



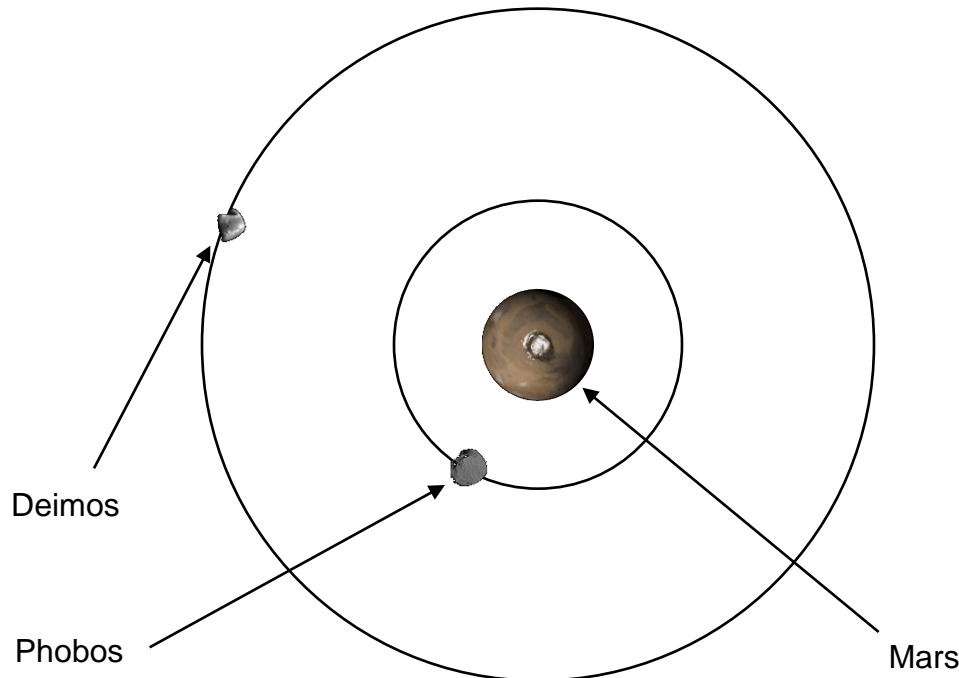
# DELTA-V BUDGETS FOR ROBOTIC AND HUMAN EXPLORATION OF PHOBOS AND DEIMOS

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# $\Delta V$ Budgets for visiting Phobos and Deimos

- **Problem statement:** Upon arrival at Mars, what is the optimal strategy for visiting Phobos, Deimos or both moons on rendezvous and return missions? What are the high-level propulsive  $\Delta V$  requirements? How beneficial is the use of aerobraking?
- Applications to both robotic and human missions
- Phobos and Deimos' near-circular and equatorial orbits enable a simplified analytical treatment



	<b>Phobos</b>	<b>Deimos</b>
<b>Semi-major axis</b>	9,376 km	23,458 km
<b>Eccentricity</b>	0.0151	0.0002
<b>Inclination</b>	1.075°	1.788°
<b>Orbital period</b>	7 hr 39 min	1 day 6 hr

