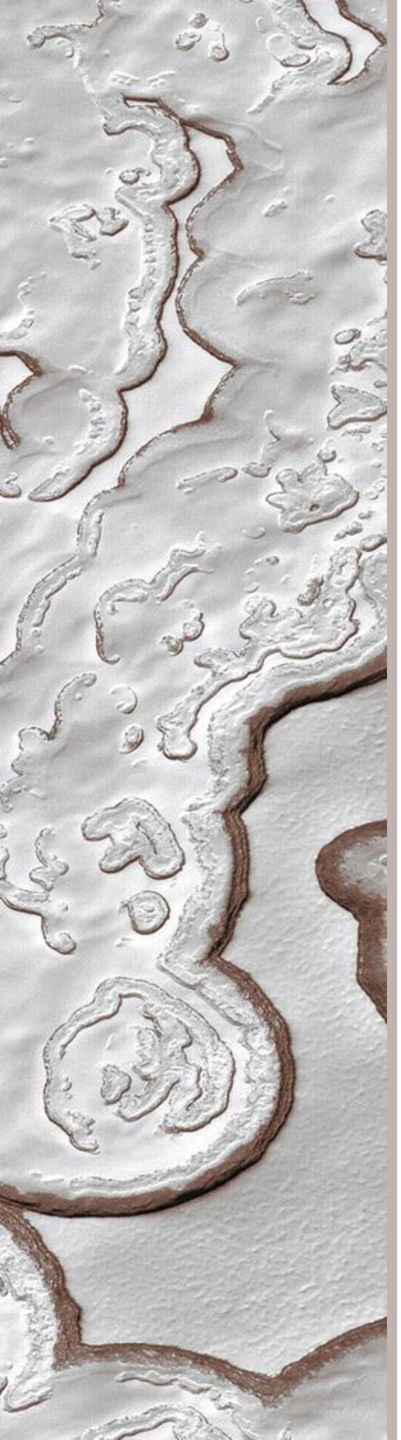

The Mission Loads Environment and Structural Design of the Mars Science Laboratory Spacecraft

June 27, 2013
FEMAP Symposium 2013
Northern Kentucky Convention Center
Covington, KY

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Spacecraft Structures and Dynamics
Jet Propulsion Laboratory
California Institute of Technology

Jet Propulsion Laboratory, California Institute of Technology
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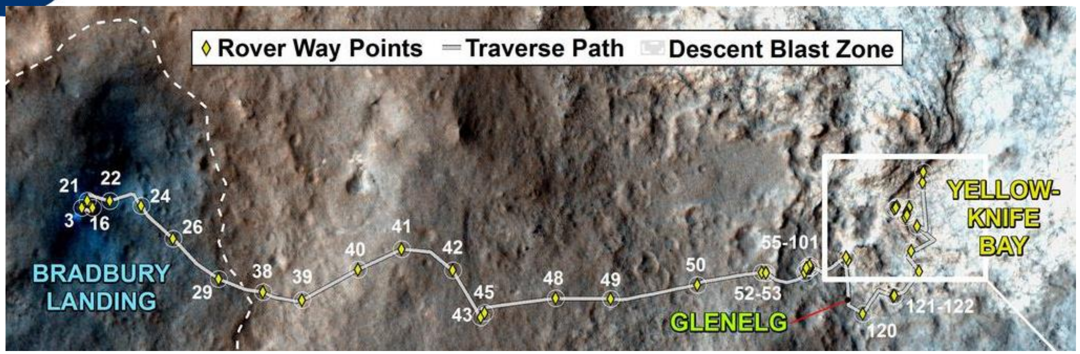
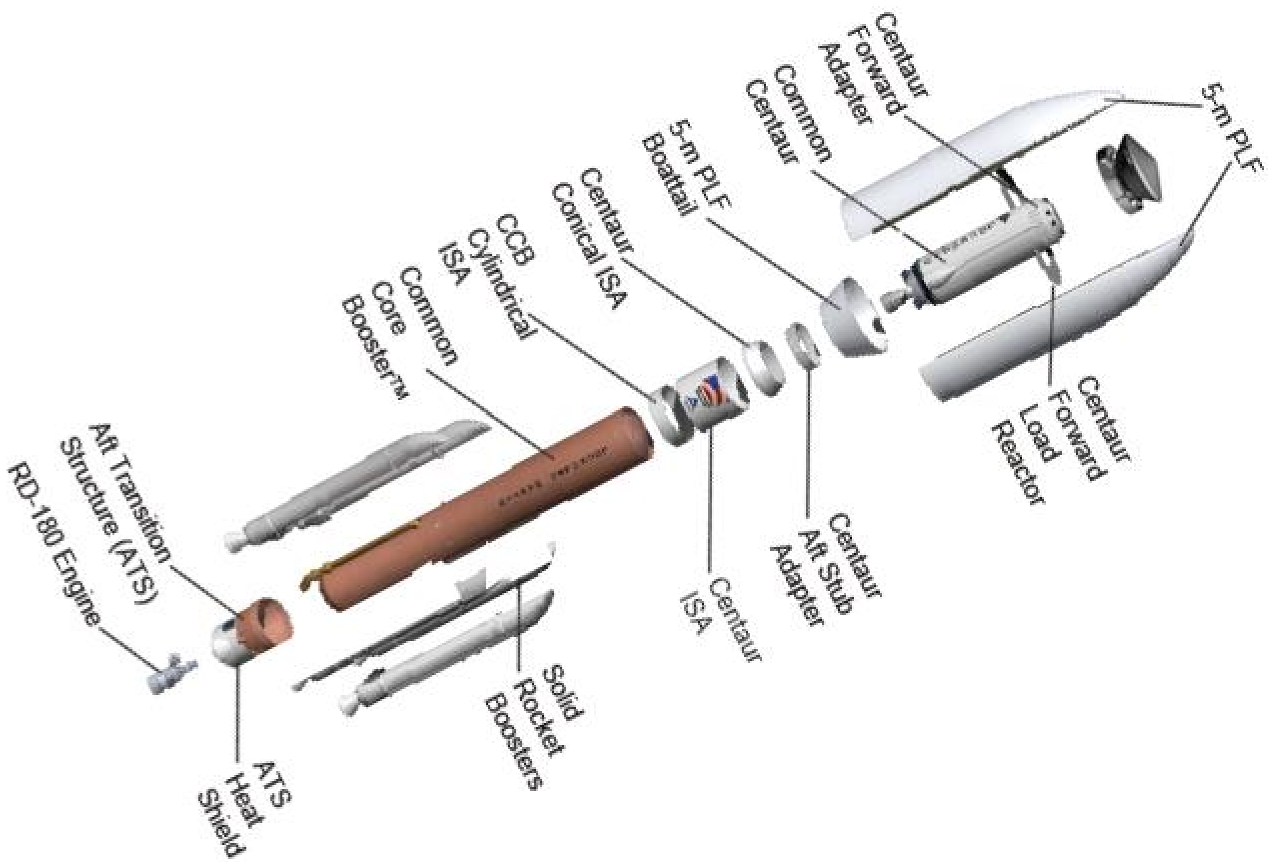
MSL: Loads Environment and Structural Design



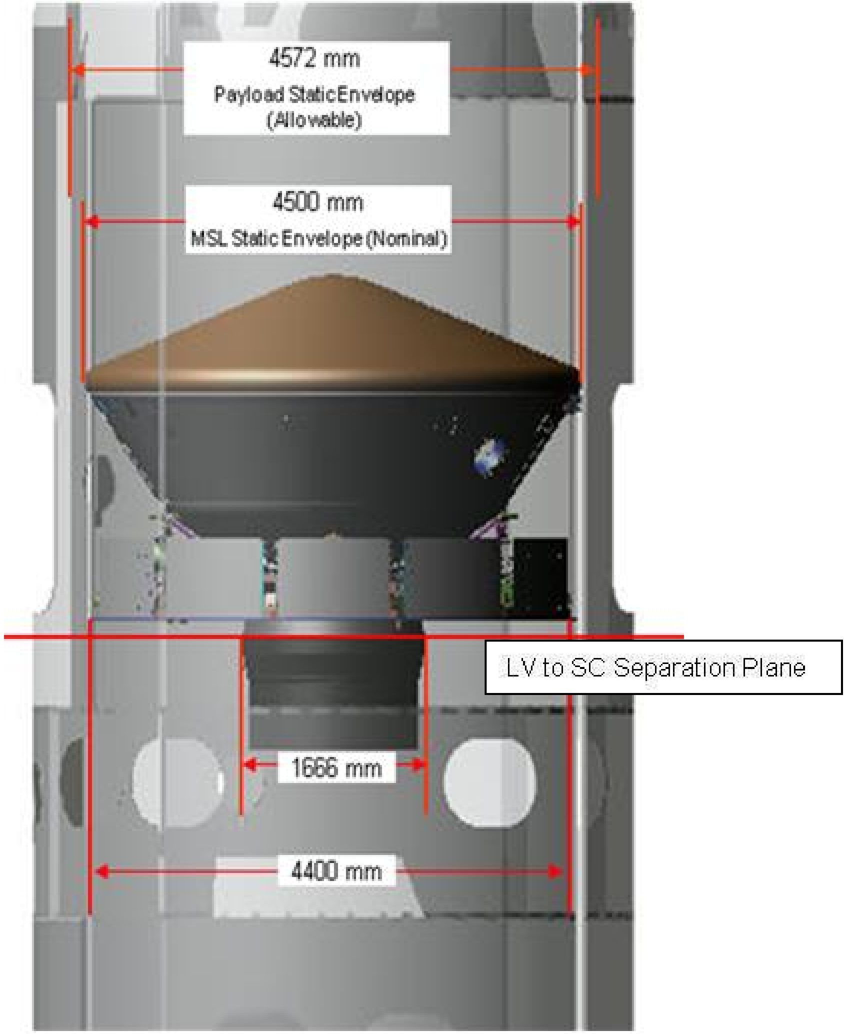
- **How hard is it to get to Mars?**
  - There have been 40 Mars missions
    - Up to year 2000, the success rate was 10/33 = 30%
    - Up to year 2011 (including MSL), the success rate was 16/40 = 40%
    - From 2000 to 2011, the success rate 6/7 = 85.7% (2003 Mars Express/Beagle, lost on arrival)
- **Successful Landed Missions to Mars**
  - 1975 Vikings 1 & 2: JPL Orbiters with Martin Marietta Landers
  - 1996 Mars Pathfinder: JPL (11 kg Rover)
  - 2003 Mars Explorer Rovers: JPL (170 kg Rovers)
  - 2007 Phoenix: JPL subcontract to Lockheed Martin (400 kg Lander)
  - 2011 Mars Science Laboratory: JPL (900 kg Rover)

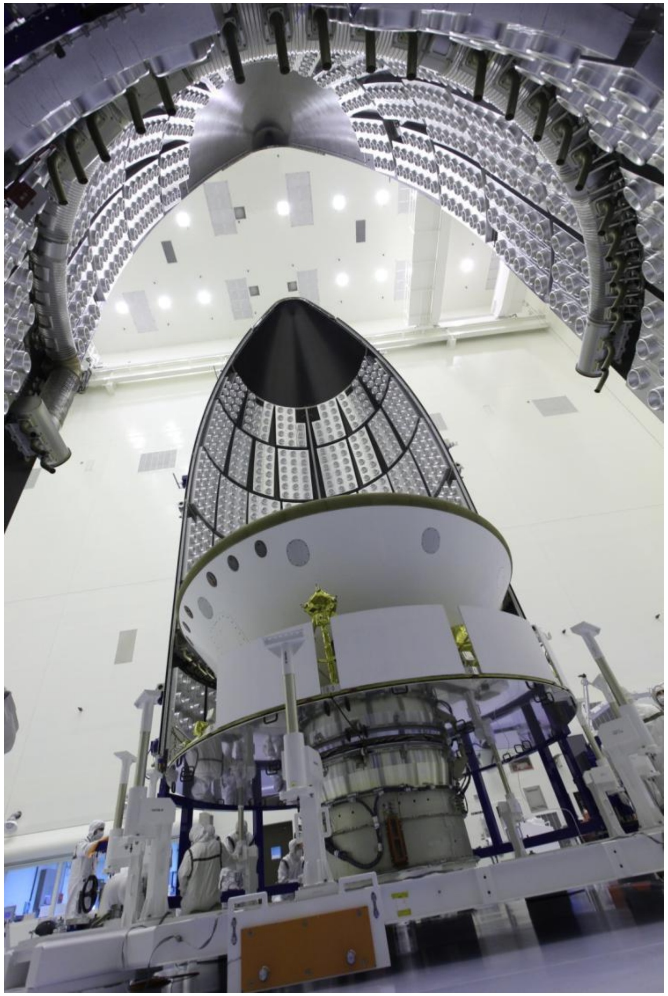
http://mars.jpl.nasa.gov/programmissions/missions/log/

