

Calibration and Traceability of the GRACE Measurements

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SI-Traceable Space-based Climate Observing System

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**National Physical Laboratory,
Hampton Road, Teddington**

TW11 0LW
United Kingdom



Gravity and Mass Change

The Earth's mass varies as geodetic *position* changes and as *time* changes

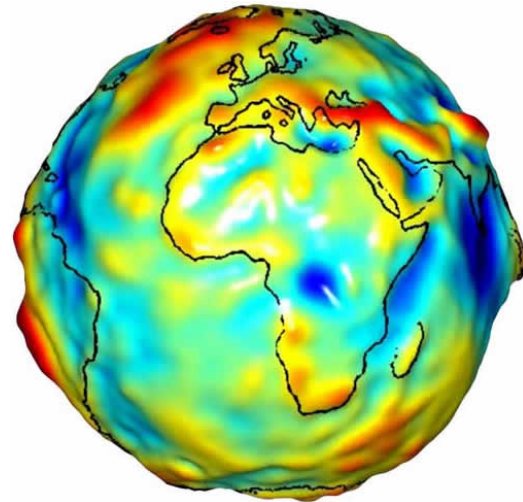
Mass has a gravitational effect.

The gravity signal will vary as position changes and as time changes

Repeated global observations of gravity can be used to infer the spatial and temporal variations of the Earth's mass.

The gravity signal associated with the spatial variations is much larger than the temporal variation signal

The gravity induced signal from mass variations provides essential information for understanding the processes involved in Earth System Dynamics



The GRACE Mission

An ESSP Mission focused on observing the Earth System Interactions through the mass change signal

Launched: March 17, 2002

Initial altitude: 485 km

Nominal mission: 5 years

15.5 years in orbit (5686 days)

90,976 orbits around the earth

Science Data

163 monthly solutions

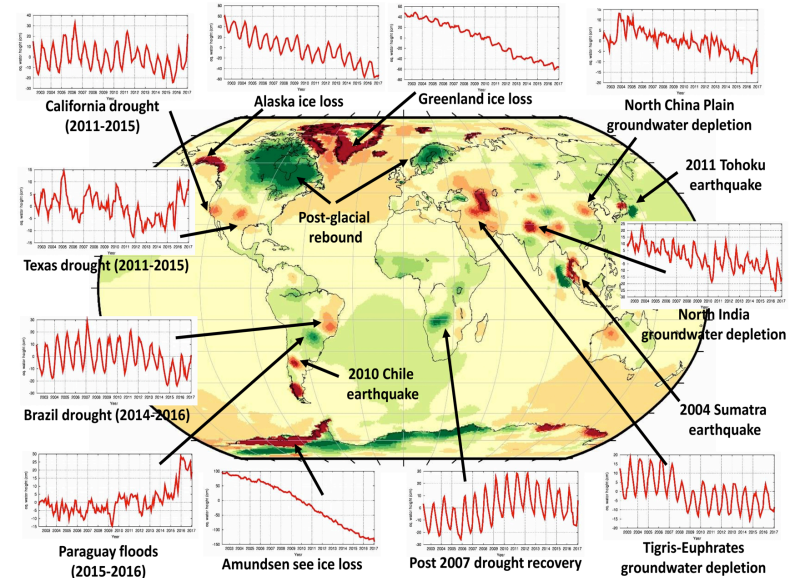
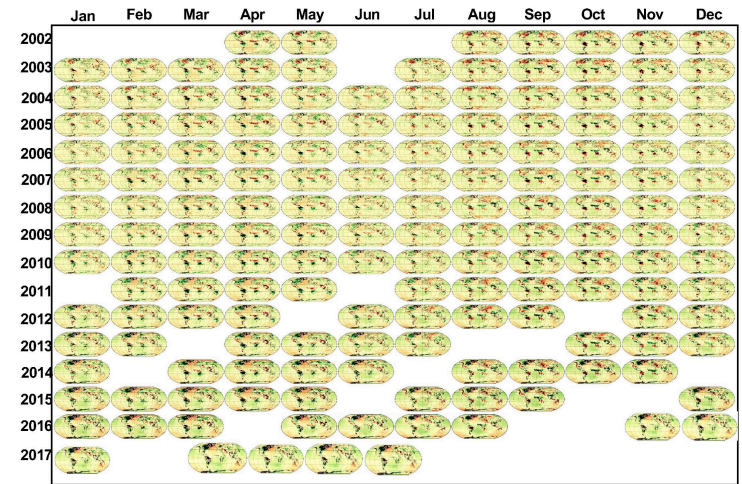
Satellite only Degree and Order 180 Mean Field

Higher D/O mean fields after combination with GOCE and Surface Gravity

Established time varying gravity as a proxy for Earth System mass change

Demonstrated importance of mass change as an Essential Climate Variable

Stimulated highly important interdisciplinary science investigations

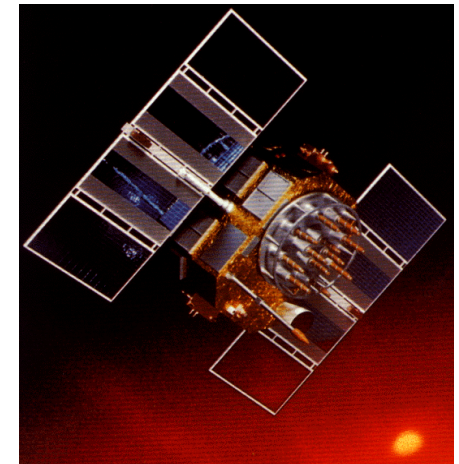
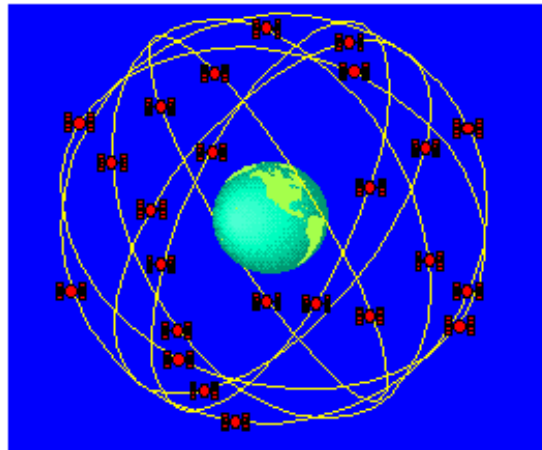
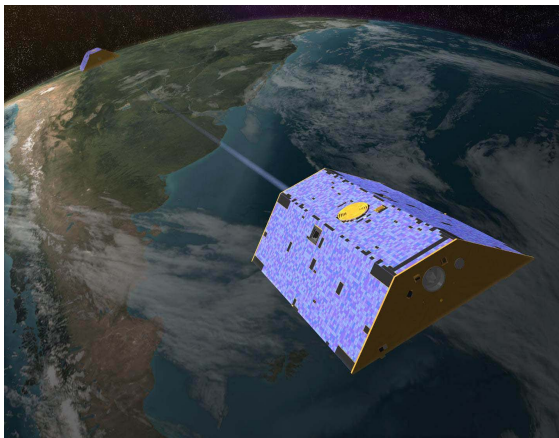
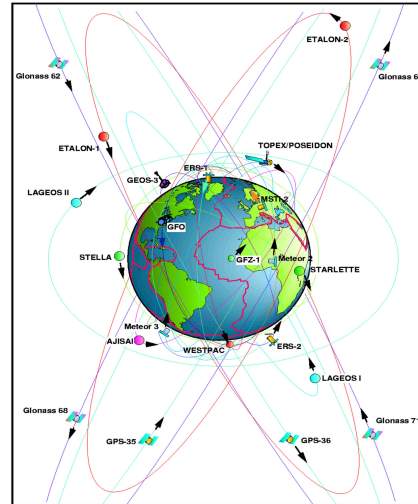
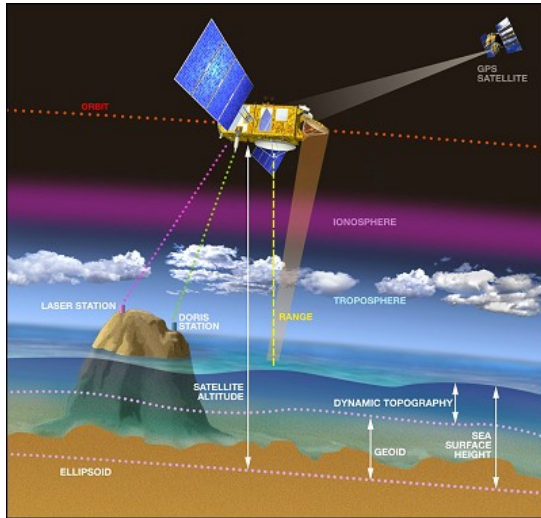


Trend signals in GRACE data from April 2002- Jan 2017

Some Comments on the GRACE Measurement

- The GRACE observation concept is **not a traditional remote sensing** approach.
- The **primary observation is distance** between two co-planar satellites, flying in loose formation. The **repeated observation of this distance** is used to **interpret the range change in terms of the gravity acceleration** acting on each satellite
 - **Satellites are the instruments; the instrument characteristics change during the mission**
 - The **primary observations** are **assimilated into a model** for the science products
 - **Gravity** science signal is imbedded in a **number of other satellite accelerations**
 - To interpret the range observation in terms of the science questions, there is a requirement for **eight primary observation sets**; four from each satellite(**HAIRS, ACC, SCA, GPS**)
 - In a laboratory environment, **each primary observation is SI Traceable**
 - There is a **significant challenge to replicating laboratory conditions “on orbit”**
 - Consequently, **On-Orbit Calibration is necessary** to satisfy observation requirements.
- The **transfer of the primary observation set into the science products involves a complicated process, involving a number of non-GRACE observations.**
- Finally, the **GRACE results** are presented as **surface based images**, but the images are **created from a mathematical model** whose **parameters are estimated** from the GRACE Observations

SI Traceability and Satellite Geodesy

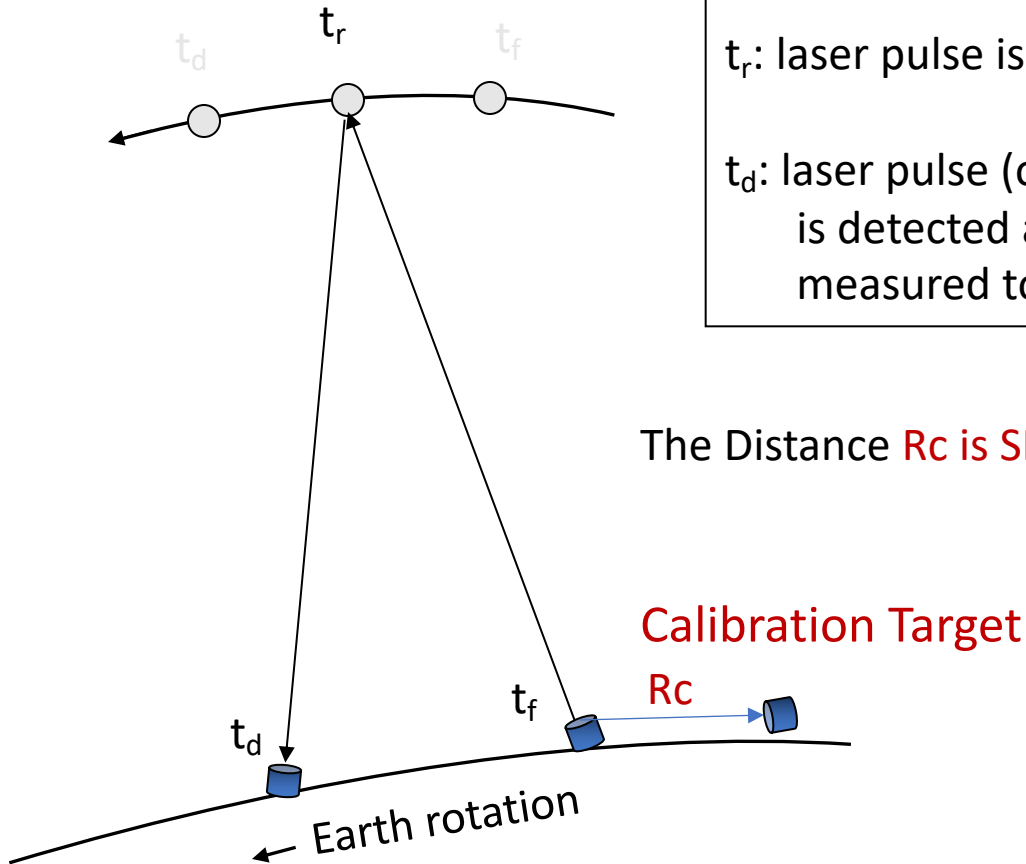


SI Traceability for Satellite Laser Ranging

t_f : an ultra-short laser pulse is fired

t_r : laser pulse is reflected by satellite

t_d : laser pulse (or just a single photon) is detected and the interval $(t_d - t_f)$ is measured to 10-100 picosec accuracy



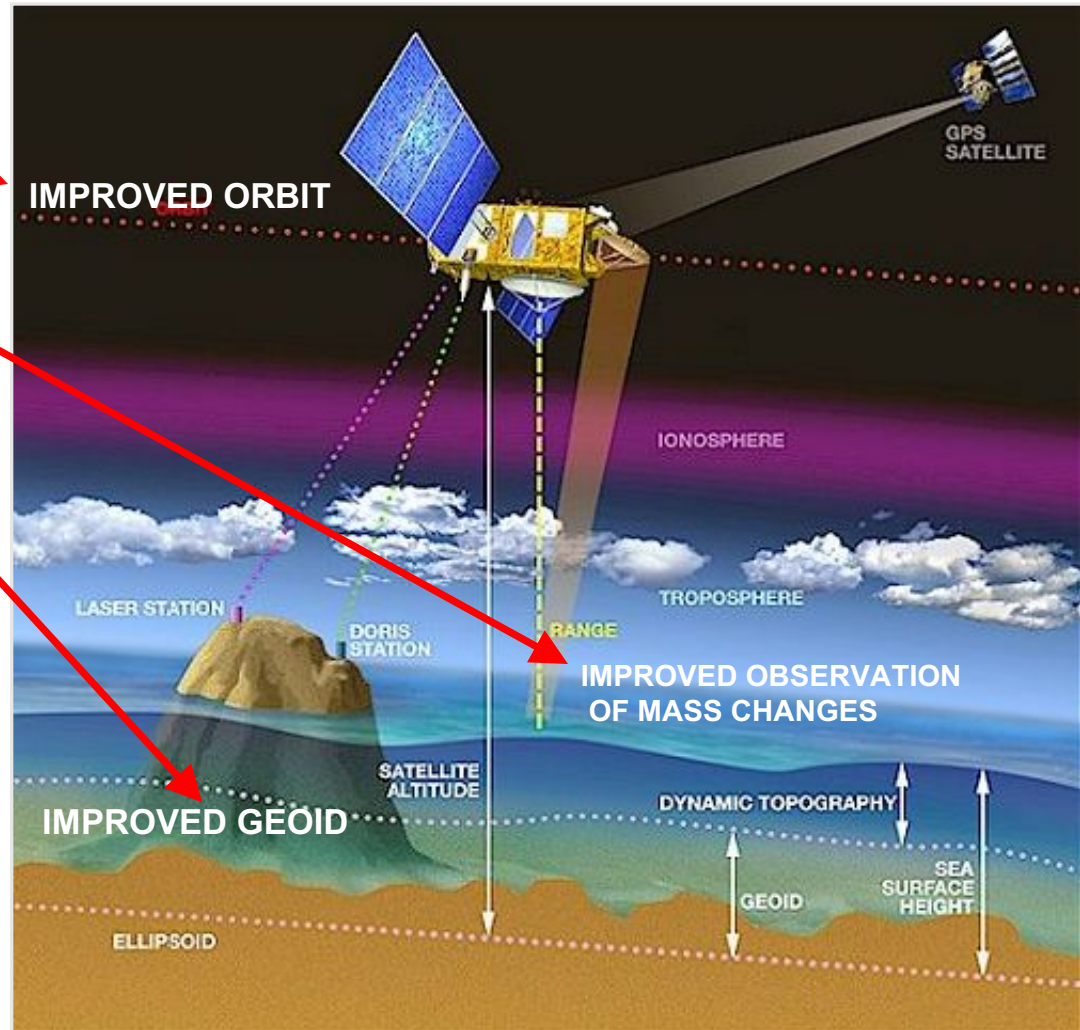
total round-trip light-time may be just a few milliseconds or more than 2 seconds (for lunar laser ranging)



SI Traceability for Ocean Altimetry

GRACE Mission Impact

The overflight of a surface based SLR system, that has satisfied SI Traceability, can calibrated the Radar altimeter



