EARTH TO MOON TRANSFERS

DIRECT VS VIA LIBRATION POINTS (L1, L2)

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Libration Point Missions

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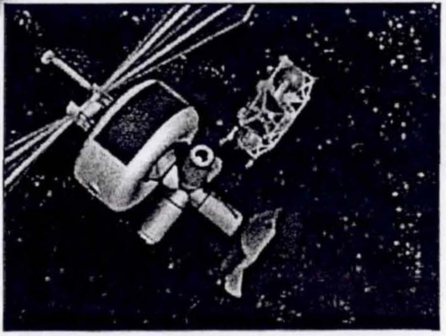
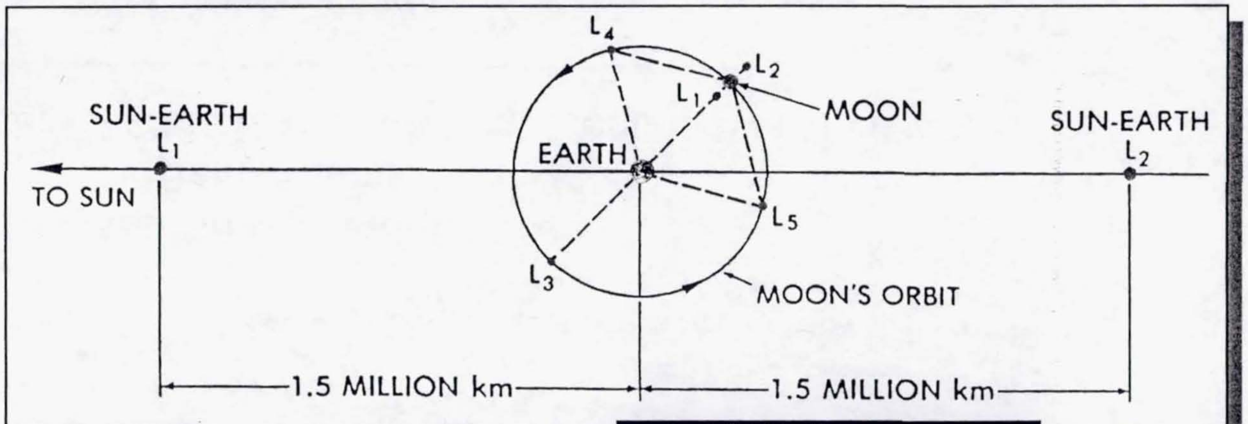
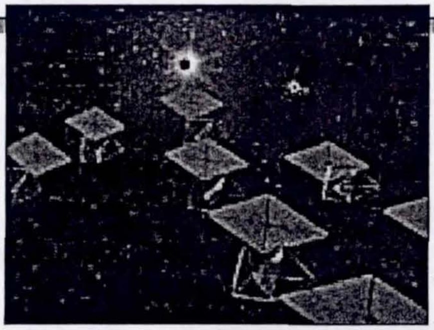
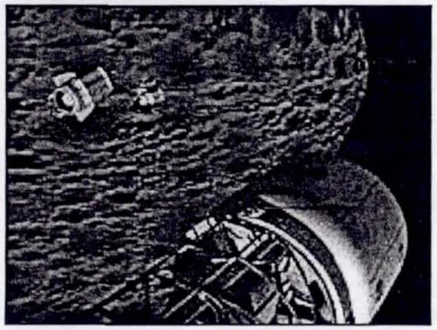




- Earth-Moon L1
  - **Gateway station**
    - Sorties to the Moon
    - Satellite deploy, servicing
      - Next Generation Space Telescope
      - Terrestrial Planet Finder
    - Staging area for interplanetary and asteroid missions
- Earth-Moon L2
  - Robotic relay satellites
    - Communications relay
    - Navigation aid
- Sun-Earth L2
  - Human missions to extend human presence in space





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Expeditionary vs. Evolutionary

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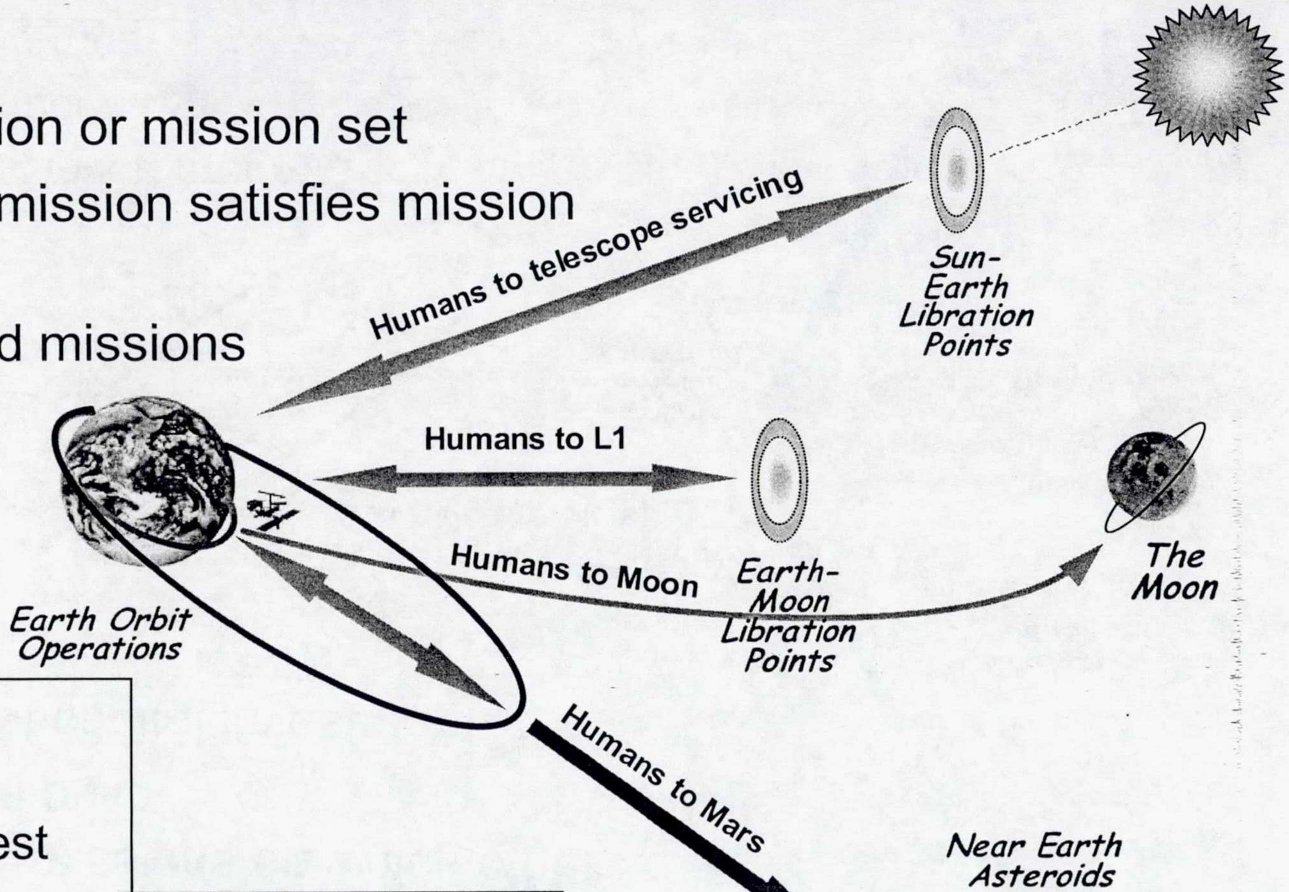
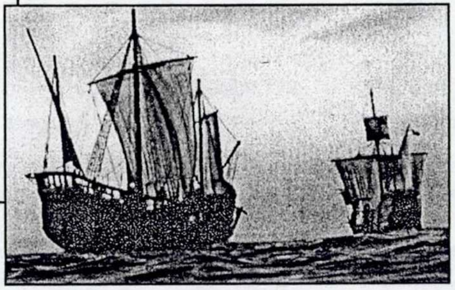
- Single mission or mission set
- Completed mission satisfies mission objectives
- Close-ended missions



Apollo
Skylab
Apollo-Soyuz Test Project
Columbus' voyage of discovery to the new world



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Expeditionary vs. Evolutionary

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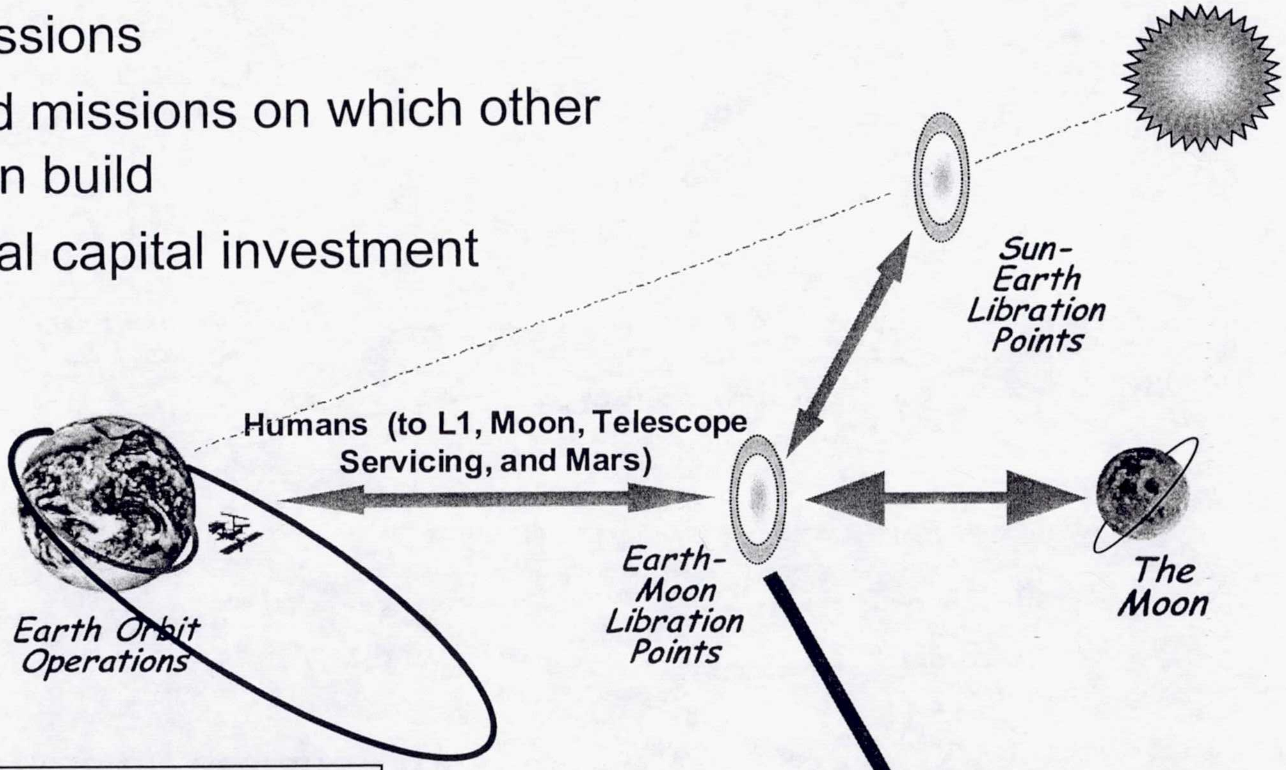
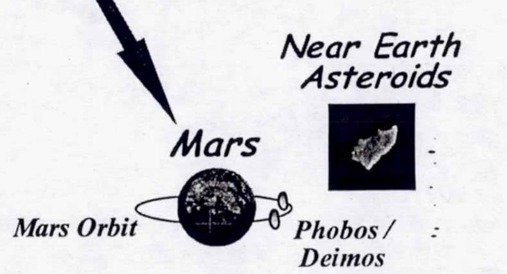
- Ongoing missions
- Open-ended missions on which other missions can build
- Greater initial capital investment





International Space Station program
Voyages of Prince Henry
the Navigator of Portugal

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Earth-Moon L1 – Gateway for Lunar Surface Operations

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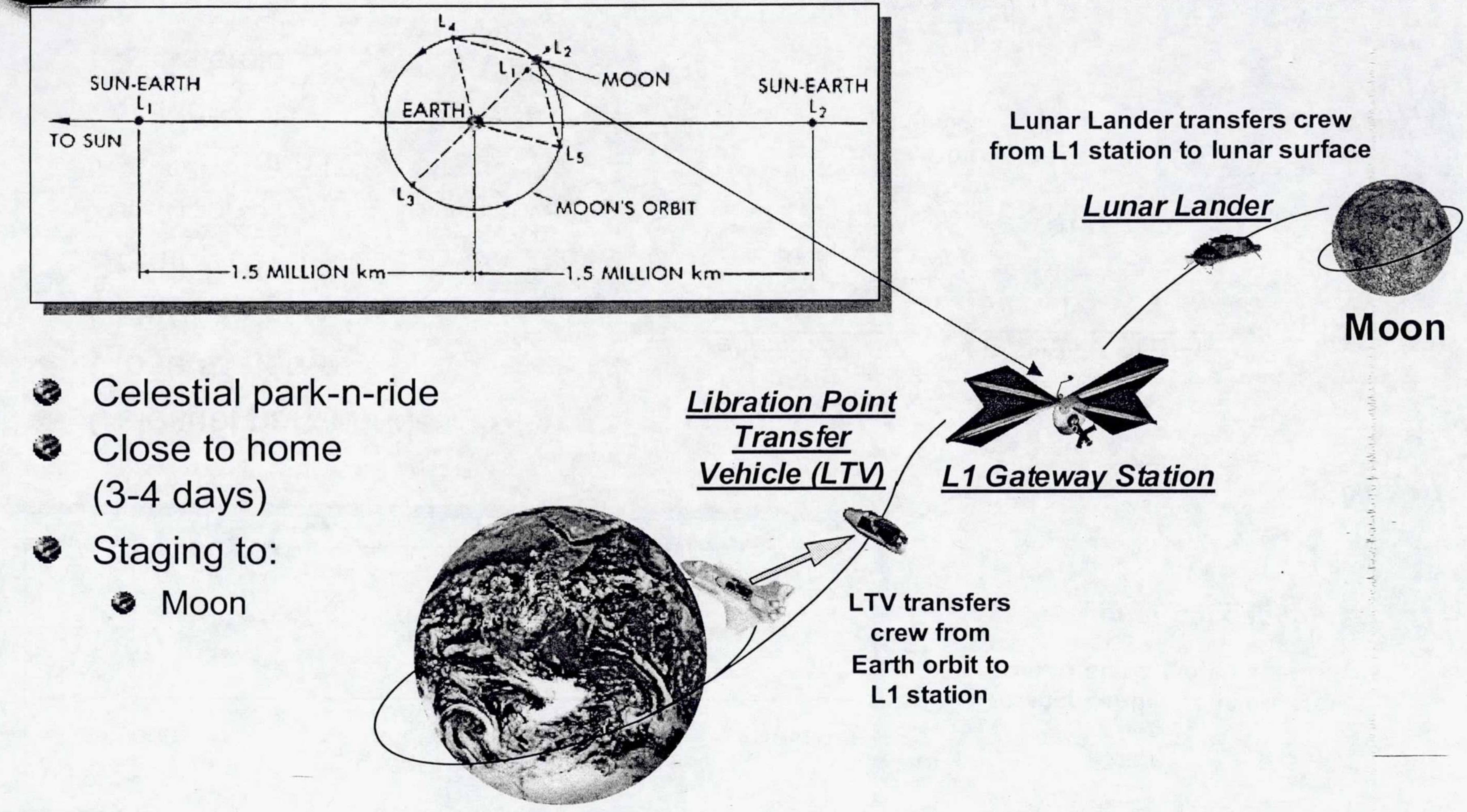

Lunar Lander transfers crew from L1 station to lunar surface

LTV transfers crew from Earth orbit to L1 station

- Celestial park-n-ride
- Close to home (3-4 days)
- Staging to:
  - Moon

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Earth-Moon L1 – Gateway for Lunar Surface Operations

