MISSION DESIGN AND OPERATIONS CONSIDERATIONS FOR NASA'S LUNAR RECONNAISSANCE ORBITER

Mr. Martin B. Houghton
NASA's Goddard Space Flight Center, Greenbelt, Maryland USA • martin.b.houghton@nasa.gov

Mr. Craig R. Tooley
NASA's Goddard Space Flight Center, Greenbelt, Maryland USA • craig.r.tooley@nasa.gov

Mr. Richard S. Saylor, Jr
Honeywell Technology Solutions Inc., Greenbelt, Maryland USA • richard.s.saylor@nasa.gov

Abstract. Set to launch in October 2008, NASA's Lunar Reconnaissance Orbiter (LRO) will be the first observatory to ever spend an entire year orbiting the moon at an unrivalled altitude of just 50 km. This will provide an extraordinary opportunity to look into the lunar landscape at resolutions and over time scales never achieved before. LRO has specific observation objectives that constrain its launch window to 2-3 day periods every two weeks, with one launch opportunity on each of those days. LRO is following a direct, minimum energy transfer to the moon, culminating in a critical lunar orbit insertion burn about 4-5 days after launch. LRO is carrying 6 primary instruments and 1 technology demonstration, and its on-board data storage and communication systems, as well as its ground station network and systems, are sized to handle the unprecedented amount of data that will be generated by these instruments. While in lunar orbit, LRO will require a number of routine maintenance activities, including bi-monthly momentum management maneuvers, monthly station-keeping maneuvers, and bi-annual spacecraft yaw maneuvers. Finally, LRO is being designed to survive the long lunar eclipses that it will encounter if operated late into the 2010 timeframe.

INTRODUCTION

The Lunar Reconnaissance Orbiter (LRO), shown in Figure 1, is at the forefront of NASA's efforts to return humans to the moon. It will provide the data required to safely return humans to the moon and will help identify candidate landing sites for future human outposts. LRO will carry several instruments into lunar orbit (ranging from passive imagers to an active altimeter), as well as one technology demonstration (a synthetic aperture radar). Figure 2 gives an overview of LRO's instrumentation and associated data products. For more information see [1].

Set to launch in October 2008, LRO will be operating in a 50 km polar lunar orbit for at least 1 year and will collect an unprecedented amount of data regarding the lunar surface and environments. Getting into the low mapping orbit will require a number of intricate insertion maneuvers. Staying there will require a number of routine maintenance maneuvers. LRO's systems (flight and ground) are specially designed to handle the large amounts of data that will be generated over the course of the mission. These orbit and data underpinnings are key drivers to the LRO mission design and operations concepts.

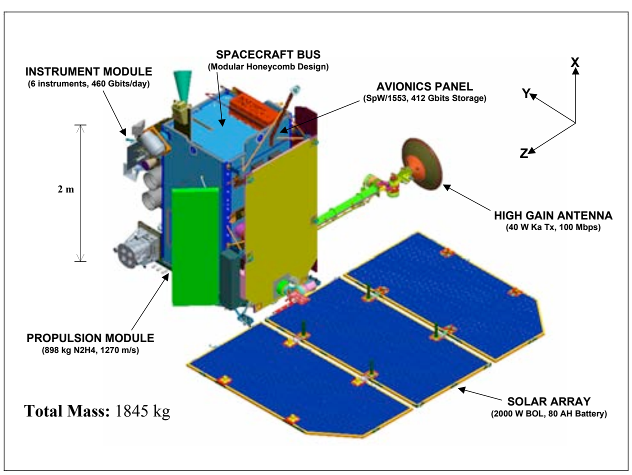

Figure 1: NASA's Lunar Reconnaissance Orbiter (LRO)

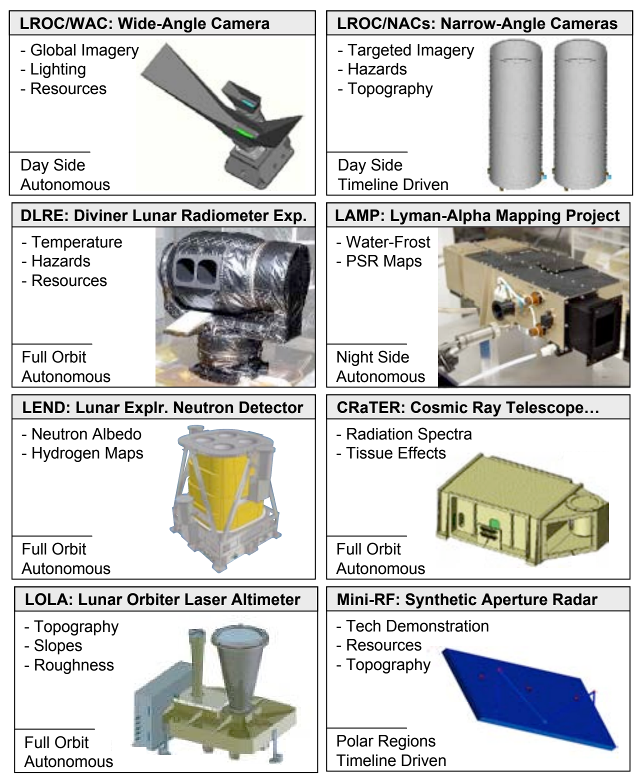

Figure 2: LRO's Instrumentation and Data Products

MISSION BASELINE

LRO will be launched on an Atlas V 401 Evolved Expendable Launch Vehicle (EELV) from the Kennedy Space Center (KSC), located on the east coast of Florida, USA. It will nominally follow a minimum energy transfer trajectory to the moon (see Figure 3), taking from 4 to about 5 days to complete the journey, depending on the exact geometry on the day of launch.

