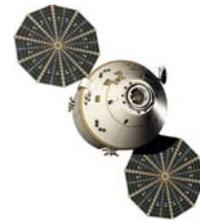**CREW EXPLORATION VEHICLE PROJECT**
FLIGHT DYNAMICS TEAM

Lunar Orbit Insertion Targeting and Associated Outbound Mission Design for Lunar Sortie Missions

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Space Administration
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Abstract

This report details the Lunar Orbit Insertion (LOI) arrival targeting and associated mission design philosophy for Lunar sortie missions with up to a 7-day surface stay and with global Lunar landing site access. It also documents the assumptions, methodology, and requirements validated by TDS-04-013, Integrated Transit Nominal and Abort Characterization and Sensitivity Study. This report examines the generation of the Lunar arrival parking orbit inclination and Longitude of the Ascending Node (LAN) targets supporting surface missions with global Lunar landing site access. These targets support the Constellation Program requirement for anytime abort (early return) by providing for a minimized worst-case wedge angle [and an associated minimum plane change delta-velocity (V) cost] between the Crew Exploration Vehicle (CEV) and the Lunar Surface Access Module (LSAM) for an LSAM launch anytime during the Lunar surface stay.

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1.0   EXECUTIVE SUMMARY

This report details the Lunar Orbit Insertion (LOI) arrival orbit targeting and associated mission design philosophy for Lunar sortie missions with a selectable surface stay (e.g., up to 7 days) and with global Lunar landing site access. It also documents the assumptions, methodology, and requirements validated by TDS-04-103, Integrated Transit Nominal and Abort Characterization and Sensitivity Study. This report examines the generation of the Lunar arrival parking orbit inclination and Longitude of the Ascending Node (LAN) targets supporting surface missions with global Lunar landing site access. These targets support the Constellation Program requirement for anytime early return by providing for a minimum wedge angle [and an associated minimum plane change delta-velocity (ΔV) cost] between the Crew Exploration Vehicle (CEV) and the Lunar Surface Access Module (LSAM) for an LSAM launch anytime[1] during the Lunar surface stay.

This report shows a technique for providing post-LOI CEV parking orbit inclination and LAN targets associated with given Lunar landing site latitudes and longitudes and for such mission design features as loiter time from LOI complete to LSAM descent and surface stay time. Additionally, this technique provides the inclination and LAN of the LSAM ascent/rendezvous following the on-orbit CEV plane change. Trajectory determination programs[2] take these targets and provide corresponding Trans-Lunar Injection (TLI) coupled with LOI ΔV and Trans-Earth Injection (TEI) ΔV requirements, respectively. This capability allows mission planners to quickly assess mission designs for various Lunar landing sites and for various mission parameters.

Analysis results using this iterative-analytic (J_2-only Lunar gravity) provide a worst-case plane change ΔV, required to align the CEV parking orbit for an in-plane LSAM ascent, that falls within 5 percent of a fully-optimized numerical solution using a high-fidelity Lunar gravity model. This technique provides targets very quickly, as compared to the numerical method, and serves well for large comparative performance analysis scans. It provides a good scan-friendly mission design capability for quickly assessing many possible Lunar missions.

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[1] The term "anytime" is tempered with the fact that an LSAM launch [and subsequent initiation of Trans-Earth Injection (TEI) by the CEV] must accommodate the CEV phase location such that the maneuver can be executed at any time, given acceptable CEV phase location associated with a 2-hour orbit period.

[2] These programs include EXLX and LXEE, which are mid-fidelity Earth-Moon trajectory performance scan programs. EXLX is a suite of four tools using the "X" as a variable representing either "orbit" or "surface." The tool used here is the Earth Orbit to Lunar Orbit (EOLO) part of EXLX. For LXEE, the "X" represents "orbit" and the tool used was the Lunar Orbit to Earth Entry (LOEE) part of LXEE.

2.0   INTRODUCTION

Human Lunar mission design must provide the crew with options for a safe return to Earth in the event of an off-nominal situation. Mission planners are charged with the task of providing safe Earth-return coverage that is as complete as possible, given such mission constraints as vehicle performance, vehicle structural or thermal limitations, and crew physiological limits.

The current mission design for global access, short-duration (up to 7 days surface stay time) Lunar sortie missions provides for a minimized worst-case-required CEV on-orbit plane change for both nominal and early return missions. The mission described here was originally developed in support of the Exploration Systems Architecture Study (ESAS) (Reference 1). In this mission design, the crew is guaranteed that the CEV on-orbit plane change, used to set up the ascent phase of the LSAM, does not exceed a specified limit. Pure plane changes are costly for the Low Lunar Orbit (LLO) altitude of the CEV parking orbit (currently set to a 100-km circular orbit altitude). This approach minimizes the CEV plane change for either a nominal or early Earth return (Reference 2).

An outgrowth of this sortie mission design is that the TLI maneuver, combined with the LOI maneuver sequence, targets to a specific Lunar Destination Orbit (LDO) inclination and LAN. This can result in a large plane change in the LOI burn (or burn sequence). The possible large plane change drove the mission design to include a three-burn LOI sequence.[3] The three-burn LOI outbound (TLI to LOI) mission phase allows for a minimized vehicle performance (propellant) requirement supporting possible large plane changes associated with LOI inclination and LAN targets for particular Lunar landing site latitudes and longitudes. Associated with the LOI targets are estimates of the maximum on-orbit CEV plane change ΔV requirement throughout the entire 7-day surface stay as a function of the Lunar landing site latitude and longitude. The CEV inclination and LAN targets were evaluated for landing site latitudes ranging from $-85°$ to $+85°$ and for all longitudes[4].

3.0   REQUIREMENTS ADDRESSED

This report addresses CEV requirements CV0008, CV0106, CV0107, CV0109, and CV0119. Specifically, it addresses the inclination and LAN targets that support a minimum ΔV on-orbit plane change requirement for global Lunar landing sites for sortie missions. This report primarily addresses CV0119 and CV0008.

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[3] For sufficiently small required Lunar arrival plane changes, the LOI can be performed in one burn.

[4] The global access sortie mission covers all latitudes ($-90°$ to $+90°$) and longitudes; however, sortie missions within 5° latitude of the poles are handled using a polar landing site mission design approach.

Requirement CV0119 states, "The CEV shall compute translational maneuver targets." This requirement descends from the Constellation Architecture Requirements Document (CARD) requirement CA0379-PO in section 3.7.1.8.5.

Requirement CV0008 states, "The CEV shall provide for early return to Earth after achieving mission destination." It descends from CARD requirement CA0448-PO in section 3.7.1.8.2, which states, "The CEV shall provide for return to Earth from any point in the mission while being operated by a single crewmember." Requirement CA0448-PO descends from CARD requirement CA0352-HQ, which states, "The Constellation Architecture shall provide the capability to perform an expedited return of the crew from the surface of the Moon to the surface of the Earth in 120 hours (TBR-001-005) or less after the decision to return has been made." CARD requirement CA0352-HQ descends from CARD section 3.2.2, specifically CA0107-HQ, which states, "The Constellation Architecture shall provide crew survival capabilities through each mission phase."

4.0   MISSION DESIGN

The outbound (Earth to Moon) flight phase employs the targeting scheme described in this report. The mission design that emerged from the ESAS (Reference 1) activity produced two fundamental techniques with regard to the targeting of the post-LOI CEV parking orbit. These techniques applied to the Lunar sortie and the Lunar outpost missions.

The Lunar sortie mission, the focus of this report, provides global Lunar landing site access for short surface stay times along with early return capability. Current mission planning includes a maximum 7-day surface stay. The Lunar sortie technique provides a minimized worst-case CEV on-orbit plane change capability that does not exceed a specified value for any sortie landing site location.

An outgrowth of the ESAS activity has the Lunar mission design depending upon the landing site location. The sortie missions can span all Lunar latitudes and longitudes; however, the nonpolar techniques described in this report apply to the sortie mission design that covers latitudes from –85° to +85° and all longitudes (see Figure 4-1). The ESAS work endeavored to produce a globally-applicable Lunar outbound targeting technique to support early analysis and preliminary vehicle sizing. The Lunar polar technique focuses on landing sites in the Lunar polar regions greater than 85° latitude or less than –85° latitude. A polar sortie mission covers a maximum 7-day surface stay, while an outpost or long-duration mission covers a surface stay on the order of 180 days plus a 30-day contingency stay, for a total possible surface stay of 210 days.