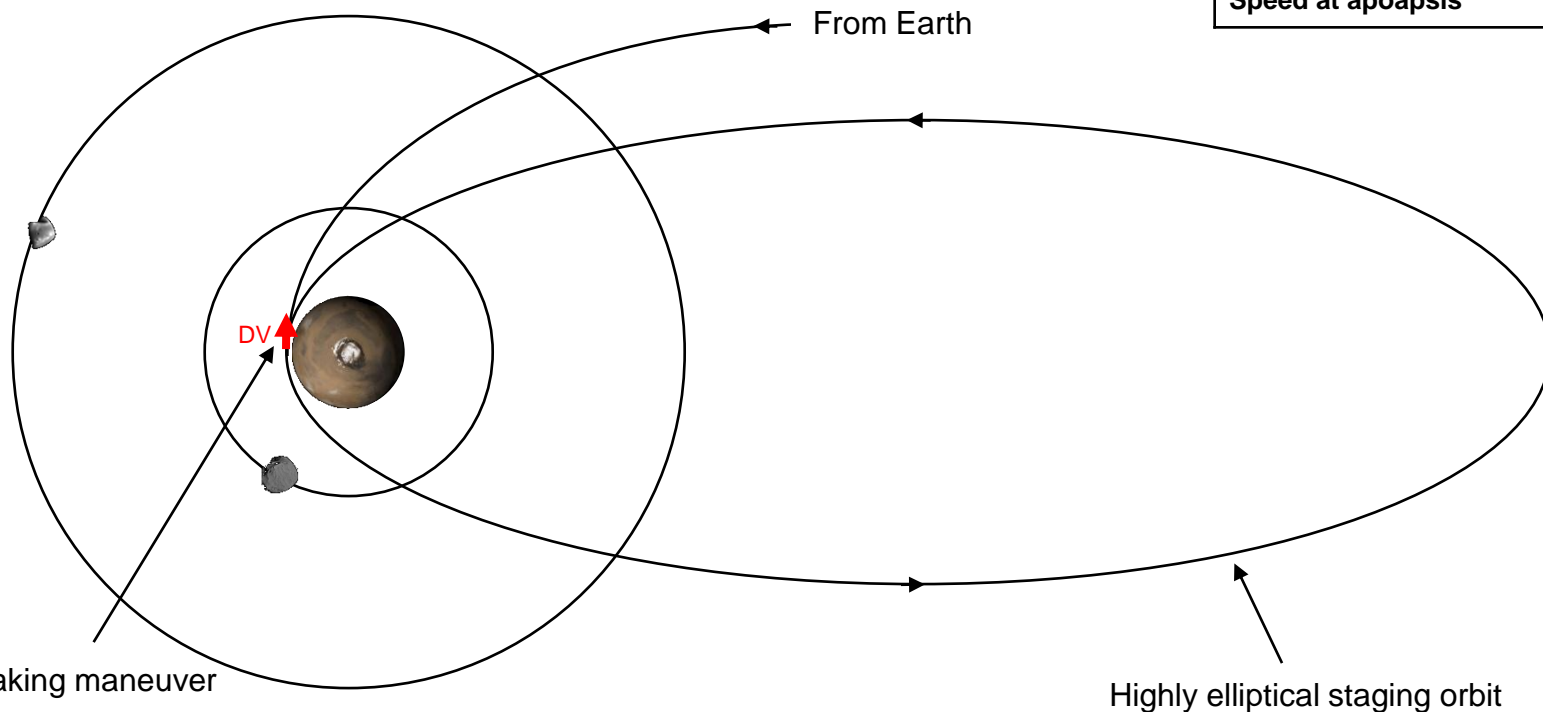
**Orbital parameters of Phobos and Deimos**

# Highly Elliptical Staging Orbit

- Represents an initial orbit a spacecraft would enter through aerocapture after an interplanetary transfer from Earth with periapsis close to Mars' atmosphere and an arbitrarily high apoapsis.
- Independent of heliocentric transfer trajectory from Earth (short-stay, long-stay, etc)
- Serves as reference orbit to compare propulsion requirements to visit either moon.

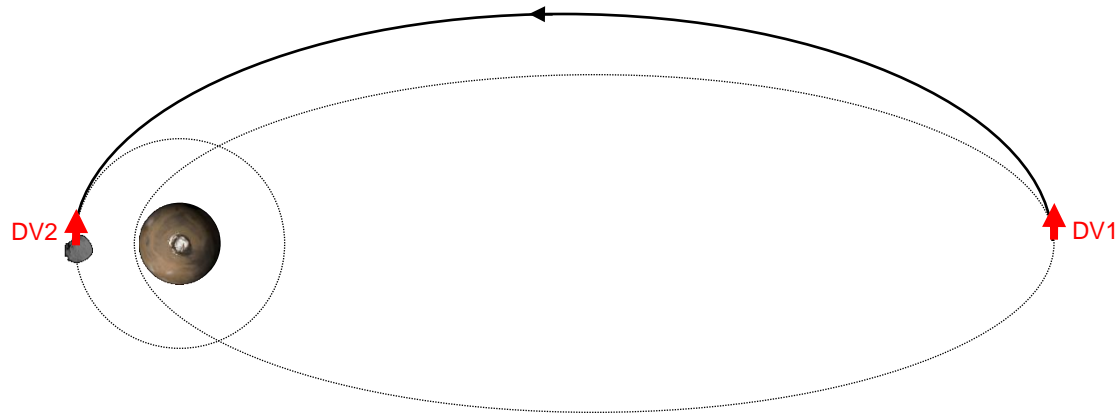
Orbital parameters used for staging orbit in this study