Once in the vicinity of the moon, LRO will begin a sequence of Lunar Orbit Insertion (LOI) maneuvers, with the first maneuver (capture) nominally lasting approximately 40 minutes. Subsequent LOI maneuvers will be performed over the next several days (see Figure 4), culminating in a low maintenance, 30 x 216 km quasi-frozen orbit [2] that LRO will make use of during its 60 day (nominal) commissioning period (see Figure 5).

After completing its commissioning activities, LRO will move to its nominal 50 km polar mapping orbit (see Figure 6), where it will remain for a minimum of 1 year, collecting data over the entire lunar surface under all possible lighting conditions.

LRO's fuel budget is dominated by the sequence of Lunar Orbit Insertion (LOI) maneuvers that put LRO into its desired orbit around the moon. The first of these maneuvers (LOI-1) provides the needed change in velocity (delta-V) to allow LRO to be captured by the moon's gravitational field. The magnitude of this particular maneuver is a function of the exact geometry of the transfer

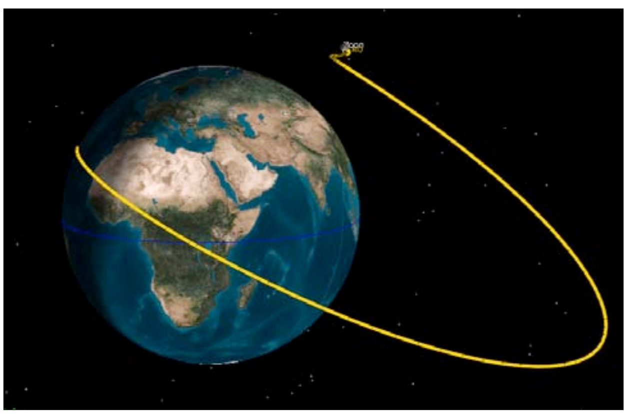

Figure 3: Minimum energy Transfer to the Moon (4-5 days)

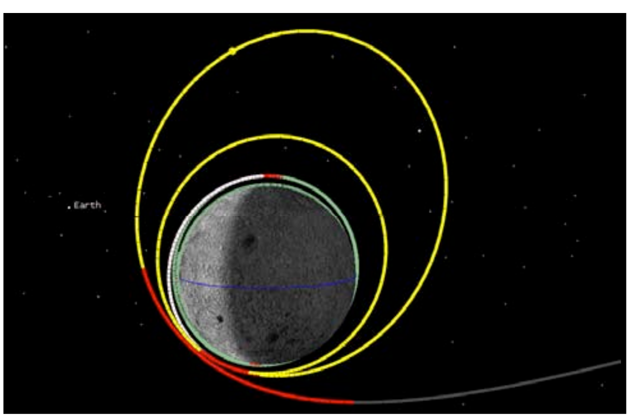

Figure 4: Lunar Orbit Insertion Sequence (4-6 days)

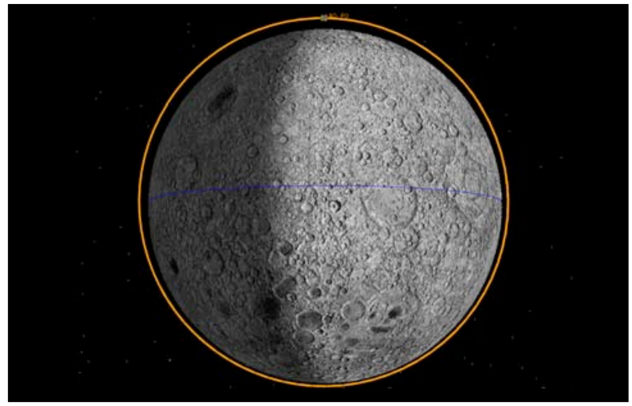

Figure 5: 30 x 216 km Quasi-frozen Orbit (up to 60 days)

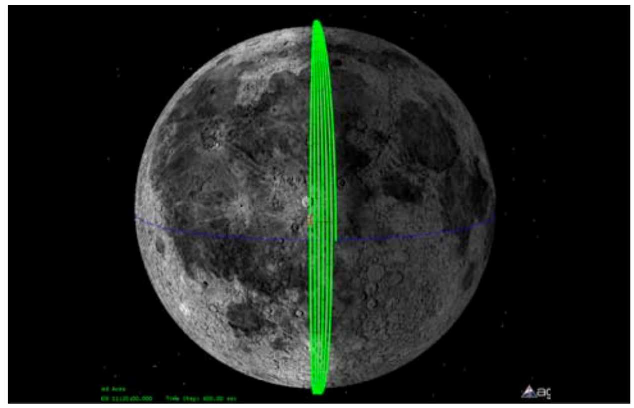

Figure 6: 50 km Polar Mapping Orbit (at least 1 year)

trajectory and fluctuates over the course of a given month.

The rest of the LOI maneuvers, as well as the majority of the remaining items in the LRO fuel budget, are deterministic and do not fluctuate over the course of a month. Therefore, by allocating an adequate amount of fuel to the LOI-1 maneuver , the fuel budget can be set for the entire mission (see Figure 7) [3]. LRO is carrying a delta-V requirement of 1270 m/s and has a maximum fuel load of 898kg (hydrazine). These two numbers, together with the expected effective specific impulse (Isp) of LRO's propulsion system (212.2 s), set the maximum allowable total liftoff mass for LRO at 1965 kg. The Atlas V 401 imposed limit on LRO is 2000 kg.