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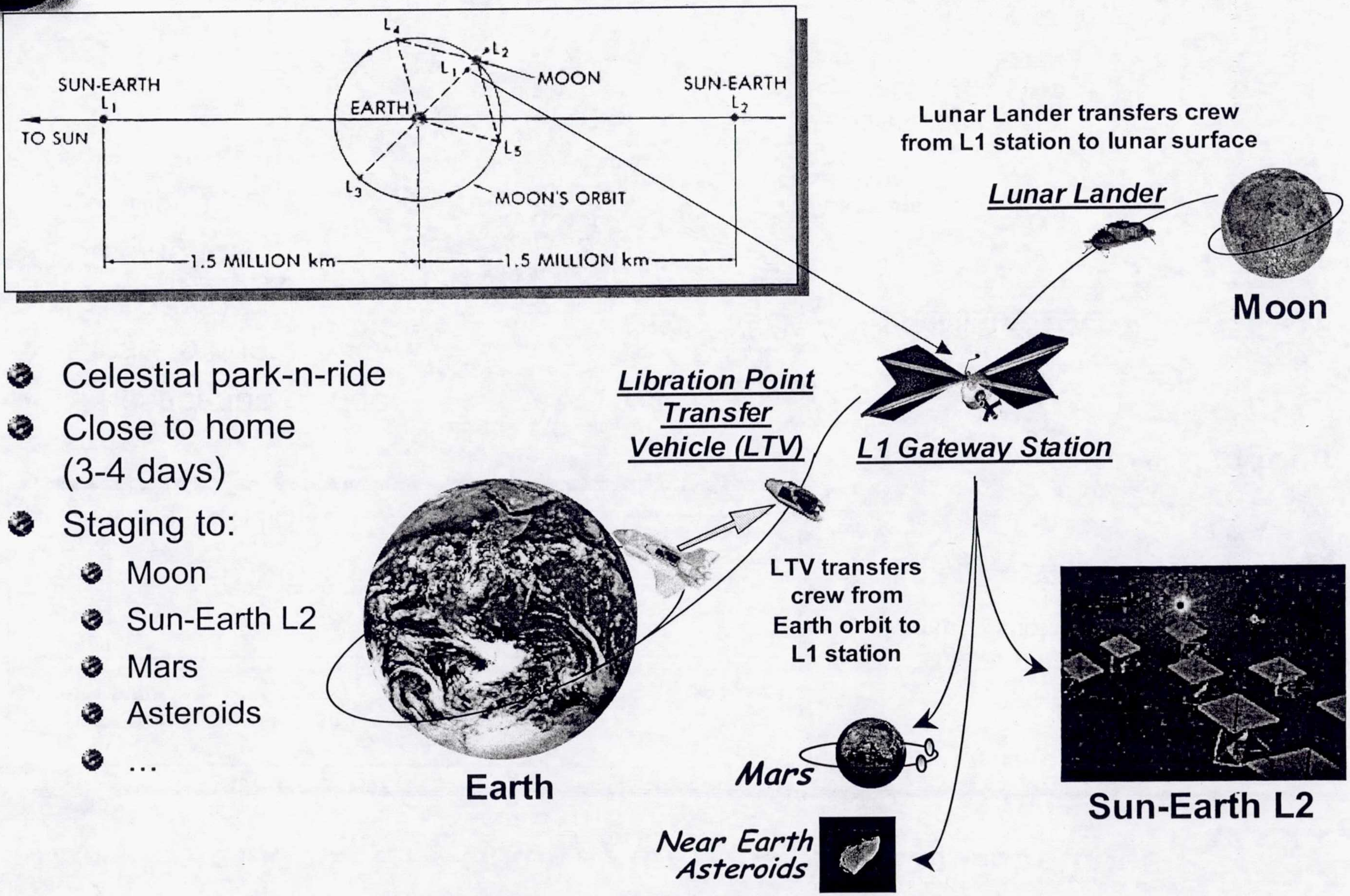

Lunar Lander transfers crew from L1 station to lunar surface

Lunar Lander

Moon

Libration Point Transfer Vehicle (LTV)

L1 Gateway Station

LTV transfers crew from Earth orbit to L1 station

Earth

Sun-Earth L2

Mars

Near Earth Asteroids

- Celestial park-n-ride
- Close to home (3-4 days)
- Staging to:
  - Moon
  - Sun-Earth L2
  - Mars
  - Asteroids
  - …

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Lunar Mission: Libration Point vs. LOR

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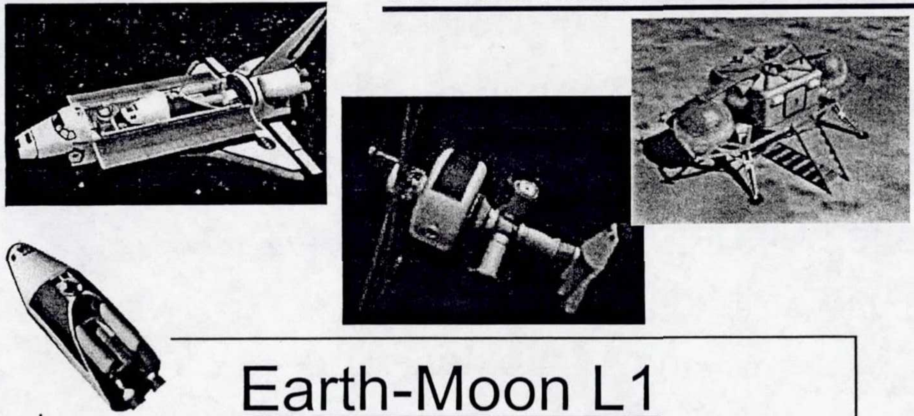
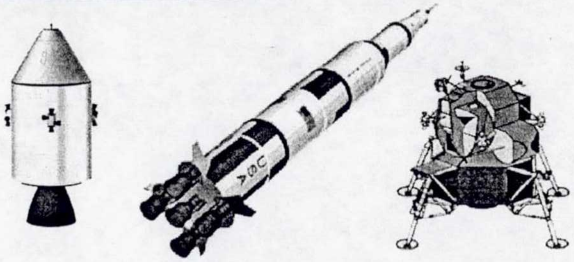
Mission Scenario Advantages





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

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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 $\geq$ 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)

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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

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- 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

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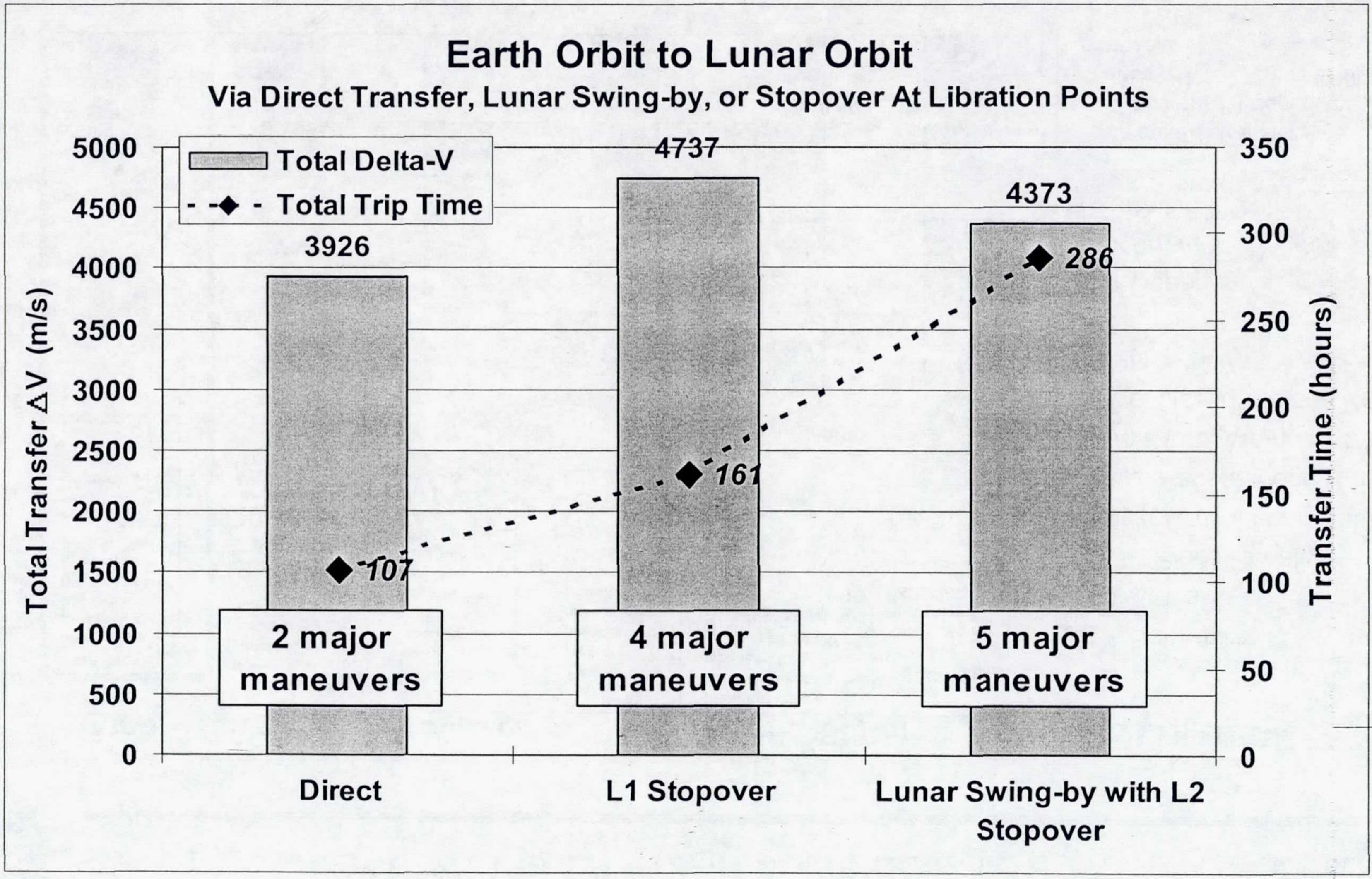

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Earth Orbit to Lunar Orbit (28.5 deg. Inclination)
Direct vs. Via L1 (3-Impulse LOI, TEI)

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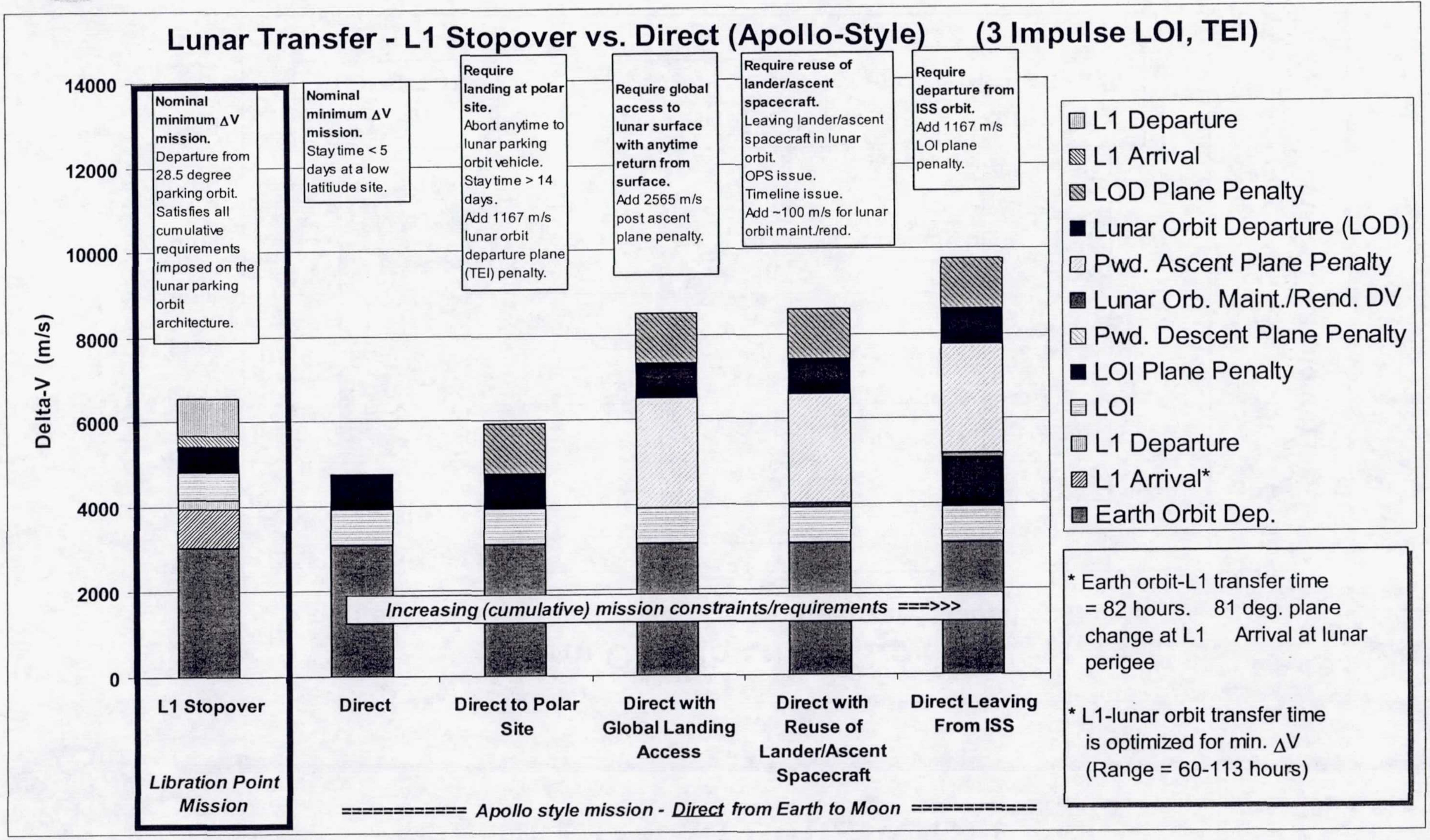

Lunar Transfer - L1 Stopover vs. Direct (Apollo-Style) (3 Impulse LOI, TEI)

Nominal minimum ΔV mission. Departure from 28.5 degree parking orbit. Satisfies all cumulative requirements imposed on the lunar parking orbit architecture.

Nominal minimum ΔV mission. Stay time < 5 days at a low latitiude site.

Require landing at polar site. Abort anytime to lunar parking orbit vehicle. Stay time > 14 days. Add 1167 m/s lunar orbit departure plane (TEI) penalty.

Require global access to lunar surface with anytime return from surface. Add 2565 m/s post ascent plane penalty.

Require reuse of lander/ascent spacecraft. Leaving lander/ascent spacecraft in lunar orbit. OPS issue. Timeline issue. Add ~100 m/s for lunar orbit maint./rend.

Require departure from ISS orbit. Add 1167 m/s LOI plane penalty.

* Earth orbit-L1 transfer time = 82 hours. 81 deg. plane change at L1 Arrival at lunar perigee

* L1-lunar orbit transfer time is optimized for min. ΔV (Range = 60-113 hours)

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

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Direct Lunar Transfer vs. Lunar Transfer via L1 Stopover

Assumptions

- Direct mission with increasing constraints/requirments.
- All LOI and TEI plane change maneuvers use a 3-impulse sequence
- 28.5 degree initial orbit for L1 transfer
- All missions return direct to surface.

