Low Cost Mission Concepts for Mars Exploration

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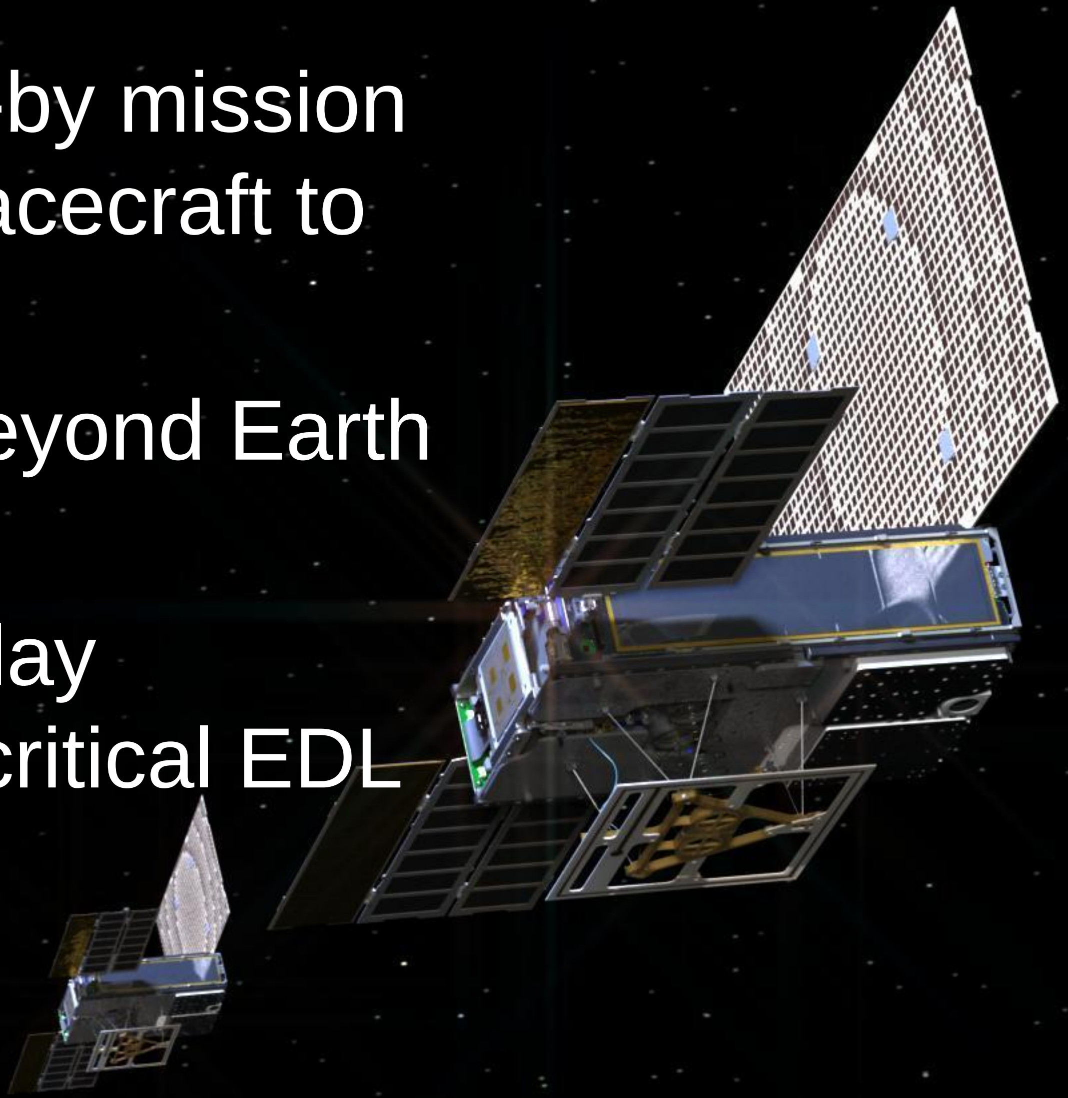
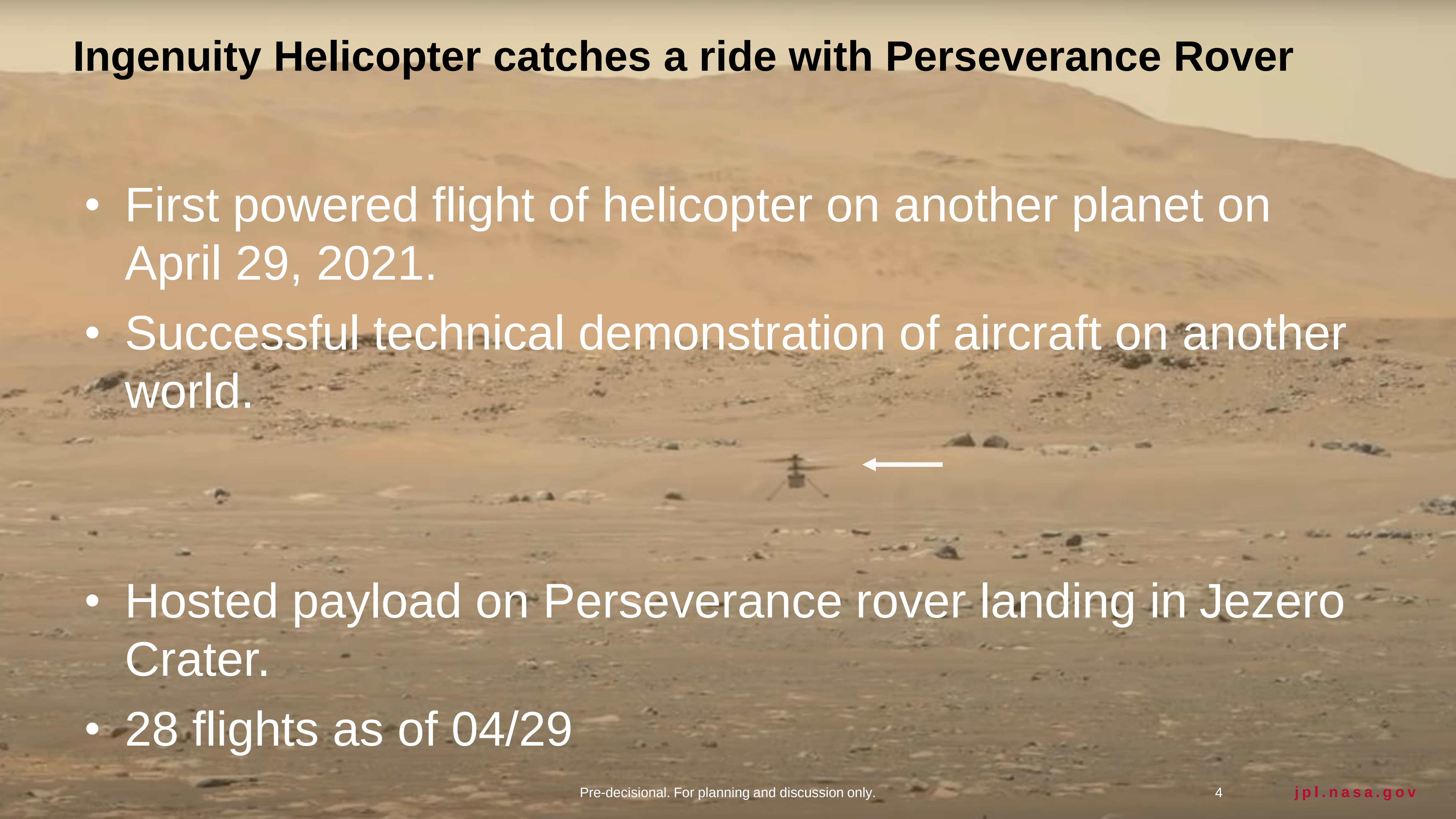
Past and Present Small Missions to Mars

Introduction – MarCO Spacecraft ride-along with InSight

- MarCO CubeSats conduct fly-by mission on May 5, 2018 as hosted spacecraft to Mars.
- First CubeSat(s) to operate beyond Earth orbit.
- Technical demonstration of relay capability of cubesats during critical EDL event for InSight Lander.