Elements of the Process

Collection of the Primary Observations

- Satellite Based

- Aging effects

- Issues of stability and calibration

Conversion into the Gravity Potential Model

- Ground based data center

- Reprocessing Techniques

- Evolving Standards

Interpret as Science Processes

- Community data processing centers

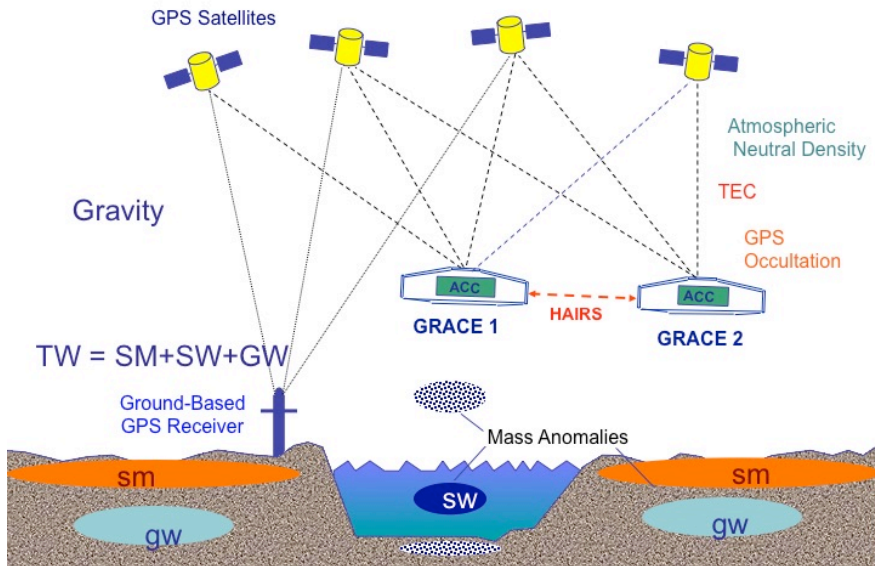
- Non-Unique results and comparative analysis

The GRACE Mission is responsible for the first two elements

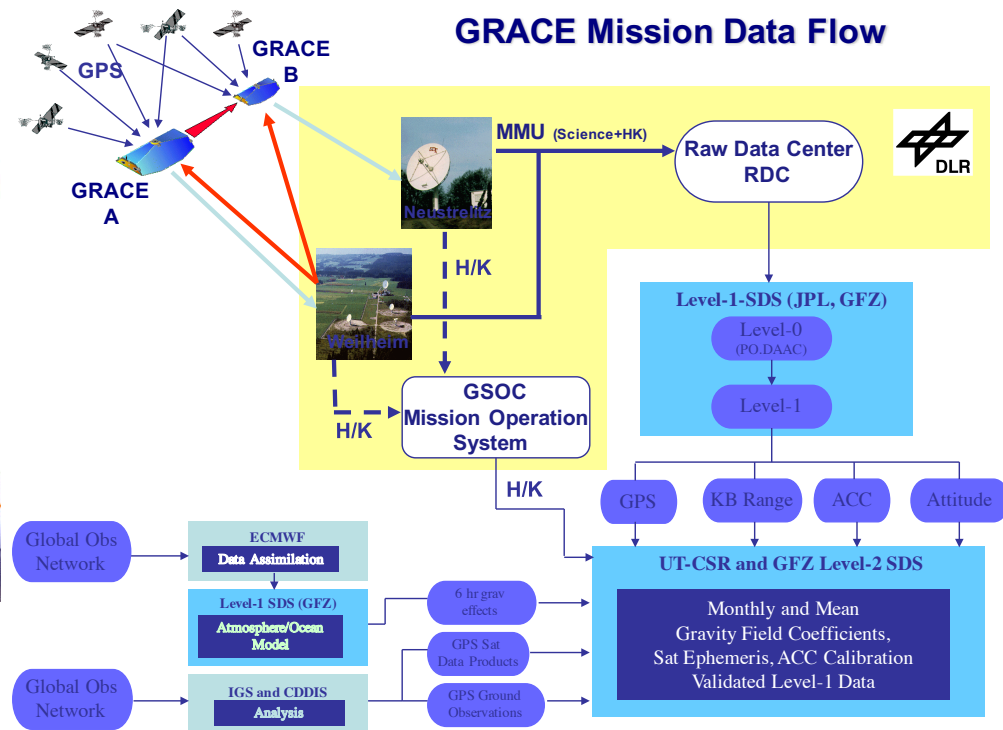
The GRACE FO Mission extends into all three elements

The GRACE Mission

Grace Mission Concept



GRACE Mission Data Flow



The primary mission objectives are to measure:

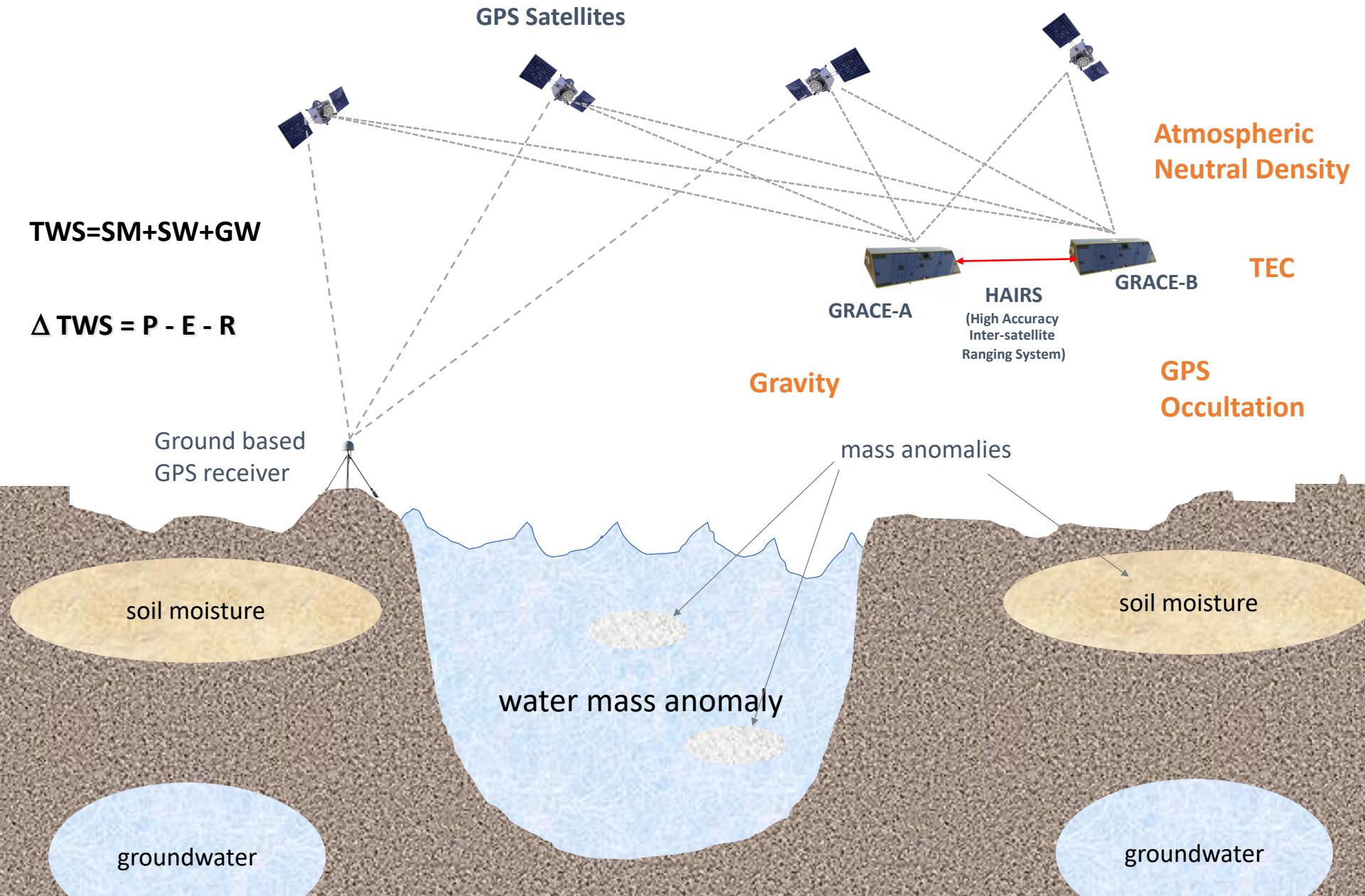
- 1) The Earth's *time-averaged (Mean) gravity field* and
- 2) The *Monthly variations* in the Mean field.

The *mean* field provides information on the *spatial variation* of the Earth's mass while the *monthly* departures from the mean provide *both spatial and temporal* Earth System mass variation.

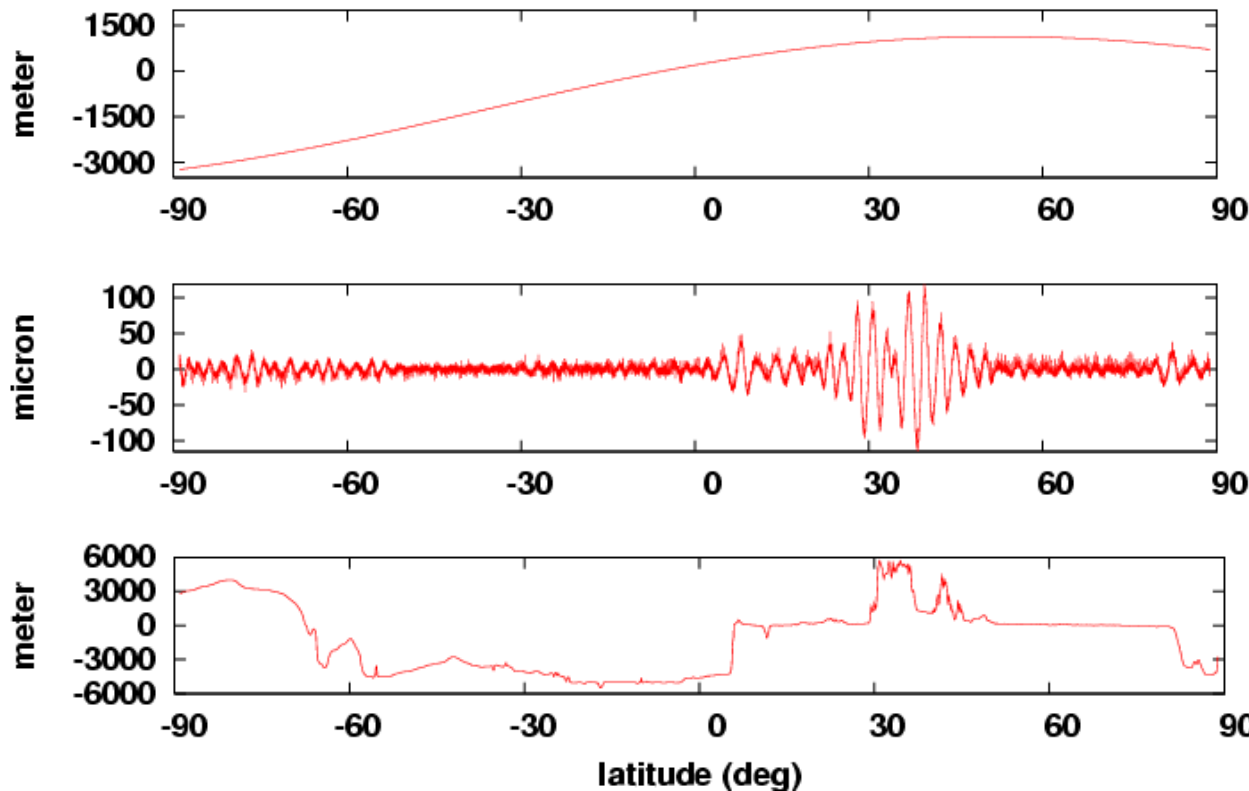
The objectives are accomplished by *measuring globally the gravity induced satellite response to the Earth's mass distribution during monthly repeat intervals.*

GRACE Measurement Concept

ACC measures the non-gravitational forces to allow focus on gravitational effects



High Frequency Content of KBR Dual One-Way Range Measurement



**Full KBR
Range - Bias**

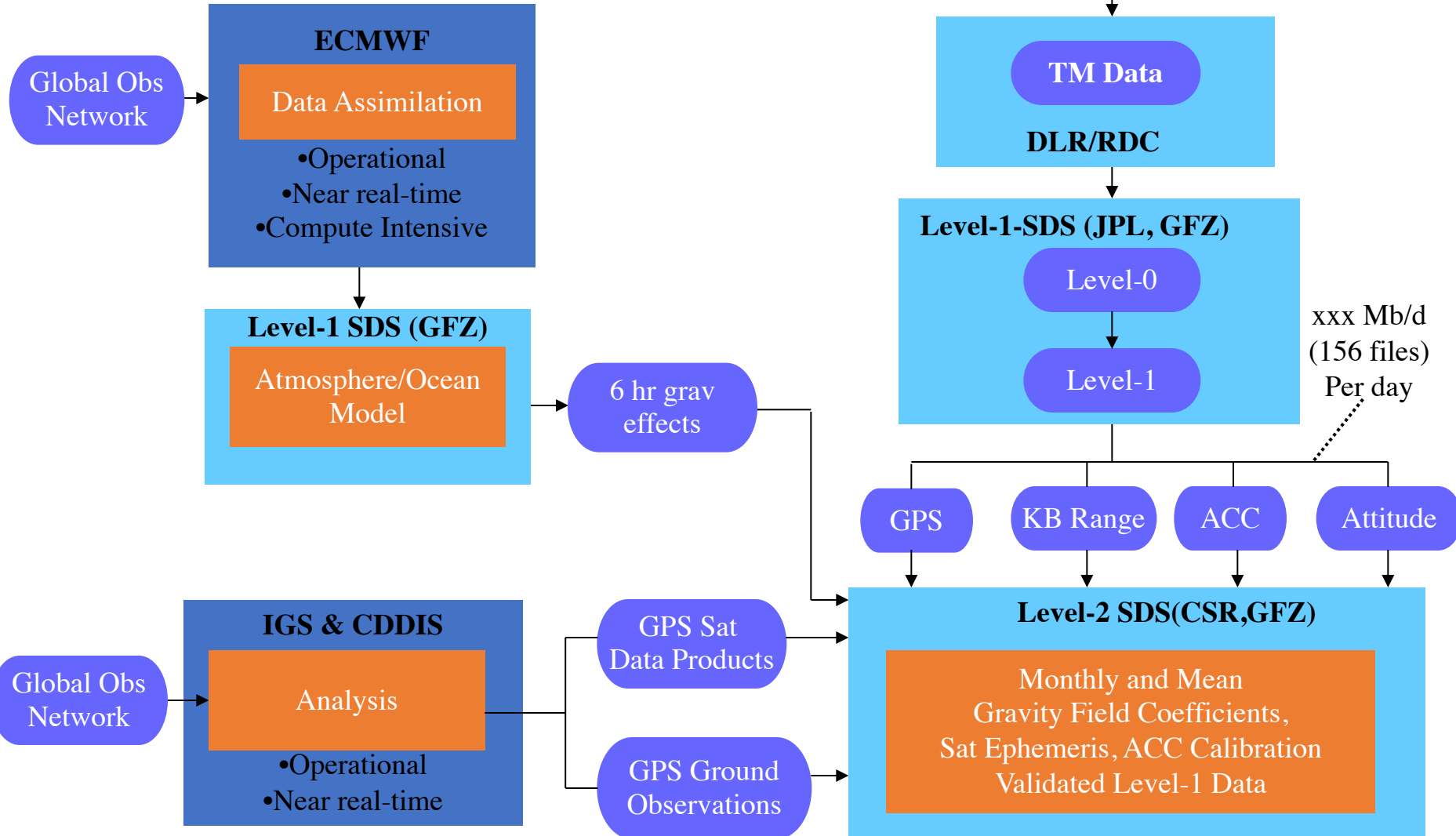
**Cubic Spline Residual
(30 second knots)**

