Navigation of the Twin GRAIL Spacecraft into Science Formation at the Moon†

P.G. Antreasian[1], R.S. Bhat[2], S.B. Broschart[3], M.K. Chung[4], K.E. Criddle[3], T.D. Goodson[5], S.J. Hatch[6], D.C. Jefferson[3], E.L. Lau[3], S. Mohan[3], J.S. Parker[2], R.B. Roncoli[7], M.S. Ryne[3], T.H. Sweetser[5], T.H. You[8], B.T. Young[2]

Jet Propulsion Laboratory, California Institute of Technology
4800 Oak Grove Drive, Pasadena, CA 91109-8099

Abstract

On February 29, 2012 the twin NASA Gravity Recovery And Interior Laboratory (GRAIL) spacecraft, Ebb and Flow, achieved precise synchronized formation for collecting highly sensitive lunar gravity data. This was accomplished after performing a total of 27 maneuvers between the two spacecraft (13 on Ebb, 14 on Flow) over six months. Each 300 kg GRAIL spacecraft independently flew a 3.8-month, low-energy trajectory to reach the Moon after separation from the launch vehicle on September 10, 2011. Accurate performance of the Delta-II 7920H 10C launch vehicle led to the cancellation of the first of five planned Trajectory Correction Maneuvers (TCMs) on each spacecraft to target the required lunar orbit insertion conditions. Each GRAIL Trans-Lunar Cruise (TLC) trajectory shown in Figure 1 was optimized using 3 TCMs (TCMs 2-4). The last maneuvers, TCM-A5, B5, which were planned to clean up trajectory errors 8 days from lunar orbit insertion were cancelled due to good performance of the earlier TCMs. The Lunar Orbit Insertion (LOI) maneuvers executed on New Year's Eve (Dec 31, 2011) and New Year's Day (Jan 1, 2012), respectively for Ebb, and Flow. Each LOI burn lasted approximately 38 min long and inserted the spacecraft into an 11.5-hour period capture orbit.

Shortly following the LOI burns, the spacecraft entered the Orbit Period Reduction Phase (OPR), where the orbit periods for both spacecraft were reduced to just below 2 hours. This was accomplished within approximately one month through the execution of 7 Period Reduction Maneuvers (PRMs) per orbiter grouped into two clusters (three in OPR-1 and four in OPR-2). To reduce operation activities, the same maneuver design (ΔV magnitude and pointing) was used for each burn in a cluster, which were executed on consecutive days in January and beginning of February 2012. During this time a collision avoidance strategy was implemented whereby the orbits were designed not to intersect. Once the orbit period for both orbiters has been reduced to less than 2 hours, the mission entered the Transition to Science Formation (TSF) Phase. During this nearly month-long phase, a series of maneuvers, referred to as Transition-to Science-Formation Maneuvers or TSMs, were performed strategically to achieve the Science formation. The TSF Phase strategy involved performing two deterministic TSMs on Ebb to establish the science orbit and three deterministic TSMs on Flow to place it 85 km ahead of Ebb in the same orbit. On March 1st, the orbiters were oriented into the orbiter–to-orbiter active pointing attitude to align the Ka-band antenna horns towards each other to collect data with the solar arrays aligned within the orbit plane.

The NASA GRAIL mission is a Discovery-class mission proposed to map the lunar gravity field to high accuracy and spatial resolution. GRAIL is the lunar analog of the Gravity Recovery And Climate Experiment (GRACE) mission, which is currently mapping the Earth's gravity field to unprecedented

