SpaceOps 2010 Conference
 <i>Delivering on the Dream</i>
 <i>Hosted by NASA Mars
25 - 30 April 2010, Huntsville, Alabama

AIAA 2010-1985

Maneuver Operations Results from the Lunar Reconnaissance Orbiter (LRO) Mission

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The Lunar Reconnaissance Orbiter was launched on June 18, 2009 to prepare the way for future study of the Moon. The NASA Goddard Space Flight Center's Navigation & Mission Design Branch was tasked with designing LRO's trajectory and planning the maneuvers needed to meet that goal. Using commercial off the shelf (COTS) and institutional software, the LRO Maneuver Team planned 10 maneuvers over the first 90 days of the mission to place LRO in its 50 km, polar mapping orbit around the Moon. So far, an additional six pairs of stationkeeping maneuvers have been supported to maintain LRO's mapping orbit. During the first three months of operations, the Maneuver Team also planned maneuvers to support coincident observations with India's Chandrayaan-1 satellite and NASA's LCROSS lunar impactor mission. Overall, LRO's maneuvers have been calibrated to within 2% of the pre-launch propulsion models. LRO will have approximately 210 m/s of ΔV remaining after the 1-year nominal mapping mission is completed in mid-September of 2010. These reserves will be available for extended mission operations.

Nomenclature

LOIn	=	Lunar Orbit Insertion Maneuver #n
MCCn	=	Mid-Course Correction Maneuver #n
MOIn	=	Mission Orbit Insertion Maneuver #n
SKnn	=	Stationkeeping Maneuver #nn

I. Introduction

The Lunar Reconnaissance Orbiter (LRO) represents NASA's first step in returning astronauts to the Moon. From its 50 km circular, lunar polar orbit, LRO's instrument suite will be used to identify safe landing sites, map out potential in situ resources, and characterize the radiation environment. NASA's Goddard Space Flight Center (GSFC) was given the responsibility to build, launch, and operate LRO for its 1-year nominal mission along with any extended mission opportunities. LRO was launched in a dual payload configuration with the Lunar CRater Observation and Sensing Satellite (LCROSS). After separation from the LCROSS\Centaur stack, LRO captured into a polar orbit about the Moon while LCROSS performed a lunar swingby to set up its impact into a crater near the lunar South Pole.

As part of GSFC's LRO mission team, the Maneuver Team was made up of 6 civil servant employees from the Navigation & Mission Design Branch (Code 595). Prior to launch, this team had the task of defining the orbit & navigation requirements, designing the trajectory, calculating the launch window, and providing targets to the United Launch Alliance (ULA) team responsible for the Atlas-V launch vehicle activities. During mission operations, the Maneuver Team was responsible for using the latest navigation solutions to plan upcoming LRO maneuvers and to provide products necessary to build the command loads to execute the maneuvers onboard the spacecraft. Maneuver Team operations were performed from the Flight Dynamics Facility's (FDF) Mission Operations Room (MOR) at GSFC. From this location, the Maneuver Team performed its work using the Satellite Tool Kit (STK) software developed by Analytical Graphics, Inc. (AGI). In particular, the LRO trajectory was developed using STK's Astrogator Module. In addition to the STK suite of software, the Maneuver Team made use

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of utilities developed using Matlab and Perl. These utilities were helpful in providing some automation of repeated procedures as well as for processing spacecraft telemetry.

II. Mission Description

The LRO spacecraft is a 3-axis stabilized spacecraft that operates in a nadir-pointing orientation in its nominal, 50 km, low lunar polar orbit. At launch, the total LRO mass was measured 1915.27 kg which included 894.4 kg of monopropellant hydrazine fuel. LRO carries a suite of seven instruments to perform its science objectives. The instruments and their functions are listed below and shown in Figure 1.

- Lunar Orbiter Laser Altimeter (LOLA) – global topography at high resolution
- Lunar Reconnaissance Orbiter Camera (LROC) – targeted images of the lunar surface
- Lunar Exploration Neutron Detector (LEND) – map the flux of neutrons from lunar surface
- Diviner Lunar Radiometer Experiment (DLRE)- map the lunar surface temperature, cold traps, and rocks
- Lyman-Alpha Mapping Project (LAMP) – observe lunar surface in far ultraviolet, observe permanently shadowed crater regions
- Cosmic Ray Telescope for the Effects of Radiation (CRaTER) – background space radiation
- Mini-RF – S and X-band synthetic aperture radar

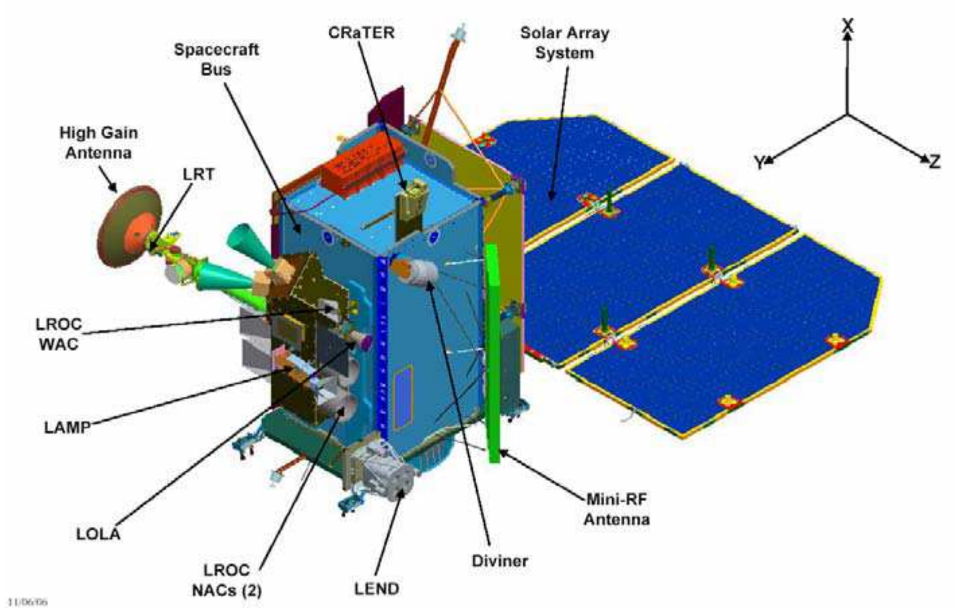

Figure 1. LRO Instrument Layout

LRO utilizes a set of 12 thrusters for performing its propulsive maneuvers. The thruster complement includes 4 insertion thrusters (NT1 – NT4) and 8 attitude thrusters (AT1 – AT8). The thrusters are arranged in two banks with the odd numbered thrusters belonging to Bank 1 and the even-numbered thrusters belonging to Bank 2. The 20 lbf (89 N) NT's are aligned with the spacecraft's body X-axis. The 5 lbf (22 N) AT's are aligned with a unit vector in the spacecraft's body frame of [cos(15°), 0, ±sin(15°)] where AT1 – AT4 have positive Z-components while AT5 – AT8 have negative Z-components. The thruster layout can be seen in Figure 2. The propulsion system is primarily a pressure regulated system, fed by a pressurized helium tank, although the first maneuver to correct for launch vehicle errors was performed in a blowdown mode prior to opening the regulator.

