National Aeronautics and Space Administration

Mars, Phobos, and Deimos Sample Return Enabled by ARRM Alternative Trade Study Spacecraft

Jacob Englander
Matthew Vavrina
Gabe Merrill
Min Qu
Bo Naasz

code 595

NAVIGATION & MISSION DESIGN BRANCH
NASA GSFC

a.i. solutions

Introduction to the Asteroid Robotic Redirect Mission (ARRM)

- The Asteroid Robotic Redirect Mission (ARRM) is a mission concept to retrieve a large sample of asteroidal material, either:
  - Option A: a small Near-Earth Asteroid (NEA) via inflatable bag
  - Option B: or a piece of a large NEA via articulated grippers
- ARRM will also test large-scale solar arrays and electric propulsion systems
- ARRM is intended to be a stepping stone to the very large propulsion and power systems that will be needed for human exploration of the solar system

Why ARRM to Mars?

- Mars sample return has been a tantalizing but unattainable goal since the beginning of planetary exploration
- A very interesting precursor mission might be to collect samples from Deimos or Phobos
  - These bodies are windows into both Mars itself and into the primitive state of the solar system
- Previous sample return studies have focused on retrieving small amounts of material, but what if a large multi-ton sample could be returned?
- The ARRM Option B spacecraft, with its articulated grippers and landing legs, could also be used to retrieve a large sample from Deimos or Phobos
- Alternatively, the same spacecraft could be used to retrieve a sample container launched from the surface of Mars

Guiding Question

- “How much mass can we retrieve from Deimos, Phobos, or low-Mars orbit (LMO)?”

Mission Architecture

- Launch from Earth on either Falcon Heavy (FH) or Space Launch System (SLS)
  - FH launch is followed by a double lunar flyby maneuver which results in ejection from the Earth-Moon system with a C3 of 2 km^2/s^2
  - SLS directly delivers the spacecraft to a heliocentric trajectory with a C3 of up to 27 km^2/s^2
- Spacecraft travels to Mars and arrives at the sphere of influence (SOI) with C3 of 0 km^2/s^2
- Spacecraft descends to the orbit of interest (Deimos, Phobos, LMO)
- Spacecraft acquires sample (stay time of 200-600 days)
- Spacecraft ascends to the Martian SOI
- Spacecraft returns to Earth-Moon system with arrival C3 of 2 km^2/s^2
- Earth flybys on the way to or from Mars are considered

Trajectory Design Assumptions

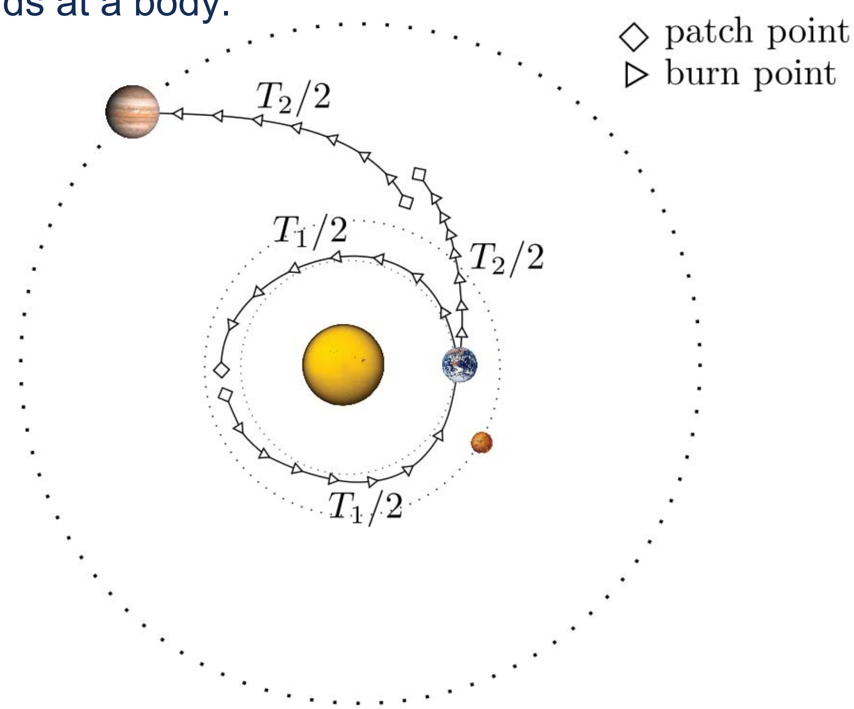
Power Assumptions	
BOL Power at 1 AU	51 kW
Array performance model	TJGA
Array decay rate	1% per year
Spacecraft bus power	0.5 kW
Power Margin	15%
Propulsion Assumptions	
Thruster model	Fixed I_{sp} and system efficiency
Input power bounds	0-40 kW
Thruster performance	2000 s I_{sp} with 55% efficiency 3000 s I_{sp} with 60% efficiency
Duty cycle	90%
Propellant margin	11 %
Launch Assumptions	
Maximum departure hyperbolic excess energy (C3)	2 km^2/s^2 (FH) 27 km^2/s^2 (SLS)
Maximum launch mass	13153 kg (FH with 2000 s I_{sp}) 13169 kg (FH with 3000 s I_{sp}) 16072 kg (SLS)
Declination of Launch Asymptote (DLA) bounds	$+/-28.5°$
Post-launch forced coast	30 days (SLS) none (FH)
Mars stay assumptions	
Desired altitude	5844 km (Phobos) 20063 km (Deimos) 400 (LMO)
Stay time at desired altitude	200-600 days
Earth Return Assumptions	
Maximum arrival C3	2.0 km^2/s^2
Post-mission Δv	100 m/s
Minimum spacecraft final mass	5170 kg (2000 s I_{sp} case) 5020 kg (3000 s I_{sp} case)

