AAS 98-323

LUNAR PROSPECTOR MISSION DESIGN AND TRAJECTORY SUPPORT

David Lozier & Ken Galal
Space Projects Division
Ames Research Center, NASA

David Folta & Mark Beckman
Guidance, Navigation, and Control Center
Goddard Space Flight Center, NASA

The Lunar Prospector mission is the first dedicated NASA lunar mapping mission since the Apollo Orbiter program which was flown over 25 years ago. Competitively selected under the NASA Discovery Program, Lunar Prospector was launched on January 7, 1998 on the new Lockheed Martin Athena II launch vehicle.

The mission design of Lunar Prospector is characterized by a direct minimum energy transfer trajectory to the moon with three scheduled orbit correction maneuvers to remove launch and cislunar injection errors prior to lunar insertion. At lunar encounter, a series of three lunar orbit insertion maneuvers and a small circularization burn were executed to achieve a 100 km altitude polar mapping orbit.

This paper will present the design of the Lunar Prospector transfer, lunar insertion and mapping orbits, including maneuver and orbit determination strategies in the context of mission goals and constraints. Contingency plans for handling transfer orbit injection and lunar orbit insertion anomalies are also summarized. Actual flight operations results are discussed and compared to pre-launch support analysis.

INTRODUCTION

Mission Overview

The January 7, 1998 launch of the Lunar Prospector spacecraft marked the return of America's space program to the moon, picking up where the Apollo program left off with a low altitude polar orbiting mission to map the entire surface of the moon. In contrast to the Apollo program, however, Lunar Prospector was a modest spacecraft funded at a cost of $63 million (including the launch vehicle) by NASA's Discovery Program[1]. Six science experiments were flown to map the composition of the lunar surface, study the moon's gravity and magnetic fields, investigate levels of tectonic and volcanic activity, and search for evidence of water ice at the lunar poles.

Spacecraft Description

The Lunar Prospector spacecraft (Figure 1) is a spin-stabilized graphite-epoxy drum, 1.4 meters in diameter by 1.22 meters in height, with three radial instrument booms located 120 degrees apart. Power is provided by solar arrays mounted on the outside of the drum. Attitude, spin rate, and velocity control are provided by a blowdown monopropellant hydrazine propulsion subsystem using six 22 N thrusters. Attitude and spin rate determination are provided by a sun sensor and an Earth/Moon limb sensor. Telemetry and command functions are provided by a single S-band transponder through either a medium gain or an omni-directional low gain antenna mounted on a mast aligned the spacecraft spin axis.

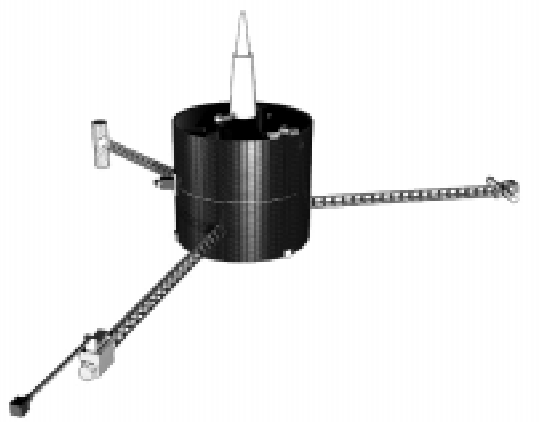

Figure 1: Lunar Prospector Spacecraft with Instrument Booms Deployed

The nominal Lunar Prospector telemetry rate is 3.6 kbps real-time with no onboard tape recorder. However, a 53.3 minute delayed transmit capability at the spacecraft permits ground capture of telemetry data taken from the backside of the Moon. The total spacecraft mass at launch was 296.4 kg, including 137.7 kg of hydrazine propellant.

NOMINAL MISSION PROFILE

Table 1 provides a summary of the nominal mission profile designed for the Lunar Prospector mission. The Lunar Prospector spacecraft was launched on January 7, 1998 at 02:28:44 GMT from the Eastern Test Range. A Lockheed Martin Athena II vehicle placed the payload (spacecraft and injection stage) in a nominal 100 nautical mile circular parking orbit after a 13-minute flight. Following a 42-minute coast to a translunar injection point over North-Western Australia, the payload was released and a Star 37FM motor was used to apply a nominal 3142 m/s delta-V over the course of a 64 second burn. The design flight time to the moon was 105 hrs from injection. A series of three lunar insertion burns were designed to place the spacecraft into its 100 km polar mapping orbit about the moon.

Launch Date Selection and Transfer Orbit Design

The approach taken by the Lunar Prospector project for establishing launch dates was to limit launch opportunities to a single set of consecutive prime and backup days each month. This approach was motivated in part by a desire to limit launch vehicle preparation costs, as well as a desire to only select launch dates which provided the best geometry in terms of minimizing both operational risk to the mission and overall propellant consumption. Monthly launch dates were identified beginning in September of 1997. Possible earlier launch dates were rejected in order to avoid the September 16, 1997 lunar eclipse by the Earth, which would have lasted several hours and necessitated a larger battery.

Table 1

LUNAR PROSPECTOR NOMINAL MISSION DESIGN PARAMETERS

Launch Conditions	**Nominal Launch Date/Time:**	January 7, 1998 02:28:42.7 UTC
	Launch Vehicle:	Athena-II
	Launch Azimuth:	97 deg E (29.2 deg inclination)
	Parking Orbit:	87.7 x 102.7 nmi
Injection Conditions	**TLI Motor:**	STAR37FM
	TLI Velocity:	3142 m/sec
	TLI Payload Mass:	1521.2 kg
	Total LP Spacecraft Mass:	296.4 kg
	LP Propellant Mass:	137.7 kg
	Trans-lunar Injection Time:	L + 56 min
	S/C Separation:	L + 57 min
	TDRS Acquisition:	at S/C Sep
	DSN Acquisition:	Sep + 22 min
Transfer Orbit Conditions	**Transfer Orbit Flight Time:**	105 hr
	Reorientation Maneuver to Cruise Attitude:	92 deg
	Spin Down Maneuver:	-30 rpm (fom 57 at TLI)
	Post-Boom Deployment Spin Up:	+5 rpm
	1st Trajectory Correction Maneuver:	TLI + 4.5 hr
	2nd Trajectory Correction Maneuver:	TCM1 + 24 hr
	3rd Trajectory Correction Maneuver:	LOI -1 -24 hr
Lunar Orbit Insertion Conditions	**Epoch of Arrival:**	1/11/98 12:00 UTC
	Radius of Closest Approach:	1819 km
	Lunar Orbit Inclination:	89.8 deg
	Reorientation Maneuver to LOI Attitude:	22 deg
	LOI #1:	354 m/sec
	LOI #2:	274 m/sec at LOI-1 + 24 hours
	LOI #3:	264 m/sec at LOI-2 + 24 hours
	Reorientation Maneuver to Mapping: Attitude:	30 deg

