Entry, Descent, and Landing

Subject: Mars Science Laboratory Case Study

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AIAA Aerodynamic Decelerator Systems Technical Committee

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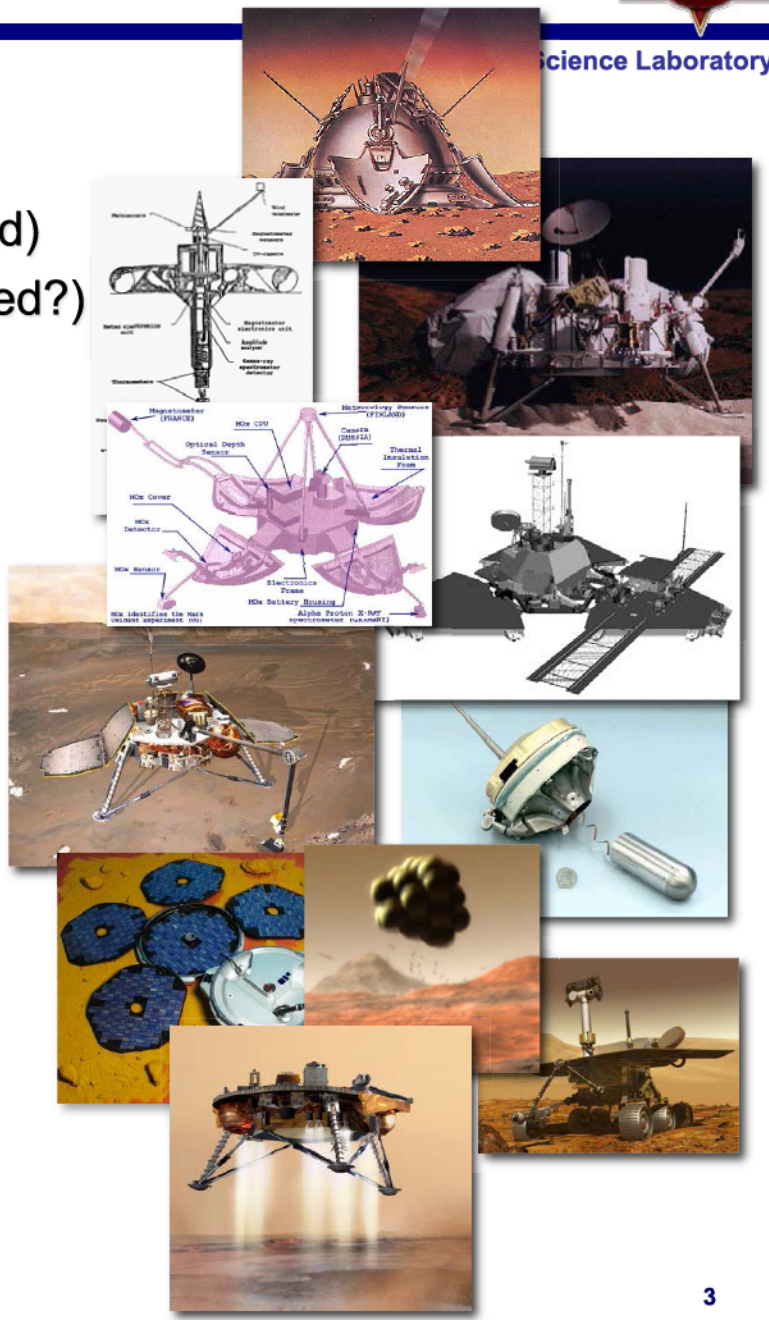
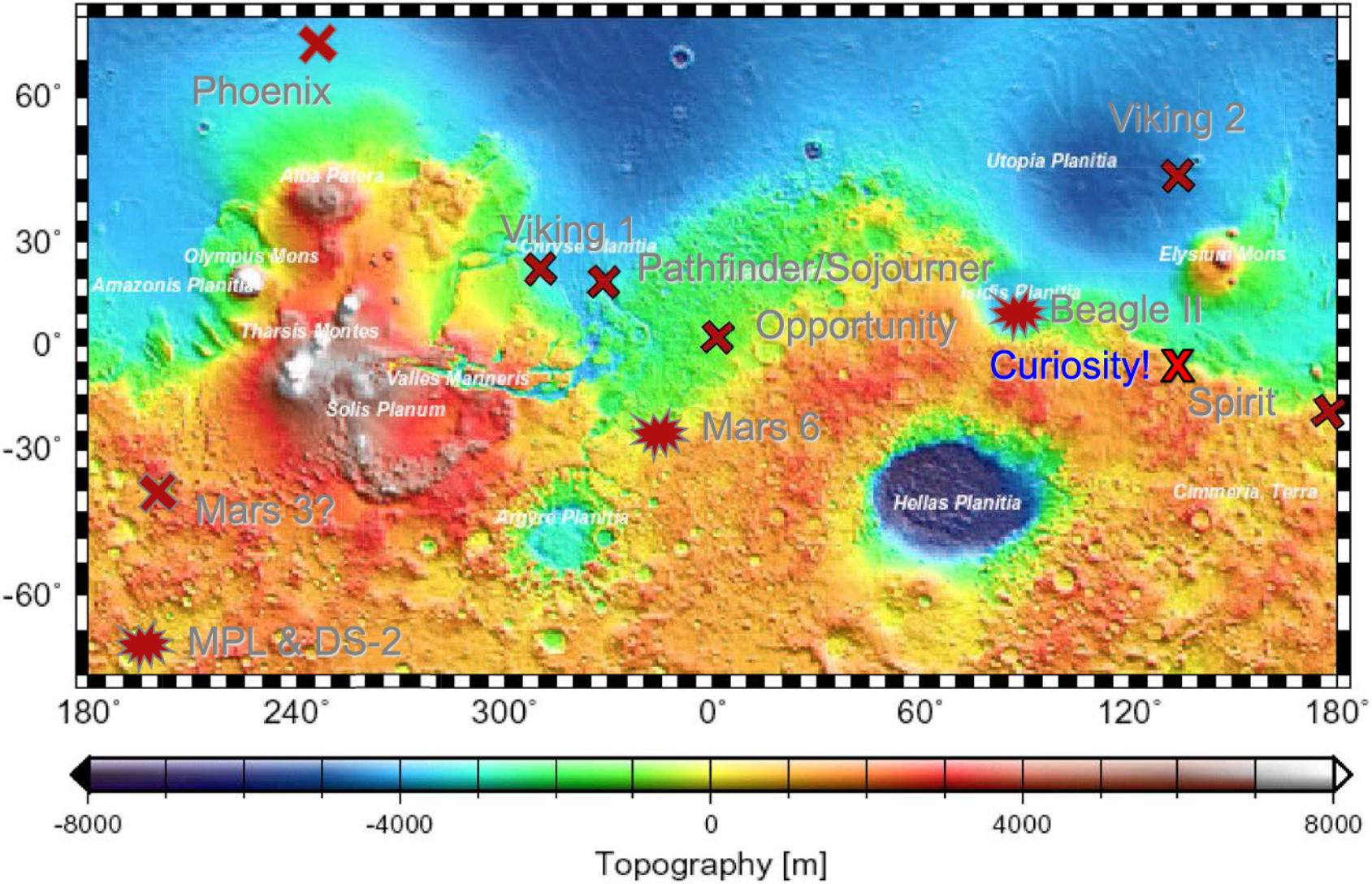
Only ~50% of Mars landers launched have worked…

USSR: Mars 2	1971 (crashed)
USSR: Mars 3	1971 (landed, radio died)
USSR: Mars 6	1973 (aero data, crashed?)
USSR: Mars 7	1974 (missed Mars)
US: Viking 1	1975
US: Viking 2	1975
USSR: Mars ’96 (2)	1996 (failed launch)
US: Mars Pathfinder	1996
US: Mars Polar Lander	1998 (crashed?)
US: DS-2 Microprobes (2)	1998 (crashed?)
Europe: Beagle II	2003 (crashed?)
US: MER Spirit	2003
US: MER Opportunity	2003
US: Phoenix	2007
US: MSL Curiosity	2011

