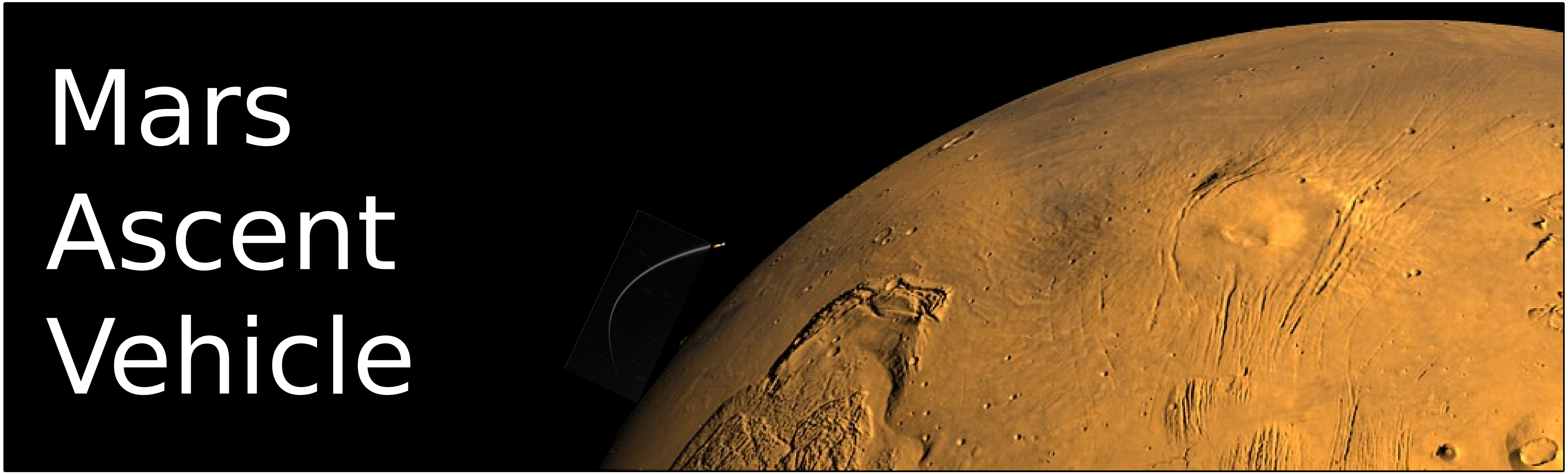

Jet Propulsion Laboratory
California Institute of Technology

MARSHALL
SPACE FLIGHT CENTER

Integrated Design for the MSR SRC Mars Ascent Vehicle

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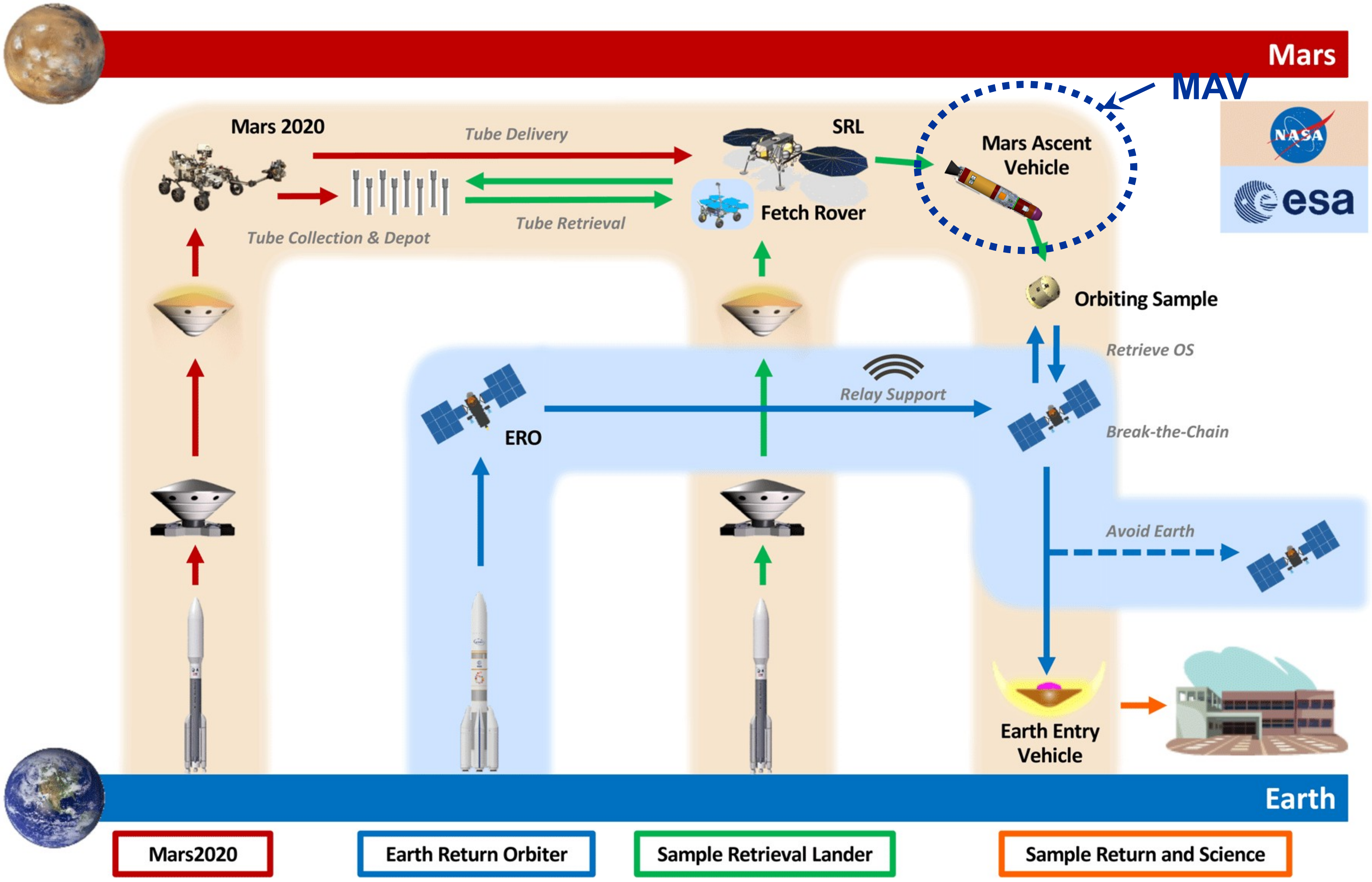
Mars Sample Return and MAV

MSR Mission Objective:

Retrieve Mars samples and return to Earth.

1. Mars 2020 rover collects Mars samples and leaves tubes in place.
2. Earth Retrieval Orbiter (ERO) sent to Mars orbit.
3. Mars Lander Platform (MLP) with Mars Ascent Vehicle (MAV) sent to Mars.
4. Fetch rover tasked with retrieving sample tubes on Mars surface.
5. MAV is loaded with the Orbiting Sample (OS) containing the sample tubes. MAV carries the OS to Mars orbit.
6. ERO rendezvous with OS, retrieves OS, and returns OS to Earth.
7. Earth Entry Vehicle returns OS to Earth's surface.

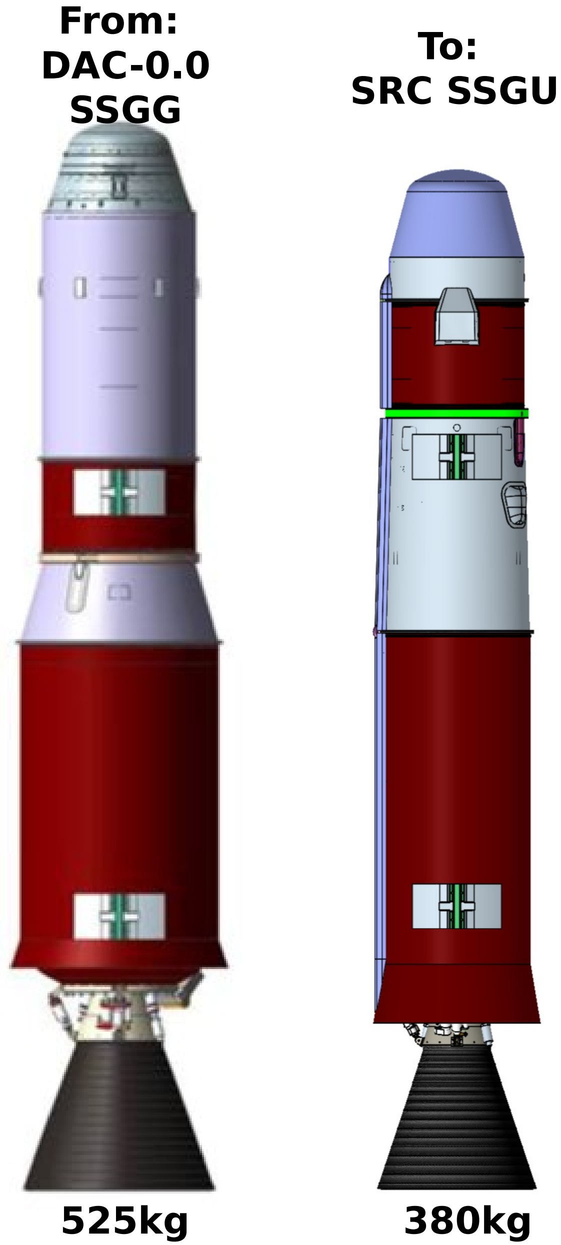
*Note, this reflects MSR CONOPS at time that paper was written. Since then, Fetch Rover and Lander have moved to a new dual-launch architecture, increasing MAV mass allocation.