**Topography
Along Groundtrack**

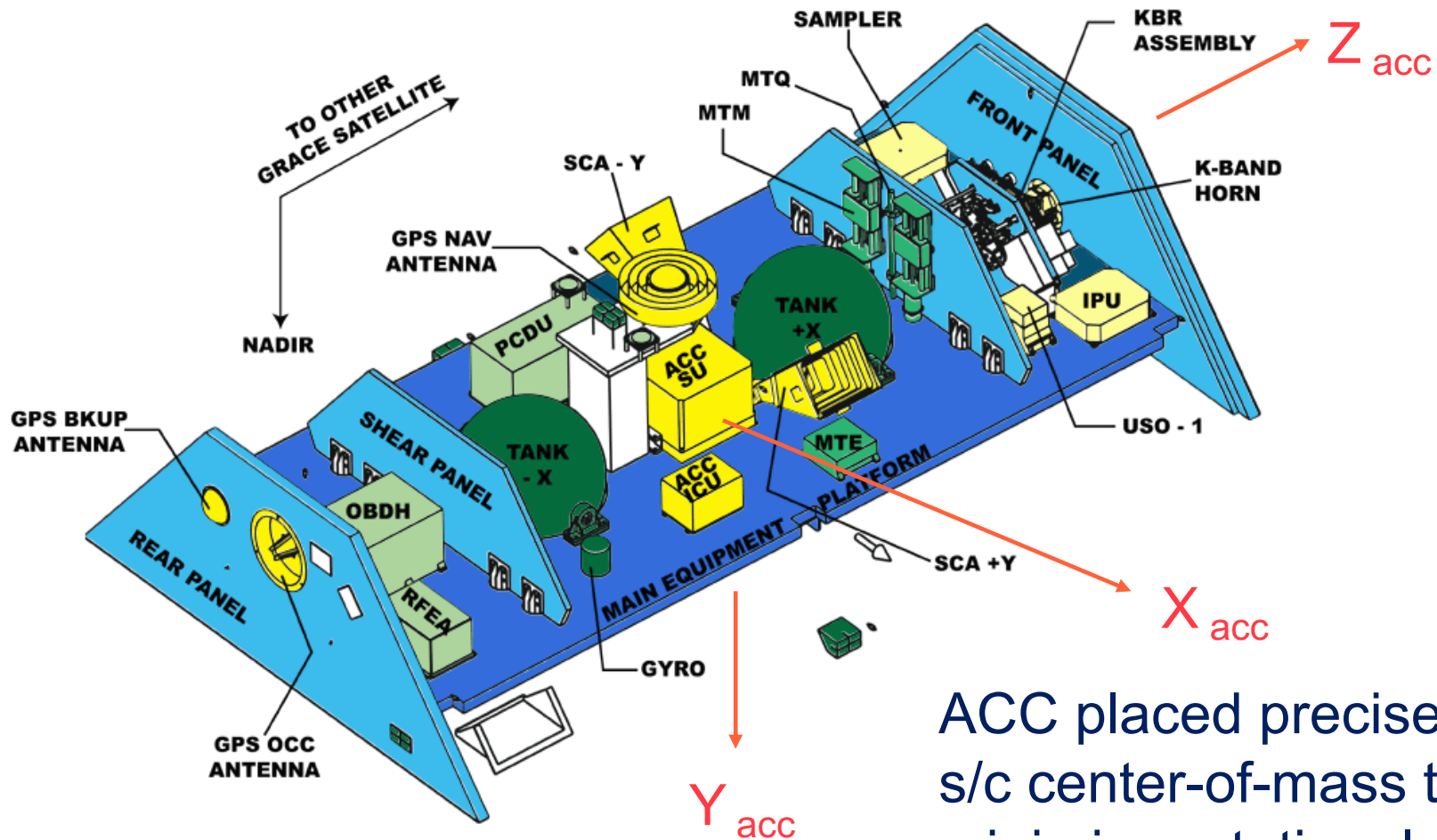
The global set of micron level range measurements can be used to define a model for the Earth's gravity field

GRACE Mission Data Flow

GRACE Satellites



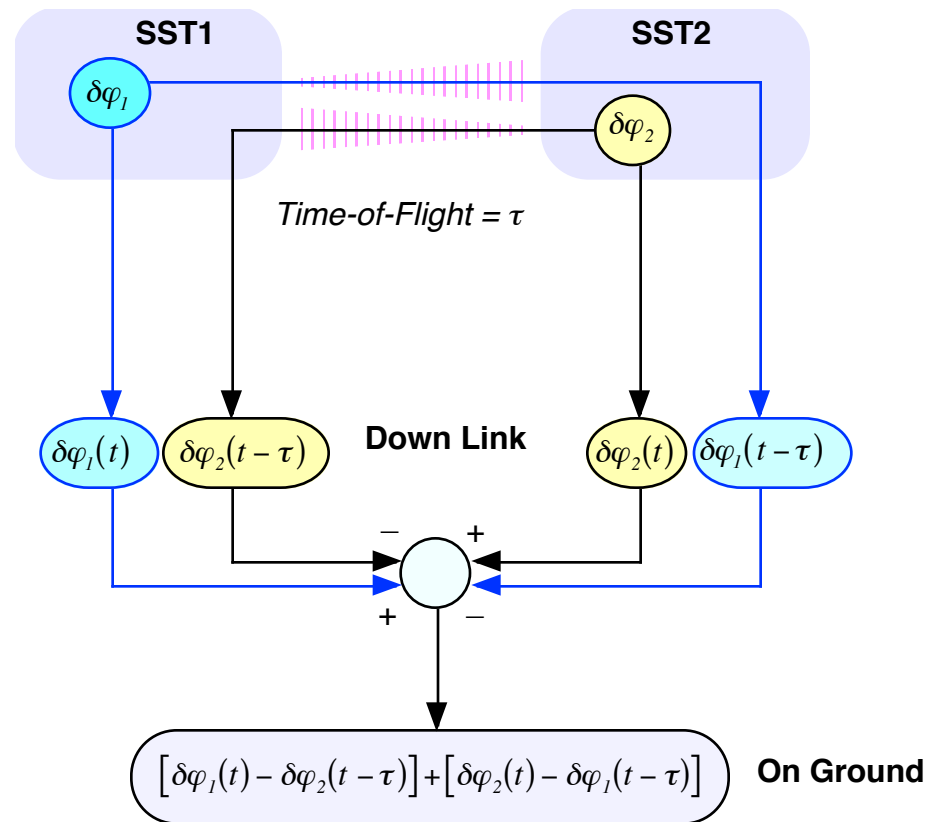
GRACE Satellite Interior



ACC placed precisely at s/c center-of-mass to minimize rotational and gravity-gradient signals

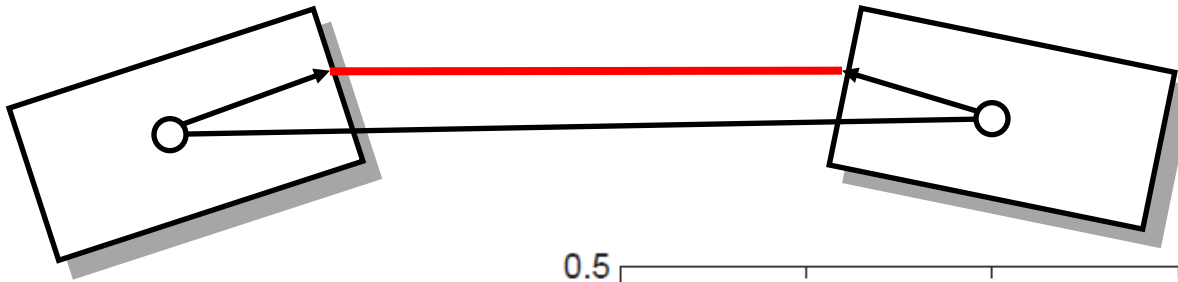
Dual One-Way Ranging

- Concept is used to reduce oscillator noise by differencing
- SST1's noise is contained in both SST1 & SST2 Measurements.
- Differencing process removes most of the oscillator noise.
- *Each one-way phase measurement is similar to GPS phase measurement*
- *Dual-frequency (24 & 32 GHz) measurements*
- *The range-change (& hence gravity) information is implicit in the time-of-flight*
- *Derivatives of range are numerically obtained in data pre-processing*



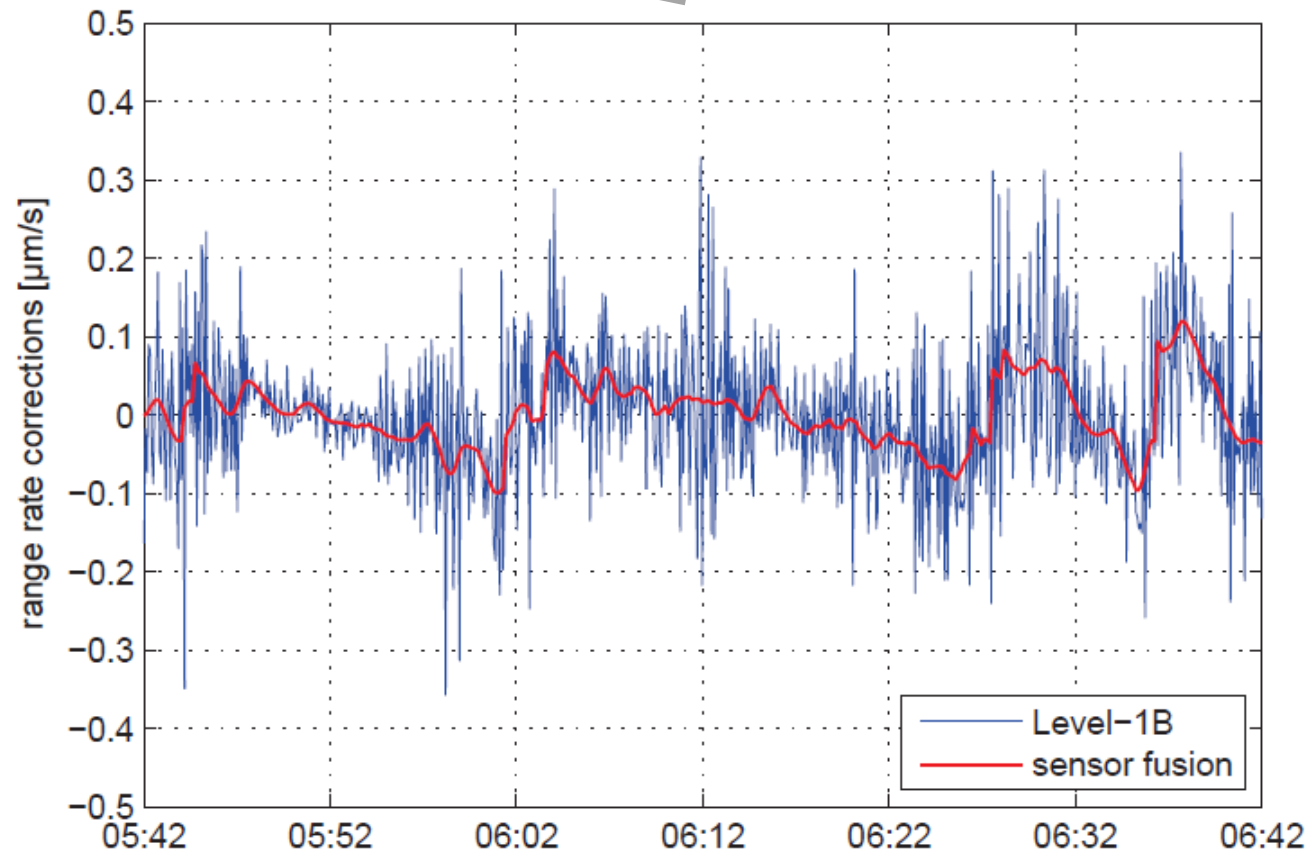
Corrected Biased Range = biased range + light time correction + antenna offset correction

Star Camera/Accelerometer Fusion (2/2)



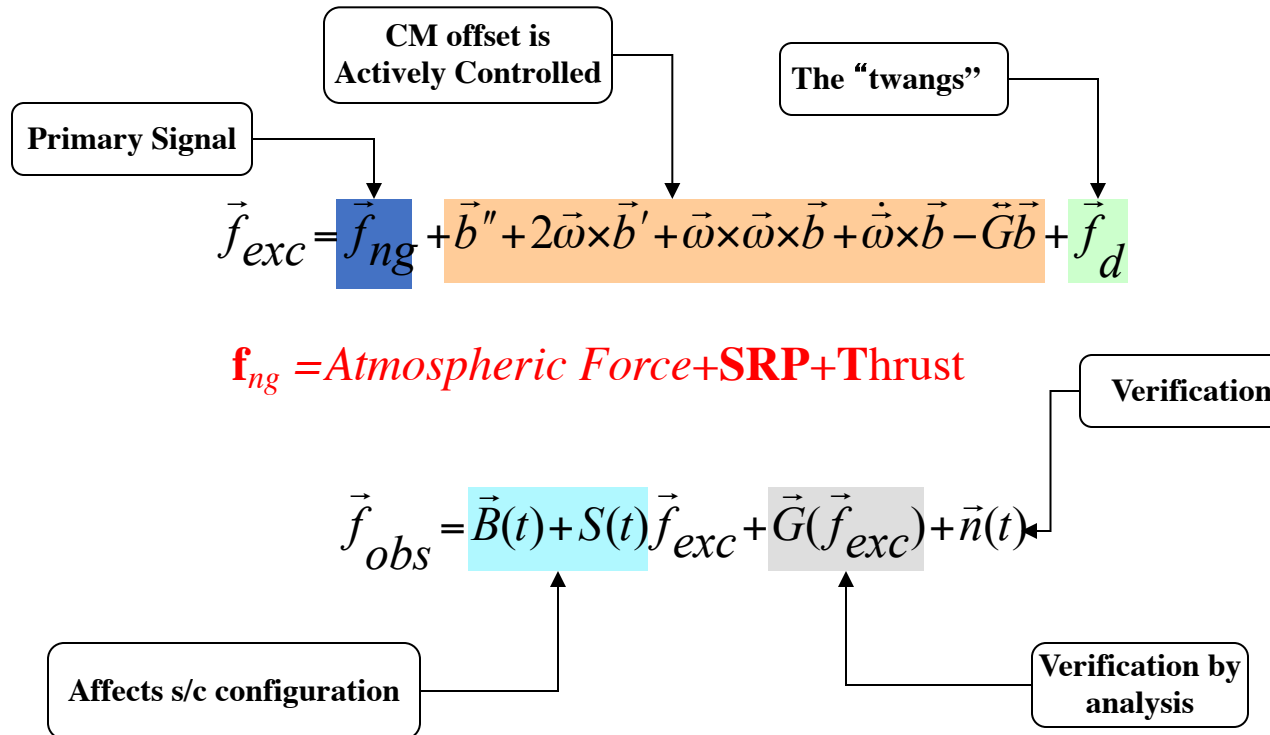
Improved quaternions are used to estimate KBR antenna center corrections

Variation in Orientation due to commanded AOCS Rotations to maintain satellite pointing requirement



The ACC Measurement

The CM offset $\mathbf{b}$ is required to be $< +/-100$ microns

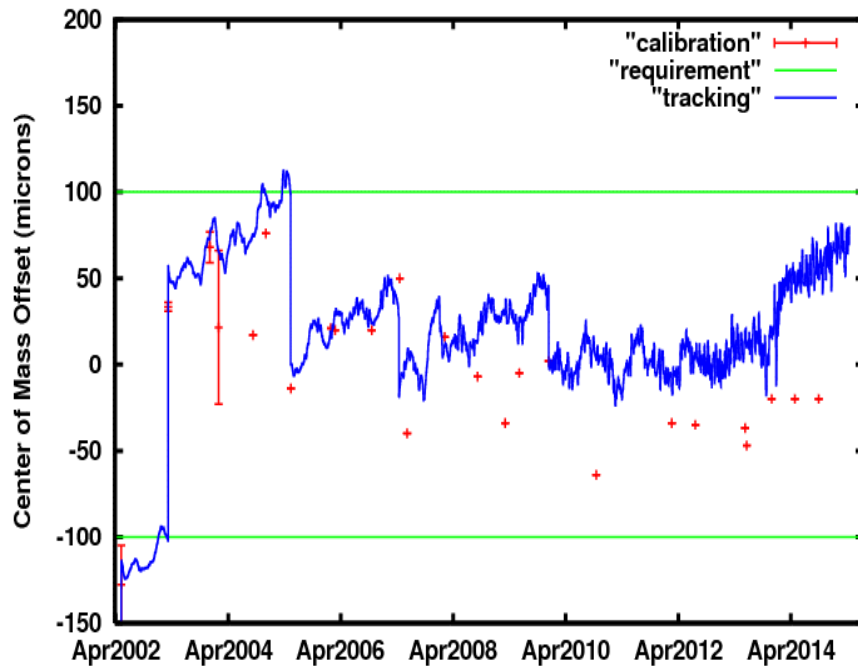


The vector $\mathbf{b}$ represents the difference between the CM and the origin of the spacecraft reference coordinate system

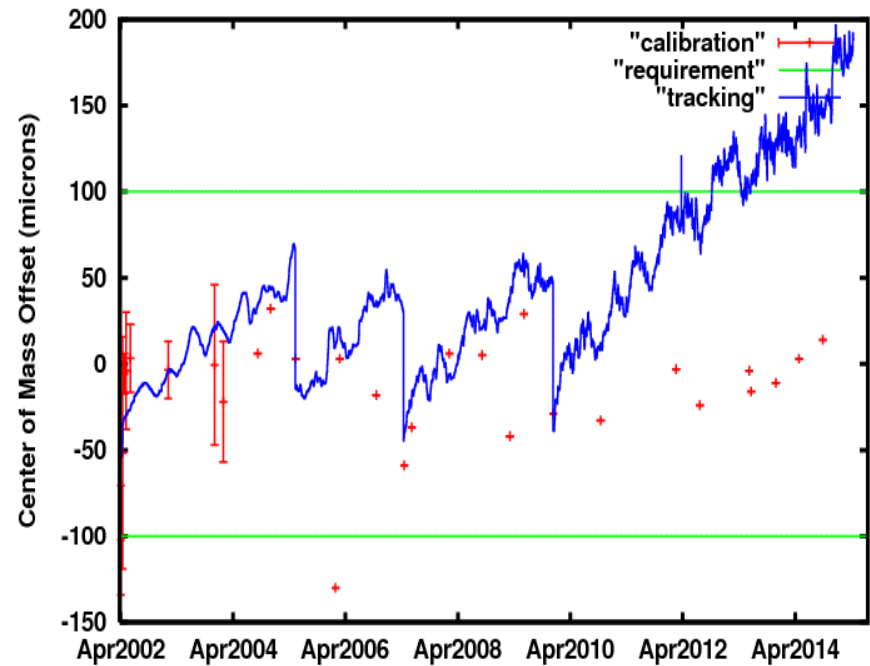
GRACE Center Of Mass (COM) Alignment History

