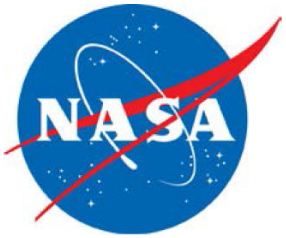
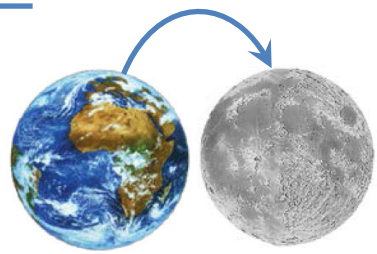
Paper AAS 11-459



Targeting Low-Energy Transfers to Low Lunar Orbit



Presented by Rodney L. Anderson

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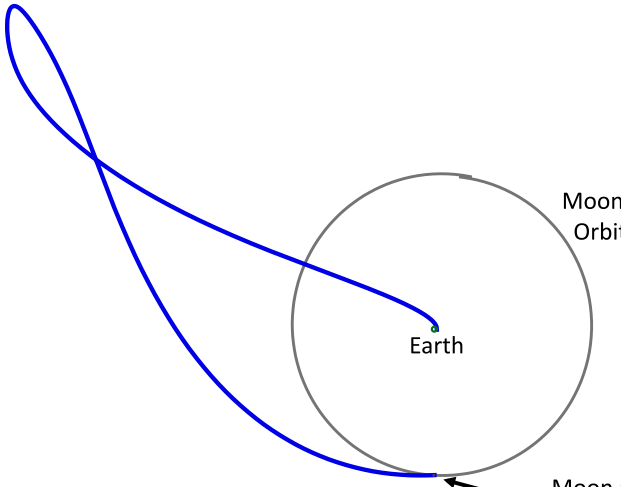
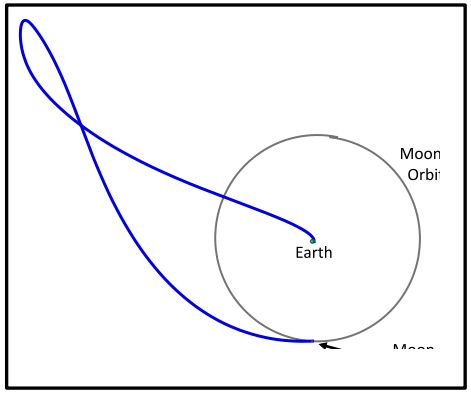
Executive Summary

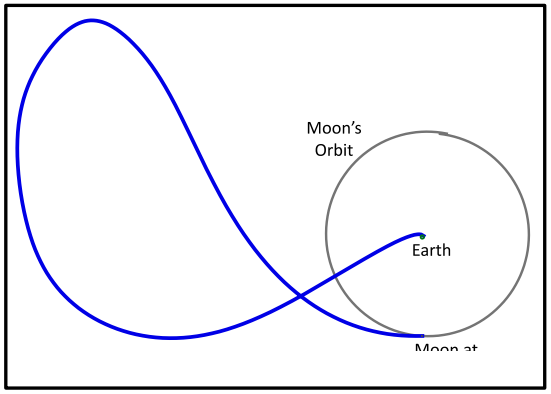
- This paper studies low-energy transfers between the Earth and the Moon:
  - Itinerary:
    - Depart the Earth
    - Ballistic coast of 70 – 160 days, with 0 – 2 TCMs
    - Lunar Orbit Insertion into a 100-km polar orbit
  - Given:
    - A 28.5°, 185-km LEO parking orbit,
    - A launch date,
    - 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?



Motivation for Research

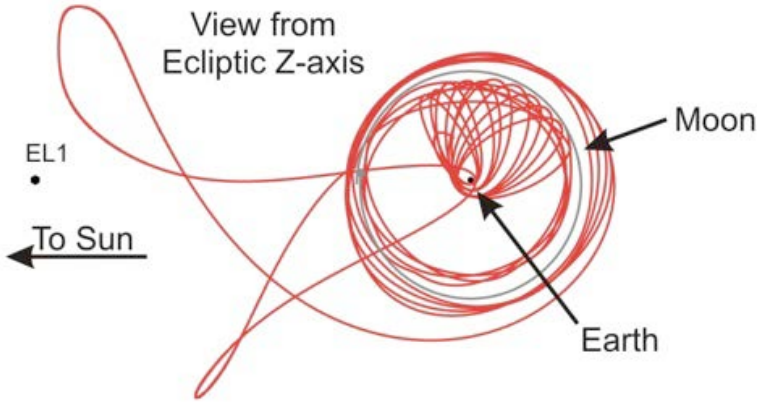
- Conventional lunar transfers are well known.
- The trade space of low-energy lunar transfers is not well known. Low-energy transfers:
  - Low-energy transfers between the Earth and Moon take advantage of the Sun's gravity to boost the spacecraft's energy.
  - Typically save 100 – 300 m/s or more to 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