Full-Mission Optimization for Sample Return Problems

- When we first began this project:
  - We modeled the Earth-Mars and Mars-Earth phases of the mission separately
  - We varied the pickup mass and stay time at Mars parametrically
  - We computed the descent and ascent spiral flight time and propellant mass in post-processing
- But is there a better way? The real question is how much mass can we bring home – can the optimizer operate on pickup mass directly?
- We constructed a full sample-return model which captures the relationship between pickup mass and flight time
- The combination of variable pickup mass and fully-modeled descent and ascent spirals is highly complex – “time is mass and mass is time”
- The full-mission sample return optimization framework presented here is implemented in the Evolutionary Mission Trajectory Generator (EMTG), Goddard’s open-source interplanetary trajectory optimization tool

Multiple Gravity Assist with Low-Thrust (MGALT) via the Sims-Flanagan Transcription

- Break mission into phases. Each phase starts and ends at a body.
- Sims-Flanagan Transcription
  - Break phases into time steps
  - Insert a small impulse in the center of each time step, with bounded magnitude
  - Optimizer Chooses:
    - Launch date
      - For each phase:
        - Initial velocity vector
        - Flight time
        - Thrust-impulse vector at each time step
        - Mass at the end of the phase
        - Terminal velocity vector



- Assume two-body force model; propagate by solving Kepler’s problem
- Propagate forward and backward from phase endpoints to a “match point”
- Enforce nonlinear state continuity constraints at match point
- Enforce nonlinear velocity magnitude and altitude constraints at flyby

Spiral Trajectory Modelling at Mars via Edelbaum's Method

- Assume:
  - The initial and final orbits are circular and coplanar
  - The thrust available to the spacecraft is relatively low
  - The thruster is operated continuously during the spiral orbit transfer and thrust is always tangent to the velocity vector