MISSION PLAN	Δv (m/sec)	Fuel (kg)	SOURCE
Mid-Course Correction	30	28.6	3σ LV errors
LOI-1 (with Checkout)	591	454.5	Deterministic
LOI-2 thru LOI-4	362	226.3	Deterministic
Mission Orbit Insertion	56	31.9	Deterministic
Orbit Station-Keeping	162	91.5	Deterministic
Ext. Mission / Margin	69	33.1	3 yrs Frozen
Momentum Unloading	–	17.0	4 years Total
Other (Residuals)	–	15.4	Conservative
Total	**1270**	**898**	

Figure 7: LRO Delta-V and Fuel Budget

LAUNCH WINDOWS

Several factors drive LRO's launch windows, but the main factor is tied to the seasonal lighting conditions on the lunar surface and a desire to definitively identify any permanently lit or permanently shadowed areas near the lunar poles. This requires a particular orbit plane orientation, relative to the solar cycle, in order to maximize the observability of the most extreme polar lighting conditions. Namely, the LRO orbit plane must be oriented such that it is near edge-on to the sun (0 deg beta-sun angle) during the lunar solstice periods (see Figure 8).

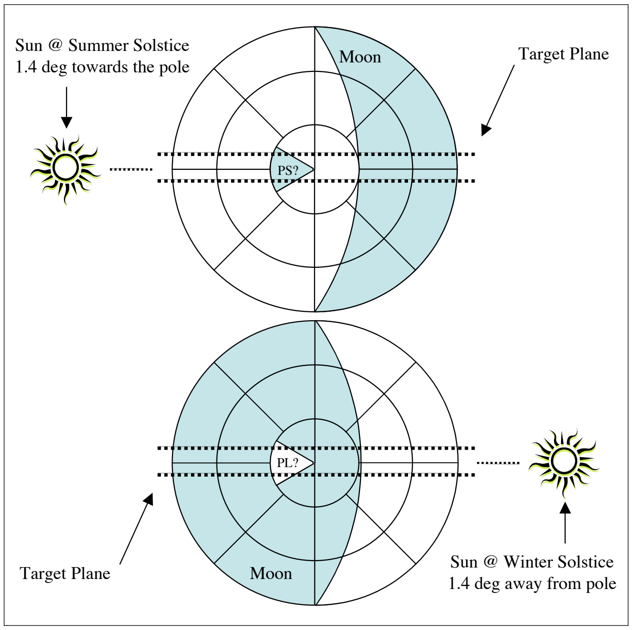

Figure 8: The Search for Permanent Light (PL) and Shadow (PS)

At insertion (LOI), LRO's orbit plane is fixed with respect to the Earth (~85 deg beta-Earth angle), regardless of the relative geometry between the Earth, moon, and sun (see Figure 9). Therefore, since the lighting constraint drives the target plane to a particular inertial orientation (low beta-sun angle at the solstices), it constrains the Earth departure (launch) to be within a few days of the point at which the natural insertion plane coincides with the inertial target plane. Forcing the difference between the

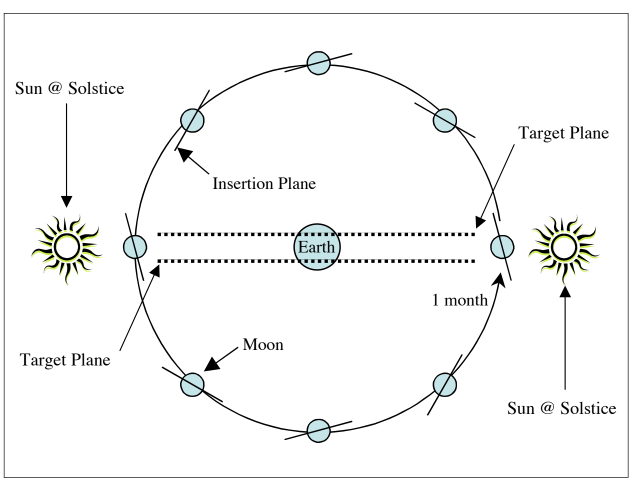

Figure 9: Insertion Plane Relative to Earth and Target Plane

two to be below 20 deg constrains the launch windows to 2-3 day periods every 2 weeks (see Figure 10). The prime launch date is 28-Oct-2008. There are at least 13 backup opportunities between 28-Oct-2008 and the end of 2008

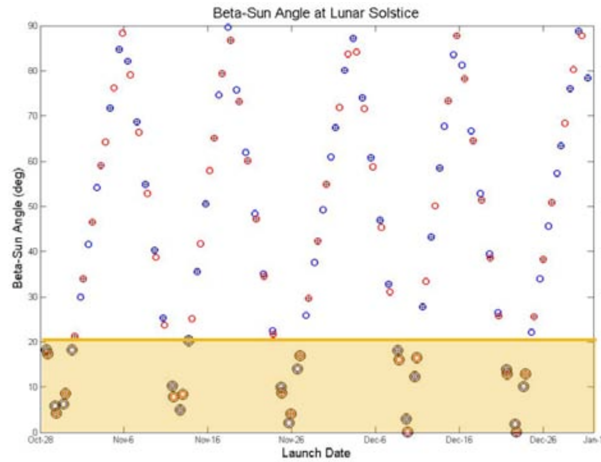

Figure 10: LRO Launch Windows; 2-3 days every 2 weeks

LUNAR ORBIT INSERTION

Regardless of the exact geometry at launch, LRO will reach the moon in about 4-5 days. When it does, it will need to execute a successful Lunar Orbit Insertion maneuver (LOI-1) in order to capture into a stable orbit around the moon. This burn is mission critical, and several steps have been taken to maximize the overall flexibility and probability of success. It starts with the fact that the burn (which will nominally last about 40 minutes), is designed such that only 50% of the delta-V is required to capture into orbit (see Figure 11). This can come in the way of thrust, or duration, and defends against possible failures in the propulsion system, as well as possible interruptions caused by software and/or processor faults.