In the Fall of 1997, two sets of prime and backup launch dates consisting of January 6/7 and February 4/5 were selected as candidate launch opportunities for the Lunar Prospector mission. These launch dates and the associated transfer trajectories were selected on the basis of the following factors:

- **Sun Angle Geometry:** A favorable sun angle of close to 90 degrees relative to the spacecraft z-axis was desired during translunar injection (TLI) and lunar orbit insertion (LOI) for power, thermal and attitude determination considerations.
- **Shadowing:** In order to minimize risk to the spacecraft, it was desired that the spacecraft be in sunlight following TLI, and for the duration of the 2-day LOI sequence to place the spacecraft into its low altitude mapping orbit. Additionally, transfer orbit geometries (for both nominal and contingency orbits) whereby the s/c-Earth-sun angle approached 180 degrees were to be avoided due to the possibility of long shadow periods (up to 9 hours in some cases) while in the transfer orbit.
- **Transfer Orbit Inclination:** A low transfer orbit inclination with respect to the Earth/Moon plane was desired in order to minimize LOI costs.
- **Moon Position:** Lunar orbit insertion with the moon close to apogee yields a slightly lower DV cost (up to 38 m/s).
- **Attitude Maneuvers:** To minimize propellant consumption and risk to the spacecraft, transfer orbit trajectories that required small turn angles to get from the transfer orbit cruise attitude to the LOI attitude and from the LOI attitude to the mapping orbit attitude were chosen.
- **Post TLI Station Acquisition:** While the station look angle changes rapidly near Earth for a given inertial TLI attitude and antenna configuration, certain trajectories enable post-TLI station coverage

sooner than others. Minimizing the time to acquire telemetry and command capability was a goal in order to minimize the time to correct launch and transfer orbit dispersions.

- **LOI Station Coverage:** As a goal, the periselene arrival time was to be maintained such that dual station coverage was available during LOI#1. Furthermore, it was desired that all subsequent LOI burns be conducted in view of a station (a 64 minute delayed command timer was available for doing burns in the blind when necessary).

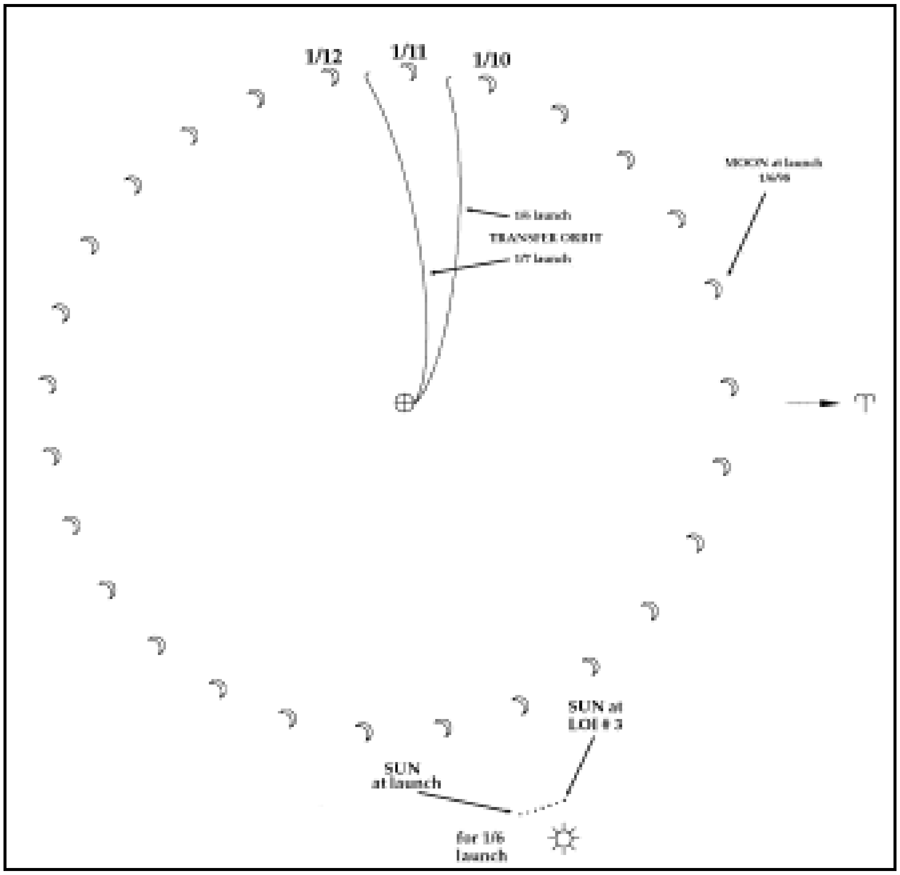

Figure 2: Lunar Prospector Transfer Orbit Geometry for Prime and Backup Launch Dates

From a given launch site, a launch to the moon is possible on each day of the month, with two launch times (roughly 12 hours apart) available on each launch date[2]. The launch date establishes the sun/Earth/moon geometry for the transfer orbit. The selection of the launch time, for a given launch date, establishes the inclination of the transfer orbit plane relative to the Earth-moon plane, and influences lighting and station coverage conditions at injection. On a given day, the transfer orbits corresponding to the two possible launch times are typically distinguished by the length of the coast time in the parking orbit (i.e. short coast or long coast), or alternatively, by the proximity of the injection point to the ascending vs. descending node. As a final option in transfer orbit design, for each launch date/time, two lunar insertion conditions are available over either the northern or southern lunar hemisphere. The selection of the lunar approach geometry affects the required LOI thrust direction and hence the magnitude of attitude turns required as part of LOI operations. Through a careful consideration of the launch date, launch time, and lunar approach geometry, transfer orbits for prime and backup launch dates (Figure 2) were arrived at that minimized both the risk to the Lunar Prospector spacecraft and the propellant required to get into orbit about the moon. The resulting transfer orbits selected were low heliocentric inclination orbits with injections near ascending node and lunar insertion in the northern lunar hemisphere.

