Trajectory Design and Orbit Determination for the Lunar CRater Observation and Sensing Satellite (LCROSS)

Ken Galal/ARC, Tony Colaprete/ARC, Steven Cooley/GSFC, Brian Kennedy/JPL, Tim McElrath/JPL

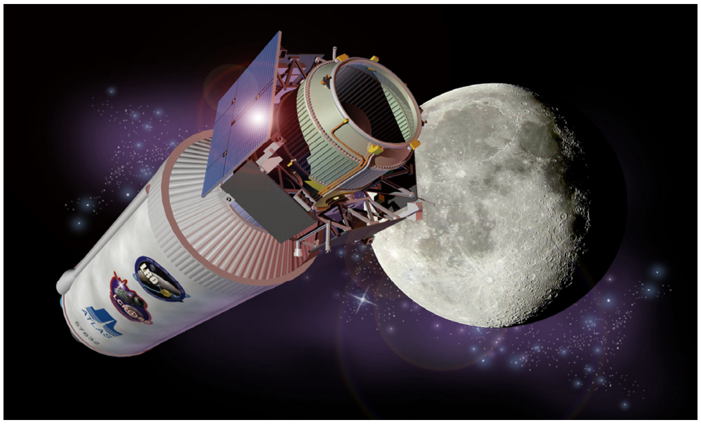


Figure 1: Artist Conception of LCROSS Spacecraft Attached to its EDUS Impactor

1.0 Introduction

The Lunar CRater Observation and Sensing Satellite (LCROSS) was competitively selected by the National Aeronautical and Space Administration (NASA) Exploration Systems Mission Directorate (ESMD) as a low-cost (<$80M) 1000 kg secondary payload to be launched with the Lunar Reconnaissance Orbiter (LRO) in October of 2008. LCROSS is a lunar impactor mission that will investigate the presence or absence of water in a permanently shadowed crater.

Following launch, trans-lunar injection (TLI) and separation from LRO, LCROSS will remain attached to the launch vehicle's ~2300 kg spent Earth Departure Upper Stage (EDUS) and will guide it toward an impact of a permanently shadowed crater at the lunar South Pole. Hours prior to impact, LCROSS will separate from the EDUS and perform a braking maneuver that will allow the spacecraft to take measurements of the resulting EDUS impact ejecta cloud for several minutes, before impacting the crater as well.

The science goals of the LCROSS mission are to confirm the presence or absence of water ice in a permanently shadowed region on the Moon, identify the form/state of hydrogen observed by Lunar Prospector at the lunar poles, quantify the amount of water that is present in the lunar regolith (with respect to hydrogen concentrations observed by Lunar Prospector) and to characterize the lunar regolith within a permanently shadowed crater on the Moon.

To achieve the science goals of the mission, LCROSS will fly a total of nine instruments, including Near/Mid-Infrared (NIR/MIR) and visible cameras, NIR and visible spectrometers and a Total Visible Luminance Photometer. These instruments will provide measurements of the total concentration of water in the sunlit ejecta cloud, detect any possible hydrogen bearing compounds, including water, hydrated minerals, and organics (including hydrocarbons) in the sunlit ejecta cloud, constrain the sunlit ejecta cloud particle physical properties -- including composition and particle size, and constrain the mechanical properties of the impact site, including minimum regolith depth and strength.

In addition to measurements taken from LCROSS, a campaign is being organized to observe the impact using available Earth-based telescopes and space-based telescopes [Reference 1].

The LCROSS mission is managed by NASA's Ames Research Center (ARC) with Northrop Grumman (NG) as the prime spacecraft contractor. ARC is procuring, assembling and testing the science payload prior to delivery to NG for integration with the spacecraft. The Mission Operations Center (MOC) and Science Operations Center (SOC) will be located at Ames. Mission and Maneuver design will be performed jointly between Ames and Goddard Space Flight Center (GSFC), and orbit determination will be performed by the Jet Propulsion Laboratory (JPL).

As a cost-capped secondary mission that must accommodate specific LRO launch dates, LCROSS faces unique challenges and constraints that must be carefully reconciled in order to satisfy an ambitious set of science observation requirements. This paper examines driving mission requirements and constraints and describes the trajectory design and navigation strategy that shape the LCROSS mission.

2.0 LCROSS Mission Design Overview

Figure 2 depicts the LCROSS mission design process, which is shaped by LRO launch dates, mission requirements, operational constraints and navigational considerations. The key mission design variables consist of the choice of candidate impact crater, ground observatory and trajectory type.

LRO Launch Dates

As a dual-manifested mission, LCROSS is constrained to launch on dates specified by LRO. LRO is a lunar polar orbiter that will be injected into a direct minimum energy transfer orbit to the moon before separating from the LCROSS/EDUS stack. LRO launch dates are driven by an LRO sun beta angle science observation constraint at lunar solstice which limits launches to bi-weekly periods of 2-4 consecutive days [Reference 2]. A total of 18 candidate launch dates in 2008 have been analyzed. The prime LRO launch dates are in late October and early November of 2008.