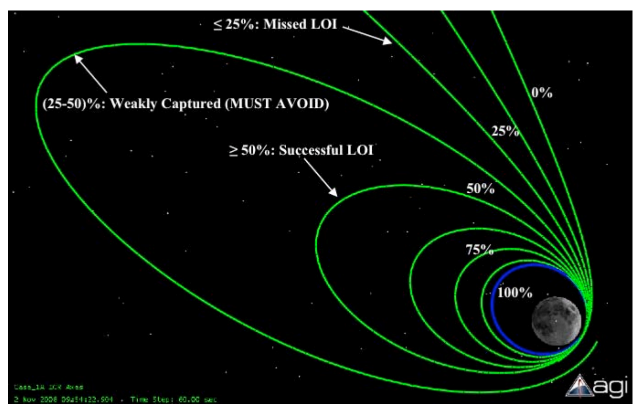

Figure 11: Lunar Orbit Insertion (LOI) Burn Completion Percentage

A diagram of the LRO propulsion system is shown in Figure 12 and clearly shows its redundant nature. There are 2 banks of two 88 N insertion thrusters and 2 banks of four 20 N attitude control thrusters. The insertion thrusters deliver a total force of ~350 N. That's twice the required thrust needed for lunar capture. In the event of any thruster failure, either of the insertion thruster banks can be used with either of the attitude thruster banks in order to successfully execute an insertion maneuver. With half the thrust, the burn duration will slightly more than dou-

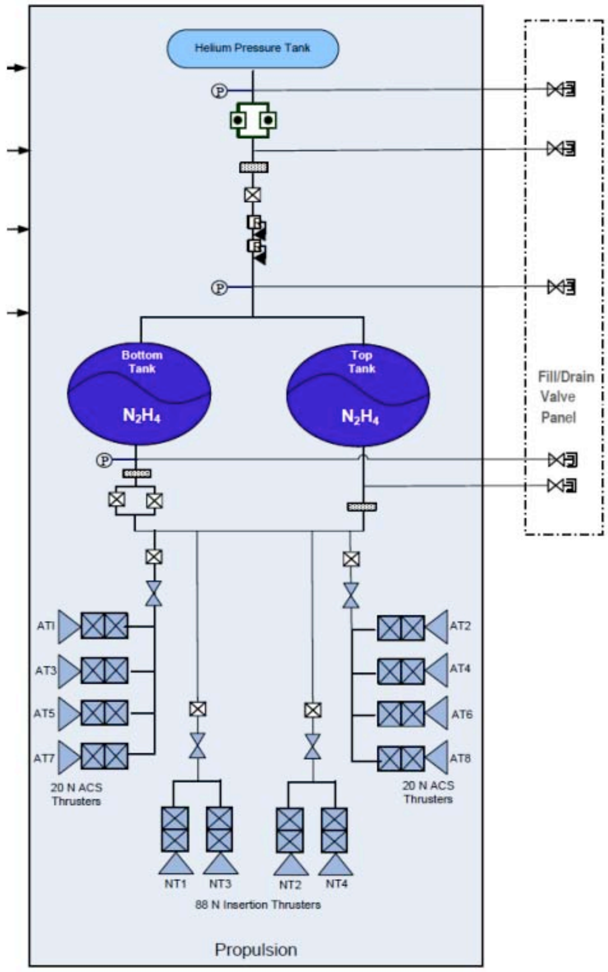

Figure 12: LRO Propulsion System Configuration

ble (due to increased finite burn losses), but the resulting orbit will be stable, and the mission can continue.

Similarly, at full thrust, a 40 minute burn duration is twice what is needed for a successful lunar capture. If the burn is interrupted for less than 20 minutes, for any reason, the resulting orbit will still be stable, and LRO will be able to continue with its mission. There will be restart procedures in place for all conceivable scenarios, and the LRO operations team will be thoroughly trained in executing these procedures.

In the event of a catastrophic failure or interruption (one that results in less than 25% of the required delta-V), LRO will not be captured by the moon's gravity (see Figure 11), but will have one final chance of getting into lunar orbit. It will require a deep space maneuver within 10 days of the first lunar encounter, which will be used to target a second lunar encounter about 90 days later (see Figure 13). This will deplete significant amounts of fuel, but LRO will still be able to get into lunar orbit, albeit with limited options in terms of orbits and durations. It would be able to fly in a higher (~215 km), circular orbit for up to a year , or go into and stay in the low maintenance, 30 x 216 km quasi-frozen orbit, originally meant for commissioning, for up to 3 years (see Figure 14).

Finally, if, as a result of failures and/or interruptions, the delivered delta-V is in the 25-50% range, LRO will be

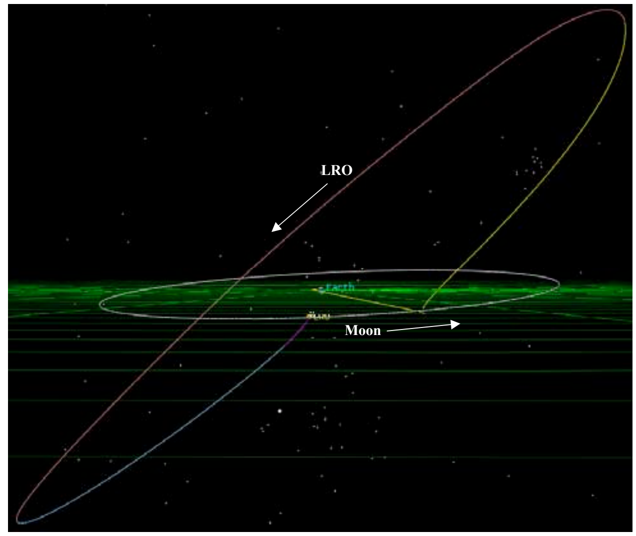

Figure 13: LRO Trajectory in Light of Missed LOI

weakly captured by the moon's gravity. This could result in chaotic behavior and have an irrecoverable effect on LRO's inclination (see Figure 11). If this happens, LRO will not be able to achieve any sort of polar lunar orbit, and its primary objectives will not be met. This threat will factor into any and all contingency/restart planning, and every effort will be made to avoid this region.

