JSC

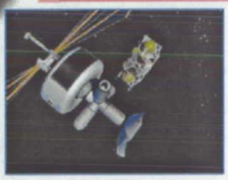
EARTH TO MOON TRANSFERS
DIRECT VS VIA LIBRATION POINTS (L1, L2)

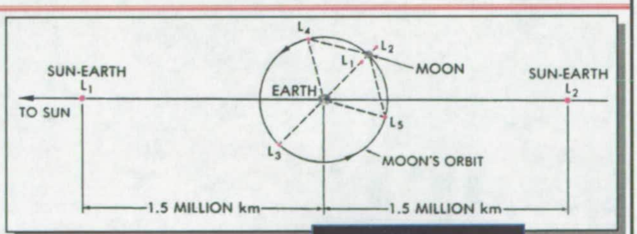
Gerald L. Condon
Sam Wilson
Johnson Space Center / Aeroscience and Flight Mechanics Division

October 9, 2002

Libration Point Missions

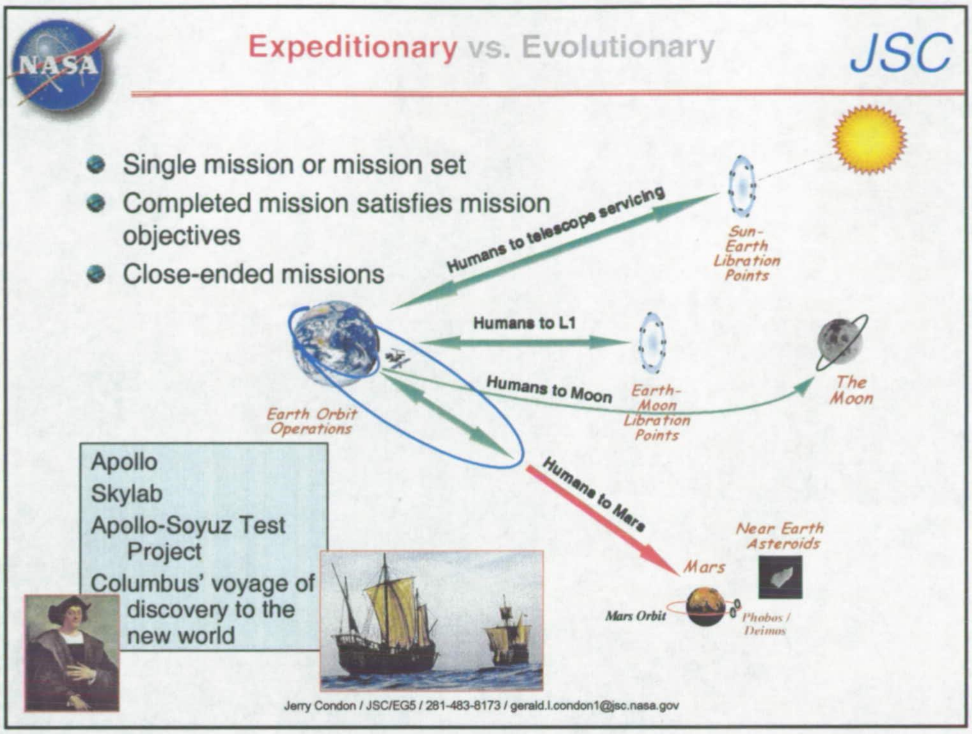
JSC

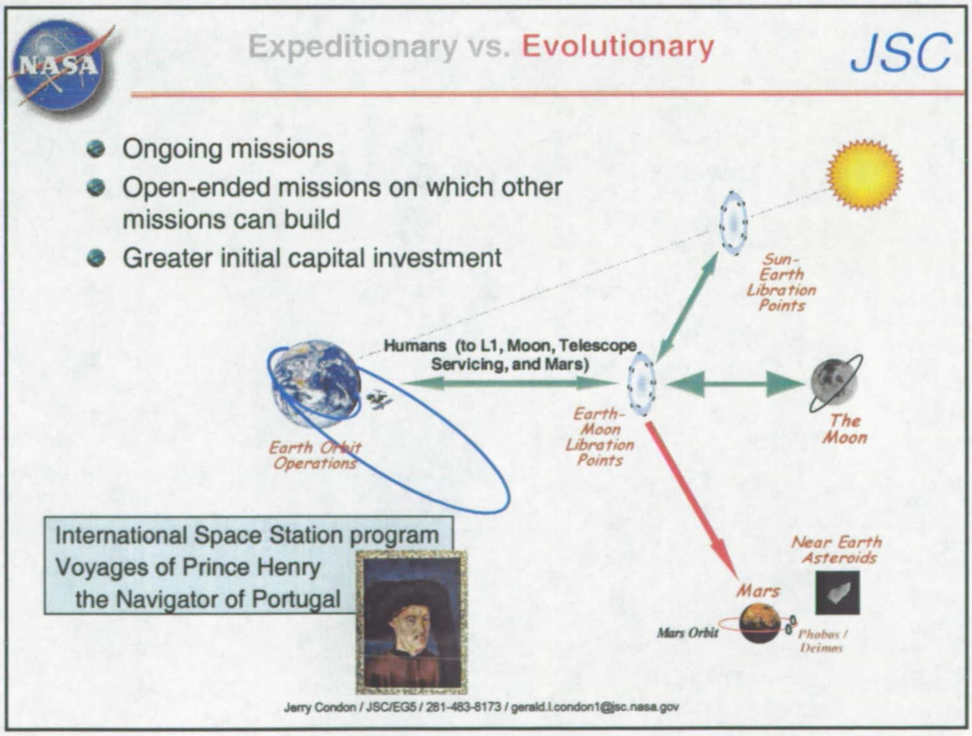




- Earth-Moon L1
  - Gateway station
    - Sorties to the Moon
    - Satellite deploy, servicing
      - Next Generation Space Telescope
      - Terrestrial Planet Finder
    - Staging area for interplanetary and asteroid missions

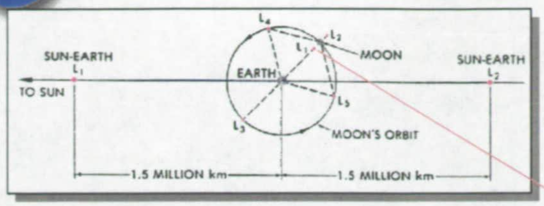
- Earth-Moon L2
  - Robotic relay satellites
    - Communications relay
    - Navigation aid
- Sun-Earth L2
  - Human missions to extend human presence in space


Expeditionary vs. Evolutionary
JSC
Single mission or mission set
Completed mission satisfies mission objectives
Close-ended missions
Humans to telescope servicing
Sun-Earth Libration Points
Humans to L1
Humans to Moon
Earth-Moon Libration Points
The Moon
Earth Orbit Operations
Humans to Mars
Near Earth Asteroids
Mars
Mars Orbit
Phobos / Deimos
Apollo
Skylab
Apollo-Soyuz Test Project
Columbus' voyage of discovery to the new world
Jerry Condon / JSC/EG5 / 281-483-8173 / gerald.l.condon1@jsc.nasa.gov

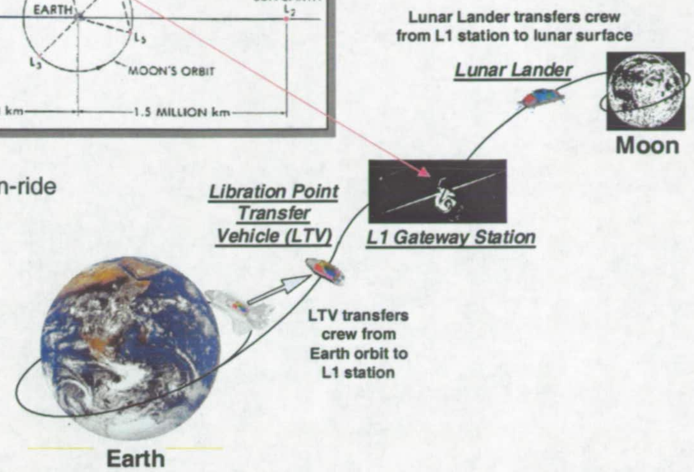

Expeditionary vs. Evolutionary
JSC
Ongoing missions
Open-ended missions on which other missions can build
Greater initial capital investment
Sun-Earth Libration Points
Humans (to L1, Moon, Telescope Servicing, and Mars)
Earth-Moon Libration Points
The Moon
Earth Orbit Operations
Near Earth Asteroids
Mars
Mars Orbit
Phobos / Deimos
International Space Station program
Voyages of Prince Henry the Navigator of Portugal
Jerry Condon / JSC/EG5 / 281-483-8173 / gerald.l.condon1@jsc.nasa.gov

Earth-Moon L1 – Gateway for Lunar Surface Operations

JSC



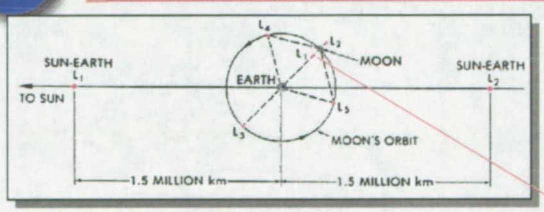
- Celestial park-n-ride
- Close to home (3-4 days)
- Staging to:
  - Moon



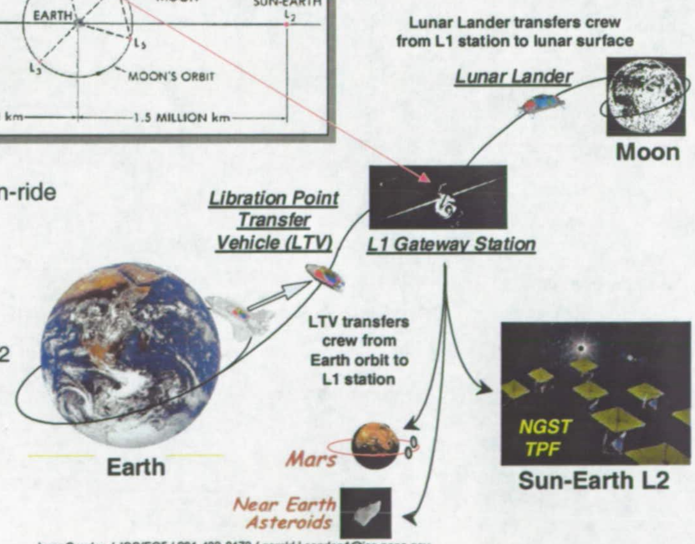
Jerry Condon / JSC/EG5 / 281-483-8173 / gerald.l.condon1@jsc.nasa.gov

Earth-Moon L1 – Gateway for Lunar Surface Operations

JSC



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

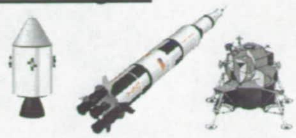


Jerry Condon / JSC/EG5 / 281-483-8173 / gerald.l.condon1@jsc.nasa.gov

Lunar Mission: Libration Point vs. LOR

JSC

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

Jerry Condon / JSC/EG5 / 281-483-8173 / gerald.l.condon1@jsc.nasa.gov

Apollo-Style Mission Characteristics – Nominal Profile

JSC

- 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

Jerry Condon / JSC/EG5 / 281-483-8173 / gerald.l.condon1@jsc.nasa.gov

Require Polar Landing Site

JSC

- 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

Jerry Condon / JSC/EG5 / 281-483-8173 / gerald.l.condon1@jsc.nasa.gov

Require Global Lunar Surface Access

JSC

- 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)