Atlas V 541 (5 m fairing, 4 SRB, 1 Centaur engine) Mission Launch Vehicle November 26, 2011



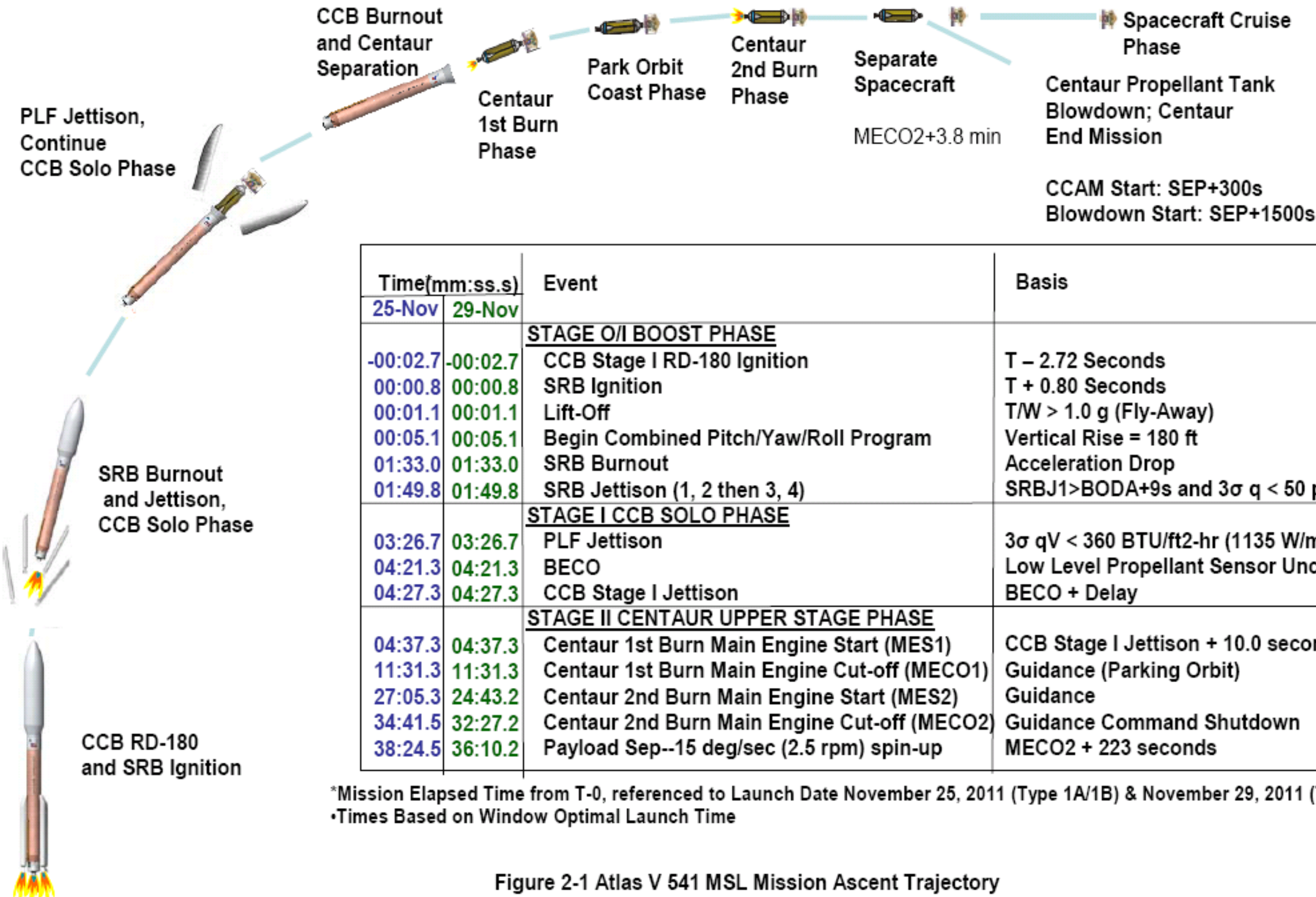
MSL S/C on Atlas V w/D-1666 Payload Adapter





MSL: Loads Environment and Structural Design

Atlas V (541) Mission Launch Ascent Profile
November 26, 2011

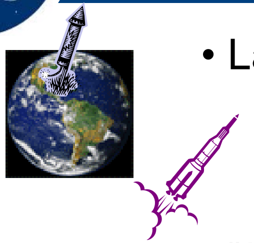


Time (mm:ss.s)		Event	Basis
25-Nov	29-Nov		
		STAGE O/I BOOST PHASE	
-00:02.7	-00:02.7	CCB Stage I RD-180 Ignition	T – 2.72 Seconds
00:00.8	00:00.8	SRB Ignition	T + 0.80 Seconds
00:01.1	00:01.1	Lift-Off	T/W > 1.0 g (Fly-Away)
00:05.1	00:05.1	Begin Combined Pitch/Yaw/Roll Program	Vertical Rise = 180 ft
01:33.0	01:33.0	SRB Burnout	Acceleration Drop
01:49.8	01:49.8	SRB Jettison (1, 2 then 3, 4)	SRBJ1>BODA+9s and 3σ q < 50 psf
		STAGE I CCB SOLO PHASE	
03:26.7	03:26.7	PLF Jettison	3σ qV < 360 BTU/ft2-hr (1135 W/m2)
04:21.3	04:21.3	BECO	Low Level Propellant Sensor Uncover
04:27.3	04:27.3	CCB Stage I Jettison	BECO + Delay
		STAGE II CENTAUR UPPER STAGE PHASE	
04:37.3	04:37.3	Centaur 1st Burn Main Engine Start (MES1)	CCB Stage I Jettison + 10.0 seconds
11:31.3	11:31.3	Centaur 1st Burn Main Engine Cut-off (MECO1)	Guidance (Parking Orbit)
27:05.3	24:43.2	Centaur 2nd Burn Main Engine Start (MES2)	Guidance
34:41.5	32:27.2	Centaur 2nd Burn Main Engine Cut-off (MECO2)	Guidance Command Shutdown
38:24.5	36:10.2	Payload Sep--15 deg/sec (2.5 rpm) spin-up	MECO2 + 223 seconds

*Mission Elapsed Time from T-0, referenced to Launch Date November 25, 2011 (Type 1A/1B) & November 29, 2011 (Type 1C)
•Times Based on Window Optimal Launch Time

Figure 2-1 Atlas V 541 MSL Mission Ascent Trajectory

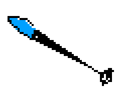
MSL: Loads Environment and Structural Design



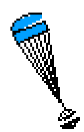
Launch
Cruise
Entry
Events

- Launch → Time = Launch + 0 *Mass = 4033 kg*
  Loads: 1.0 g's X-Dir; 1.1 g's Y-Dir; 2.6 g's Z-Dir (Max lateral: Mach-1/Max-Q)
- CCB Burn → Time = Launch +3 min 30 Sec
  Loads: 0.3 g's X-Dir; 0.2 g's Y-Dir; 6.1g's Z-Dir (Max vert)
- Cruise → Time = Launch +187 to 215 Days (TCM 1, 2, 3)
- Approach → Time = Entry –45 days
  TCM 4 at E – 8 days
- Start of EDL Sequence → Time = Entry –5 days
  TCM 5, 6 at E-2 days to E-9 hours
- Cruise Stage Separation → Time = Entry –9 minutes
  TCM 5, 6 at E-2 days to E-9 hours
- Entry → Time = Entry + 0 *Mass = 3316 kg*
  Altitude = 125 km (Mars r = 3522 km), velocity = 5,800 m/sec

- Peak Heating → Time = Entry +85 seconds
  Altitude = 26 km, velocity = 4,600 m/sec
- Peak Deceleration → Time = Entry +96 seconds
  Altitude = 19 km, velocity = 3,700 m/sec
  Loads: 0.65 g's X-Dir; 15 g's Z-Dir
  (At E+231 sec, Alt=12km, velocity=525 m/sec)



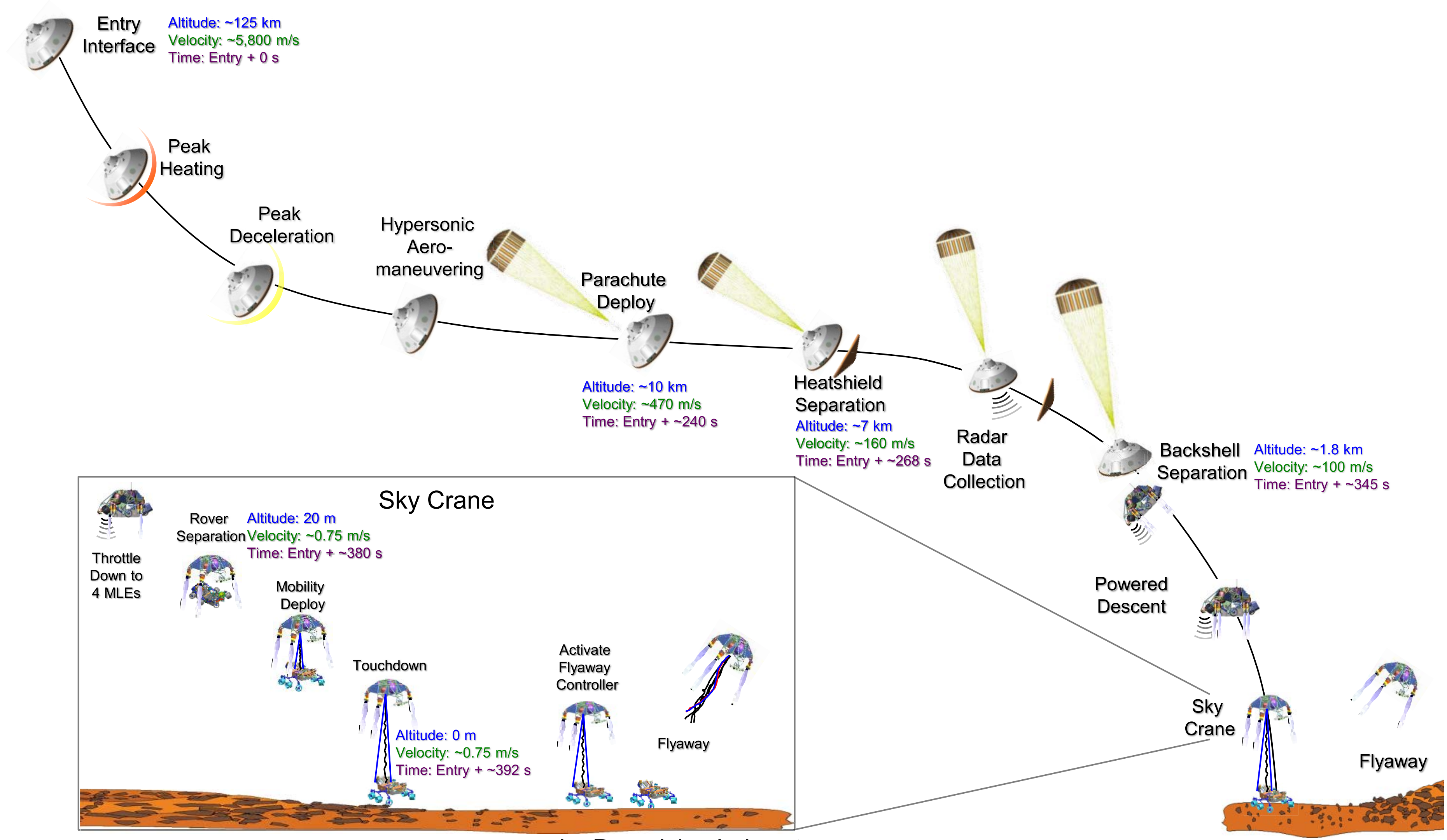
- Parachute Deployment → Time = Entry +245 seconcs
  Altitude = 10 km, velocity = 470 m/sec
  65,0000 lbs Cord load ~ 9.7 g's with 37 radian/sec^2



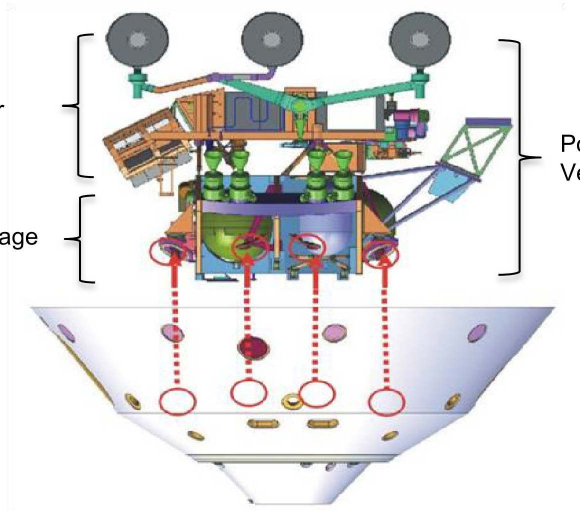
- Heatshield Separation → Time = Entry +274 seconds
  Altitude = 7 km, velocity = 160 m/sec

