EARTH TO MOON TRANSFERS
DIRECT VS VIA LIBRATION POINTS (L1, L2)

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Libration Point Missions

Earth-Moon L1
- Gateway station
  - Sorties to the Moon
  - Satellite deploy, servicing
    - Next Generation Space Telescope
    - Terrestrial Planet Finder
  - Staging area for interplanetary and asteroid missions

Earth-Moon L2
- Robotic relay satellites
- Communications relay
- Navigation aid

Sun-Earth L2
- Human missions to extend human presence in space
Expeditionary vs. Evolutionary

**Expeditionary**
- Single mission or mission set
- Completed mission satisfies mission objectives
- Close-ended missions

**Evolutionary**
- Ongoing missions
- Open-ended missions on which other missions can build
- Greater initial capital investment

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**Expeditionary**
- Apollo
- Skylab
- Apollo-Soyuz Test Project
- Columbus’ voyage of discovery to the new world

**Evolutionary**
- International Space Station program
- Voyages of Prince Henry the Navigator of Portugal
Earth-Moon L1 – Gateway for Lunar Surface Operations

- Celestial park-n-ride
- Close to home (3-4 days)
- Staging to:
  - Moon
  - Sun-Earth L2
  - Mars
  - Asteroids
  - ...
Lunar Mission: Libration Point vs. LOR

Mission Scenario Advantages

**Earth-Moon L1**
- No lunar departure injection window
- Global lunar access
- Reusability
- Protection from failed station-keeping
- Specialized vehicle design

**Lunar Orbit Rendezvous (LOR)**
- Shorter mission duration
- Lower overall ΔV cost
- Fewer critical maneuvers required

Apollo-Style Mission Characteristics – Nominal Profile

- Start with modified Apollo-style sortie mission having lunar surface stay time ≤ 5 days, expendable LM, and lunar orbit rendezvous after ascent from the surface.
- Short stay in low-altitude earth parking orbit after launch from Cape Canaveral
- Nominal 4-day transit time between earth and moon (outbound & inbound)
  - No free return, but
  - Nonstop abort capability with LOI or LM descent stage
- **Low-latitude** lunar landing site
- Park CSM in 100 km lunar orbit
- Return to directly to earth surface after rendezvous with CSM
Require Polar Landing Site

- Require surface stay time ≥ 14 days at a **polar** site; anytime abort to CSM
- Necessitates polar orbit at moon
- Establishes 14-day interval between minimum-ΔV \( TEI \) opportunities
  - Necessitates extra CSM consumables for 14-day pre-\( TEI \) loiter in lunar orbit, or
  - Necessitates extra ΔV for \( TEI \) plane change for 90° worst case
    - ΔV cost = 1167 m/s for 3-impulse departure
    - ΔV cost = 2223 m/s for 1-impulse departure

Require Global Lunar Surface Access

- Require access to **any** site on lunar surface
  - Takes away anytime-return to CSM, or
  - Necessitates extra ΔV for ascent plane change (≥ 2565 m/s for 90° worst case)
Require Reuse of LM and Descent Propulsion Stage

- Require re-use of LM and its descent/ascent propulsion stage
  - Necessitates a higher parking orbit altitude and/or extra ΔV for long-term LM orbit maintenance
  - Necessitates an additional lunar orbit rendezvous between CSM and LM before DOI (except for the very first flight, which establishes the LM orbit).
  - Establishes 14-day interval between minimum-ΔV LOI opportunities after the first flight

Observation re: Added Constraints to Direct Mission vs. L1-Based Mission

- Observe that, after adding all the new constraints:
  - the round-trip ΔV and time requirements for rendezvous at L1 are comparable (maybe lower) than what is needed for rendezvous in lunar orbit, and
  - with rendezvous at L1, these requirements are essentially independent of the coordinates of the landing site
Require Earth Departure from ISS Orbit