Jerry Condon / JSC/EG5 / 281-483-8173 / gerald.l.condon1@jsc.nasa.gov

Require Reuse of LM and Descent Propulsion Stage

JSC

- 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

Jerry Condon / JSC/EG5 / 281-483-8173 / gerald.l.condon1@jsc.nasa.gov

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

JSC

- 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

Jerry Condon / JSC/EG5 / 281-483-8173 / gerald.l.condon1@jsc.nasa.gov

Require Earth Departure from ISS Orbit

JSC

- 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

Jerry Condon / JSC/EG5 / 281-483-8173 / gerald.l.condon1@jsc.nasa.gov

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

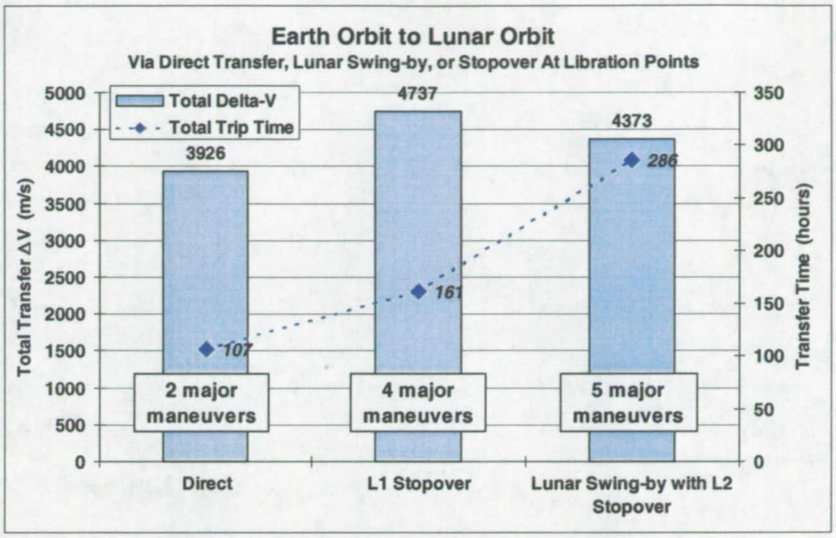
JSC

- 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.

Jerry Condon / JSC/EG5 / 281-483-8173 / gerald.l.condon1@jsc.nasa.gov

Earth Orbit to Lunar Orbit

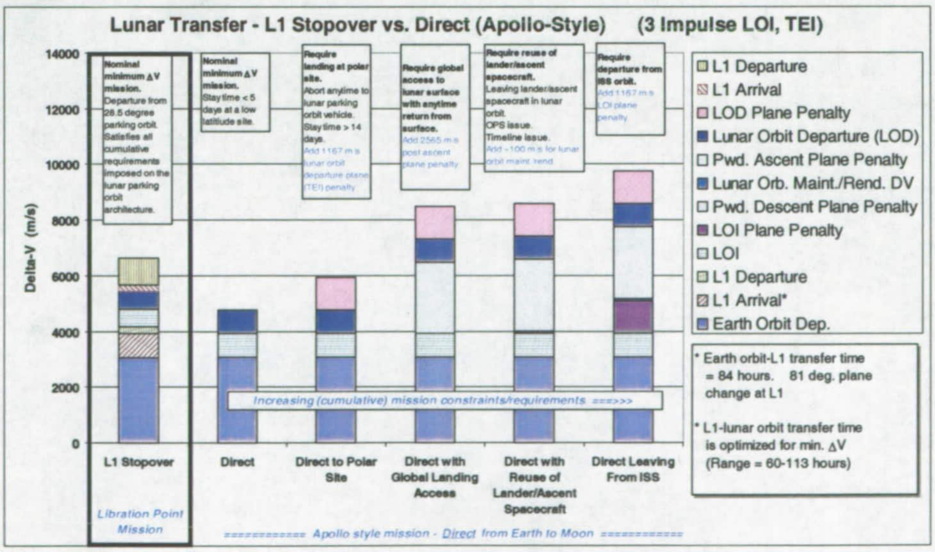
JSC



Jerry Condon / JSC/EG5 / 281-483-8173 / gerald.l.condon1@jsc.nasa.gov

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

JSC



Jerry Condon / JSC/EG5 / 281-483-8173 / gerald.l.condon1@jsc.nasa.gov

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

JSC

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.

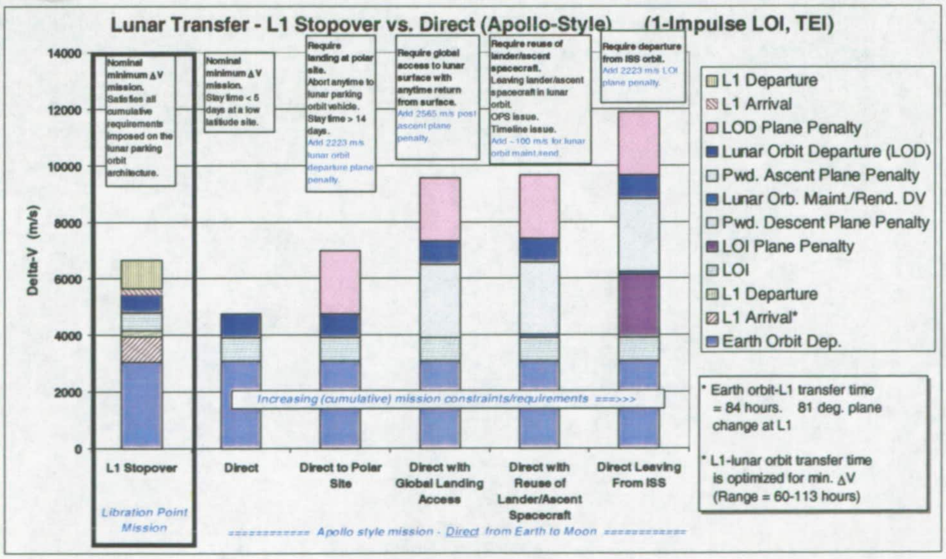
Order of increasing missions constraints (constraint are cumulative) ===>

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, 84 hour xfer, 81 deg pl	889	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, 84 hour xfer, 81 deg. pln. chg.	984	0	0	0	0	0
Total	6653	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

Jerry Condon / JSC/EG5 / 281-483-8173 / gerald.l.condon1@jsc.nasa.gov

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

JSC



Jerry Condon / JSC/EG5 / 281-483-8173 / gerald.l.condon1@jsc.nasa.gov

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

JSC

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.

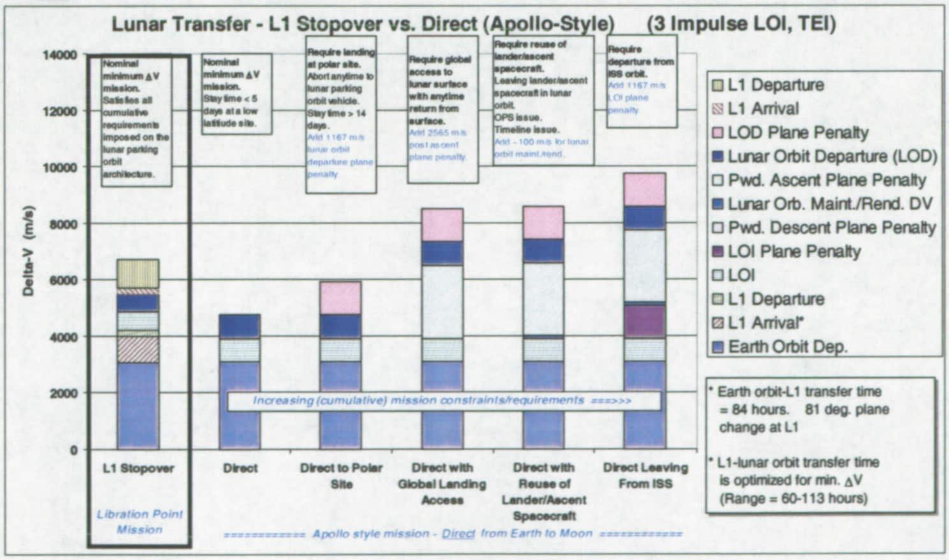
Order of increasing missions constraints (constraint are cumulative) ===>

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, 84 hour xfer, 57.1 deg	889	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, 84 hour xfer, 81 deg. pln. chg.	984	0	0	0	0	0
Total	**6653**	**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

Jerry Condon / JSC/EG5 / 281-483-8173 / gerald.l.condon1@jsc.nasa.gov

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

JSC



Jerry Condon / JSC/EG5 / 281-483-8173 / gerald.l.condon1@jsc.nasa.gov

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

JSC

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.

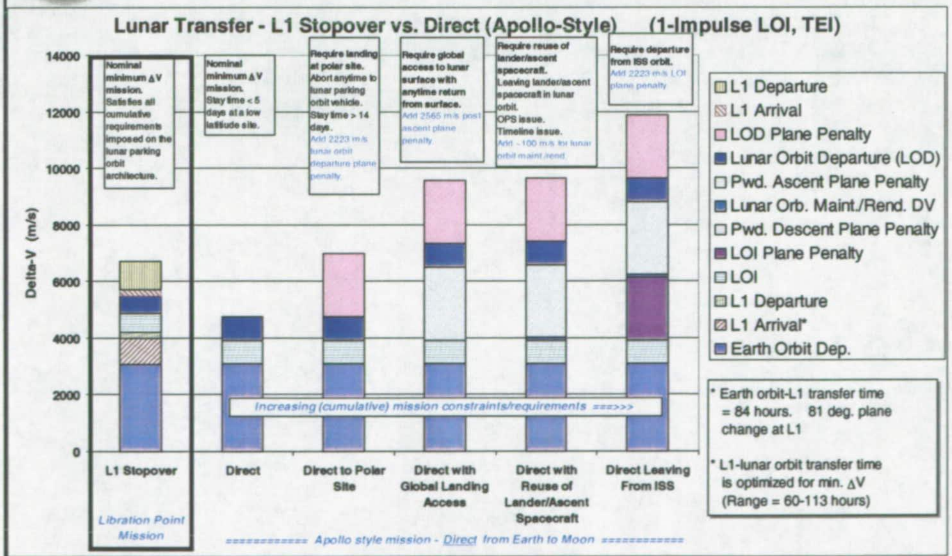
Order of increasing missions constraints (constraint are cumulative) ===>

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	3074	3086	3086	3086	3086	3086
L1 Arrival, 84 hour xfer, 81 deg pl	919	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, 84 hour xfer, 81 deg. pln. chg.	984	0	0	0	0	0
Total	6703	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