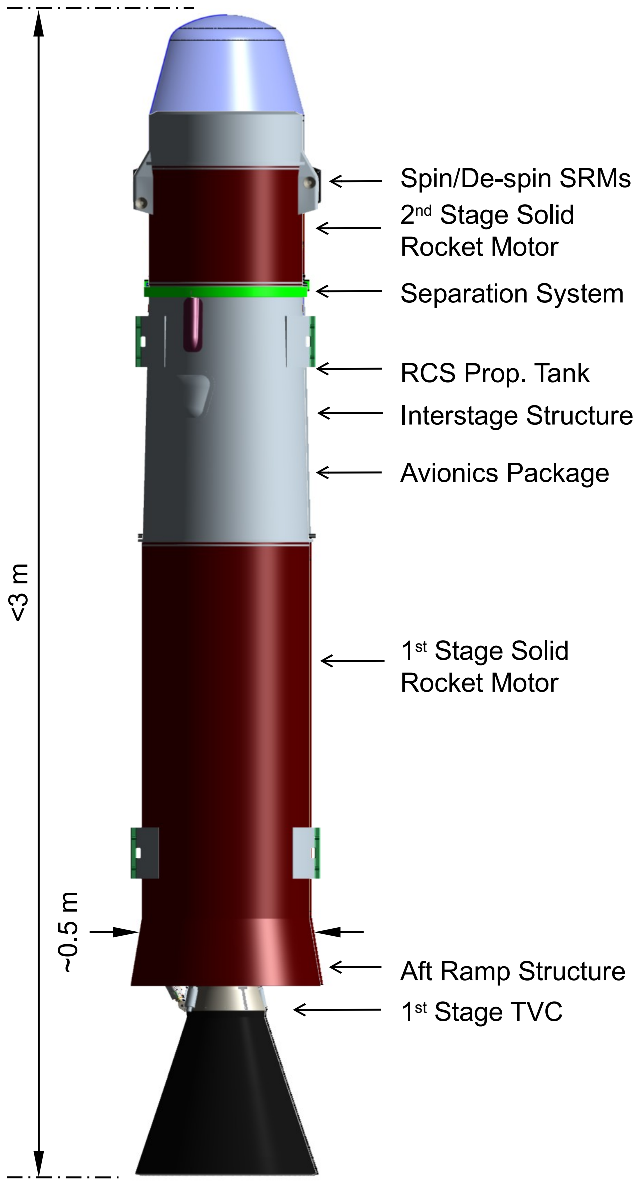
Pre-decisional. For planning and discussion purposes only.

Major Changes from Previous Publications

- SSGU second stage is unguided and spin-stabilized
- Overall vehicle dimensions are smaller
- Mass has decreased
- Orbit trim thrusters removed
- Resized SRMs with associated performance and burn times
- Avionics and RCS have moved to first stage
- Second stage avionics will consist only of a timing circuit, beacon, antenna, and associated batteries/heaters
- Second stage features two spin and two de-spin motors
- Unguided second stage has reduced orbital insertion accuracy

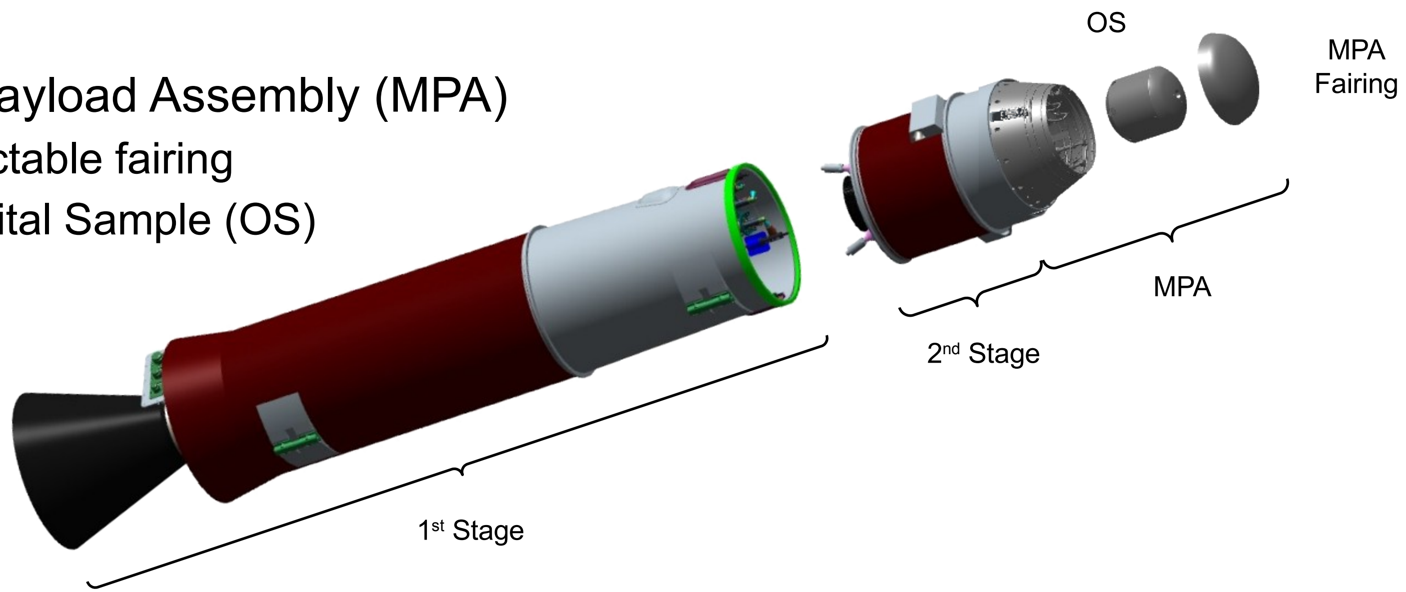


MAS Overview



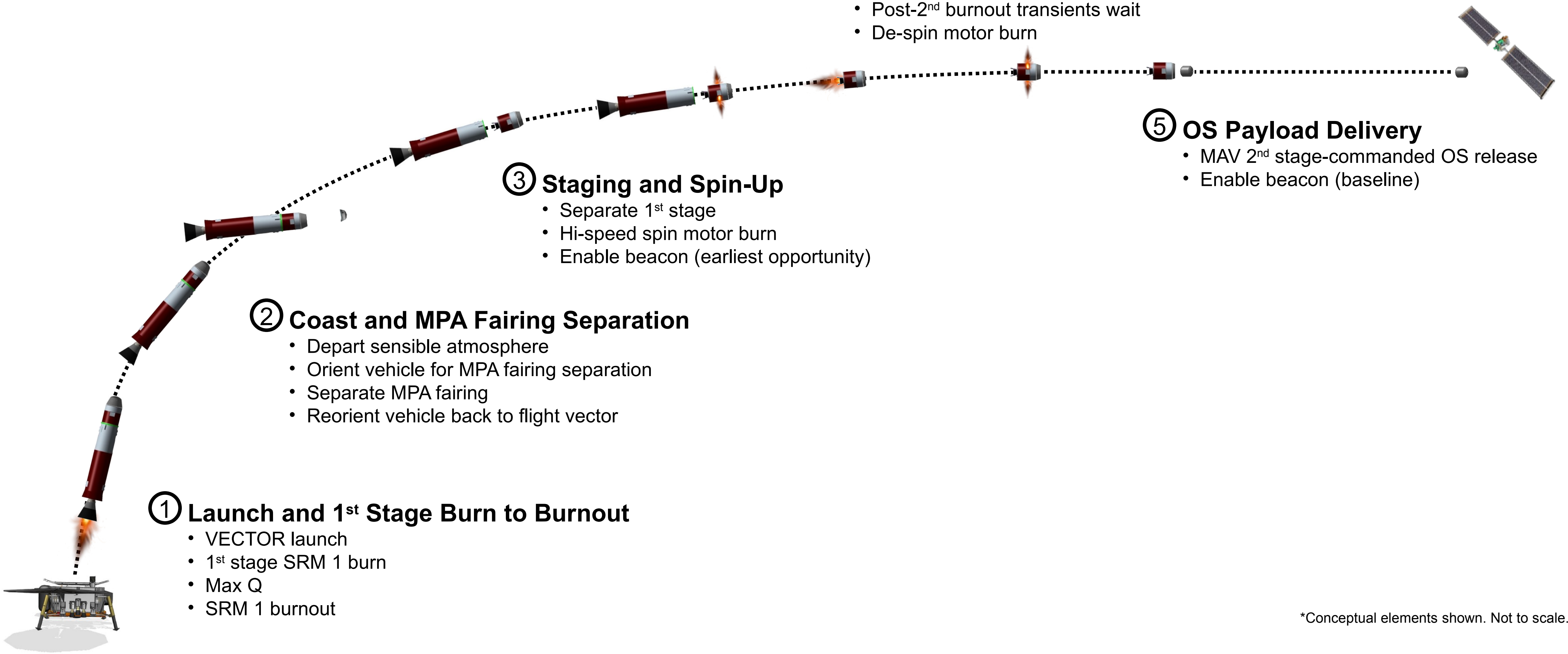
SRC Mars Ascent System (MAS) consists of:

- Mars Ascent Vehicle (MAV)
  - Two-stage (guided, unguided) solid motor vehicle
  - Pyrotechnic stage separation
  - Electrical-mechanical Thrust Vector Control (TVC) with supersonic splitline nozzle on 1st stage
  - 2x Spin Motors and 2x De-spin motors on 2nd stage
  - Monopropellant Reaction Control System (RCS)
- MAV Payload Assembly (MPA)
  - Ejectable fairing
  - Orbital Sample (OS)



MAV Ascent Mission Operations Overview

National Aeronautics and Space Administration
Jet Propulsion Laboratory / Marshall Space Flight Center
Mars Ascent Vehicle Study



④ **2nd Stage Burn to Burnout and Spin-Down**
- 2nd stage SRM 2 burn to burnout
- Post-2nd burnout transients wait
- De-spin motor burn

⑤ **OS Payload Delivery**
- MAV 2nd stage-commanded OS release
- Enable beacon (baseline)

③ **Staging and Spin-Up**
- Separate 1st stage
- Hi-speed spin motor burn
- Enable beacon (earliest opportunity)

② **Coast and MPA Fairing Separation**
- Depart sensible atmosphere
- Orient vehicle for MPA fairing separation
- Separate MPA fairing
- Reorient vehicle back to flight vector

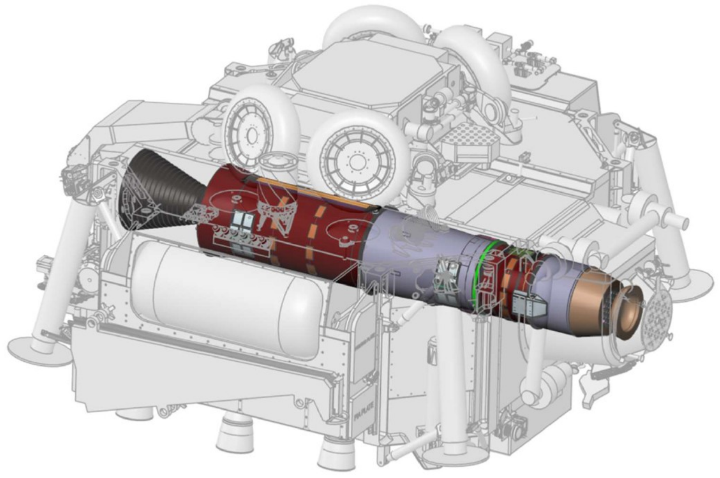
① **Launch and 1st Stage Burn to Burnout**
- VECTOR launch
- 1st stage SRM 1 burn
- Max Q
- SRM 1 burnout

*Conceptual elements shown. Not to scale.

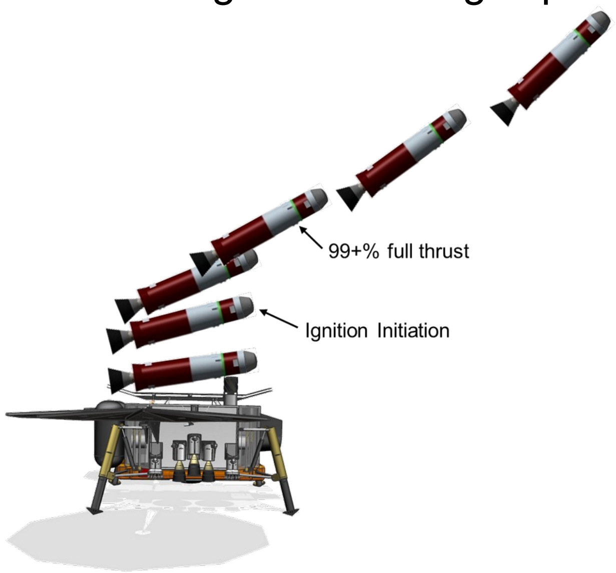
1st Burn	Coast, Staging and Spin-Up	2nd Burn and Spin-Down	OS Release	Loiter
~78s	~374s	~22s and ~Minutes	~Minutes	~Days

Systems Requirements Cycle

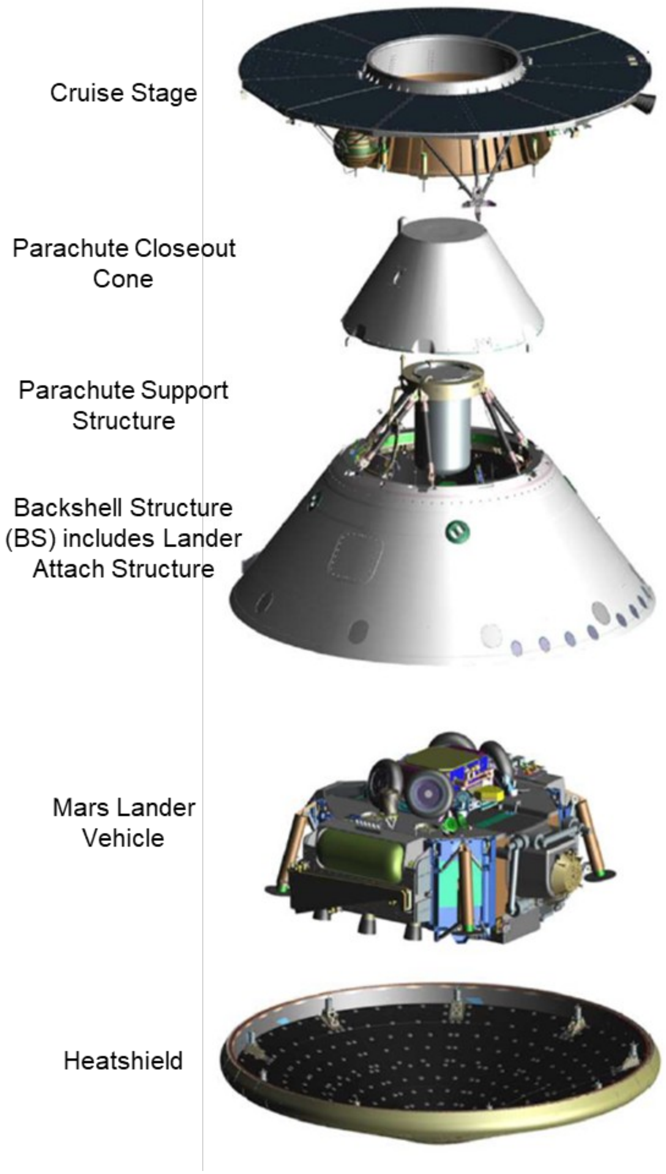
- SRC performed November 2020 - June 2021. This was MAV's second major development cycle.
- The primary purpose of SRC was to develop the system-level requirements for the vehicle in preparation for the System Requirements Review (SRR), held November 2021. SRR passed successfully.
- Although not principal goal, technical fidelity of vehicle design was also advanced.
  - Technical design based upon preliminary high-level requirements
  - MAV risk class increased to Class A. MAV was now designated a "Flagship Mission".