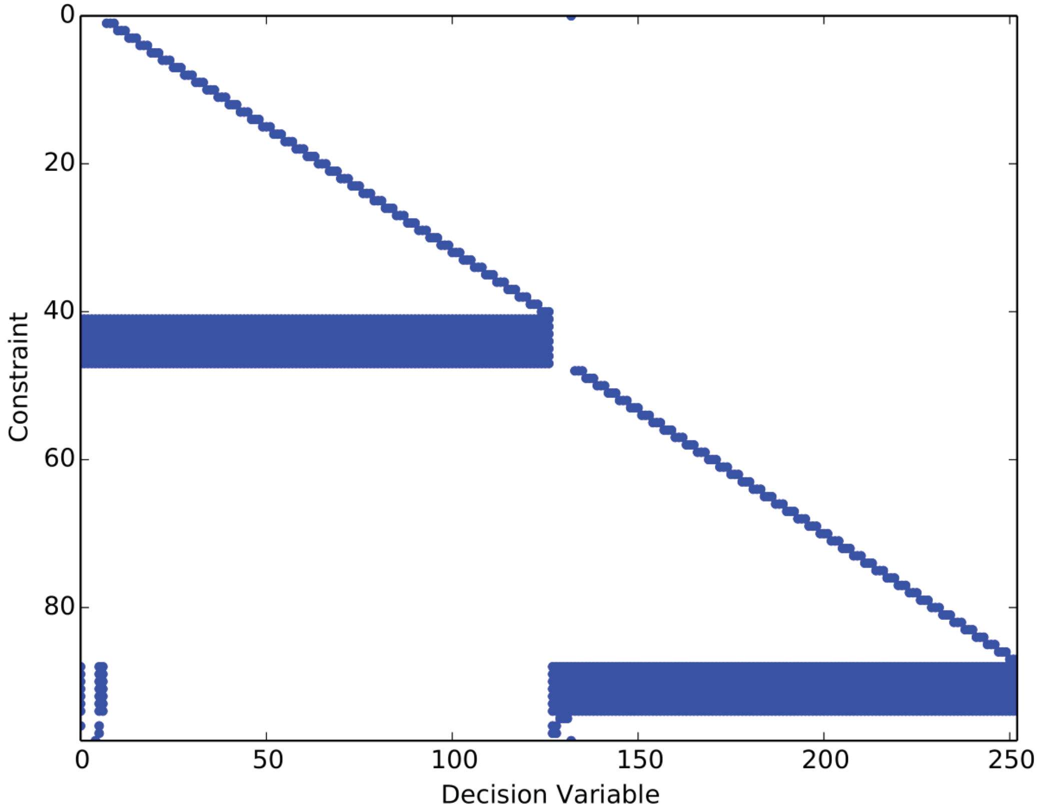
$$\Delta v_{Edelbaum} = \sqrt{\frac{\mu_{planet}}{r_0}} - \sqrt{\frac{\mu_{planet}}{r_f}}$$

$$m_{propellant} = m_{before-spiral}\left(1 - \exp\left(-1000\frac{\Delta v_{Edelbaum}}{I_{sp}g_0}\right)\right)$$

$$t_{Edelbaum} = \frac{m_{propellant}}{\dot{m}}$$

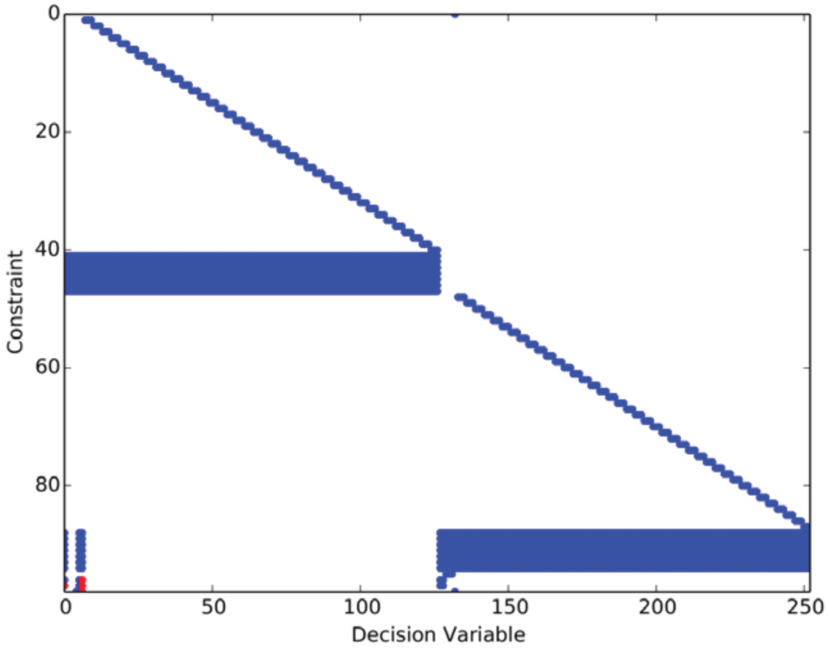
- Note: For ascent spirals, $m_{before-spiral}$ is dependent on any mass added at the bottom of the gravity well, hence "time is mass and mass is time"