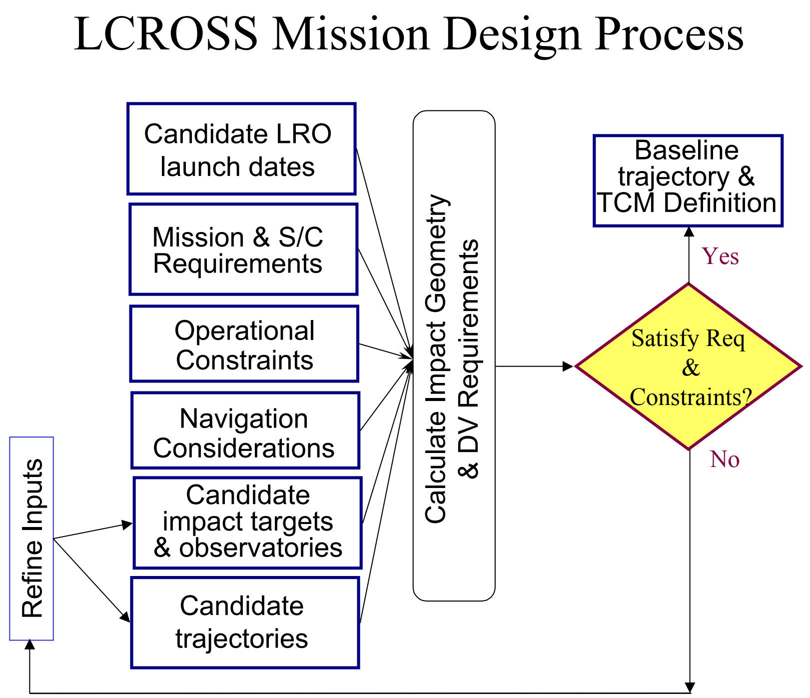


Figure 2: LCROSS Mission Design Process

Driving Mission Requirements

Chief among requirements that shape the LCROSS mission are those limiting mission duration, impact accuracy and impact geometry.

The LCROSS mission duration is set at less than 120 days due to a desire to limit qualification costs associated with the separation mechanisms to be used to separate the LCROSS spacecraft from the EDUS a few hours before impact. The short mission duration is also consistent with the need to contain mission operations costs, while affording LRO an opportunity to complete its lunar orbit insertion and commissioning phase in time to provide improved crater targeting data to LCROSS and to take advantage of the LCROSS impact event.

A second driving requirement is the LCROSS impact accuracy requirement of +/-10 km, with a goal of +/-1.75 km. The impact accuracy requirement was specified with the intent of allowing LCROSS to target a crater the size of Shackleton (20 km diameter), while the goal exists to allow LCROSS to more narrowly target regions within a crater that contain elevated signatures of hydrogen, possibly in the form of water-ice.

Finally, LCROSS has several impact geometry requirements governing spacecraft and ground telescope observing conditions:

Ground Observatory Coverage

The impact of the EDUS will be timed to occur in view of key ground telescopes in order to supplement the measurements taken by the LCROSS spacecraft. The prime observatories under consideration include those at Hawaii and Chile, which span the +/-28 deg range in lunar declination.

45 deg Lunar Elevation Angle

A 45 deg minimum lunar elevation angle is required for viewing the LCROSS impact event from a given observatory in order to minimize atmospheric attenuation.

Lunar Phase Angle

The lunar phase angle at impact is required to be greater than 30 deg from new or full moon. This requirement is driven by a need to manage lighting conditions during impact observation to prevent ground telescopes from being saturated by either lunar (near full moon) or solar (near new moon) background lighting. The combination of elevation and lunar phase angle requirements results in the effective lunar phase angle limits depicted in Figure 3.

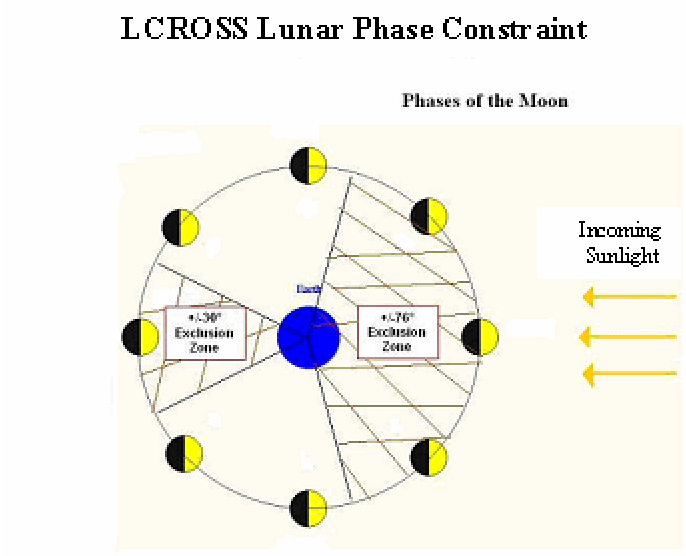


Figure 3: Effective LCROSS Lunar Phase Angle Limits for Ground Observation of Impact Event

Impact Angle and Velocity

A minimum impact angle of 60 deg and a velocity magnitude of 2.5 km/sec are required to maximize impact ejecta height. Impact angle varies with latitude of the targeted impact crater and is equivalent to the trajectory flight path angle at impact.

Sun and Earth Tilt Angle

The sun and Earth tilt angles -- defined as the angles between the normal to the crater floor and the sun and Earth, respectively -- are key to observing of the impact ejecta from space and Earth. The sun tilt angle determines how high the ejecta cloud must rise relative to crater walls before it is illuminated by the sun. Similarly, the Earth tilt angle determines how high the ejecta cloud must rise above the crater floor before it can be observed from Earth. Craters near the lunar poles will have sun and Earth tilt angles that are close to 90 degrees. Tilt angles below 90 degrees are desired to maximize viewing.

Operations Constraints

While the LCROSS spacecraft relies on up-to-date satellite technology and incorporates a number of clever design features, efforts to contain development cost did result in added responsibilities for ground operations. Examples of such cost-containment measures include the exclusive use of thrusters for attitude control (i.e., no reaction wheels to limit thrusting), the lack of accelerometers that could have aided in orbit maneuver calibration (particularly in support of the LCROSS braking burn that occurs prior to impact), and the reliance on the ground to supply open loop quaternion profiles in support of instrument and antenna pointing during lunar fly-by and impact. Other operational responsibilities include managing thermal, power and instrument pointing limits that constrain the duration and range of off-sun attitudes.

Navigation Considerations

A number of navigation considerations factored into the baseline LCROSS mission design, driven by the need to minimize orbit determination and impact uncertainties. Considerations included the number, timing and maximum size of orbit maneuvers, the maximum allowable Attitude Control System (ACS) disturbances and outgassing, the size of orbit maneuver dispersions, the spacing of final impact events and the availability of tracking coverage during key phases of the mission.

