“Exploration in the Earth’s Neighborhood” Architecture Analysis

“A Work in Progress”
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B. Kent Joosten
JSC/Exploration Office
281/483-4645
kent.joosten@jsc.nasa.gov
Agenda

• Lunar Architecture
• L₂ Evolution
• L₂ Stepping Stone
Lunar Architecture
Lunar Exploration Scenarios

- Lunar south polar region represents an excellent initial foothold for human exploration
  - Science potential is high
  - Potential access to resources
  - Environmental conditions probably most benign on lunar surface
  - Power storage problems significantly reduced or eliminated for extended stays

- Apollo-class sortie capabilities to anywhere on lunar nearside (or farside with comm relay)
  - Focused, high value objectives requiring reduced exploration resources (crew, time, surface infrastructure)
Human Lunar Architecture Concept

- Crew departs from and returns to ISS
- GPS Constellation
- Formation-Flying Science Spacecraft (perhaps)
- L$_1$ “Depot”
- Lunar Transfer Vehicle
- Lunar Excursion Vehicle
• Important considerations
  – Requirement for high-capacity launch capability deferred
  – “Safe haven” at L₁ and ISS
• Technology “freeze” in ’05 – assumes ISTP tech goals are met
• Initial LTV operations by ‘09
• No commitment regarding extensive lunar surface infrastructure
  – Transportation capabilities established allowing future expansion for science and commercialization
Domestic ELV Options

P/L to LEO

- 24,494 kg
- $135M
- 02/03

- 28,991 kg
- $140M
- ~05

- 35,380 kg
- ~$155M
- TBD

BOEING PROPRIETARY
Architecture Elements

• L₁ “Gateway”

• Lunar Transfer Vehicle (LTV)
  – Human transport from ISS to L₁ Depot and return

• High-Energy Injection Stage
  – Initial boost for LTV

• Lunar Excursion Vehicle (LEV)
  – Human transport from L₁ Depot to lunar surface and return

• Solar Electric Transfer Vehicles (SETV)
  – Delivery of L₁ Depot and LEVs to L₁
Lunar Transfer Vehicle

• **“Requirements”**
  – Based at ISS for timing flexibility
  – Launch and recovery in Space Shuttle
  – Utilizes space storable propellants
  – Crew of 4 with \( \Delta V \) capability of >1700 m/s
  – Operations in automated mode, or with crew onboard - automated rendezvous and proximity operations
  – Aerocapture manuevers at lunar return speeds to ISS orbit

• **Preliminary Concept**
  – Lifting body for crew g reduction
  – Integral LOX/CH\(_4\) propulsion system
  – Eighteen day independent mission capability
  – Lightweight docking system
High Energy Injection Stage

- "Requirements"
  - Launch on EELV / Shuttle
  - Sufficient performance that when combined with fuelled Lunar Transfer Vehicle, missions to L₁ and return
  - Capability to achieve vicinity of ISS and maintain for > 30 days after launch
    - Rationale Lunar Transfer Vehicle and crew at ISS, represents two missed lunar injection opportunities
  - Ability to be structurally docked to Lunar Transfer Vehicle

- Preliminary Concepts
  - Derivative of Delta IV 5.1-m Configuration Stage
    - LOX/LH₂, P&W RL10B-2
    - On-orbit life extension via small solar array (size TBD)
    - Propellant storage via cryo-cooler or propellant densification
Lunar L₁ “Gateway”

“Requirements”
- Docking capability for Lunar Transfer Vehicle and Lander and pressurized crew transfer
- Crew habitation for ≥12 days per lunar mission for return phasing or advanced system testing
- Vehicle support (power, att. control) for Lunar Transfer Vehicle and Lander
- Launch on EELV or Shuttle
- Habitat delivered via solar electric propulsion from LEO to L1

