Powered Flight Design and Reconstructed Performance Summary for the Mars Science Laboratory Mission

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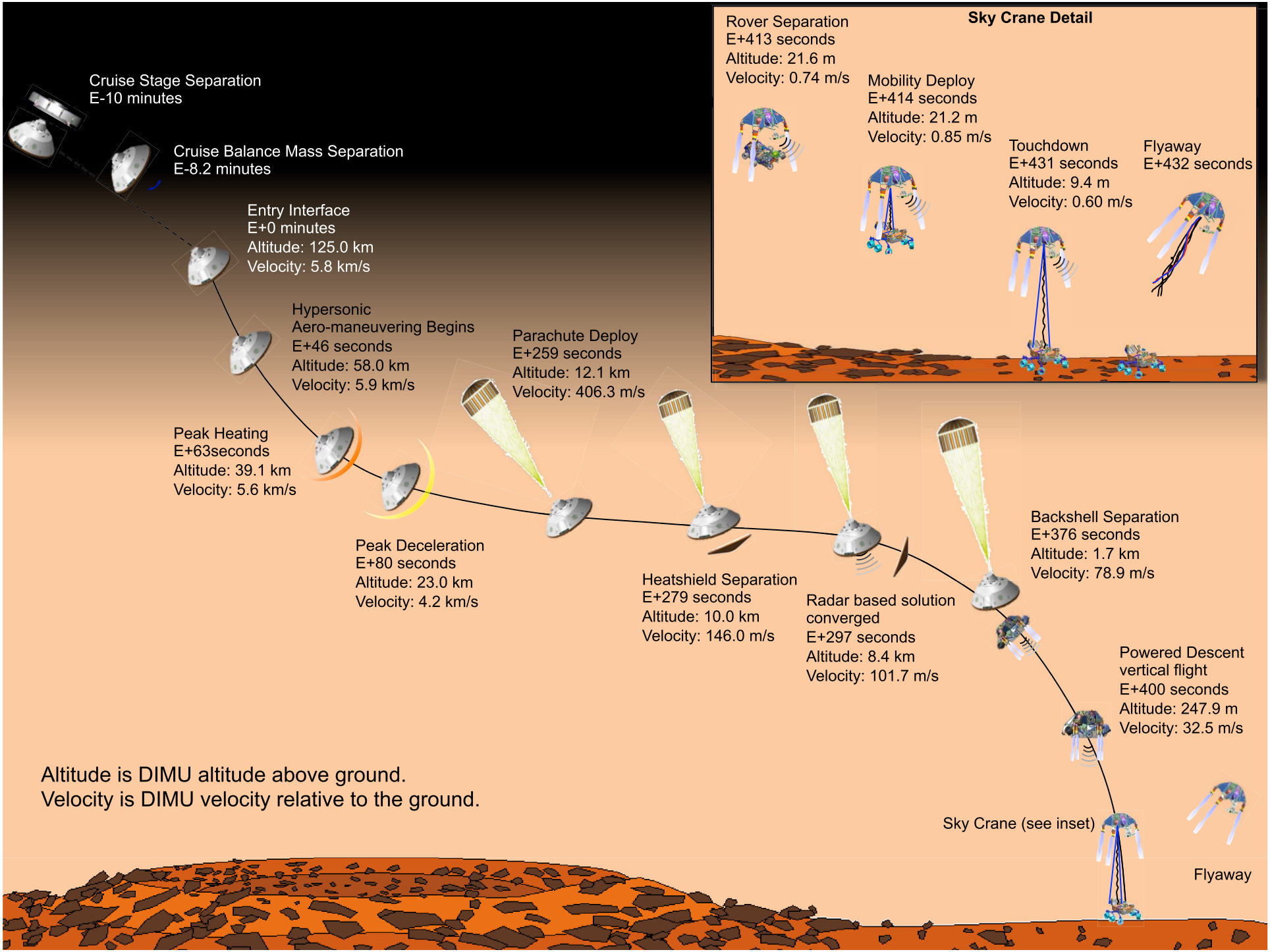
Cruise Stage Separation
E-10 minutes
Cruise Balance Mass Separation
E-8.2 minutes
Entry Interface
E+0 minutes
Altitude: 125.0 km
Velocity: 5.8 km/s
Hypersonic
Aero-maneuvering Begins
E+46 seconds
Altitude: 58.0 km
Velocity: 5.9 km/s
Peak Heating
E+63seconds
Altitude: 39.1 km
Velocity: 5.6 km/s
Peak Deceleration
E+80 seconds
Altitude: 23.0 km
Velocity: 4.2 km/s
Parachute Deploy
E+259 seconds
Altitude: 12.1 km
Velocity: 406.3 m/s
Heatshield Separation
E+279 seconds
Altitude: 10.0 km
Velocity: 146.0 m/s
Radar based solution
converged
E+297 seconds
Altitude: 8.4 km
Velocity: 101.7 m/s
Backshell Separation
E+376 seconds
Altitude: 1.7 km
Velocity: 78.9 m/s
Powered Descent
vertical flight
E+400 seconds
Altitude: 247.9 m
Velocity: 32.5 m/s
Sky Crane (see inset)
Flyaway
Sky Crane Detail
Rover Separation
E+413 seconds
Altitude: 21.6 m
Velocity: 0.74 m/s
Mobility Deploy
E+414 seconds
Altitude: 21.2 m
Velocity: 0.85 m/s
Touchdown
E+431 seconds
Altitude: 9.4 m
Velocity: 0.60 m/s
Flyaway
E+432 seconds
Altitude is DIMU altitude above ground.
Velocity is DIMU velocity relative to the ground.