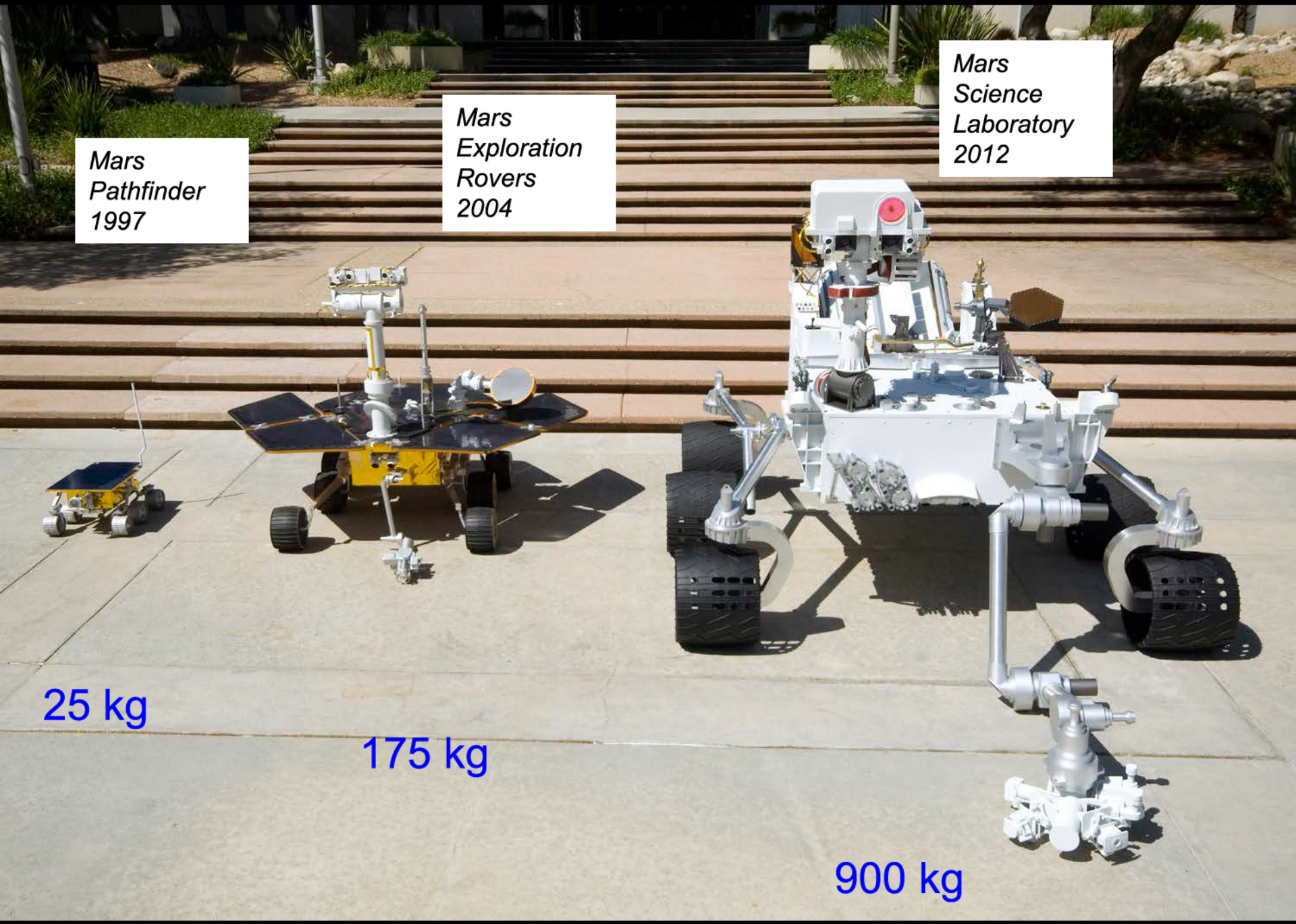


X's Mark the Lucky Ones…

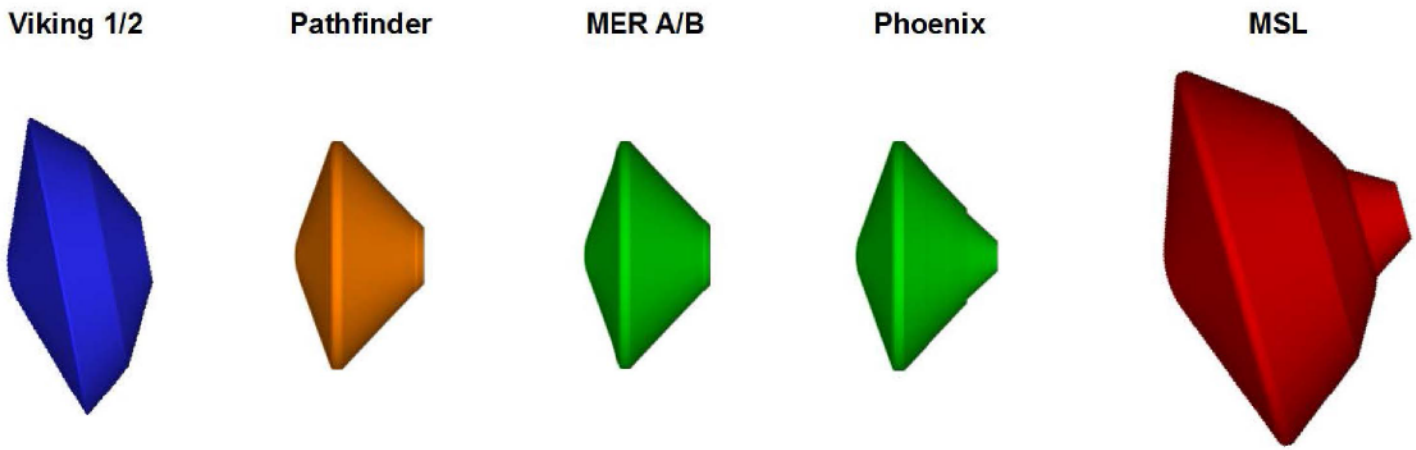


The Challenges of EDL for Mars Science Laboratory

- Deliver more rover to more places
  - Land the biggest rover ever
  - Land precisely in tight spots
- Contend with the Martian environment
  - Atmosphere: enough to be really annoying, but not enough to be as helpful as on Earth
  - Terrain: complex environment of rocks, craters, dust, and more
- Prove we can do it
  - ~~Test as you fly, fly as you test~~
  - Dealing with the inability to execute high fidelity end to end tests


Mars
Pathfinder
1997
Mars
Exploration
Rovers
2004
Mars
Science
Laboratory
2012
25 kg
175 kg
900 kg

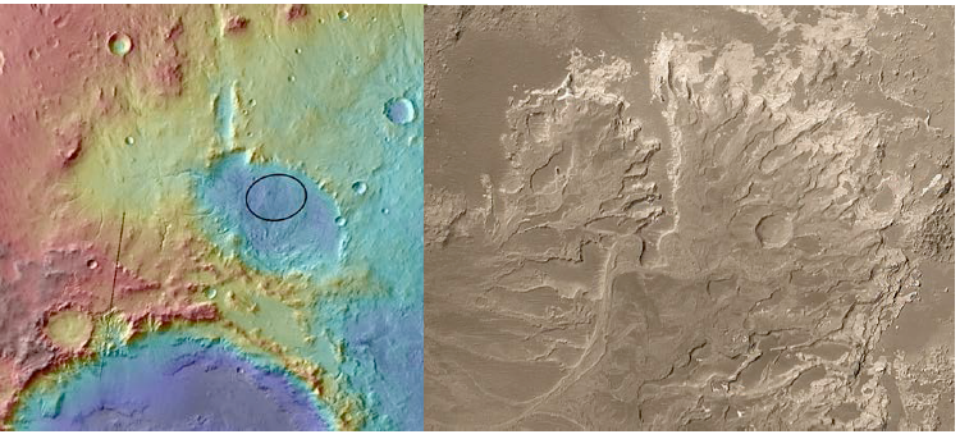
Entry Vehicle Comparison



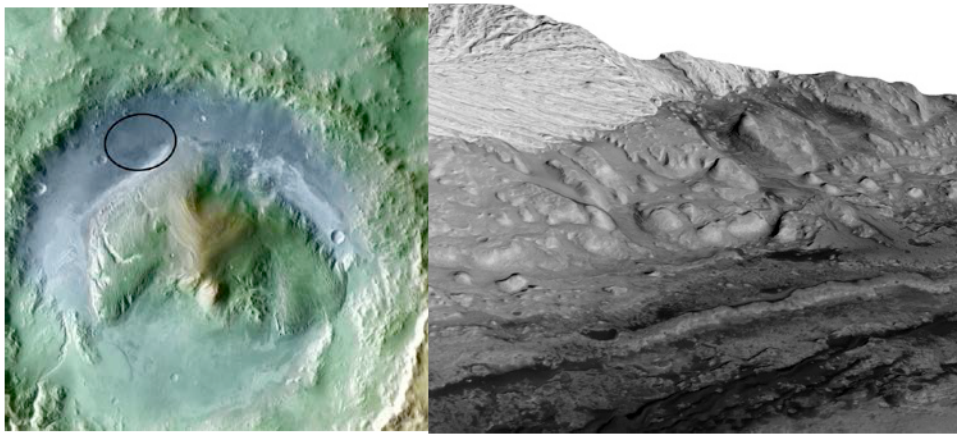
	Viking	MPF	MER	Phoenix	MSL
Diameter (m)	3.505	2.65	2.65	2.65	**4.5**
Entry Mass (kg)	930	585	840	602	**3152**
Hypersonic Angle of Attack (°)	-11.2	0	0	0	-16
Ballistic Coefficient (kg/m^2)	63.7	62.3	89.8	65	136