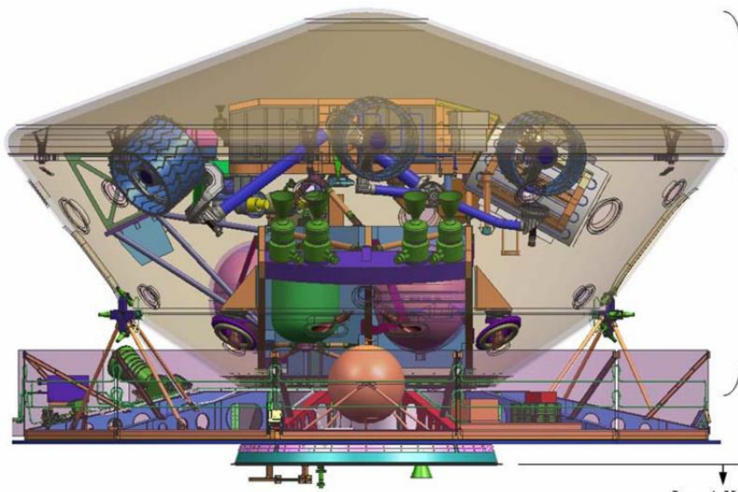
MSL: Loads Environment and Structural Design

Entry - Descent - Landing Events

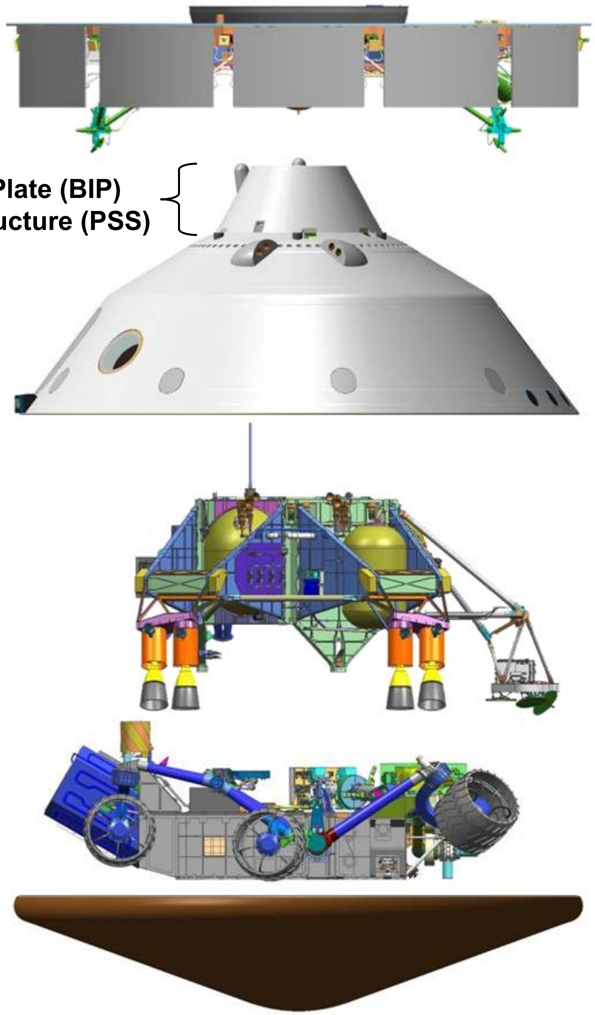


- MSL spacecraft flight system Assemblies
  - Cruise Stage
  - Entry Vehicle
    - Aeroshell
    - Powered Descent Vehicle
      - Descent Stage
      - Rover





MSL Spacecraft Primary Interfaces



PAF/LVA I/F

- **Marmon Clamp (dia = 66")**

Cruise Stage/BIP I/F (bolt circle dia = 54")

- **6 - 5/8" bolts**

BIP/Descent Stage I/F (bolt circle dia = 58")

- **6 - 5/8" bolts**

Descent Stage/Rover I/F (bolt circle dia = 47")

- **3 - 5/8" bolts**

Heat Shield/Backshell (bolt circle dia = 157")

- **9 - 3/8" bolts**

Note: Permanent I/F's are Cruise stage to LVA, Aeroshell to BIP, Parachute Can to BIP

Weight = 4015 kg (= 8852 lbs)

MSL Spacecraft Masses (VLC Model)

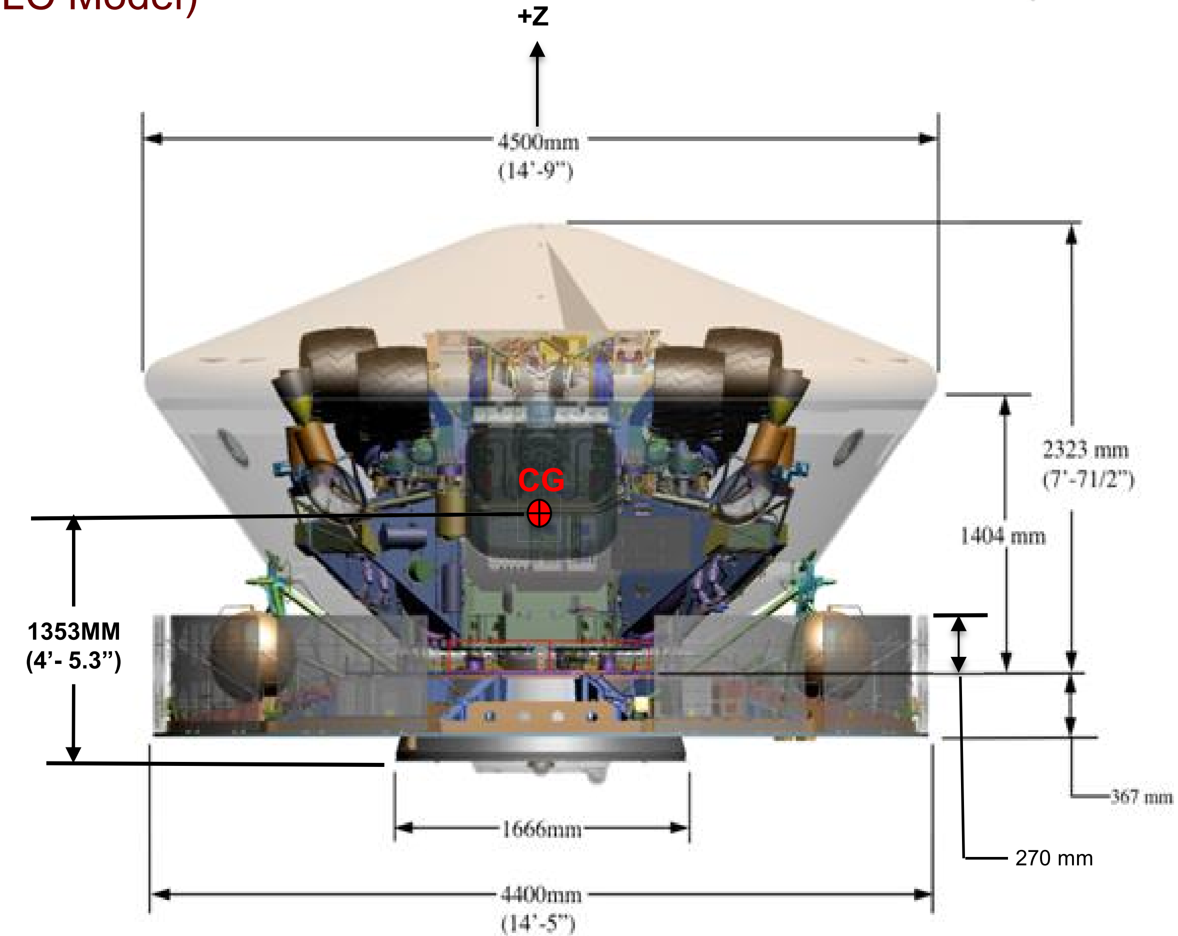
- **Rover** **943.8 kg**
  - Rover Chassis 723.4 kg
  - Rover Mobility 220.4 kg
- ***Landing Mass*** ***943.8 kg***

- **Descent Stage** **1121.5 kg**
  - Descent stage 581.7 kg
  - 3 Full Fuel Tank 459.8 kg
  - 8 MLE's 80.0 kg
- ***Powered DV mass*** ***2065.3 kg***

- **Aeroshell/BIP** **1390.0 kg**
  - Heatshield 475.4 kg
  - Backshell W/ BIP 418.7 kg
  - Parachute W/ Lid 168.0 kg
  - Entry Balance Mass 175.6 kg
  - Cruise Balance Mass 153.3 kg (Jettisoned from Aeroshell)
- ***Entry mass*** ***3301.9 kg***

- **Cruise Stage** **560.0 kg**
  - Cruise Stage 455.7 kg
  - Secondary Structure Incl Above
  - 2 Full Full Tank 104.3 kg
- ***Total Launch Mass*** ***4015 kg (= 8852 lbs)***

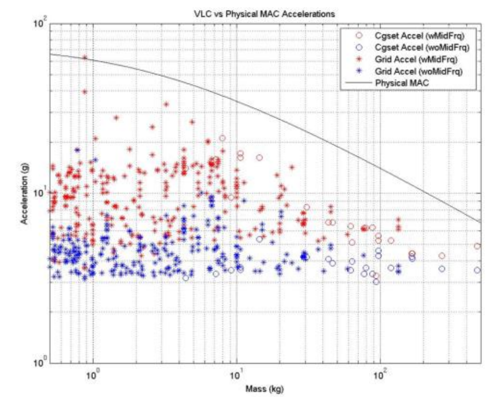
- ***Z_{cg} = 1353 mm = 53.28" (Measured to bottom of Cruise Stage)***



Launch Loads Methods

Objectives: estimate loads and accelerations for strength margins assessment

- **Physical MAC Method – no Finite Element Model required**
  - Conservative "bound" of acceleration as a function of mass
  - Applicability
    - Cantilevered masses 1 – 500 kg
    - Frequencies 0 to 80 Hz
  - Curve is verified/adjusted by subsequent loads analyses

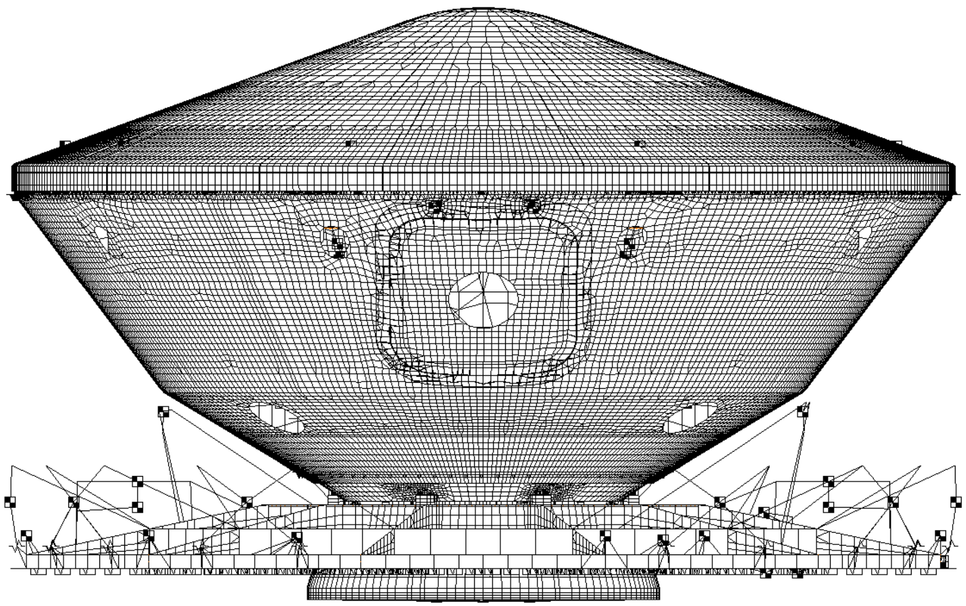


- **Modal MAC Method – requires Finite Element Model**
  - Extension of physical MAC concept to modes of the structure
    - Each mode represents spring-mass system cantilevered from S/C Interface with some "effective mass"
    - Modal MAC is developed to "bound" modal response as a function of effective mass
    - Element loads are the RSS of the modal bounds
  - Applicability – lumped mass and distributed mass systems
  - Curve is verified/adjusted by CLA
- **Launch Vehicle Coupled Loads Analyses**
  - Send stiffness and mass matrix modal models to Launch Vehicle provider for launch loads analyses

Finite Element Model Statistics (VLC Model)

