Solar Electric Propulsion for Mars Mission Applications

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Pre-Decisional: For planning and discussion purposes only.
Overview

• Where Are We Now?
  – Mars Sample Return (MSR) and the Sample Return Orbiter (SRO)
  – Why Solar Electric Propulsion (SEP)?

• Mission Design for SRO
  – Database of trajectories
  – Key outputs / figures / interesting findings

• Reference Mission Concept
  – Spacecraft and mission overview
  – Comparison with ballistic mission

• Future Work
  – Other SEP mission architectures
  – Current studies
Where Are We Now?
(Mars Formulation and MSR)

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MSR Campaign Concept – circa 2010

1. 2018 Atlas V 551
   - Caching Mission

2. 2022 Atlas V 541
   - MSR Orbiter

3. 2024 Atlas V 551
   - MSR Lander

4. Earth Entry Vehicle (EEV)
   - Sample Receiving Facility (SRF)

Sky Crane descent

Caching rover deposits cache
Cache
Fetch rover retrieves cache
Lander collects contingency sample

500 km orbit
Rendezvous and capture of OS

Mars Ascent Vehicle (MAV)
Orbiting Sample (OS)

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Current MSR Concept

Mars Surface
- Caching Rover
- Sample Cache
- Mobile MAV

Mars Atmosphere
- Mars Cruise Stage
- Entry & Descent Stage, Direct Entry
- Orbiting Sample (OS)

Mars Orbit
- Orbiter Spirals to Mars Orbit
- (Science Phase)
- Orbiting Sample (OS)
- Expended MAV
- Mars Ascent Vehicle
- Orbiter Captures OS
- Orbiter Spirals Out

Earth
- Sample Caching Rover
  - Atlas V 541 (candidate)
  - 2020
- MSR-Orbiter
  - Atlas V 421 (candidate)
  - ~2024
- MSR-Lander
  - Atlas V 551 (candidate)
  - ~2028
- Release EEV
  - ~2033

Sample Receiving and Curation Facility

Note: MSR-Lander and MSR-Orbiter can be launched in either order.

Notes:
- Changes since Decadal Survey in 2010
- Lunar DRO Orbit is an option
- Note: MSR-Lander and MSR-Orbiter can be launched in either order.

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Why SEP for Mars?

- Solar Electric Propulsion offers high Isp (5-10 x Biprop)
- SEP for basic orbiter missions is a hard sell
- SEP shines in high ΔV missions (i.e. Mars Sample Return)

Other benefits of SEP:
- High maturity of SEP thrusters (BPT-4000)

More Flexibility
- Trade-able parameters:
  - mass
  - power
  - flight time
- Long launch periods
- Launch Year robustness

Risk Reduction
- No critical events
  - No MOI
  - No aerobraking
  - No TEI
- Tailor arrival conditions at Earth
- Flexible margins
Aerojet BPT-4000

**Design Characteristics**
- Propellant: Xenon
- Mass (Thrust & Cathode): 4.7 kg
- Envelope Dimensions: 16 x 22 x 27 cm
- Nominal Input Power: 4500 Watt
- Operational Power Range: 2000 – 6000 Watt
- Nominal Voltage: 350 Volt
- Operational Voltage Range: 250 – 400 Volt

**Status**
- 6000hr Accelerated Life Test Program Complete

**Performance at 4.5 kW**
- Thrust: 210 mN
- Specific Impulse: 1950 sec
- Efficiency: 50%
- Life (Continuous): >6000 hr
- Total Impulse: >5.8 x 10^6 N-sec
- Nominal Pmax: 14.1 mN/sec
- On/Off Cycles: >6000 cycles

* Corrected for facility back pressure effects
** Based on accelerated life tests and analysis

- Can be run in high thrust or high Isp modes
- Successfully flown on Advanced EHF satellites
- Highest power SEP engine flown to date

**From AIAA 2010-6623, Hofer (2010)**

**Isp:** 1800 – 2000 sec
**Thrust:** 0.25 N
**Eff.:** 50 – 55%
**Power:** 0.3 – 4.8 kW
Mission Design Work
MALTO Software

- Mission Analysis Low-Thrust Optimization
- Developed at JPL
- Fast, medium-fidelity
- Simulates low-thrust via multi-segment, 2-body impulsive maneuvers
- Core in FORTRAN 95, GUI and post processing in MATLAB
- Spiral to/from Mars added analytically