Significantly higher mass, ballistic coefficient and angle of attack

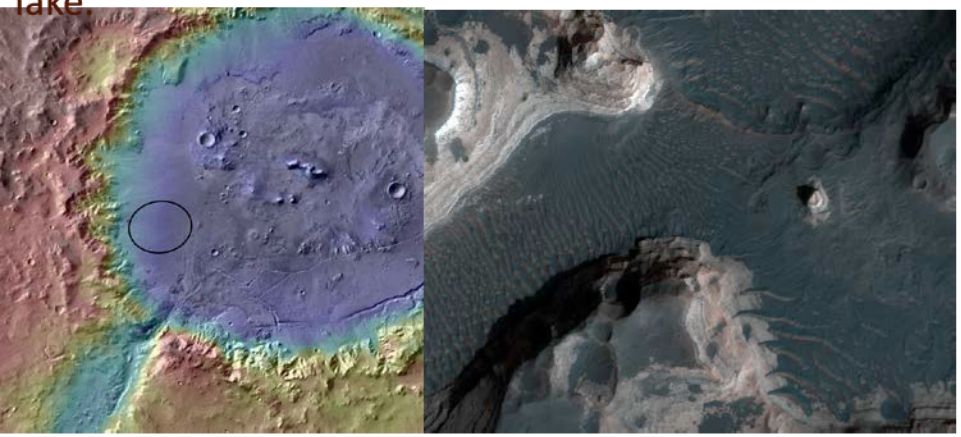
Final Candidate Landing Sites



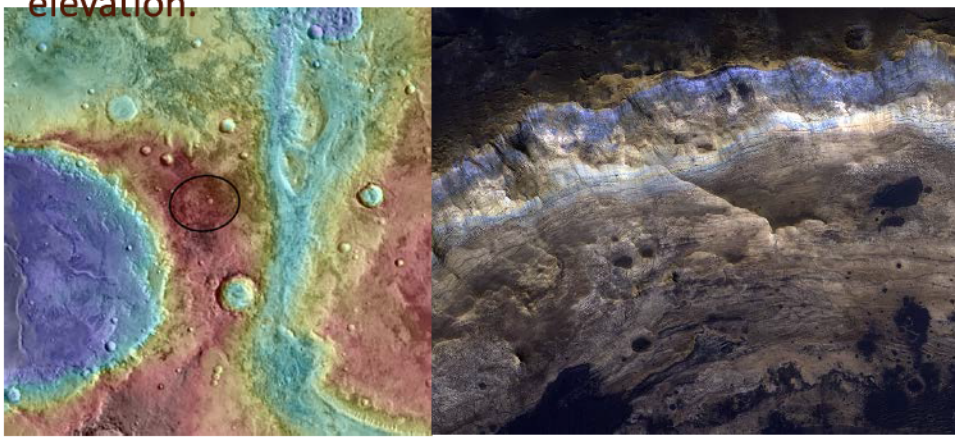
Eberswalde Crater (24° S, 327° E, -1.5 km) contains a clay-bearing delta formed when an ancient river deposited sediment, possibly into a lake.



Gale Crater (4.5° S, 137° E, -4.5 km) contains a 5-km sequence of layers that vary from clay-rich materials near the bottom to sulfates at higher elevation.

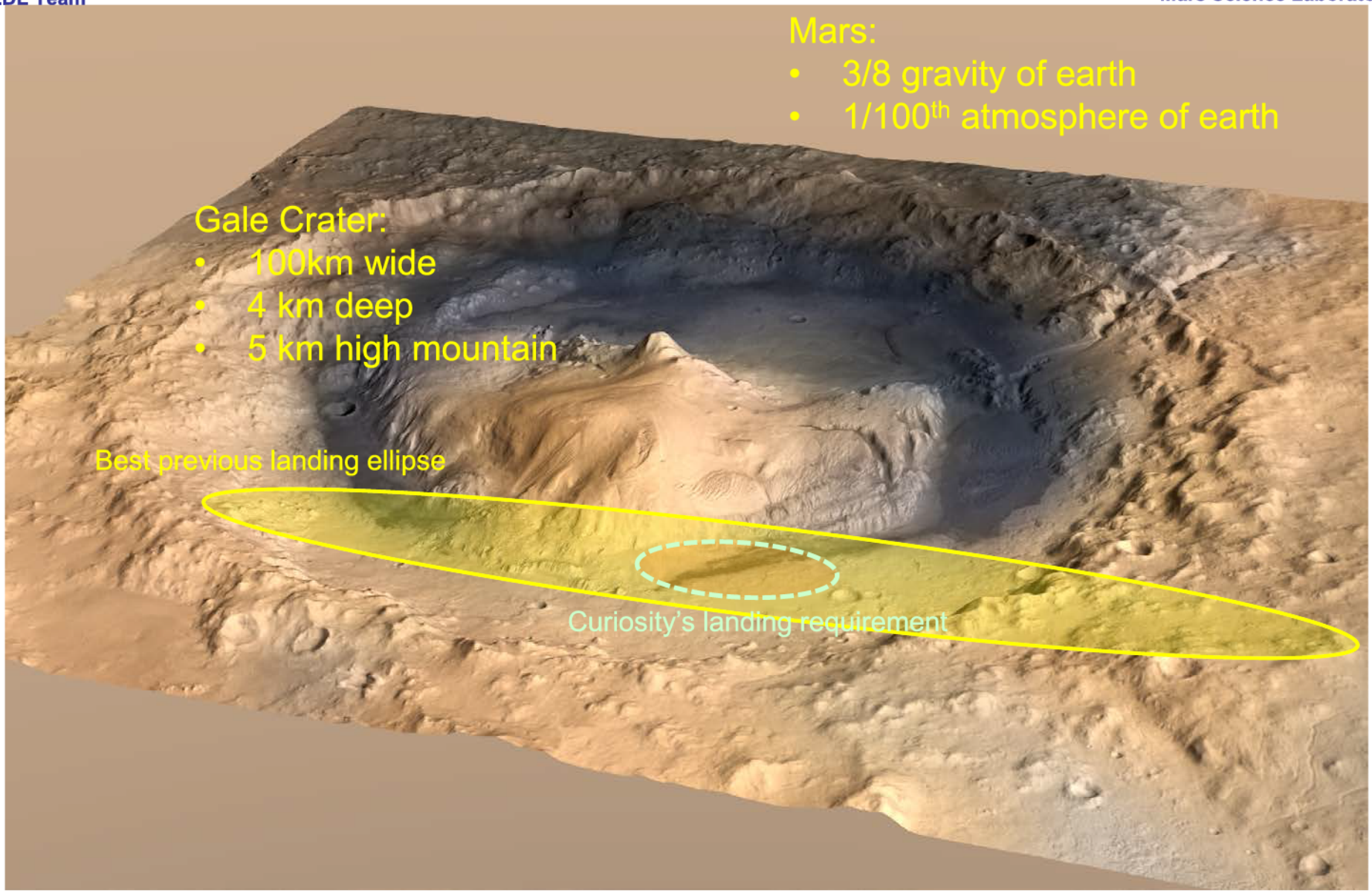


Holden Crater (26° S, 325° E, -1.9 km) has alluvial fans, flood deposits, possible lake beds, and clay-rich sediment.



Mawrth Vallis (24° N, 341° E, -2.2 km) exposes layers within Mars' surface with differing mineralogy, including at least two kinds of clays.

Gale Crater


Mars:
• 3/8 gravity of earth
• 1/100th atmosphere of earth
Gale Crater:
• 100km wide
• 4 km deep
• 5 km high mountain
Best previous landing ellipse
Curiosity's landing requirement

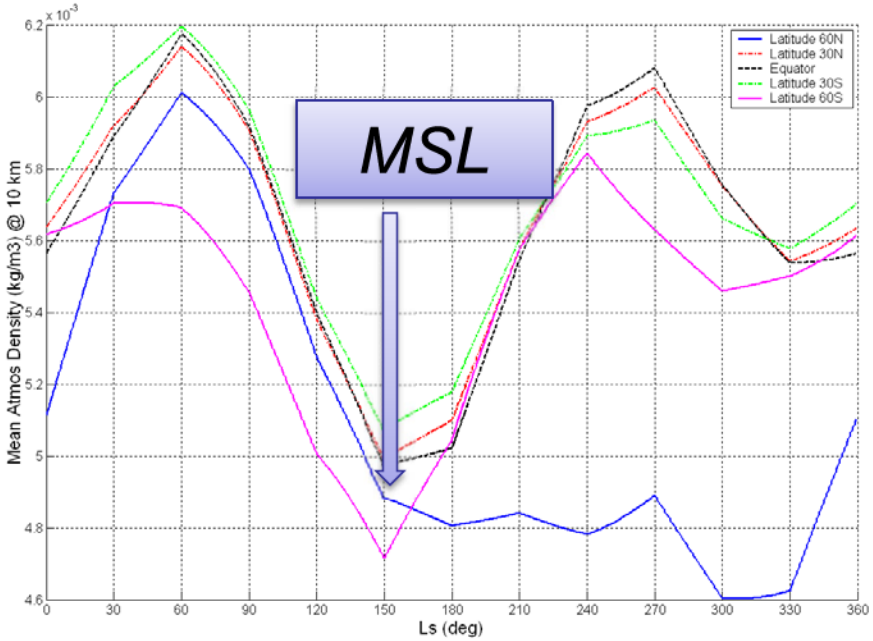
The Mars Atmosphere: Good or Bad?