- Require earth departure from ISS orbit
  - Limits minimum-ΔV TLI opportunities to about 3 per month
  - Combined with the 14-day interval between minimum-ΔV LOI opportunities described previously, this
    - Necessitates extra CSM consumables for 14-day loiter in lunar orbit between LOI and DOI, or
    - Necessitates extra ΔV for LOI plane change for 90° worst case
      - ΔV cost = 1167 m/s for 3-impulse departure
      - ΔV cost = 2223 m/s for 1-impulse departure

Observation re: Direct vs. L1-Based Lunar Mission Profiles

- Observe that the time and ΔV requirements for a round trip utilizing L1 rendezvous vary only slightly within any month. This is in stark contrast to the requirements for lunar orbit rendezvous with a reusable LM, and it makes a big difference in the stability of operational schedules for such missions if they are to be launched from an ISS orbit.
Earth Orbit to Lunar Orbit

Via Direct Transfer, Lunar Swing-by, or Stopover At Librational Points

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</table>

2 major maneuvers

4 major maneuvers

5 major maneuvers

Earth Orbit to Lunar Orbit (28.5 deg. Inclination)

Direct vs. Via L1

(3-Impulse LOI, TEI)

Lunar Transfer - L1 Stopover vs. Direct (Apollo-Style)

(3-Impulse LOI, TEI)

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Earth Orbit to Lunar Orbit (28.5 deg. Inclination)
Direct vs. Via L1 (3-Impulse LOI, TEI)

Direct Lunar Transfer vs. Lunar Transfer via L1 Stopover

<table>
<thead>
<tr>
<th>Transfer Scenario</th>
<th>L1 Stopover</th>
<th>Direct</th>
<th>Direct to Polar Site</th>
<th>Direct with Global Landing Access</th>
<th>Direct with Reverse of Landing/Ascend Spacelabcraft</th>
<th>Direct Leasing From ISB</th>
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<tr>
<td>Earth Orbital Departure</td>
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Nominal minimum DV mission with no sovereign or requirement violations

- Stay time > 14 hr to ensure landing orbit rendezvous
- Requires leaving landing/ascend orbit in lunar orbit
- ORS lease
- Timeline
- Required departure from ISB

Earth orbit to lunar orbit via L1, 81 deg.
L1 stopover at L1

Earth orbit to 80 deg. lunar orbit (100 km) Min. DV, 11/09
Earth orbit to 90 deg. lunar orbit (100 km) Min. DV, 11/09
Earth orbit to 90 deg. lunar orbit (100 km) Min. DV, 11/09
Earth orbit to 90 deg. lunar orbit (100 km) Min. DV, 11/09

Earth orbit/L1 transfer time = 84 hours. 81 deg. plane change at L1

L1-lunar orbit transfer time is optimized for min. DV (Range = 50-113 hours)
Earth Orbit to Lunar Orbit (28.5 deg. Inclination) Direct vs. Via L1 Stopover

Direct Lunar Transfer vs. Lunar Transfer via L1 Stopover

Assumptions:
- Direct mission with increasing constraints/requirements.
- All LOI and TEI plane change maneuvers use a 1-impulse sequence
- 28.5 deg. initial orbit for L1 transfer
- All mission return direct to surface

Order of increasing mission constraints (constraint are cumulative):  
- Earth Orbit Departure
- L1 Arrival, 84 hour stay
- Delta Plane Penalty
- Lunar Orbit Departure
- Delta Plane Penalty
- L1 Arrival, 84 hour stay
- Delta Plane Penalty
- Earth Orbit Departure
- Delta Plane Penalty
- Total

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<thead>
<tr>
<th>Transfer Scenario</th>
<th>L1 Stopover</th>
<th>Direct</th>
<th>Direct to Polar Site</th>
<th>Direct with Global LANDING Access</th>
<th>Direct with Reuse of Lander/Ascendent Spacecraft</th>
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Nominal minimum DV mission with no constraint or requirement
- Earth orbit to Lunar orbit via L1, 81 deg, 100 km
- Earth orbit to Lunar orbit (100 km) in 11000 hrs
- Earth orbit to Lunar orbit (100 km) in 11000 hrs
- Earth orbit to Lunar orbit (100 km) in 11000 hrs
- Earth orbit to Lunar orbit (100 km) in 11000 hrs