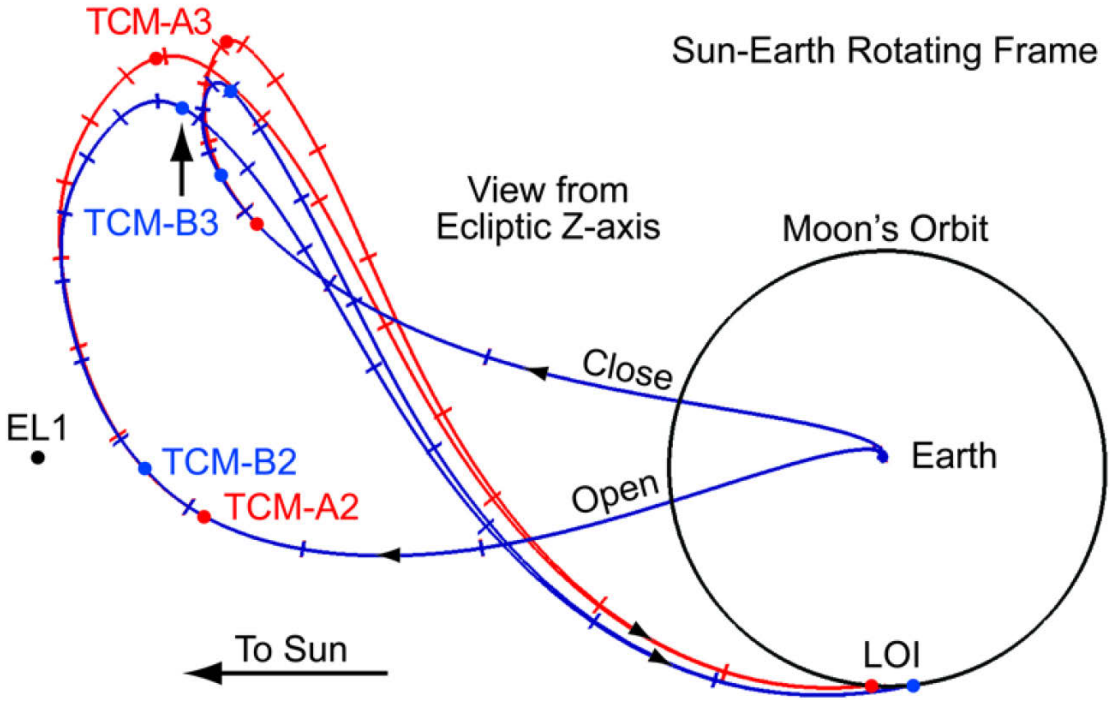
- 1st Launch Opportunity: Sept 8, 2011
  - 115 days to reach the Moon
- TLI C_3: -0.65 km^2/s^2
- TLI Inclination: 28.5°

