Gravity Recovery And Climate Experiment (GRACE)

- Joint NASA and German DLR satellite mission launched in 2002
  - Follow-on mission due for launch in August 2017
- Twin satellites in similar low Earth orbits (\sim 500 \text{ km altitude})
  - Low-Low Satellite-to-Satellite Tracking (\sim 220 \text{ km separation})
  - Microwave ranging instrument
  - Long-baseline gravimeter
  - Positions mapped with GPS
- Measurements of the Earth’s static and time-variable gravity field
- Directly estimate mass variations

Image Credits: Airbus Defence and Space (Atrium)
How GRACE Senses Changes in Gravity

Ranging system measures the change in distance between satellites

1. As the satellites approach a mass anomaly: leading satellite “feels” a greater gravitational attraction and accelerates $\rightarrow$ distance increases

2. As the trailing satellite approaches: greater gravitational attraction $\rightarrow$ accelerated by the mass anomaly $\rightarrow$ distance decreases

3. Leading satellite passes the anomaly: gravitational attraction pulls backwards $\rightarrow$ decelerated by the mass anomaly $\rightarrow$ distance decreases

4. When the trailing satellite passes the anomaly and leading satellite is far from the anomaly: trailing satellite decelerated by mass anomaly $\rightarrow$ distance increases back to standard separation

Image Credits: NASA Earth Observatory: GRACE
Video: GRACE: Tracking Water from Space, American Museum of Natural History
Newton’s Law of Universal Gravitation: \( F = G \frac{m_1 m_2}{r^2} \)

Derivations: Barthelmes (2009), Hofmann-Wellenhof and Moritz (2005) and Wahr et al. (1998)
Physical Geodesy: The Physics of GRACE

- Gravitational Potential: scalar potential energy per unit mass at each point in space associated with a gravitational field

\[ V = G \iiint_v \frac{dm}{l} \]

Gravitational force on \( P \) is the gradient of the potential:

\[ \mathbf{F} = \frac{\partial V}{\partial x} + \frac{\partial V}{\partial y} + \frac{\partial V}{\partial z} \]

- Gravitational potential for an arbitrary body at coordinates \((x, y, z)\) by an attracting body at coordinates \((\xi, \eta, \zeta)\)

\[ V(x, y, z) = G \iiint_v \frac{\rho(\xi, \eta, \zeta)}{\sqrt{(x - \xi)^2 + (y - \eta)^2 + (z - \zeta)^2}} \, dv \]

Element of volume: \(dv = d\xi \, d\eta \, d\zeta\)
Physical Geodesy: Laplace’s Equation

- In general: Potential $V$ satisfies Poisson’s Equation

$$\nabla^2 V = -4\pi G \rho$$

$$= \frac{\partial^2 V}{\partial x^2} + \frac{\partial^2 V}{\partial y^2} + \frac{\partial^2 V}{\partial z^2}$$

- In empty space: $\rho = 0 \rightarrow$ Laplace’s equation

$$\frac{\partial^2 V}{\partial x^2} + \frac{\partial^2 V}{\partial y^2} + \frac{\partial^2 V}{\partial z^2} = 0$$

- Solutions to Laplace’s equation are **harmonic functions** (Have continuous second partial derivatives)

Pierre-Simon Laplace (1749–1827)
Gravity potential often expressed in Spherical Harmonics ($\tilde{C}_{lm}, \tilde{S}_{lm}$)

$$V(r, \theta, \phi) = \frac{GM}{r} \sum_{l=0}^{l_{max}} \sum_{m=0}^{l} \left( \frac{a}{r} \right)^l \tilde{P}_{lm}(\cos \theta)[\tilde{C}_{lm} \cos m\phi + \tilde{S}_{lm} \sin m\phi]$$

$r, \theta$ and $\phi$ are the radius, colatitude, and longitude coordinates

$a$ is the reference radius of the earth (6371 km)

$l$ and $m$ are spherical harmonic degree and order

$\tilde{P}_{lm}$'s are normalized associated Legendre Polynomials

Zonal ($m = 0$)  
Sectorial ($l = m$)  
Tesseral ($l \neq m$ & $m \neq 0$)
Physical Geodesy: The Geoid

- Geoid: hypothetical geopotential surface
  - Coincides with the global mean sea level if the oceans were at rest
  - Instantaneous shape of the Earth’s gravitational field
- Geoid height (geoidal undulation): distance between the geoid and an Earth reference ellipsoid (e.g. WGS-84)

\[ N(\theta, \phi) = a \sum_{l=0}^{l_{\text{max}}} \sum_{m=0}^{l} \tilde{P}_{lm}(\cos \theta)[\tilde{C}_{lm} \cos m\phi + \tilde{S}_{lm} \sin m\phi] \]

Difference between **ellipsoid height**, **geoid height** and **topographic height**
CSR GIF48 Geoid Height (max d/o = 4)