Earth Orbit to Lunar Orbit (51.6 deg. Inclination) Direct vs. Via L1 Stopover

Lunar Transfer - L1 Stopover vs. Direct (Apollo-Style) (3 Impulse LOI, TEI)

- L1 Departure
- L1 Arrival
- L1 Stopover
- Direct to Polar Site
- Direct with Global LANDING Access
- Direct with Reuse of Lander/Ascendent Spacecraft
- Direct Leaving From ISS
- Earth Orbit Dep.
- Earth orbit-L1 transfer time = 84 hours. 81 deg. plane change at L1
- L1-lunar orbit transfer time is optimized for min. 1\(\nu\)

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**Earth Orbit to Lunar Orbit (51.6 deg. Inclination)**

**Direct vs. Via L1 (3-Impulse LOI, TEI)**

**Direct Lunar Transfer vs. Lunar Transfer via L1 Stopover**

<table>
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<tr>
<th>Transfer Scenario</th>
<th>L1 Stopover</th>
<th>Direct</th>
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**Lunar Transfer - L1 Stopover vs. Direct (Apollo-Style) (1-Impulse LOI, TEI)**

- **L1 Departure**
- **L1 Arrival**
- **LOI Plane Penalty**
- **Lunar Orbit Departure (LOD)**
- **Lunar Orb. Maint./Rend.**
- **Lunar Orb. Maint./Rend.**
- **Lunar Orb. Maint./Rend.**
- **LOI Plane Penalty**
- **L1 Arrival**
- **Earth Orbit Dep.**

Earth orbit-L1 transfer time = 84 hours. 81 deg. plane change at L1.
**Earth Orbit to Lunar Orbit (51.6 deg. Inclination)**

**Direct vs. Via L1 (1-Impulse LOI, TEI)**

### Direct Lunar Transfer vs. Lunar Transfer via L1 Stopover

**Assumptions:**
- Direct mission with increasing constraints/requirements.
- All LOI and TEI plane change maneuvers use a 1-Impulse sequence.
- 1-Impulse LOI initial orbit for L1 transfer.
- All missions return direct to parking orbit.

#### Order of Increasing Missions Constraints (increment are cumulative):

<table>
<thead>
<tr>
<th>Transfer Scenario</th>
<th>L1 Stopover</th>
<th>Direct</th>
<th>Direct to Polar Site</th>
<th>Direct with Global Landing Access</th>
<th>Direct with Rescue of Landing失败/Deploy spacecraft</th>
<th>Direct Landing From ISS</th>
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</tbody>
</table>

#### Nominal minimum DV mission with no constraints or requirements
- Stay time ≥ 14 days
- About anytime to lunar parking orbit attendance
- Requires lunar landing/landing a/se in lunar orbit. OPER.
- Return to ISS. TIMELINE issue.
- Return departure from ISS plane.

| Earth orbit to lunar orbit via L1, 81 deg. LOI | 3068        | 3068   | 3068                 | 3068                             | 3068                                           | 3068                   |
| Earth orbit direct to 90 deg, lunar orbit (100 km) | 1/1/09    | 1/1/09 | 1/1/09               | 1/1/09                           | 1/1/09                                          | 1/1/09                 |
| Earth orbit direct to 90 deg, lunar orbit (100 km) | 1/1/09    | 1/1/09 | 1/1/09               | 1/1/09                           | 1/1/09                                          | 1/1/09                 |
| Earth orbit direct to 90 deg, lunar orbit (100 km) | 1/1/09    | 1/1/09 | 1/1/09               | 1/1/09                           | 1/1/09                                          | 1/1/09                 |
| Earth orbit direct to 90 deg, lunar orbit (100 km) | 1/1/09    | 1/1/09 | 1/1/09               | 1/1/09                           | 1/1/09                                          | 1/1/09                 |