Jerry Condon / JSC/EG5 / 281-483-8173 / gerald.l.condon1@jsc.nasa.gov

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

JSC



Jerry Condon / JSC/EG5 / 281-483-8173 / gerald.l.condon1@jsc.nasa.gov

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

JSC

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) ===>

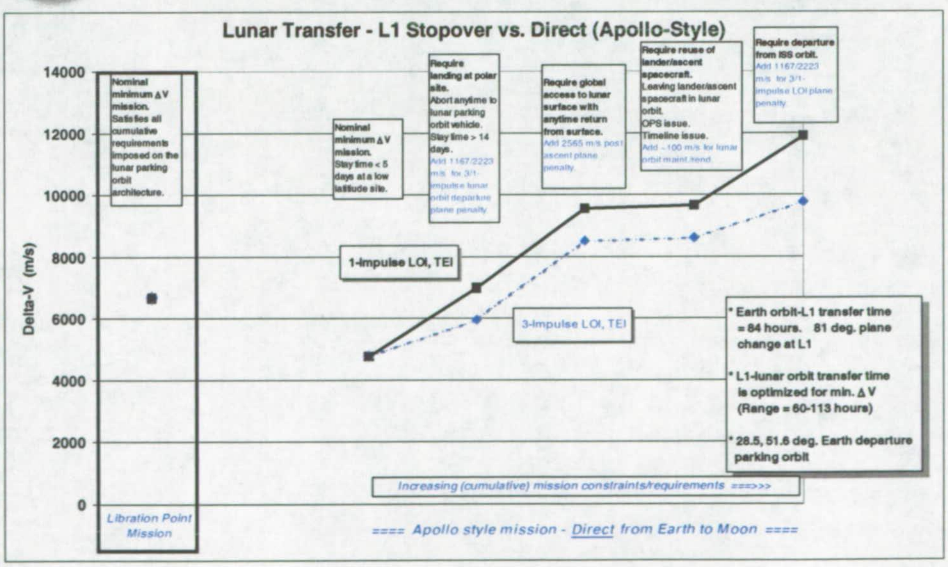
Transfer Scenario	L1 Stopover	Direct	Direct to Polar Site	Direct with Global Landing Access	Direct with Reuse of Lander/Ascent Spacecraft	Direct Leaving From ISS
Earth Orbit Departure	3074	3086	3086	3086	3086	3086
L1 Arrival, 84 hour xfer, 81 deg pl	919	0	0	0	0	0
L1 Departure	228	0	0	0	0	0
LOI	635	841	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, 84 hour xfer, 81 deg. pln. chg	984	0	0	0	0	0
Total	6703	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

Jerry Condon / JSC/EG5 / 281-483-8173 / gerald.l.condon1@jsc.nasa.gov

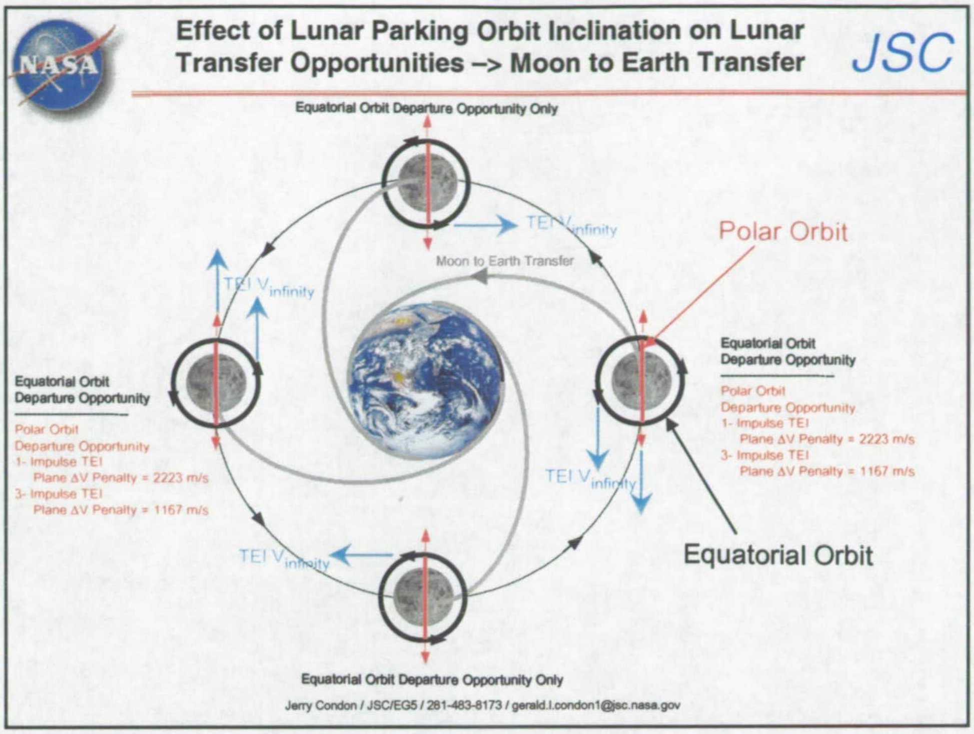
Total Mission ΔV L1 Stopover vs. Direct (Apollo Style)

1-Impulse, 3-Impulse LOI, TEI

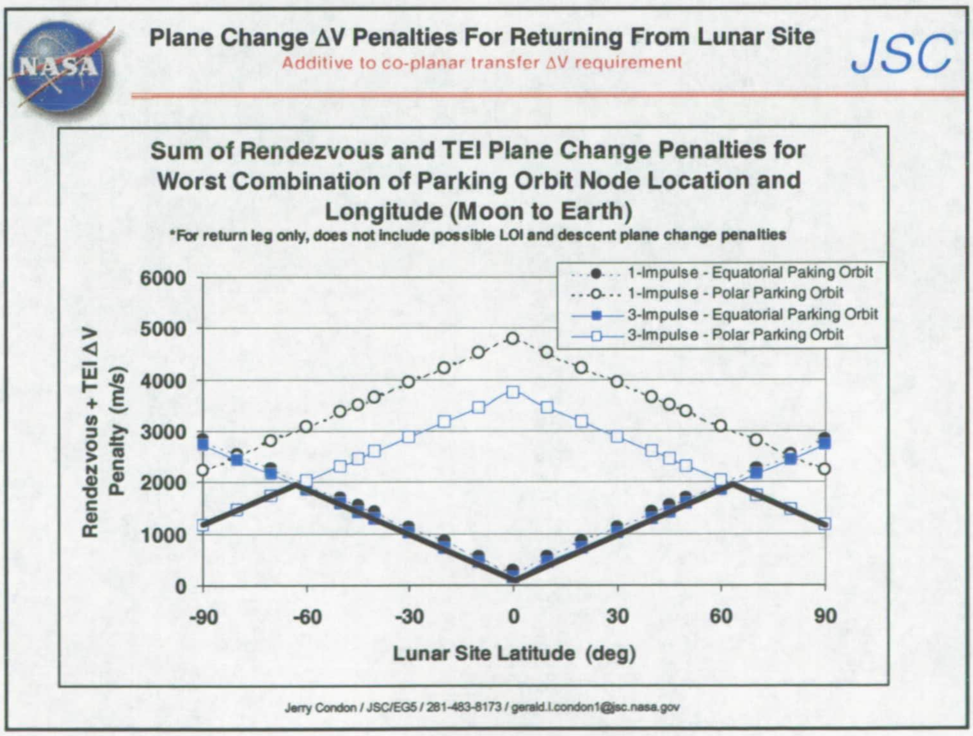
JSC



Jerry Condon / JSC/EG5 / 281-483-8173 / gerald.l.condon1@jsc.nasa.gov



Effect of Lunar Parking Orbit Inclination on Lunar Transfer Opportunities –> Moon to Earth Transfer
JSC
Equatorial Orbit Departure Opportunity Only
TEI V infinity
Moon to Earth Transfer
Polar 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
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
TEI V infinity
Equatorial Orbit
Equatorial Orbit Departure Opportunity Only
Jerry Condon / JSC/EG5 / 281-483-8173 / gerald.l.condon1@jsc.nasa.gov



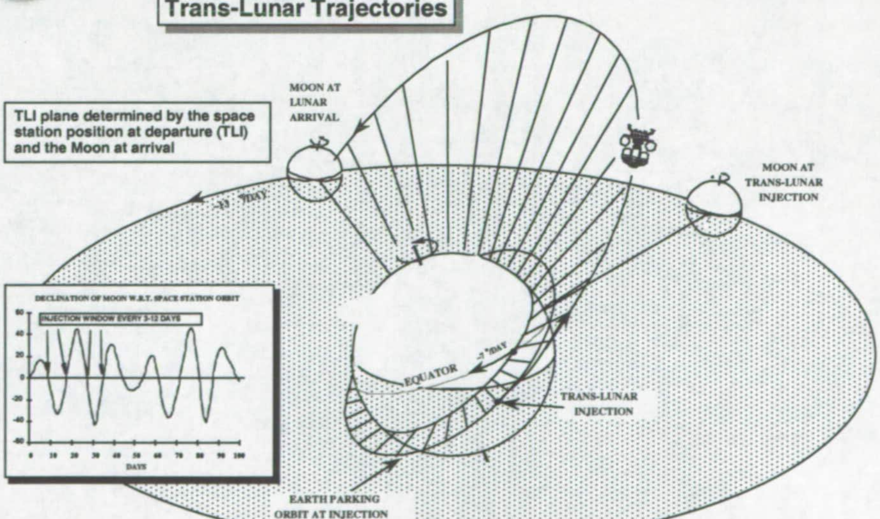
Plane Change ΔV Penalties For Returning From Lunar Site
Additive to co-planar transfer ΔV requirement
JSC
Sum of Rendezvous and TEI Plane Change Penalties for Worst Combination of Parking Orbit Node Location and Longitude (Moon to Earth)
*For return leg only, does not include possible LOI and descent plane change penalties
1-Impulse - Equatorial Paking Orbit
1-Impulse - Polar Parking Orbit
3-Impulse - Equatorial Parking Orbit
3-Impulse - Polar Parking Orbit
Rendezvous + TEI ΔV Penalty (m/s)
6000
5000
4000
3000
2000
1000
0
-90
-60
-30
0
30
60
90
Lunar Site Latitude (deg)
Jerry Condon / JSC/EG5 / 281-483-8173 / gerald.l.condon1@jsc.nasa.gov