Sunlight during missions can be a constraint and would affect mission design, as the sun angle (above/below the horizon) can be very low when the sun is visible. This makes the mask angle, caused by elevated regions near the landing site, a concern. Further, particularly for polar missions, the sun could be visible for several consecutive months (above the horizon), but also

could lie below the horizon for months at a time. There are a wide range of lighting conditions for Lunar sortie missions. In lower latitudes, sunlight appears on a bimonthly basis with the sun above the local horizon for about 2 weeks and below the horizon for about 2 weeks. Concerns about lighting at the landing site can affect the ranges of dates that missions are conducted. Ongoing analyses will examine the effects of lighting constraints on mission opportunities and performance.

The current polar outpost mission design targets the CEV/LSAM to a 90° inclined parking orbit. From that orbit, the LSAM descends to the surface of the Moon. Assuming that the landing site is within 5° latitude of the pole, the worst-case on-orbit plane change (required to set up an in-plane LSAM launch) would be 5° (based on Figure 4-1). However, Lunar orbit propagation studies employing high-order gravity models (Reference 3) reveal perturbations in the inclination and LAN of the CEV parking orbit that result in a larger plane change requirement (about 6.2°, worst case).

Figure 4-1: Lunar sortie and Lunar outpost mission landing site regions.

4.1 LOI Maneuver Sequence

During the Apollo Program, the LOI maneuver consisted of a single burn. In the Constellation Program, the potential for large wedge angle changes during Lunar arrival (LOI) and/or departure (TEI) necessitates availability of a three-burn sequence (see Figure 4-2). The inclination and LAN targets associated with a particular landing site latitude and longitude, the focus of this report, are achieved at the conclusion of the LOI maneuver sequence on arrival in the LDO. The spacecraft achieves an LDO inclination and LAN target through a combination of

the TLI and the LOI burn, which is reinforced with as-needed post-TLI Trajectory Correction Maneuvers (TCMs).

Intermediate transfer orbit

LOI Burn 1
This maneuver creates an intermediate transfer orbit. It is primarily an orbit energy maneuver with possible plane change.

LDO

LOI Burn 2
This maneuver primarily changes the plane with possible radial component to assure fail-safe scenario in the event of premature engine cutoff.

LOI Burn 3
This maneuver performs final circularization burn with possible small plane change. It achieves LDO inclination and LAN targets for the CEV/LSAM stack such that, after a pre-determined check-out loiter period, the LSAM can perform an in-plane descent to the surface.

TCM-4

TCM-3

Desired inclination and LAN, associated with a particular landing site latitude and longitude, are targeted to occur upon insertion onto the LDO following the final LOI maneuver.

TCM-2

TCM-1

TLI

Inclination and LAN targets are translated into a TLI ΔV maneuver, which is reinforced with subsequent TCMs, as needed.
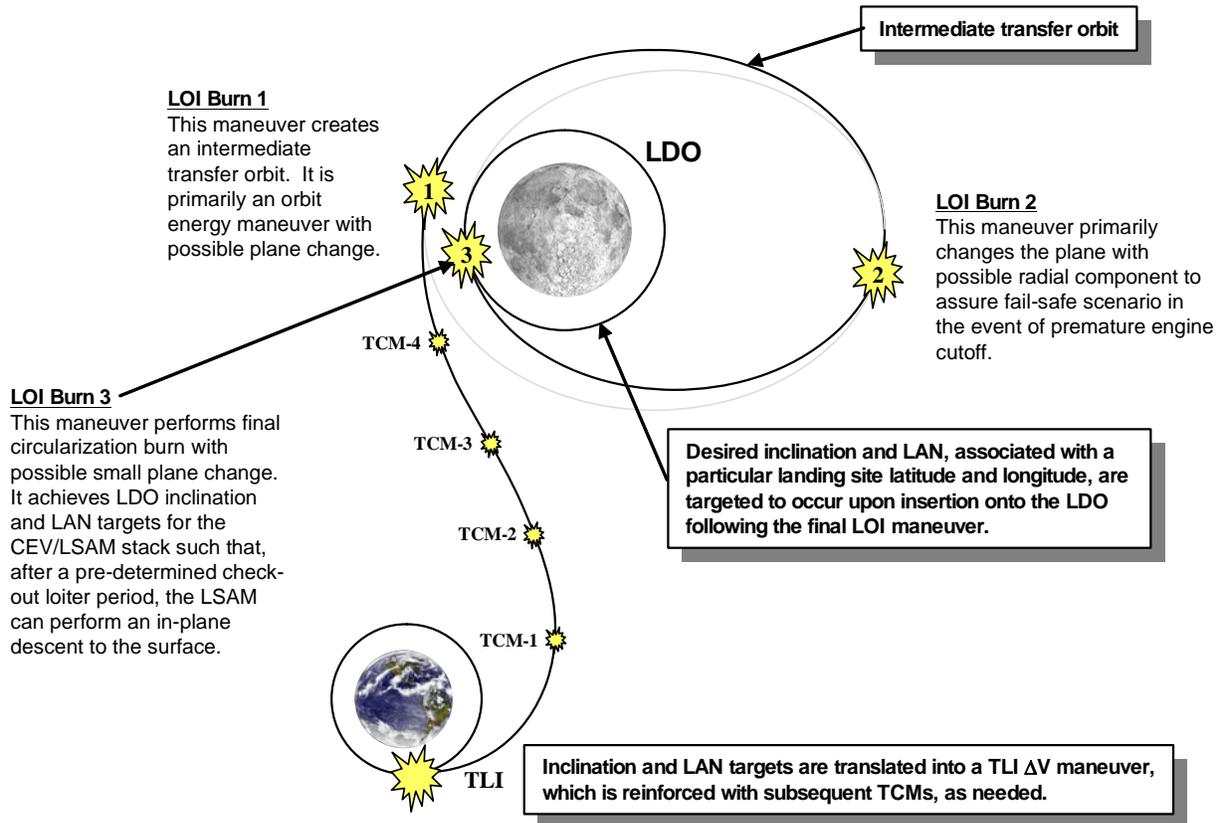
Figure 4-2: Three-burn LOI maneuvers provide Lunar capture to desired LDO inclination and LAN associated with a particular landing site latitude and longitude.

4.2   Lunar Sortie Mission Design

As stated in section 3.0, CARD requirement CA0352-HQ states, "The Constellation Architecture shall provide the capability to perform an expedited return of the crew from the surface of the Moon to the surface of the Earth in 120 hours (TBR-001-005) or less after the decision to return has been made." This requirement, combined with the global access requirement, demands a crew capability to depart any Lunar landing site location before the nominal end of mission. This combination of global access and anytime early return capability, along with the desire to minimize the CEV required ΔV (and its associated propellant mass), results in a flight technique that identifies a specific Lunar orbit inclination and LAN that supports a particular landing site latitude and longitude. This technique would allow the crew to perform an in-plane landing and be assured that the on-orbit plane change, executed in this case by the CEV to set up the LSAM for a near in-plane ascent after (up to) a 7-day surface stay, does not exceed a specified (minimized worst-case) value for either a nominal or early return scenario. Here, the phrase "near in-plane" refers to the fact that, while an in-plane launch to the CEV parking orbit could

occur when it contains the landing site, the LSAM ascent may occur only when the CEV is in the proper phase location to effect a timely rendezvous sequence.

The overall nominal design example for a maximum surface stay time sortie (see Figure 4-3) reflects a mission duration of about 21.5 days with 7 days on the Lunar surface. Assuming a pre-emplaced Earth Departure Stage (EDS) and LSAM in Low Earth Orbit (LEO), the Crew Launch Vehicle (CLV) launches the CEV into orbit where it docks with the EDS/LSAM. About 6 days after the CLV launch, the EDS executes the TLI maneuver targeted to a particular Lunar orbit inclination and LAN realized at the conclusion of the LOI burn sequence. After a day of loiter for crew reconfiguration, operations activities, and checkout prior to LSAM descent, the CEV/LSAM orbit contains the landing site, allowing for an in-plane LSAM descent to the surface. After approximately 6 days on the Lunar surface, the CEV performs an orbit plane change in preparation for the LSAM ascent on surface day 7. The new CEV orbit inclination and LAN provides for a nominal in-plane launch of the LSAM on day 7[5]. About a day after the LSAM ascent and rendezvous with the CEV, the CEV performs an approximately 1-day-long TEI maneuver sequence, placing it on a 3.5-day flight to Earth[6]. A more detailed look at the mission design for the surface stay portion of the sortie mission from Lunar descent through Lunar ascent appears in Figure 4-4.

