Space Geodesy:
for COSMIC and using COSMIC

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J_2 (Earth's oblateness)

- by far the largest gravity "anomaly"
- ~100% due to rotational equilibrium
- = 0.0010826265…
- corresponds to a geoid "flattening" ~1/300

  ~ centrifugal force / gravity

  ~ equatorial bulge / Earth radius
- varies at and beyond the last digit, due to geophysical and climatic mass redistributions.

<u>Sputnik 1, 1957</u>

The plane of the satellite orbit remains fixed in space (except for the effects of perturbations) while the earth turns on its axis within the orbit. These diagrams, based on releases from Moscow, show every third circuit of the first artificial satellite, over Russia, western Africa, United States, the eastern Pacific Ocean, and China.

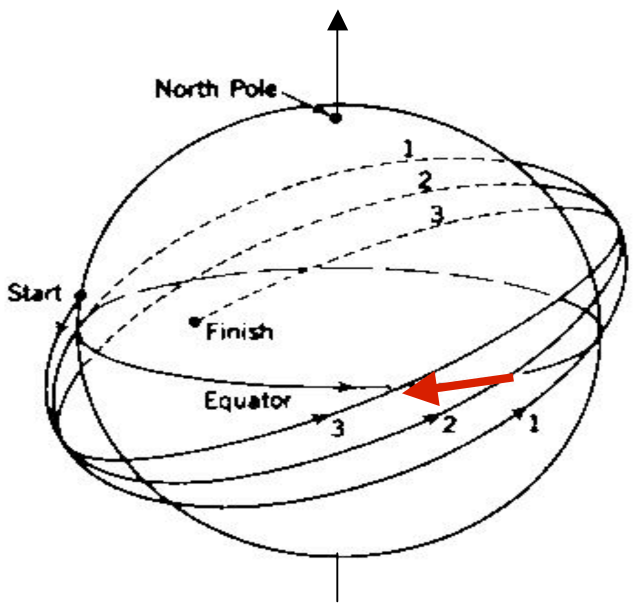
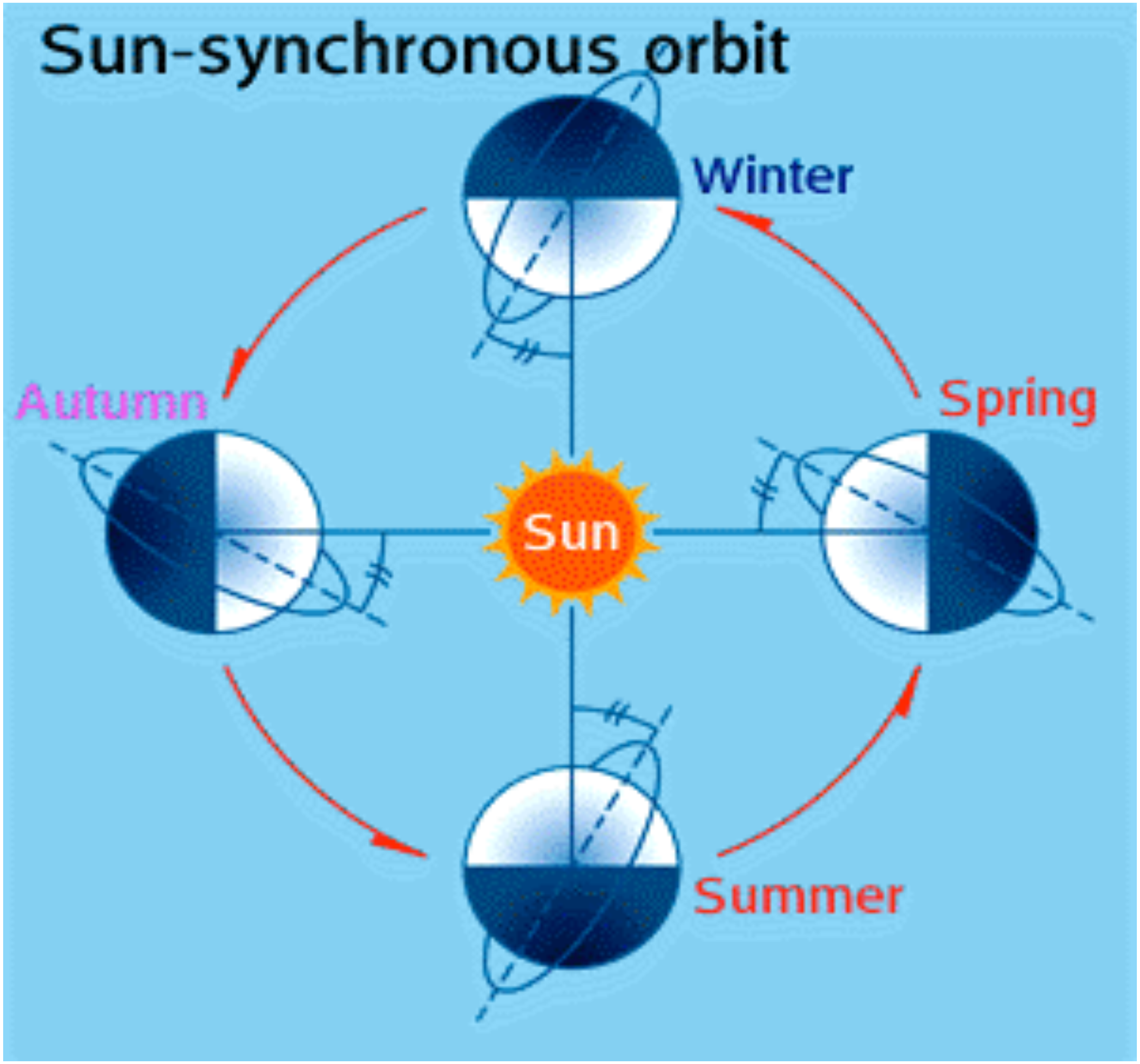
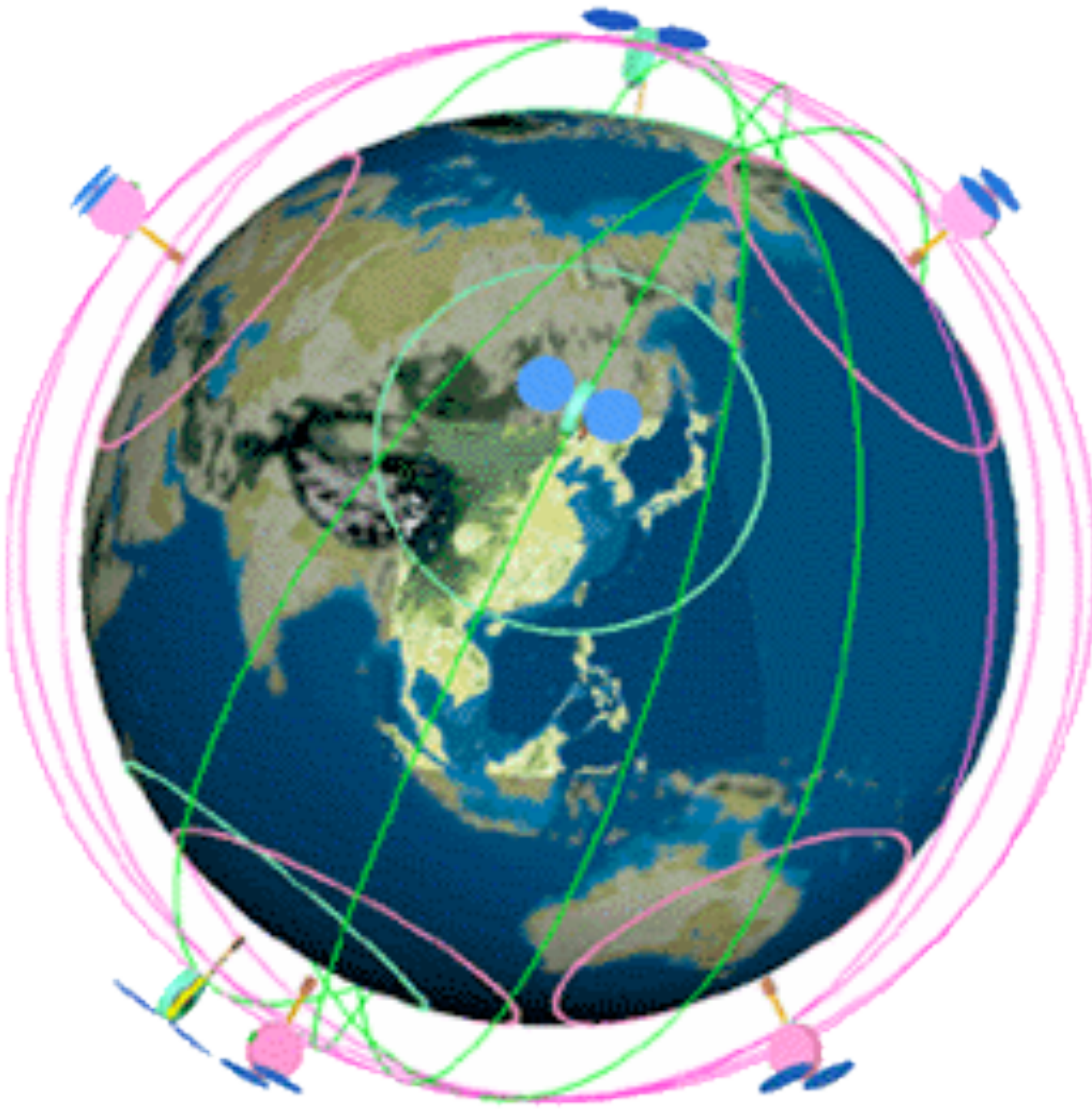


Figure 5–11 The regression of the nodes.

Satellite nodal precession (around an oblate Earth)

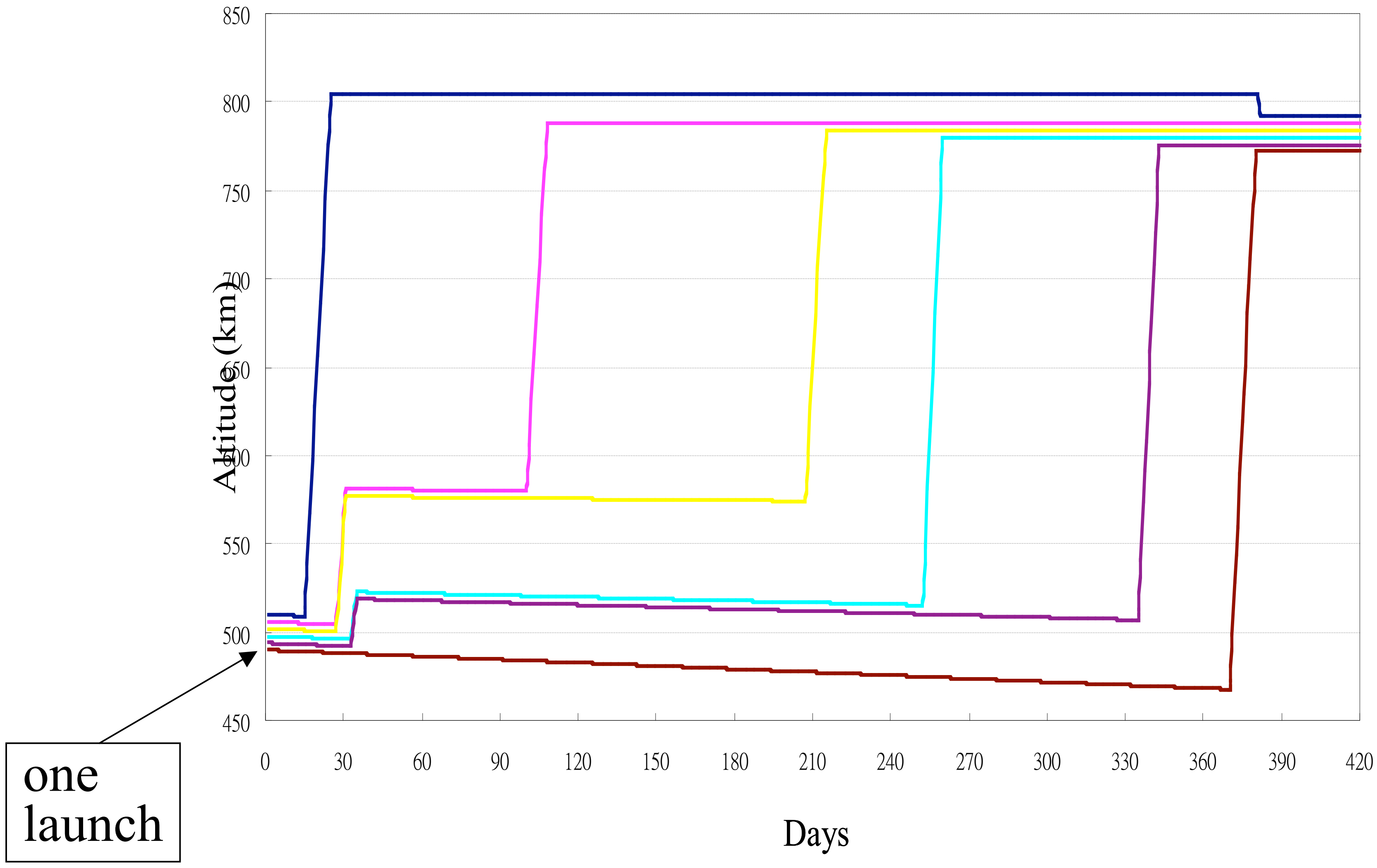
→ Orbits separation of COSMIC satellites at different altitudes


Sun-synchronous orbit
Winter
Autumn
Spring
Sun
Summer



COSMIC constellation:
6 satellites
6 orbits:
800 km altitude
71° inclination

COSMIC Constellation (6 satellites)
Deployment Phase



Space geodesy for COSMIC and using COSMIC

- COSMIC needs space geodesy
  - precise orbit/timing for GPS constellation (IGS)
  - precise orbit/timing for COSMIC LEO constellation (COSMIC Project)

  - NASA's Space Geodesy program provides the precise GPS technology, making GPS into a precise geodetic tool

    → "COSMIC IS a space geodetic mission!"

