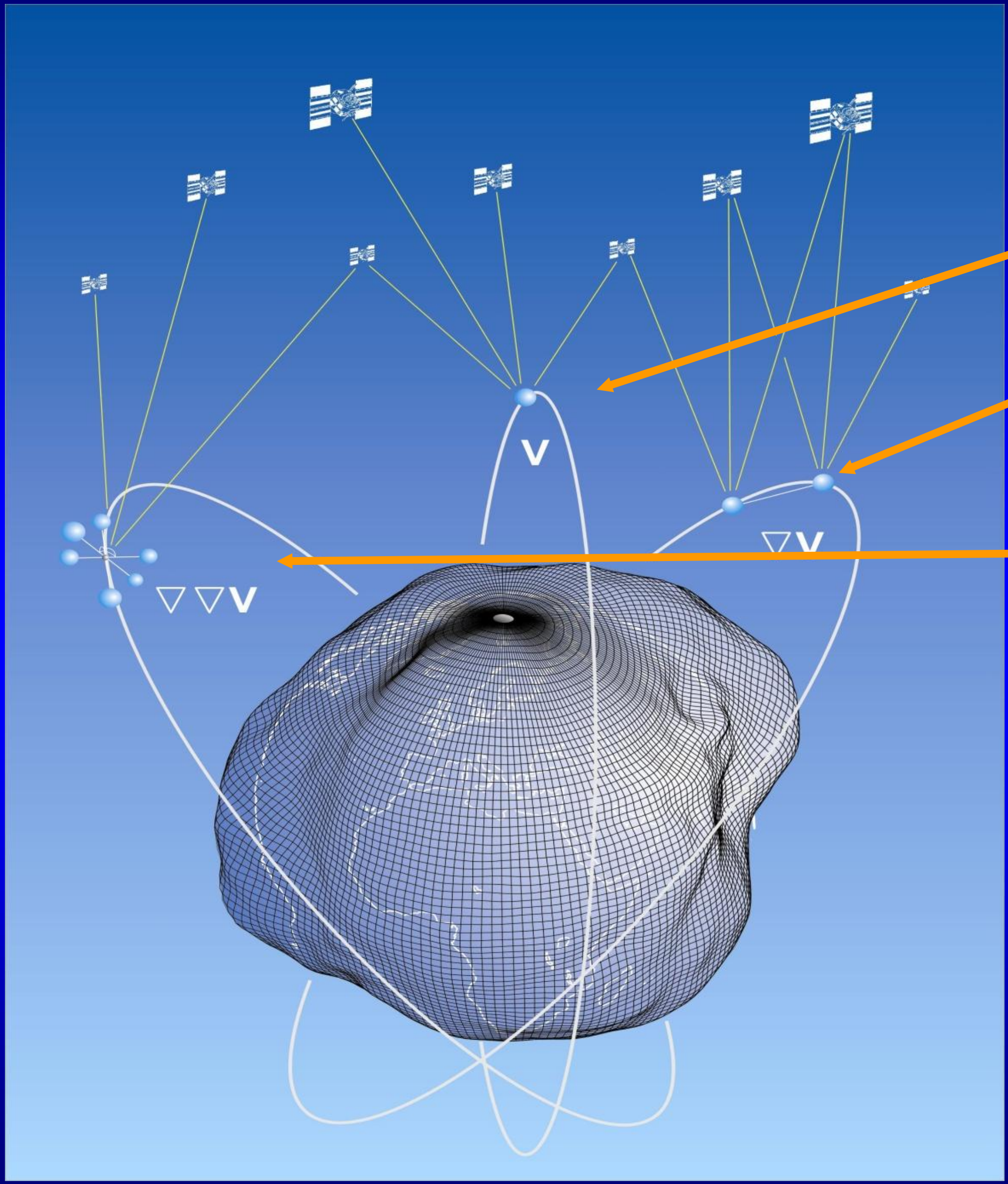
GFZ/GRGS gravity model improvements over time (GRIM and EIGEN models)



Source Biancale et al., 2011

GFZ POTSDAM

New Observation Techniques



Satellite-to-Satellite Tracking

- ♦ ***high- low***

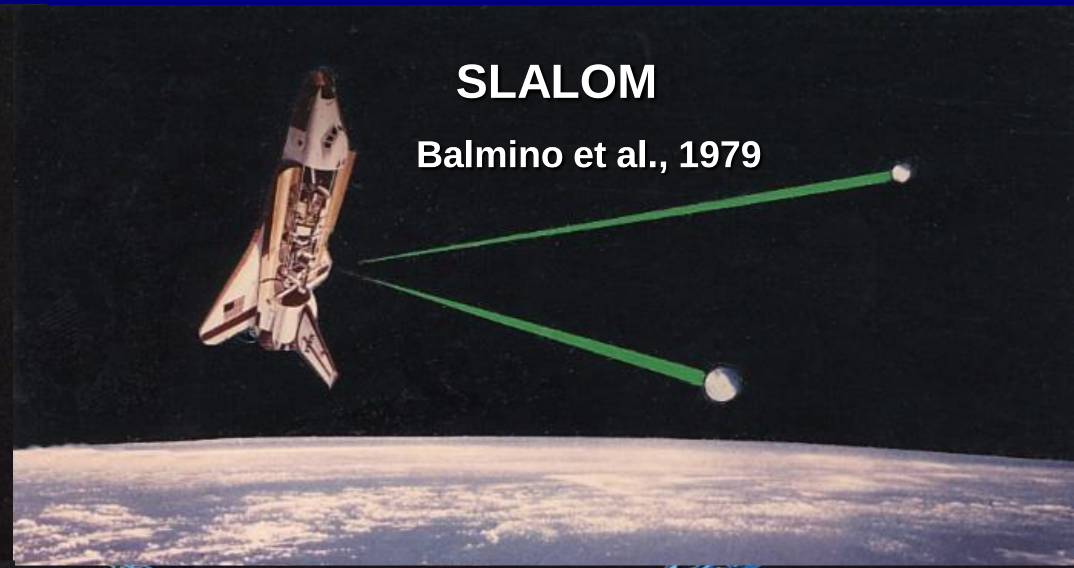
  Wolff, 1969

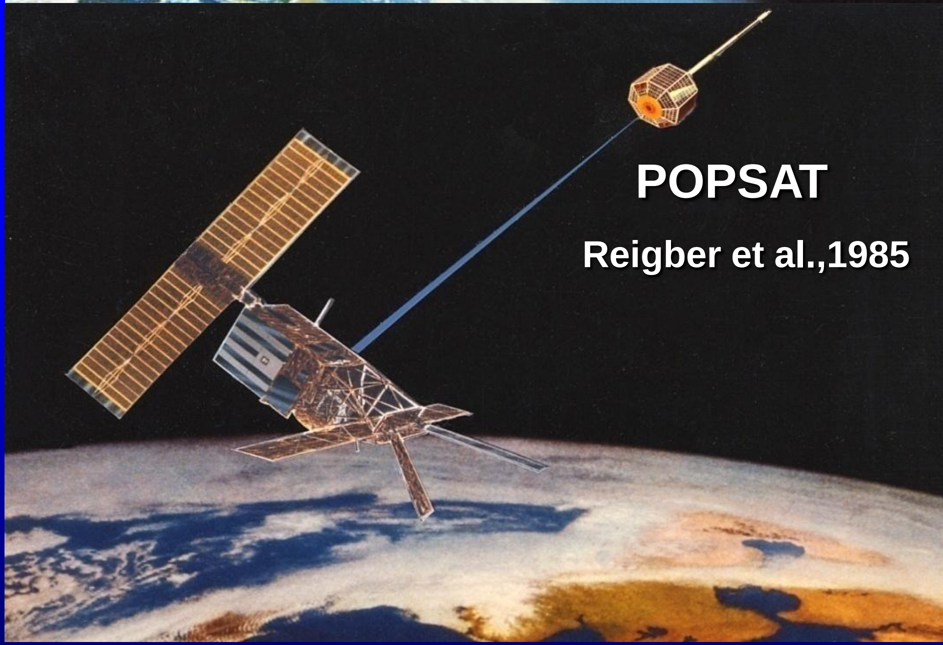
- ♦ ***low- low***

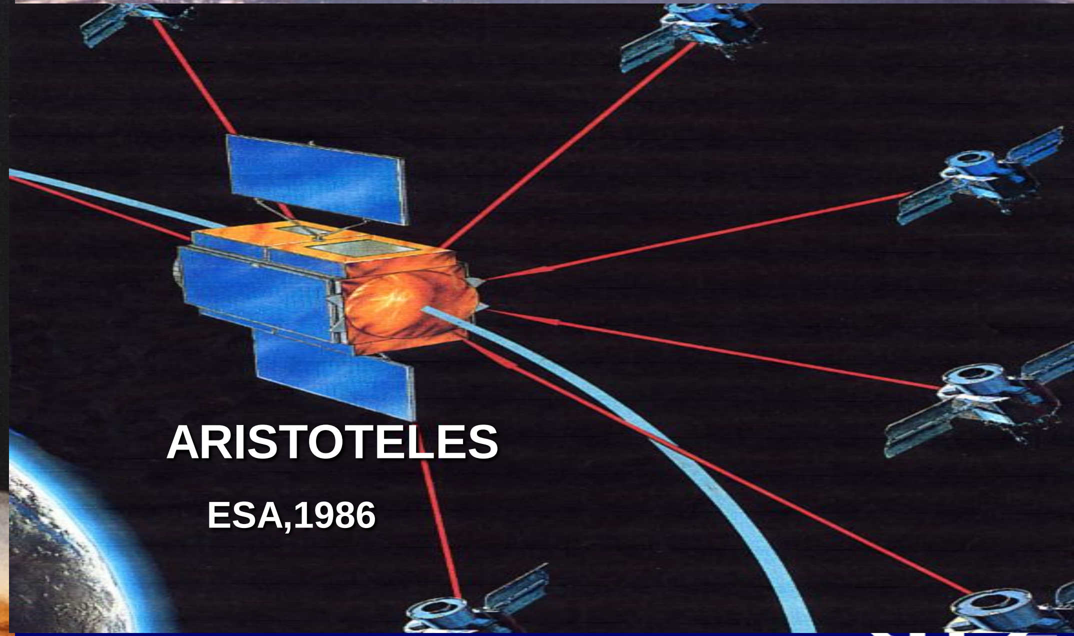
Satellite Gravity Gradiometry

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

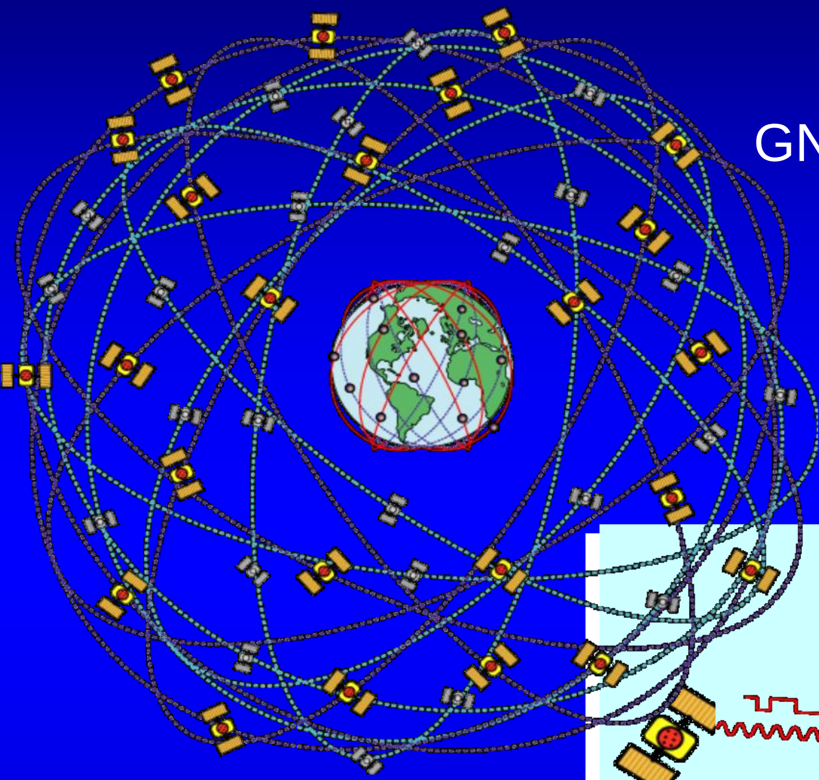
Early SST& SGG Mission Proposals





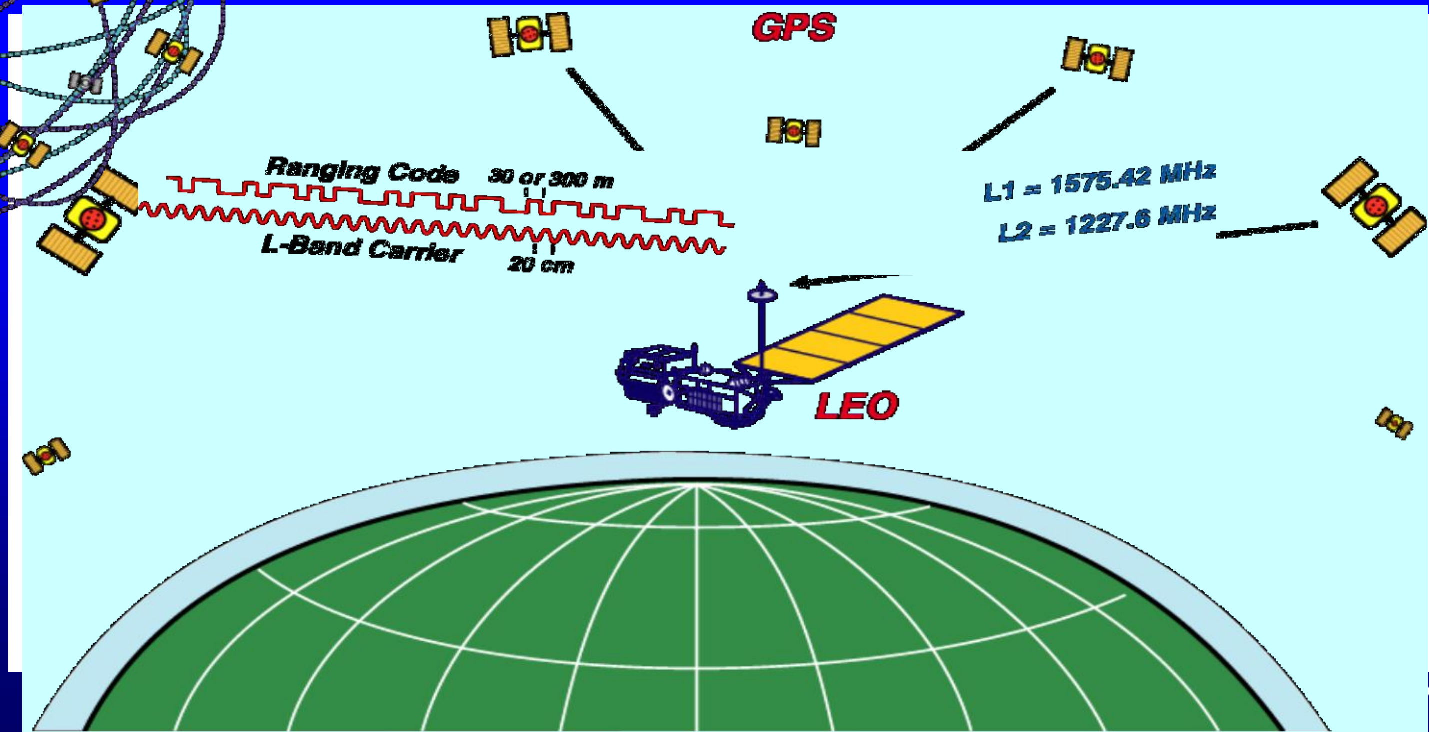


Global Navigation Satellite System (GNSS)



GNSS constellation

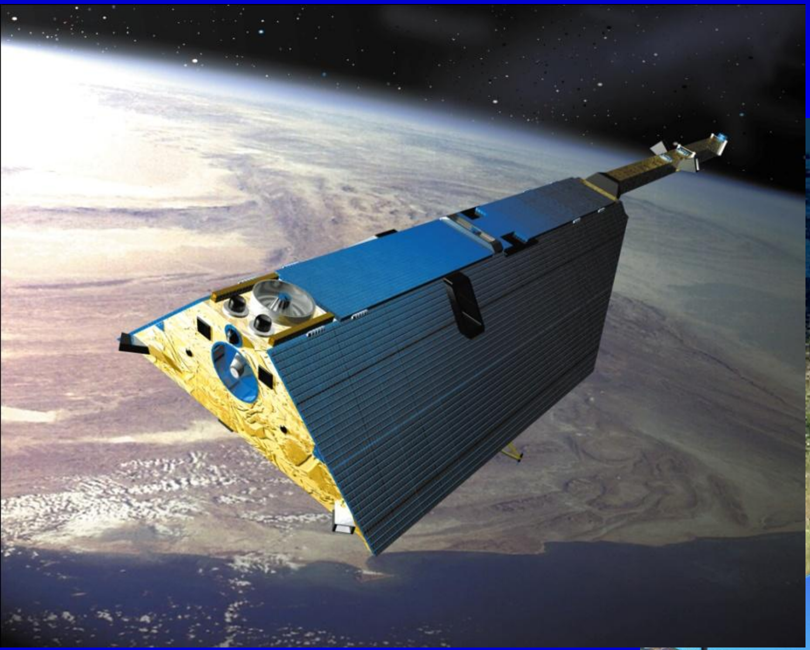
GPS Code & Trägerphasen-
messungen im L-Band



The Breaking New Missions ….

CHAMP (2000-2010)

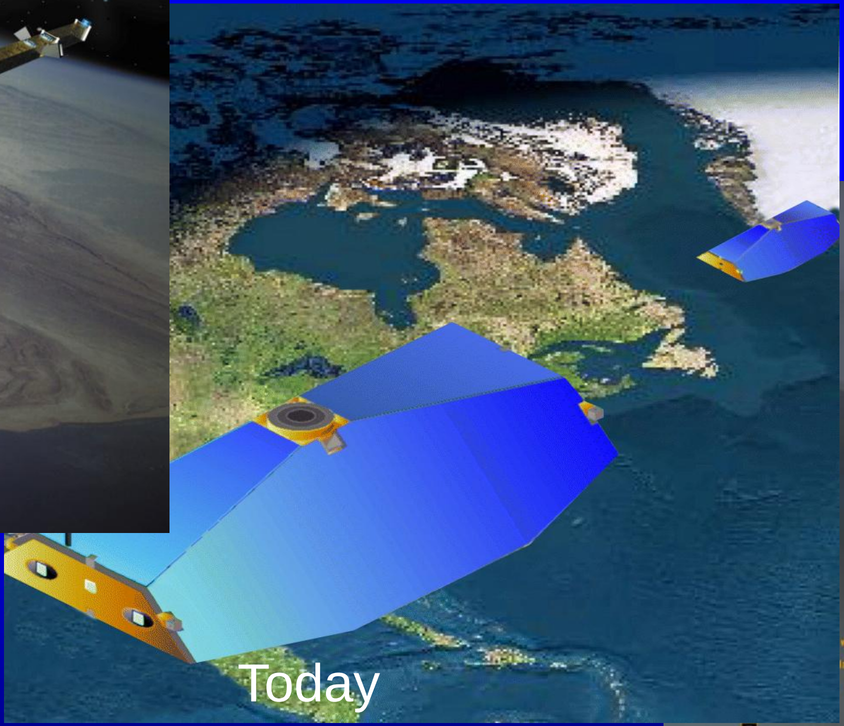
Germany



EoL: Sep.19, 2010
3717 days in orbit
58277 revolutions

GRACE (2002)

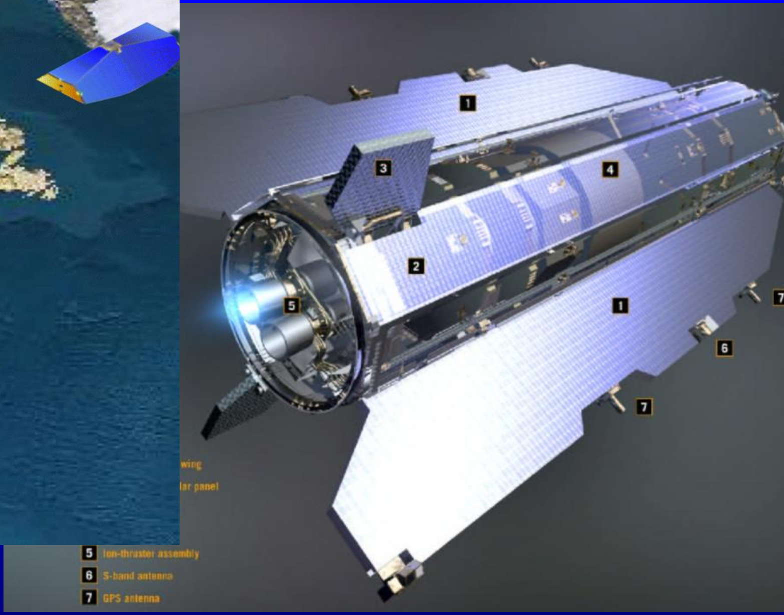
USA-Germany



Today
3364 days in orbit
51506 revolutions

GOCE (2009)

European

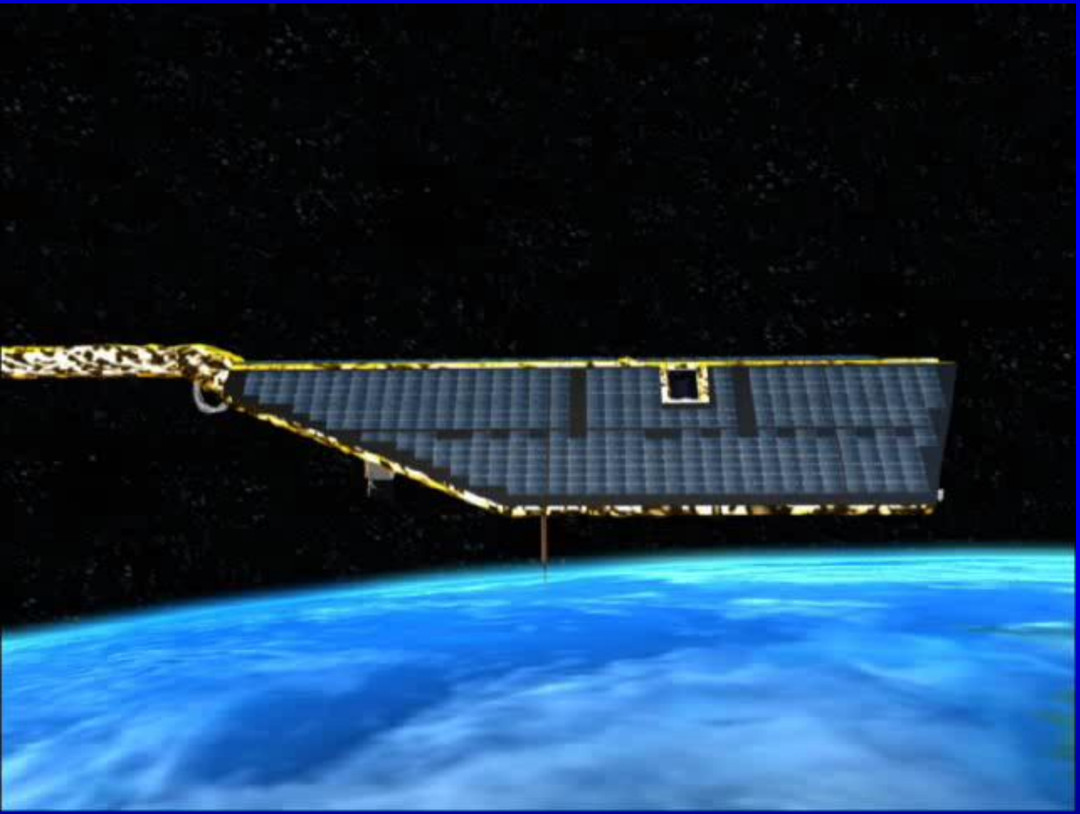


GFZ
POTSDAM

CHAMP

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

Launch: Juli 2000 **Planned Mission duration:** 5 years
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:

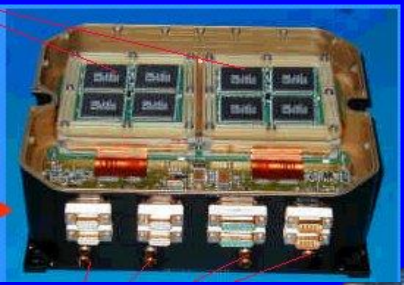
- **3-D accelerometer (3×10^{-9} m/s^2).**
- **16-channel GPS receiver (high-low SST)**
- **Laser-retro-reflector**
- **Magnetometer**
- **Ion drift meter**
- **Star sensors**

PI : Ch. Reigber / H. Lühr GFZ

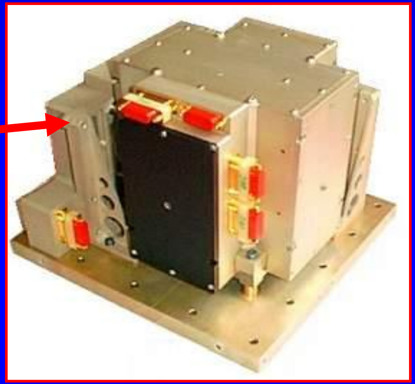
GFZ POTSDAM

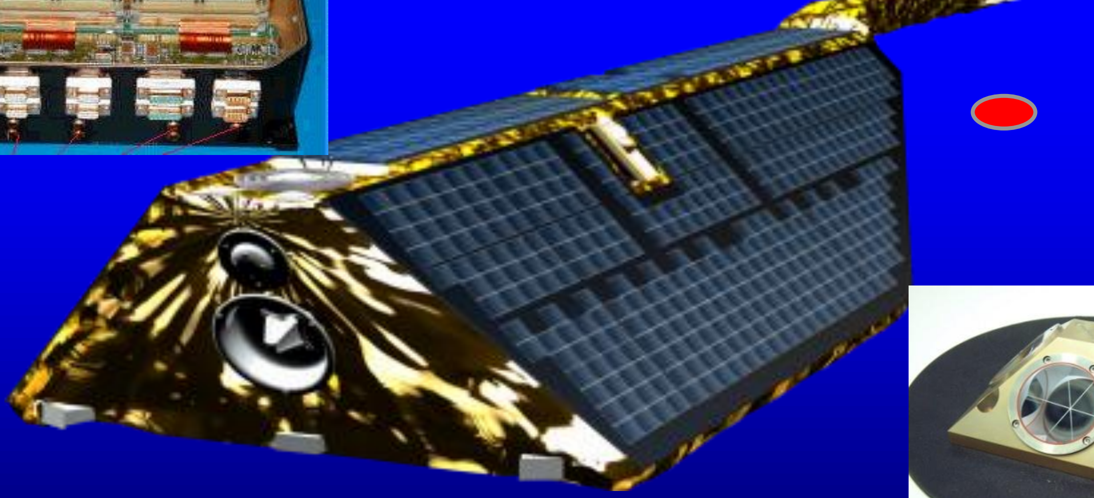
CHAMP Mission Supports Fundamental Progress in Static Gravity Field Recovery due to:

- **continuous high-low GPS SST tracking at a very low altitudes (450 - 200 km)**

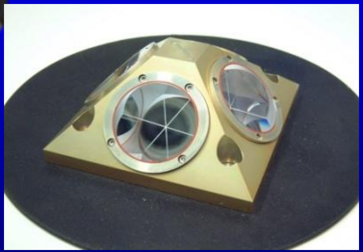


- **Accelerometry for direct measurements of difficult to model non gravitational surface forces**



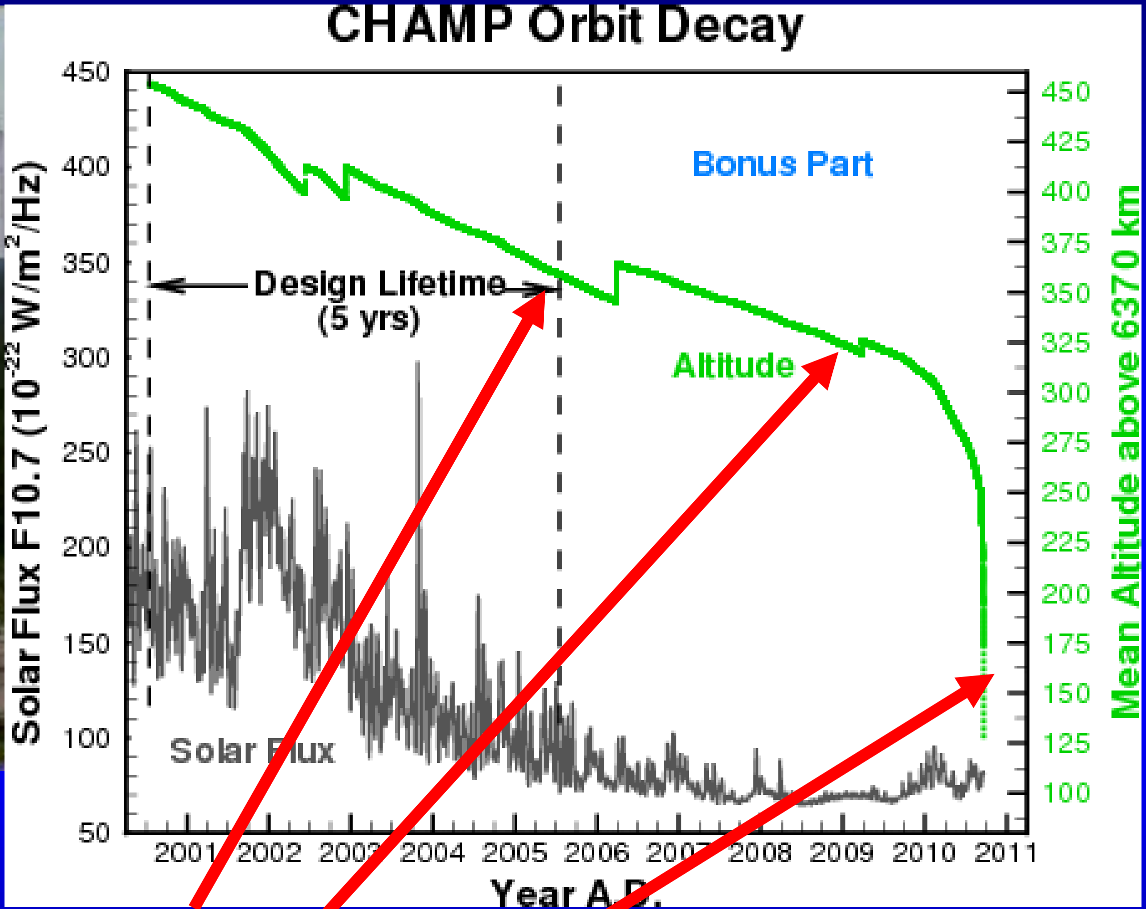


- **Polar orbit (87deg) for an almost complete coverage of the Earth**



- **Long mission duration to resolve temporal gravity field variations**

CHAMP Orbit Profile

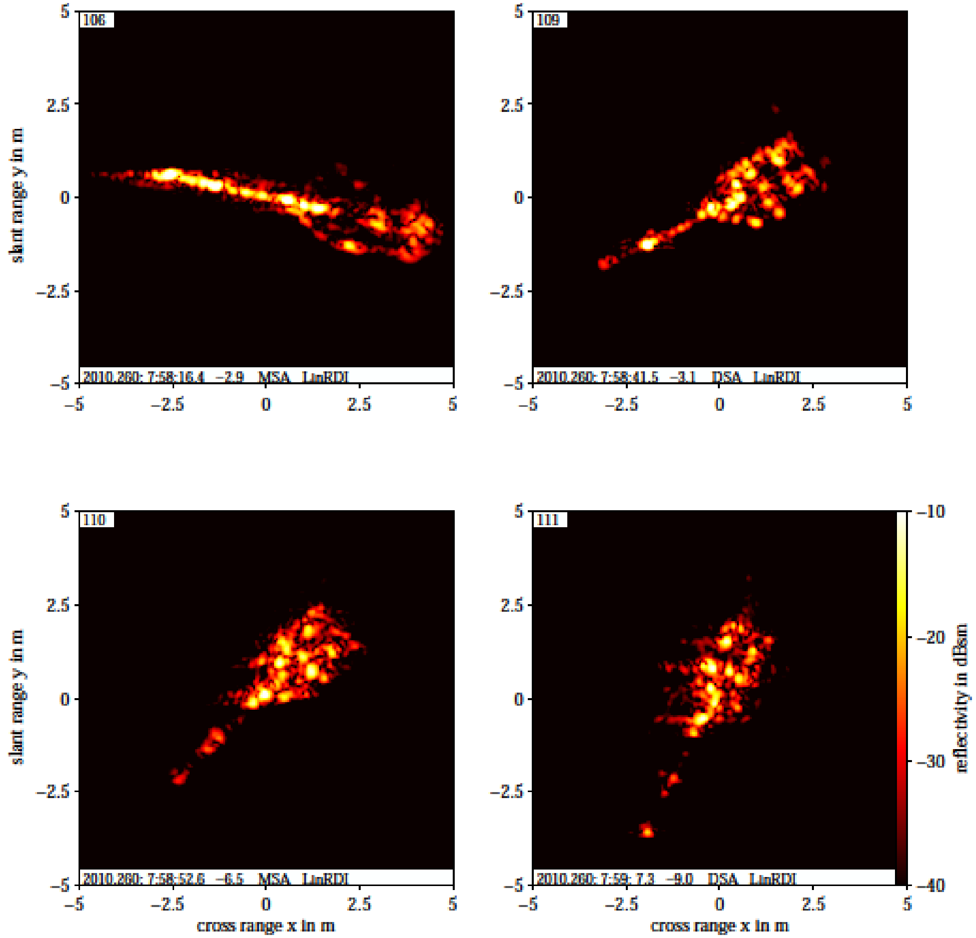


Mission:

- Launch: July 15, 2000
- Planned mission duration: 5 years
- Four orbit change manovers (uplifts)
- Final mission duration: 10 years, 2 month
- End of mission: September 19, 2010

GFZ POTSDAM

ISAR imaging of object 26405



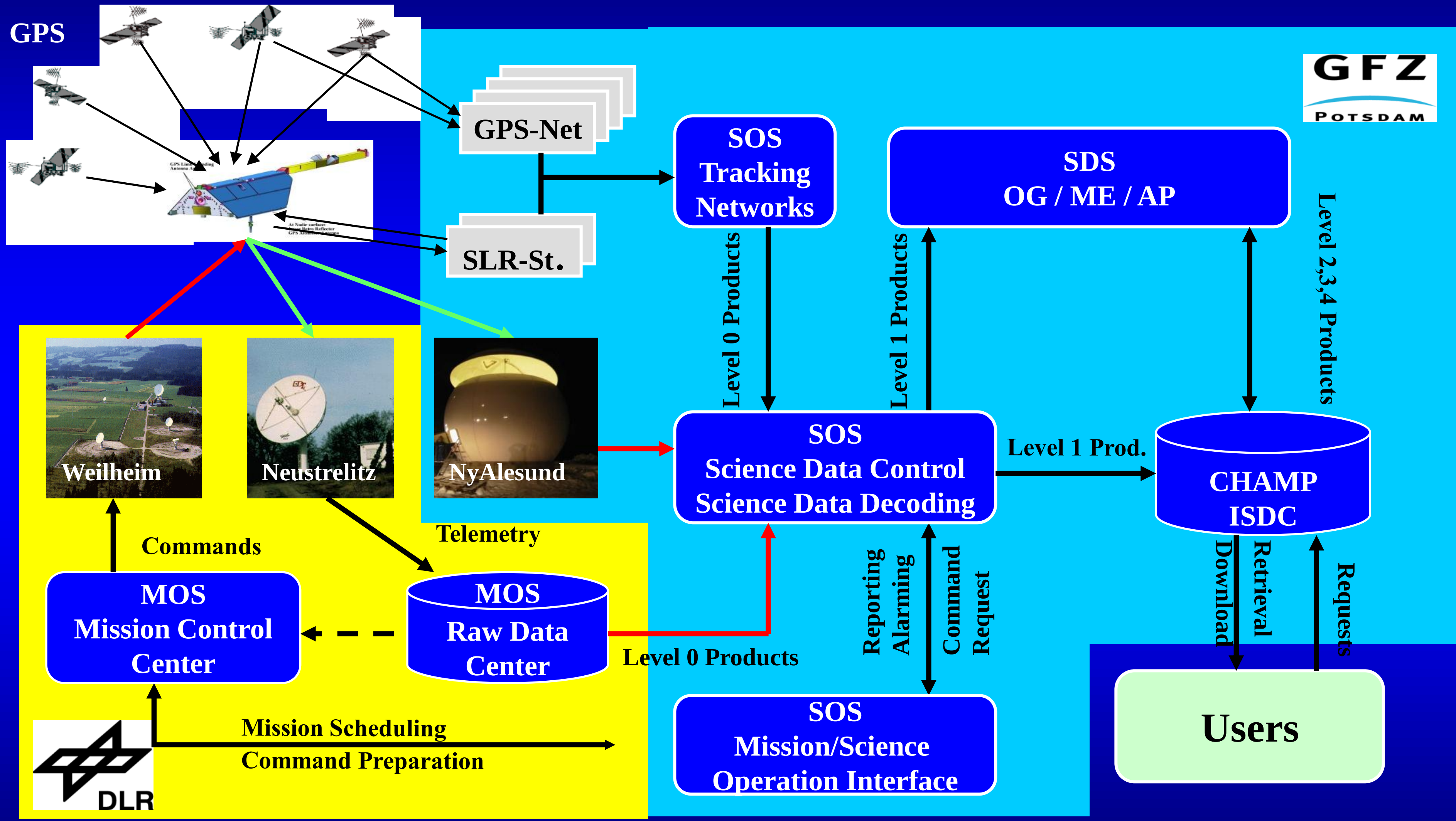
Object No: 26405
Date of observation: 17 09 (260) 2010, 07:56:00 (UTC)
Window: Hamming, $\Delta\phi$ = 5.56°, Δt = 3.70 s, δ_x = 0.12 m, δ_y = 0.12 m
Parameters: year, day, time (UTC), maxRCS/dBsm, autofocus, RDI method