Lunar Transfer/Orbit Diagrams

Jerry Condon / JSC/EG5 / 281-483-8173 / gerald.l.condon1@jsc.nasa.gov

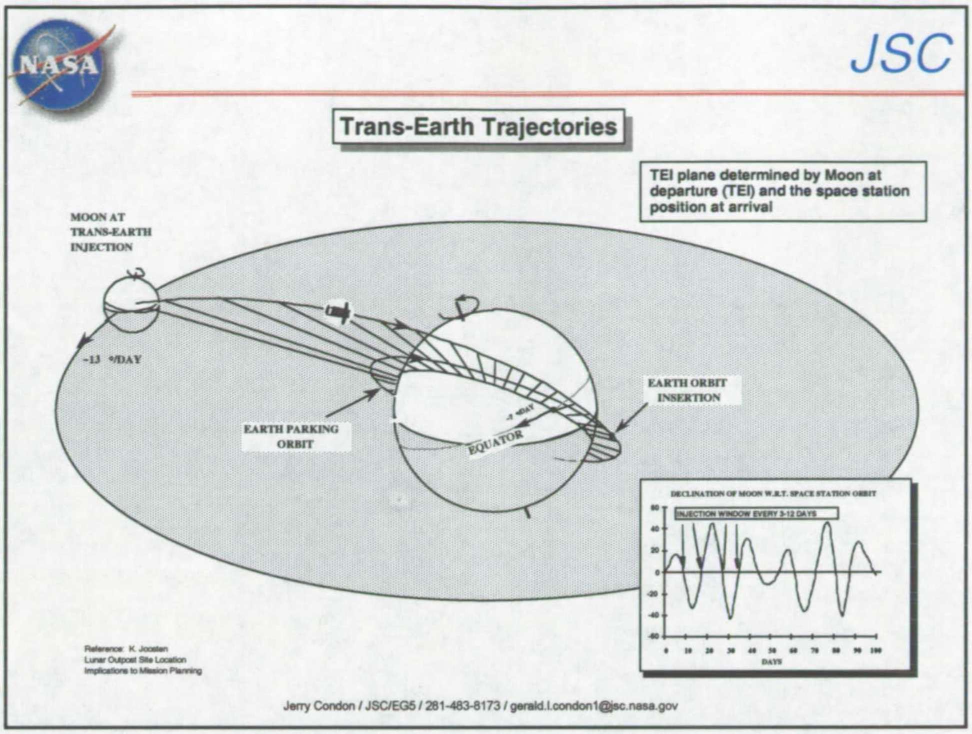
JSC

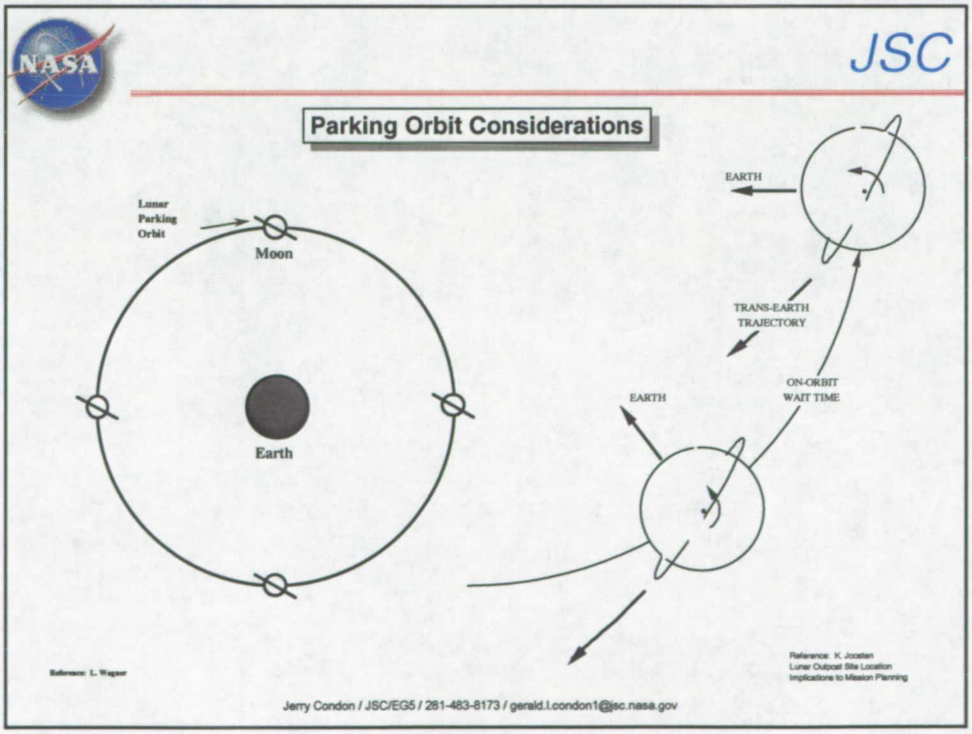
Trans-Lunar Trajectories



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

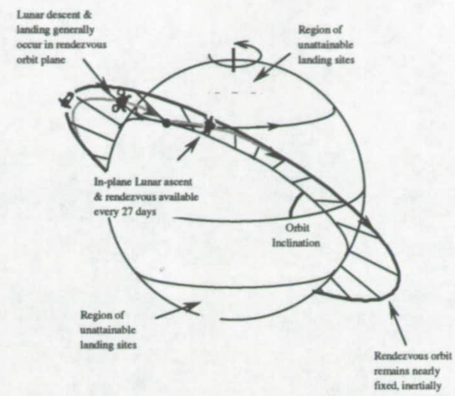
Jerry Condon / JSC/EG5 / 281-483-8173 / gerald.l.condon1@jsc.nasa.gov


JSC
Trans-Earth Trajectories
TEI plane determined by Moon at departure (TEI) and the space station position at arrival
MOON AT TRANS-EARTH INJECTION
~13 °/DAY
EARTH PARKING ORBIT
EQUATOR
EARTH ORBIT INSERTION
DECLINATION OF MOON W.R.T. SPACE STATION ORBIT
INJECTION WINDOW EVERY 3-12 DAYS
DAYS
Reference: K. Joosten
Lunar Outpost Site Location
Implications to Mission Planning
Jerry Condon / JSC/EG5 / 281-483-8173 / gerald.l.condon1@jsc.nasa.gov


JSC
Parking Orbit Considerations
Lunar Parking Orbit
Moon
Earth
EARTH
TRANS-EARTH TRAJECTORY
ON-ORBIT WAIT TIME
EARTH
Reference: L. Wagner
Reference: K. Joosten
Lunar Outpost Site Location
Implications to Mission Planning
Jerry Condon / JSC/EG5 / 281-483-8173 / gerald.l.condon1@jsc.nasa.gov

JSC

Landing Latitude Restrictions

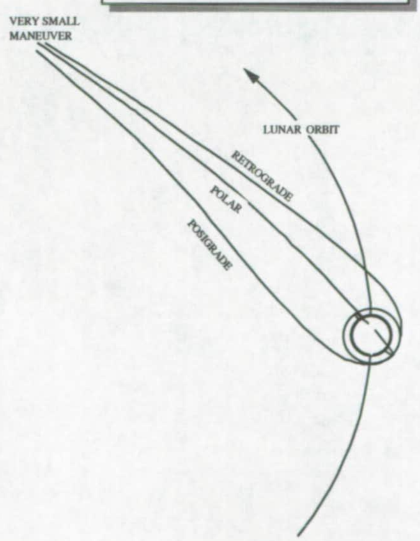


Reference: K. Joosten
Lunar Outpost Site Location
Implications to Mission Planning

Jerry Condon / JSC/EG5 / 281-483-8173 / gerald.l.condon1@jsc.nasa.gov

JSC

Variable Lunar Inclination

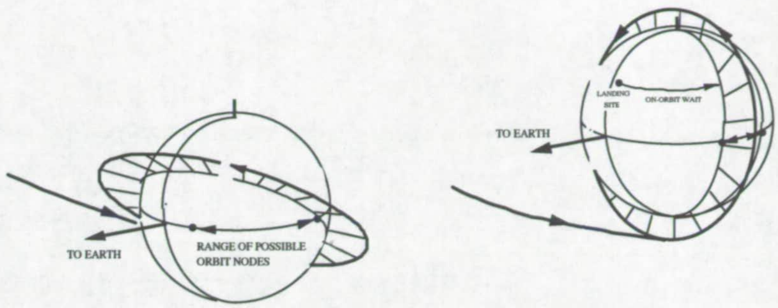


Reference: K. Joosten
Lunar Outpost Site Location
Implications to Mission Planning

Jerry Condon / JSC/EG5 / 281-483-8173 / gerald.l.condon1@jsc.nasa.gov

JSC

Variable Lunar Orbit Alignment



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

Jerry Condon / JSC/EG5 / 281-483-8173 / gerald.l.condon1@jsc.nasa.gov

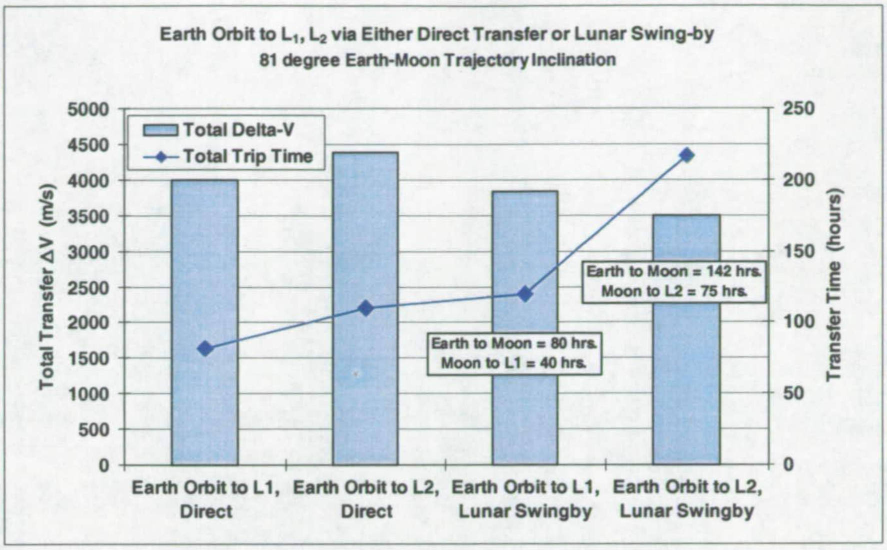
JSC

Additional Charts

Jerry Condon / JSC/EG5 / 281-483-8173 / gerald.l.condon1@jsc.nasa.gov

Earth Orbit to Earth-Moon L1, L2

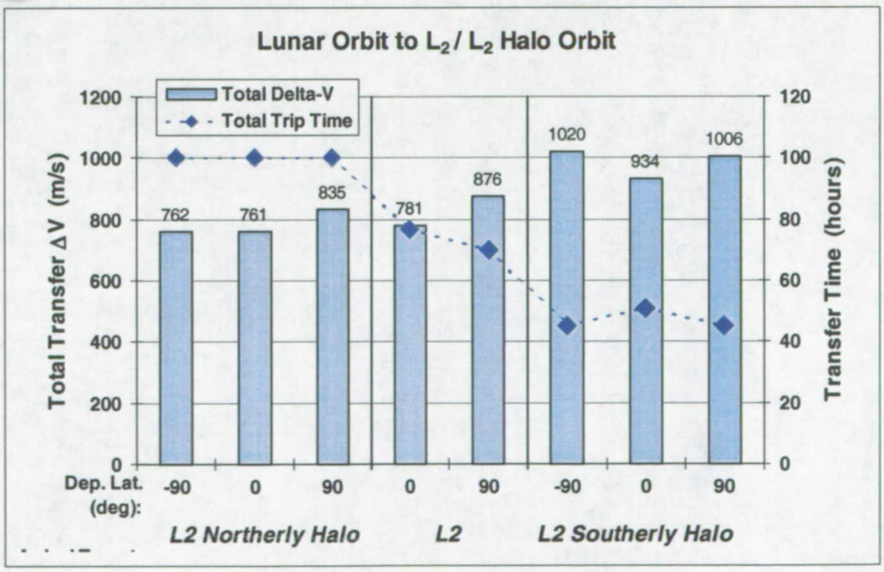
JSC



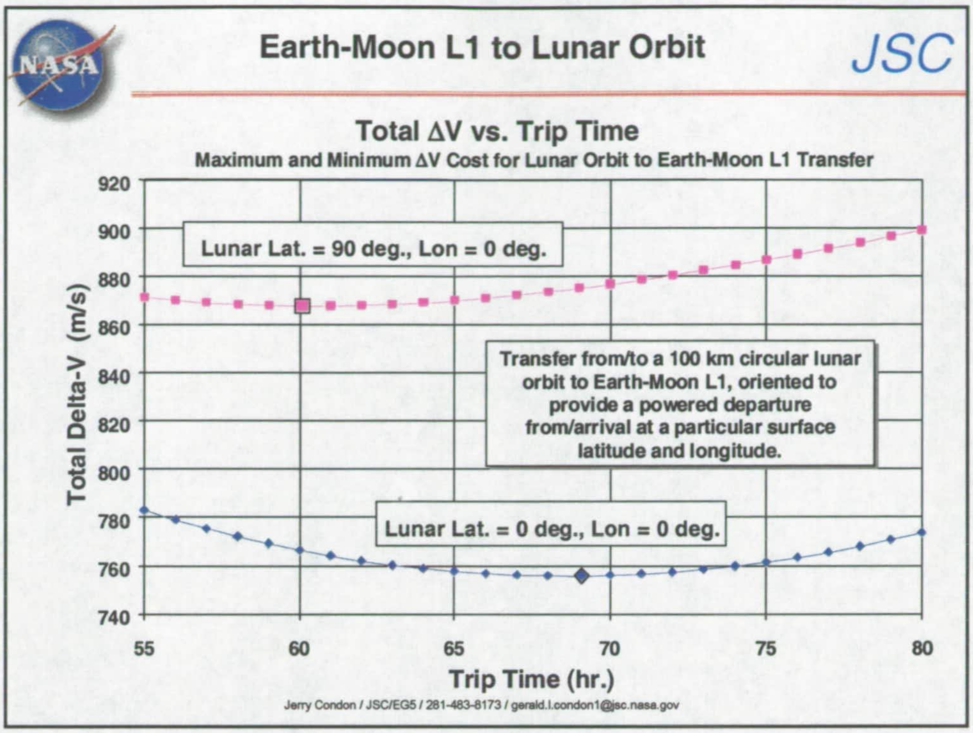
Jerry Condon / JSC/EG5 / 281-483-8173 / gerald.l.condon1@jsc.nasa.gov