Space geodesy for COSMIC and using COSMIC

- COSMIC can benefit space geodesy
  - LEO orbits can solve for gravity, especially time-variable gravity during the mission lifetime (a "by product!")

    → an active NASA research interest in space geodesy (e.g., GRACE mission)
  - better determination of GPS constellation orbit
  - better determination of lower-atmosphere pressure (supporting studies of time-variable gravity, Earth rotation variation, altimetry,…)

Measuring Gravity

- Surface
  - centrifugal (pseudo-)force correction
  - free-air anomaly
  - Bouguer anomaly
- Air-borne, Ship-borne
  - centrifugal (pseudo-)force correction
  - Coriolis (pseudo-)force correction (Eötvös effect)
  - platform acceleration ("noise")
- Space-born
  - gravity canceled by centrifugal force (free fall)

“Measuring” Gravity from Space

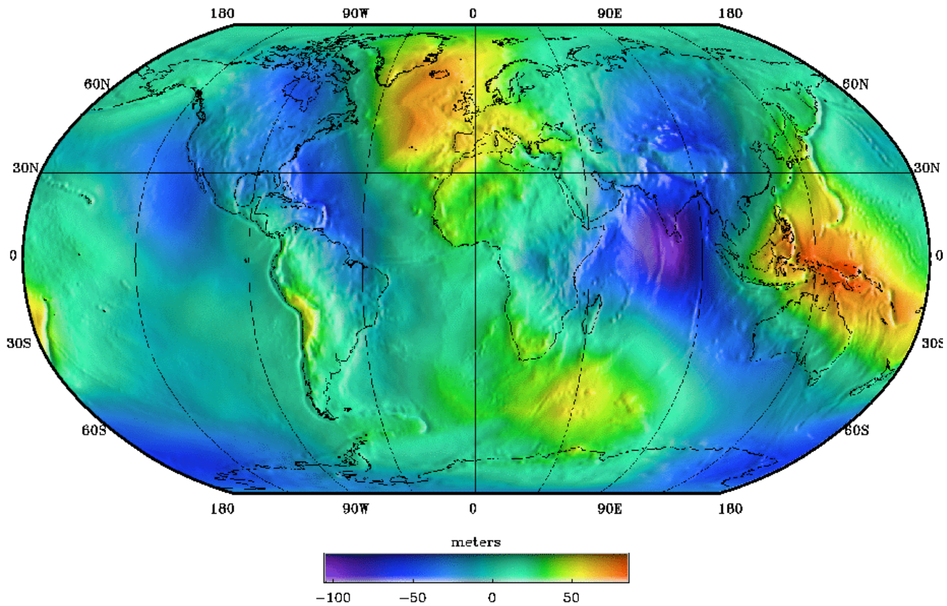
- Space-borne gravimeter won’t work! (free fall)
- Gravity gradiometer --- GOCE (2003)
- Low-Earth orbit (LEO) satellite’s **precise orbit determination (POD)**
  - Ground tracking for >4 decades (since Sputnik 1!)
    - positioning, range, Doppler/range-rate
    - Optical, radio, laser
  - Satellite-to-satellite tracking
    - “high-low” (GPS-LEO): CHAMP (2000), GRACE (2002), GOCE, **COSMIC**, altimeter missions, many future ones….
    - “low-low” (LEO-LEO): GRACE, Follow-ons
  - Need to correct for non-gravitational forces (air drag, radiation pressure)
    - on-board accelerometer (CHAMP, GRACE)
    - “drag-free”/proof mass system (GOCE, GP-B)
    - modeling: past ones, **COSMIC**.
    - common-mode cancellation (e.g., tandem constellation): **COSMIC**
    - smaller surface-to-mass ratio always helps
- Additional information (for geoid) provided by ocean altimetry and surface gravity

“Measuring” Gravity from Space : Milestones

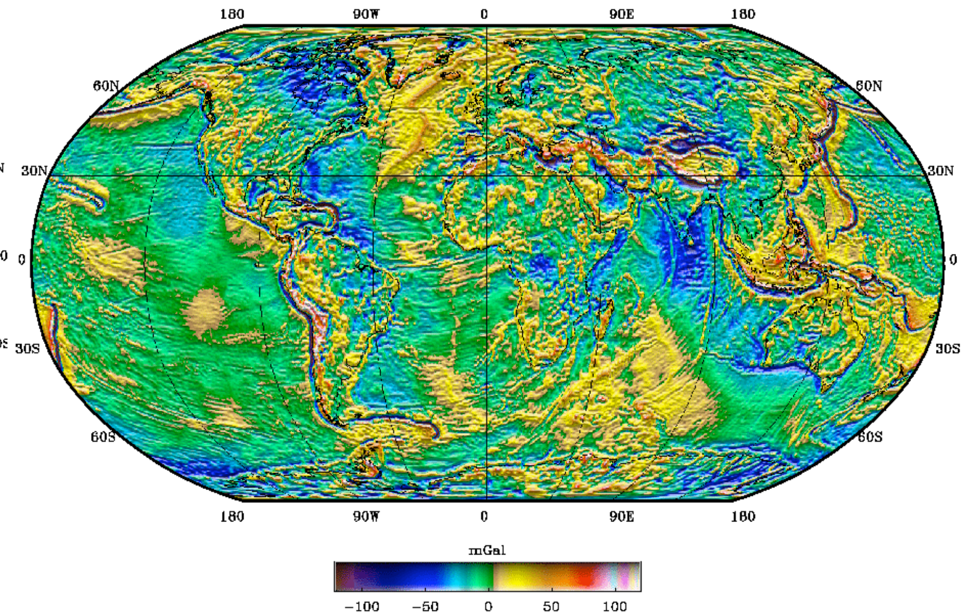
- 1957 Sputnik 1 – J_2 (Earth oblateness)
- Kaula’s (1966) theory (spherical harmonics)
- Early 1970s, Satellite-laser-ranging
- Spherical harmonic solutions
  - ~1970s, 10 x 10
  - ~1980s, 36 x 36, 70 x 70
  - ~1990s, 180 x 180, 360 x 360
- time-variable: “J_2 dot” (1980s)
- time-variable: J_2 and low-degree variations (1990s)
- CHAMP (2000), GRACE (2002), GOCE (2006) +…

•What about COSMIC?