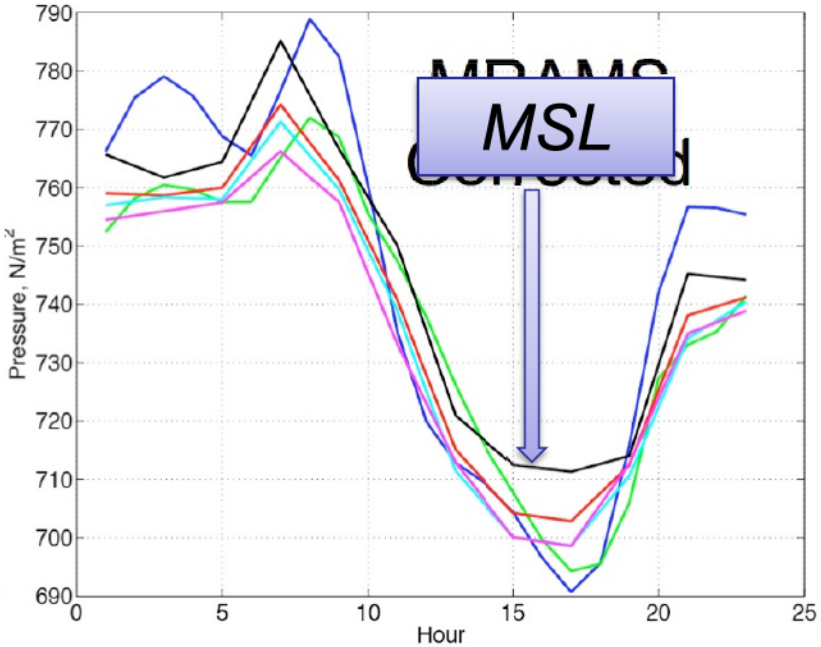
- Too much atmosphere to land like we do on the Moon
  - Thick enough to create substantial aero-heating
  - Can't be ignored
- Too little atmosphere to land like we do at Earth
  - Too thin to provide a lot of drag
    - Density = 1% of Earth's
    - Mars atmosphere surface density roughly equivalent to Earth atmosphere density at ~130,000 ft!
  - But enough that it makes sense to attempt to use it
- Significant seasonal and landing location variability
- Poorly characterized to date

Large Atmospheric Seasonal and Daily Variations

- Lack of significant water and eccentricity of Mars' orbit leads to large seasonal and diurnal variations
  - ~20% seasonal density differences (larger at high altitudes)
  - ~10% diurnal surface pressure differences

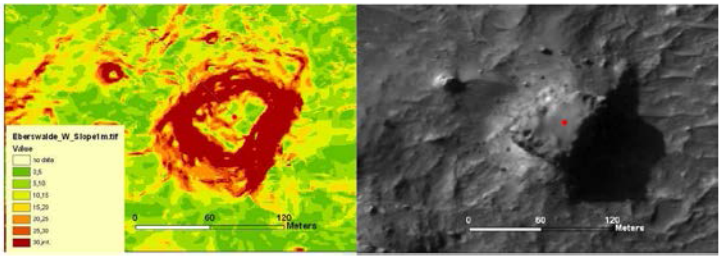
- *Curiosity landed at the worst time of year and worst time of day*
  - At the minimum of the seasonal pressure cycle
  - Near the minimum of diurnal pressure cycle
  - At the worst time of day for dust events

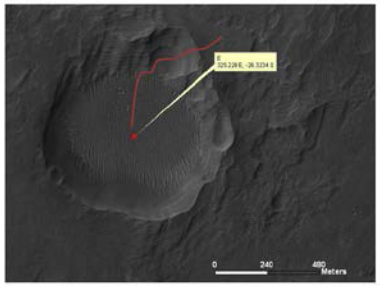


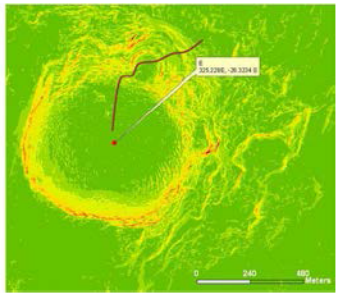


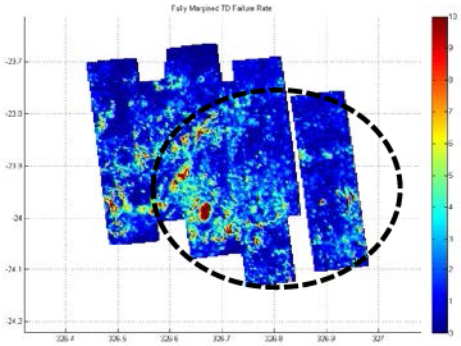
Terrain Hazards

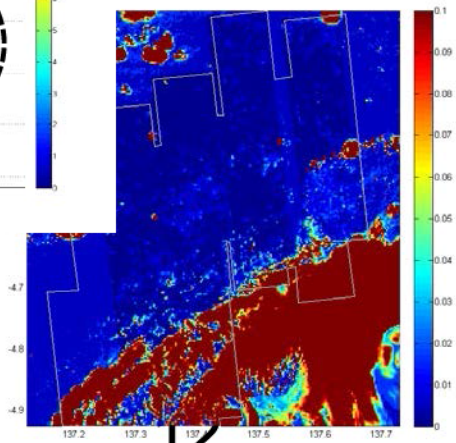
- Numerous potential landing hazards
  - Mountains, canyons, craters, scarps, dunes, rocks, local slopes, etc.
  - Many of these features exist at Gale and at other MSL candidate landing sites
- Need to understand landing system terrain capability and sensitivities
- Requires detailed characterization of candidate landing sites











Verification and Validation

- ~~TEST AS YOU FLY, FLY AS YOU TEST~~

- EDL for Mars generally cannot be tested as it is flown

- No high fidelity end-to-end system test was possible for MSL

- MSL EDL V&V is accomplished by:
  - Constrained design (design for V&V)
    - Avoid systems that are difficult to analyze/are empirical by nature
  - Component testing that demonstrates the function of EDL components and validates models of component function
  - System simulation that utilizes component models and validates end-to-end EDL function

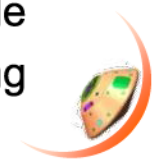
Meeting the Challenges

Key Challenges:

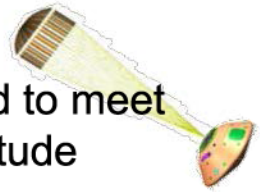
- Land more rover in more places
- Contend with the Martian environment
  - Atmosphere: thin, poorly characterized, and variable
  - Terrain: hazardous at the sites where scientists want to land
- Prove we can do it
  - No end to end test (among other testing limitations)

Key Design Responses:

- Guided Entry
  - Lifting entry and entry control to deliver mass to desired altitude
  - Entry guidance to meet landing precision requirement