Benefits
- Fast
- Robust convergence
- Parametric mode
- Accurate results

“Great Taste, Better Value”*
*This slogan is a trademark of Malt-O-Meal Company

Pre-Decisional: For planning and discussion purposes only.
The Trade Space

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value(s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Launch Vehicle</td>
<td>F9 1.1, <strong>Atlas V 421</strong>, 431, 551, FH</td>
</tr>
<tr>
<td>Launch Years</td>
<td>2022, <strong>2024</strong>, 2026, 2028</td>
</tr>
<tr>
<td>Return Years</td>
<td>2028, 2030, <strong>2033</strong>, 2035</td>
</tr>
<tr>
<td>Engines (#)</td>
<td><strong>BPT-4000</strong> (2-3), others</td>
</tr>
<tr>
<td>Duty Cycle</td>
<td>95%</td>
</tr>
<tr>
<td>Spacecraft Bus Power</td>
<td>700 W</td>
</tr>
<tr>
<td>Post-Launch Coast</td>
<td>30 days</td>
</tr>
<tr>
<td>Pre-Earth-Arrival Coast</td>
<td>30 days</td>
</tr>
<tr>
<td>Mars Science Orbit Altitude (circular)</td>
<td>320 km</td>
</tr>
<tr>
<td>Earth Arrival $V_\infty$</td>
<td><strong>1.5 km/s</strong>, 4.5 km/s</td>
</tr>
<tr>
<td>Power Levels</td>
<td>8 – 29 kW (38 kW for 3 engines)</td>
</tr>
<tr>
<td>Heliocentric TOF</td>
<td>200 – 600 days</td>
</tr>
</tbody>
</table>

MALTO is run in parametric mode to loop through as many cases as possible
MALTO Database Runs

• So far we have run:
  – 21,348 Outbound cases
  – 84,032 Inbound cases

• Dozens of case configurations
  – Mostly varied around baseline
  – Case configurations tracked in Excel spreadsheet (right)

• Typical case run times
  – 1-3 hours (outbound)
  – 3-15 hours (inbound)

• Thousands of runs added daily

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Earth → Mars – Falcon 9, 1 Engine

Pre-Decisional: For planning and discussion purposes only.
SRO Spacecraft Modeling

User’s Design Inputs
- Year
- LV
- Power
- Thruster
- Margins

Basic Bus Functions
- ADCS
- CDHS
- Thermal
- Telecom

Spacecraft Model
- Bus
- Power
- Propulsion
- Structure

Spacecraft Dry Mass
- SEP Power

Propellant Mass
- Flight Times

Trajectory
- Prop Margin
- Mars-Earth Trajectory
- Maneuvers at Mars
- Earth-Mars Trajectory

Converged Design Figures of Merit

Implemented in MATLAB. Tool Smiths: Austin Nicholas, Zach Bailey, Erick Sturm

Pre-Decisional: For planning and discussion purposes only.
Reference Mission Concept
Spacecraft Concept Overview

- Launch October 2024 on Atlas V421 from KSC
- Mission life of 9 years (design life of 13 years)
- Three-axis stabilized
- Sample capture HW and Earth Entry Vehicle
- 200 kg allocation for science instruments
- SEP propulsion
  - Baseline 2+1 BPT-4000 thrusters
- Powered by 65 m² solar array
  - Baseline 17.5 kW BOL @ 1 AU
- Margin Strategy
  - 43% Dry Mass Contingency
  - 43% Bus Power Contingency
  - 15% SEP Power Contingency
  - 10% SEP Propellant Contingency
SRO Reference Mission
Notional Timeline and Launch Dates

SRO Mission Duration 3300 days (~9 yrs)

Earth to Mars
400d
Spiral In
280d
Low Mars Orbit, 1930 days (~3 Mars Years)
Science and Relay Operations (~2.5 Mars Years)

Check-out
SRL Support (~1 Mars Year)
MAV Support

SRL Launch (2028)
SRL Arrival
MAV Launch
Earth Arrival (2033)

SRL and MAV Support

OS Rendezvous & Capture

Pre-decisional: for planning and discussion purposes only
Mission Design (Reference Case)

Earth to Mars Trajectory (Outbound)

- Depart Earth: October 2024
- Atlas V421
  - Launch mass: 3250 kg
  - 25% Launch Vehicle Margin
    - Extra 700 kg delivered for 150 days TOF
  - C3: 17 km²/s² (can be as low as 11)
- Total TOF: 680 days (1.9 years)
  - Heliocentric TOF: 400 d (14 mos.)
  - Spiral Duration: 280 d (8 mos.)
  - 30-day check-out period post launch

Mars to Earth Trajectory (Inbound)

- Arrive at Earth: November 2033 (9 years)
- In Low Mars Orbit: 5.3 years
- Begin spiral out: December 2031
- Total TOF: 680 days (1.9 years)
  - Heliocentric TOF: 400 d (14 mos.)
  - Spiral Duration: 280 d (8 mos.)
  - 30-day no-burn period pre-Earth arrival
- Arrival $V_\infty$: 1.5 km/s
### SRO Chemical vs SEP comparison