Static Gravity Field



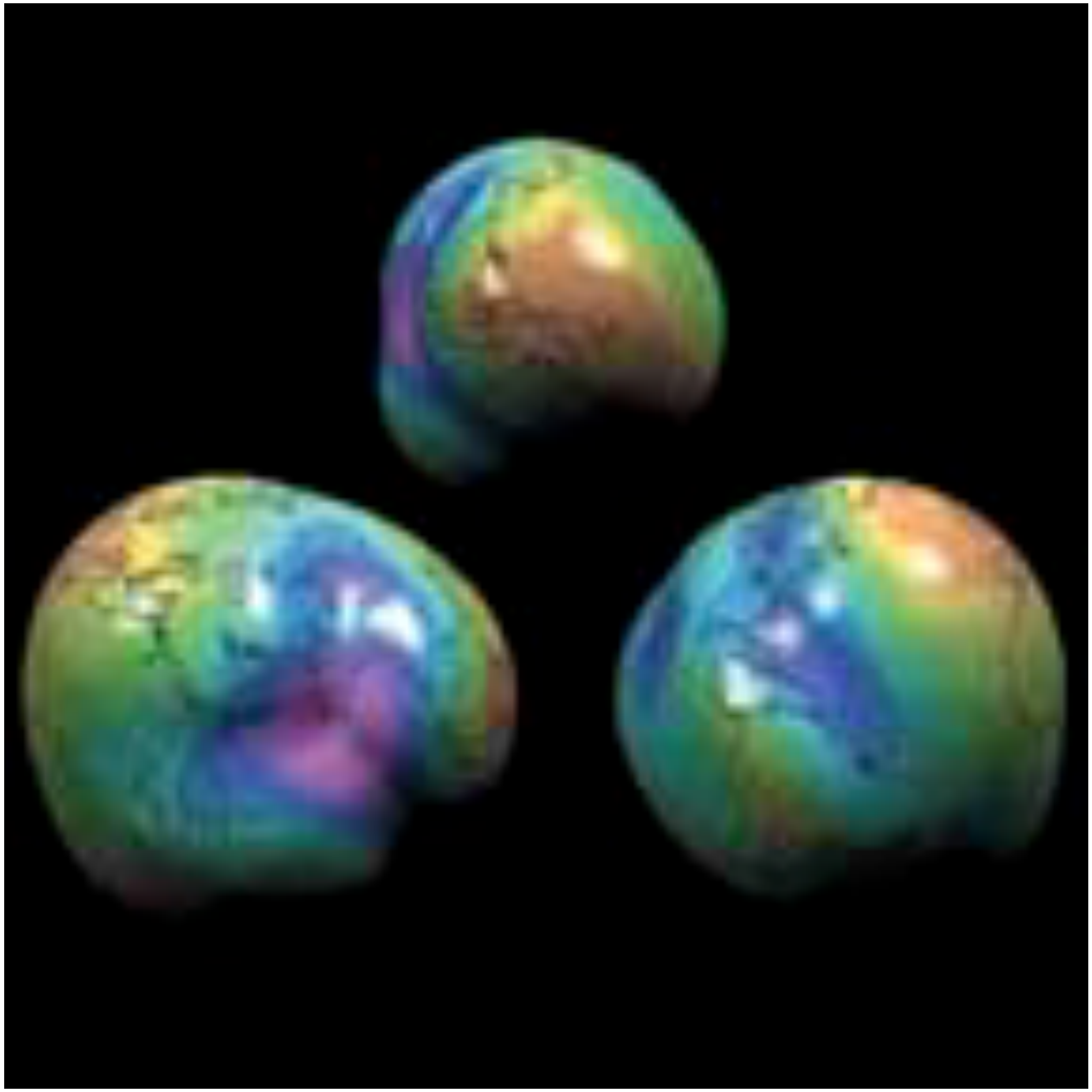
Geoid



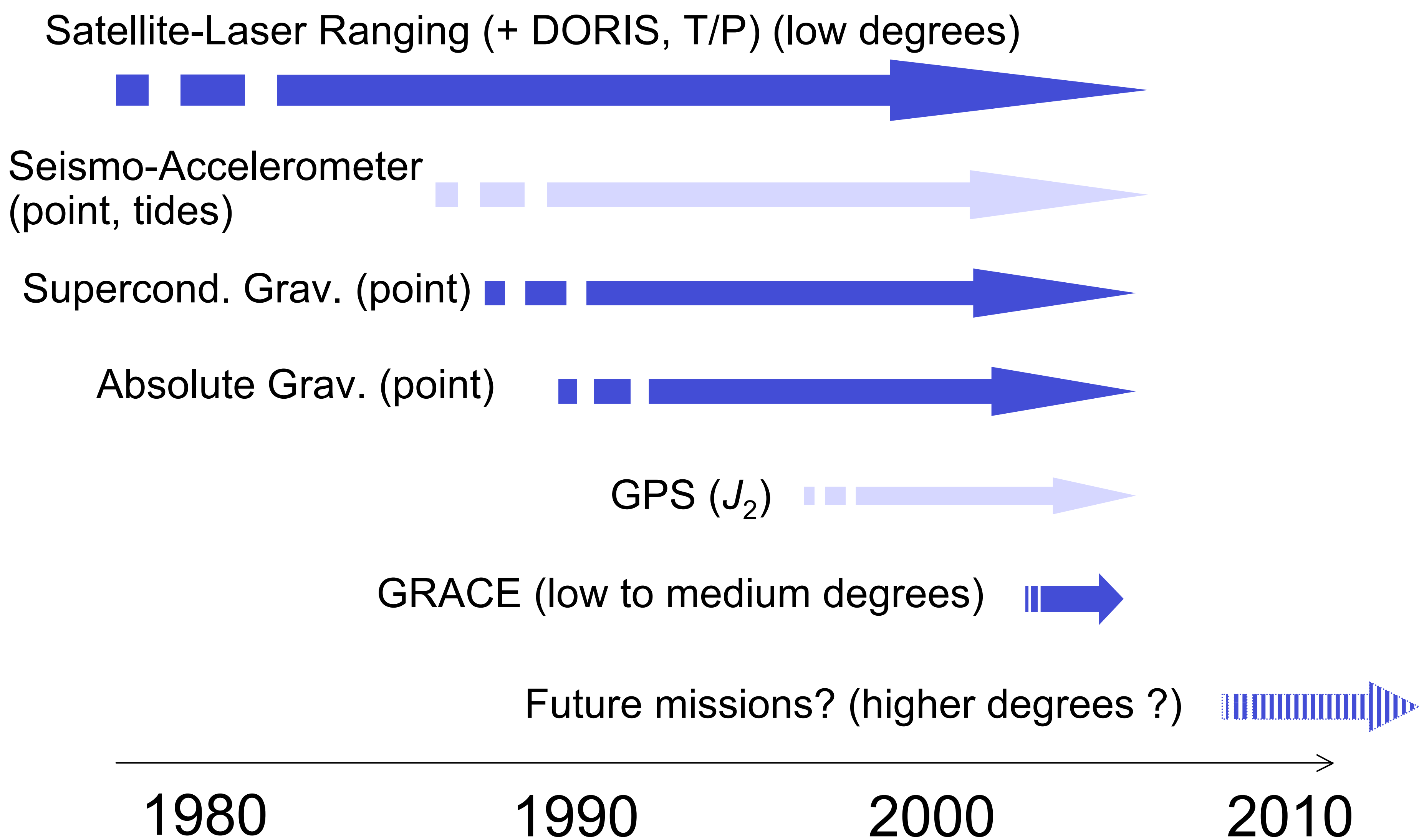
Gravity Anomaly

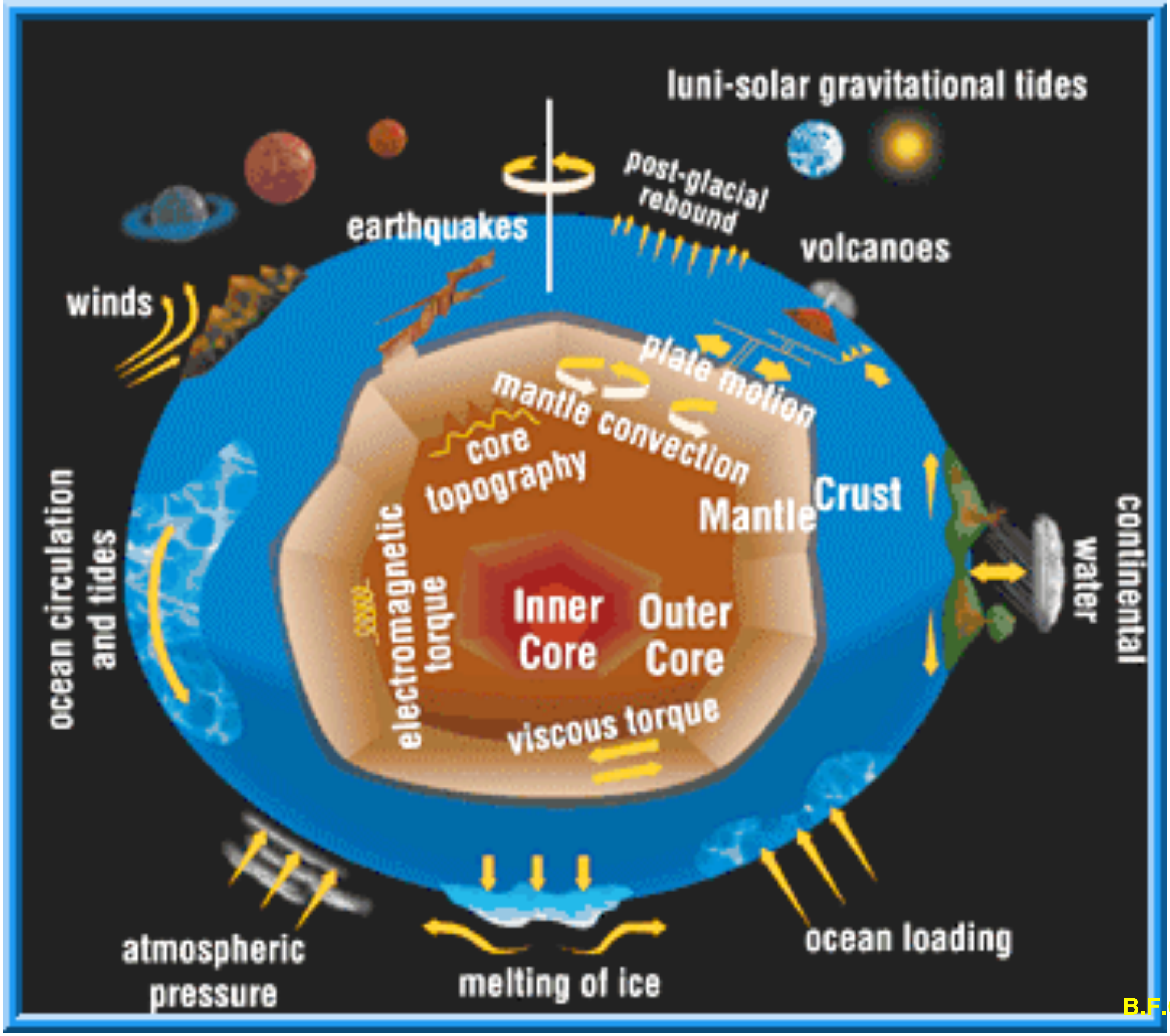
EGM96

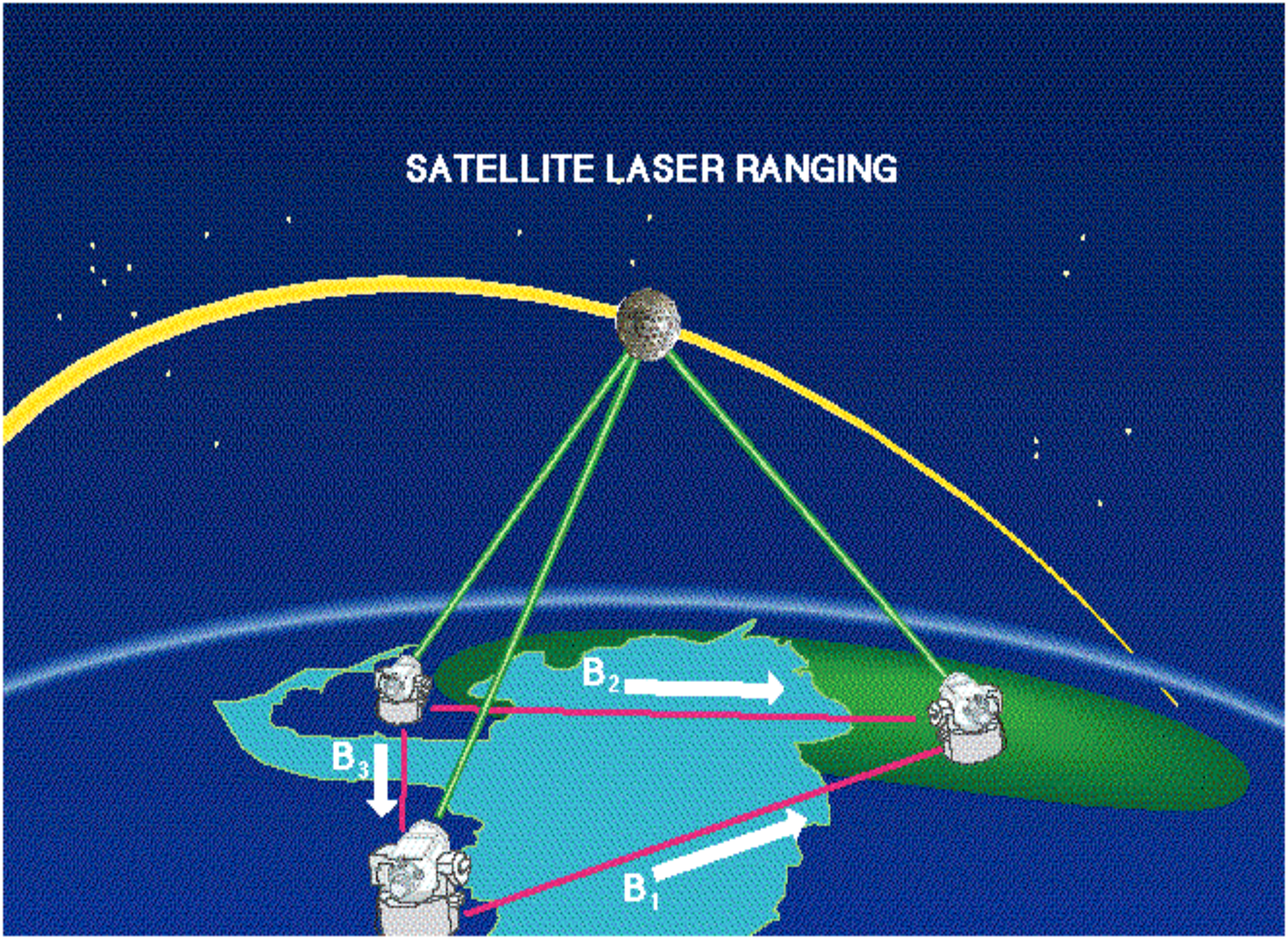
Earth’s Geoid (equi-potential surface) Model



