Jet Propulsion Laboratory
California Institute of Technology

Optimized Low-Thrust Missions from Geosynchronous Transfer Orbit to Mars

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Getting a Small Spacecraft to Mars

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1. Dedicated Launch

Pro: Custom, full control

Con: $$$

2. Hitchhike to Mars

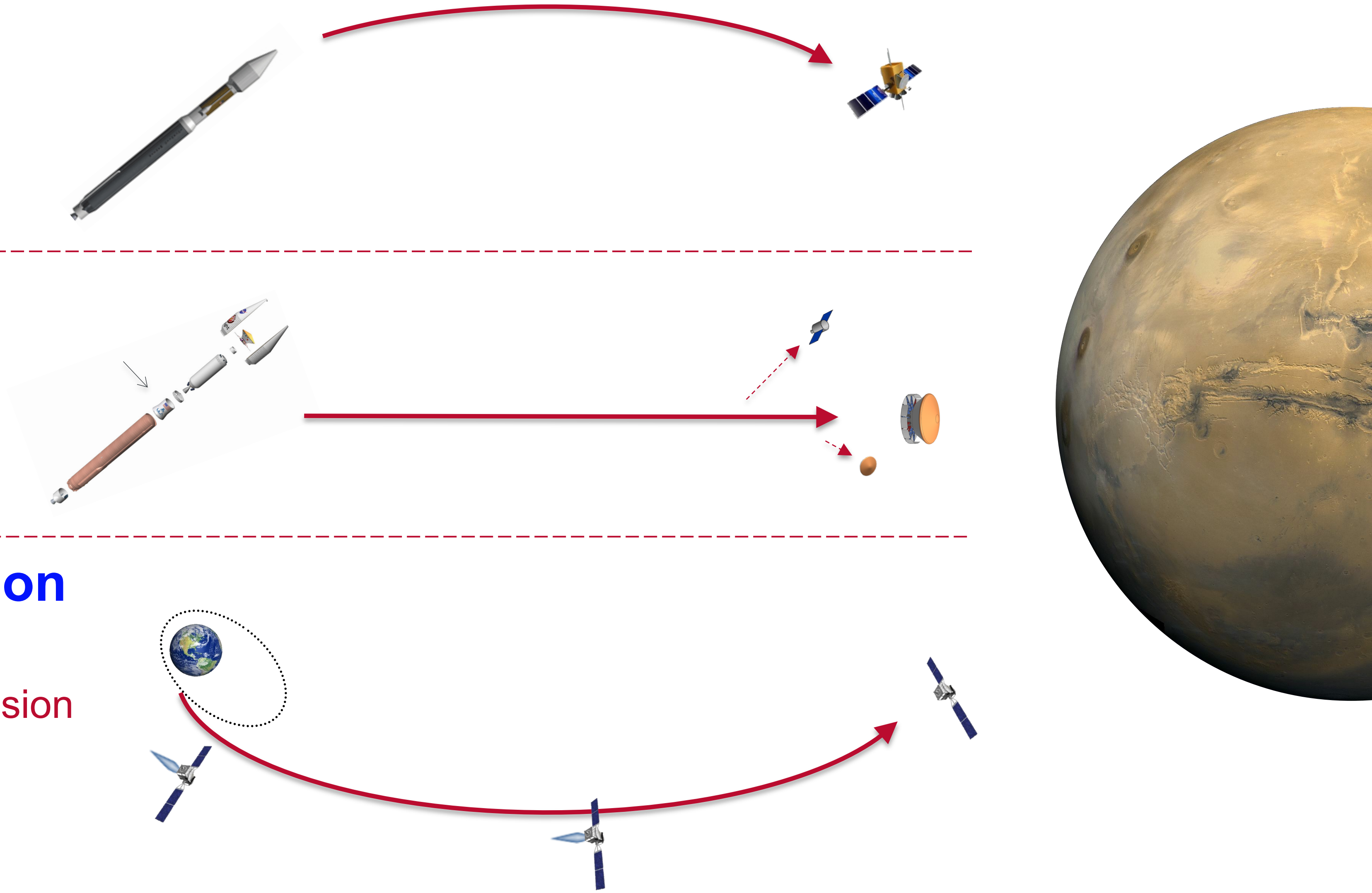
Pro: Cheap, direct delivery

Con: Few reliable options

3. Rideshare + Propulsion

Pro: Cheap, lots of options

Con: Secondary, need propulsion



Solar Electric Propulsion for Mars

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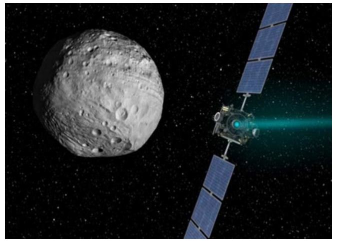
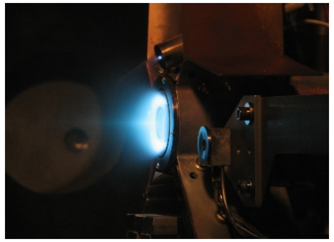
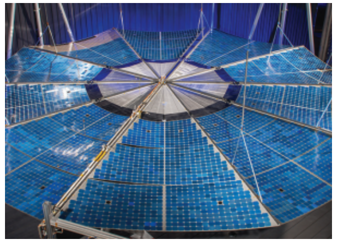