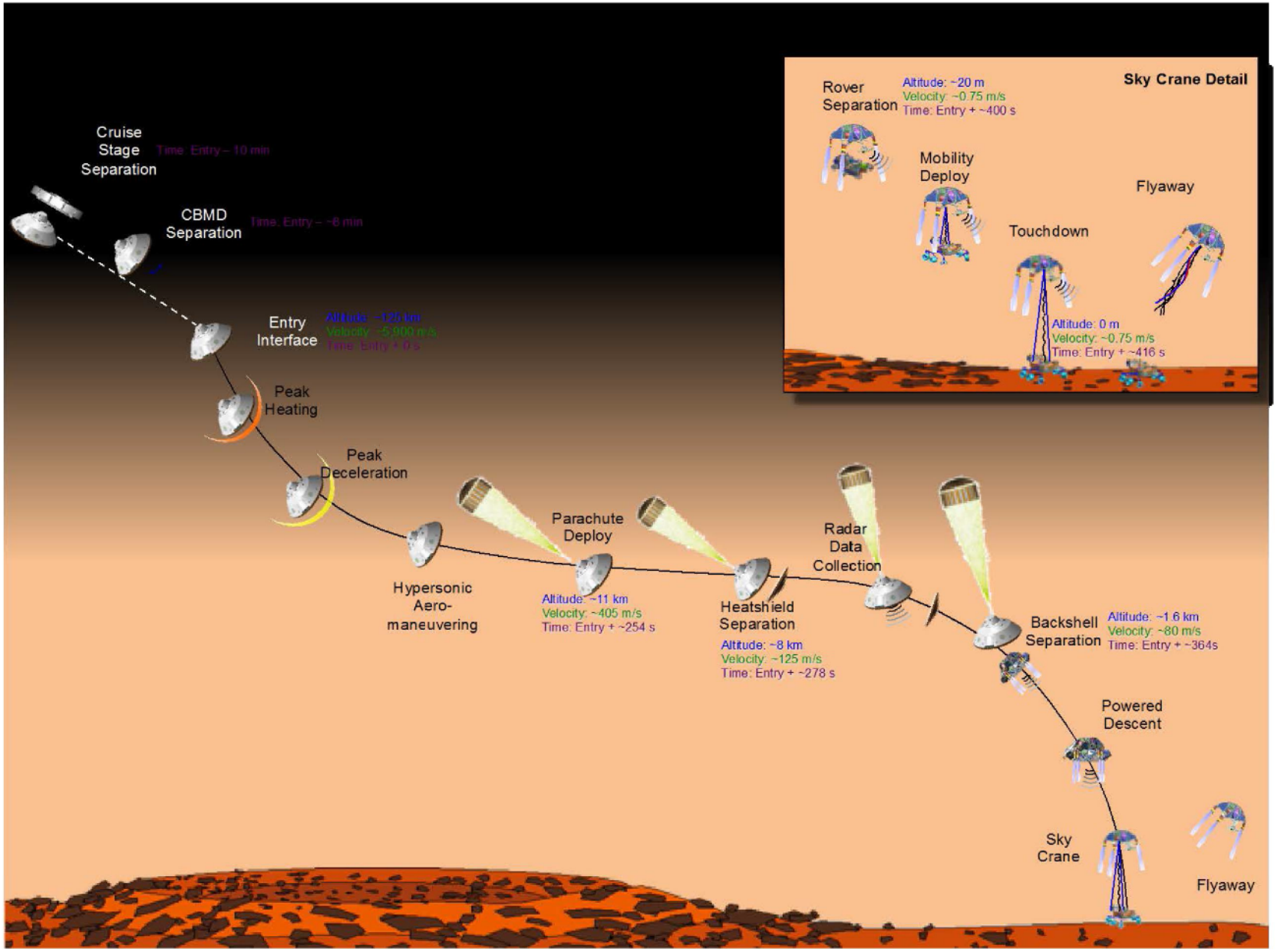


- Parachute
  - Parachute size selected to meet delivered mass and altitude requirements

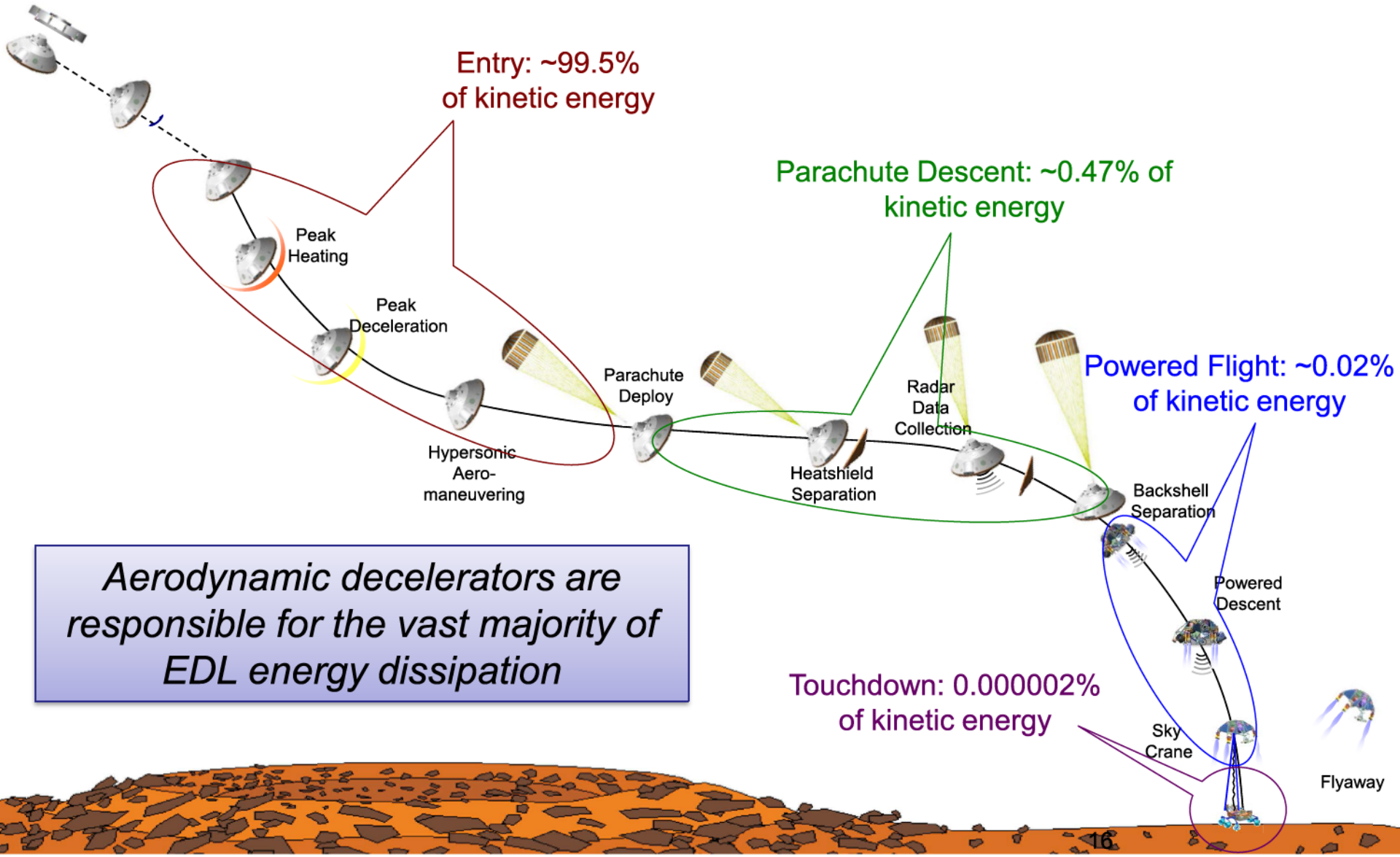


- Throttled Powered Descent/Sky Crane
  - Delivered mass and interfaces eliminates use of airbag landing system
  - Terrain requirements drive powered descent profile and touchdown system architecture

MSL Entry Descent and Landing



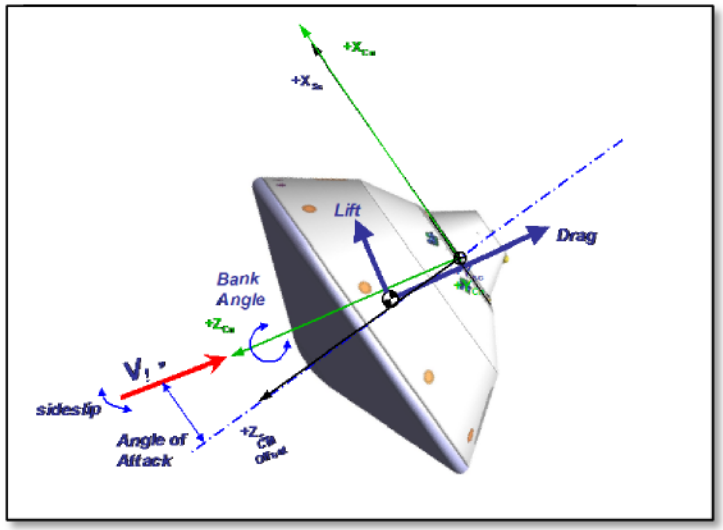
EDL Energy Management

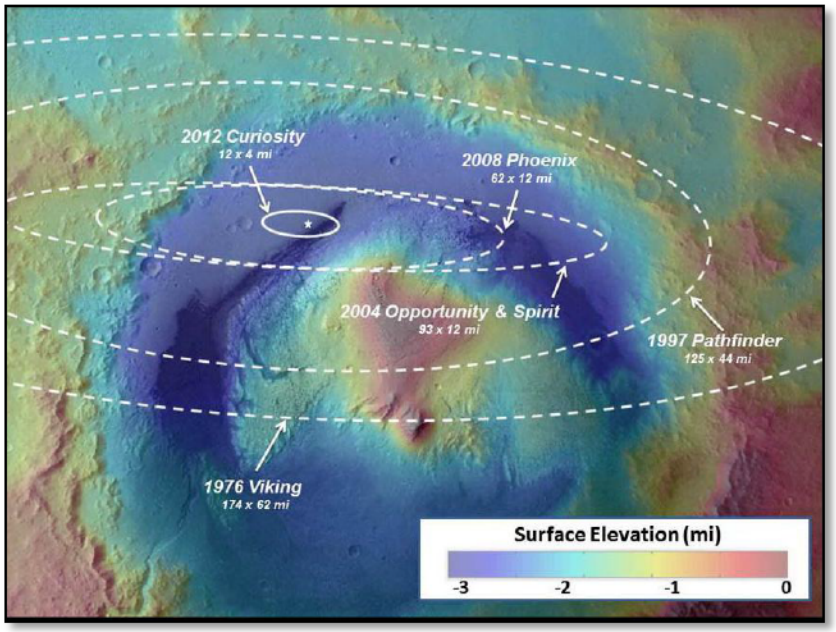


Aerodynamic decelerators are responsible for the vast majority of EDL energy dissipation

Entry

- Unlike previous systems, MSL's entry system isn't just trying to decelerate and survive
- "More rover in more places" enabled by lifting entry guidance
  - For given entry and landed mass, raises landing elevation capabilities by 6 km (no viable sites on Mars without it)
  - Significantly increases landing precision
- Spacecraft can "fly out" atmosphere dispersions
  - Huge error source for previous missions
  - Allows access to safe sites surrounded by hazardous terrain
- Introduced new challenges: characterizing aerodynamics, new heatshield TPS, entry control system