Order of increasing missions constraints (constraint are cumulative) ===>

Transfer Scenario	L1 Stopover	Direct	Direct to Polar Site	Direct with Global Landing Access	Direct with Reuse of Lander/Ascent Spacecraft	Direct Leaving From ISS
Earth Orbit Departure	3054	3086	3086	3086	3086	3086
L1 Arrival, 82 hour xfer, 57.1 deg pln. chng. (28.5 deg due east inclination plus 28.6 max lunar inclination wrt Earth equator)	890	0	0	0	0	0
L1 Departure	228	0	0	0	0	0
LOI	635	841	841	841	841	841
LOI Plane Penalty	0	0	0	0	0	**1167**
Powered Descent Plane Penalty	0	0	0	0	0	0
Lunar orbit maintenance/ Rendezvous DV penalty	0	0	0	0	**100**	**100**
Powered Ascent Plane Penalty	0	0	0	**2565**	**2565**	**2565**
Lunar Orbit Departure	635	841	841	841	841	841
Lunar Orbit Departure Plane Penalty	0	0	**1167**	**1167**	**1167**	**1167**
L1 Arrival, Opt. Xfer time	228	0	0	0	0	0
L1 Departure, 82 hour xfer, 57.1 deg pln. chng. (28.5 deg due east inclination plus 28.6 max lunar inclination wrt Earth equator)	890	0	0	0	0	0
Total	**6560**	**4768**	**5935**	**8500**	**8600**	**9767**
		Nominal minimum DV mission with no constraint or requirement penalties.	Stay time > 14 days	Abort anytime to Lunar parking orbit vehicle	Requires leaving lander/ascent s/c in lunar orbit. **OPS Issue. TIMELINE Issue.**	Require departure from ISS plane.
	Earth orbit to lunar orbit via L1, 81 deg. Pln chg to L1	Earth orbit direct to **90 deg.** lunar orbit (100 km); Min DV, 1/1/09	Earth orbit direct to 90 **deg.** lunar orbit (100 km); Min DV, 1/1/09	Earth orbit direct to **90 deg.** lunar orbit (100 km); Min DV, 1/1/09	Earth orbit direct to **90 deg.** lunar orbit (100 km); Min DV, 1/1/09	Earth orbit direct to **90 deg.** lunar orbit (100 km); Min DV, 1/1/09

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Earth Orbit to Lunar Orbit (28.5 deg. Inclination)
Direct vs. Via L1 (1-Impulse LOI, TEI)

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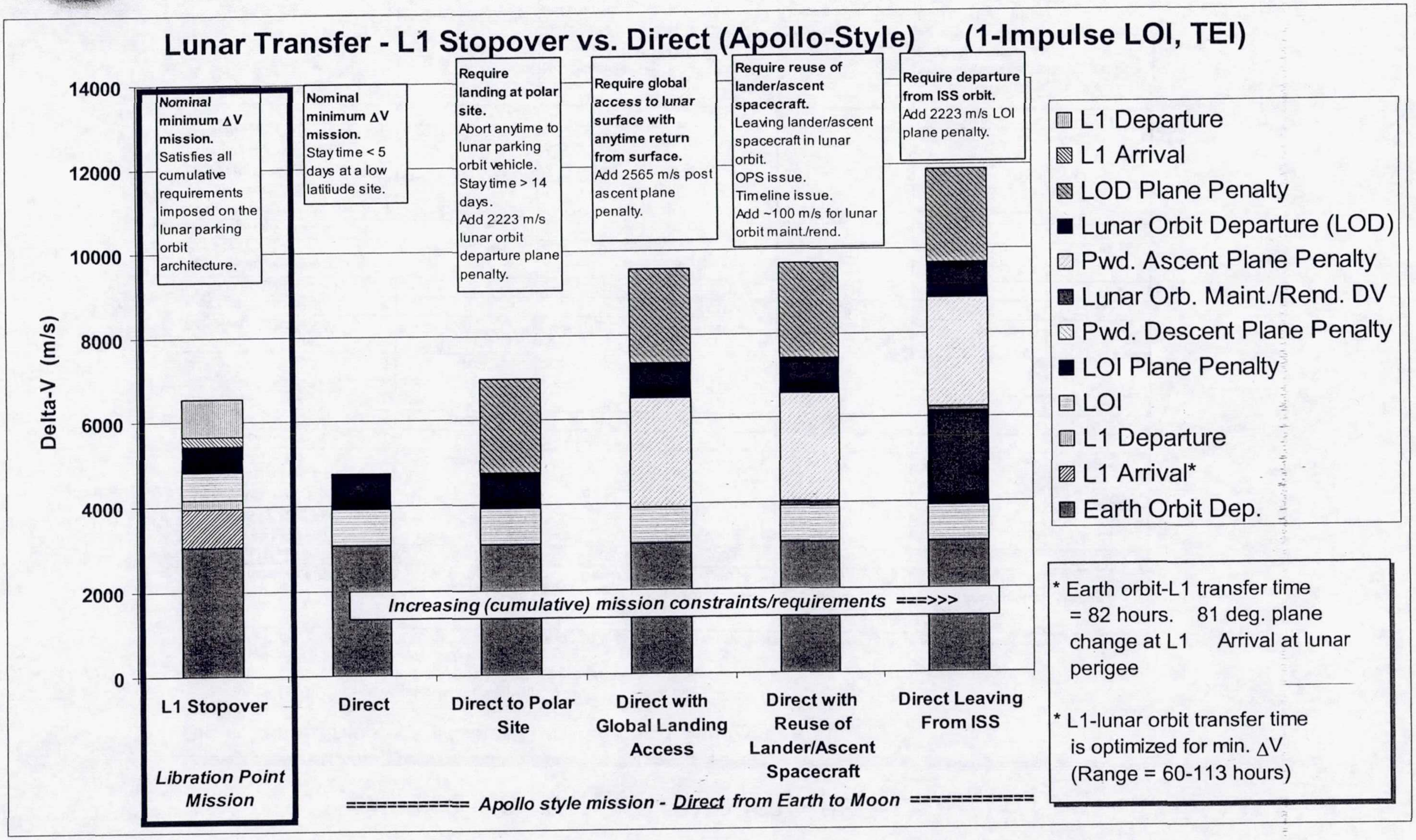
Lunar Transfer - L1 Stopover vs. Direct (Apollo-Style) (1-Impulse LOI, TEI)



***Nominal* minimum ΔV mission.** Satisfies all cumulative requirements imposed on the lunar parking orbit architecture.

Nominal minimum ΔV mission. Stay time < 5 days at a low latitiude site.

Require landing at polar site. Abort anytime to lunar parking orbit vehicle. Stay time > 14 days. Add 2223 m/s lunar orbit departure plane penalty.

Require global *access to lunar* surface with anytime return from surface. Add 2565 m/s post ascent plane penalty.

Require reuse of lander/ascent spacecraft. Leaving lander/ascent spacecraft in lunar orbit. OPS issue. Timeline issue. Add ~100 m/s for lunar orbit maint./rend.

Require departure from ISS orbit. Add 2223 m/s LOI plane penalty.

Increasing (cumulative) mission constraints/requirements ===>>>

Libration Point Mission

=========== *Apollo style mission - Direct from Earth to Moon* ===========

* Earth orbit-L1 transfer time = 82 hours. 81 deg. plane change at L1 Arrival at lunar perigee

* L1-lunar orbit transfer time is optimized for min. ΔV (Range = 60-113 hours)

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Earth Orbit to Lunar Orbit (28.5 deg. Inclination) Direct vs. Via L1 (1-Impulse LOI, TEI)

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Direct Lunar Transfer vs. Lunar Transfer via L1 Stopover

Assumptions

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

Order of increasing missions constraints (constraint are cumulative) ===>

Transfer Scenario	L1 Stopover	Direct	Direct to Polar Site	Direct with Global Landing Access	Direct with Reuse of Lander/Ascent Spacecraft	Direct Leaving From ISS
Earth Orbit Departure	3054	3086	3086	3086	3086	3086
L1 Arrival, 82 hour xfer, 57.1 deg pln. chng. (28.5 deg due east inclination plus 28.6 max lunar inclination wrt Earth equator)	890	0	0	0	0	0
L1 Departure	228	0	0	0	0	0
LOI	635	841	841	841	841	841
LOI Plane Penalty	0	0	0	0	0	**2223**
Powered Descent Plane Penalty	0	0	0	0	0	0
Lunar orbit maintenance/ Rendezvous DV penalty	0	0	0	0	**100**	**100**
Powered Ascent Plane Penalty	0	0	0	**2565**	**2565**	**2565**
Lunar Orbit Departure	635	841	841	841	841	841
Lunar Orbit Departure Plane Penalty	0	0	**2223**	**2223**	**2223**	**2223**
L1 Arrival, Opt. Xfer time	228	0	0	0	0	0
L1 Departure, 82 hour xfer, 57.1 deg pln. chng. (28.5 deg due east inclination plus 28.6 max lunar inclination wrt Earth equator)	890	0	0	0	0	0
Total	**6560**	**4768**	**6991**	**9556**	**9656**	**11879**
		Nominal minimum DV mission with no constraint or requirement penalties.	Stay time > 14 days	Abort anytime to Lunar parking orbit vehicle	Requires leaving lander/ascent s/c in lunar orbit. **OPS Issue. TIMELINE Issue.**	Require departure from ISS plane.
	Earth orbit to lunar orbit via L1, 81 deg. Pln chg to L1	Earth orbit direct to **90 deg.** lunar orbit (100 km); Min DV, 1/1/09	Earth orbit direct to **90 deg.** lunar orbit (100 km); Min DV, 1/1/09	Earth orbit direct to **90 deg.** lunar orbit (100 km); Min DV, 1/1/09	Earth orbit direct to **90 deg.** lunar orbit (100 km); Min DV, 1/1/09	Earth orbit direct to **90 deg.** lunar orbit (100 km); Min DV, 1/1/09

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Earth Orbit to Lunar Orbit (51.6 deg. Inclination)
Direct vs. Via L1 (3-Impulse LOI, TEI)

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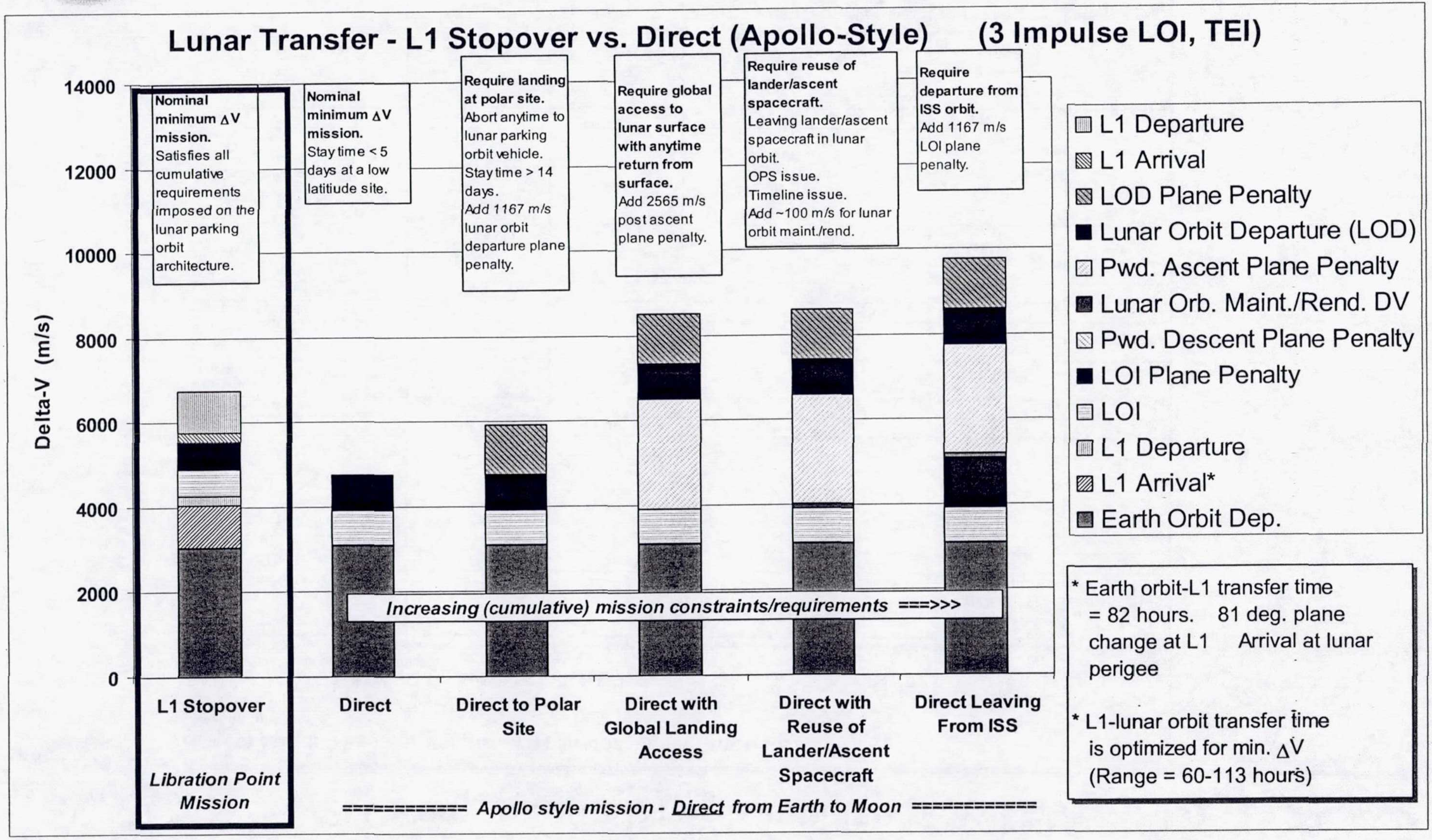

Nominal minimum ΔV mission. Satisfies all cumulative requirements imposed on the lunar parking orbit architecture.

Nominal minimum ΔV mission. Stay time < 5 days at a low latitiude site.

Require landing at polar site. Abort anytime to lunar parking orbit vehicle. Stay time > 14 days. Add 1167 m/s lunar orbit departure plane penalty.

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Earth Orbit to Lunar Orbit (51.6 deg. Inclination)
Direct vs. Via L1 (3-Impulse LOI, TEI)

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Direct Lunar Transfer vs. Lunar Transfer via L1 Stopover

Assumptions

- Direct mission with increasing constraints/requirments.
- 51.6 degree initial orbit for L1 transfer
- All LOI and TEI plane change maneuvers use a 3-impulse sequence
- All missions return direct to surface.

		Order of increasing missions constraints (constraint are cumulative) ===>				
Transfer Scenario	**L1 Stopover**	**Direct**	**Direct to Polar Site**	**Direct with Global Landing Access**	**Direct with Reuse of Lander/Ascent Spacecraft**	**Direct Leaving From ISS**
Earth Orbit Departure	3055	3086	3086	3086	3086	3086
L1 Arrival, 82 hour xfer, 81 deg p	986	0	0	0	0	0
L1 Departure	228	0	0	0	0	0
LOI	635	841	841	841	841	841
LOI Plane Penalty	0	0	0	0	0	**1167**
Powered Descent Plane Penalty	0	0	0	0	0	0
Lunar orbit maintenance/ Rendezvous DV penalty	0	0	0	0	**100**	**100**
Powered Ascent Plane Penalty	0	0	0	**2565**	**2565**	**2565**
Lunar Orbit Departure	635	841	841	841	841	841
Lunar Orbit Departure Plane Penalty	0	0	**1167**	**1167**	**1167**	**1167**
L1 Arrival, Opt. Xfer time	228	0	0	0	0	0
L1 Departure, 82 hour xfer, 81 deg. pln. chg.	986	0	0	0	0	0
Total	**6753**	**4768**	**5935**	**8500**	**8600**	**9767**
		Nominal minimum DV mission with no constraint or requirement penalties.	Stay time > 14 days	Abort anytime to Lunar parking orbit vehicle	Requires leaving lander/ascent s/c in lunar orbit. **OPS Issue. TIMELINE Issue.**	Require departure from ISS plane.
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Earth Orbit to Lunar Orbit (51.6 deg. Inclination)
Direct vs. Via L1 (1-Impulse LOI, TEI)

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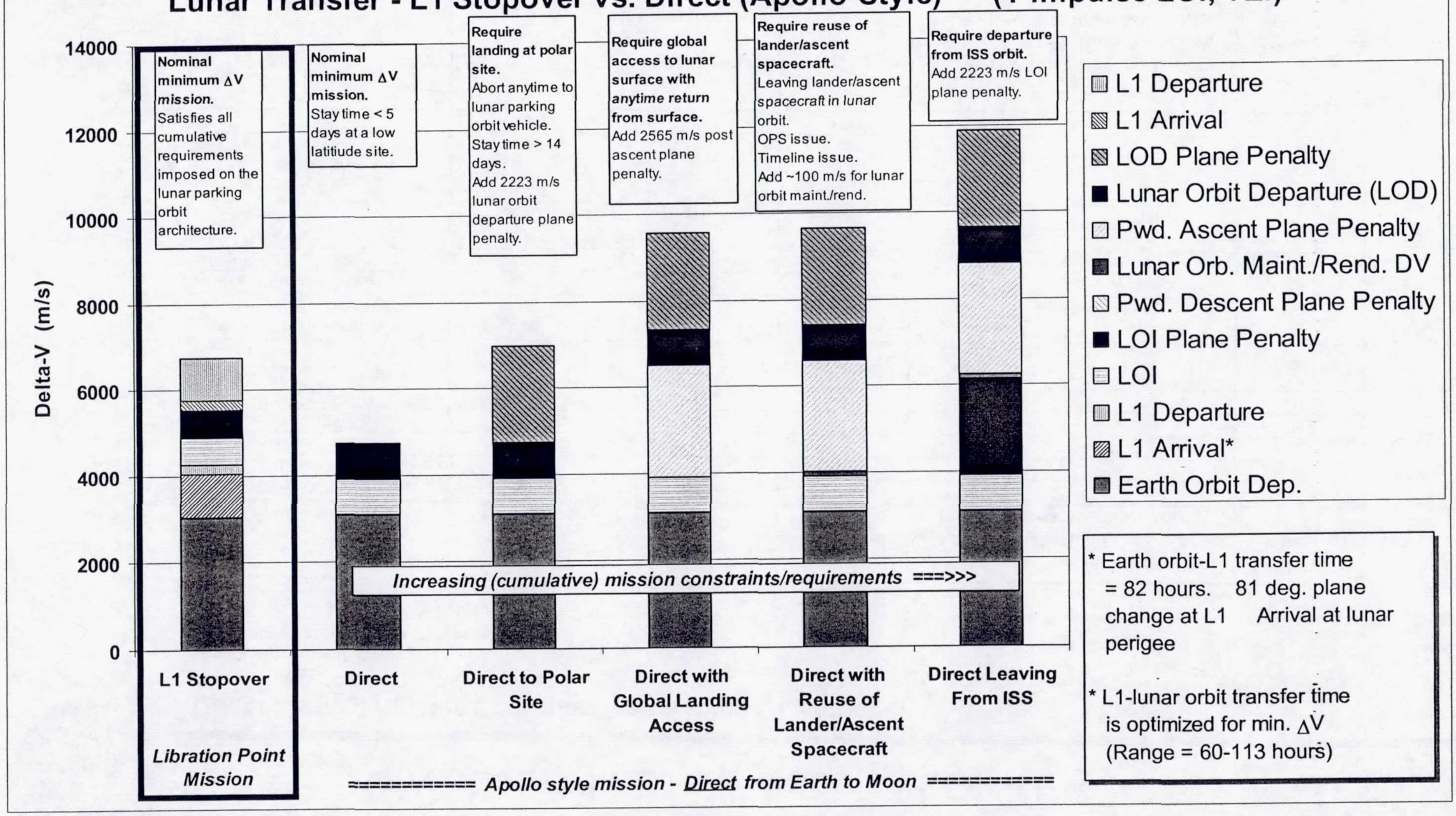
Lunar Transfer - L1 Stopover vs. Direct (Apollo-Style) (1-Impulse LOI, TEI)



Nominal minimum ΔV *mission.* Satisfies all cumulative requirements imposed on the lunar parking orbit architecture.