- Six interplanetary SEP missions have flown:
  - Deep Space 1 (1998) – comet
  - Hayabusa (2003) – asteroid
  - SMART-1 (2003) – Moon
  - Dawn (2007) – Vesta and Ceres
  - Hayabusa 2 (2014) – asteroid
  - Bepi-Colombo (2018) – Mercury
- Lots of technology advancement over past decade
  - Both Large and small electric thrusters
  - Lightweight solar arrays (UltraFlex, ROSA, etc.)

Engine	Pmax [W]	Pmin [W]	Thrust [mN]	Isp [sec]	Est. Life [kg]
MaSMi (JPL) [1]	900	150	45	1733	150+
SPT100 (Fakal)	1560	720	89	1562	120
PPS 1350-G (Safran)	1560	590	89	1650	140
BHT-600 (Busek)	887	229	46	1683	30



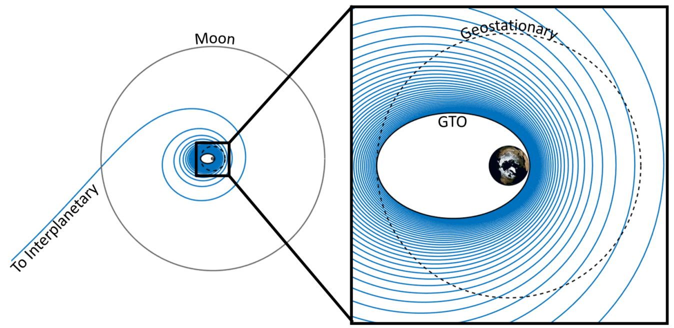




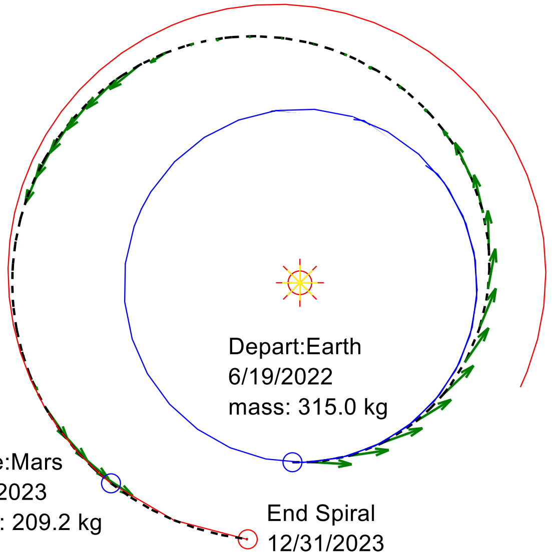
Getting from GTO* to Mars Orbit

*Geostationary Transfer Orbit (~185 km x 35700 km)

