Entry System Design and Performance

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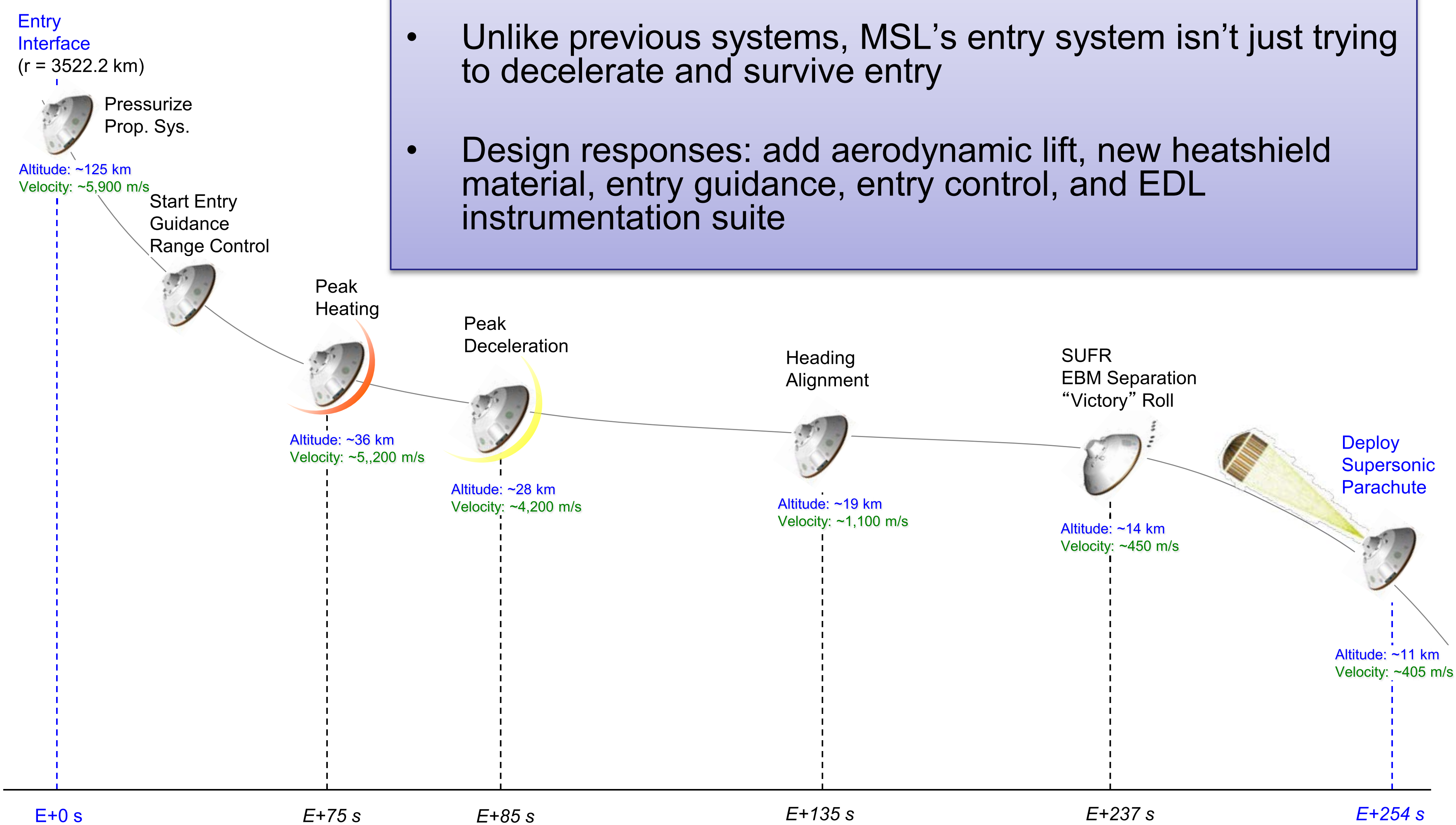
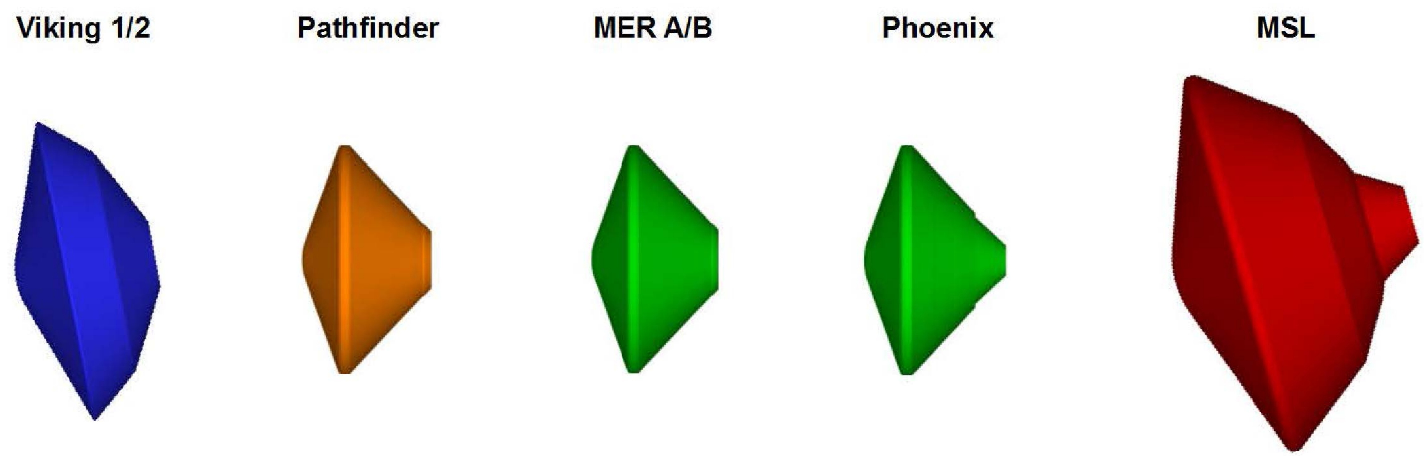
Entry Overview