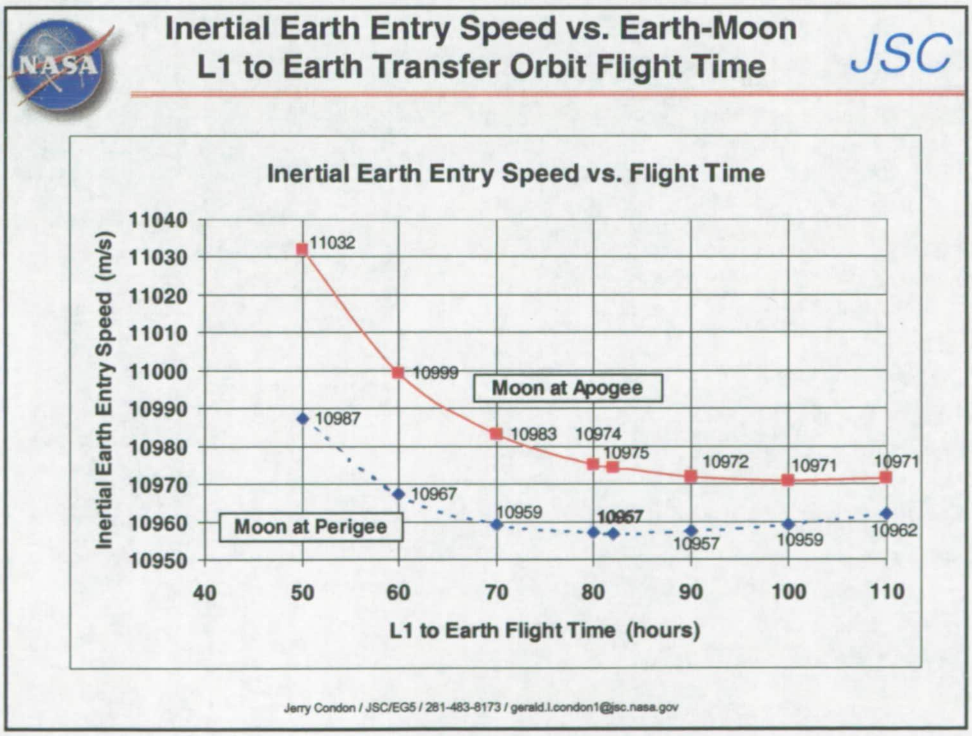
Lunar Orbit to Earth-Moon L2/L2 Halo

JSC



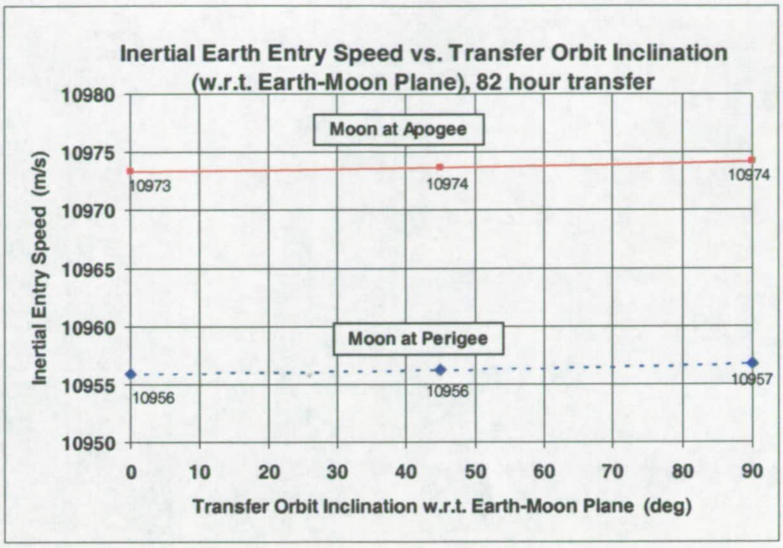
Jerry Condon / JSC/EG5 / 281-483-8173 / gerald.l.condon1@jsc.nasa.gov


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.
Total Delta-V (m/s)
920
900
880
860
840
820
800
780
760
740
55
60
65
70
75
80
Trip Time (hr.)
Jerry Condon / JSC/EG5 / 281-483-8173 / gerald.l.condon1@jsc.nasa.gov


Inertial Earth Entry Speed vs. Earth-Moon L1 to Earth Transfer Orbit Flight Time
JSC
Inertial Earth Entry Speed vs. Flight Time
Inertial Earth Entry Speed (m/s)
11040
11030
11020
11010
11000
10990
10980
10970
10960
10950
11032
10999
Moon at Apogee
10987
10983
10974
10975
10972
10971
10971
10967
10959
10957
10957
10959
10962
Moon at Perigee
40
50
60
70
80
90
100
110
L1 to Earth Flight Time (hours)
Jerry Condon / JSC/EG5 / 281-483-8173 / gerald.l.condon1@jsc.nasa.gov

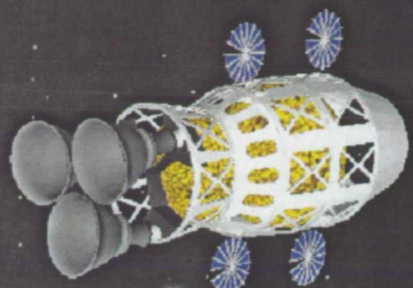
Inertial Earth Entry Speed vs. Earth-Moon L1 to Earth Transfer Orbit Inclination

JSC



Jerry Condon / JSC/EG5 / 281-483-8173 / gerald.l.condon1@jsc.nasa.gov

Earth Moon Libration Point (L1) Gateway Station – Libration Point Transfer Vehicle Kickstage Disposal Options

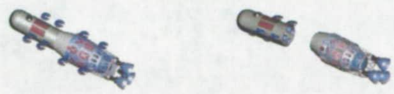


Presented to the International Conference On Libration Point Orbits and Applications
June 10-14, 2002, Parador d'Aiguablava, Girona, Spain

G. L. Condon, NASA – Johnson Space Center / EG5, 281-483-8173, gerald.l.condon1@jsc.nasa.gov
C. L. Ranieri, NASA – Johnson Space Center
S. Wilson, Elgin Software, Inc.

Acknowledgements

JSC



- Chris Ranieri* – orbit lifetime analysis
- Joey Broome# – STK/Astrogator validation/movie
- Sam Wilson+ – software development / analysis
- Daniel M. Delwood + – analysis

2

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

Outline

JSC

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

Introduction

JSC

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

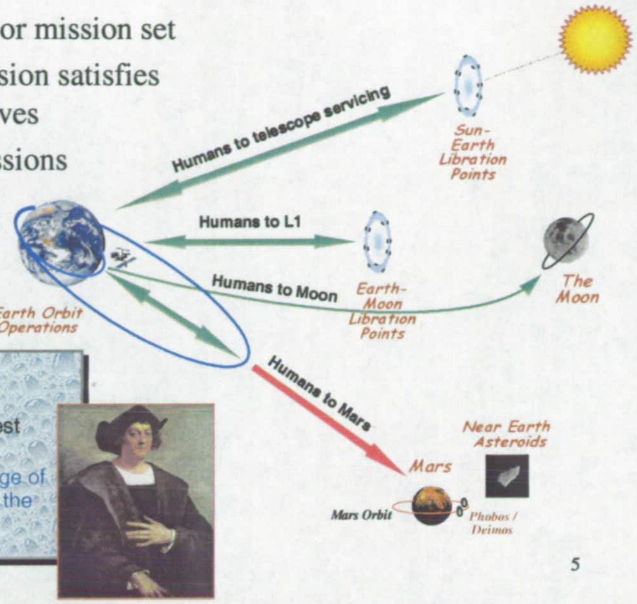
A human-tended Earth-Moon (EM) libration point (L1) Gateway Station could support an infrastructure expanding human presence beyond low Earth orbit and serve as a staging location for human missions to:

- 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 JSC

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



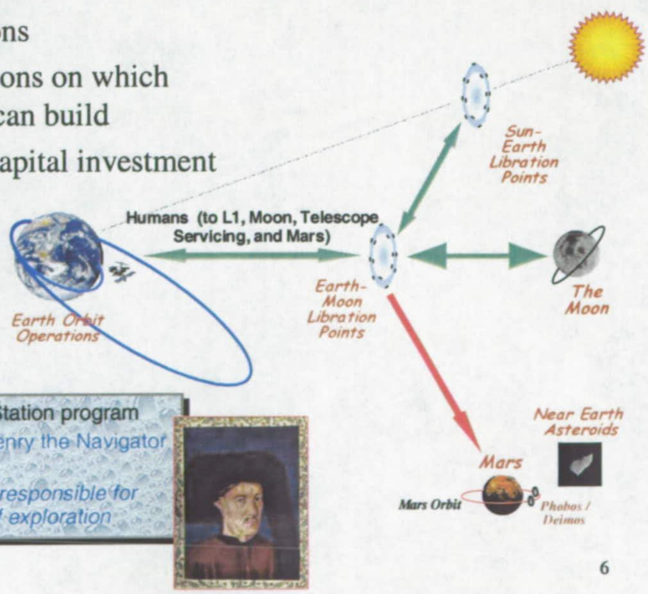
Examples

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

5

Expeditionary vs. Evolutionary JSC

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



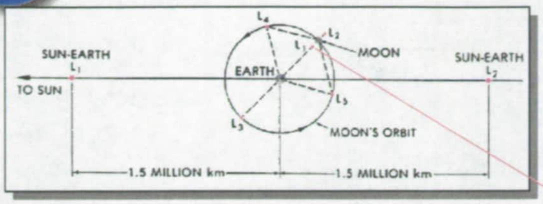
Examples

- International Space Station program
- Voyages of Prince Henry the Navigator of Portugal
  - *The man chiefly responsible for Portugal's age of exploration*

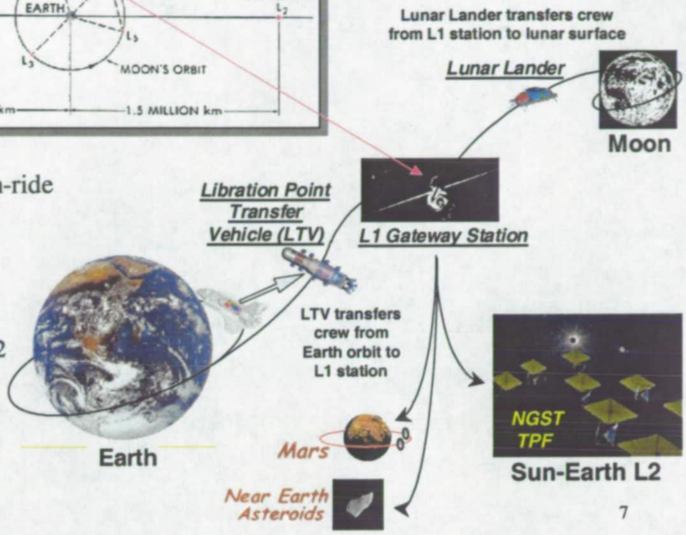
6

Earth-Moon L1 – Gateway for Lunar Surface Operations

JSC



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



7

Gateway Operations – LTV Kickstage Disposal

JSC

- 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

8

Purpose

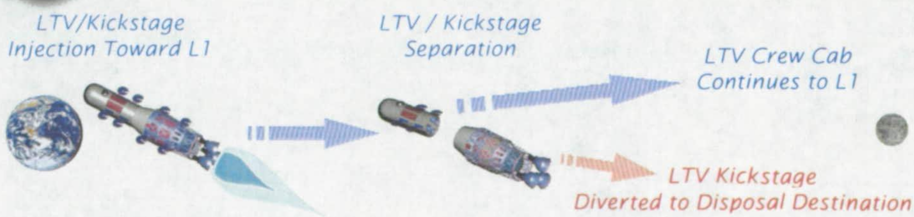
JSC

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 (ΔV) cost to retarget Earth-Moon L1 Gateway-bound LTV spacecraft kickstage to a selected disposal destination**