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[1] GRAIL Navigation Team Chief, Jet Propulsion Laboratory
[2] GRAIL Navigation Maneuver Designer Analyst, Jet Propulsion Laboratory
[3] GRAIL Navigation Orbit Determination Analyst, Jet Propulsion Laboratory
[4] GRAIL Navigation Trajectory and Maneuver Designer, Jet Propulsion Laboratory
[5] GRAIL Navigation Deputy Team Chief, Jet Propulsion Laboratory
[6] GRAIL Navigation Trajectory Designer, Jet Propulsion Laboratory
[7] GRAIL Mission Design Lead, Deputy Mission Manager, Jet Propulsion Laboratory
[8] Inner-Planet Navigation Group Supervisor, Jet Propulsion Laboratory

resolution. The science payload consists of the Lunar Gravity Ranging System (LGRS), which was derived from GRACE. The LGRS measures the gravity field via the Ka-band ranging data telecommunicated between the two nearly identical spacecraft Ebb (GR-A) and Flow (GR-B) separated by distances of 65–225 km in a low near-circular, near-polar orbit. The primary activity of the nine-month prime mission was the 82-day Science Phase consisting of 3 gravity-mapping cycles (or 3 lunar sidereal periods of 27.3 days each). The orbit mean altitude during this phase was approximately 55 km. The highly sensitive LGRS data will enable scientist to characterize the internal structure and thermal evolution of the moon from crust to core. Each spacecraft also carries an education and public outreach imaging system called MoonKam, which consists of five camera heads.

The GRAIL Project is managed at the Jet Propulsion Laboratory in Pasadena, CA, while the spacecraft were built and are operated by the Lockheed-Martin Corporation in Denver, CO. This paper will discuss the navigation strategy and performance of the twin GRAIL spacecraft from the September 10, 2011 launch through the beginning of the Science Phase in March 2012.

Trans-lunar cruise (TLC) navigation of the GRAIL spacecraft was performed using the traditional navigation data types of 2-way S band Doppler and range acquired through the Deep Space Network in Goldstone, CA, Canberra, Australia, and Madrid Spain. The TLC tracking schedule included continuous DSN coverage for both spacecraft for several days from launch, LOI and around maneuvers. Otherwise the data schedule was alternating 1 track per spacecraft every other day. Maneuvers, TCM-2–4, on each spacecraft were designed as part of a multi-TCM optimization strategy, which targeted the 6-coordinate spacecraft state at LOI using pre-launch LOI targets. The final maneuvers, TCM-A4 and B4, targeted time to periapsis, inclination, and radius of periapsis at the time of LOI. Tables 1 and 2 compares the actual maneuver ΔV designs against the pre-launch expected TLC ΔV costs, respectively, for Ebb and Flow. The actual ΔV costs were within the 14th percentile of the expected performance for Ebb and 23th percentile for Flow. Tables 3 and 4, respectively, compare the achieved post-LOI orbit elements to the targeted values. The achieved post-LOI orbit periods were less than 4 minutes from the targeted values.