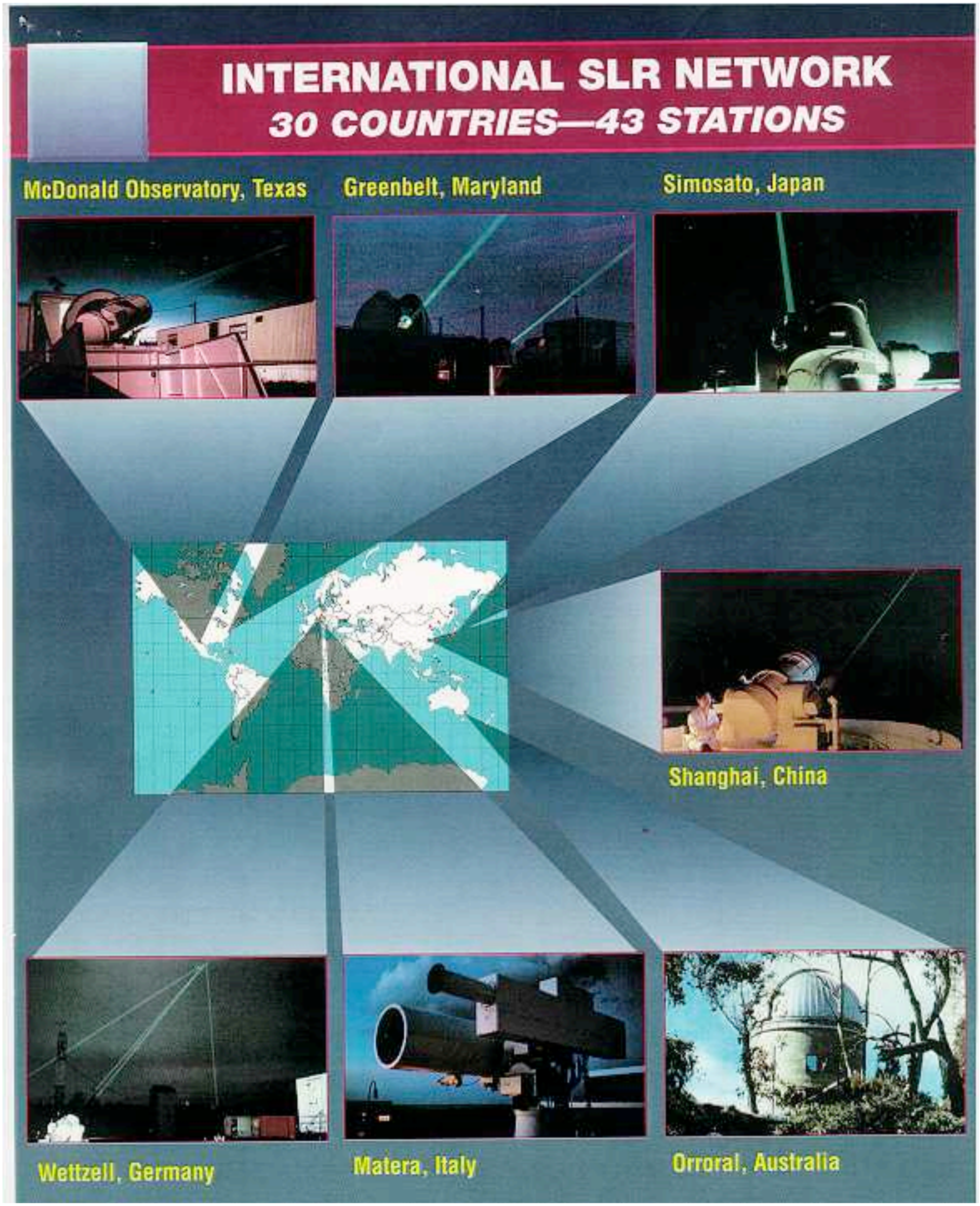
Time-Variable Gravity Observations

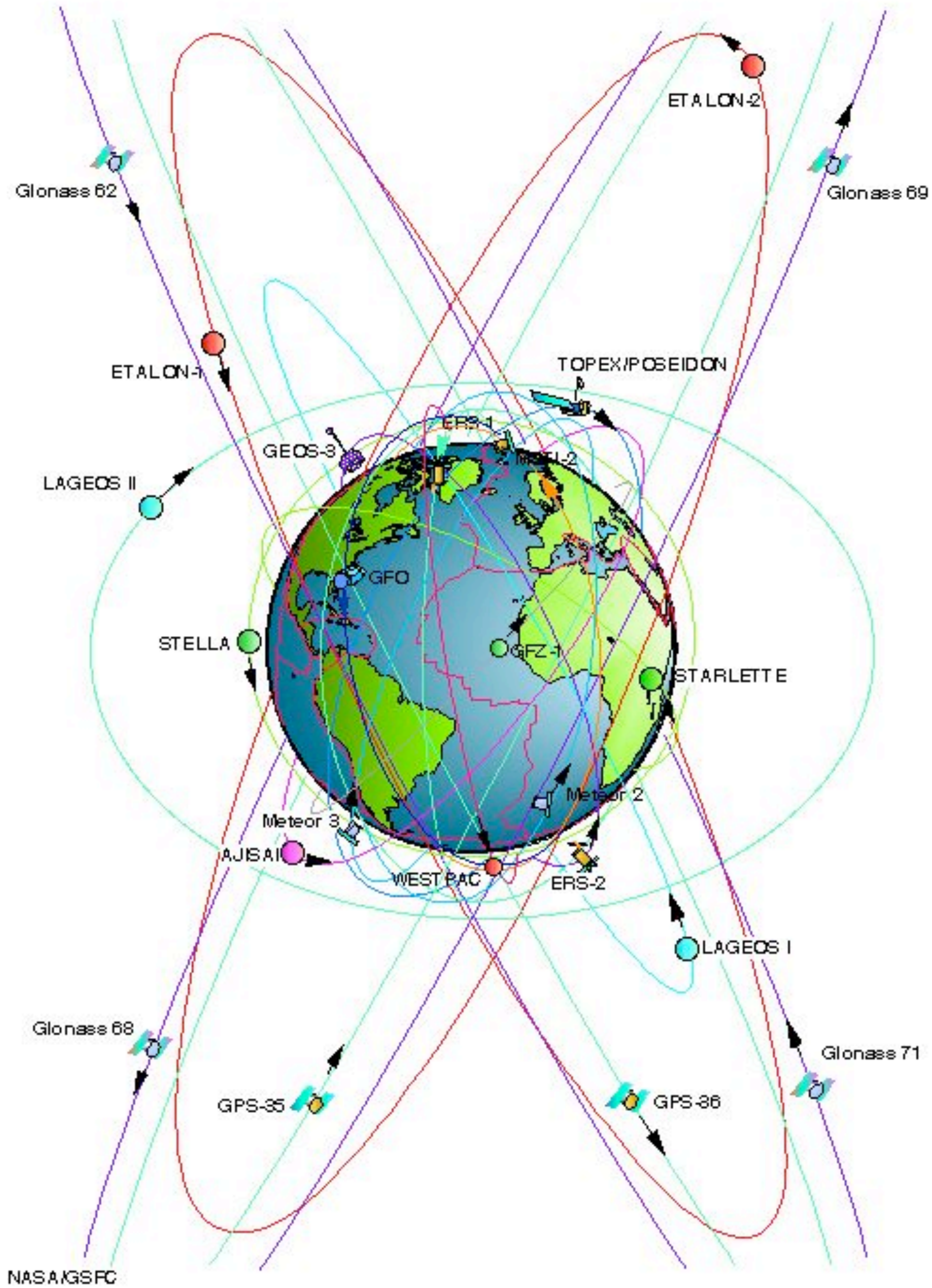



luni-solar gravitational tides
post-glacial rebound
earthquakes
volcanoes
winds
plate motion
mantle convection
core topography
Crust
Mantle
electromagnetic torque
Inner Core
Outer Core
ocean circulation and tides
continental water
viscous torque
atmospheric pressure
melting of ice
ocean loading
B.F.Chao



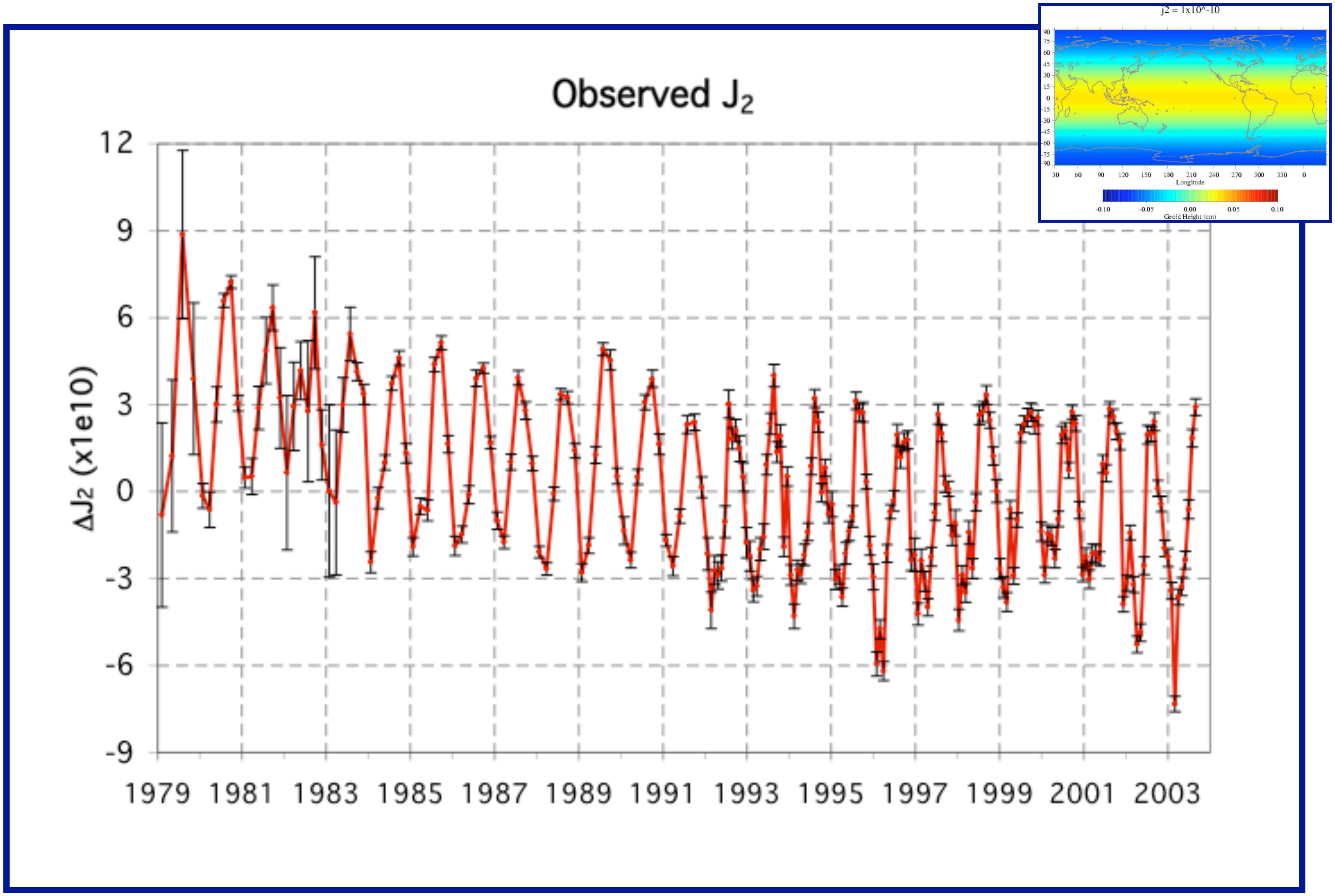
SATELLITE LASER RANGING
B2
B3
B1


INTERNATIONAL SLR NETWORK
30 COUNTRIES—43 STATIONS
McDonald Observatory, Texas
Greenbelt, Maryland
Simosato, Japan
Shanghai, China
Wettzell, Germany
Matera, Italy
Orroral, Australia



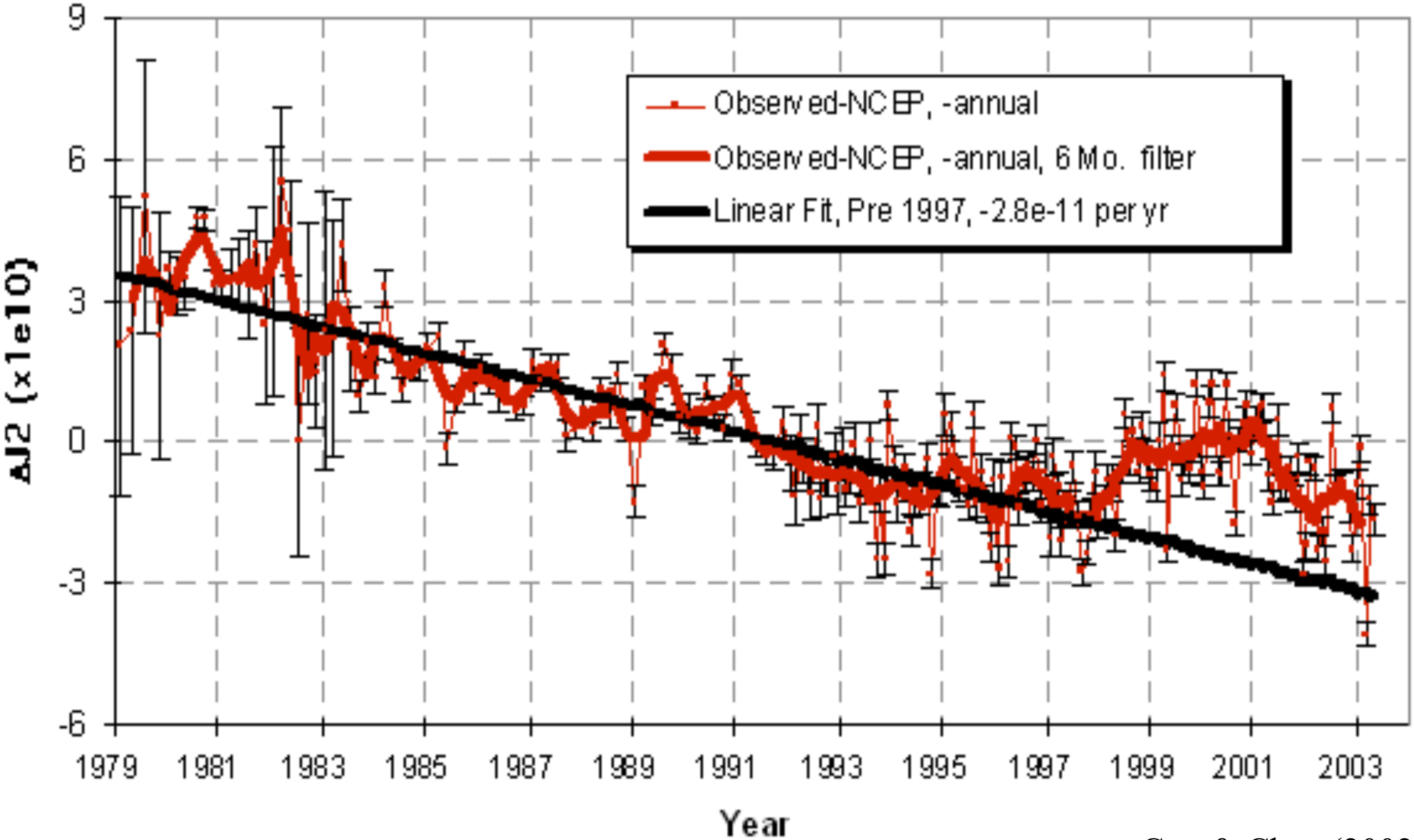
Satellites tracked by the Laser Ranging network (in addition to the Moon)

SLR Observed Earth oblateness J_2

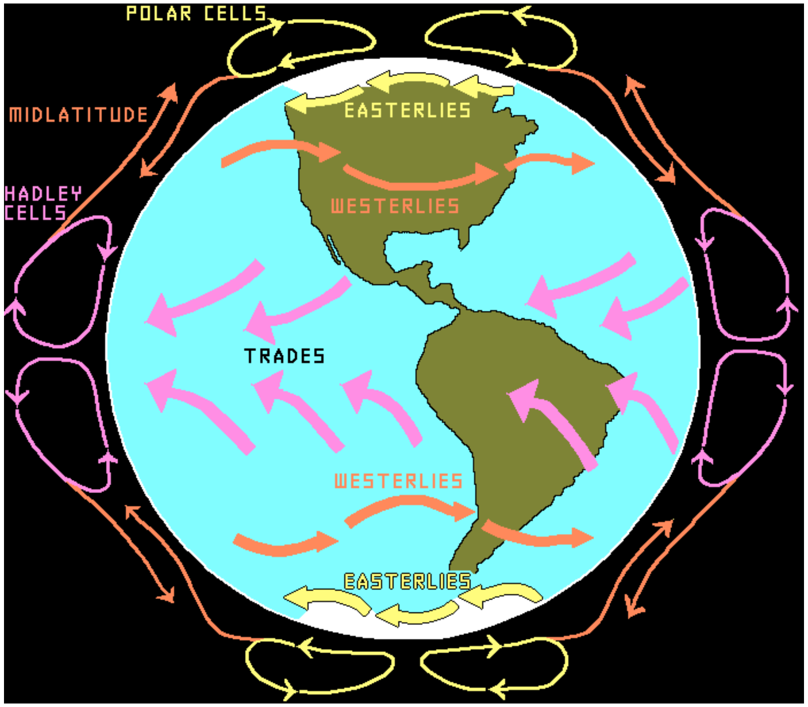


SLR observed J_2

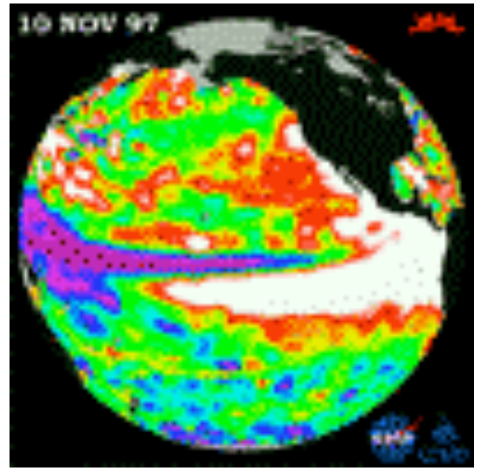
(non-seasonal, non-atmosphere, non-tidal)