Candidate Impact Targets and Observatories

For a given LCROSS launch date, the choice of trajectory sets the impact date and the corresponding lunar phase angle and impact crater geometry. Four lunar south-pole impact craters (all within ~5 degrees of the South Pole) are under consideration by the LCROSS Science Team: Shoemaker, Faustini, Shackleton and Cabeaus. The impact geometry varies significantly as a function of impact date and crater selection, due to variations in the lunar libration angle with respect to the Earth and sun (from the 1.5 deg tilt of the lunar equator with respect to the ecliptic plane and the 6.7 deg tilt of the lunar equator with respect to the lunar orbit plane), and due to the location of each target crater on the moon. Figure 4 shows how these variations occur with monthly and annual frequencies for Shoemaker crater. Not all craters satisfy impact geometry requirements for a given impact date, therefore, proper selection of crater and mission duration must be exercised to ensure compliance with impact observation requirements.

The impact date also establishes the declination of the moon in Earth equator coordinates and determines whether observatories in the southern or northern hemisphere will be in the best position to view the impact. The impact time is chosen such that Deep Space Network (DSN) station coverage, observatory viewing conditions and impact lighting conditions are satisfied. Figure 5 shows ground station and observatory coverage conditions at the current impact time chosen for the baseline Oct. 28, 2008 launch date and 3.5-month trajectory. The plot shows the moon at impact near the center of the required 45 deg elevation field of view limit (shown in red) for telescopes located in Hawaii, with impact occurring approximately 2hrs (30 deg in longitude) from the solar terminator (dusk) and in view of the 70m DSN station at Goldstone.

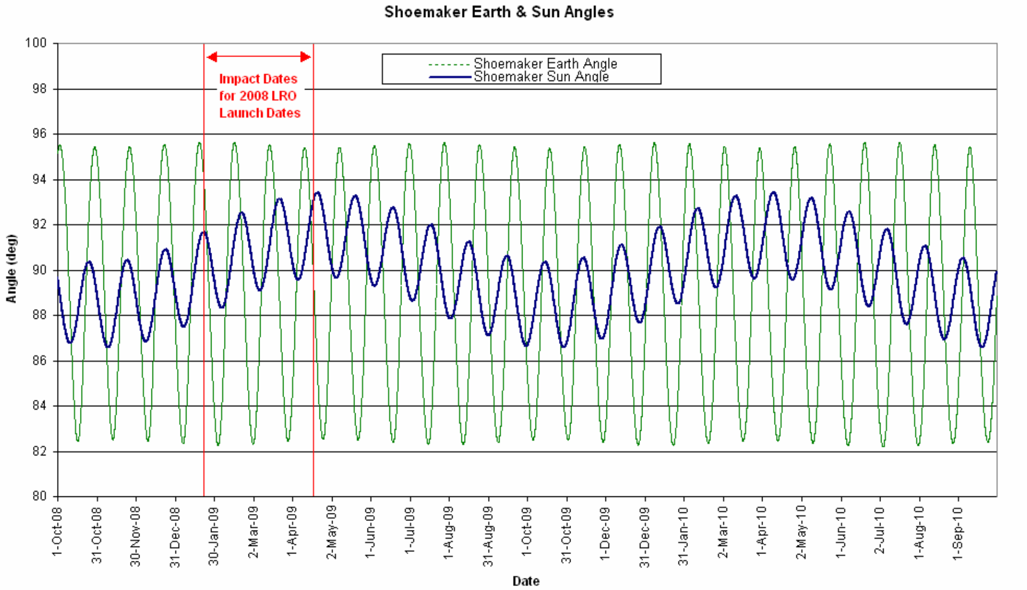


Figure 4: Variations in Crater Sun and Earth Geometry with Time due to Lunar Libration

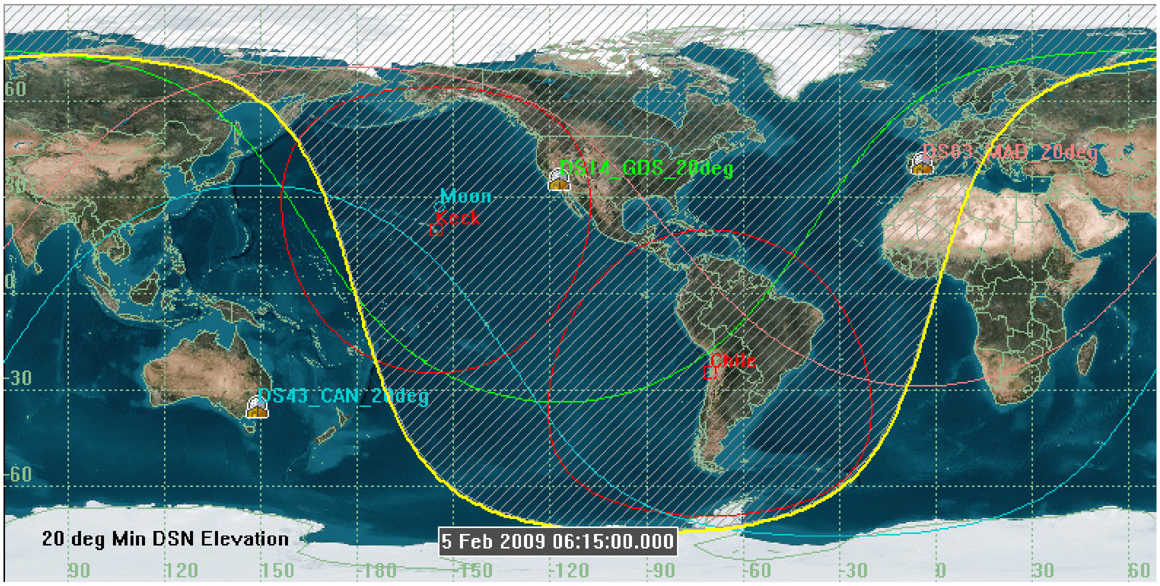


Figure 5: Nominal Impact Viewing Conditions for Baseline Oct. 28, 2008 3.5M Trajectory

Candidate LCROSS Trajectories

The LCROSS mission will utilize a Lunar Gravity Assist, Lunar Return Orbit (LGALRO), which requires a swingby of the moon from the lunar transfer orbit to get into a high ecliptic inclination cruise orbit. The lunar swingby sets the right ascension of the ascending node and apogee of the orbit and affords an opportunity for a high-energy, low-angle-of-incidence impact of the moon, which takes place an integer number of lunar half-months (13.6 days) later. The resulting

LGALRO impact conditions offer a marked improvement over impacts attempted from lunar orbit, such as that of the Lunar Prospector Mission (Reference 3).