MAV Stowed Within Lander



VECTOR: Vertically Ejected, Controlled Tip-Off Rate



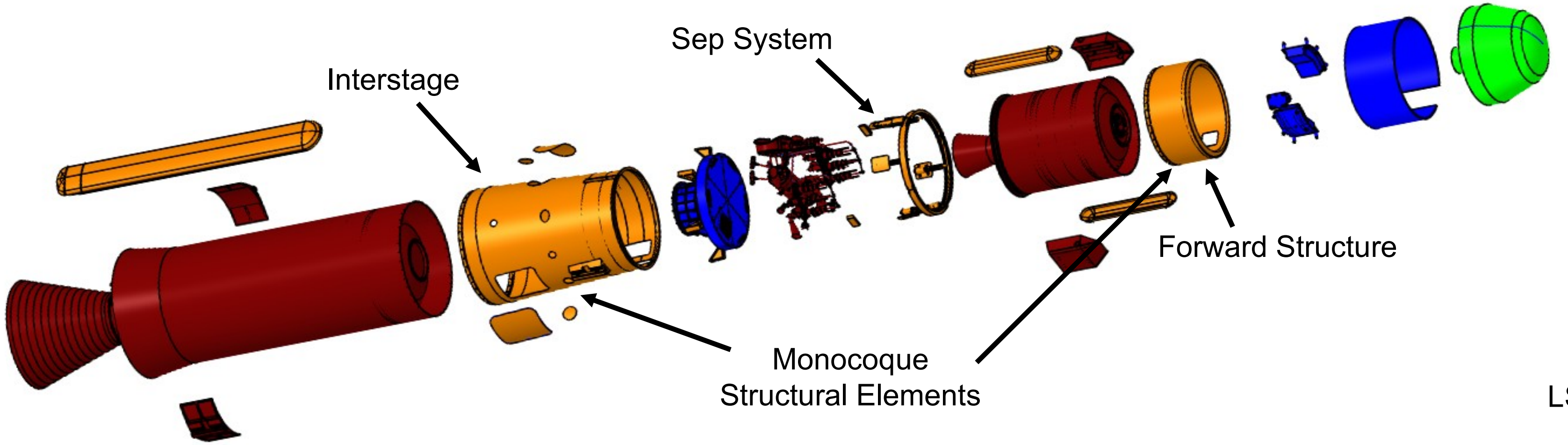
MAV Integration with Cruise Stage

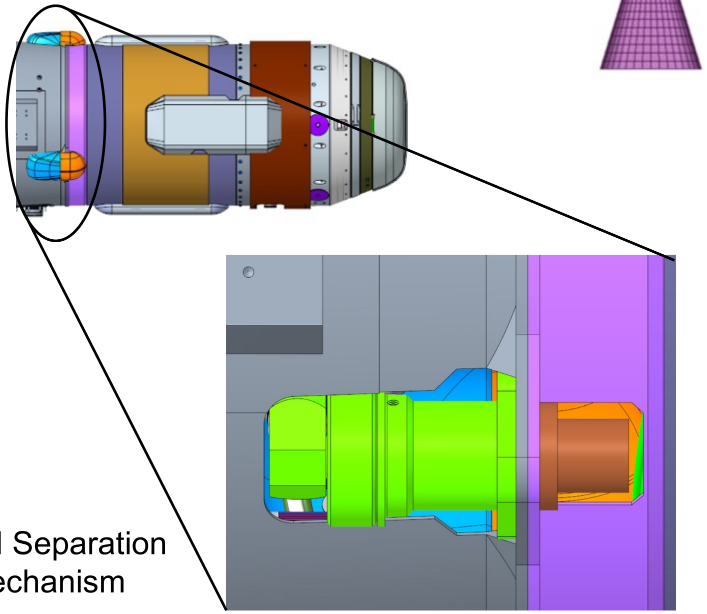
*Conceptual elements shown.

Structural and Mechanical Design

- Unique structural design challenge as vehicle must survive approximately 15g lateral loads during Mars EDL.
- Primary load path travels through SRM1 and interstage via VECTOR attach points.
- Structural design based upon quasi-static loads analysis during Earth ascent/EDL and dynamic loads during VECTOR ejection and Mars ascent. FEM developed.
- Non-propulsive structural elements designed of high TRL machined monocoque construction from simple ring forgings.
- Detailed trade study determined Low-Shock Separation Nuts (LSSN) as most viable mechanism for stage separation.

Mars Ascent FEM

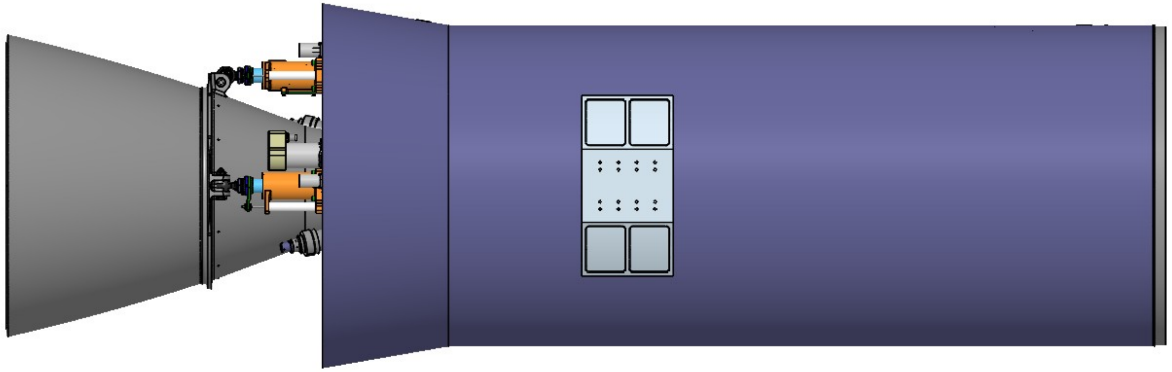




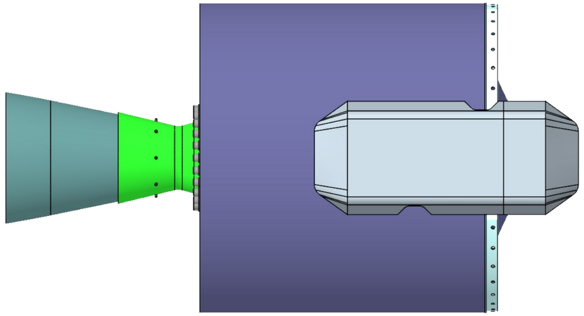
LSSN Separation Mechanism

Main Propulsion Design

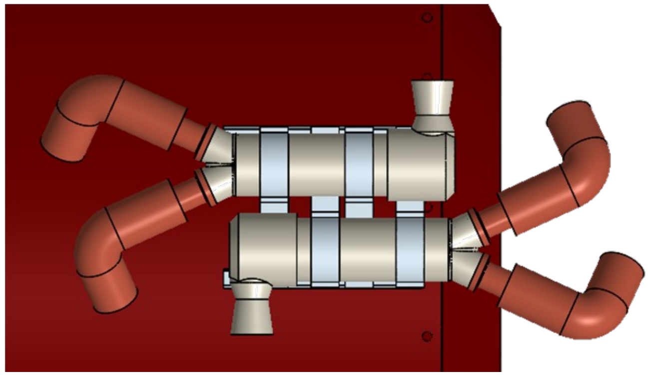
- Main propulsion system consists of two solid rocket motors, using high Technology Readiness Level (TRL) propellant with heritage in Mars missions.*
- TVC on SRM1, with no active control on SRM2.
- Entire main propulsion system designed for 400kg Gross Liftoff Mass (GLOM).
- Computational Fluid Dynamics (CFD) used to optimize nozzle designs for increased performance.
- SRM cases feature carbon-composite design, driven by expected loads and thermal environments.
- Four small-scale SRMs on SRM2 used for spin-up and spin-down on unguided second stage. Each spin/de-spin motor mounted tangentially with redundant pyrotechnic igniters.



Solid Rocket Motor (SRM) 1



SRM2

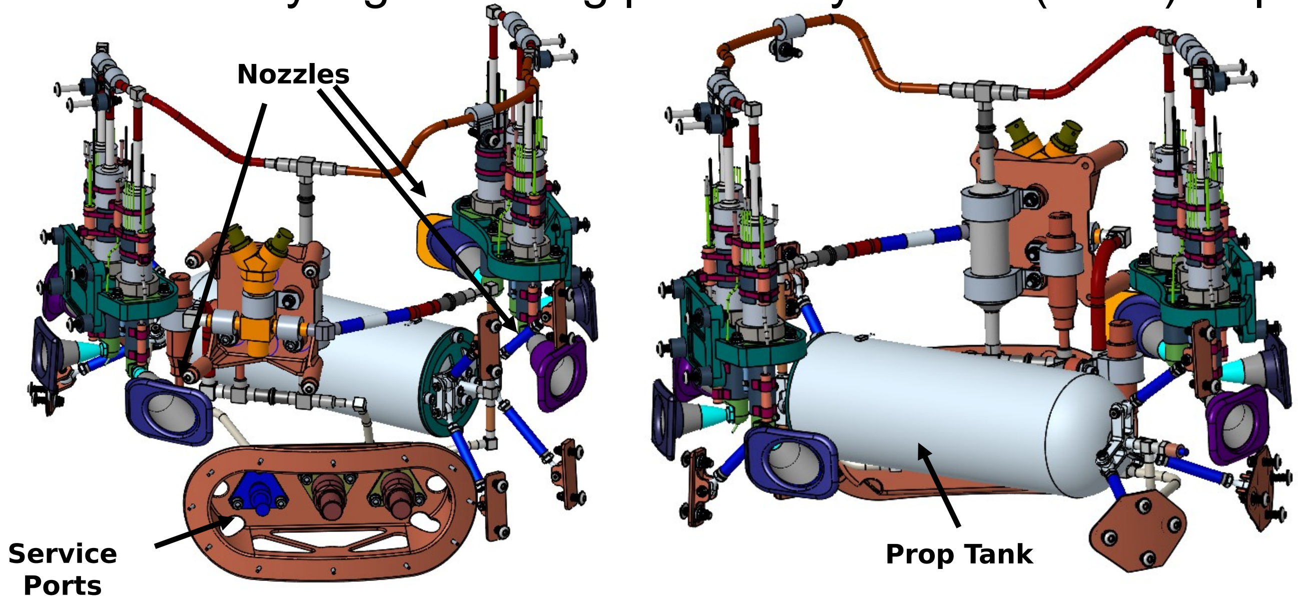


Spin & De-Spin Motors
(No Aero Housing)