<b>Altitude at Periapsis</b>	250 km
<b>Altitude at Apoapsis</b>	82 173 km
<b>Eccentricity</b>	0.92
<b>Orbital period</b>	3 days 7 hr
<b><math>\Delta V</math> required for escape</b>	100 m/s
<b>Speed at apoapsis</b>	202 m/s

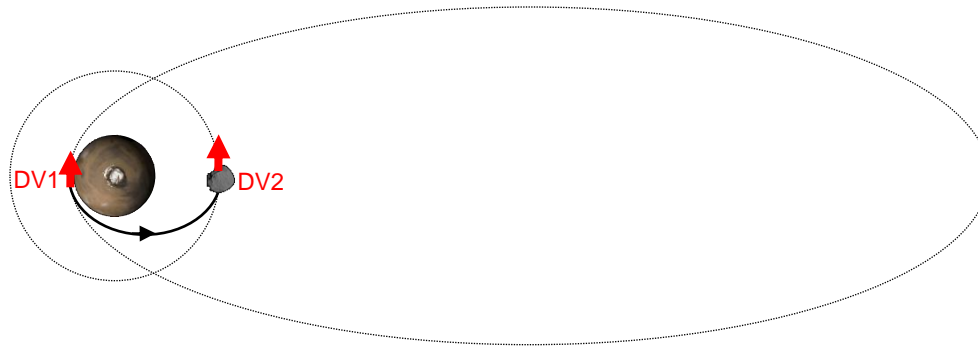


# Staging orbit to Phobos/Deimos transfers

- Two options for transfer from staging orbit to either moon
- Out-of-plane maneuvers are best made at the staging orbit's apoapsis where orbital speed is  $\sim 200$  m/s



**Option 1:** Begin transfer at staging orbit's apoapsis



**Option 2:** Begin transfer at staging orbit's periapsis

Propulsive $\Delta V$	Option 1	Option 2	Option 2 with aerobrake
<b>Phobos</b>	845 m/s	1171 m/s	538 m/s
<b>Deimos</b>	604 m/s	888 m/s	651 m/s

Min  $\Delta V$  option for Phobos if aerobrake is not available

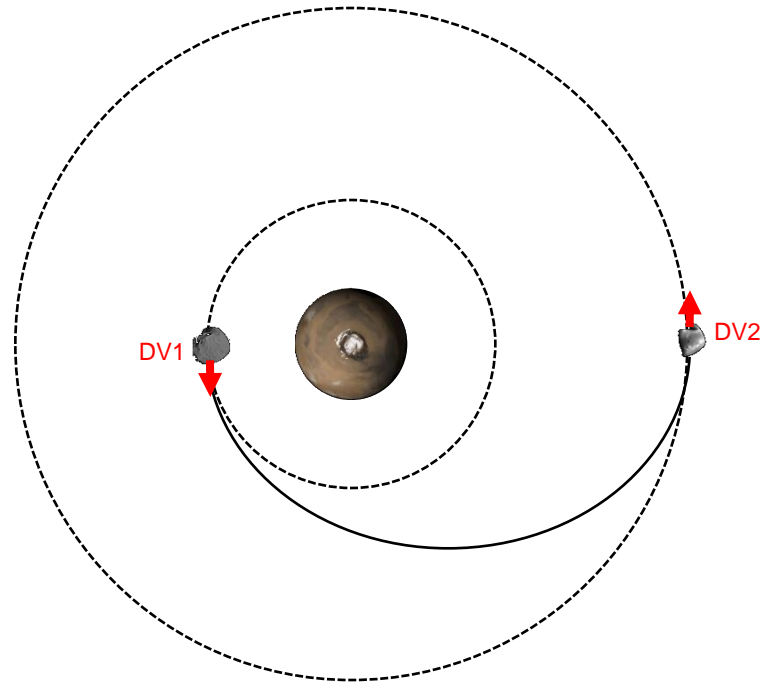
Min  $\Delta V$  option for Phobos if aerobrake is available

Min  $\Delta V$  option for Deimos regardless of aerobrake capability

$\Delta V$  requirements by transfer option

# Phobos ↔ Deimos transfers

- Hohmann transfer available every 10.24 hr synodic period.