- **Total Mass** **4015 kg**
- **Model Size**

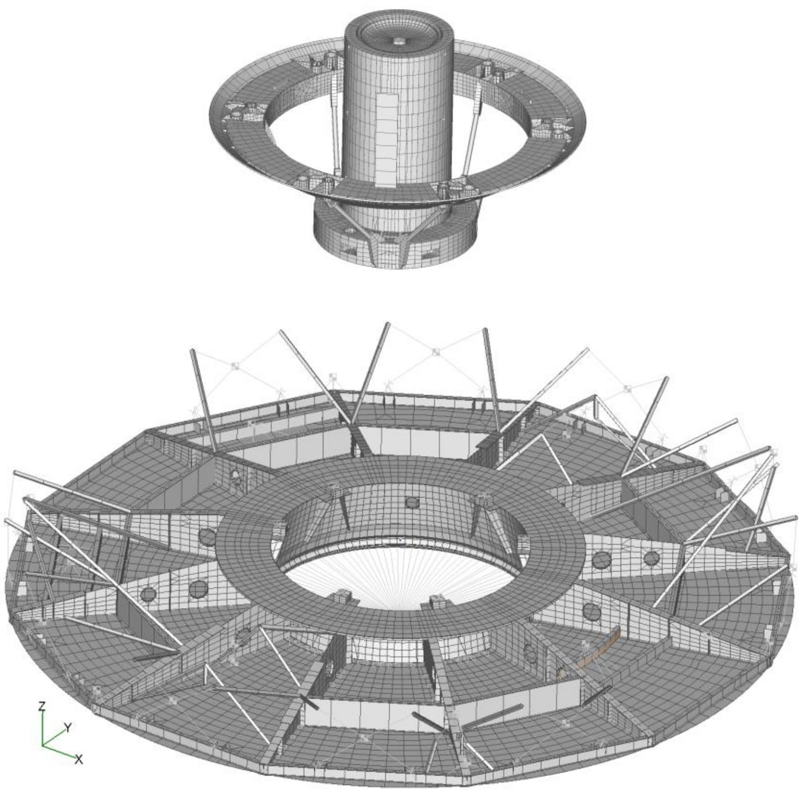
TOTAL NUMBER OF GRID POINTS	**= 76574**
TOTAL NUMBER OF ELEMENTS	**= 91908**
NUMBER OF CBAR ELEMENTS	= 7307
NUMBER OF CBEAM ELEMENTS	= 3479
NUMBER OF CBEND ELEMENTS	= 619
NUMBER OF CBUSH ELEMENTS	= 279
NUMBER OF CELAS2 ELEMENTS	= 3314
NUMBER OF CHEXA ELEMENTS	= 3218
NUMBER OF CONM2 ELEMENTS	= 466
NUMBER OF CPENTA ELEMENTS	= 828
NUMBER OF CQUAD4 ELEMENTS	= 65798
NUMBER OF CROD ELEMENTS	= 60
NUMBER OF CSHEAR ELEMENTS	= 695
NUMBER OF CTRIA3 ELEMENTS	= 4123
NUMBER OF GENEL ELEMENTS	= 6
NUMBER OF PLOTEL ELEMENTS	= 91
NUMBER OF RBE2 ELEMENTS	= 1361
NUMBER OF RBE3 ELEMENTS	= 264



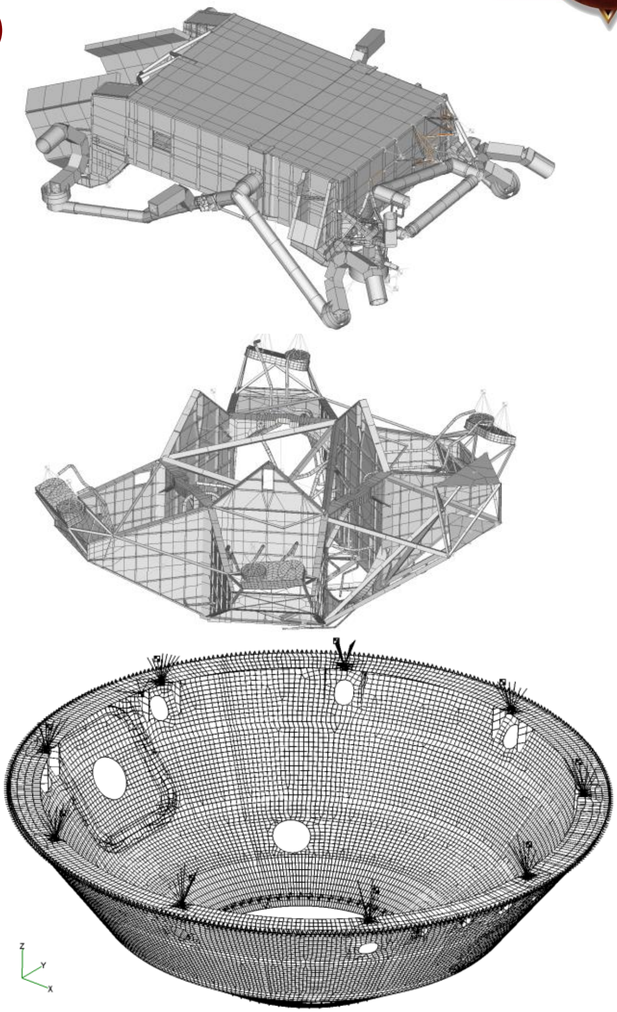
- **Modal Results**
  - Frequencies: Lateral X = 9.7 Hz; Lateral Y = 10.9 Hz; Axial Z = 24.3 Hz
  - Total % Effective Mass Cumulated to 80 Hz:

X-Trans	Y-Trans	Z-Trans	X-Rot	Y-Rot	Z-Rot
91%	91%	94%	99%	99%	99%

Finite Element Model (VLC model)



Cruise Stage, BIP, and PSS

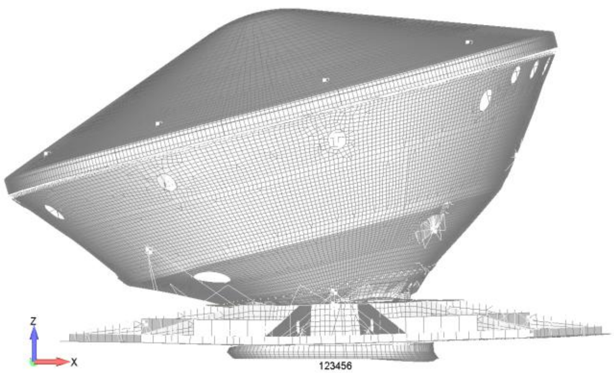


Backshell, Descent Stage, and Rover

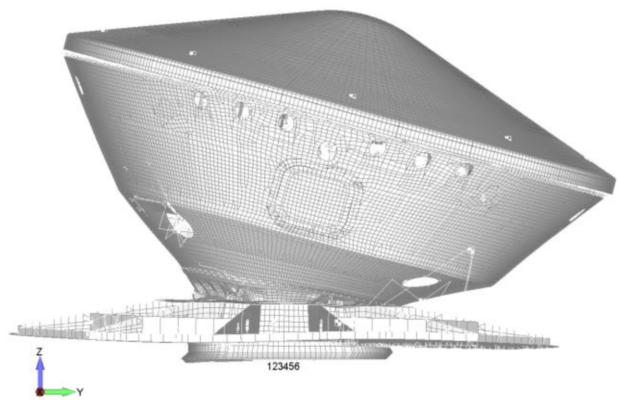
Primary Spacecraft Mode Shapes

- Spacecraft Lateral Modes
  - f_{lat} = 9.67 Hz X-dir (goal 8 Hz)
  - f_{lat} = 10.87 Hz Y-dir (goal 8 Hz)
- Spacecraft Vertical Modes
  - f_{vert} = 24.27 Hz Z-Dir (goal 15 Hz)

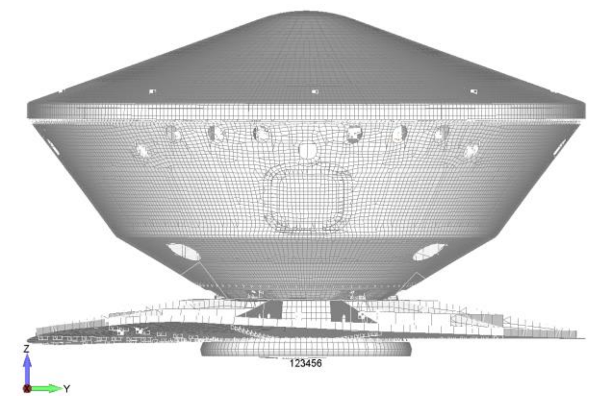
f_1 = 9.69 Hz



f_2 = 10.87 Hz

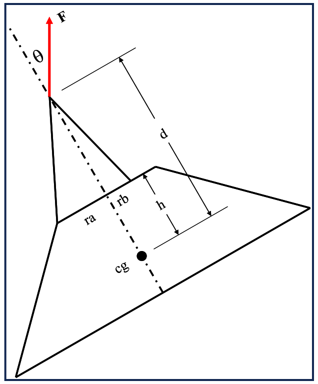


f_{20} = 24.27 Hz

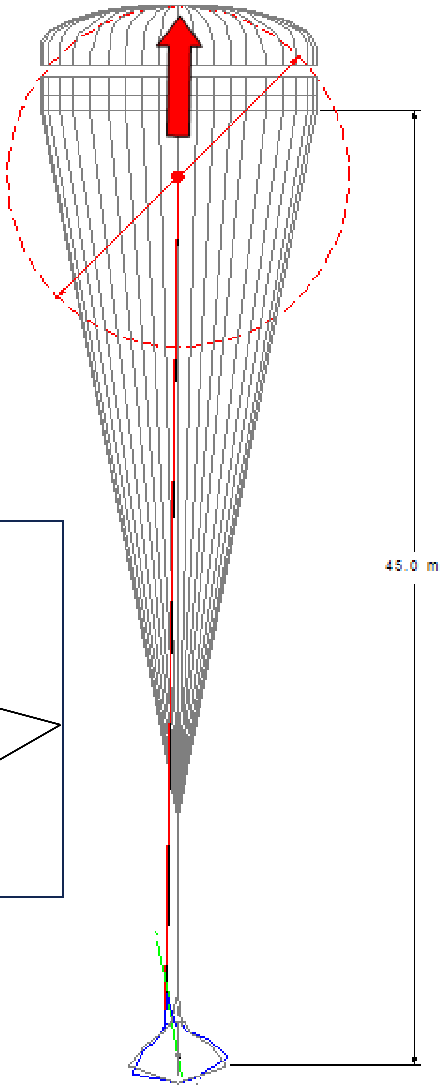


Entry, Parachute Inflation, Powered Descent Loads Analyses

- **Entry Loads**
  - Derived from 05-22 POST simulations (via Langley Research Center)
  - 10,000 cases with 1.16 Loads Uncertainty: 15 g's axial with .65 g's lateral X-direction
- **Parachute Inflation Loads**
  - Derived from classical Pflanz semi-empirical method
  - 4 Degree of Freedom entry body: translation along velocity and 3 rotational DOF
  - 15,000 cases with 1.50 uncertainty on bridle angle and 1.1 LUF on peak inflation load
  - Load Cases where angle θ is combined with bridle slacking
    - 65,000 lbs at θ = 0 degree (3 bridles)
    - 65,000 lbs at θ = 7.5 degrees (2 & 3 bridles)
    - 35,000 lbs at θ =12 degrees (2 & 3 bridles)
    - 20,000 lbs at θ = 22.5 degrees (1 & 2 bridles)



- **Powered Descent Loads**
  - Acceleration loading based on static thrust (mass/thrust)
  - Load Case: 1.4 g's vertical with .15 g's lateral and 11.1 rad/sec^2