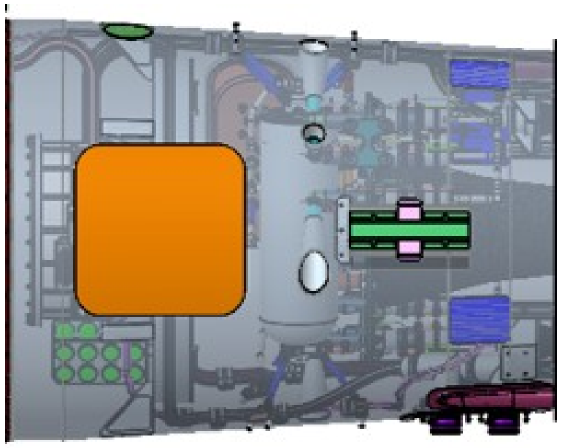
*TP-H-3062 solid propellant, used in Mars exploration rovers Spirit and Opportunity and Mars Pathfinder Entry/Descent/Landing

Reaction Control System Design

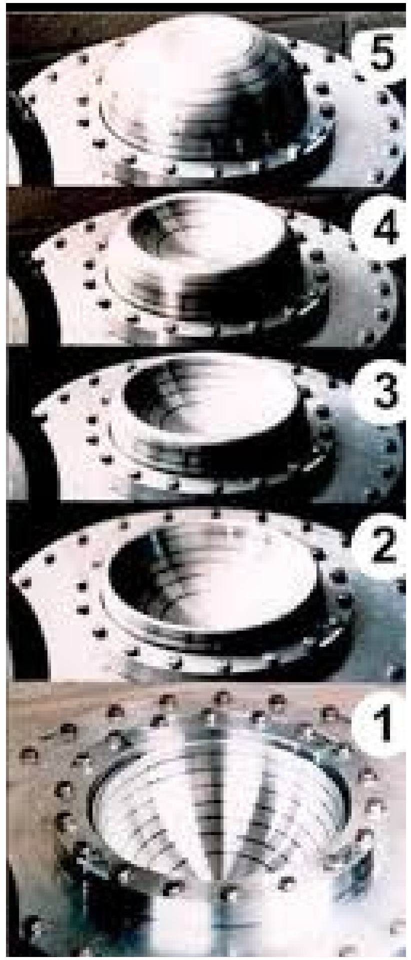
- RCS provides roll control during SRM1 burn and full attitude control during coast. No RCS hardware exists following stage separation.
- RCS consists of monopropellant hydrazine 2:1 blowdown system with high TRL commercial hardware.
- Six lateral thrusters with customized propellant tank with elastomeric diaphragm. Thrusters angled from pitch and yaw axes due to packaging constraints.
- Unique design constraint in that RCS cannot be located on unguided S2. Location on interstage creates a very short control moment arm.
- Relatively high freezing point of hydrazine (+2°C) requires additional heaters.



RCS Internals, +Z and –Z sides (Mech Coord. Frame)



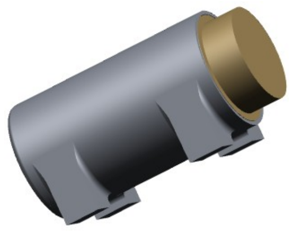
RCS Located Between Avionics and SRM2



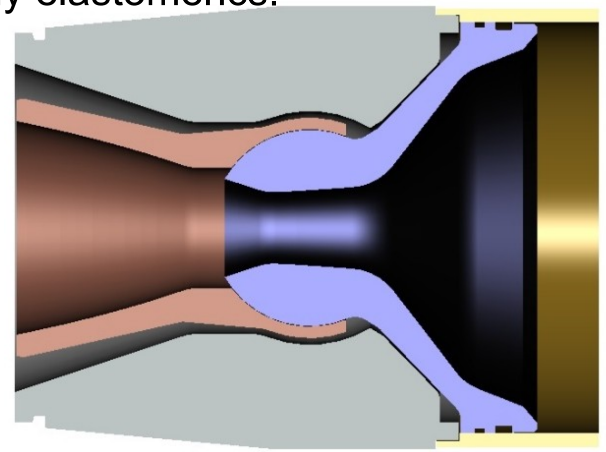
Example Diaphragm

Thrust Vector Control Design

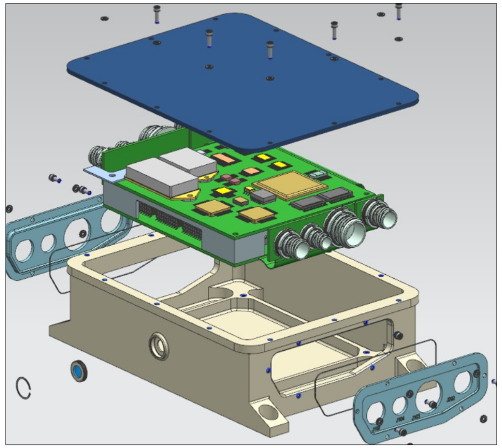
- TVC provides pitch and yaw control during motor burn.
- Nozzle gimbal performed with traditional ElectroMechanical Actuators (EMAs), mounted on aft end of SRM1. No TVC on SRM2.
- Actuators sized to gimbal SRM1 nozzle while under expected mission propulsive loads ascent loads.
- Additional hardware includes pyro-activated thermal battery, and Field-Programmable Gate Array (FPGA) controller. Commands sent to FPGA from flight computer.
- Gimbal nozzle features a Supersonic Splitline (SSSL) with a trapped ball design.
  - Joint is located downstream of nozzle throat, reducing erosion.
  - Typical TVC systems do not operate at such low temperatures due to material incompatibilities. SSSL does not feature any elastomerics.