- Spacecraft COM needs to be within 100 μm of ACC proof mass COM for all coordinate axes X,Y and Z
- Spacecraft X-axis COM estimated from
 - Dedicated COM maneuvers (limited by twangs in ACC measurement)
 - Differential gas consumption between the two (aging of temperature and pressure sensors)
- The last mass trim occurred in 2009
- Since 2010 X-axis COM estimates from both methods show a discrepancy

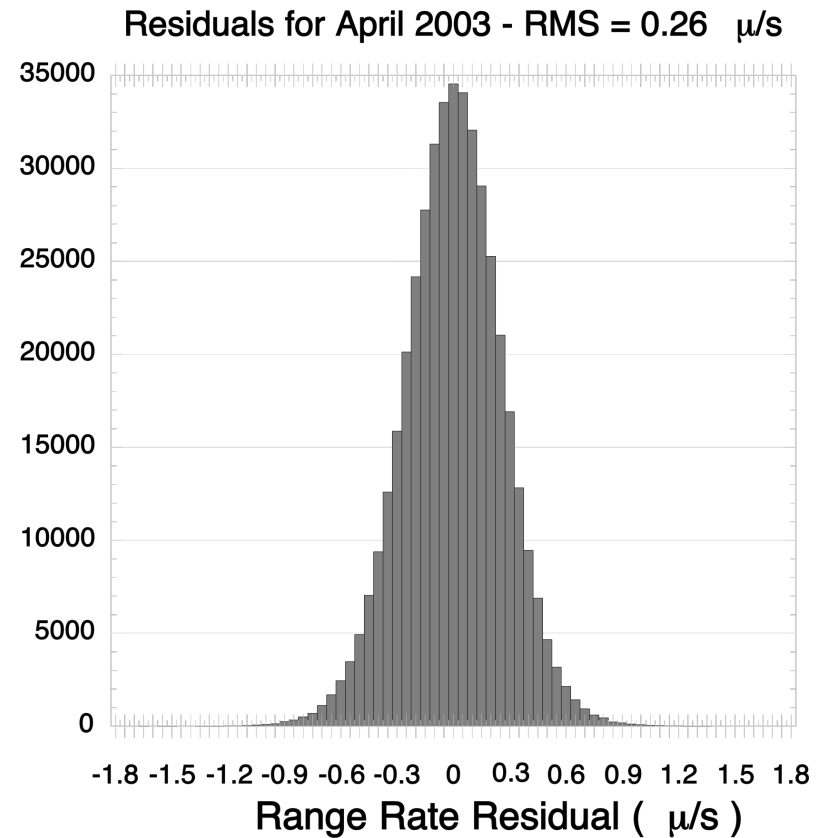
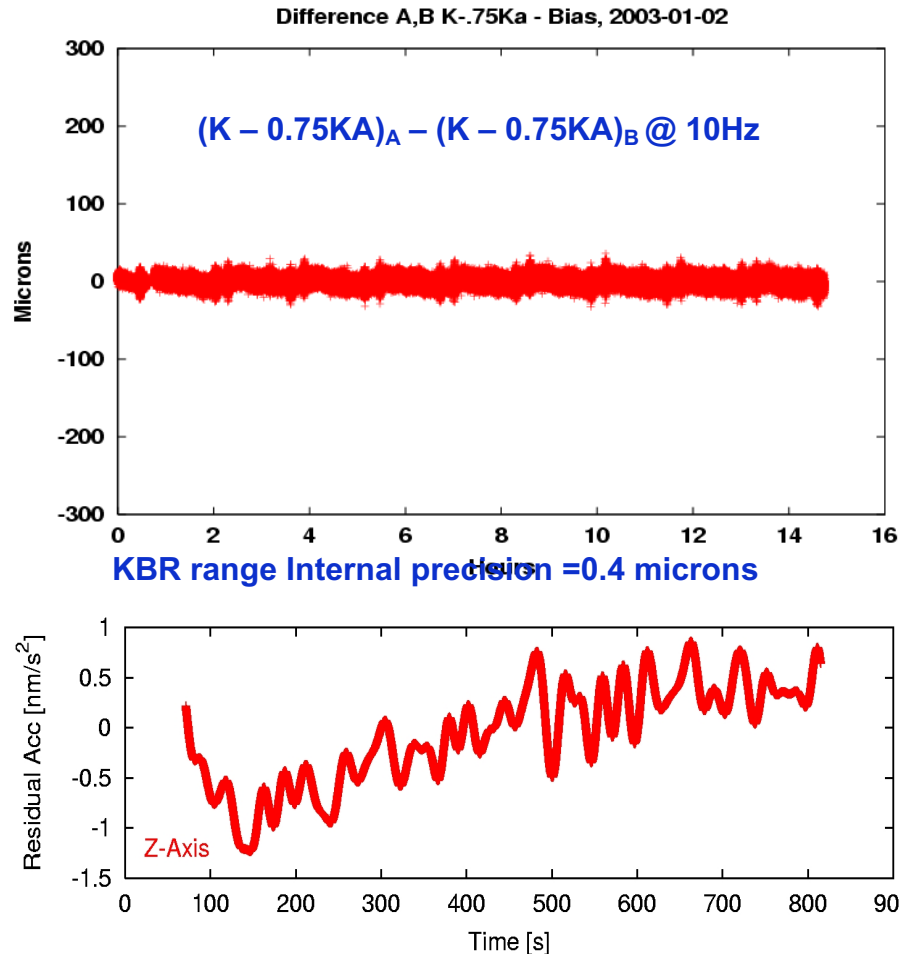
GRACE-A



GRACE-B



GRACE Payload Performance



- The very challenging GRACE science measurement requirements are satisfied.
 - Instrument payload systems are performing at the original design level
 - The monthly post-fit inter-satellite range-rate residuals have an RMS of $\approx 0.25 \text{ m/s}$
 - Accelerometer Error RMS Upper Bound is less than 0.5 nm/s^2 in all 3 directions

GRACE On-Orbit Procedures

Receiver time tag synchronized with GPS time to 70 picosecs

Star Tracker Alignment

HAIRS Feed Horn Distance Correction

CoM Offset Calibration and Correction

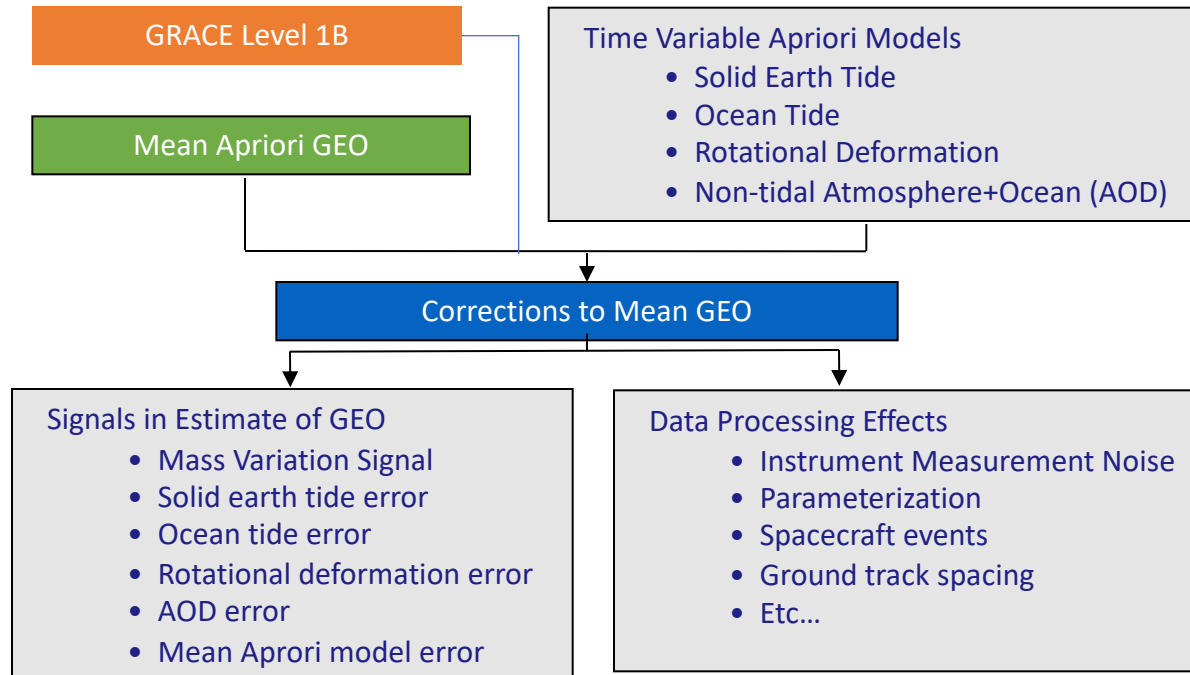
Accelerometer Bias and Scale factor

USO Drift Correction from Dual One way Ranging Approach

Observational residual analysis illuminates thermal effects and deficiencies in background models

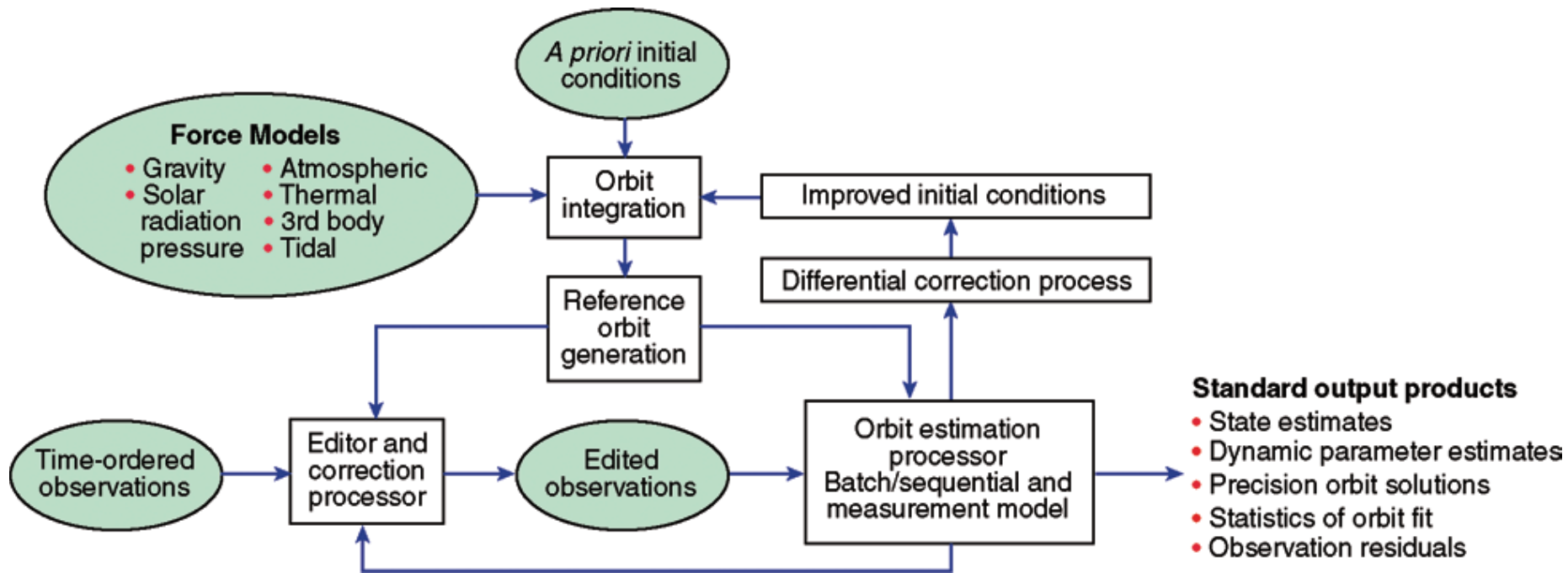
Grace Monthly Gravity Solution

$$U_{ns}(r, \phi, \lambda, t) = \frac{\mu}{r} \sum_{n=2}^{\infty} \sum_{m=0}^n \left(\frac{R_e}{r} \right)^n \bar{P}_{nm}(\sin \phi) (\bar{C}_{nm}(t) \cos m\lambda + \bar{S}_{nm}(t) \sin m\lambda)$$

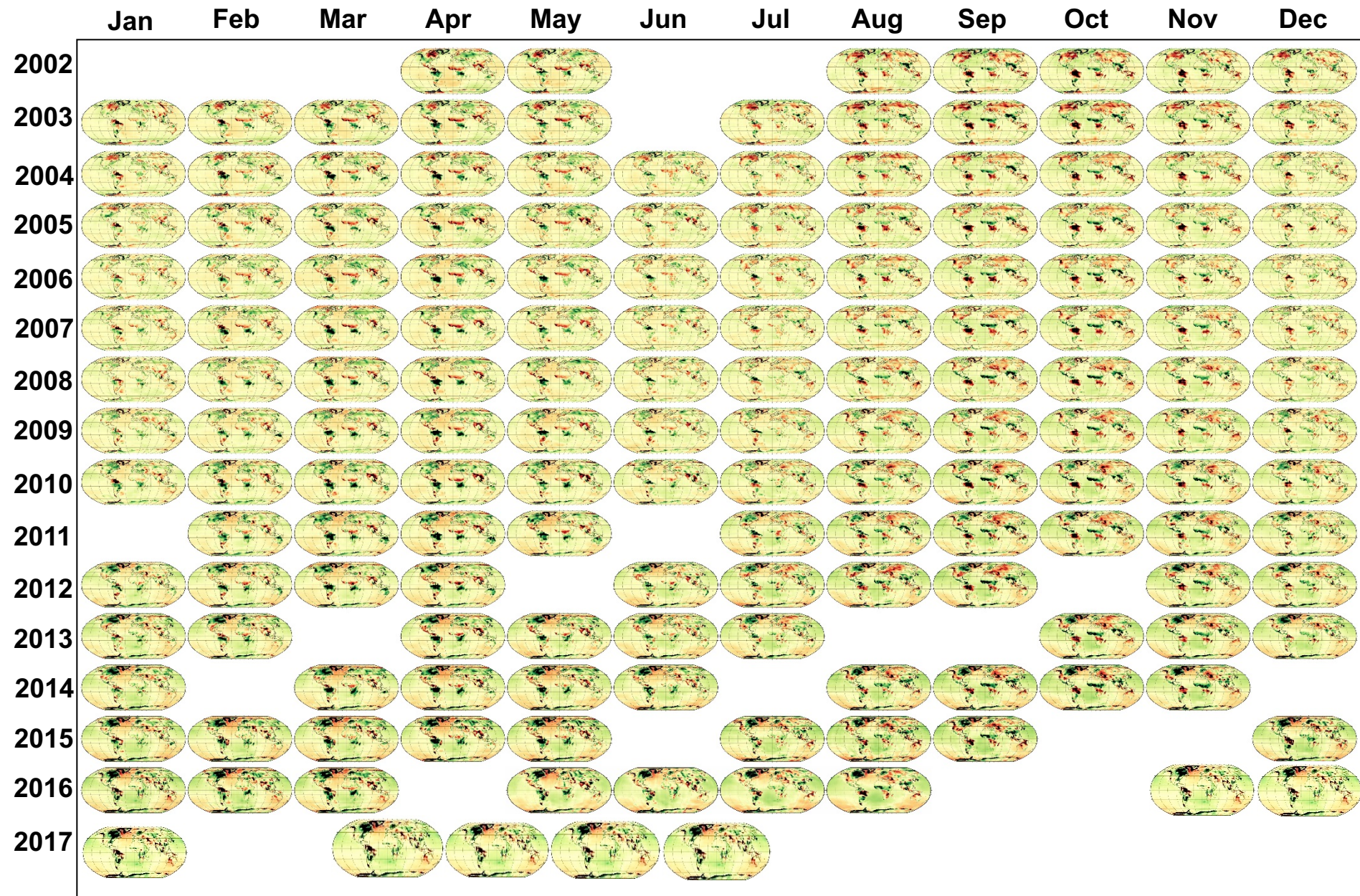


$$\text{ewh}(\lambda, \varphi) = \frac{1}{\rho} \frac{GM}{R} \sum_{n=0}^N \frac{1}{4\pi R G} \frac{2n+1}{1+k'_n} \sum_{m=0}^n a_{nm} Y_{nm}(\lambda, \varphi)$$