The propulsive trajectory maneuvers performed during operations utilized several different thruster configurations. These configurations (NT x AT) were identified by the number of insertion thrusters (NT's) and attitude thrusters (AT's) used for each of the maneuvers (Table 1). Smaller maneuvers (e.g. mid-course corrections, MCC's; stationkeeping, SK's; etc.) were performed using a 0x4 configuration (i.e. 0 NT's and 4 AT's). On the other hand, the large, lunar orbit insertion maneuver (LOI1) and the preceding engineering maneuver, LOIE, utilized a 4x8 configuration, using all 12 thrusters during the maneuver. The remaining LOI's and the mission orbit insertion maneuvers (MOI's) utilized 2x8 configurations using 2 NT's and all 8 AT's. The finite maneuvers were modeled in

STK's Astrogator module using polynomial curve fits for both the thrust and the specific impulse of each type of thruster.

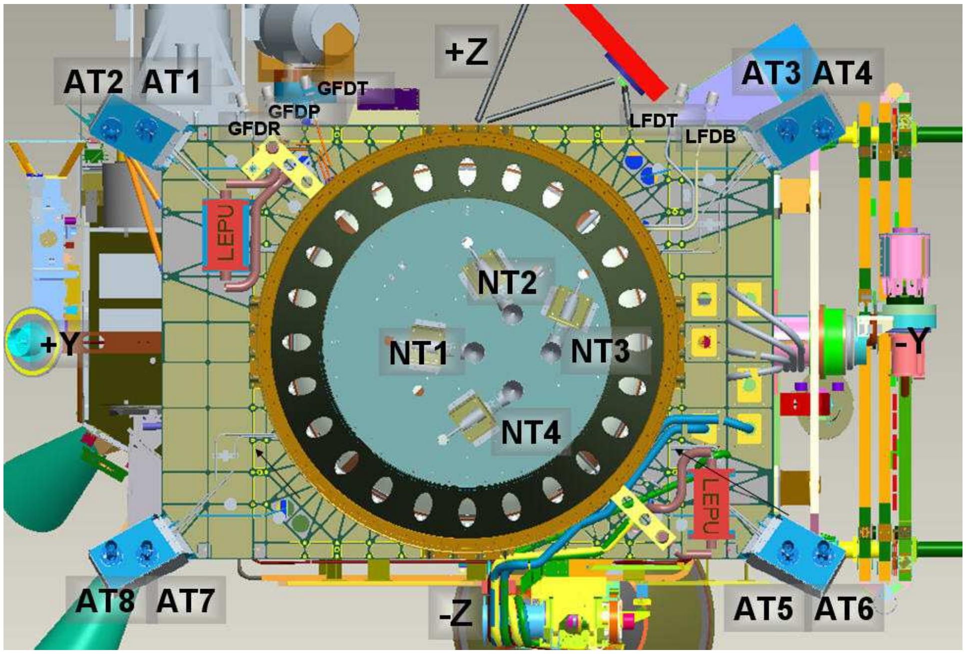

Figure 2. LRO Thruster Layout

Table 1. LRO Thruster Configurations

Maneuver(s)	Thruster Configuration (NT x AT)	Mode
MCC's	0 x 4	Blowdown
LOIE	4 x 8	Pressure Regulated
LOI1	4 x 8	
LOI2 – LOI5	2 x 8	
MOI's	2 x 8	
SK01 – SK13	0 x 4	

LRO operations were split into four distinct phases (Figure 3). The transfer phase began with LRO's launch on an Atlas V 401 launch vehicle. Launch occurred on June 18, 2009 at 21:32:00 UTC – the end of the day's 20 minute launch window. Roughly 45 minutes later, LRO separated from the LCROSS\Centaur stack at 22:16:45 UTC to begin the transfer phase of the mission. During LRO's 4.5 day minimum energy transfer to the Moon, the spacecraft underwent checkout activities and the mid-course correction (MCC1) maneuver was planned for 24 hours after spacecraft separation to correct for any launch vehicle errors. The Lunar Orbit Insertion (LOI) sequence took 5 days and began with an engineering maneuver (LOIE) 6.5 hours prior to the lunar orbit capture maneuver (LOI1). The LOI2 – LOI5 maneuvers further lowered the orbit apoapsis and established the commissioning orbit – a 2 hour, 30 km x 216 km quasi-frozen polar orbit. During the Commissioning Phase, the instruments were activated and preliminary science was performed. At the end of the Commissioning Phase, a series of mission orbit insertion (MOI) maneuvers were planned to establish the 50 km (± 20 km) low, lunar mapping orbit. Nominally, LRO will spend 1 year in its mapping orbit having to perform stationkeeping (SK) maneuvers roughly every 27-28 days (i.e. each lunar cycle). Further details on the trajectory design can be found in Reference 1.

The pre-launch ΔV budget for the June 18th launch date through the commissioning phase is shown in Table 2. The table includes the nominal times for the statistical (MCC's) as well as the deterministic maneuvers (all others) along with their expected values. At the right is the pre-launch ΔV allocation for the maneuvers. The allocations account for both the 3σ statistical allocations (for launch vehicle and maneuver performance errors) as well as for the variances in the LOI1 maneuver that are a function of the launch date. LRO gained 74 m/s of margin when compared to the conservative, pre-launch allocation. This margin comes from better than expected launch vehicle performance as well as a LOI1 maneuver that falls below the value allocated in the budget. This net gain is added to the pre-existing 115 m/s to give almost 189 m/s available for margin and potential extended mission operations.

