Gravity Recovery and Interior Laboratory Mission (GRAIL) Orbit Determination†

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Abstract

The twin GRAIL spacecrafts, Ebb and Flow (aka GRAIL-A and GRAIL-B), were launched on 10 September 2011 at the Cape Canaveral Air Force Station, Florida. The mission's primary objective is to generate the lunar gravity map with an unprecedented resolution via the Ka-band Lunar Gravity Ranging System (LGRS). This will help scientists to characterize the Moon's internal core structure and its thermal history. In addition to the LGRS payload, each GRAIL spacecraft also carries the MoonKAM lunar-imaging system for educational purposes.

Shortly after liftoff, GRAIL was in-view from the Tracking and Data Relay Satellite System (TDRSS) for telemetry relay. Approximate ninety minutes after liftoff, the Goldstone complex of the Deep Space Network (DSN) acquired downlink signals. Sixty minutes after that, two-way tracking data were acquired. The orbit determination (OD) teams delivered their first OD solutions around launch plus six hours. These solutions enabled the successful signal acquisition of GRAIL-A and B at the subsequent DSN stations at Canberra complex, Australia. Refined launch OD solutions were also mapped back to the Target Interface Point (TIP) to assess the launch vehicle performance in terms of Earth-relative target parameters. The results indicated they were within 0.3σ of expected values.

Five Trans-Lunar Cruise (TLC) Trajectory Correction Maneuvers (TCMs) were planned for each spacecraft to satisfy the Lunar Orbit Insertion (LOI) targets. Four were deterministic maneuvers and one was a statistical maneuver. Figure 1 illustrates the post-TCM-A4 OD solution history projected on the LOI target requirement plane. The TCM-A5 was cancelled because the solutions were well within the LOI-A target requirements. TCM-B5 was also cancelled a day later for the same reason. To establish the science formation orbit, excluding the LOI-A and LOI-B maneuvers, there were 9 additional maneuvers for GRAIL-A and 10 additional maneuvers for GRAIL-B performed in the orbital phases.

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After successfully executing nearly 30 maneuvers on their six-month journey, Ebb and Flow established the most stringent planetary formation orbit on 1 March 2012. The Science Phase started six days earlier than planned. Figure 2 shows the relative orbital element differences between Ebb and Flow after reaching formation. It was a novel accomplishment.

GRAIL consists of one structural subsystem (bus) and two solar arrays. To shield and protect flight sub-systems, the solar-array side of the bus panel extends 70% longer than its main body. To model the non-gravitational accelerations such as outgassing, solar radiation, and lunar albedo (during lunar orbit), the physical structure of GRAIL was decomposed into 8 representative components. The spacecraft orientation changes have been modeled through quaternion representations on top of a default background attitude profile.

Solar radiation pressure was the dominant non-gravitational force during the TLC phase. To improve this model, solar pressure calibration activities were conducted during the mid-cruise phase. Other non-gravitational forces such as outgassing due to the evaporation of residual substance and small forces induced by momentum desaturation events were investigated. To characterize the small force behavior, one active thruster calibration was performed per spacecraft. In the orbit phase, the lunar gravity mis-modeling becomes the dominant error source. An updated OD filter strategy was introduced to reduce the gravity signature while also improving the spacecraft ephemeris predictability.

The S-band two-way Doppler and two-way range (TLC phase only) are the standard data types used in OD solutions. Most of time, the USO enabled one-way X-band Doppler was not included in the solutions, which was contrary to the pre-launch plan to use it as a complimentary data type. This was due to the USO system interfering when the heater was cycled on and off to maintain the temperature profile. Although the USO X-band one-way Doppler was corrupted in the early mission phases, it still serves as a good source for solution validations.

This paper describes OD filter configurations, analyses, and results during the Trans-Lunar Cruise, Orbit Period Reduction, and Transition to Science Formation phases. The maneuver reconstruction strategy and their performance will be discussed. It will also summarize the requirements, major dynamic models, and challenges. GRAIL will be the first mission to generate a never before known high-resolution gravity field of the only natural satellite of the Earth. It not only enables scientists to understand the detailed structure of the Moon but also further extends their knowledge of the evolutionary histories of the rocky inner planets. Robust and successful navigation is the key to making this a reality.