Animation

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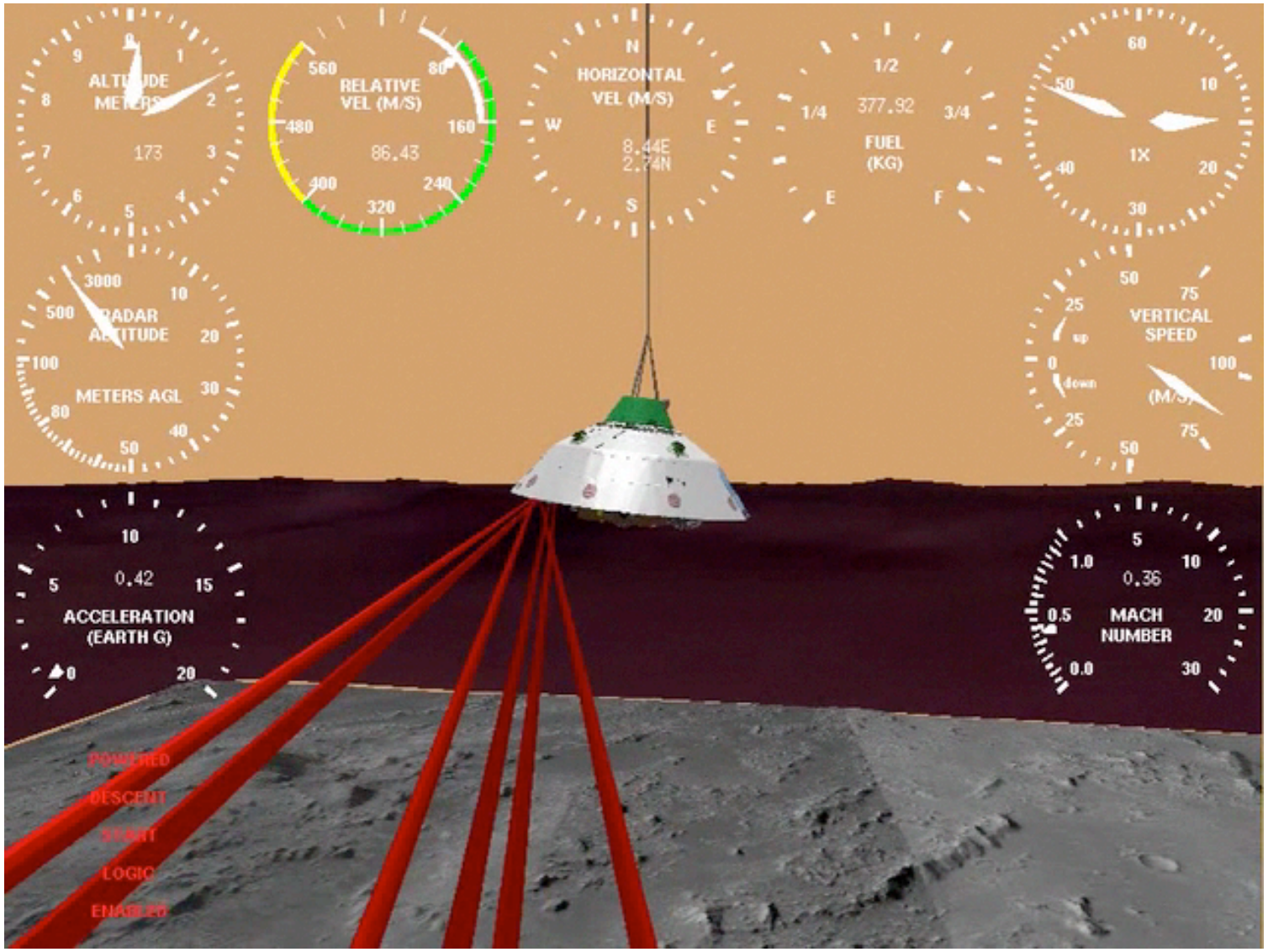
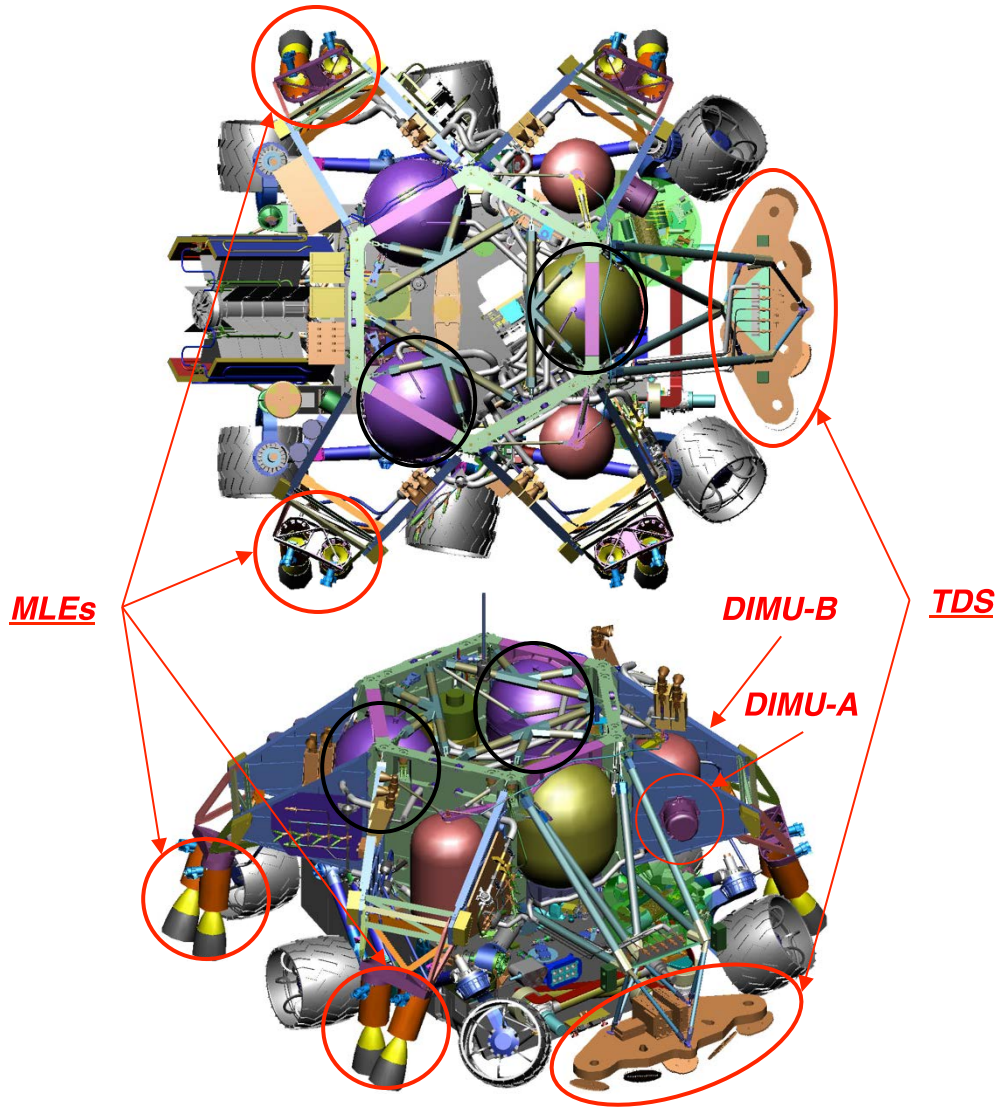