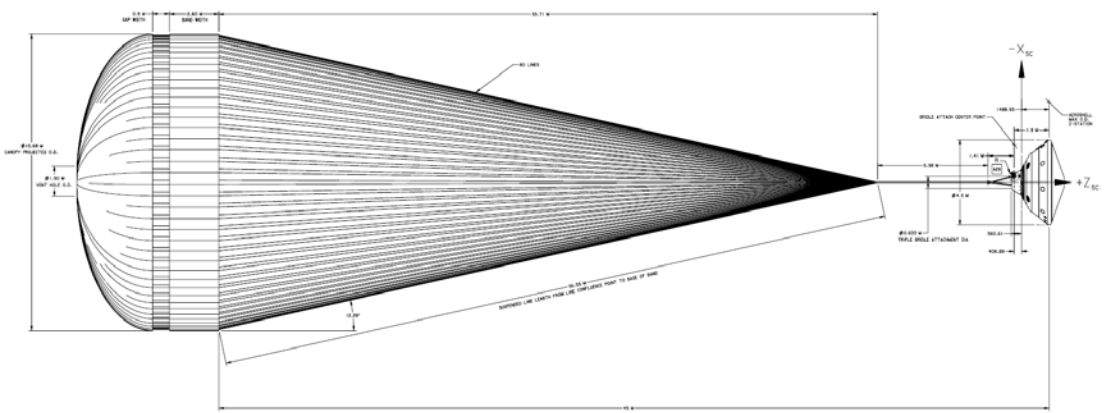


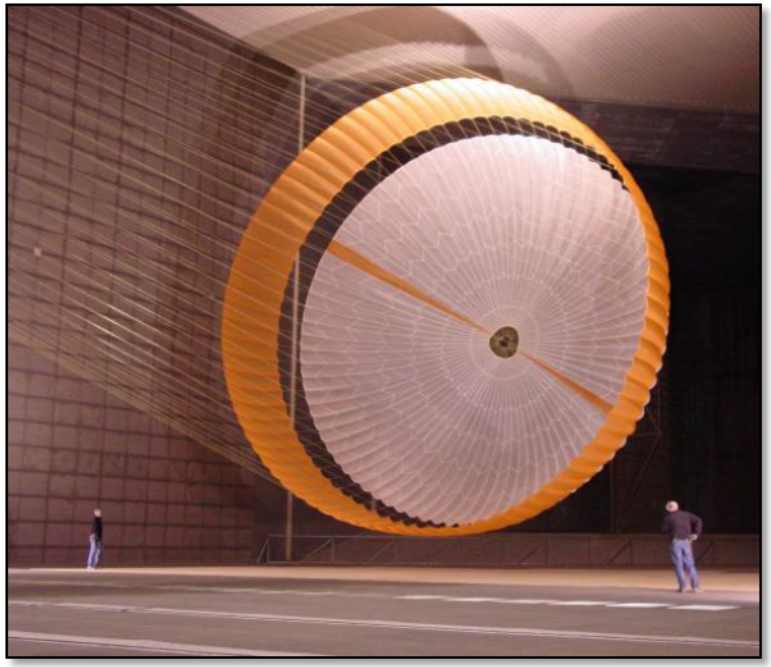


Parachute Descent

- Even with guided entry, still can't land this much mass at high landing site elevations without a large supersonic parachute
  - Capsule terminal velocity is supersonic; prohibitively high propulsive descent
  - Need to get to heatshield separation and powered descent conditions quickly

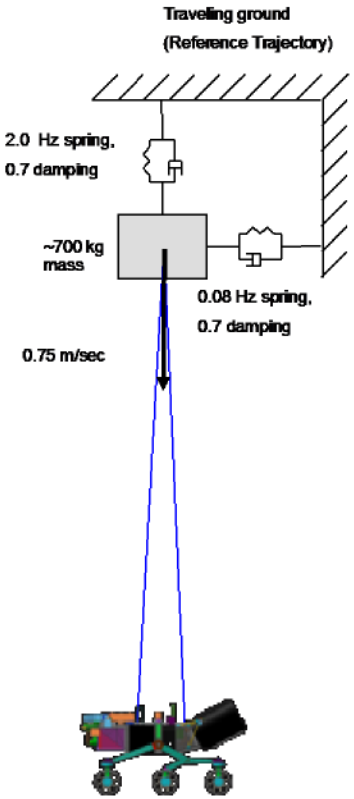
- Smaller parachute would waste altitude performance afforded by guided entry because of insufficient deceleration and might have left insufficient propellant for powered flight

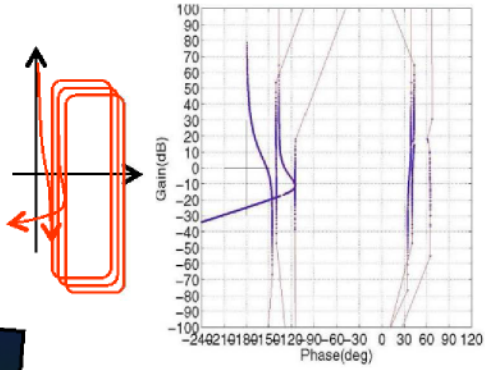




Powered Descent and Sky Crane

- Increased landing mass made MER-style airbags untenable
  - Driven towards a soft landing system
- Large rover and mobility naturally yield significant terrain capability
  - High ground clearance
  - Excellent stability on slopes
  - No egress challenges
- Sky crane intended to be tractable analytically
  - Separate GNC analysis of descent stage from rover touchdown





Simulate As You Fly, Fly as You Simulate

- EDL performance simulations are utilized for system validation because it is usually not possible to conduct meaningful end-to-end systems tests on Earth

- To produce meaningful results, simulation input models must be verified by completion of the following activities:

<u>Element Tests and Analysis</u>
  - Does each EDL element survive its interaction with the environment?
  - Does each element deliver its functional performance as advertised?
  - What forces are generated and how does it fly through the atmosphere?

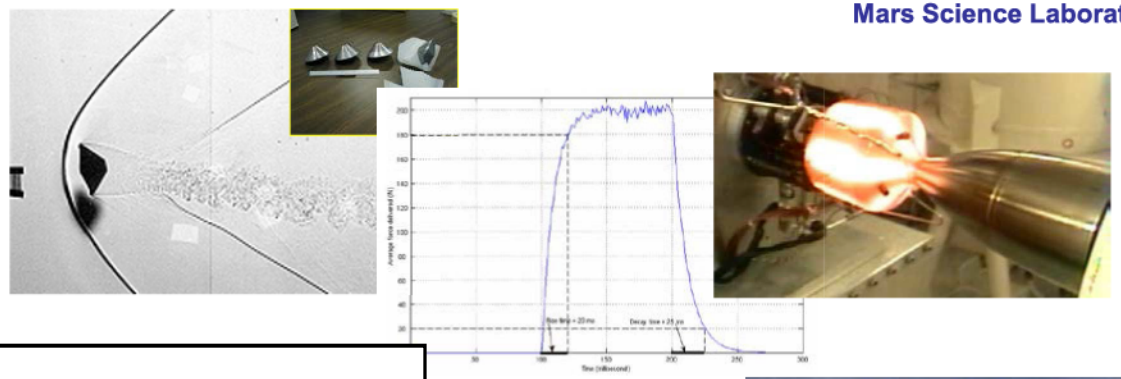
<u>Interaction Tests</u>
  - How do two or more elements behave when working and interacting with each other?

<u>Testbed and ATLO</u>
  - Are the proper commands (with the proper timing) generated by avionics and flight software when presented with a set of flight-like sensor data?

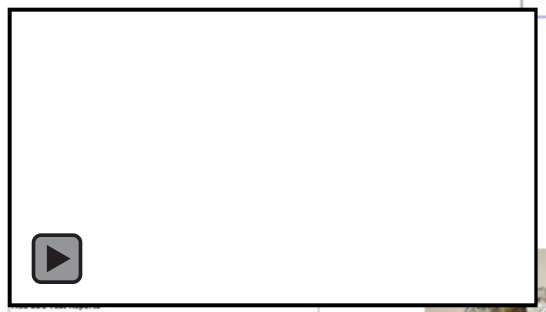
<u>Environmental Modeling</u>
  - What conditions (e.g., atmosphere, terrain) will the vehicle encounter during flight?