Transfer Orbit Maneuver Strategy

The nominal Lunar Prospector transfer orbit maneuver plan called for a total of three trajectory correction maneuvers (TCMs) with TCM#1 planned at 4.5 hours after separation, TCM#2 at 24 hours after TCM#1, and finally, TCM#3 at 24 hours prior to lunar orbit insertion. A total of 80 m/s was nominally allocated to cover corrections to possible launch and TLI dispersions.

Key to this maneuver strategy was a desire to execute TCM#1 as soon as possible after TLI in order to minimize losses associated with burning away from perigee. It was felt that given all the spacecraft events that had to occur before a nominal burn could take place (e.g. 90 deg reorientation to the cruise attitude, boom deployment, orbit/attitude determination, maneuver planning, command load generation/execution), a burn 4.5 hour into the mission was an achievable goal, assuming a nominal post-separation timeline of events. Ideally, for this maneuver time, the required correction for any launch/TLI dispersions would have grown by a factor of 3.5 by the time of the maneuver. However, given Lunar Prospectors attitude and thruster firing mode (where both axial and tangential thrusters are fired in a vector mode), and a desire to maintain a fixed time of flight to the moon, it was expected that a 1 m/s launch/TLI error would require 4.5 m/s of equivalent propellant to correct for an orbit maneuver at 4.5 hours after TLI.

TCM#2 was nominally scheduled 24 hours after TCM#1 in order to provide sufficient time to collect tracking data for an orbit solution and plan the maneuver, as well as to permit the prime operations shift to rest between burns. TCM#3 was scheduled 24 hours prior to lunar insertion to provide any required final corrections to the approach trajectory.

Lunar Orbit Insertion Maneuver Strategy

Three LOI maneuvers were designed to capture the spacecraft into lunar orbit and lower apoapsis most of the way into the nominal 100 km polar mapping altitude. Each LOI burn was to be performed from an inertial attitude using 2 axial jets along the aft side of the spacecraft (axial jets on the antenna end of the spacecraft could not be used for long burns due to antenna heating concerns). The LOI maneuver sequence was designed with the following goals/constraints in mind:

- **S/C Pointing**: There was a desire to maintain a single attitude throughout the LOI maneuver sequence in order to minimize propellant use and operational complexity. By maintaining a fixed argument of periapsis for each intermediate orbit in the LOI sequence, no attitude maneuvers would be required.
- **Maneuver Duration and Frequency**: While the there was no hardware limitation on the maximum time to burn during each LOI maneuver, burn efficiency considerations suggested keeping the burns as small as possible in order to minimize thrust losses over the burn arc. On the other hand, operational considerations suggested keeping the overall number of burns at a manageable number.
- **Intermediate Orbit Perturbations**: It was recognized that smaller LOI#1 burns would result in an initial capture orbit that was more susceptible to third body perturbations (largely from the Earth, and affecting mostly orbit inclination). Such perturbations can be nullified to some degree by biasing the lunar orbit insertion conditions to counteract the anticipated evolution of the orbit. However, the possibility always exists that unforeseen delays might result in an extended stay in the initial capture orbit, whereby excessive orbit errors could accumulate which would require subsequent correction.

Based on the above guidelines, a three-burn LOI sequence was designed to first capture the spacecraft into a 12 hour period orbit, lower it into a 3.5 hour period orbit, and finally drop apoapsis most of the way into the 100 km nominal mapping altitude. This sequence resulted in three LOI maneuvers of roughly equal size (approximately 30 minutes each), with an initial orbit that experienced relatively small perturbations. The lunar arrival conditions were biased slightly from the nominal 90 degree inclination and 1838 km periselene radius (to 89.8 deg and 1819.7 km, respectively) to allow for inclination growth due to third body perturbations while in the 12 hour capture orbit, and to allow for expected growth in periapsis altitude resulting from LOI finite burn losses. A constant argument of periapsis was targeted for the first two burns to avoid the need for attitude maneuvers between burns.

Orbit Determination Strategy

The orbit determination strategy for Lunar Prospector was broken into two phases: cislunar phase and mapping phase. Both phases were analyzed pre-mission using covariance analysis and simulated tracking data. The simulations assumed tracking by the Deep Space Network (DSN) stations in California, Australia, and Spain. The DSN stations were expected to provide range, Doppler, and XY angle (DSN 26 m stations only) measurements.

There were two primary goals during the transfer/LOI phase: (1) provide predicted ephemerides for mission planning and trajectory design, and (2) provide near-real-time assessments of orbit maneuver performance. During the transfer/LOI phase, there were seven maneuvers nominally planned: four deterministic (TLI and LOI#1-3) and three corrective (TCM#1-3). During this phase, it was expected that the spacecraft would be continuously tracked by the DSN. After each maneuver, range, Doppler, and XY angles (only for DSN 26 m stations) would be collected and processed to determine the new trajectory. Due to reduced dynamics as the spacecraft moved away from perigee, the time required to obtain an accurate converged solution increased with each maneuver in the transfer orbit. Once captured in lunar orbit, the required convergence time was mostly a function of the orbit period. Table 2 shows the expected tracking arc required after each maneuver to obtain a full state batch orbit estimation.

Table 2

LUNAR PROSPECTOR ORBIT DETERMINATION TURN-AROUND TIMES

Maneuver	TLI	TCM-1	TCM-2	TCM-3	LOI-1	LOI-2	LOI-3
Planned Post-Maneuver OD Time	30 min*	6 hrs	8 hrs	12 hrs	4 hrs	3 hrs	2 hrs

Following each LP orbit maneuver, an updated orbit state was computed in support of preliminary maneuver planning of subsequent burns. The state would be updated several hours prior to the upcoming maneuver as an input to the final maneuver plan. In each case, the predicted velocity uncertainty of the solution at the time of a maneuver was at least an order of magnitude less than the planned delta-V for that maneuver. This ensured that the maneuver plan was not corrupted by trajectory uncertainties.