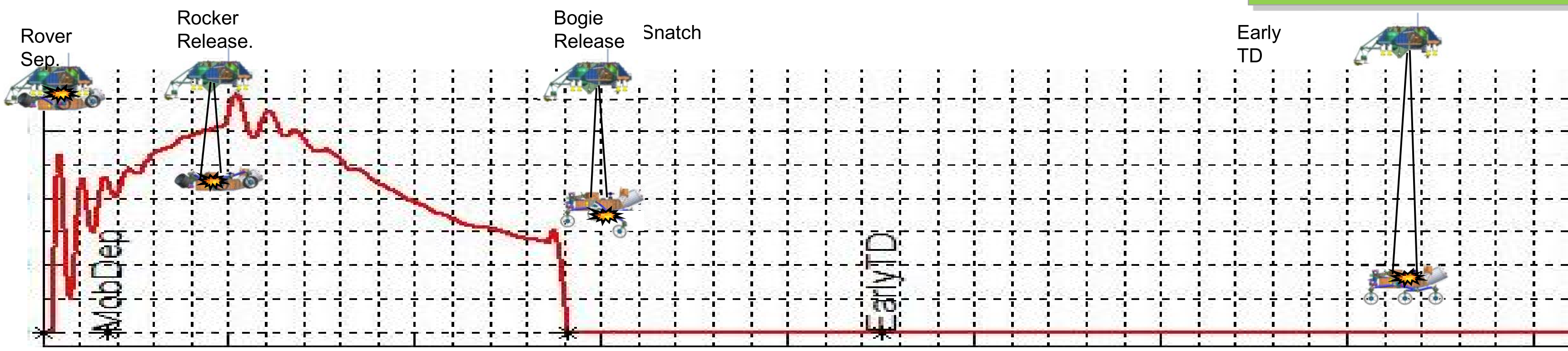


MSL: Loads Environment and Structural Design

Mobility Deploy and Touchdown Landing Loads Analyses

ADAMS Mobility Deploy Sims

ADAMS Touchdown Sims

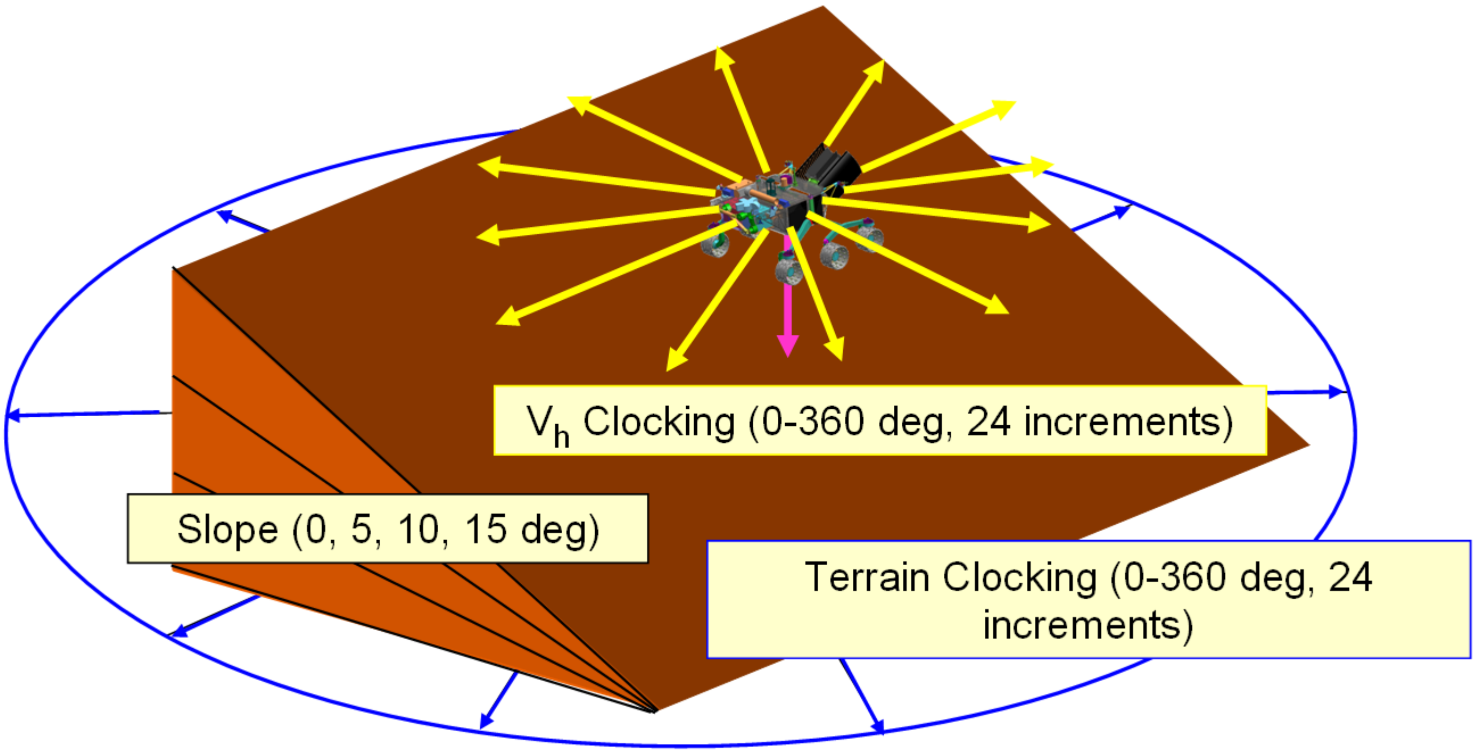


- **Objectives: estimate loads and accelerations for strength margins assessment**
  - Compute the loads in the mobility elements and joints
  - Compute the loads at deployed appendages
  - Compute the accelerations on the rigid body Rover chassis
  - Evaluate ground clearance
- **In-house Three Stage Development: ADAMS Transient Analyses**
  - Preliminary Design: Loads Bowl and Rock Strike
  - Final Design: Monte Carlo Approach
  - Verification Loads: End-to-End Simulations

Touchdown Loads Development (cont.)

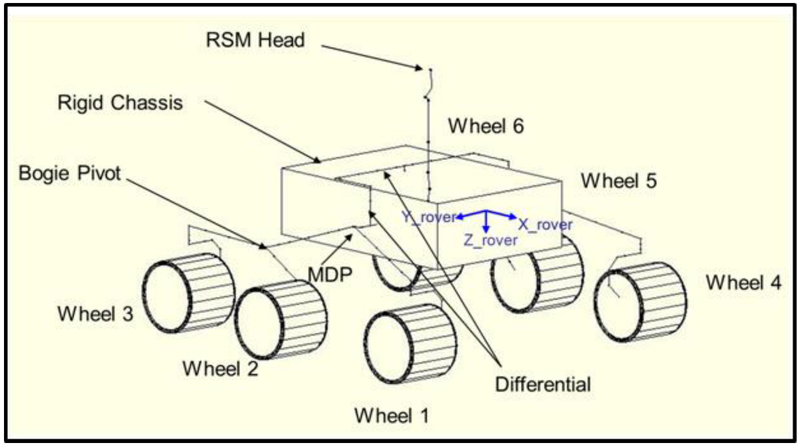
"Loads Bowl" of Touchdown Load Cases

- A "Super Bowl" of 1,752 load cases have been developed to cover all the possible combinations of slope angles (0°,5°,10°,15°), slope orientations (0°-360°, 24 increments), and the clocking of horizontal landing velocity (0.5 m/sec, 0°-360°, 24 increments).

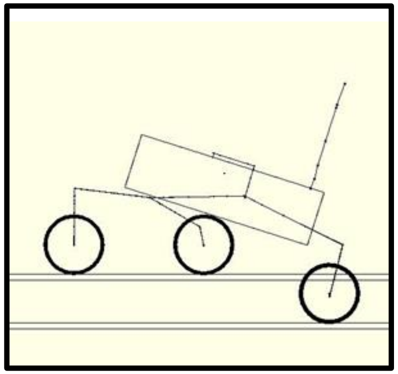


Mobility Traverse Loads Analyses

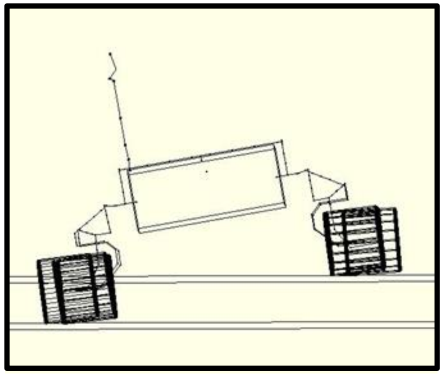
- **Objectives**
  - Compute maximum wheel impact loads and suspension system station cut loads for design
  - Compute loads at deployed appendages
  - Compute chassis accelerations
- **Loads Analysis Methodology**
  - Use ADAMS simulation software transient analysis to generate time domain loads
  - Includes all reasonable egress and surface mobility cases
  - Assume maximum wheel drop of 40 cm in 3/8 Mars gravity field
  - Assume μ_{fr} = 1.0 between wheel and infinitely stiff ground
- **General Configuration**
  - Deployed mobility system with latched rocker arms
  - Deployed RSM
  - Total Rover system mass = 960kg
  - Seven traverse cases: Cases 2 & & were critical



Traverse Rover Configuration

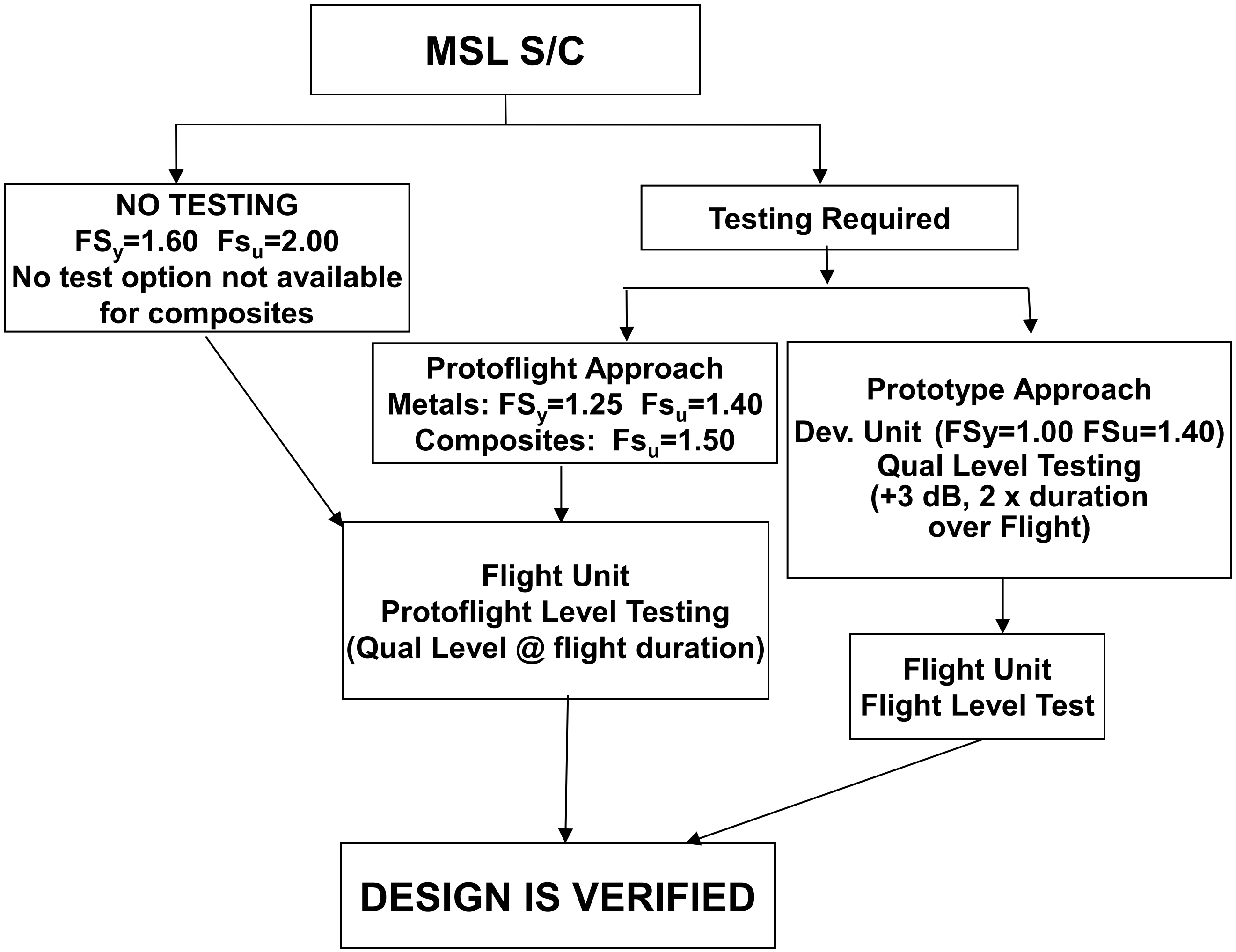


Load Case 2



Load Case 7

Structural Verification Plan - Test



Cruise Stage

- Aluminum Structure
- Flight unit (1)

Descent Stage

- Aluminum structure
- DTM, Flight unit (1)

Aeroshell

- M55J face sheet H/C sandwich panels
- Flight unit (1) – Backshell
- DTM, Flight unit (1) – Heat Shield

Rover

- Aluminum chassis
- Titanium Mobility, RSM mast, RTG struts
- Honeycomb Heat Exchanger and Belly Pan
- DTM, Flight unit (1)

Structural Verification Plan – FOS and Loads

- All Structure must demonstrate Positive Margins of Safety against Yield and Failure

$$\text{M.S.} = \frac{\text{Allowable Load or Stress}}{\text{Limit Load or Stress} \times \text{F.S.}} - 1 \geq 0$$