MSL Examples

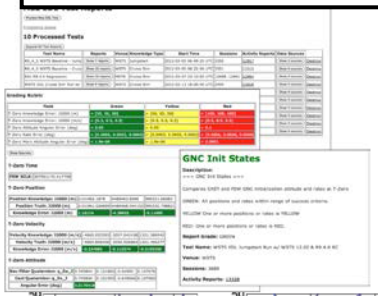
Element Tests and Analysis

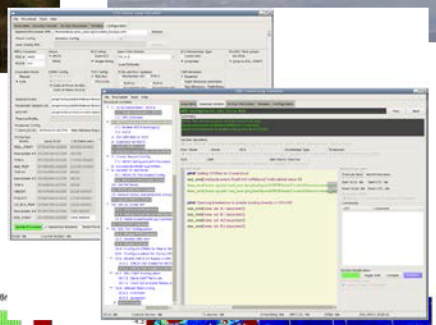


Interaction Tests

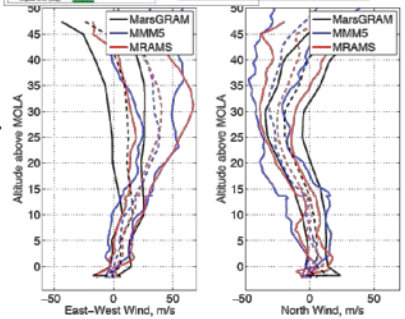


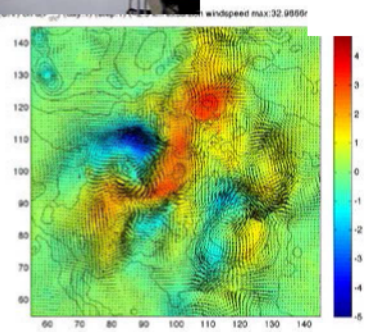
Testbed and ATLO

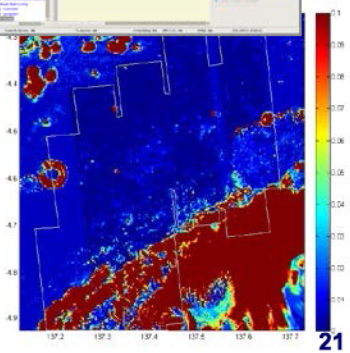




Environmental Modeling



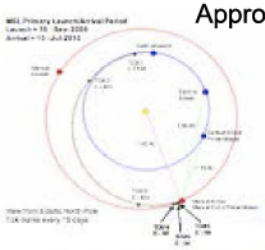




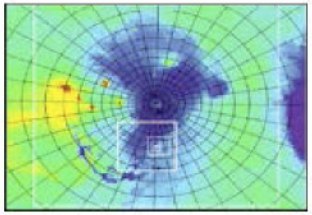
Assemble in Trajectory Simulations

Mass Properties (JPL)

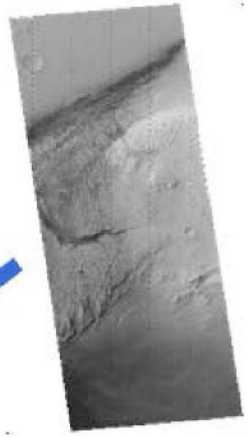
Entry Conditions & Approach Navigation (JPL)



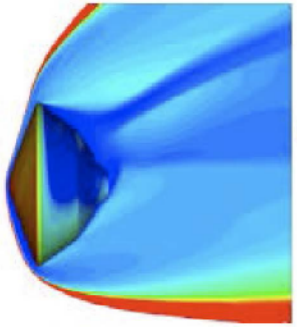
Meso-Scale Atmosphere Model (SwRI, OSU)



Digital Elevation Map (USGS)



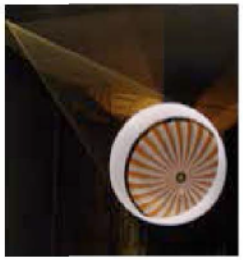
Aerodynamics & Aerothermodynamics (LaRC)



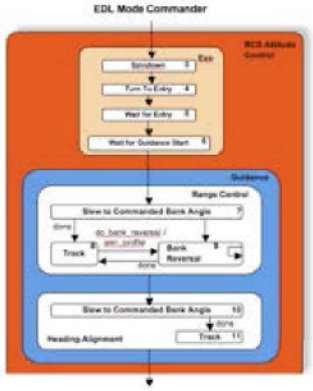
Subsystem models are brought together and integrated into an end-to-end EDL trajectory simulation

POST2 is the prime simulation for assessing MSL EDL performance

Parachute Model (LaRC)

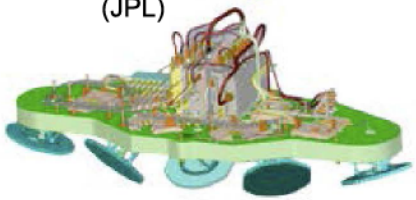


Flight Software (JPL)



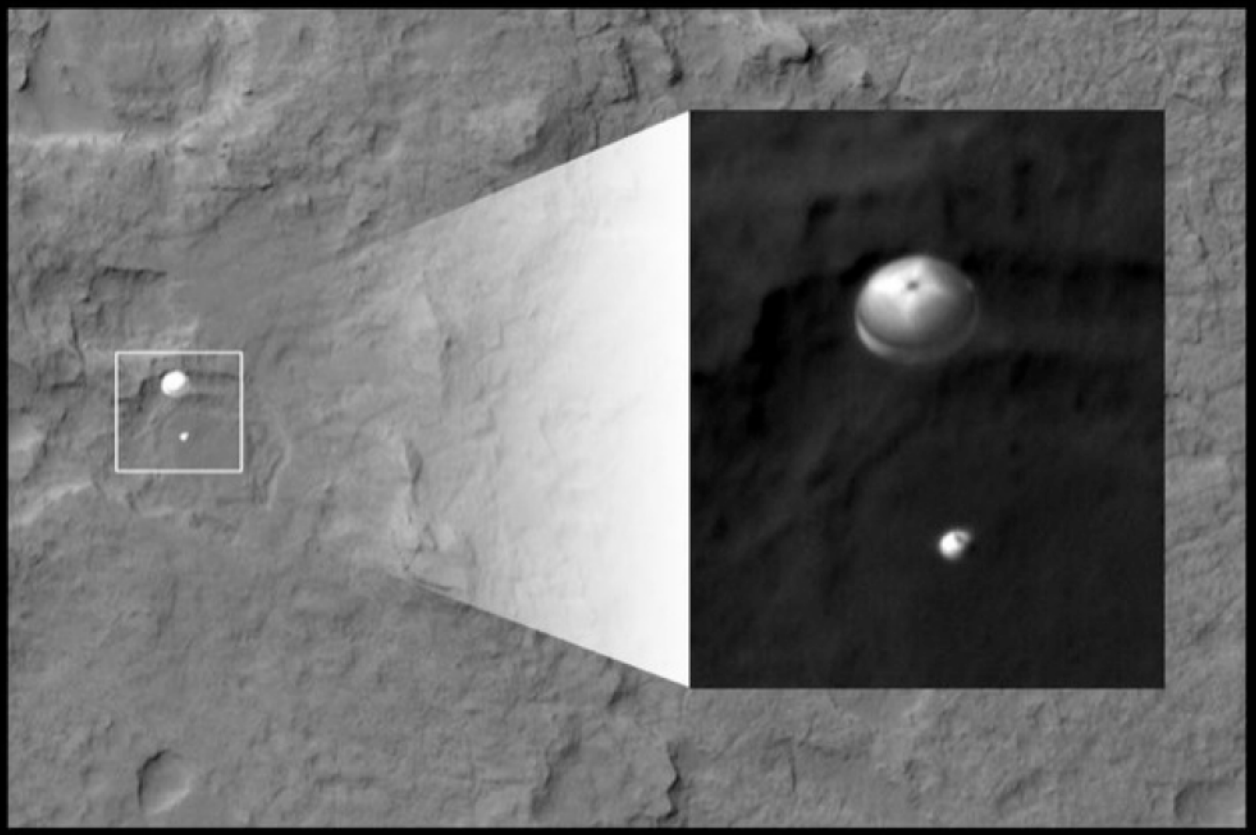
RCS Model (JPL)