The capability for near-real-time maneuver assessments was required in support of Lunar Prospector contingency plans --- particularly in support of the critical TLI and LOI-1 burns. The near-real-time assessment would be made by monitoring DSN Doppler residuals. Once a final maneuver plan was available several hours before an upcoming maneuver, the predicted finite burn ephemeris was used to generate simulated nominal Doppler measurements. These Doppler measurements were processed using orbit estimation software and compared to the pre-maneuver state in order to generate a baseline plot of the expected Doppler residual signature over time. Next, simulated finite burn ephemerides were generated assuming a hot or cold maneuver, and corresponding Doppler residuals from these off-nominal cases were also plotted. Once the maneuver began, Doppler residuals were compared in near-real-time against the previously generated plots to enable a quick assessment of the maneuver performance. Pre-mission analysis had indicated that for each of the planned deterministic maneuvers, the difference between residual signatures for a nominal and a 5% off-nominal maneuver was greater than the expected residuals associated with state/measurement uncertainties during that maneuver. Thus, any deviation in maneuver performance of 5% or greater would be observable.

During the mapping phase of the mission, the main challenge to orbit determination support was that of meeting accuracy requirements. The mission requirement for post-processed solutions (using LP derived lunar gravity models) was 1 km 1-sigma position accuracy in each of radial, cross-track, and along-track directions. A pre-launch covariance analysis indicated that the lunar potential model was the leading source

---

* Use of combined tracking data from TDRSS (available at TLI and lasting approximately 45 minutes) and the DSN (available starting at 19 minutes after TLI) would have enabled a preliminary solution to be computed within 30 minutes of TLI and a final solution 2 hrs after TLI.

of orbit estimation error. The lunar potential model to be used initially was GLGM-2 developed at Goddard by F. Lemoine using tracking data from the 1994 Clementine mission[3]. The covariance analysis indicated that the mission requirements could only be partially met using this model, and only with extensive post-processing. For certain geometries (e.g. when orbit normal was perpendicular to the Earth-Moon line and lunar occultation occurred) the mission requirements would not likely be met[4].

As part of one of the experiments to be conducted by Lunar Prospector, tracking measurements were to be used by A. Konopliv at JPL to develop a new lunar potential model. It was planned that a switch to the new potential model would be made when the model became available (approximately two months into the mapping mission) and that LP definitive orbit data would be regenerated using the new model to ensure that orbit accuracy requirements could be met. The actual orbit accuracy attainable using the new model would not be known until it became available.

Contingency Planning

Several orbit contingency plans were devised to handle possible off-nominal performance of the spacecraft, ground system, and launch/injection sequence. Naturally, Lunar Prospector obit contingency plans centered around critical mission phases consisting of transfer orbit injection and lunar orbit insertion and included the following:

- **Emergency Post-TLI Correction:** In the event of a TLI overburn by greater than 20 m/s, or a TLI underburn of between 20 and 35 m/s, an emergency correction burn was to be executed approximately 40 minutes following spacecraft separation from the TLI stage.
- **Contingency Phasing Orbit:** In the event of a TLI under-performance by more than 35 m/s, a plan was devised whereby the spacecraft would be initially left in its anomalous orbit about the Earth, then placed into a phasing orbit for several revolutions, with an attempt to capture into lunar orbit approximately one lunar sidereal month (27 days) beyond the nominal capture date.
- **LOI #1 Under-Performance Contingency:** In the event that a near-real-time assessment of the LOI#1 maneuver indicated a significant under-performance, plans were in place to extend the burn via command upon completion of the nominal LOI burn duration.
- **Delayed LOI #1 Contingency (3 hours or less):** For delays in the nominal start time of LOI#1 of 3 hours or less, it was planned that a maneuver with a ΔV essentially along the negative velocity vector of the outgoing hyperbola would be executed to capture into a 2-day period (or less) lunar orbit. For a 3 hour delay in LOI#1 start time, it was estimated that a penalty on the order of 400 m/s would be incurred, which would severely jeopardize the mission.

- **Delayed LOI #1 Contingency Delay (greater than 3 hours):** For delays in the nominal start time of LOI#1 longer than 3 hours, it was found that a direct capture was not the most efficient method to get into lunar orbit. Instead, for the nominal Lunar Prospector January 7 launch trajectory, it was more efficient to delay any orbit correction until 3 days past periselene and target for a lunar insertion 41 days after periselene 1. The propellant penalty associated with this contingency strategy is approximately the same as that of a direct capture after a 3-hour delay in LOI#1 start time (400 m/s).

Key to these plans was the early detection of anomalous maneuver conditions through near-real-time orbit assessment using the Doppler residual method described in the previous section. In preparation for these contingencies, procedures and data bases of required attitude and burn conditions as a function of time were prepared for quick implementation in the event of a contingency.

LP MANEUVER RESULTS

Table 3 contains a history of orbit conditions following each maneuver in the transfer and lunar orbit insertion phases of the mission. It should be noted that target maneuver ΔV values listed in the table may in some cases be slightly different from ideal ΔV values expected from a propagation of the pre-maneuver state with nominal maneuver end states targeted. This is due to the existence of slightly different Lunar Prospector propulsion models (all consistent to within a few percent) that were available during the mission. As a result, in some cases the selected burn time was based on an average of the models in an effort to provide an added measure of safety (e.g. a slightly longer burn was used during LOI#1). The estimated performance values in Table 3 are based on the trajectory team's baseline propulsion model and are computed relative to actual commanded maneuver times and the best available thrust calibration estimates going into each burn. Possible calibration error sources include attitude uncertainties and propulsion system adiabatic cooling effects. All post-maneuver states are represented in terms of Mean-of-J2000 Keplerian elements relative to the equatorial plane of the central body indicated.

Table 3

LUNAR PROSPECTOR MANEUVER SUMMARY

	TLI	**TCM#1**	**TCM#2**	**LOI#1**	**LOI#2**	**LOI#3**	**MOC#1**
Target Maneuver ΔV	3142 m/s	50.2 m/s	7.4 m/s	364.4 m/s	271.8 m/s	262.3 m/s	12.1 m/s 2.6 m/s
Estimated Performance	99.7%	99%	99%	99.3%	99.1%	97.6%	100.4%
Post-ΔV State	1/ 7/98	1/ 7/98	1/ 8/98	1/11/98	1/12/98	1/13/98	1/16/98
Epoch (GMT):	03:30:00	12:30:00	8:45:00	12:20:00	12:05:00	12:10:00	00:00:00
a (km):	182799	197202	196231	6014.6	2712.2	1860.4	1838.3
e :	0.96403	0.96727	0.96886	0.69714	0.32713	0.01653	0.00046
i (deg):	29.20	29.27	29.26	89.72	89.87	90.01	90.55
Ω (deg):	318.58	318.20	318.16	192.59	192.49	192.39	192.76
ω (deg):	318.09	318.70	318.32	150.37	150.32	147.86	224.02
MA (deg):	0.14	13.34	43.74	10.63	90.13	59.16	317.04
Period (hrs):	216.1	242.1	240.3	11.63	3.52	2.000	1.965
$R_{Apoapsis}$ (km):	359023	387949	386351	10207.6	3599.4	1891.2	1837.8
Central Body	Earth	Earth	Earth	Moon	Moon	Moon	Moon