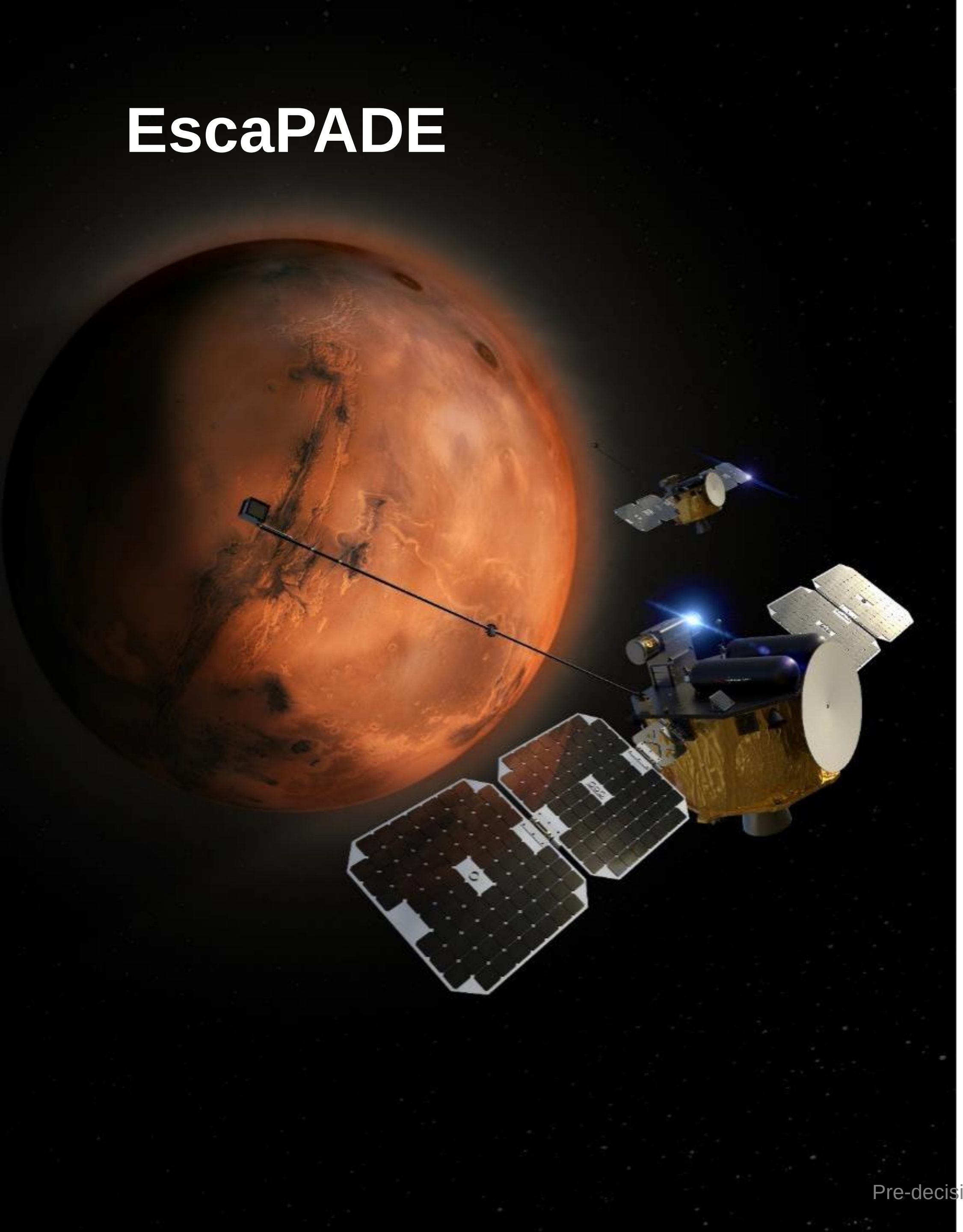
Ingenuity Helicopter catches a ride with Perseverance Rover



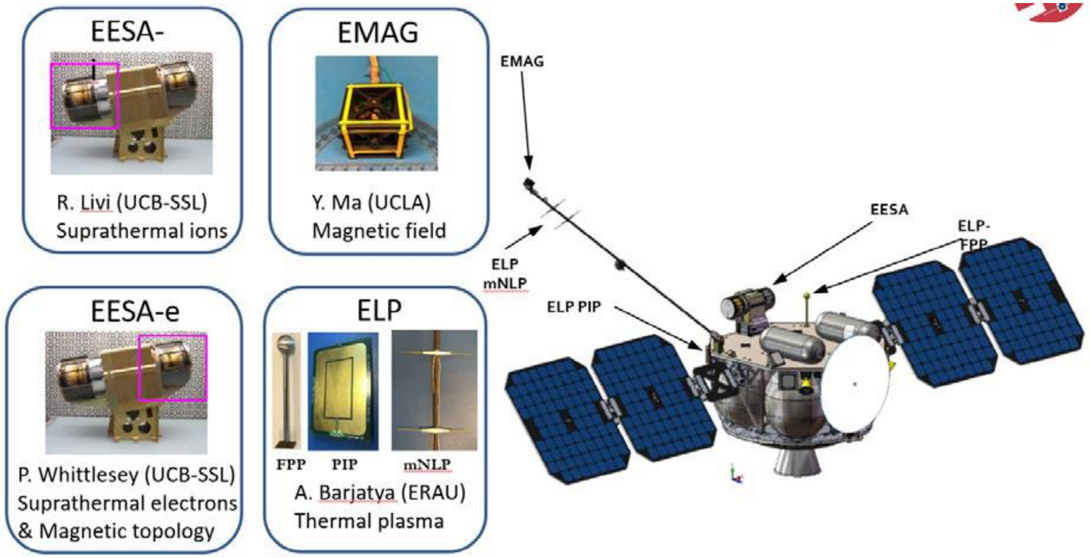
- First powered flight of helicopter on another planet on April 29, 2021.
- Successful technical demonstration of aircraft on another world.

- Hosted payload on Perseverance rover landing in Jezero Crater.
- 28 flights as of 04/29

EscaPADE



- PI: Rob Lillis; Project Scientist: Shannon Curry (Berkeley)
- Two identical spacecraft mission that take simultaneous observations at multiple spatial locations to study ion and sputtered escape from Mars.
- Part of NASA Small Innovative Missions for Planetary Exploration (SIMPLEx) program.
- High ΔV chemical propulsion bus based on



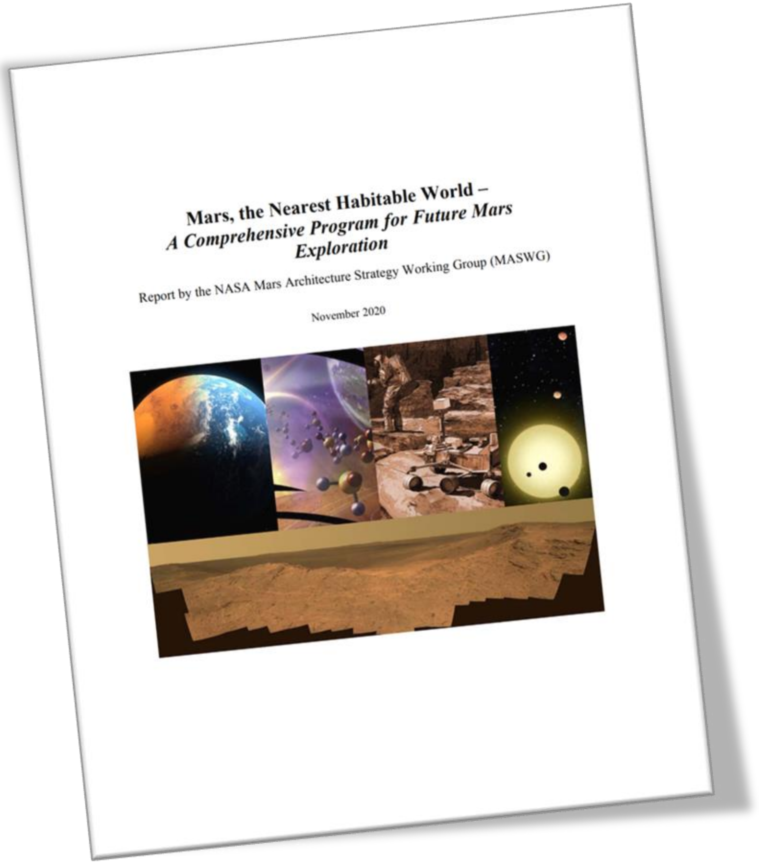
Source: Lillis, R. et al. ESCAPADE: A TWIN-SPACECRAFT SIMPLEX MISSION TO UNVEIL MARS' UNIQUE HYPRID MAGNETOSPHERE, Low-Cost Science Mission Concepts for Mars Exploration., 2022.

Science Motivation

Motivation - Mars Architecture Strategy Working Group (MASWG)

- Published Report in Nov. 2020
- Key Finding:
  - Finding 6: “Small-spacecraft technology. Rapidly evolving small-spacecraft technologies could enable measurements that address many key science objectives at Mars. This class of missions could become an important component of robotic exploration of Mars by enabling a higher cadence of scientific discovery at affordable cost.”

- Provided example architectures for Mars Exploration with Mission Arcs
- Within the arcs is a small spacecraft class, is defined as range between $100 M and $300 M FY20 full life-cycle costs including launch.