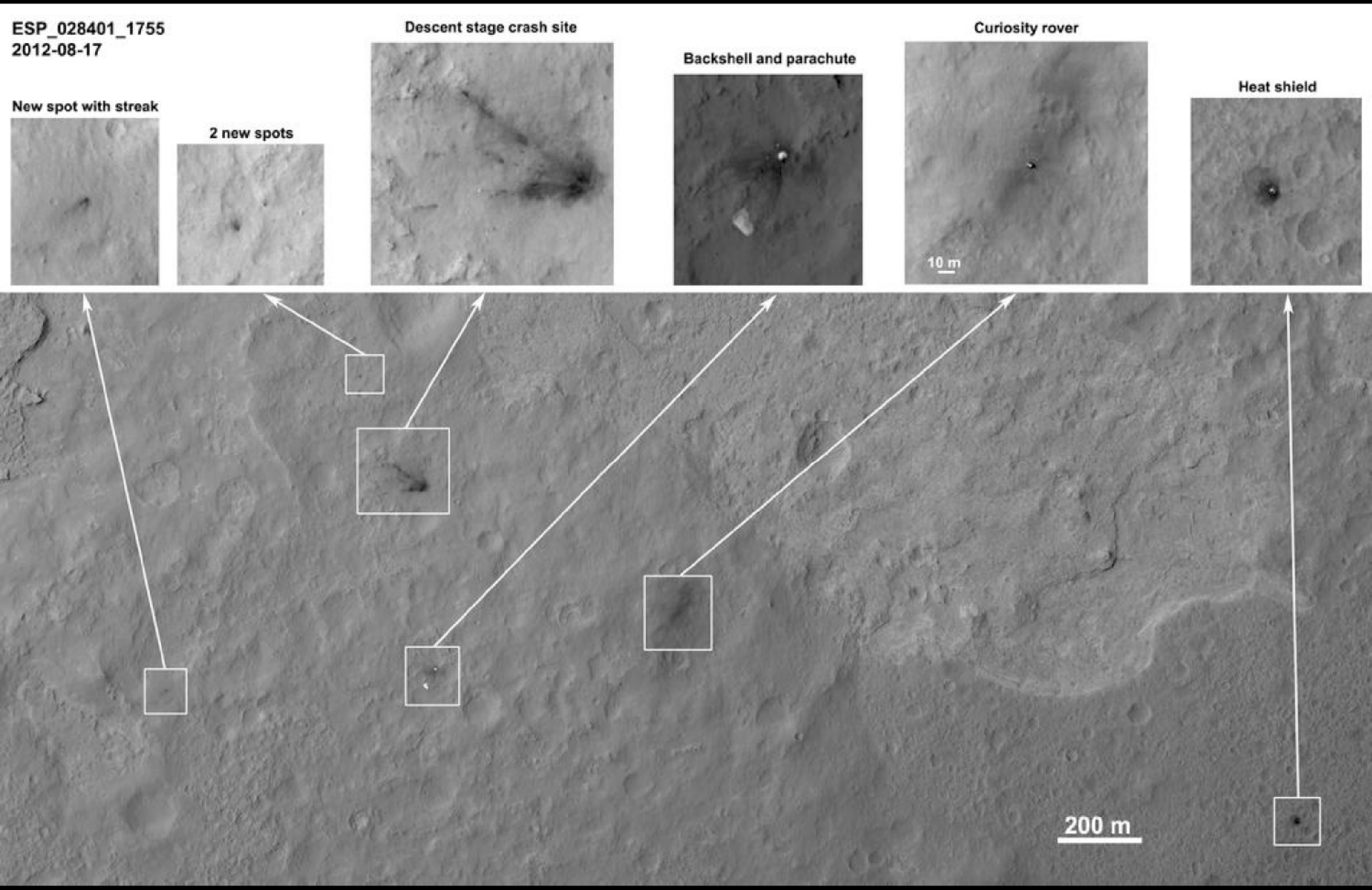
TDS Model (JPL)

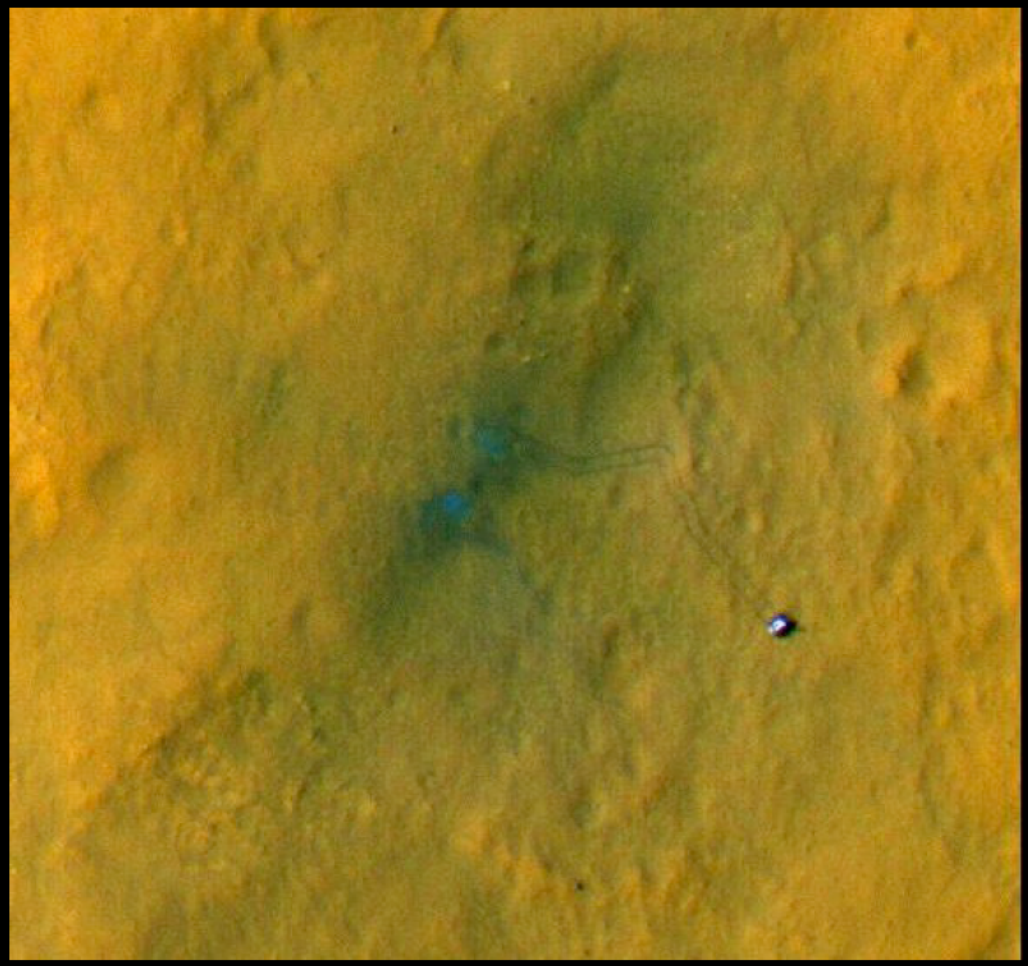


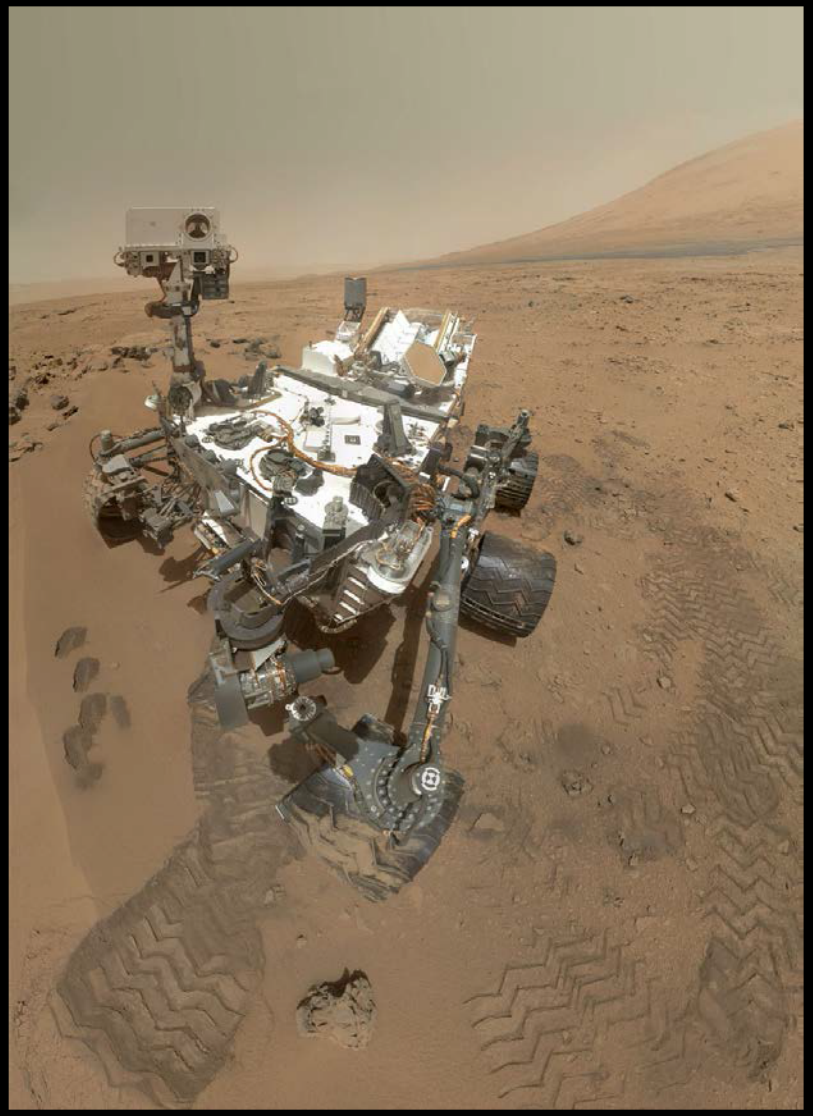
IMU Model (JPL)

MLE Model (JPL)




ESP_028401_1755
2012-08-17
New spot with streak
2 new spots
Descent stage crash site
Backshell and parachute
Curiosity rover
10 m
Heat shield
200 m





Jet Propulsion Laboratory
California Institute of Technology
Mars Science Laboratory,
Curiosity Rover
Full-Scale Model
About the size of a car, Curiosity is the largest rover ever sent to Mars. Its size allows it to carry the most advanced set of science tools.
The rover uses these tools to study whether Mars ever had an environment that could support small life forms called microbes. This mission pioneers new technologies for landing on and exploring Mars.
Learn more: http://mars.jpl.nasa.gov/msl/
Launch: November 26, 2011
Landing: August 5, 2012

Great works and great folly may be indistinguishable at the outset