Key EDL Powered Flight Hardware

- To accomplish Powered Descent and Flyaway, EDL relies on three main sensors and actuators
  - Mars Lander Engines (MLEs)
  - Descent stage Inertial Measurement Unit (DIMU)
  - Terminal Descent Sensor (TDS)



The Task at Hand

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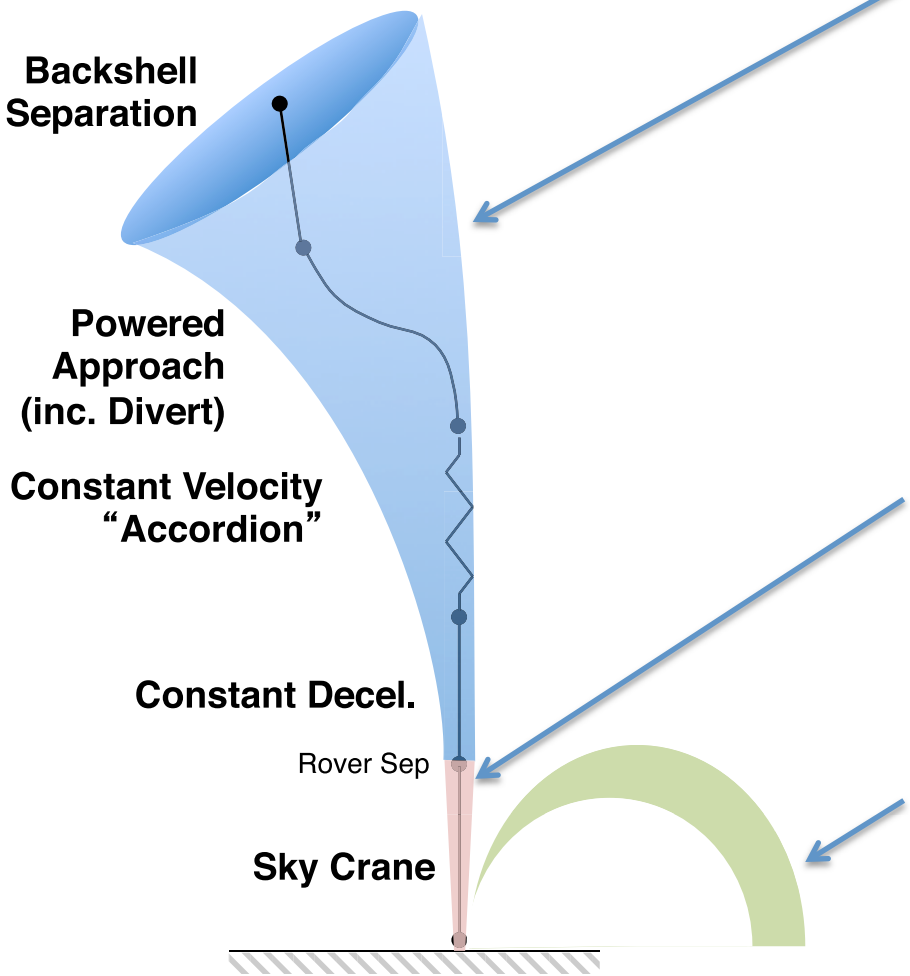


- Powered Descent
  - Start at the Backshell Sep
  - Execute Divert
    - 300 m
  - Deliver the PDV to the Rover Separation Conditions
    - Altitude: 21.3 m
    - Velocity: 0.75 m/s
    - Attitude: 3 deg, 3 deg/s
- Sky Crane
  - Start at the Rover Sep Conditions
  - Deliver a deployed Rover to the Touchdown Conditions
    - Velocity: < 0.85 m/s vert, < 0.5 m/s hor
- Flyaway
  - "Throw" the DS > 150m from the TD point