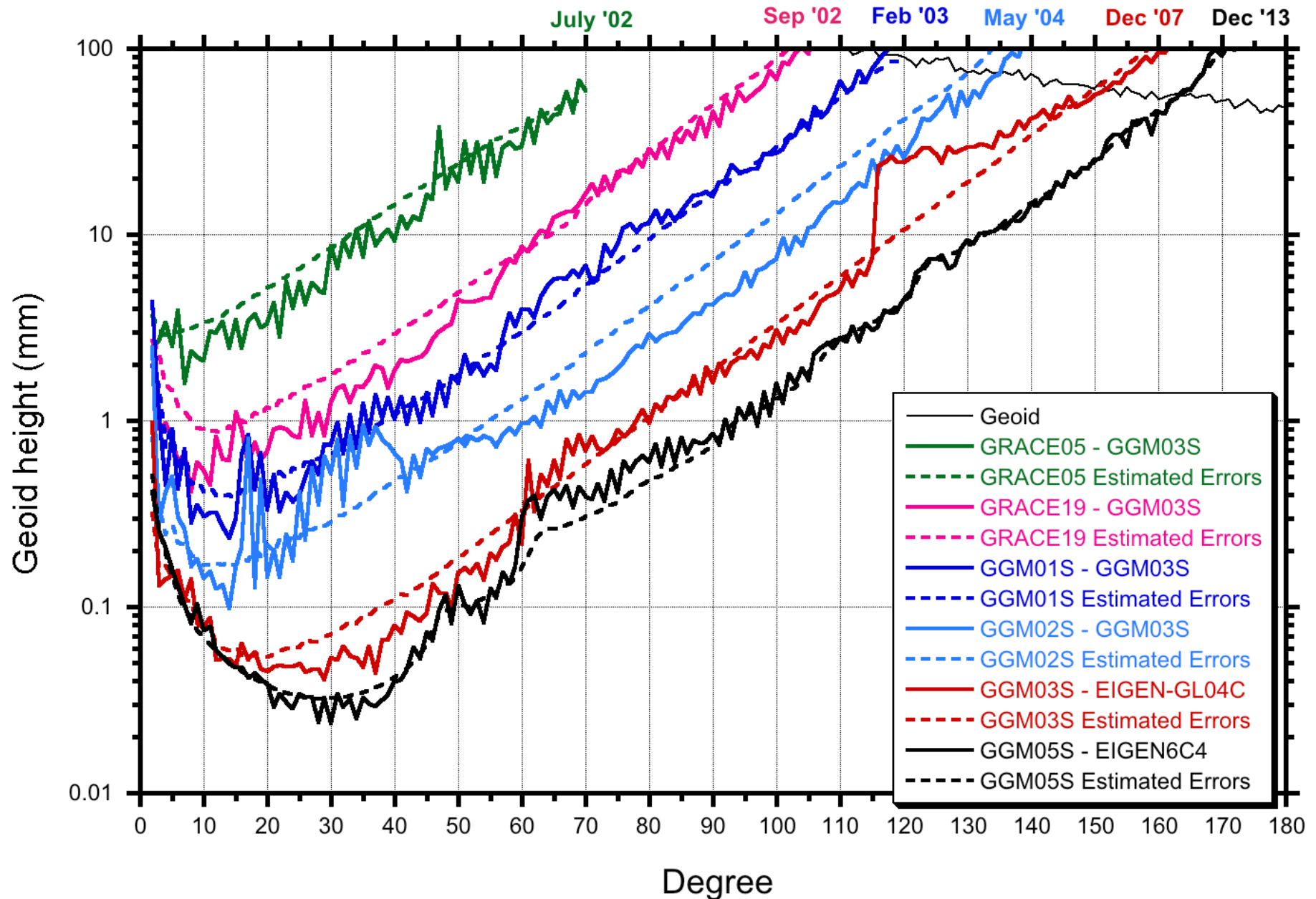
General Parameter Estimation Process



Over 15 Years in Orbit – 163 Global Gravity Solutions

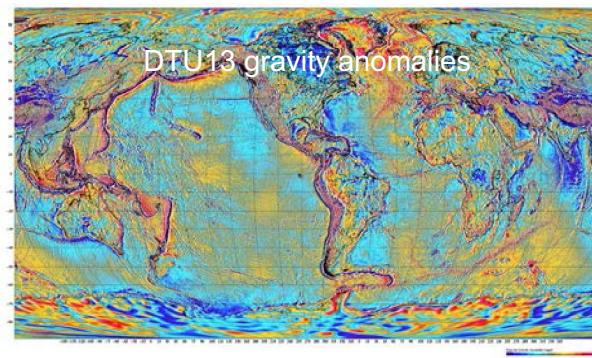
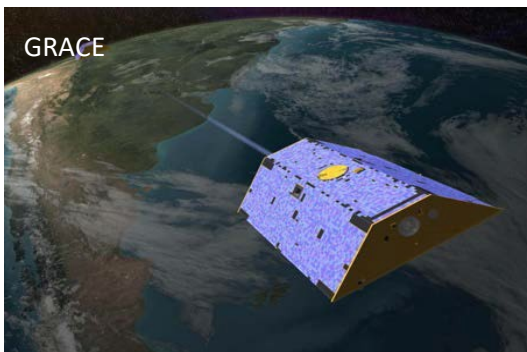


Progress in Mean Gravity Field Models

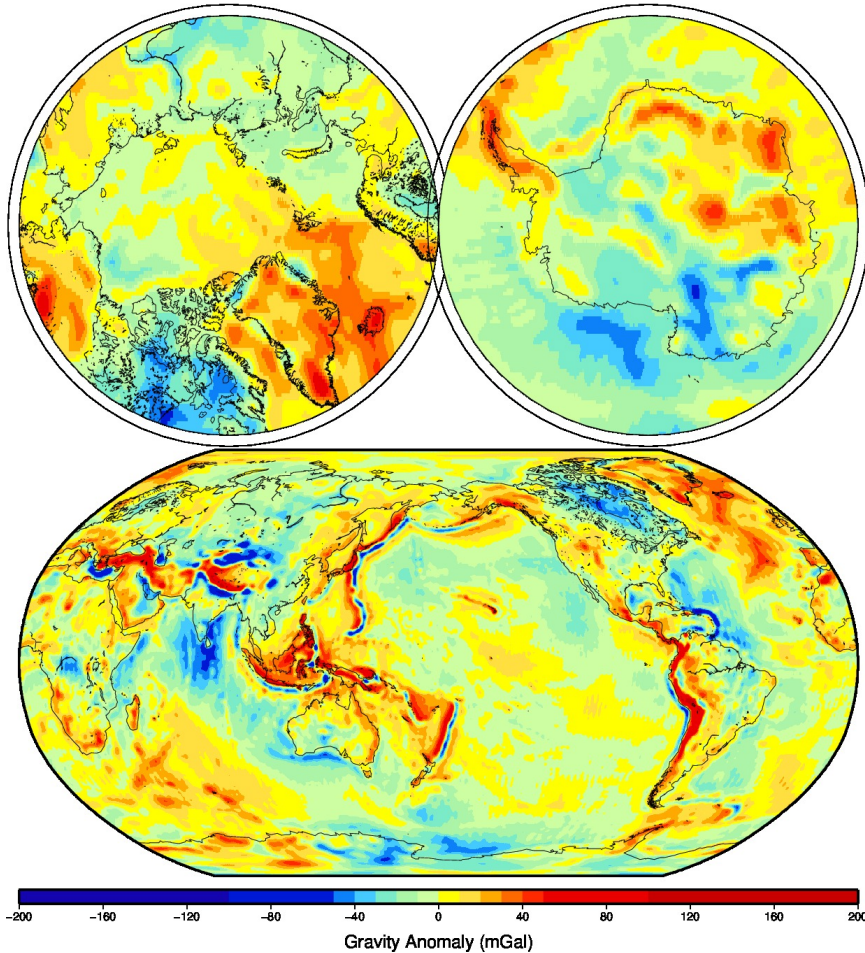


GRACE Gravity Model 5 (GGM05)

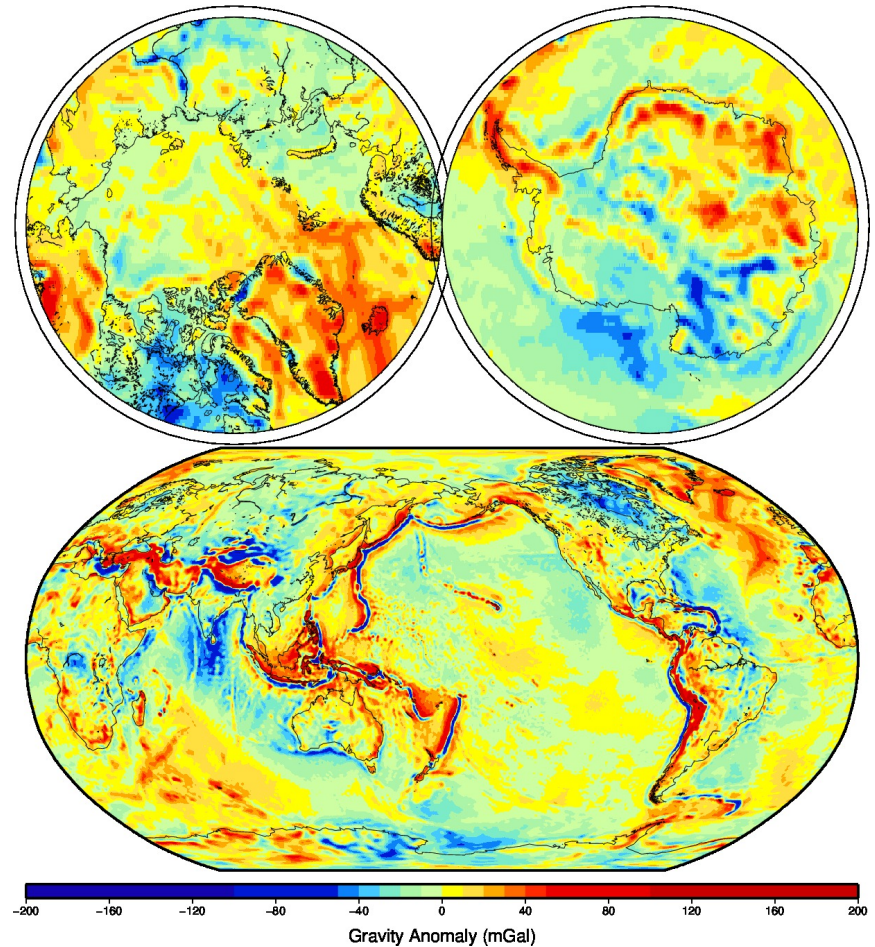
- GGM05S – GRACE-only solution complete to 180x180 (released December 2013)
 - Ten years of RL05 solutions spanning March 2003 to May 2013
 - C20 from satellite laser ranging
- GGM05G – GRACE/GOCE combination complete to 240x240 (released June 2015)
 - XX, YY, XZ and ZZ processed for entire mission (Nov 2009 – Oct 2013)
 - Polar gap fill = ZZ gradients computed at altitude based on GGM05S
- GGM05C – GRACE/GOCE/DTU13 combination complete to 360x360
 - DTU13 anomalies = DTU13 mean sea surface + EGM2008 over land



Satellite-Only Mean Models (GGM05S and G)



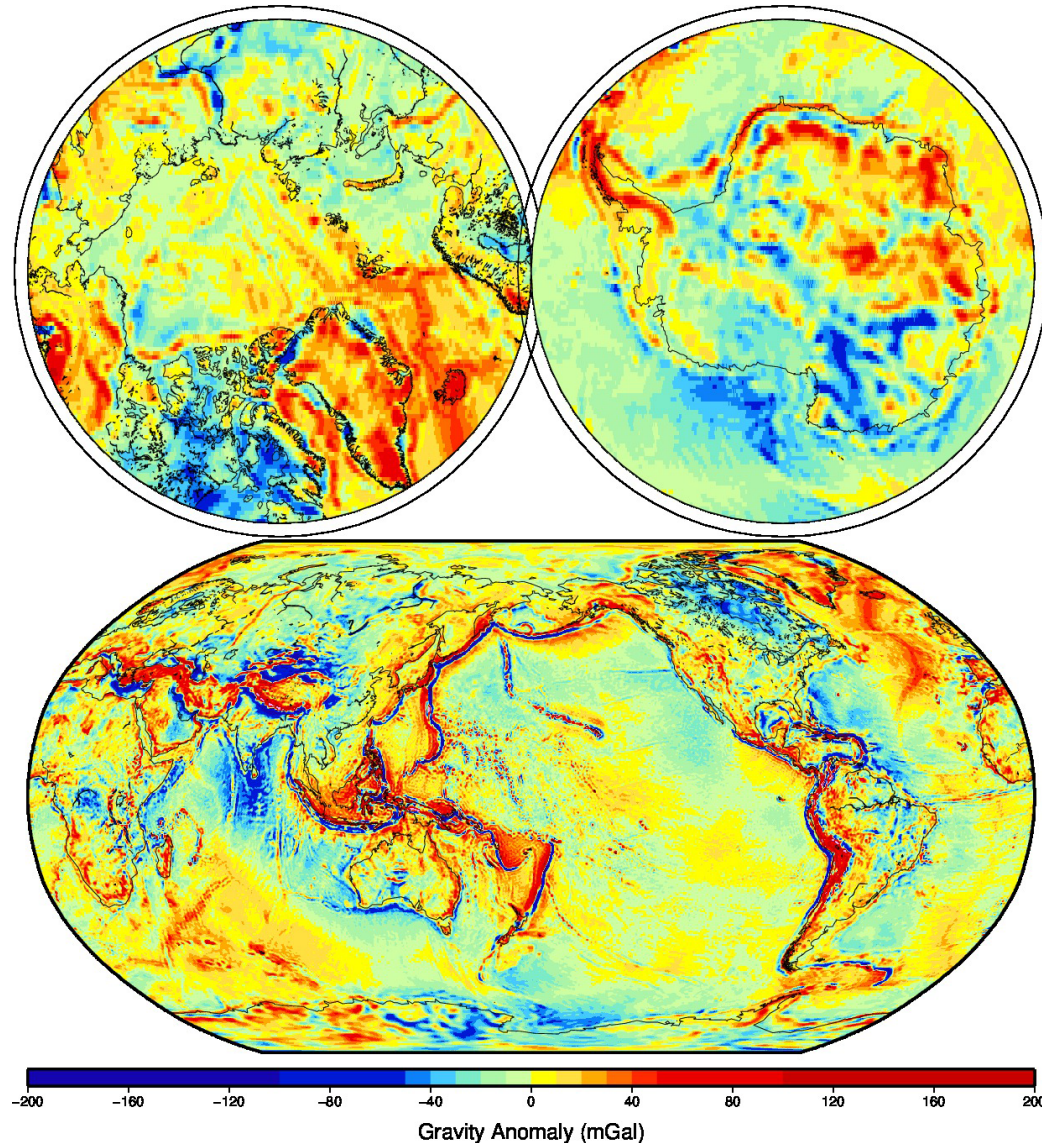
Gravity anomalies from GGM05S to
degree/order 180 (100 km smoothing)



Gravity anomalies from GGM05G to
degree/order 240 (50 km smoothing)

Acceleration Units: 1 milli-Gal = 10^{-5} m/s² $\approx$ 1 micro-g; 100 mGal = 1 mm/s²