- Greater than 99% of the spacecraft's arrival kinetic energy is dissipated during entry
- Unlike previous systems, MSL's entry system isn't just trying to decelerate and survive entry
- Design responses: add aerodynamic lift, new heatshield material, entry guidance, entry control, and EDL instrumentation suite



Entry Vehicle Comparison

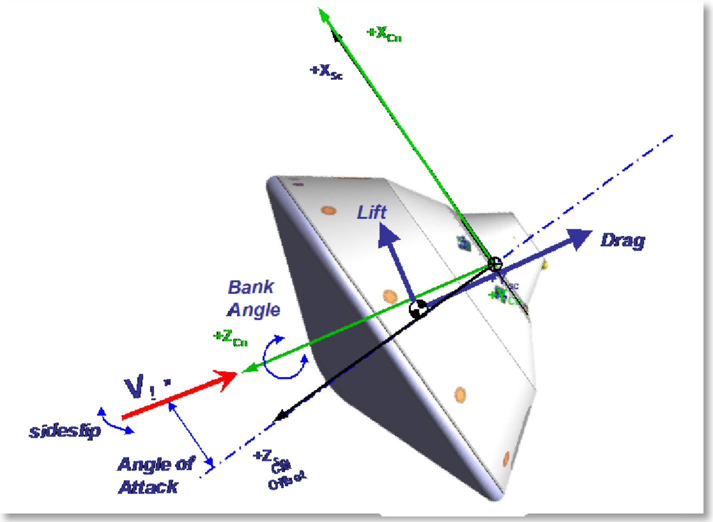


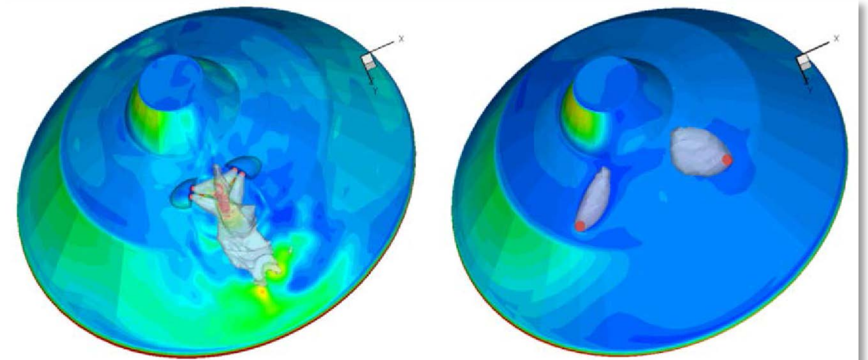
	Viking	MPF	MER	Phoenix	MSL
Diameter (m)	3.505	2.65	2.65	2.65	4.5
Entry Mass (kg)	930	585	840	602	3152
Hypersonic Angle of Attack (°)	-11.2	0	0	0	-16
Ballistic Coefficient (kg/m^2)	63.7	62.3	89.8	65	136