Fraunhofer
FHR

Radar for Space Observation

GFZ
POTSDAM

CHAMP Mission Space & Ground System



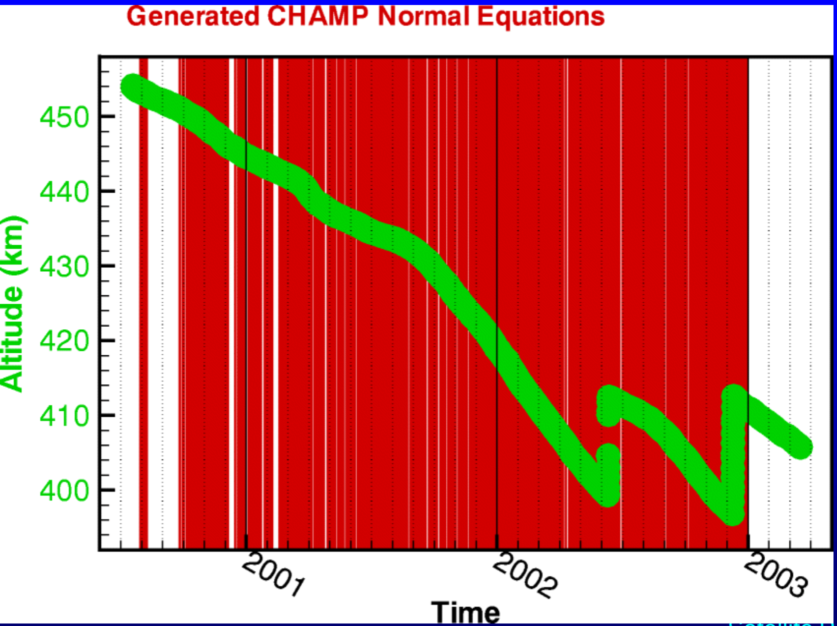
GFZ POTSDAM

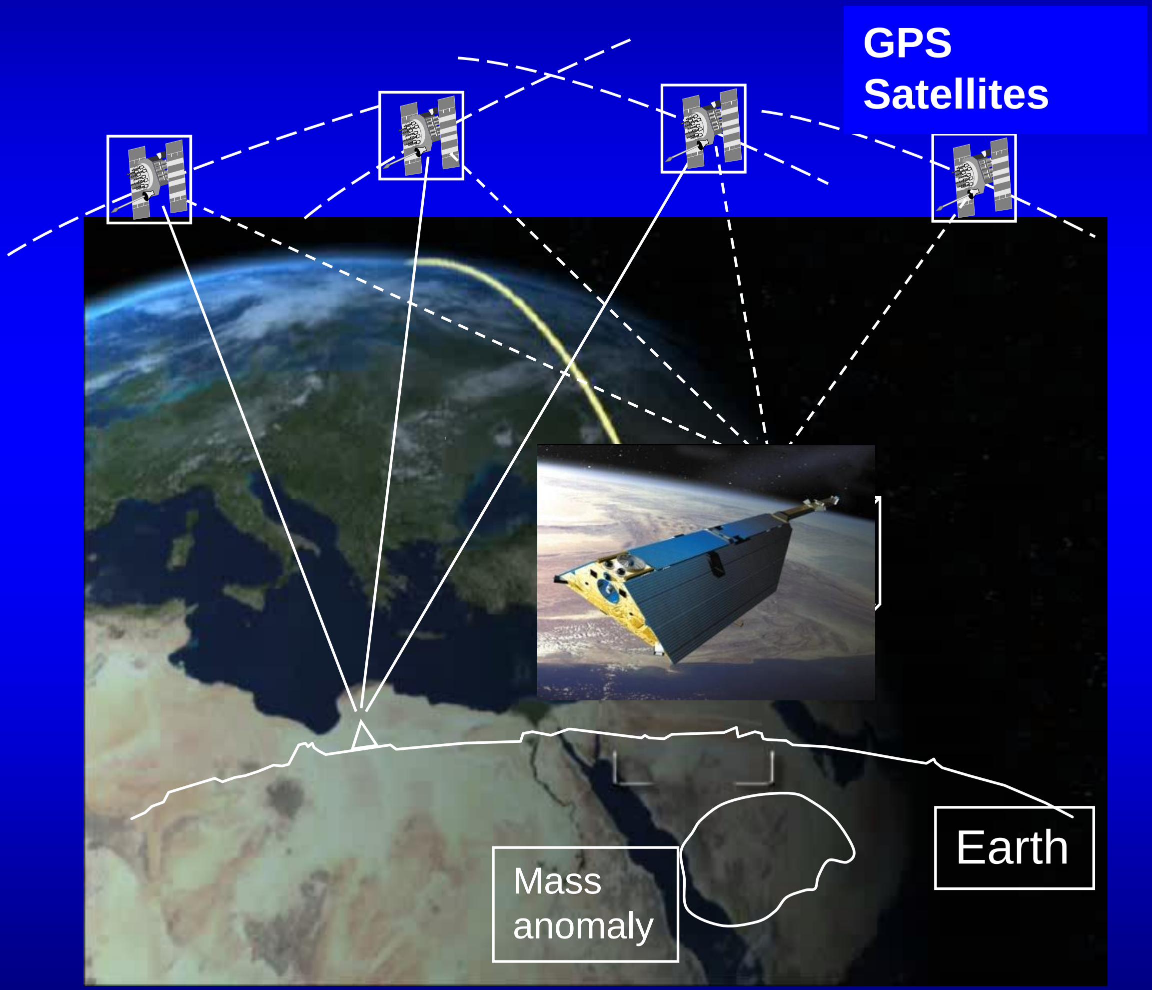
The CHAMP Mission- Gravity Recovery Part

Principle:

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

Computed Normal Equations:

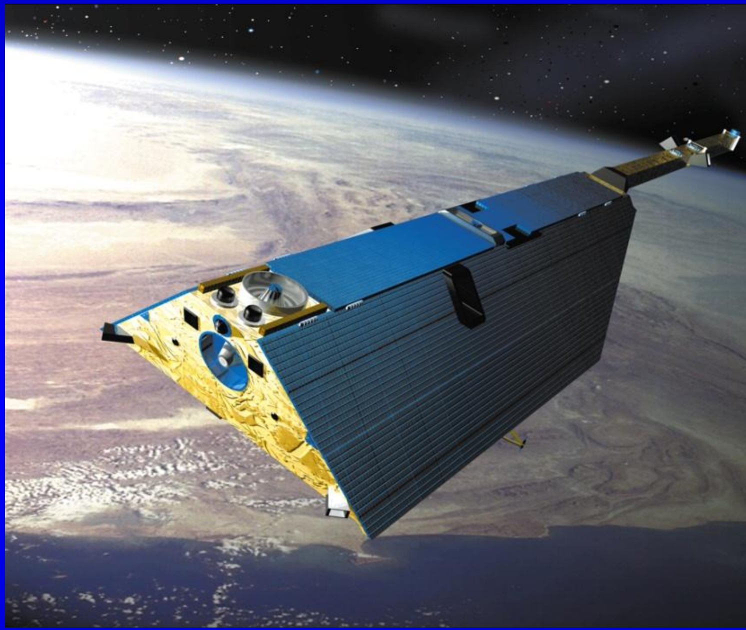




GFZ POTSDAM

CHAMP- Major Achievements

- Mission operation:
  - Almost uninterrupted and smooth operation of the satellite and instrumentation over more than 10 years
  - Almost complete recovery of all science data (>98%) with the receiving antennas in Neustrelitz, Weilheim and Ny Alesund
  - Routine processing of all science data within the CHAMP Science Data System
- Science output:
  - First continuous long-term occultation data set f or GPS climatology
  - First precision crustal magnetic anomalies field and field variability due to ocean water flow
  - Best pre-GRACE gravity field from a single satellite data set
  - Application of new gravity recovery approaches



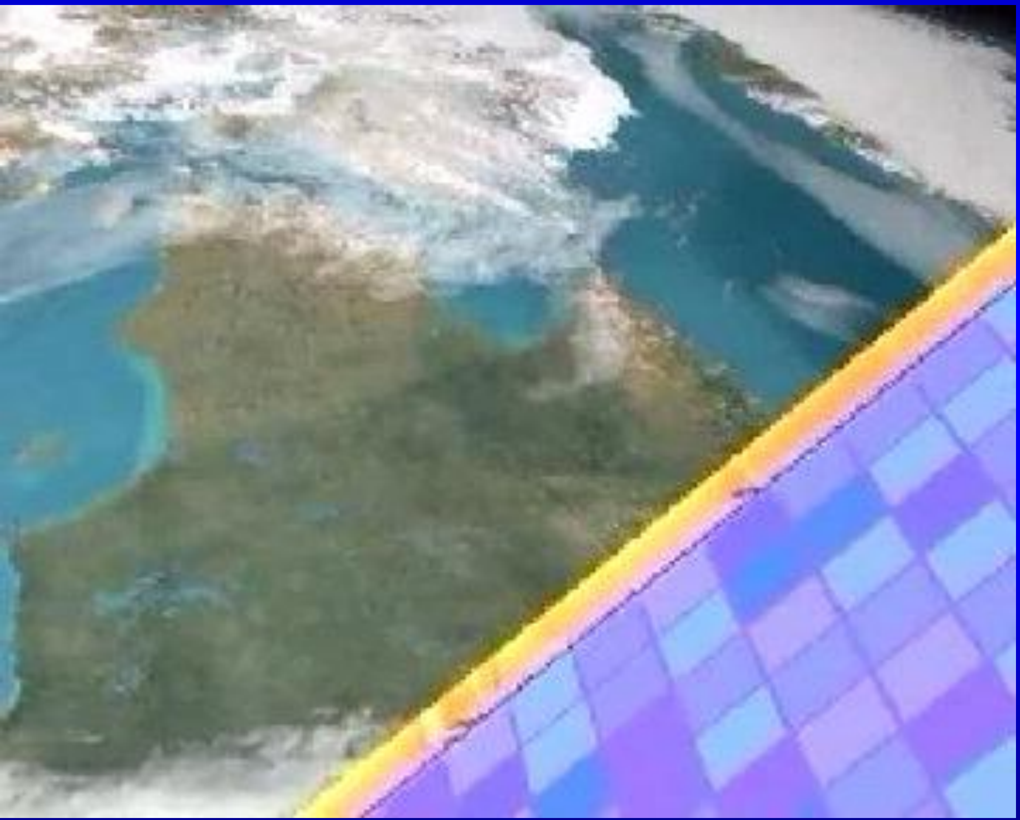
Mission life: 200 % of design life

GFZ POTSDAM

GRACE

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

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



PI: Byron D. Tapley / CSR Austin

Mission goals:

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

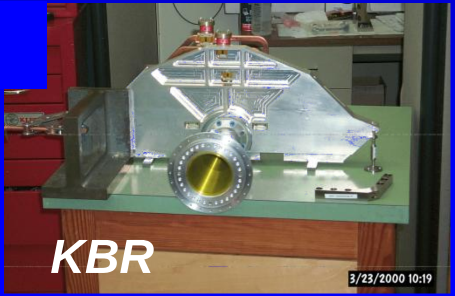
Payload:

- **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**

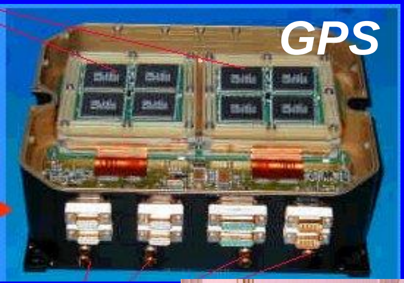
GFZ POTSDAM

GRACE Mission Supports Fundamental Progress in Static & Time Variable Gravity Field Recovery due to:

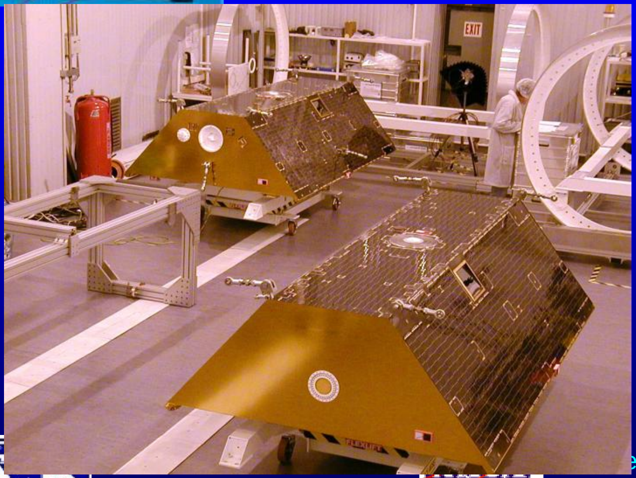
- **Continuous high-low & low-low SST tracking at a low altitude (approx. 490 km)**

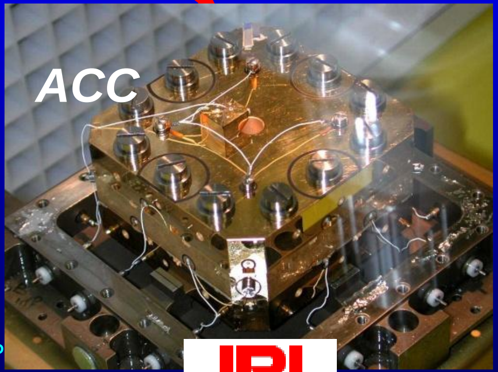


- **Super precise accelerometry for direct measurements of non gravitational surface forces**



- **Polar orbit (89 deg) for a complete coverage of the Earth**

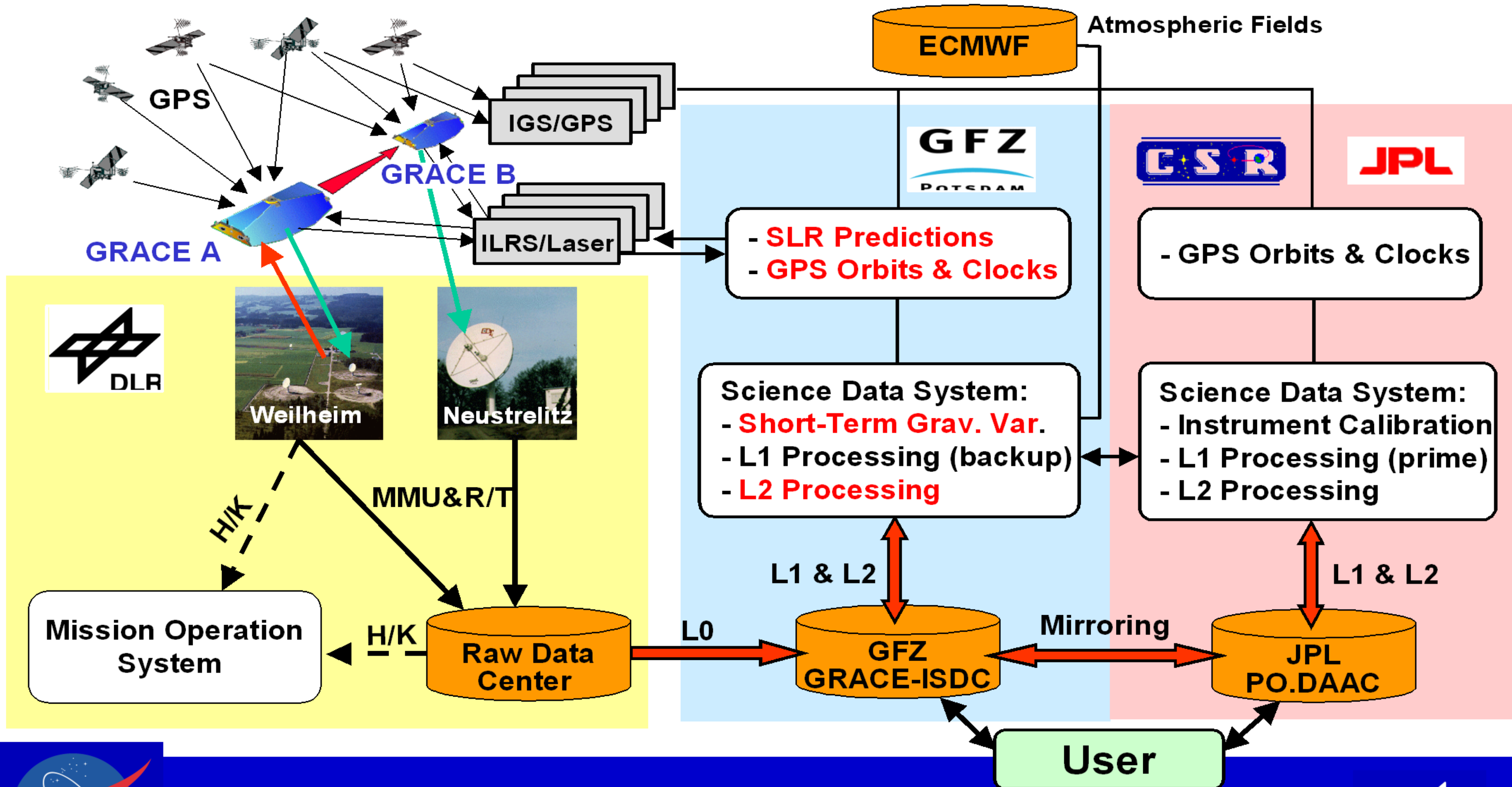




- **Long mission duration to resolve temporal gravity field variations**

JPL DLR GFZ POTSDAM

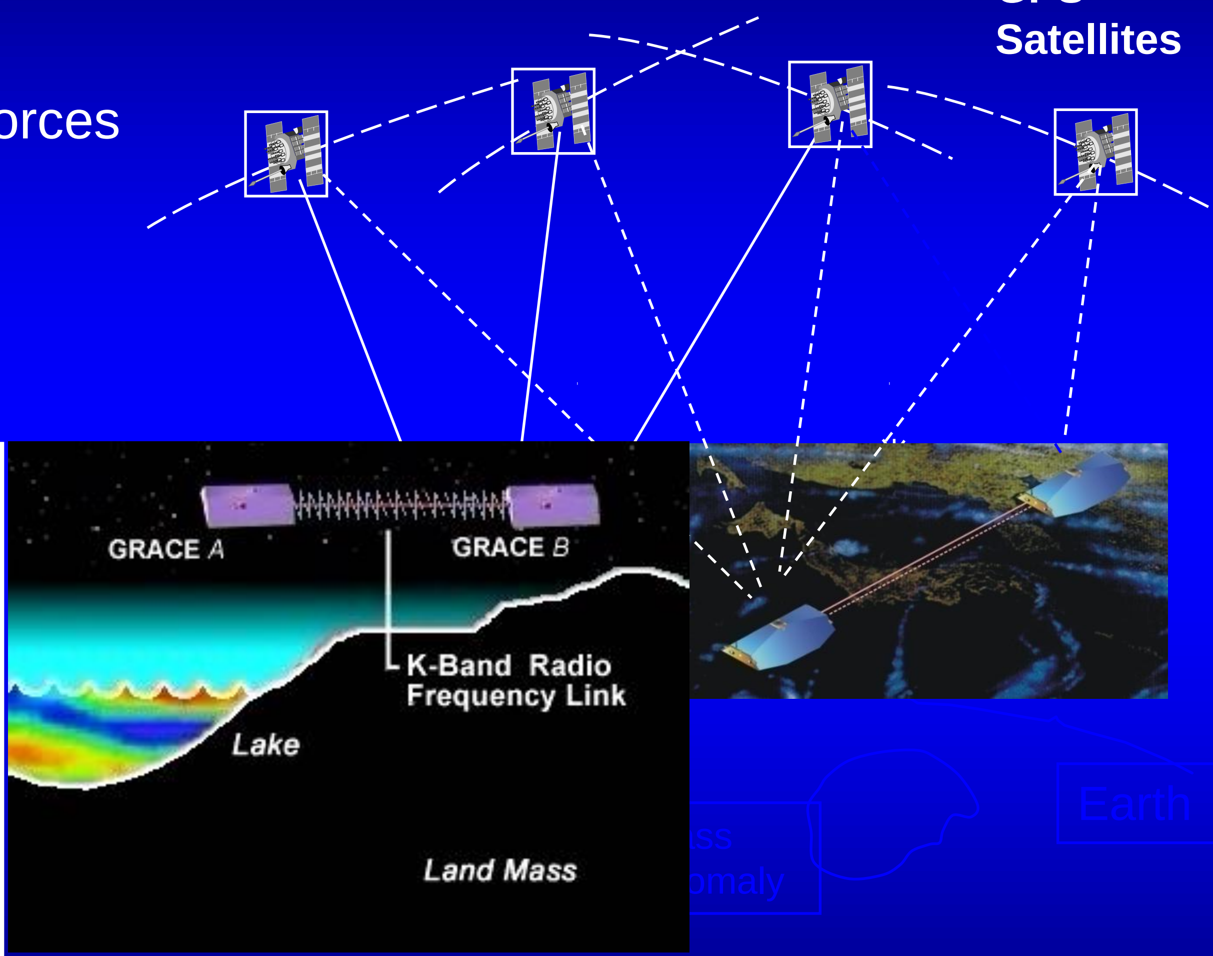
GRACE Ground Segment Operations



GRACE Mission - Gravity Recovery Part

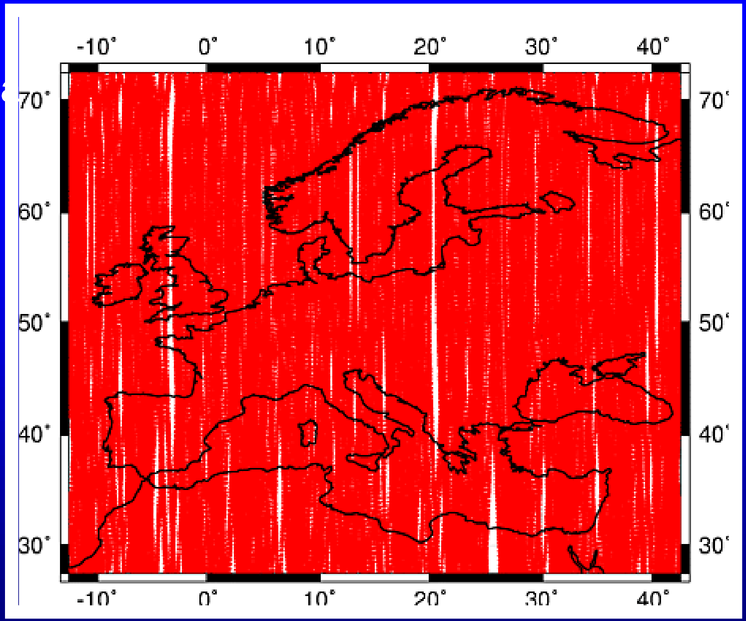
Principle:

- 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 coverage over Europe:

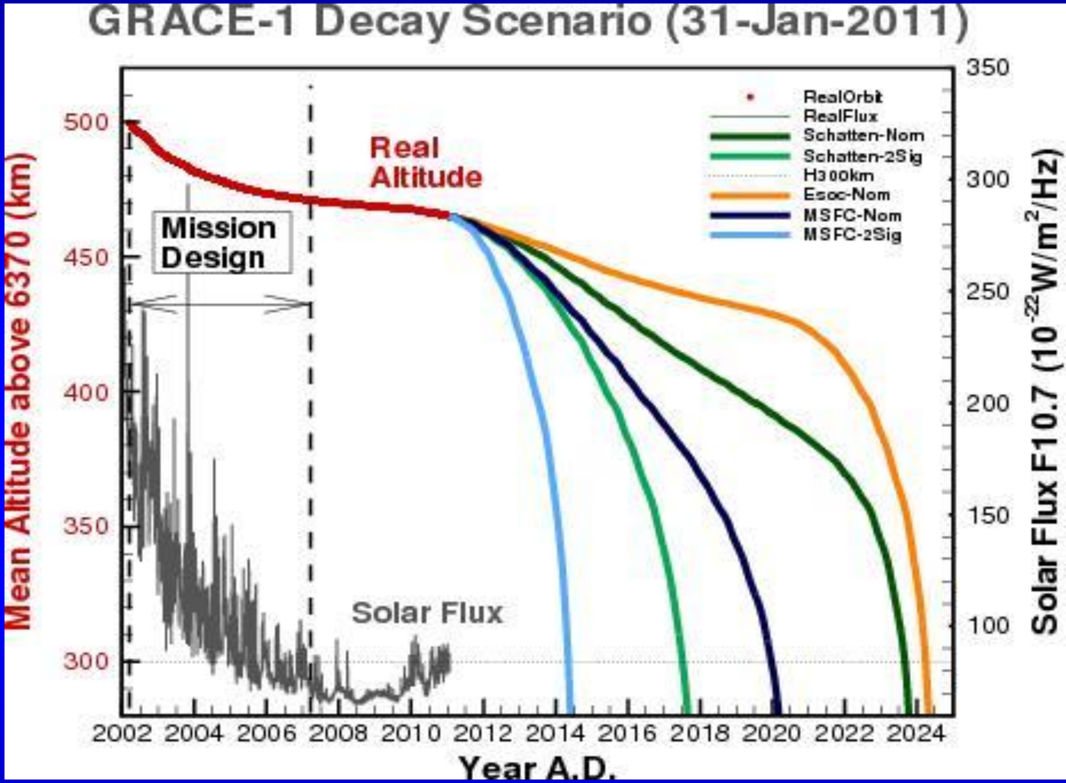


GFZ POTSDAM

Current Status of GRACE Satellites and Instruments

- All science instruments in good health

- A major star-camera software upload was completed 4 weeks ago, significantly reducing the outages in the attitude measurement data.



- Battery Status
  - The battery capacity is diminished compared to the time of launch
  - Individual cells (2nd out of 20) show signs of “weakness”

- Operate the satellite by
  - preventing overcharging of the battery
  - limiting the power consumption during adverse conditions (e.g. switch off the GRACE-B accelerometer in January 2011 = no gravity field could be obtained!)

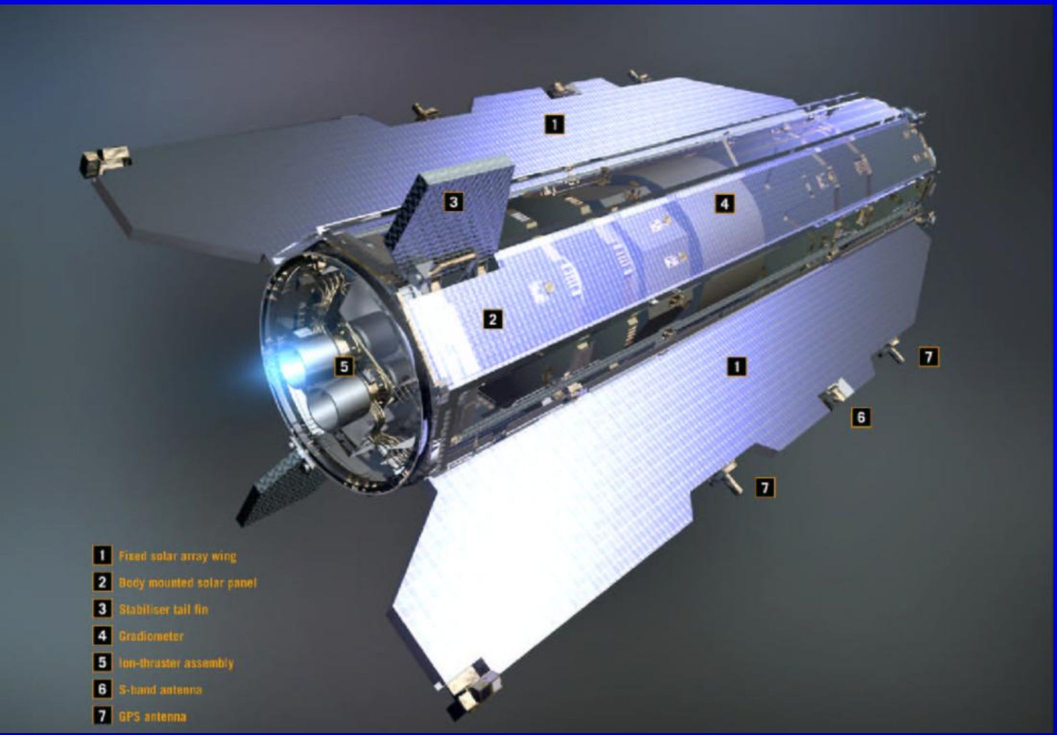
- The life time of GRACE is limited!

GFZ POTSDAM

GOCE

Mission of European Space Agency ESA within the *Living Planet Programme* as one of the first *Earth Explorer Missions*

Launch: ~2009 **Planned Mission duration:** 20 months
Orbit: nearly circular, sun-synchronous orbit (96°), 250 km altitude



Mission goal:

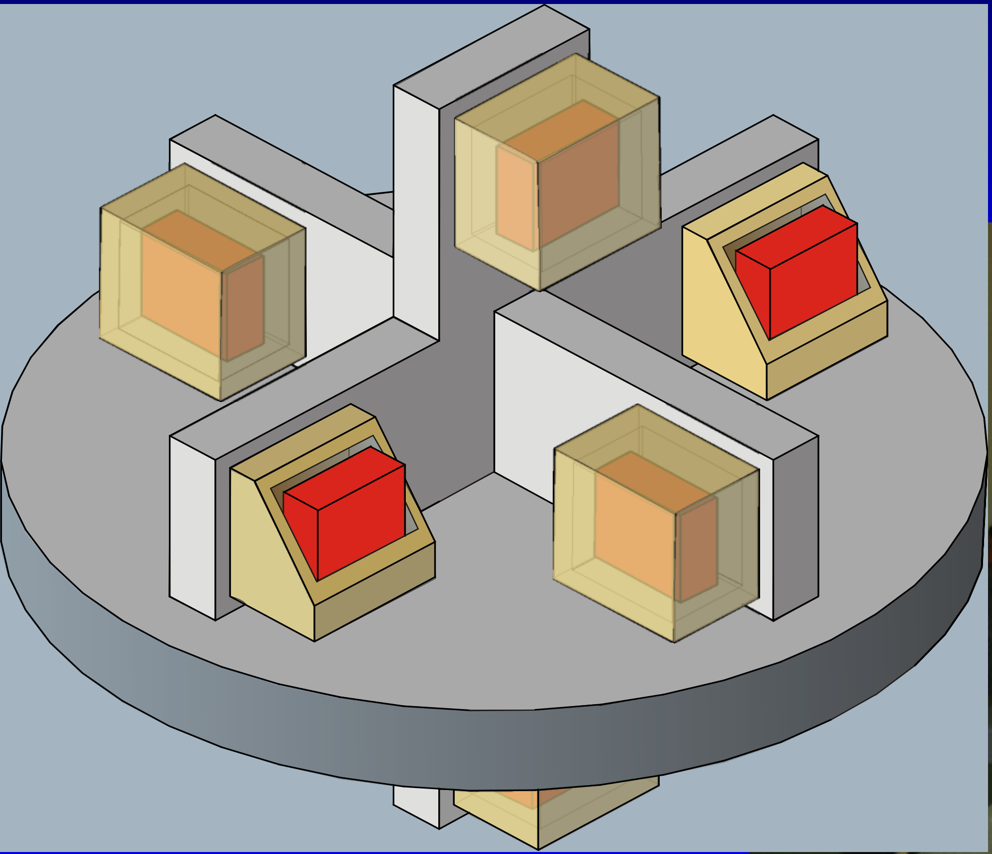
Determination of the geoid with 1 cm accuracy and 100 km spatial resolution

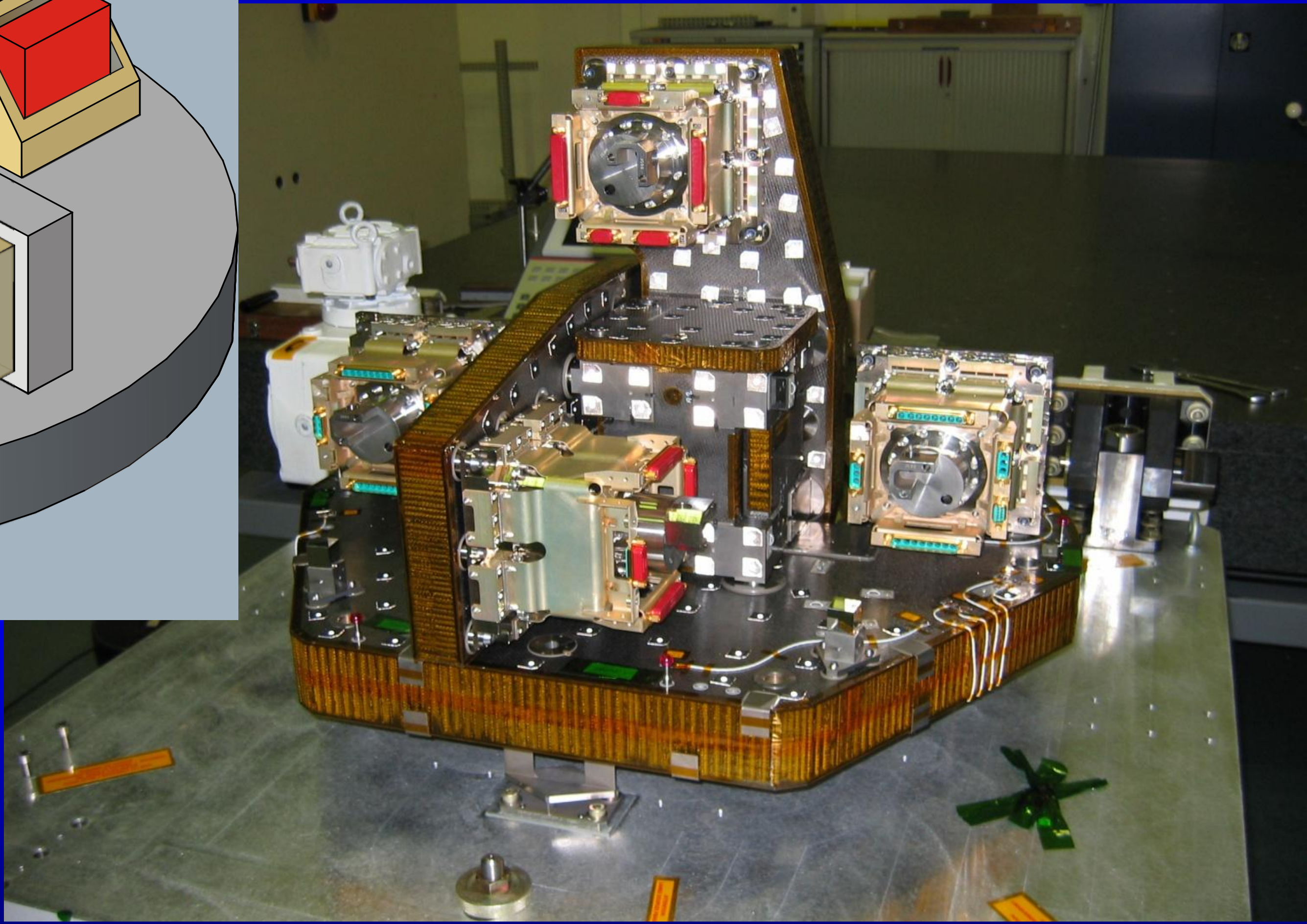
Payload:

- **Gradiometer consisting of 3 pairs of 3-axis accelerometers (3×10^{-12} s^{-2})**
- **Drag-free compensation system**
- **12-channel GPS receiver (high-low SST)**
- **Laser-retro-reflector**
- **SREM: Standard Radiation Environment Monitor**
- **Star sensors**