Combination Model GGM05C



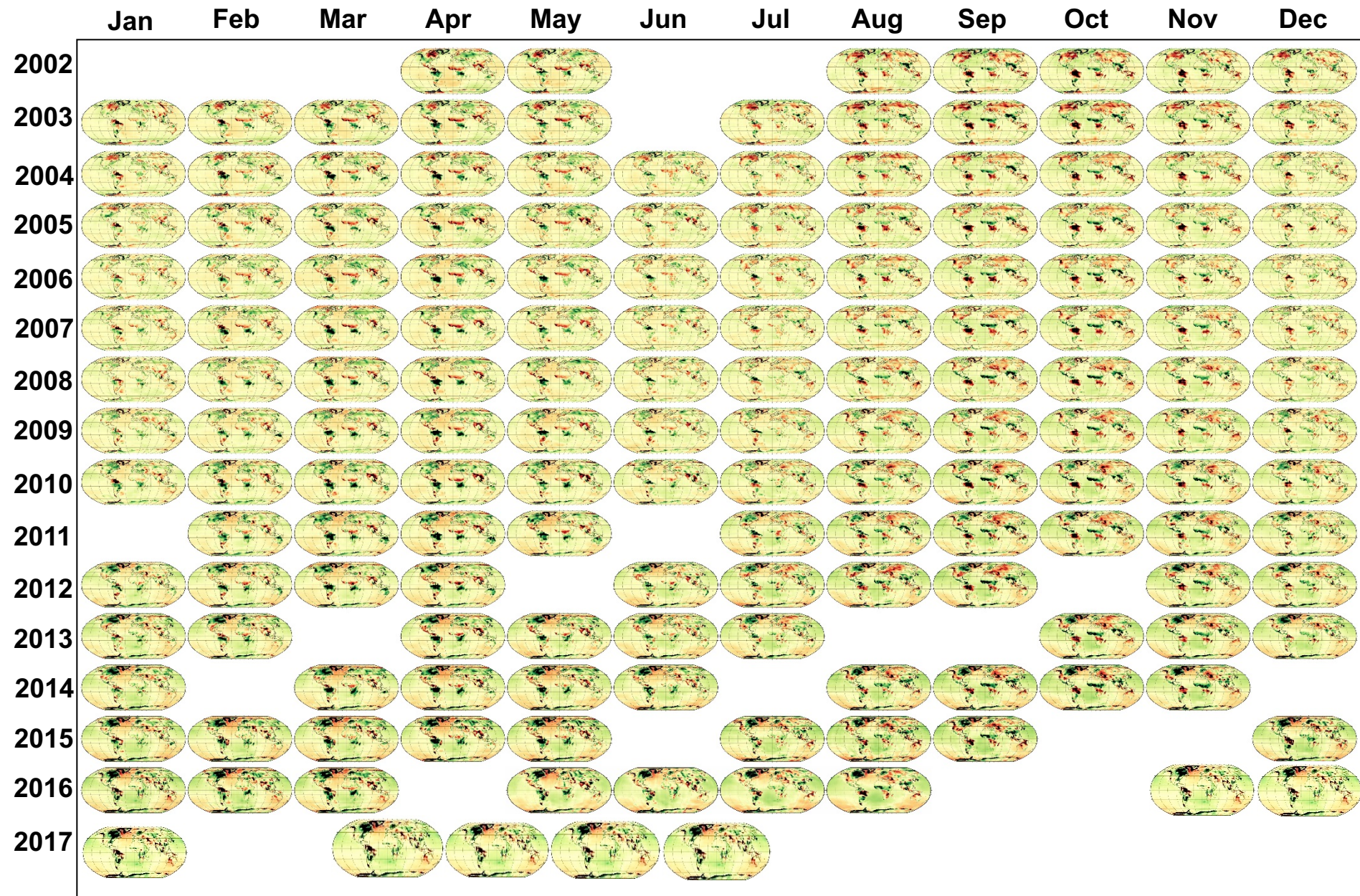
Gravity anomalies from GGM05C to degree/order 360 (no smoothing)

Acceleration Units: 1 milli-Gal = 10^{-5} m/s² $\approx$ 1 micro-g; 100 mGal = 1 mm/s²

GGM 05C Compared with Independent Surface gravity Measurements

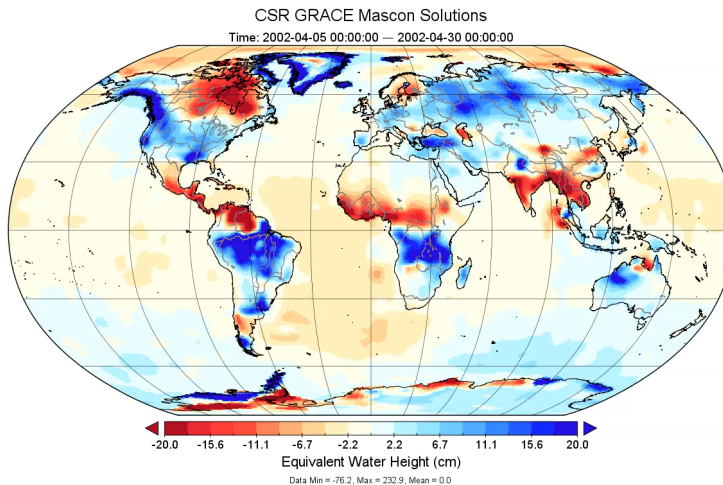
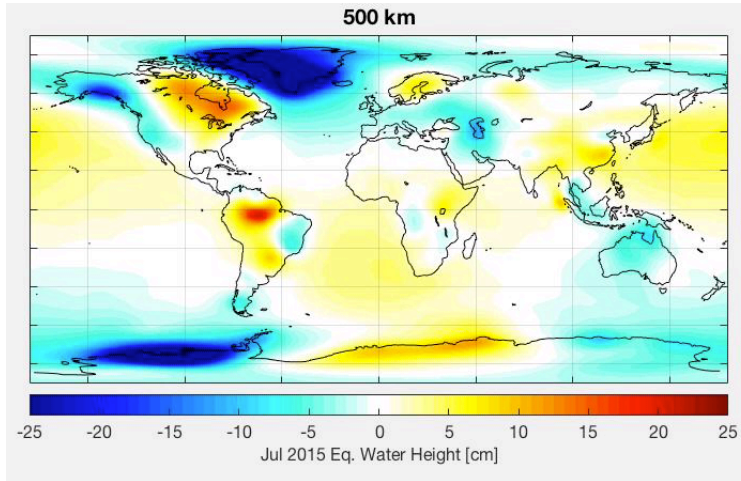
Field	Remark	Grav-D (CS02)	Grav-D(ES03)	Grav-D(AN05)	Grav-D(PN01)	NGA(Indonesia) 34.87'/'1959.2	NGA (Tanzania) -3.33'/'627.8	NGA (Chile) 19.93'/'5773.9	NGA (Nepal) 3.04'/'14497
(All fields to Nmax=240)	(All units for variances in mGal^2)	Raw	Raw	Raw	Raw	Raw	Raw	Raw	Raw
EGM08		13.72	79.13	121.1	176.9	306.34	297.73	528.73	807.89
EIGEN6C3		13.46	80.03	118.42	177.15	301.39	320.48	508.45	705.96
GOCO03S		23.36	107.01	132.5	193.86	304.76	345.27	664.68	668.72
v4goce008a	No DTU10 (GGM05S+Goce)	14.72	80.71	116.87	174.85	307.49	317.51	516.74	644.66
v4goce008g	No GGM05S (Goce + DTU10)	13.68	79.64	118.64	176.02	298.38	302.24	508.93	681.77
v4goce008c	Nominal Wt DTU10	13.55	79.5	119.03	176.38	298.05	304.43	504.11	663.64
v4goce008d	Downweight DTU10	13.62	79.6	119.09	176.37	298.07	306.77	504.03	660.6

Over 15 Years in Orbit – 163 Global Gravity Solutions

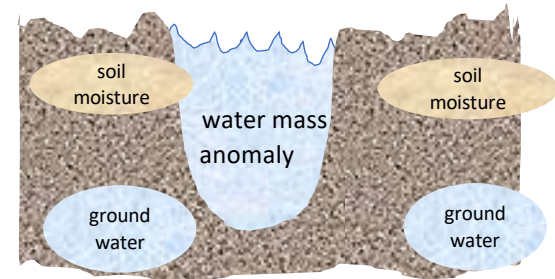
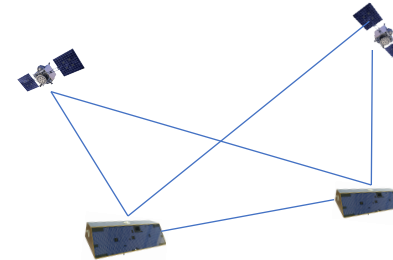


Downward Continuation of the GRACE Measurement

$$U_{ns}(r, \phi, \lambda, t) = \frac{\mu}{r} \sum_{n=2}^{\infty} \sum_{m=0}^n \left(\frac{R_e}{r} \right)^n \bar{P}_{nm}(\sin \phi) (\bar{C}_{nm}(t) \cos m\lambda + \bar{S}_{nm}(t) \sin m\lambda)$$



$GM = 398600.4415 \pm 0.0002 \text{ km}^3/\text{s}^2$,
Ries, et al, 1989



$$\text{ewh}(\lambda, \phi) = \frac{1}{\rho} \frac{GM}{R} \sum_{n=0}^N \frac{1}{4\pi R G} \frac{2n+1}{1+k'_n} \sum_{m=0}^n a_{nm} Y_{nm}(\lambda, \phi)$$

Data Quality Issues for Monthly Solutions

Without the ability to maintain satellite configuration, the **satellites decay under the influence of atmosphere drag**.

The decay will place the **orbit ground track into a repeating period** on occasion.

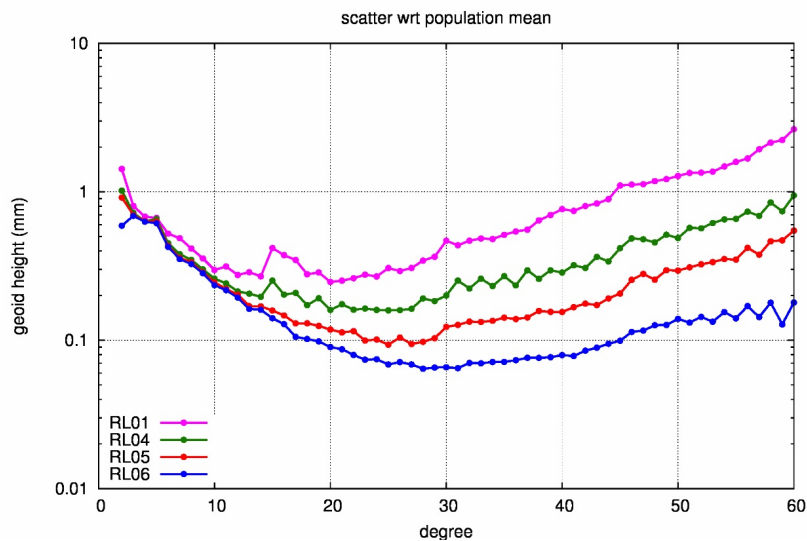
During this period, the orbit will be in a **resonance mode** where the **quality of the gravity information will degrade**

After, **2011 thermal control was eliminated** and the effects of **thermal induced instrument error** must be accounted for.

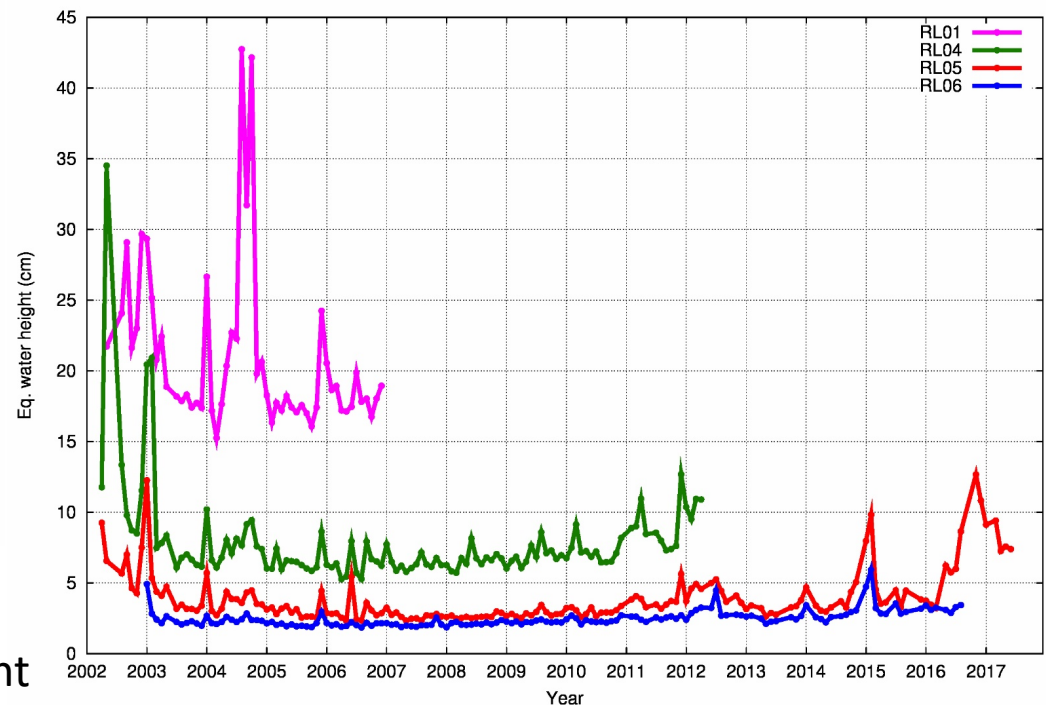
In the **last seven months of the final mission mode**, battery problems forced turning off the accelerometer on GRACE B. In this mode, the **accelerometer measurements from GRACE A were transplanted to GRACE B** to account for the surface forces. Additional quality control issues occurred from this process.

GRACE Monthly Solution History (RL01 to RL06)

DDV Scatter from Signal and Error



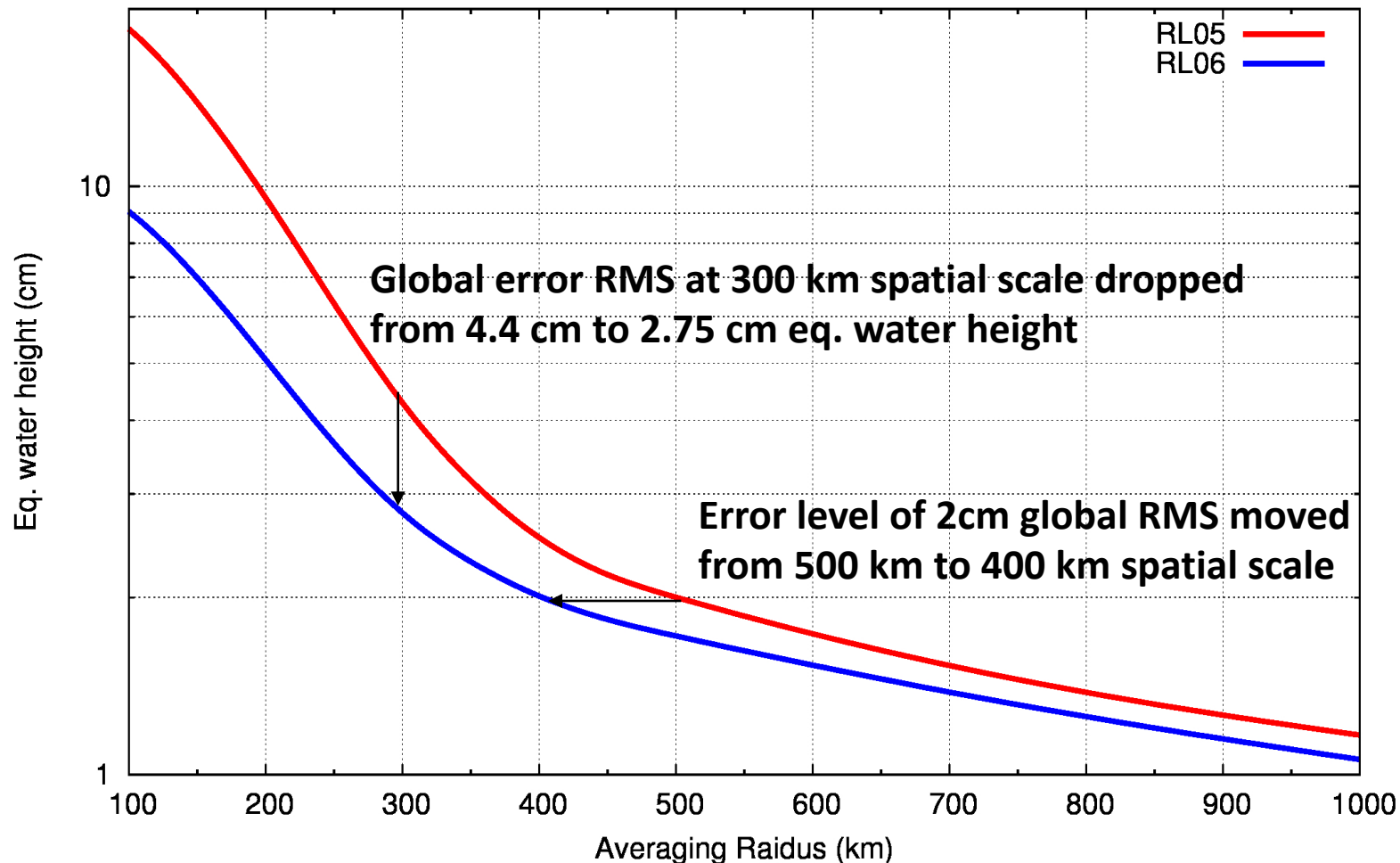
Estimate of the Errors in CSR GRACE Gravity Model releases after 300 km smoothing