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[5] The LSAM is not required to perform a large ascent plane change due to the cooperative CEV on-orbit plane change maneuver. Generally, however, at the time of LSAM launch, the CEV orbit plane will not contain the landing/launch site due to rendezvous-driven constraints on the phase location of the CEV. Thus, the LSAM will perform some yaw steering during the nominal ascent flight phase.

[6] The 3.5-day trip time from TEI-3 to Earth Entry Interface (EI) (400,000 ft altitude) represents a minimum flight time, based on CEV performance capability. CEV active orbit lifetime provides for a longer flight time. A 24-hour extension of the flight time allows the CEV to accommodate up to 360° of Earth return longitude variation.
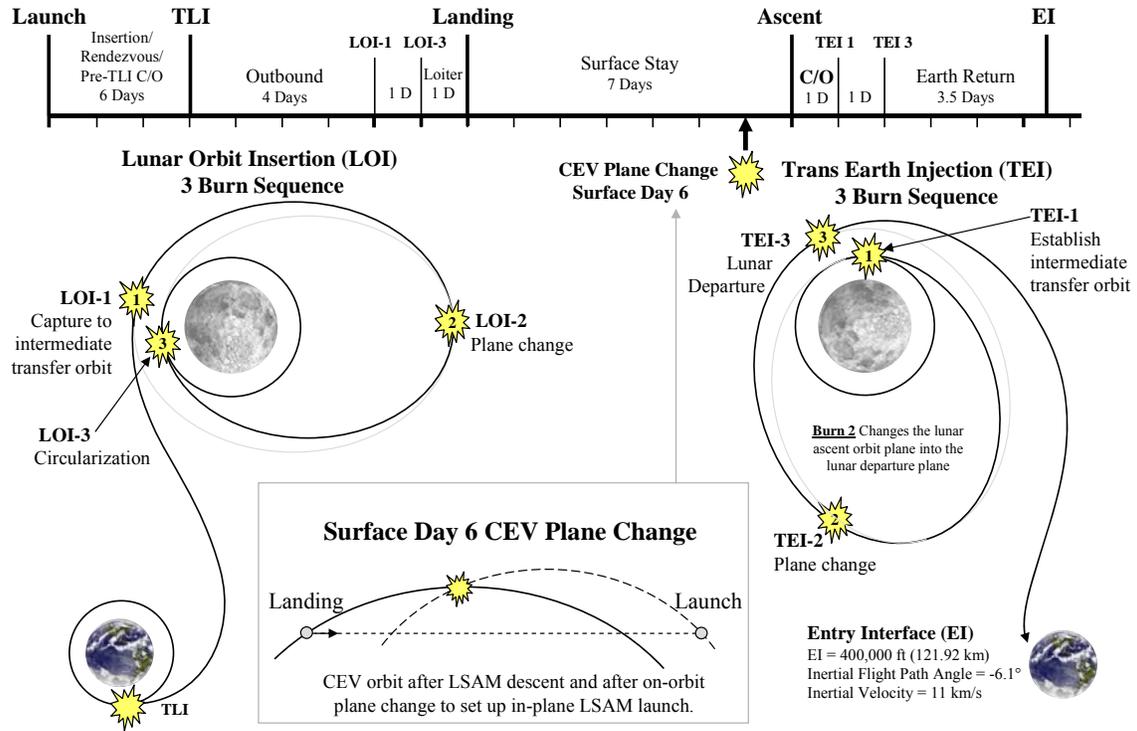
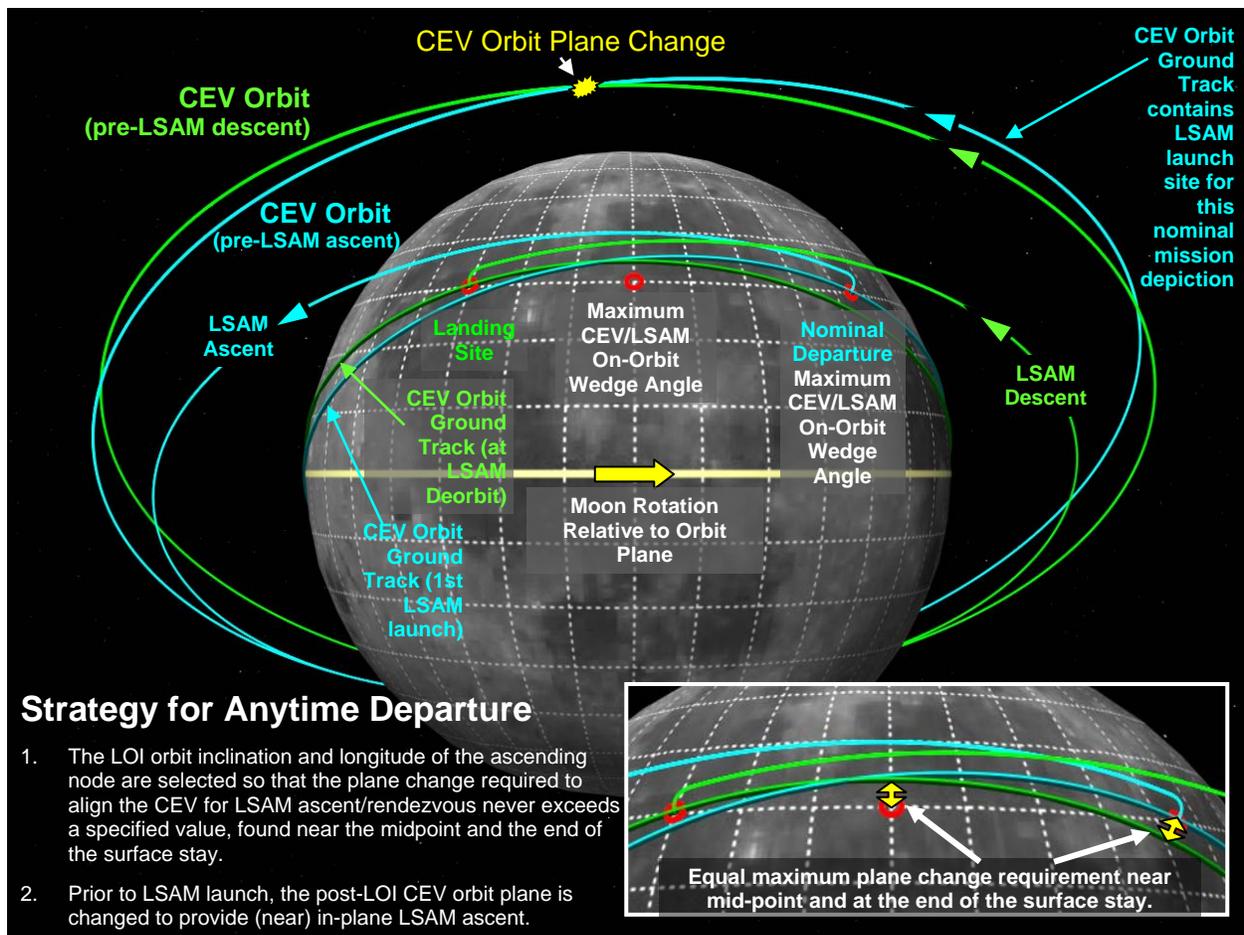Figure 4-3: Overview of Lunar sortie mission design.

Figure 4-4: CEV parking orbit prior to LSAM descent and LSAM ascent, including on-orbit CEV plane change.

In addition to the magnitude of the on-orbit plane change required to align the CEV for in-plane LSAM ascent, the LSAM performance and launch windows also are affected by this sortie mission design (References 4, 5, and 6). The performance benefit of using an on-orbit plane change to effect this alignment between the CEV and LSAM was confirmed in a separate study (Reference 4).

4.3   Lunar Outpost Mission

Current plans (i.e., ESAS) call for the Lunar outpost mission to occur in the Lunar polar region. The ESAS focused on the south pole region with a landing site within 5° latitude of the south pole, though outpost missions also could occur within this latitude band at the north pole. The targeting for the outpost mission differs from the sortie mission due to the proximity to the Lunar pole. Current plans call for a polar (i.e., 90° inclination) CEV parking orbit with a free LOI LAN. This allows for a minimum ΔV LOI that can be accomplished in a single burn. The Lunar outpost mission design, however, is not like that of the sortie mission and, thus, is not a focus of this report.