Equirectangular projection centered on 0.00°E

Data Min = -76, Max = 66

International Centre for Global Earth Models (ICGEM)
CSR GIF48 Geoid Height (max d/o = 8)

International Centre for Global Earth Models (ICGEM)
CSR GIF48 Geoid Height (max d/o = 12)

Equirectangular projection centered on 0.00°E

Data Min = -104, Max = 73

International Centre for Global Earth Models (ICGEM)
Physical Geodesy: Surface Mass Density

- Geopotential at a fixed location is variable in time as masses move and are exchanged between the Earth system components.
- With GRACE we assume the mass variation occurs in a thin layer

\[
\Delta \sigma(\theta, \phi) = \int_{\text{thin layer}} \Delta \rho(r, \theta, \phi) \, dr
\]

\(\sigma(\theta, \phi)\) is the surface mass density (typically expressed in cm w.e.). Equivalent to specific mass balance in a glaciological context

1 cm water equivalent equal to 1 g/cm\(^2\) \( (\rho_w = 1 \text{ g/cm}^3)\)

- Changes in surface loads deform the underlying solid Earth:
  - Leads to a density anomaly at depth (not in thin layer)
  - Need to compensate for the elastic deformation of the Earth
  - Load Love number for degree \(l\): \(k_l\)

\[
\begin{pmatrix}
\Delta C_{lm}^{\text{solid Earth}} \\
\Delta S_{lm}^{\text{solid Earth}}
\end{pmatrix}
= k_l 
\begin{pmatrix}
\Delta C_{lm}^{\text{surface mass}} \\
\Delta S_{lm}^{\text{surface mass}}
\end{pmatrix}
\]
Set of spherical harmonics from a surface mass density field:

\[
\begin{align*}
\{ \Delta C_{lm}, \Delta S_{lm} \} &= \frac{3 \rho_w}{4 \pi a \rho_E} \frac{1 + k_l}{(2l + 1)} \int \Delta \sigma(\theta, \phi) \tilde{P}_{lm}(\cos \theta) \left\{ \begin{array}{c} \cos m\phi \\ \sin m\phi \end{array} \right\} \sin \theta \, d\theta \, d\phi 
\end{align*}
\]

Surface mass density field from a set of spherical harmonics:

\[
\Delta \sigma(\theta, \phi) = \frac{a \rho_E}{3 \rho_w} \sum_{l=0}^{l_{\text{max}}} \sum_{m=0}^{l} \frac{2l + 1}{1 + k_l} \tilde{P}_{lm}(\cos \theta) \left[ \Delta \tilde{C}_{lm} \cos m\phi + \Delta \tilde{S}_{lm} \sin m\phi \right]
\]

\( \rho_E \) is the average density of the Earth (5517 kg/m³)
With GRACE we have the total time-dependent geopotential: Summation of several different time-varying components. Each component might represent one or more parts of the total Earth system or a specific geophysical phenomenon.
Glacial Isostatic Adjustment (GIA)
Key source of uncertainty for determining ice sheet mass balance with GRACE

- Weight of the ice sheets induces flow in underlying mantle
- Areas depressed by the paleo-ice sheets are gradually uplifting
  - Affects both surface elevation and the gravitational field
  - Apparent in GRACE as a longterm secular signal
- Viscoelastic response of the solid Earth depends on:
  - Lithospheric Thickness
  - Mantle viscosity structure
  - History of deglaciation
GRACE data has not been corrected for Glacial Isostatic Adjustment.
Data smoothed with a r300km Gaussian Averaging Function. N-S filter has not been applied.
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GRACE Datasets

Main GRACE Data Processing Centers:
- Center for Space Research, University of Texas (UTCSR)
- German Research Centre for Geosciences (GFZ)
- Jet Propulsion Laboratory (JPL)

GRACE Processing Levels:
- Level 1-B Data: All of the necessary inputs to derive monthly variations in the Earth's gravity field
  - Corrected raw measurements
  - Range and range-rate data (KBRR)
- Level 2 Data: Spherical harmonic coefficients
- Level 3 Data: Smoothed and filtered spatial fields

Available in the US from the Physical Oceanography Distributed Active Archive Center (PO.DAAC): podaac.jpl.nasa.gov

Available in Europe from the GFZ Information System and Data Center: isdc.gfz-potsdam.de
Main GRACE Processing Approaches

JPL Harmonic Solution (Post-Processed)

Hydrology Comparison
Wiese et al., "JPL RL05M Mascons," GSTM 2013

2003-2012 Trend for Continental United States

JPL RL05M Mascons
JPL RL05 Harmonics, Destriped, 300 km Smoothed

*Application of scale factors is not suitable for studying long-term (trend) signals since the models do not represent these signals well (Landerer and Swenson, 2012)

10/23/13

Hydrology Comparison
Wiese et al., "JPL RL05M Mascons," GSTM 2013

Spherical Harmonics

- GRACE Level-2 data
- Correlated N-S “striping” errors and higher-degree noise

Mascons (Mass Concentrations)