For LCROSS, cruise orbits with durations of 3 and 4 months were initially considered. Later on, a further assessment of possible LRO launch dates suggested a need for a 3.5-month orbit as well. This expanded set of baseline trajectories provides increased flexibility in accommodating LRO launch dates and meeting impact geometry requirements (including lunar phase and crater sun/Earth tilt angle). For example, if the arrival geometry for a given 3-month trajectory does not satisfy lunar phase requirements, use of the 3.5-month trajectory will provide an impact date that is two weeks later, with an offset in lunar phase angle of 180 deg. Similarly, a 4-month trajectory offers a change in lunar phase angle of approximately minus 27 deg relative to that of the 3-month trajectory. Figure 6 shows samples of the 3, 3.5 and 4-month LCROSS trajectories. The 3- and 4-month trajectories are similar, in that they are established through a fly-by of the lunar south pole and have an ecliptic argument of perigee (AP) that is, for most cases, close to zero. The 3.5-month trajectory requires a fly-by of the lunar north pole and requires an ecliptic AP near 90 deg to prevent close approaches of the moon during crossings of the ecliptic plane subsequent to lunar fly-by.

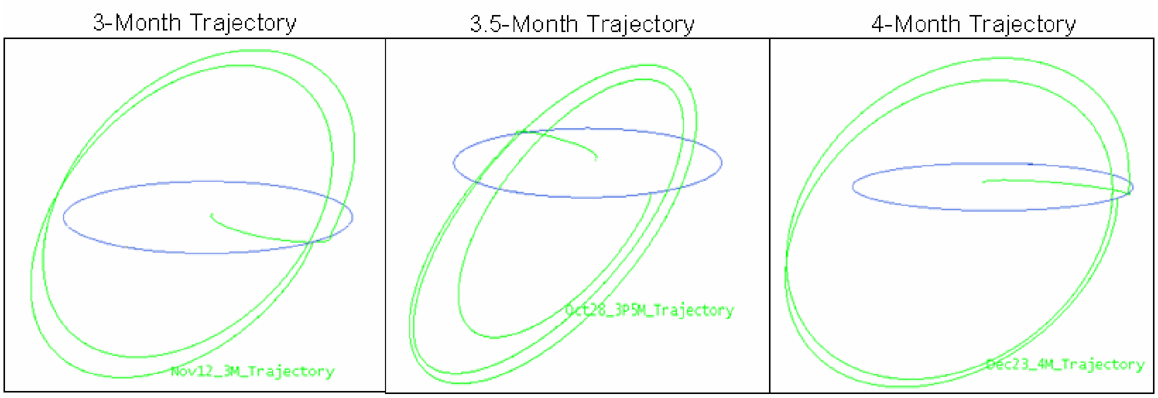


Figure 6: Sample 3-, 3.5 and 4-Month LCROSS Trajectories

3.0 LCROSS Maneuver Design

The LCROSS lunar impact trajectory will be achieved through a combination of launch vehicle injection and swingby re-targeting maneuvers, and a series of LCROSS transfer orbit (pre-swingby) and cruise orbit (post-swingby) maneuvers to adjust impact time and target the crater coordinates.

Launch Vehicle Injection

LRO and LCROSS will be injected into a minimum energy lunar transfer orbit (~3240 m/s) with periselene over the lunar South Pole. Following TLI and separation of LRO, the launch vehicle (LV) upper stage will contribute up to 50 m/s to retarget LCROSS toward its desired lunar fly-by conditions. The extent of the post-TLI retargeting delta-V required to achieve LCROSS fly-by conditions will depend on the launch date and the corresponding selection of the impact trajectory (i.e., 3-, 3.5- or 4-month). For trajectories with a southern lunar fly-by (3 and 4 month trajectories), a 10-30 m/s contribution by the LV is sufficient. For northern lunar fly-by trajectories (3.5 month), the full 50 m/s LV allocation is required plus an additional ~40 m/s (assuming a maneuver one day after TLI) must be supplied by LCROSS to achieve the required fly-by conditions. Note that the effectiveness of the LV contribution to the retargeting of LCROSS swingby conditions is diminished due to the higher velocity experienced close to TLI (as compared to maneuvers occurring later, when the velocity would be lower). Following completion of the LV venting (to eliminate propellants that could affect measurements of the impact plume) and retargeting operations, the LV upper stage will be shut down and LCROSS will assume control of the entire stack a few hours into the mission.

Lunar Transfer Orbit

Three Trajectory Correction Maneuvers (TCMs) are planned during the LCROSS transfer orbit, beginning with TCM1 scheduled one day after TLI. In addition to completing any remaining retargeting of periselene conditions, TCM1 will correct for any observed launch dispersions (particularly velocity magnitude errors which grow with time). TCM2 will take place two days after TLI (1 day after TCM1), while TCM3 will take place at periselene minus one day (2 days after TCM2). A fourth maneuver, TCM4, is nominally scheduled to occur two days after the swingby, in the event that any residual swingby errors need to be removed.

"B-plane" parameters at lunar periselene are used as a preliminary part of the trajectory design process. The maneuvers both before and after the lunar swingby are designed to achieve a lunar impact at a fixed location and time. However, as an intermediate trajectory design step, the B-plane parameters are used to help guide the design process. The approximate range of LCROSS B-plane parameters as a function of trajectory type is listed in Table 1.