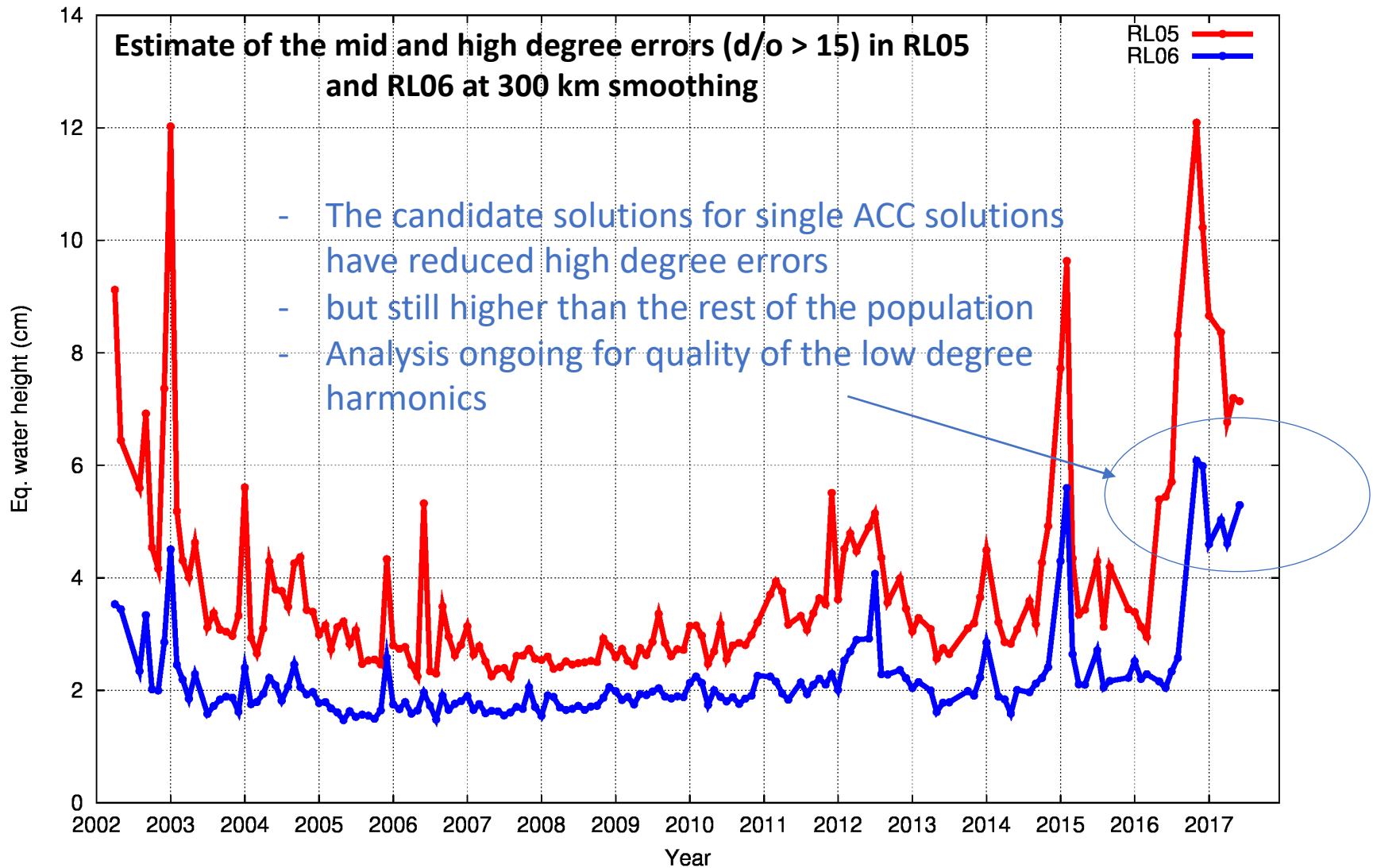
We have achieved roughly 2x improvement with every reprocessing after RL01

Resolution: RL06 vs RL05

Upper bound of the error in the spherical harmonic solutions



High Degree Error: RL06 vs RL05



Improvement in Sucessive Solutions

300 km smoothing

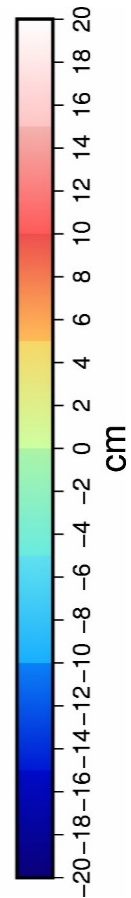
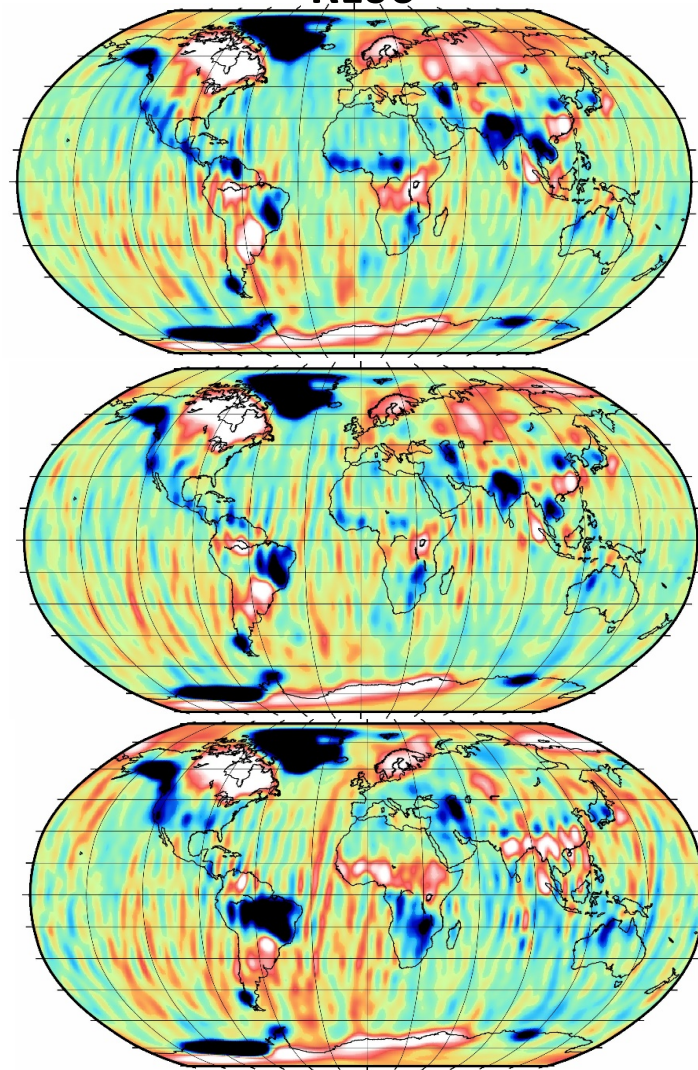
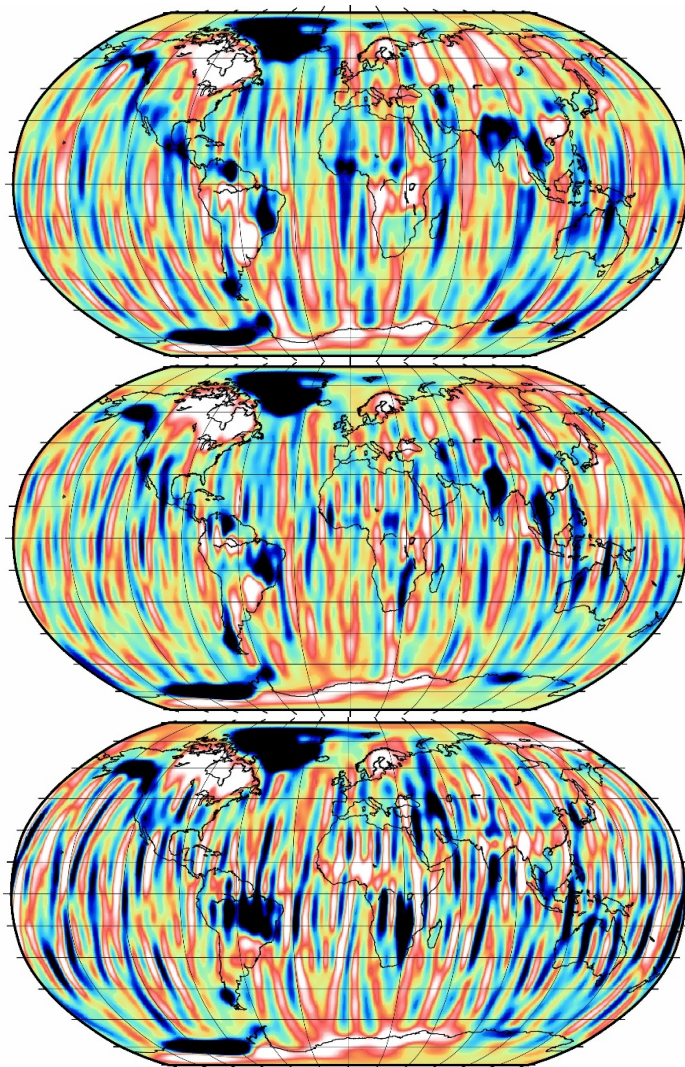
RL05

RL06

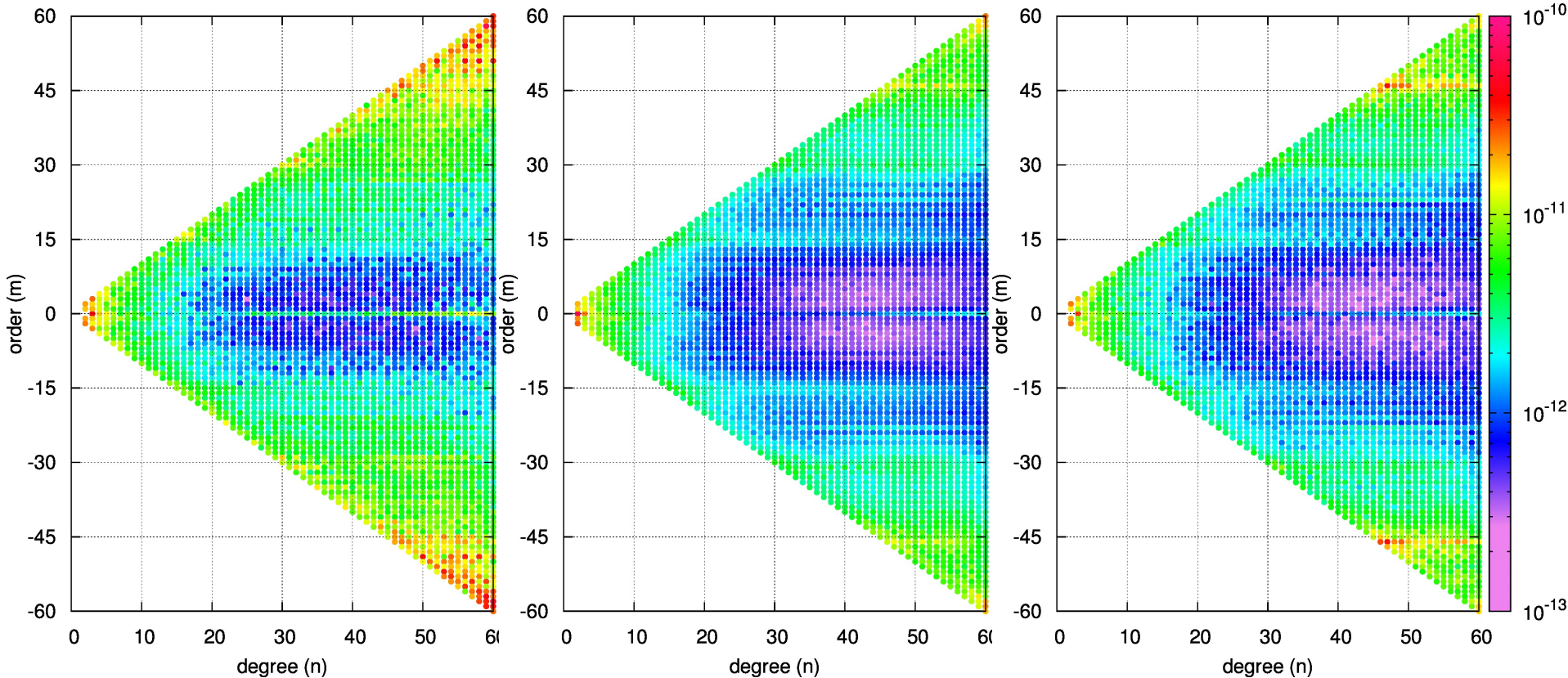
May 2016

Jun 2016

Aug 2016



Degree/Order Distribution of Error

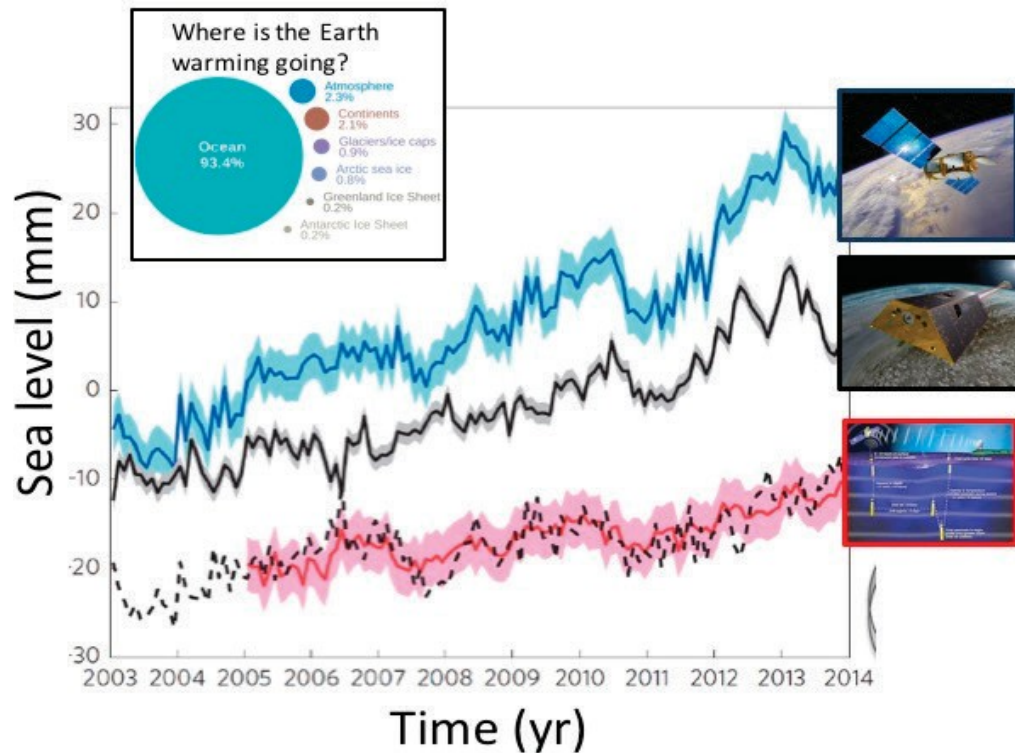


Launch until May-2003
Early months limited by
the star camera noise

2003-07 until 2010-12
Best quality products

2011-Jan until present
Limited by absence of
thermal control

Global Sea Level Change



Climate Variability and Change

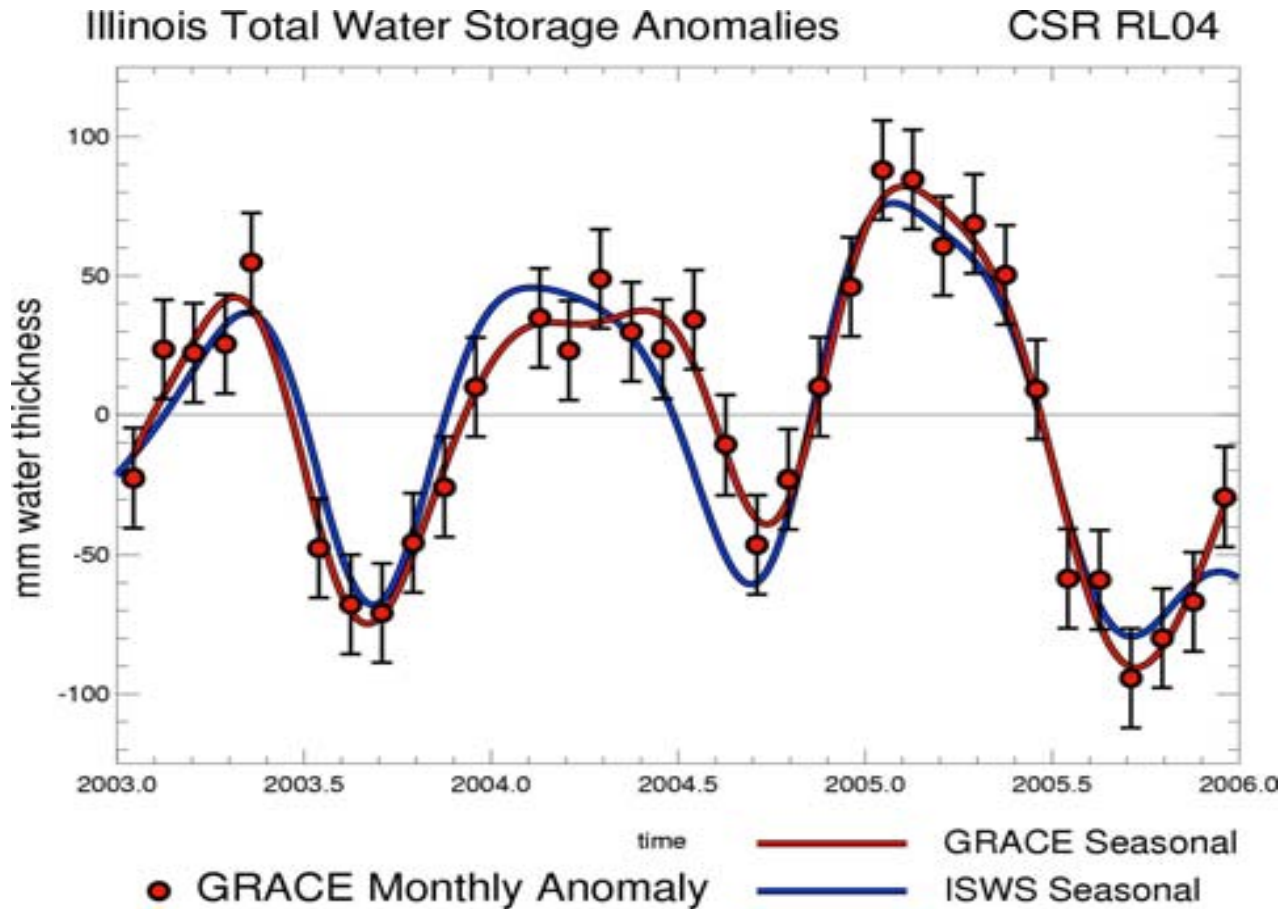
C-1 Sea Level Change

NAS 2017 Earth Science Decadal Survey

The need to quantify the rates of sea-level change and its driving processes at global, regional, and local scales is of great importance as discussed by the Climate Panel. Quantifying and understanding sea-level changes requires use of several satellite-based instruments including using radar altimeters over the oceans, and radar and laser altimeters over the ice sheets, along with GPS, InSAR, and **GRACE gravity measurements**. Gravity measurements provide critical information not only on the contributions of ice sheets and glacier systems to sea-level rise, but also changes and movement of mass throughout the Earth (Box 3.7).