Mars, the Nearest Habitable World –
A Comprehensive Program for Future Mars Exploration

Report by the NASA Mars Architecture Strategy Working Group (MASWG)

November 2020

https://mepag.jpl.nasa.gov/reports/MASWG%20NASA%20Final%20Report%202020.pdf

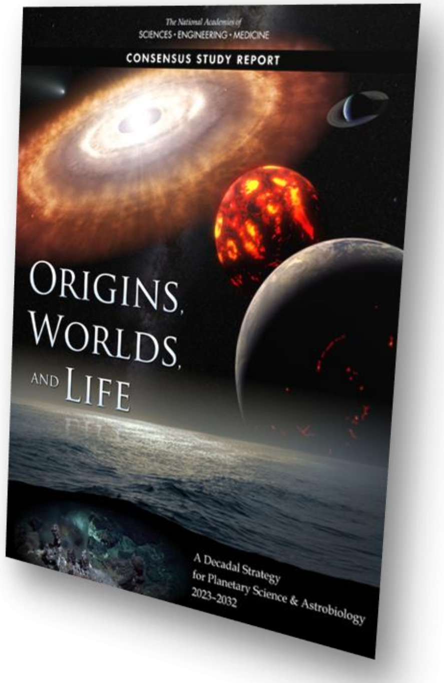
Motivation – Low Cost Mars Workshop

- Held in-person/hybrid on March 29-31, 2022 in Pasadena, CA
- Workshop Objective: "*provide a forum for the Mars community - including scientists, engineers, technologists, and industry representatives - to share ideas and approaches for low-cost exploration of the Red Planet*"
- Nearly 400 registered participants with remote participation from 16 countries. 39 mission concept abstracts accepted.
- Stakeholders representing science, technology, engineering, commercial, launch, and programmatic perspectives.

Key Science Takeaway: Strong consensus that focused missions can achieve compelling science at mission costs ranging from $100M to $300M.

Motivation – Origins, Worlds, and Life – Planetary Decadal Survey 2023-2032

- Published on April 19, 2022
- Excerpt from PSDS Sec 22-11: “Thanks to Mars’s relative accessibility, international partners eager to pursue partnerships with NASA, and increasing capabilities of small spacecraft, effective coordination by MEP this decade can support a mission cadence to enable ongoing discovery along multiple arcs of priority science goals (see MASWG report). New, rapid, and low-cost exploration techniques using proven technology advancements, such as innovative landing methods, small satellites, and aerial vehicles, can be part of the MEP strategy to advance scientific and human exploration goals. MEP may also have opportunities this decade to prioritize science on future human exploration missions (see Chapter 19).”



National Academies of Sciences, Engineering, and Medicine. 2022. Origins, Worlds, and Life: A Decadal Strategy for Planetary Science and Astrobiology 2023-2032. Washington, DC: The National Academies Press.

Motivation for Small Spacecraft Missions

- There is clear community recognition that small spacecraft missions will be essential for providing opportunities for *affordable* Mars missions during the MSR era
- Consensus among Mars community for possible new competed mission class between SIMPLEx and Discovery to conduct parallel science in era of MSR.
- Options for science, technology demonstration, and HEO precursor mission concepts.

SSc: Small Spacecraft-Class
DSc: Discovery-Class
NFc: New Frontiers-Class

Getting to Mars

Three Key Methods to Get Small Spacecraft to Mars

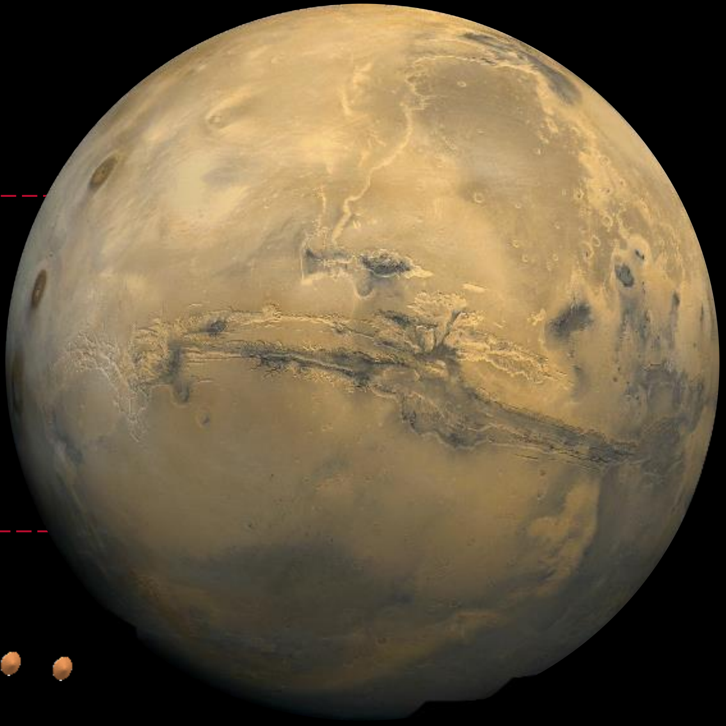
1. Piggyback to Mars

Pro: Cheap, direct delivery

Con: Few reliable options

Mass: varies
Frequency: > 2 years

Seek piggyback opportunities on primary Mars mission and/or Mars fly-by missions

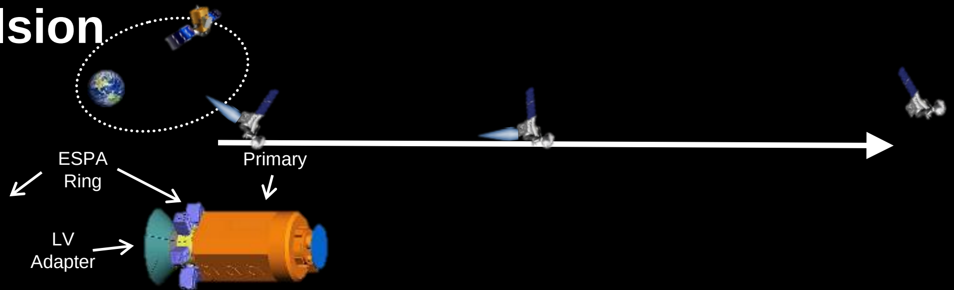


2. Earth Rideshare + Propulsion

Pro: Cheap, lots of options

Con: Secondary, need propulsion

Mass: 100-400 kg
Frequency: > 6 per yr

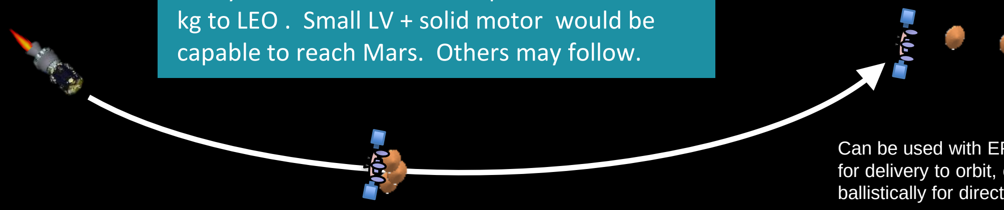


3. Dedicated Launch

Pro: Custom, full control

Con: Kick stage, low TRL

Mass: 100-300 kg
Frequency: 2024+



Many small LVs are in development with > 1000 kg to LEO . Small LV + solid motor would be capable to reach Mars. Others may follow.

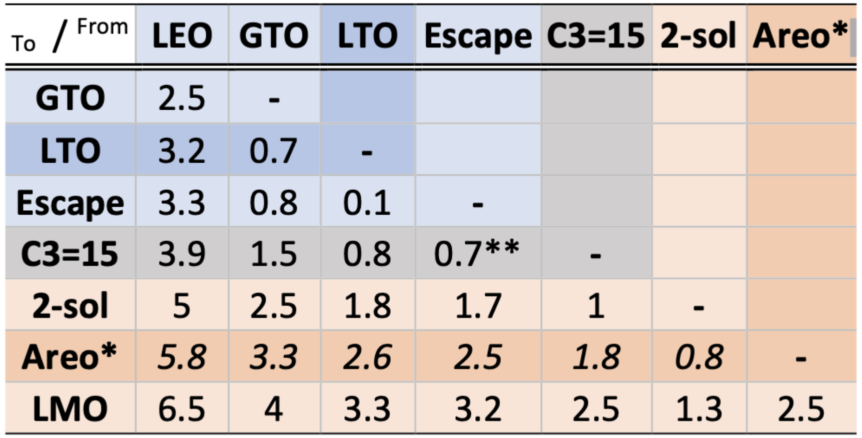
Can be used with EP for delivery to orbit, or ballistically for direct entry