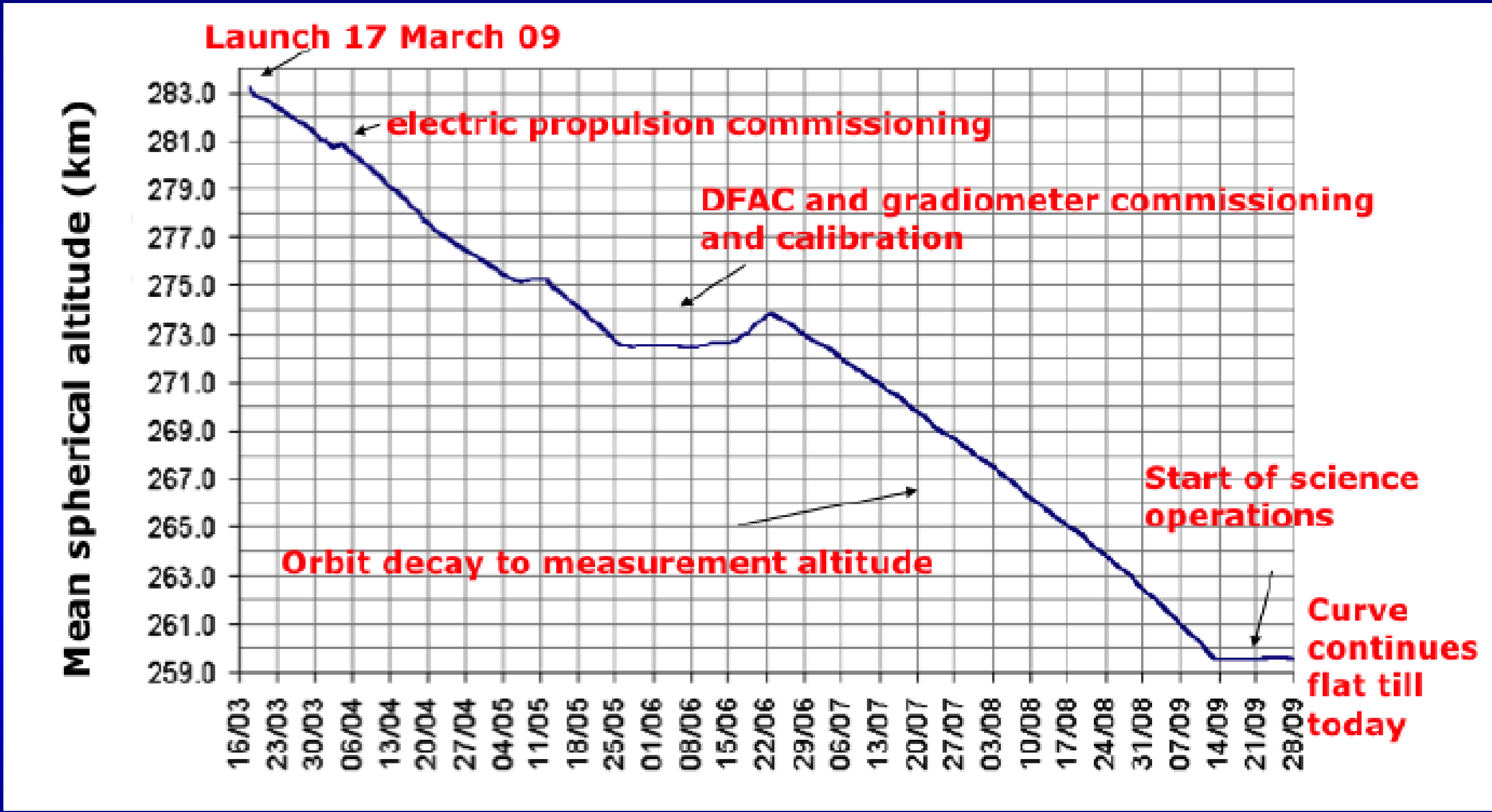
GFZ POTSDAM

Electrostatic Gravity Gradiometer





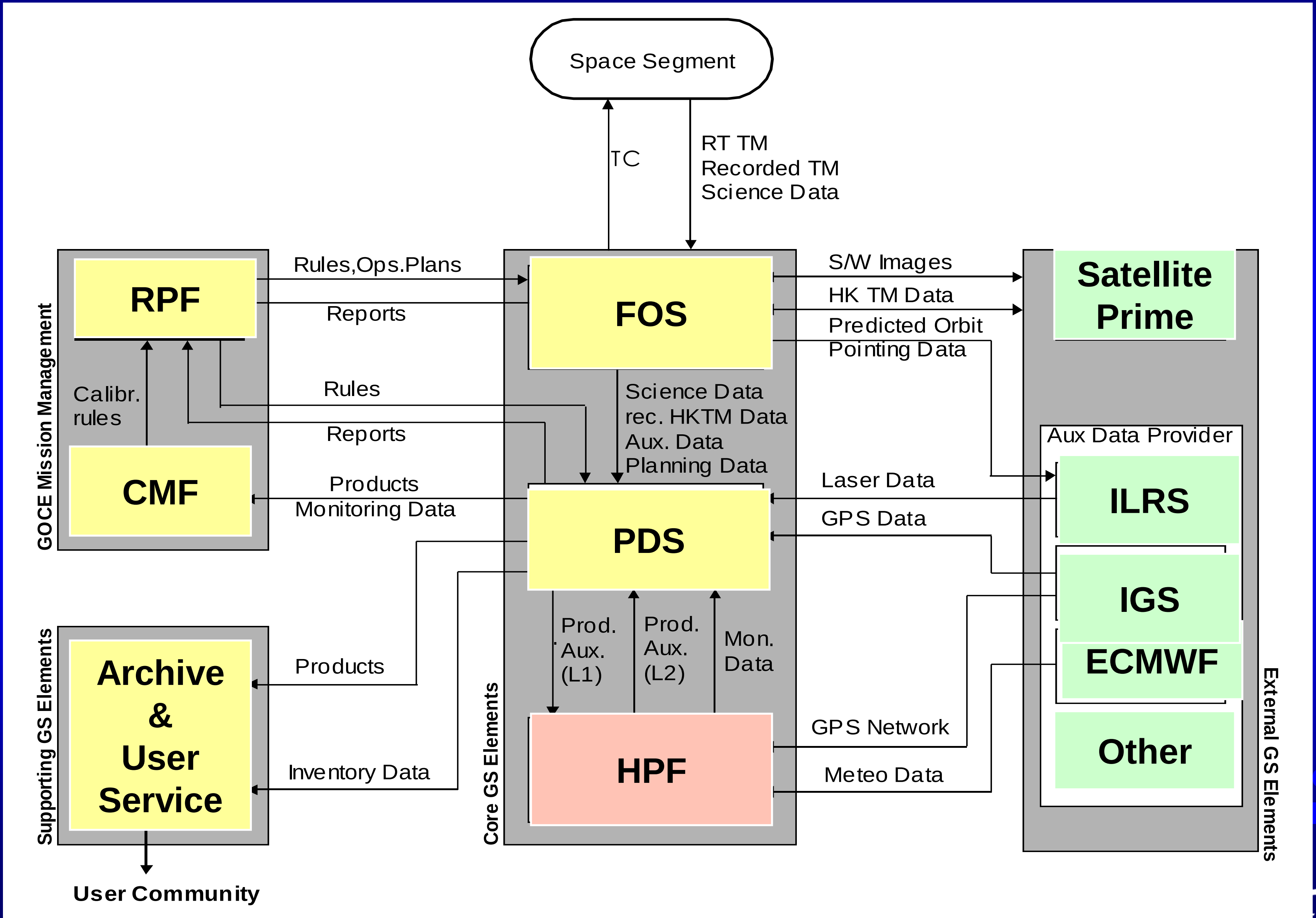
GOCE Orbit Profile

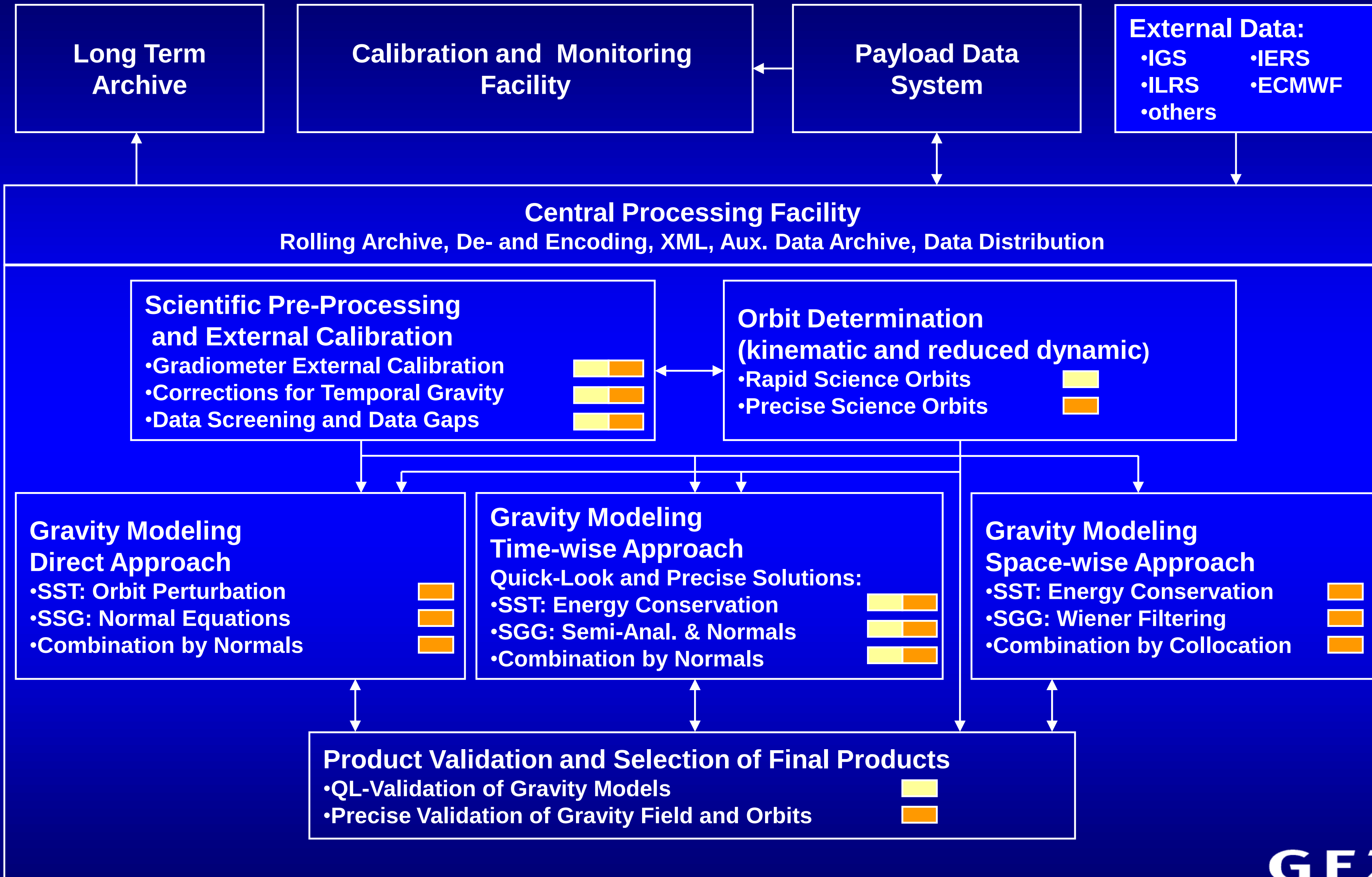


Flohberghagen et al.,2011

GFZ POTSDAM

GOCE Ground Segment





Source ESA

Rapid & Quick Look Processing

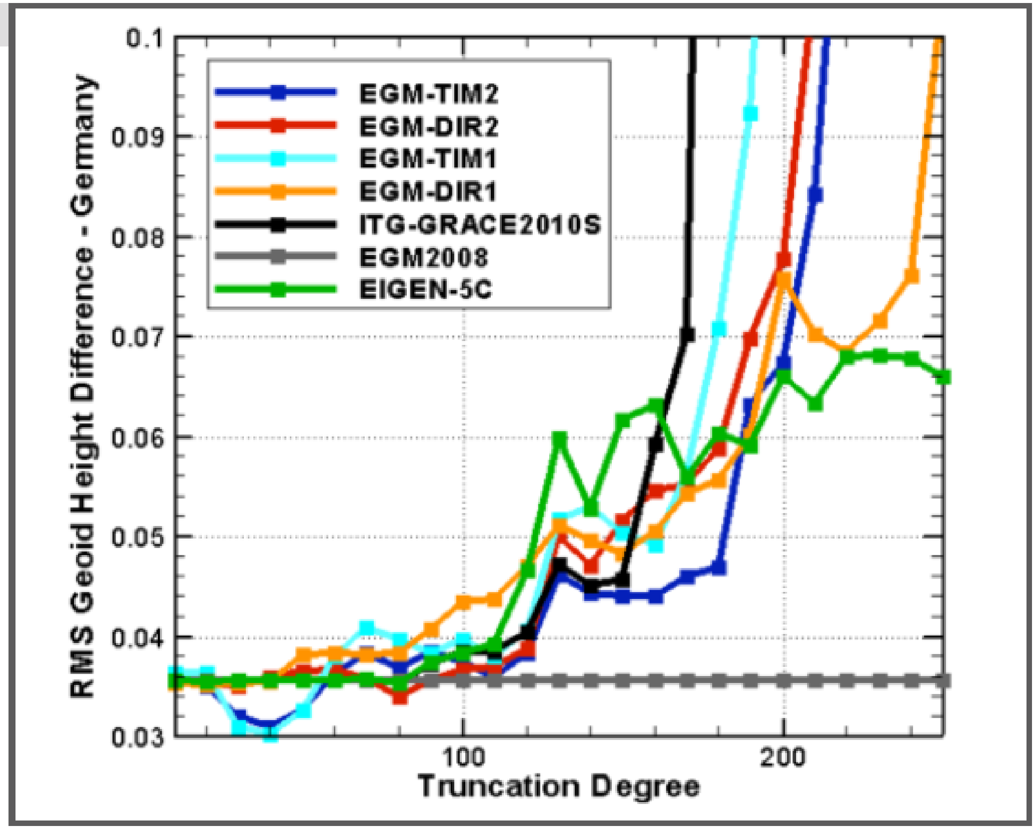
Off-line Processing Facility

Current Status of GOCE Spacecraft and Instruments

- The GOCE satellite and its payload are in good health and deliver top science data (SGPS and gradiometer).

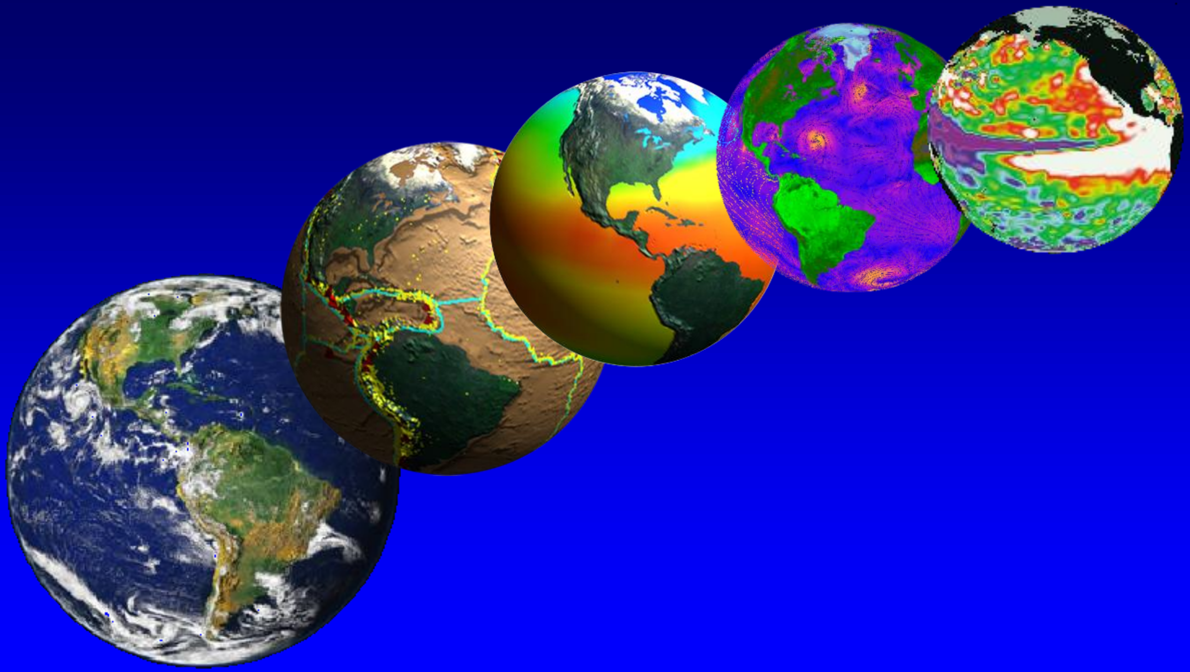
- The persistent low solar activity in 2010/11, the good health of the power subsystem and the excellent thermo-elastic stability of the satellite and the gradiometer have allowed to continue science measurements also during eclipse phases. More data than originally planned will be available.

- Two satellite anomalies were encountered.
– First an anomaly in the data communication between the main computer and the telemetry module
– Secondly a software problem with the GPS payload
– Both anomalies are solved and no impact on successful mission continuation



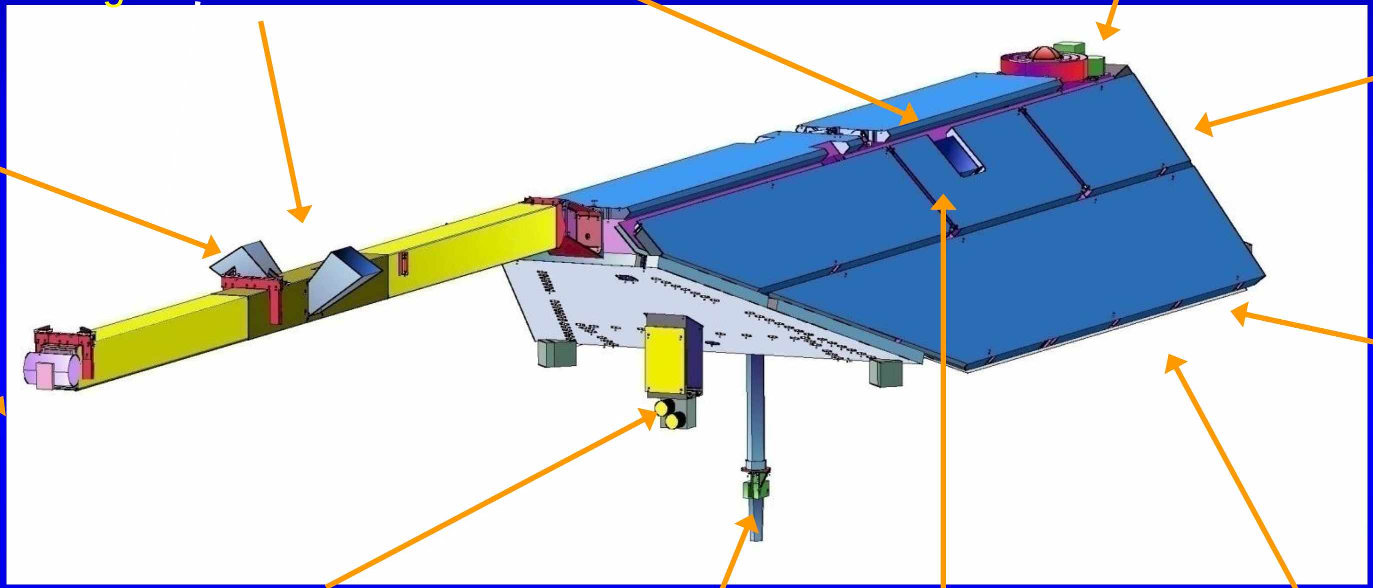
- Operation will be extended until end of 2012 !

GFZ POTSDAM



CHAMP/GRACE /GOCE and the Atmosphere

What do we measure?



Boom Star Sensors
Orientation of Magnetometers

Fluxgate Magnetometers
Components of Magnetic Field Vector

Body Star Sensors
Orientation of Accelerometer

GPS POD Antenna
Position & velocity, Gravity field

GPS RO Antenna
Refractivity Atmosphere / Ionosphere

GPS Nadir Antenna
Ocean / Ice Altimetry / Scatterometry

Overhauser Magnetometer
Magnetic Field Intensity

Digital Ion Driftmeter and Langmuir Probe
Electrical Field

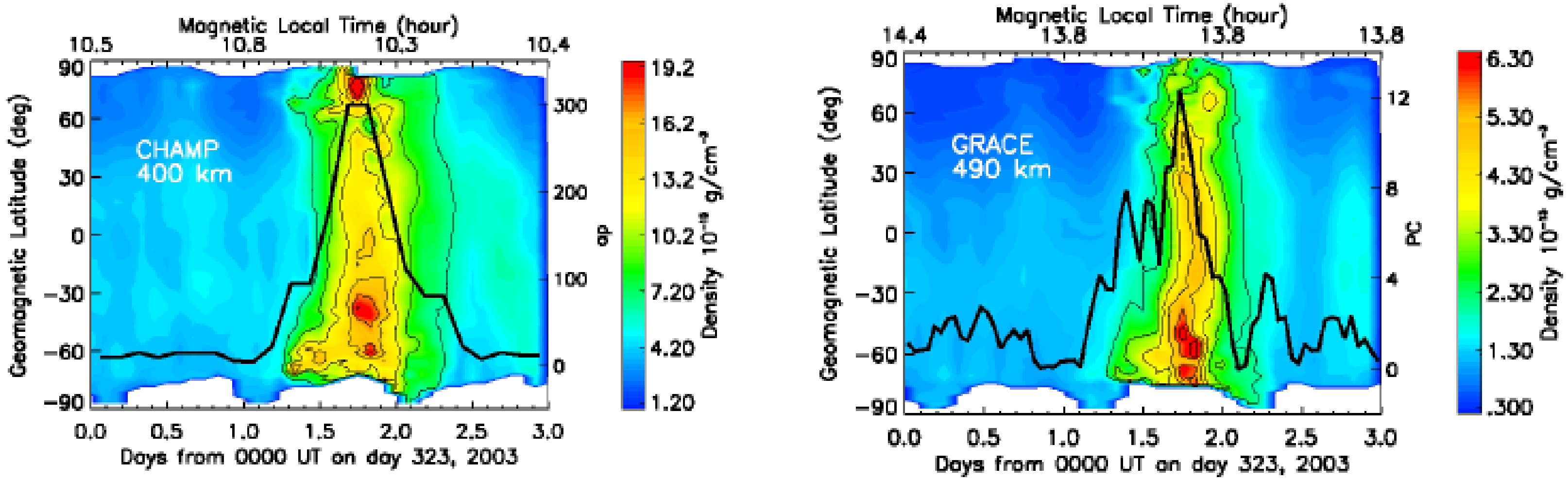
S-Band Antenna
Data Transfer

STAR Accelerometer
Surface Force Accelerations

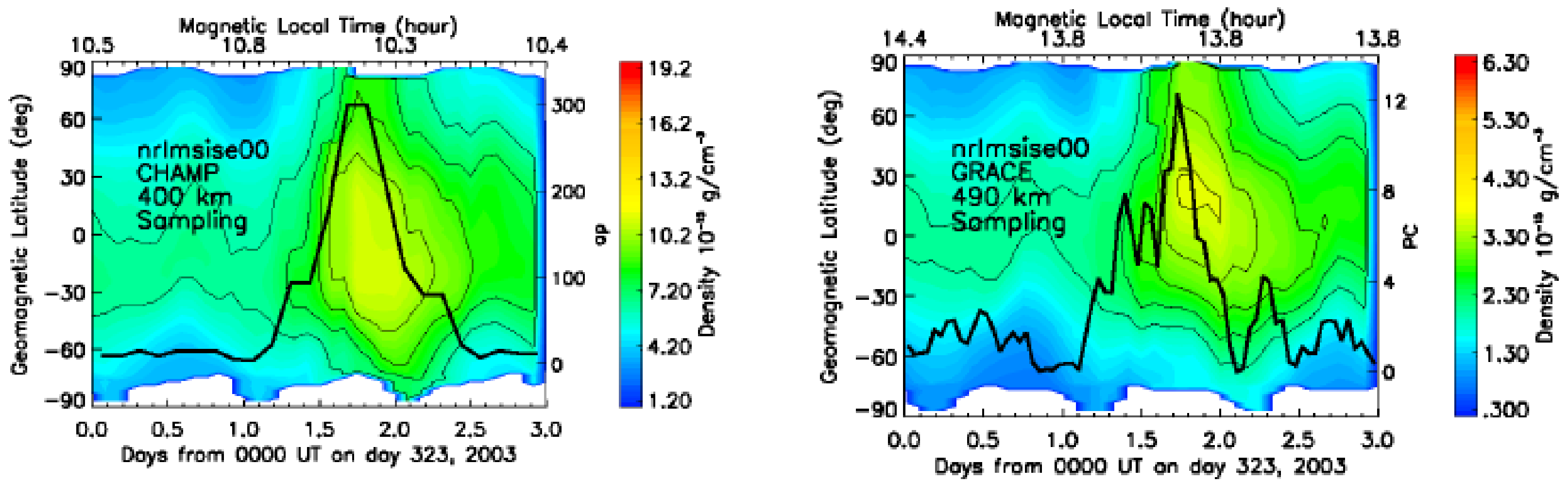
Laser Retro Reflector
Precision Range,

Atmospheric Density Observations

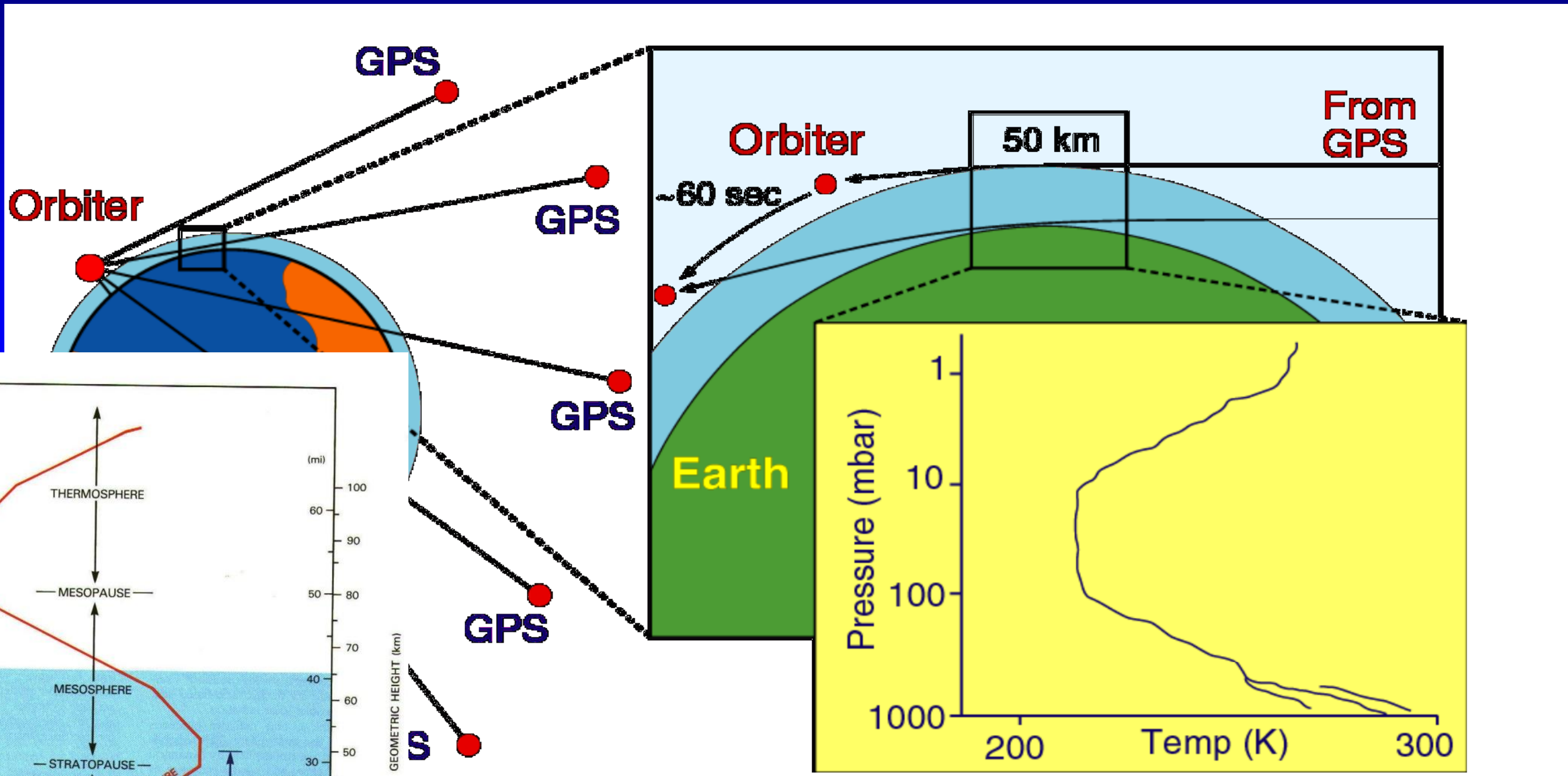
Variabilité atmosphérique observée par accélérométrie

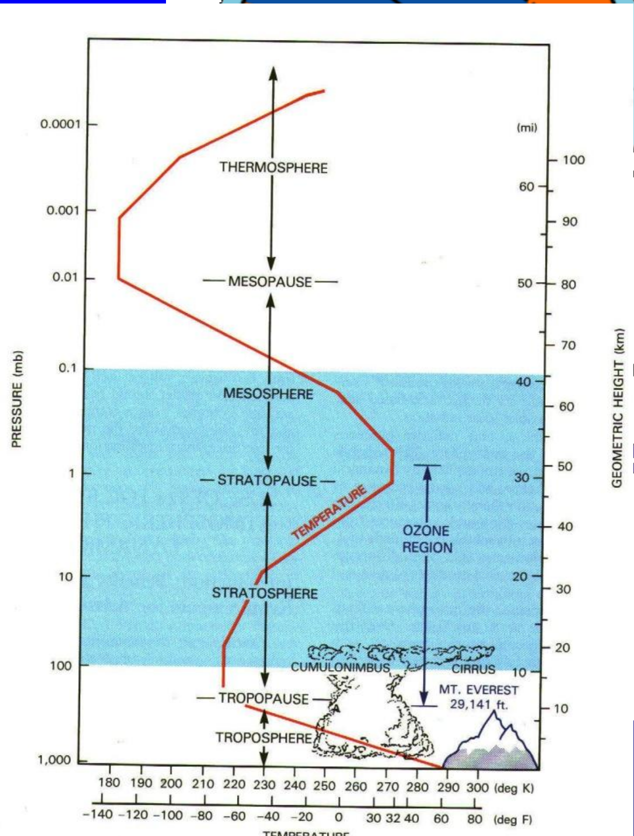


Variabilité atmosphérique modélisée (450-500km d'altitude)