Launch and Trans-Lunar Injection

Lift-off of the Lunar Prospector mission occurred on time — approximately 2 seconds into its 4-minute launch window. Following a nominal launch and parking orbit insertion of the Athena II launch vehicle, the STAR37 motor burned for 64 seconds to place the spacecraft into its transfer orbit to the moon. The computed post-TLI orbit state vector is presented in Table 3, while the target injection state (impulsive) is shown in Table 4. The TLI burn occurred over the North-Western coast of Australia (LON = 125 E, LAT = 18 S). The ground track from launch to TLI +18 hours is shown in Figure 3. The solid arc just east of Florida consists of the 13 minute boost phase. The ground track for the 42 minute coast in the parking orbit (represented by the dashed line beginning at the end of the boost phase) crosses over southern Africa and ends at the TLI point on the NW coast of Australia. The post TLI ground track is labeled with tic marks every hour and is shown for the first 18 hours of the transfer orbit. The combination of Lunar Prospector launch and injection errors is estimated at –9.1 m/s. Planar orbit dispersions (i.e., inclination, ascending node, and argument of perigee) were very small --- on the order of a few hundredth of a degree.

Table 4

LUNAR PROSPECTOR NOMINAL TRANSFER ORBIT INJECTION STATE

injection epoch, January 7, 1998	03:25:02 GMT
semi-major axis	200240.3 km
eccentricity	0.967225
inclination	29.184 deg
longitude of ascending node	318.534 deg
argument of periapsis	318.068 deg
True Anomaly	.207 deg

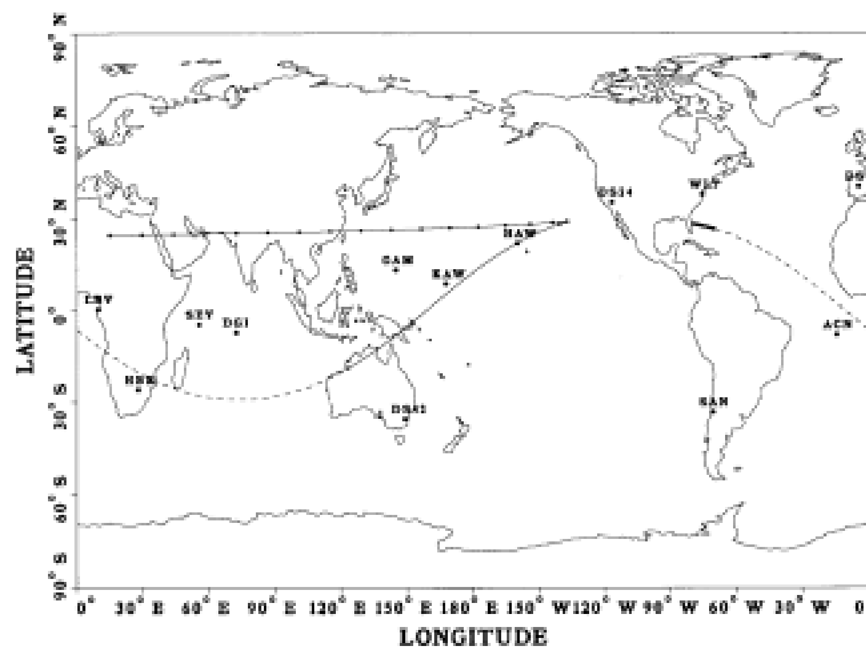

Figure 3: Lunar Prospector Launch and Transfer Orbit Injection Ground Track

Transfer Orbit Maneuvers

Table 5 lists the timeline of key events in the transfer orbit. TCM#1 was nominally planned for TLI + 4.5 hours, however, a number of factors conspired to delay the maneuver until 8.5 hours after TLI. The nominal post-TLI timeline called for immediate acquisition of the spacecraft in 2-way mode using NASA's Tracking and Data Relay Satellite (TDRS) – West spacecraft and for use of the telemetry and Doppler to verify the health of the Lunar Prospector s/c and the performance of the TLI burn. The TDRS support was planned on a best effort basis as part of an on-going effort to establish the potential use of TDRS to support non-TDRS (i.e. not equipped with a TDRS-compatible transponder) missions. Unfortunately, due to limited test data on the LP transponder frequency characteristics, and the limited sweep capability of the TDRS spacecraft, TDRS was initially unable to lock up on the LP telemetry stream. At TLI + 21 minutes, the Deep Space Network's Goldstone station locked on the LP transmit signal in two-way mode, and within a few minutes, data from the 300 bits per second (bps) telemetry stream was received. However, the telemetry data observed was noisy (due to a combination of the low bit rate and marginal LP antenna aspect angle geometry*) and commanding was suspended until the antenna geometry improved and the health of the spacecraft could be ascertained.

Table 5

TRANSFER ORBIT TIMELINE OF KEY EVENTS

Event Start	Time Relative to TLI (dd hh:mm)
LP Separation	TLI + 00 01:00
DSN Acquisition	TLI + 00 00:21
Receipt of First Telemetry (Noisy)	TLI + 00 00:24
90 deg LP Reorientation to Cruise Attitude	TLI + 00 02:27
Spin Down from 51 to 31 rpm	TLI + 00 03:05
Science Boom Deployment	TLI + 00 03:44
21 deg Attitude Adjustment Maneuver	TLI + 00 05:58
Trajectory Correction Maneuver (TCM) #1	TLI + 00 08:30
Trajectory Correction Maneuver (TCM) #2	TLI + 01 04:50
31 deg Reorientation to LOI Attitude	TLI + 02 03:05
Periselene	TLI + 04 08:35

After the successful DSN acquisition of LP in two-way mode, TDRS was able to lock up on the telemetry stream. However, as TDRS visibility was expected to end a short time later, mission controllers were reluctant to risk re-configuring the ground system to accept the data, and instead decided to concentrate on the Goldstone coverage.