5.0   CONSTRAINTS AND ASSUMPTIONS

The following assumptions were made for the generation of inclination target data presented in this report:

a. LDO apoapse altitude = 100 km (54 nm).

b. LDO periapse altitude = 100 km (54 nm).

c. Intermediate transfer orbit apoapse altitude = 15,925 km (8,599 nm) supporting a one-day orbit period.

d. Intermediate transfer orbit periapse altitude = 100 km (54 nm).

e. Lunar equatorial radius = 1737.4 km (938.1 nm).

f. Lunar rotation rate = 13.17635815 deg/day.

g. Lunar gravitational constant = 4902.801076 km³/s². This value is based on the LP150Q Lunar gravitational potential model (Reference 7) and assumes that it will be used in conjunction with the J_2 zonal harmonic term.

h. The zonal harmonic, J_2 = 2.033542482111609e-4.

i. Post-LOI loiter time (to LSAM in-plane descent) = 1 day.

j. Lunar surface stay time = 7 days.

k. On-orbit plane change is performed by the CEV, which aligns the CEV orbit for an in-plane LSAM ascent and rendezvous.

6.0   METHODOLOGY

The inclination and LAN targets for LOI are computed using a Matlab processor. This processor can compute these targets for either a posigrade or retrograde post-LOI CEV parking orbit; however, the lower outbound mission abort propellant requirement for retrograde parking orbit targets drove the target inclination range to vary between 90° and 180°. Initially, the LOI inclination and LAN targets were generated and externally passed to EXLX, which assesses the performance (e.g., ΔV) of outbound Lunar transfers to specific post-LOI target orbits. This processor takes the inclination and LAN targets (and other previously mentioned assumptions) and generates a TLI ΔV vector at Earth departure along with a three-burn LOI ΔV vector maneuver sequence that delivers the CEV to the desired parking orbit (see Figure 6-1). The targeted CEV parking orbit supports the anytime early return without exceeding a minimized on-orbit plane change.

Including the inclination and LAN LOI target generation capability within EXLX allows the user simply to input the latitude and longitude of the intended landing site. The outbound (TLI to LOI) processor was used, in conjunction with the inclination and LAN targets, to provide performance scan data over an entire metonic cycle.
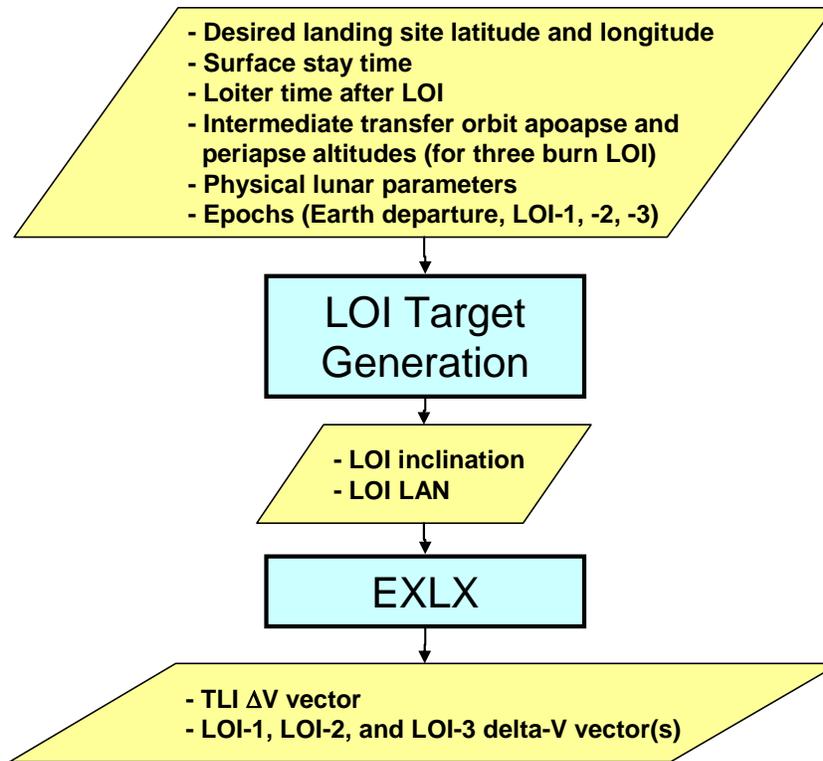
Figure 6-1: Flowchart for generation of LOI inclination and LAN
and associated TLI and LOI ΔV vectors.

7.0 INCLINATION AND LAN TARGET DESIGN

The LOI arrival inclination and LAN are an integral part of the overall mission design and relate the required on-orbit plane change (required to align the CEV for in-plane LSAM launch) to the surface stay time and landing site latitude. Once the location of the landing site and duration of the Lunar surface stay are selected for a given sortie mission, such processors as EXLX can calculate the cost to perform either a single-maneuver or three-maneuver burn sequence to place the CEV in the required LLO (i.e., achieve the inclination and LAN targets). EXLX computes both the TLI and LOI maneuver combination. Selectable minimizations of the TLI and LOI combination can be employed in an attempt to minimize the overall initial mass in LEO. The selection of the inclination and LAN at LOI completion also determines the inclination and LAN of the post-LSAM ascent orbit; therefore, the arrival orbit (inclination and LAN) targets will affect the TEI ΔV requirement, since the post-CEV plane change orbit (supporting in-plane LSAM launch) is constrained.

7.1 Minimum CEV Wedge Angle Technique

The LOI inclination and LAN targets are dependent on a number of factors, including the Lunar landing site latitude and longitude, surface stay time, loiter time after LOI and prior to LSAM deorbit, and the size of the LLO. The diagrams in Figure 7-1 reflect a technique employed to provide the minimum possible on-orbit CEV plane change (i.e., wedge angle), while at the same

time providing for anytime LSAM liftoff. This technique achieves a minimum plane change angle by launching the LSAM such that it intercepts the CEV orbit plane 90° downrange from the launch site (at the time of launch) (Reference 2). The left portion of the notional diagram in Figure 7-1 shows the CEV orbit containing the landing site (blue curve) at the beginning of the 7-day surface stay. The solid blue CEV orbit curve in the right portion of the figure reflects an LSAM ascent, immediately after landing, with a very small wedge angle. As time progresses, the landing site moves to the east, relative to the CEV parking orbit. About 3 days after landing, the minimum attainable plane difference between the CEV parking orbit and a post-LSAM ascent/rendezvous has reached a maximum. This difference, shown in the left portion of the figure as W1, is reflected in the right portion with a maximum wedge angle (and associated plane change ΔV). Approximately midway between the fifth and sixth day of the surface stay, the CEV orbit again contains the landing site, and an in-plane LSAM ascent can occur. Again, this is shown in the left portion of the figure and reflected in the right portion as a zero wedge angle. At the end of the 7-day surface stay, the landing site becomes the launch site. The left portion of the figure shows the minimum attainable wedge angle between the landing/launch site and the CEV parking orbit to have a magnitude of W2. The CEV would have to perform a wedge angle of W2 degrees to contain the LSAM landing/launch site and provide an in-plane launch (per the left and right side of the figure, respectively). If the magnitude of the wedge angles near the midpoint (W1) and end (W2) of the 7-day mission are equal, the maximum that the wedge angle could be is minimized. With this technique, the on-orbit wedge angle required to provide an in-plane LSAM ascent never exceeds W = W1 = W2 throughout the entire surface stay. If the CEV carries enough propellant to accomplish this wedge angle (W), it will possess the ability to set up the LSAM to perform an in-plane ascent anytime during the Lunar surface stay.