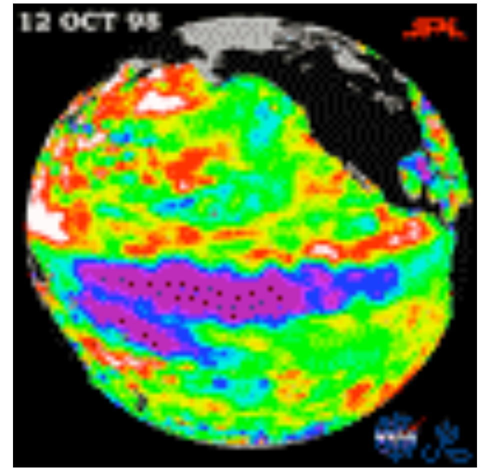
Cox & Chao (2002)

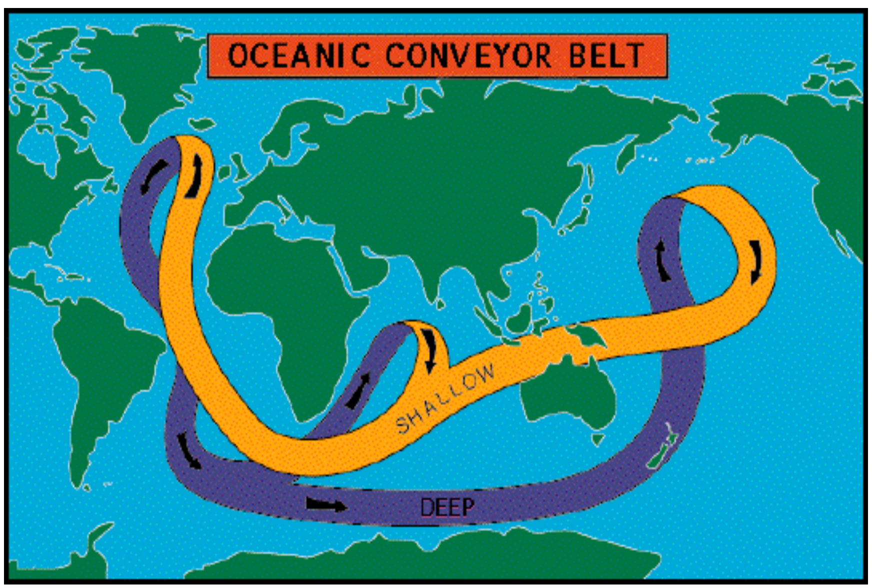


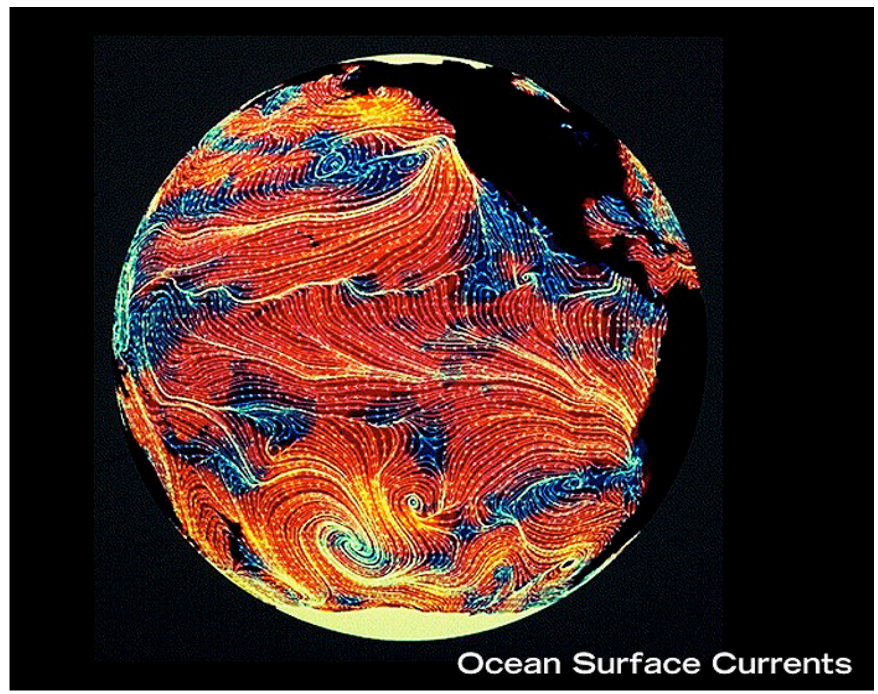
El Niño (11/1997)

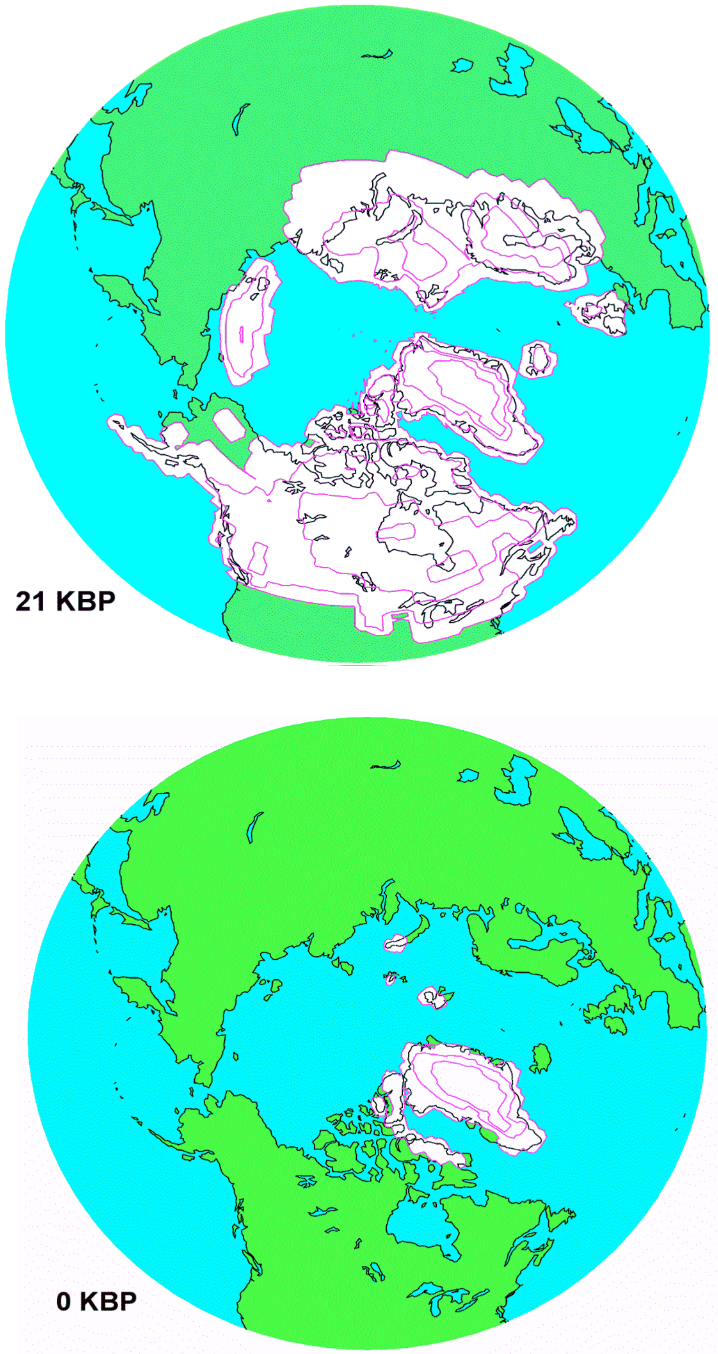


La Niña (10/1998)