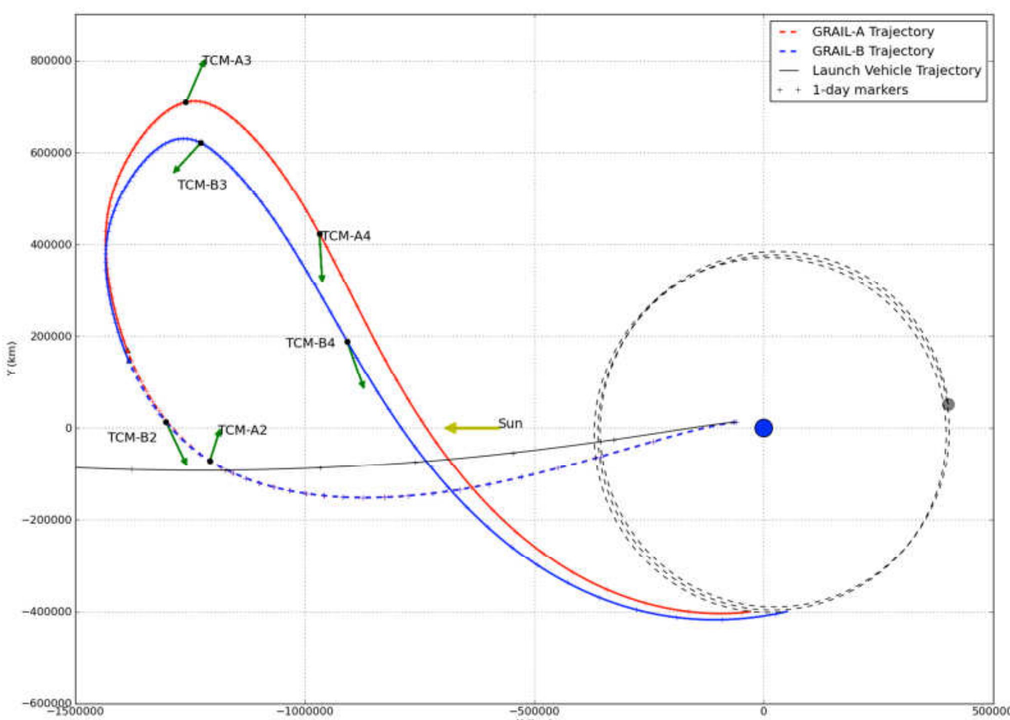

Figure 1: Ebb's (GRAIL-A, red) and Flow's (GRAIL-B, blue) Trans-Lunar Cruise trajectories are shown from the ecliptic-North pole in the Sun-Earth rotating frame.

Table 1: Ebb (GRAIL-A) designed ΔV compared to pre-launch expected (Mean ΔV) TLC ΔV cost

Maneuver	Epoch	Median ΔV (m/s)	Design ΔV (m/s)	Percentile (%)
TCM-A1	16-SEP-2011 18:00:00 UTC	3.806	0.000	0.0%
TCM-A2	30-SEP-2011 18:00:00 UTC	14.233	13.968	37.4%
TCM-A3	16-NOV-2011 17:59:59 UTC	6.072	6.452	58.1%
TCM-A4	09-DEC-2011 18:00:00 UTC	0.124	0.234	86.8%
Cumulative		24.512	20.653	13.7%

Table 2: Flow (GRAIL-B) designed ΔV compared to pre-launch expected (Mean ΔV) TLC ΔV cost

Maneuver	Epoch	Median ΔV (m/s)	Design ΔV (m/s)	Percentile (%)
TCM-B1	17-SEP-2011 18:00:00 UTC	4.701	0.000	0.0%
TCM-B2	05-OCT-2011 18:00:00 UTC	23.422	25.089	100.0%
TCM-B3	21-NOV-2011 18:00:00 UTC	9.219	8.843	43.8%
TCM-B4	14-DEC-2011 17:59:59 UTC	0.213	0.260	63.6%
Cumulative		37.116	34.192	23.1%

Table 3: Ebb (GRAIL-A) and Flow (GRAIL-B) achieved post-LOI orbits compared to targeted values.

GRAIL-A Parameter	Target Value	Achieved Value	Error
Semi-major Axis (km)	5970.745	5948.200 ± 0.012	-22.545
Eccentricity	0.694	0.692 ± 0.000	-0.002
Inclination (deg)	87.435	87.463 ± 0.000	0.028
Longitude of Ascending Node (deg)	115.679	115.680 ± 0.000	0.001
Arg. o f Periapsis (deg)	355.714	356.020 ± 0.000	0.306
Period (sec)	41400.021	41166.000 ± 0.126	-234.021
Time to Periapsis (sec)	20700.011	20583.000 ± 0.063	-117.011
Periapsis Range (km)	1827.108	1830.900 ± 0.006	3.792

GRAIL-B Parameter	Target Value	AchievedValue	Error
Semi-major Axis (km)	5970.745	5955.500 ± 0.021	-15.245
Eccentricity	0.690	0.689 ± 0.000	-0.001
Inclination (deg)	88.331	88.326 ± 0.000	-0.005
Longitude of Ascending Node (deg)	115.552	115.520 ± 0.000	-0.032
Arg. of Periapsis (deg)	354.132	354.500 ± 0.000	0.368
Period (sec)	41400.021	41241.000 ± 0.219	-159.021
Time to Periapsis (sec)	20700.011	20621.000 ± 0.109	-79.011
Periapsis Range (km)	1850.931	1851.800 ± 0.011	0.869