Human Exploration of Earth’s Neighborhood and Mars

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Mission Scenario

1) Injection to Minimum-Energy Mars Transfer Trajectory

2) Direct Mars Entry (Mid L/D Aeroshell), Precision Landing w/Hazard Avoidance

3) Ascent to Low Mars Orbit (Chemical Propulsion)

4) Ion Propulsion to Earth Transfer Trajectory

5) Heliocentric Coast Targeted to Miss Earth

6) Ion Propulsion Targets Capture into Very High Earth Orbit (HEO)

7) Ion Propulsion Performs Gradual Orbit Transfer from HEO to LEO

8) LEO Rendezvous & Acquisition by Shuttle

9) Shuttle Entry and Landing
Direct Entry Landing Locations

Entry Interface

Max Uprange (Heel)
Max Downrange (Toe)
Crossrange

Annulus of Landing Site Locations

Entry Interface
Heel of Landing Footprint (Max Uprange)
Toe of Landing Footprint (Max Downrange)

V_\infty

i_{pole}
2005 Opportunity - Type I

Landing Lighting and Latitude for Direct Entry JSC Mars Sample Return
(2005 Opportunity, Date/Time August 10, 2005 12:00:00.0, Trip Time 199 Days)

V-Infinity = 3.08 km/s
Inertial Entry Velocity = 5.81 km/s
Min. Landing Latitude = -71.7 deg
Max. Landing Latitude = 52.3 deg

Earth Departure Date
8/10/05

Earth Departure Energy
C3 = 15.9 km^2/s^2

Mars Arrival Date
2/25/06

Trip Time
199 days

Mars Inertial Entry Speed
5.81 km/s

Landing Site Latitude Access
-71.7° -> 52.3°
Earth-Mars Superior Conjunction

Sun-Earth-Mars Angle (deg)

0 10 20 30 40 50 60 70 80 90

05-Sep-05 24-Mar-06 10-Oct-06 28-Apr-07 14-Nov-07 01-Jan-08 18-Dec-08 06-Jul-09 22-Jan-10 10-Aug-10 26-Feb-11 14-Sep-11 01-Apr-12

2005 Mission Opportunity
2/25/06
199
15.9
5812

2007 Mission Opportunity
4/20/08
210
18.8
6284

2009 Mission Opportunity
6/10/10
228
16.1
6364

KEY
Mars Arrival Date
Trip Time (days)
Earth Departure C3 (km^2/s^2)
Mars Entry Speed (m/s)

7/1/06
340
18.2
5700

10/1/06
409
15.8
6114

11/17/06
432
15.8
6338

12/1/06
450
16.2
6572

12/29/06
365
12.8
5653

12/18/08
706
9.0
7473*

12/26/10
675
8.9
7341

* Exceeds 7.36 km/s Mars entry speed limit
Low Thrust – Earth Return Phase

- Two-body assumption with mass-matching at transition points, no shadowing
- Initial Conditions*
  - Mass = 350 kg
  - Power to thruster = 2.567 kW
  - Efficiency = 55.3%
  - Isp = 3127 sec.

*Based on advanced NSTAR engine similar to that used with Deep Space 1
**SEP Earth Return Sequence**

**Mars Spiral Out**
- Depart 300 km circular parking orbit
- Initial mass = 350 kg
- Thrust along velocity vector
- Spiral to zero energy condition
- No shadow
- Transfer Time = 131 days
- Propellant = 34 kg

**Earth ‘Spiral’ Down**
- Depart 150,000 x 20,000 parking orbit
- Apogee Reduction to 20,000 km
  - Thrust perpendicular to line of apsides near perigee
- Spiral down to 500 km circular orbit
  - Thrust opposite velocity vector
- Preliminary 60 kg estimate for spiral down propellant (later optimized to 38 kg)

**Heliocentric Transfer**
- Depart Mars state
- Initial mass = 316 kg
- Optimal thrust direction (Calculus of Variations)
- Capture to a 150,000 x 20,000 km parking orbit
- Transfer time = 370 to 490 days
- Required mass in LEO > 200 kg
  - Assumes 60 kg propellant required to capture into HEO and spiral down to LEO
Ballistic Outbound Trajectories and Mars Low Thrust Return Departure Window

Ballistic Outbound Trajectories

Departure Window for Low Thrust Return Trajectory

Superior Conjunction:
Sun-Earth-Spacecraft Angle < 5°
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

- **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

- 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
Expeditionary vs. Evolutionary

- 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
Earth-Moon L1 – Gateway for Lunar Surface Operations