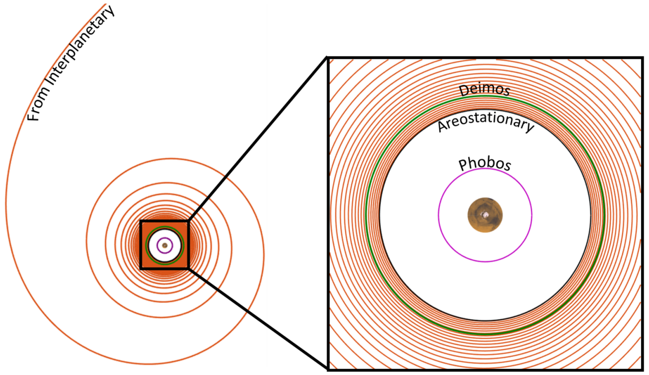
1) Earth Escape Spiral



2) Earth → Mars



3) Mars Capture Spiral



- Duration vs. mass trade
- Thrusting around perigee to increase spiral efficiency

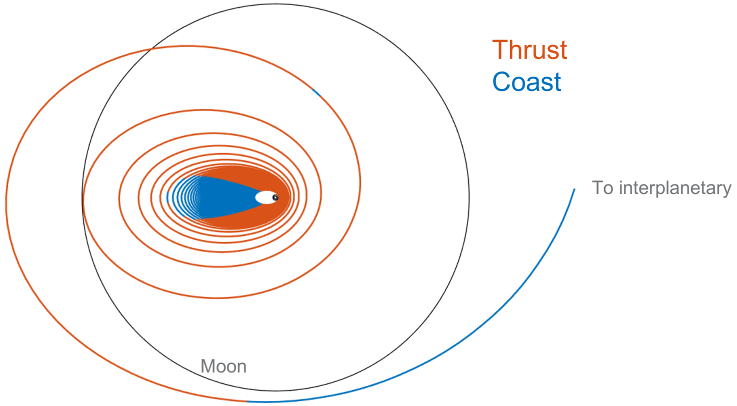
- Optimal dates lead to ΔV of around 5.7 – 6.5 km/s
- Use low-thrust optimizer to calculate thrust profile

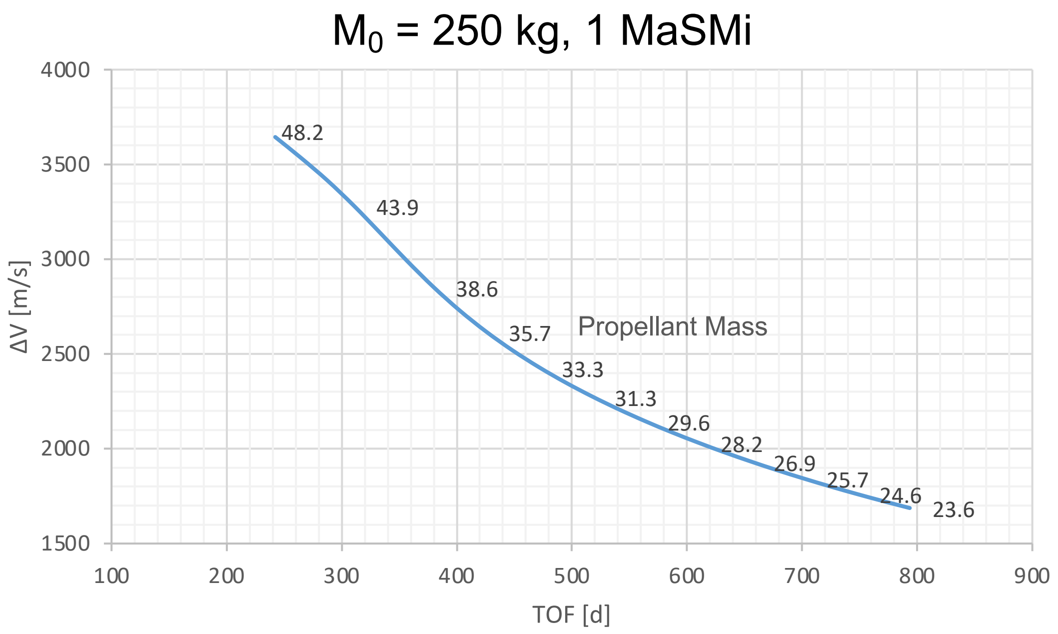
- Circular spiral can be approximated using Edelbaum method
- Phobos, Deimos, and Areostationary have similar propellant requirements