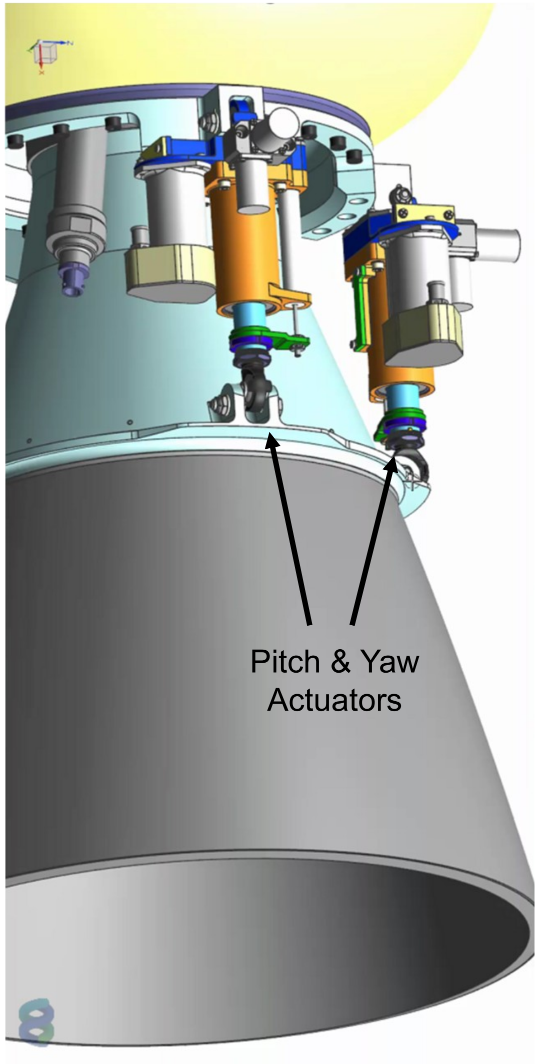
Concept Thermal Battery



Sample SSSL



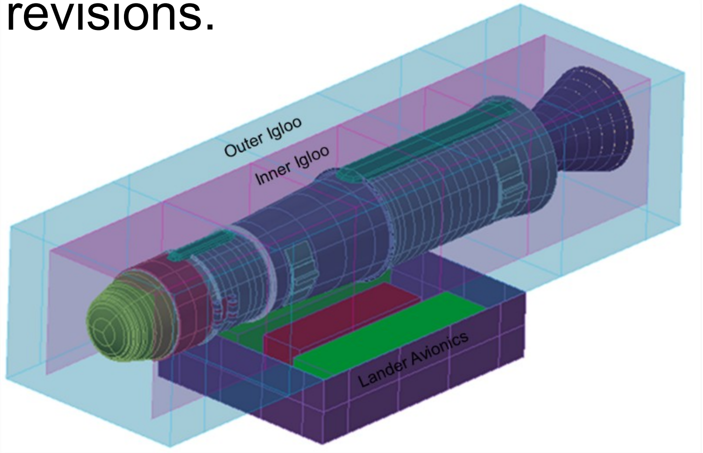
TVC Controller



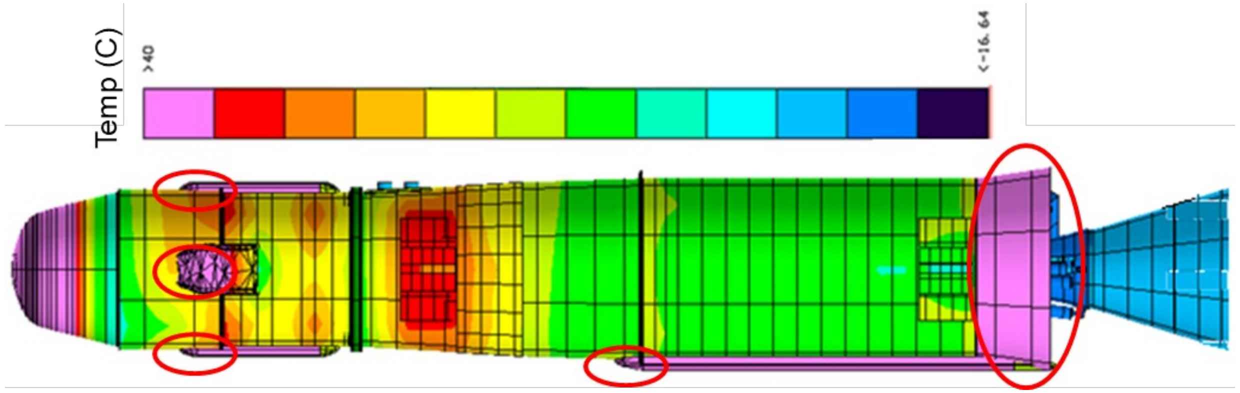
TVC Design

Thermal Design

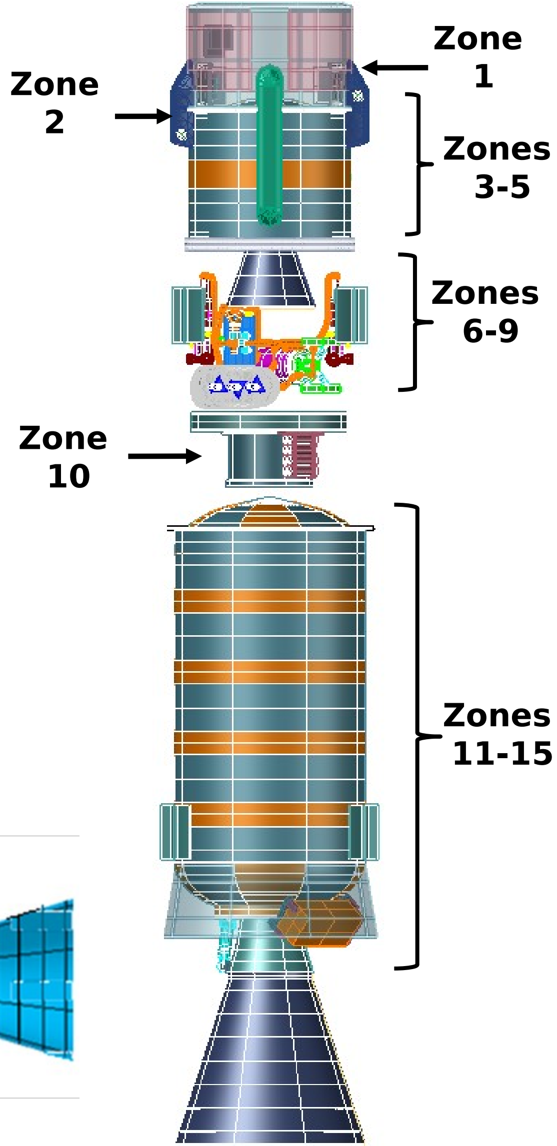
- MAV stored within thermal "igloo" during cruise to Mars and on surface, maintaining constant external temperature.
- Expected worst-case hot and cold mission environments used to bound heater design. 15 active heater zones.
  - Each zone has different components with different thermal constraints
  - RCS considered a special case due to freezing point of hydrazine.
  - No active heating* during ascent due to relatively short ascent mission time.
- Passive thermal protection based upon ascent heating profile, considering induced environments such as aeroheating, plume radiation, and SRM nozzle soak back.
- Additional passive thermal protection may be necessary to add in future design revisions.



Thermal Igloo Enclosure Concept



Thermal Distribution During First Stage Flight

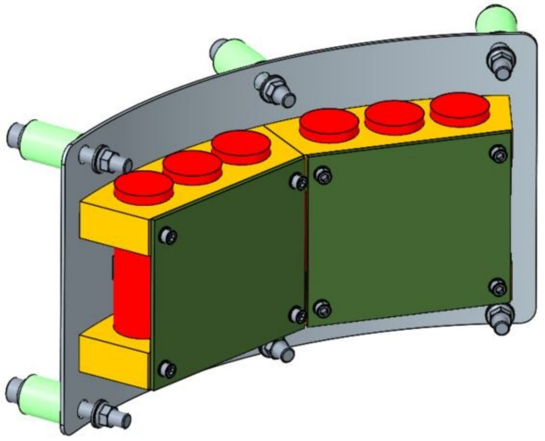


Thermal Control Zones

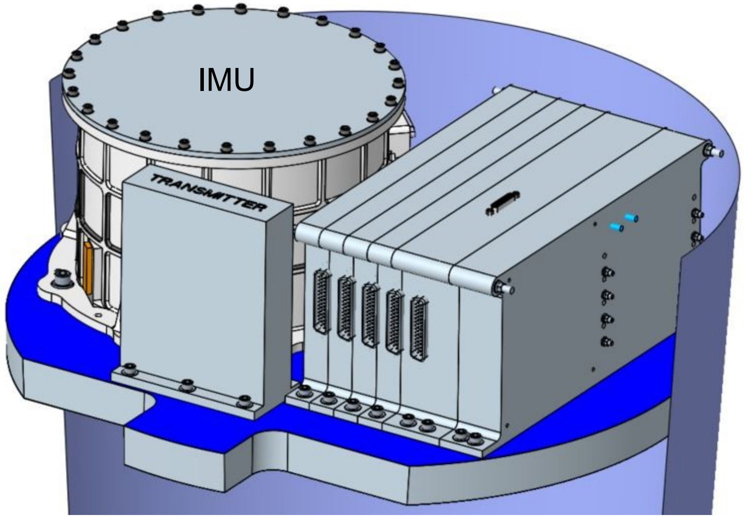
*Excluding beacon operation.

Avionics Design

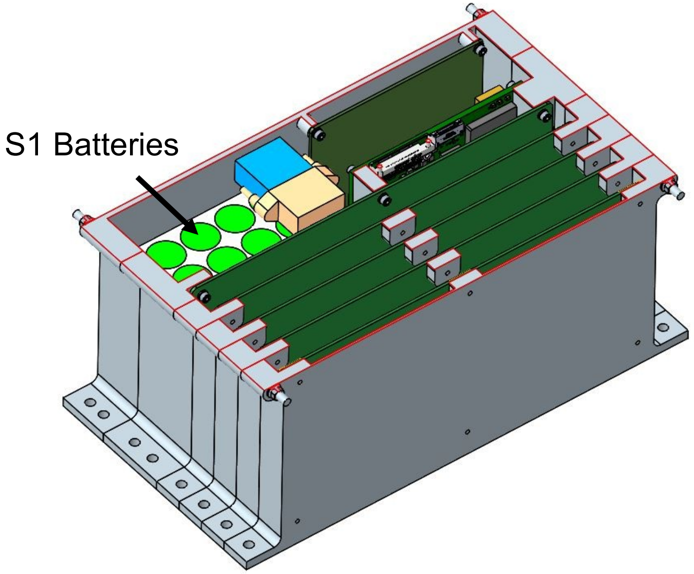
- Avionics divided among stages, providing command and data handling, communication, and power.
  - Primary avionics on S1, holding IMU, flight computer, transmitter, batteries, and various controller/distribution boards
  - Secondary avionics on S2, holding timing circuit, antenna, batteries, and beacon
- Flight software algorithms loaded into computer. Autonomous control of entire flight including ignition and mechanisms.
- Beacon in operation for up to 25 days* following orbital insertion. Beacon will aid in rendezvous and capture of OS by ERO.
- Umbilicals with lander provides power and direct control of several systems while stowed, including pyro inhibits.
- All avionics have to function in extremely atypical environments such as temperature, radiation, and shock.



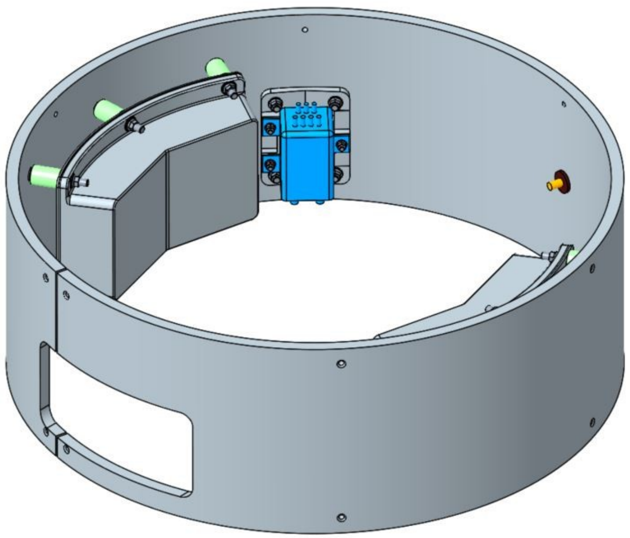
Secondary Avionics Battery/Beacon Boards



Primary Avionics (inverted for clarity)