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 ΔV ~ 0.67 km/s



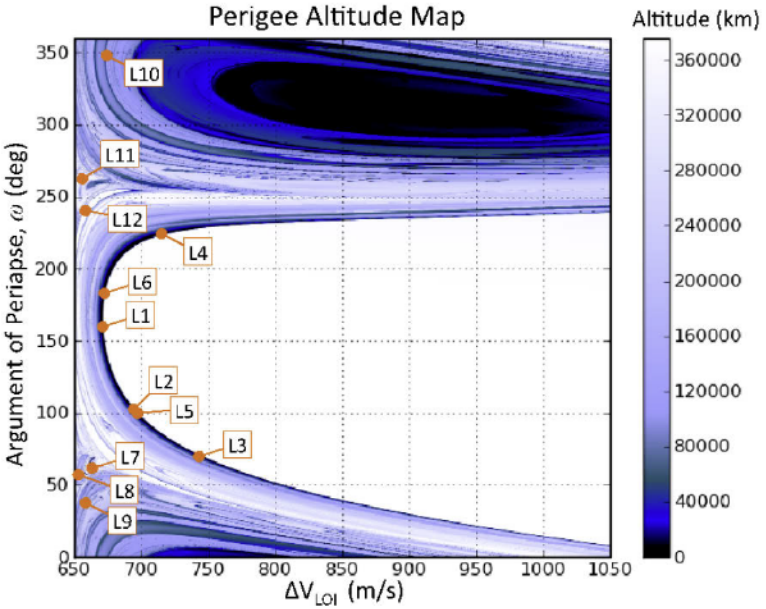
Survey of Low-Energy Lunar Transfers

Earth

Moon at Arrival

Transfer L10

sfer L11



Moon's Orbit

Earth

oon at Arrival

Transfer L6

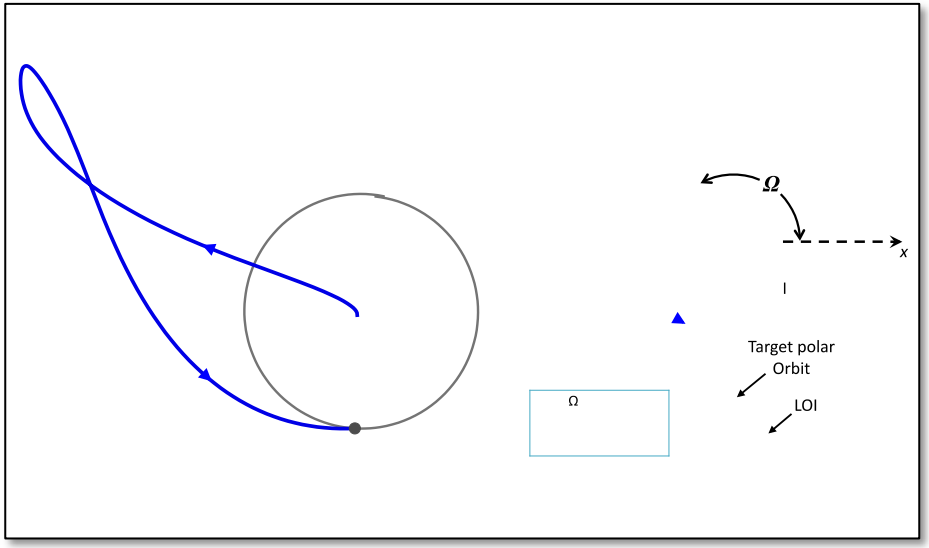
Complex Transfers

Simple Transfers

Methodology

Targeting a low-energy lunar transfer

1. Build the target orbit
   - 100 km ~circular polar lunar orbit
   - Specify ω and Ω
2. Build the LOI maneuver
   - Specify date, t_{LOI}
   - Specify impulsive ΔV, performed at perilune
3. Propagate backward to perigee
   - Full DE421 ephemeris, <= 160 days
4. Build the LEO orbit
   - 185 km ~circular 28.5° inclined LEO parking orbit
   - Specify initial guesses for ω and Ω
5. Build the TLI maneuver
   - Specify date, t_{TLI}
   - Specify impulsive ΔV, performed at perilune
6. Connect TLI and LOI
   - Add two TCMs
   - Build a bridge
   - Minimize ΔV (TCM+LOI)

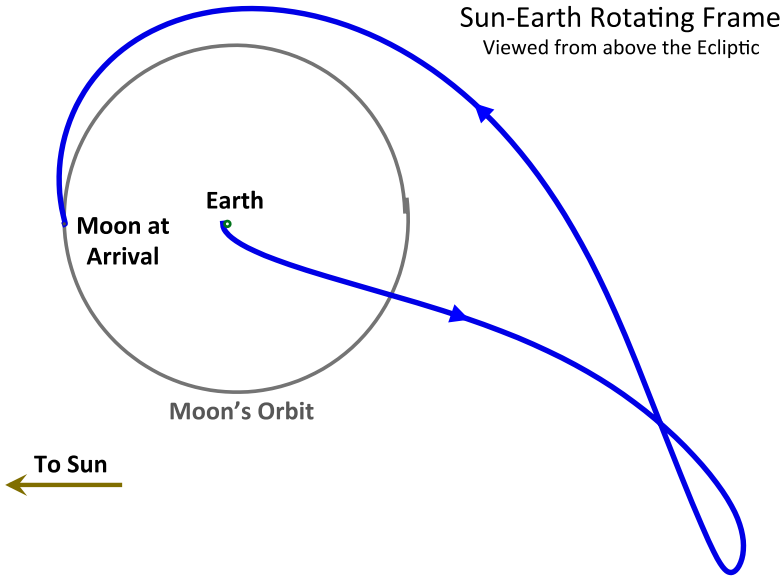


8 Optimization Variables:

- LEO ω and Ω
- TLI ΔV magnitude
- TCM1 and TCM2 epochs
- LOI ΔV 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