Table 1: Range of Lunar B-Plane Targeting Conditions for LCROSS Trajectories

Target B-plane parameter	Trajectory Type		
	3 Month	3.5 Month	4 Month
Periselene Altitude (km)	2000 to 3700 (Mean = 2900)	3700 to 5000 (Mean = 4400)	1900 (Mean = 1900)
B-Theta (deg)	81 to 105 (Mean = 93)	-85 to -53 (Mean = -61)	105 (Mean = 105)

Cruise Orbit

Following the lunar swingby, a series of TCMs are planned during the 3-4 month cruise phase to target the lunar impact at the desired time and location. For each launch date, there exists a minimum delta-V trajectory that requires minimal (<5 m/s) post-swingby deterministic maneuvers. However, as previously described, the need to fix the impact time for observatory coverage can require a maximum time adjustment of up to +/-12 hours. As a rule of thumb, it costs 5 m/s to change the impact time by one hour. Consequently, a large mid-cruise TCM may be required for some launch dates. Follow-on cruise orbit TCMs are scheduled to correct dispersions from any large impact time adjust maneuvers, to compensate for attitude control system disturbance errors and to precisely target the desired impact location.

Shadow Avoidance

Earth shadowing could potentially present a serious danger for LCROSS, with a maximum possible umbra (full) shadow of nearly 3 hrs at ecliptic crossings near apogee for the 3-month trajectory. Penumbra (partial) shadowing could contribute an additional ~4.5 hours, for a maximum total shadow time of approximately 7.5 hours during a worst-case passage.

Given LCROSS thermal constraints, it is expected that worst-case Earth shadowing in the cruise orbit would pose a serious risk to the mission. Consequently, shadows must be checked for throughout the mission, and the trajectory design must be able to avoid such shadows when necessary.

Use of a Shadow Avoidance Maneuver (SAM) to deflect passage through shadows during ecliptic crossings was investigated. Preliminary analysis for a case where shadowing was predicted indicated that the introduction of a SAM shortly after the lunar swingby (e.g., 2 days) gave the best results, as opposed to adjustments of B-plane targets during the transfer orbit. For the case investigated, a SAM costing ~13 m/s was sufficient to avoid a 60% penumbral shadow that was predicted to occur approximately three weeks after swingby.

LCROSS Delta-V Budget

A maximum of 155 m/s is budgeted for LCROSS orbit maneuvers while attached to the EDUS impactor, with a separate 15 m/s allocated to the post-separation braking burn.

Figure 7 presents an estimate of the LCROSS pre-separation delta-V budget associated with prospective 2008 LRO launch dates. The total LCROSS Delta-V requirements vary greatly according to launch date, depending on the required trajectory (i.e., Northern vs. Southern swingby) and the amount of impact time adjustment required. This results in a wide disparity in the amount of delta-V margin associated with each launch date.

Based on the results of a preliminary dispersion analysis, 30 m/s is currently being carried to compensate for possible launch vehicle dispersions. An additional 20% velocity dispersion factor is currently budgeted for each deterministic TCM to account for possible TCM dispersions and any associated nonlinearities in the required delta-V to correct such errors during subsequent maneuvers.