MISSION PHASE	ΔV (m/sec)
Mid-Course Correction	30
LOI-1 (1st attempt)	**MISSED**
Deep Space Maneuver*	300
LOI-1 (2nd attempt)	575
LOI-2 and LOI-3	320
LOI-4	N/A
Mission Orbit Insertion	N/A
Left for Mission**	45
Total	**1270**

* 10 days later; will leave Earth/Moon system if missed

** 215 km circular for ~1 year, or 30x216 km for ~3 years

Figure 14: Revised LRO Delta-V Budget in Light of Missed LOI

ON-ORBIT OPERATIONS

Once in orbit around the moon, LRO's universe becomes essentially moon-centered (see Figure 15). From this perspective, the Earth circumnavigates the moon once a month, and the sun circumnavigates the moon once a year. LRO's orbit will have a mean period of 113 minutes and a maximum eclipse time of 48 minutes, which occurs at 0 deg sun-beta angle. As mentioned previously, LRO's orbit will be targeted so that the lunar solstices occur near these 0 deg sun-beta angle periods. These also mark the points at which LRO will need to execute a 180 deg yaw flip, in order to keep the sun on the solar-array-side of the

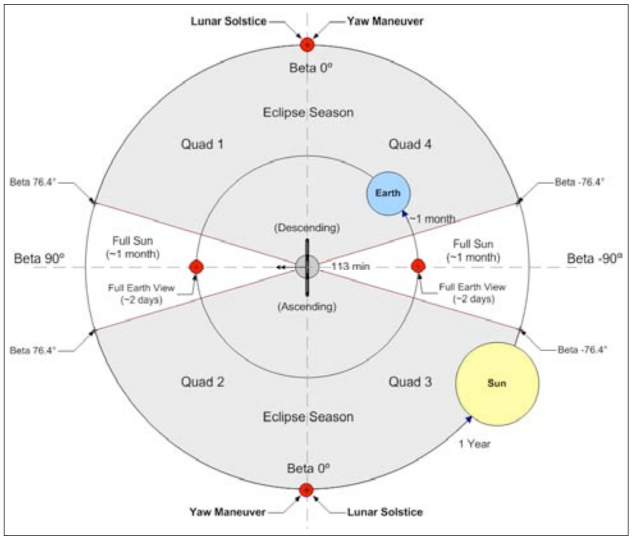

Figure 15: LRO's Moon-Centered Universe

spacecraft. Twice a month, LRO's orbit will be in full view of the Earth for ~2 days, and twice a year, LRO's orbit will be in full view of the sun for ~1 month. LRO's momentum management and station-keeping maneuvers will be done while the orbit is in full view of the Earth.

LRO will make use of a global network of S-band ground stations for nominal spacecraft tracking (roughly 30 minutes per orbit) and one Ka-band station for downlink of all the stored instrument and spacecraft data. LRO will nominally never be out of contact with the ground for more than 1 hour at a time.

Figure 16 gives a snapshot of the nominal on-orbit operations over 3 different time scales. Station-keeping maneuvers and instrument calibrations occur once a month. Momentum management maneuvers occur every 2 weeks. There is an S-band pass every orbit (12 per day), and 4 (on average) Ka-band passes every day. Most of the instruments operate autonomously over the course of a single orbit, while one requires a tailored command timeline. Nominally, LRO will receive a new command timeline from the ground once per day.

DATA DOWNLINK

On a given day, about 460 Gbits of data is generated on-board the LRO spacecraft (see Figure 17). This data is downlinked at 100 Mbps through a single Ka-band ground station at White Sands, New Mexico, USA (WS1). On average, there are 4 passes between LRO and WS1 every day, each lasting 45 minutes, but the actual number fluctuates between 2 and 6, as the moon moves through its entire latitude range each month (as seen from the Earth). Figure 18 shows the effect that this has on the Ka-band link utilization. Even in the worst case (2 passes), there is sufficient time to downlink the entire day's data volume.