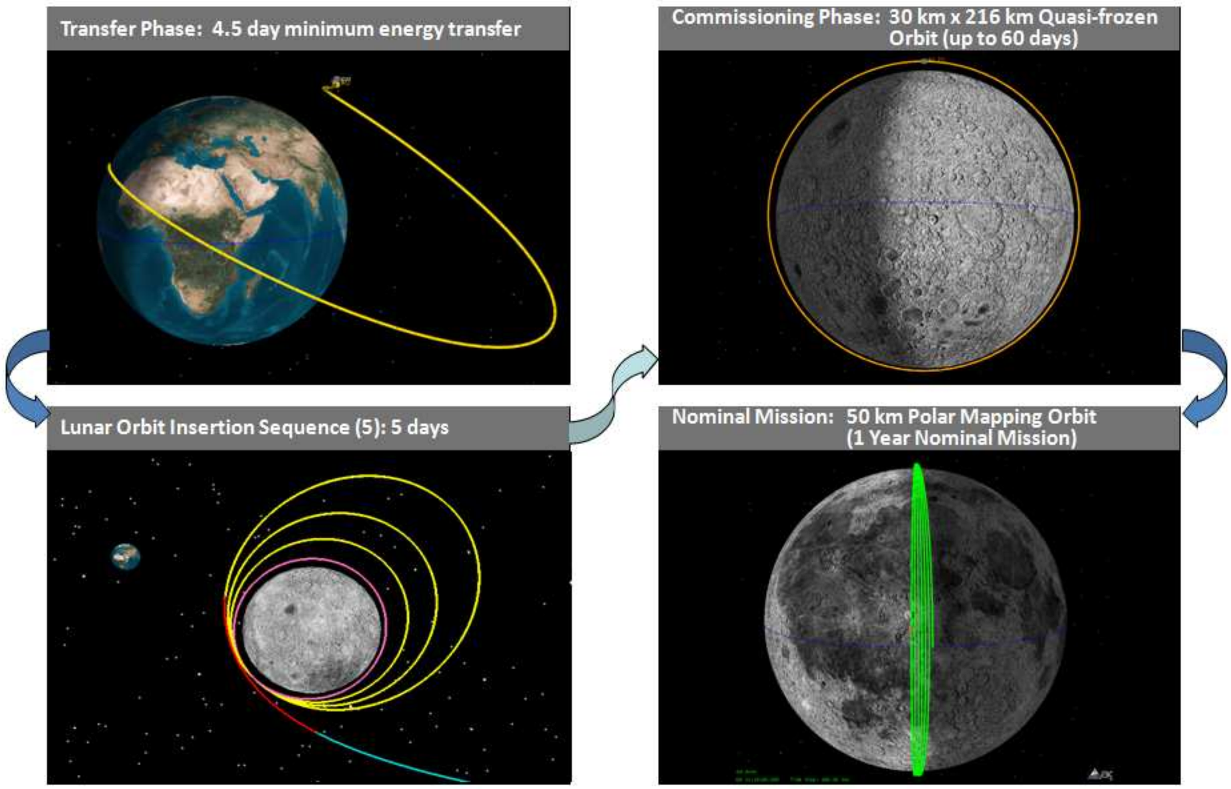

Figure 3. LRO Mission Phases

Table 2. LRO June 18 Pre-Launch ΔV Budget & Allocation

Maneuver	**Start Time (UTC)**	**ΔV (m/s)**	**ΔV Budget Allocation (m/s)**
MCCE	19 Jun 2009 20:16:40	0.0	2
MCC1	19 Jun 2009 22:16:40	11.3*	28
MCC2	21 Jun 2009 10:16:40	0.0	0
LOIE	23 Jun 2009 03:01:12	6.3	8
LOI1	23 Jun 2009 09:43:24	555.5	583
LOI2	24 Jun 2009 10:54:30	98.7	362
LOI3	25 Jun 2009 11:50:10	102.8	
LOI4	26 Jun 2009 12:12:57	113.2	
LOI5	27 Jun 2009 12:31:27	37.4	
MOI1	30 Aug 2009 16:29:40	32.9	56
MOI2	31 Aug 2009 16:15:09	5.3	
MOI3	01 Sep 2009 15:40:34	2.0	
		965.4	**1039**

* 3σ value based on June 18th expected launch vehicle performance

III. Maneuver Operations

With a few exceptions, maneuver operations were performed around the clock for the first 10 days of the mission, from launch through the end of the LOI sequence. The operations were broken up into two main functions – planning and calibration.

A. Maneuver Planning

The maneuver planning process began with the Maneuver Team receiving an orbit state vector (epoch, position, & velocity) from the LRO Orbit Team who worked out of the same Flight Dynamics Facility as the Maneuver Team enabling a rapid exchange of information and products. The navigation state was computed with the batch, least-squares processing of LRO tracking data from various sites including the 34 meter Deep Space Network (DSN), the Universal Space Network (South Point, HI; Weilheim, Germany; Kiruna, Sweden; and Dongara, Australia), and the LRO dedicated antenna at White Sands, NM. Further details on orbit determination activities can be found in Reference 2.

Upon receipt of the orbit state vector, the Maneuver Team would plan the upcoming maneuver using the differential corrector targeter found in STK's Astrogator module. The targeter would vary maneuver control parameters (e.g. maneuver start time, duration, attitude, etc.) to meet desired constraints (e.g. lunar orbit inclination, apses altitudes, etc.) which varied depending on the maneuver being planned.

After the maneuver was successfully targeted, products were prepared and delivered to the mission planners in LRO's Mission Operations Center (MOC). These products included the maneuver details (start time, duration, thruster complement, etc.) and attitude targets. Additional products (e.g. predicted state ephemerides, ground station view predicts, etc.) were produced by the Orbit Team using the STK satellite file prepared by the Maneuver Team. MOC personnel processed these files to build a command load for the maneuver.

Once the command load was generated it was tested on the ground on FlatSat – a hardware-in-the-loop simulator. LRO's FlatSat simulator was used to test out the entire command sequence on the ground prior to uploading and executing it on the spacecraft. Upon completion of the FlatSat simulation, simulated telemetry (e.g. thruster on-times, "observed" quaternions) was sent back to the Maneuver Team to validate the tested maneuver. The Maneuver Team used the simulated telemetry to reconstruct the maneuver and verify that all targeted orbit constraints were met. This closed-loop planning process was performed for both the preliminary and the final maneuver plans prior to the actual maneuver. After the final plan was tested and validated the command sequence was uplinked to the spacecraft and executed at the appropriate time. A flow chart of this process can be seen in Figure 4. Maneuver Team functions are illustrated in blocks 1-3 & 7 while MOC functions are shown in blocks 4 - 6, & 8.

This planning process typically began at 13 hours prior to the maneuver with the Maneuver Team's receipt of the orbit state followed two hours later with the delivery of the preliminary products. The processing and FlatSat activities took roughly 4 hours. During the final planning phase, products were delivered roughly 5 hours prior to the start of the maneuver.