**Overall Mission durations are comparable (9 years), but SEP spends 600 less days in Mars orbit.**

#### Masses

<table>
<thead>
<tr>
<th></th>
<th>SEP</th>
<th>Chem</th>
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<tbody>
<tr>
<td><strong>Total</strong></td>
<td>2940</td>
<td>3150</td>
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<tr>
<td><strong>Propellant</strong></td>
<td>1448</td>
<td>2036</td>
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<td>Inbound</td>
<td>415</td>
<td>911</td>
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<tr>
<td>At Mars</td>
<td>28</td>
<td>253</td>
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<tr>
<td>Outbound</td>
<td>837</td>
<td>872</td>
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<tr>
<td>Margin Xe</td>
<td>126</td>
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<td><strong>Bus</strong></td>
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<td>Payload</td>
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<td>Structures</td>
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<td>206</td>
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<td>Thermal</td>
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<td>31</td>
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<td>Power</td>
<td>274</td>
<td>100</td>
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<td>Harness</td>
<td>45</td>
<td>33</td>
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</table>

**SEP has more dry mass but less fuel mass.**

#### 

<table>
<thead>
<tr>
<th></th>
<th>SEP</th>
<th>Chem</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>ΔV</strong> Budget</td>
<td><strong>SEP</strong></td>
<td><strong>Chem</strong></td>
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<tr>
<td>To Mars</td>
<td>3325</td>
<td>30</td>
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<tr>
<td>Capture</td>
<td>2968</td>
<td>983</td>
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<tr>
<td>Mission</td>
<td>223</td>
<td>350</td>
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<tr>
<td>Return</td>
<td>6340</td>
<td>2133</td>
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<tr>
<td><strong>Total</strong></td>
<td>12856</td>
<td>3497</td>
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</tbody>
</table>

SEP requires 4x the ΔV but has 6x the Isp.

#### Timeline

<table>
<thead>
<tr>
<th>Event</th>
<th>SEP</th>
<th>Chem</th>
</tr>
</thead>
<tbody>
<tr>
<td>Launch</td>
<td>10/16/2024</td>
<td>9/24/2024</td>
</tr>
<tr>
<td>Arrive</td>
<td>11/23/2025</td>
<td>403 days</td>
</tr>
<tr>
<td>LMO</td>
<td>8/25/2026</td>
<td>275 days</td>
</tr>
<tr>
<td>Depart</td>
<td>12/5/2031</td>
<td><strong>1948 days</strong></td>
</tr>
<tr>
<td>End Spiral</td>
<td>9/26/2032</td>
<td>276 days</td>
</tr>
<tr>
<td>Earth</td>
<td>11/2/2033</td>
<td>402 days</td>
</tr>
</tbody>
</table>

SEP has **2526 days** whereas Chem has **180 days**.
Pros/Cons of SEP

• Pros
  – Extra power for science
  – Possible Phobos/Deimos flybys or rendezvous
  – Flexible timeline – launch periods, phasing, margins
  – No critical events at Mars
  – Earth $v_\infty = 1.5$ – allows late decision to DRO orbit
  – Inert Xe propellant

• Cons
  – Requires equivalent mass, due to:
    • Extra mass for prop. system and power (450 kg vs. 230 kg)
    • Quadruple the mission $\Delta V$
  – Longer transfer times $\rightarrow$ 600 less days at Mars
  – Must leave Mars earlier (probably can’t do 2030 return)
  – Extra cost?
Current and Future Work
Mission Concept Cases

• Deimos or Phobos Boulder Return
  – “Land” in micro-g, grab a boulder and return to Earth

![Deimos or Phobos Boulder Return Diagram]

2 ARM SEP Engines
50 kW Arrays
Can return 10-20 Tons From Phobos or Deimos

• Large telecom orbiter drops off small science orbiter
  – Drop off in LMO, return to ASO

![Large telecom orbiter drops off small science orbiter Diagram]

Optical and X/Ka-band DTE
Odyssey-class Science/Relay

• MSR Orbiter drops off multiple Telecom orbiters at ASO
  – Also performs science at Phobos, Deimos, and LMO

![MSR Orbiter drops off multiple Telecom orbiters Diagram]

Sample Return and MRO-Class Science
TelSats (X-band + Optical)

• Science orbiter drops off several daughter-craft
  – Landers at Phobos & Deimos
  – Telsat at ASO
  – Cubesats anywhere

![Science orbiter drops off several daughter-craft Diagram]

TelSat (X-band + Optical)
Phobos/Deimos Landers
MRO-Class Science/Relay Orbiter

Pre-Decisional: For planning and discussion purposes only.
Near Term Studies

• MALTO trajectories
  – Additional thrusters and types - NEXT, XIPS, HiVHAc, ARM
    • Early results show significant mass reduction with NEXT (4000 sec Isp)
    • Mission easily fits on Falcon 9
  – Additional launch vehicles, configurations
  – “Porkchop Plots” for outbound and inbound departure/arrival conditions