**Total Mission ∆V**

**L1 Stopover vs. Direct (Apollo Style)**

1-Impulse, 3-Impulse LOI, TEI

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**Lunar Transfer - L1 Stopover vs. Direct (Apollo-Style)**

- Earth orbit-L1 transfer time = 8-16 hours. 81 deg. plane change at L1
- L1-lunar orbit transfer time is optimized for min. ∆V (Range ≈ 80/133 hours)
- 28.5, 51.6 deg. Earth departure parking orbit

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Effect of Lunar Parking Orbit Inclination on Lunar Transfer Opportunities → Moon to Earth Transfer

Plane Change ΔV Penalties For Returning From Lunar Site
Additive to co-planar transfer ΔV requirement

Sum of Rendezvous and TEI Plane Change Penalties for Worst Combination of Parking Orbit Node Location and Longitude (Moon to Earth)

*For return leg only, does not include possible LOI and descent plane change penalties
Lunar Transfer/Orbit Diagrams

Trans-Lunar Trajectories

TLI plane determined by the space station position at departure (TLI) and the Moon at arrival
Trans-Earth Trajectories

TET plane determined by Moon at departure (TEI) and the space station position at arrival.

Parking Orbit Considerations

Laser Parking Orbit

Reference: J. Condon

Jerry Condon | JSC/EGS / 201-453-8173 | jerald condol1@nasa.gov
Landing Latitude Restrictions

Lunar descent & landing generally occur in rendezvous orbit plane.

Region of sustainable landing sites.

In-plane Lunar ascent & rendezvous available every 27 days.

Region of sustainable landing sites.

Rendezvous orbit remains nearly fixed, locally.

Variable Lunar Inclination

VERY SMALL MANEUVER

Lunar Orbit

Earth Plane

Variable Lunar Inclination Reference:

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Variable Lunar Orbit Alignment

Additional Charts
Earth-Moon L1 to Lunar Orbit

Total $\Delta V$ vs. Trip Time
Maximum and Minimum $\Delta V$ Cost for Lunar Orbit to Earth-Moon L1 Transfer

Lunar Lat. = 90 deg., Lon = 0 deg.

Lunar Lat. = 0 deg., Lon = 0 deg.

Transfer from/to a 100 km circular lunar orbit to Earth-Moon L1, oriented to provide a powered departure from/arrival at a particular surface latitude and longitude.

Inertial Earth Entry Speed vs. Earth-Moon L1 to Earth Transfer Orbit Flight Time

Inertial Earth Entry Speed vs. Flight Time

Moon at Apoeee

Moon at Perigee

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Inertial Earth Entry Speed vs. Earth-Moon L1 to Earth Transfer Orbit Inclination

Inertial Earth Entry Speed vs. Transfer Orbit Inclination (w.r.t. Earth-Moon Plane), 82 hour transfer

Moon at Apogee

Moon at Perigee

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Joey Broome# – STK/Astrogator validation/movie
Sam Wilson+ – software development / analysis
Daniel M. Delwood † – analysis

* JSC Co-op  # JSC Engineer  + Elgin Software, Inc.
Outline

- Introduction
- Expeditionary vs. Evolutionary Missions
- Libration Point Transfer Vehicle (LTV) Kickstage Disposal Options
- Geocentric Orbit Lifetime
- Conclusion

Introduction

The notion of human missions to libration points has been proposed for more than a generation.

A human-tended Earth-Moon (EM) libration point (L1) Gateway Station could support an infrastructure expanding human presence beyond low Earth orbit and serve as a staging location for human missions to:

- The lunar surface
- Mars
- Asteroids, comets
- Other libration point locations (NGST, TPF)
- ...