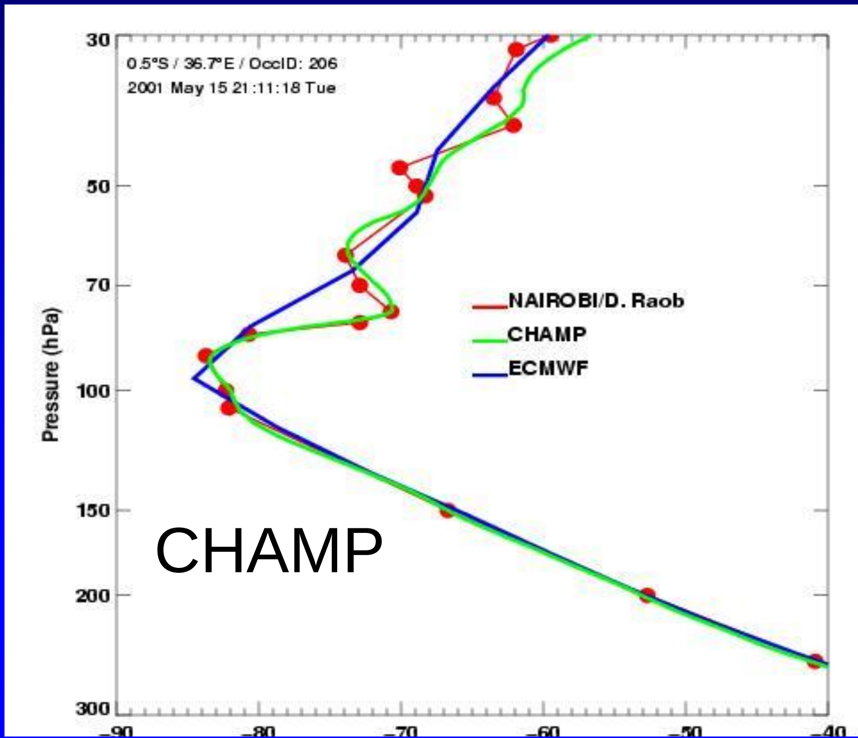
GPS-Atmosphere-Limb-Sonding

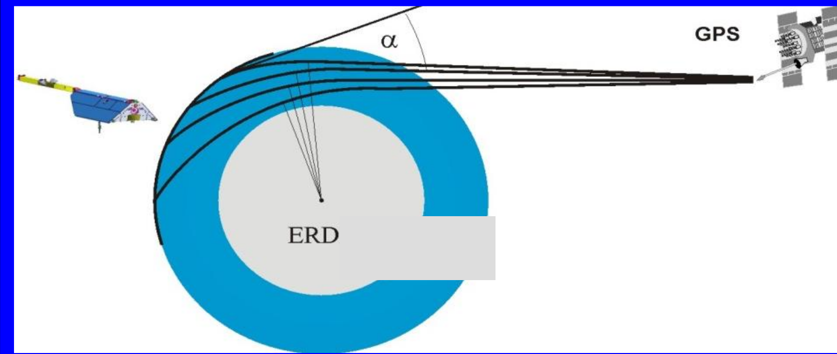


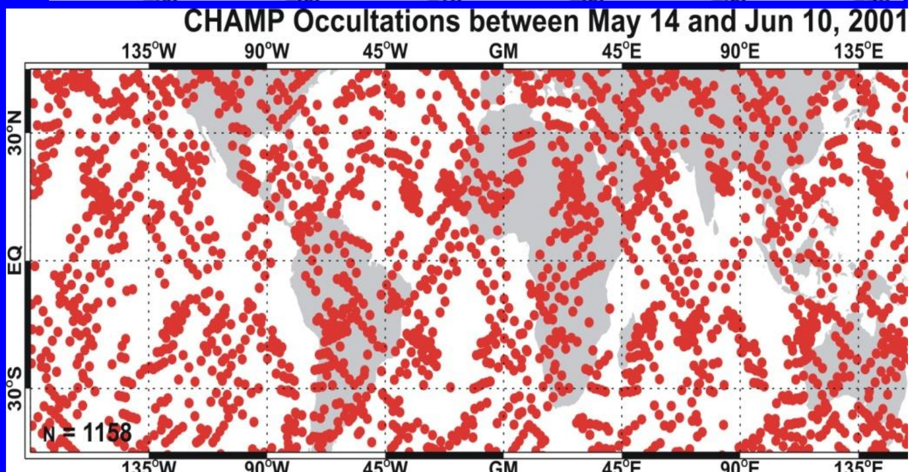


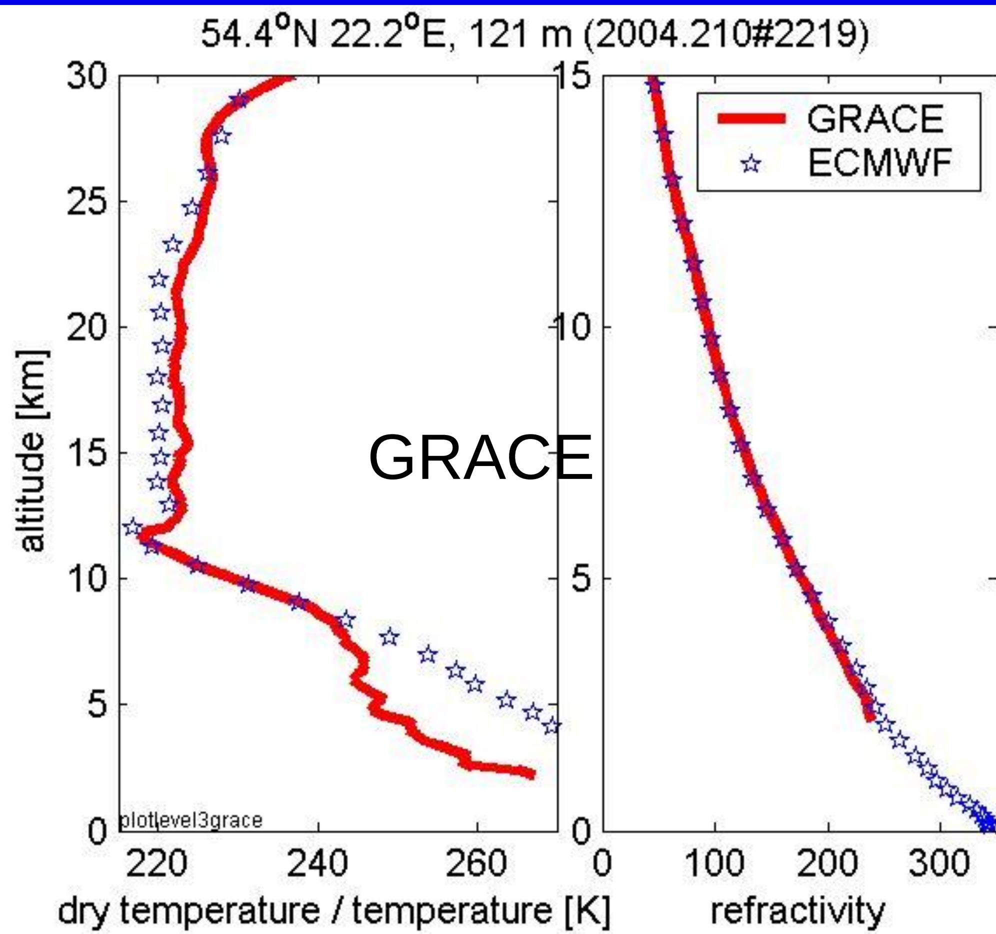
Source T. Yunk

CHAMP/GRACE First RO Profiles

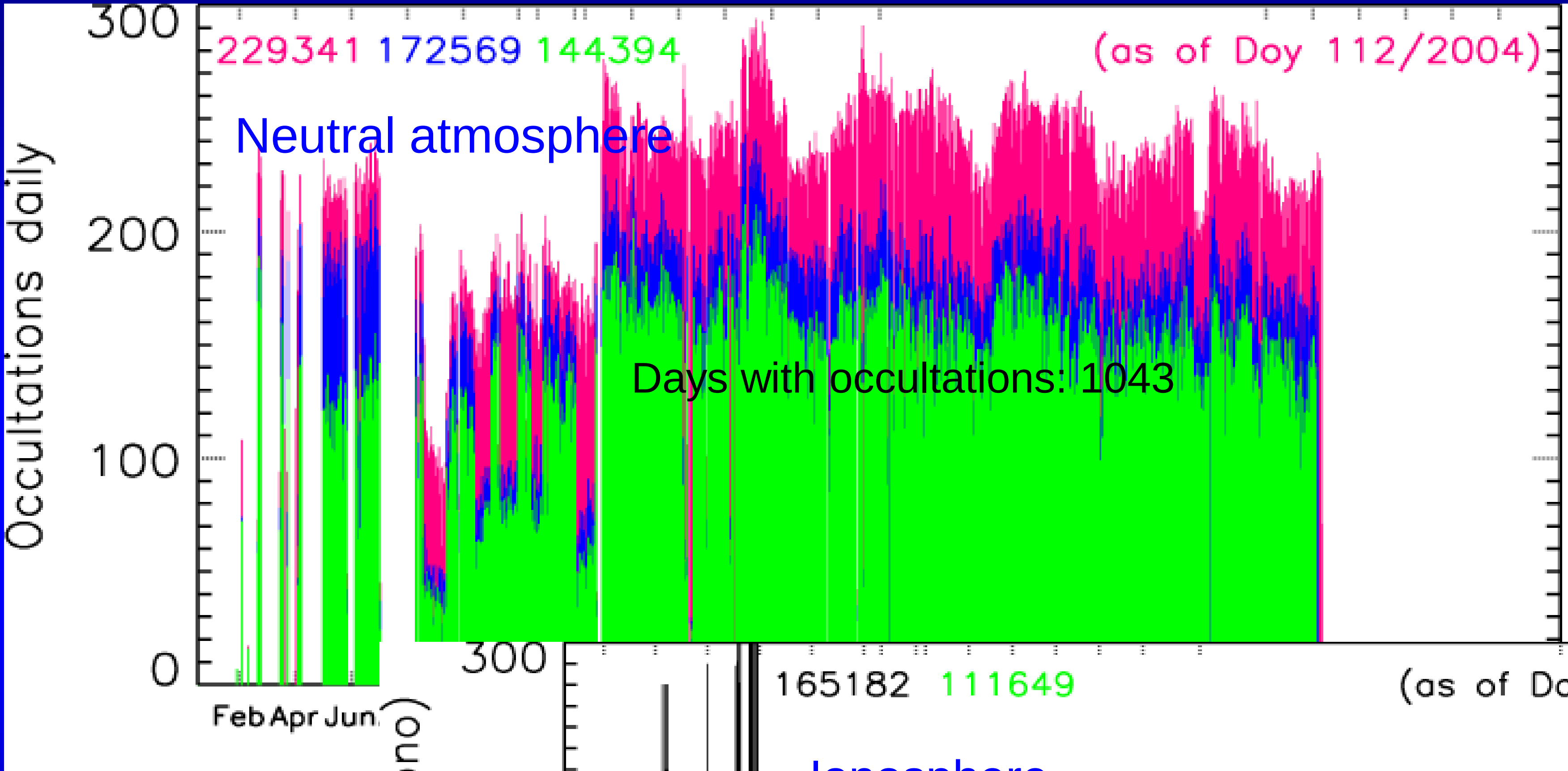


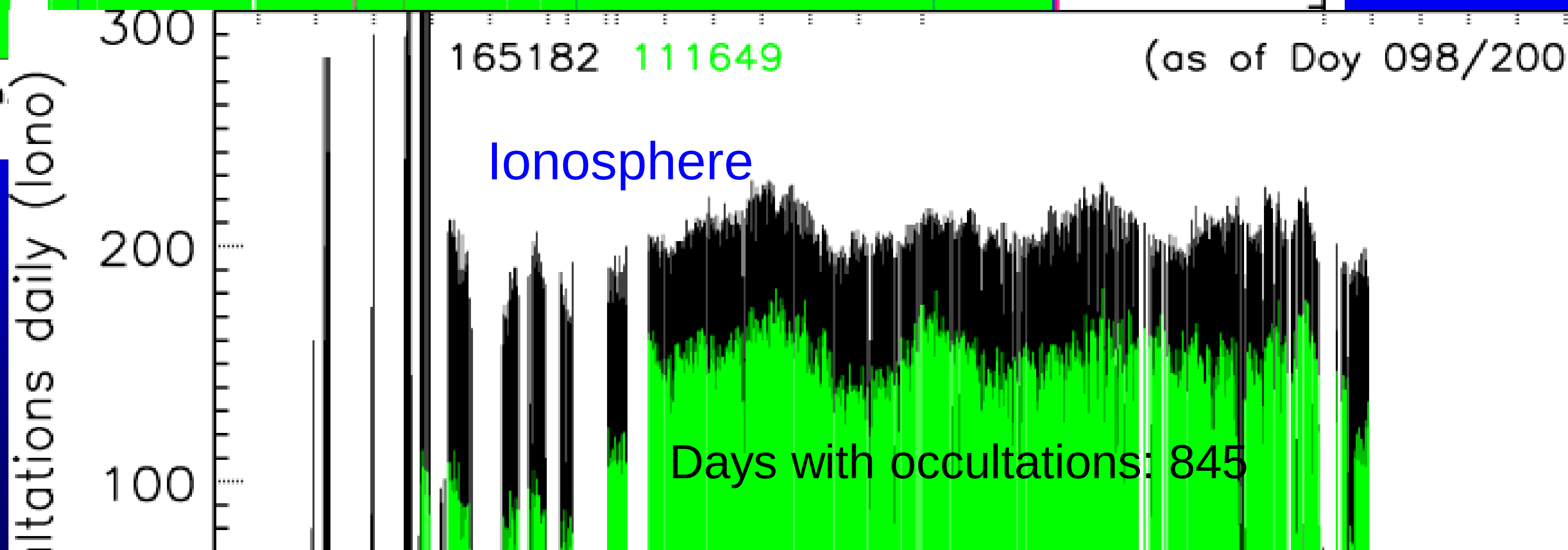




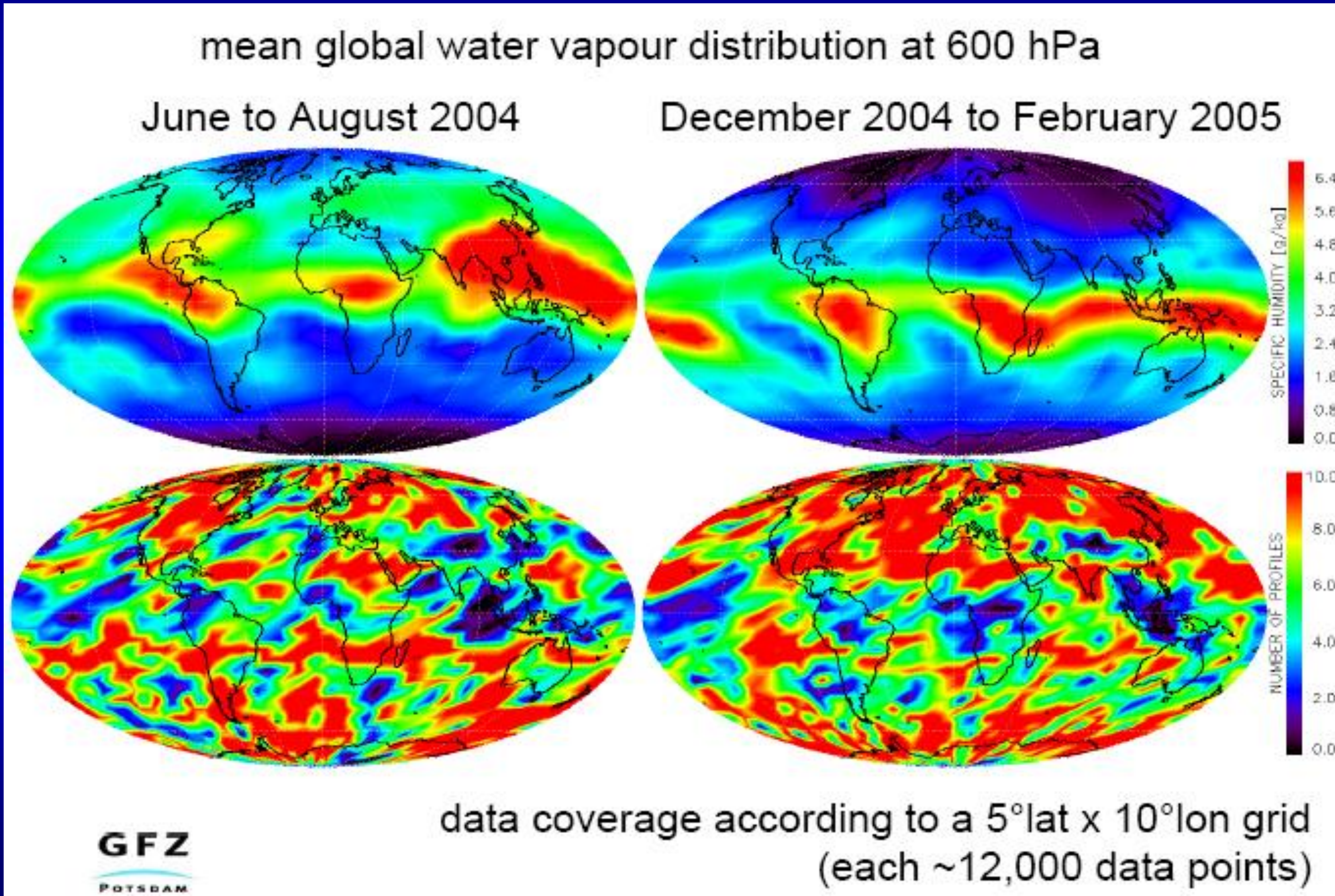


Occultation statistics: Atmosphere/Ionosphere



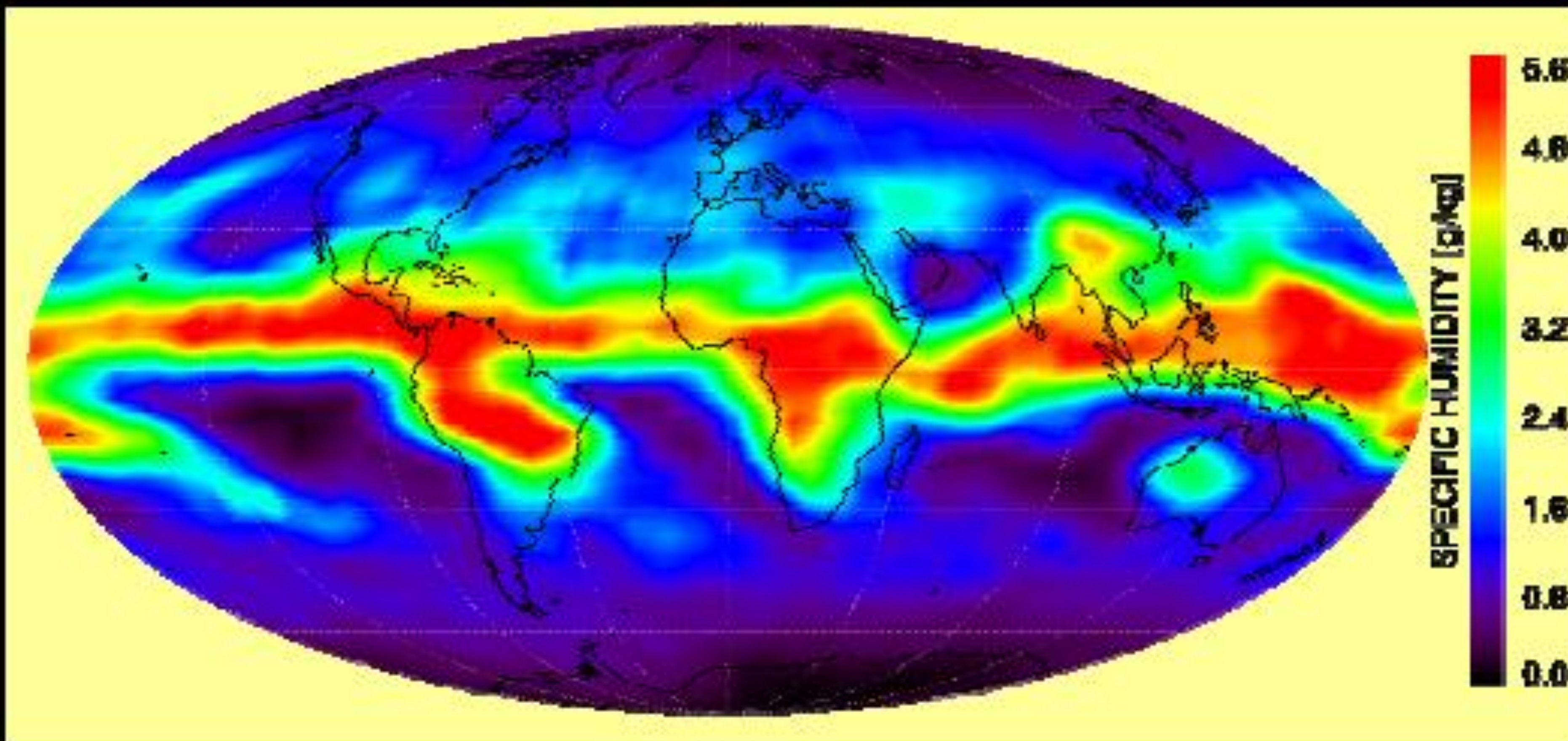


CHAMP Water Vapour- Global Application

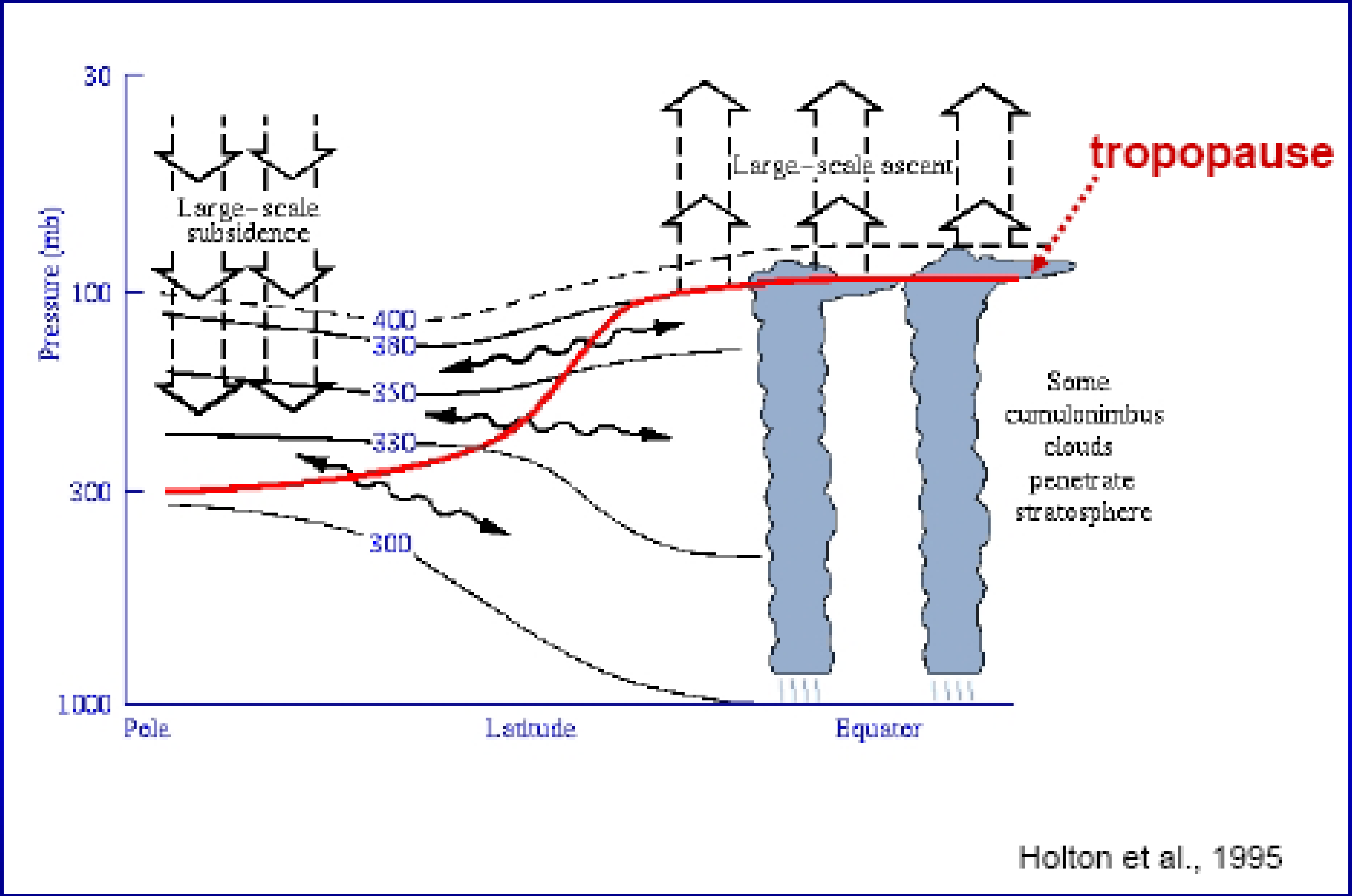


Global Water Vapour (Oct.2006)

CHAMP + GRACE + COSMIC (2.5°lat, 5°lon)



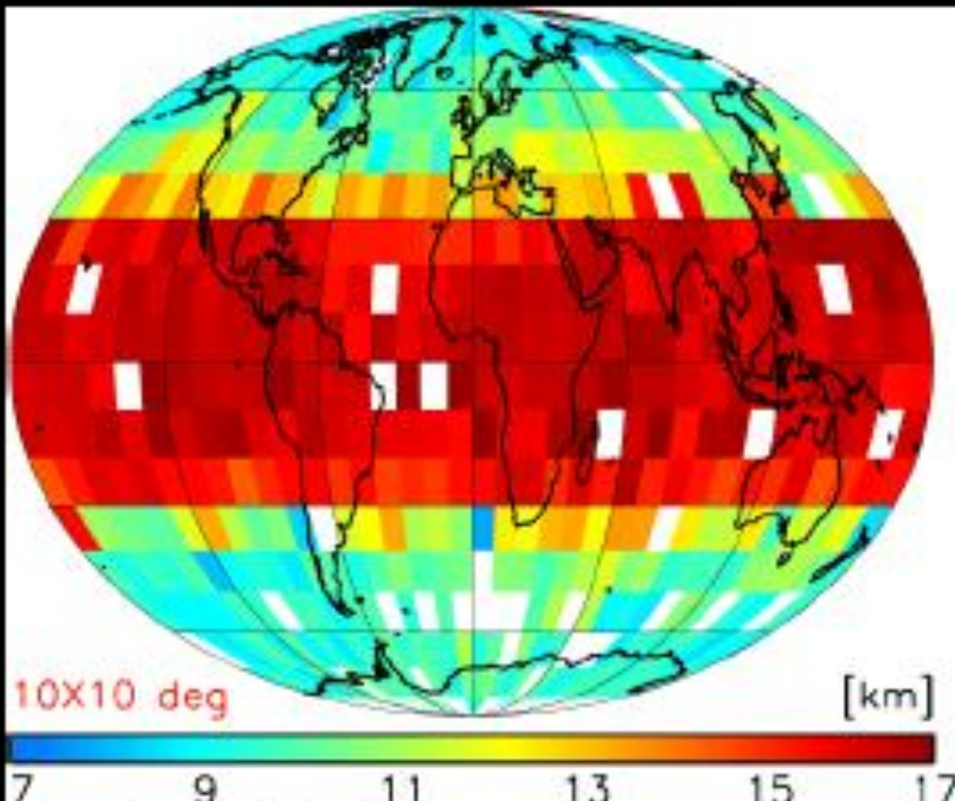
Troposphere/Stratosphere Boundary Region



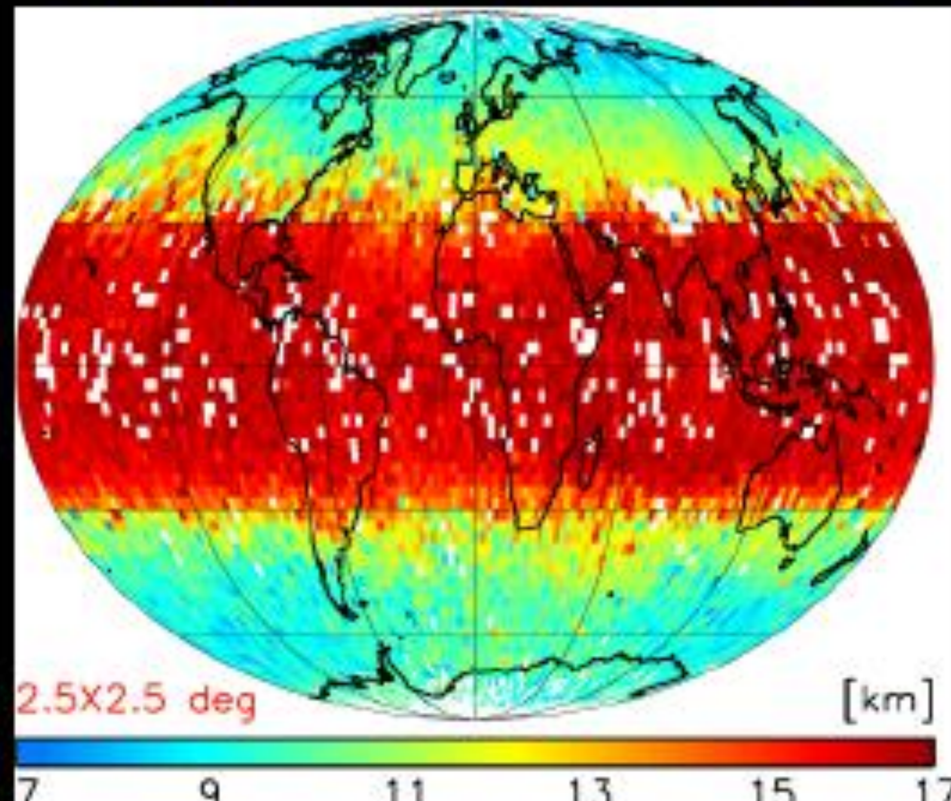
GFZ POTSDAM

Tropopause Altitude Oct. 2006

CHAMP



CHAMP+GRACE+COSMIC



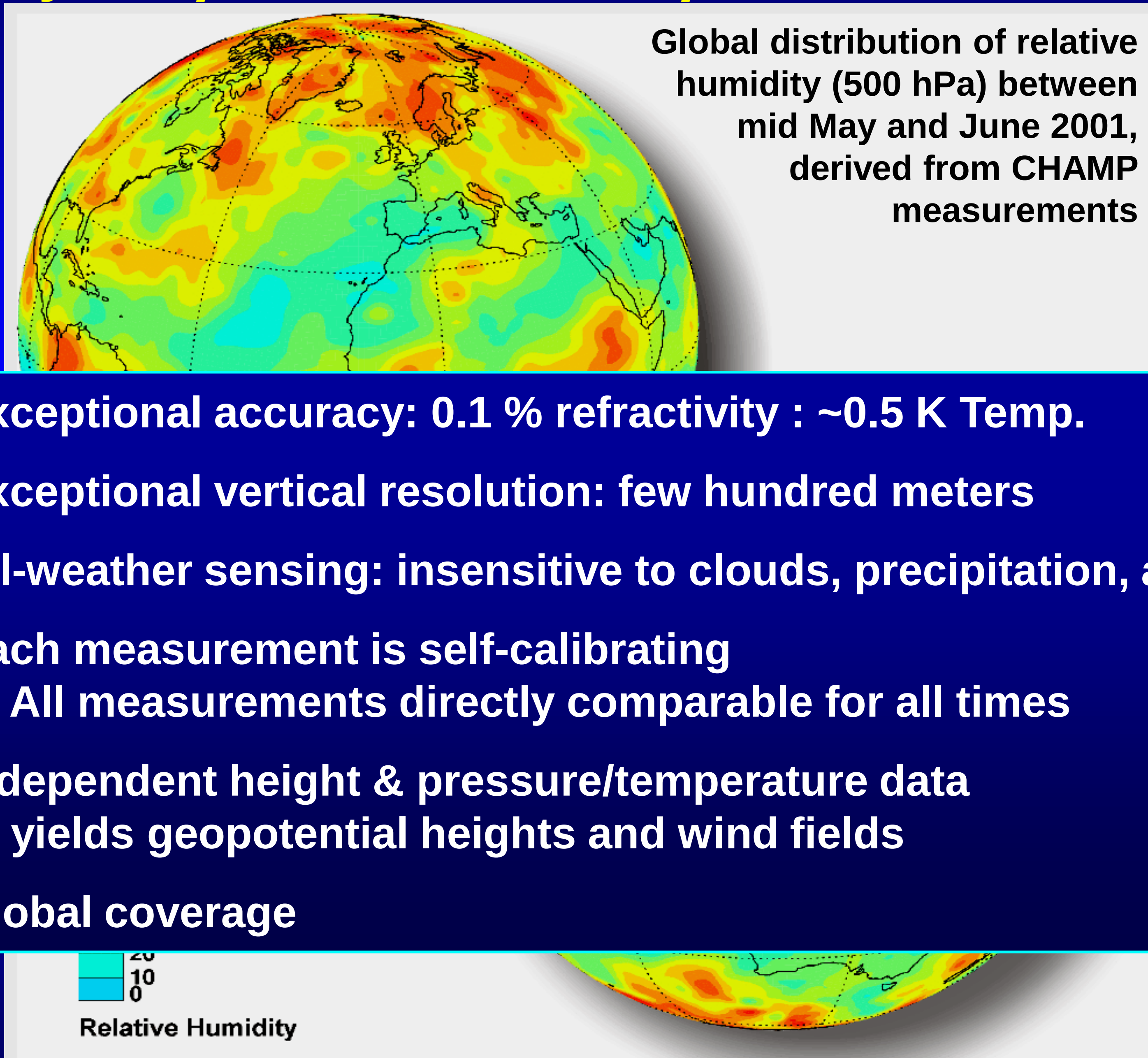
Tropopause

46.235 profiles

Much higher resolution in time and space with new missions,

But: CHAMP long term data set is unique

Key Properties of Atmospheric Occultation Data

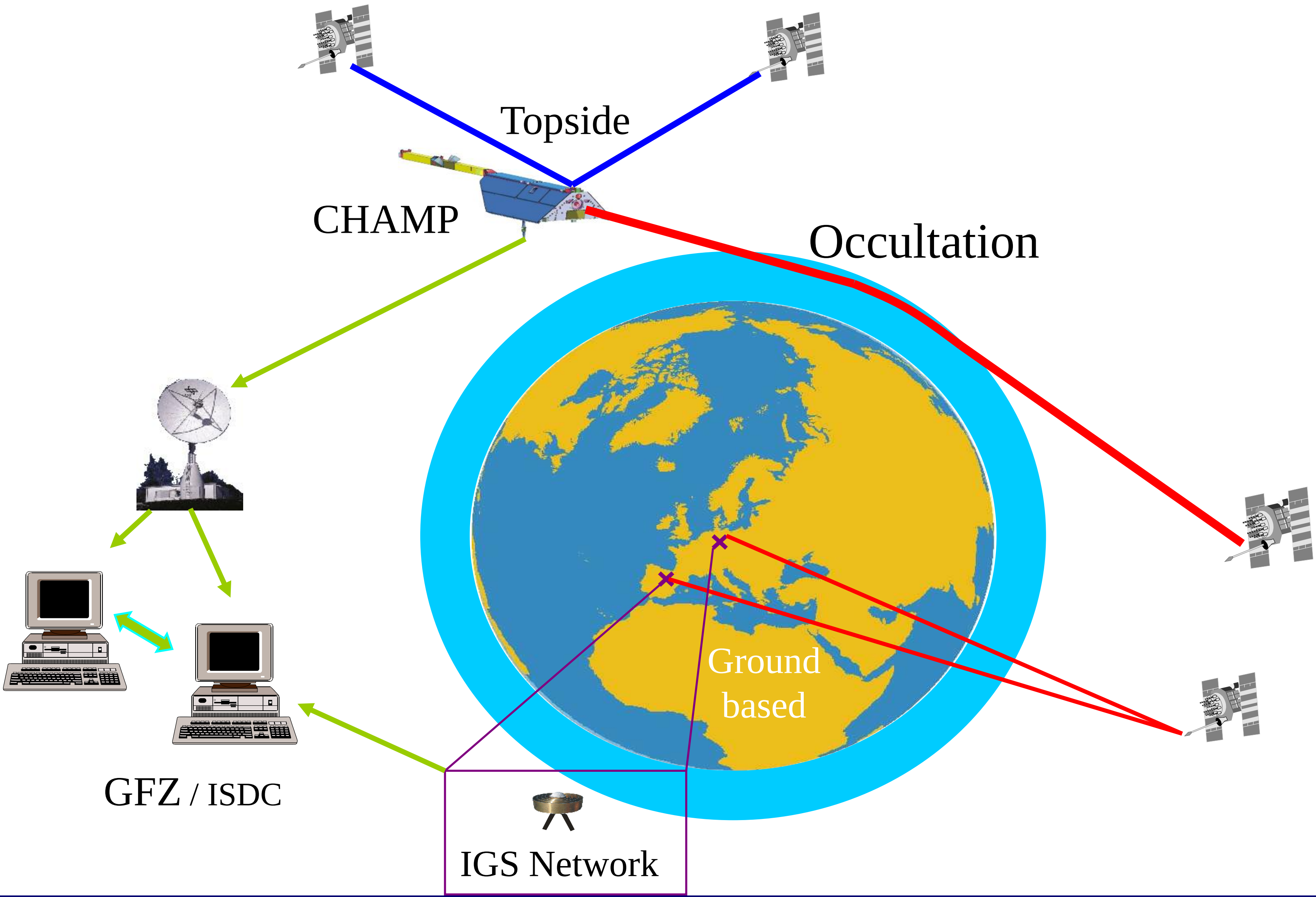


Global distribution of relative humidity (500 hPa) between mid May and June 2001, derived from CHAMP measurements

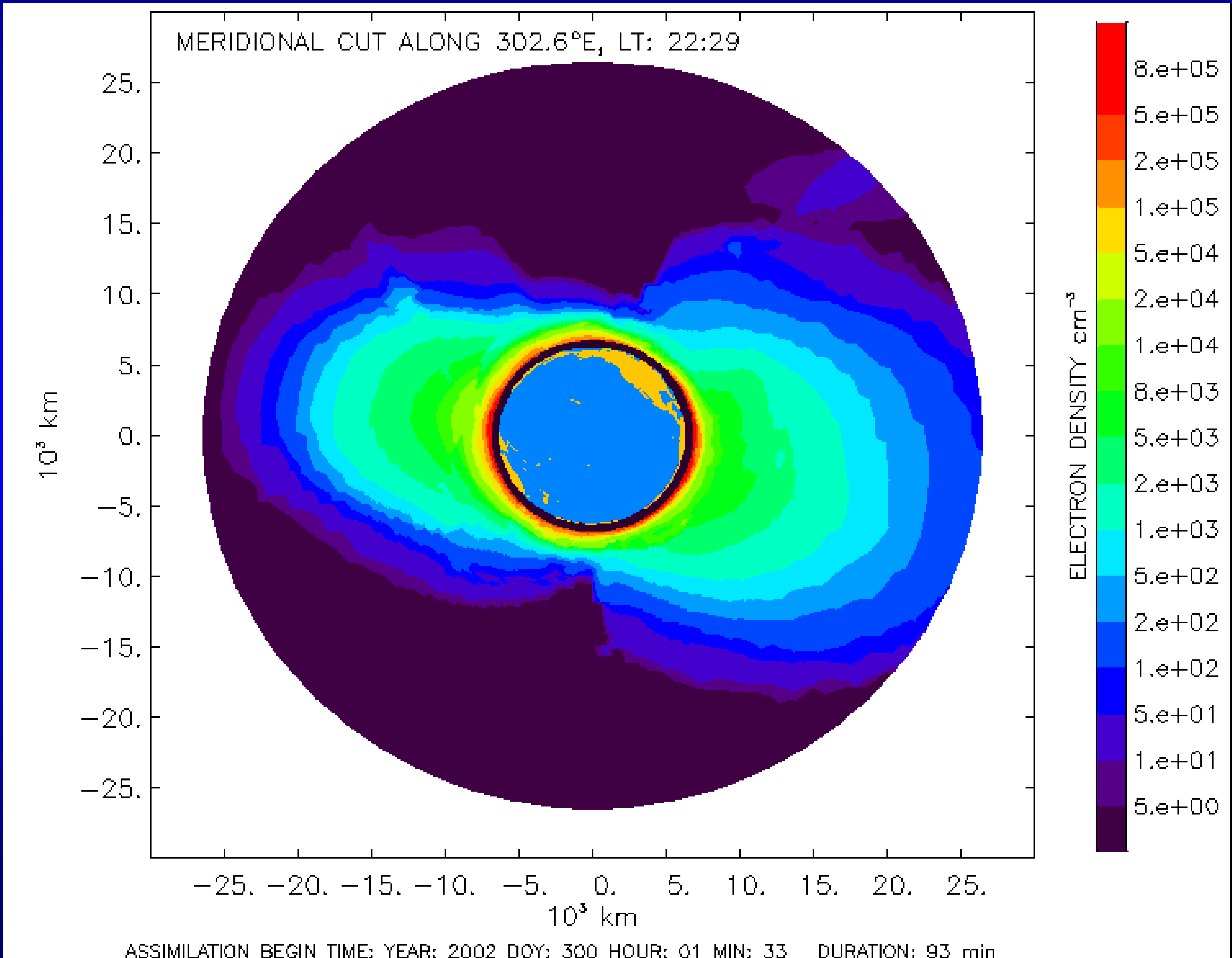
- **Exceptional accuracy: 0.1 % refractivity : ~0.5 K Temp.**
- **Exceptional vertical resolution: few hundred meters**
- **All-weather sensing: insensitive to clouds, precipitation, aerosols**
- **Each measurement is self-calibrating**
  → All measurements directly comparable for all times
- **Independent height & pressure/temperature data**
  → yields geopotential heights and wind fields
- **Global coverage**

GFZ POTSDAM

CHAMP/GRACE GPS Ionosphere Sounding Principle



Top-side ionosphere/plasmasphere



Electron density reconstruction of the days:

27 - 28 Oct 2002

Time resolution:

T ≈ 93 min

Source: Heise et al.,2004

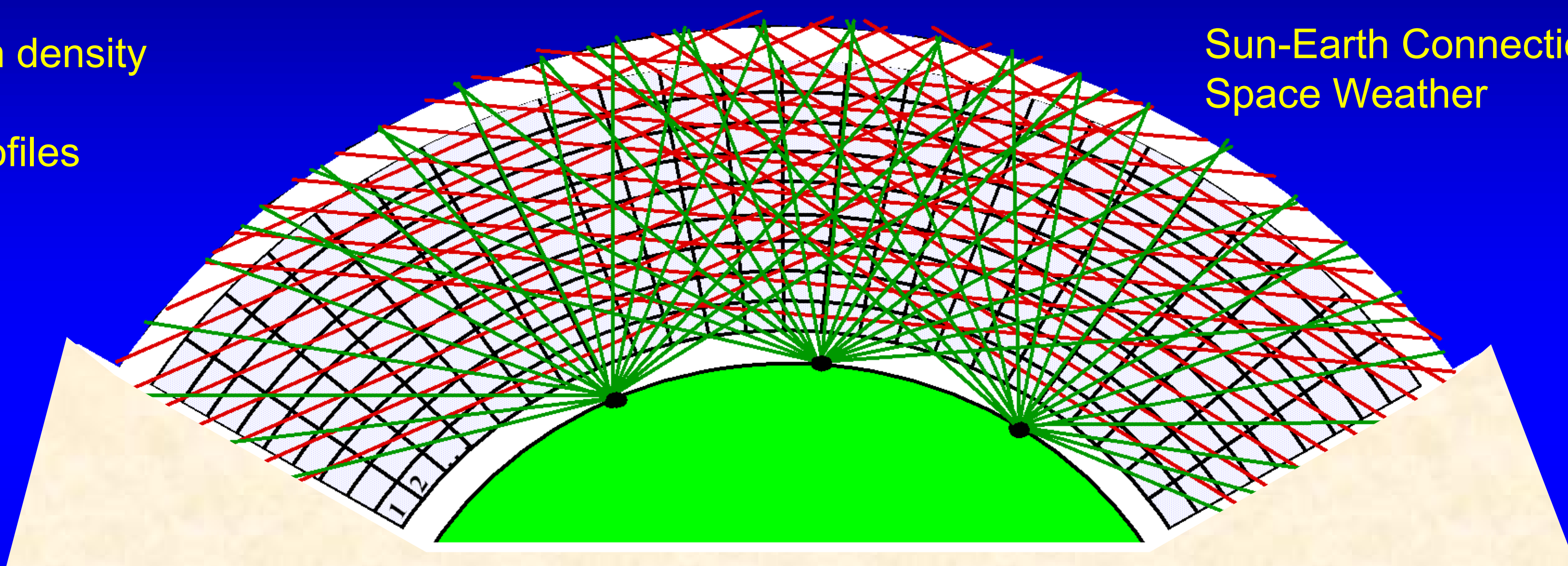
GFZ POTSDAM

Key Applications of Ionospheric Data

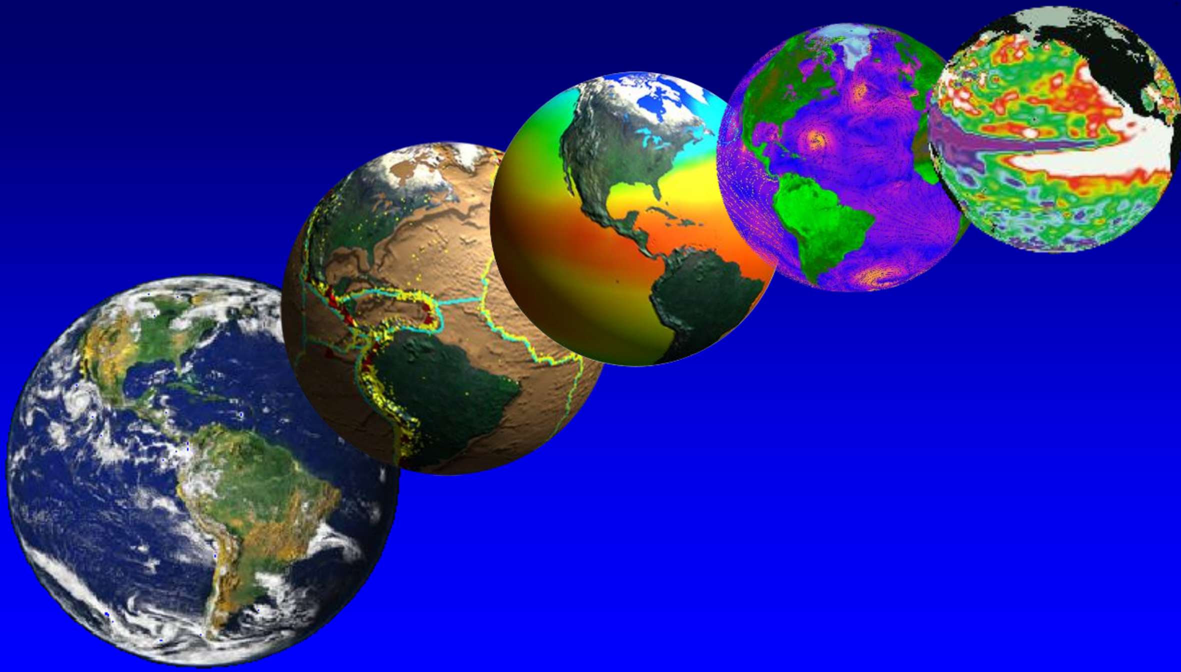
Snapshot 3D Ionospheric Imaging

Electron density
and
TEC profiles

Sun-Earth Connections
Space Weather

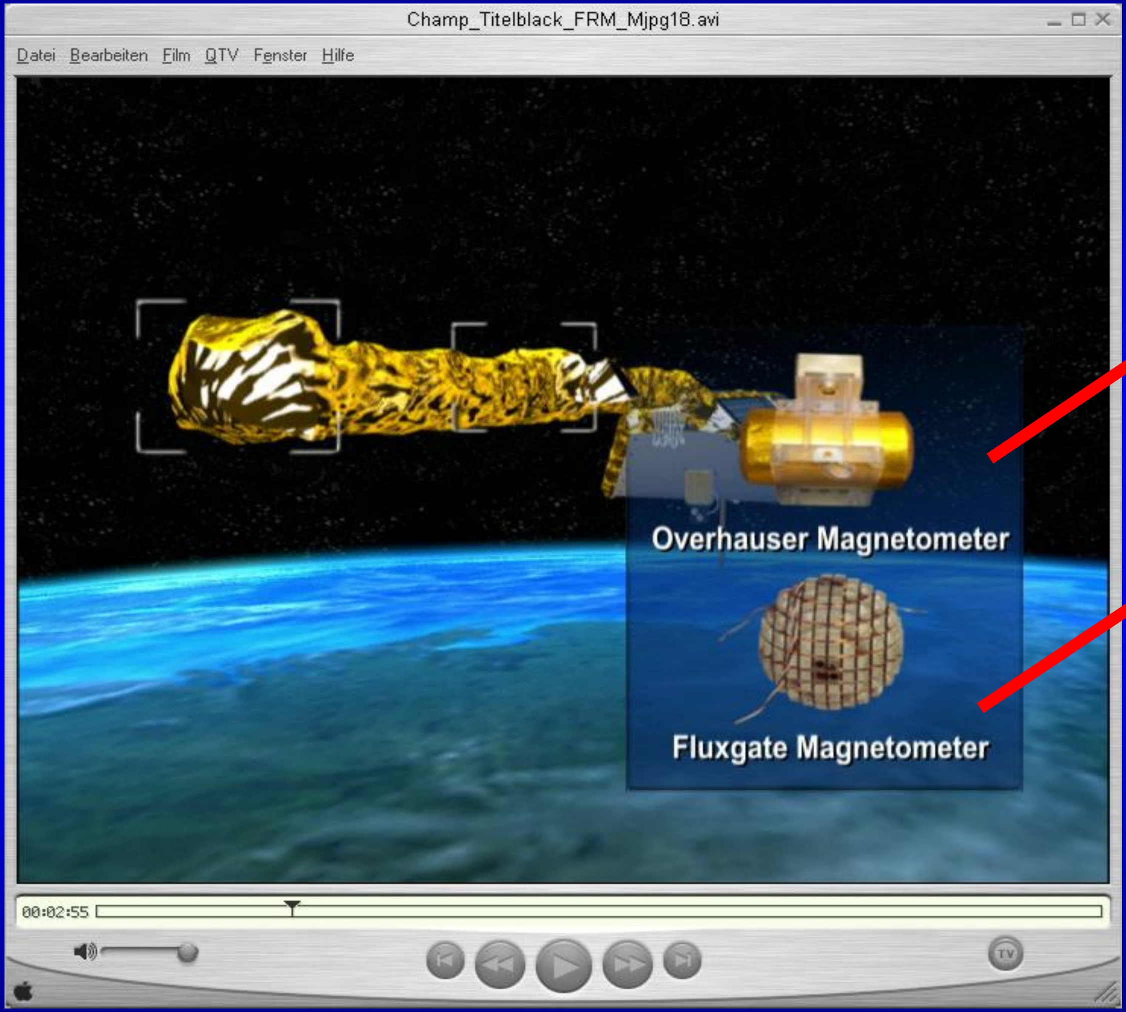


- **Observe ionospheric dynamics**
- **3D reconstruction of the ionosphere**
- **Near term predictions of space weather**
- **Chart full course and evolution of space storms**



CHAMP/GRACE/GOCE and Geodesy/Geophysics

Magnetic field measurements with CHAMP



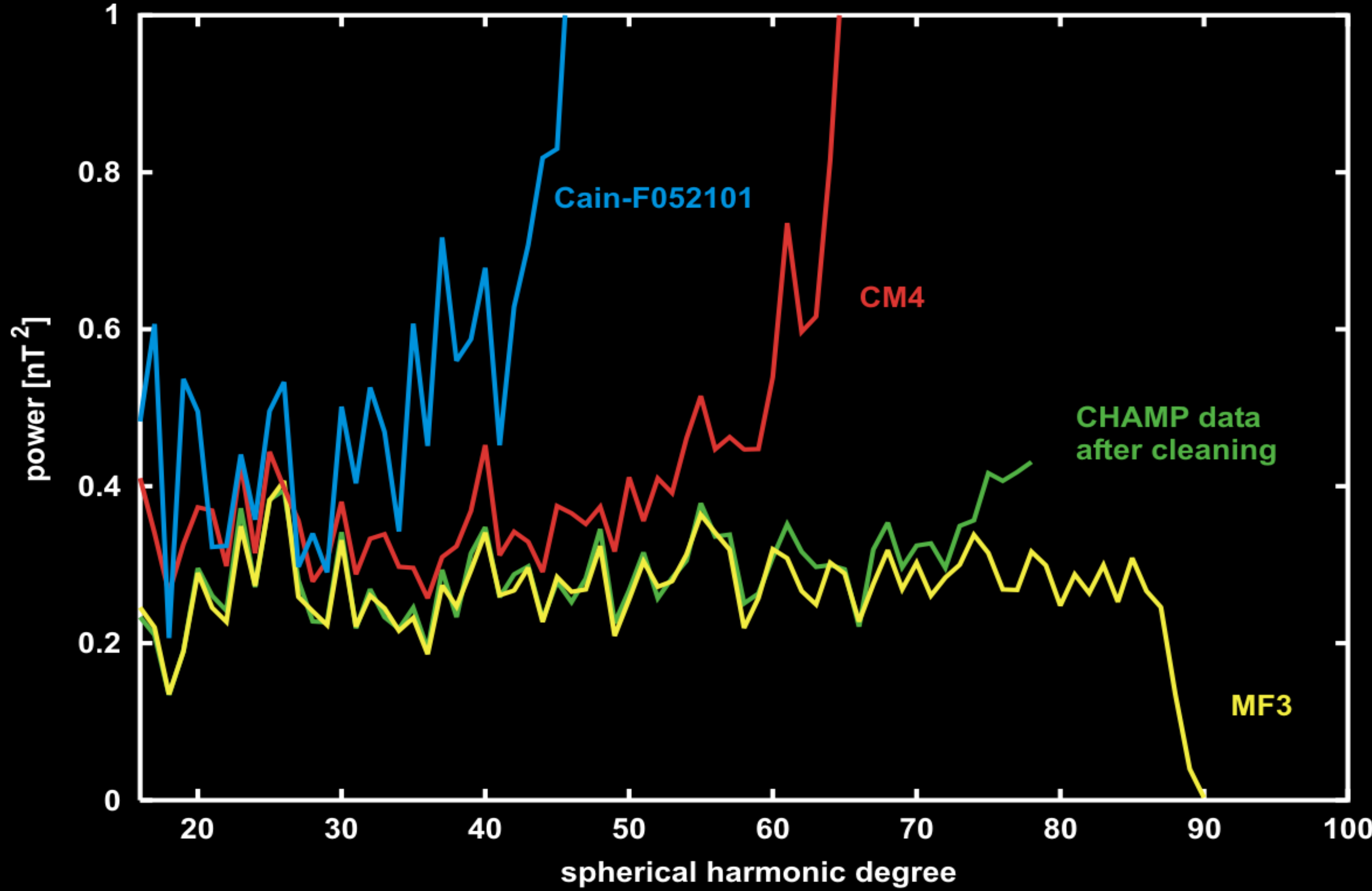
Magnetic field intensity

+

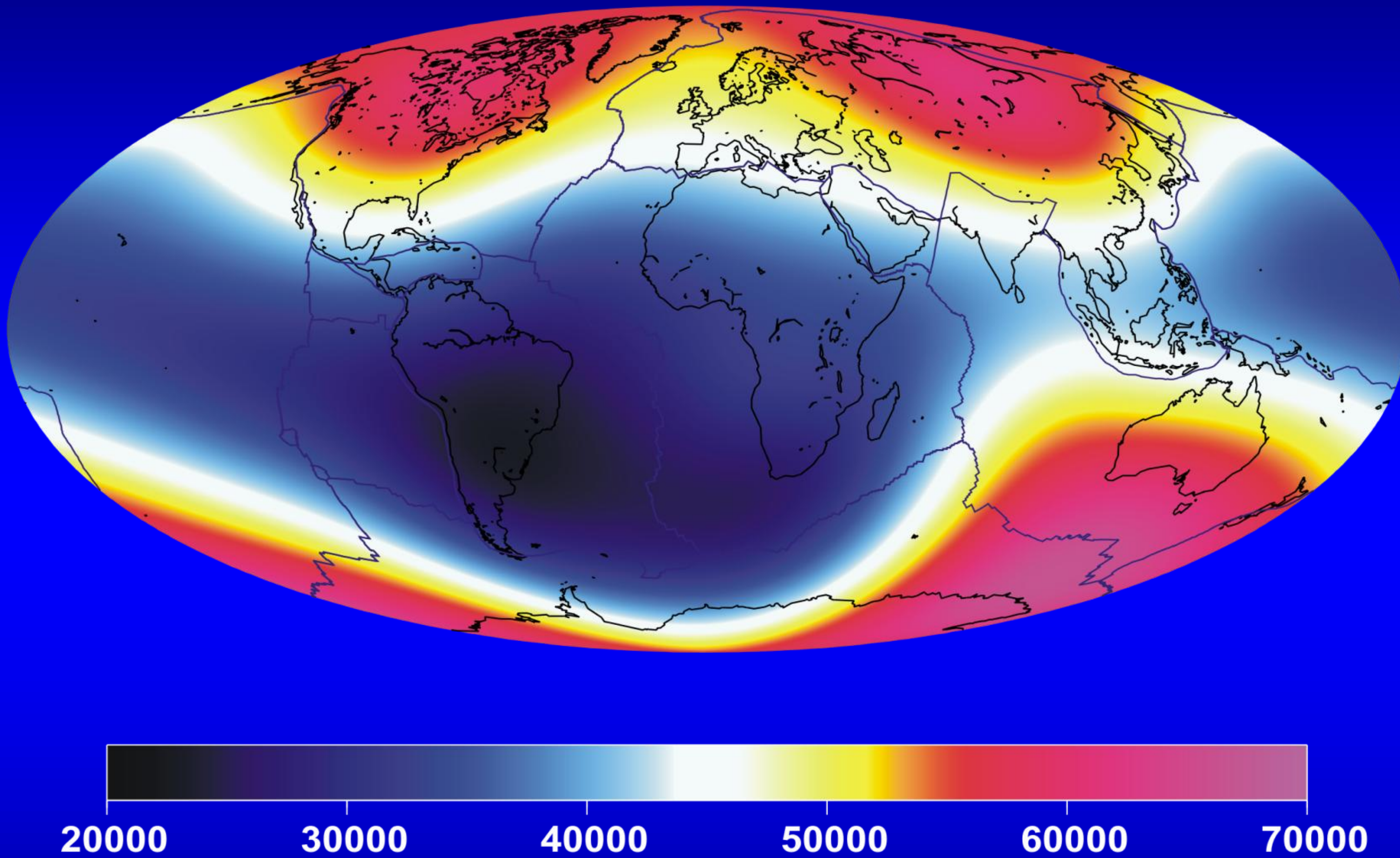
Components of megnetic field vector

GFZ POTSDAM

Improvement since Magsat



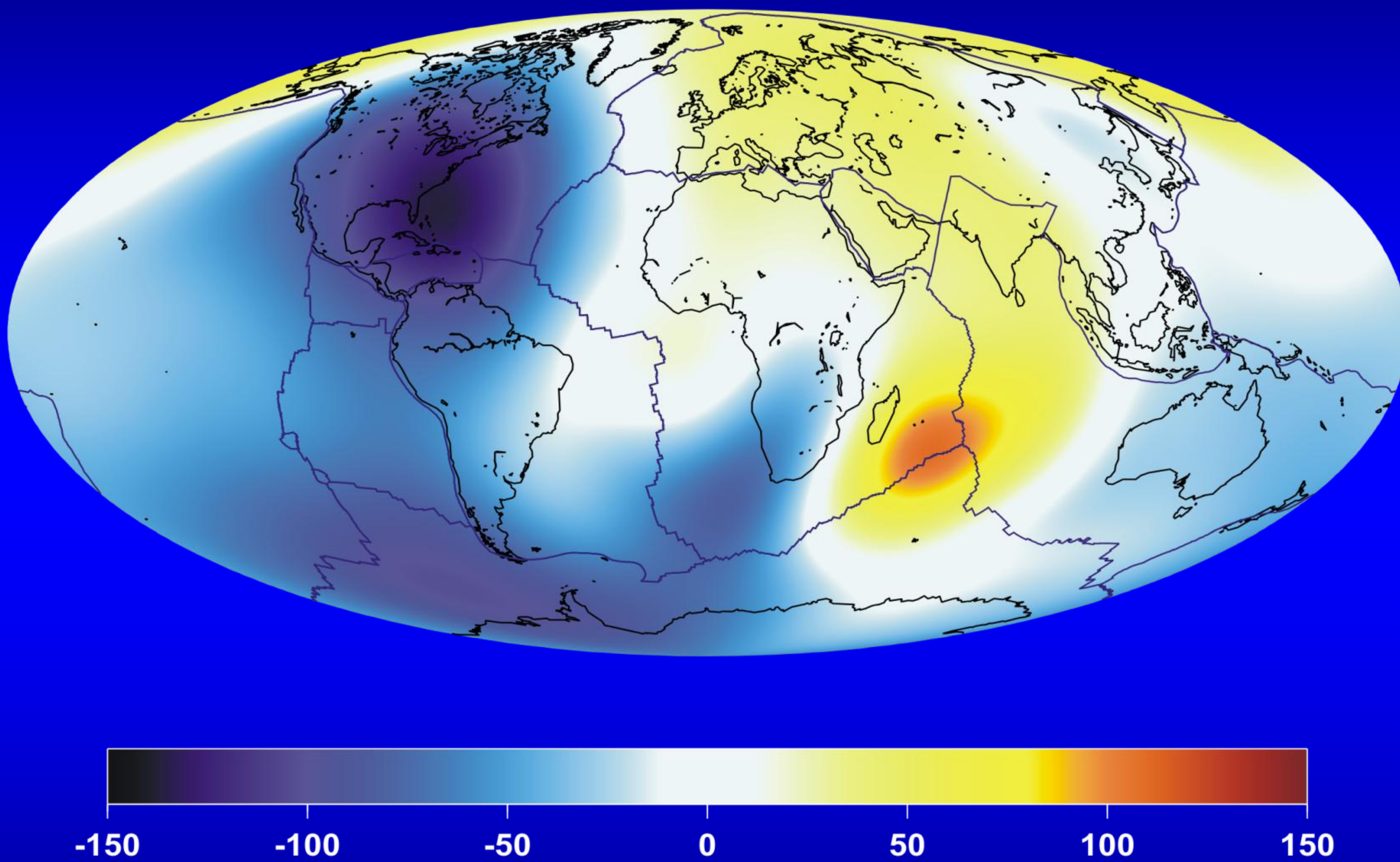
CHAMP: Main Magnetic Field Strength in 2002



Total intensity on Earth surface [nT]

GFZ POTSDAM

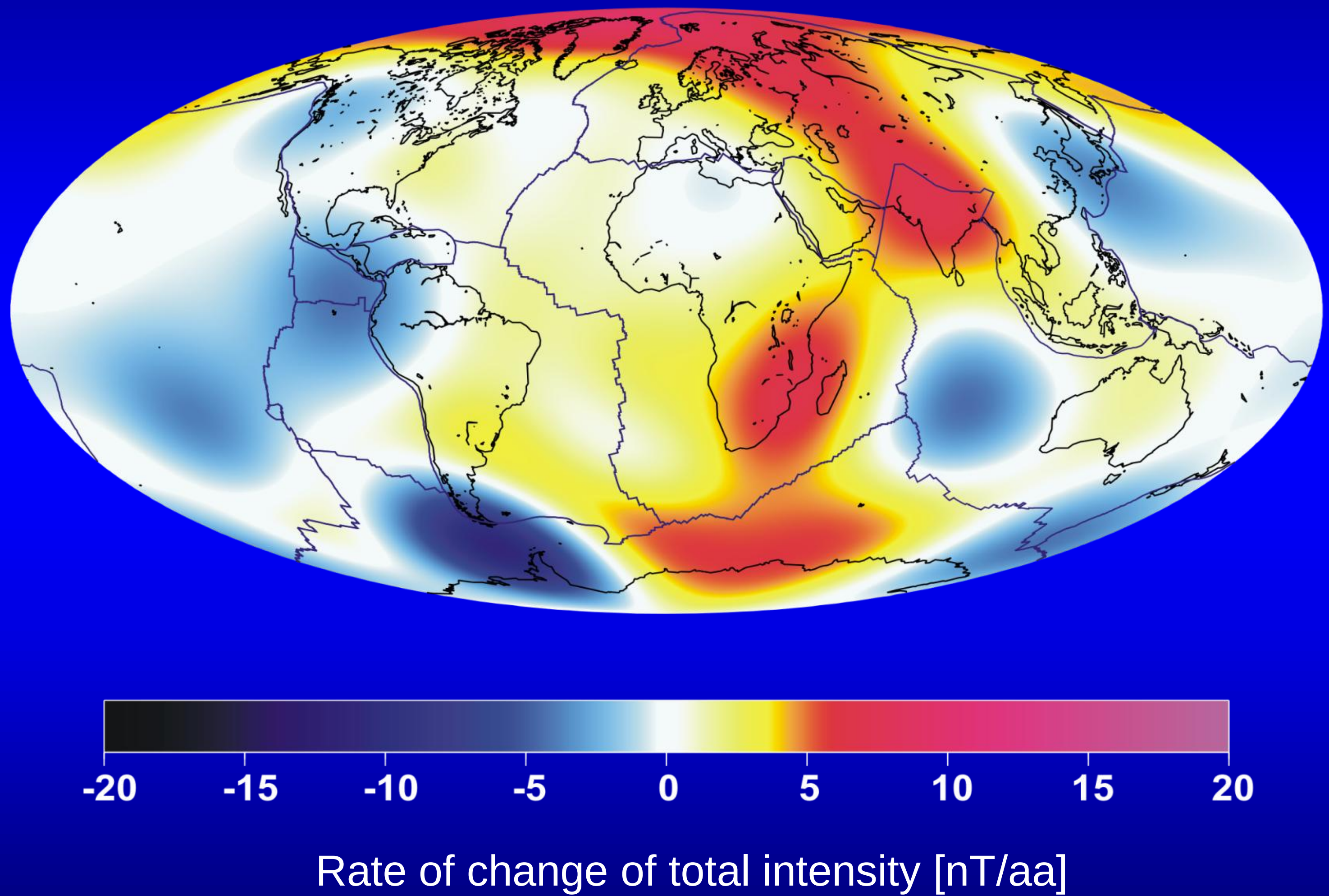
CHAMP: Secular change in strength in 2002



Change in total intensity [nT/a]

GFZ POTSDAM

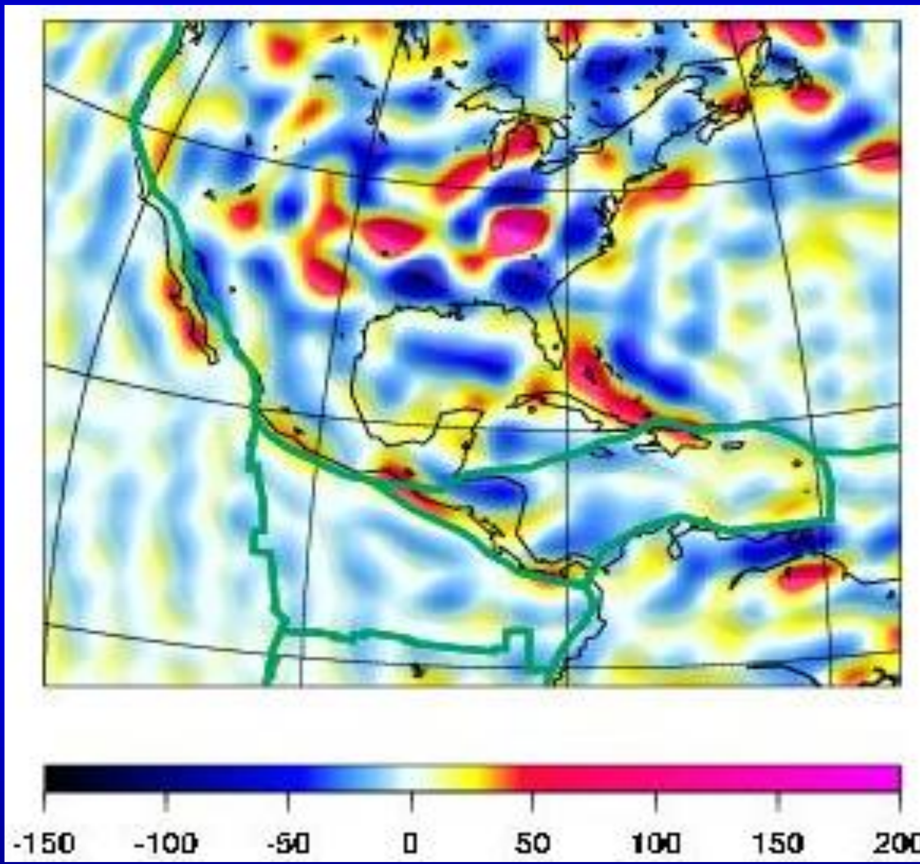
CHAMP: Change in secular variation, 2002



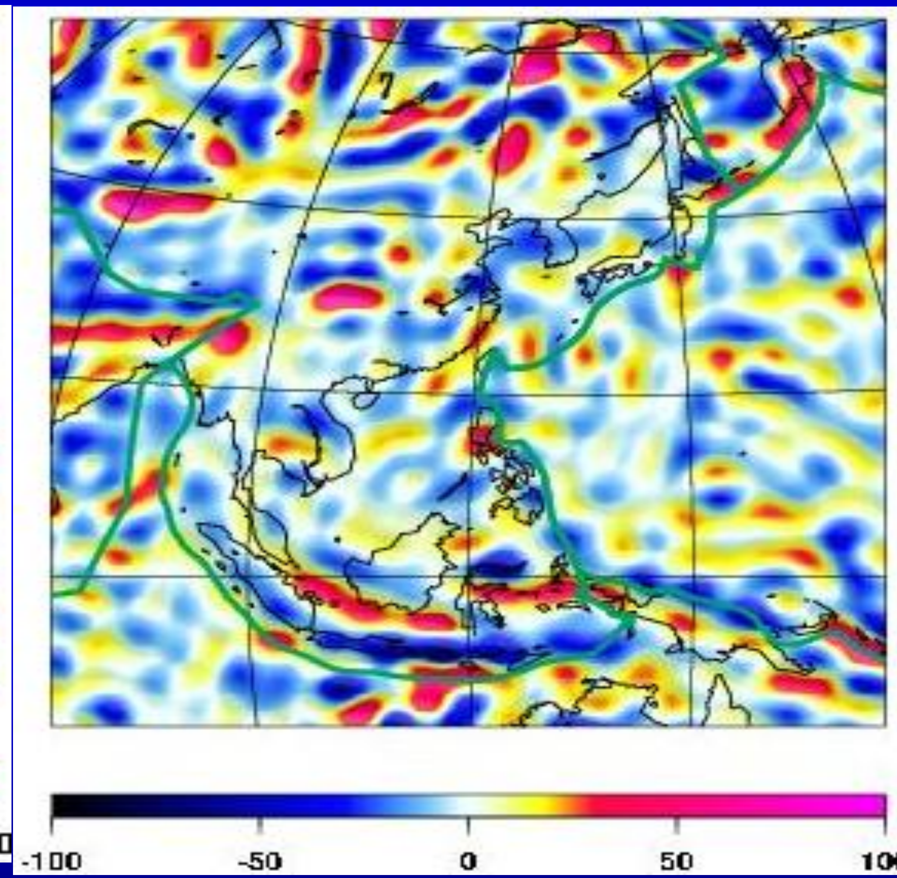
GFZ POTSDAM

Model anomaly maps of Bz at 50 km altitude above the reference sphere

Mittelamerika



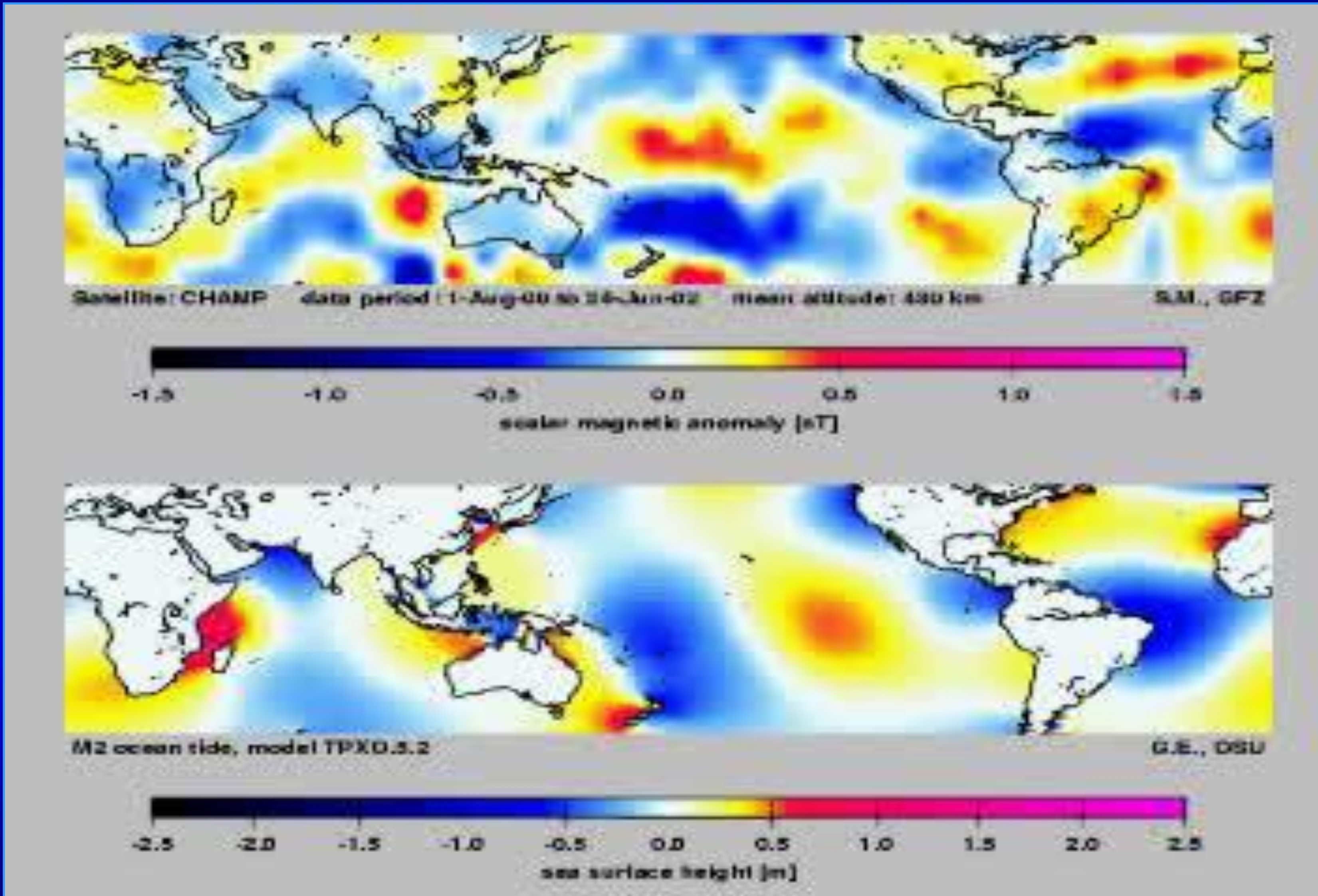
Südostasien



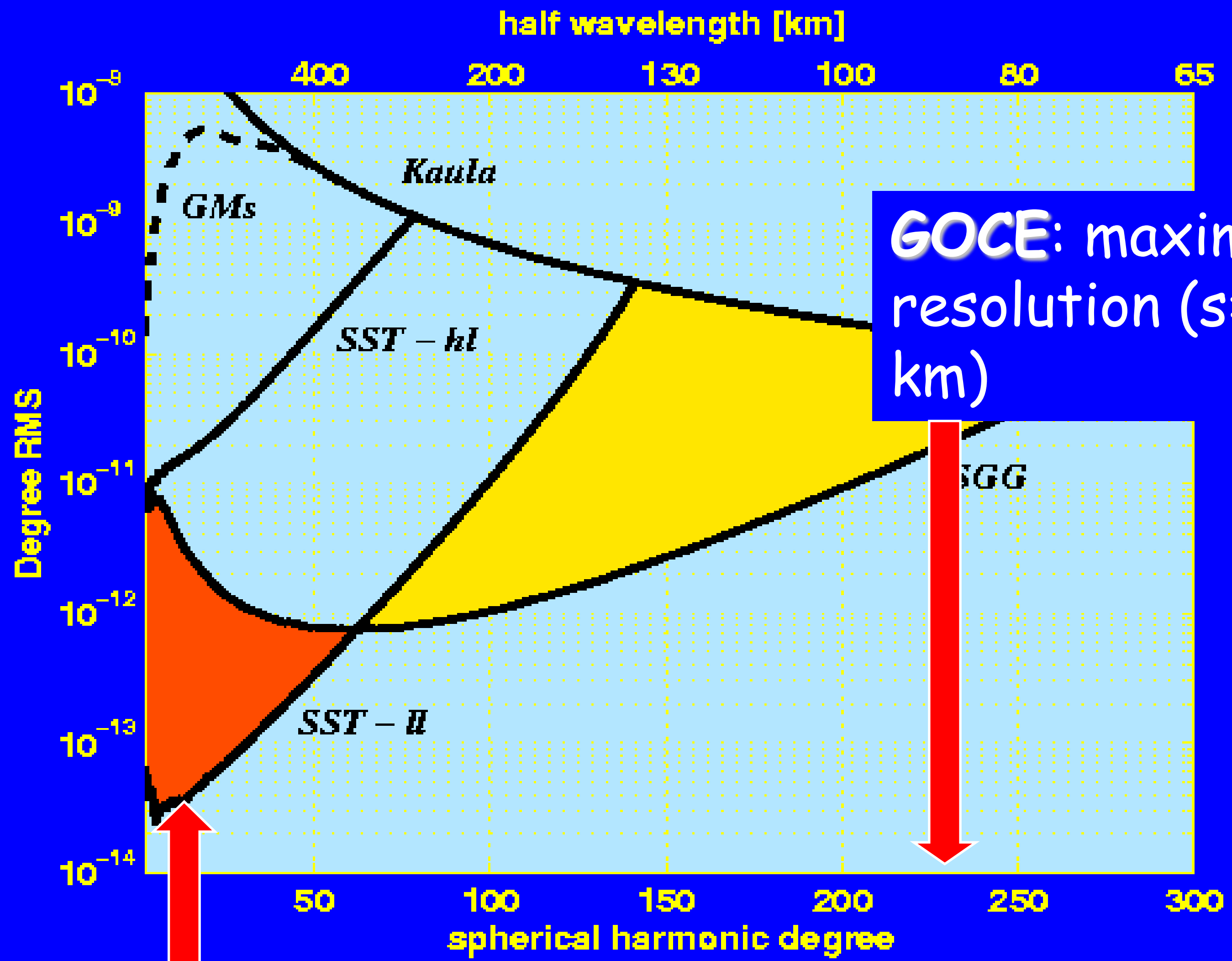
B_2 in 50 km Höhe [nT]