Groundwater Monitoring

Estimates match groundwater well measurements



Swenson, 2007



280,000 sq km

Method is applied in regions where groundwater is not well monitored, but depletion is likely: Africa, Middle East, etc.

Amundsen Sea Sector

The mass anomaly computed in the Amundsen sea sector from CSR global mascon solutions, without any post processing, reproduces the results published by *Sutterly et. at., 2014*.

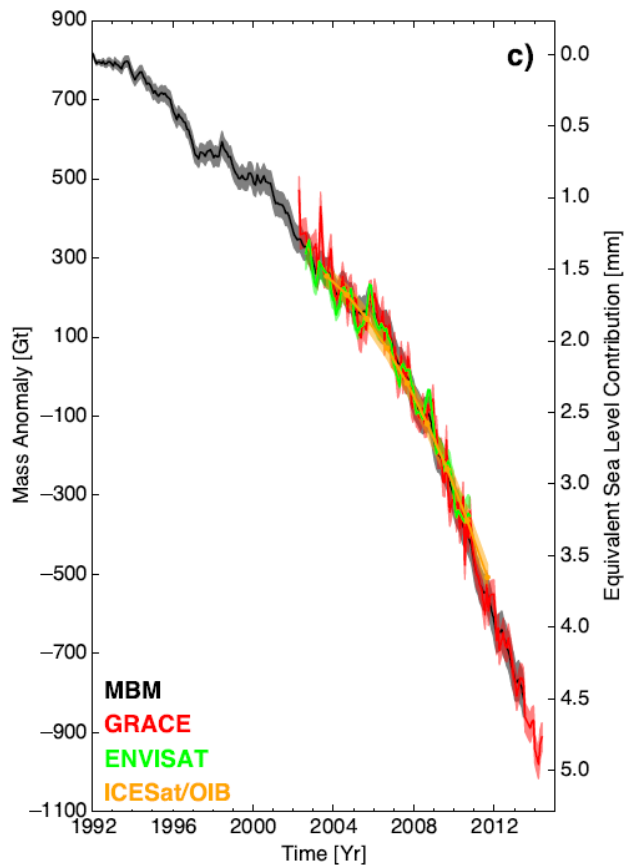
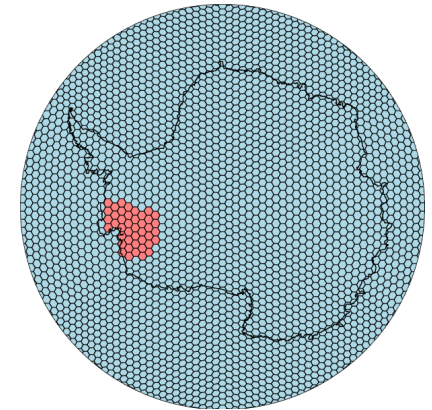
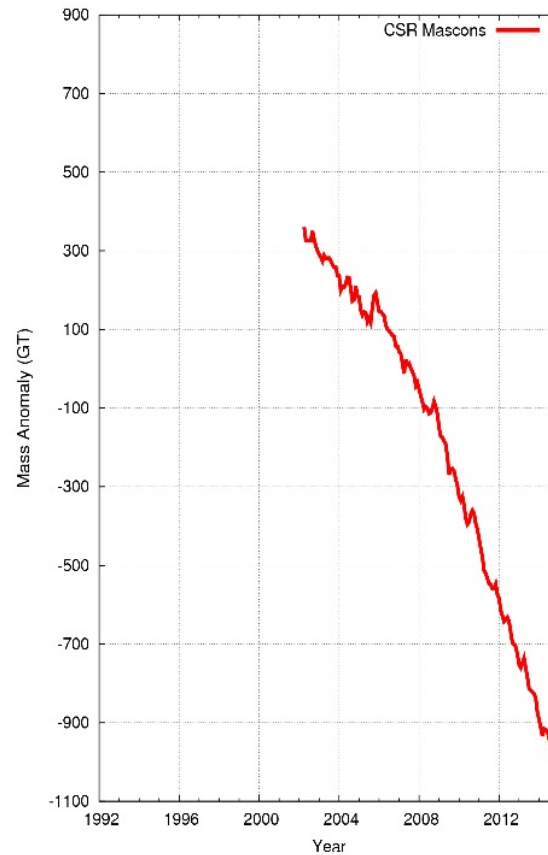


Image from Sutterley et. at. 2014



The GRACE/GRACE FO Gap Issue

The GRACE Science data Mission ended in June 2017

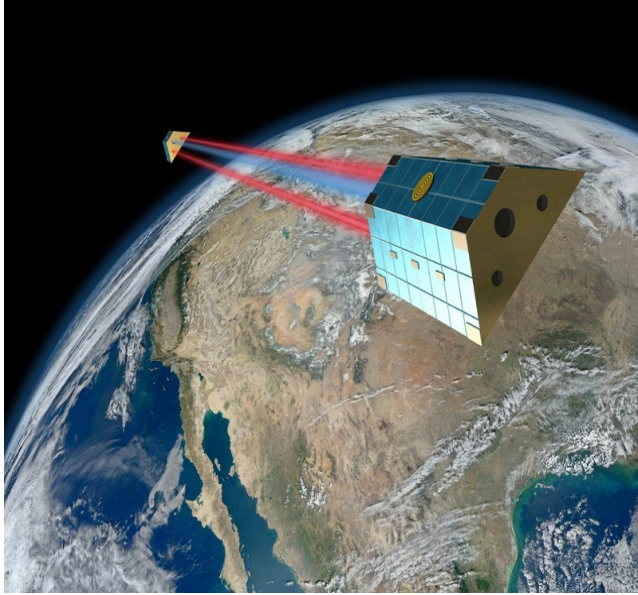
GRACE FO was launched in May 2018

There will be a gap of at least 12 months in the science products from the two missions

A gap bridging effort is required.

The issues of stability, overlap and calibration come into play here

Mission Continuity Issues for GRACE and GRACE FO



In 2010, NASA's Earth Science Division was assigned responsibility for **maintaining continuity of a number of measurements** deemed important to understanding the Earth system processes.

*Continuation of the time series of GRACE measurements was one of the specified observation sets and **responsibility for extending the GRACE Mission's 15-year observation record** of key earth system processes **was assigned to GRACE-FO.***

Maintaining science quality data records requires that differences in science conclusions drawn from the two data sets be resolved as physical signals and cross calibration of the data two data sets is a primary requirement. **Overlap of the two missions** would have enabled this calibration process.

Final stage GRACE mission activity focused on minimizing the projected gap between the GRACE Mission End and the GRACE-FO Launch, but this was not achieved.

An acceptable bridge for the gap between GRACE and GRACE FO is needed.

A Gap Bridging Approach

Some Gap Bridging issues

- Must cover the ~ 12 to 24 month gap between the GRACE mission end and the GRACE-FO Science Mission initiation
- Objective is to connect science conclusions from the two missions, so the approach must focus on science trends
- Must account for the difference in satellite environment
- Must account for problems in GRACE final stage and initiation of GRACE FO
 - Dedicated and collaborative analysis between two missions during this effort
 - Selection of appropriate science science efforts, where the science records are determined from both GRACE and other independent observations.

Proposed approach is based on interpolation of science signal trends observed by GRACE and GRACE FO and by non-GRACE methods.

- For each science record, an overlap of two years with each mission is required
- Science records selected from a subset of larger global signal trends and well observed regional signals; examples include:
 - Global sea level mass is an example of a large “global” signal
 - Regional polar ice sheets and selected continental aquifers

To be successful, the team effort must involve GRACE, GRACE FO and members from the Science User Community

Future Technology Concepts: Potential for Improvement

The 2017 Earth Science and Applications Decadal Survey recommended a Mass Continuity Mission as one of five directed missions.

- Continuity of the measurement series from the previous missions is the rationale for the recommendation

Technology-Improved Measurement

- Improved Ranging and Optical clocks

- Thruster technology to allow lower mission altitudes

Constellation- Improved data coverage

- Improved spatial and temporal resolution

Modeling and Data Assimilation

- Improved spatial and temporal resolution

- Column disaggregation

- Combined complementary data

Satellite Determination of Mass Variation

The **GRACE Mass Variation** determination is based on an approach founded in the application of accurate measurements in a non-linear parameter estimation approach. SI Traceability is difficult, but Validation of the Observations and Calibration of the Science Results should be a goal.

Both the **data analysis** and **parameter estimation algorithms** are based on well founded theoretical and computational approaches. The validation of the **model recovered at satellite altitude** is best satisfied by **downward continuation** of the satellite results, converting the modeled gravity into **surface mass elements** related to water change and interpreting the predicted change in the context of the actual process. Where other measurements of the science process are available, additional confirmation of the GRACE results may be used as a calibration process.

On-Orbit calibration is an essential component of the observation strategy

Extensive post estimate **Observation Residual Analysis** is a crucial element in achieving best results

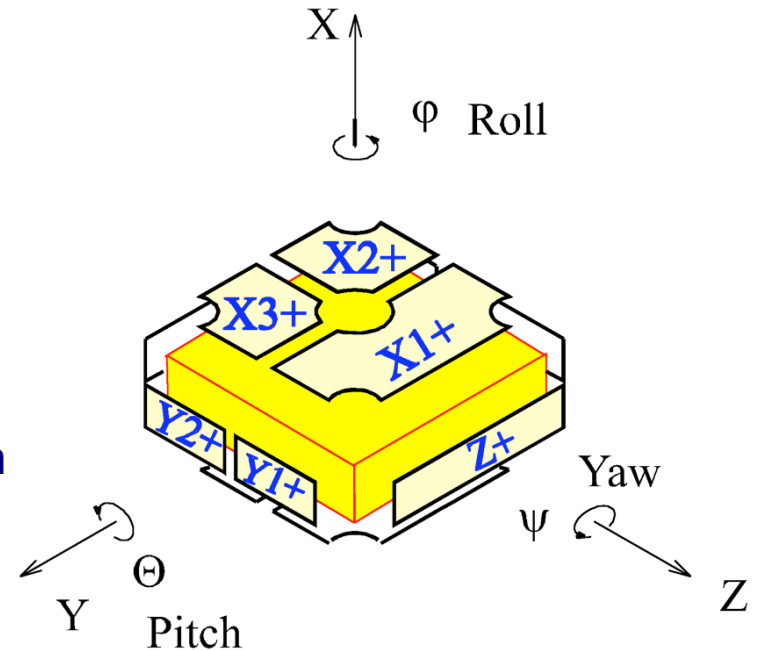
Future missions should plan for **pre-mission component test** as well as **enhanced on-orbit calibrations** to ensure traceability of mission results to those of previous missions.

Future mission implementation should ensure **adequate mission overlap** between new and existing missions to enable dual mission collaboration activities

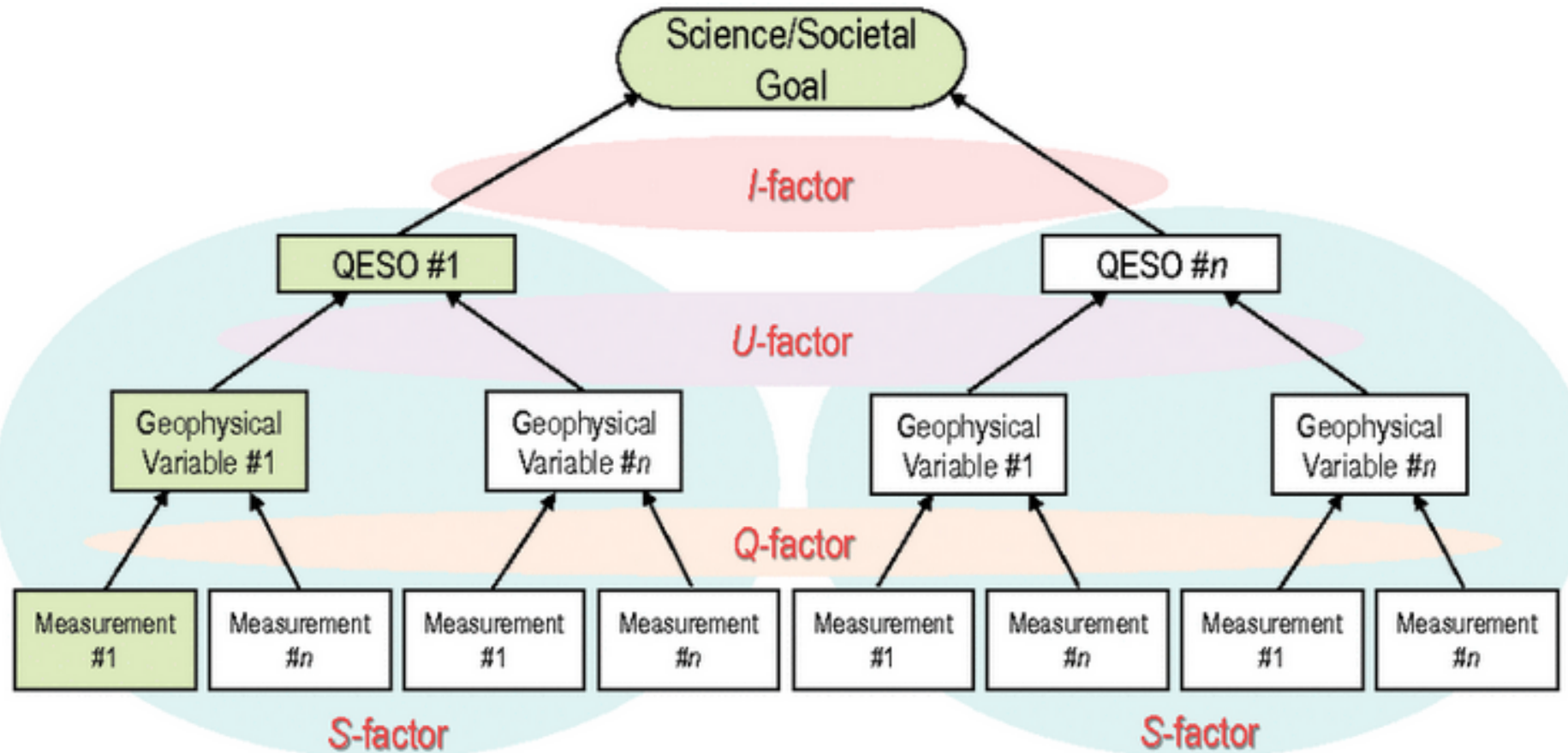
- END

SuperSTAR Accelerometer

- Bandwidth: ~ 40 mHz and 50 mHz
 - Noise & stability requirements stated within this region
 - Measurement bandwidth is ≈ 3 Hz (analog low-pass filter, Butterworth, 4th order)
- Instrument Dynamic Range
 - $\pm 50 \mu/s^2$ in Y/Z; $\pm 500 \mu/s^2$ in X
 - Least sensitive axis (X) is cross-track
 - 24 bit analog-digital conversion (precision $\approx$ order 10^{-11})
- Stringent requirements on
 - Bias/Scale value & stability in thermal & magnetic environment
 - Instrument transfer function characteristics



Relating Measurement Characteristics to Value



$$V^* = B \times A = (I \times U \times Q \times S) \times A$$

An Example of the Process