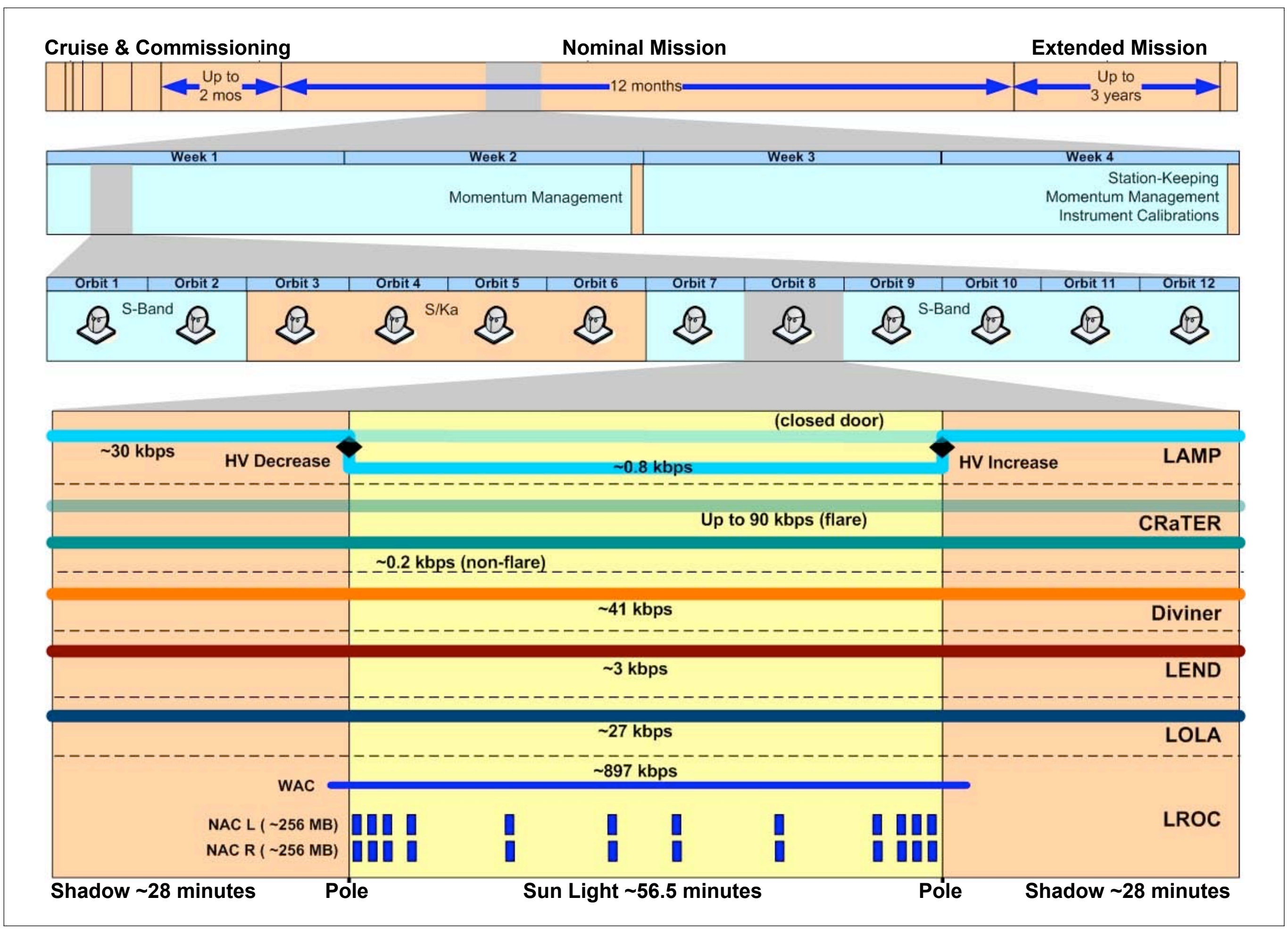

Figure 16: LRO's Primary Space Communication Network Ground Stations

LRO Data Volume Budget				
Type	Data per Orbit (Mbits)	Data per Day (Gbits)	Files per Orbit	File per Day
CRaTER	610.20	7.78	2.00	25.49
Diviner	180.52	2.30	22.60	288.00
LAMP	168.22	2.14	2.00	25.49
LEND	20.52	0.26	2.00	25.49
LOLA	226.29	2.88	2.00	25.49
LROC	34,659.16	441.67	28.00	356.81
Spacecraft	379.65	4.84	2.00	25.49
Total (Gbits):	36.24	461.88	61	772

Figure 17: Breakdown of LRO's Daily Data Volume

Ka-band Downlink Utilization*					
Passes	2	3	4	5	6
No.	Pass Utilization (minutes)				
1	45.0	45.0	45.0	45.0	45.0
2	40.1	33.4	26.7	20.0	13.3
3	–	6.7	6.7	6.7	6.7
4	–	–	6.7	6.7	6.7
5	–	–	–	6.7	6.7
6	–	–	–	–	6.7
Used	94.6%	63.0%	47.3%	37.8%	31.5%
Margin	5.4%	37.0%	52.7%	62.2%	68.5%

* Based on D/L rate of 100 Mbps - 10% overhead

Figure 18: Ka-band Downlink Utilization

STATION-KEEPING

Lunar orbits can be characterized by the evolution of their eccentricity and argument of periapsis over time. The moon's non-uniform gravitational field causes significant perturbations to these two parameters. Figure 19 illustrates the evolution of these parameters, over time, for LRO's two main lunar orbits (the 30 x 216 km quasi-frozen commissioning orbit and the 50 km polar mapping mission orbit). The quasi-frozen orbit shows virtually no

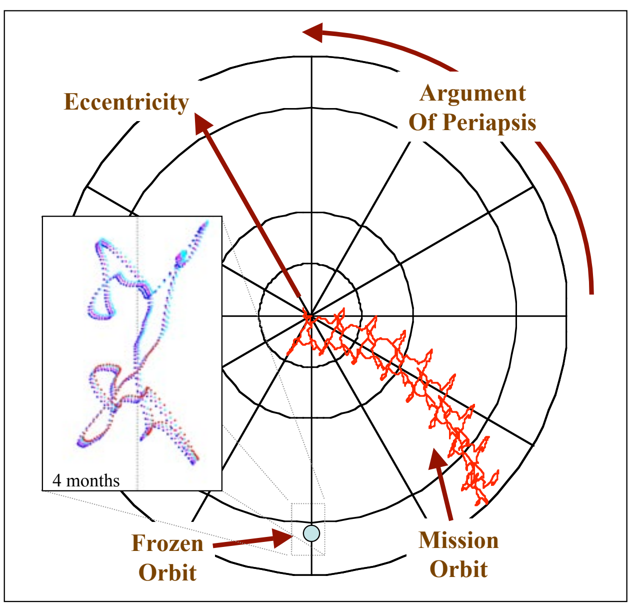

Figure 19: Evolution of Eccentricity and Argument of Periapsis

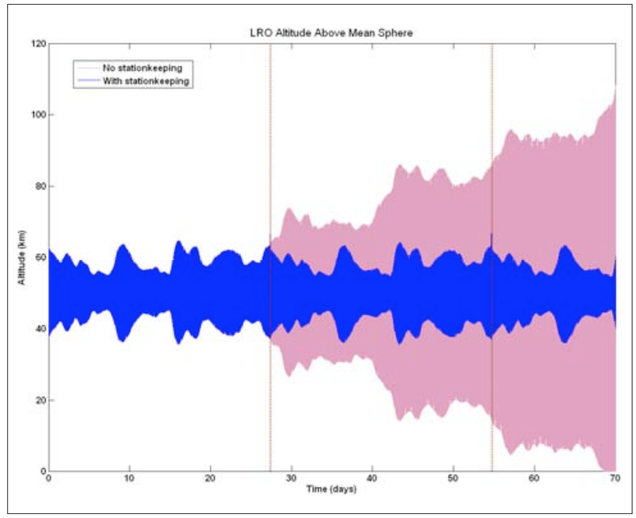

Figure 20: Mission Orbit With and Without Station-keeping

secular growth in eccentricity or argument of periapsis over time. The altitude is bounded, and the periselene remains over the south pole. This orbit requires very little station-keeping fuel (about 5 m/s per year).