GFZ
POTSDAM

M2 Tide induced Magnetic Field Variations Observed by CHAMP Satellite



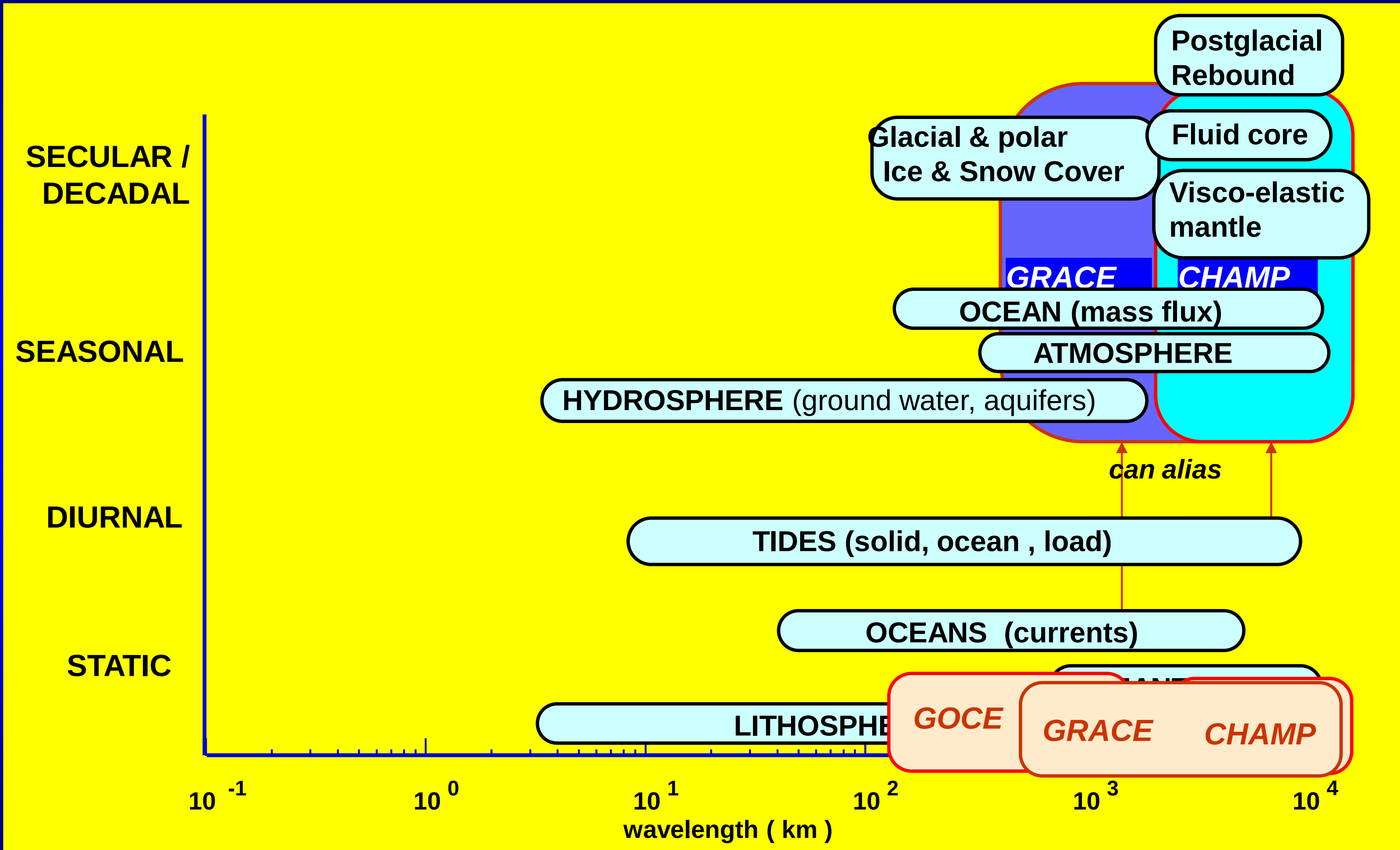
GFZ POTSDAM



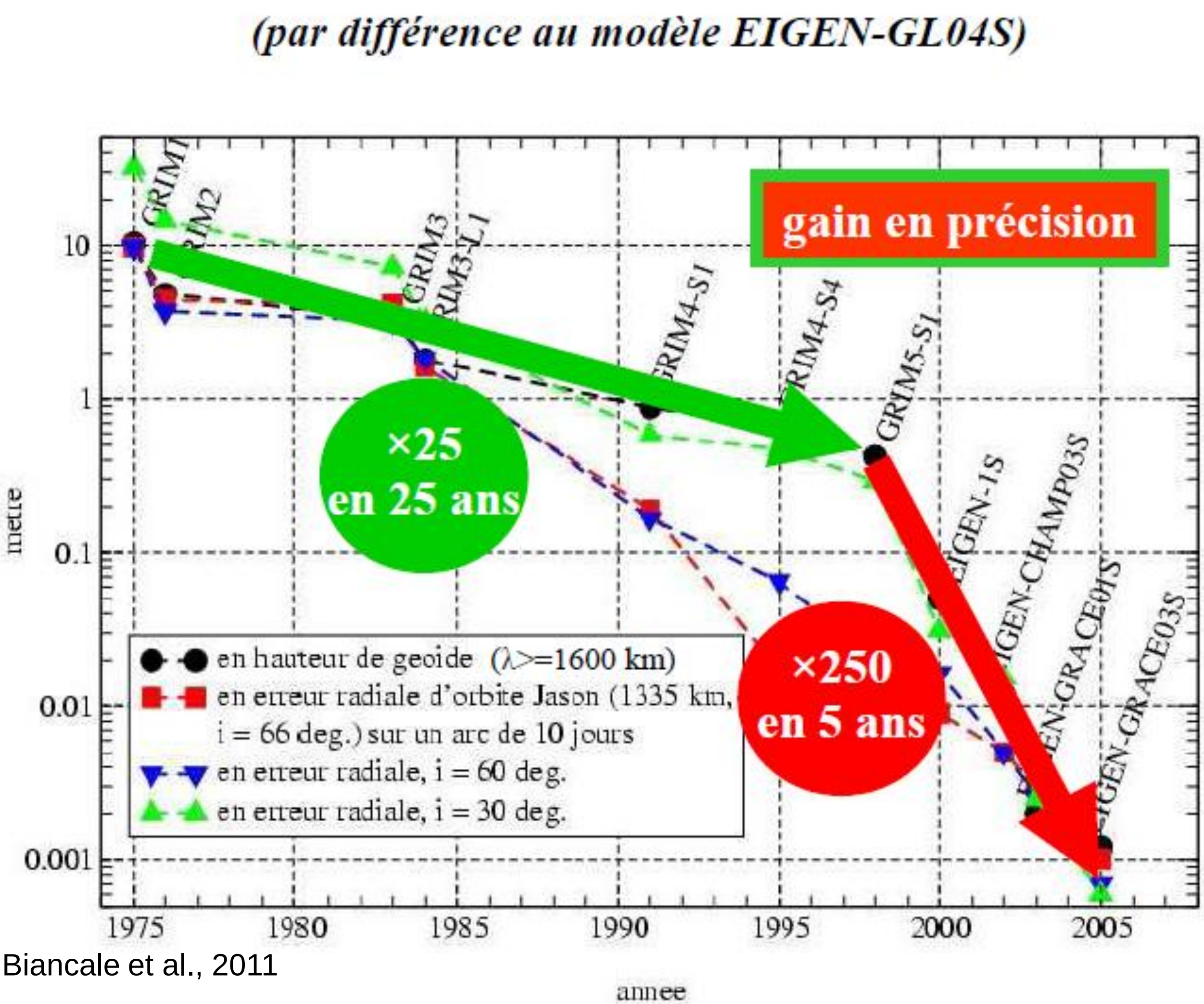
GOCE: maximum resolution (s= 80 km)

GRACE: maximum precision (geoid < µm)

Signals Producing Temporal Gravity Changes



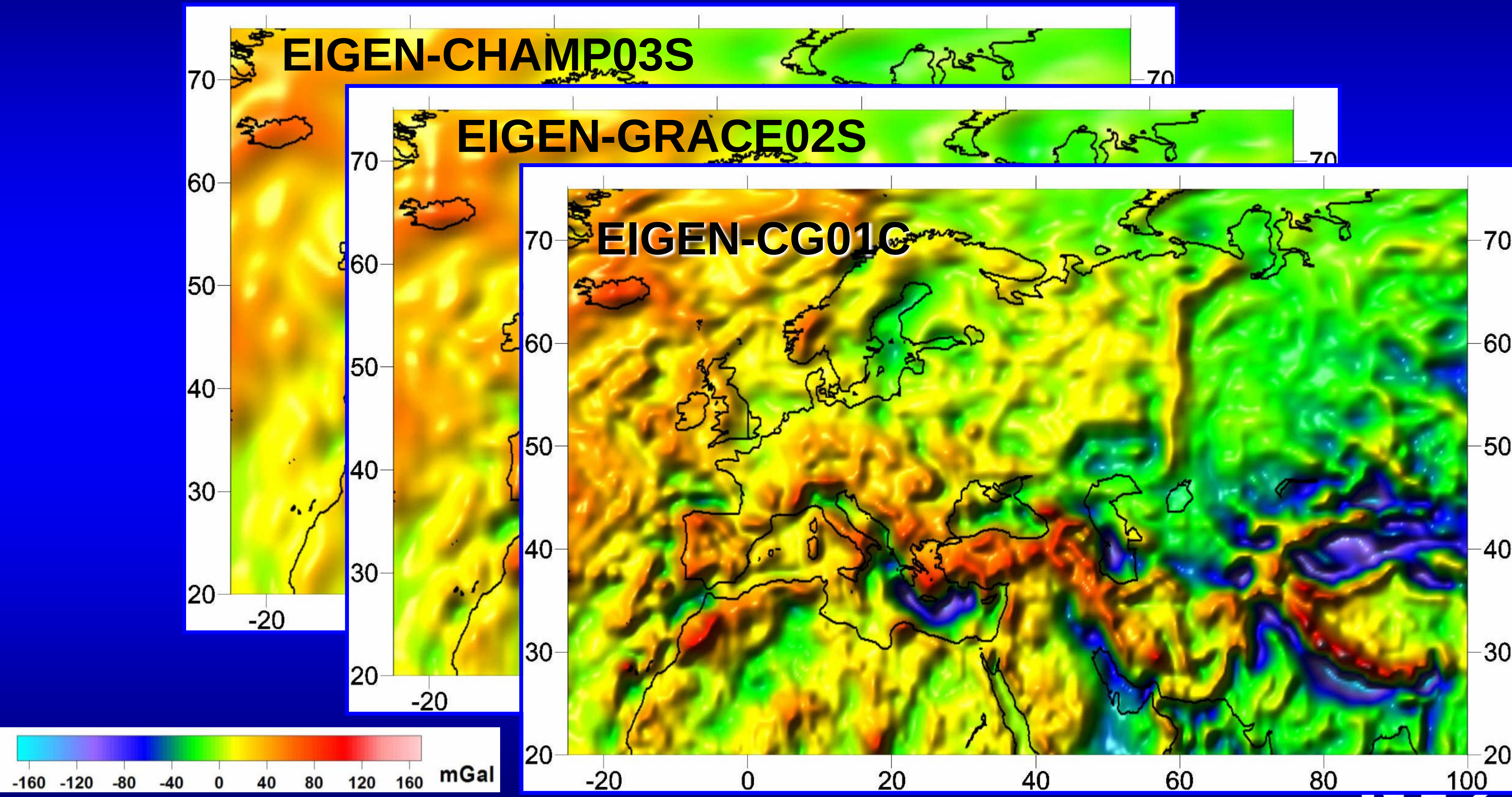
GFZ/GRGS gravity model improvements over time (GRIM and EIGEN models)



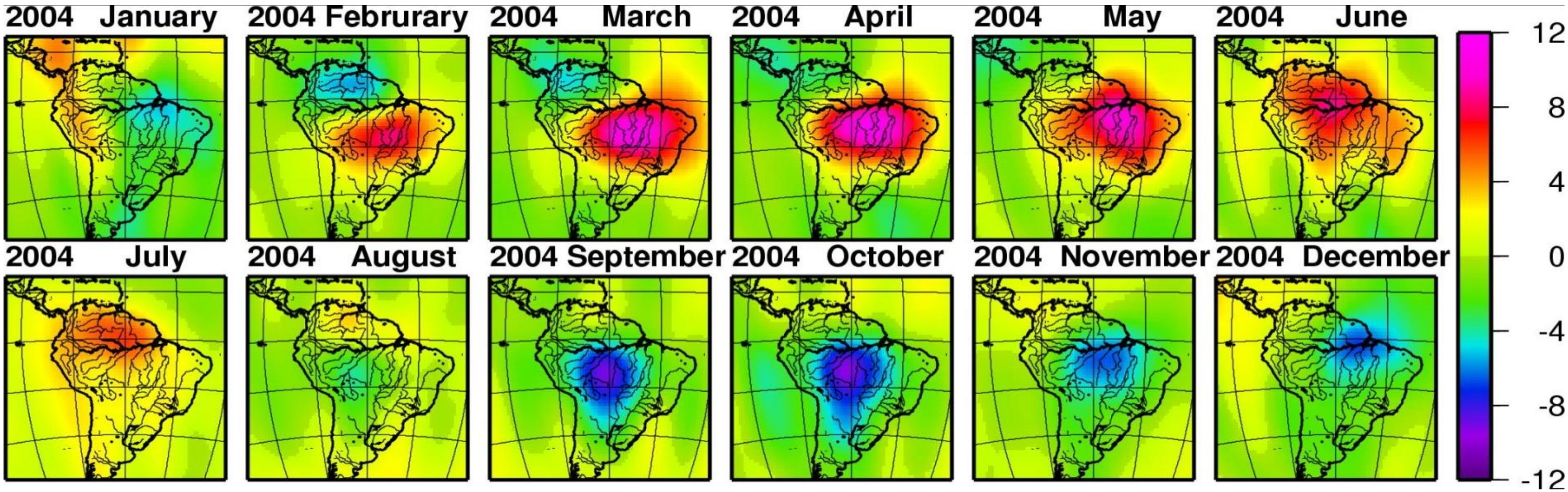
Source Biancale et al., 2011

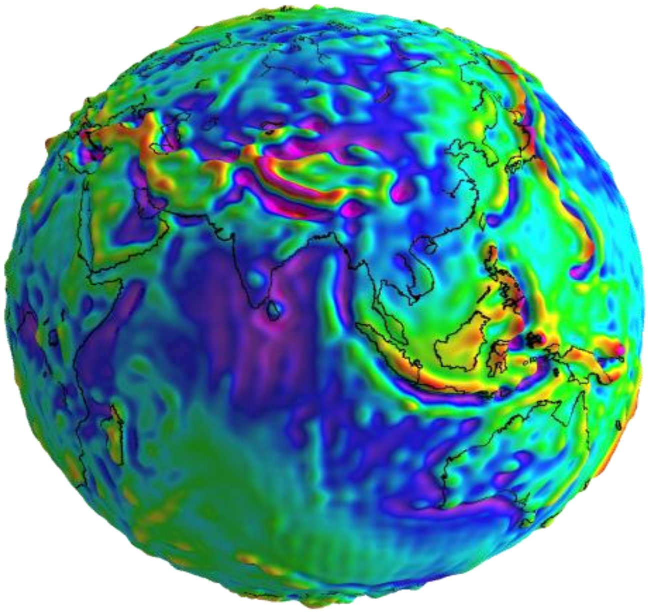
GFZ POTSDAM

Gravity over Europe as Seen by Different Missions



GRACE Gravity Field Models





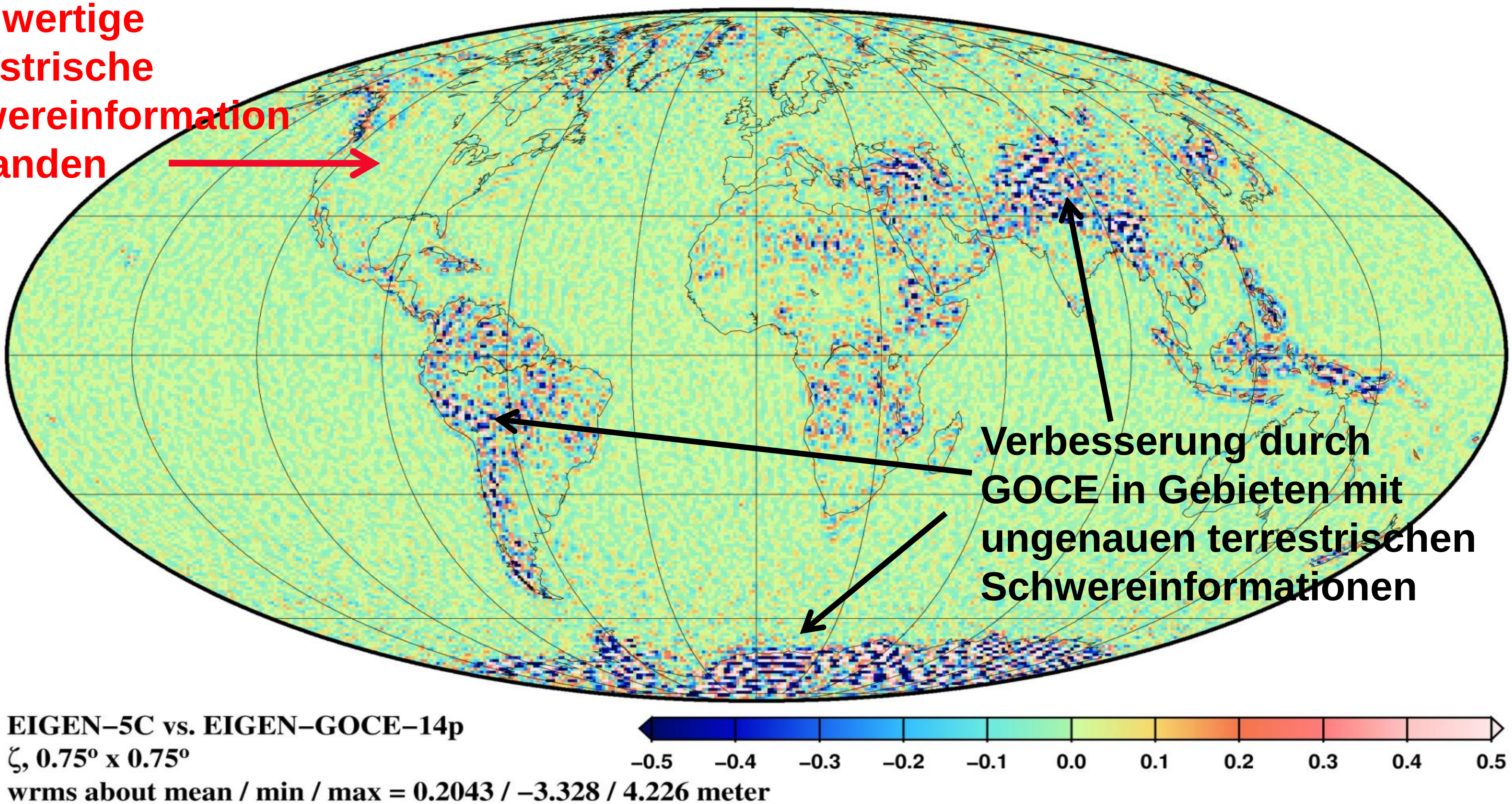
- 100+ monthly gravity field models between April 2002 and December 2010 with 167/333 km resolution
- Static (mean) satellite-only and combined (with terrestrial data) gravity models with 55km resolution
- GRACE gravity fields provide information on mass transport and mass distribution in the system Earth → breakthroughs in the understanding of changes in Earth system components

First GOCE Results (Bergen, ESA EO Symposium)

Förste et al., 2010

Geoid height differences EIGEN-GOCE14p und EIGEN-5C (GRACE)

Hochwertige Terrestrische Schwereinformation vorhanden



Verbesserung durch GOCE in Gebieten mit ungenauen terrestrischen Schwereinformationen

Combination scheme of EIGEN-6C

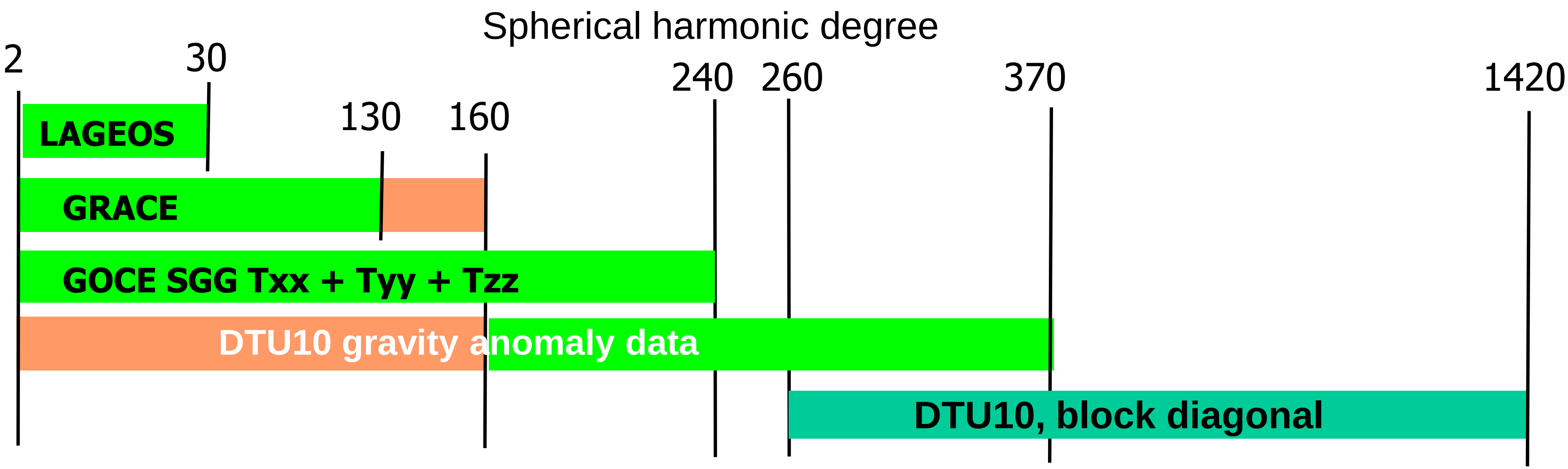
Accumulation of a full normal matrix up to d/o 370:

~200.000 parameters, ~ 250 GByte

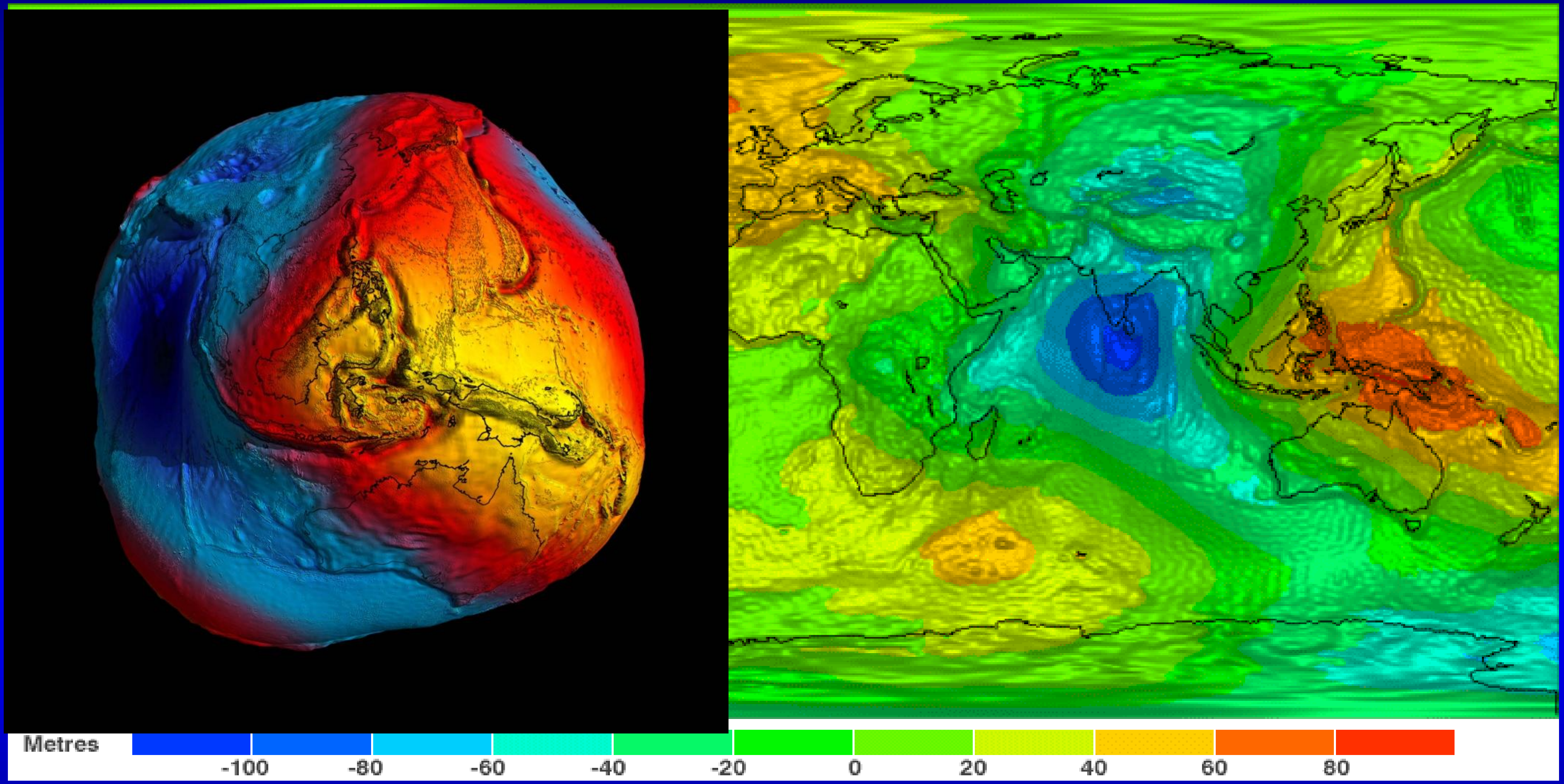
contribution to the solution:

kept separately:

Separate block diagonal solution:

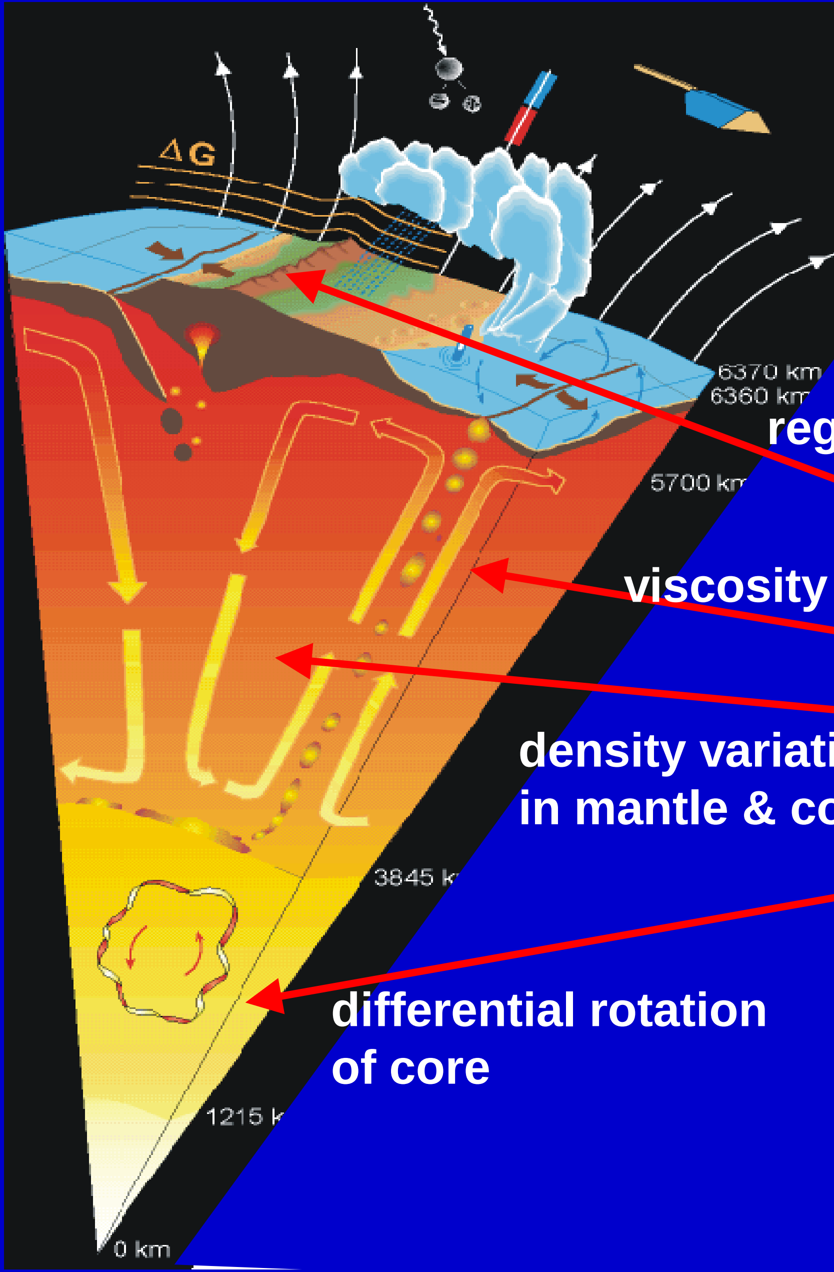


Recent Results from GOCE Symposium/Workshop



GOCE Geoid

CHAMP-GRACE -GOCE & Solid Earth Physics



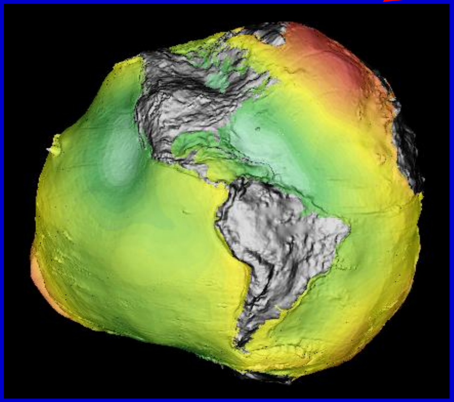
regional structures & post-glacial rebound

viscosity distribution & mantle convection

density variations in mantle & core

differential rotation of core

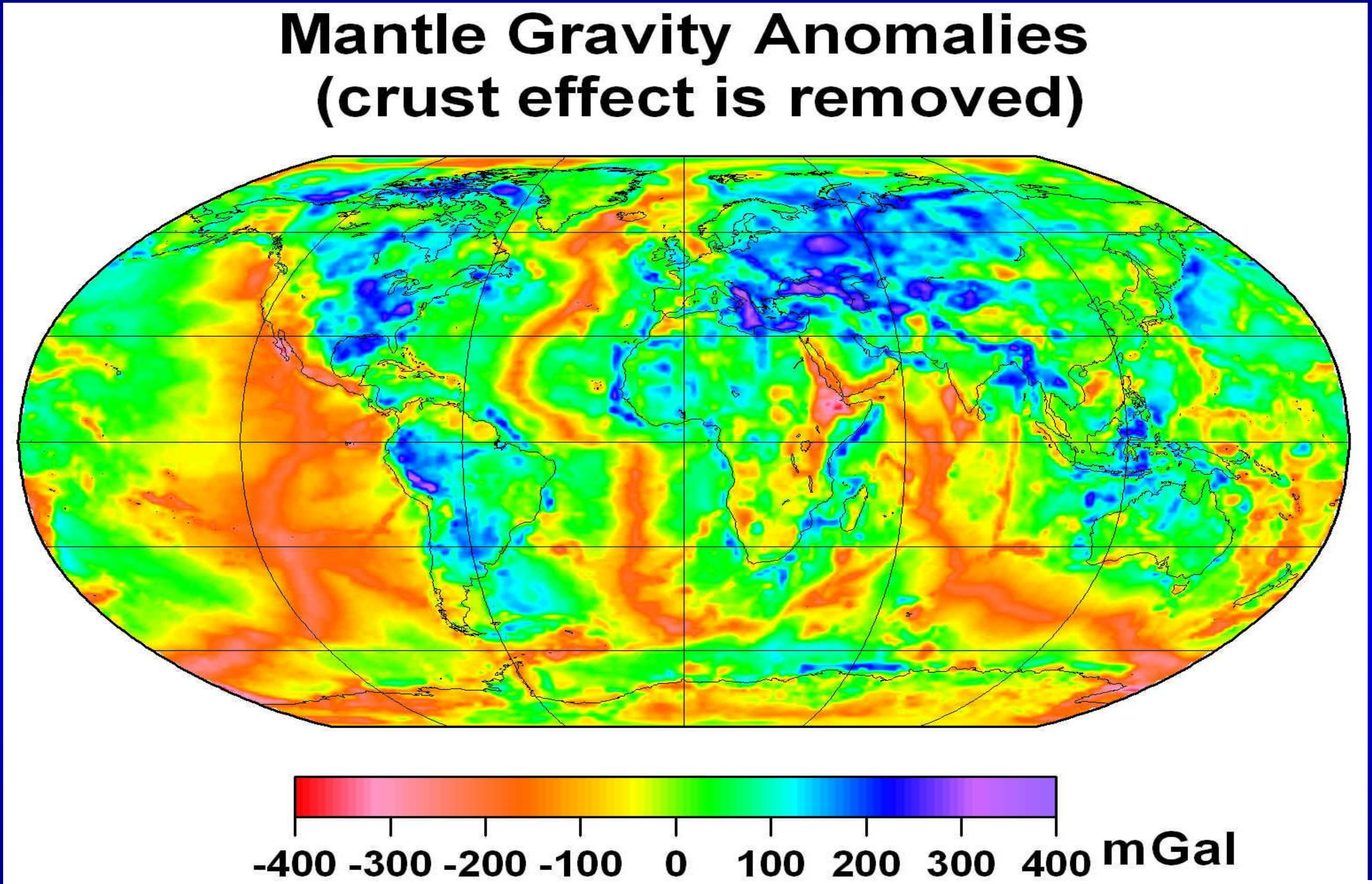
GRACE/GOCE mission impact



precision geoid

GFZ POTSDAM

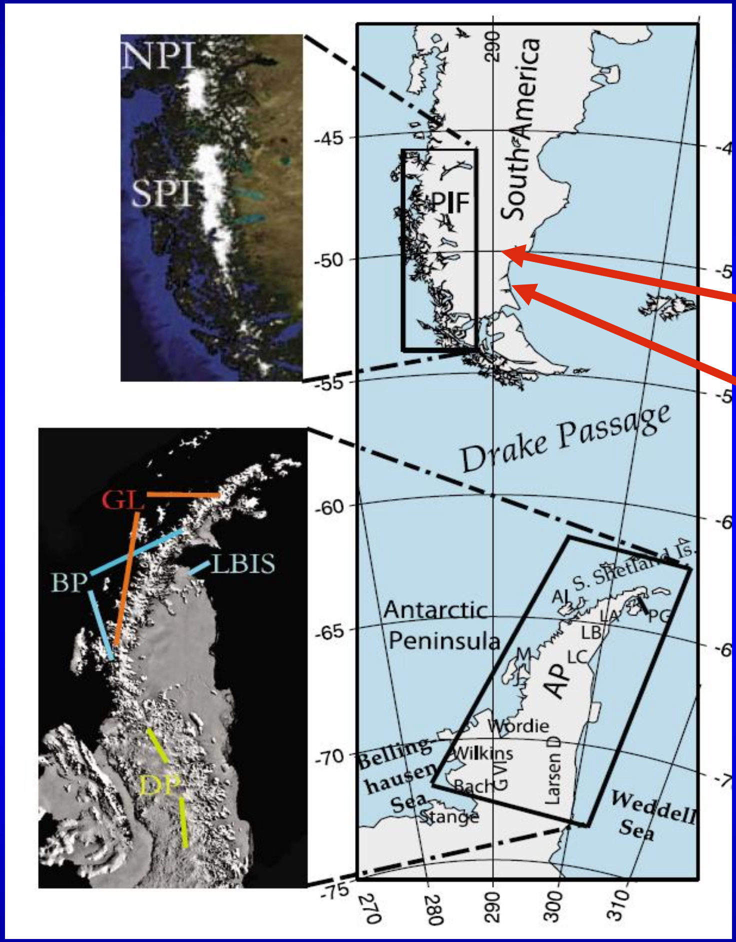
Mantle Gravity Anomalies Derived from GRACE Combination Solution
A Contribution to Modeling the Earth Interior

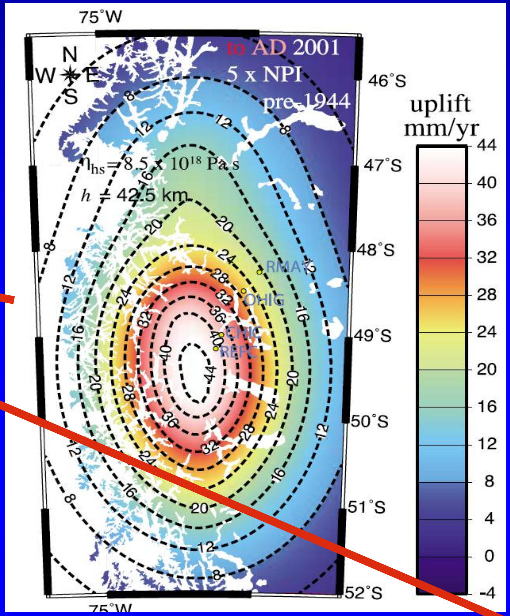


Satellite Positioning Me... ...w University

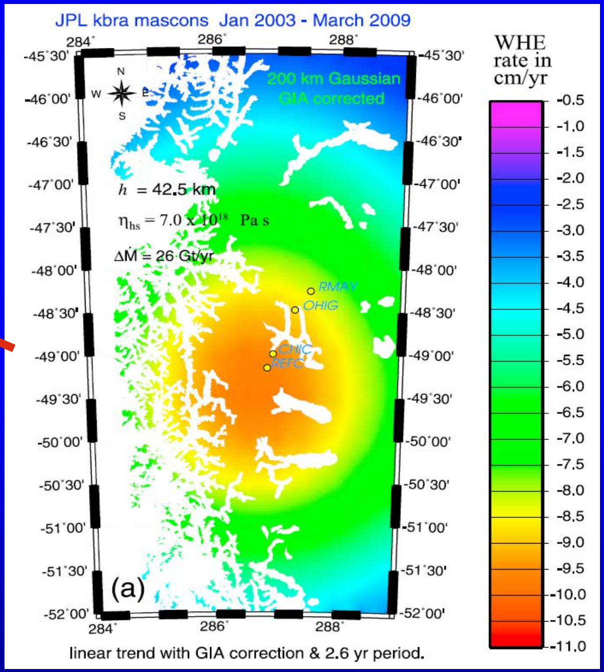
Recent results from the GRACE mission
- solid Earth -

Glacial isostatic adjustment (response to past melting) from GRACE





ICE5G/IJ05/VM2

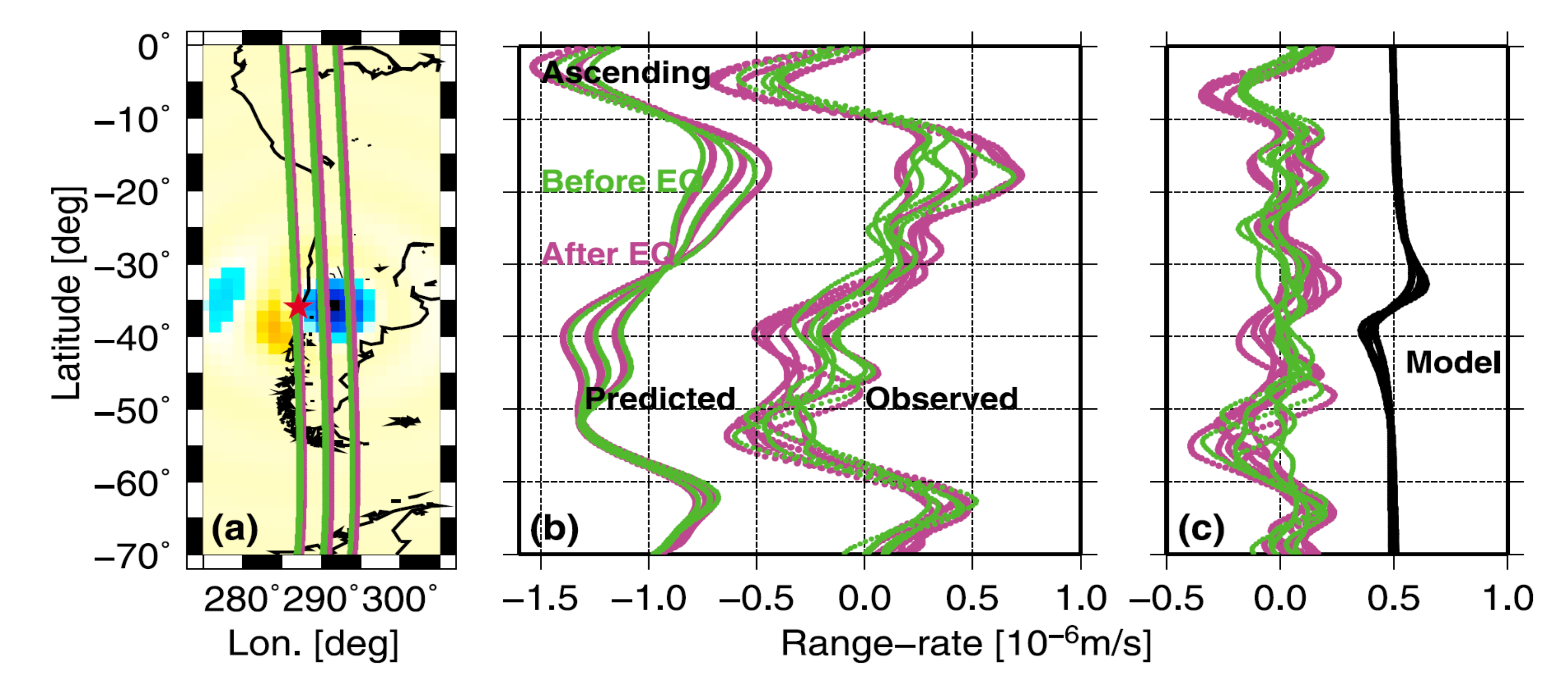


Ivins et al. in JGR (2011) reconstruct glacier ice mass loss and GIA effect by adjusting regional Earth parameters (lithosphere thickness, viscosity) to GRACE and GPS uplift.