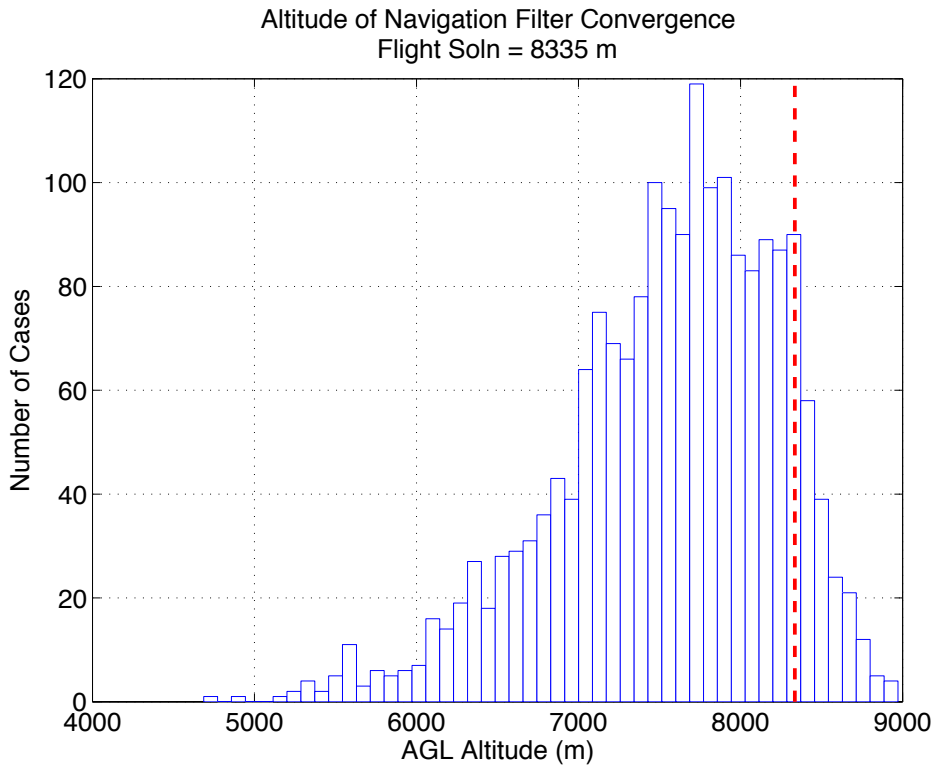
In-Flight Performance

- On-board Navigated Velocities used as “truth”
  - Comparison with reconstructed reverse-integrated IMU trajectory shows good accuracy
    - Altitudes in Powered Flight agree within < 1m
    - Velocities agree to < 0.1 m/s

- Pre-flight predictions are based on 8,000 run Monte Carlo using the POST2 end-to-end EDL simulation
  - Seeded with final navigation solution state prior to entry (OD230)

First Radar-based Altitude Solution

- Heatshield was dropped at ~10 km AGL
  - Radar begins “pinging” to provide range and velocity measurements to Navigation Filter
  - Once Nav Filter has ingested enough measurements to produce valid alt/vel solution, it’s considered to be converged
  - Solution now used for navigation, triggers, etc.
- Pre flight predictions based on conservative radar performance
  - In-flight performance was better than 1-sig above the mean