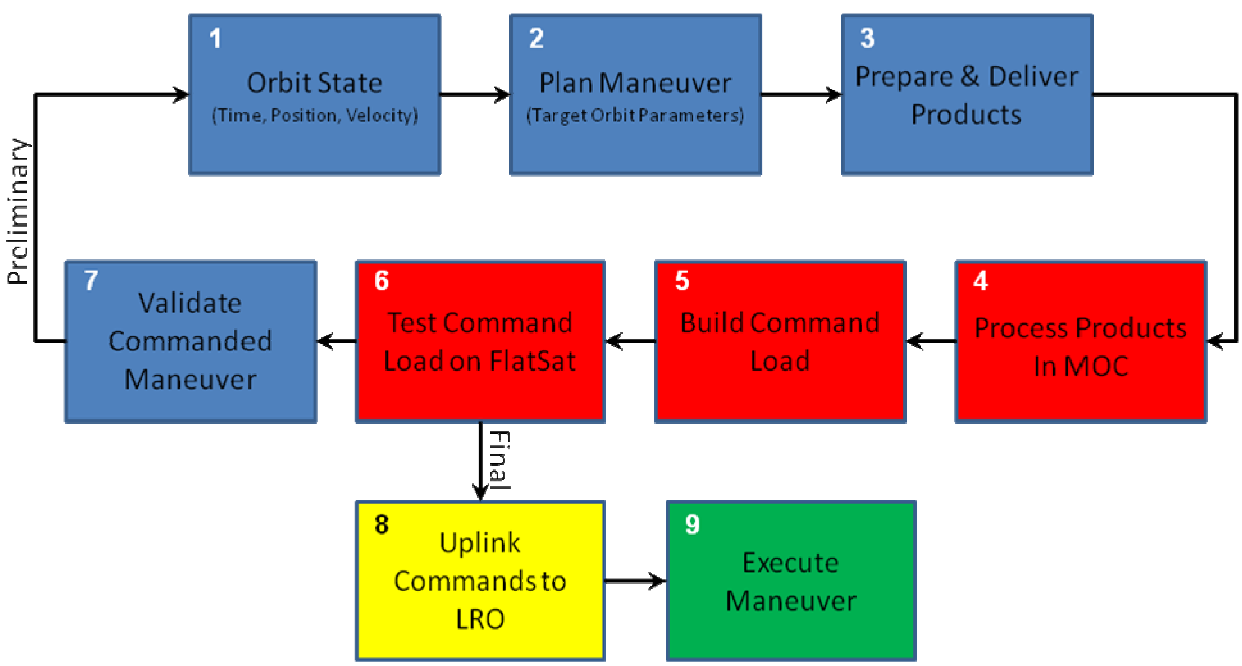

Figure 4. Maneuver Planning Process

B. Maneuver Calibration

Maneuver calibration activities occurred after receipt of spacecraft telemetry. The relevant telemetry included thruster on-times, observed attitude (in the form of quaternions), and fuel tank pressure. This observed data was used to reconstruct the maneuver using the best available pre-maneuver orbit state. Once a suitable post-maneuver state was determined by the Orbit Team, an iterative process began whereby the Maneuver Team used a single thrust scale factor, TSF, to scale the propulsion system performance to match post-maneuver results, usually orbit energy. Then, the calibrated TSF, which was specific to each thruster configuration (e.g. 4x8, 2x8, 0x4, etc.), could be used to better plan future maneuvers which used the same configuration. This was especially important for the LOI2-5 & MOI1 maneuvers which all used the 2x8 configuration and for the SK maneuvers (0x4 configuration). The calibration for the LOI maneuvers had to be performed within 12 hours after the maneuver in order to be used to plan the next subsequent maneuver.

IV. Maneuver Results

This section will describe the maneuvers as they happened during operations. At the end, a comparison will be made relative to the pre-launch nominal values previously discussed in Table 2.

A. Mid-Course Correction Maneuvers

The purpose of the MCC maneuvers was to adjust an off-nominal launch trajectory to achieve the desired arrival conditions at the Moon. The first mid-course correction maneuver (MCC1) was planned to occur 24 hours after spacecraft separation. If MCC1 was required, an MCC engineering maneuver (MCCE) would be performed 2 hours prior to MCC1. MCCE was designed to be a 30 second maneuver to check out LRO's attitude control performance for the MCC1 0x4 thruster configuration. Additionally, there was a placeholder for an MCC2 maneuver to occur at MCC1 + 36 hours in case MCC1 didn't adequately target the lunar orbit arrival conditions.

The Maneuver Team designed a two-maneuver targeting sequence using the MCC1 and LOI1 maneuvers to achieve post-LOI1 constraints on inclination (89.9°), periapsis altitude (216 km), and orbit period (5 hours). After the Orbit Team processed the first 6.5 hours of tracking data (range and Doppler), it was determined that LRO received a very good ride from the Atlas V launch vehicle and that a small MCC1 maneuver would be necessary. In fact, the MCC1 was small enough, 37.8 seconds, to eliminate the need for the 30 second MCCE maneuver in accordance with pre-launch discussions with LRO's systems engineers.

The 37.8 second (1.3 m/s) MCC1 maneuver occurred as planned on June 19, 2009 at 22:16:42 UTC (Table 3). Post-maneuver calibration of the 0x4, blowdown maneuver yielded a thrust scale factor of 0.996. In other words, propulsion system was performing "cold" by roughly 0.4%. Despite a slightly cold maneuver, it was determined that a MCC2 maneuver was unnecessary and that the Maneuver Team would commence with planning the LOI1 lunar capture maneuver.

Table 3. MCC1 Performance

	Final Plan	Calibration
Tank Pressure (psi)	204.3	204.2
Thrust Scale Factor	1.000	0.996
Duration (sec)	37.8	37.8
ΔV (m/s)	1.318	1.312
Propellant Use (kg)	1.150	1.150

B. Lunar Orbit Insertion Maneuvers

There were 5 retrograde (anti-velocity) LOI maneuvers planned for LRO to capture and reduce the size of the lunar orbit. The most important of these was the LOI1 maneuver which would enable LRO to capture into a stable lunar orbit. Additionally, an LOI engineering maneuver (LOIE) was planned to occur approximately 6.5 hours prior to LOI1 to confirm LRO's attitude control performance for the 4x8, pressure regulated LOI1 thruster configuration. Six and a half hours prior to the LOI1 maneuver, the command was given to open the helium tank pressure regulator and a 30 second engineering maneuver, LOIE, was performed. The LOIE (30 seconds) and LOI1 (39 minutes, 49.6 seconds) maneuvers occurred on June 23, 2009 at 03:05:03 UTC and 09:47:18 UTC, respectively. The performance of these two maneuvers is shown in Table 4. The LOI1 maneuver was calibrated to a thrust scale factor of 1.025 (2.5% "hot"). The LOIE maneuver was not calibrated because a good orbit solution could not be determined in the time between the LOIE & LOI1 maneuvers and attempts to calibrate the maneuvers together proved unsuccessful. After LOI1, LRO was in a 208.5 km x 3081.4 km lunar orbit with periapsis in the Moon's southern hemisphere.

Table 4. LOIE & LOI1 Performance

	LOIE		LOI1	
	Final Plan	**Calibration**	**Final Plan**	**Calibration**
Tank Pressure (psi)	270.0	267.5	270.0	267.0
Thrust Scale Factor	1.000	1.000	1.000	1.025
Duration (sec)	30.0	30.0	2349.6	2349.6
ΔV (m/s)	6.290	6.222	554.604	559.676
Propellant Use (kg)	5.316	5.260	415.068	409.492

The accuracy of the post-LOI1 orbit constraints is shown in Table 5. The most important parameter here was the lunar orbit inclination. The 0.14° error was bigger than the required 0.05° tolerance. The tight tolerance is to ensure that LRO meets its mean inclination of 90° over the entire 1 year of the nominal mission while accounting for the non-spherical lunar gravity effects. After some discussion, it was decided to correct the inclination error using the LOI2 maneuver. The periapsis altitude and orbit period for the capture orbit had very loose requirements and no adjustment was necessary.

