**GRAIL Gravity Field Determination Using the Celestial Mechanics Approach**

**Introduction**

To determine the gravity field of the Moon, the two satellites of the NASA mission GRAIL (Gravity Recovery and Interior Laboratory) were launched on September 10 2011 and reached their lunar orbits in the beginning of 2012 (Zuber et al., 2013). The concept of the mission was inherited from the Earth orbiting mission GRACE (Gravity Recovery and Climate Experiment) in that the key observations consisted of ultra-precise inter-satellite Ka-band range measurements. Together with the one- and two-way Doppler observations from the NASA Deep Space Network (DSN), the GRAIL data allows for a determination of the lunar gravity field with an unprecedented accuracy for both the near- and the far-side of the Moon. The first official GRAIL gravity field models contain spherical harmonic coefficients up to degree and order 660 (Konopliv et al., 2012, Lemoine et al., 2013).

**Orbits**

In a first step, we estimate a priori orbits using the GNITB positions and KBRB observations. Fig. 1 shows that their quality strongly depends on the prior gravity field used.

![Orbit determination](Image)

**Gravity field**

We set up stochastic processes every 40 minutes. This value is a compromise between mixing up for model deficiencies and not absorbing too much of the gravity signal. Fig. 3 (left) shows the difference degree amplitudes (w.r.t. GCRB60PRIM) for different intervals between the stochastic processes.

![Degree amplitudes](Image)

An important feature of the CMA is its relative insensitivity for the used a priori field. Fig. 5 shows difference degree amplitudes of solutions obtained with the indicated a priori fields. Already in the first iteration the SELENE field is improved basically to the same field as when starting with GCRB60PRIM up to degree and order 120. The Lunar Prospector field (much poorer on the far-side) leads to a comparable result after the second iteration.

**Doppler data processing**

Besides the KBRB observations, GRAIL orbit and gravity field determination is based on the Doppler tracking by several Earth-based stations of the DSN. The basic signal is the frequency registered at the reception station based on cycles accumulated over a given time. In practice, Doppler observables are reconstructed from the travel time of a series of radio signals between the satellite and the DSN station over a given “counting interval” \( T \), (Moyer, 2000) as

\[
D_C = N(t) C_C - N(t) \rho \Omega_C
\]

where \( D_C \) is the computed Doppler \( C \), \( N \), and \( \rho \) are precision light-time for the first and last signal of the series, \( M_j \) is the spacecraft tumour (constant scaling factor applied by the probe to the frequency of the tracking signal) and \( f(t) \) is the transmitter frequency.

The orbits determined in the first step serve as a priori orbits for a common-orbit and gravity field estimation on a daily basis. A classical least-squares adjustment is used. The daily normal equation systems (NEQs) are stacked to weekly, monthly and finally three-monthly NEQs, which are then inverted. Fig. 3 (right) shows the difference degree amplitudes of the degree-200 solution (a priori field was GCRM/PRIM60 up to degree and order 200). The solution strongly improves when the data of 12 problematic days with larger residuals is completely skipped (blue vs. red curve). Data and residual screening still have to be refined to keep the maximum amount of data without degrading the solution. Fig. 4 shows the gravity anomalies of the degree-200 solution.

**Conclusions**

- The adaption of the CMA from GRAIL to GRAIL allows for first lunar gravity fields obtained with the Bernese GNSS software.
- Further investigations are necessary to fully exploit the precision of the Ka-band observations. Both the force model (especially radiation pressure) and the data screening have to be refined.
- We are making progress in the implementation of DSN data analysis. More work is needed before DSN Doppler observations instead of the GNITB products may be used for orbit and gravity field determination, which is necessary to obtain full independent solutions.

**References**


Moyer (2000) Formulation for Observed and Computed Values of Deep Space Network Data Types from the Post-Processing of DSN. JPL Publication

Zuber et al. (2013) Gravity field of the Moon from the gravity recovery and interior laboratory (GRI) mission. J. Geophys. Res. 118, 648-673

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