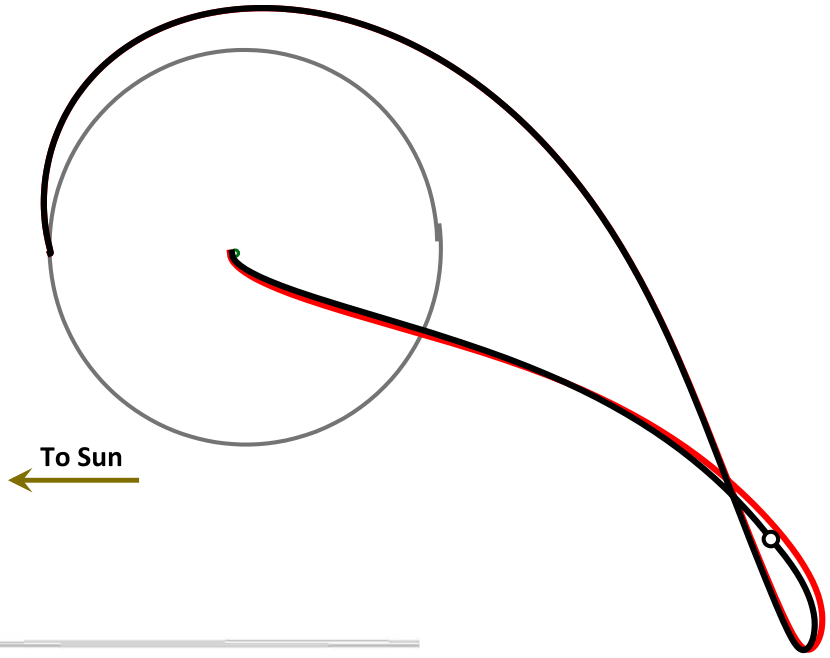


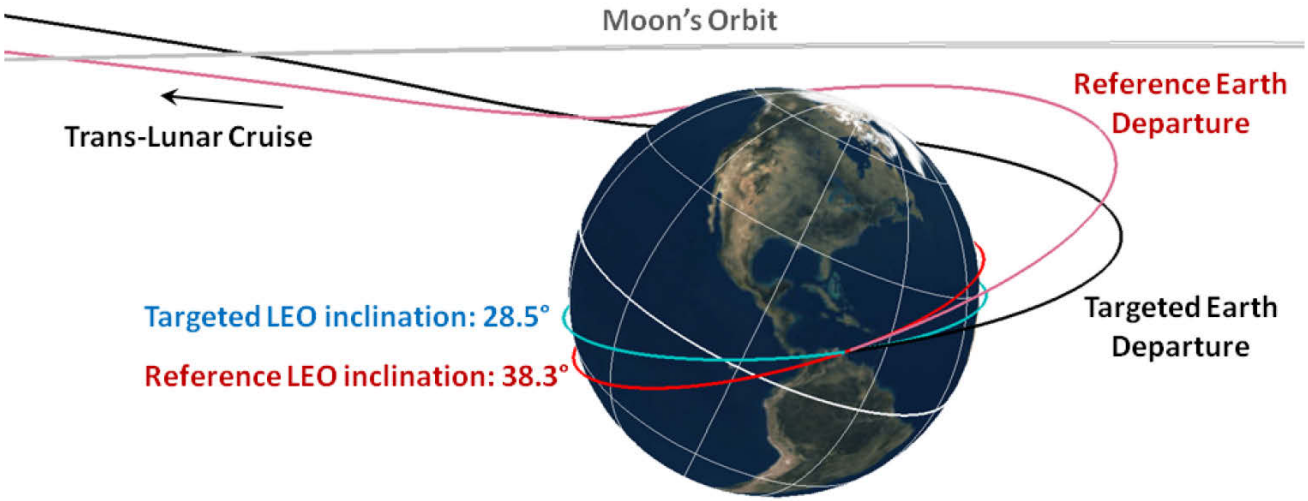
TLI Parameters			TCM1		TCM2		LOI	Total
Ω deg	ν deg	ΔV m/s	Δt days	ΔV m/s	Δt days	ΔV m/s	ΔV_x, ΔV_y, and ΔV_z m/s, EME2000	Transfer ΔV, m/s
-	-	-	-	-	-	-	-87.728, -271.090, -583.108	-
-	-	-	-	-	-	-	-87.732, -271.103, -583.138	-
0.00	0.00	3197.44	-	-	-	-	-87.732, -271.103, -583.138	-
-25.00	27.18	3196.77	-	-	-	-	-87.732, -271.103, -583.138	-
-25.00	27.18	3196.77	21.00	26.10	34.84	6.37	-87.732, -271.103, -583.138	681.500
-25.08	27.32	3196.79	20.63	24.09	34.86	0.00	-87.736, -271.118, -583.167	673.155

Targeted Lunar Transfer

Reference Transfer
- TLI on Apr 1st 2010 from 38.3° inc
- TCM ΔV: 0 m/s
- LOI ΔV: 649.0 m/s