Nominal minimum ΔV mission. Stay time < 5 days at a low latitude site.

Require landing at polar site. Abort anytime to lunar parking orbit vehicle. Stay time > 14 days. Add 2223 m/s lunar orbit departure plane penalty.

Require global access to lunar surface with anytime return from surface. Add 2565 m/s post ascent plane penalty.

Require reuse of lander/ascent spacecraft. Leaving lander/ascent spacecraft in lunar orbit. OPS issue. Timeline issue. Add ~100 m/s for lunar orbit maint./rend.

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Increasing (cumulative) mission constraints/requirements ===>>>

Libration Point Mission

============ Apollo style mission - <u>Direct</u> from Earth to Moon ============

* Earth orbit-L1 transfer time = 82 hours. 81 deg. plane change at L1 Arrival at lunar perigee

* L1-lunar orbit transfer time is optimized for min. ΔV (Range = 60-113 hours)

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Earth Orbit to Lunar Orbit (51.6 deg. Inclination)
Direct vs. Via L1 (1-Impulse LOI, TEI)

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Direct Lunar Transfer vs. Lunar Transfer via L1 Stopover

Assumptions

- Direct mission with increasing constraints/requirments.
- All LOI and TEI plane change maneuvers use a 1-impulse sequence
- 51.6 degree initial orbit for L1 transfer
- All missions return direct to surface.

Order of increasing missions constraints (constraint are cumulative) ===>

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L1 Departure	228	0	0	0	0	0
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L1 Departure, 82 hour xfer, 81 deg. pln. chg.	986	0	0	0	0	0
Total	**6753**	**4768**	**6991**	**9556**	**9656**	**11879**
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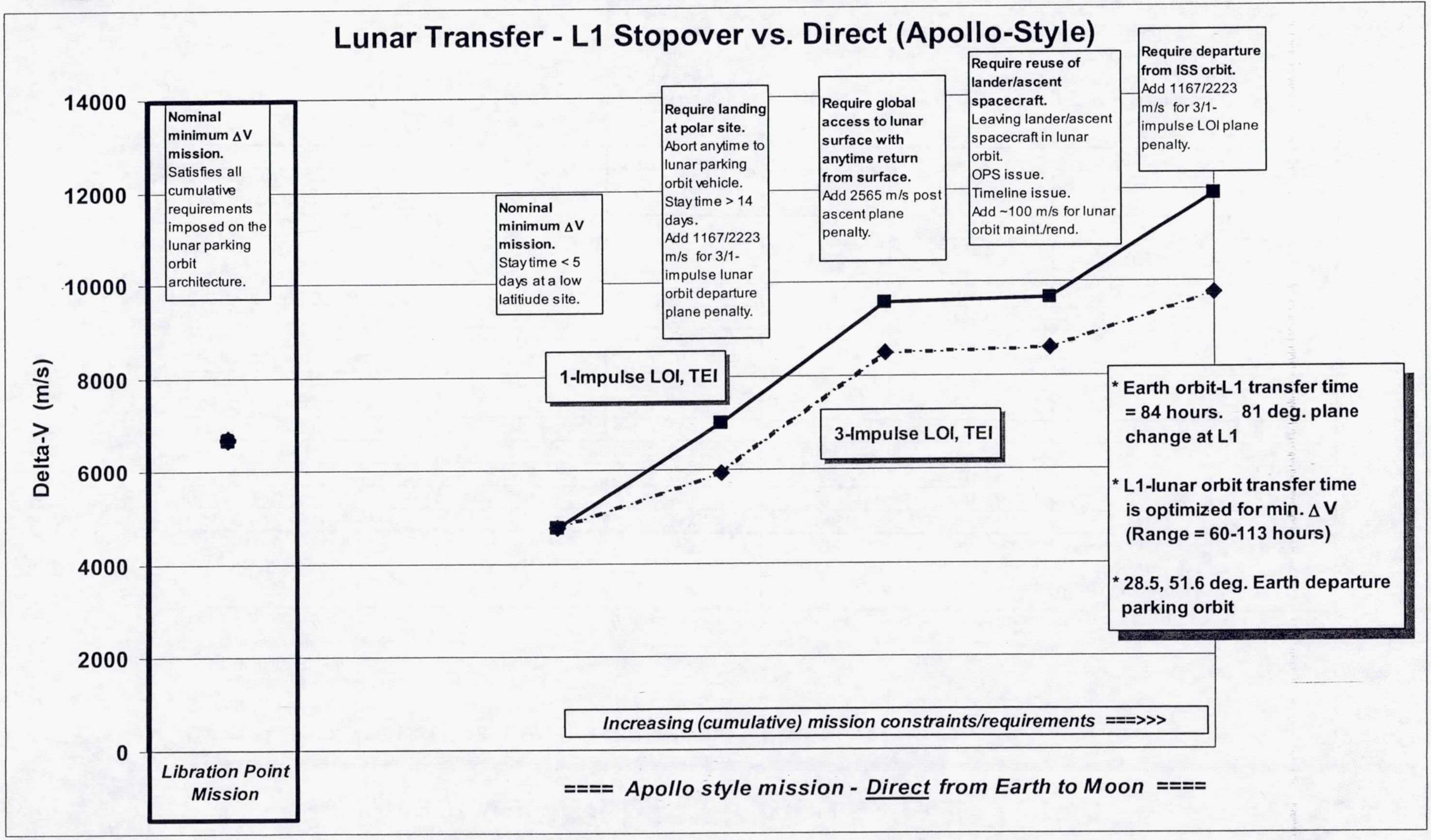
Total Mission ΔV
L1 Stopover vs. Direct (Apollo Style)
1-Impulse, 3-Impulse LOI, TEI

JSC



Nominal minimum ΔV mission. Satisfies all cumulative requirements imposed on the lunar parking orbit architecture.

Nominal minimum ΔV mission. Stay time < 5 days at a low latitude site.

Require landing at polar site. Abort anytime to lunar parking orbit vehicle. Stay time > 14 days. Add 1167/2223 m/s for 3/1-impulse lunar orbit departure plane penalty.

Require global access to lunar surface with anytime return from surface. Add 2565 m/s post ascent plane penalty.

Require reuse of lander/ascent spacecraft. Leaving lander/ascent spacecraft in lunar orbit. OPS issue. Timeline issue. Add ~100 m/s for lunar orbit maint./rend.

Require departure from ISS orbit. Add 1167/2223 m/s for 3/1-impulse LOI plane penalty.

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

*** L1-lunar orbit transfer time is optimized for min. ΔV (Range = 60-113 hours)**

*** 28.5, 51.6 deg. Earth departure parking orbit**

Increasing (cumulative) mission constraints/requirements ===>>>

==== Apollo style mission - Direct from Earth to Moon ====

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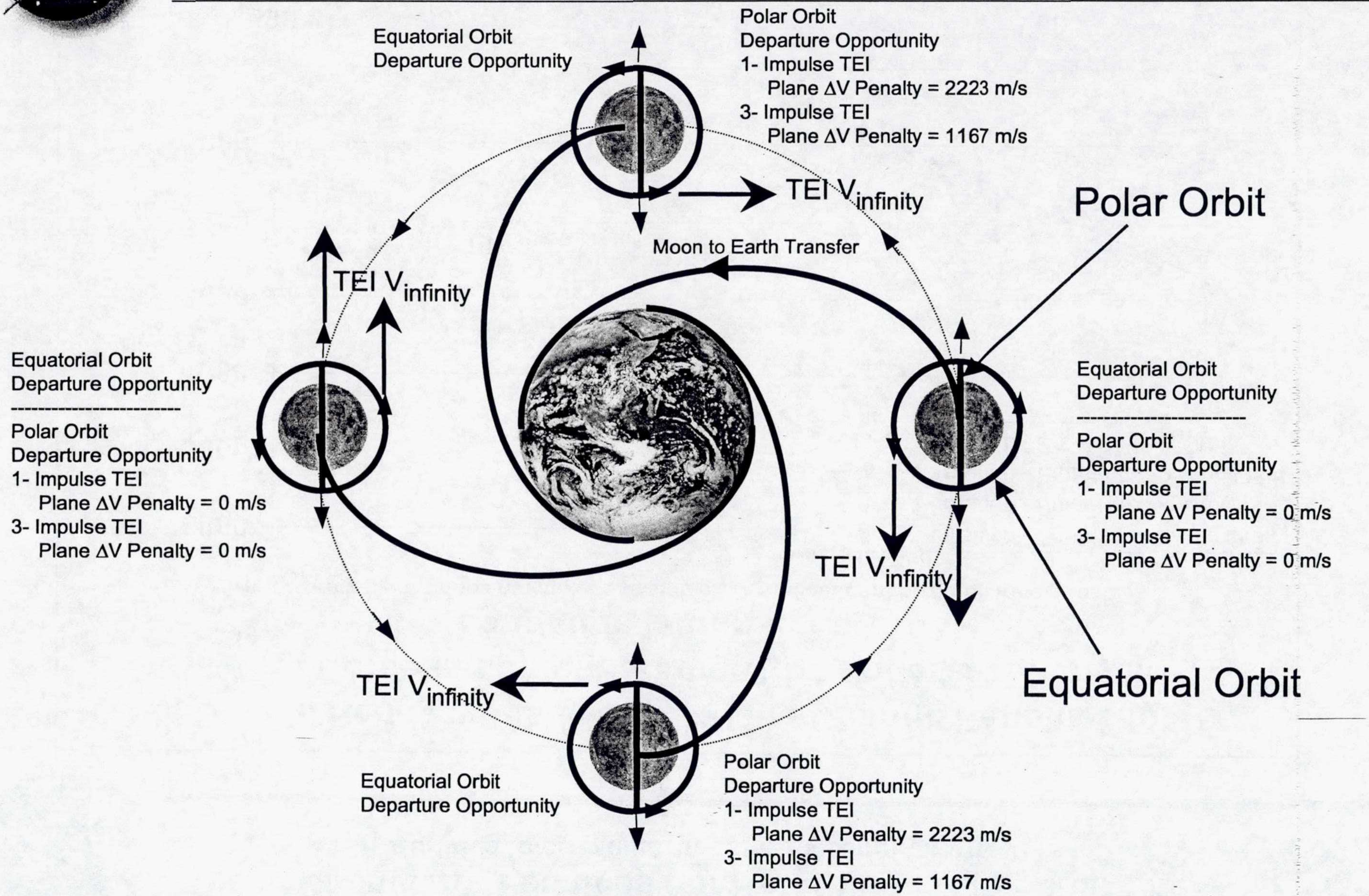
Effect of Lunar Parking Orbit Inclination on Lunar Transfer Opportunities –> Moon to Earth Transfer

JSC



Equatorial Orbit
Departure Opportunity

Polar Orbit
Departure Opportunity
1- Impulse TEI
Plane ΔV Penalty = 2223 m/s
3- Impulse TEI
Plane ΔV Penalty = 1167 m/s

TEI $V_{infinity}$

Polar Orbit

Moon to Earth Transfer

TEI $V_{infinity}$

Equatorial Orbit
Departure Opportunity

Polar Orbit
Departure Opportunity
1- Impulse TEI
Plane ΔV Penalty = 0 m/s
3- Impulse TEI
Plane ΔV Penalty = 0 m/s

Equatorial Orbit
Departure Opportunity

Polar Orbit
Departure Opportunity
1- Impulse TEI
Plane ΔV Penalty = 0 m/s
3- Impulse TEI
Plane ΔV Penalty = 0 m/s

TEI $V_{infinity}$

Equatorial Orbit

TEI $V_{infinity}$

Equatorial Orbit
Departure Opportunity

Polar Orbit
Departure Opportunity
1- Impulse TEI
Plane ΔV Penalty = 2223 m/s
3- Impulse TEI
Plane ΔV Penalty = 1167 m/s

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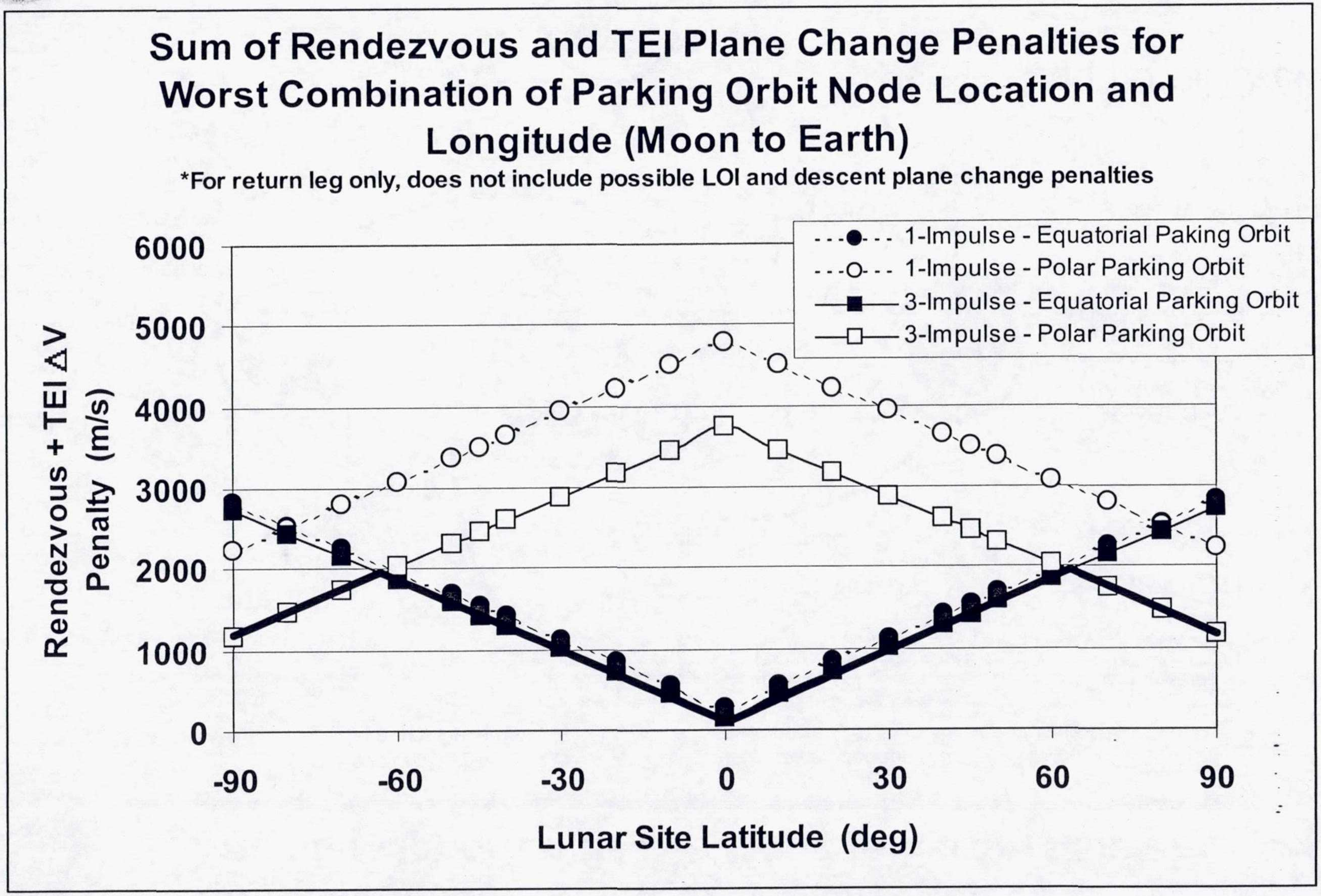
Plane Change ΔV Penalties For Returning From Lunar Site