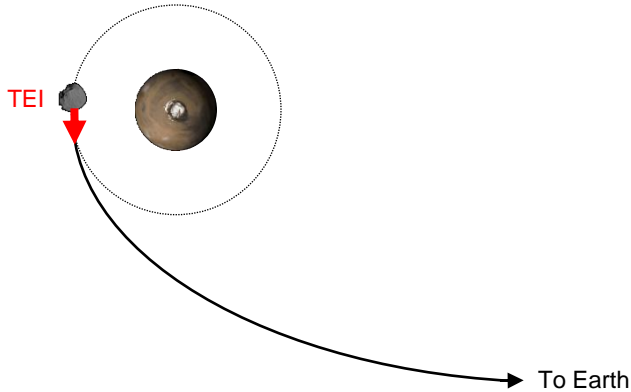


	Total $\Delta V$
Phobos ↔ Deimos	748 m/s

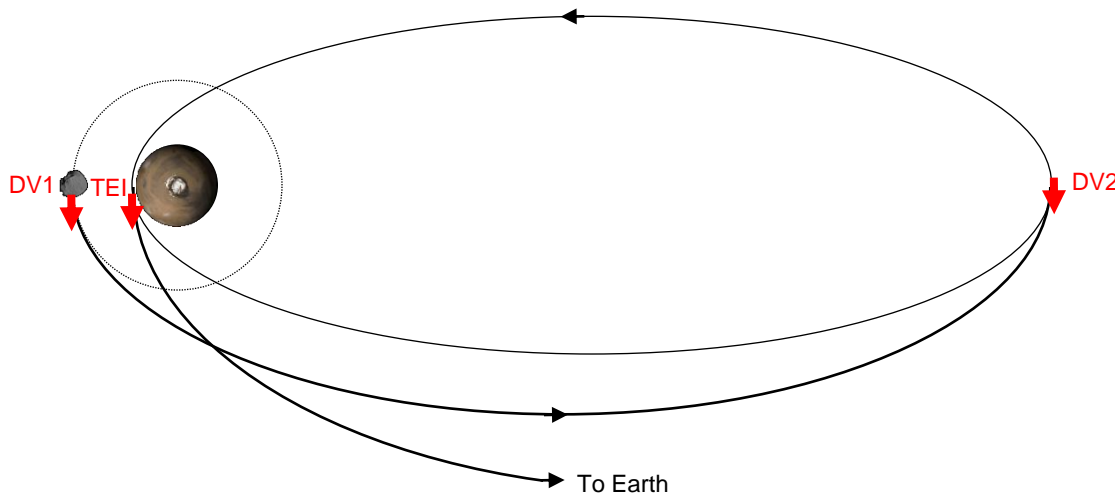
**Inter-moon  $\Delta V$  requirement**

# Phobos/Deimos to Trans-Earth Injection (TEI)

- Out-of-plane maneuvers are best made at the staging orbit's apoapsis where orbital speed is  $\sim 200$  m/s



**Option 1:** Perform TEI maneuver directly from the moon's orbit



**Option 2:** Return to staging orbit then perform TEI at periapsis

→ For the range of  $V_\infty$ 's required for TEI on short-stay and long-stay missions, option 2 has lower  $\Delta V$  requirements than option 1 for both Phobos and Deimos

# $\Delta V$ Budgets for visiting Phobos and/or Deimos

$\Delta V$  chart of optimal transfers

From \ To	Staging orbit	Phobos	Deimos
Staging orbit	-	540 m/s (w/ aero) or 848 m/s (w/o aero)	604 m/s
Phobos	848 m/s	-	748 m/s
Deimos	604 m/s	748 m/s	-

Example mission  $\Delta V$  budgets

	Round-trip $\Delta V$ from staging orbit	
	w/ aerobrake	w/o aerobrake
Phobos	1388 m/s	1696 m/s
Deimos	1208 m/s	1208 m/s
Phobos & Deimos	1892 m/s	2200 m/s