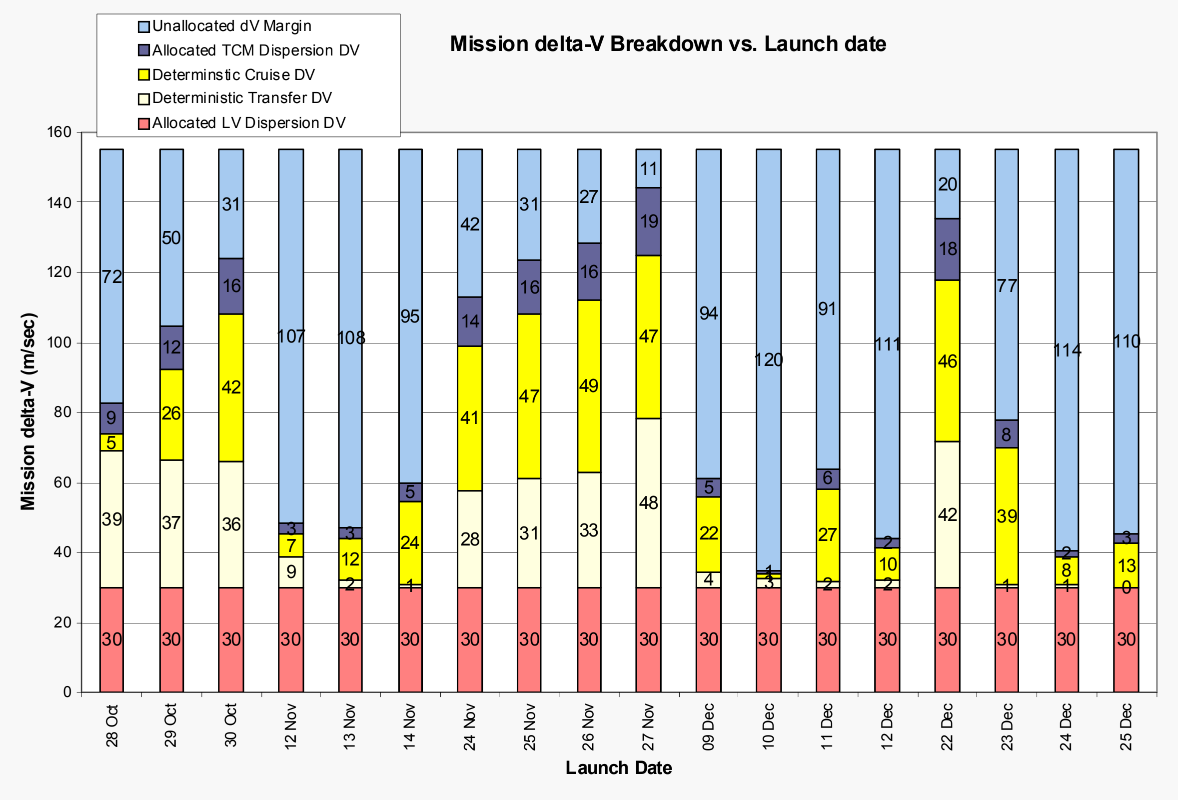


Figure 7: LCROSS Delta-V Budget for Prospective 2008 Launch Dates

LCROSS Launch Window

In order to increase the likelihood of launching on any given day, LCROSS may be required to support a launch window of several minutes for each candidate LRO launch date. Figure 8 shows the expected LCROSS delta-V penalty associated with a +/-30 minute launch window for the baseline Oct. 28, 2008 launch date. While accommodating a sizable launch window would impose a significant penalty on the LCROSS delta-V budget, it may be possible for LCROSS to accommodate a modest window with manageable penalties for most launch dates, particularly if an offset window is permitted (e.g., a -15 to +10 min window for the Oct. 28 launch date would limit the delta-V penalty to under 10 m/s).

4.0 LCROSS Orbit Determination

LCROSS cost and schedule considerations precluded the use of reaction wheels and accelerometers to help mitigate attitude control thrust disturbances and characterize orbit maneuver performance. Consequently, careful consideration has been given to bounding and managing expected non-gravitational trajectory perturbations using a maneuver, tracking and orbit determination (OD) strategy that satisfies impact and pointing accuracy requirements.

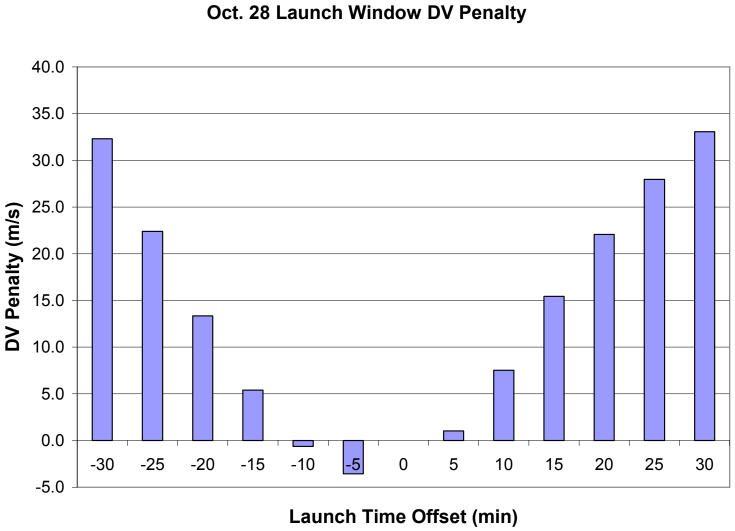


Figure 8: LCROSS Launch Window Delta-V Penalty

The expected knowledge and control of the LCROSS spacecraft along a particular trajectory is determined by linear covariance analysis based on planned tracking data and statistical error models for the spacecraft and measurement data. A batch-sequential filter is used with a wide assortment of filter parameters, each of which can be treated as an estimated and/or stochastic parameter. In addition, the effect of errors in non-estimated (also known as "consider") parameters can be included.

The main requirements for OD analysis are: 1) the EDUS impactor delivery (1.75 km radius, 3-sigma), 2) LCROSS Shepherding Spacecraft (S-S/C) pointing control at 600 km from the impact point (0.25 degrees, 3 sigma allocated to Nav), 3) sufficiently accurate knowledge before each maneuver design to fit within the propellant budget (most of which is driven by deterministic errors and maneuver execution errors), and 4) prediction of s/c angular position to within 0.06 to 0.12 degrees (DSN 34m S-band beamwidth is 0.12 degrees). Most of the analysis to date has concentrated on items 1 and 2. The main interest in item 3 is the OD knowledge of the delivery to the lunar flyby, which can have a significant multiplying effect on the post-flyby maneuver magnitudes. The results of analyzing the performance of items 1-3 are discussed in this paper.

Modeling of LCROSS Representative Trajectories

While the orbital knowledge resulting from the observation of a given LCROSS trajectory will be different in principle, it is expected that similar trajectories will have qualitatively similar results. The characteristics of a trajectory that most affect OD sensitivity are the magnitudes of the deterministic cruise maneuvers and the DSN geometric visibility of the critical braking maneuver.

Three families of trajectories that span these characteristics have been identified, and a representative from each family has been studied (see table 2).

Table 2: Representative LCROSS Orbit Types

LRO 2008 Launch Date	LCROSS Flyby Pole	TCM1 Magnitude	Imp. Time Adjustment Magnitude	Braking Burn Direction (deg)		Dual DSN Coverage of Braking Burn
				RA	Dec	
Oct. 28	North	Large	Large	103	35	Yes
Nov. 12	South	Small	Large	114	-58	Yes
Dec. 23	South	Small	Large	2	-62	No

For each trajectory, the tracking station view-periods and the requested tracking data quantity are combined to produce a file of simulated tracking data measurements. The simulated measurements are then processed to produce filtered covariance results. The nominal tracking data is as follows: 1) nearly continuous from launch to just past the lunar flyby, 2) nearly continuous for the last week before impact, 3) 2 hours every 3 days during the middle of the trajectory, 4) 2-hour and 4-hour tracking passes as needed to support maneuver design.

The statistical trajectory uncertainties are represented by parameters that describe the measurement system and the spacecraft dynamics. Errors in the Earth-Moon ephemeris and gravity are considered, but in practice are too small to matter for this mission. All of the measurement system parameters use standard S-band models, with nominal weighting of 1 mm/s for Doppler measurements, and 2 meters for ranging measurements. The remaining errors in the spacecraft dynamic model are essentially all non-gravitational, and may be divided into steady-state errors (solar pressure, attitude maintenance) impulsive delta-V events (cruise maneuvers, separations, slews) and finite burns (braking maneuver).