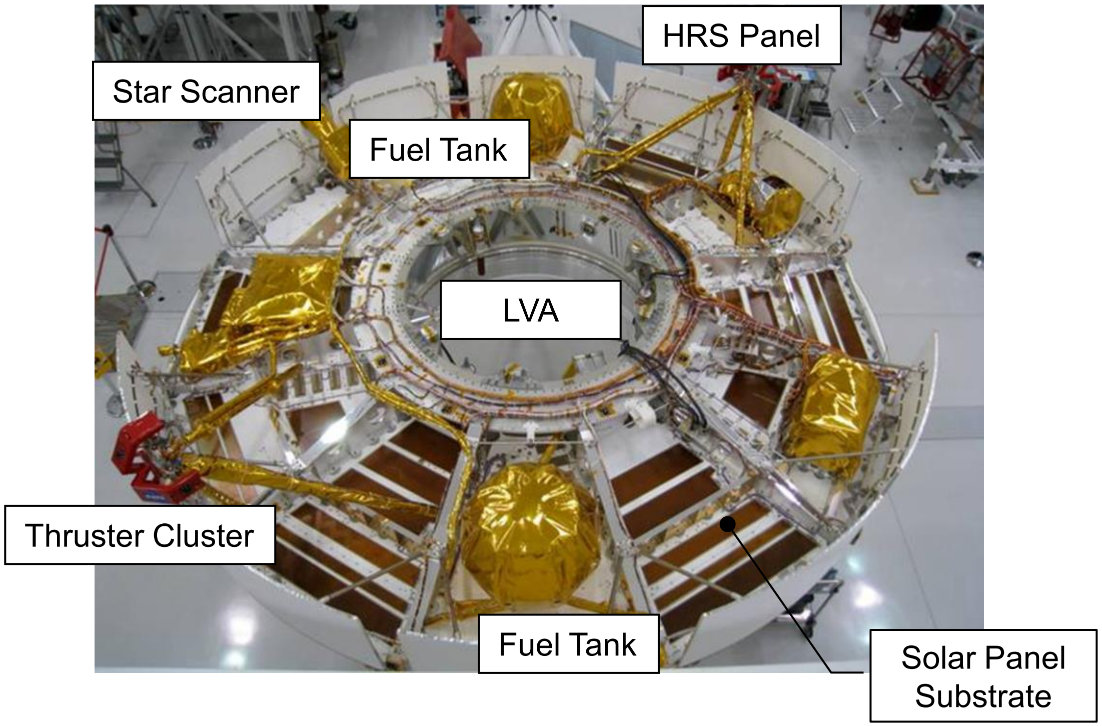
Factor of Safety:

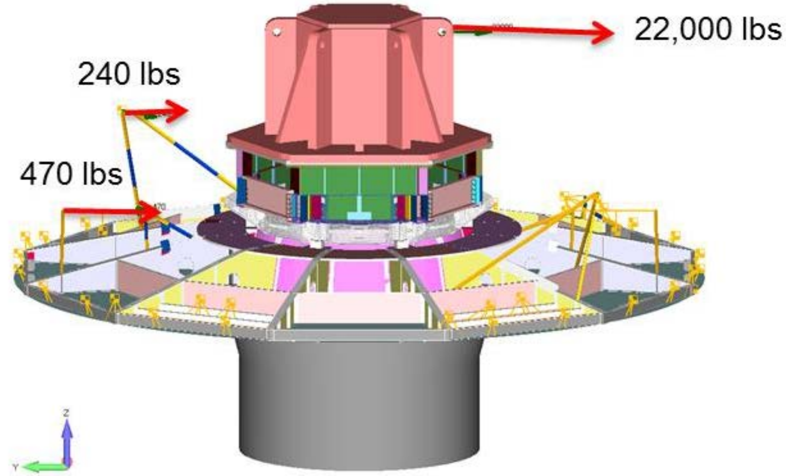
	Qual by Test FLT	Qual by Test FLT	Not Tested
	Metallic	Composite	
$F.S._{ult}$	1.40	1.50	2.00
$F.S._{yield}$	1.25		1.60

Additional Fitting Factor = 1.15 where applicable

- Limit Loads must envelope worst case environment
  - Quasi-static accelerations
  - Low (<40 Hz) and Mid-frequency (40-80 Hz) launch vehicle transients
  - Structurally significant vibro-acoustic excitations
  - Entry, descent, landing and maneuvering loads

Cruise Stage Configuration and Tests





Cruise Stage weight = 560 kg total

21.5 m Parachute

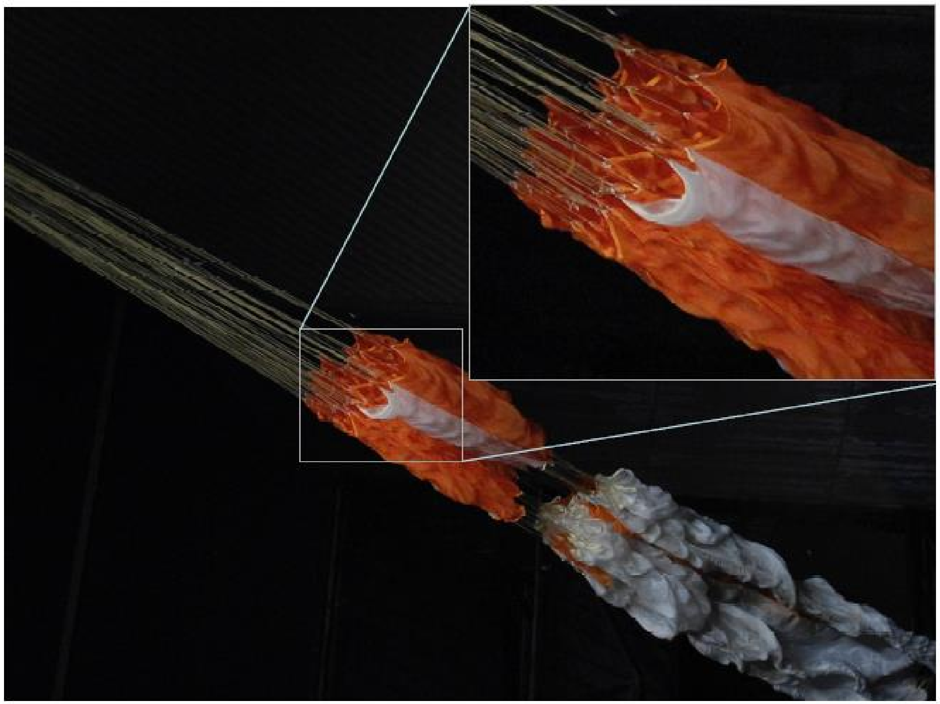


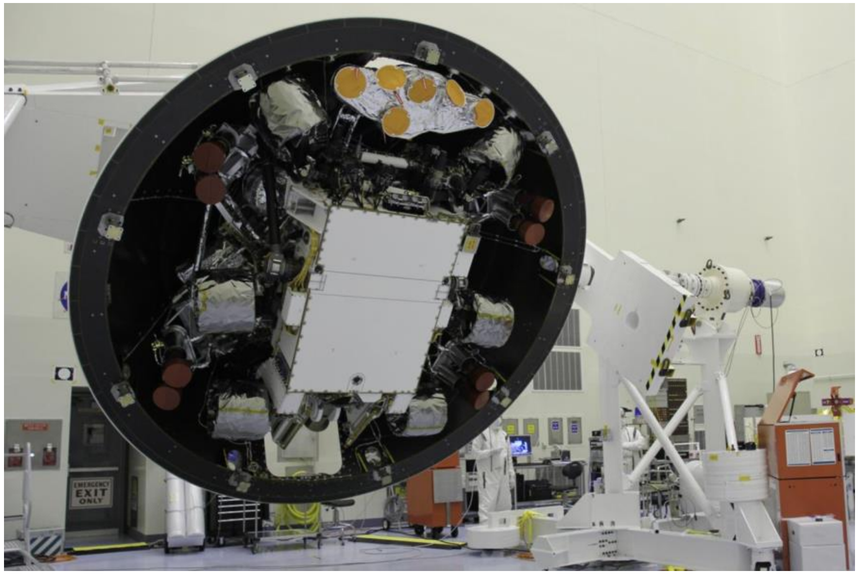
Figure 4. Initial stage of the MD8 inversion evident as the air scoop shape or sail shape in the white gore.

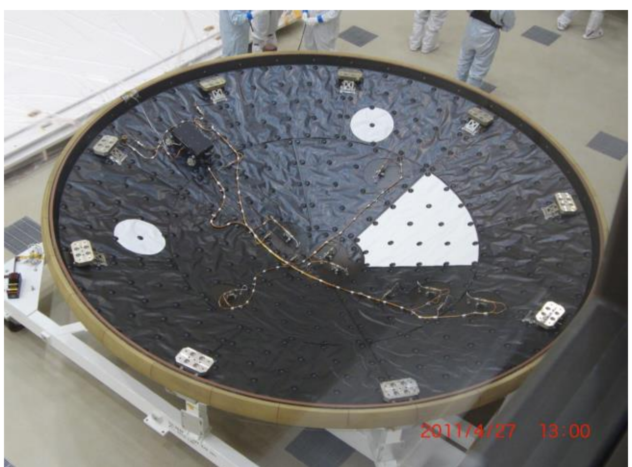
Figure 13. MSL 21.5 m DGB augmented with anti-inversion netting fully deployed at NFAC.

- **Leading Edge Cross-over** (testing in wind tunnel recorded with high definition cameras)
  - Leads to catastrophic failure of parachute
  - Anti-inversion used to prevent Cross-over inversion

Ref: AIAA 209-2956

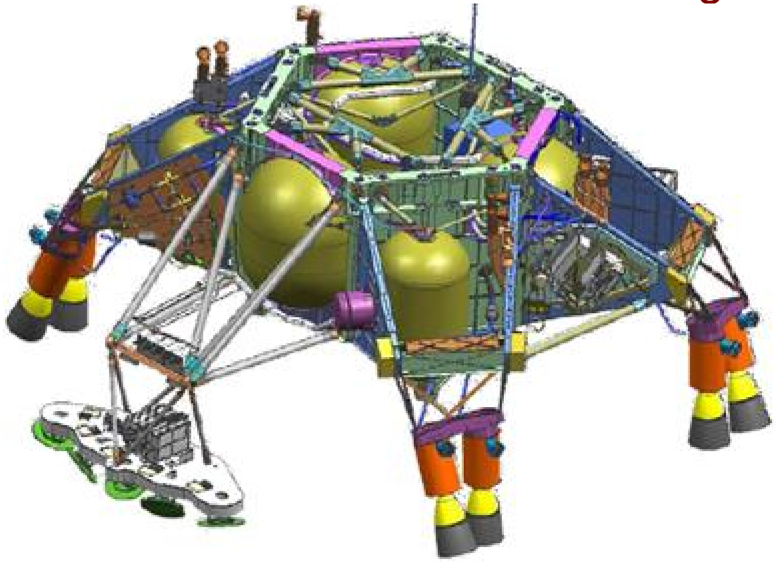
4.5 m Aeroshell

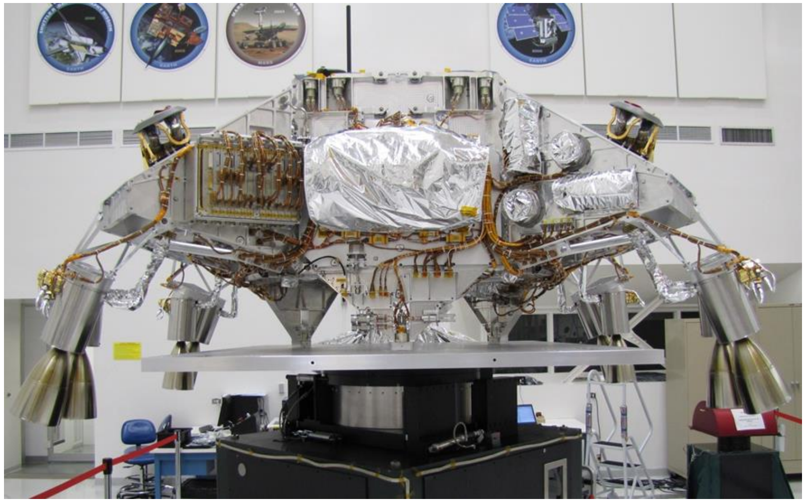




- **Static Test Levels**
  - Heat Shield Entry Deceleration (15 g's): 131,700 lbs total pressure (compression in Back Shell)