Table 5. Post-LOI1 Targeting Accuracy

Post-LOI1 Target	Target	Achieved
Periapsis Altitude (km)	216.0	208.5
Inclination (°)	89.9	90.04
Period (sec)	18,000 (5.0 hrs)	17651 (4.9 hrs)

The remaining LOI maneuvers (2 – 5) were designed roughly 24 hours apart from each other and would be used to establish the nominal 30 km x 216 km commissioning orbit. These retrograde maneuvers used a 2x8 thruster configuration (different from LOI1) to provide better controllability due to the center of gravity shift following LOI1. The LOI2 and LOI3 maneuvers were designed as fixed duration maneuvers (760 seconds) to lower the orbit apoapsis (Table 6). Because of the new thruster configuration, the LOI2 maneuver was planned using a TSF of 1.0. The LOI2 maneuver occurred nominally, beginning at 10:28:50 UTC on June 24, 2009. After the maneuver, a TSF of 1.021 (2.1% "hot") was computed for LOI2 and used for the final plan for LOI3. As mentioned above, the LOI2 maneuver was used to correct for the inclination error seen after LOI1. A small yaw angle offset was held during the maneuver to effect this change. After LOI2, LRO met its inclination target to within 0.002°, well within the mission requirement. The LOI3 maneuver also executed nominally, starting at 10:32:39 UTC on June 25, 2009. For LOI3, the Maneuver Team computed a TSF of 1.020– very close to LOI2's 1.021 TSF indicating excellent repeatability for the propulsion system in the 2x8 thruster configuration. After LOI3, LRO was in a 200 km x 740 km, 2.6 hour orbit.

Table 6. LOI2 & LOI3 Performance

	LOI2		LOI3	
	Final Plan	**Calibration**	**Final Plan**	**Calibration**
Tank Pressure (psi)	269.0	268.5	268.5	268.65
Thrust Scale Factor	1.000	1.021	1.021	1.020
Duration (sec)	760	760.0	760	760.0
ΔV (m/s)	103.582	105.466	110.513	110.723
Propellant Use (kg)	67.217	67.022	67.022	67.230

The LOI4 and LOI5 maneuvers were each targeted maneuvers with separate goals. Details on the LOI4 and LOI5 maneuvers can be found in Table 7. LOI4 was a retrograde maneuver performed at periapsis to circularize the orbit. The LOI4 maneuver began at 12:24:55 UTC on June 26, 2009 and lasted for 627.6 seconds. LOI4 was calibrated with a TSF of 1.020 again demonstrating the consistency of the propulsion system. After LOI4, LRO was in a 197 km x 199 km orbit.

The final LOI maneuver, LOI5, was performed at the Moon's North Pole (i.e. at an argument of latitude of 90°) to lower LRO's periapsis altitude to 30 km over the South Pole. With periapsis at the South Pole, LRO could meet the quasi-frozen orbit condition by having an argument of periapsis of 270°. The LOI5 maneuver began at 12:34:55 UTC on June 27, 2009 and lasted for 230.8 seconds. LOI5 was calibrated with a TSF of 1.014 – 0.7% colder than expected. This resulted in a periapsis altitude of 31.5 km instead of the 30 km goal; however, this orbit was sufficiently stable for the commissioning phase of the mission. The LOI5 TSF was likely lower due the much shorter duration (230 seconds) as compared to the LOI2 – LOI4 maneuvers (627 seconds – 760 seconds).

Table 7. LOI4 & LOI5 Performance

	LOI4		LOI5	
	Final Plan	**Calibration**	**Final Plan**	**Calibration**
Tank Pressure (psi)	268.65	268.56	268.56	268.92
Thrust Scale Factor	1.021	1.020	1.019	1.014
Duration (sec)	627.6	627.6	230.8	230.8
ΔV (m/s)	95.730	95.326	36.051	35.684
Propellant Use (kg)	55.518	55.352	20.356	20.241

C. Commissioning Orbit

After the LOI5 maneuver, LRO was in a stable 31.5 km x 199 km polar orbit with periapsis over the South Pole. The achieved orbit parameters (eccentricity near 0.043, argument of periapsis near 270°, mean altitude < 500 km) sufficiently met the conditions for a quasi-frozen, polar lunar orbit [References 3 & 4]. The orbit is considered "quasi-frozen" because the line of apsides is perturbed very little by the lunar potential field. This can be seen graphically in Figure 5, a polar phase plot (R, Theta) of the eccentricity (R) and the argument of periapsis, ω, (Theta). This phase plot illustrates the stability of the eccentricity and argument of periapsis throughout the planned 60 days of the commissioning orbit. Figure 6 further demonstrates the stability by showing the bounded perturbations of the periapsis and apoapsis altitudes. The periapsis altitude varies between 30 km and 50 km while the apoapsis varies between 180 km and 200 km. The lower than planned apoapsis altitude was beneficial to LRO's LOLA team as it now meant that they could operate during the entire commissioning phase – their instrument was not designed to operate at altitudes above 200 km.