9

LTV Kickstage Disposal Options

JSC



Options considered for LTV kickstage disposal:

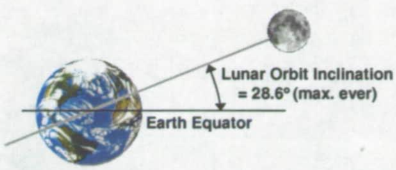
1. Lunar Swingby to Heliocentric Orbit (HO)
2. Lunar Vertical Impact (LVI), typifies any lunar impact
3. Direct Return to Remote Ocean Area (DROA)
4. Lunar Swingby to Remote Ocean Area (SROA)
5. Transfer to Long Lifetime Geocentric Orbit (GO)

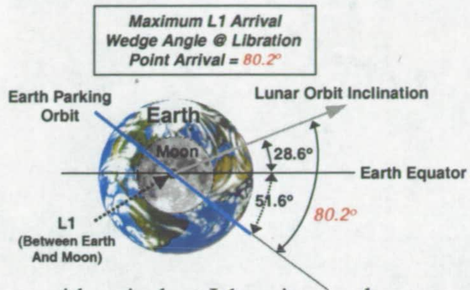
10

Methodology

JSC

- 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)

11

Methodology (continued)

JSC

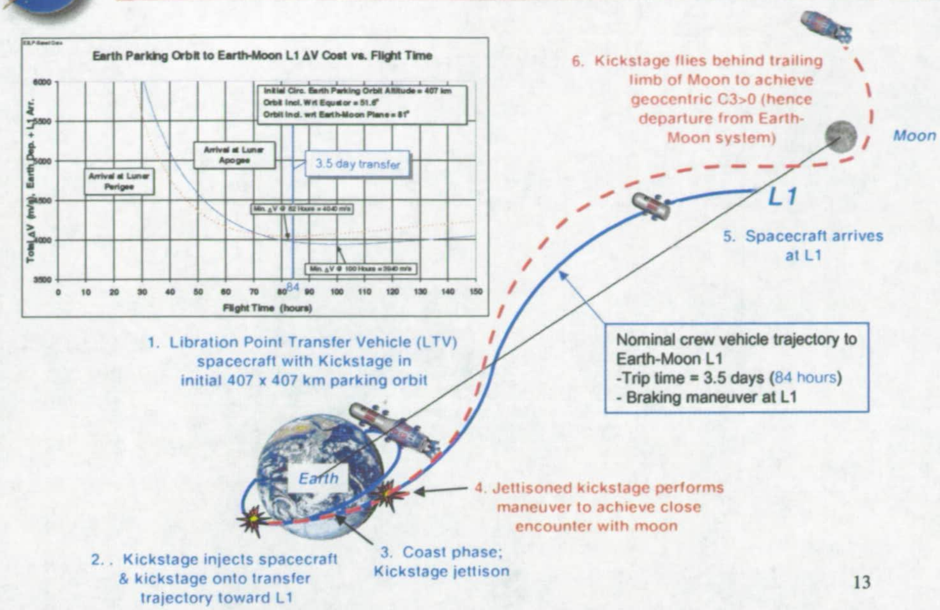
- HO, LVI, DROA, SROA, and GO maneuver times designed to minimize ΔV for stage disposal subject to imposed constraints
  - Solutions considered to be a practical attempt to minimize these maneuver ΔVs (e.g.: coplanar kickstage deflection maneuver *assumed* optimal for some disposal options) and not rigorous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

