Targeting Low-Energy Transfers to Low Lunar Orbit

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Executive Summary

• This paper studies low-energy transfers between the Earth and the Moon:
  – Itinerary:
    • Depart the Earth
    • Ballistic coast of 70 – 160 days, with 0 – 2 TCMs
    • Lunar Orbit Insertion into a 100-km polar orbit
  – Given:
    • A 28.5°, 185-km LEO parking orbit,
    • A launch date,
    • An arrival date, and
    • A target 100-km polar lunar orbit.
  – Question:
    • What is the least expensive ΔV to connect the LEO and LLO orbit?
    • What is the ΔV cost to establish a 21-day launch period?
• Conventional lunar transfers are well known.

• The trade space of low-energy lunar transfers is not well known. Low-energy transfers:
  – Low-energy transfers between the Earth and Moon take advantage of the Sun’s gravity to boost the spacecraft’s energy.
  – Typically save 100 – 300 m/s or more to transfer into a 100 km low lunar orbit.
  – Flexible trajectories permit convenient launch periods, relaxed operational schedules, and avoid Van Allen Belts.

• ARTEMIS has recently taken advantage of two such low-energy transfers.
• GRAIL will launch onto a low-energy lunar transfer next month.
Motivation for Research

• Low-energy transfers: difficulties
  – No analytical methods have been found to build low-energy transfers!
  – No Patched Conic approximation
  – Time-intensive work to design one transfer. Impractical to design every contingency situation and/or extended mission.
    • Missed maneuvers
    • Missions of opportunities
    • Extended missions

• On-going research:
  – Mapping out the trade-space of low-energy transfers
  – Development of a rapid-design tool for building low-energy transfers.

ARTEMIS’ complex lunar transfer
Background: GRAIL’s Lunar Transfer

Launch
- 1st Launch Opportunity: Sept 8, 2011
  - 115 days to reach the Moon
- TLI $\Delta V$: -0.65 km$^2$/s$^2$
- TLI Inclination: 28.5°

Trans-Lunar Cruise
- Two deterministic TCMs per S/C
- 2 – 3 statistical TCMs per S/C

Lunar Orbit Insertion
- GRAIL-A 12/31/2011
- GRAIL-B 1/1/2012
- Vel @ 100 km ~ 2.30 km/s
- 100 km LOI $\Delta V$ ~ 0.67 km/s
Methodology

Targeting a low-energy lunar transfer

1. **Build the target orbit**
   - 100 km ~circular polar lunar orbit
   - Specify $\omega$ and $\Omega$

2. **Build the LOI maneuver**
   - Specify date, $t_{\text{LOI}}$
   - Specify impulsive $\Delta V$, performed at perilune

3. **Propagate backward to perigee**
   - Full DE421 ephemeris, $\leq 160$ days

4. **Build the LEO orbit**
   - 185 km ~circular 28.5° inclined LEO parking orbit
   - Specify initial guesses for $\omega$ and $\Omega$

5. **Build the TLI maneuver**
   - Specify date, $t_{\text{TLI}}$
   - Specify impulsive $\Delta V$, performed at perilune

6. **Connect TLI and LOI**
   - Add two TCMs
   - Build a bridge
   - Minimize $\Delta V$ (TCM+LOI)

8 Optimization Variables:
- LEO $\omega$ and $\Omega$
- TLI $\Delta V$ magnitude
- TCM1 and TCM2 epochs
- LOI $\Delta V$ components
Targeting Process

- Build Reference Transfer
  - Has desirable lunar orbit and LOI date
- Select launch date and LEO parking orbit
- Construct guess
- Optimize using SNOPT

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Targeted Lunar Transfer

Reference Transfer
• TLI on Apr 1\textsuperscript{st} 2010 from 38.3° inc
• TCM ΔV: 0 m/s
• LOI ΔV: 649.0 m/s

Final Transfer
• TLI on Apr 2\textsuperscript{nd} 2010 from 28.5° inc
• TCM ΔV: 24.1 m/s
• LOI ΔV: 649.1 m/s
Example Launch Period

- Targeting process repeated over 61 days
  - Reference TLI date ± 30 days
  - Each departure from a 28.5° LEO parking orbit
- Best 21-day launch period identified
Survey Data Set

- Random reference transfers selected from a large collection of simple low-energy transfers from previous paper.
- # Transfers studied: 288
- Arrive at 8 different times in a given month, between 7/11/2010 and 8/6/2010
- Reference LOI ΔV values between 640 m/s and 1080 m/s
  - Most 640 – 750 m/s
- Reference transfer durations between 65 and 160 days.
- Enforcing them all to depart from 185-km, 28.5° inclined LEO parking orbits.
Several Surveyed Launch Periods
Observations:
• 21 days may be in 1, 2, or sometimes 3 segments
• Lunar influences in outbound segment every ~28 days
• Most contain reference launch date; some don’t
• Note: gaps are required to be 14 days or less in duration
Results: Launch Period ΔV

• Range of transfer ΔV in 21-day launch period
  – Transfer ΔV = TCM1 + TCM2 + LOI

• Observations:
  – Most transfers require more ΔV than their reference (different TLI inclination)
  – Launch period ΔV requirement: 71.7 ± 29.7 m/s (1σ) more ΔV than reference.
Results: Launch Period Breadth

• Launch period $\Delta V$ as a function of # days in launch period (gaps ignored)

• Observations:
  – Large jump from 1-day to 2-day launch periods. This is due to lunar disturbances.
  – Launch period $\Delta V \approx 2.480$ m/s per launch day.
Results: Transfer Durations

• Range of transfer durations in 21-day launch period

• Observations:
  – Minimum transfer duration: 10.91 ± 7.75 days shorter than reference
  – Maximum transfer duration: 15.95 ± 8.66 days longer than reference
  – Launch period breadth: 26.86 ± 6.95 days (one-sided distribution)
Results: Transfer $\Delta V$ vs. Duration

- Launch period $\Delta V$ range as a function of the reference transfer duration.

- Observations:
  - Large range of $\Delta V$s. There are low-$\Delta V$ missions for most transfer durations.
  - Transfer $\Delta V$ climbs for transfer durations < 90 days.
Results: Transfer ΔV vs. Ref TLI Inc.

- Transfer ΔV range as a function of the reference transfer’s TLI inclination.

- Observations:
  - Little dependency of launch period ΔV on the reference TLI inclination.
  - Linear fit has a slope of 0.206 m/s per degree of inclination away from 28.5°.
  - More in the paper. Any one transfer is very dependent on TLI inclination, but the launch period is not. A 21-day launch period absorbs ΔV variations.
Summary

• 288 simple low-energy transfers surveyed.
• LEO parking orbits: 185 km, 28.5°
• Target lunar orbit: 100 km, 90°
• Each reference transfer is used to generate a 21-day launch period.

Conclusions

• Launch period ΔV requires ~2.480 m/s per launch day in the period.
  – The average 21-day launch period requires 50 m/s more ΔV than a 1-day launch period for that reference transfer.
• The average cost for a 21-day launch period for the 288 transfers studied was 71.7 ± 29.7 m/s above the reference transfer’s ΔV.
• The average launch period required 26.9 days. Majority are contained within 40 days.
• Not a significant correlation between launch period ΔV and the reference transfer’s departure inclination.
The End

Any Questions?

Acknowledgments

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