Descent Stage Configuration

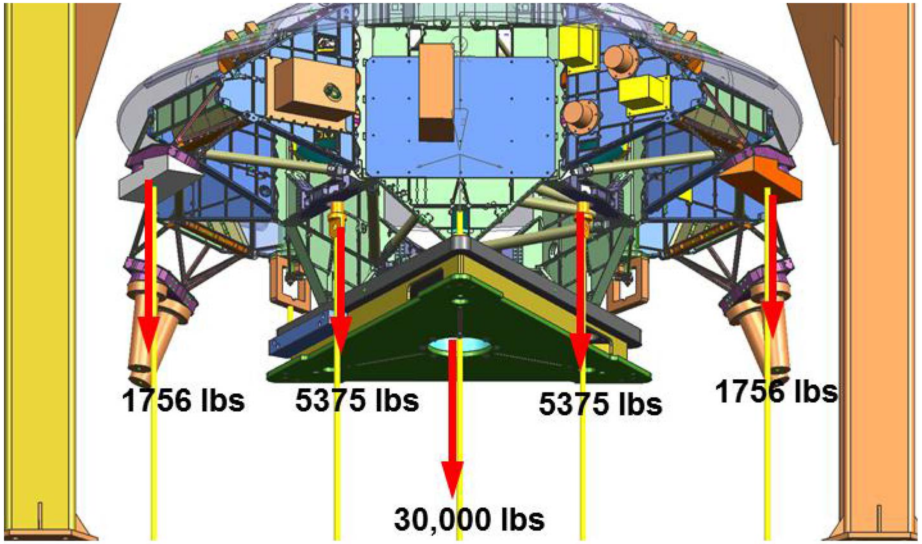




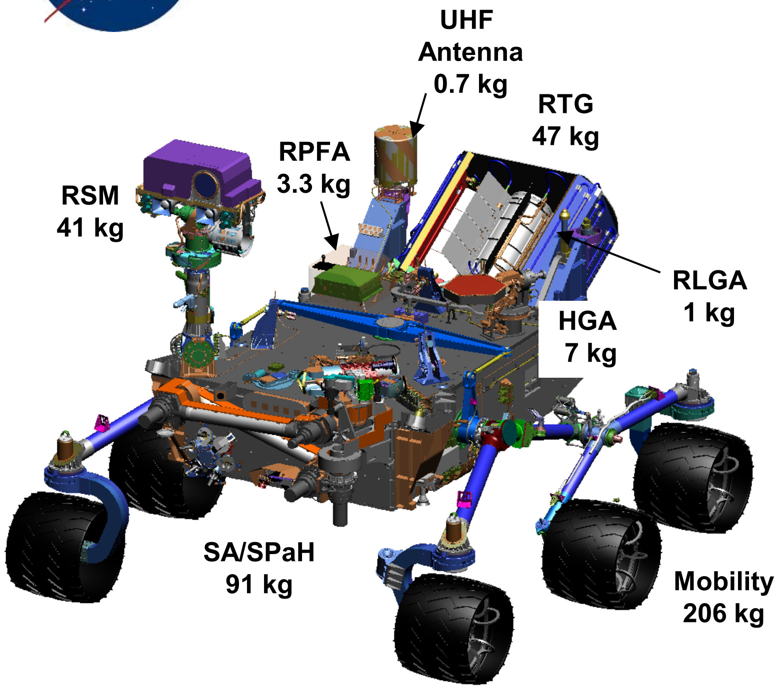
- Primary Structure
  - Aluminum panels, beams, and tube trusses.
- Propulsion & Thermal Support Structure for:
  - 3 fuel tanks (23"x29")
  - 2 pressurant tanks (16"x29")
  - 8 Mars Lander Engines (MLE)
  - 8 entry RCS thrusters
  - Pressurant & Fuel Control Assemblies (PCA & FCA)
  - Two and Six Pyro Valve Plates (2PV, 6PV)
  - Fuel lines, helium lines, pyro valves, filters, etc
  - HRS lines to X-Band plate and Avionics Plate
- CDH & Power Support Structure for:
  - Descent Power Assembly (DPA)
  - Descent Power and Analog Module (DPAM)
  - Descent Motor Control Assembly (DMCA)
  - Pyro Thermal batteries (PYTB) (2)
  - Power Thermal batteries (PWTB) (2)
  - Base Load Resistor Assembly (BLRA)
- GNC Support Structure for:
  - Descent Inertial Measurement Unit (DIMU)
  - Terminal Descent Sensor (TDS)
- Telecom Support Structure for:
  - 1 UHF Di-Pole Relay Antenna & coax routing
  - X-Band HRS Plates (with TWTA, SDST, Diplexer, etc)
  - 1 DTE Low Gain Antenna and dual waveguide routing
- Pyro-Mechanical Devices
  - Mega Cutters (4)
  - 5/8" Separation Nuts (15)
- Major Interfaces
  - Rover/DS: 'kinematic' 3 point bi-pod interface
  - DS/BIP cup/cones (6)
  - DS/Cruise Stage interfaces (6)
  - DS/BS rails/rollers (3)
  - Bridle and Umbilical Device (BUD)
  - RCS Window Seal hw (4)

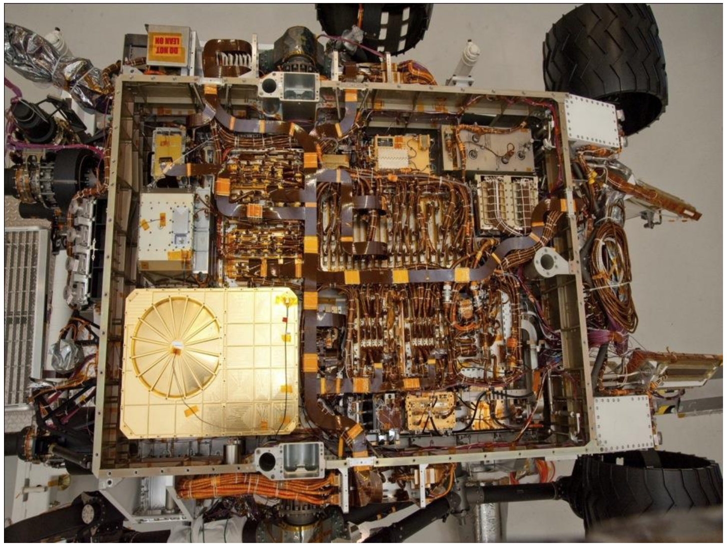
Descent Stage Structural Configuration and Test

- **Structural configuration and concept**
  - Hexagonal structural core with alternating shear panels and open frames to accommodate propulsion tanks
    - Shear panel terminate with pseudo bipods to interface with Rover top deck (three point attachment)
    - Corners of Hex Core interface to the BIP/Aeroshell with six separation bolts for Entry case
    - Pairs of separation bolts located on the top of each shear panel attach through the BIP to the Cruise Stage for the launch interface with total of six bolts



Rover Equipment

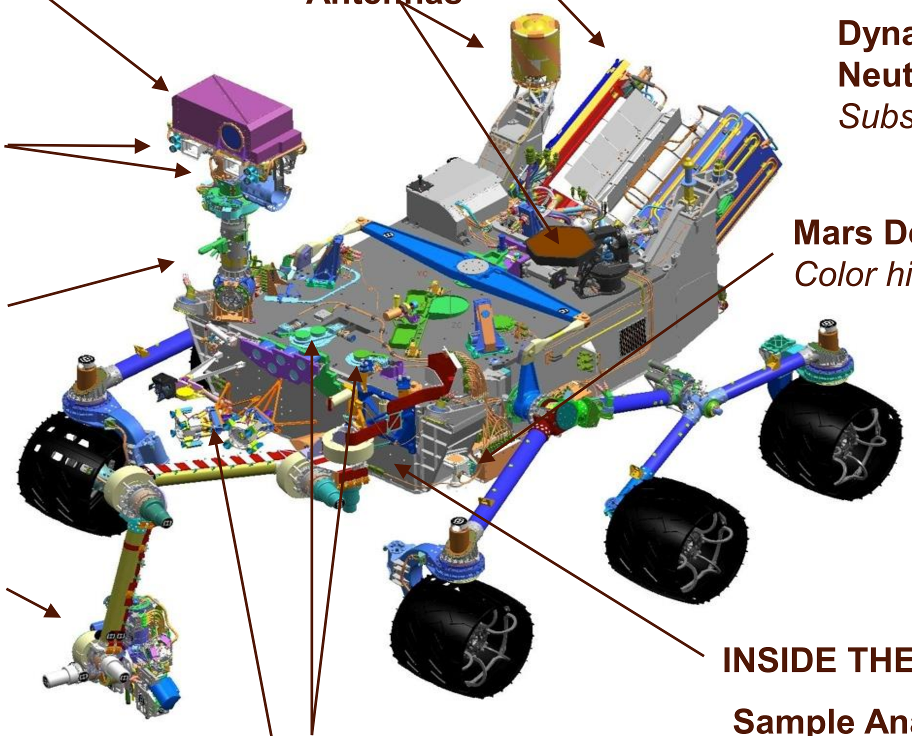




- **Primary Structure**
  - Aluminum panels, aluminum honeycomb panels, titanium RTG adapter
- **Thermal Support Structure for:**
  - RTG Heat Exchangers
  - HRS Tubing
  - Thermal Enclosures for warm components
- **Avionics & Power Support Structure for:**
  - Rover Pyro FET Assembly (RPFA)
- **GNC Support Structure for:**
  - 4 Hazard avoidance cameras

- **Telecom Support Structure for:**
  - 1 UHF quad helix antenna and coax routing
  - 1 X-Band RLGA Low Gain Antenna and waveguide routing
  - 1 High Gain Antenna (HGA)
- **Major Interfaces**
  - Remote Sensing Mast (RSM)
  - Sample Acquisition/Sample Processing and Handling (SA/SPaH) System
  - Rover/DS Separation interface: 'kinematic' 3 point bi-pod interface, cup/cones (3)
  - BUD exit guides and soft goods
  - RTG
  - Mobility system – differential
  - Mobility system – corner mobility supports

MSL: Loads Environment and Structural Design



Chemistry and Camera (ChemCam)
Chemical composition
High-res imaging

Mast Cameras (Mastcam): *Color imaging and video, Medium and high resolution*

Rover Environmental Monitoring Station (REMS)
Meteorology and UV

ON THE TURRET:

Mars Hand Lens Imager (MAHLI)
Color microscopic imaging

Alpha Particle X-Ray Spectrometer (APXS)
Chemical composition

Power Source

Antennas

Sample Inlets

Spare Drill Bits

Sampling System: *Arm, powdering drill, brush, scoop, and sieves*

NOT VISIBLE:

Radiation Assessment Detector (RAD)
Natural high-energy radiation

Dynamic Albedo of Neutrons (DAN)
Subsurface hydrogen

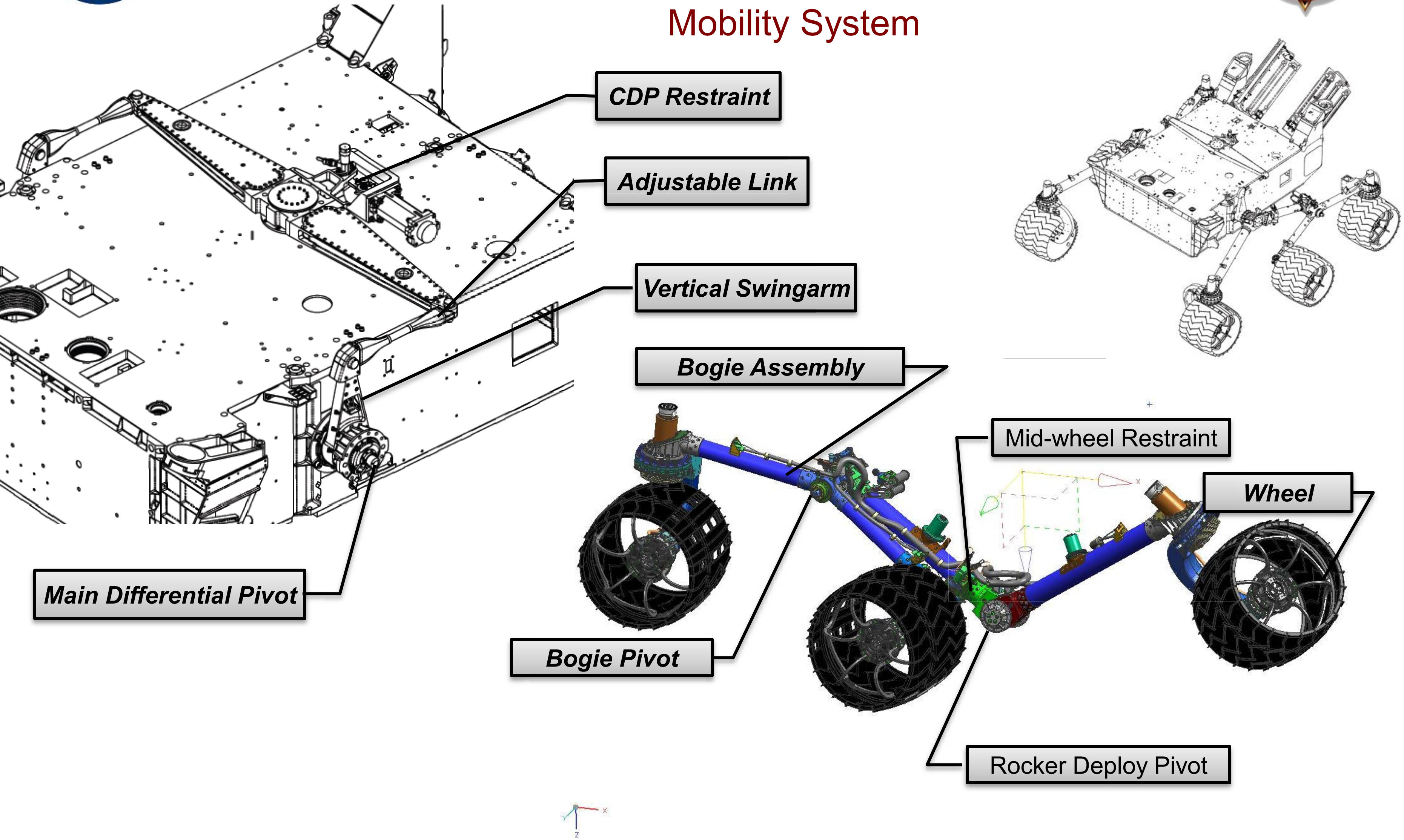
Mars Descent Imager (MARDI)
Color high-definition descent movie