Computer/Controller/Battery Stack

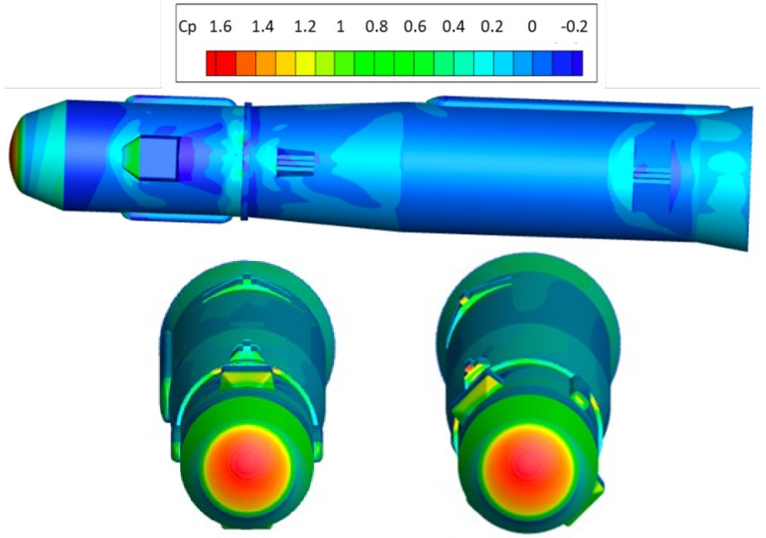


Secondary Avionics, Wraparound Antenna Omitted

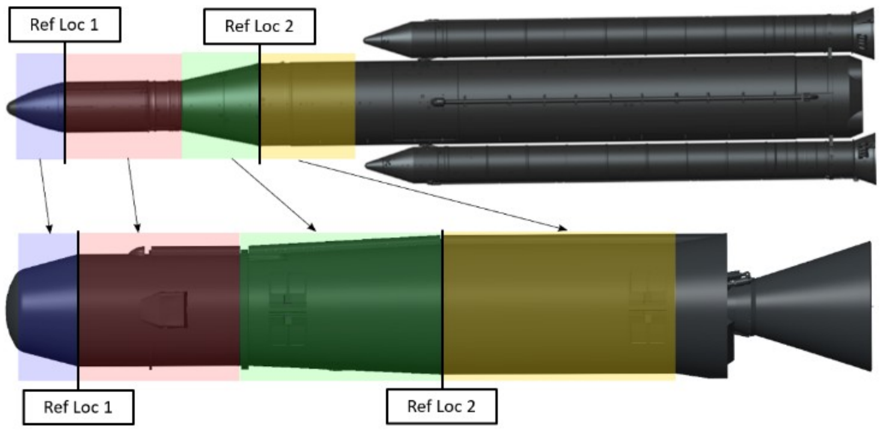
*Recently reduced to 15 days

Aeroscience Environments

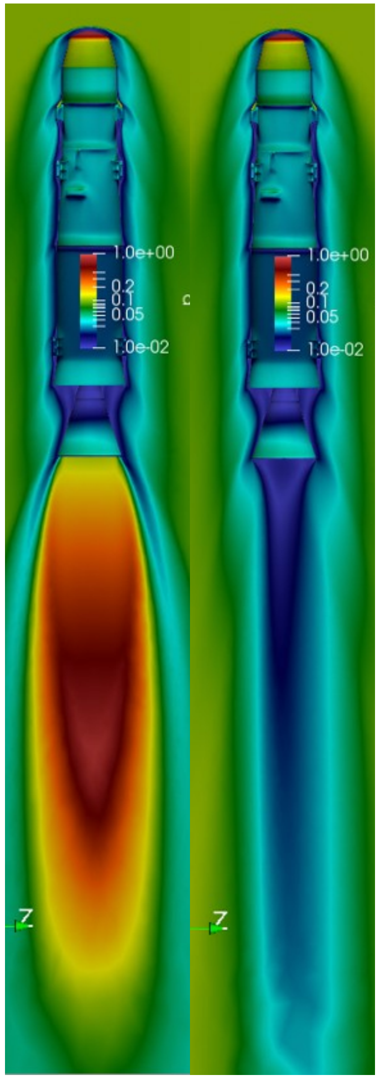
- Vehicle performance affected by interaction with thin Martian environment
  - Aerodynamics, aerothermodynamics, buffet environments, and induced acoustics analyzed.
- CFD performed to assess aerodynamic stability and develop aero coefficients, aerothermal environments, and aero line loads for other aspects of vehicle design.
  - Included aerodynamic contributions of SRM1 plume
  - Vehicle found to be aerodynamically unstable for most of ascent
  - Passive thermal system sized based upon aerothermal considerations.
- Buffet environments, liftoff acoustics, plume-induced acoustics, and ascent aeroacoustics used as inputs to integrated vehicle loads model.



Sample Pressure Distributions



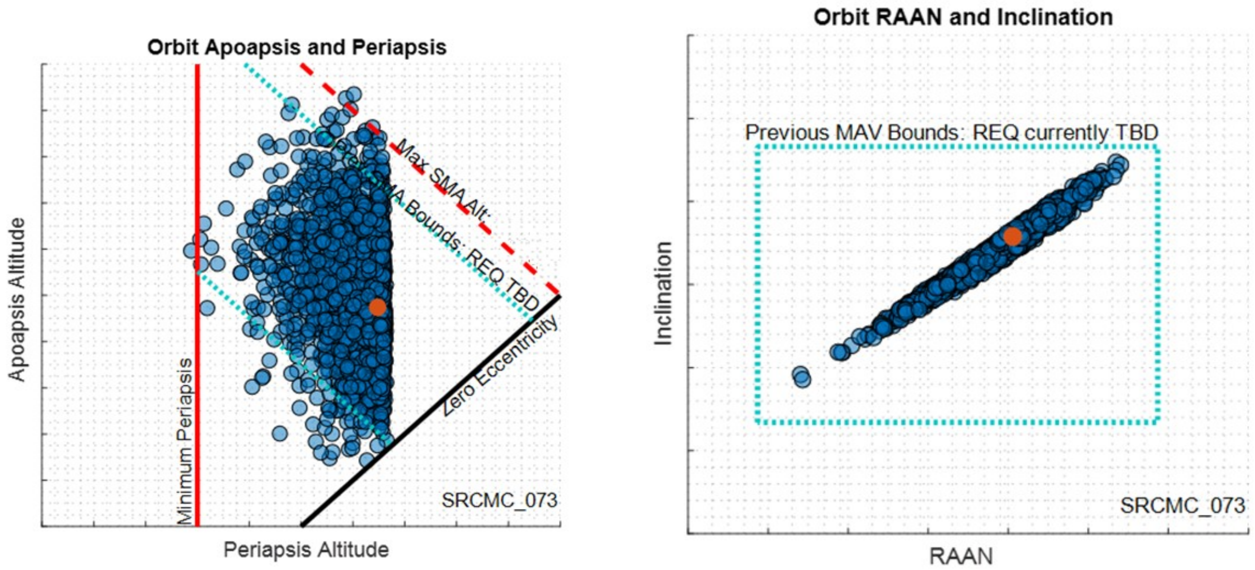
Buffet Model Scaled from SLS Wind Tunnel Model



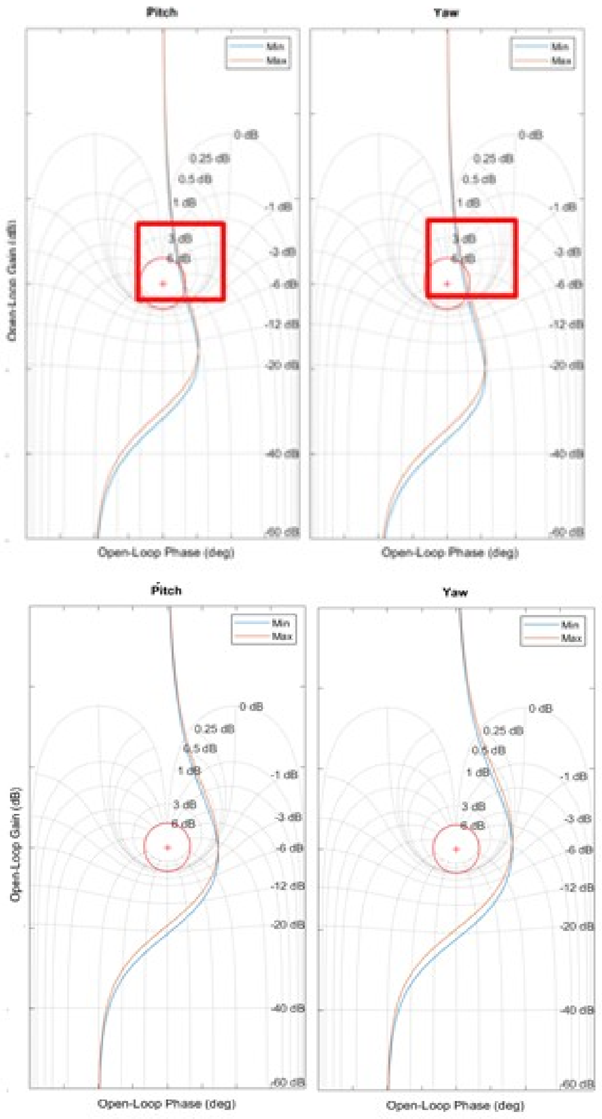
SRM Plume Contributions to Aero Environment

Guidance, Navigation, and Control Design

- Vehicle designed to deliver 16kg payload to 380km @ 27° inclination. Unguided second stage meant a robust GNC scheme was necessary following stage separation.
- High fidelity 6 Degree of Freedom (6DOF) simulation developed, considering mass, motor performance, environments, and mission-specific activities such as spin-stabilization.
- Closed-loop guidance employed during first stage flight. Energy management maneuver employed prior to stage separation to reduce dispersions from solid motor performance.
- Uncertainty parameters addressed via Monte Carlo simulations. Significantly more scatter compared to previous guided configurations.
- Small RCS moment arm initially resulted in stability violations in pitch & yaw. Although improved through controller optimization, a larger moment arm was still deemed necessary.