About an hour later, with the antenna geometry improving and engineers reassured that the LP attitude, orbit and subsystems were nominal, spacecraft commanding was resumed. At TLI + 02:27, the spacecraft was re-oriented 90 degrees toward its cruise attitude and commanded to its nominal 3600 bps telemetry rate. As a result of the delays and concerns over cooling of the spacecraft boom deployment mechanisms, a decision was made to alter the target cruise attitude by approximately 10 degrees in order to provide

* The marginal antenna angle geometry was expected, but it was hoped that data quality would hold up until the spacecraft could be commanded into its cruise attitude. It is suspected that poor geometry was only partially to blame for the noisy data, and that another factor was the low transmit bit rate in use initially to improve chances for TDRS acquisition. The LP transponder was an off-the-shelf item with a 1024 kHz subcarrier frequency designed for higher bit rates. At the 300 bps telemetry rate the LP subcarrier to data rate ratio was not optimal for ensuring ground station acquisition, despite pre-launch efforts to configure ground equipment in such a way as to maximize performance using this signal.

additional solar heating of those areas. The science booms were successfully deployed at TLI + 03:44. A 21 degree attitude trim maneuver was performed at TLI + 05:58 for thermal reasons.

As a result of these delays in the timeline, the first trajectory correction maneuver was not performed until TLI + 8.5 hours. This delay raised the required ΔV magnitude of the correction from 38 m/sec (for a TCM#1 at TLI + 4.5 hours) to 50 m/sec. However, this was still well within the budgeted 80 m/sec allocated for transfer orbit maintenance. TCM#1 consisted of a vector burn with a 13 m/s axial component and 48.5 m/s tangential component.

TCM#2 took place on schedule and consisted of a 7.4 m/s vector burn (1.2 m/s axial and 7.3 m/s tangential). A final TCM#3 was scheduled to take place at LOI – 24 hours, but was called off when a propagation of the post-TCM#2 state yielded a projected periselene condition within 10 km of the target radius and .1 deg of the target inclination.

Lunar Orbit Insertion Maneuvers

Lunar Prospector LOI maneuvers occurred according to plan, with the propulsion system performing to between 1 and 3 percent repeatability. LOI burns #1 and #2 placed the spacecraft into an 11.63 hour, then a 3.52 hour orbit, and LOI#3 dropped apoapsis down to within 50 km of the target mapping orbit altitude. LOI#3 was purposely targeted 3% short as an extra margin of safety, since it was predicted that a 9% hot LOI#3 burn would have dropped apoapsis down to lunar radius. A final mapping orbit correction (MOC-1) maneuver on January 15, 1998 circularized the orbit at a 100 km altitude. This maneuver consisted of two axial burns to lower apoapsis and raise periapsis to a target radius of 1838 km. The second burn was executed slightly off-apses to permit DSN coverage of the burn.

Mapping Orbit Maintenance

The strategy for maintaining the LP 100 km altitude polar orbit was developed with the following goals:

1. Maintain an altitude band of 100 km +/- 20 km
2. Conduct maneuvers in view of a ground station
3. Minimize the number of maneuvers
4. Use axial maneuvers instead of vector burns if possible

The last goal was established for reasons of operational simplicity, since LP vector burns cannot be performed readily during shadow periods for lack of a reference sun pulse. Since the nominal LP spin-axis attitude is within a few degrees of the ecliptic normal (and therefore almost normal to the lunar equator), this goal required that the argument of periapsis be close to zero degrees to allow axial maneuvers to take place parallel to the velocity direction at periapsis/apoapsis. Furthermore, as LP maneuvers consist of a two-burn Hohmann sequence, the second goal requires that maneuvers be conducted when the orbit plane is normal to the Earth/moon line — a condition that occurs approximately every 14 days.

Figure 4 shows a history of the LP orbit periapsis/apoapsis altitude and argument of periapsis through the first orbit maintenance maneuver in the mapping orbit, followed by a prediction of the orbit evolution assuming no further maneuvers are conducted. The dashed vertical lines reflect the actual date of the first LP MOC maneuver (MOC#2) and the planned date of the second (56 days apart and coincident with periods of full station coverage). Furthermore, as the plot of orbit argument of periapsis shows, the maneuver dates occur when the line of apsides is within 15 degrees of the equator, allowing axial maneuvers to take place with only minor losses in efficiency. Without maneuvers, the orbit could be expected to impact the moon within approximately 150 days.

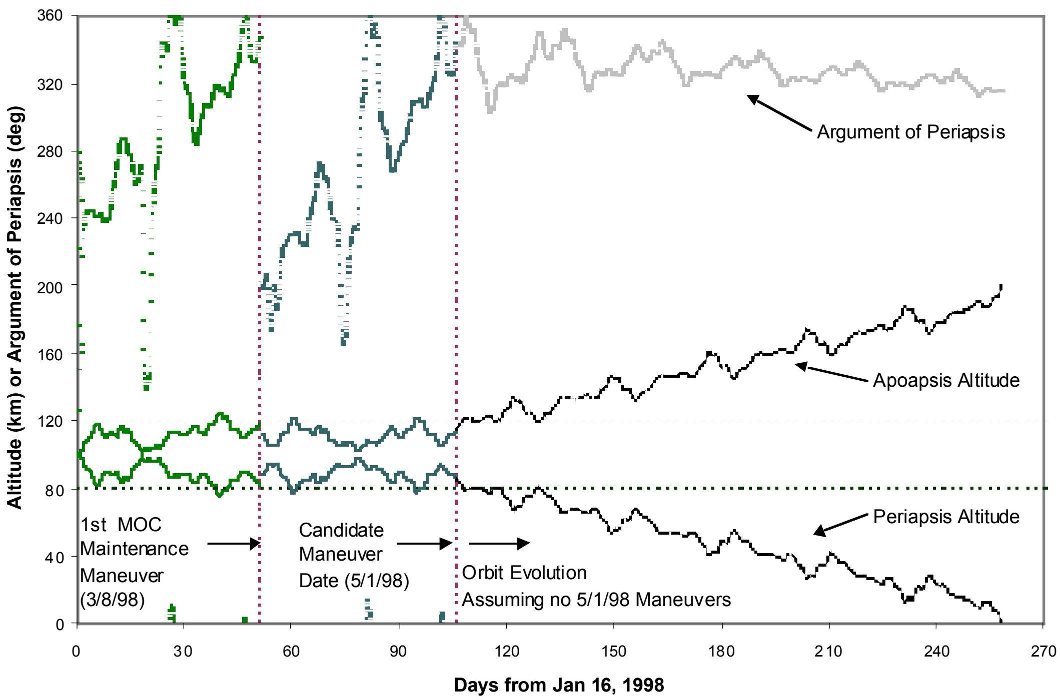

Figure 4: LP Orbit Evolution of Apoapsis/Periapsis Altitude and Argument of Periapsis Beyond the First Mapping Orbit Maintenance Maneuver (LP75D lunar potential model)