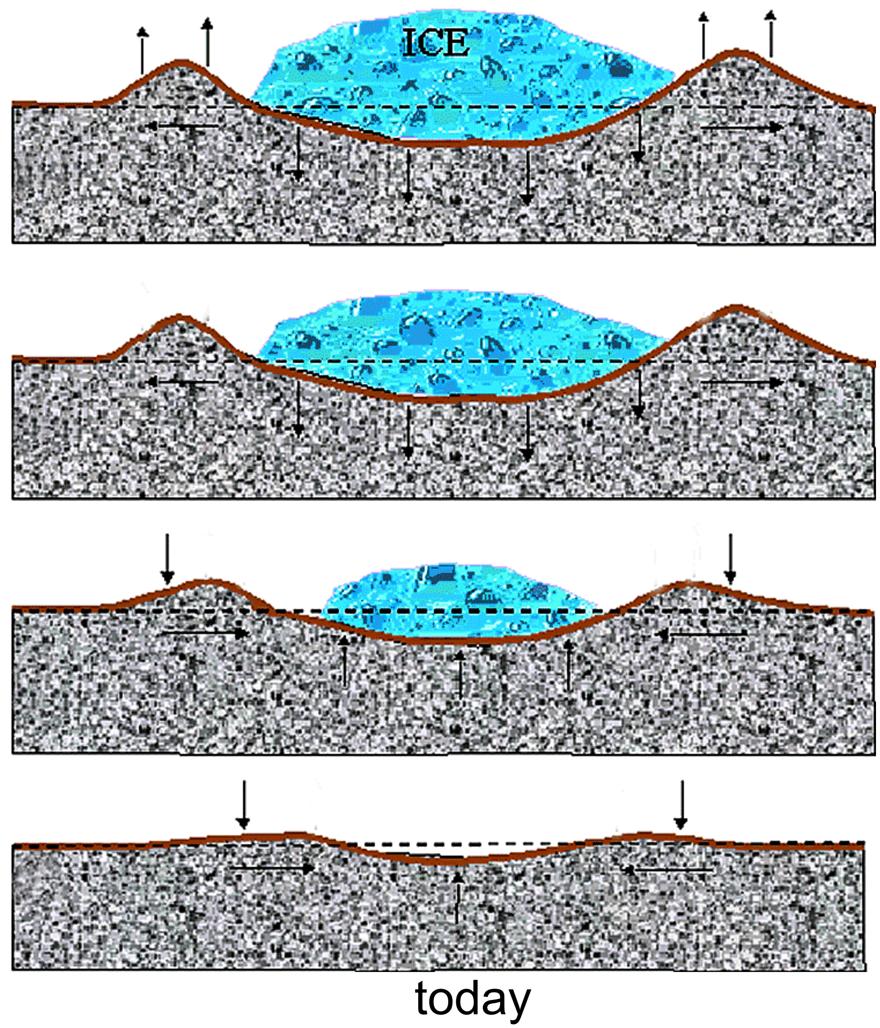




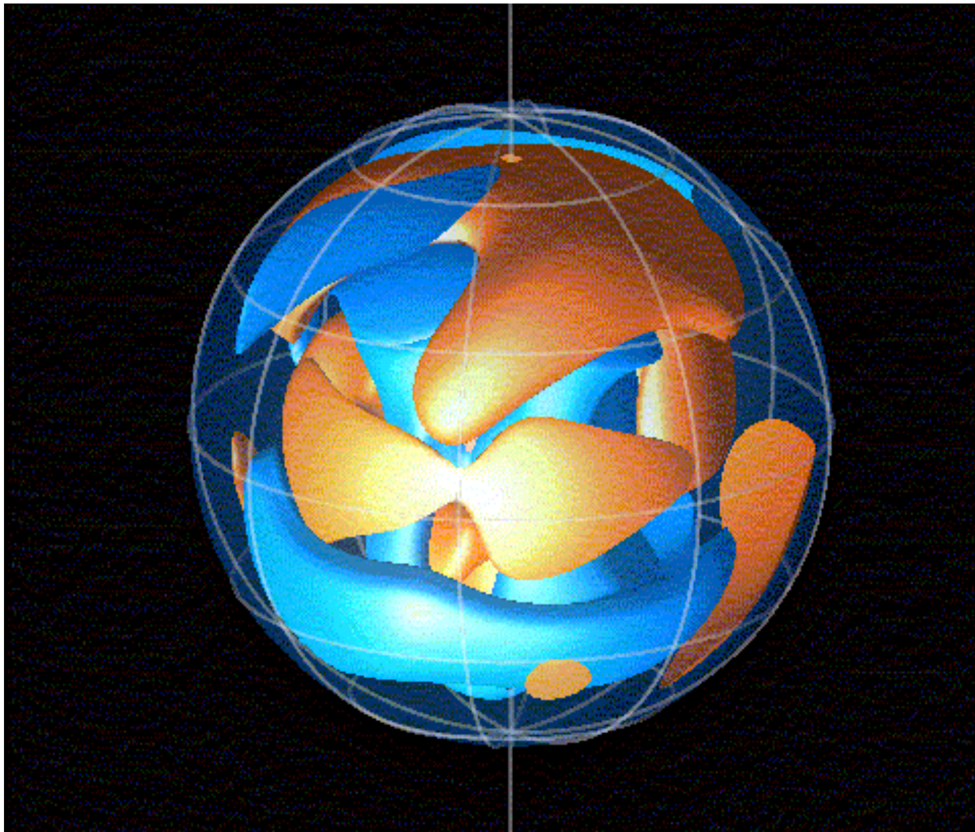


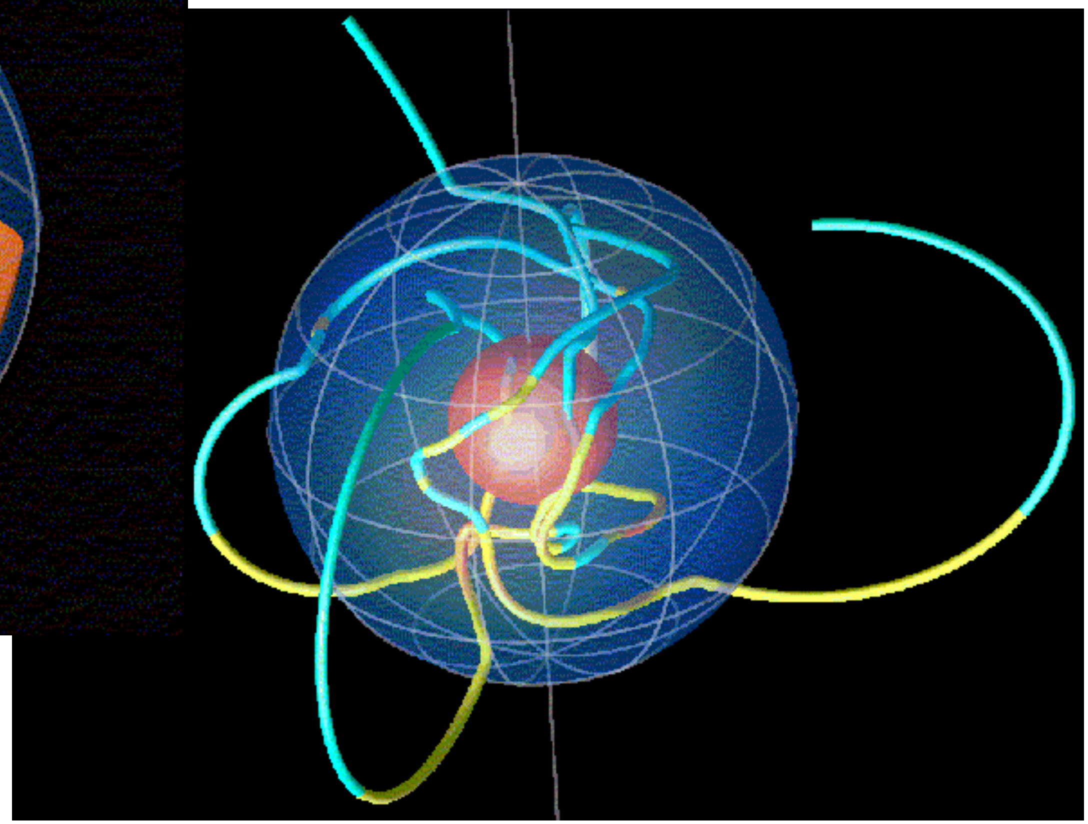


Since the peak of last great ice age, 20K years ago...

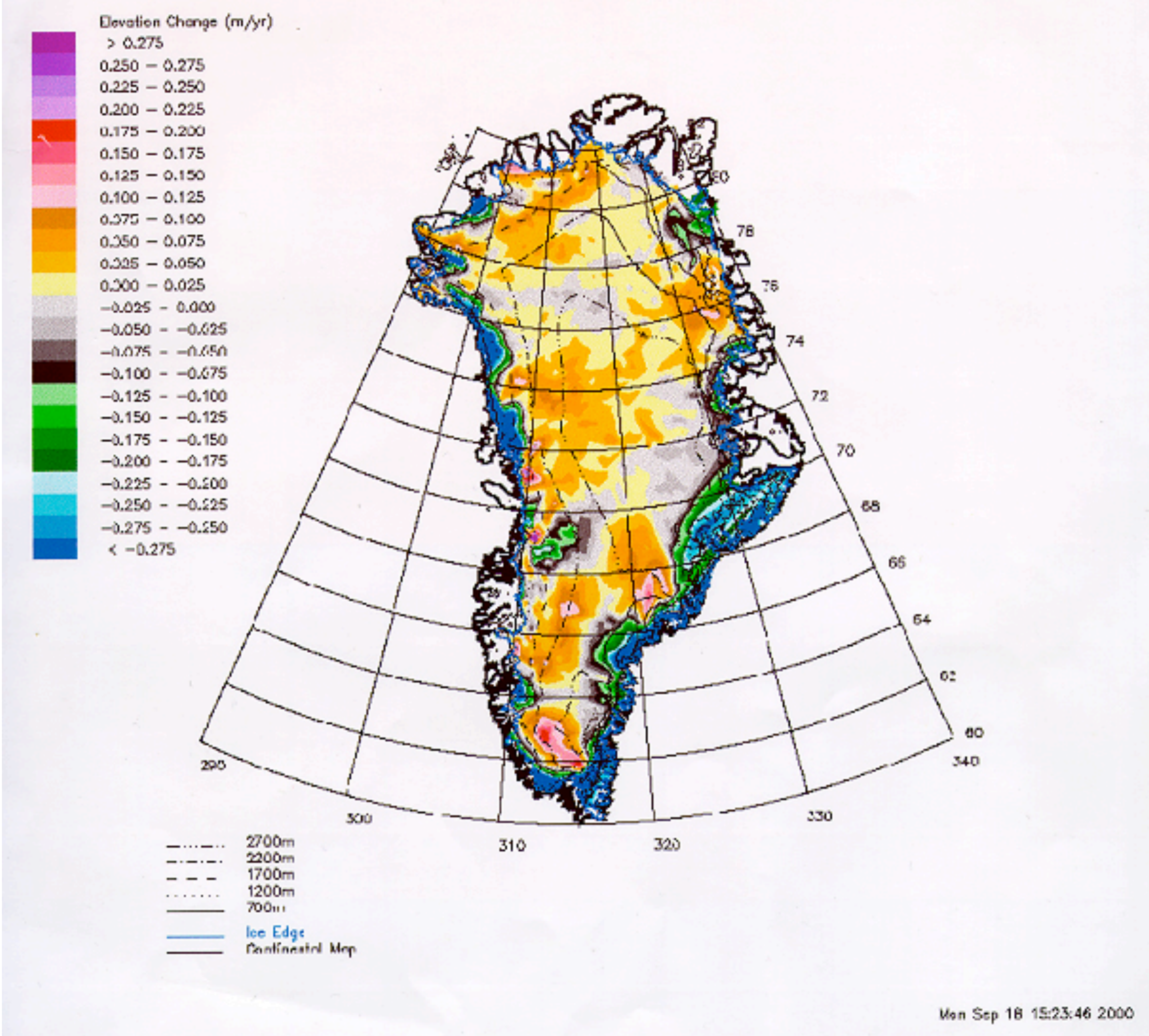


Fluid Core Motions and Geomagnetic Field



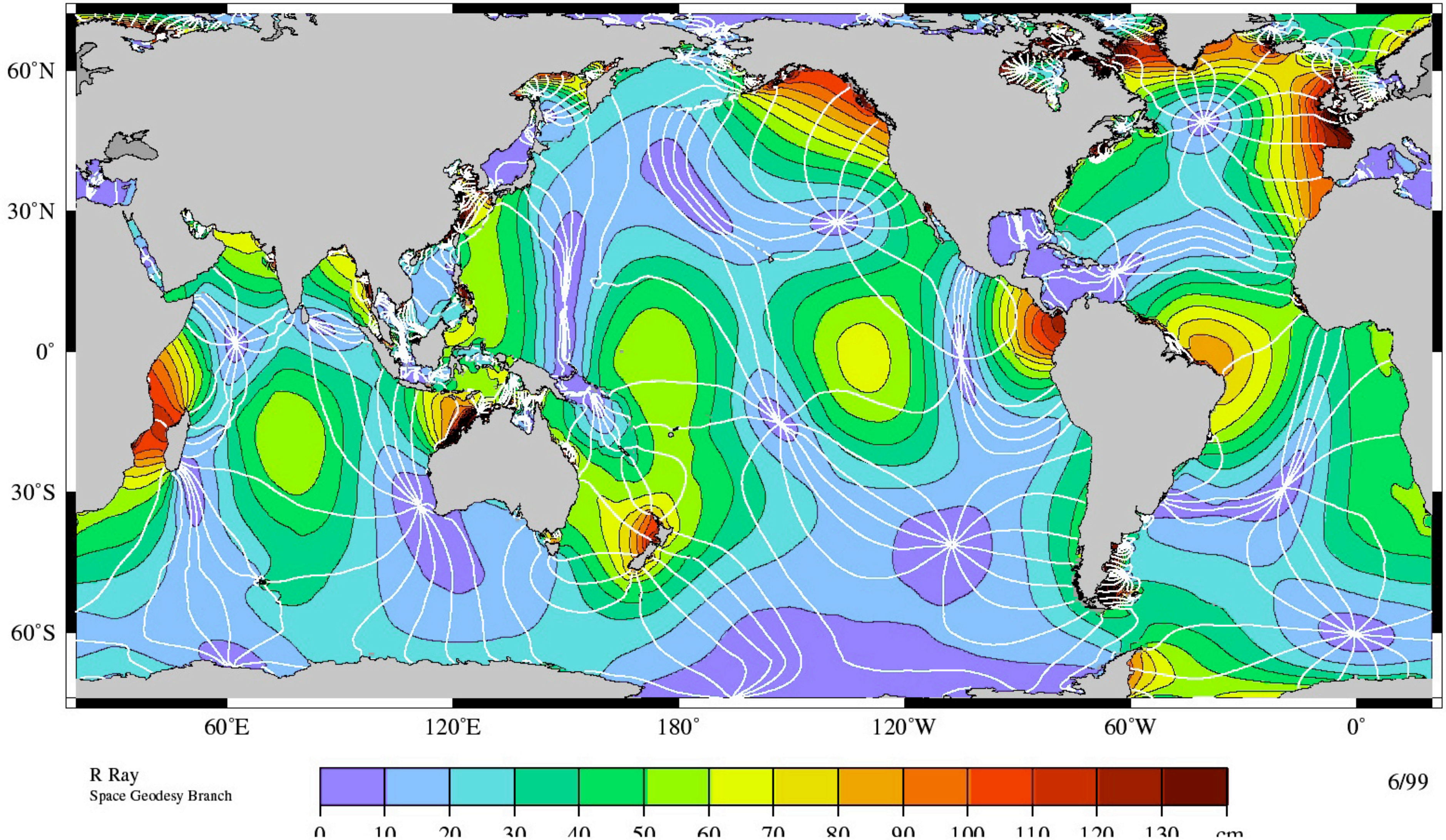


MoSST geodynamo model

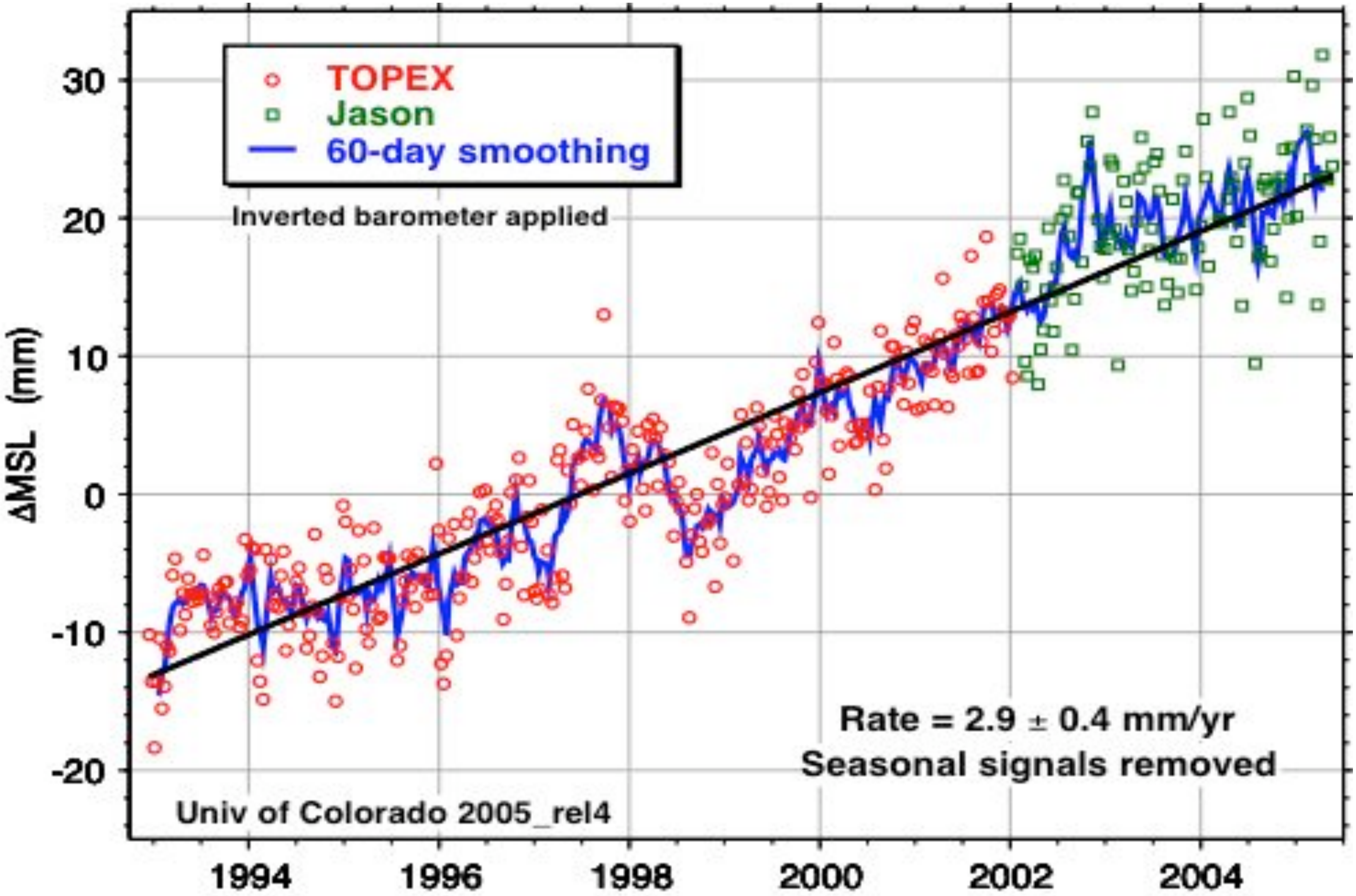


Elevation Change (m/yr)
> 0.275
0.250 – 0.275
0.225 – 0.250
0.200 – 0.225
0.175 – 0.200
0.150 – 0.175
0.125 – 0.150
0.100 – 0.125
0.075 – 0.100
0.050 – 0.075
0.025 – 0.050
0.000 – 0.025
−0.025 – 0.000
−0.050 – −0.025
−0.075 – −0.050
−0.100 – −0.075
−0.125 – −0.100
−0.150 – −0.125
−0.175 – −0.150
−0.200 – −0.175
−0.225 – −0.200
−0.250 – −0.225
−0.275 – −0.250
< −0.275
78
76
74
72
70
68
66
64
62
60
290
300
310
320
330
340
2700m
2200m
1700m
1200m
700m
Ice Edge
Continental Map
Mon Sep 18 15:23:46 2000