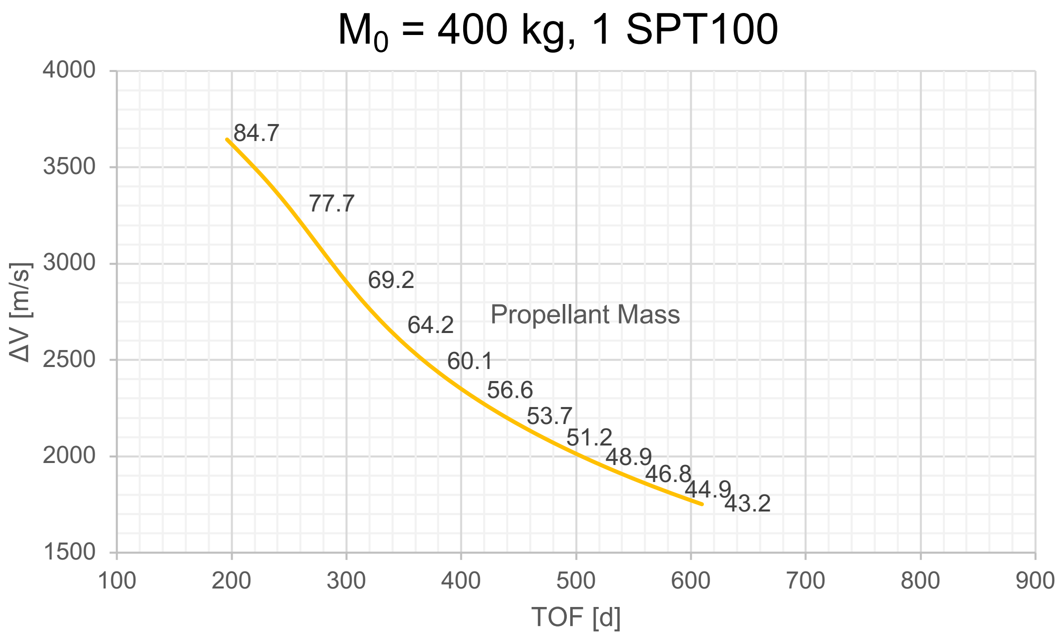
Step 1: Building a Mission Design Database

Earth Departure Spirals (parametric model)