Significantly higher mass, ballistic coefficient and angle of attack

Aerodynamics Overview

- Given the entry and landing mass, there are no viable landing sites on Mars without aerodynamic lift
  - Provided by 10 cm center of gravity offset
  - Improves altitude performance by ~6 km
- Lifting entry and guided entry added new challenges
  - Predicting lift to drag ratio and trim angle throughout the trajectory
  - Understanding aerodynamic coefficients and uncertainties
  - Characterizing RCS jet interactions





Early MSL RCS configuration with large yaw interactions

Final MSL flight RCS configuration

Aerodynamics Performance Summary

- Reconstructing performance with the aid of MEDLI/MEADS instrumentation

- Aerodynamic performance very close to preflight predictions
  - Axial and normal force coefficients within 1σ
  - Hypersonic trim angle of attack almost exactly on predictions
  - Dynamic stability more benign than conservatively predicted

- Pathological phenomena did not appear to occur
  - No evidence of aerodynamics/RCS jet interactions
  - No evidence of significant roll torque

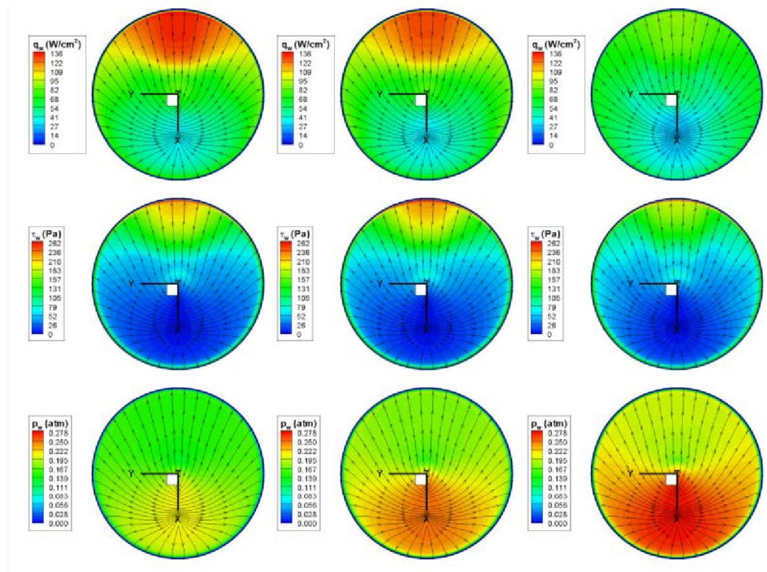
- Two notable deviations (with no overall system performance impact)
  - Growth in sideslip prior to parachute deploy
  - Supersonic axial force coefficient diverged from preflight prediction

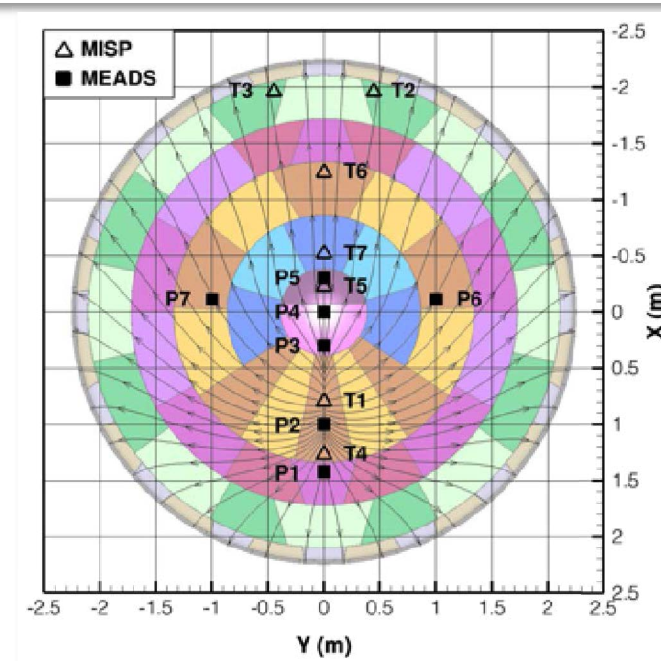
Aerothermal Overview

- Vehicle size, ballistic coefficient, and angle of attack combine to produce aerothermal challenges
  - Predicted transition to turbulence prior to peak heating
  - Peak heating away from the stagnation point
  - Roughness augmented heating
  - Significantly higher "design to" heating rates
  - High pressure and shear stresses