- Different basis function for calculating mass anomalies
- Processed directly from the Level-1 data
- JPL and Goddard Space Flight Center process mascon solutions
- Easier to implement geophysical constraints than the spherical harmonic solutions: solutions will be less noisy than harmonics

Presented by Dr. David Wiese at the 2013 GRACE Science Team Meeting
GRACE senses the total mass signal: need to remove non-glacial components (Geophysical Leakage)

- GSM already has non-tidal ocean and atmosphere removed
- Solid Earth: Glacial Isostatic Adjustment + Elastic Response ($k_l$)
- Continental hydrology and Sea level variations

Truncation and processing leads to a different type of leakage (Signal Damping or Statistical Leakage)

- Cannot simply integrate over area of interest

Effects of Truncation and Smoothing from Velicogna and Wahr, GRL (2013)
In Level-2 Processing: Optimized Averaging Kernels:

- Accuracy of surface mass anomaly estimates improved by spatial averaging

\[ \vartheta(\theta, \phi) = \begin{cases} 
0 & \text{Outside of region} \\
1 & \text{Inside of region} 
\end{cases} \]

\[ \Delta \sigma_{\text{region}} = \frac{1}{\Omega_{\text{region}}} \int \Delta \phi(\theta, \phi) \vartheta(\theta, \phi) \, d\Omega \]

- Create specialized averaging functions minimizing:
  - Satellite measurement errors
  - Contamination from leakage
- Scaling factors: signal is damped

Optimized Averaging Function used for Antarctic Ice Mass Estimates

Level-2 Processing: Forward Modeling

- Examples from Dr. Jianli Chen at UTCSR (e.g. JGR, 2011)
- Modeling key sectors of ice mass imbalance
- Create a synthetic map and process to be “GRACE-like”
- Iteratively adjust mass until processed map (b) matches the original GRACE map (a)
Level-2 Processing: Least-Squares Mascons

- Create a set of mascons regions and process to be “GRACE-like” harmonics
- Simultaneously least-squares fit mascon kernels to each GRACE month
- Summation of individual mascon time-series for regional time-series
Mascon Formulation

- Geographically specific correction to a mean gravity field
- Each mascon represents a surplus or deficit of surface mass
  - Surplus/Deficit expressed in centimeters water equivalent
- Compute a set of scale factors for the differential Stokes coefficients of each mascon
- First used to map gravitational anomalies of the moon

Credit: Anthony Arendt
GSFC Constrained Mascons Solutions

- Presented in Luthcke et al., *Journal of Glaciology* (2014)
- Solution solved directly from the GRACE Level-1B KBRR data
- Location-specific geophysical constraints applied to estimate the global mass change
- Ice-covered regions divided into smaller constraint regions
- Iteratively solved to reduce the GRACE KBRR residuals
- Forward modeling oceanic, atmospheric and hydrologic, variations and GIA

GSFC Antarctic Mascons:

GSFC Alaskan Mascons:
The GIS annual mass balances and mean annual mass balance determined from the EEMD analysis of the v12 mascon solution. The mascon solution for the GOA glacier region is summarized in Table 5 and Figures 8b and 15. The overall peninsula acceleration of the southern area gives rise to the acceleration signal in the southern peninsula shown in Figure 13, and the overall peninsula acceleration of the 2004–10 balance years (Fig. 9). Most of the GIA losses from peripheral glaciers and ice caps in the region result from uplift corrections due to climatic warming in the region. Our observations agree with model estimates of increasing mass loss in the Glacier Bay region of Alaska. Our correction in this region results from uplift corrections due to LIA mass loss in the Glacier Bay region of Alaska. Our observations agree with past satellite observations of surface lowering (Fricker and Padman, 2012) and model estimates of increasing mass loss (Hock and others, 2009).
JPL Constrained Mascons Solutions

- Presented by Dr. David Wiese at the 2013 GRACE Science Team
- Equation for orbit determination:
  \[
  \left( H^T W H + \bar{P}_0^{-1} \right) \hat{x}_0 = H^T W y + \bar{P}_0^{-1} \bar{x}_0
  \]
- Apriori covariance \( \bar{P}_0^{-1} \) using RMS values from:
  - Land: GLDAS-NOAH
  - Ocean: ECCO2/OMCT
  - Inland Seas: Altimetry
  - Earthquake models
  - GIA models
  - Land Ice: Empirical 2-Step
- With unconstrained spherical harmonic solutions: \( \bar{P}_0^{-1} = 0 \)

GRACE senses the total mass anomaly each month

Different approaches for calculating mass balance

Limitations in spatial scale

Necessary processing steps for accurate analysis

1. Remove mean field
2. Account for geocenter variations (degree-1)
3. Replace $C_{2,0}$ with SLR-derived coefficients
4. N-S “striping” errors and higher-degree noise
5. Account for non-glacial processes (e.g. GIA)
6. Leakage and scaling

Greenland data from Velicogna et al., GRL (in review, 2014).