“Preliminary Concept”
- “Half-length” inflatable habitat
- Delivered to L₁ via Solar Electric Propulsion System
- SEP remains attached to provide power, attitude control
“Requirements”
- LEV will be designed for round-trip piloted missions from L₁ to lunar surface and back to L₁
- LEV will be delivered to L₁ by transfer stage
- LEV will be able to remain at L₁ for extended period to allow for delay in crew arrival
- LEV will interface with L₁ Depot
- LEV will allow easy lunar surface egress/ingress of suited crewmembers

Preliminary Concept
- LOX/CH₄ propulsion stages (ascent and descent)
- Seven day independent mission capability
Mission Concept

1) L1, Gateway with Solar Electric Propulsion Stage to L1
2) Solar Electric Propulsion Stage to LEO
3) Lunar Excursion Vehicle (LEV) to LEO, Auto RNDZ & Dock
4) LEV to L1 Gateway
5) Lunar Transfer Vehicle (LTV) and Crew to ISS
6) High Energy Injection Stage to ISS Vicinity
7) LTV and Crew to L1 Gateway
8) Crew and LEV to Lunar Surface
9) Crew and LEV to L1
10) Crew and LTV Aerobrake to ISS
11) Crew and LTV to Earth via Shuttle

Currently Under Review
ISS Support - Why?

- **LTV Reusability**
  - Direct entry and landing would probably take one of two forms
    - “Apollo-style” - most of vehicle discarded to achieve reasonable recovery system masses (drogues and parachutes)
    - “Lifting-body style” - aerosurfaces, control surfaces, landing gear or drogue/parafoil/skids
  - **Launch “Decoupling”**
    - Best efforts still imply two launches for L₁ mission - STS for Lunar Transfer Vehicle and crew, EELV for high-energy injection stage
    - First launch establishes orbital angular momentum, injection to L₁ must be nearly in-plane which occurs ~every ten days
    - On-orbit wait without depleting STS Orbiter or Lunar Transfer Vehicle life-support, attitude control, and power
    - “Space storable” propellant used for Lunar Transfer Vehicle
    - Bottom line: with ISS, LTV and lunar crew are “stable” on-orbit, only one launch coupled to trans-lunar injection window (injection stage)

- **Reduce Vehicle Mass**
  - By eliminating supersonic, transonic, subsonic flight and landing, the following systems are eliminated (and do not need to be taken to L₁ and back):
    - Aerosurfaces, control surfaces, EMAs, landing gear
    - Drogues, parachutes, parafoils, airbags

- **Operations**
  - Landing site weather not an issue for LTV return (would have to be predicted four days in advance)
Issues with Utilizing ISS

- No “anytime return” from L₁ or L₂ - discreet return windows
- Support for lunar/L₂ crewmembers at ISS while waiting for injection window (life support, crew return, etc.)
  - Additional capabilities or impact to ISS crew size?
  - Potential impacts to ISS science ops
Future Work

- Lander definition and operational scenario
- Gateway system definition and outfitting requirements
- Gateway logistics and resupply strategy
L₂ “Evolution” Architecture
- Similar approach taken as for lunar architecture
- **L2 Gateway**
  - Delivered to E-S L2 via SEP, remains in L2 vicinity
  - Provides extended life-support and EVA support for operations
  - Provides power, attitude control, etc. to Transfer Vehicle

- **L2 Transfer Vehicle**
  - Volumetrics associated with 18-day 4-person lunar capability should suffice for trans-L2 and trans-earth mission phases
  - Extended power storage and consumables to support maximum of 70-day contingency mission (unable to dock with Gateway)
L₂TV Transfer Vehicle

“Requirements”
- Based at ISS for timing flexibility
- Launch and recovery in Space Shuttle
- Utilizes space storable propellants
- Crew of 4 with ΔV capability of >1700 m/s
- Operations in automated mode, or with crew onboard - automated rendezvous and proximity operations
- Aerocapture maneuvers to ISS orbit