INSIDE THE ROVER BODY:

Sample Analysis at Mars (SAM)
Composition and isotopes of rock, soil, and air samples; organics

Chemistry and Mineralogy (CheMin): *Mineralogy of rock and soil samples*

Mobility System



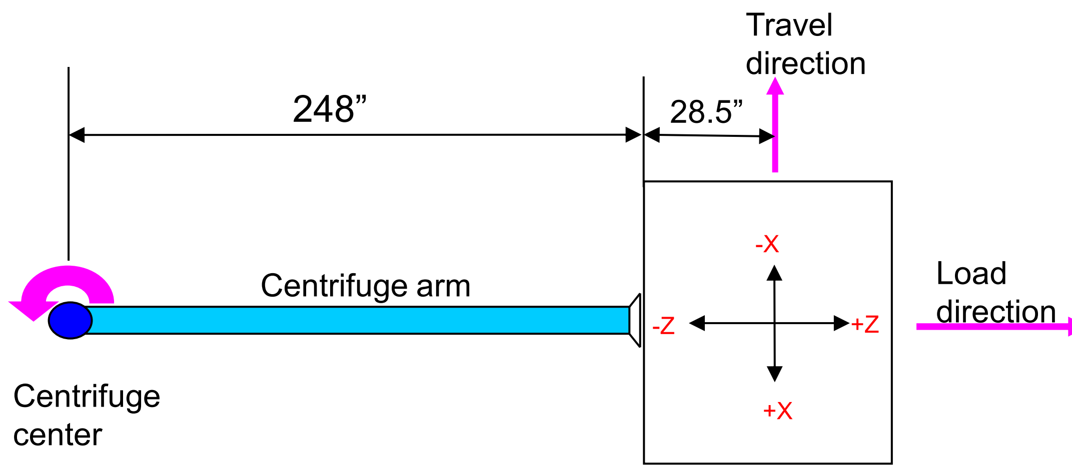
Rover Traversing

Wheel Development Program

- **Prototype program**
  - Verify design to 1.4 x Flight Limit Loads by testing to relevant load case
  - No detrimental yielding at 1.0 x FLL
- **Radial Stiffness**
  - Wheels are first defense against minimizing touchdown and traverse loads →nominal stiffness 2174 lbs/in used in final ADAMS model (design goal was 2500 lbs/in)
- **Strength Analyses**
  - $FS_{yield} = 1.00$ $FS_{ult} = 1.40$
  - The low stiffness of the wheel assembly (aluminum tire and titanium flexures) undergoes considerable deflection →perform material and geometric nonlinear analyses
  - Margins were computed in the flexures against strain to rupture capacity (rupture strain is .08 in/in, yield strain is .011 in/in)
- **Verification**
  - June 2007 Development Unit Test, July 2008 Flight Design Test
  - Titanium flexures test verified in static testing
  - Wheel cleats and surfaces thoroughly tested for odometry, wheel impact, functionality – localized denting & rupture, ovalization permitted

Development Unit Test

- **Sine Pulse Test Objective:** To verify the MSL Rover structure primary interface for launch lateral loads (~4 g's lateral)

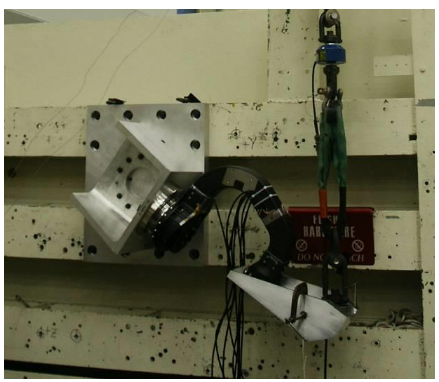


- **Centrifuge Test Objective:** Demonstrate the structural integrity of the MSL DTM rover chassis and mobility restraint for the 15 g's Mars entry case

MSL: Loads Environment and Structural Design

Suspension System Tests

Objective: Verify maximum element loads at Forward Rocker, Aft Rocker, Aft Bogie, and Fwd Bogie



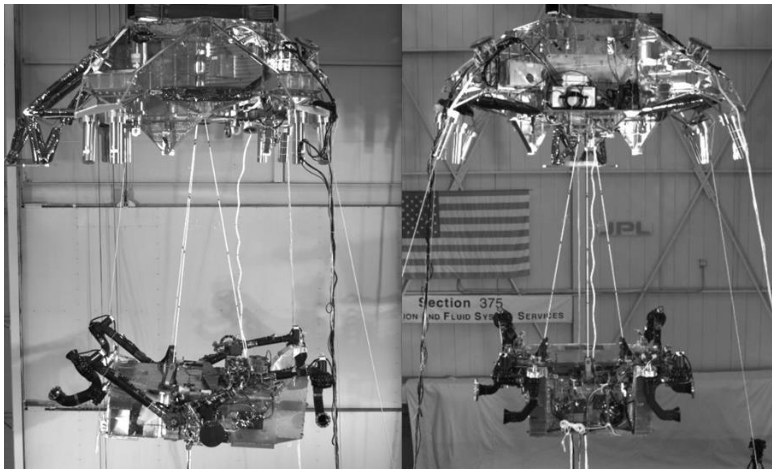
Fwd CLSA Test

Aft CLSA Test

Corner Landing Strut Tests

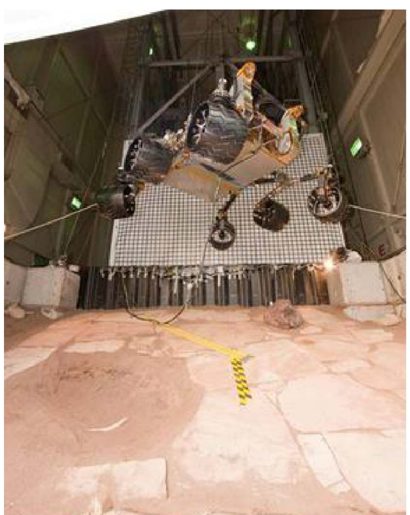
Objective: Verify maximum element loads at Fwd and Aft Corner Landing Strut Assemblies (CLSA)

ADAMS Model Validation - Rover Touchdown and Deployment Tests



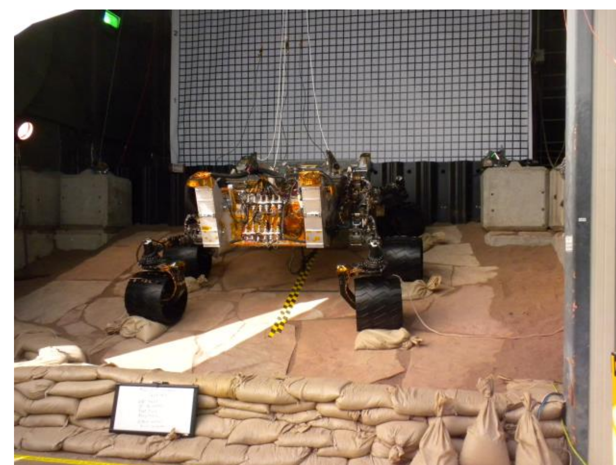
Mobility Deploy Validation – Skycrane Full Motion Drop Test (Jan 2011)

Test: PDV supported by SAF facility crane, pyro release of Rover, BUD deploy with simultaneous Mobility Deploy
Objectives: Validate loads models using loads and rover kinematic data



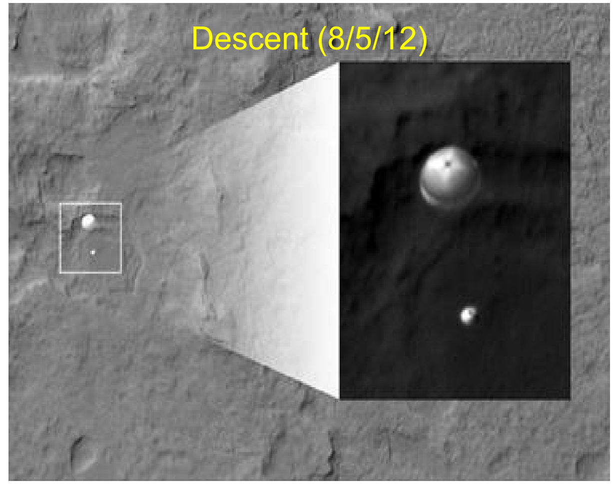
Touchdown Loads Validation (Feb 2011)

Test: DTM Rover and nylon bridles lowered from over-head winch, TD on sloped surface tiled with flagstones, rocks, and ditches
Objectives: Validate loads, look for TD modeling escapes

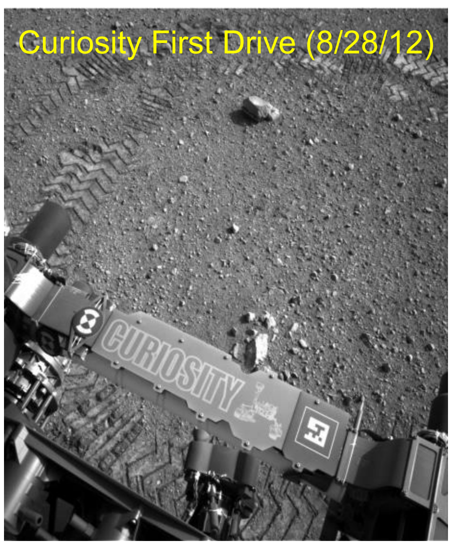


Mars Science Laboratory Success

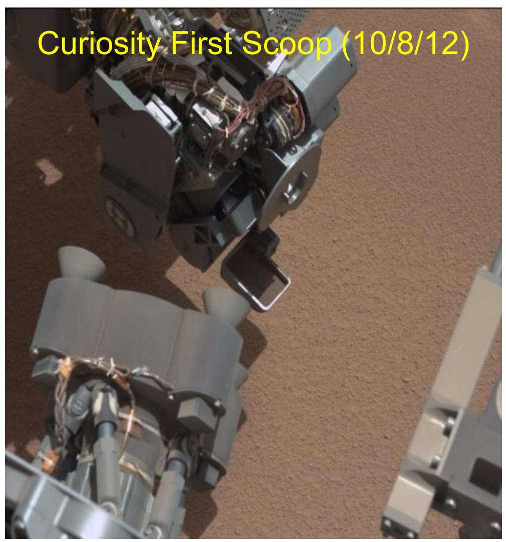

Launch (11/26/11)


Descent (8/5/12)

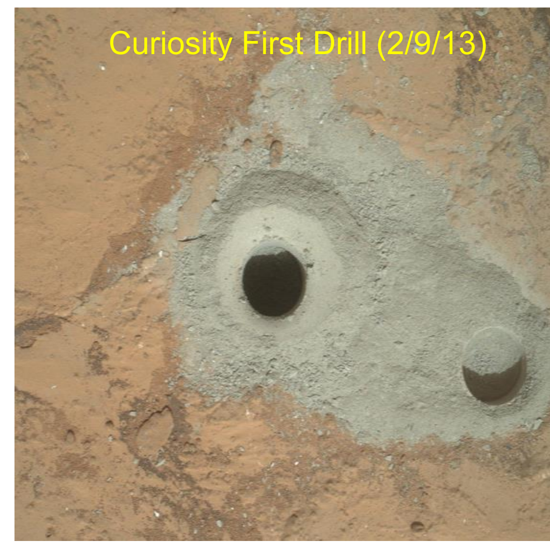

Curiosity First Image (8/5/12)



Curiosity First Drive (8/28/12)


Curiosity First Scoop (10/8/12)


Curiosity Self-Portrait (11/1/12)


Curiosity First Drill (2/9/13)

http://mars.jpl.nasa.gov/msl/

Jet Propulsion Laboratory

California Institute of Technology under contract with NASA

MSL: Loads Environment and Structural Design

- **What does it take to get to Mars?**

  Innovation, Boldness, Openness, Excellence, Integrity

  →Believe in yourself !!