This scenario, which evolved from the ESAS (Reference 1), uses the CEV to perform the on-orbit plane change; however, this on-orbit maneuver also could be performed by the LSAM if it possessed enough propellant.
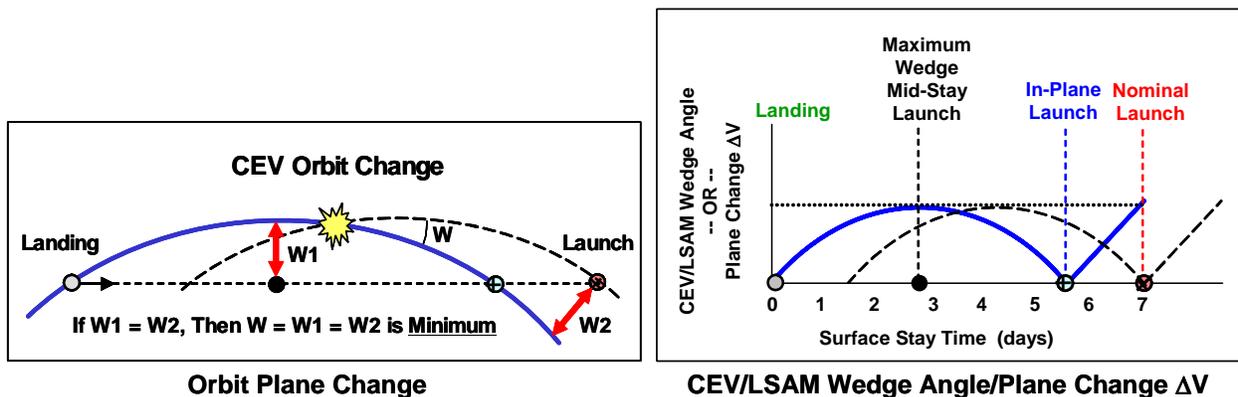

Figure 7-1: Comparison of CEV orbit plane change and corresponding magnitude of plane change wedge angle and associated plane change ΔV for a 7-day Lunar surface stay.

This technique applies to any surface stay time. The example used in this report reflects a maximum surface stay time of 7 days. This technique also could be applied to surface stays greater than 7 days, though it tends to be less effective as a mission design strategy for longer surface stay times (about 10 to 11 days or longer). If a long-duration sortie mission with an early return capability were desired, an alternate mission design strategy may be more appropriate. The next sections provide a detailed description of the calculation of the LOI inclination and LAN targets.

7.2   Computation of Inclination

The outbound Lunar sortie LOI inclination and LAN targets can be computed using the following algorithm. This algorithm assumes that the full motion of the landing site relative to the CEV parking orbit is due to the Lunar rotation rate combined with the nodal precession rate of the orbit due to J_2 (only). Figure 7-2 shows a representation of the CEV parking orbit at the beginning of the Lunar surface stay. Figure 7-2 shows the CEV parking orbit containing the Lunar landing site, supporting an in-plane LSAM descent to the surface; however, for a surface mission, the LOI arrival targets (inclination and LAN) would be offset from this position to allow for checkout loiter time prior to the LSAM landing. The diagram also shows that, upon landing, the landing site moves to the right, relative to the CEV parking orbit. The wedge angle (W) between the CEV orbit and the LSAM ascent orbit is maximized prior to the halfway point in the surface stay and also at the end of the surface stay (i.e., liftoff). This maximum wedge angle is minimized for the overall mission if it is equal at both points (i.e., near the midpoint and at the end of the mission at liftoff).
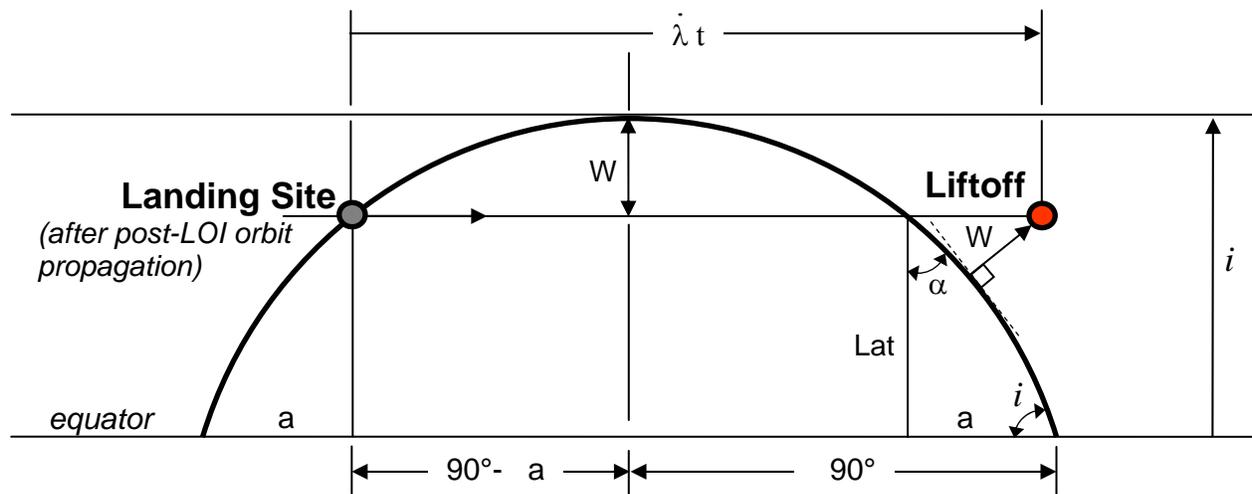

Figure 7-2: CEV LOI inclination target (i).

The determination of the inclination (i) for a given landing site latitude (Lat) and given a surface stay time (t) and net movement of the landing site ($\dot{\lambda}\,t$), relative to the CEV parking orbit over

that surface stay time, is an iterative process. Initially, this process employs an initial guess of the CEV parking orbit inclination (i) and employs the following equations to generate a mismatch between the initial guess and the maximum orbit latitude (W+ Lat) which, in a selenocentric frame, should be equal to the CEV parking orbit inclination.

$$A = \sin(\text{Lat}) \cos(\text{Lat}) (1 - \cos(\dot{\lambda} t)) \tag{1}$$

$$B = \cos(\text{Lat}) \sin(\dot{\lambda} t) \tag{2}$$

$$\sin(\alpha) = \cos(i) / \cos(\text{Lat}) \tag{3}$$

$$W = \sin^{-1}(\,|(A \sin(\alpha) - B \sqrt{(1 - \sin(\alpha)^2)}\,|\,) \tag{4}$$

Compute the mismatch between the CEV parking orbit inclination and the maximum latitude in the parking orbit.

$$f = |\,i - (W + \text{Lat})| \tag{5}$$

The mismatch (f) and the resulting wedge angle (W) are iterated until the mismatch is driven below a preselected error tolerance. This process converges on a minimized maximum wedge angle (W) between the CEV and LSAM ascent orbit and the inclination of the CEV at the time it contains the Lunar surface landing site (i.e., on LSAM descent and the beginning of the surface mission).

Note that the wedge angle, obtained from the above-described iterative process, reflects a posigrade inclination. This wedge angle corresponds also to a retrograde orbit inclination, obtained by taking the difference between the posigrade inclination and 180° (i.e., retrograde inclination = 180° - posigrade inclination).

When the CEV inclination and the associated maximum on-orbit wedge angle are computed, the corresponding LSAM ascent orbit inclination can be determined. In the ESAS mission design, the CEV performs an on-orbit plane change into an LSAM ascent orbit plane with this LSAM inclination target (see Figure 4-3). Subsequently the LSAM performs an in-plane launch and rendezvous with the CEV. The magnitude of the CEV on-orbit plane change is determined by the time it is executed during the Lunar surface stay. In this formulation, the plane change occurs at the line of common node of the current CEV orbit and the anticipated LSAM post-ascent orbit[7]. This placement of the maneuver minimizes the orbit plane change ΔV requirement and, in the general case, results in both an orbit node and inclination change.

The difference between the CEV inclination at LSAM descent and the corresponding LSAM ascent inclination, shown in Figure 7-3, is a minimum for equatorial or polar orbits and a

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[7] In a detailed mission design, the CEV sets up the in-plane time and the LSAM, through yaw steering, sets up a phantom plane used in its rendezvous maneuver.