- After failure of original TPS (SLA-561V) to withstand "design to" conditions, adopted PICA for use in flight

- Include MEDLI/MISP instrumentation for aerothermal environment and material performance reconstruction

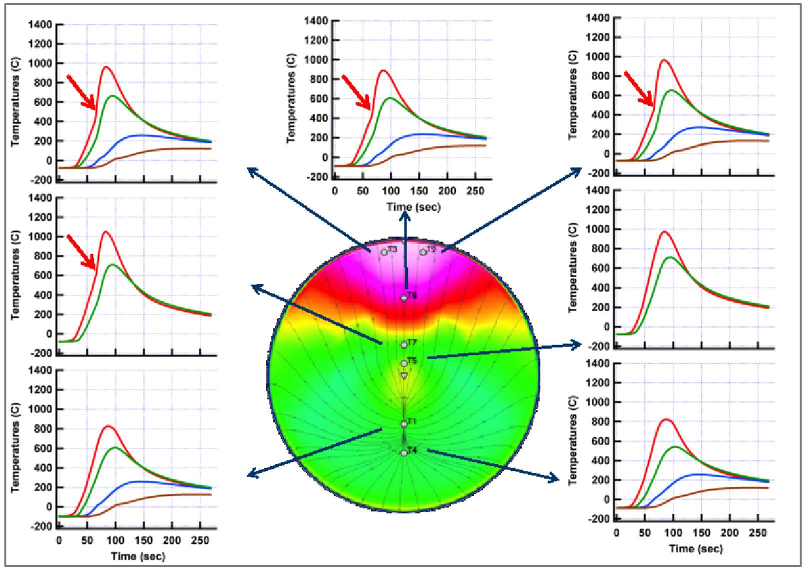




Aerothermal Performance Summary

- Reconstructing aerothermal environments and TPS material response with the aid of MEDLI/MISP instrumentation

- Aerothermal reconstruction results are still preliminary
  - Difficult to separate material response from environments
  - Analysis ongoing



Prediction	Basis for Prediction	Flight Observations
Heatshield boundary layer transition prior to peak heating	CFD, wind tunnel testing	Transition observed at all 4 leeside locations. Transition occurred near expected conditions for 3 of 4 locations.
Highest heatshield heat flux at leeside shoulder	CFD	Leeside shoulder did see highest heat flux, but by smaller ratio than predicted relative to other locations
Heat flux augmentation in stagnation point region possible	Wind tunnel testing	No heating augmentation near stagnation point observed

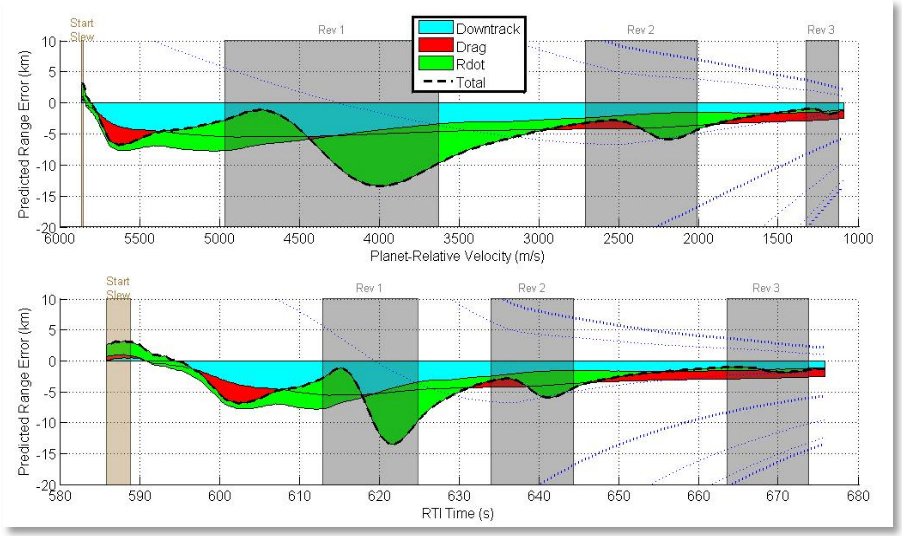
Entry Guidance Overview

- Uses a modified Apollo entry guidance algorithm
  - Two major phases: range control and heading alignment
- Controls downrange flown during range control by modulating lift
  - Lift modulated by bank angle commands
  - Periodic bank reversals to manage crossrange within a specified envelop
- Transitions to heading alignment at 1100 m/s and heads for the landing target
  - No longer attempting to control range
  - Flying in direction of target while preserving altitude margin