A 56 day interval between maneuvers was chosen to minimize the number of maneuvers performed, from the standpoint of reducing operational risk to the mission and minimizing perturbations to science data collection. Therefore, the goal of each mapping orbit correction was to adjust the orbit eccentricity and argument of periapsis in order to maintain an altitude variation within +/- 20 km over the next 56-days. The phase space approach of plotting argument of periapsis and eccentricity discussed in References 5 and 6 is a useful tool in understanding LP orbit evolution. Figure 5 contains such a polar plot with eccentricity plotted along the radial direction and argument of periapsis plotted along the angular direction. In this plot, LP orbit evolution is plotted for a 1-year duration, starting with the initial 100 km circular orbit attained after MOC#1 on January 15, 1998. Figure 5 describes how eccentricity grows with time, as argument of periapsis gravitates toward a value of 270 degrees. In order to limit excursions beyond the +/- 20 km range, initial values of 180 deg for argument of periapsis and approximately 0.0065 for eccentricity (88 x 112 km orbit) were targeted as maneuver end conditions for subsequent maneuvers. This forced the orbit to evolve through the zero eccentricity point and permitted a longer time between maneuvers. It is expected that such a strategy will figure even more prominently during the extended mission phase when frequent maneuvers will be required to maintain the 10 km periapsis altitude.

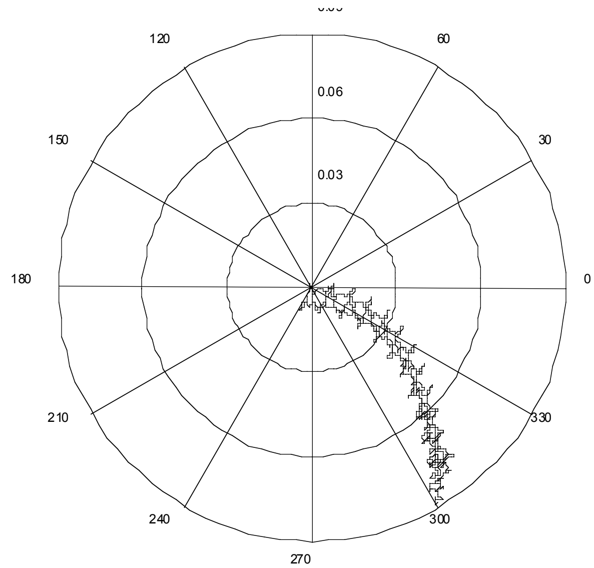

Figure 5: Lunar Prospector Mapping Orbit Eccentricity and Argument of Periapsis Evolution [Eccentricity along radial direction and argument of periapsis along angular direction]

LP ORBIT DETERMINATION RESULTS

Upon launch of the LP spacecraft, the first task of the orbit team was to assess the performance of the TLI maneuver. The failure to acquire TDRSS data delayed that assessment. When coherent DSN Doppler was received, approximately 23 minutes after TLI, the residuals indicated a slightly cold burn. The expected residuals for several off-nominal cases, along with the actual residuals obtained, are shown in Figure 6. The off-nominal cases modeled are -20 and -35 m/s TLI magnitude error and +/- 0.8 and -2.4 deg in argument of perigee error.

The first full state estimate was not obtained until 2.5 hrs after TLI due to the failure to acquire TDRSS tracking data and due to dropouts in the DSN data. The calibrated TLI magnitude error was estimated at -9.1 m/s, which matched the near-real-time Doppler assessment data fairly well. TCM#1 was not preformed until 8.5 hours after TLI.

After each of the TCMs, a Doppler assessment was made in near-real-time. In each case, the assessment indicated that the maneuver was slightly cold. The final calibrated efficiencies of these maneuvers (Table 3) are consistent with these initial Doppler-based assessments. The first orbit solution after TCM#1 was obtained after seven hours. The goal was to obtain this solution within six hours of the maneuver, however since TCM#1 was performed much farther away from perigee than planned, additional data were needed for a solution. After TCM#2, the first orbit estimate was available eight hours later — exactly as expected. TCM#3 was cancelled, which meant the orbit trajectory would be well determined for the LOI#1 maneuver.

During the 30 minute LOI#1 maneuver, the DSN lost coherent lock on the spacecraft. As a result, no Doppler data were obtained until immediately after the maneuver. A Doppler assessment at that point indicated a successful lunar capture with only a slightly cold burn. A full orbit state was obtained 1.5 hrs after LOI#1, which was slightly over 2 hours earlier than expected.