As a function of the total incident solar radiation, solar pressure uncertainty is 30% along the Sun line and 10% in each perpendicular direction. The attitude maintenance errors (due to dead-banding using a reaction control system that is not quite balanced) are expressed as an acceleration error that is divided equally between a correlated term (over 1 week) and a random term, as a function of dead-band size. For 10 deg dead-bands, the total error is required to be less than 1.5e-10 km/sec^2 over 6 hours, 3-sigma. From this requirement, the limit for 0.5 deg control is derived to be 3.0e-9 km/sec^2, and the limit for 0.1 deg control is derived to be 1.5e-8 km/sec^2, both 3-sigma. The 0.5 deg dead-band is used from impact-2 hours, and the 0.1 deg dead-band from impact-1 hour, to minimize perturbations to the S-S/C trajectory.

For the impulsive non-gravitational errors, the separation event is modeled as a 5% uncertainty (3 sigma) on a 50 cm/sec relative velocity, with the uncertainty apportioned according to the mass ratio between the EDUS and the S-S/C. Perturbations to the orbit from attitude maneuvers (“slews”) performed using thrusters (before delta-V maneuvers and science pointing) are required to be less than 6 mm/sec (3-sigma) for each slew. Delta-V maneuvers are accomplished without accelerometers, and so are allocated a magnitude error of 10% (3 sigma). A 5.5% (3-sigma) side-velocity error is also book-kept to account for transient pointing errors that occur due to torque from the 22N Delta-V thrusters during orbit maneuvers.

Flyby Performance

The results leading up to the flyby following a nominal October 28th launch are listed in Table 3 (in km, 1-sigma). These results reflect the OD analyses performed by the Mission Design subsystem in May of 2007. For all mission trajectories, there are three TCMs planned. TCM1 is scheduled for Launch plus one-day, TCM2 is scheduled for Launch plus two-days, and TCM3 is scheduled for Flyby minus one day. It is worth pointing out that the flyby delivery errors incurred by the execution of TCM3 are on the kilometer level. During the lunar flyby calibration, these are more than sufficient to meet the instrument pointing allowances due to orbit determination and prediction.

Table 3: Flyby B-Plane Errors

Lunar Flyby Errors (all 1-sigma)				
Event	B-Mag (km)	B_θ (deg)	Time (sec)	Maneuver Error
TCM1 knowledge	4.7	0.02	1.8	N/A
TCM1 delivery	260.1	1.65	213.5	67 cm/s spherical
TCM2 knowledge	3.9	0.01	1.9	N/A
TCM2 delivery	10.2	0.05	8.8	3.3 cm/s spherical
TCM3 knowledge	0.4	0.001	0.3	N/A
TCM3 delivery	0.5	0.002	0.4	1.0 cm/s spherical

Final Targeting Maneuver

One trade undertaken during the mission timeline development was the examination of the sensitivity of the final targeting accuracy to the magnitude of the final targeting burn. For all trajectories, the final targeting burn is designated as TCM-10, and is scheduled for Impact - 11 hours. Of interest is assessing the capability of Orbit Determination to recover the errors expected from the execution of TCM-9, which is scheduled for Impact minus 2-days for all mission trajectories. If OD is unable to recover all of the TCM-9 execution error by the time of the Data Cutoff (DCO) for TCM-10, then the targeting accuracy of TCM-10 will be degraded.

This study was performed in the context of the impact event at the completion of a mission launching on December 23rd. This represents the limiting case in terms of tracking geometry, and the results are shown in Table 4. Findings from this study indicate that a DCO of more than 1-day from impact is not recommended for impacts occurring when visibility from the DSN is constrained by low lunar declination at impact. Also, the sensitivity to large TCM-10 execution errors is noted, and the maneuver trim plan leading up to the TCM-10 should be designed to minimize the position dispersions at the TCM-10 epoch.

Table 4: EDUS Delivery Error Sensitivity to Tracking Data Cutoff (DCO) Time for Limiting Case Associated with December 23rd Trajectory

Size of TCM-10 (1-sigma errors)	**LI-36h DCO** (3-sigma pos.,time)	**LI-24h DCO** (3-sigma pos.,time)	**LI-20h DCO** (3-sigma pos.,time)
20 cm/s (4 mm/s)	960 m, 1.3 s	670 m, 0.7 s	630 m, 0.7 s
70 cm/s (12 mm/s)	1.6 km, 1.8 s	1.4 km, 1.4s	1.4 km, 1.4 s

Impact and Impact Observation Performance

Table 5 shows the 3-sigma performance for the EDUS delivery and the S-S/C pointing knowledge for the three representative LCROSS trajectories described earlier. The S-S/C pointing knowledge is presented based on data cutoffs at 40, 60, 80 and 100 minutes after the Braking Burn (BB), for braking burns which occur at impact - 7 hours or impact - 9 hours.

For each launch study, assumptions of the Braking Burn side velocity errors are book-kept at 5.5% of the magnitude (3-sigma), per maneuver side-velocity requirement. Sensitivity studies were also performed in which 1.7% (3-sigma) side velocity errors were assumed. In addition, the burn magnitude error is assumed to be 10% (un-calibrated), since the Braking Burn will be performed with what is effectively a new flight system. Also, assumptions of orbital perturbations due to reaction control system contributions have been built around ACS capabilities and ACS requirements