12

* Developed and updated by Sam Wilson

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

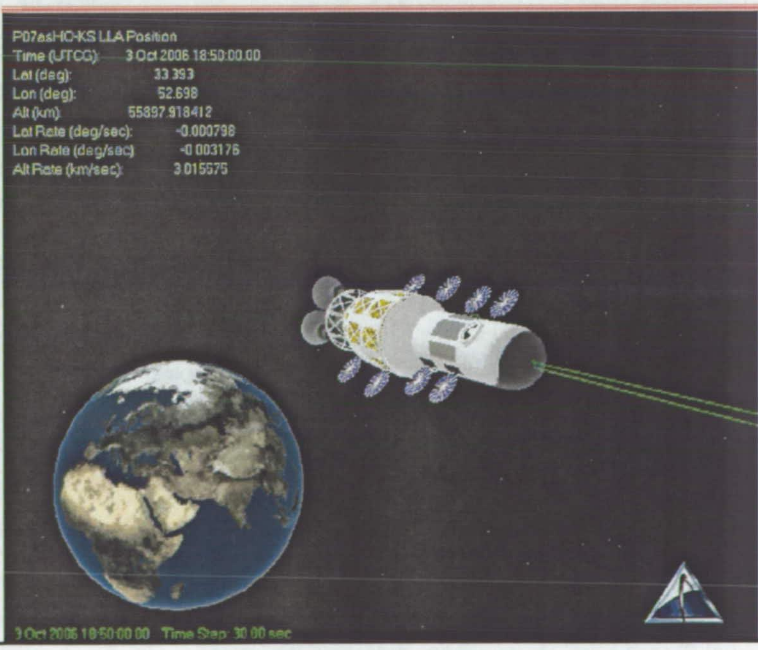
JSC



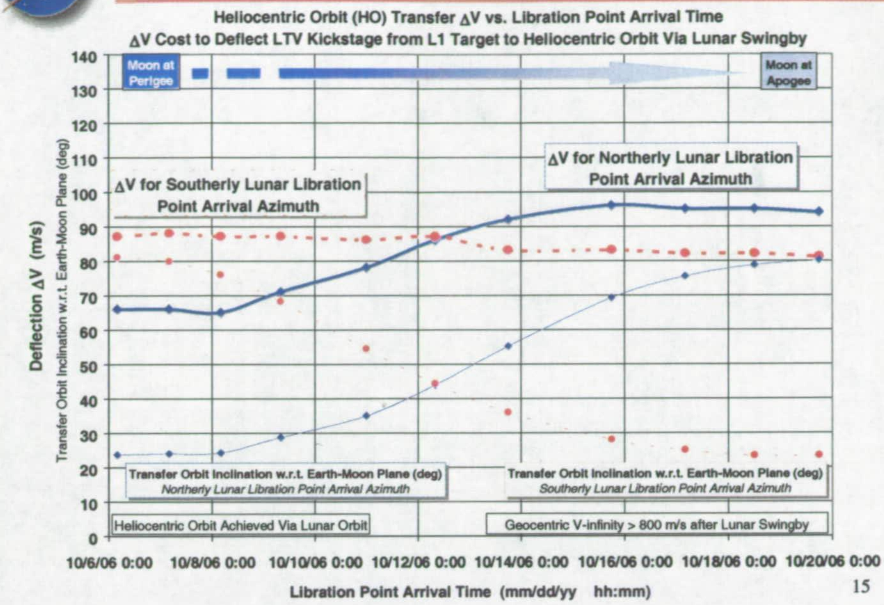
13

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

JSC



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



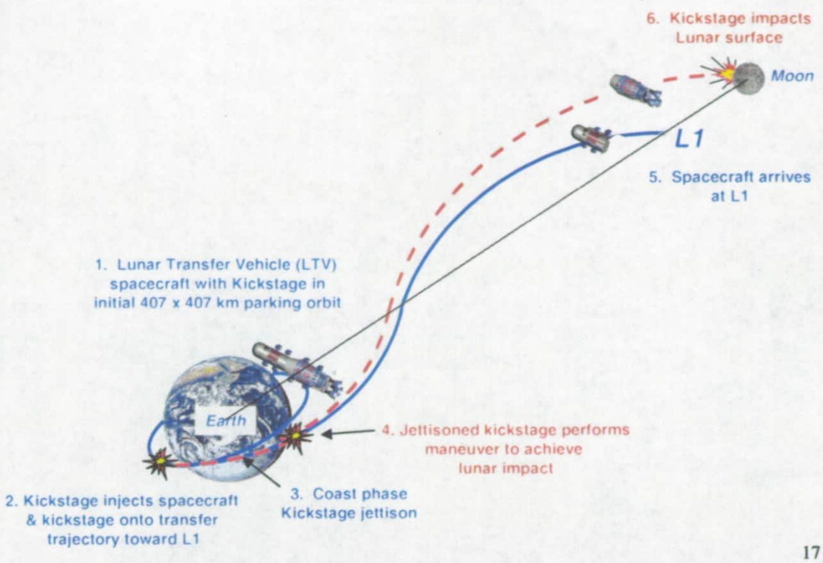
15

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

- 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

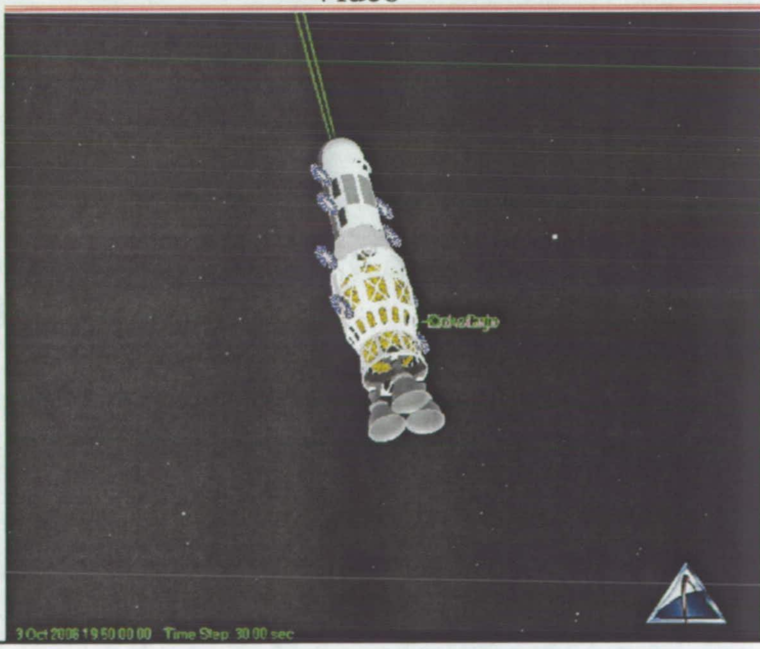
16

Option 2. Lunar Vertical Impact (LVI) JSC

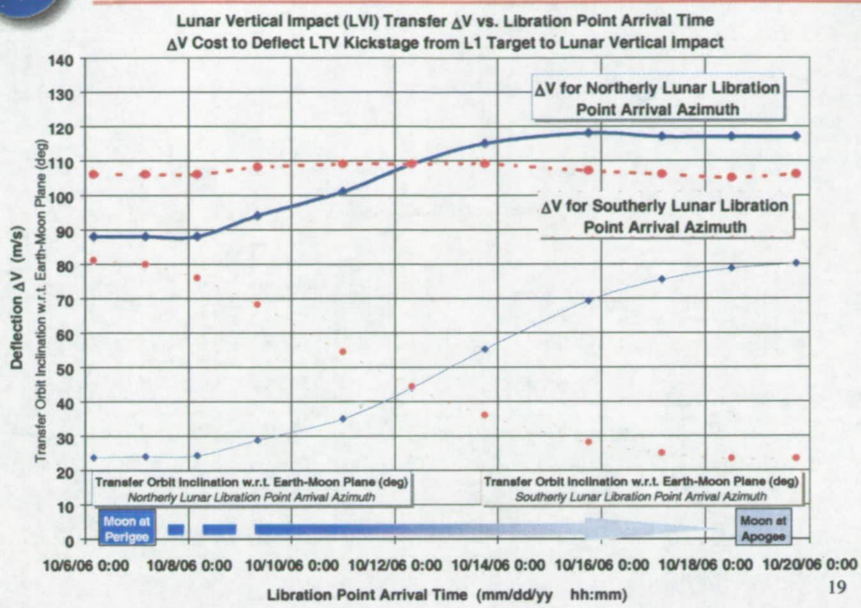


17

Option 2. Lunar Vertical Impact (LVI) Video JSC



Option 2. Lunar Vertical Impact (LVI) *JSC*



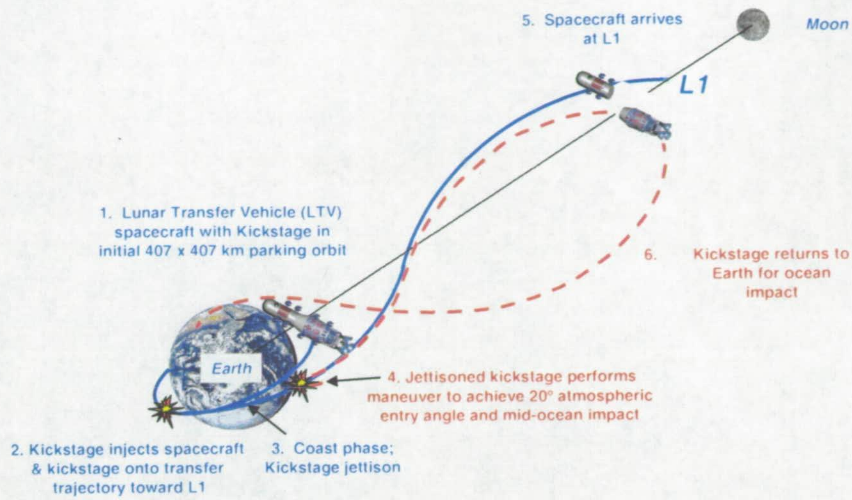
19

Option 2. Lunar Vertical Impact (LVI) *JSC*

- Advantages
  - No Earth disposal issues (e.g., impact location, debris footprint, litter, possible recontact)
- Disadvantage
  - Lunar litter
  - Relatively high disposal ΔV cost

20

Option 3. Direct Return to Remote Ocean Area (DROA) JSC



21

Option 3. Direct Return to Remote Ocean Area (DROA) ΔV Budget Gives 240° Longitude Control JSC

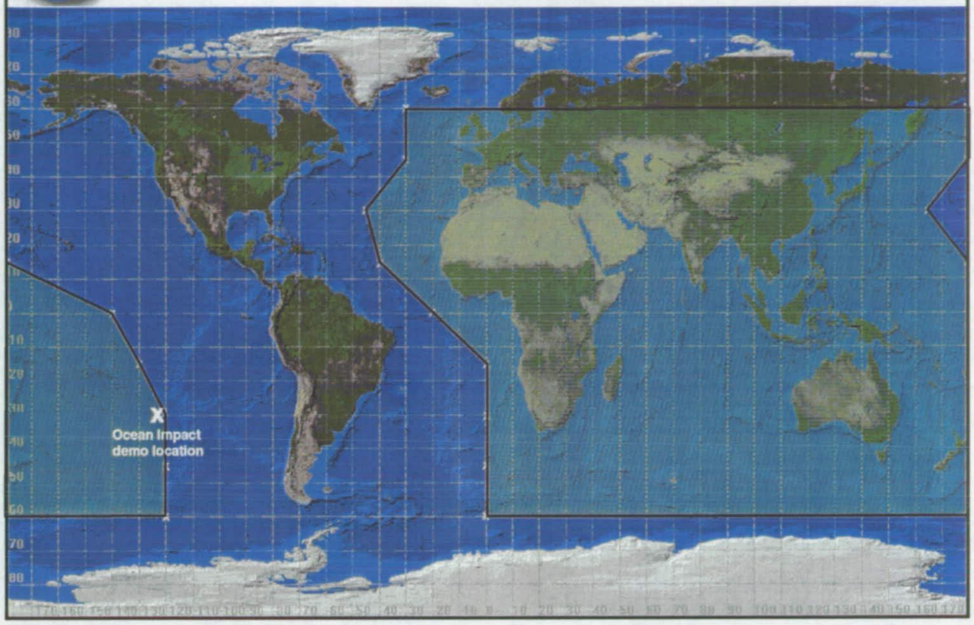
- Entry flight path angle = -20° selected
  - Confines surface debris footprint
- Impact latitude is determined by:
  1. Spacecraft date of arrival at L1 and
  2. Choice of northerly or southerly velocity azimuth at L1 arrival
     - From an established (e.g., ISS) earth orbit, these two degrees of freedom 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).

22

Option 3. Direct Return to Remote Ocean Area (DROA)

Shaded Region Contains Max Longitude Difference (240°) Between Mid-Atlantic and Mid-Pacific Target Lines

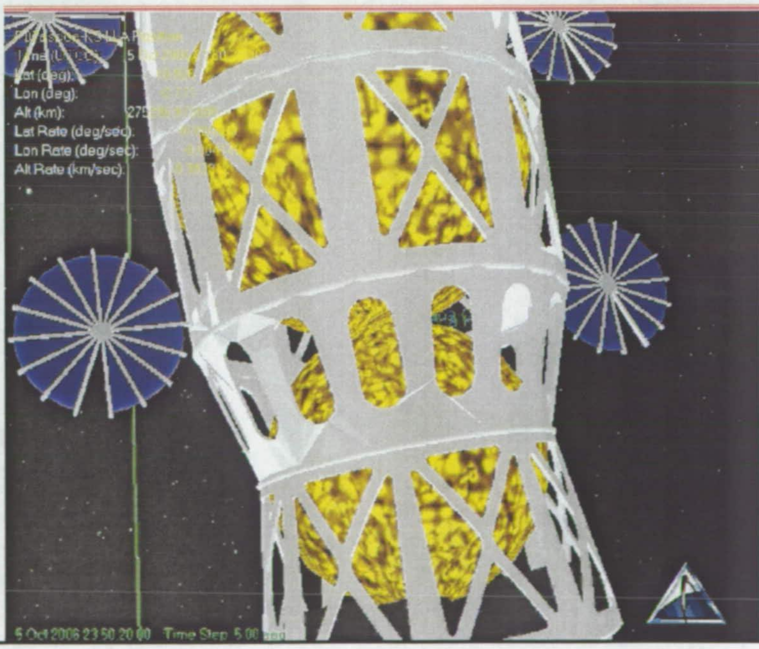
JSC



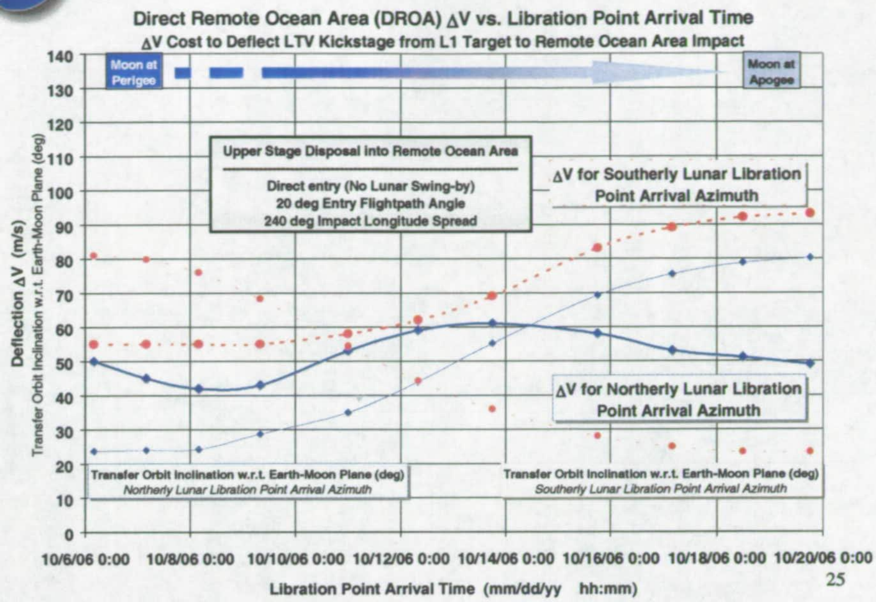
Option 3. Direct Return to Remote Ocean Area (DROA)

Video

JSC



Option 3. Direct Return to Remote Ocean Area (DROA) JSC



25

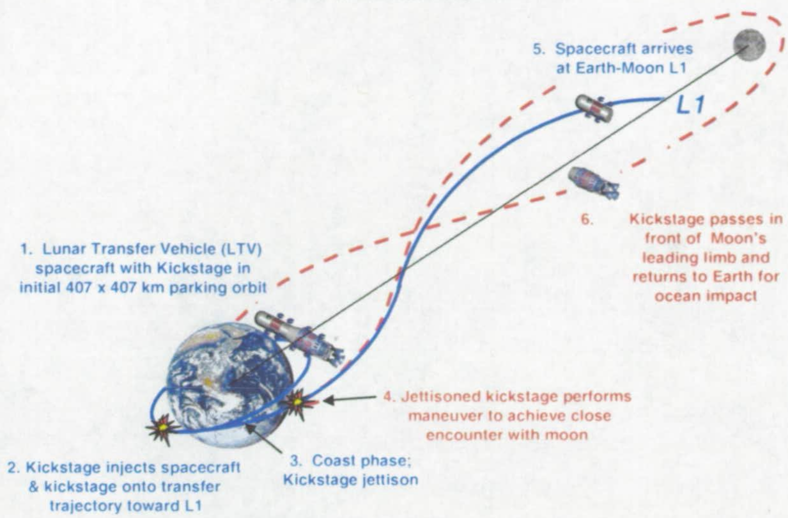
Option 3. Direct Return to Remote Ocean Area (DROA) JSC