Entry Guidance Performance Summary

- Spacecraft arrival with minimal delivery error and onboard state knowledge error

- No significant surprises or performance anomalies observed
  - 3 bank reversals during range control, as predicted
  - Completed range control and heading alignment well within expected performance envelope
  - Guidance not challenged by any unexpected phenomena
  - Range control started slightly earlier than predicted, likely a result of higher than expected density in upper atmosphere, but had no impact on overall performance

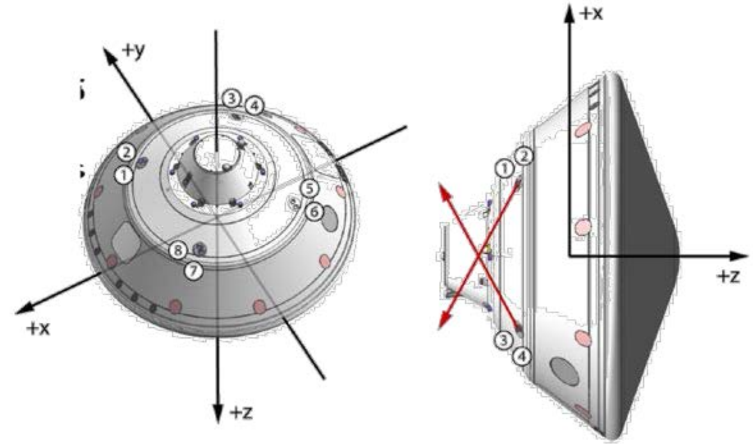


- Guidance did great

Entry Control Overview

- Entry vehicle utilizes onboard entry controller and RCS thrusters

- Entry controller functions:
  - Provide 3-axis control using RCS thrusters
  - Follow guidance bank angle commands
  - Execute bank reversals
  - Maintain angle of attack and sideslip
  - Damp attitude rates

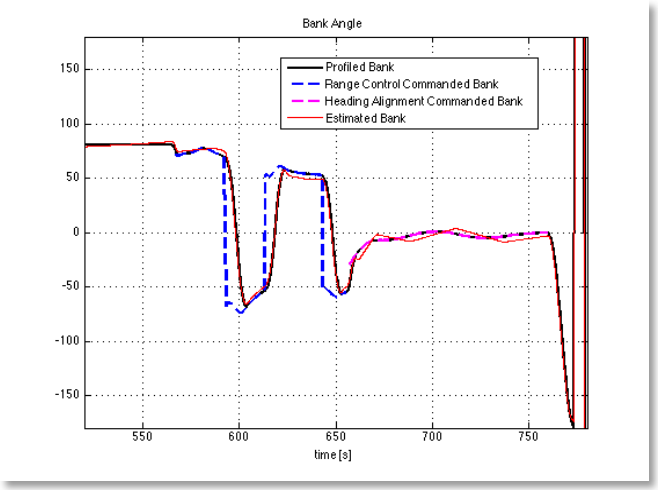


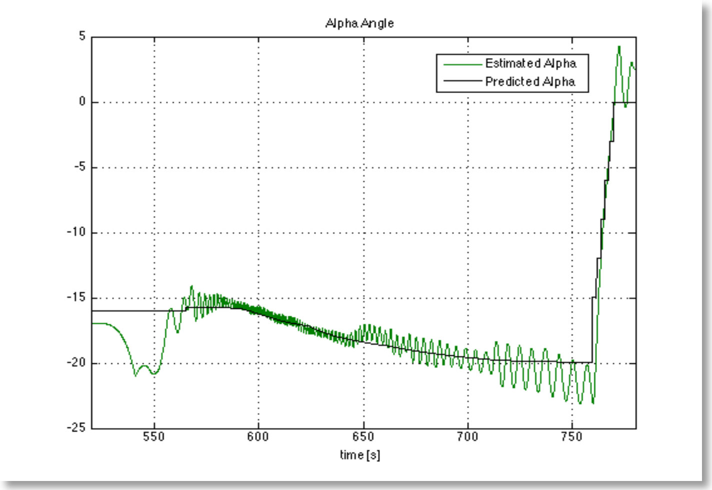
- RCS thrusters configured to minimize aerodynamics/RCS interactions while providing required control authority

- Designed to overcome potential extreme or pathological conditions
  - Roll torques
  - Large aerodynamics/RCS jet interactions