Small Spacecraft Mission Design Considerations

- Multiple options exist for low-cost delivery of small spacecraft to Mars
  - Piggyback or ride-along with a Mars-bound primary spacecraft
    - Lowest cost option, but requires availability of and coordination with a primary Mars-bound vehicle
  - Rideshare to an Earth orbit and provide own propulsion
    - Many GTO+ launch opportunities
  - Dedicated launch vehicle
    - New players and competitive marketplace are bringing down launch costs for dedicated LV
    - New small LV providers offering very low-cost LEO launch; powered cruise stage could complete delivery of a small spacecraft to Mars
  - Mission ΔV requirements are strongly dependent on starting/ending points (function of launch mode and final science orbit) as well as propulsion modality (Chemical vs. Solar Electric Propulsion)

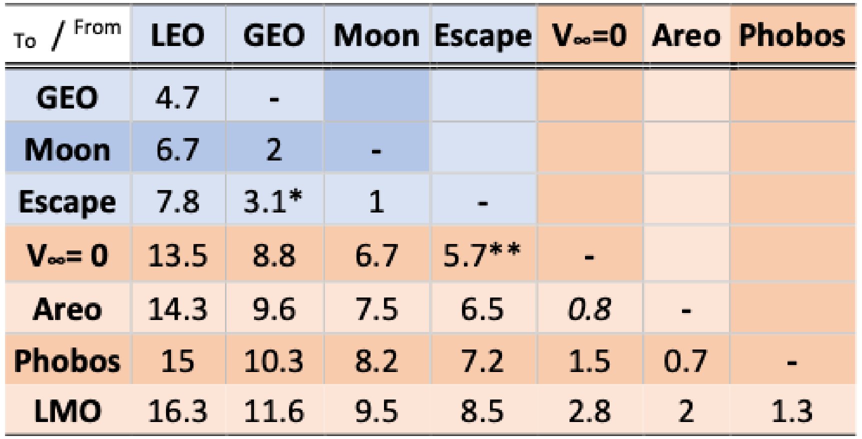
Representative ΔV Requirements

Chemical Propulsion option:



To / From	LEO	GTO	LTO	Escape	C3=15	2-sol	Areo*
GTO	2.5	-					
LTO	3.2	0.7	-				
Escape	3.3	0.8	0.1	-			
C3=15	3.9	1.5	0.8	0.7**	-		
2-sol	5	2.5	1.8	1.7	1	-	
Areo*	*5.8*	*3.3*	*2.6*	*2.5*	*1.8*	*0.8*	-
LMO	6.5	4	3.3	3.2	2.5	1.3	2.5

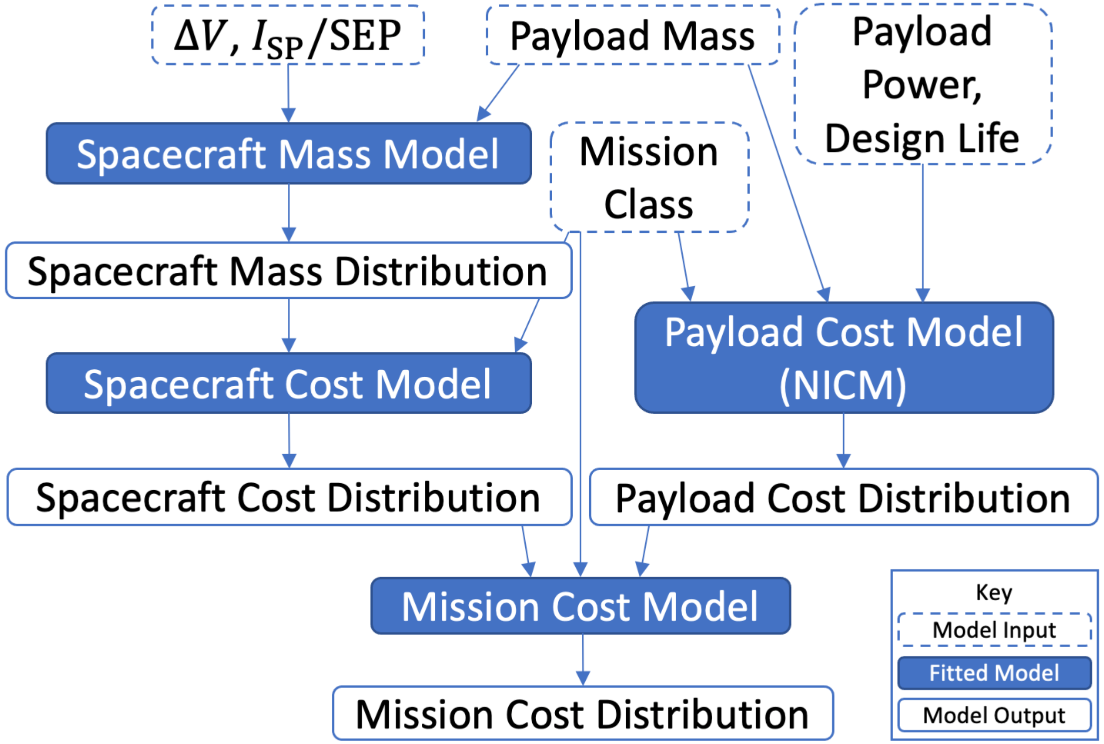
Solar Electric Propulsion option:



To / From	LEO	GEO	Moon	Escape	V_∞=0	Areo	Phobos
GEO	4.7	-					
Moon	6.7	2	-				
Escape	7.8	3.1*	1	-			
V_∞= 0	13.5	8.8	6.7	5.7**	-		
Areo	14.3	9.6	7.5	6.5	*0.8*	-	
Phobos	15	10.3	8.2	7.2	1.5	0.7	-
LMO	16.3	11.6	9.5	8.5	2.8	2	1.3

Low-Cost Mars Mission Model & Methods

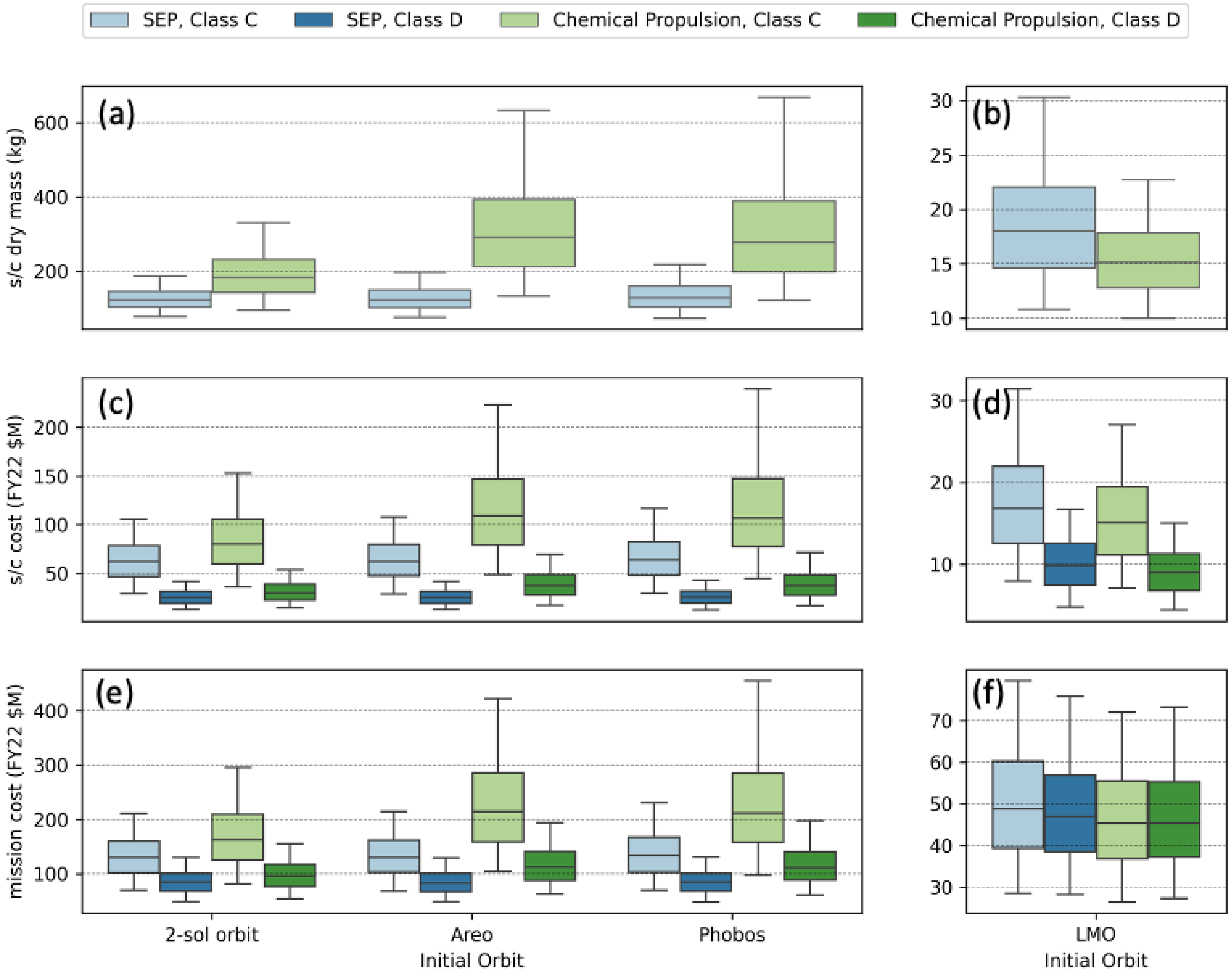
- Key aspects of the mission cost model
  - Incorporates the Tsiolkovsky rocket equation to estimate propellant mass as a function of ΔV
  - Models the relationship between spacecraft dry mass and propellant mass based on as-flown data and JPL mission concept studies
  - Jointly solves the spacecraft mass relationship with the rocket equation to fully incorporate laws of physics
  - Uses Bayesian modeling selection techniques to capture sources of uncertainty/variation