GFZ
POTSDAM

Recent results from the GRACE mission
- solid Earth -

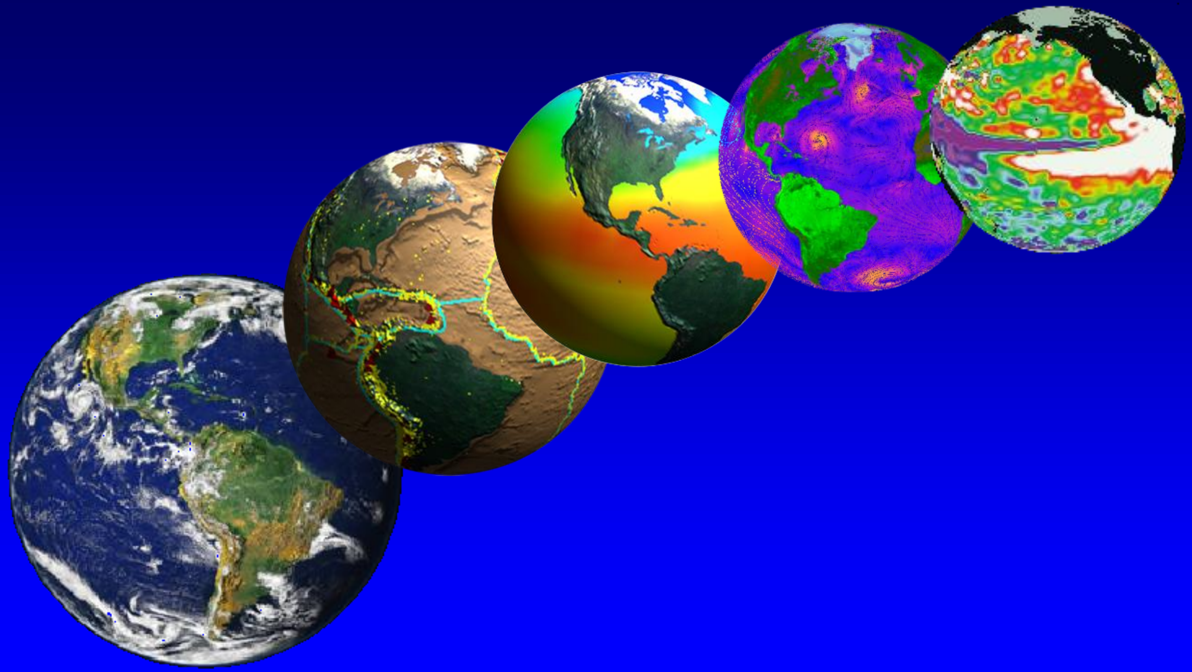
Mass dislocation by large Earthquakes (Chile M8.8 2010)



GRACE observes coseismic gravity effect of the M8.8 2010 Chile Earthquake.

According to **Han et al (2010, GRL),** different fault models may be testable

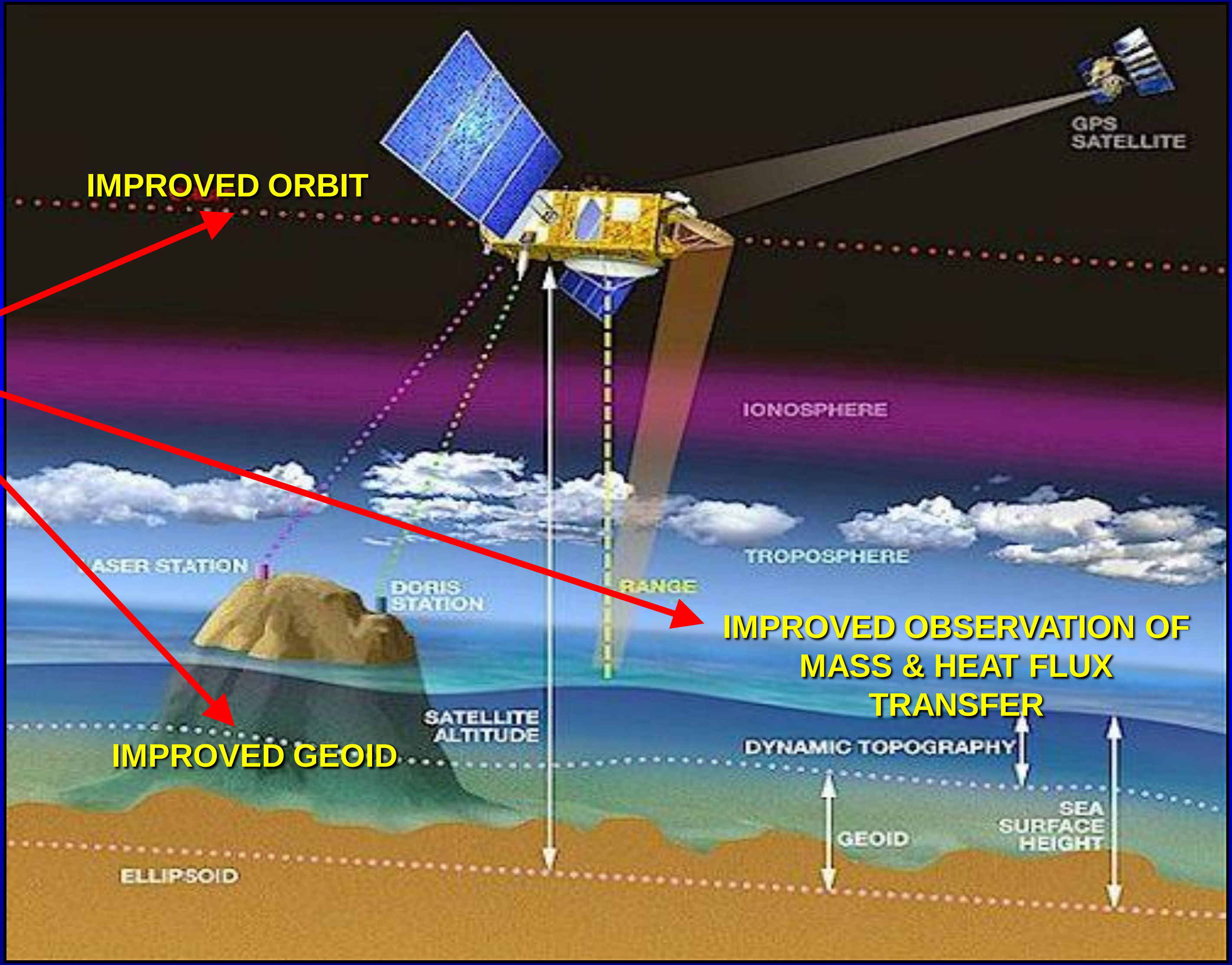
→ Recent papers Panet and Einarsson on postseismic gravity change Sumatra EQ



GRACE/GOCE and Oceanography

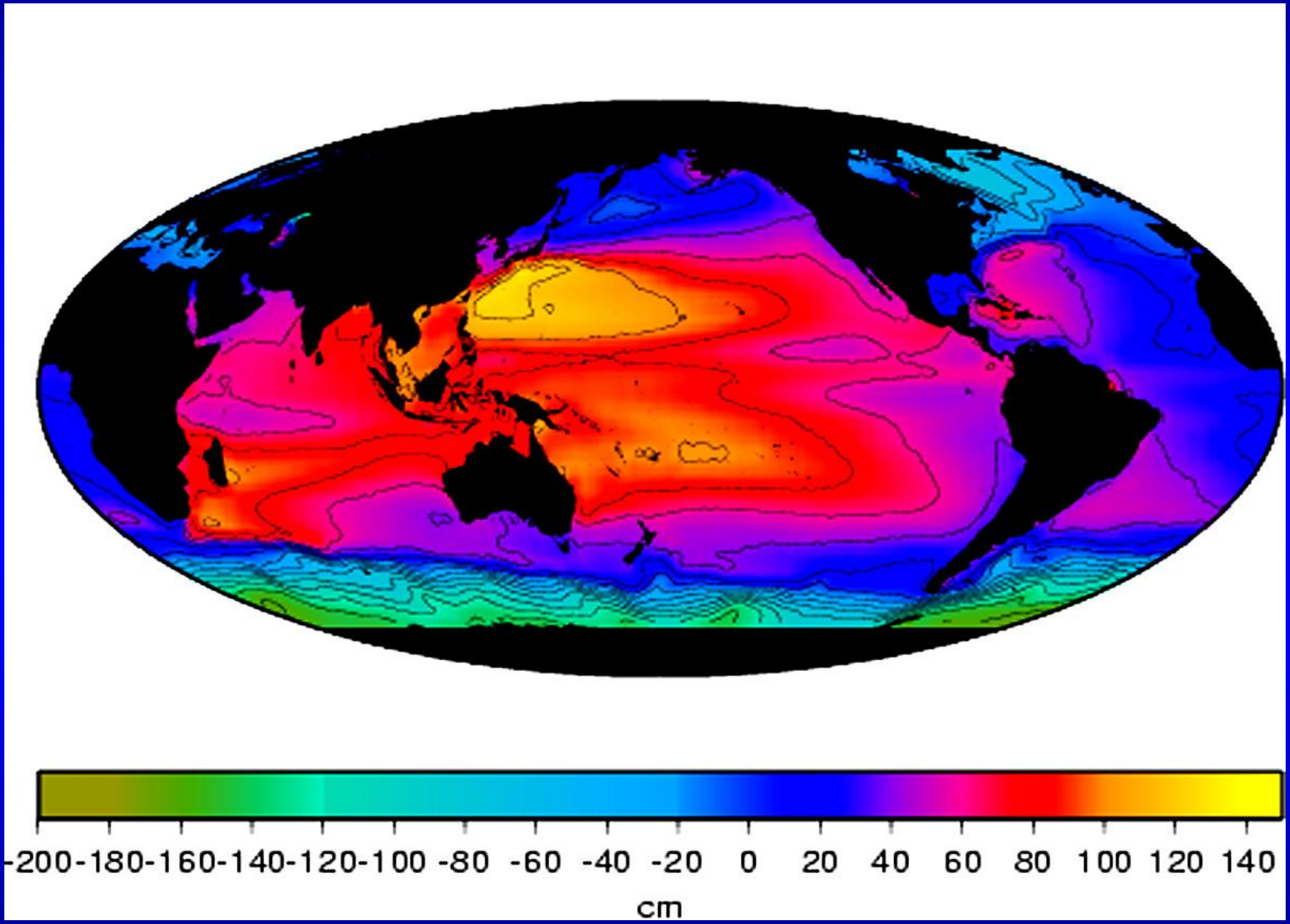
Gravity Missions and Ocean Dynamics

GRACE&GOCE missions impact



Source: CNES

Dynamic Ocean Topography from GRACE Gravity Model



The dynamic ocean topography is the difference between the mean sea surface (observed from altimeter data) and the geoid.

This difference is caused by the ocean currents.

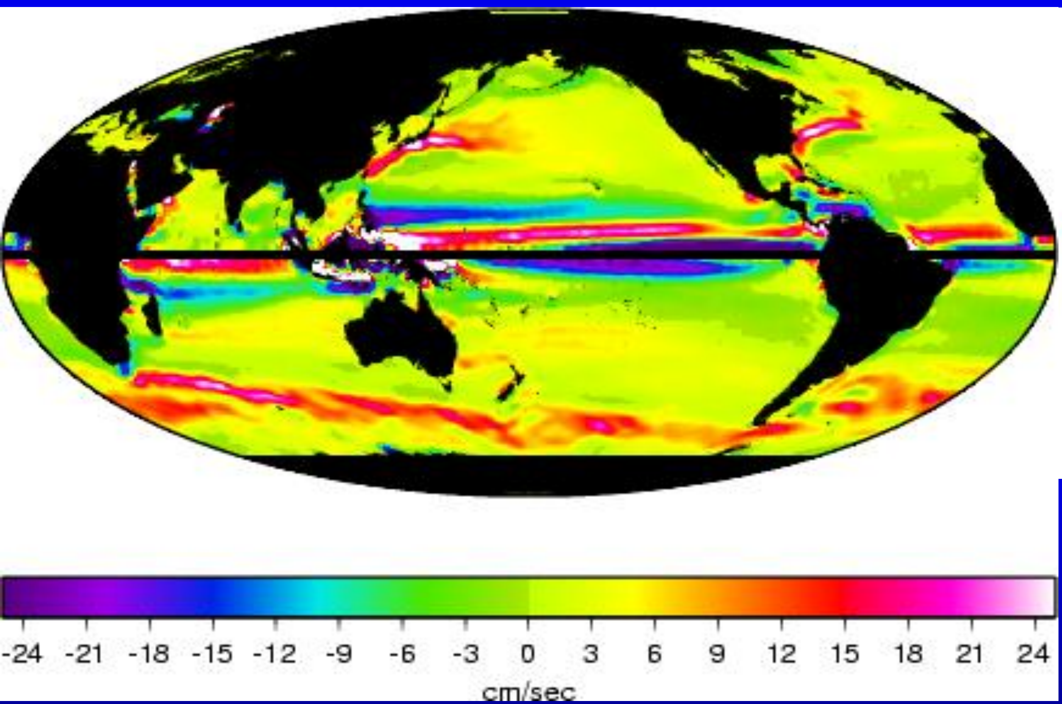
With no currents, the ocean surface would coincide with the geoid.

GFZ POTSDAM

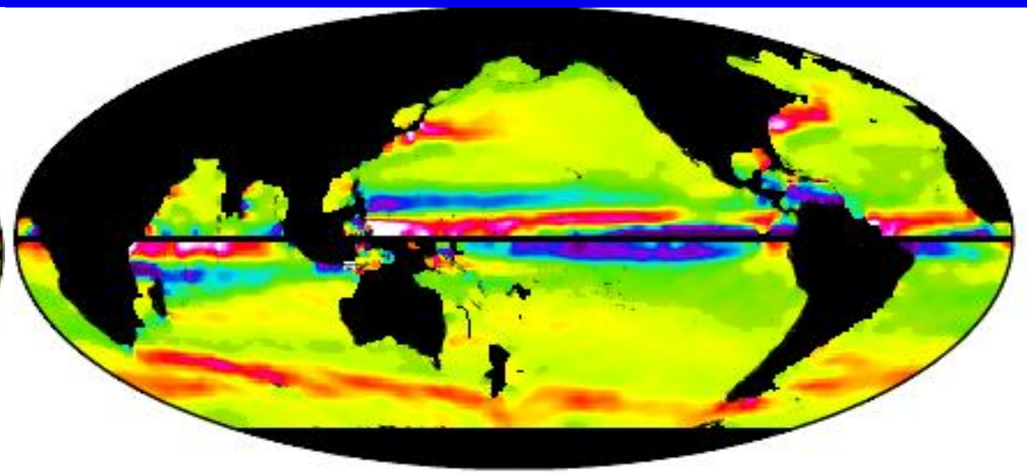
Zonal Circulation Estimates from GRACE and GOCE

East-west currents are much more clearly seen with a GRACE gravity model than with previous models and even better with GOCE models.

Altimeter MSS with GRACE gravity model



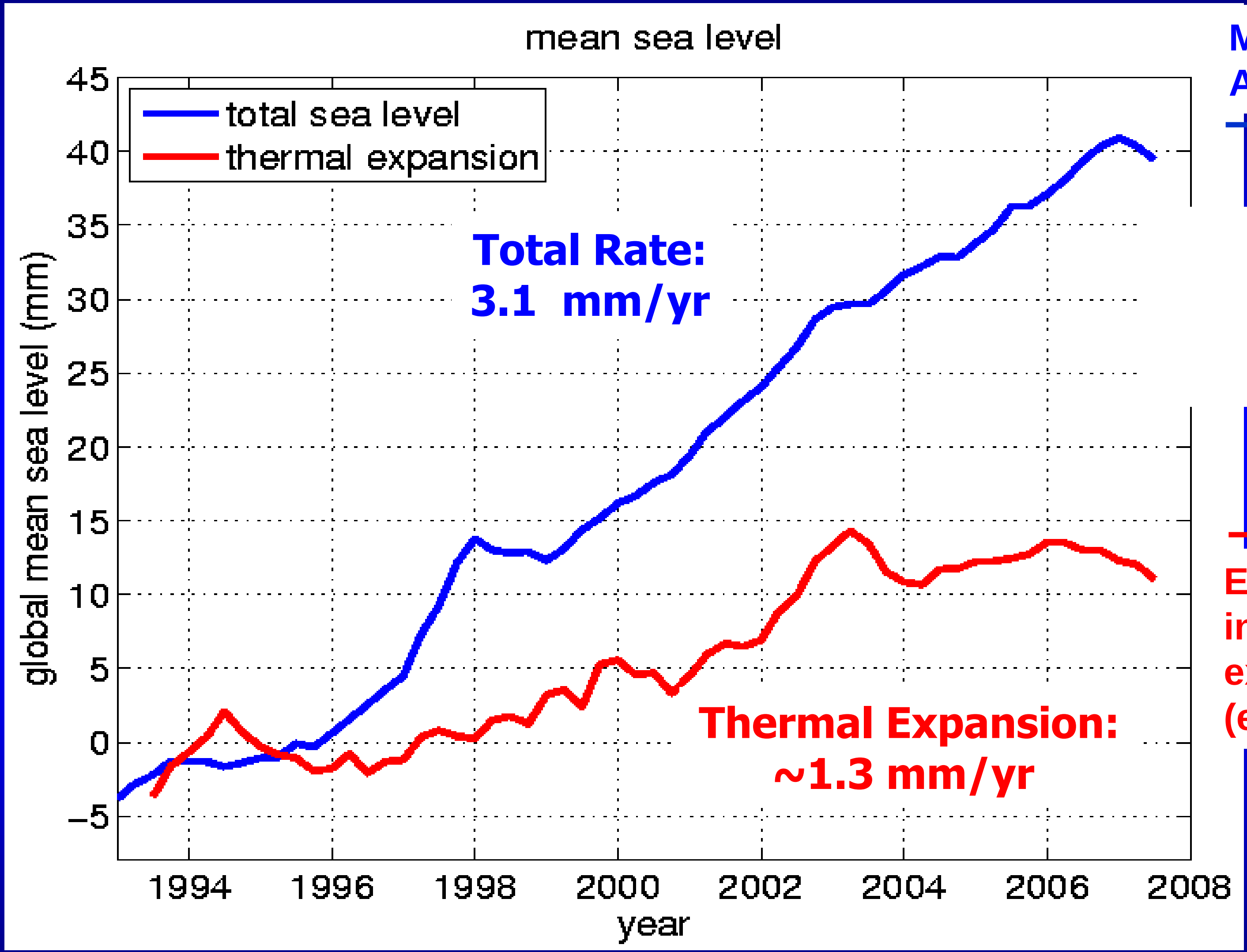
WOA01 Hydrography



Tapley, et al, GRL, 2004

GFZ POTSDAM

Sea level change: dM/dV components



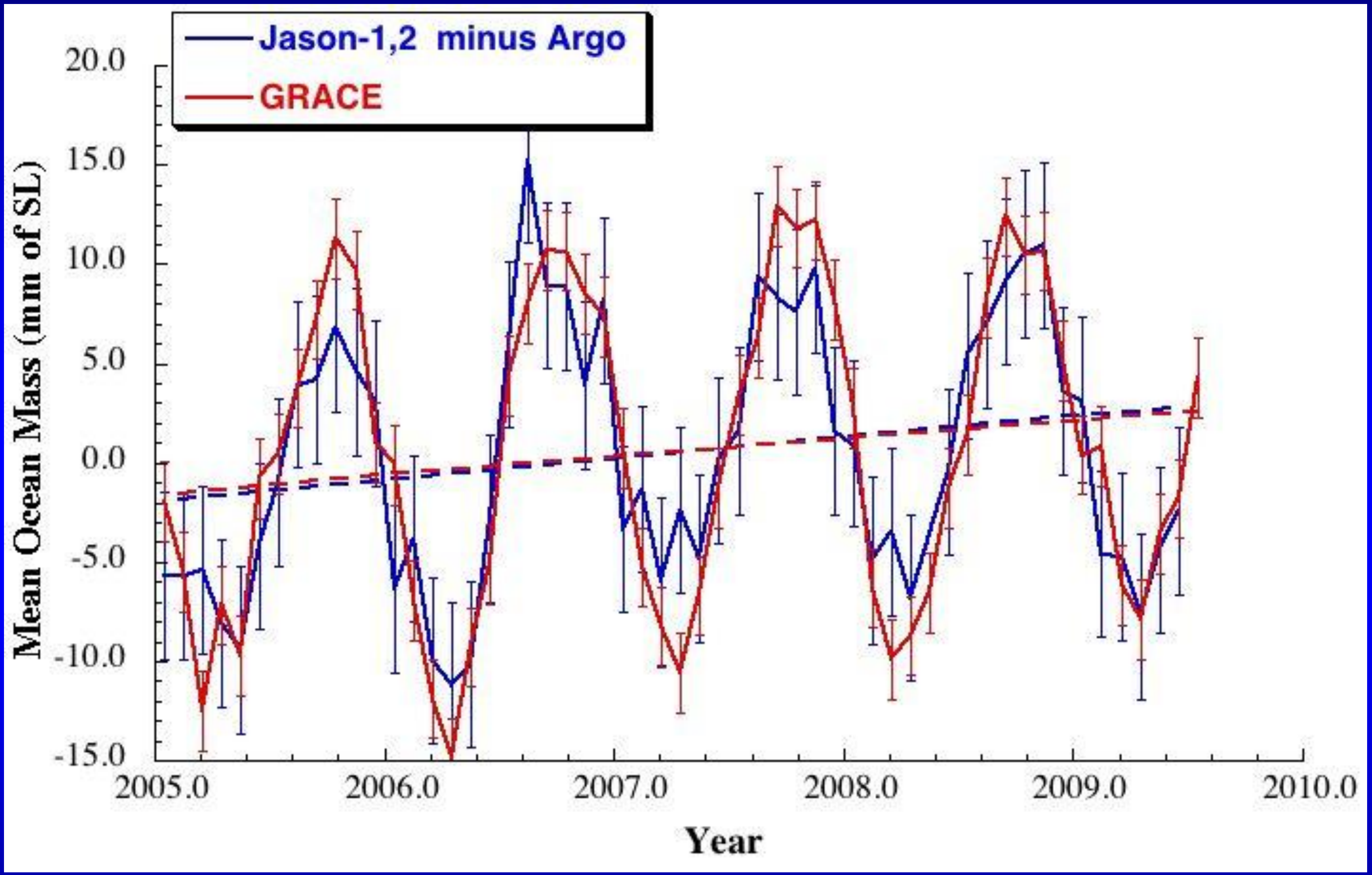
Measured by Altimeters

Most of this Difference is due to melting ice

Estimated change in volume due to thermal expansion (e.g. ARGO Floats)

Courtesy : Josh Willis, JPL

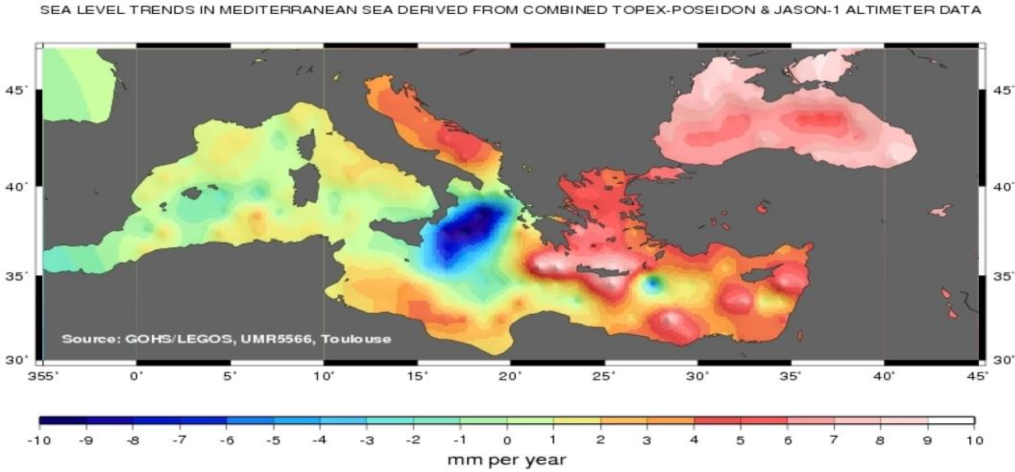
Sea Level Budget 2003 – 2009.5

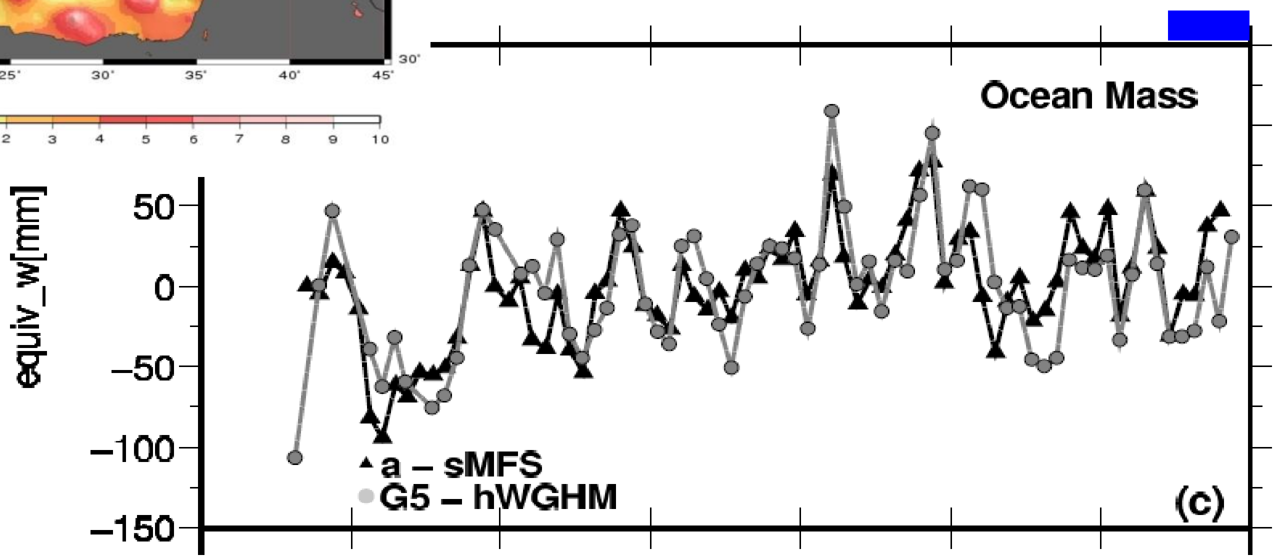


Grace Trend(2003-2009.5) = 1.3 ± 0.8 mm/yr

Recent results from the GRACE mission
- ocean and sea level -

GRACE enables separation of sea level contributions in Med Sea



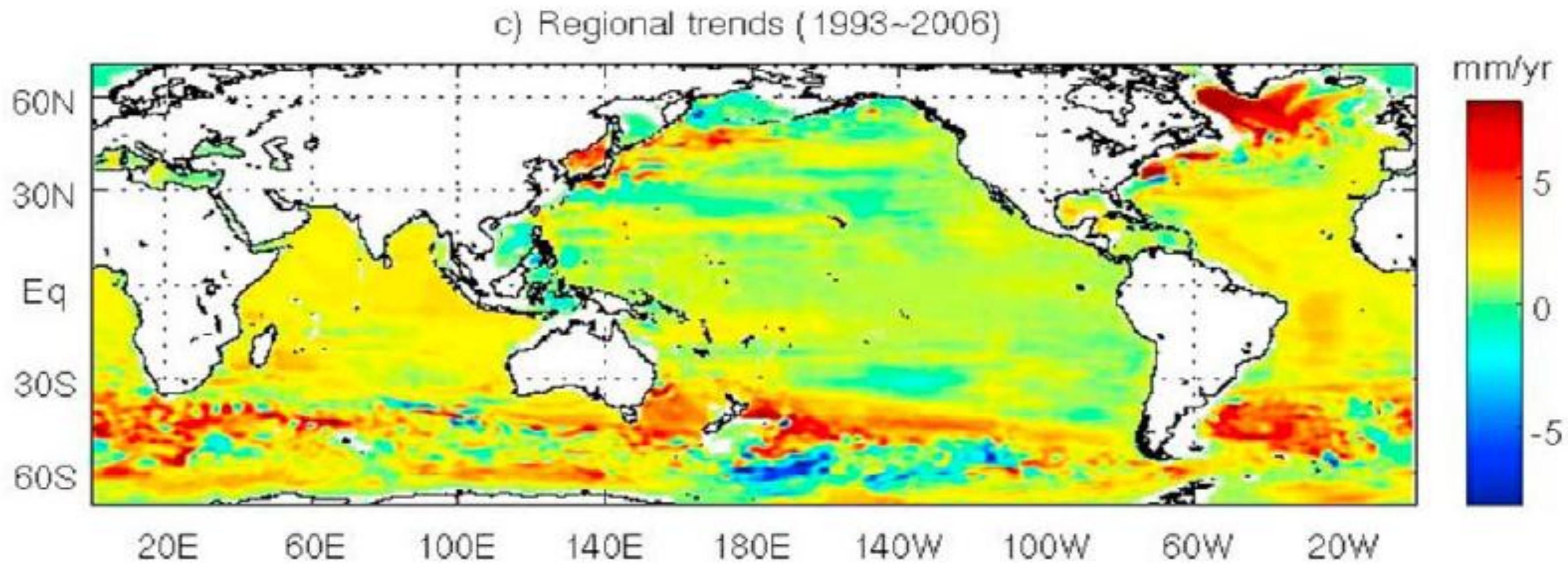


Fenoglio et al (submitted, J. Geodyn.):

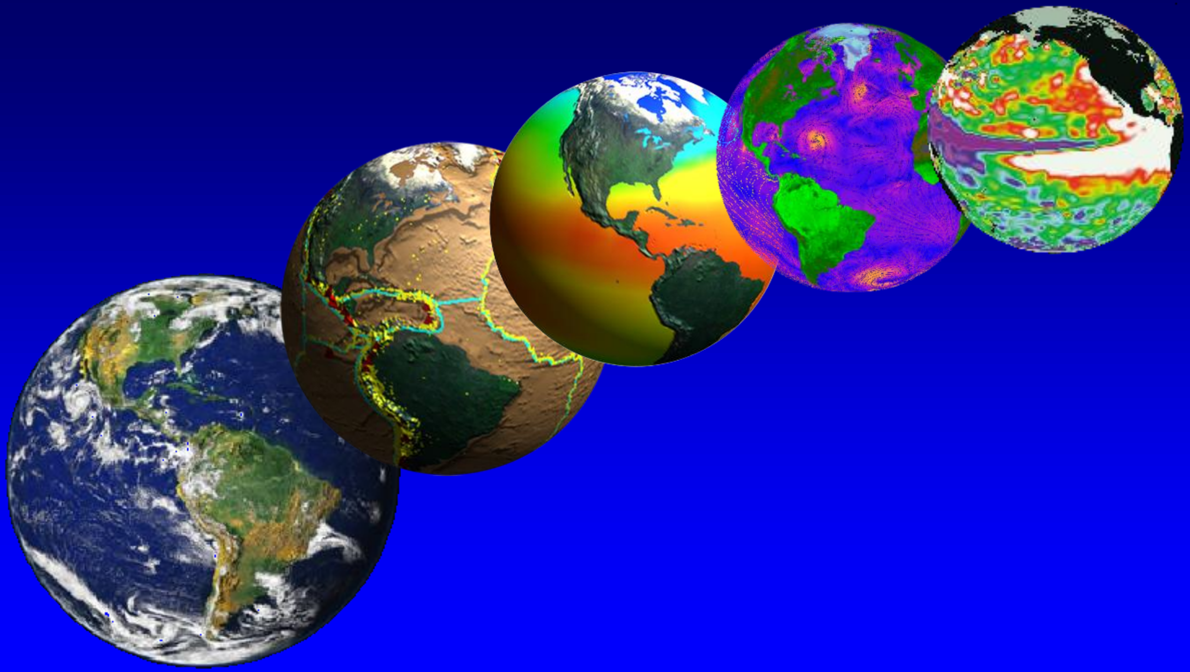
- In 2002-2008, total altimetric sea level observed shows no significant trend (0.9 mm/y)
- GRACE reveals that mass is increasing by 6.3 mm/y, on top there is a warming
- Mass increase and warming is compensated by salinity increase (invisible for altimeter)

Recent results from the GRACE mission
- ocean and sea level -

Deep ocean warming cannot be assessed by in-situ observation



Song and Colberg (2011) combine GRACE, altimetry, observation of the warming of the upper 700m and modelling, to obtain 1.1mm/y contribution from deep ocean (=1/3 of observed sea level rise).