Rendezvous Sample-Return with Fixed Pickup Mass



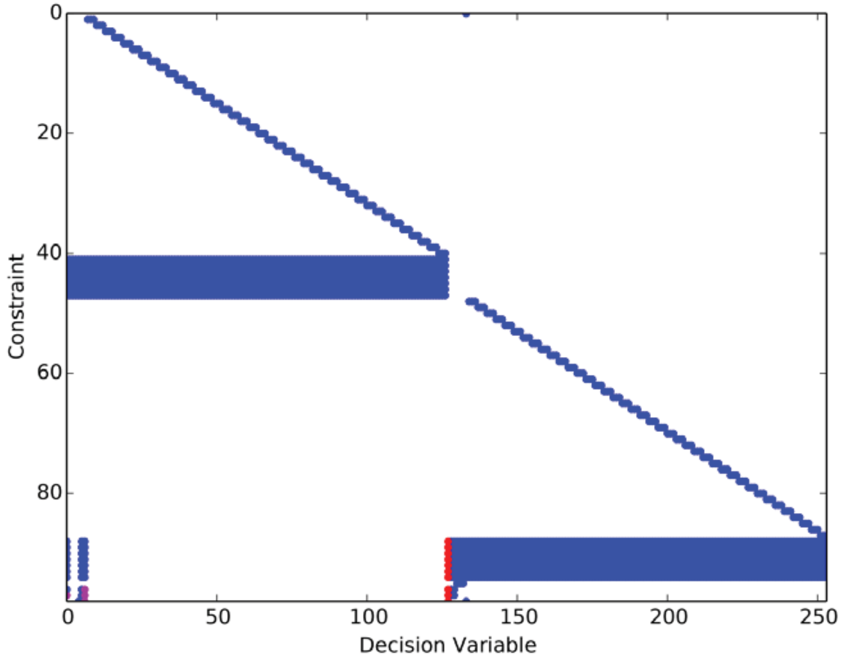
This is the standard Sims-Flanagan Jacobian sparsity pattern for a two-phase mission with bounded flight time, a bounded return date, and a dry mass constraint

Sample Return with Fixed Pickup Mass and Low-Thrust Spiral Modeling



- Dependency of flight time constraint on the launch date (launch date influences arrival at Mars, which influences spiral time, which influences flight time)
- Dependency of Earth return date constraint on outbound flight duration

Sample Return with Variable Pickup Mass and Low-Thrust Spiral Modeling



- Dependency of return-phase match point constraints on pickup mass
- Dependency of Earth return date and total flight time on pickup mass
- Dependency of dry mass constraint on pickup mass due to its affect on propellant used for the ascent spiral

Nonlinear Programming via SNOPT

Minimize $f(\boldsymbol{x})$

Subject to:

$$\boldsymbol{x}_{lb} \leq \boldsymbol{x} \leq \boldsymbol{x}_{ub}$$
$$\boldsymbol{c}(\boldsymbol{x}) \leq \mathbf{0}$$
$$\boldsymbol{A}\boldsymbol{x} \leq \mathbf{0}$$

where:

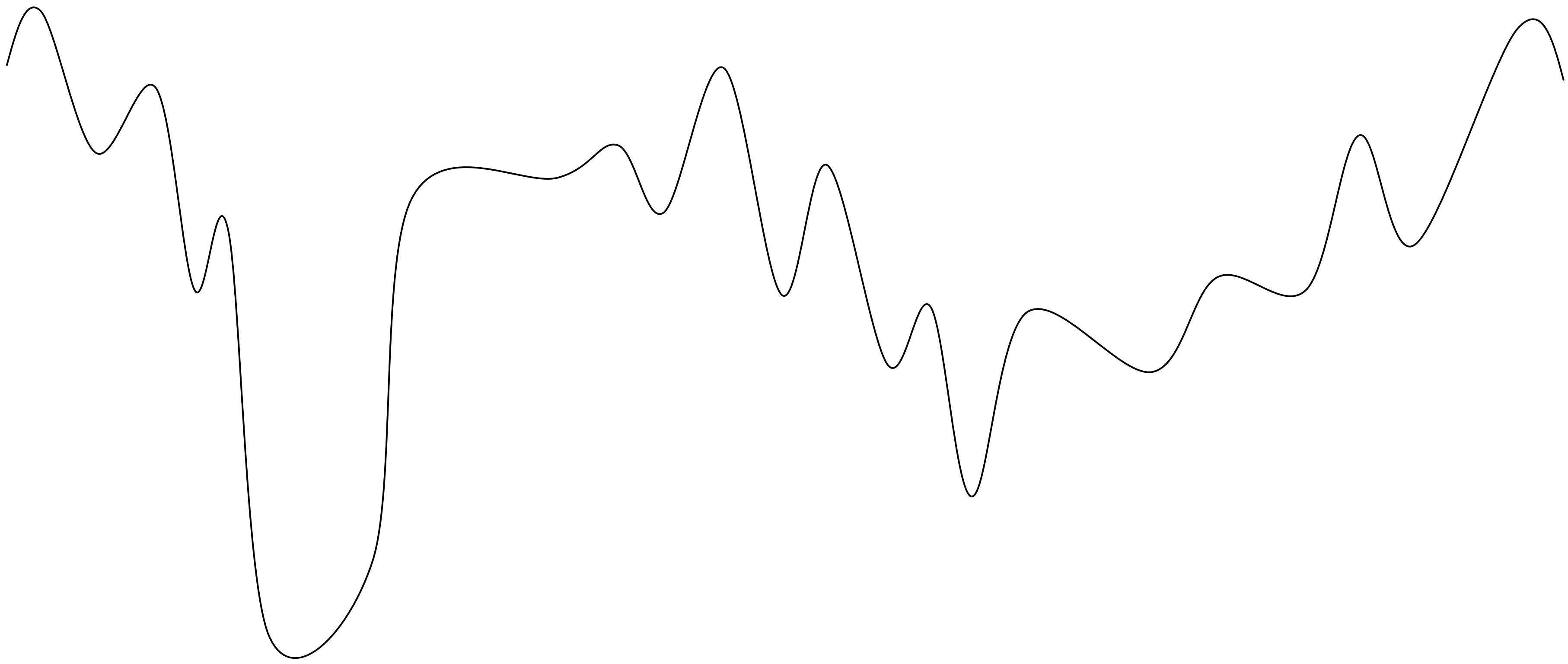
$\boldsymbol{x}_{lb}, \boldsymbol{x}_{ub}$ are lower and upper bounds on the decision variables

$\boldsymbol{c}(\boldsymbol{x})$ is a vector of nonlinear constraints

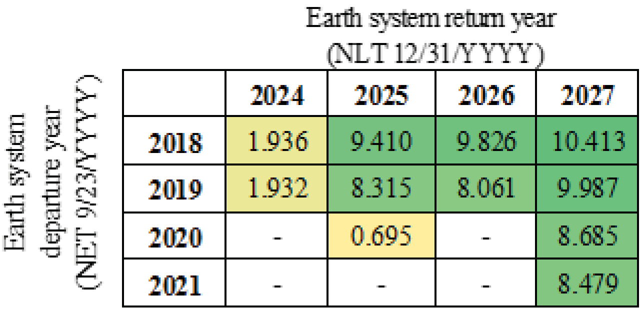
$\boldsymbol{A}\boldsymbol{x}$ is a vector of linear constraints

- We use SNOPT as our NLP problem solver
- But all NLP solvers require an initial guess…

Monotonic Basin Hopping



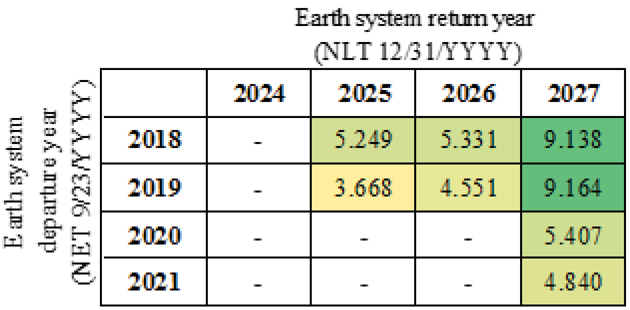
Results



Earth system return year (NLT 12/31/YYYY)

