# GRACE

## Gravity Science & Its Impact on Mission Design

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http://www.csr.utexas.edu/grace/publications

# Relation to Gravity Field

- <u>Inter-satellite Range & Derivatives</u>

$$\rho(t) = \left\| \vec{r}_1(t) - \vec{r}_2(t) \right\|$$

$$\dot{\rho}(t) = \left[ \vec{v}_1(t) - \vec{v}_2(t) \right] \cdot \hat{e}_\rho$$

$$\ddot{\rho}(t) = \left[ \vec{f}_1 - \vec{f}_2 \right] \cdot \hat{e}_\rho + \frac{1}{\rho} \left[ \delta v^2 - \dot{\rho}^2 \right]$$

- <u>Relationship to Gravity Field Model</u>

$\vec{r}_i, \vec{v}_i$ : Are implicitly determined by the following

$\vec{r}_{i_0}, \vec{v}_{i_0}$ – *Initial position/velocity, estimated from data*

$\vec{f}_g$ – *Gravitational forces, model parameters estimated from data*

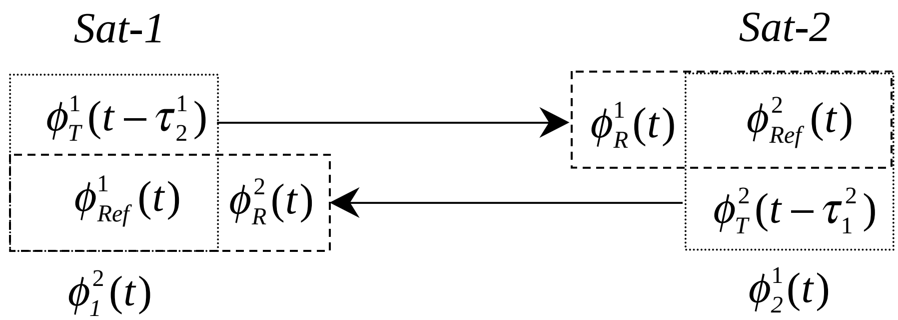
$$C_{lm}(t) = \langle C_{lm} \rangle \quad : \text{ Mean Gravity Field}$$

$$+ \delta C_{lm}(t) \quad : \text{ Time Variable Gravity Field}$$

(Atmosphere, Ocean Tides & Variability, Hydrology, ...)

$\vec{f}_{ng}$ – *Non-gravitational forces, modeled using the accelerometer measurements*

# Range Change Measurements (1)




$$\tau_1^2 = \frac{1}{c}\left\|\vec{r}_1(t) - \vec{r}_2(t-\tau_1^2)\right\|$$
$$\tau_2^1 = \frac{1}{c}\left\|\vec{r}_2(t) - \vec{r}_1(t-\tau_2^1)\right\|$$

- *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 will be numerically obtained in data pre-processing*

# Range Change Measurements (2)

## <u>Impact on satellite design</u>

- Accurate antenna offset knowledge : In-flight Calibration
- Thermally stable structural design
  - Hardware test results: 4 μ distortion for (worst-case) 1.5° - 2° C temperature variations at near 1 cpr
  - CHAMP test results: Expected variations ~ 0.5-1° C
- Temperature controlled instruments for noise reduction
  - All electronics units controlled to within 0.1° C
- Simultaneous GPS measurements for time-tag corrections
  - GPS & KBR measurements concurrent to within few picoseconds
- Precision attitude control for multipath reduction
  - Robust design to meet 0.5 mRad pointing control
- Minimize satellite CM variations in-flight
  - Fuel tanks isolated from each other

# Accelerometer Measurement (1)

*The instrument is sensitive to the sum of non-grav and rotational & gravity gradient accelerations*

$$\vec{f}_{exc} = \vec{f}_{ng} + \vec{b}'' + 2\vec{\omega} \times \vec{b}' + \vec{\omega} \times \vec{\omega} \times b + \dot{\vec{\omega}} \times \vec{b} - \vec{\vec{G}} \cdot \vec{b}$$

*The instrument introduces errors in the output accelerations*

$$\vec{f}_{obs} = \overline{B} \quad \text{(Variable "Bias")}$$
$$+ \sum \cdot \vec{f}_{exc} \quad \text{(Variable Scale, Cross-coupling)}$$
$$+ \quad \text{Non-linear effects}$$
$$+ \quad \text{Noise}$$

*When used in data analysis, the instrument output must be transformed to the inertial frame*

$$\vec{f}_m = R(t) \cdot \vec{f}_{obs} \; : \; \text{Needs satellite attitude info}$$

# Accelerometer Measurement (2)

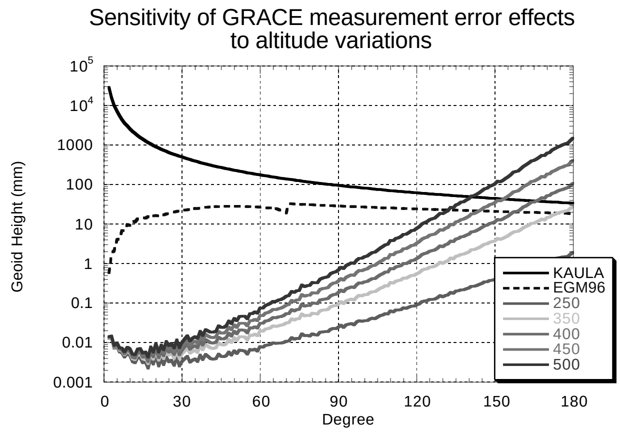
## **Impact on satellite design**

- ACC must be located at the satellite CG
  - CG control to 20 μ is possible
  - CG determination to 10-50 μ is possible
- Stable ACC alignment relative to attitude sensors
  - Alignment is stable to 0.3 mRad under flight loads
- Thermal control for noise reduction
  - Electronics controlled to within 0.1° C
- Thermal control for scale/bias stability
  - Sensor unit housed in vacuum & controlled to 0.1° C
  - Scale/Bias temperature sensitivity lower than expected
- Reduce angular rates (attitude control design)
  - Variations mostly from changing aerodynamic disturbance environment.