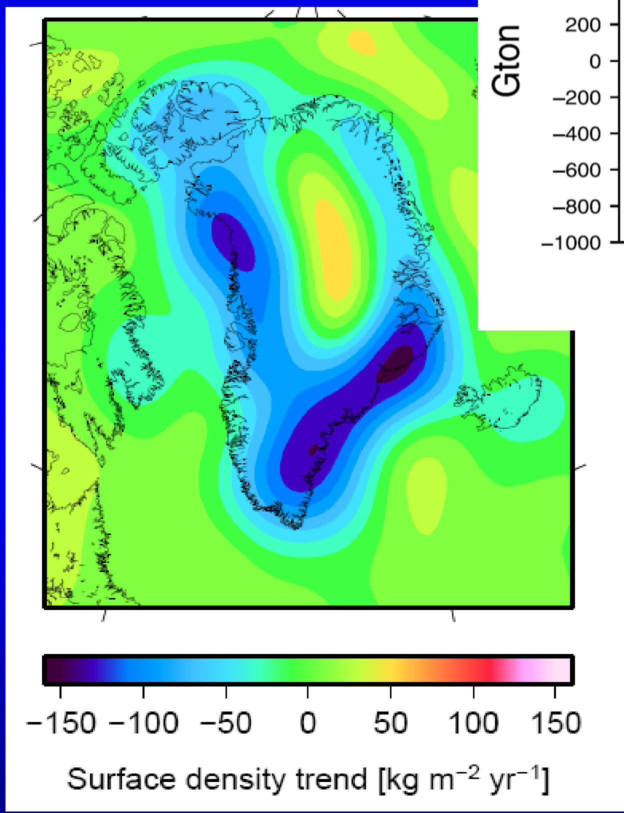


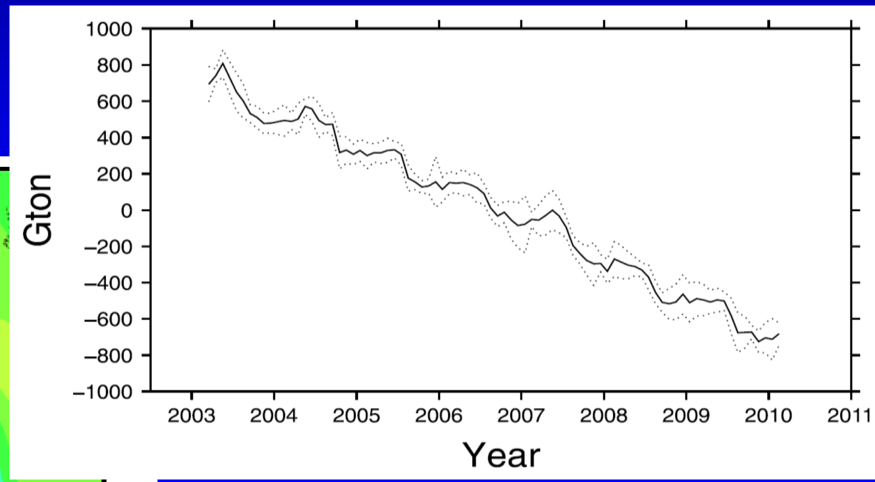
GRACE and Cryosphere

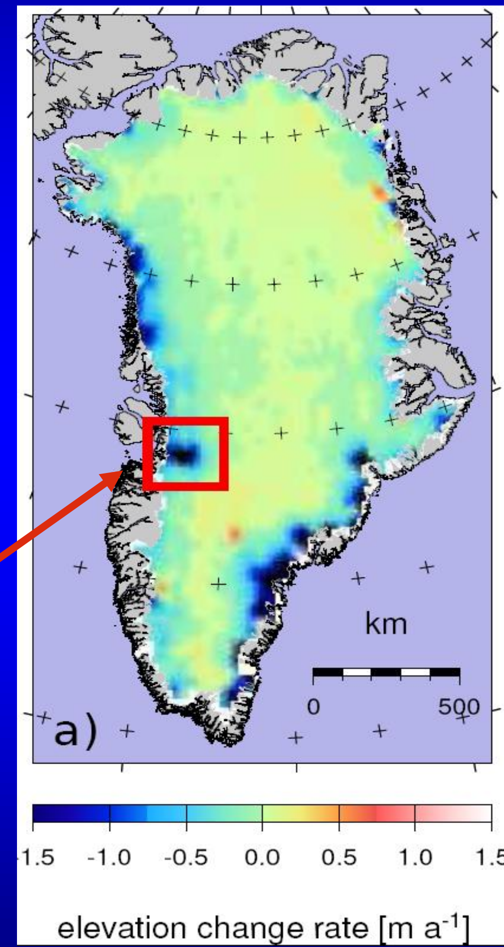
GFZ
POTSDAM

Recent results from the GRACE mission
- cryosphere -

Greenland ice sheet shrinking from GRACE: estimates converge







Jakobshavn Isbrae

Blue: shrinking, Red/White: thickening

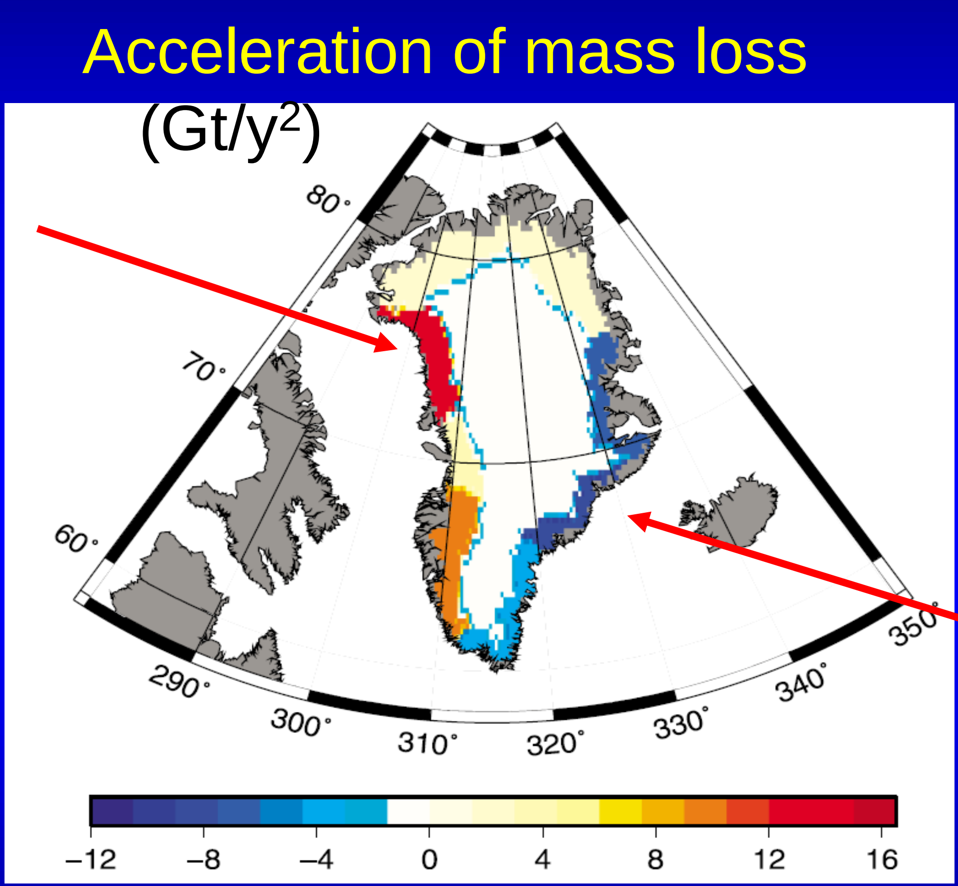
Schrama and Wouters in JGR (2011, top) find a total rate of -201Gt/y from GRACE

Ewert et al. (subm., J. Geodyn.): −191.2Gt/y from GRACE (left), -184.8Gt/y from ICESat.(right)

Recent results from the GRACE mission
- cryosphere -

Greenland ice sheet shrinking from GRACE: not uniform

Shrinking at increasing speed



Shrinking at decreasing speed

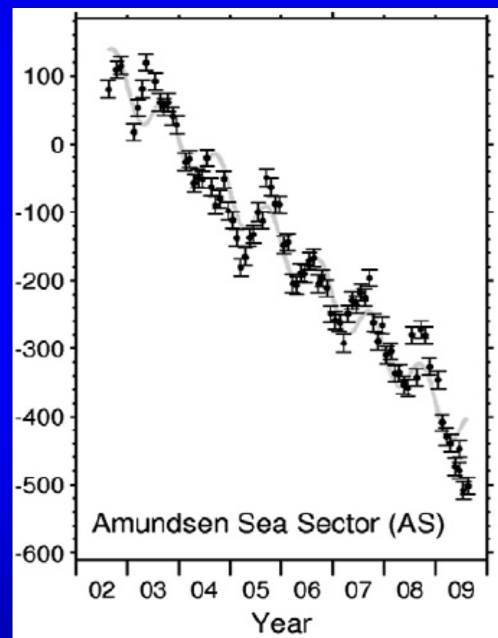
Schrama and Wouters in JGR (2011) find a total acceleration of -8.3 Gt/y², which is less than e.g. Velicogna (2009) (-30Gt/y²), Rignot et al. (2011) (-17Gt/y²)

GFZ POTSDAM

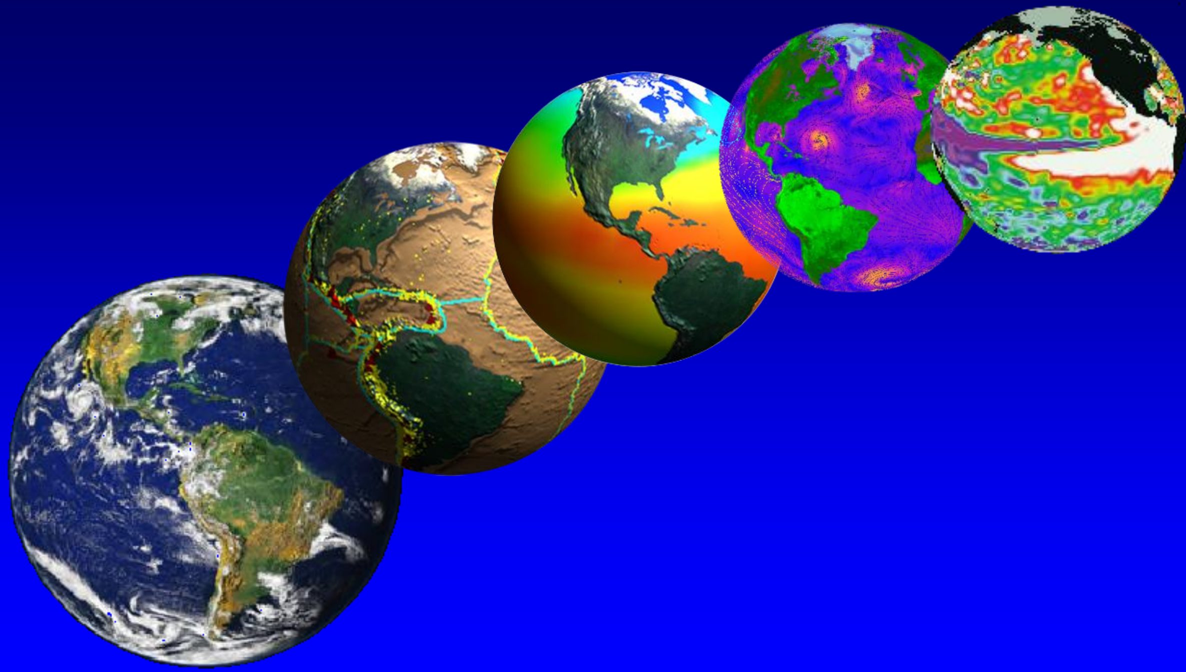
Recent results from the GRACE mission
- cryosphere -

GRACE measures interannual snow accumulation in West Antarctis

ECMWF, GRACE (trend/annual removed)

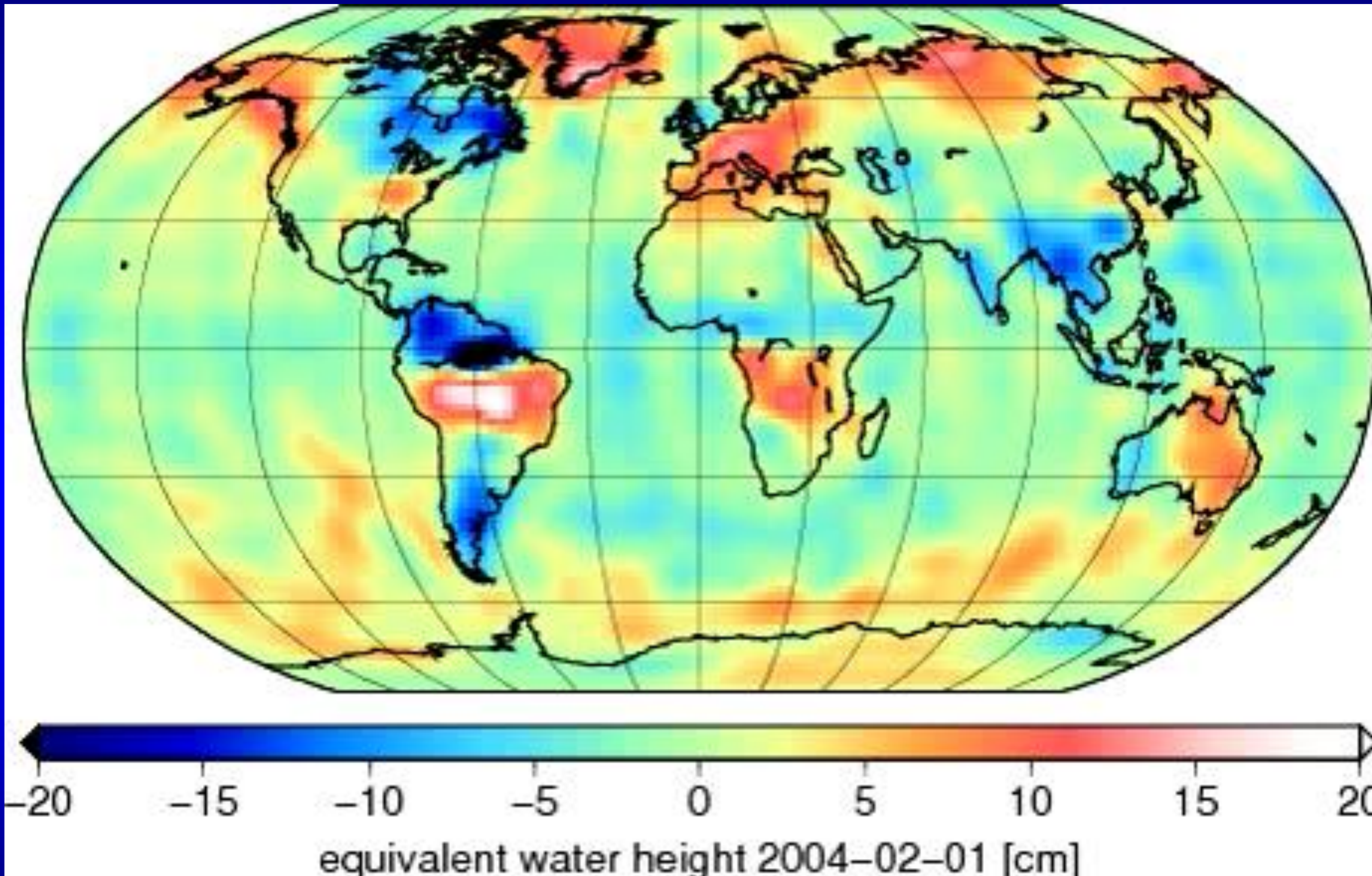


Interannual mass change in Antarctic Peninsula + Amundsen Sea Sector are governed by changes in precipitation rates. They clearly contain El-Nino Southern Oscillation signatures. **Sasgen et al. (2010, EPSL).**



GRACE and Hydrology

Recent results from the GRACE mission
- global mass transport -

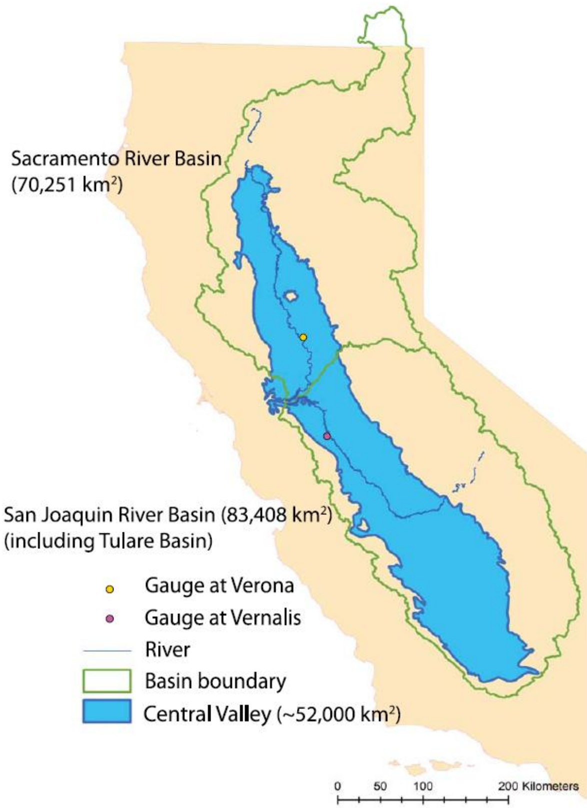


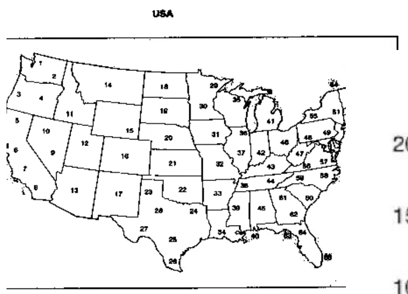
Enrico Kurtenbach, Univ. of Bonn

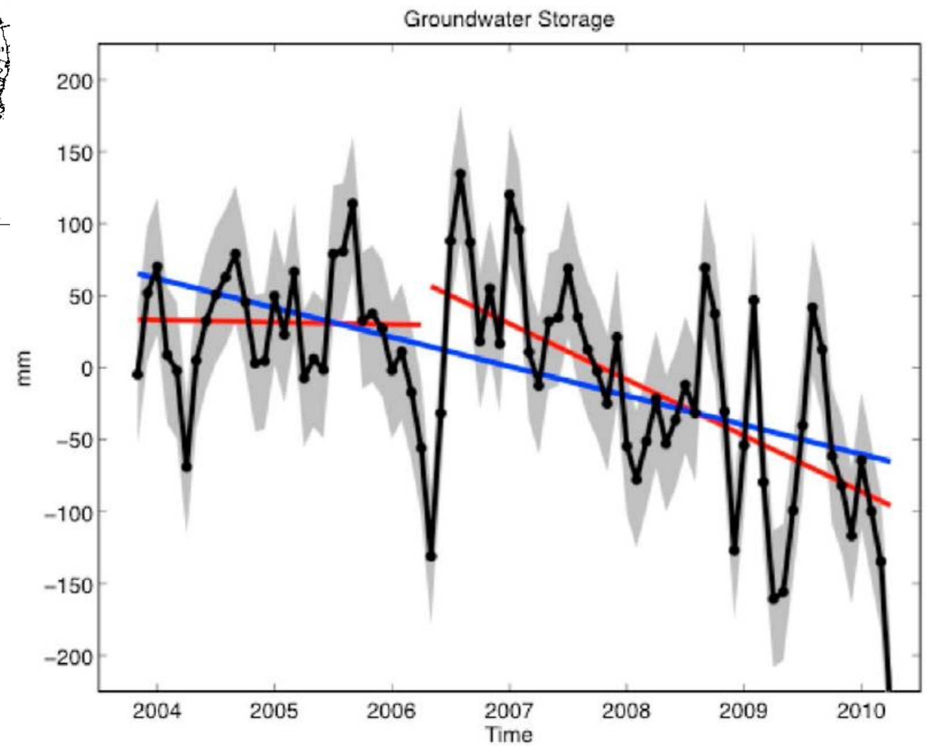
GFZ POTSDAM

Recent results from the GRACE mission
- changes in the terrestial water cycle -

GRACES measures changes of groundwater storage





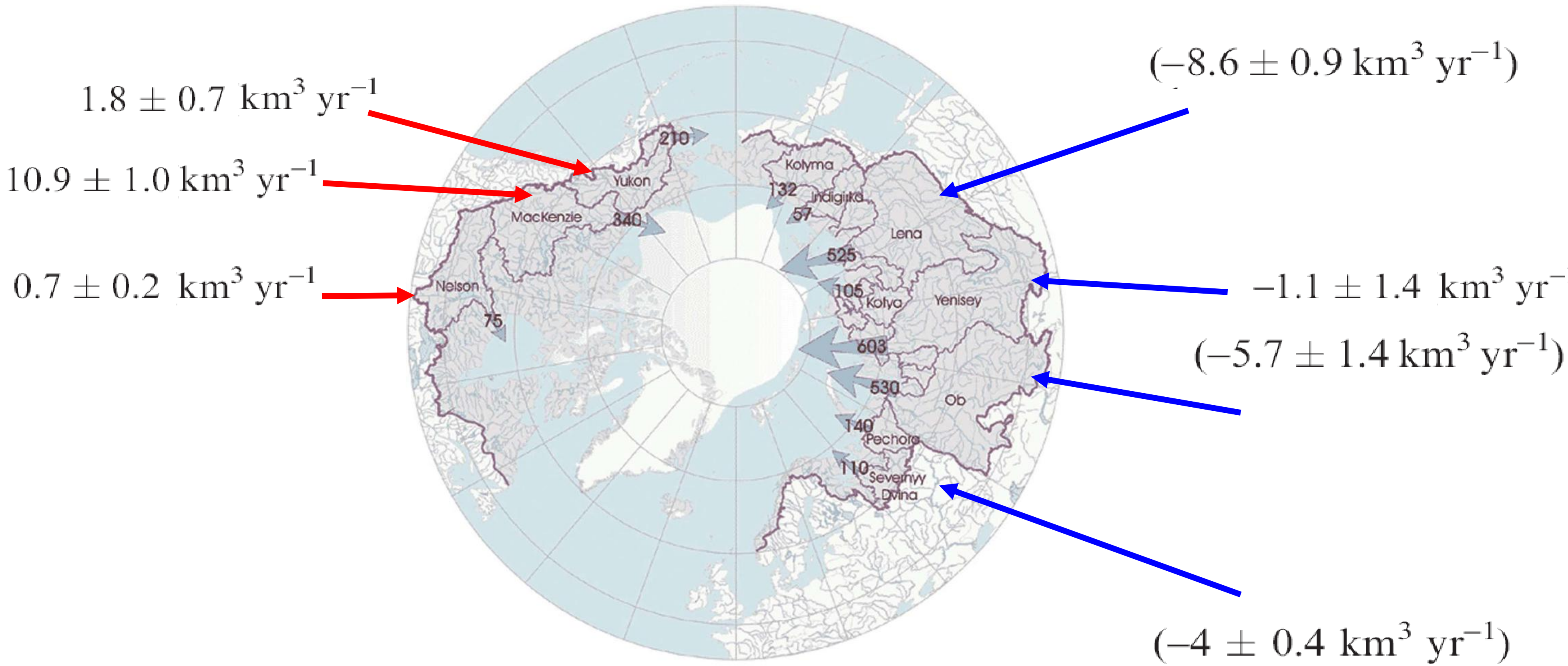


Groundwater depletion at a rate of 20.4mm/y in California central valley (52.000km^2),

20.3km^3 within 6.5y study period, **Famiglietti et al. in GRL (2011)**

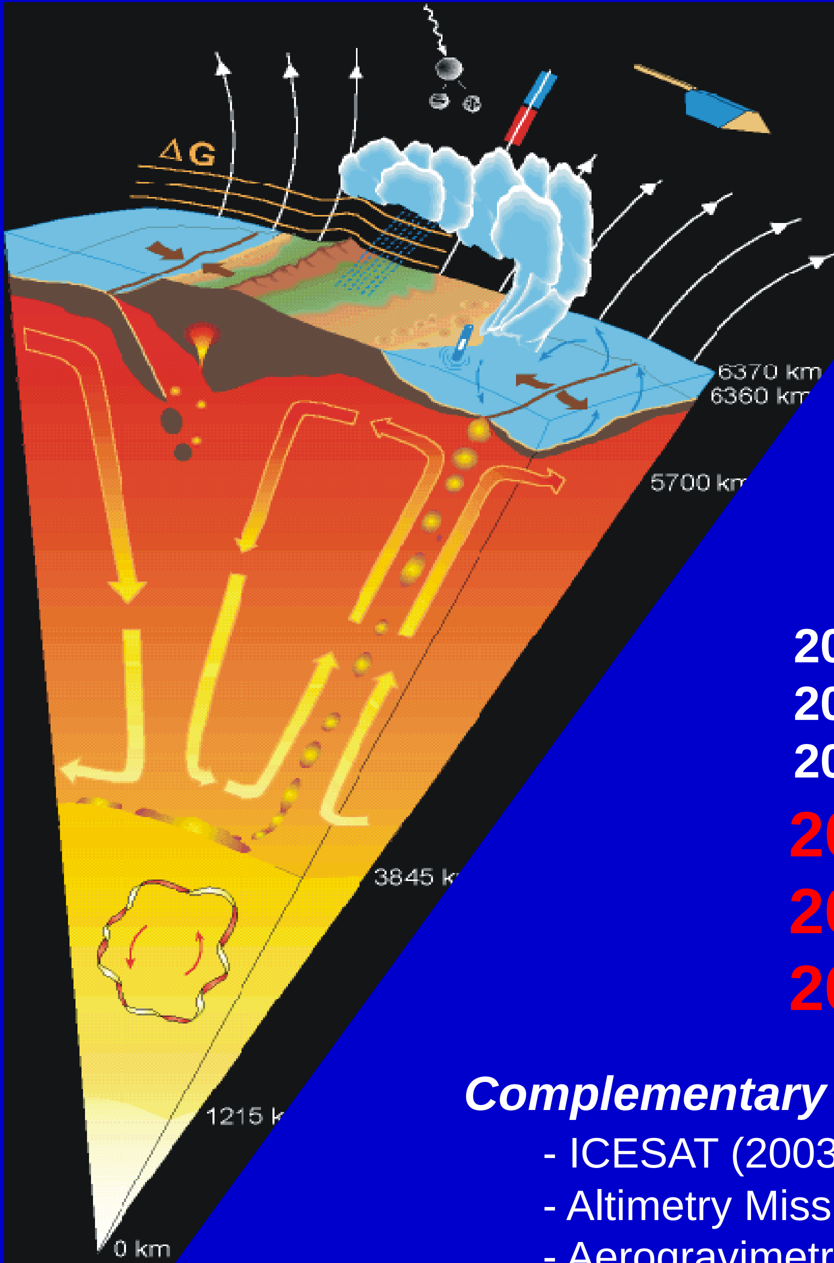
Recent results from the GRACE mission
- changes in the terrestial water cycle -

Water balance of the Arctic drainage system – warming, snow and permafrost



Frappart et al. in Int. J. Rem. Sens. (2011):

- Eurasian basins loose snow mass, N-American basins gain mass.
- In accordance with large measured increase of European river discharge and small decrease of N-American river discharge.



The New Satellite Gravity Missions

have and will greatly contribute to

- ***Geodesy***
- ***Solid Earth Physics***
- ***Oceanography***
- ***Ice Physics***
- ***Meteorology***
- ***Climatology***

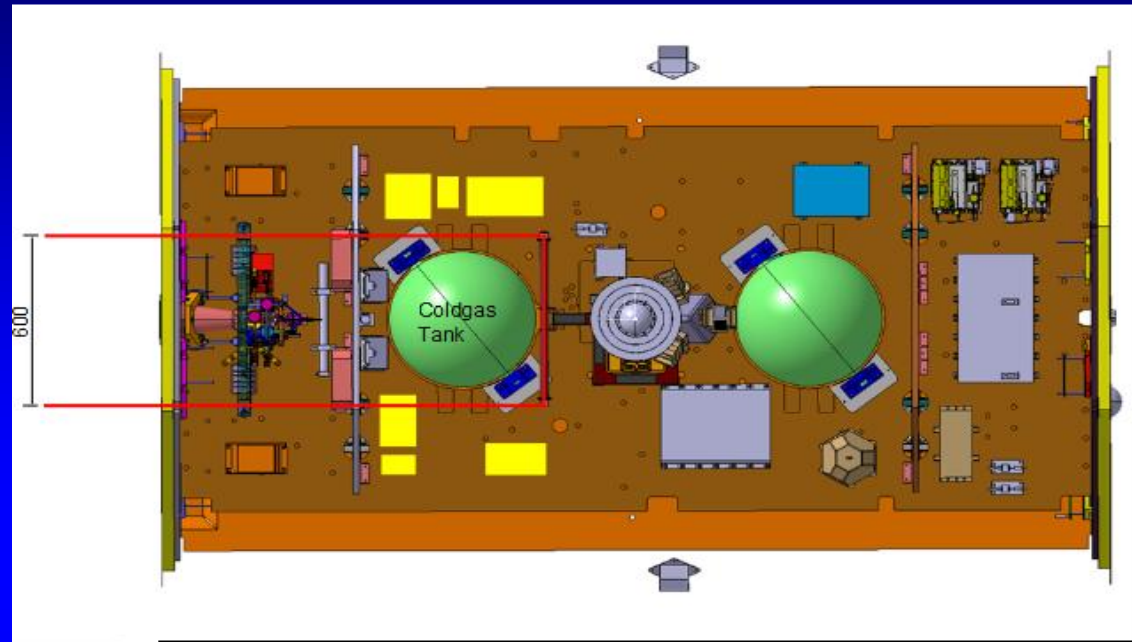
2000-2010	**CHAMP**
2002-2015	**GRACE**
2009-2012	**GOCE**
2012	**SWARM**
2016	**GRACE FO**
2022	**NG2/GRACE 2**

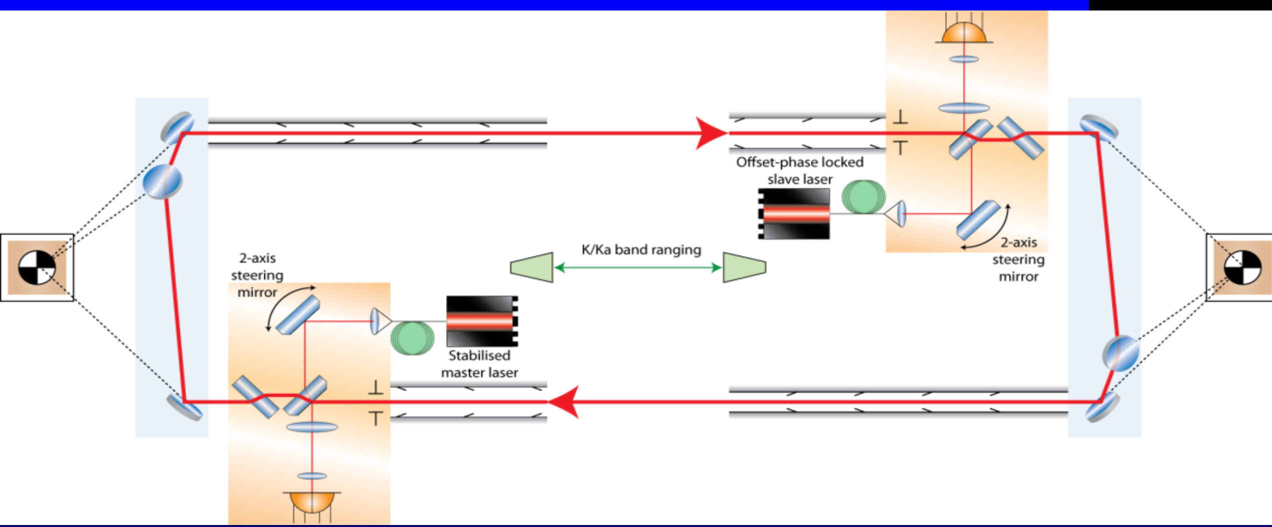
Complementary Missions:

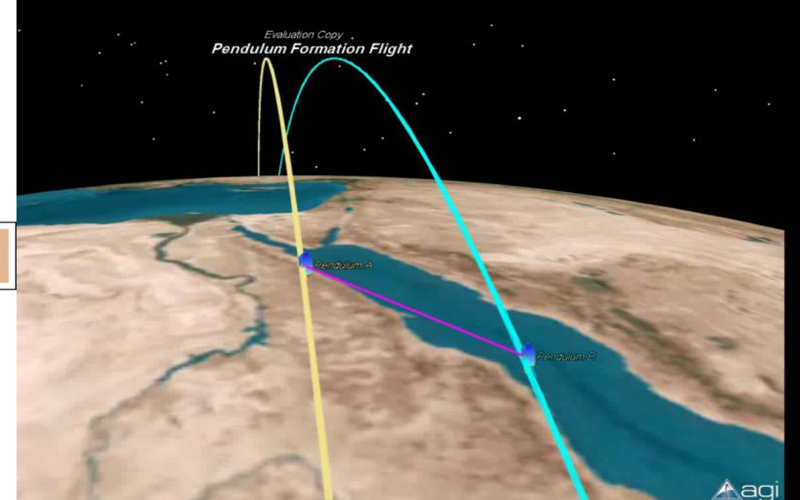
- ICESAT (2003) / CRYOSAT2 (2008), Tandem-X (2010)
- Altimetry Missions: Jason (2002), Envisat (2002)
- Aerogravimetry

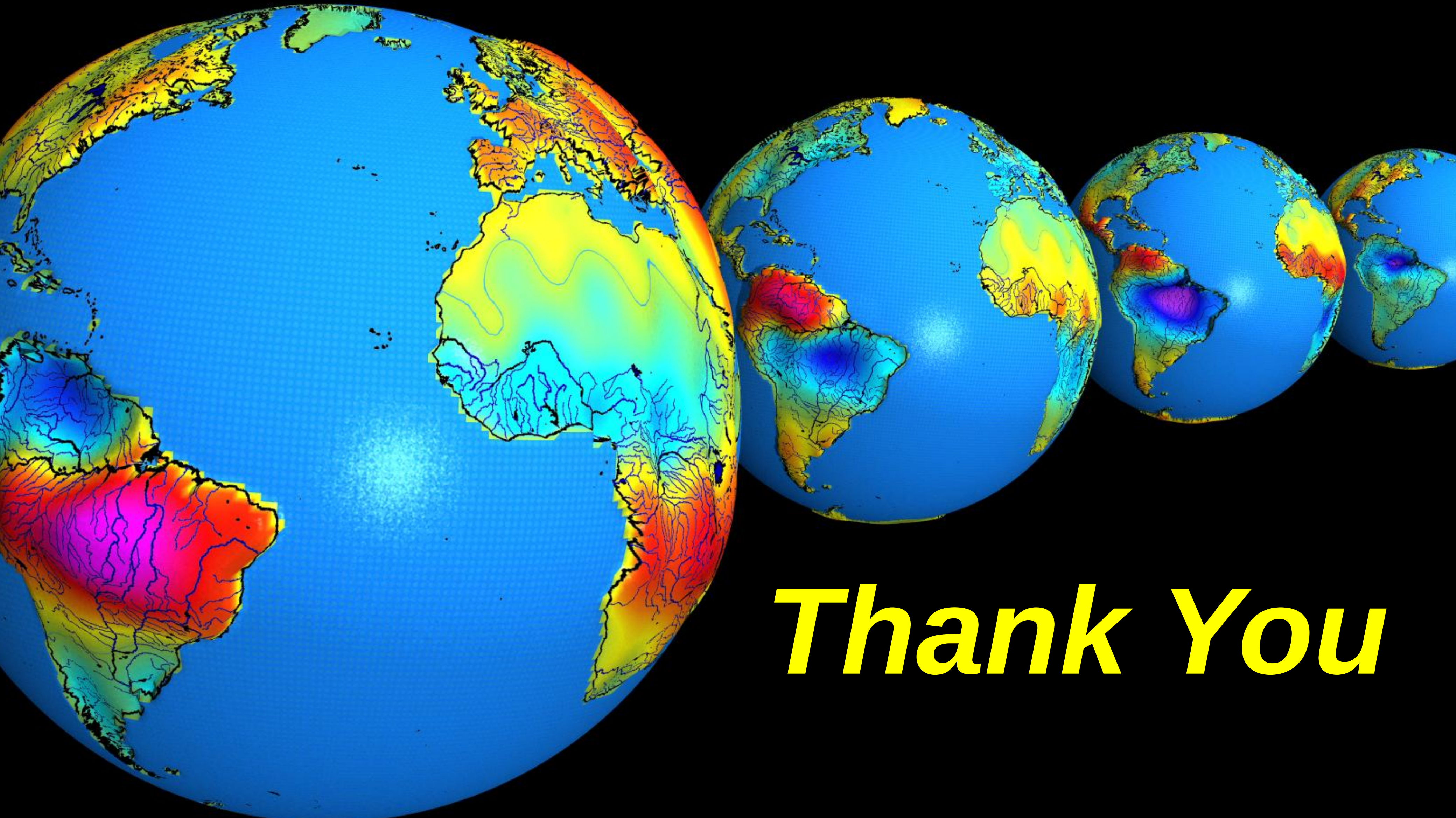
GRACE Follow-on

- Again US/D project
- Launch 2016, 7 years lifetime
- GRACE "Clone" with
  - Lessons learnt from GRACE
  - Add-on Laser Ranging Instrument (factor of 20 improved SST)
  - Improved orbit
- Funding not yet settled








Thank You