Entry Control Performance Summary

- Entry control performed nominally
  - Control errors remained small and within predictions throughout entry
  - Thruster activity and propellant use were nominal
  - Followed guidance bank angle commands and performed bank reversals as expected

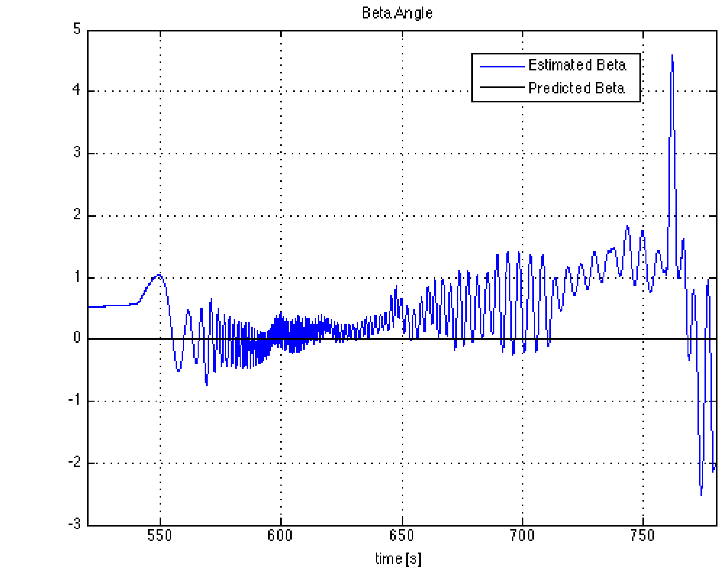


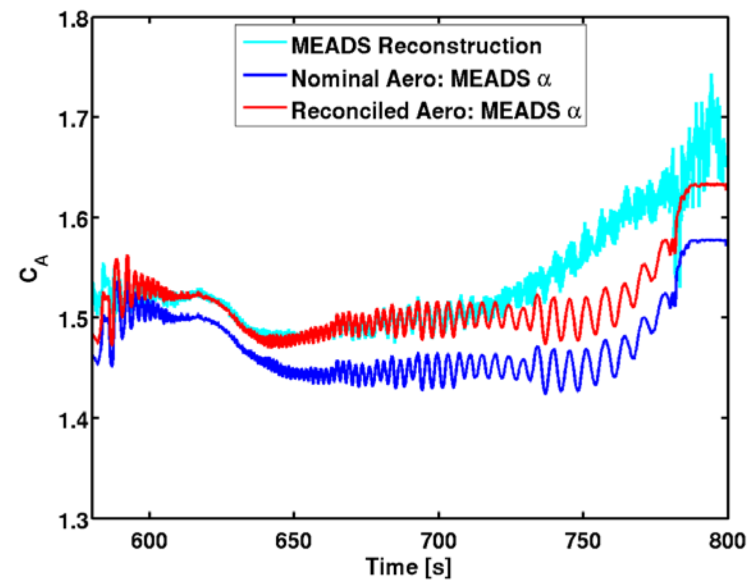


- Not challenged by any significant or unexpected disturbances
  - No evidence of severe roll torques or aerodynamics/RCS jet interactions
  - No large deviations from predicted aerodynamic trim

Residual Issues

- The team has identified residual issues during reconstruction
- Gradual departure of sideslip from predictions at end of heading alignment
  - No overall system performance impact
  - Cause currently unknown
- Total drag during heading alignment was as expected, but aerodynamic contribution appears higher than expected
  - Requires lower drag contribution from atmosphere
  - May result from measurements outside the valid dynamic pressure range for MEADS
- SUFR start to parachute deploy time was longer than expected
  - May indicate a larger than expected tailwind