- GTO → Escape
- Depends on acceleration and coast arcs







**Equation for generic parametric model given in paper*

Heliocentric Trajectory Sweeps

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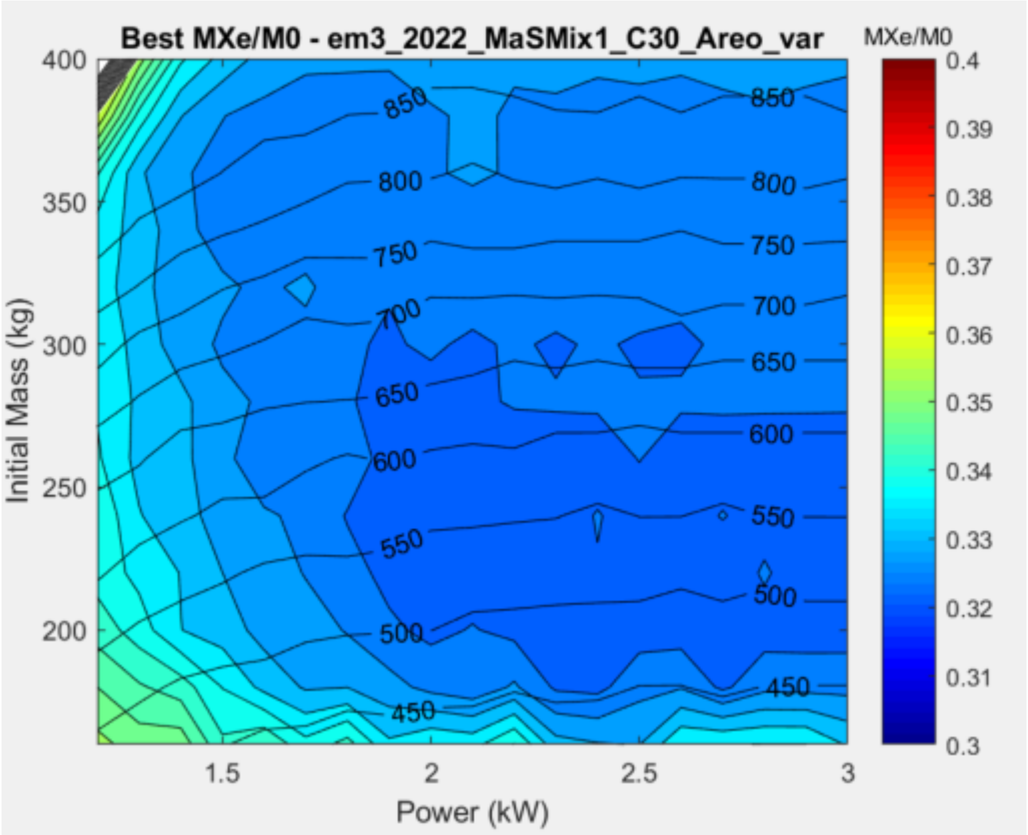
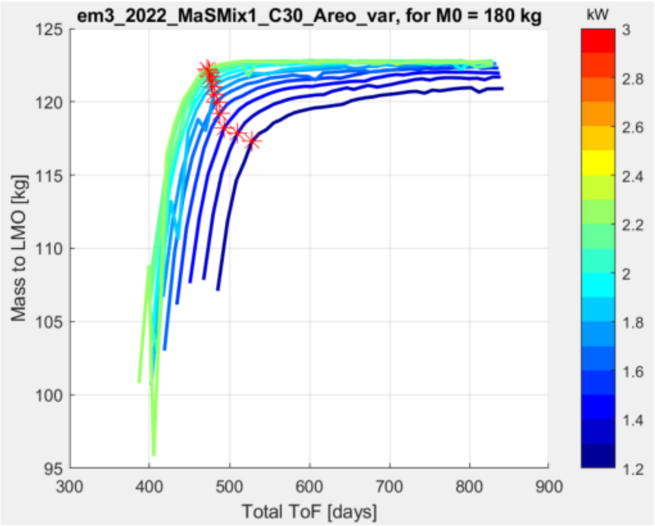
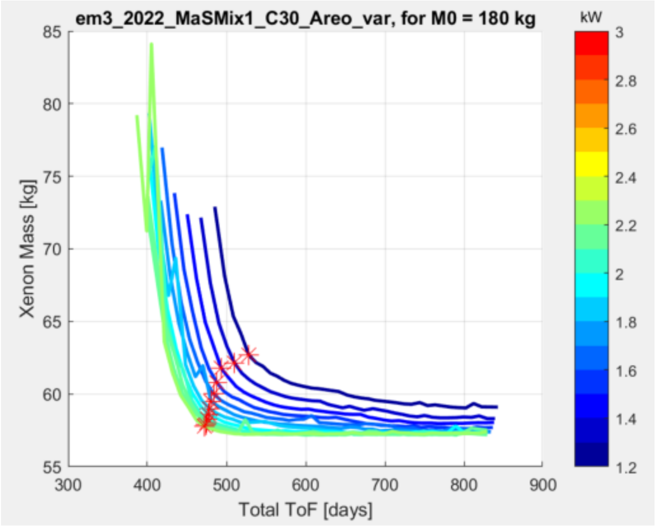
MaSMi x1 Trajectory Sweep