maximum in the mid-latitude region. The CEV parking orbit has an inclination magnitude slightly higher (posigrade orbits) or lower (retrograde orbits) than the landing site latitude. This provides that the landing site is in the CEV orbital plane twice during a surface mission.
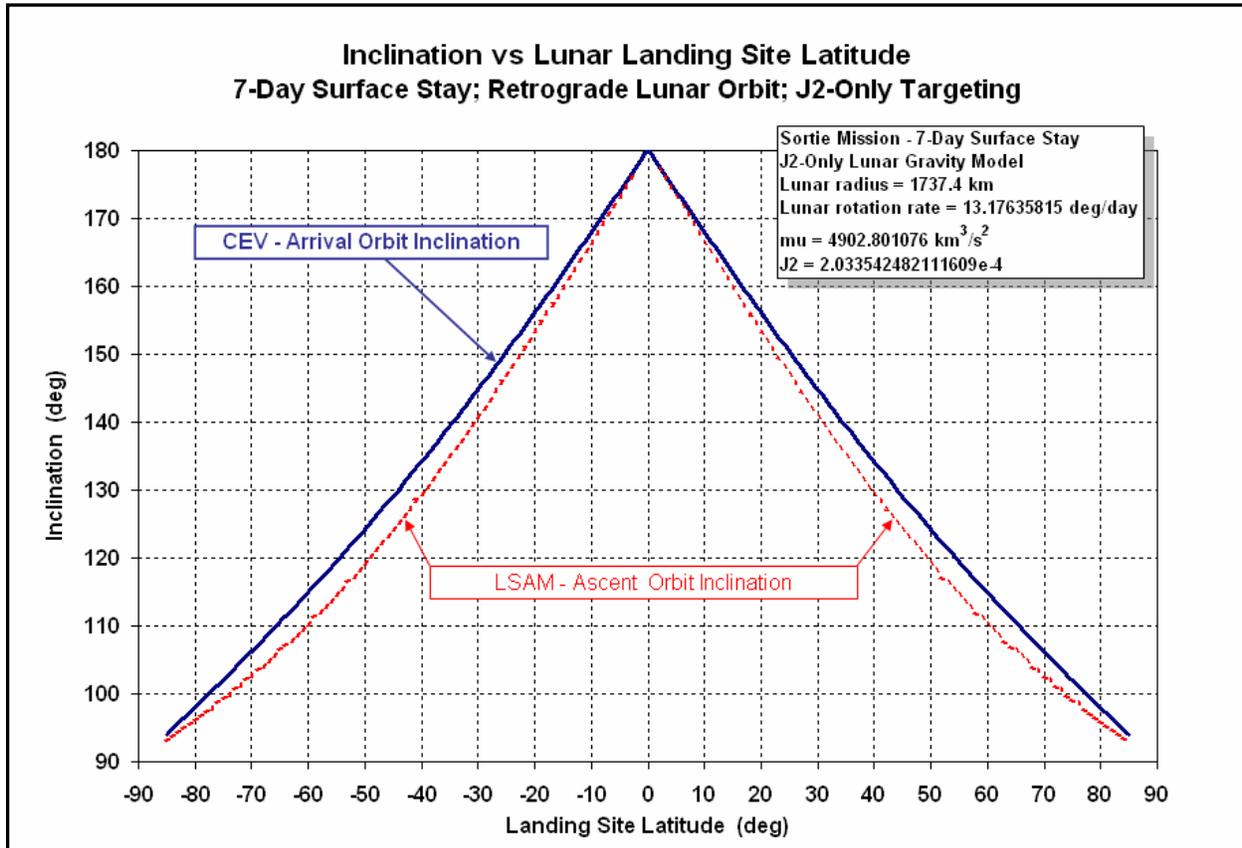

Figure 7-3: CEV retrograde orbit inclination and corresponding LSAM
ascent inclination for a 7-day Lunar surface mission.

For a J_2-only gravitational environment, the inclination will be independent of a landing site longitude; however, if higher order Lunar gravity terms are used in the propagation environment, the actual early return or end of mission CEV/LSAM wedge angle will differ from the J_2-only based prediction. The J_2-only approach provides a reasonable assessment of the wedge angle size and associated performance requirement, CEV inclination, and LSAM inclination target for a selectable surface mission duration (in this case, 7 days). There does not currently exist an analytic iterative approach for determining CEV LOI inclination targets for high-order Lunar gravity models. These targets can be numerically determined at the expense of greater computational demands. Figure 7-4 shows that the analytical (J_2-only Lunar gravity) approach reveals a maximum plane change wedge angle requirement of about 5.9°. For a 100-km circular Lunar orbit altitude, the associated on-orbit plane change would cost about 168.2 m/s. A more detailed numerical optimization employing a 50x50 resolution of the LP150Q Lunar gravitational model results in a slightly higher wedge angle of about 6.2° with an associated

plane change cost of 177 m/s (Reference 3). In both cases, the maximum wedge angles occur in the mid-latitude regions near 45° latitude.
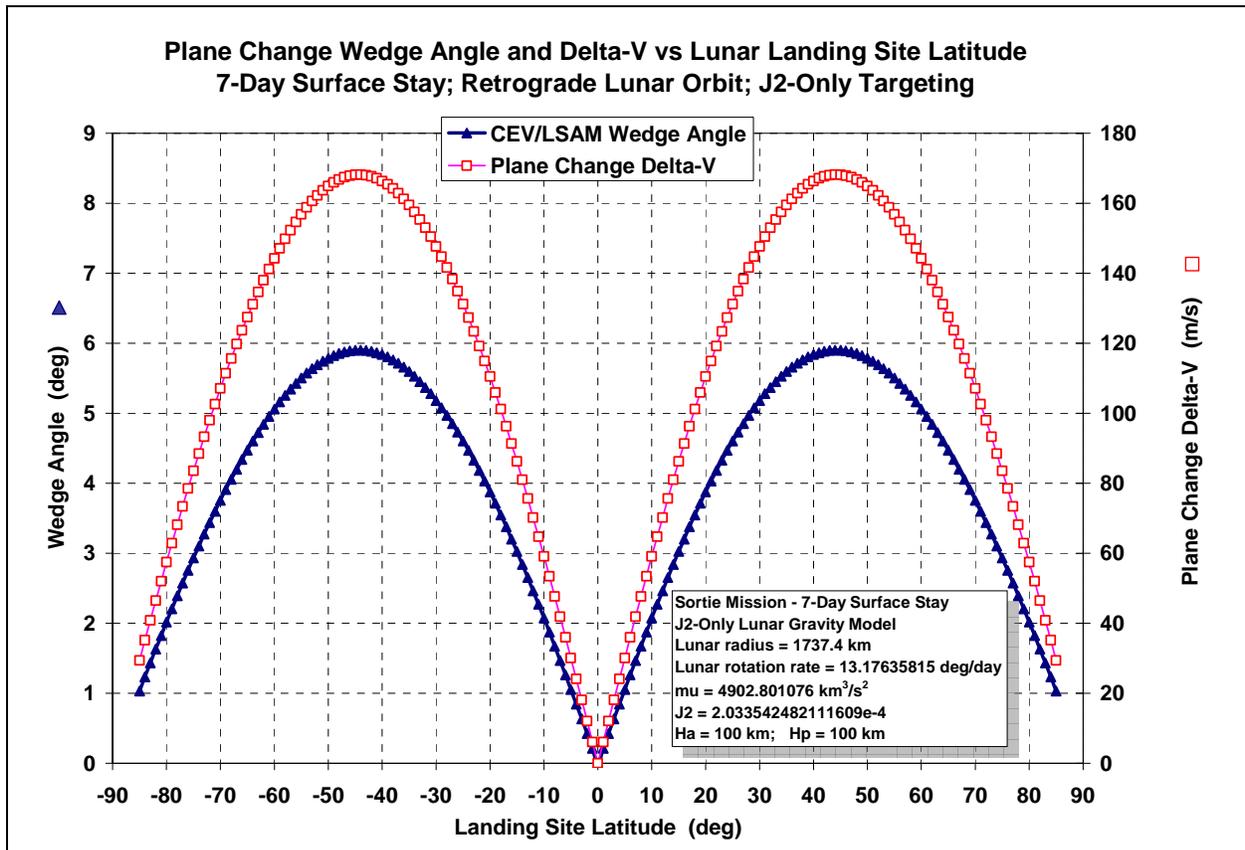

Figure 7-4: Plane change wedge angle and associated ΔV as a function of
Lunar landing site latitude for a 7-day surface mission.

7.3   Computation of LAN

After the CEV parking orbit inclination has been established, the LAN associated with a given landing site can be determined to support an in-plane LSAM landing. Computation of the CEV parking orbit LAN is dependent on several factors, including CEV orbit inclination, landing site latitude and longitude, and surface stay time.

For manned missions the retrograde orbit is preferred, as it provides a lower propellant requirement for outbound aborts back to Earth. While powered descent and ascent are more expensive for retrograde orbits than posigrade, this cost is small (Reference 8).