The Gateway concept supports an Evolutionary vs. Expeditionary approach to exploration...
Expeditionary vs. Evolutionary

**Expeditionary**
- Single mission or mission set
- Completed mission satisfies mission objectives
- Closed-end missions

**Examples**
- Apollo
- Skylab
- Apollo-Soyuz Test Project
- Columbus "voyage of discovery to the new world"

**Evolutionary**
- Ongoing missions
- Open-end missions on which other missions can build
- Greater initial capital investment

**Examples**
- International Space Station program
- Voyages of Prince Henry the Navigator of Portugal
- The man chiefly responsible for Portugal's age of exploration
• Celestial park-n-ride
• Close to home (3-4 days)
• Staging to:
  - Moon
  - Sun-Earth L2
  - Mars
  - Asteroids
  - ...

Gateway Operations – LTV Kickstage Disposal

• Ongoing Gateway operations require robust capability for delivery & retrieval of a crew
• Human occupation of the Gateway Station requires a human transfer system in the form of a Libration Point Transfer Vehicle (LTV) designed to ferry the crew between low Earth orbit and the Gateway Station.

A key element of such a system is the proper and safe disposal of the LTV kickstage
1. Identify concepts concerning the role of humans in libration point space missions

2. Examine mission design considerations for an Earth-Moon libration point (L1) gateway station

3. Assess delta-V ($\Delta V$) cost to retarget Earth-Moon L1 Gateway-bound LTV spacecraft kickstage to a selected disposal destination

Options considered for LTV kickstage disposal:

1. Lunar Swingby to Heliocentric Orbit (HO)
2. Lunar Vertical Impact (LVI), typifies any lunar impact
3. Direct Return to Remote Ocean Area (DROA)
4. Lunar Swingby to Remote Ocean Area (SROA)
5. Transfer to Long Lifetime Geocentric Orbit (GO)
Methodology

Evaluation Timeframe - 2006 Mission Year Chosen
- Survey two week period of L1 arrivals yielding max (80.2°) and min (23.0°) plane changes ever possible at L1 for crewed spacecraft
  - 28.6° lunar orbit inclination; coplanar departure from 51.6° ISS orbit
  - Moon goes from perigee to apogee during the chosen 2-week period; begins and ends on the equator

Combine max and min plane changes with arrivals at L1 perigee and apogee by looking at both choices of arrival velocity azimuth (northerly and southerly) for every arrival date (requires arbitrary ISS orbit nodes)

Methodology (continued)

HO, LVI, DROA, SROA, and GO maneuver times designed to minimize ΔV for stage disposal subject to imposed constraints
- Solutions considered to be a practical attempt to minimize these maneuver ΔVs (e.g.: coplanar kickstage deflection maneuver assumed optimal for some disposal options) and not rigorous global optimizations Analysis

Analysis Tools
- Earth Orbit to Lunar Libration (EOLL) scanner*
  - Four-body model
    - Earth, moon, sun, spacecraft
    - Jean Meeus's analytic lunar and solar ephemerides
  - Overlapped conic split boundary value solutions individually calibrated to multiconic accuracy
- Validation with STK/Astrogator

* Developed and updated by Sam Wilson
Option 1. Lunar Swing-By to Heliocentric Orbit (HO) JSC

1. Libration Point Transfer Vehicle (LTV) spacecraft with Kickstage in initial 401 x 401 km parking orbit

2. Kickstage injects spacecraft & kickstage onto transfer trajectory toward L1

3. Coast phase; Kickstage jettison

4. Jettisoned kickstage performs maneuver to achieve close encounter with moon

5. Spacecraft arrives at L1

6. Kickstage flies behind trailing limb of Moon to achieve geocentric C3=0 (hence departure from Earth-Moon system)

Nominal crew vehicle trajectory to Earth-Moon L1:
- Trip time = 3.5 days (84 hours)
- Braking maneuver at L1

Video

Option 1. Lunar Swing-By to Heliocentric Orbit (HO) JSC Video

P07aHCKS LLA Position
- Time (UTC): 1853:03:03.00
- Lat (deg): 32.353
- Lon (deg): 85.619
- Alt (km): 563.97
- Lat Rate (deg/sec): -0.000769
- Lon Rate (deg/sec): -0.0033179
- Alt Rate (km/sec): 3.0105275