Preliminary Concept
- Lifting body for crew g reduction
- Integral LOX/CH₄ propulsion system
- 65 day independent mission capability
- Lightweight docking system
High Energy Injection Stage

• “Requirements”
  – Launch on EELV / Shuttle
  – Sufficient performance that when combined with fuelled L₂ Transfer Vehicle, missions to L₂ and return
  – Capability to achieve vicinity of ISS and maintain for > 30 days after launch
    • RationaleL Lunar Transfer Vehicle and crew at ISS, represents one missed L₂ injection opportunity
  – Ability to be structurally docked to L₂ Transfer Vehicle

• Preliminary Concepts
  – Derivative of Delta IV 5.1-m Configuration Stage
    • LOX/LH₂, P&W RL10B-2
    • On-orbit life extension via small solar array (size TBD)
    • Propellant storage via cryo-cooler or propellant densification
Mission Concept

L2 Depo with Solar Electric Propulsion Stage to L1

1) L1 DEPOT WITH SOLAR ELECTRIC PROPULSION STAGE TO L1

LEO

1A) POTENTIAL OUTFITTING MISSION

2) L2 TRANSFER VEHICLE (L2TV) AND CREW TO ISS

3) HIGH ENERGY INJECTION STAGE TO ISS VICINITY

4) L2TV AND CREW TO L2 GATEWAY

5) CREW AND L2TV AEROBRAKE TO ISS

6) CREW AND LTV TO EARTH VIA SHUTTLE
L1 Earth Sun: Arrival $\Delta V$ vs. Flight Time from LEO
Initial Earth Circular Parking Orbit: 407 km
Sun-Earth Libration Point (L2) Mission Opportunities

Earth Parking Orbit: Circular Altitude = 407 km, Inclination = 51.6°

- **Max Mission Time**
  - 1st Departure Opportunity: 68 Days
  - 2nd Departure Opportunity: 104 Days

- **Min Mission Time**
  - 1st Departure Opportunity: 70 Days
  - 2nd Departure Opportunity: 92 Days

- **Outbound Trip Time**: 25 days
- **Inbound Trip Time**: 25 days

Earth Departure Date:
- 1/7/2009
- 2/9/2009
- 3/12/2009
- 4/8/2009
- 5/14/2009
- 6/6/2009
- 7/12/2009
- 8/8/2009
- 9/8/2009
- 10/11/2009
- 11/5/2009
- 12/10/2009

Earth Arrival
2nd Available Departure
1st Available Departure
L2 Arrival
Earth Departure
L2 “Evolution” Capabilities

Advanced Habitation
- Lunar L1 Habitat
- Deep-Space L2 Habitat
- Mars Transit Habitat

Advanced EVA
- Lunar Surface Habitat
- Deep-Space EVA
- Mars Surface Habitat

Electric Propulsion
- Lunar L1 SEP
- Deep-Space L2 SEP
- Mars SEP/NEP

Near Earth Transportation
- Lunar LTV / Inj. Stage
- L2 LTV / Inj. Stage
- Mars Taxi Vehicle
L₂ “Stepping Stone” Architecture
L₂ Architecture Options

- Two architecture options being examined
  - L₂ “Evolution”
    - L₂ science operations primary requirements and schedule driver
  - L₂ “Stepping Stone”
    - Human Mars mission primary requirements driver
    - Approaches, technologies, schedule reflect emerging Mars exploration architecture

- Primary differences due to eventual Mars architecture:
  - L₂ Gateway and scale of L₂ capabilities (crew, duration) may be much more robust in “Stepping Stone” approach
  - Gateway becomes “Mars Transfer Vehicle” (MTV) hab
  - Extensive testing of MTV systems in interplanetary environment (L₂)
L2 “Stepping Stone” Capabilities

Advanced Habitation
- Lunar L1 Habitat
- Lunar Surface Habitat
- Lunar L1 SEP
- Deep-Space L1 Habitat
- Deep-Space EVA
- Mars Transit Habitat
- Mars Surface Habitat
- Mars SEP/NEP
- Mars Crew Taxi Vehicle