In contract, the 50 km mission orbit shows significant evolution in eccentricity and argument of periapsis from month to month. If left uncorrected, these perturbations will cause LRO to hit the lunar surface within about 60 days (see Figure 20). The LRO station-keeping strategy makes use of the repeating pattern that can be seen in the eccentricity and argument of periapsis parameters (see Figure 21). The goal is to precisely reset the pattern at the end of each month, so that the evolution is bounded. This is accomplished with a 2-burn sequence that first circularizes the orbit and then de-circularizes it in the proper direction so as to center the repeating pattern around zero eccentricity. By doing so, LRO's altitude is kept to within 15 km of the target 50 km orbit, and far away from the lunar surface. This is an unavoidably expensive procedure, consuming about 150 m/s of fuel per year.

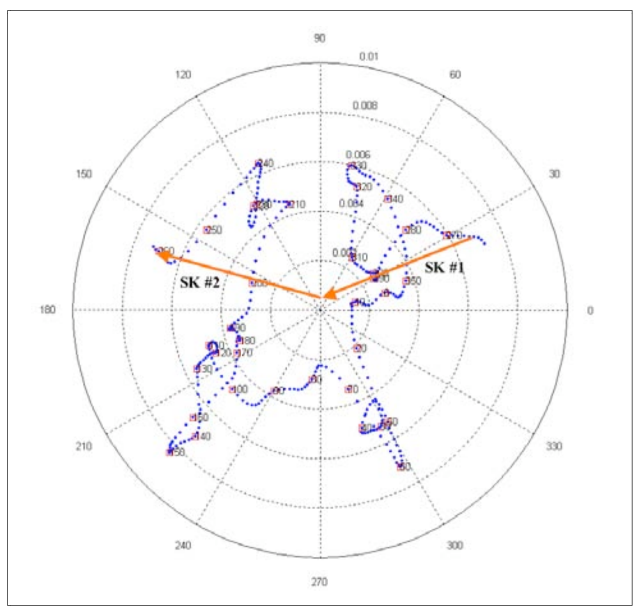

Figure 21: Mission Orbit Station-keeping Strategy

LUNAR ECLIPSES

Looking back at Figure 15, it's clear that the Earth will pass between the sun and the moon every month. Most months it will pass far enough above or below the sun-moon line that its shadow will not fall on the moon. But, twice a year (on average), it will pass close enough to that line to cast a significant shadow on the moon. These lunar eclipses vary in severity over roughly a 4 year cycle, with a peak occurring in the middle of 2011 (see Figure 22). For descriptive purposes, these eclipses have been labeled as Type 1 (benign) thru Type 4 (severe), based on existing data like that shown in Figure 23 [4].

In order to assess the effects of these lunar eclipses on the LRO spacecraft, geometric models were developed to estimate the amount of solar input that would be received during each event (see Figure 24). These show LRO coiling through space as it orbits the moon, while it (the moon) passes through the Earth's shadow. A corresponding solar input curve was computed for each model, taking into account both the Earth's shadow, as well as the regular occultations associated with LRO's orbit (see Figure 25). A simple power model was used to estimate the LRO state of charge (SOC) throughout each event.

Lunar Eclipses: 2009-2013				
Date	Type	Penum.	Partial	Total
2009 Feb 09	(2)	4:03	–	–
2009 Jul 07	(1)	2:12	–	–
2009 Aug 06	(1)	3:16	–	–
2009 Dec 31	(2)	4:15	1:02	–
2010 Jun 26	(3)	5:26	2:44	–
2010 Dec 21	(4)	5:38	3:29	1:13
2011 Jun 15	(4)	5:39	3:40	1:41
2011 Dec 10	(4)	6:00	3:33	0:52
2012 Jun 04	(3)	4:33	2:08	–
2012 Nov 28	(2)	4:41	–	–
2013 Apr 25	(2)	4:12	0:32	–
2013 May 25	(1)	0:54	–	–
2013 Oct 18	(2)	4:04	–	–