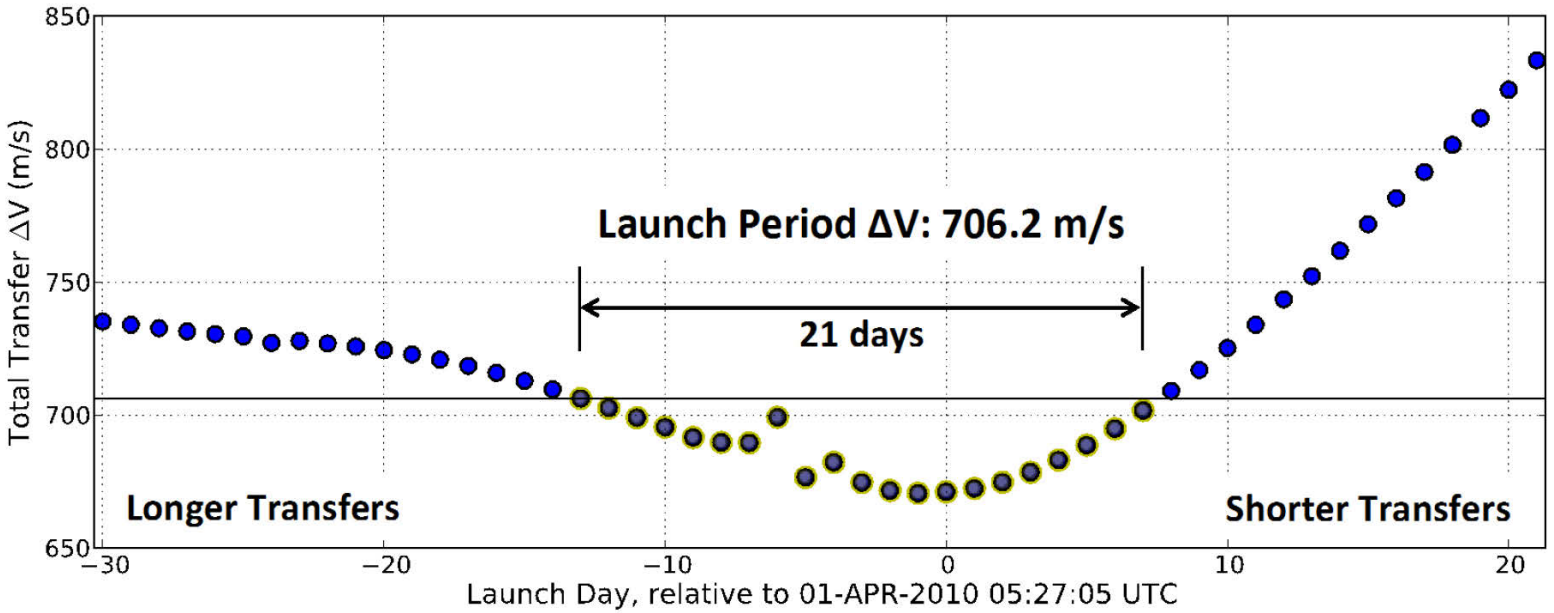
Final Transfer
- TLI on Apr 2nd 2010 from 28.5° inc
- TCM ΔV: 24.1 m/s
- LOI ΔV: 649.1 m/s

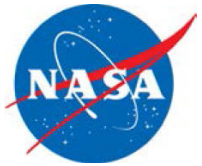




Example Launch Period

- 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



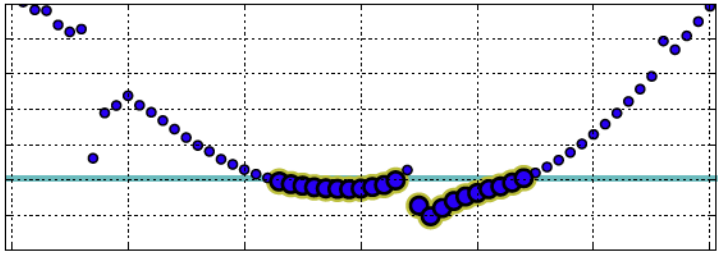


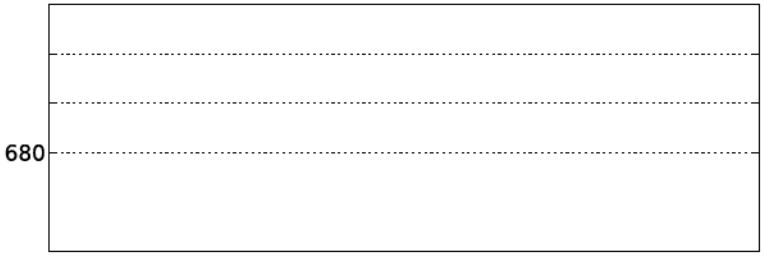
Survey Data Set

- 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

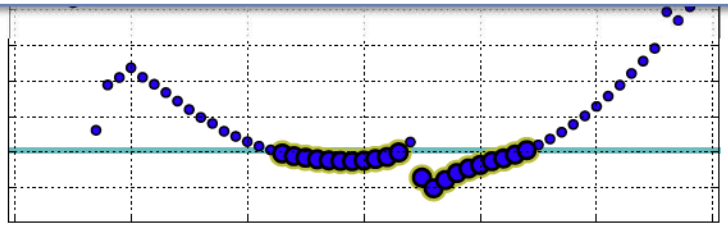


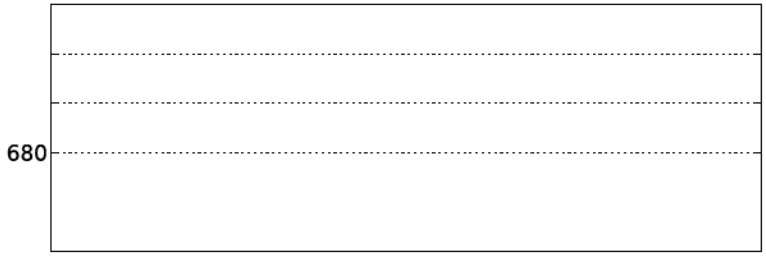


ch Periods

Observations:

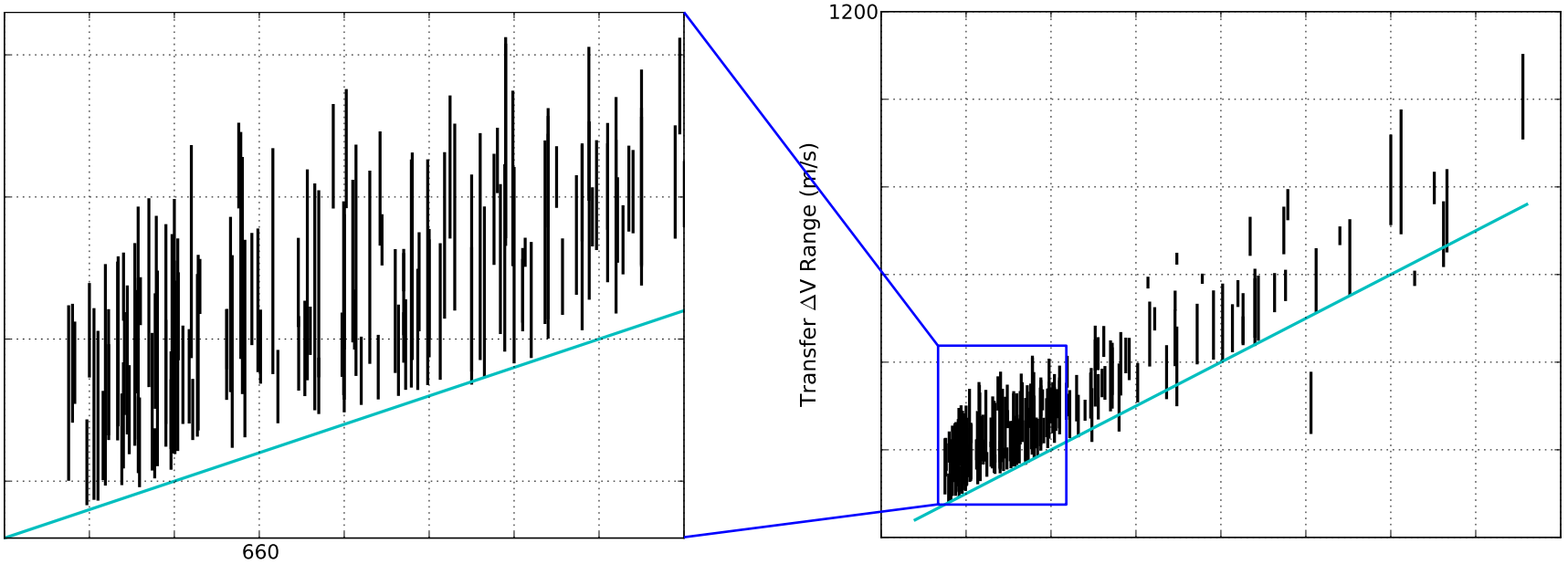
- 21 days may be in 1, 2, or sometimes 3 segments
- Lunar influences in outbound segment every ~28 days
- Most contain reference launch date; some don't
- Note: gaps are required to be 14 days or less in duration