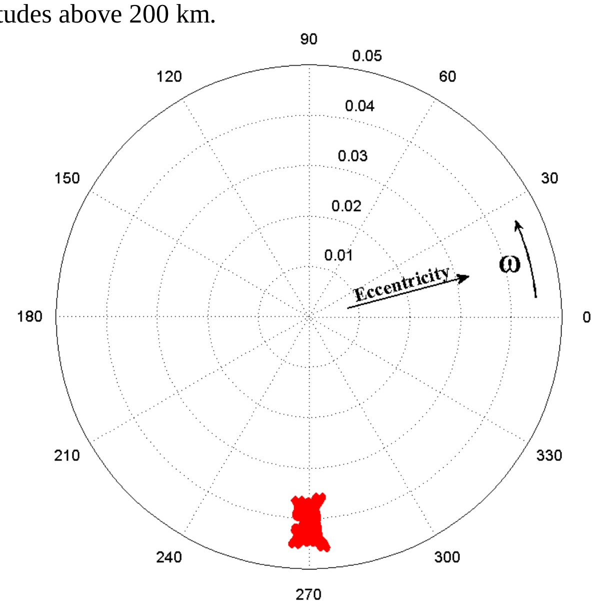

Figure 5. Commissioning Orbit Phase Plot

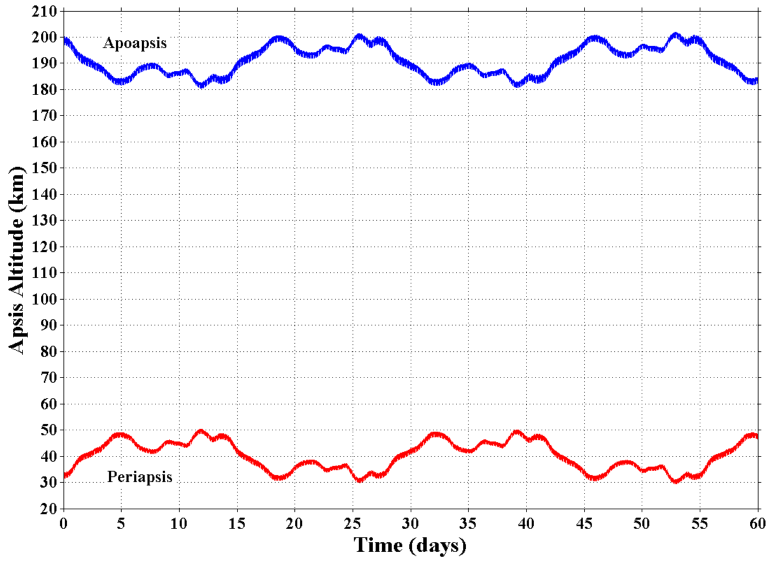

Figure 6. Commissioning Orbit Apsis Altitudes

During the commissioning phase, it was determined that LRO could perform coordinated observations with the Indian Science Research Organization's (ISRO) Chandrayaan-1 spacecraft (launched on October 22, 2008). As part of its instrument suite, Chandrayaan-1 (CH1) carried the miniSAR instrument – a synthetic aperture radar and sister instrument to LRO's Mini-RF instrument. The goal for the coordinated observation was to perform a Bi-Static Radar (BSR) experiment whereby CH1 would transmit from miniSAR into a lunar South Pole crater and both CH1 and LRO would attempt to receive the return signal with their sister instruments. The experiment would attempt to find water ice in Erlanger Crater (Longitude: 29.16°, Latitude: -87.01°), one of the permanently shadowed craters at the lunar South Pole. It was decided that LRO would do any maneuvers necessary to support this experiment due to CH1's deteriorated health at the time of the experiment. In order to properly phase LRO with CH1, LRO performed a small in-plane maneuver (22.8 seconds, 1.377 m/s) on August 19, 2009, the day prior to the observation. The experiment took place on August 20, 2009 with the corresponding instruments' sensor footprints overlapping over Erlanger crater for roughly 35 seconds. The close approach between the satellites was approximately 22.5 km, a majority of the difference being in the radial direction. After analyzing the encounter data, ISRO determined that, due to deteriorating spacecraft hardware, CH1 was not pointing at Erlanger Crater during the experiment time. A second attempt using a different crater was being investigated when communications were lost with CH1 on August 29, 2009 and the CH1 mission was terminated.

The pre-launch maneuver plan to transition LRO from the commissioning orbit to the mission orbit had included 3 MOI maneuvers, spaced approximately 24 hours apart, to begin roughly 60 days after entering the commissioning orbit. During the commissioning phase and prior to the BSR experiment, it was decided that the mission orbit insertion activities would commence on August 31, 2009. However, the inclusion of the BSR experiment caused an interruption in commissioning activities and delayed the mission orbit insertion until September 15. This shift in activities also meant that LRO's orbit plane would not be "face-on" to the Earth to allow for continuous communications coverage during all three MOI maneuvers.

After some analysis, the Maneuver Team determined that LRO could perform a single mission orbit insertion maneuver, MOI1, to lower the orbit to the nominal 50 km mapping orbit. The MOI1 maneuver was designed to be a retrograde maneuver performed at periapsis using the 2x8 thruster configuration. The MOI1 maneuver began at 19:32:25 UTC on September 15, 2009 and lasted for 184 seconds. MOI1 was calibrated with at TSF of 1.013, very close to the LOI5 TSF thus verifying that maneuver's drop in efficiency relative to the LOI2 – LOI4 maneuvers.

After the MOI1 maneuver, LRO was in an orbit with an average altitude of 50 km. Figure 7 shows the periapsis and apoapsis history around the MOI1 period. The MOI1 maneuver lowered the apoapsis altitude by almost 140 km. Orbit perturbations were reducing the eccentricity and LRO officially met its mapping orbit requirement of 50 km ± 20 km on September 18, 2009. Ultimately, LRO stayed in its commissioning orbit for roughly 80 days, from June 27, 2009 to September 15, 2009.

Table 8. MOI1 Performance

	Final Plan	Calibration
Tank Pressure (psi)	268.9	269.8
Thrust Scale Factor	1.014	1.013
Duration (sec)	184.0	184.0
ΔV (m/s)	28.892	28.909
Propellant Use (kg)	16.132	16.156

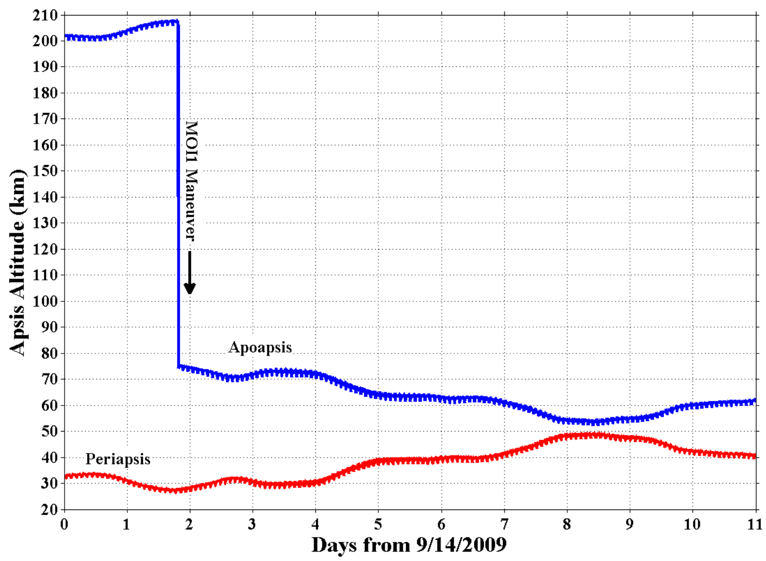

Figure 7. Apses Altitude History Near MOI1

After reaching the mapping orbit, we could make a full comparison of the achieved ΔV against the pre-mission ΔV budget. We can see from Table 9 that the achieved orbit gained us an additional 21 m/s of margin over the pre-launch expected values. This additional 21 m/s came from both the excellent ride from the Atlas V launch vehicle as well as from the abbreviated MOI plan that was implemented. Ultimately, the overall margin against the ΔV budget allocation added up to 210 m/s. This margin is over and above and ΔV required for the 1-year of stationkeeping in the mission orbit. Following MOI1, LRO had used 644 kg of fuel and had 250 kg of fuel remaining. The ΔV reserves will be available for extended mission operations after LRO finishes its nominal mission in mid-September of 2010.

Table 9. Maneuver ΔV (m/s) Comparison

Maneuver	Pre-Launch Expected	ΔV Budget Allocation	Achieved
MCCE	0.0	2	
MCC1	11.3	28	1.3
MCC2	0.0	0	
LOIE	6.3	8	6.2
LOI1	555.5	583	559.7
LOI2	98.7	362	105.5
LOI3	102.8		110.7
LOI4	113.2		95.3
LOI5	37.4		35.7
BSR			1.4
MOI1	32.9	56	28.9
MOI2	5.3		
MOI3	2.0		
Total	**965.4**	**1039.0**	**944.7**

D. Stationkeeping

In LRO's low-lunar orbit, the predominant perturbing factor is the Moon's potential field. Without periodic orbit maintenance, LRO's mapping orbit would be perturbed such that it would impact the lunar surface within 41 days. Given that LRO's Moon-centered orbit is essentially fixed, it was decided to perform stationkeeping maneuvers (SK) once every lunar cycle (27.4 days). Each stationkeeping maneuver is in fact a pair of maneuvers separated by an orbit and a half (3 hours). The stationkeeping maneuvers take place when the orbit's longitude of the ascending node (LAN) is near 270°. At this LAN, the orbit is "face-on" to the Earth allowing for continuous ground station coverage for the maneuvers. In practice, the pair of stationkeeping maneuvers takes the form of an optimal, 2-burn line of apsides rotation. An exaggerated illustration of this sequence is shown in Figure 8. The first maneuver (SKa Δv) is along the velocity direction and puts LRO into a transfer orbit with a larger semi-major axis ($\approx$ +10 km). Three hours (1.5 orbits) later, the second maneuver (SKb ΔV), in the anti-velocity direction, completes the line of apsides rotation. A detailed discussion of the stationkeeping design can be found in References 1 & 5.