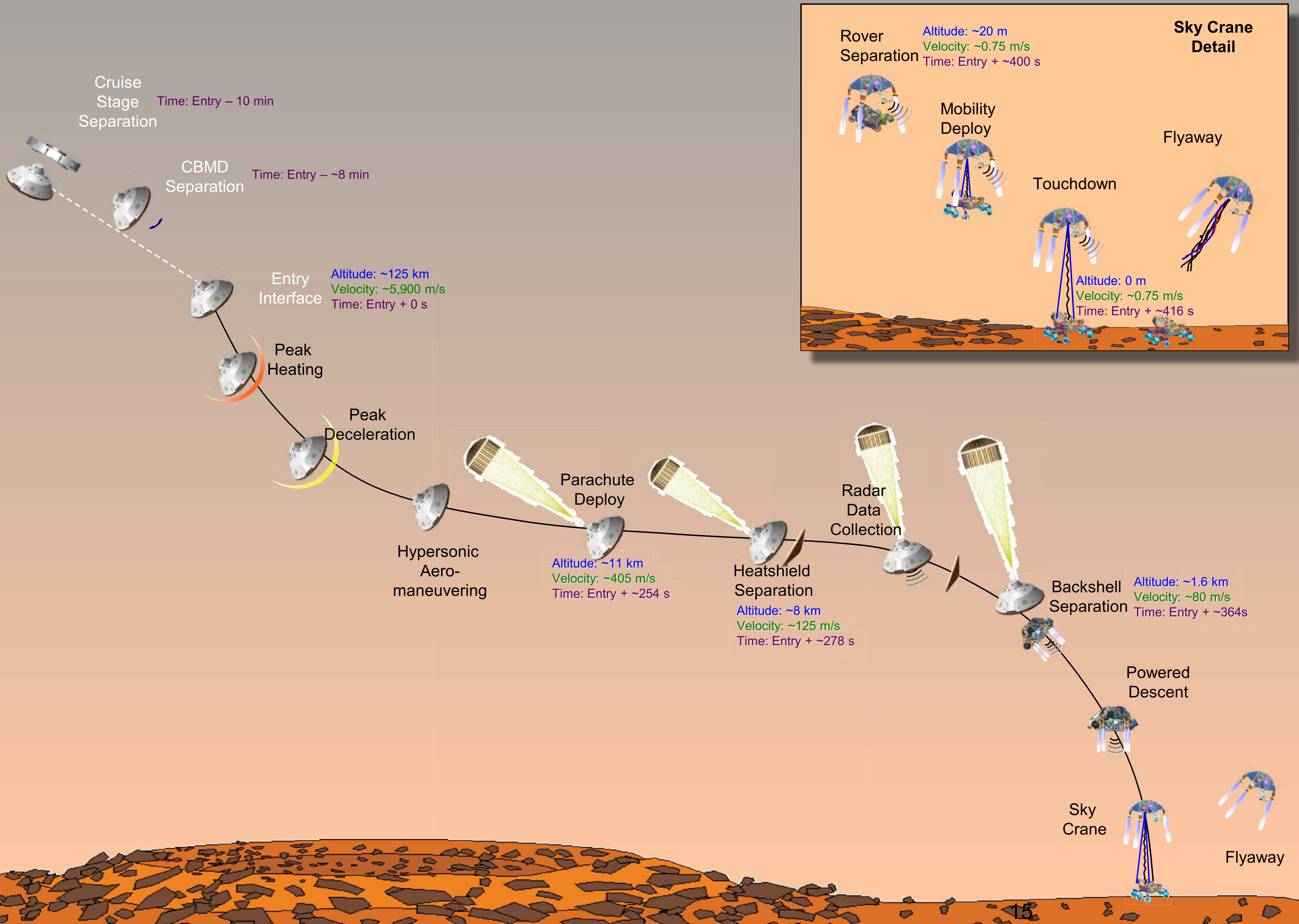




Conclusion

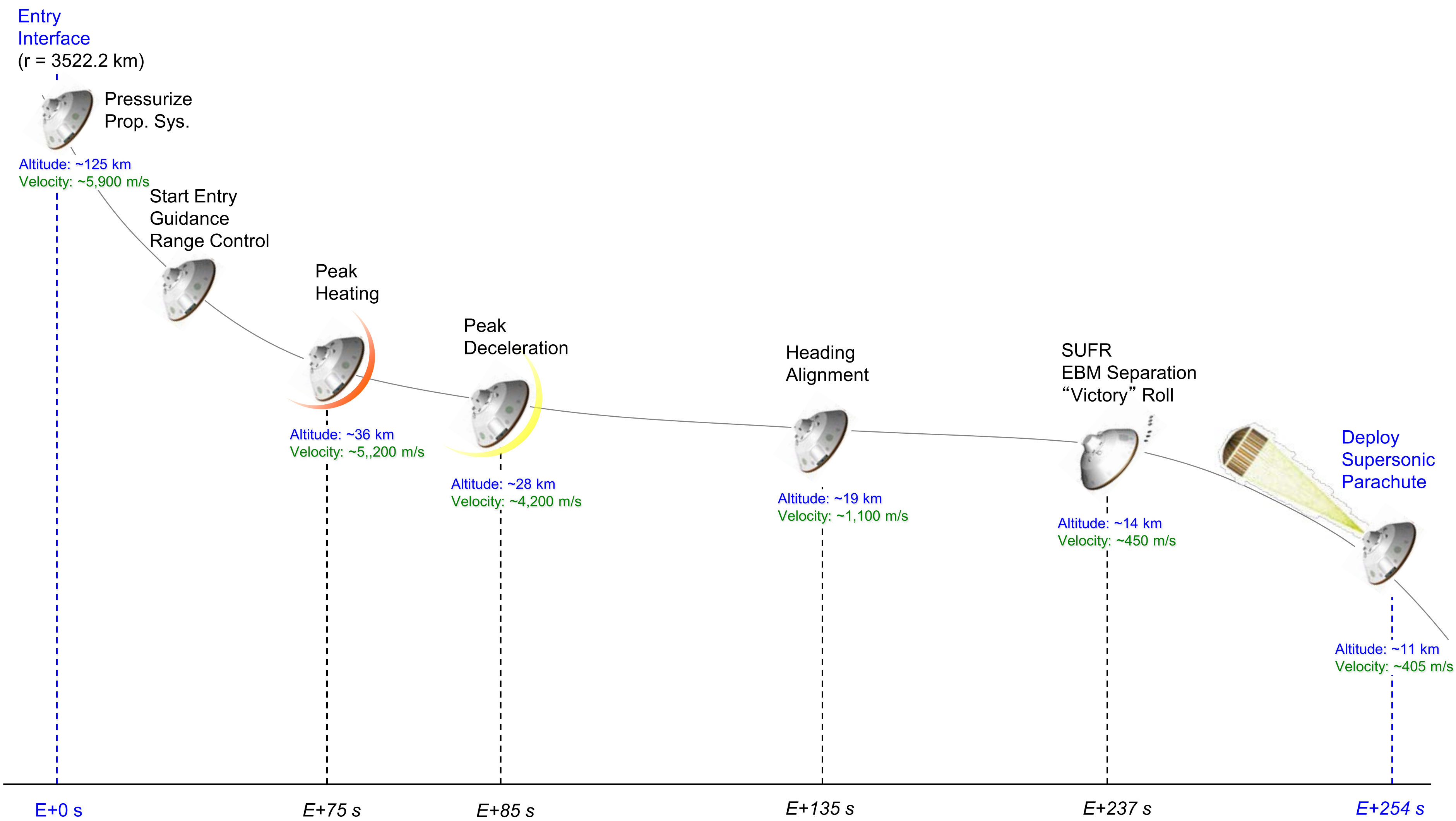
- The MSL entry system successfully blended many disciplines to survive entry and deliver the spacecraft to the right conditions to complete the rest of EDL
- Overall system performance was well within family of preflight predictions with only minor exceptions
- The success of the entry system provides a useful template for future Mars missions of similar scope

Backup



Cruise Stage Separation
Time: Entry – 10 min
CBMD Separation
Time: Entry – ~8 min
Entry Interface
Altitude: ~125 km
Velocity: ~5,900 m/s
Time: Entry + 0 s
Peak Heating
Peak Deceleration
Hypersonic Aero-maneuvering
Parachute Deploy
Altitude: ~11 km
Velocity: ~405 m/s
Time: Entry + ~254 s
Heatshield Separation
Altitude: ~8 km
Velocity: ~125 m/s
Time: Entry + ~278 s
Radar Data Collection
Backshell Separation
Altitude: ~1.6 km
Velocity: ~80 m/s
Time: Entry + ~364s
Powered Descent
Sky Crane
Flyaway
Sky Crane Detail
Rover Separation
Altitude: ~20 m
Velocity: ~0.75 m/s
Time: Entry + ~400 s
Mobility Deploy
Touchdown
Altitude: 0 m
Velocity: ~0.75 m/s
Time: Entry + ~416 s
Flyaway

Entry Events



The Challenges of Entry

- Greater than 99% of the spacecraft's arrival kinetic energy is dissipated during entry
  - Ready to survive aerodynamic deceleration of up to 15 Earth g's
  - Designed for aerothermal heating rates in excess of 200 W/cm^2
- Unlike previous systems, MSL's entry system isn't just trying to decelerate and survive entry
  - Land the largest mass and volume
  - Land at higher elevation landing sites
  - Land with greater precision
  - Add entry instrumentation
- Required design responses: add aerodynamic lift, entry guidance, entry control, and accommodate instrumentation suite
  - Exacerbates aerodynamic and aerothermal challenges