Co-contributors: Alex Austin, Patrick Bjornstad, Chad Edwards, Sam Fleischer, Jairus Hihn, Anto Kolanjian, Michael Saing, and Ryan Woolley.

Mission Cost Analysis Results

- Significant cost savings for missions with low ΔV budget requirements.
- Model suggests propulsion modality may also be cost driver.
- Analysis suggest mission classification (C vs. D) may also be a cost driver.



Findings – Low Cost Mars Workshop

- Key Challenges and Risks

Key Challenge: Spacecraft propulsion DV is tightly coupled to cost. Recurring low-cost transportation. Many options available like LV reusability, piggyback, rideshare, small LV's, and delivery vehicles.

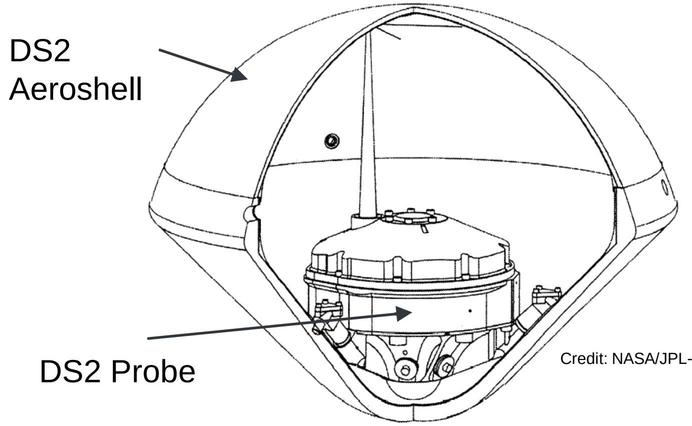
Key Challenge: Telecommunications infrastructure could eliminate need for individual small s/c to carry their own high-rate DTE link with significant reduction in mass, volume, and cost.

Key Challenge: Risk tolerance/ programmatic approach. Need to create a positive feedback loop to lower mission cost, reduce risk posture, and increase mission cadence.

Low-cost access to the Martian Surface

Hard Impact Landers

Deep Space 2



Credit: NASA/JPL-Caltech

DS2 Probe and Areoshell Cut-away

Credit: NASA/JPL-Caltech

Design iterations of DS2 Impact Lander

Deep Space 2 mission from 1999

2 Micro-Probes part of failed Mars Polar Lander Mission.

30,000 g impact acceleration survival requirement on fore-body

60,000 g impact acceleration survival requirement on aft-body

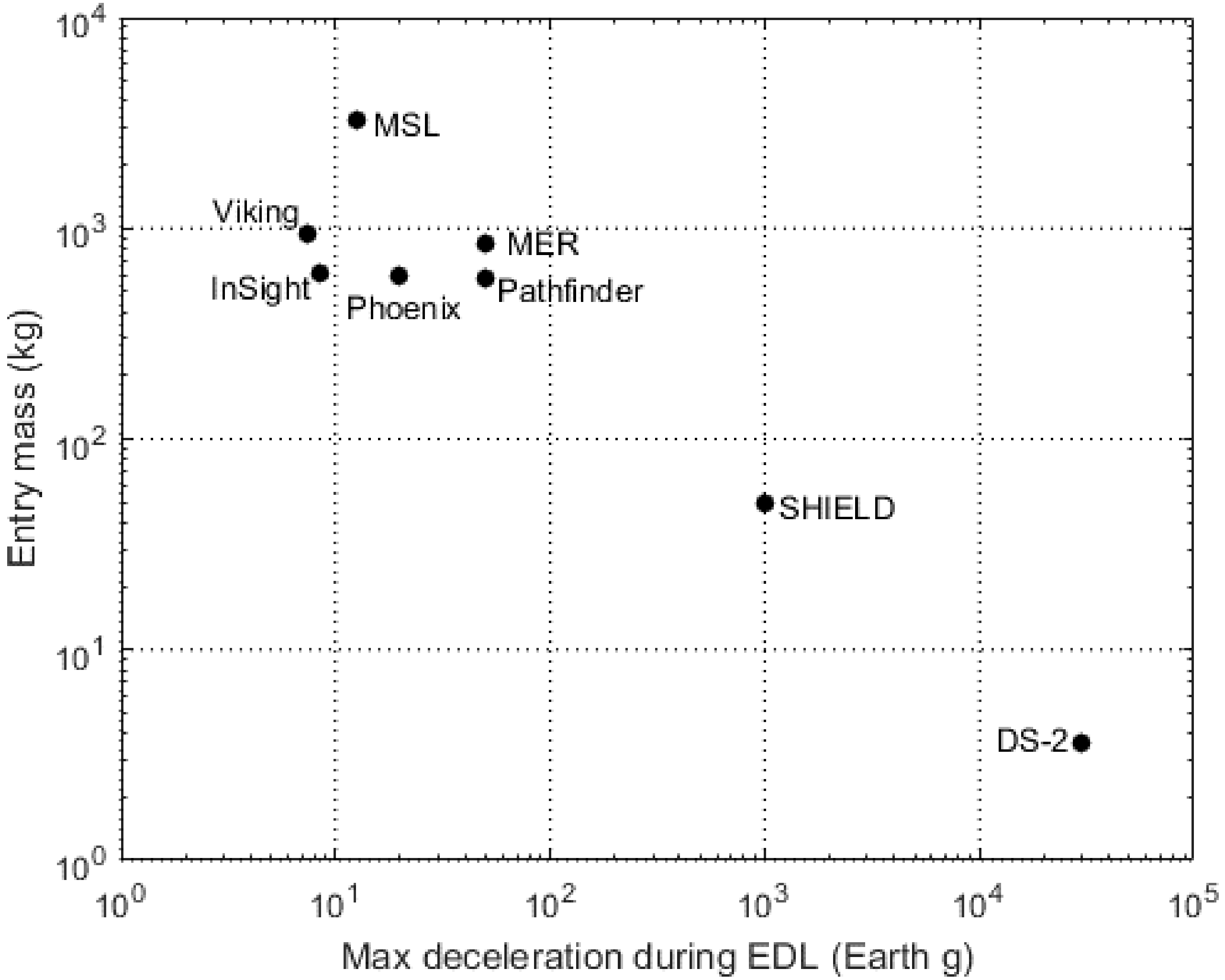
Touchdown Velocity: ~190 m/s

Probe Mass: **3.57 kg**

Aeroshell designed to shatter on impact.

SHIELD Landing Impact

Entry Mass vs Max Deceleration



What is SHIELD???

PI: Lou Giersch

SHIELD: A Small, High Impact Energy Landing Device for Low-Cost Access to the Martian Surface

- Enables a broad suit of potential missions utilizing low cost access to the Martian surface:
  - Low cost missions with 1 or 2 landers
  - Networks of landers
  - 1 or more secondary landers deployed from orbiters
- Does not have propulsive decelerator or parachute system. Instead utilizes a drag skirt to decelerate using Mars atmosphere and an impact attenuation mechanism to absorb the energy during impact.