Earth system departure year (NET 9/23/YYYY)	2024	2025	2026	2027
2018	1.936	9.410	9.826	10.413
2019	1.932	8.315	8.061	9.987
2020	-	0.695	-	8.685
2021	-	-	-	8.479

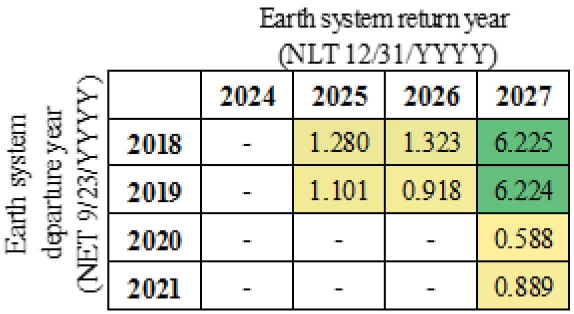
Best performance for Deimos sample return on FH



Earth system return year (NLT 12/31/YYYY)

Earth system departure year (NET 9/23/YYYY)	2024	2025	2026	2027
2018	-	5.249	5.331	9.138
2019	-	3.668	4.551	9.164
2020	-	-	-	5.407
2021	-	-	-	4.840

Best performance for Phobos sample return on FH

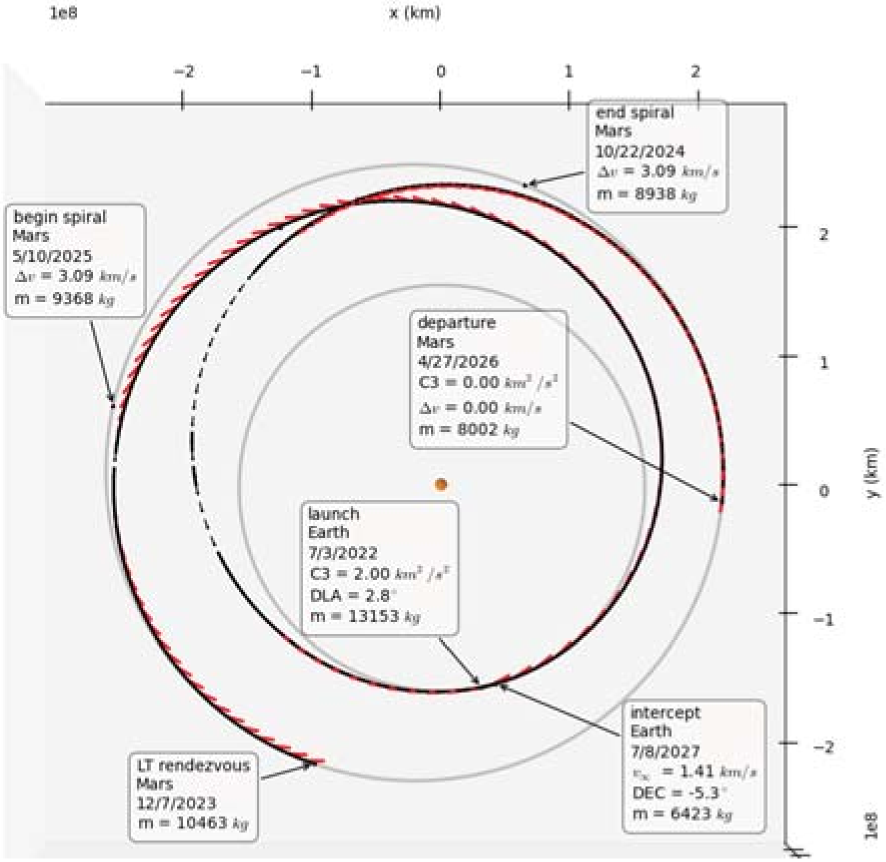


Earth system return year (NLT 12/31/YYYY)

Earth system departure year (NET 9/23/YYYY)	2024	2025	2026	2027
2018	-	1.280	1.323	6.225
2019	-	1.101	0.918	6.224
2020	-	-	-	0.588
2021	-	-	-	0.889