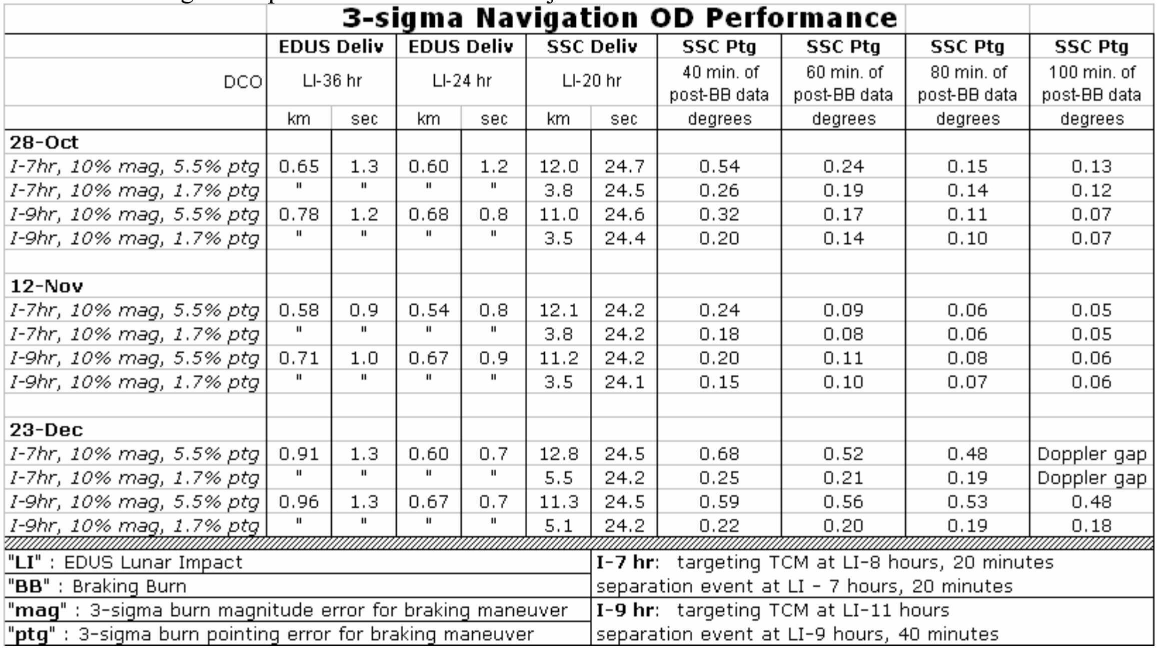
It is worth noting in Table 5 that the current studies for the October and November launch dates show that our system performance is within requirements. Specifically, EDUS impact location and impact time are within requirements, and the required pointing performance is met with 60 minutes of post braking maneuver tracking data.

For impacts that occur when the moon is at low declinations, such as that associated with the December 23rd launch date, the EDUS impact location and timing requirements are still satisfied. However, the S-S/C orbit determination accuracy is degraded substantially due to a lack of dual-facility visibility from the DSN, and consequently there is negative margin in the OD allowances for instrument pointing performance, assuming a 5.5% side-velocity requirement. Current work is being directed towards improving the fidelity of the maneuver model in the OD process. The resulting improvement in reconstructed maneuver knowledge, coupled with flight system performance that is antcipated to exceed requirements, is expected to be sufficient to meet instrument pointing error allowances. This is borne out in OD results reflecting 1.7% side-velocity errors in Table 5.

Conclusion

Baseline LCROSS trajectories and a corresponding orbit determination strategy have been designed to achieve EDUS impact requirements/goals while satisfying spacecraft operational constraints. Sufficient flexibility is provided through the choice of trajectories and impact craters to accommodate prime LRO launch dates, while satisfying onboard and Earth-based science observation requirements. Additional work is underway to ensure that follow-on backup LRO launch dates can be fully accommodated by LCROSS.

Table 5: 3-sigma EDUS Delivery Performance, 3-sigma S-S/C Pointing Knowledge and Braking Burn Pointing for Representative LCROSS Trajectories



	3-sigma Navigation OD Performance									
	EDUS Deliv		**EDUS Deliv**		**SSC Deliv**		**SSC Ptg**	**SSC Ptg**	**SSC Ptg**	**SSC Ptg**
DCO	LI-36 hr		LI-24 hr		LI-20 hr		40 min. of post-BB data	60 min. of post-BB data	80 min. of post-BB data	100 min. of post-BB data
	km	sec	km	sec	km	sec	degrees	degrees	degrees	degrees
28-Oct										
I-7hr, 10% mag, 5.5% ptg	0.65	1.3	0.60	1.2	12.0	24.7	0.54	0.24	0.15	0.13
I-7hr, 10% mag, 1.7% ptg	"	"	"	"	3.8	24.5	0.26	0.19	0.14	0.12
I-9hr, 10% mag, 5.5% ptg	0.78	1.2	0.68	0.8	11.0	24.6	0.32	0.17	0.11	0.07
I-9hr, 10% mag, 1.7% ptg	"	"	"	"	3.5	24.4	0.20	0.14	0.10	0.07
12-Nov										
I-7hr, 10% mag, 5.5% ptg	0.58	0.9	0.54	0.8	12.1	24.2	0.24	0.09	0.06	0.05
I-7hr, 10% mag, 1.7% ptg	"	"	"	"	3.8	24.2	0.18	0.08	0.06	0.05
I-9hr, 10% mag, 5.5% ptg	0.71	1.0	0.67	0.9	11.2	24.2	0.20	0.11	0.08	0.06
I-9hr, 10% mag, 1.7% ptg	"	"	"	"	3.5	24.1	0.15	0.10	0.07	0.06
23-Dec										
I-7hr, 10% mag, 5.5% ptg	0.91	1.3	0.60	0.7	12.8	24.5	0.68	0.52	0.48	Doppler gap
I-7hr, 10% mag, 1.7% ptg	"	"	"	"	5.5	24.2	0.25	0.21	0.19	Doppler gap
I-9hr, 10% mag, 5.5% ptg	0.96	1.3	0.67	0.7	11.3	24.5	0.59	0.56	0.53	0.48
I-9hr, 10% mag, 1.7% ptg	"	"	"	"	5.1	24.2	0.22	0.20	0.19	0.18

"**LI**" : EDUS Lunar Impact "**BB**" : Braking Burn	**I-7 hr**: targeting TCM at LI-8 hours, 20 minutes separation event at LI - 7 hours, 20 minutes
"**mag**" : 3-sigma burn magnitude error for braking maneuver "**ptg**" : 3-sigma burn pointing error for braking maneuver	**I-9 hr**: targeting TCM at LI-11 hours separation event at LI-9 hours, 40 minutes

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