- 15,000+ trajectories



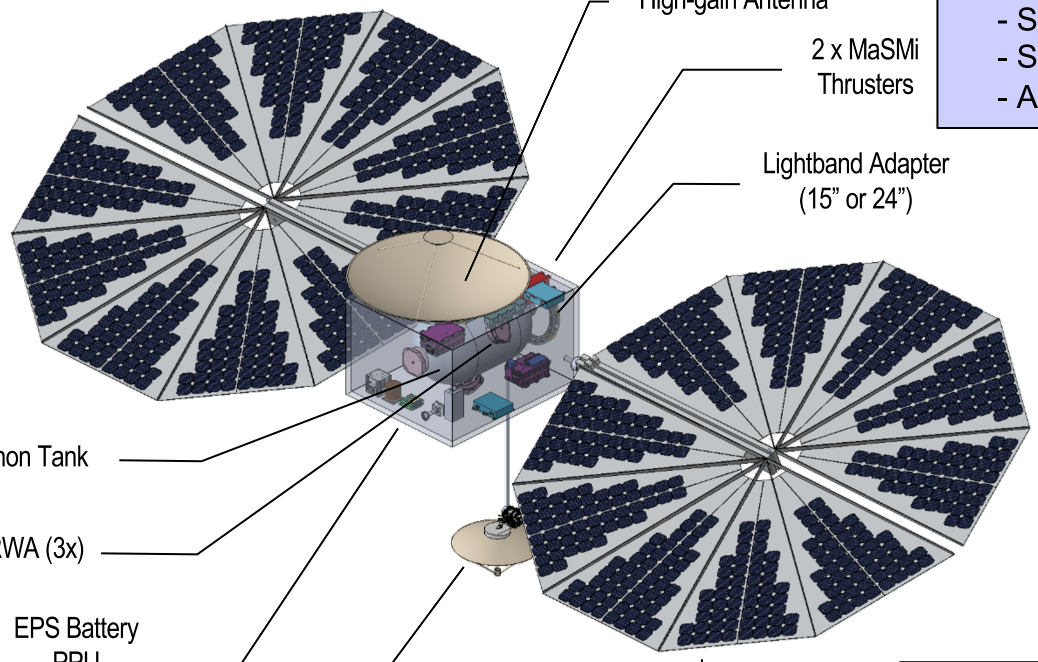


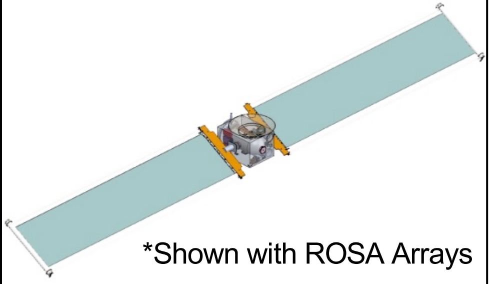


Step 2: Spacecraft Model

- Simple parametric models for:
  - – Propulsion system
  - – Power system
  - – Structures and mechanical
  - – Harness and cabling
- Fixed mass estimates:
  - – Payload
  - – Command and Data Handling
  - – Telecom
  - – Thermal
  - – Reaction Control System
- Add desired margins

- 3-axis stabilized
  - IMU/SS/Star Tracker
  - Reaction Wheels
  - Optional RCS propulsion
- Basic Telecom
- Secondary Li-Ion Batteries
- Sphinx Avionics Card (TBR)
- Active and Passive Thermal