Additive to co-planar transfer ΔV requirement

JSC



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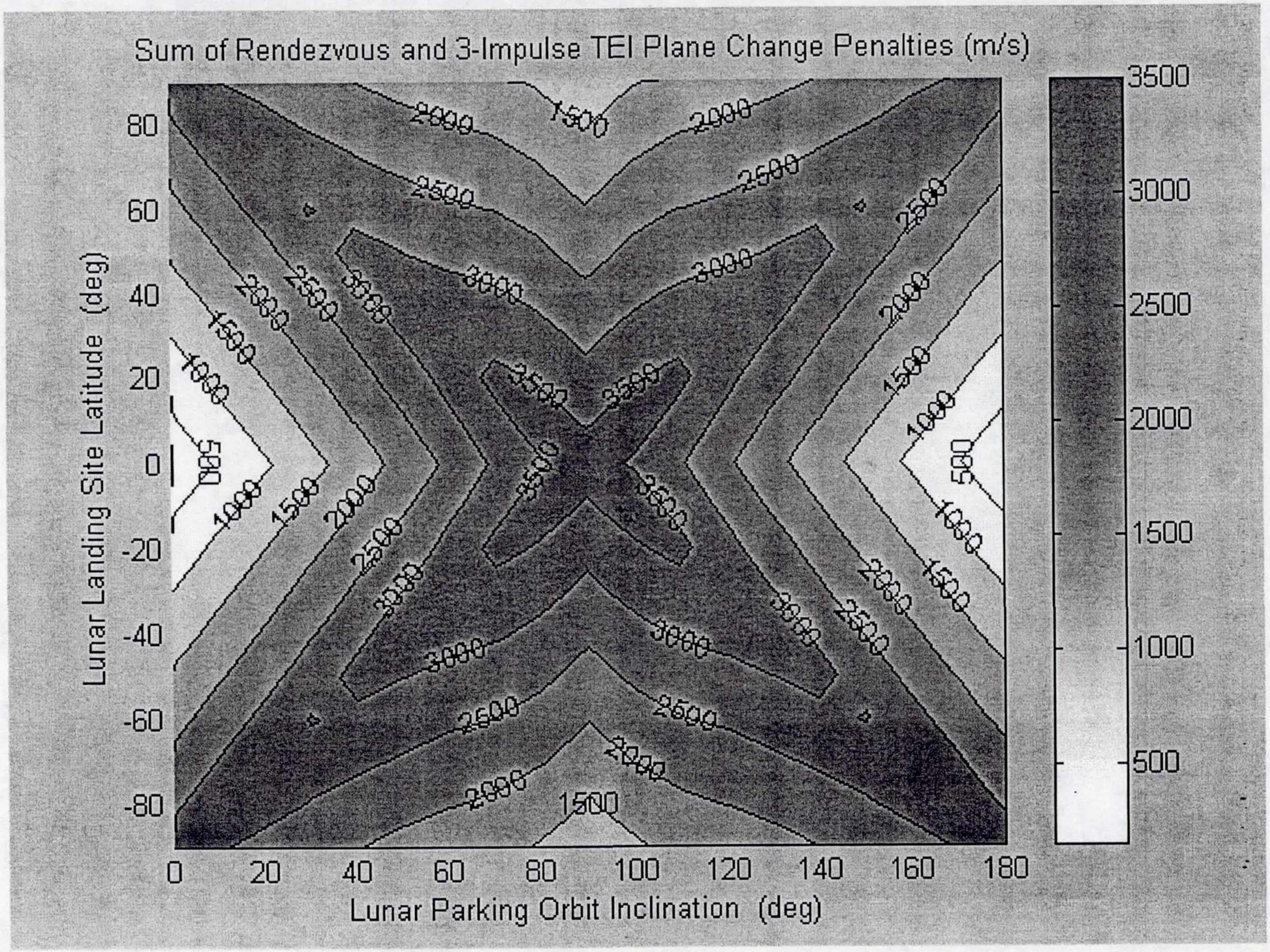
Plane Change ΔV Penalties For Returning From Lunar Site

Additive to co-planar transfer ΔV requirement

Worst Case - Ascent/rendezvous plus 3-Impulse TEI plane changes

JSC



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Plane Change ΔV Penalties For Returning From Lunar Site

Additive to co-planar transfer ΔV requirement

Worst Case - Ascent/rendezvous plus 3-Impulse TEI plane changes

JSC

Sum of Rendezvous and 3-Impulse TEI Plane Change Penalties (m/s)

for

Worst Combination of Parking Orbit Node Location and Site Longitude

Parking Orbit Inclination (deg)

Site Latitude (deg)	***0***	10	20	30	40	45	50	60	70	80	***90***	100	110	120	130	135	140	150	160	170	***180***
NaN																					
90	2715	2532	2352	2178	2013	1936	1862	1734	1633	1452	1167	1452	1633	1734	1862	1936	2013	2178	2352	2532	2715
80	2430	2817	2637	2463	2298	2221	2147	2019	1918	1737	1452	1737	1918	2019	2147	2221	2298	2463	2637	2817	2430
70	2145	2532	2922	2748	2583	2506	2432	2304	2203	2022	1737	2022	2203	2304	2432	2506	2583	2748	2922	2532	2145
60	1860	2247	2637	3033	2868	2791	2717	2589	2488	2307	2022	2307	2488	2589	2717	2791	2868	3033	2637	2247	1860
50	1575	1962	2352	2748	3153	3076	3002	2874	2773	2592	2307	2592	2773	2874	3002	3076	3153	2748	2352	1962	1575
45	1433	1820	2210	2606	3011	3218	3145	3017	2916	2735	2450	2735	2916	3017	3145	3218	3011	2606	2210	1820	1433
40	1290	1677	2067	2463	2868	3076	3287	3159	3058	2877	2592	2877	3058	3159	3287	3076	2868	2463	2067	1677	1290
30	1005	1392	1782	2178	2583	2791	3002	3444	3343	3162	2877	3162	3343	3444	3002	2791	2583	2178	1782	1392	1005
20	720	1107	1497	1893	2298	2506	2717	3159	3628	3447	3162	3447	3628	3159	2717	2506	2298	1893	1497	1107	720
10	435	822	1212	1608	2013	2221	2432	2874	3343	3732	3447	3732	3343	2874	2432	2221	2013	1608	1212	822	435
0	150	537	927	1323	1728	1936	2147	2589	3058	3447	3732	3447	3058	2589	2147	1936	1728	1323	927	537	150
-10	435	822	1212	1608	2013	2221	2432	2874	3343	3732	3447	3732	3343	2874	2432	2221	2013	1608	1212	822	435
-20	720	1107	1497	1893	2298	2506	2717	3159	3628	3447	3162	3447	3628	3159	2717	2506	2298	1893	1497	1107	720
-30	1005	1392	1782	2178	2583	2791	3002	3444	3343	3162	2877	3162	3343	3444	3002	2791	2583	2178	1782	1392	1005
-40	1290	1677	2067	2463	2868	3076	3287	3159	3058	2877	2592	2877	3058	3159	3287	3076	2868	2463	2067	1677	1290
-45	1433	1820	2210	2606	3011	3218	3145	3017	2916	2735	2450	2735	2916	3017	3145	3218	3011	2606	2210	1820	1433
-50	1575	1962	2352	2748	3153	3076	3002	2874	2773	2592	2307	2592	2773	2874	3002	3076	3153	2748	2352	1962	1575
-60	1860	2247	2637	3033	2868	2791	2717	2589	2488	2307	2022	2307	2488	2589	2717	2791	2868	3033	2637	2247	1860
-70	2145	2532	2922	2748	2583	2506	2432	2304	2203	2022	1737	2022	2203	2304	2432	2506	2583	2748	2922	2532	2145
-80	2430	2817	2637	2463	2298	2221	2147	2019	1918	1737	1452	1737	1918	2019	2147	2221	2298	2463	2637	2817	2430
-90	2715	2532	2352	2178	2013	1936	1862	1734	1633	1452	1167	1452	1633	1734	1862	1936	2013	2178	2352	2532	2715

Notes:

1. Data apply to a circular parking orbit at 100 km altitude.

2. All maneuvers use fail-safe steering, which maintains osculating periapse altitude greater than or equal to 100 km throughout burn.

3. Three-impulse TEI does plane change near the 7000 km apoapse altitude of an intermediate orbit having a period of 9 hours and 35 minutes.

*** Three-impulse TEI does final burn at periapse of intermediate ellipse. When the relative declination is very large, the sum of velocity increments can be reduced (as much as 300 m/s at 90 degrees) by doing final burn before reaching periapse.

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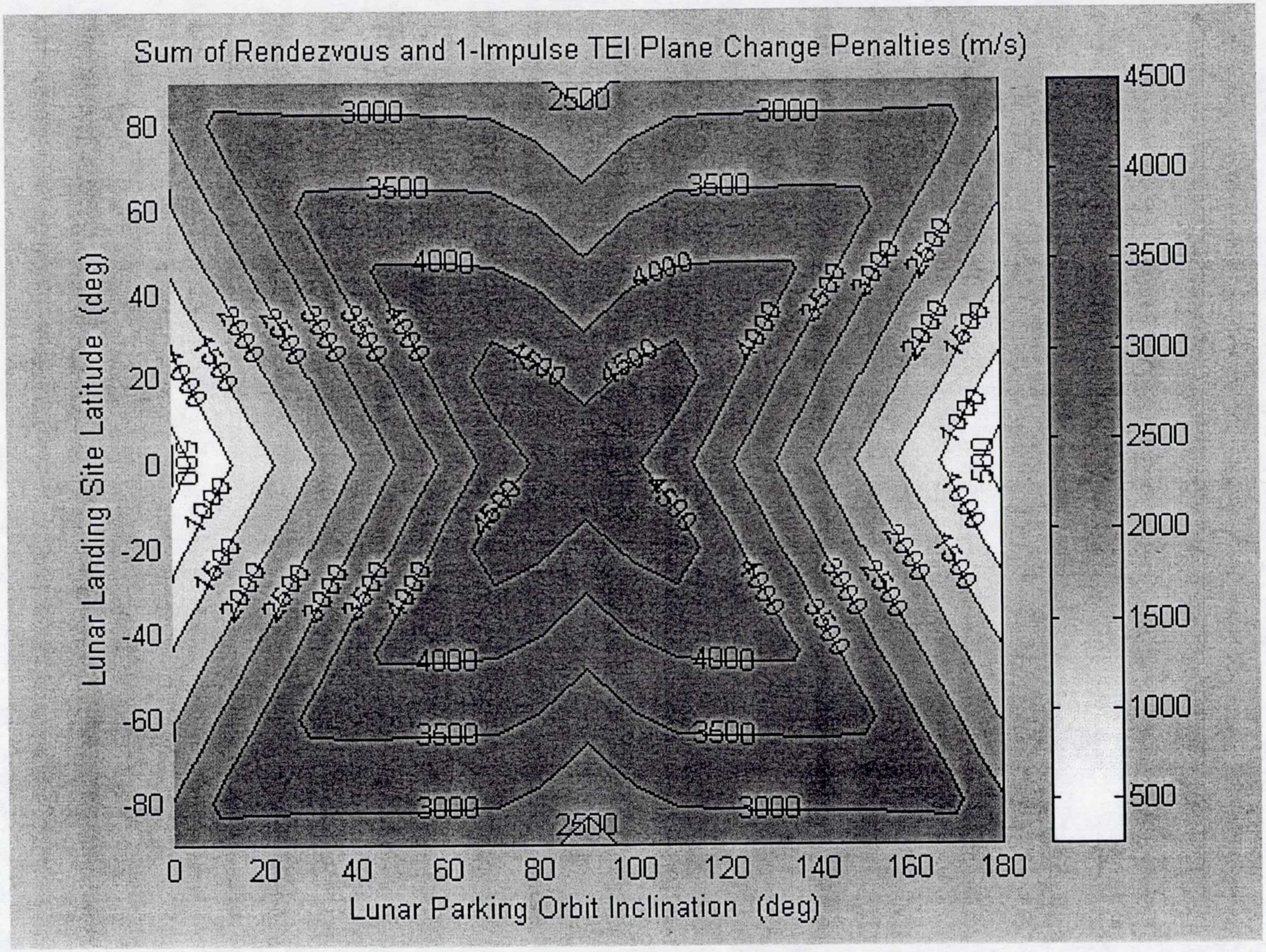
Plane Change ΔV Penalties For Returning From Lunar Site

Additive to co-planar transfer ΔV requirement

Worst Case - Ascent/rendezvous plus 1-Impulse TEI plane changes

JSC



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Plane Change ΔV Penalties For Returning From Lunar Site

Additive to co-planar transfer ΔV requirement

Worst Case - Ascent/rendezvous plus 1-Impulse TEI plane changes

JSC

Sum of Rendezvous and 1-Impulse TEI Plane Change Penalties (m/s)

for

Worst Combination of Parking Orbit Node Location and Site Longitude

Site Latitude (deg) NaN	***0***	10	20	30	40	45	50	60	70	80	***90***	100	110	120	130	135	140	150	160	170	***180***
90	2826	2809	2796	2777	2782	2781	2779	2771	2754	2601	2316	2601	2754	2771	2779	2781	2782	2777	2796	2809	2826
80	2541	3094	3081	3062	3067	3066	3064	3056	3039	2886	2601	2886	3039	3056	3064	3066	3067	3062	3081	3094	2541
70	2256	2809	3366	3347	3352	3351	3349	3341	3324	3171	2886	3171	3324	3341	3349	3351	3352	3347	3366	2809	2256
60	1971	2524	3081	3632	3637	3636	3634	3626	3609	3456	3171	3456	3609	3626	3634	3636	3637	3632	3081	2524	1971
50	1686	2239	2796	3347	3922	3921	3919	3911	3894	3741	3456	3741	3894	3911	3919	3921	3922	3347	2796	2239	1686
45	1544	2097	2654	3205	3780	4063	4062	4054	4037	3884	3599	3884	4037	4054	4062	4063	3780	3205	2654	2097	1544
40	1401	1954	2511	3062	3637	3921	4204	4196	4179	4026	3741	4026	4179	4196	4204	3921	3637	3062	2511	1954	1401
30	1116	1669	2226	2777	3352	3636	3919	4481	4464	4311	4026	4311	4464	4481	3919	3636	3352	2777	2226	1669	1116
20	831	1384	1941	2492	3067	3351	3634	4196	4749	4596	4311	4596	4749	4196	3634	3351	3067	2492	1941	1384	831
10	546	1099	1656	2207	2782	3066	3349	3911	4464	4881	4596	4881	4464	3911	3349	3066	2782	2207	1656	1099	546
0	261	814	1371	1922	2497	2781	3064	3626	4179	4596	4881	4596	4179	3626	3064	2781	2497	1922	1371	814	261
-10	546	1099	1656	2207	2782	3066	3349	3911	4464	4881	4596	4881	4464	3911	3349	3066	2782	2207	1656	1099	546
-20	831	1384	1941	2492	3067	3351	3634	4196	4749	4596	4311	4596	4749	4196	3634	3351	3067	2492	1941	1384	831
-30	1116	1669	2226	2777	3352	3636	3919	4481	4464	4311	4026	4311	4464	4481	3919	3636	3352	2777	2226	1669	1116
-40	1401	1954	2511	3062	3637	3921	4204	4196	4179	4026	3741	4026	4179	4196	4204	3921	3637	3062	2511	1954	1401
-45	1544	2097	2654	3205	3780	4063	4062	4054	4037	3884	3599	3884	4037	4054	4062	4063	3780	3205	2654	2097	1544
-50	1686	2239	2796	3347	3922	3921	3919	3911	3894	3741	3456	3741	3894	3911	3919	3921	3922	3347	2796	2239	1686
-60	1971	2524	3081	3632	3637	3636	3634	3626	3609	3456	3171	3456	3609	3626	3634	3636	3637	3632	3081	2524	1971
-70	2256	2809	3366	3347	3352	3351	3349	3341	3324	3171	2886	3171	3324	3341	3349	3351	3352	3347	3366	2809	2256
-80	2541	3094	3081	3062	3067	3066	3064	3056	3039	2886	2601	2886	3039	3056	3064	3066	3067	3062	3081	3094	2541
-90	2826	2809	2796	2777	2782	2781	2779	2771	2754	2601	2316	2601	2754	2771	2779	2781	2782	2777	2796	2809	2826

Parking Orbit Inclination (deg)

Notes:

1. Data apply to a circular parking orbit at 100 km altitude.
2. All maneuvers use fail-safe steering, which maintains osculating periapse altitude greater than or equal to 100 km throughout burn.