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

Lunar Lander transfers crew from L1 station to lunar surface

Libration Point Transfer Vehicle (LTV)

L1 Gateway Station

LTV transfers crew from Earth orbit to L1 station

Earth

Moon
Earth-Moon L1 – Gateway for Lunar Surface Operations

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

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

Mars

NGST TPF

Sun-Earth L2

Near Earth Asteroids
Lunar Mission: Libration Point vs. LOR

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
Lunar Transfer/Orbit Diagrams
Trans-Lunar Trajectory from ISS Parking Orbit

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

Moon at Lunar Arrival

Moon at Trans-Lunar Injection

Trans-Lunar Injection (TLI)

Earth Parking Orbit at Injection

DECLINATION OF MOON W.R.T. SPACE STATION ORBIT

INJECTION WINDOW EVERY 3-12 DAYS

Reference: K. Joosten
Lunar Outpost Site Location
Implications to Mission Planning
Trans-Earth Trajectories

Moon at Trans-Earth Injection (TEI)

-13 deg/Day

Earth Parking Orbit

EQUATOR

Earth Orbit Insertion

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

Reference: K. Joosten
Lunar Outpost Site Location
Implications to Mission Planning
Effect of Lunar Parking Orbit Inclination on Lunar Transfer Opportunities → Moon to Earth Transfer

Equatorial Orbit Departure Opportunity

Equatorial Orbit Departure Opportunity

Polar Orbit Departure Opportunity
1- Impulse TEI
- Plane $\Delta V$ Penalty = 2223 m/s
3- Impulse TEI
- Plane $\Delta V$ Penalty = 1167 m/s

Polar Orbit Departure Opportunity
1- Impulse TEI
- Plane $\Delta V$ Penalty = 0 m/s
3- Impulse TEI
- Plane $\Delta V$ Penalty = 0 m/s

Equatorial Orbit Departure Opportunity

Equatorial Orbit Departure Opportunity

Equatorial Orbit Departure Opportunity

Polar Orbit Departure Opportunity
1- Impulse TEI
- Plane $\Delta V$ Penalty = 2223 m/s
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Reference: G. Condon
Exploration Blueprint
Landing Latitude Restrictions

- Lunar descent & landing generally occur in rendezvous orbit plane
- In-plane Lunar ascent & rendezvous available about every 27 days
- Region of unattainable landing sites
- Rendezvous orbit remains nearly fixed, inertially

Equator
Parking orbit inclination

Source: K. Joosten
Lunar Outpost Site Location Implications to Mission Planning
Comparison of
Opposition Class (Short-Stay) and
Conjunction Class (Long-Stay)
Missions for the Human Exploration of Mars

Exploration Office
NASA/JSC
March 1998
Mars Mission Planning

- **Earth-Mars Mission Planning**
  - Trips to Mars and back are, in effect, a double rendezvous problem
  - First rendezvous outbound must be developed considering influence of the rendezvous inbound
  - Practical considerations dictate favorable (and different) planetary alignments relative to the sun for both transfers

- **Synodic Period**
  - is the period of time necessary for the phase angle between Earth and Mars to repeat itself
  - Repetition rate for identical Earth-Mars phasing, and therefore launch opportunities for similar mission classes, is ~26 months
  - The eccentricity of Mars' orbit causes significant variations in Earth-Mars relative distance and velocity from one opportunity to the next
  - The entire range of Earth-Mars geometry is encompassed by seven launch opportunities, or about 15 years
  - Before definitive claims of mission characteristics or propulsion system capabilities are made, analysis across the 15-year cycle should be performed
Earth-Mars Orbital Characteristics

**Conjunction:** Maximum Earth-Mars distance varies from 350-400 million km. Round-trip communication time varies from 40-45 minutes; also solar occultations (i.e., no communication) for approx. 2 weeks.

**Opposition:** Minimum Earth-Mars distance varies from 60-100 million km. Round-trip communication time varies from 6-11 minutes.