When the CEV arrival inclination for a given landing site latitude and longitude has been determined, it can be used to calculate the LAN of the arrival orbit. In Figure 7-5, a retrograde CEV orbit contains the landing site, thus posturing the LSAM for an in-plane landing. The figure reflects LAN calculations for landing sites in the northern and southern hemispheres. This

figure depicts the LAN at the time of LSAM deorbit. Practically speaking, the mission planner must offset the arrival LAN (using the Lunar rotation rate and orbit precession) to allow post-LOI loiter time for the crew to reconfigure and check out the spacecraft for powered Lunar descent. LOI inclination and LAN targeting must accommodate these offsets.
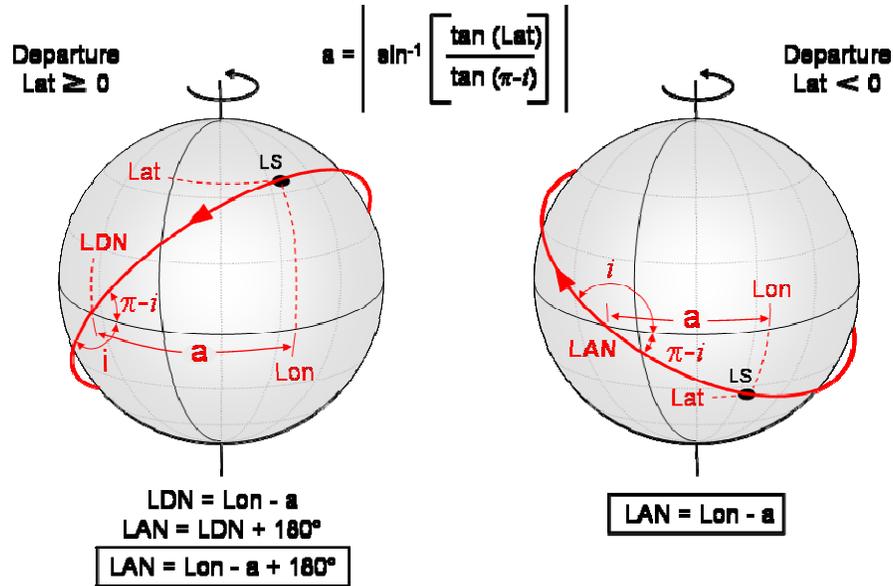

Figure 7-5: ARRIVAL: Northern and southern latitude LAN calculations given inclination (*i*) and Landing Site (LS) latitude (Lat) and longitude (Lon), for a retrograde CEV parking orbit at the time of an in-plane LSAM descent.

The LOI LAN targets, as a function of selenographic landing site latitude and longitude, are shown in Figure 7-6. The LOI LAN target is offset such that the CEV/LSAM stack achieves the desired (anytime ascent) LAN target at the conclusion of the 1-day post-LOI loiter. After the post-LOI loiter period, the LSAM performs an in-plane descent to the surface.
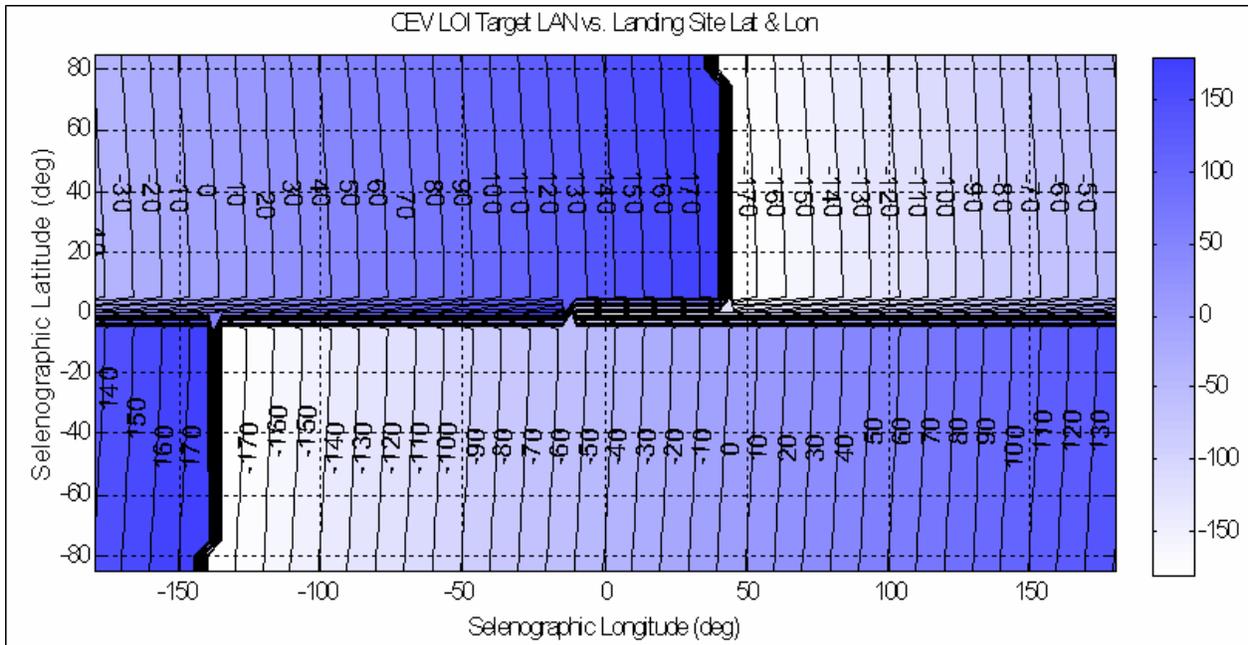
Figure 7-6: CEV pre-TEI LAN targets versus selenographic latitude and longitude.

After determination of the LSAM inclination target (discussed in section 7.2), the LSAM post-ascent/rendezvous LAN can be calculated. Figure 7-7 shows the LAN calculation for a retrograde orbit. After the LSAM achieves the inclination and LAN targets at CEV/LSAM docking, an on-orbit loiter begins, allowing for operations activities, crew transfer from the LSAM to the CEV, and pre-TEI checkout. This parking orbit serves as the point of departure for the TEI burn sequence.
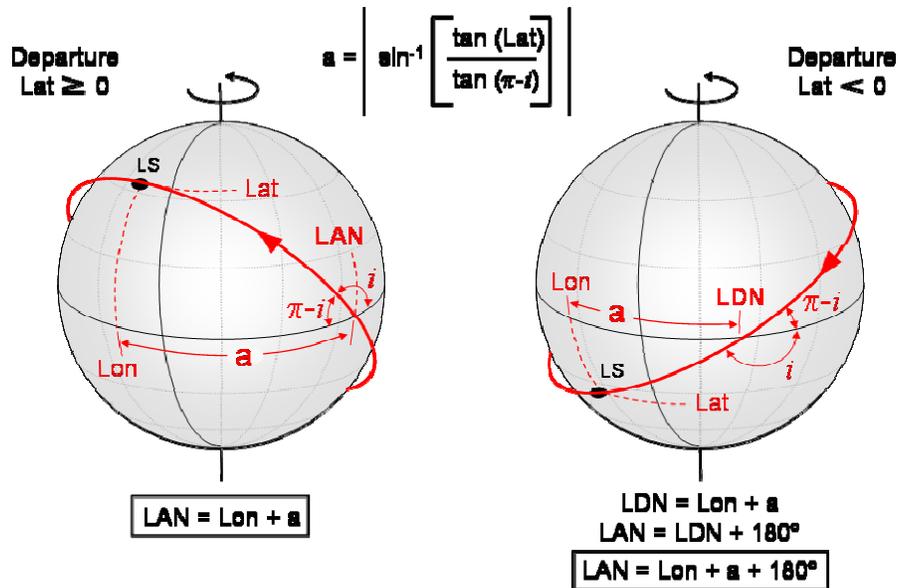
Figure 7-7: DEPARTURE: Northern and southern latitude LAN calculations given inclination (*i*) and LS lat and lon, for a retrograde CEV parking orbit at the time of an in-plane LSAM ascent.