- 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

26

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

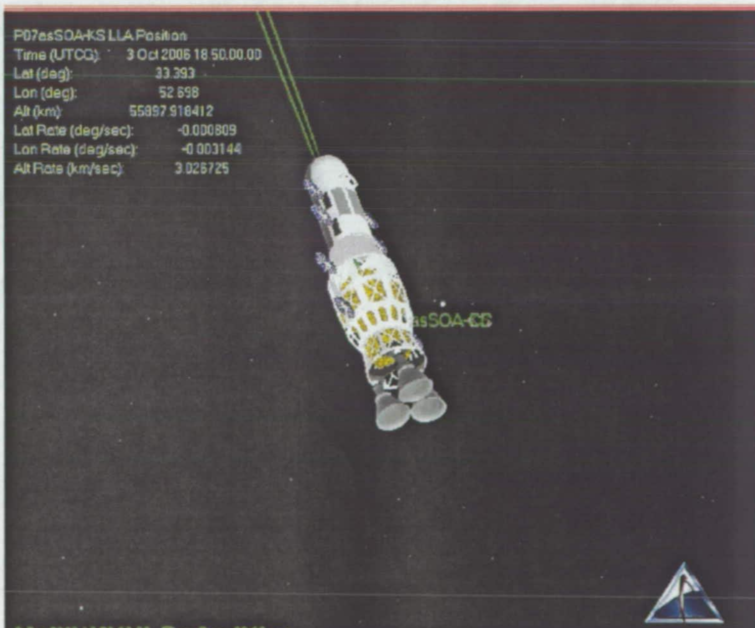
JSC



27

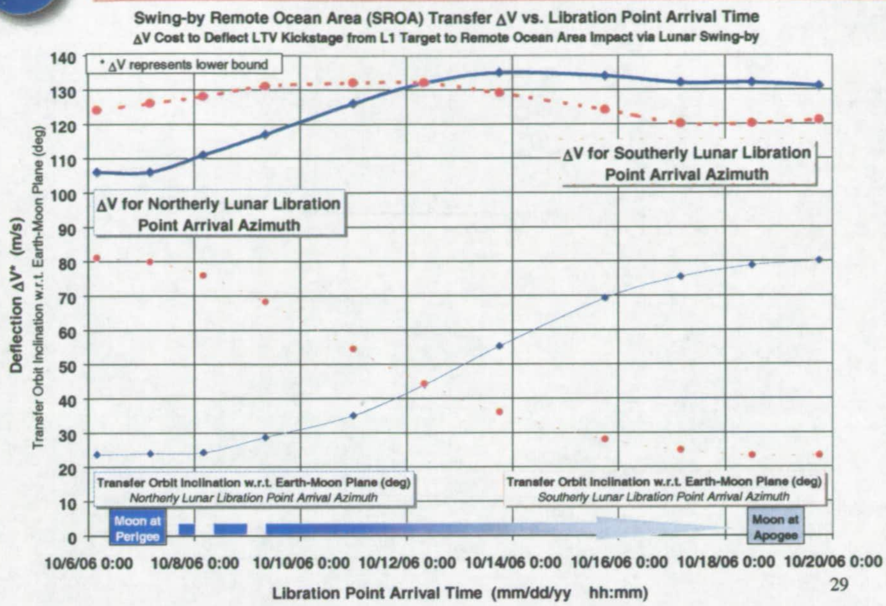
Option 4. Lunar Swingby to Remote Ocean Area (SROA)

JSC



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

JSC



29

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

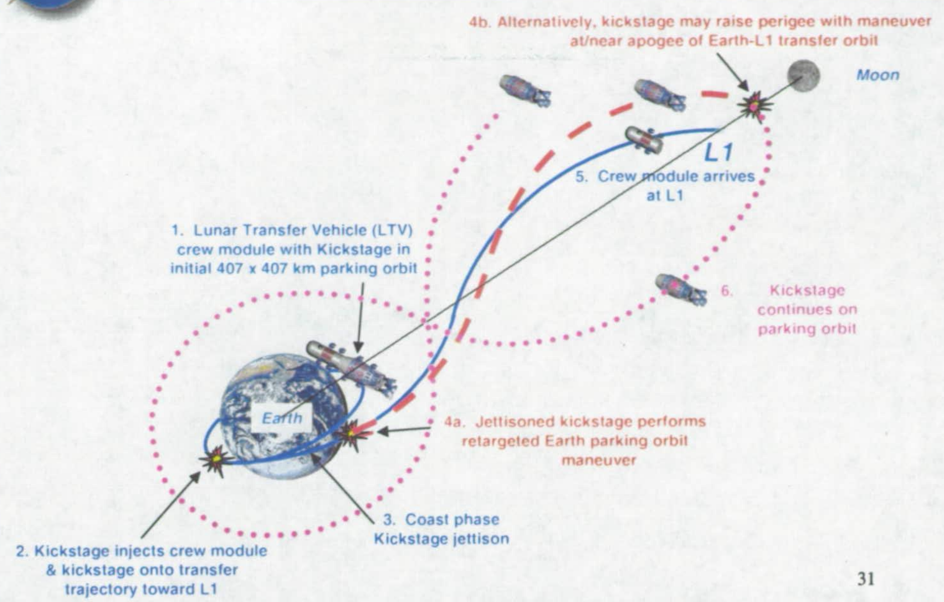
JSC

- 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

30

Option 5. Transfer to Long Lifetime Geocentric Orbit (GO)

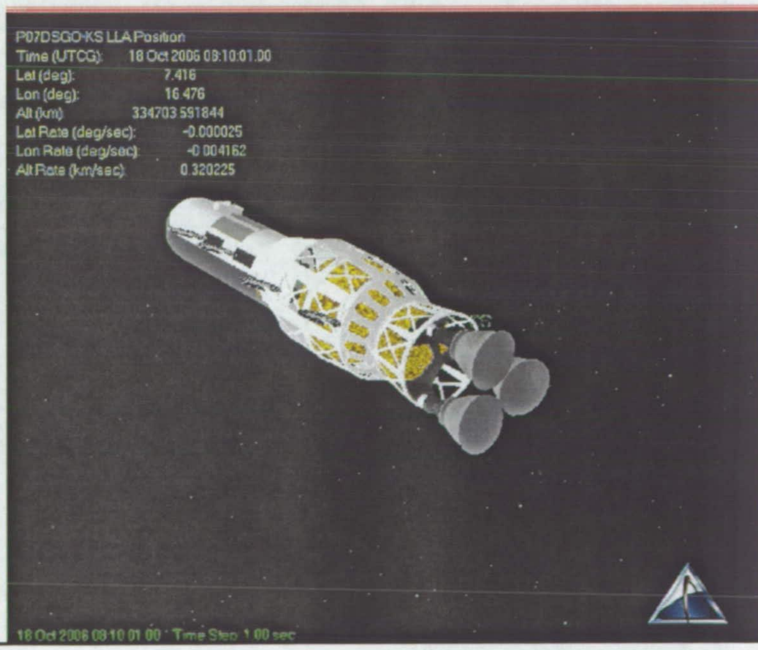
JSC



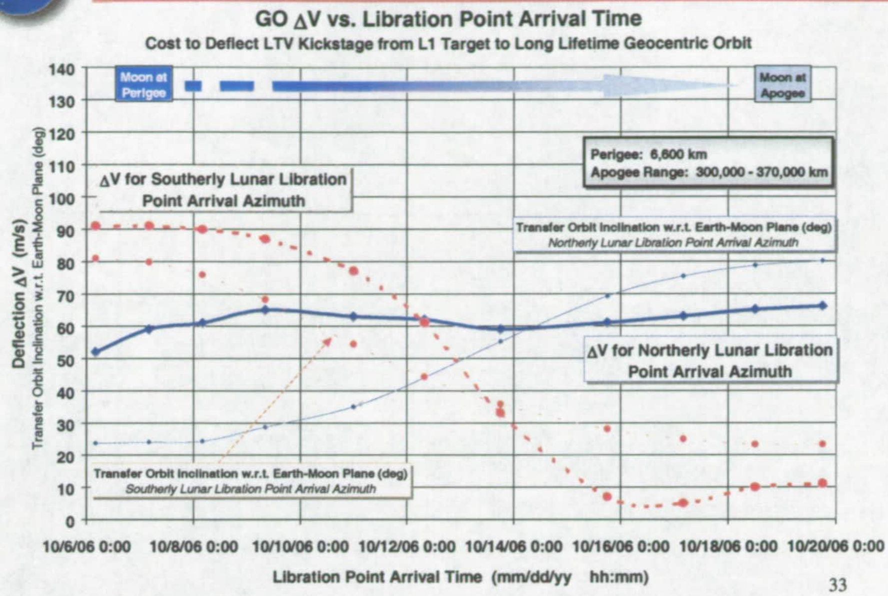
31

Option 5. Transfer to Long Lifetime Geocentric Orbit (GO) Video

JSC



Option 5. Transfer to Long Lifetime Geocentric Orbit (GO) *JSC*



33

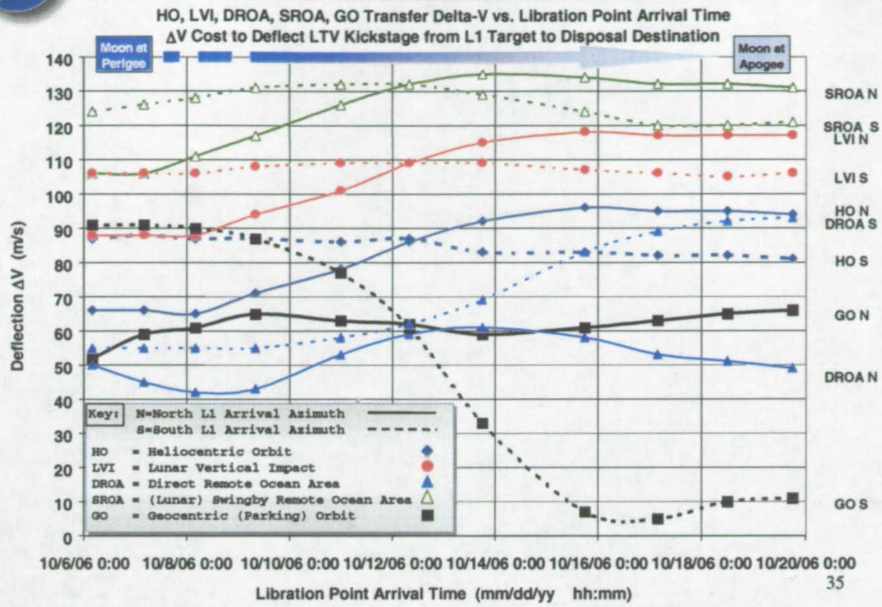
Option 5. Transfer to Long Lifetime Geocentric Orbit (GO) *JSC*

- 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 permissable 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.

34

Summary Results

JSC



35

JSC

Geocentric Orbit Lifetime Study

Geocentric Orbit Lifetime

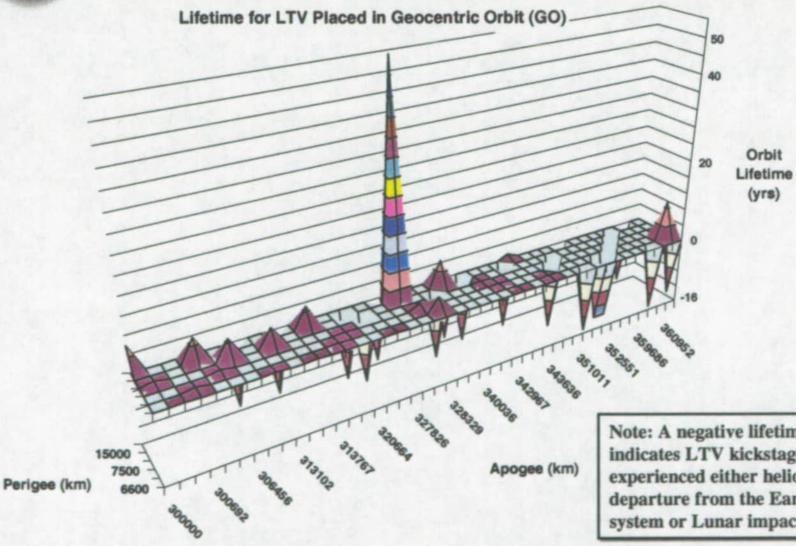
JSC

- 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

37

LTV Orbit Lifetime

JSC



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

38

45 transfer orbits in sample space

Summary

JSC

- Recommend Direct Remote Ocean Area impact disposal for cases <u>without</u> 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 <u>with</u> 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

39