*Shown with ROSA Arrays

Step 3: Optimization Tool

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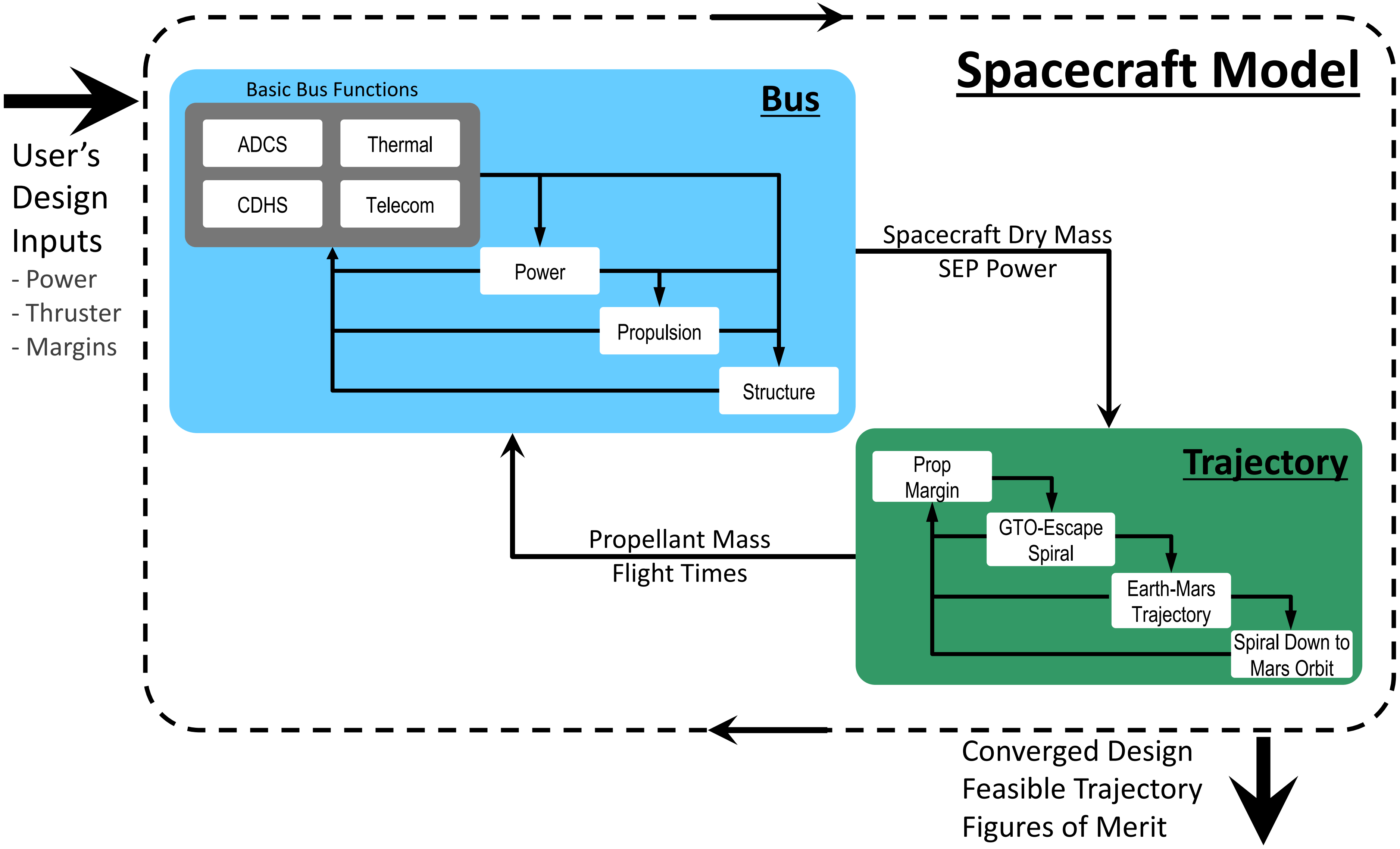

Initial Concept and Design Rules-of-Thumb

- It is important to select a propulsion system that is sufficiently sized for the mass and ΔV of the desired mission.
  - We have found that a good rule-of-thumb is to select engines and power levels to give **initial acceleration levels of 0.15 – 0.3 mm/s^2** at Earth
  - Approximate **ΔV's** from GTO to high Mars orbit:

    Spiral out - **3 km/s**, Heliocentric - **6 km/s**, Spiral Down: **1 km/s** (3 km/s for LMO), **Total: ~10 km/s**
  - Use I_{sp} and rocket equation to give approximate propellant mass
- Approximate tank mass: 5-10% of propellant mass (1-2 kg/L, optimal ~1.4)
- Solar array power density for flexible systems is around **11-15 kg/kW**
- Initial size estimate for arrays – **80% of thruster saturation at Mars**

Conclusions

- Key take-aways for SEP missions from GTO to Mars
  - It takes about 10 km/s of low-thrust DV
  - Size propulsion system and power to give 0.15 – 0.3 mm/s^2
  - Typical TOF: 2 years (but there is a trade between mass and time)
  - S/C will typically be ~50% propellant by mass
  - Be sure thrusters can handle the required throughput