Figure 22: Lunar Eclipses in the LRO Timeframe

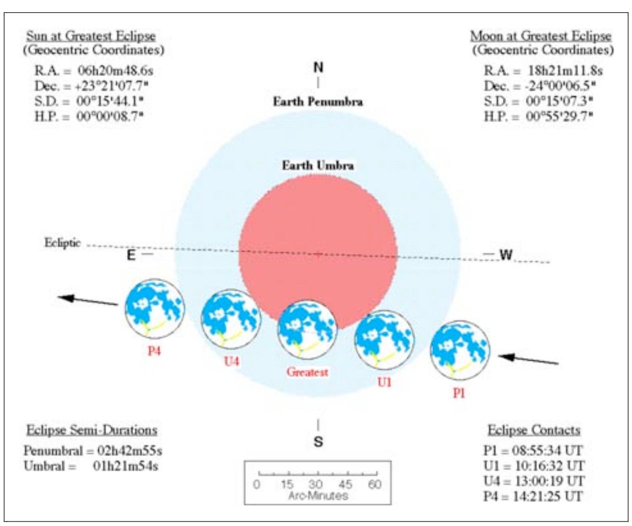

Figure 23: Information for 26-Jun-2010 Lunar Eclipse

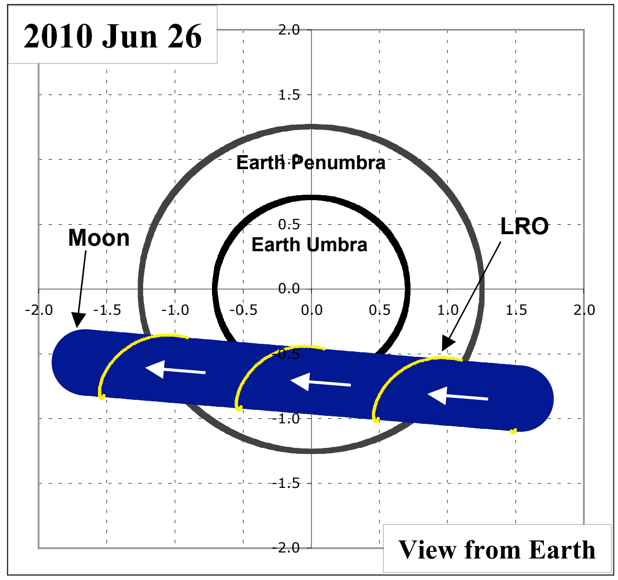

Figure 24: Geometric Model of 26-Jun-2010 Lunar Eclipse

During its nominal mission, LRO will only encounter Type 1 and Type 2 lunar eclipses. The worst of these will occur on 31-Dec-2009 (see Figure 26). This event will result in a worst case depth of discharge (DOD = 1 – SOC) of ~30%. This poses no threat to the LRO spacecraft.

EXTENDED MISSION

Once its 1 year nominal mission is complete, LRO will likely have a significant amount of fuel left over. At a minimum, there is 65 m/s allocated in the fuel budget for an extended mission. This will likely take on one of two forms. At a cost of 150 m/s per year, 65 m/s could be used to stay in the nominal 50 km mission orbit for an additional 5 months. Alternatively, that fuel could be used

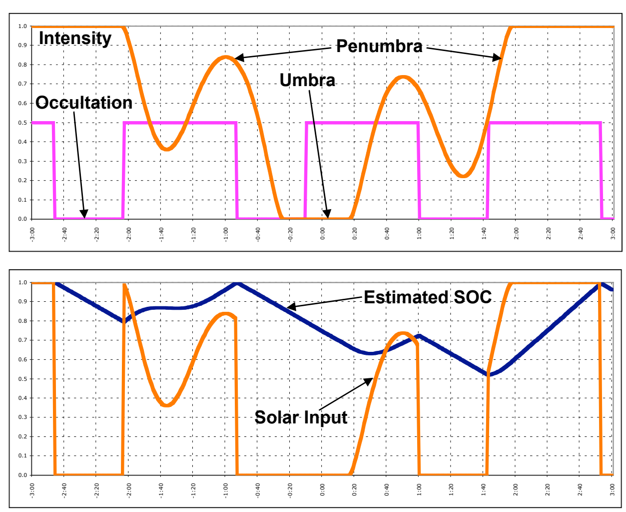

Figure 25: Solar Input and Estimated State of Charge for 26-Jun-2010

to transition back to the 30 x 216 km quasi-frozen commissioning orbit (~50 m/s) and stay there for up to 3 years (5 m/s per year). Other options exist, and additional fuel not consumed during the nominal mission may add to the range of possibilities.

Looking again at Figure 22, it's clear that any mission that extends significantly beyond the end of 2009 will begin to encounter increasing more severe lunar eclipses, culminating with the worst of the cycle on 15-Jun-2011 (see Figure 27). This event will result in a worst case

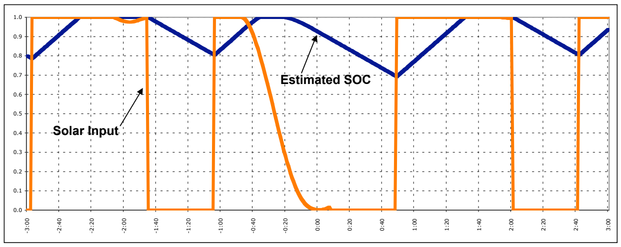

Figure 26: Worst Case Nominal Mission Lunar Eclipse (31-Dec-2009)

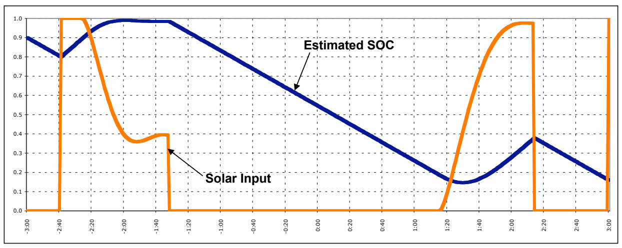

Figure 27: Worst Case Extended Mission Lunar Eclipse (15-Jun-2011)

depth of discharge of almost 90%. This is a dangerously high DOD, but one that LRO will be able to survive, as long as its key systems are still functioning at that point in the extended mission (more than 2 years after launch).

Regardless of what is done during the extended mission, LRO will eventually impact the lunar surface. Once its fuel is depleted, it will no longer be able to maintain its orbit, and the perturbations caused by the non-uniform gravitational field (even in the frozen orbit) will eventually result in an impact. Nothing can be done to stop this.

SUMMARY

LRO is an ambitious mission, set to explore the lunar landscape like never before. It's data products will enable future lunar exploration for decades to come. It's a challenging mission with several key driving factors, all of which have been met with robust design margins and innovative operations concepts. These mission design and operations concepts work together to bolster the probability of a successful LRO mission.

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