- Limit landing impact decelerations to < **2000** Earth g

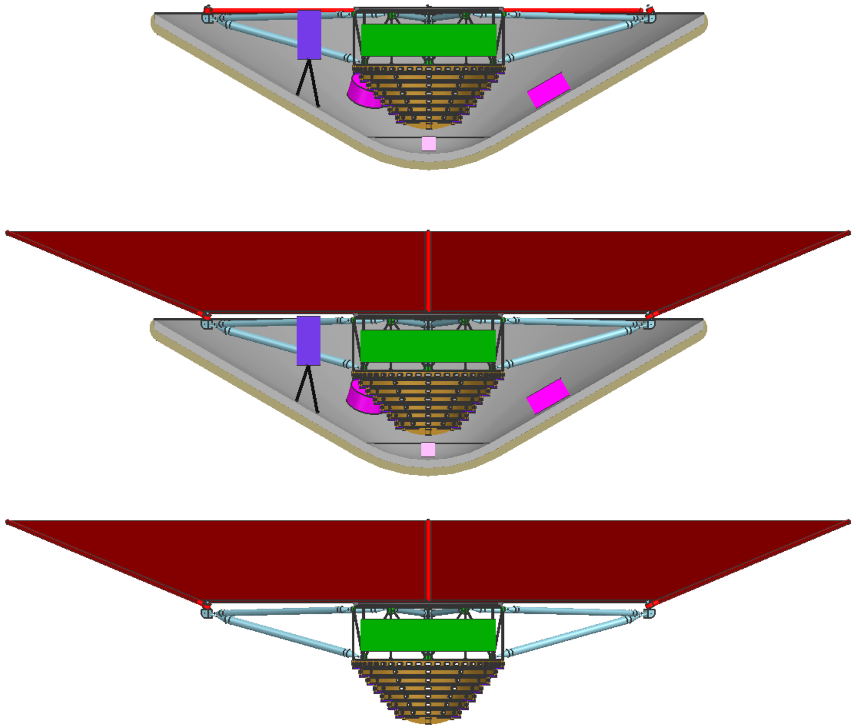
- Mission Cost target: ~ 150M FY21 for Phases A-D; not including launch

How does SHIELD work?

- Reduce cost by removing parachute, propulsive decelerators, and supporting sensors.
- Reduce cost to get to Mars by utilizing rideshare or dedicated small launch vehicle.
- Utilize low-complexity deployed drag skirt to decelerate to 50 m/s and impact deceleration mechanism (IDM) to mitigate effects of shock.

SHIELD uses a low ballistic coefficient (BC) to slow down using Mars atmosphere.

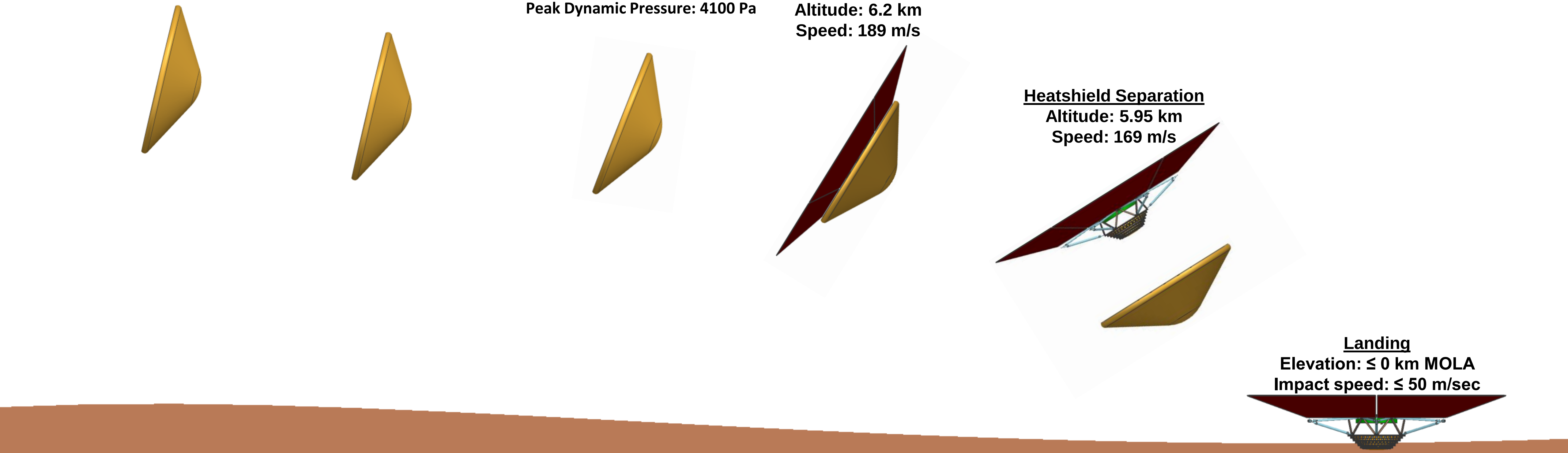
SHIELD has a low mass, and uses a deployed drag skirt to increase its cross-sectional area during entry to reduce ballistic coefficient during entry



Parameter	Value	Unit
Aeroshell Diameter	3.5	m
Aeroshell Nose Cone Angle	60	deg
Entry Mass (MEV)	300	kg
Landed Mass (MEV)	100	kg
Payload Capability	<15	kg
Separation Interface Diameter	937, 1194	mm
Power during cruise	20	W

Profile of Entry, Descent, and Landing Events

PI: Lou Giersch



Entry Interface
Altitude: 125 km
Speed: 6.5 km/s
Entry flight path angle: -11.5°

Peak Heating
Altitude: 54 km
Speed: 5.92 km/s
Peak stagnation heating: 34 W/cm²

Peak Dynamic Pressure
Altitude: 45 km
Speed: 4.37 km/s
Peak Dynamic Pressure: 4100 Pa

Dragskirt Deploy
Altitude: 6.2 km
Speed: 189 m/s

Heatshield Separation
Altitude: 5.95 km
Speed: 169 m/s

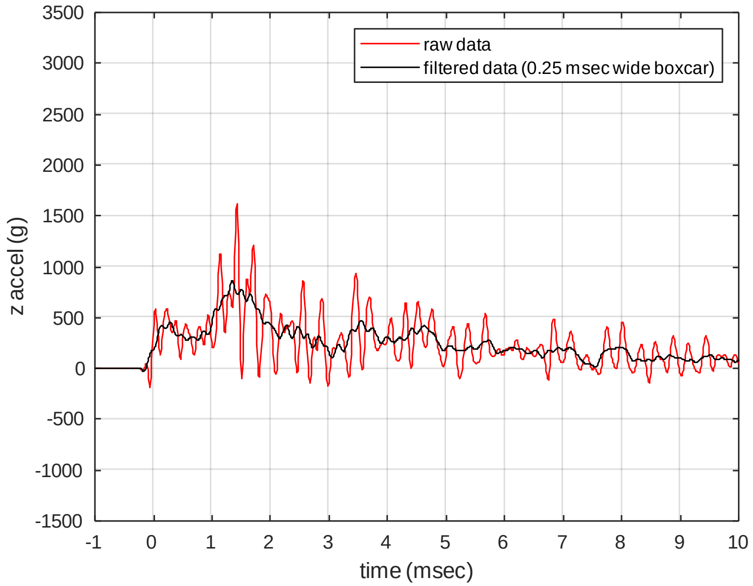
Landing
Elevation: ≤ 0 km MOLA
Impact speed: ≤ 50 m/sec

Initial trajectory and aerodynamics analysis from Marcus Lobbia and Evgeniy Sklyanskiy at the NASA Jet Propulsion Laboratory
Initial trajectory, CFD, and heatshield TPS design from Hannah Alpert, Ryan McDaniel, Mairead Stackpoole, Marc Rezin, Frank Milos and Paul Wercinski at the NASA Ames Research Center

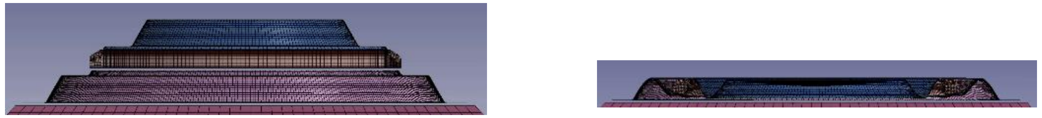
Drop Test #2

March 05, 2021

- Second drop test, two test articles, new IDM design, and drop into soil/playa surface.
- ¼ scale, ½ speed



FEM Expected Stroke Compression



Experimental Stroke Compression

SHIELD Drop Test #3

On 9/24/2021, the first full-speed (≈ 50 m/sec) SHIELD impact test was conducted

Predicted peak deceleration ≈ 1400 “Earth G” for ≈ 5 msec (1 Earth G = 9.8 m/sec^2)
An onboard accelerometer was installed and recorded data

High speed video was also recorded (10,000 FPS) with a “calibration image” of a scale bars also taken

- Indicated impact speed between 49.5 and 49.7 m/sec
- Indicated acceleration ≈ 1400 G

Can instruments survive?

– Some ruggedized components are available off the shelf

    - High-G Imagers
    - High-G Accelerometers
    - High-G Data Acquisition

- During development of DS2 several impact tests conducted at NASA on instrument and components
- Development of methods and testing of high-g avionics and sensor systems.