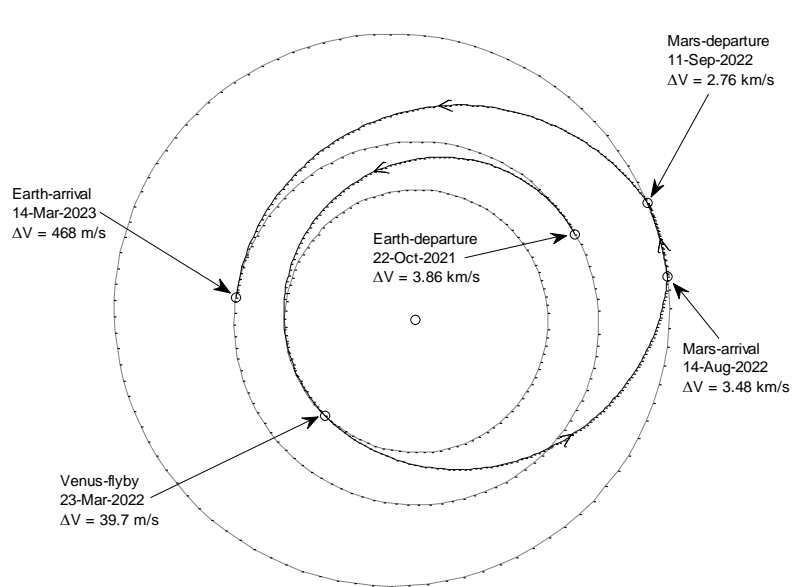
- If visiting both moons on a round-trip mission the lowest  $\Delta V$  option is to visit Phobos first then Deimos when aerobrake is available (otherwise the order of visit does not matter).
- $\Delta V$ 's do not include any possible out-of-plane maneuvers dictated by geometry of incoming and outgoing hyperbolic asymptotes from the Mars system. Out-of-plane maneuvers are best made at the staging orbit's apoapsis where orbital speed is  $\sim 200$  m/s

# Getting to Mars

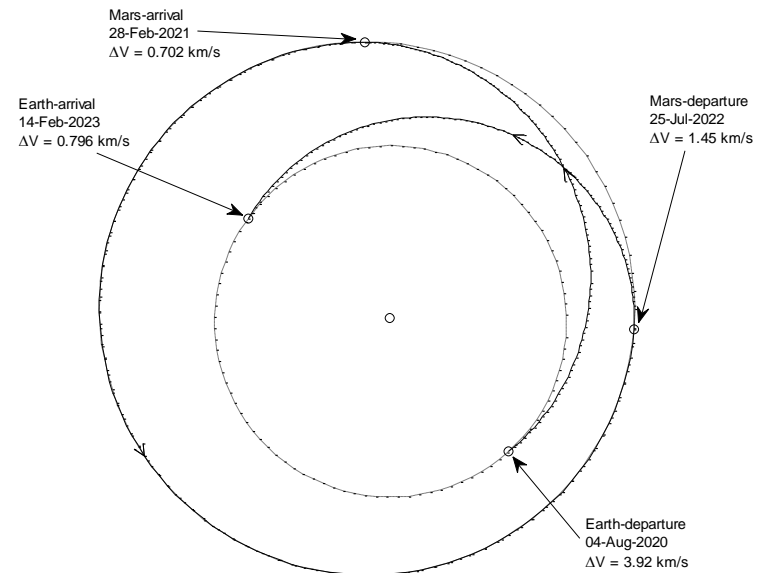
$\Delta V$  budget for round-trip mission from Earth to Mars staging orbit.

Values indicate averages over missions spanning the 2015-2025 decade

	Short-stay	Long-stay
<b>Mission duration (yrs)</b>	1.49	2.57
<b>Mars stay time (months)</b>	1	15
<b>Earth departure C3 (km<sup>2</sup>/s<sup>2</sup>)</b>	16.2	13.0
<b>Mars aerocapture (km/s)</b>	2.72	0.92
<b>Mars departure (km/s)</b>	2.30	1.02



**Short-stay mission (includes Venus flyby)**



**Long-stay mission**