# Mission Altitude

## Science

- Variable Field:
  - Signal @ lower harmonics
  - Need longest possible data span
- Mean Field
  - Need highest possible resolution




- <u>Operational Constraints</u>
  - Limited fuel & Lifetime (launch near solar maximum)
  - Launcher capacity limitations
- <u>Data Quality Constraints</u>
  - Increased drag at lower altitudes degrades data quality
  - Certain errors are proportional to drag amplitude, e.g.
    - Errors due to ACC mis-alignment
    - Errors induced by satellite angular rates
- <u>Possibilities:</u> For a 500 km initial altitude
  - Low Drag: 5 years to 450 km altitude
  - High Drag: (no re-boost)
    - 3 years to 420 km altitude
    - +1 year to 370 km, re-enter in one year

# Inclination & Eccentricity

- <u>Inclination</u>
  - Effects of polar gaps (for non-polar orbits) on gravity field estimates is well known
  - To ensure global coverage, GRACE inclination has been changed to 89°.
    - Constraint: 70 kg payload penalty per degree

- <u>Eccentricity</u>
  - Science motivation to circularize the orbit
    - Uniformity of data quality
      - Attitude related errors in ACC due to aerodynamic disturbance environment
      - Mis-alignment errors in ACC proportional to drag amplitude
    - Facilitate "Local" methods of data analysis, which appear to benefit from smaller altitude variations

  - Resulting constraints on mission operations
    - Launch Eccentricity : < 0.0025 ($3\sigma$)
    - Orbit maneuvers designed to "conserve" eccentricity

# Inter-Satellite Separation

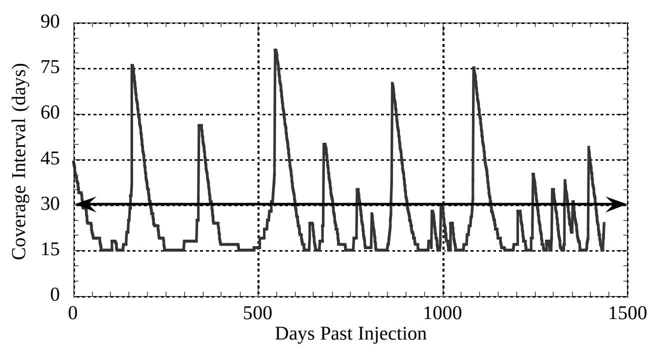
- Science Motivation
  - Avoid non-observability of lower gravity harmonics

$$S_{max} \leq \frac{360^{\circ}}{N_{max}}$$

  - Uniformity of separation is a virtue: Ensures uniform sensitivity of measurements to gravity field
- Effect of Increasing Separation
  - Signal:
    - Low frequency gravity signal is amplified
  - Noise:
    - Oscillator & system noise contributions increase
- Constraints on station-keeping
  - Maneuvers should be required no more than once every 60 to 90 days, to minimize data gaps in a solution period
- Mission Baseline
  - Nominal Separation : 2° ( 220 km ± 50 km)

# Ground-Track Control

- Science & Mission Constraints
  - For coverage repeatability, as with other remote-sensing missions, Repeat Ground Track control is desirable
  - However, insufficient fuel available for ground-track repeat
- Ground-Track Profile: Freely drifting
  - In general, over 30 days, sufficient global track density is obtained to enable degree/order 180 solution
  - Exceptions: Certain episodes of short-period repeat




- Impact on Mission
  - Orbit re-boost/de-boost to avoid short repeat periods
  - Schedule orbit/satellite maintenance activity
- Impact on Data Analysis
  - Extend solution interval until sufficient coverage obtained
  - Overlapping gravity field solution intervals
  - Unique, high (time) resolution science ?

# Data Analysis

- Signal Variations
  - Large gravity variations exist at all spatio-temporal spectral domains
  - Mapping into SST signal domain is complicated
    - Mean field aliasing due to omission/commission
    - Time variable field aliasing due to under-sampling
- Analysis Constraints
  - Global sampling to desired data density takes time
  - As a result, slower gravity field variations can be tracked by GRACE gravity solutions (~ 30 days or longer)
- **GOAL:** Minimize aliasing due to non-estimatable high frequency variations
- Analysis Requirements
  - Need a-priori models for time-variable gravity phenomena (in particular, the high frequency variations)
    - Atmosphere, Oceans, Tides, etc…
  - Need a good, high resolution a-priori mean field model
  - Open Questions:
    - Trade between aliasing & spatio-temporal resolution
    - Algorithms for input gravity corrections data
    - Use "constraints" based on available knowledge

*(Answers available following the Fall '01 AGU meeting ?!?!)*