Best performance for LMO sample return on FH

An interesting example:
LMO Sample Return on FH, 2022-2027



end spiral
Mars
10/22/2024
Δv = 3.09 km/s
m = 8938 kg

begin spiral
Mars
5/10/2025
Δv = 3.09 km/s
m = 9368 kg

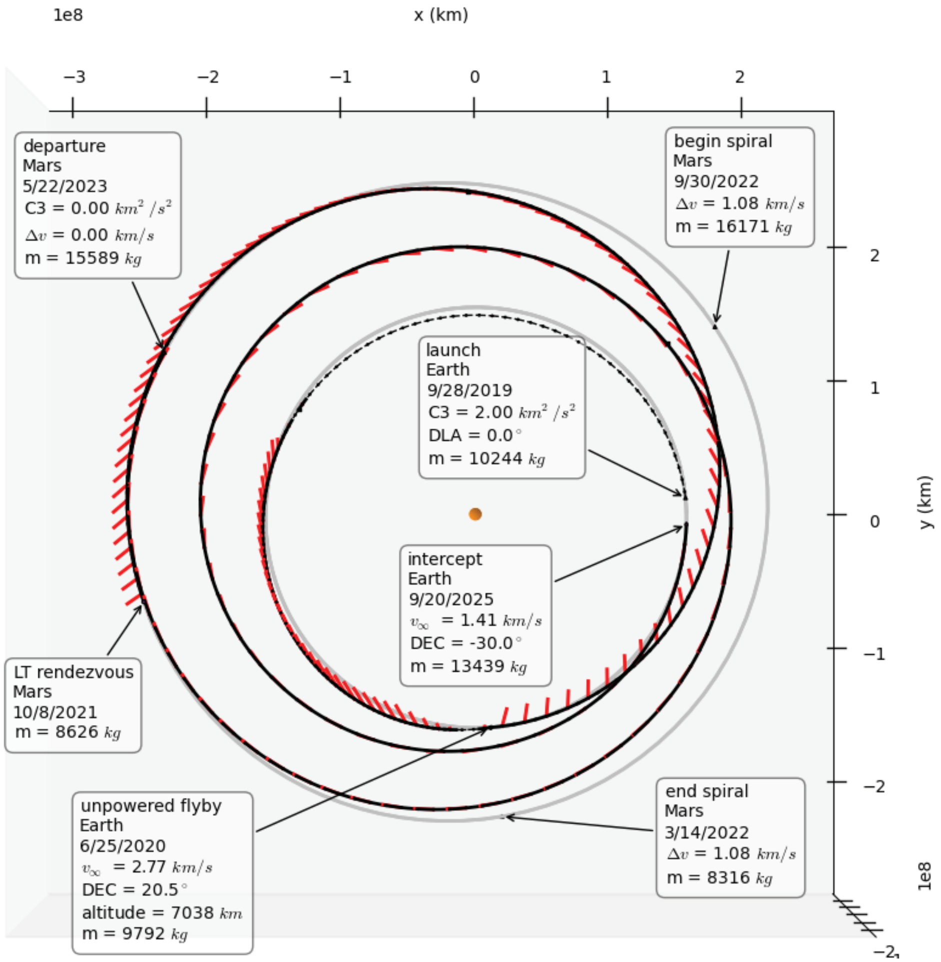
departure
Mars
4/27/2026
C3 = 0.00 km^2/s^2
Δv = 0.00 km/s
m = 8002 kg

launch
Earth
7/3/2022
C3 = 2.00 km^2/s^2
DLA = 2.8°
m = 13153 kg

intercept
Earth
7/8/2027
v_∞ = 1.41 km/s
DEC = -5.3°
m = 6423 kg

LT rendezvous
Mars
12/7/2023
m = 10463 kg

Another interesting example:
Deimos Sample Return on FH, 2019-2025 with Earth flyby



Conclusions

- We constructed a full-mission optimization framework for sample return problems which includes both variable pickup mass and low thrust descent/ascent spiral modeling
- Our approach allows pickup mass to be optimized directly and captures the dependencies of all of the problem constraints on the pickup mass
- This technique is efficient and reduces the human work-load necessary to design sample return missions without requiring large parametric runs
- The complexity of the problem increases, but this complexity is well-handled by the autonomous optimization algorithms in EMTG
- Using this technique, we found viable applications of the ARRM spacecraft to Deimos, Phobos, and Mars surface sample return in the 2020s

Thank You

EMTG is available open-source at

https://sourceforge.net/projects/emtg/