M_2 Lunar Tide in the Ocean



(GOT99, courtesy R. Ray)



Global Sea Level Rise From Topex/Poseidon

(courtesy S. Nerem)

The Three-Gorges Dam Project

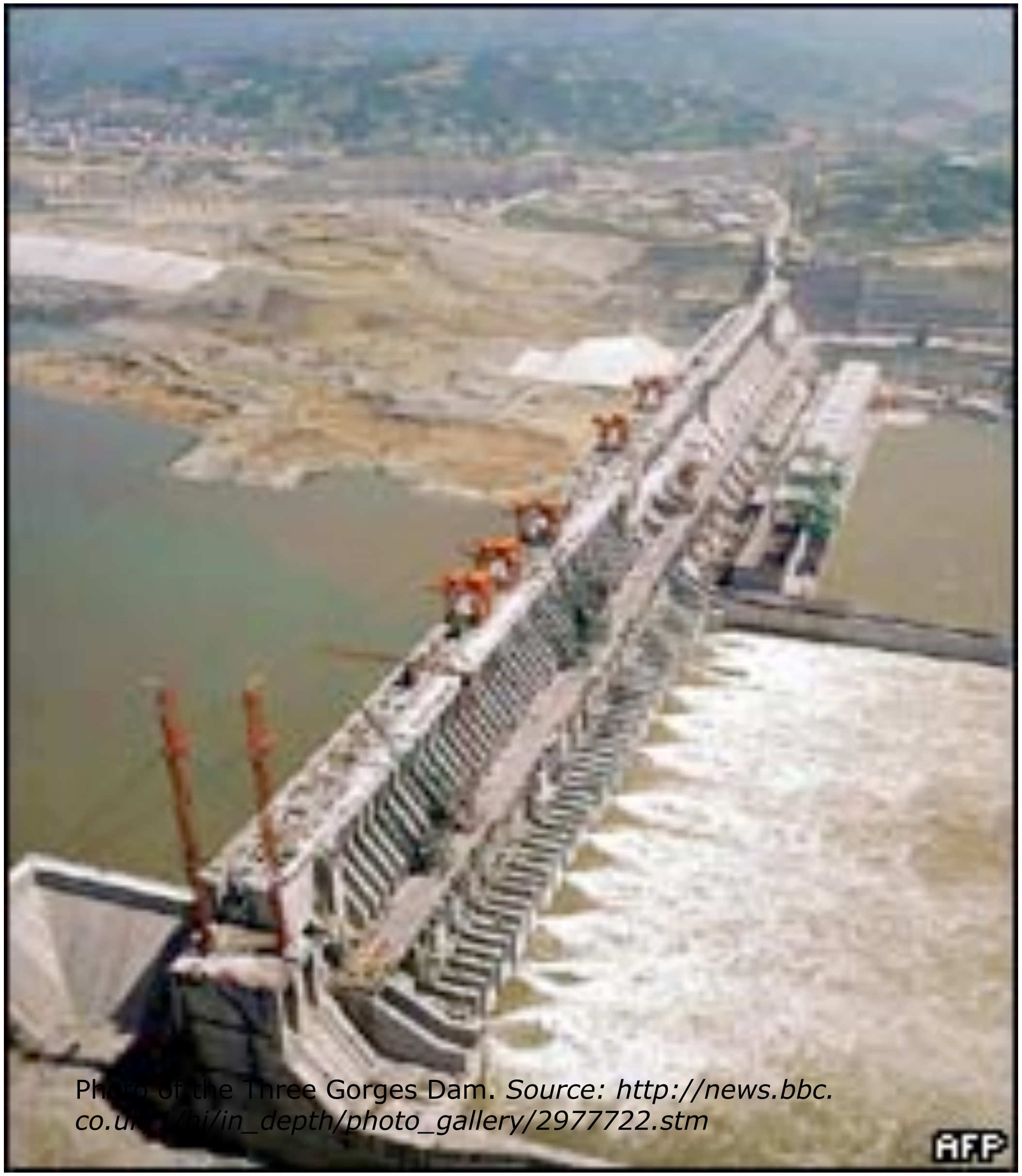


Photo of the Three Gorges Dam. *Source: http://news.bbc.co.uk/1/hi/in_depth/photo_gallery/2977722.stm*

History:

Dr. Sun Yatsen, 1917

Savage Report, 1940s

Debates in 1950-60s

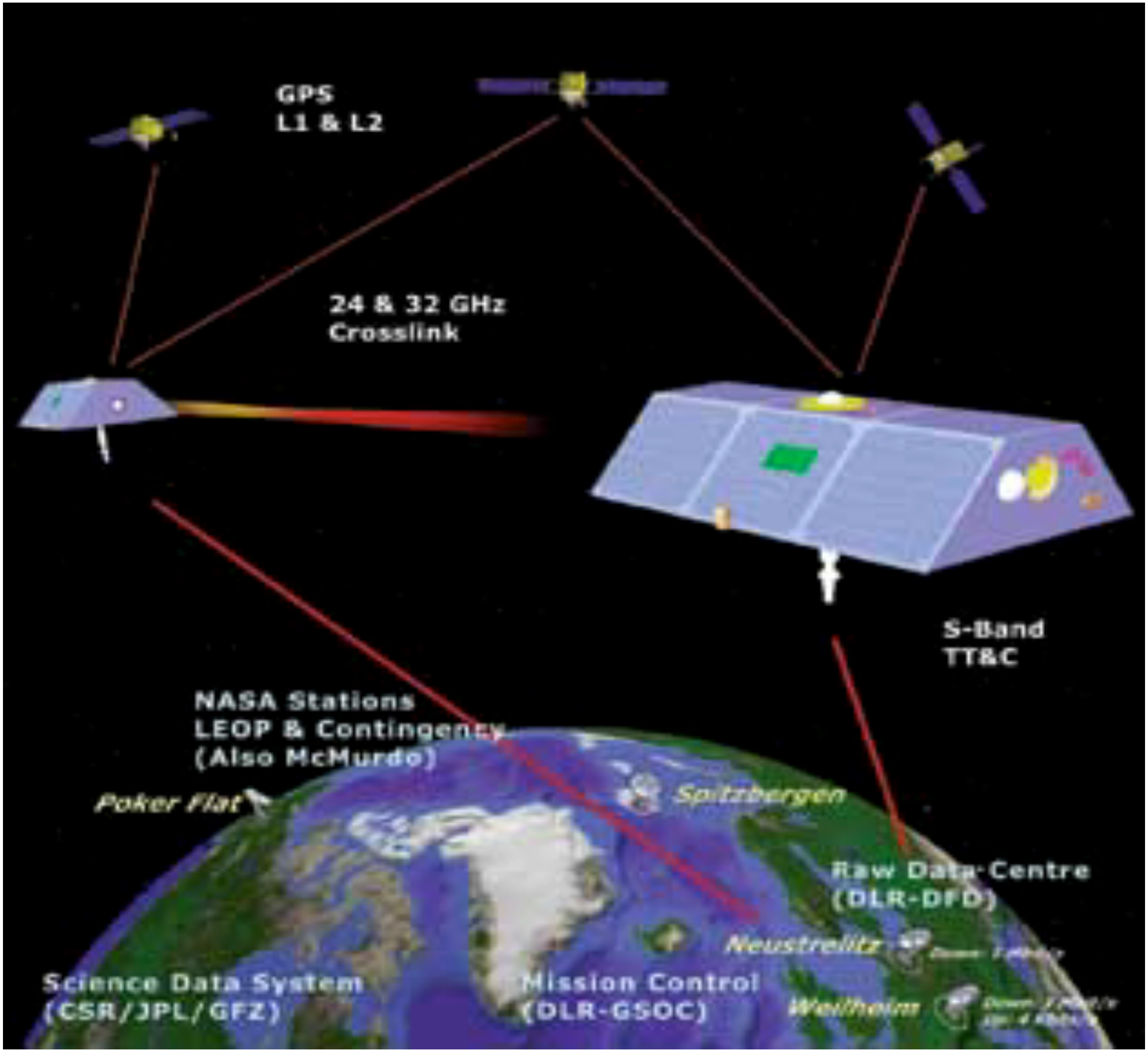
GeZhouBa Project, 1981

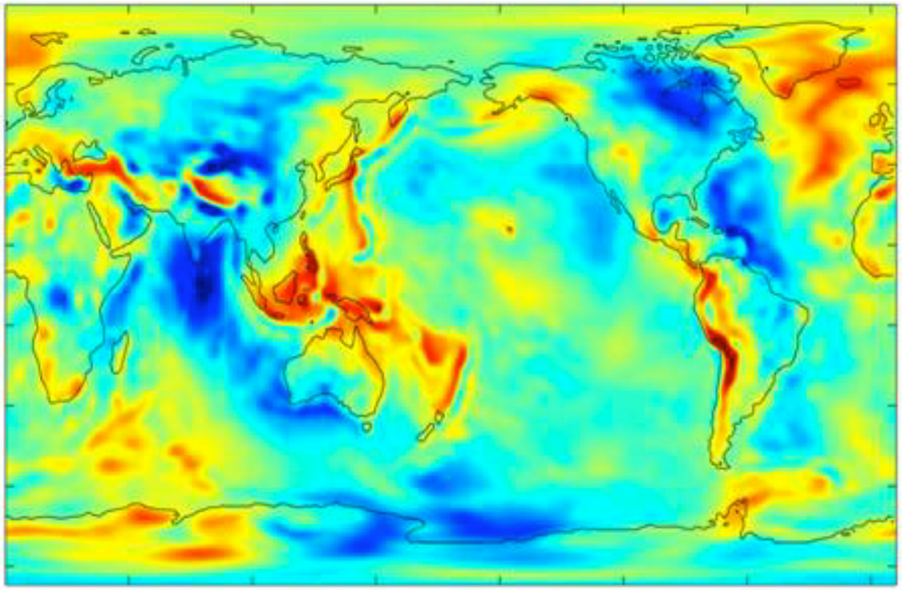
Three-Gorges Dam decided in 1992.

Phase 1 (1993-1997): Block the river and divert the flow.

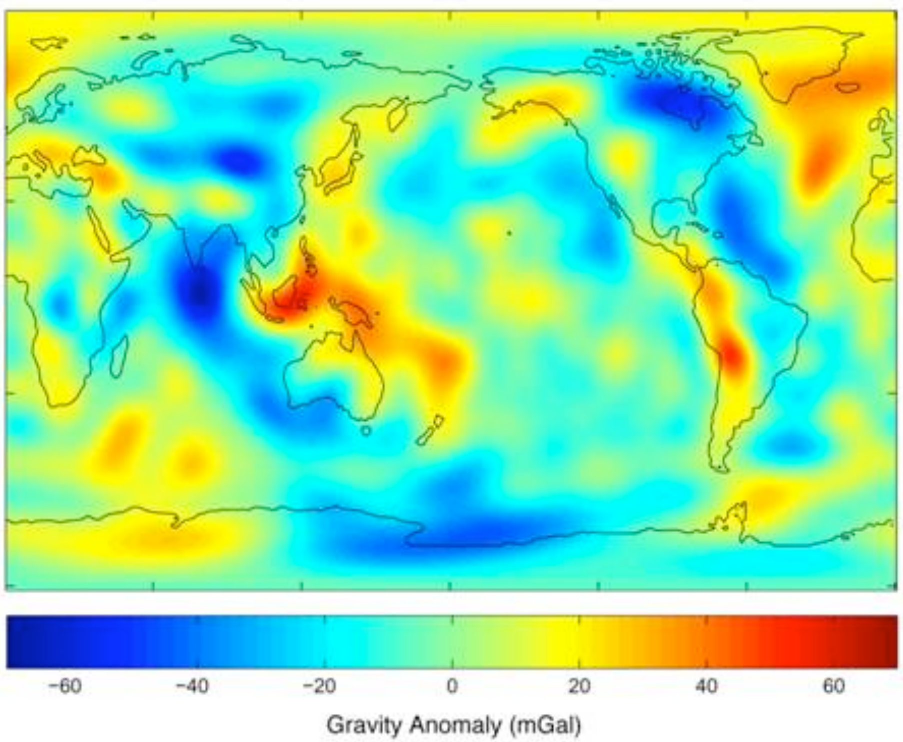
Phase 2 (1998-2003): First power generation units in operation and permanent boat locks. Also, the reservoir will begin to fill to a level of 135 meters.