The LSAM ascent LAN targets, as a function of landing site selenographic latitude and longitude, are shown in Figure 7-8. These LAN targets are related to the LOI LAN targets, given the assumptions (e.g., surface stay time, loiter times, landing site latitude and longitude) in this report. In this case, the LAN target supports a minimum required CEV on-orbit wedge angle change to support an in-plane LSAM ascent.
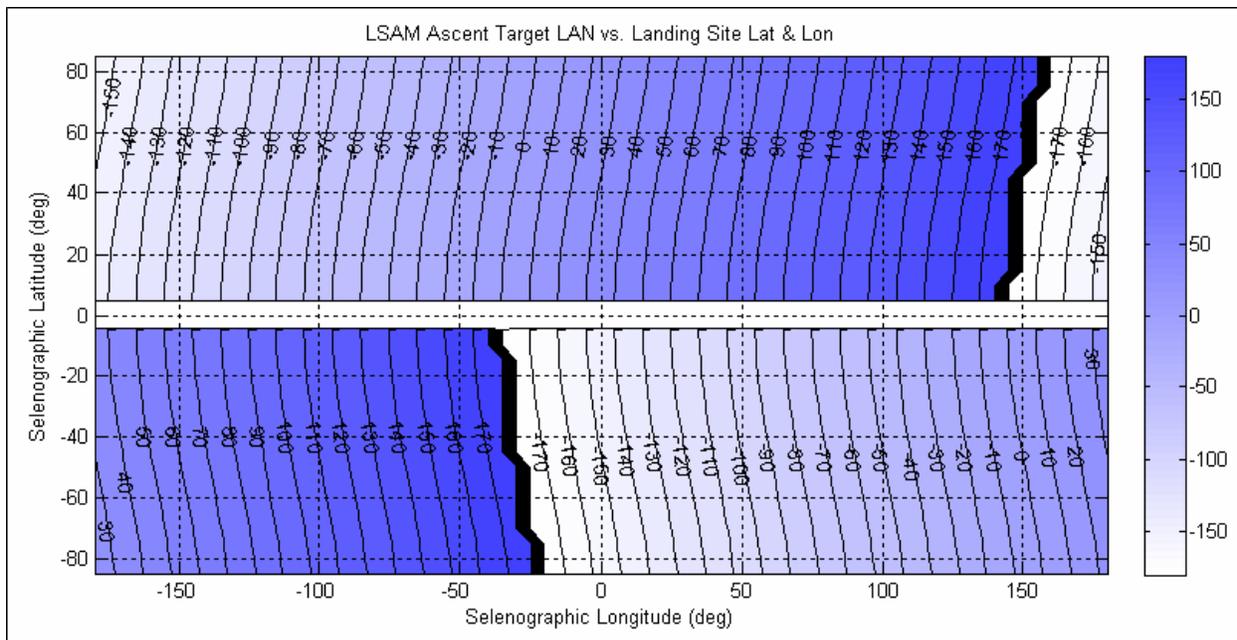
Figure 7-8: CEV LSAM ascent LAN targets versus selenographic latitude and longitude.

8.0   ANALYSIS RESULTS

The iterative-analytic approach (described in section 7.0) was used to develop LOI inclination and LAN targets for given landing site latitudes and longitudes. The inclination was used to provide performance (ΔV) requirements for a minimized worst-case plane change associated with a given landing site latitude[8]. Further, it provided a worst-case plane change requirement of 5.9° for any global access latitude. For a pure plane change maneuver at a 100 km (54 nm) Lunar orbit altitude, this 5.9° plane change carries a ΔV cost of 168.2 m/s (551.8 ft/s). For the J_2-only gravity model, this plane change cost is independent of the landing site longitude (see Table 8.1, first column).

In the approach described in this report, the highest gravity term used was the J_2 zonal harmonic. Unlike the Earth J_2, which represents the dominant perturbation to the central force term, the Lunar J_2 plays a lesser role in the possible perturbation of orbits. Subsequent analysis (Reference 3) explored the plane change performance cost when applying a high-order Lunar gravity model to the mission design. Generating the LOI inclination and LAN targets for a 7-day surface stay at specific landing sites using the J_2 gravity approach and integrating that post-LOI A CEV state using a 50x50 order LP150Q Lunar gravity model (Reference 7) produced a global worst-case end-of-mission plane change angle of 7.1° (see Table 8.1, second column) at the end of the surface stay. This 7.1° plane change carried a ΔV cost of 202.3 m/s (663.7 ft/s). This plane change angle is about 1.2° higher than the predicted 5.9°, obtained using the J_2-only technique (and when the CEV orbit also is propagated in a J_2-only environment). Application of high-order integration to a J_2-only target set can result in plane changes even greater than 7.1° during the midpoint of the mission (Reference 3).

Further inspection of this result shows that if the CEV post-LOI state is integrated into a high-fidelity gravity field (LP150Q, 50x50), the initial inclination and LAN targets could be modified slightly to reduce the required CEV on-orbit plane change (as shown in the third column of Table 8.1). If the inclination and LAN are adjusted to minimize the maximum plane change occurring at any time during the 7-day surface stay, the overall worst-case plane change for this case can be reduced to 6.2°, with an associated ΔV cost of 176.7 m/s (579.7 ft/s). This is accomplished by adjusting the LOI inclination and LAN to equalize the midpoint and end-of-mission plane changes (see Figure 7-1) for a given surface stay[9].

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[8] For inclination targets generated using only J_2 Lunar gravity perturbations, the required on-orbit plane change angle (needed to set up an in-plane LSAM launch) is independent of the landing site longitude. If a higher Lunar gravity model is used for propagation of the CEV orbit, the landing site longitude will affect this plane change angle.

[9] The technique applies to any surface stay time. In the case of this report, the surface stay time is 7 days.

TABLE 8.1: PLANE CHANGE WEDGE ANGLE AND ASSOCIATED ΔV COST

	Targeting with J_2 Lunar gravity	Targeting with J_2 Lunar gravity	Refine (optimize) original J_2-based inclination LAN targets using (50x50) LP150Q Lunar gravity
	Propagation with J_2 Lunar gravity	Propagation with (50x50) LP150Q Lunar gravity (Reference 3)[10]	Propagation with (50x50) LP150Q Lunar gravity (Reference 3)
Plane change	5.9°	7.1°	6.2°
ΔV	551.8 ft/s (168.2 m/s)	663.7 ft/s (202.3 m/s)	579.7 ft/s (176.7 m/s)
Latitude	44.2°	46°	46°
Longitude	Independent	10°	10°

9.0   RECOMMENDATIONS AND CONCLUSIONS

The targeting technique described in this report provides post-LOI CEV parking orbit inclination and LAN targets associated with given Lunar landing site latitudes and longitudes. These targets include such mission design features as loiter time from completion of LOI to LSAM descent and surface stay time. Additionally, this technique can provide the inclination and LAN targets for an in-plane LSAM ascent and rendezvous following an on-orbit CEV plane change. A trajectory determination program can take these targets and provide corresponding TLI/LOI ΔV vectors. This capability allows mission planners to quickly assess mission designs for various Lunar landing sites and for various mission parameters, including (but not limited to) surface stay time, epoch of arrival, post-LOI loiter time, flight time, and landing site latitude and longitude.

From the perspective of the performance assessment, the iterative-analytic (J_2-only) LOI inclination and LAN targeting provides the mission planner with a quick performance assessment and comparison for (CEV) plane change and associated ΔV estimates. It provides a general view of the locations of hard-to-achieve (i.e., higher ΔV) landing sites.

This technique provides targets very quickly, as compared to numerical methods, and serves well for large comparative performance analysis scans. It provides a good scan-friendly mission design capability for quickly assessing many possible Lunar missions. This "lay of the land" scan capability can direct the mission planner to areas of interest for further analysis with higher-order tools.

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[10]The 7.1° maximum wedge angle occurs at the end of a 7-day mission. The mid-mission value could be larger. With proper selection of the LOI inclination and LAN, however, this wedge can be reduced to the 6.2° shown in the last column.

It is recommended that the analytic technique described herein be employed for comparative scan studies that require many run cases in a relatively short time and that can accommodate mid-level fidelity results. For such specific mission designs as design reference missions and actual mission designs, a target set employing higher fidelity Lunar gravity models should be employed.

10.0 REFERENCES

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APPENDIX A – ACRONYM LIST

ΔV	delta-velocity
CARD	Constellation Architecture Requirements Document
CEV	Crew Exploration Vehicle
CLV	Crew Launch Vehicle
EDS	Earth Departure Stage
EG	Aeroscience and Flight Mechanics Division (organization code)
EI	Earth Interface
EOLO	Earth Orbit to Lunar Orbit
ESAS	Exploration Systems Architecture Study
FAM	Functional Area Manager
IAU	International Astronomical Union
JSC	Johnson Space Center
LAN	Longitude of the Ascending Node
Lat	Latitude
LDO	Lunar Destination Orbit
LEO	Low Earth Orbit
LLO	Low Lunar Orbit
LOEE	Lunar Orbit to Earth Entry
LOI	Lunar Orbit Insertion
Lon	Longitude
LS	Landing Site
LSAM	Lunar Surface Access Module
NASA	National Aeronautics and Space Administration
SBU	Sensitive But Unclassified
TCM	Trajectory Correction Maneuver
TDS	Task Description Sheet
TEI	Trans-Earth Injection
TLI	Trans-Lunar Injection