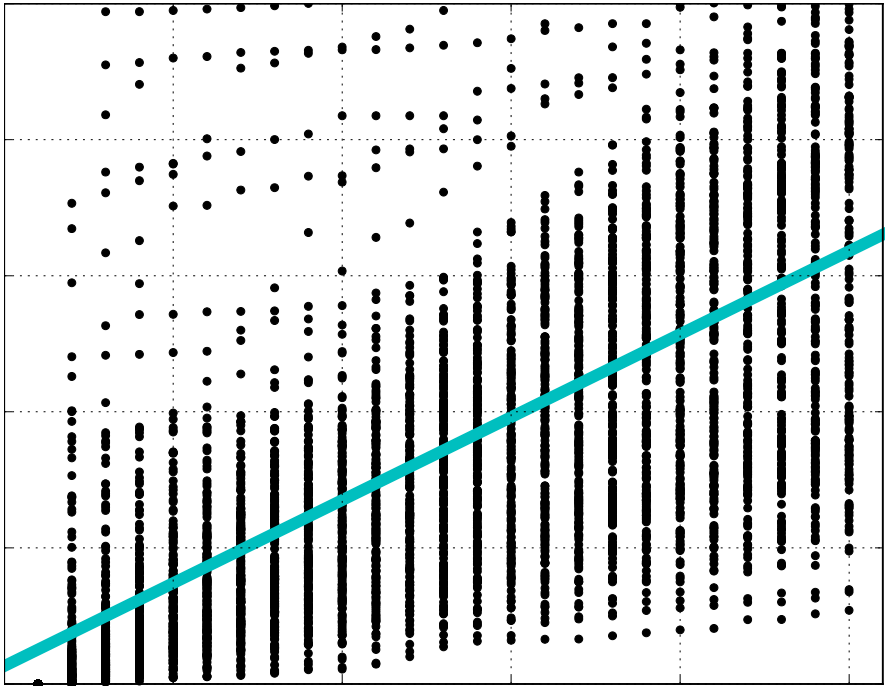
Results: Launch Period ΔV

- 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

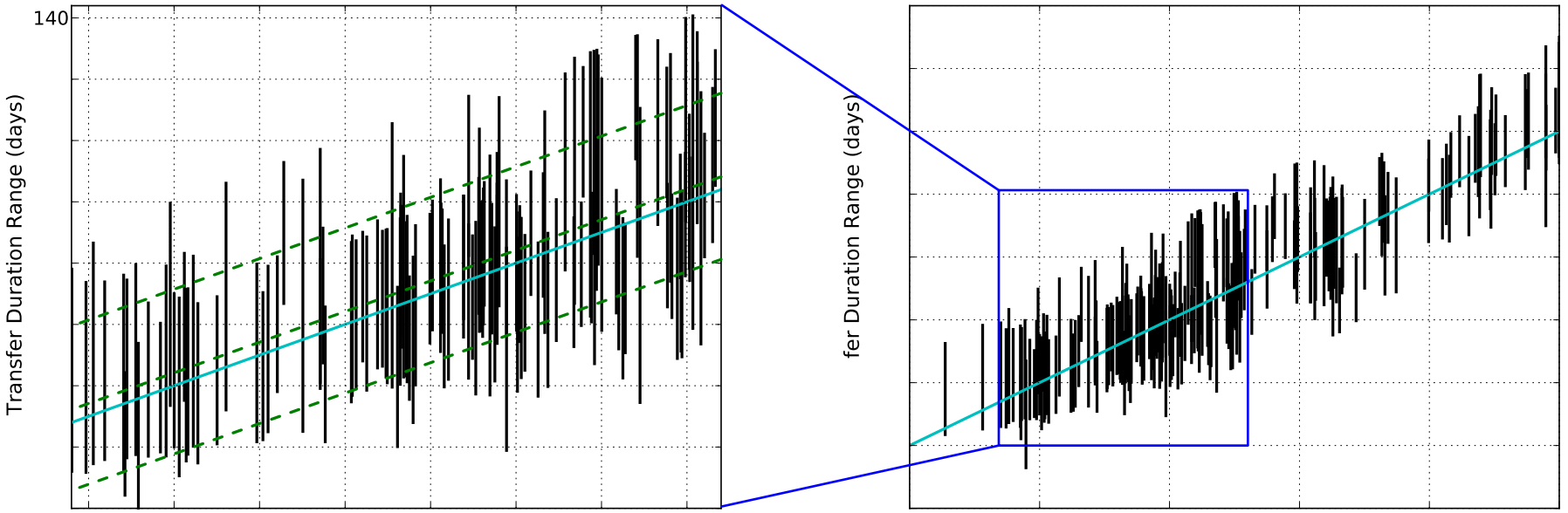
- Launch period ΔV as a function of # days in launch period (gaps ignored)
- Observations:
  - Large jump from 1-day to 2-day launch periods. This is due to lunar disturbances.
  - Launch period ΔV ≈ 2.480 m/s per launch day.