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Lunar Transfer/Orbit Diagrams

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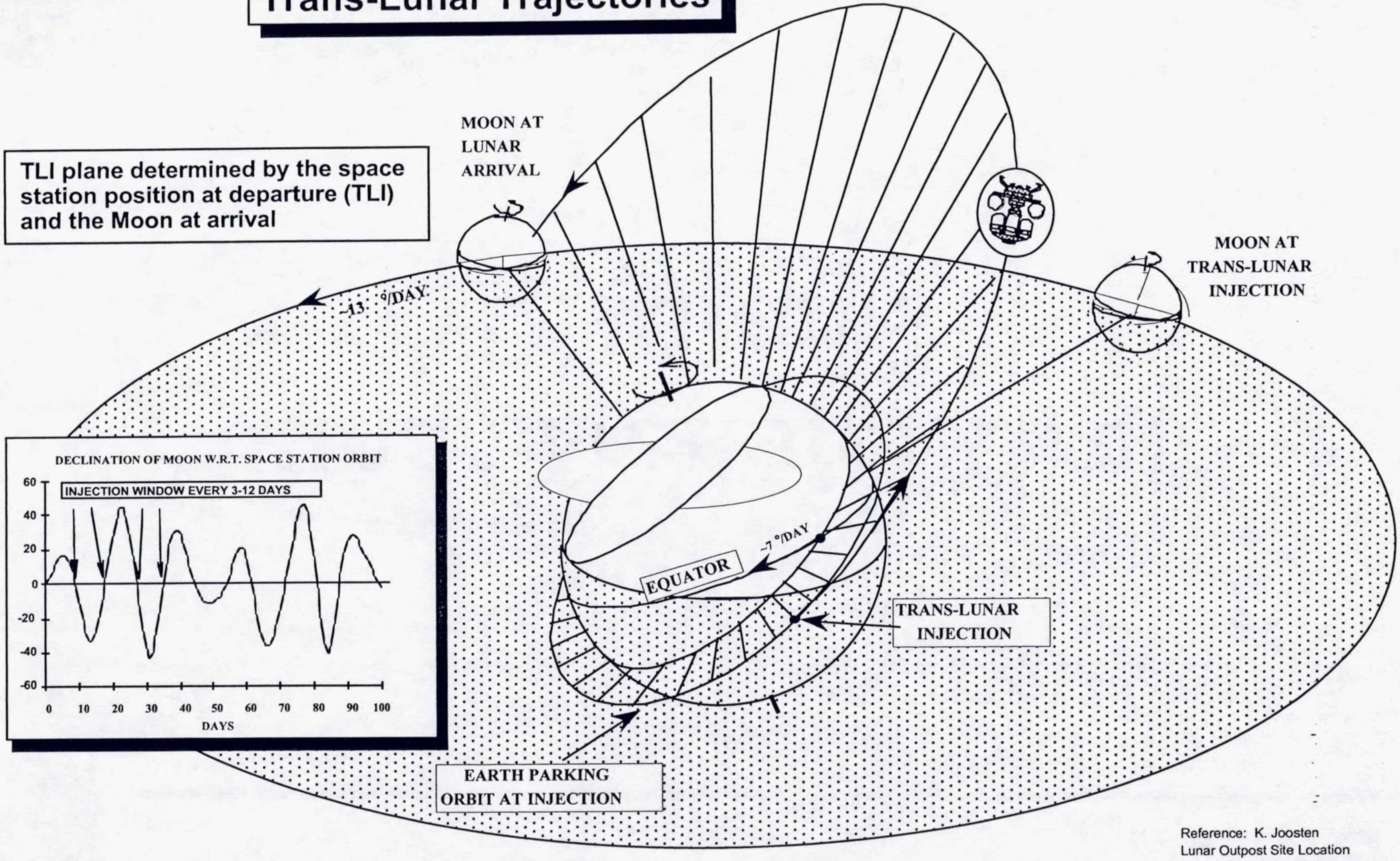
Trans-Lunar Trajectories

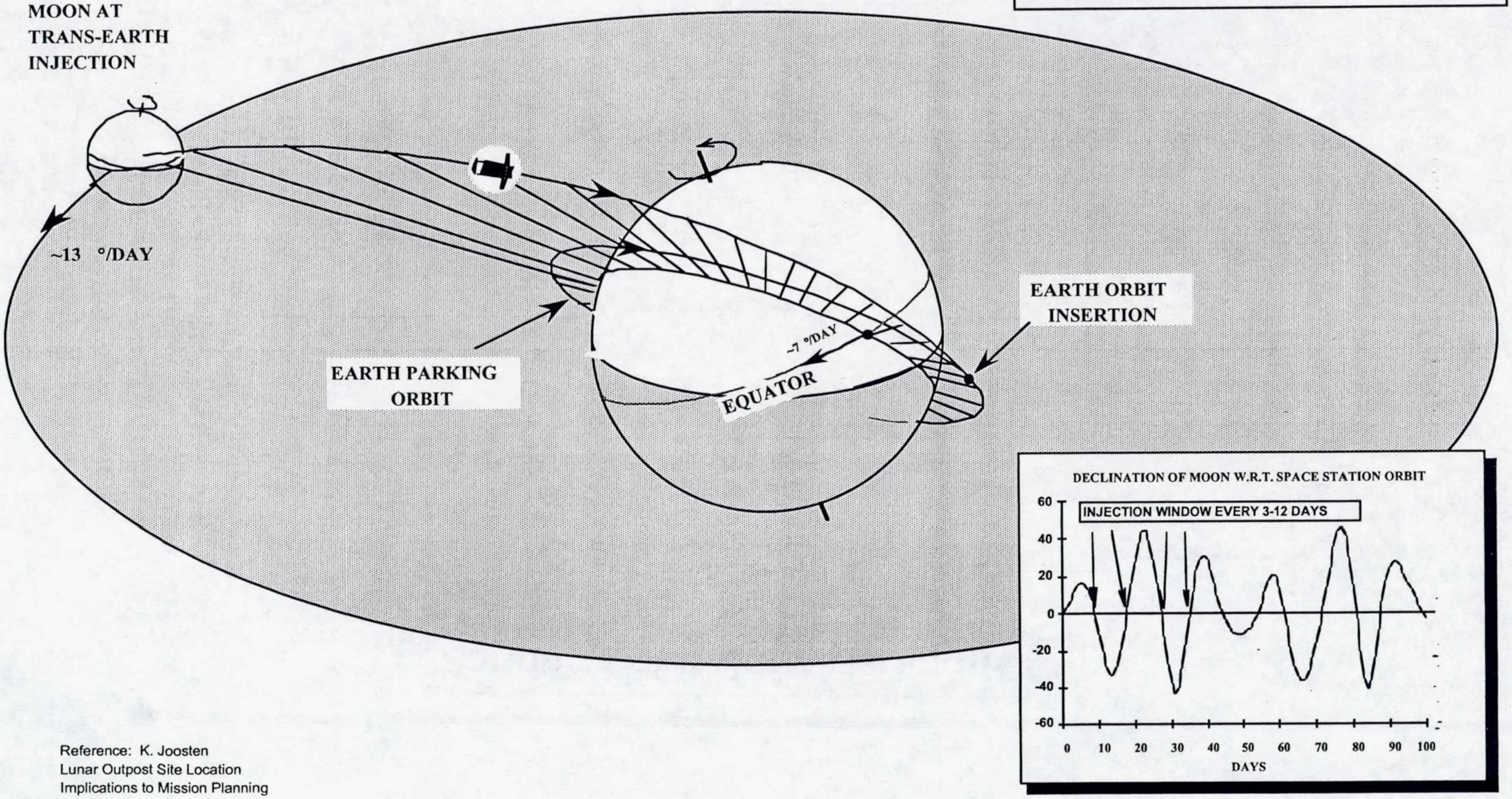
TLI plane determined by the space station position at departure (TLI) and the Moon at arrival



Reference: K. Joosten
Lunar Outpost Site Location
Implications to Mission Planning

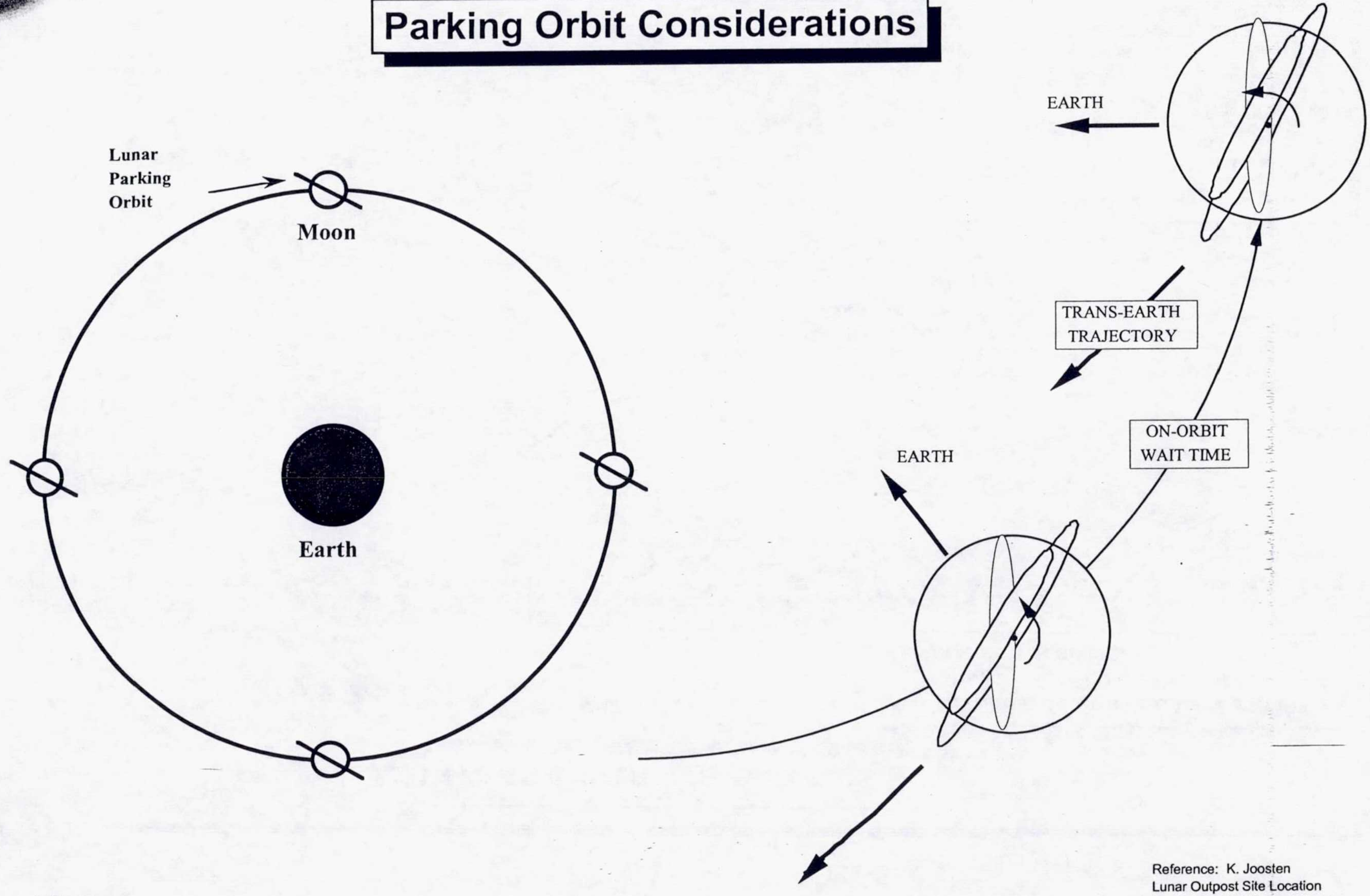
Trans-Earth Trajectories

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



Reference: K. Joosten
Lunar Outpost Site Location
Implications to Mission Planning

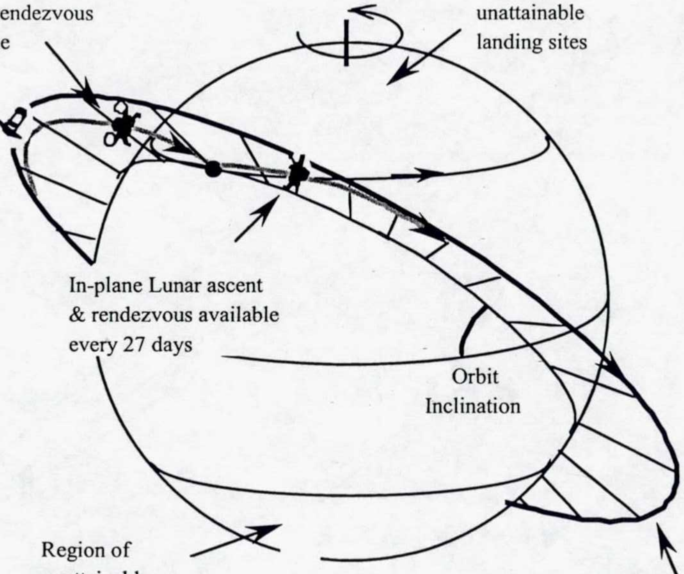
Parking Orbit Considerations



Reference: L. Wagner

Reference: K. Joosten
Lunar Outpost Site Location
Implications to Mission Planning

Landing Latitude Restrictions



Lunar descent & landing generally occur in rendezvous orbit plane

Region of unattainable landing sites

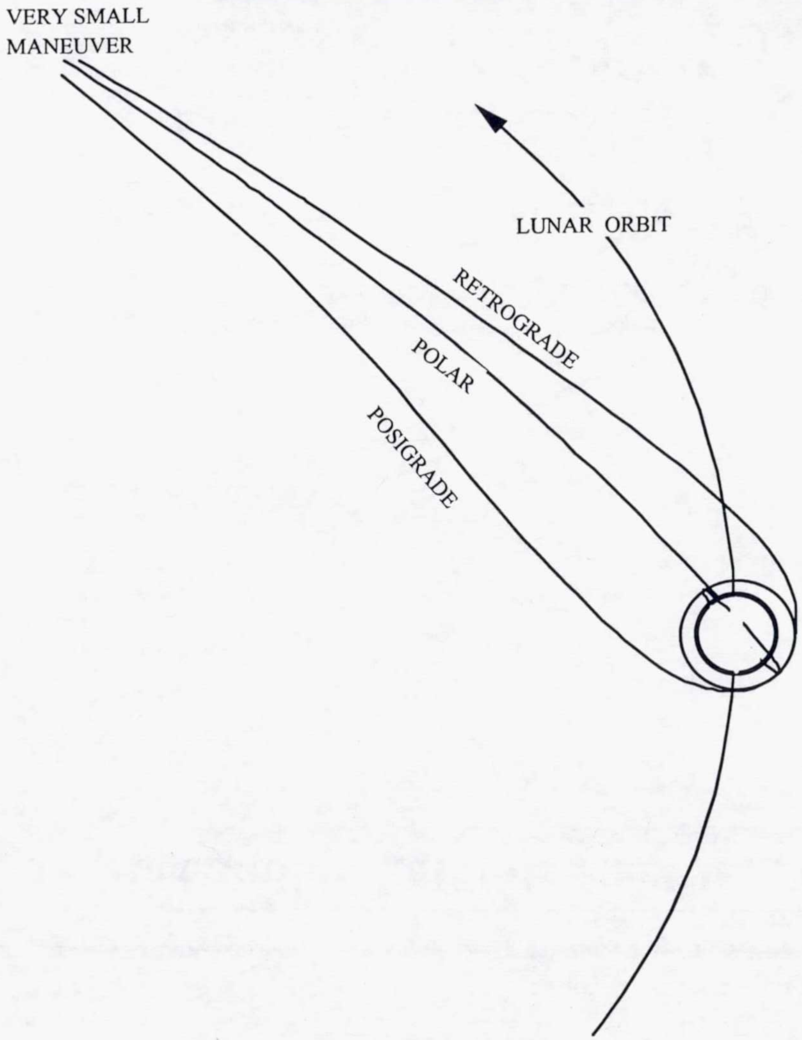
In-plane Lunar ascent & rendezvous available every 27 days

Region of unattainable landing sites

Rendezvous orbit remains nearly fixed, inertially

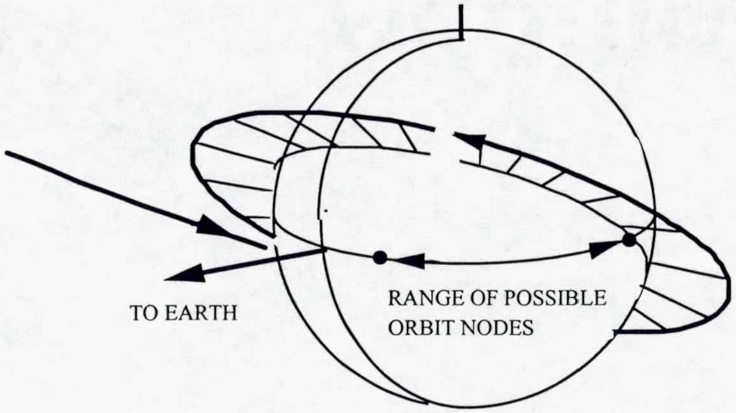
Reference: K. Joosten
Lunar Outpost Site Location
Implications to Mission Planning