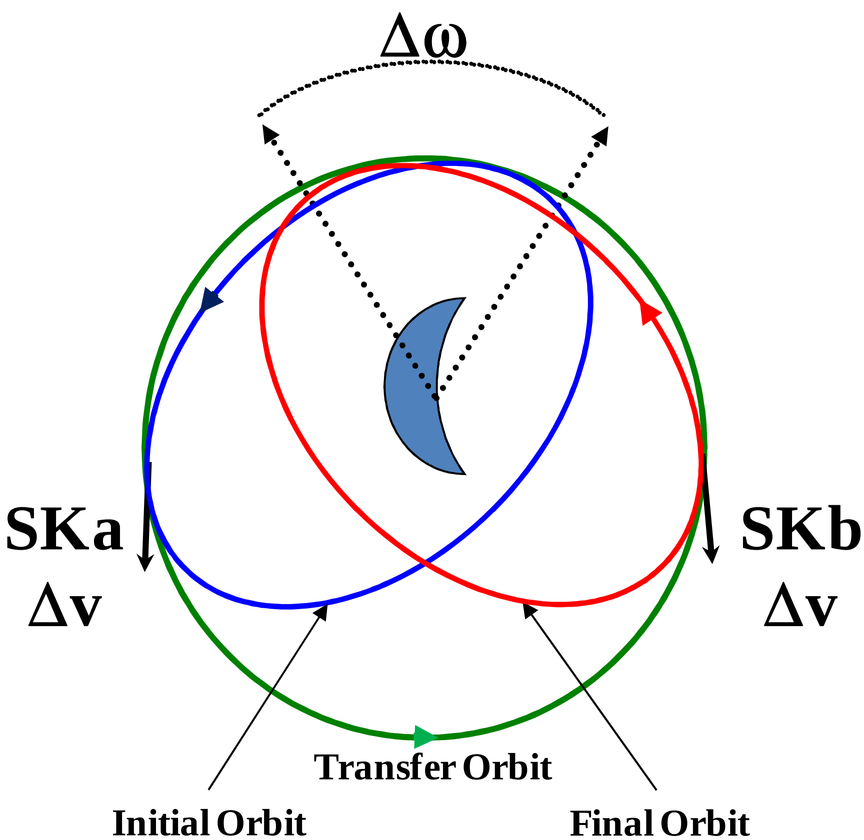

Figure 8. 2-Burn Line of Apsides Rotation

Similar to the quasi-frozen orbit, the easiest way to visualize the stationkeeping sequence is in an eccentricity & argument of periapsis polar phase plot. Figure 9 shows a typical mapping orbit stationkeeping cycle in a phase plot. The cycle begins with an eccentricity around 0.008 and an argument of periapsis near 140°. Over time, the lunar potential field perturbs these orbit parameters until, one lunar cycle later, the eccentricity is again near 0.008 but the argument of periapsis is near 40°. Then, the first maneuver, "SKa", establishes a transfer orbit followed 3 hours later by the "SKb" maneuver which completes the argument of periapsis rotation. Once the SKb maneuver is completed, the cycle begins again.

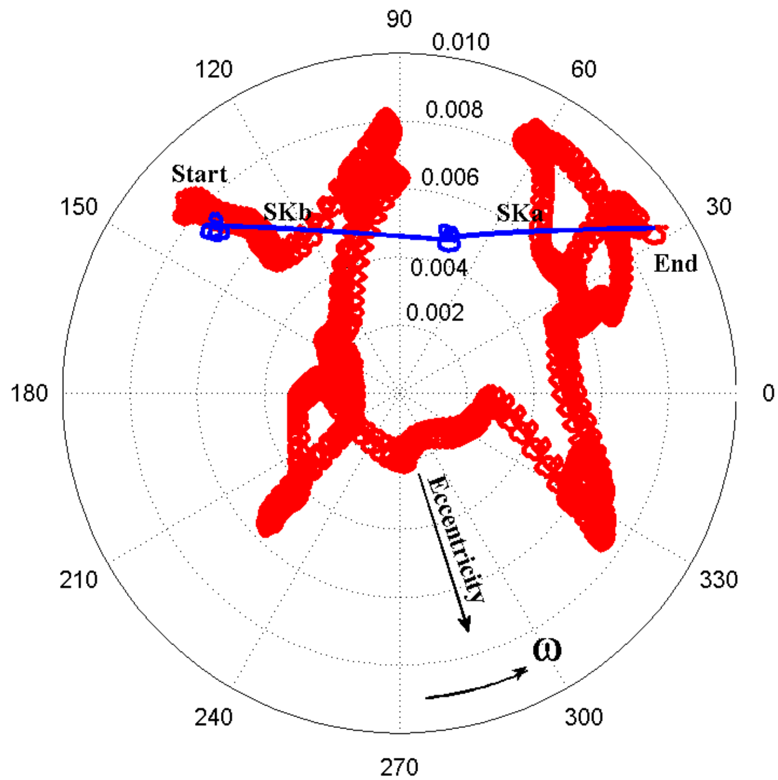

Figure 9. Typical Mapping Orbit Phase Plot

A summary of the stationkeeping maneuvers performed to date can be found in Table 10. While typically performed 3 hours apart, the SK01 maneuvers (a & b) were performed a day apart as it was the first time that we had used the 0x4 thruster configuration in the pressure regulated mode. As shown, all of the stationkeeping maneuvers have been calibrated to have TSF's very near 1.0. In other words, the propulsion system is working as planned in the 0x4, pressure-regulated mode. Furthermore, the average size of a stationkeeping pair is 11 m/s – consistent with the pre-launch estimates.