Summary of Component Shock-Test Data

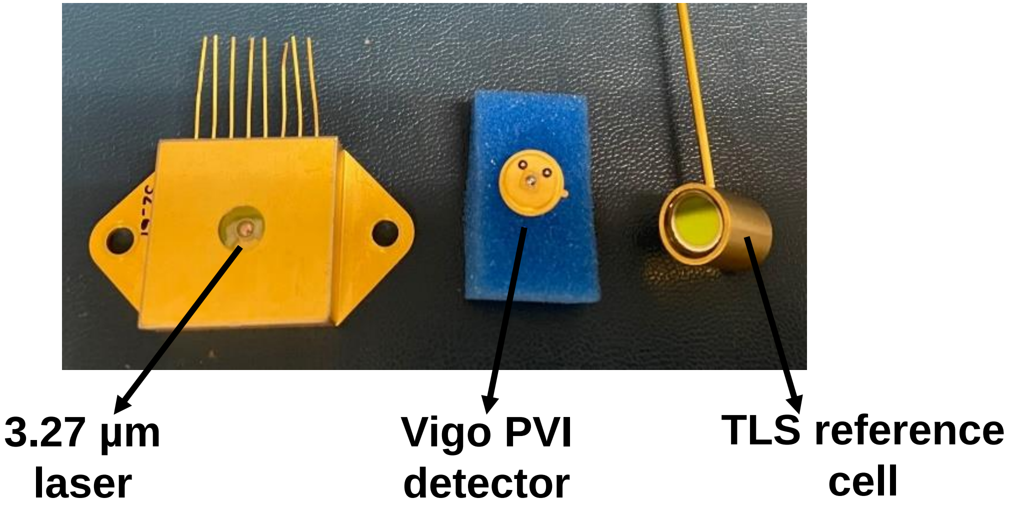
Mars penetrator experiment	Components/ hardware	Shock requirement, g	Program	Components	Shock Environment
Seismic	Biaxial bubble tiltmeter	2,000	Ames Research Center	Plans to test in the future	N/A
Seismic	Force balance accelerometer	2,000	Ames Research Center		N/A
Magnetometry	Triaxial fluxgate magnetometer	20,000	Copperhead (AD)	Ferromagnetic core device	10,000
Meteorology	Thermocouple	20,000	Copperhead (AD)	Thermocouple	10,000
Meteorology	Pressure Sensor	20,000	Copperhead (AD)	Endevco commercial parts	10,000
Stratigraphy	Accelorometer	2,000	Copperhead (AD)	Endevco commercial parts	10,000
Stratigraphy	Accelorometer	2,000	Navy guided projectile		100,000
Camera	Imager	20,000	Ames Research Center	Fairchild 100 x100 CCD	19,500
Camera	Imager	20,000	Copperhead (AD)	Plastic lens and electronic parts	10,000
Camera	Imager	20,000	Navy guided projectile	Silcon wafer and ceramic rings	30,000
Telemetry	Receiver	20,000	Copperhead (AD)	Diodes; Semiconductors; Capcacitors; Resistors, Coil	10,000
Telemetry	Transmitter	20,000	Copperhead (AD)	Tramitters, Capacitors, Diodes, Resistors, Coils	10,000
Telemetry	Antenna	20,000	Copperhead (AD)		
Data processing and control	Memory	2,000	Copperhead (AD)	Integrated Circuit	10,000
Data processing and control	Microprocessor (12-bit CMOS integrated circuits)	2,000	Copperhead (AD)	CMOS integrated Mark Pak I & II	10,000
Data processing and control	Microprocessor (12-bit CMOS integrated circuits)		Navy guided projectile		30,000
Power Source	Battery	2,000	Copperhead (AD)	Thermal battery Ni-Cad battery	9,300
Heat Flow	Thermocouple	2,000	Copperhead (AD)	Thermocouples	10,000

J. Murphy, R. Reynolds, M. Blanchard, U. Clandton, “Surface Penetrators for Planetary Exploration: Science Rationale and Development Program,” NASA Technical Memorandum 81251, March. 1981

Drop Test of TLS components

- SHIELD team wanted to understand the survivability of a tunable laser spectrometer's (TLS) major components in a 1000 g landing environment.
- TLS engineers suggested shock test of TLS components as pathfinder for instrument ruggedization design considerations.

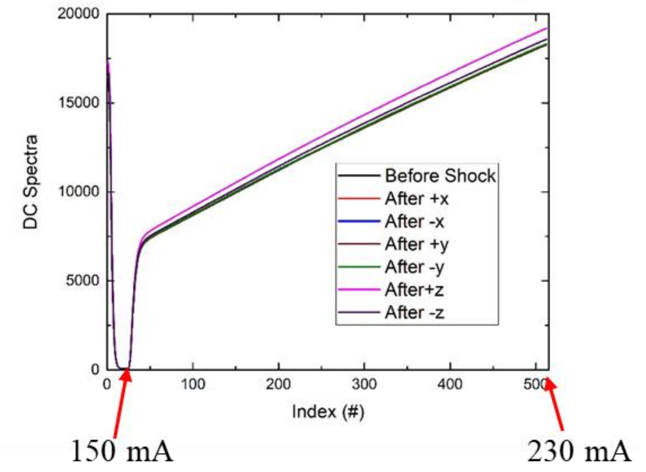
TLS components used for shock tests



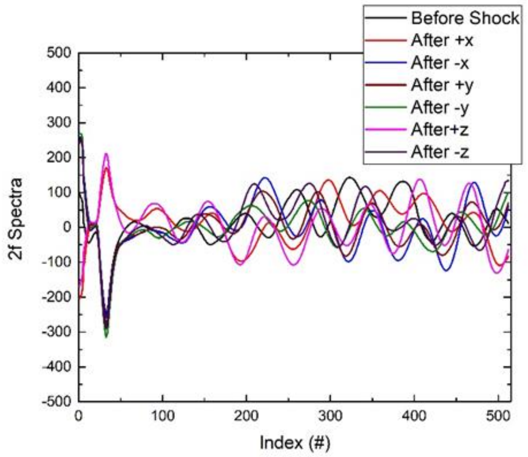
Characterization of components throughout test

Test conducted by: Mathieu Fradet

- After each shock test, a functional test was performed
  - At a fixed laser temperature (15 ℃), the detector signal was recorded for a 100 ms current sweep of the laser from 150 mA to 230 mA
  - A modulation of the current amplitude is added on top of the current ramp (±10 mA)



Direct current intensity measured at the detector for a current sweep



Demodulated detector signal at twice the modulation frequency

The different shock load tests had no effect on the laser or detector performance.

The alignment of the system was shown to be sensitive to forces in the z-direction.

Conclusions

Conclusions

- Low-cost spacecraft architectures could be used to address key science questions.
- Technology advances could be enabling for delivery, in-space propulsion, next-gen telecom relay, miniatured instruments and avionics, and low-cost access to the Mars surface.
- Commercial, academic, and international partnerships could further reduce cost and risk for future low-cost missions.
- Access to the surface of Mars at low-cost may be possible with innovative approaches and acceptance of higher risk posture.
- Key enablers for future low-cost missions are reliable low-cost transportation to Mars, next generation relay infrastructure, a new approach to programmatic risk tolerance at all phases of mission development, and the introduction a new competed Mars small mission program with a cost cap between SIMPLEx and Discovery.

Low Cost Mission Concepts for Mars Exploration

Thank you!

For more info: nbarba@jpl.nasa.gov

NASA/JPL-Caltech/University of Arizona

Mars Parametric Mission Cost Analysis

- Goal: Parametric sensitivity analysis of Mars orbiter mission costs as a function of quantitative and categorical parameters.
- Determine what are cost drivers for missions to Mars?