3 Oct 2009 1853:03:03  Time Step: 30 sec
Option 1. Lunar Swing-By to Heliocentric Orbit (HO)

- Advantages
  - No Earth or Lunar disposal issues (e.g., impact location, debris footprint, litter)
  - Relatively low disposal ΔV cost
- Disadvantages
  - Heliocentric space litter (kickstage heliocentric orbit near that of the earth)
  - Periodic possibility of re-contact with Earth
**Option 2. Lunar Vertical Impact (LVI)**

1. Lunar Transfer Vehicle (LTV) spacecraft with Kickstage in initial 407 x 407 km parking orbit

2. Kickstage injects spacecraft & Kickstage onto transfer trajectory toward L1

3. Coast phase, Kickstage jettison

4. Jettisoned kickstage performs maneuver to achieve lunar impact

5. Spacecraft arrives at L1

6. Kickstage impacts Lunar surface

---

**Video**

- 6 Oct 2023 19:03:39
- Time Day: 30:30 sec
Option 2. Lunar Vertical Impact (LVI)

Advantages
- No Earth disposal issues (e.g., impact location, debris footprint, litter, possible recontact)

Disadvantage
- Lunar litter
- Relatively high disposal ΔV cost
Option 3. Direct Return to Remote Ocean Area (DROA)

Entry flight path angle = -20° selected
- Confines surface debris footprint

Impact latitude is determined by:
1. Spacecraft date of arrival at L1 and
2. Choice of northerly or southerly velocity azimuth at L1 arrival
   - From an established (e.g., ISS) earth orbit, these two degrees of freedom typically yield two or three transfer opportunities to L1 every month.

Impact longitude depends on (1.) and (2.) above, plus
3. Atmospheric entry time chosen for the kickstage
   - Minimizing the kickstage deflection ΔV determines an unique (and essentially random) impact longitude for an arbitrary transfer opportunity.

Kickstage budget gives 240 degrees of longitude control
- If kickstage disposal is not to constrain the primary mission, the kickstage ΔV budget must be sufficient to allow the impact point to be moved from its minimum-ΔV location to an Atlantic or a Pacific mid-ocean line.
- At any latitude, the maximum longitude difference between the chosen mid-ocean lines is 240 degrees (see next chart).
Option 3. Direct Return to Remote Ocean Area (DROA)

Shaded Region Contains Max Longitude Difference (240°) Between Mid-Atlantic and Mid-Pacific Target Lines
Option 3. Direct Return to Remote Ocean Area (DROA)

**Data shown represent best of two solution subtypes**
- Generally there are two local optima for the location of the kickstage maneuver point in the earth-to-L1 transfer trajectory, of which the better one was always chosen

**Advantages**
- Assuming kickstage disposal is not allowed to constrain the primary mission, this option is one of three (HO, DROA, GO) requiring the lowest ΔV budget that could be found (slightly more than 90 m/s in all three cases)
- Avoidance of close lunar encounter, combined with steep entry over wide areas of empty ocean minimizes criticality of navigation and maneuver execution errors

**Disadvantages**
- Not appropriate if kickstage contains radioactive or other hazardous material
Option 4. Lunar Swingby to Remote Ocean Area (SROA)

1. Lunar Transfer Vehicle (LTV) spacecraft with Kickstage in initial 407 x 407 km parking orbit

2. Kickstage injects spacecraft & kickstage onto transfer trajectory toward L1

3. Coast phase; Kickstage jettison

4. Jettisoned kickstage performs maneuver to achieve close encounter with moon

5. Spacecraft arrives at Earth-Moon L1

6. Kickstage passes in front of Moon’s leading limb and returns to Earth for ocean impact

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Option 4. Lunar Swingby to Remote Ocean Area (SROA)

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<th>Time (UTC)</th>
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Option 4. Lunar Swingby to Remote Ocean Area (SROA)