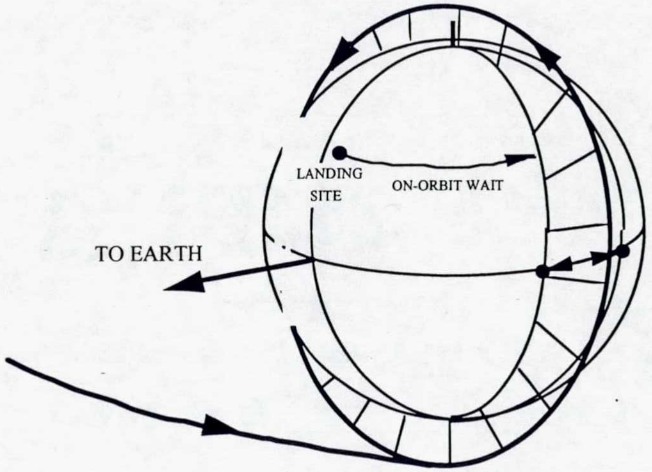
Variable Lunar Inclination



Reference: K. Joosten
Lunar Outpost Site Location
Implications to Mission Planning

Variable Lunar Orbit Alignment



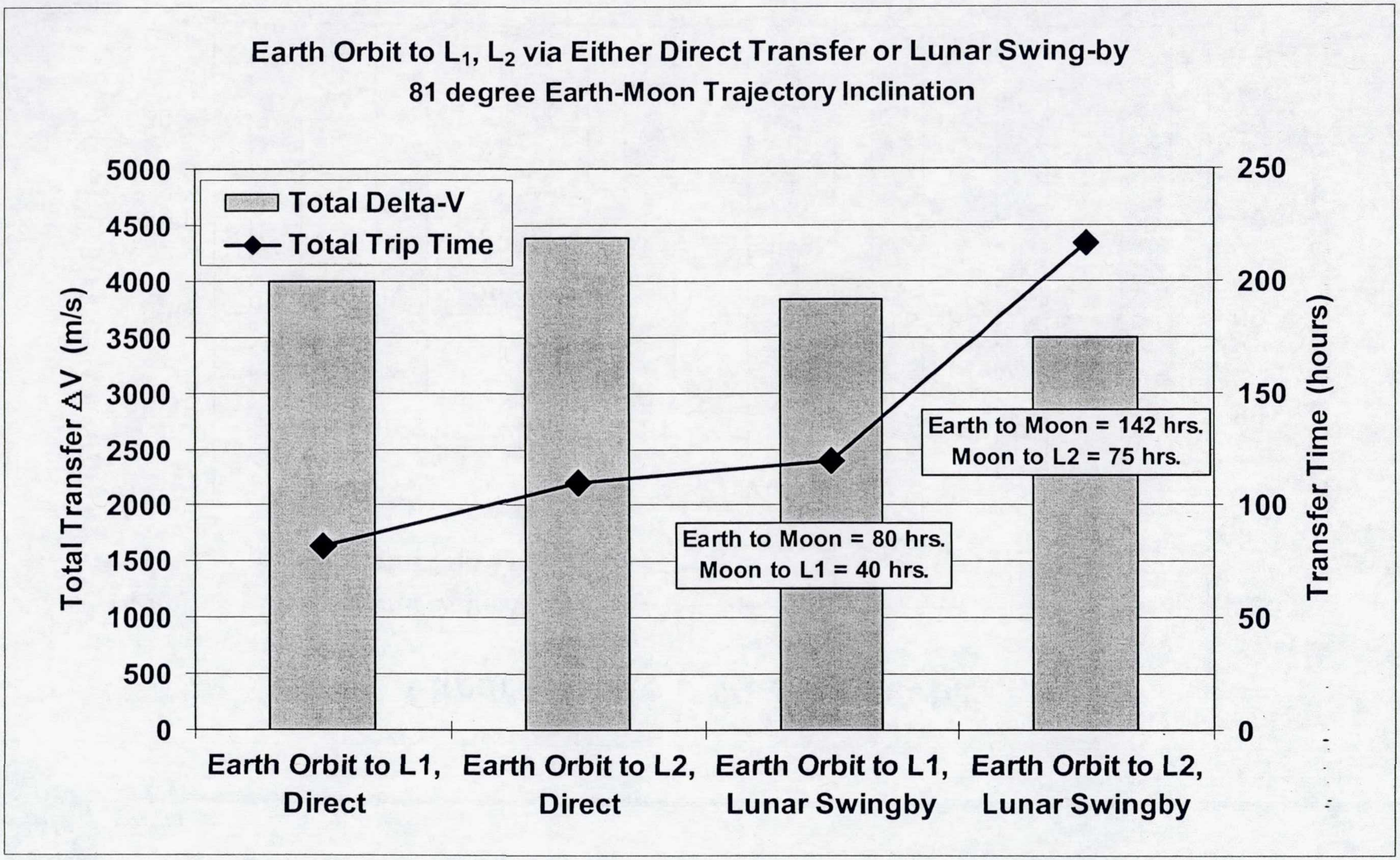


Reference: K. Joosten
Lunar Outpost Site Location
Implications to Mission Planning

Additional Charts

Earth Orbit to Earth-Moon L1, L2

JSC



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Lunar Orbit to Earth-Moon L2/L2 Halo

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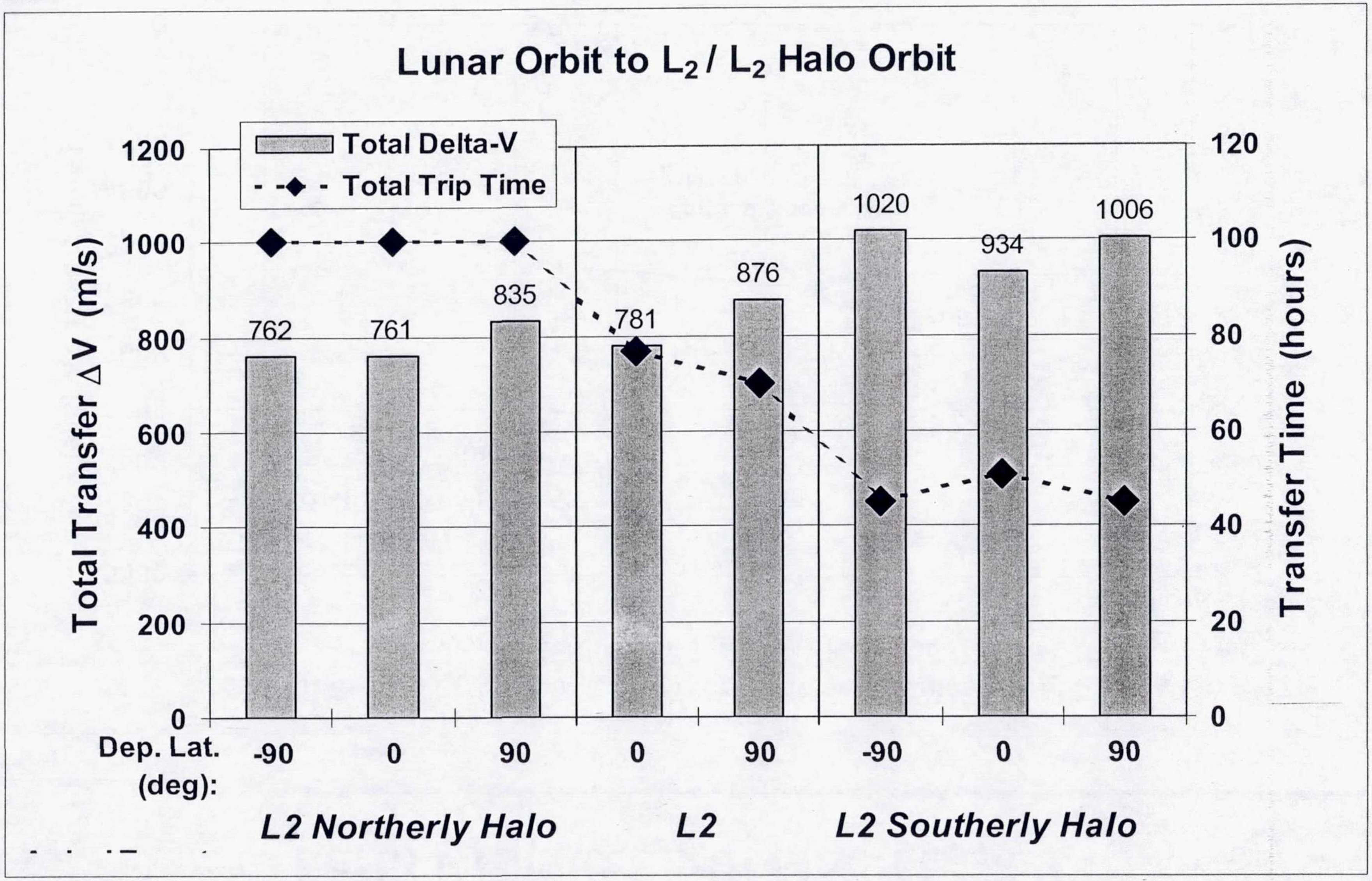
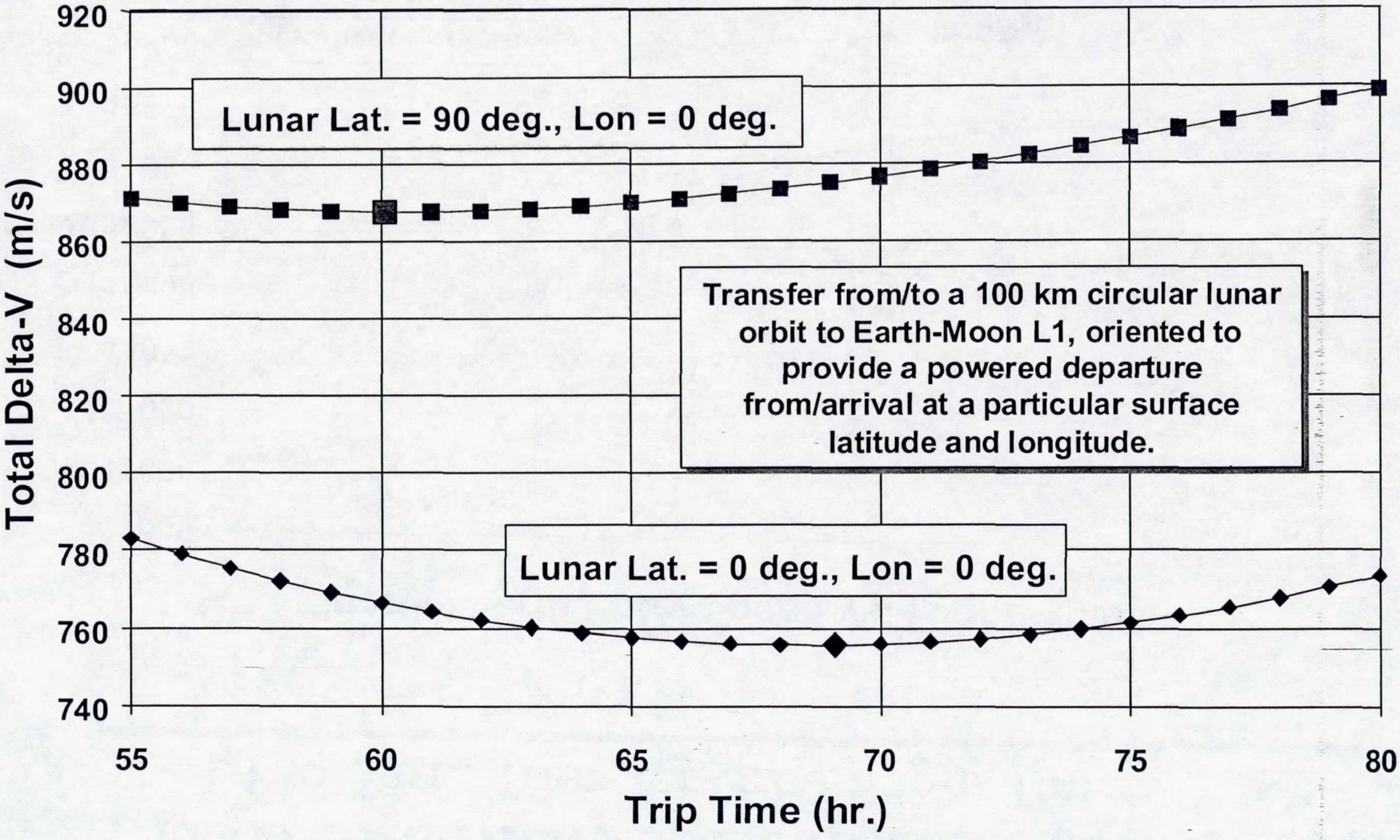


Earth-Moon L1 to Lunar Orbit

JSC



Total ΔV vs. Trip Time

Maximum and Minimum ΔV Cost for Lunar Orbit to Earth-Moon L1 Transfer

Lunar Lat. = 90 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.

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

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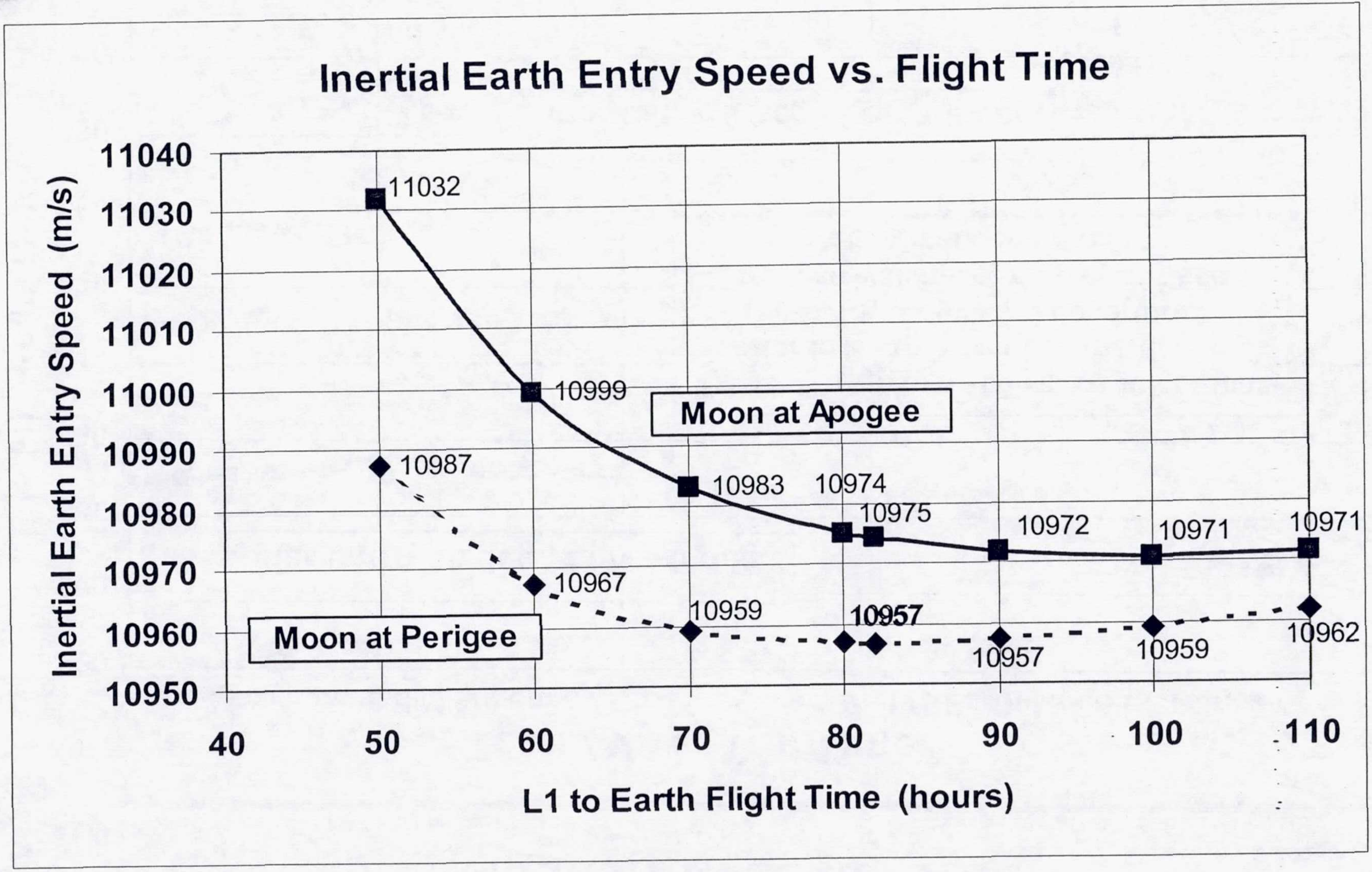
Inertial Earth Entry Speed vs. Earth-Moon L1 to Earth Transfer Orbit Flight Time