Advanced EVA
- Lunar Surface EVA
- Deep-Space EVA
- L2 LTV / Inj. Stage

Electric Propulsion
- Lunar LTV / Inj. Stage

Near Earth Transportation
- L2

EXPLORATION OFFICE
Issues

- **Crew Radiation Protection**
  - **Solar proton events**
    - Current strategy is to provide water-jacketed “storm shelter” (both in transfer vehicles and gateways)
    - Strategy may not work for lunar landers (mass penalties), however, two-day transit to gateway should be within SPE prediction capability
  - **Galactic cosmic radiation**
    - Risk increases with mission duration
    - Risk increases with secondary particle production via interaction with surrounding material – *materials selection and vehicle geometry is key*
    - Risk has to be assessed in context of crew exposure in various environments (EVA, spacecraft, gateways)
    - Research required for:
      - Biological effects (JSC) – on Life Sciences critical Path Roadmap
      - Materials interaction (LaRC, JSC)
      - Environment definition (Codes S, U, M)
Future Work

• More detailed EVA system definition and operational scenarios
• Gateway system definition and outfitting requirements
• Gateway logistics and resupply strategy
Backup
The Role of Lunar Exploration

Development of Core Capabilities*
- Advanced Systems
- Advanced Technologies

Commercial Potential*
- Lunar Oxygen or Water Production
- Regolith Materials Processing

Operational Experience
- Autonomous Deep Space Operations
- Planetary Surface Operations
- Mars Analog at Lunar Pole

Science Return*
- Impact History in Near-Earth Space
- Composition of Lunar Mantle
- Past and Current Solar Activity
- Lunar Ice at Poles - History of Volatiles in Solar System

*Draft, HEDS Strategic Plan
Earth-Moon L₁ Characteristics

• Environment
  – No orbital debris. Weak instability of L₁ will actively remove artificially created debris.
  – Nearly continuous solar energy (>99.91%), no thermal cycling
  – Nearly continuous full sky viewing (>99.96%)
  – True deep space radiation, thermal environment, zero-g
  – Continuous view of Lunar nearside, Earth, terrestrial magnetosphere
  – No atmospheric drag

• Operations
  – Excellent transportation node for lunar surface, particularly polar regions
  – Four days from Earth, two days from Moon (high thrust)
  – Formation flying spacecraft mutually accessible with minimal delta-v, slow relative motion
  – Potential staging point for deep-space exploration missions

### Moon’s Orbit

- **L₁**: 326740 km from Earth’s Center, 57660 km from Moon’s Center
- **L₂**: 449748 km from Earth’s Center, 65348 km from Moon’s Center
- **L₃**: 380556 km from Earth’s Center, 764956 km from Moon’s Center
- **L₄**: 384400 km from Earth’s Center, 384400 km from Moon’s Center
- **L₅**: 384400 km from Earth’s Center, 384400 km from Moon’s Center

Sun - Earth: 1.5 million km
Moon’s Orbit: 150 million km
**L₁ Staging - Why?**

- **Operational Considerations**
  - **Lunar Orbit Rendezvous (LOR)**
    - Access to lunar poles would require polar orbit if LOR mission mode utilized
    - Lunar polar orbit provides infrequent opportunities for trans-Earth injection (once every 14 days)
      - Orbit orientation inertially fixed, aligns with efficient trans-Earth trajectory twice a month
    - Access to ISS orbit would probably be impractical
      - Trans-Earth trajectory would also need to be synchronized with ISS orbit regression
    - Little control over Earth landing location without aerocapture and phasing
    - Total $\Delta V = 9461$ m/s
  - **Libration Point Rendezvous**
    - Continuous access from $L_1$ to lunar surface and return
      - Lunar rotation and libration point motion naturally synchronized
    - Continuous access to Earth - landing point partially controllable
    - Access to ISS orbit every ten days
    - Total $\Delta V = 10746$ m/s