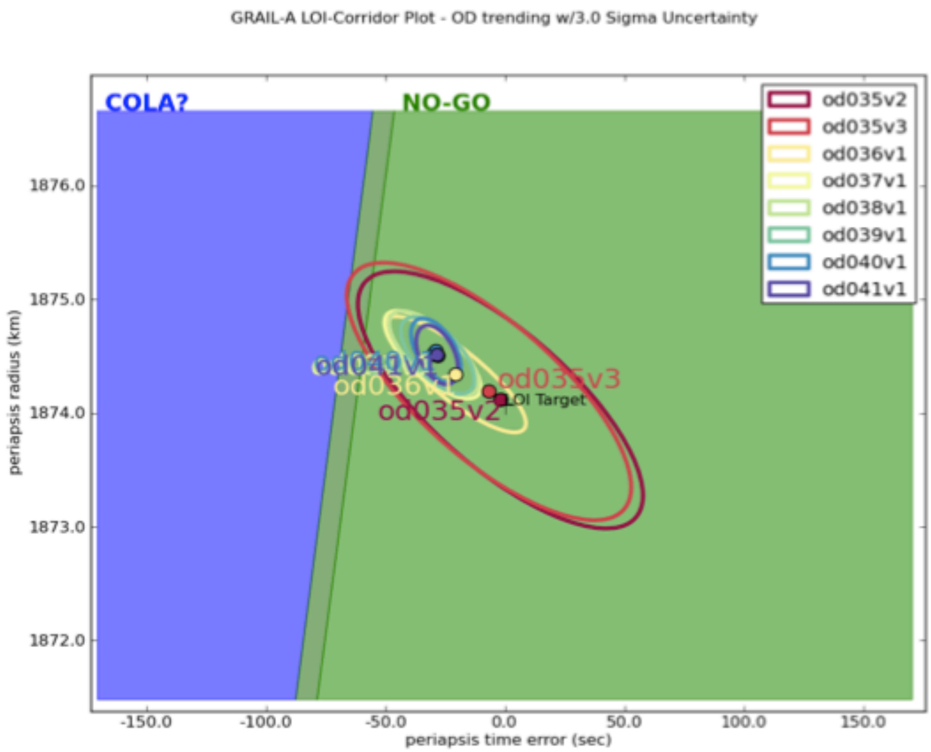

Figure 1: Post-TCM4A OD solutions for TCM5A Go-No-Go decisions

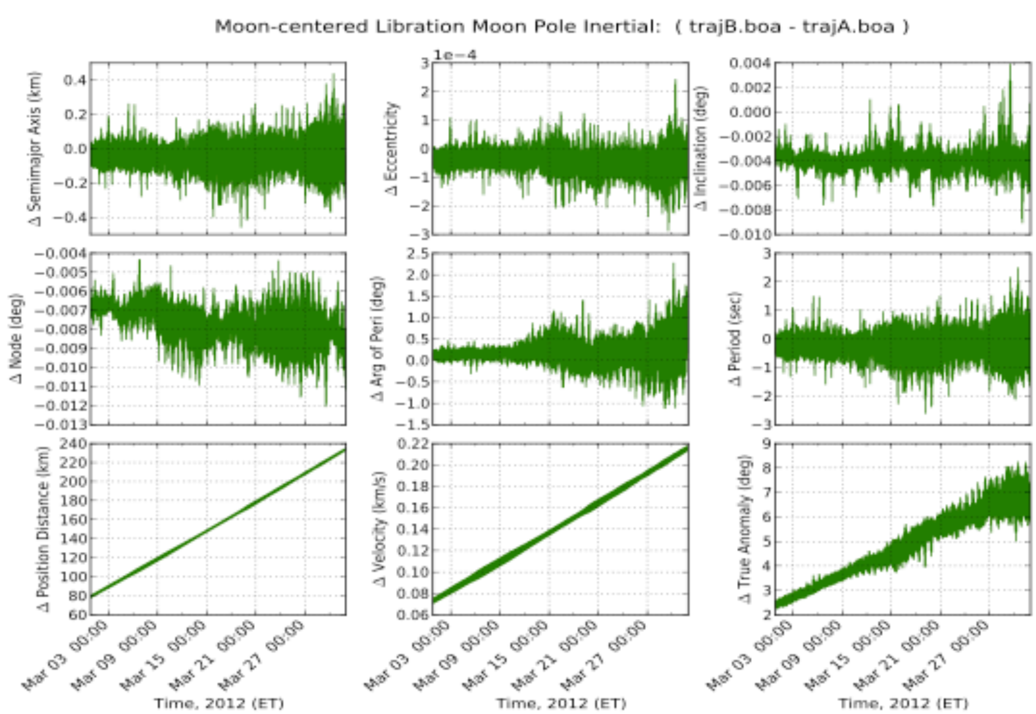

Figure 2: Ebb and Flow Orbital Element differences after the formation achieved