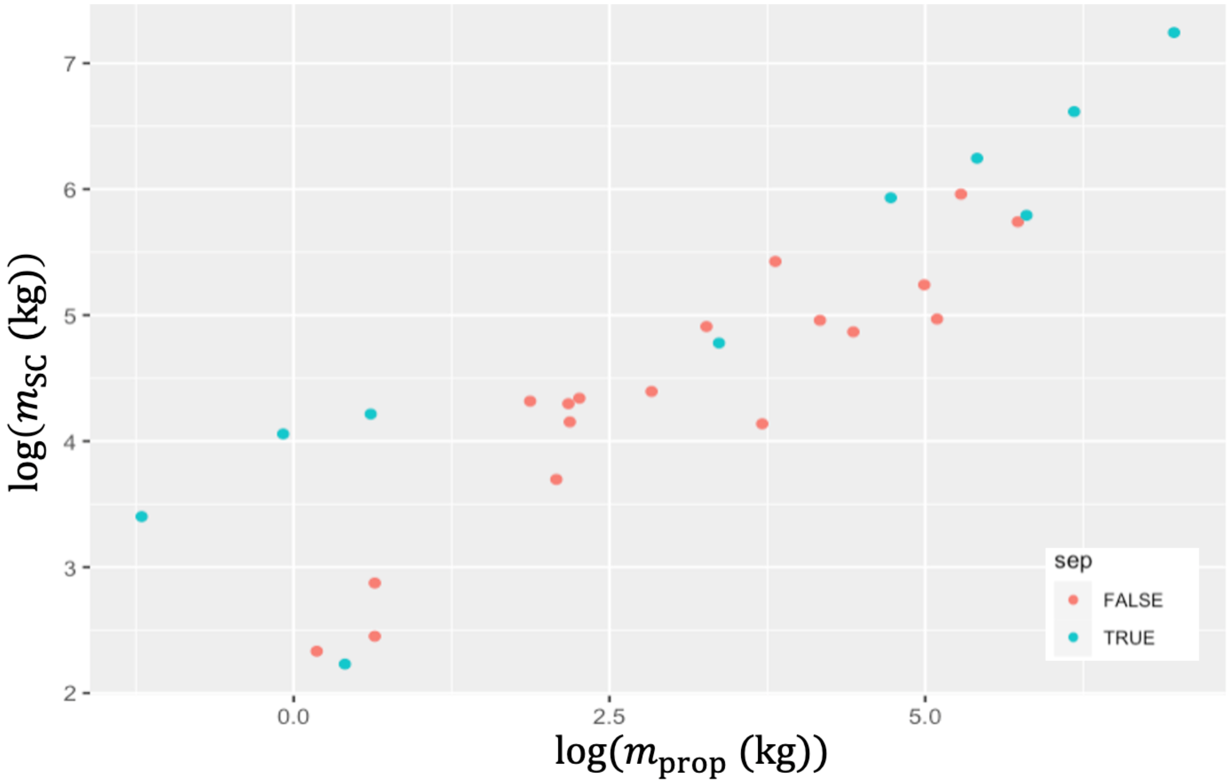
Quantitative Parameters

- Mass – P/L, S/C
- Power – P/L, SC
- S/C ΔV

Categorical Parameters

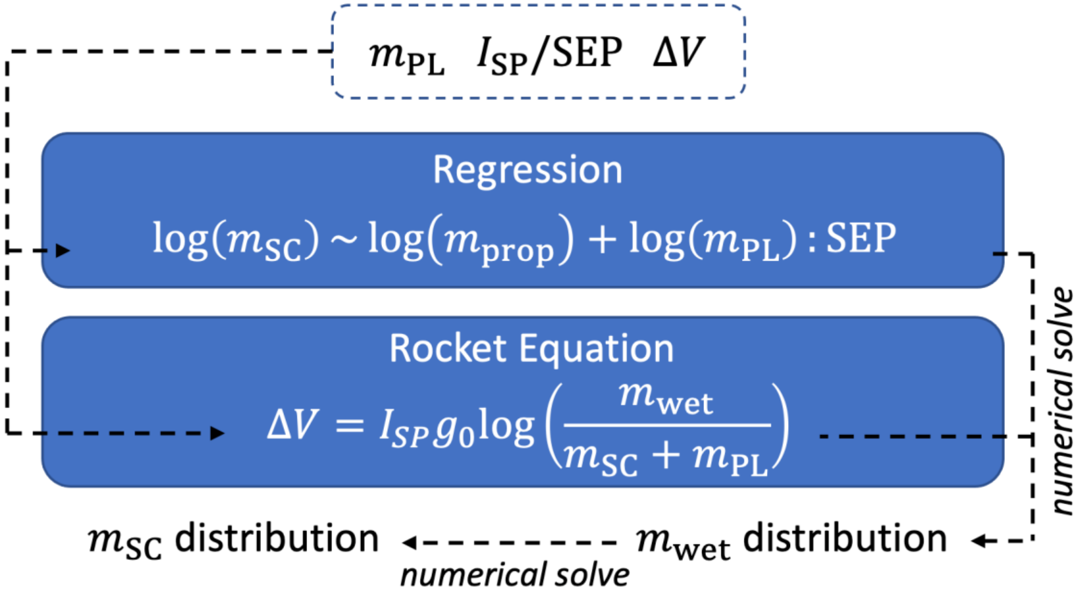
- Propulsion Type
    - S/C Initial Position
    - S/C Destination
- Risk Class

Parametric Cost Model Details



Spacecraft Mass Model:

- *Input:*
  - Payload mass (m_{PL})
  - Propellant type
  - Required ΔV
- *Output:*
  - Spacecraft dry mass (m_{SC})
  - Spacecraft wet mass (m_{wet})



m_{PL} I_{SP}/SEP ΔV

Regression

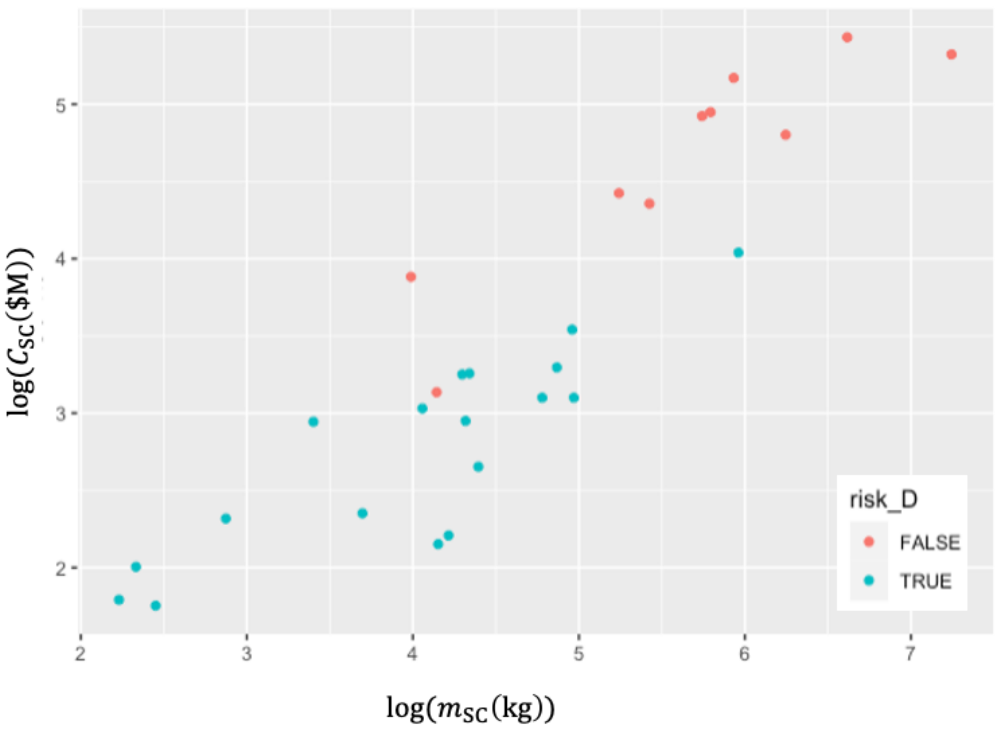
$$\log(m_{SC}) \sim \log(m_{prop}) + \log(m_{PL}) : \mathrm{SEP}$$

Rocket Equation

$$\Delta V = I_{SP} g_0 \log\left(\frac{m_{wet}}{m_{SC} + m_{PL}}\right)$$

m_{SC} distribution ← *numerical solve* ← m_{wet} distribution ← *numerical solve*

Parametric Cost Model Details (cont’d)



Spacecraft cost/mass relationship, dependent on mission class ($\boldsymbol{N_{\mathrm{D}} = 10}$, $\boldsymbol{N_{\mathrm{B,C}} = 18}$).

- Spacecraft Cost Model:

$$\log(c_{SC}) = \gamma_0 + (\gamma_1 + \gamma_2 \mathrm{MC_D}) \log(m_{\mathrm{SC}}) + \epsilon$$

Mission Class

- Payload Cost Model
  - NASA Instrument Cost Model (NICM9) System Tool
  - Inputs: instrument type (optical, active or passive microwave, particles, or fields), mission class, payload mass, power, and design life:

$$\log(c_{\mathrm{PL}}) = \delta_0 + \delta_m \log(m_{PL}) + \delta_p \log(p_{PL}) + \delta_d \log(d_{PL}) + \epsilon$$

- Mission Cost Model (A-D)
  - Apply “wraps” to s/c and payload cost for other WBS elements (Management, Sys Eng, Mission Assurance, Science, Mission Ops Prep, Ground Data Systems, ATLO, Education and Public Outreach, Mission and Nav Design)