- **Unique science opportunities may exist at $L_1$**
- **Deep-space human exploration analogs exist at $L_1$**
- **Support for deep-space human exploration missions at $L_1$ may advantageous**
Mission Constraints

- **Injection Windows from ISS to L₁**
  - Combination of ISS Nodal Regression and Lunar Motion provides injection opportunity every ten days
- **Injection Windows from L₁ to Moon**
  - Apollo-type landing lighting constraints eliminated if polar location chosen
  - L₁ Synchronized with Lunar Surface
- **Symmetry in Return to ISS**

**Table: ISS Orbit Regression Rate**

<table>
<thead>
<tr>
<th>Event</th>
<th>MET</th>
<th>Days</th>
<th>Time from Nodal Alignment, Days</th>
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</thead>
<tbody>
<tr>
<td>TLI</td>
<td>0.000</td>
<td>00:00</td>
<td>4.125 days</td>
</tr>
<tr>
<td>Nodal Alignment</td>
<td>2.993</td>
<td>02:23</td>
<td>2.993 days prior to nodal alignment</td>
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<tr>
<td>L₁I</td>
<td>4.125</td>
<td>04:03</td>
<td>4.125 days</td>
</tr>
<tr>
<td>TEI</td>
<td>11.772</td>
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<td>11.772 days prior to nodal alignment</td>
</tr>
<tr>
<td>Nodal Alignment</td>
<td>12.904</td>
<td>12:21</td>
<td>12.904 days</td>
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<tr>
<td>EOI</td>
<td>15.897</td>
<td>15:21</td>
<td>15.897 days</td>
</tr>
</tbody>
</table>

**Graph: ISS Orbit Regression Rate in Moon’s Orbit Plane**

- **Lunar Rate**: 13.1764 deg/day
- **Orbit Regression Rate**: -4.984 deg/day
- **Alignment Interval**: 9.912 days
- **Trip Time**: 4.125 days
- **TLI**: 2.993 days prior to nodal alignment
- **TEI**: 1.132 days prior to nodal alignment
Lunar Polar Characteristics

- Terrain in south polar sites may provide nearly continuous sunlight (>80%)
- Low sun elevation provides nearly constant surface temperatures (-50ºC vs. -170º to +120ºC at equator)
- Region proximate to large permanently shadowed areas (-230ºC) and potential location of ice deposits
- Site is within largest impact basin known in solar system. Lower crust/upper mantle of Moon exposed here or nearby.
- Complete and continuous view of southern sky
- Terrain masking from terrestrial radio sources

After D.B.J. Bussey, et. al., 1999
The Moon can be thought of as a 4.5 billion old impact detection instrument
- Unique record of impact history in near-Earth space
- Crater dating can address validity of terrestrial mass extinction theories
- Current impact fluxes can be measured
- Advanced telescope could accurately search for potential impactors

Ice in lunar cold traps (if it exists) can provide history of volatiles in the solar system

South Pole Aitken Basin is largest impact on Moon,
- Can provide data on Earth-Moon cataclysms
- Lower crust / upper mantle exposed

Ancient galactic and solar particle fluxes can be determined from analysis of regolith
**Relevant Environmental and Operational Characteristics**

- Low sun elevation provides nearly constant surface temperatures (-53° ± 10°C)
- Region proximate to large permanently shadowed areas (-230 °C) and potential location of ice deposits
- Line-of-site to Earth dependent upon terrain and lunar latitude libration

**Human Mars Analog Objectives**

- Testing of Mars surface equipment in lunar polar environment
  - Thermal, low-pressure, hypogravity, dusty conditions “similar” to Mars
  - May be relevant for EVA, habitation, life-support, mobility system testing
- Science Operations
- Autonomous operations may be required when Earth out of line-of-site
- Lunar ice utilization technologies may be similar to those relating to Martian permafrost