- Advantages
  - None identified

- Disadvantages
  - This option requires a greater ΔV budget than any other one examined.
    - The ΔV values shown are minimum values for impact at an essentially random location.
    - The ΔV required for longitude control will be even higher
  - Inherent sensitivity of this kind of trajectory is almost certain to require extended lifetime of the control system to perform midcourse corrections before and after perisel passage
Option 5. Transfer to Long Lifetime Geocentric Orbit (GO)

1. Lunar Transfer Vehicle (LTV) crew module with Kickstage in initial 407 x 407 km parking orbit

2. Kickstage injects crew module & kickstage onto transfer trajectory toward L1

3. Coast phase Kickstage jettison

4a. Jettisoned kickstage performs retargeted Earth parking orbit maneuver

4b. Alternatively, kickstage may raise perigee with maneuver at near apogee of Earth-L1 transfer orbit

5. Crew module arrives at L1

6. Kickstage continues on parking orbit
Option 5. Transfer to Long Lifetime Geocentric Orbit (GO)

Advantages
- Preferable to deliberate ocean impact if kickstage carries hazardous material
- In 4 of the 22 cases studied, the ΔV requirement for GO disposal (into an orbit having a perigee altitude of 6600 km and an apogee altitude in the range of 300000 – 370000 km) was less than 12 m/s, which is much lower than that found for any other option considered.
- Assuming the 22 cases represent an unbiased sample of all possible transfers between earth orbit and L1, this implies that a 12 m/s budget would suffice if it were permissible to forgo all but about 20% of the otherwise-available transfer opportunities.

Disadvantages
- More orbital debris in the earth-moon system
- The 12 m/s budget described above would increase the average interval between usable transfers to something like 50 days, as opposed to 10 days if transfer utilization were not allowed to be constrained by the disposal ΔV budget (which would then have to be more than 90 m/s).
- To achieve acceptable orbit lifetime, lunar and solar perturbations may necessitate a higher perigee and/or lower apogees, either of which will increase the required ΔV.
Summary Results

JSC

HO, LVI, DROA, SROA, GO Transfer Delta-V vs. Libration Point Arrival Time

\[ \Delta V \text{ Cost to Deflect LTV Kickstage from LI Target to Disposal Destination} \]

Moon at Apogee

Moon at Perigee

10/6/06 0:00 10/9/06 0:00 10/12/06 0:00 10/14/06 0:00 10/16/06 0:00 10/18/06 0:00 10/20/06 0:00

Libration Point Arrival Time (mm/dd/yyyy hh:mm)

15

10

5

0

HO = Heliocentric Orbit
LVI = Lunar Vertical Impact
DROA = Direct Remote Ocean Area
SROA = (lunar) Swingby Remote Ocean Area
GO = Geocentric (Parking) Orbit

Geocentric Orbit Lifetime Study
Geocentric Orbit Lifetime

- Spacecraft (kickstage) initial condition – Apogee of LEO to EM L1 transfer orbit
  - Apogee range: 300,000 km – 371,000 km
  - Perigee range: 6600 km – 20,000 km
- 45 test case runs
- Results
  - 56% of the test cases impacted the Earth within 10 years
  - Spacecraft cannot be left on transfer orbit
  - Further study to determine safe Apogee and Perigee Ranges

LTV Orbit Lifetime

Note: A negative lifetime indicates LTV kickstage experienced either heliocentric departure from the Earth-Moon system or Lunar impact.
## Summary

- **Recommend Direct Remote Ocean Area impact disposal for cases without hazardous (e.g., radioactive) material on LTV kickstage**
  - Controlled Earth contact
  - Relatively small disposal ΔV
  - Avoids close encounter with Moon
  - Trajectories can be very sensitive to initial conditions (at disposal maneuver)
    - ΔV to correct for errors is small
- **Recommend Heliocentric Orbit disposal for cases with hazardous material on LTV kickstage**
  - No Earth or Lunar disposal issues (e.g., impact location, debris footprint, litter)
  - Relatively low disposal ΔV cost
  - Further study required to determine possibility of re-contact with Earth