Inertial Earth Entry Speed vs. Flight Time

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

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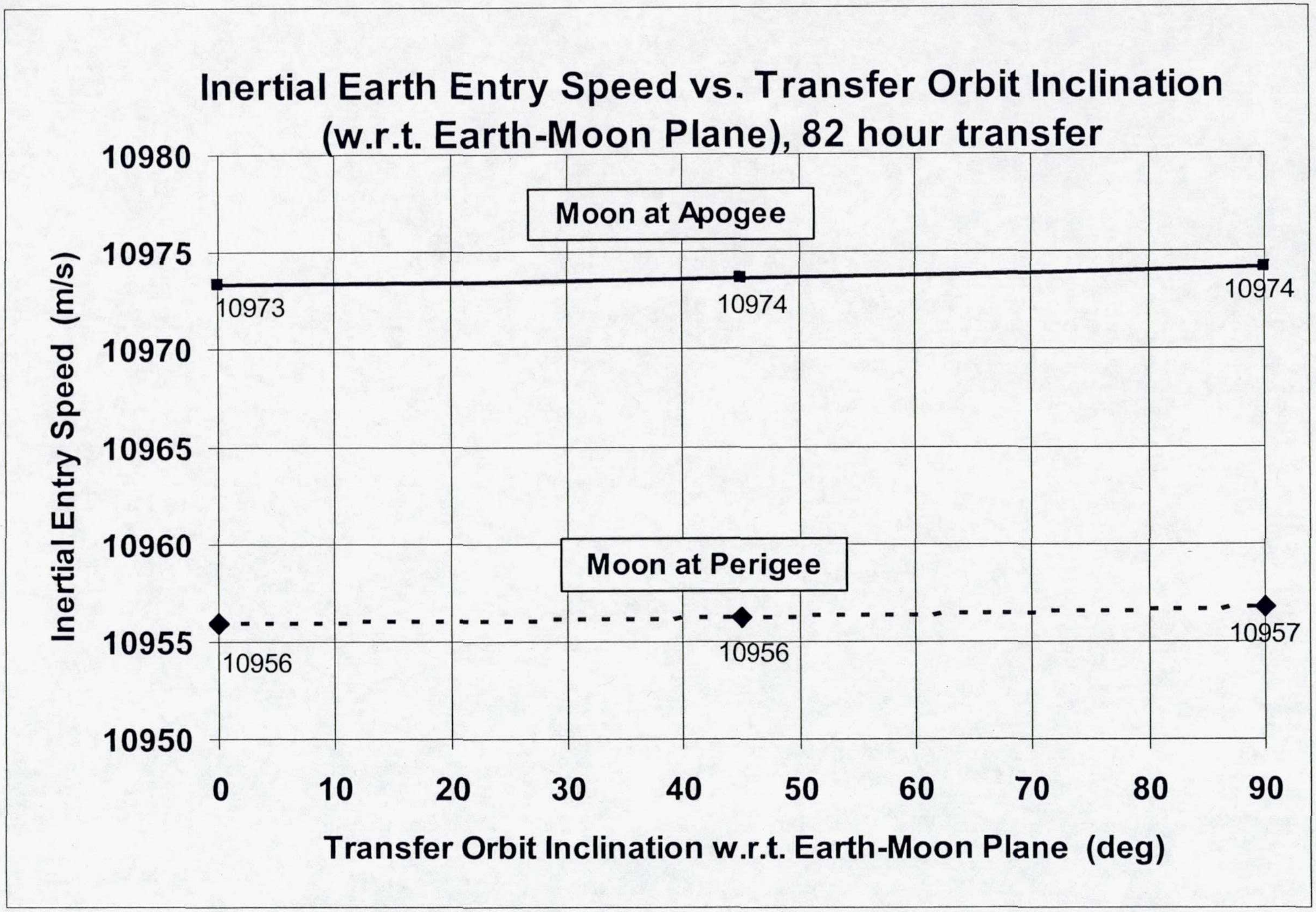

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American Astronautical Society

October 17, 2003

Jerry Condon
NASA/JSC
Advance Mission Design Branch
Mail Code EG5
2101 NASA Parkway
Houston, TX 77058

Dear Jerry:

I am pleased to inform you that your paper, *"Apollo Style vs. Libration Point Stopover Methodologies For Human Lunar Missions,"* has been selected for presentation in the *Back to the Moon* session at the 2004 AAS Guidance and Control Conference, and will be presented on February 07, 2004. Your paper designation is: *04-066*. Your paper will also be included in the publication of the Conference Proceedings.

Please prepare your paper and presentation in accordance with our conference guidelines available on our website **http://www.aas-rocky-mountain-section.org**. A sample cover sheet is also available on the website. If you do not have access to the web site, let me know and I will send the information to you. Deliver a camera-ready copy of your paper to me no later than the beginning of your session at the conference. Also bring 160 copies of your paper to the conference for distribution during your session, since the proceedings are published after the conference. If you prefer to mail the copies, they should be sent to: Beaver Run Resort, 620 Village Road, Breckenridge, CO 80424, Attn: *Your Name*, AAS Guidance and Control Conference.

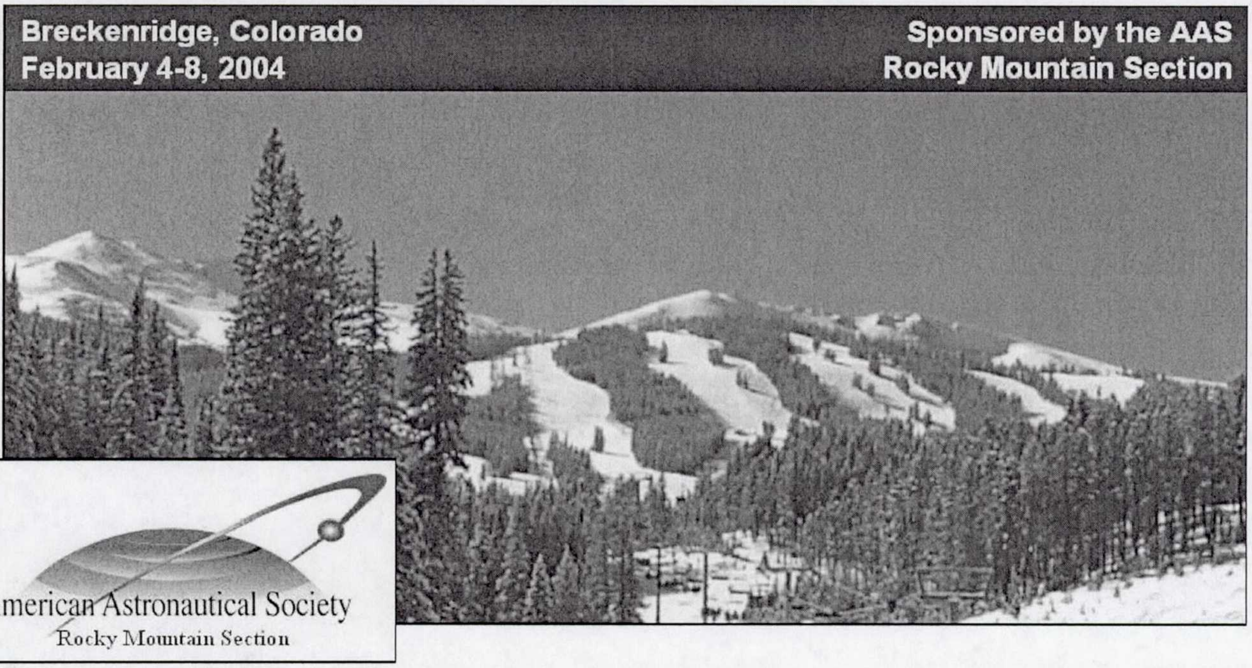
Please stay in touch with me regarding any issues with the production or clearance of your paper. **You are responsible for obtaining all of the appropriate releases and clearances required by your organization.** A standard PC-based projection system (incl. PowerPoint and Adobe Acrobat) as well as a standard viewgraph projector will be available for your use. Let me know if you need any special audiovisual equipment (e.g., video tape player). If possible, identify an alternate presenter who could fill in for you if you are unable to attend the conference. Since our format is a single session format, the loss of a paper is a disappointment to everyone.

Thank you for your commitment and support of this conference and I look forward to seeing you and enjoying your presentation at the conference.

Sincerely,

Michael Drews
Session V Local Chairperson
2004 AAS G&C Conference

27th ANNUAL AAS GUIDANCE & CONTROL CONFERENCE



Breckenridge, Colorado
February 4-8, 2004

Sponsored by the AAS
Rocky Mountain Section

American Astronautical Society
Rocky Mountain Section

Please see our website: http://www.aas-rocky-mountain-section.org for additional information on the Conference, Beaver Run Resort, recreational activities, and the town of Breckenridge, CO.

CONFERENCE AGENDA

Wednesday, February 4

Evening: Registration

Room check-in at the Beaver Run Resort front desk.

Conference registration and a **Wine and Cheese Social** from 5:30 to 7:30 at the Beaver Run Conference Center.

Thursday, February 5

Morning: Session I – "Advances in Guidance and Control"

THEME: This session features papers offering innovative ideas in G&C. The scope includes theoretical developments, unique mission possibilities, system architecture, autonomous operations, and new applications. The papers also offer advances in system simulation approaches and testing.

Co-Chairperson: Leslie Livesay, NASA/Jet Propulsion Laboratory, 818-354-2705 – *leslie.l.livesay@jpl.nasa.gov*
Co-Chairperson: Luisella Giulicchi, European Space Agency, +31 71 565 5652 – *luisella.giulicchi@esa.int*
Local Chairperson: Eileen Dukes, Consultant, 303-838-9806 – *eileendukes@earthlink.net*

Afternoon: Session II – "Unmanned Aerial Vehicle Guidance and Control"

THEME: Unmanned aerial vehicles are rapidly becoming the remote sensing platform of choice when long-dwell observations are required over particular regions of interest. Applications can include tactical operations support, environmental monitoring, and planetary exploration. This session address the guidance, navigation, and control aspects of these missions, including issues associated with remote piloting and autonomous flight.

Co-Chairperson: Robert Braun, NASA/Langley Research Center, 757-864-4507 – *robert.braun@aerospace.gatech.edu*
Co-Chairperson: Mark Skoog, NASA/Dryden Flight Research Center, – *mark.a.skoog@nasa.gov*
Local Chairperson: William Frazier, Ball Aerospace & Technologies, 303-939-4986 – *wfrazier@ball.com*

(Conference Agenda Continued on Reverse Side)

Friday, February 6

Morning: Session III – "Enabling Technologies for Precision Pointing Spacecraft"

THEME: Emerging spacecraft missions employing large deployable structures, constellations of free-flyers, and robotic assembly and servicing demand precision pointing. This session features papers addressing guidance, navigation and control system architectures, hardware, and algorithms critical to achieving the pointing control requirements for advanced spacecraft. The scope will include technology requirements, system trade studies, high-fidelity modeling and simulation, hardware-in-the-loop testing, and on-orbit flight data.

Co-Chairperson:	Albert Bosse, Naval Research Laboratory, 202-767-0899 – *albert.bosse@nrl.navy.mil*
Co-Chairperson:	Jesse Leitner, NASA/Goddard Space Flight Center, 301-286-2630 – *jesse.leitner@nasa.gov*
Local Chairperson:	Jay Brownfield, Honeywell, 303-681-3316 – *jay.brownfield@honeywell.com*
Assisted by:	Lawrence Germann, Left Hand Design, 303-652-2786 – *lgermann@lefthand.com*

Evening: Session IV – "Storyboards"

THEME: This session is an important opportunity to display and present advances in guidance, navigation, and control components. In addition, qualified papers associated with the hardware or other qualified papers submitted for consideration can be presented in this session and are eligible for publication in the Conference Proceedings. Conference attendees are able to discuss the innovative hardware and papers with presenters and authors in an interactive environment. *Attendees and family welcome to participate!*

Chairperson:	Joseph Vellinga, Lockheed Martin Space Systems, 303-971-9309 – *joseph.m.vellinga@lmco.com*
Co-Chairperson:	Rick Jackson, Consultant, 303-985-1972 – *ricski_jackson@yahoo.com*

Saturday, February 7

Morning: Session V – "Back to the Moon"

THEME: New missions to the moon, including orbital, surface, and sample returns, have become of increasing interest both to the NASA science community and to certain commercial interests – even including Hollywood! The recent release of the Decadal Survey has placed a very high priority on the Aitkin Basin lunar sample return mission. NASA entities and their partners are vying for NASA's New Frontiers Program funding. In addition, international interest is growing and China has announced intent to carry out human exploration on the moon. The guidance and control challenges of executing successful lunar landings have not diminished in the 35 years since the last Apollo mission. This session features papers that explore the history of G&C in lunar missions, and then looks at upcoming challenges facing our community with these exciting new missions.

Co-Chairperson:	Karen Frank, NASA/Johnson Space Center, 281-483-8297 – *karen.d.frank@nasa.gov*
Co-Chairperson:	Richard Phillips, Draper Laboratory, 617-258-2430 – *rphillips@draper.com*
Local Chairperson:	Michael Drews, Lockheed Martin Space Systems, 303-971-3622 – *michael.e.drews@lmco.com*
Assisted by	Steven Jolly, Lockheed Martin Space Systems, 303-971-6758 – *steven.d.jolly@lmco.com*

Evening: Banquet

Dinner with Prof. Richard Battin, Massachusetts Institute of Technology, presenting "A Funny Thing Happened on the Way to the Moon." Prof. Battin is an engineer, applied mathematician, and educator who developed and led the analytic and software design of the Apollo spacecraft primary control, guidance, and navigation system that landed men on the moon. His other important and fundamental contributions to space flight mechanics include the key discovery that made possible the first ever gravity-assisted multiple fly-by orbit from Earth to Venus to Mars to Earth on Jan. 2, 1961. Three of his students from MIT walked on the moon, and the first woman space shuttle astronaut from MIT was his teaching assistant.

Sunday, February 8

Morning: Session VI – "Recent Experiences"

THEME: Lessons learned through experience prove most valuable when shared with others in the G&C community. This session, which is a traditional part of the conference, provides a forum for candid sharing of insights gained through successes and failures. Past conferences have shown this session to be most interesting and informative.

Co-Chairperson:	Michael Hughes, NASA/Jet Propulsion Laboratory, 818-354-8558 – *michael.p.hughes@jpl.nasa.gov*
Co-Chairperson:	Brent Robertson, NASA/Goddard Space Flight Center, 301-286-6392 – *brent.robertson@gsfc.nasa.gov*
Local Chairperson:	Charlie Schira, Ball Aerospace & Technologies, 303-939-6619 – *cschira@ball.com*
Assisted by	Heidi Hallowell, Ball Aerospace & Technologies, 303-939-6131 – *hhallowe@ball.com*

2004 AAS Guidance & Control Conference, Feb 4-8, 2004
Beaver Run Resort and Conference Center, Breckenridge, Colorado

For more information, visit our website at *http://www.aas-rocky-mountain-section.org*

ADVANCE REGISTRATION

We encourage Advance Registration to help the Committee in advanced planning and to minimize congestion at the conference registration desk.

The conference fee is $360.00 for AAS members, $400.00 for nonmembers, and $180.00 for students. A special offer of $45.00 added to the nonmember registration ($445.00 total) will include a one-year membership to the National AAS. All registration fees include continental breakfast each day, storyboard buffet, banquet, and lecture notes. Additional banquet tickets for guests are available for an additional $35.00 each. Copies of the 2004 Conference Proceedings, which may be ordered below, will be available in mid-2004. For further information, contact Marv Odefey at 303-683-7541, *m.odefey@comcast.net*, or Deb Wright at 303-971-6962, *deborah.l.wright@lmco.com*.

Reservations for lodging must be made directly with Beaver Run Resort in Breckenridge, 800-525-2253 or 970-453-6000 (see enclosed registration form). The block of rooms reserved for AAS fill up fast—to assure availability, make your reservations by early December. Please mention you are attending the AAS Conference (#647) when making your hotel reservation.

Advance AAS registration forms must be received by January 15, 2004. Please fill out and return this form. Online Registration also available at *http://www.aas-rocky-mountain-section.org*

2004 ANNUAL AAS GUIDANCE & CONTROL CONFERENCE ADVANCE REGISTRATION FORM

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Abstract

The 27th annual AAS Guidance and Control Conference
will be held at the Beaver Run Resort in Breckenridge, Colorado,
Dates: February 4 - 8, 2004.

Apollo Style vs. Libration Point Stopover Methodologies For Human Lunar Missions

For some three decades, the Apollo-style mission has served as a proven baseline technique for transporting flight crews to the Moon and back with expendable hardware. This approach provides an optimal design for expeditionary missions, emphasizing operational flexibility in terms of safely returning the crew in the event of a hardware failure. However, its application is limited essentially to low-latitude lunar sites, and it leaves much to be desired as a model for exploratory and evolutionary programs that employ reusable space-based hardware. This study compares the performance requirements for a lunar orbit rendezvous mission type with one using the cislunar libration point (L1) as a stopover and staging point for access to arbitrary sites on the lunar surface. For selected constraints and mission objectives, it contrasts the relative uniformity of performance cost when the L1 staging point is used with the wide variation of cost for the Apollo-style lunar orbit rendezvous.