GRACE
Gravity Science & Its Impact on Mission Design

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(& several others with the GRACE Project)
Relation to Gravity Field

**Inter-satellite Range & Derivatives**

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

**Relationship to Gravity Field Model**

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

- Initial position/velocity, estimated from data
- Gravitational forces, model parameters estimated from data
- Mean Gravity Field
  \[ C_{lm}(t) = \langle C_{lm} \rangle \]
- Time Variable Gravity Field
  \( \delta C_{lm}(t) \)
  (Atmosphere, Ocean Tides & Variability, Hydrology, ...)
- Non-gravitational forces, modeled using
  the accelerometer measurements

\[ \vec{f}_{ng} \]
Range Change Measurements (1)

- 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

\[
\tau_1^2 = \frac{1}{c} \| \vec{r}_1(t) - \vec{r}_2(t - \tau_1^2) \|
\]

\[
\tau_2^1 = \frac{1}{c} \| \vec{r}_2(t) - \vec{r}_1(t - \tau_2^1) \|
\]
Range Change Measurements (2)

Impact on satellite design

• 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

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

The instrument introduces errors in the output accelerations

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

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

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

• Operational Constraints
  – Limited fuel & Lifetime (launch near solar maximum)
  – Launcher capacity limitations

• Data Quality Constraints
  – 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

• Possibilities: 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

- **Inclination**
  - 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

- **Eccentricity**
  - 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 (3σ)
    - Orbit maneuvers designed to “conserve” eccentricity
Inter-Satellite Separation

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

\[ S_{\text{max}} \leq \frac{360^\circ}{N_{\text{max}}} \]

  - 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 ?!?!)*