Phase 3 (2004-2009): Put all generation units into operation. The height of the water will reach 175 meters high.

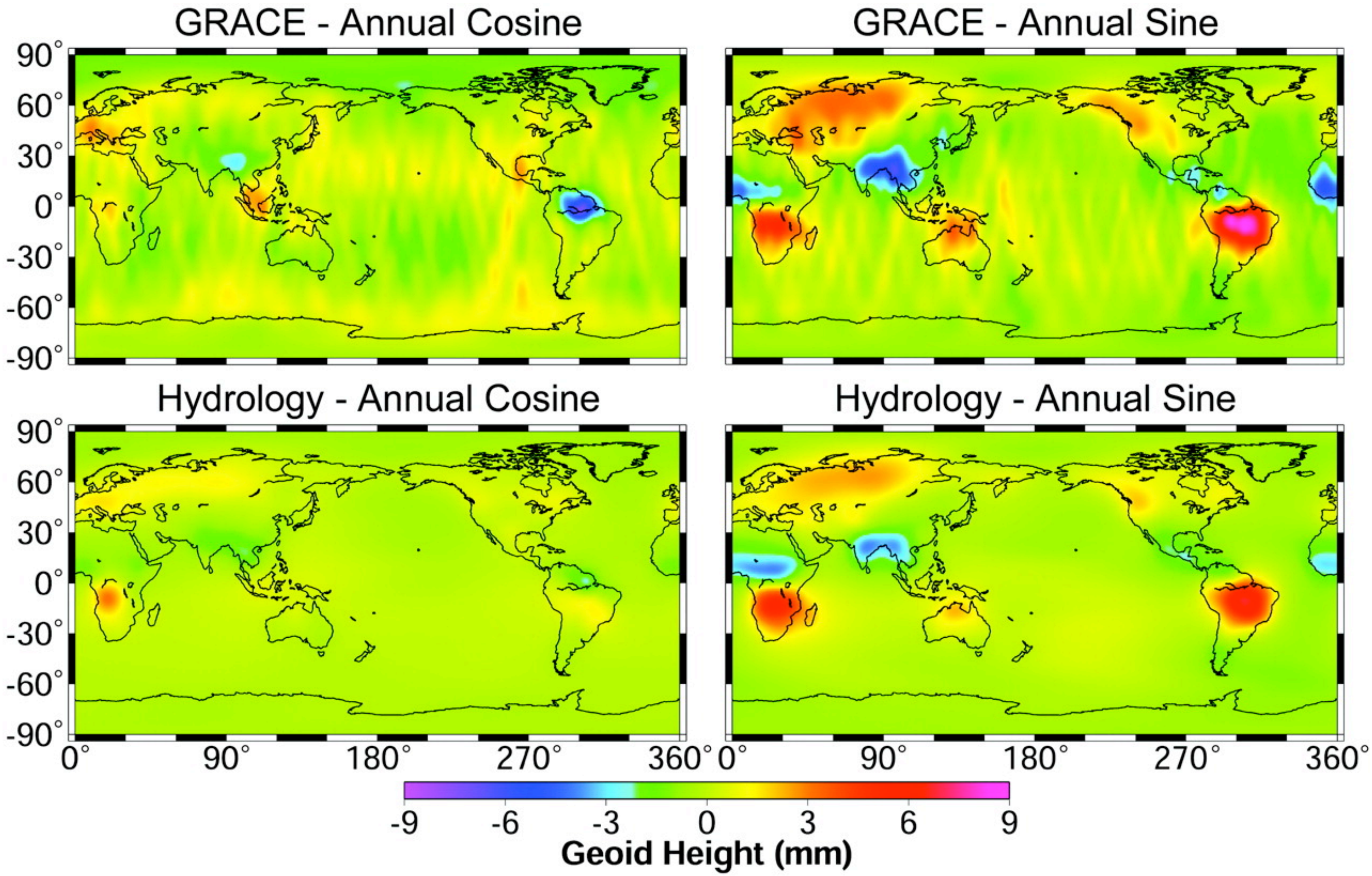

GPS
L1 & L2
24 & 32 GHz
Crosslink
S-Band
TT&C
NASA Stations
LEOP & Contingency
(Also McMurdo)
Poker Flat
Spitzbergen
Raw Data Centre
(DLR-DFD)
Neustrelitz
Science Data System
(CSR/JPL/GFZ)
Mission Control
(DLR-GSOC)
Weilheim



GRACE (2002 -)
gravity map



pre-GRACE (~ 40 years)
gravity map



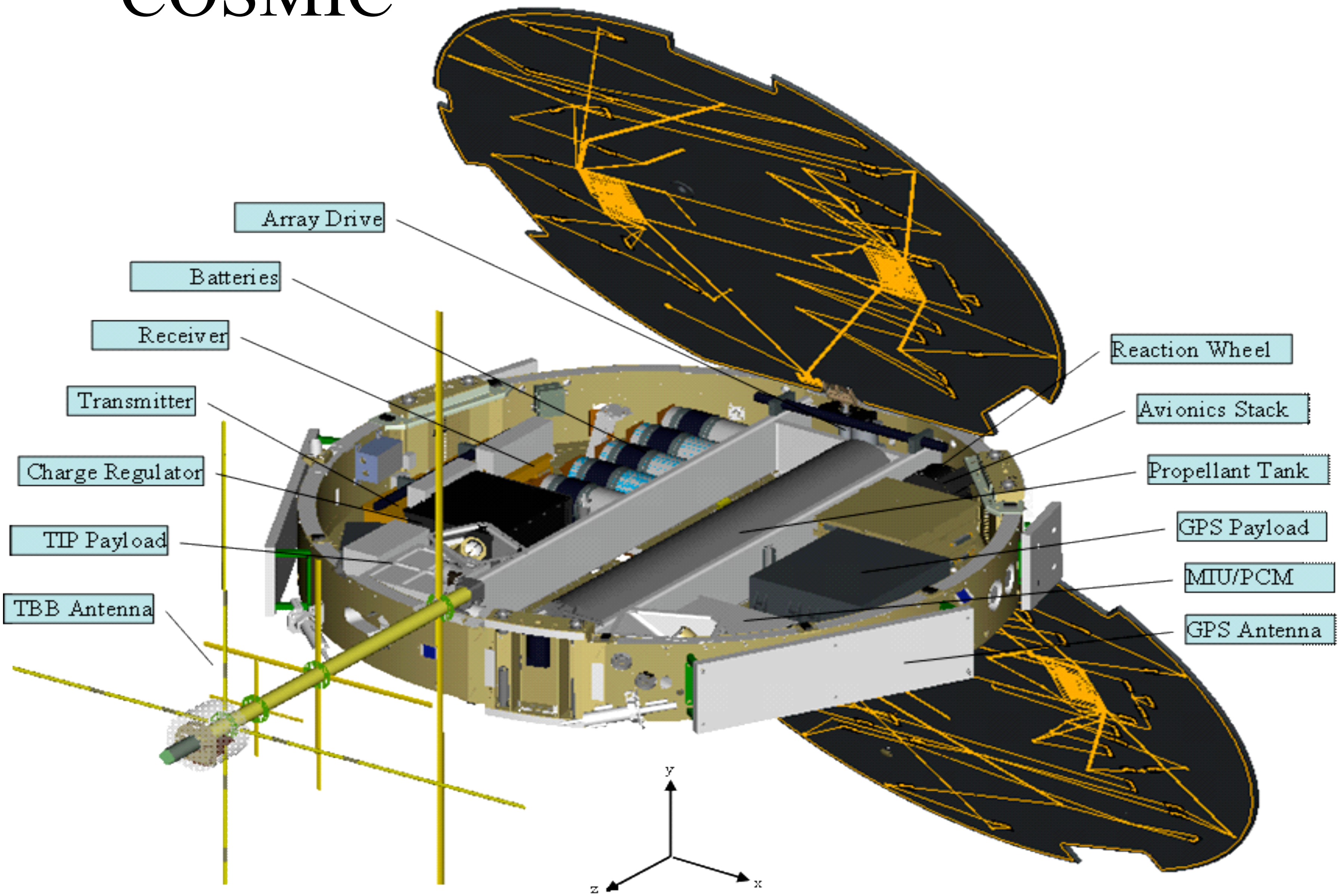
Tapley et al. (2004)

What are troubling GRACE?

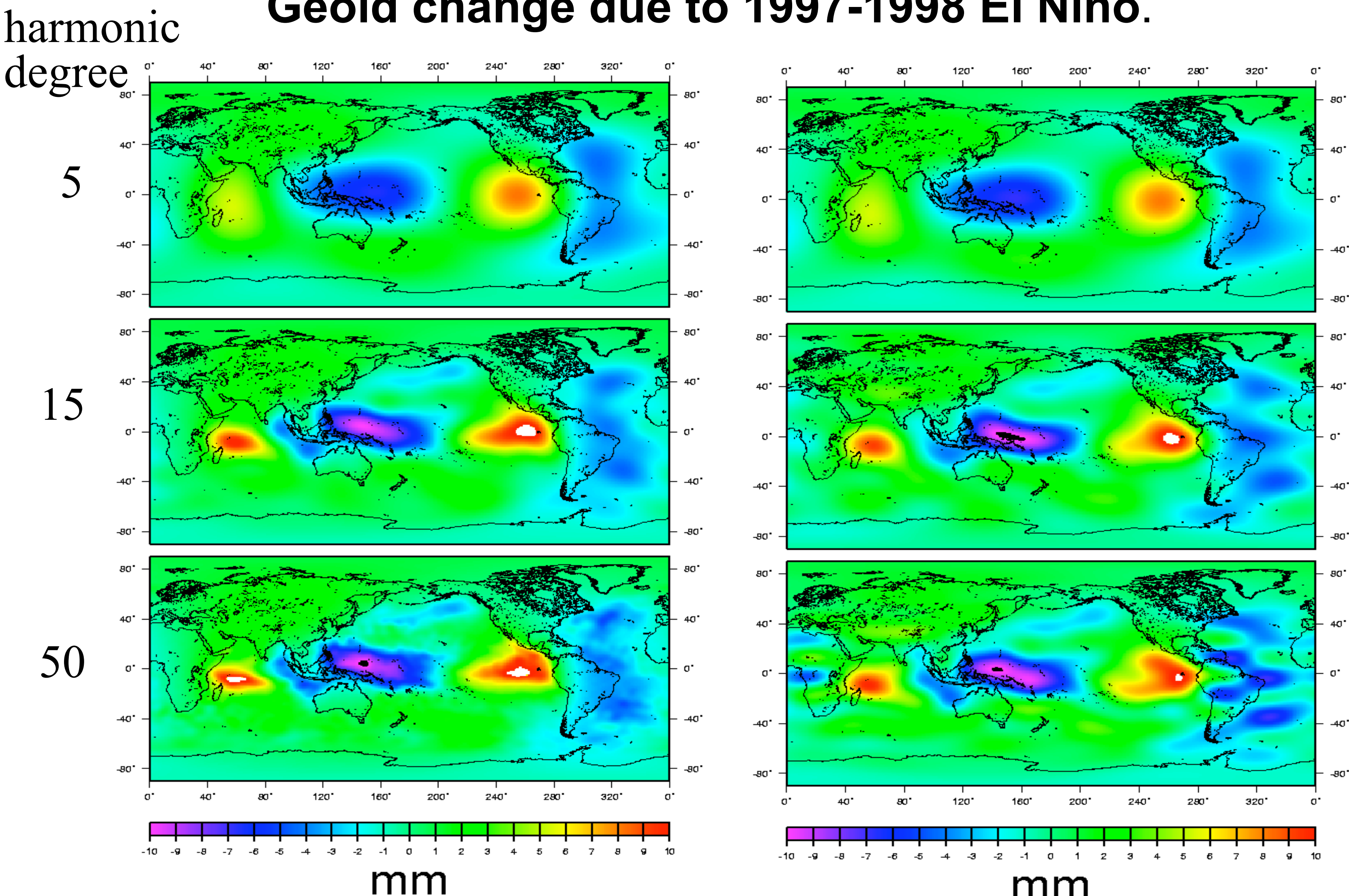
(other than "usual" on-board noise sources)

- Nominal temporal resolution is too long, ~1 month (can tradeoff with precision to ~ 10 days).
- Geophysical signals with period shorter than ~1 month become aliasing errors: atmospheric pressure, oceanic mass transports, tides, hydrological mass…
- Spatial resolution hardly finer than ~500 km, realistically 1000-1500 km.
- Wishful accuracy in surface mass variation is sub-cm equivalent water thickness for the above spatial and temporal resolution, but realistically >1 cm.

COSMIC


Array Drive
Batteries
Receiver
Transmitter
Charge Regulator
TIP Payload
TBB Antenna
Reaction Wheel
Avionics Stack
Propellant Tank
GPS Payload
MTU/PCM
GPS Antenna
y
z
x

Geoid change due to 1997-1998 El Niño.



Input "data"

Simulated "recovery" by 1-week of COSMIC data

(Hwang, 2005)

Gravity from COSMIC

- **Orbit**
  - Number (+) (6 after differential nodal precession)
  - Altitude (–,+) (800 km, attenuation)
  - Inclination (+,–) (71º, polar hole)
- **POD data** amount & homogeneity (+)
- **Spatial sampling** (+) (6 orbit plans)
- **Temporal resolution** (+) (6 orbit plans)
- **Accuracy** limitations
  - No accelerometer for non-gravitational force correction (–)
  - GPS/LEO orbit errors and data noise (–)
- **Time span**
  - Relative to GRACE etc. (–,+)
  - Solar max/min (+)
- **Latency**: week-months (?)