• System Margin Strategies
  – Statistical methods of assessing interdependent margins

• Adapting model for multiple orbiter types (daughter craft, non-SRO orbiters)
SRO Team List

- **Team Lead:** Rob Lock
- **Mission Design:** Ryan Woolley
- **Systems:** Austin Nicholas, Charles Budney
- **Planetary Protection:** Bob Gershman
- **Configuration/Mechanical:** Scott Howe, Cassandra Mercury
- **Science:** Laura Kerber, Serina Diniega, Lindsay Hays
- **Summer Interns:** Andrew Ferguson, Brenden Hogan, Frank Laipert, Sean Lawlor, Jason Reiter, Anirudh Tadanki, Patrick Wang
Earth Arrival

Baseline Option – Direct Earth Entry
• Mass at arrival: 1420 kg
• Incoming $V_\infty = 1.5$ km/s (10.7 km/s Entry)
• EEV Options
  • Hard-landing (no chute)
  • Soft-landing (chute)
  • Air-grab (chute)
• EEV separation at [TBD] days
• Divert S/C to escape orbit

Contingency Option - Divert to Lunar DRO
• 1.5 km/s arrival $V_\infty$ allows for divert to stable DRO orbit
• Long-term Stability
• Earth flyby into DRO capture for later pickup (by human or robotic mission)
• Many months to achieve final orbit
• $\Delta V$ [TBD] (likely small)
Phobos and Deimos Science

<table>
<thead>
<tr>
<th>Inclination</th>
<th>Encounters</th>
<th>$\Delta V$ Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>Science Orbit</td>
<td>Targeted Flybys</td>
<td>Free</td>
</tr>
<tr>
<td>Equatorial</td>
<td>Rendezvous</td>
<td>1-2 km/s</td>
</tr>
</tbody>
</table>

Altitude

Science ~300 km

Phobos 6400 km

Deimos 20400 km

Opportunity to target multiple moon fly-bys during inbound spirals

Credit: Sean Lawlor and Anirudh Tadanki

Pre-Decisional: For planning and discussion purposes only.
SEP “Porkchop” Plot

Spiral Start Date

Arrival Date

me_2033_BPTx2-14kW_320km_1.5-1500kg_pcp

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Launch Period Implications

Best Departure Date

Best Arrival Date

Pre-Decisional: For planning and discussion purposes only.
Outbound Trajectory (to Mars)

- Interplanetary flight time and solar array power (at 1 AU) are parametrically varied
- Spiral durations computed analytically

- Optimization variables
  - Launch & arrival dates
  - Launch C₃
  - Launch mass (tied to C₃ per the LV parametric model)
  - Thrust vector magnitudes (subject to available power limitations) and directions

- MALTO maximizes mass delivered to Mars
Earth → Mars – Falcon 9, 2 Engines

Pre-Decisional: For planning and discussion purposes only.
Inbound Trajectory (to Earth)

- Departing Mars, the spacecraft first spirals up then leaves with $C_3=0$
- Departure mass not tied to departure $C_3$ (no launch vehicle)
- Opted to fix the mass at Earth arrival to 250 – 2500 kg at 250 kg intervals
- Parametrically vary power and time-of-flight for each mass
- MALTO minimizes interplanetary propellant mass

- Two Earth arrival $V_\infty$ limits:
  - 1.5 km/s: 2 options
    - Lower velocity direct entry
    - Use lunar flybys to capture into a long-term stable orbit
  - 4.5 km/s: direct entry (future)
Mars ➔ Earth Output

Pre-Decisional: For planning and discussion purposes only.
Mars → Earth – 1000 kg

me_2028_BPTx2_320km_1.5_var, for Mf = 1000 kg

Xenon Mass [kg]

Total ToF [days]

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Earth → Mars – Atlas V 421, 2 Engines

Pre-Decisional: For planning and discussion purposes only.
Earth → Mars – Atlas V 551, 3 Engines

Pre-Decisional: For planning and discussion purposes only.
Earth → Mars – Falcon Heavy, 3 Engines

Pre-Decisional: For planning and discussion purposes only.

Delivered Mass [kg] vs. Total Time of Flight [days]

Power (kW) Legend:
- 18 kW
- 20 kW
- 22 kW
- 24 kW
- 26 kW
- 28 kW
- 30 kW
- 32 kW
- 34 kW
- 36 kW
- 38 kW

Graph showing the relationship between delivered mass and total time of flight for various power levels.
Total $\Delta V$

Atlas V 421, 2 Engines

Pre-Decisional: For planning and discussion purposes only.