Table 10. Stationkeeping Maneuver Summary

Maneuver	Date	Time (UTC)	Duration (sec)	TSF	ΔV (m/s)	Fuel Used (kg)	Total
SK01a SK01b	09/25/2009 09/26/2009	18:27:46 17:55:25	92.0 81.6	1.011 1.003	5.776 5.095	3.299 2.925	10.871 m/s 6.224 kg
SK02a SK02b	10/23/2009	14:27:18 17:21:45	88.6 95.4	1.000 1.000	5.545 5.986	3.185 3.430	11.531 m/s 6.615 kg
SK03a SK03b	11/20/2009	14:05:08 16:54:53	82.6 95.8	1.001 0.998	5.199 5.998	2.965 3.423	11.197 m/s 6.388 kg
SK04a SK04b	12/17/2009	18:16:08 21:08:23	85.4 88.0	0.996 0.997	5.366 5.531	3.061 3.144	10.897 m/s 6.205 kg
SK05a SK05b	01/13/2010	16:50:58 19:41:59	85.4 86.8	0.999 0.996	5.397 5.473	3.055 3.099	10.870 m/s 6.154 kg
SK06a SK06b	02/09/2010	15:24:28 18:18:24	84.0 92.4	0.994 0.995	5.317 5.847	3.008 3.296	11.164 m/s 6.304 kg
						Total	**66.530 m/s** **37.890 kg**
						Average	**11.088 m/s** **6.315 kg**

E. Momentum Unloading

From time to time, LRO needs to perform momentum unloading maneuvers using thrusters to de-saturate the reaction wheels. The momentum buildup is due primarily to maintaining the nadir pointing attitude in the presence of gravity gradient and solar pressure torques. In the mapping orbit, the momentum unloads (ΔH) occur roughly every 14 days (i.e. half of a lunar cycle). This places the ΔH's two weeks from the prior stationkeeping maneuvers and on the same day as the subsequent 2-burn stationkeeping pair. Because LRO's propulsion system was not designed to provide forceless torques, each ΔH provides a residual ΔV. While the ΔH maneuvers are small in magnitude (< 0.5 m/s), the resultant orbit perturbation (ΔH maneuvers are performed in the velocity or anti-velocity direction) can cause problems with science observation targeting for the LROC instrument. Because of the unpredictability of the size of the ΔH's, a new scheme is being investigated to perform the maneuvers in the orbit normal direction. This new scheme would require 90° yaw slews to and from the ΔH but it would minimize along-track errors caused by performing the maneuvers in-plane. This new scheme is still under investigation as of the writing of this paper. From launch through February 9, 2010 LRO has performed 19 momentum unloads while expending only 1.9 kg of fuel.

F. LCROSS Interactions

As mentioned above, LRO was launched in a dual payload configuration with the Lunar CRater Observation Sensing Satellite (LCROSS). While LRO maneuvered to capture into its lunar orbit, LCROSS performed a lunar swingby to change its orbit plane and set up its impact into a lunar South Pole crater on October 9, 2009. On the transfer out to the Moon, the LRO Project was only concerned that there might be a close approach with LCROSS. However, after the handoff of LCROSS from the Atlas V launch team to the LCROSS flight team, LCROSS was never within 200 km of LRO during the transfer to the Moon. At LRO's lunar orbit insertion on June 23rd, there was over 4000 km of separation between LRO and LCROSS.

Although it was not an LRO mission requirement and was to be performed on a best effort, minimal interference basis, the LRO MOC and Maneuver Team worked closely with the LCROSS to coordinate LRO's observing of the LCROSS shepherding spacecraft and Centaur upper stage impacts. Using preliminary targets as a starting point, LCROSS finalized its target crater identification utilizing LRO science data collected during the commissioning orbit in early August of 2009. Once the target was selected, the LRO Maneuver Team planned the maneuvers to phase LRO's orbit so that the LRO instruments could view the LCROSS impacts. After several iterations, the LCROSS team settled on the Cabeus crater, a South Pole crater with coordinates of 314.6° in longitude and -84.7° in latitude. The timing of LRO's close approach to Cabeus was controlled using small in-plane maneuvers that adjusted LRO's arrival time relative to the impact. Because this crater would be off to LRO's "left" side as it flew nearby, LRO would simply perform a roll to point its instruments to view the impact. LRO scientists decided that arriving after impact would allow the debris cloud to rise above the limb and provide for optimal viewing conditions. After many discussions regarding the size and velocity of the impact debris, systems engineers and scientists from both LRO and LCROSS determined that LRO would be safe in arriving 90 seconds after the Centaur impact with a tolerance goal of ±10 seconds. Maneuver planning for this close approach was very similar to the planning the phasing maneuver performed for the CH1 experiment. Initially, the Maneuver Team planned to use only the SK01 maneuvers to target the close approach but quickly realized that an LCROSS Phasing Maneuver (LPM) was necessary to fine tune the encounter due to potential LRO maneuver execution errors and the uncertainty in the LCROSS orbit predictions. The LPM began at 19:15:00 UTC on October 7, 2009 and lasted for 9.4 seconds. LPM was calibrated with at TSF of 0.964 (Table 11). Despite being 3.6% cold, LRO's orbit met the science team's close approach arrival tolerance, flying by the Cabeus crater on 10/09/2009 at 11:32:53 UTC, 94 seconds after the Centaur impact. At the closest approach, LRO was within 77 km of the Cabeus crater at an altitude of 47.7 km. The LCROSS & Centaur debris clouds were not as large as predicted nevertheless the LRO instruments were able to view the Centaur impact as well as providing before & after images of the Cabeus crater. There was no evidence of LRO contamination due to the impact debris reported.

Table 11. LPM Performance

	Final Plan	Calibration
Tank Pressure (psi)	271.6	271.7
Thrust Scale Factor	1.000	0.964
Duration (sec)	9.4	9.4
ΔV (m/s)	0.588	0.567
Propellant Use (kg)	0.338	0.338

V. Conclusion

As of the writing of this paper, the LRO Maneuver Team has supported 41 propulsive events (22 maneuvers and 19 momentum unloads). The maneuver calibration activities have shown that the propulsion system and the models used by the Maneuver Team are consistent with observed performance and demonstrate very good repeatability. Maneuvers using the large NT insertion thrusters (LOI's & MOI's) consistently showed a slightly hot performance of +2%. The stationkeeping maneuvers, which use only the AT attitude thrusters, have all been calibrated to within 1%.

The Maneuver Team was often required to plan unscheduled, additional activities during the first 90 days of the mission. Close approach analysis of LRO and LCROSS was performed throughout the transfer trajectory phase. During the commissioning phase, the Maneuver Team was able to respond to several unplanned activities such as the Chandrayaan-1 BiStatic Radar experiment which resulted in a change to the mission orbit insertion plan. During the nominal mission phase, the Maneuver Team designed maneuvers to allow for the successful viewing of the LCROSS impact on October 9, 2009. Maneuvering LRO for the LCROSS impact viewing included many iterations and re-plans to adapt to changing requirements for viewing the impact. Examining all of the maneuvers and comparing against the pre-launch allocations, LRO has significant ΔV reserves (210 m/s) available for extended mission operations. Ultimately, the maneuver operations effort contributed to the successful LRO mission.

Acknowledgments

The authors would like to acknowledge Frank Vaughn from GSFC's Navigation and Mission Design Branch for his contribution to the Maneuver Team. Mr. Vaughn was brought onto the team several months before launch to help provide operations support. His effort greatly helped in the successful maneuver operations for the Lunar Reconnaissance Orbiter.

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