er of Days in Launch Period

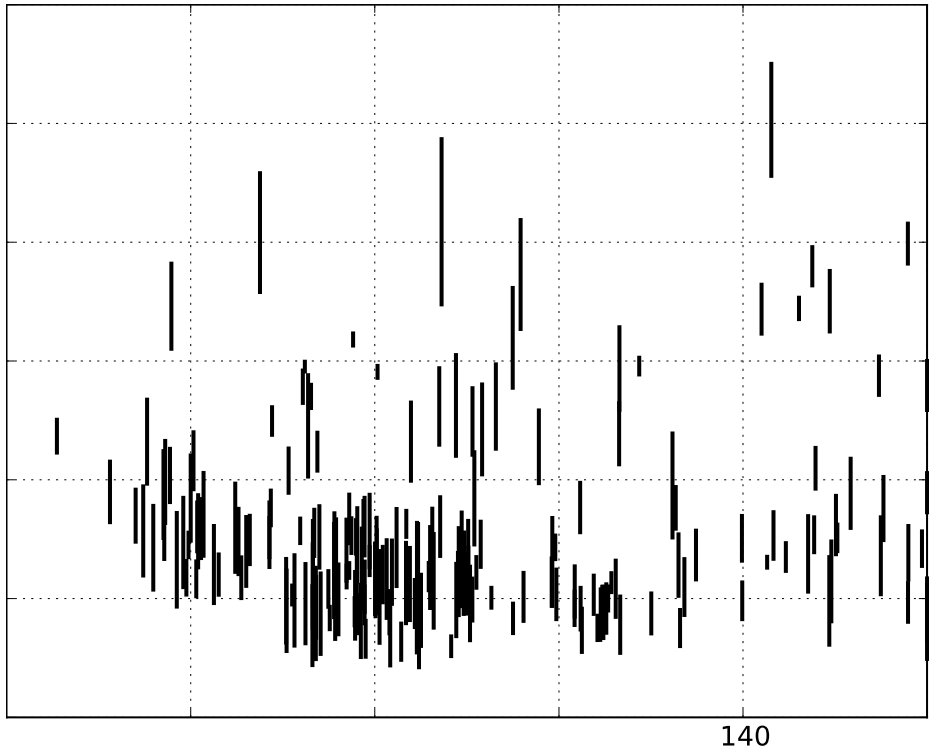
Results: Transfer Durations

- 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)



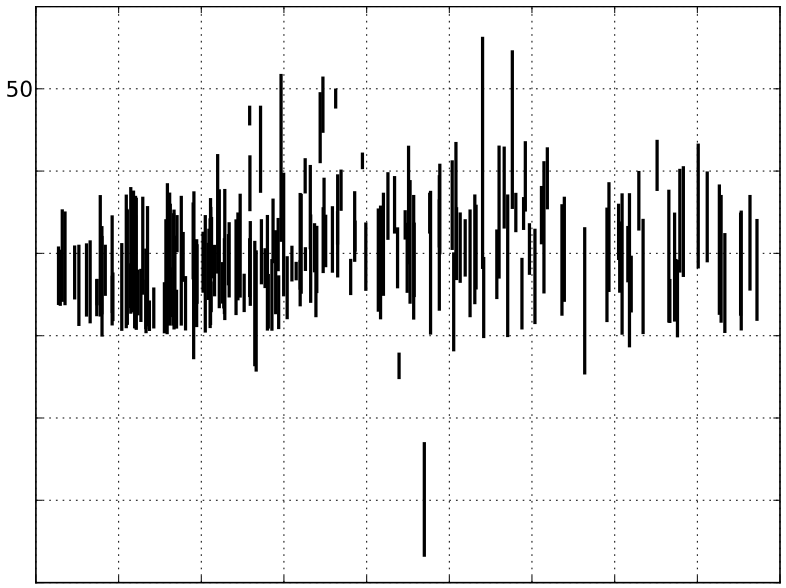
Results: Transfer ΔV vs. Duration

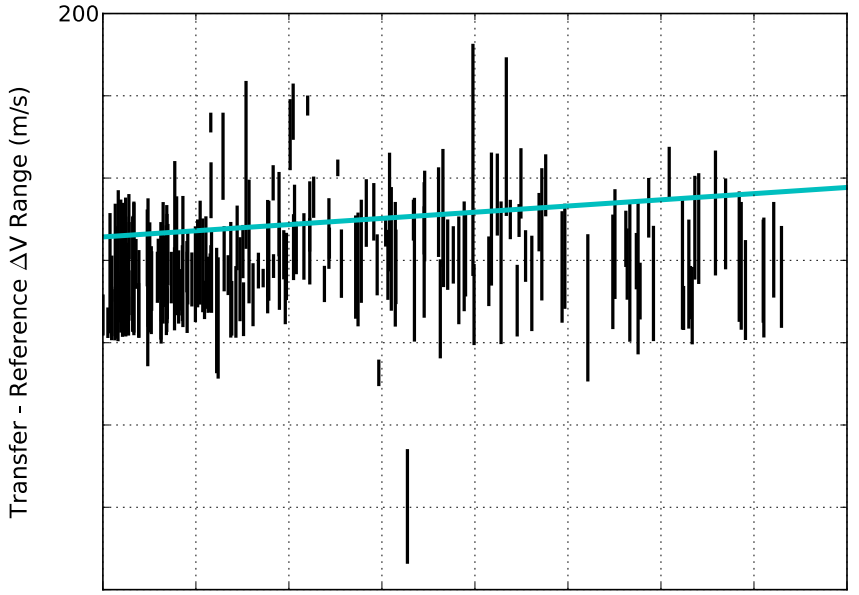
- Launch period ΔV range as a function of the reference transfer duration.
- Observations:
  - Large range of ΔVs. There are low-ΔV missions for most transfer durations.
  - Transfer ΔV climbs for transfer durations < 90 days.



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 and Conclusions

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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