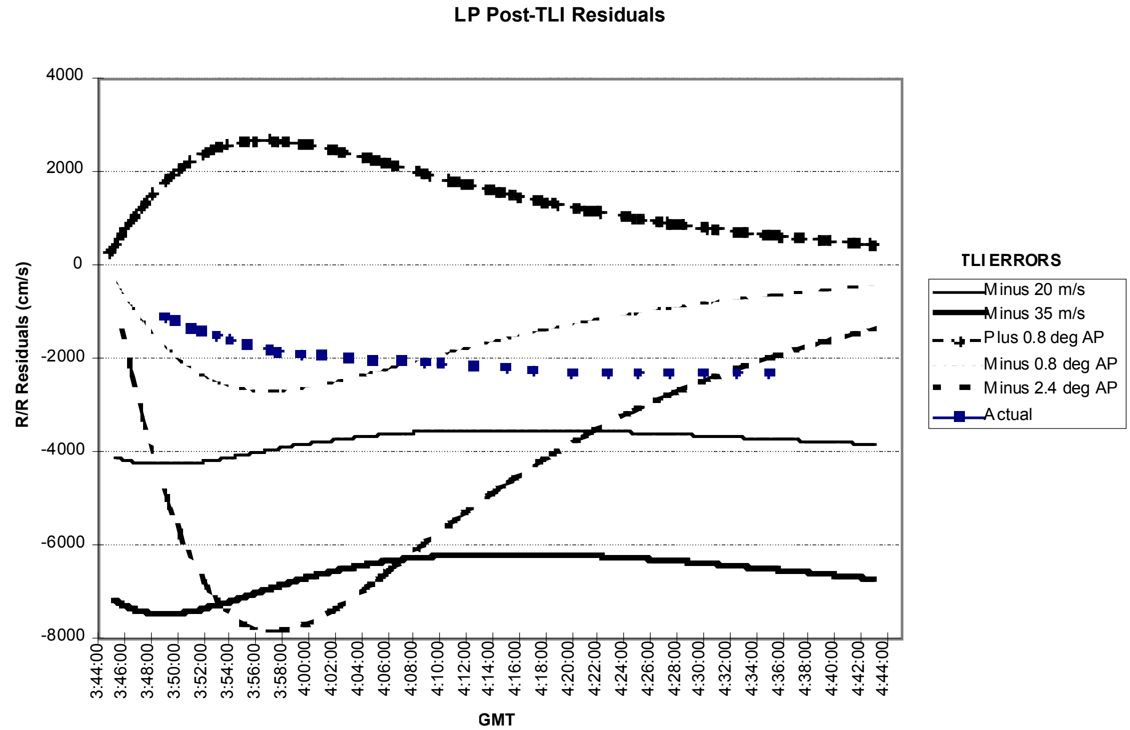

Figure 6: Lunar Prospector Doppler Residual Signatures for Post-TLI Maneuver Assessment

LOI#2 and LOI#3 were nominal. Doppler assessments were used during each maneuver to estimate maneuver efficiency. In particular a near-real-time assessment of LOI#3 was performed out of concern for an over-burn beyond the 100 km target apoapsis altitude. Full state estimates were available 2 hrs after LOI#2 and 3.5 hrs after LOI#3. The trend for the amount of tracking data needed to converge after LOI#1, 2 & 3 was exactly opposite of what was expected. This has been attributed to the inadequacy of the GLGM-2 potential model at lower altitudes. This effect was not seen in the covariance analysis.

Once the mapping orbit was achieved, different batch arc lengths were attempted with the goal of extending them as long as possible to reduce the amount of processing time (since it was expected that definitive ephemerides would be regenerated with the new potential model at a later date). A 14 hr tracking arc was chosen with a 2 hr overlap between two consecutive tracking arcs. Thus two 12 hr definitive ephemerides per day were placed on the Goddard Lunar Prospector web site (http://fdd.gsfc.nasa.gov/lp/) for use by the LP mission control center and science community.

The first updated LP potential model was available after just two weeks in the mapping orbit. The new model, LP75A, was developed by A. Konopliv of the Jet Propulsion Laboratory. A final model, LP75D[7], was available after one month and was used to generate updated ephemerides. A comparison of the orbit accuracy achievable with each of these three models is shown in Table 6. The orbit accuracy is measured as the difference between two consecutive definitive ephemerides over the period of overlapping tracking data. The LP75A solutions consisted of 26 hr arcs with a 2 hr overlap. The LP75D solutions consisted of 55 hr arcs with a 7 hr overlap.

Clearly the LP75D solutions meet the LP mission requirements. As of February 23, updated definitive ephemerides were being generated using the LP75D model. The regeneration of the first five weeks of definitive ephemerides will be completed by mid-April. The entire lunar mapping orbit definitive ephemeris history is available on the Goddard Lunar Prospector web site.

Table 6

LUNAR PROSPECTOR MAPPING ORBIT DETERMINATION ACCURACY

Model	Radial RMS	Cross-track RMS	Along-track RMS	Position RMS	Maximum Position	Average Doppler Residual
GLGM-2	475 m	4.0 km	4.4 km	6.6 km	31.6 km	21 cm/sec
LP75A	NA	NA	NA	1.9 km	7.3 km	5.5 cm/sec
LP75D	11 m	192 m	169 m	240 m	532 m	8.3 mm/sec

CONCLUSION

Lunar Prospector orbit operations occurred largely according to plan and resulted in the successful attainment of the 100 km altitude polar mapping orbit within budgeted orbit maneuver propellant allocations. A large share of the credit for the success of the Lunar Prospector mission can be attributed to the straightforward design of the spacecraft and the overall mission, and to a well-build and well-tested spacecraft that performed flawlessly. In particular, the spacecraft propulsion system was well modeled and provided excellent repeatability. Finally, a robust orbit determination strategy, characterized by accurate solutions and fast-turnaround, was also an important factor that contributed to maneuver targeting accuracy and low propellant consumption.

ACKNOWLEDGMENTS

Special thanks to Greg Marr, Karen Richon, Marco Concha, Osvaldo Cuevas, Pat Johnson and Joe Toth of NASA/Goddard, and to Marcie Smith of NASA/Ames, Dan Swanson of Lockheed Martin, Mark Ryne and Alex Konopliv of JPL and Dr. Alan Binder of the Lunar Research Institute for their excellent contributions to the success of Lunar Prospector trajectory operations.

REFERENCES

1. Hubbard, G. S., et al., "The Lunar Prospector Discovery Mission: A New Approach to Planetary Science", IAF-97-Q.4.01, October 1997.
2. Clarke, V. C., Jr., "Design of Lunar and Interplanetary Ascent Trajectories," AIAA Journal, Vol. 1, No. 7, July 1963.
3. Lemoine, F. G., et al., "A 70th Degree Lunar Gravity Model (GLGM-2) from Clementine and Other Tracking Data," Journal of Geophysical Research Vol. 102, No. E7, Pgs 16339-16,359 July 25, 1997
4. Folta, D., et al., "Lunar Prospector Mission Design," Flight Mechanics Symposium, Greenbelt, MD, May 19-21, 1997.
5. Cook, R. A. and Sweeter, T. H., "Orbit Maintenance for Low Altitude Near-Circular Lunar Orbits", AAS Paper 92-185, February 1992.
6. Konopliv, A. S., et al., "A High Resolution Lunar Gravity Field and Predicted Orbit Behavior", AAS Paper 93-622, August 1993.
7. Konopliv, A. S., "Lunar Prospector Gravity Results", to be presented at AGU Spring Meeting, May 26-29, 1998, Boston, MA.