**Mars**
- Perihelion: 1.4 AU
- Aphelion: 1.6 AU
- Orbital period: 687 days
- Mean velocity: 24 km/sec
- Equatorial radius: 3398 km

**Earth**
- Perihelion: 1.0 AU
- Aphelion: 1.0 AU
- Orbital period: 365 days
- Mean velocity: 30 km/sec
- Equatorial radius: 6378 km
Delta-V Variations

Short-Stay Missions (Opposition Class)

Long-Stay Missions (Conjunction Class)

Earth Departure Delta-V (m/s)

Earth Departure Date

Minimum Total Propulsive DV (Km/Sec)


Earth Launch Date
Mars Mission Duration Comparison

Example Lift Capability Needed* (Magnum-Class)

Long-Stay Mission
(180-Day Transits)

Short-Stay Mission
(Minimum Energy)

Vasco Da Gamma
(1497)

Amerigo Vespucci
(1501)

Return Transit
Time at Destination
Outbound Transit

Mission Duration, Days

* Assuming NTP=925 sec Propulsion
Artificial Gravity for Human Exploration Missions

NEXT Status Report
July 16, 2002
Current Configuration

- **Masts**
  - Deployable
  - Element zero-g positional control
  - Power, data cable support
  - Light compression during spinup/spindown

- **Main Power**
  - Redundant Reactors
  - Redundant Power Conversion
  - Reactor Rad Shielding

- **Suspension Cables**
  - Main rotational tension loads

- **Control Jets**
  - Spinup/spindown Steering

- **Spars**
  - Guy Cable Support

- **Main Thrusters**
  - Primary TVC via vehicle pointing

- **Main Power Radiators**
  - Flexible, Deployable

- **Guy Cables**
  - Rotational acceleration/deceleration loads
  - Transfer RCS torques
  - Mass normalization

- **Zero-G Docking Port**

- **Crew Module**
  - Inflatable Pressure Shell
  - Radiation Shielding
  - Micrometeoroid Protection
  - Life Support
  - EVA Support
  - Body-Mounted Radiator

- **Propellant Tanks**

- **125 m**
<table>
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<th></th>
<th>Original Asymmetric</th>
<th>Symmetric Central (Selected Config.)</th>
<th>Symmetric Terminal</th>
<th>Asymmetric CG</th>
<th>Asymmetric Counter</th>
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<tbody>
<tr>
<td><strong>Power Level</strong></td>
<td>-- High Power Variation</td>
<td>+ Counter-cycling (near constant power)</td>
<td>+ Counter-cycling (near constant power)</td>
<td>+ Counter-cycling (near constant power)</td>
<td>+ Counter-cycling (near constant power)</td>
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<tr>
<td><strong>Power Lines</strong></td>
<td>+ Short power lines</td>
<td>-- Long power lines</td>
<td>-- Long power lines (no worse than previous)</td>
<td>-- Long power lines</td>
<td>+ Short power lines</td>
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<tr>
<td><strong>Prop Lines</strong></td>
<td>-- Long prop lines</td>
<td>+ Short prop lines</td>
<td>-- Long prop lines</td>
<td>-- Long prop lines</td>
<td>-- Long prop lines</td>
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<tr>
<td><strong>Turn Rates</strong></td>
<td>+ Higher turn rates</td>
<td>-- Lower turn rates</td>
<td>+ Best turn rates</td>
<td>+ Higher turn rates</td>
<td>-- Lower turn rates</td>
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*For constant mass flow rate approach*
• Technique for rotating thrust vector 180°
• Rotation about vehicle z-axis
• Applications:
  - Midcourse turnaround
  - Planetary spirals (if required)
    - ~36% loss of propulsive efficiency vs. tangential thrusting
• Other possible implementation: second set of thrusters (-x thrust direction)
  - Thruster mass/expense vs. propellant required for rotation
Example Load Paths (cont)

Mast loads for spinup, spindown
- Mast will be under compression only during period when Hab Module/Power Module “weight” is less than compression load
  - Only mast loads identified to date
- After that, no load (suspension cables support loads)
- For spinup/spindown times less greater than 24 hours, compression loads will not exceed 100N (22 lbs)
- Maximum mast loads may result from zero-g operations (hard to quantify at this time)
  - Docking forces
  - Plume impingements

LaRC Analysis
- Providing finite element modeling and analysis for load conditions
  - 1-g
  - Spina/spindown
  - Maneuvers during transit
- From loads analysis, determine low lightweight a structure (such as inflatable/rigidizable structures) could be used for mast
- Status
  - Modeling nearly complete
  - Analysis to begin shortly

<table>
<thead>
<tr>
<th>Thrust Level, N</th>
<th>Spinup Time, hrs.</th>
<th>Anchor Power, kW</th>
<th>Guy Tension, N</th>
<th>Max. Mast Compression, N</th>
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<tr>
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</tr>
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ArcJet Computations Assume:
Efficiency 30%
isp 800 sec

Mast Compression
Guy Tension
RCS Thrust
Hab “Weight”

Finite Element Model