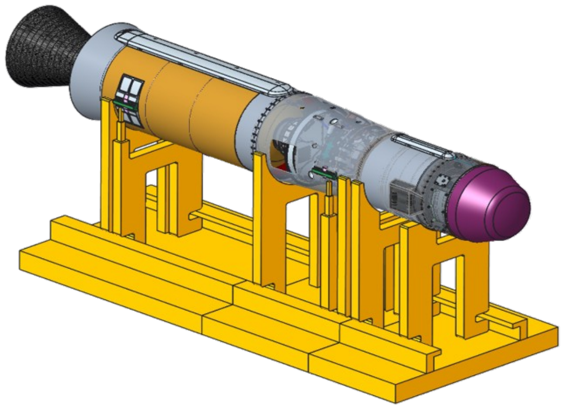
MC Simulation Orbit Dispersions

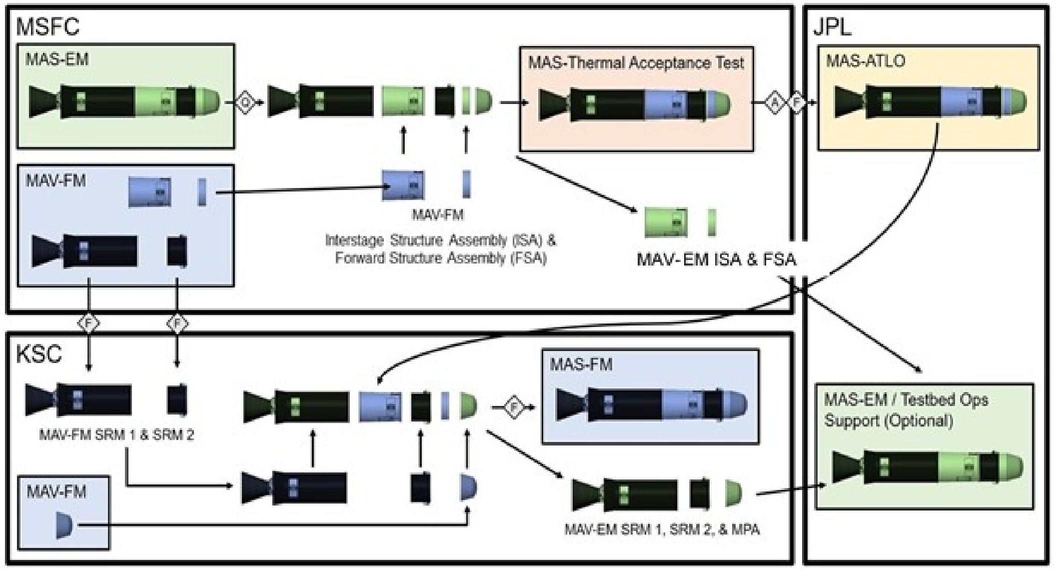


Pitch & Yaw Phase Margin Violations & Effect of Controller Optimization

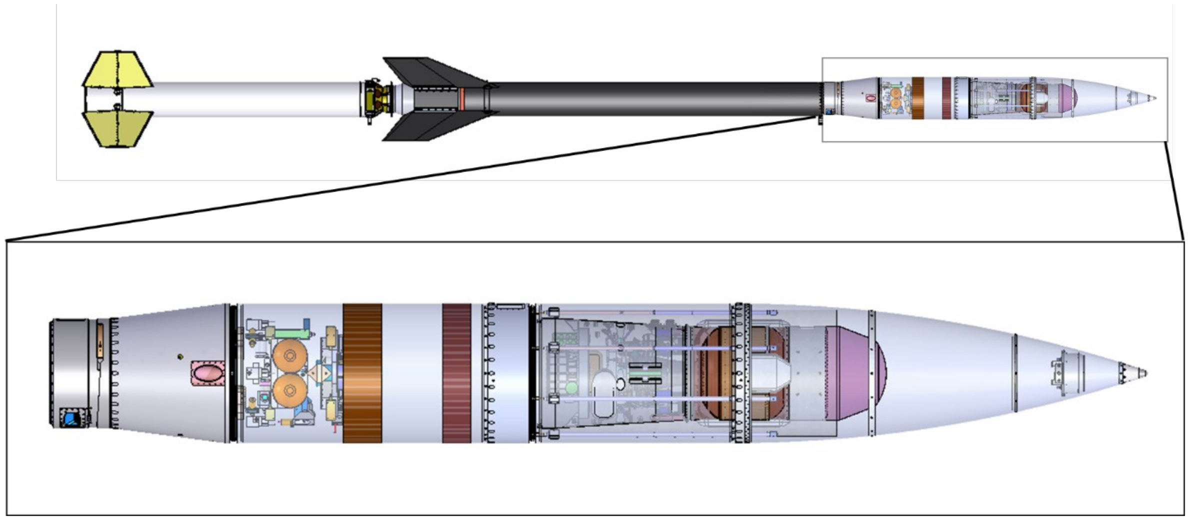
Assembly, Integration, & Testing

- AI&T planning included vehicle assembly from subsystem components, integration with external elements, Verification & Validation (V&V) activities, and the development of a concept for an Earth-based flight test program.
- Four MAV units planned as part of SRC: Engineering Model (EM), Flight Test (FT) unit, Assembly/Test/Launch Operations (ATLO) unit and Flight Mission (FM) unit.
- Rigorous ground-based qualification and acceptance testing planned for individual subsystem assemblies, including hardware-in-the-loop and flight software integration, where applicable. Eleven major test activities for V&V.
- Integrated S2 Earth-based flight test planned, delivered to high altitude via sounding rocket to replicate Martian surface environments.


Notional Qualification Test Article

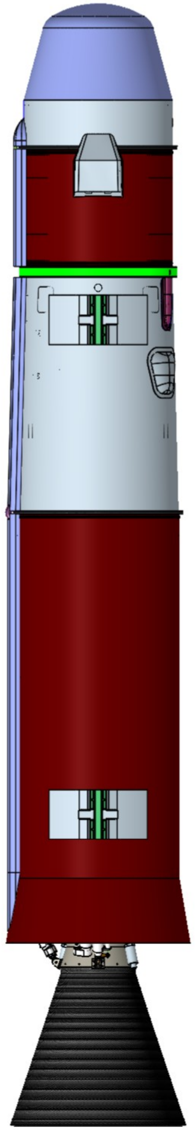


Assembly & Integration of EM, FM, and ATLO

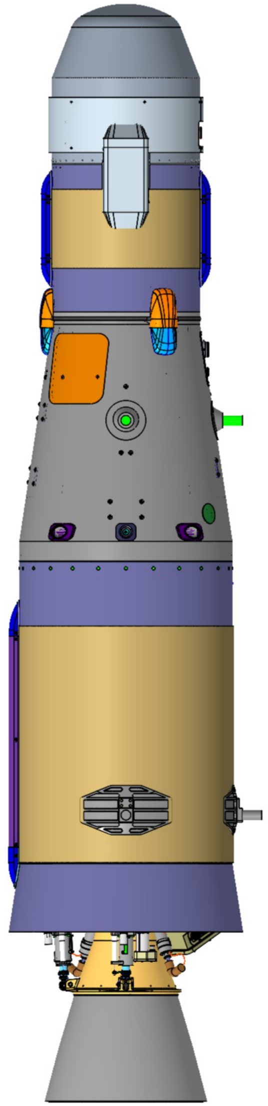

Flight Test Unit as Payload in Sounding Rocket

SRC Technical Design and Beyond

- SRR held November 2021. System requirements passed.
- SRC vehicle analysis concluded concept can successfully deliver 16kg payload including 30 sample tubes to target Martian orbit, meeting all stowage size and mass constraints.
- Architecture shift to unguided upper stage allowed for significant mass savings in overall vehicle at expense of orbital insertion accuracy.
- Following SRR, design advanced based campaign architecture shift to dual landers. SRL on separate lander meant increased mass allocation for MAV at expense of budget.
  - Refined MAV allowed for larger SRMs with larger mass margins.
  - Budget restraints resulted in reduced scope of flight test.
- Current design cycle in work ahead of Preliminary Design Review, Feb 2023



SRC Rev2 Design
May 2021



PDC Rev1 Design
December 2020

Questions
?

Perseverance Rover drill arm collecting surface samples.
Jezero Crater, Mars. Future launch site of MAV.

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