Backshell Separation

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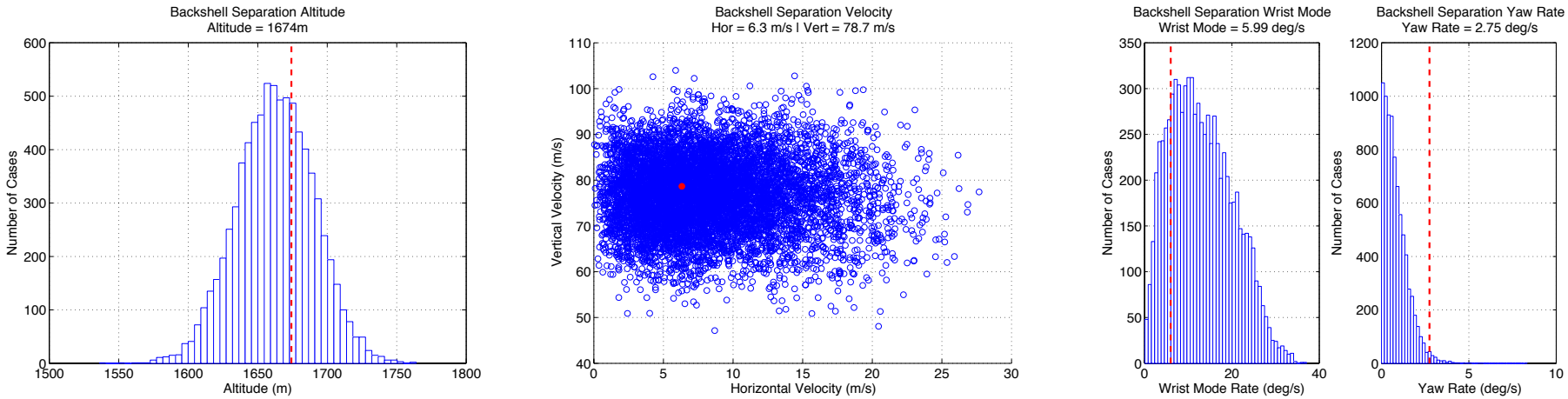
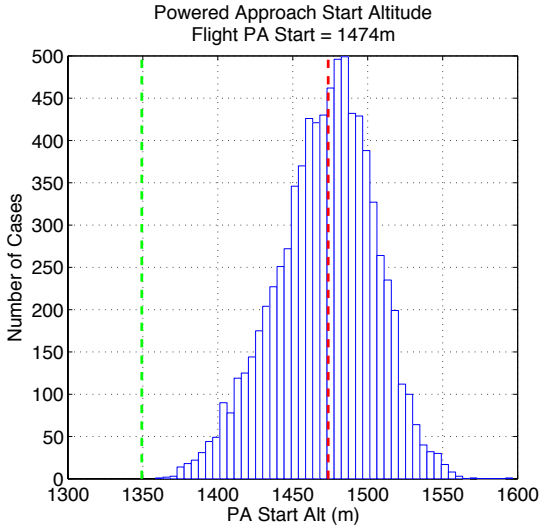
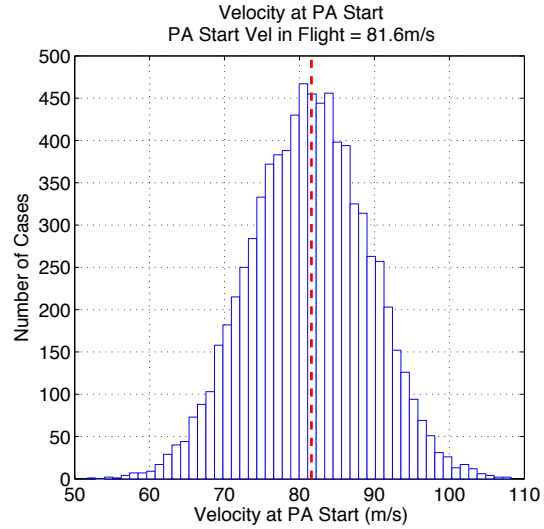
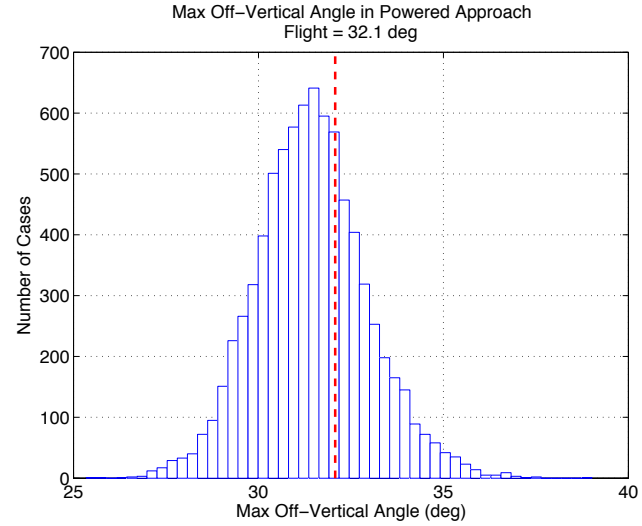


- Backshell Separation
  - Given expected on-chute terminal velocity of ~80 m/s, predicted BSS altitude was expected to be 1.6 km
  - Velocity and Wrist mode both as expected
  - Yaw rate higher than predicted at 2.75 deg/s, but well below requirement of 10 deg/s

Powered Approach



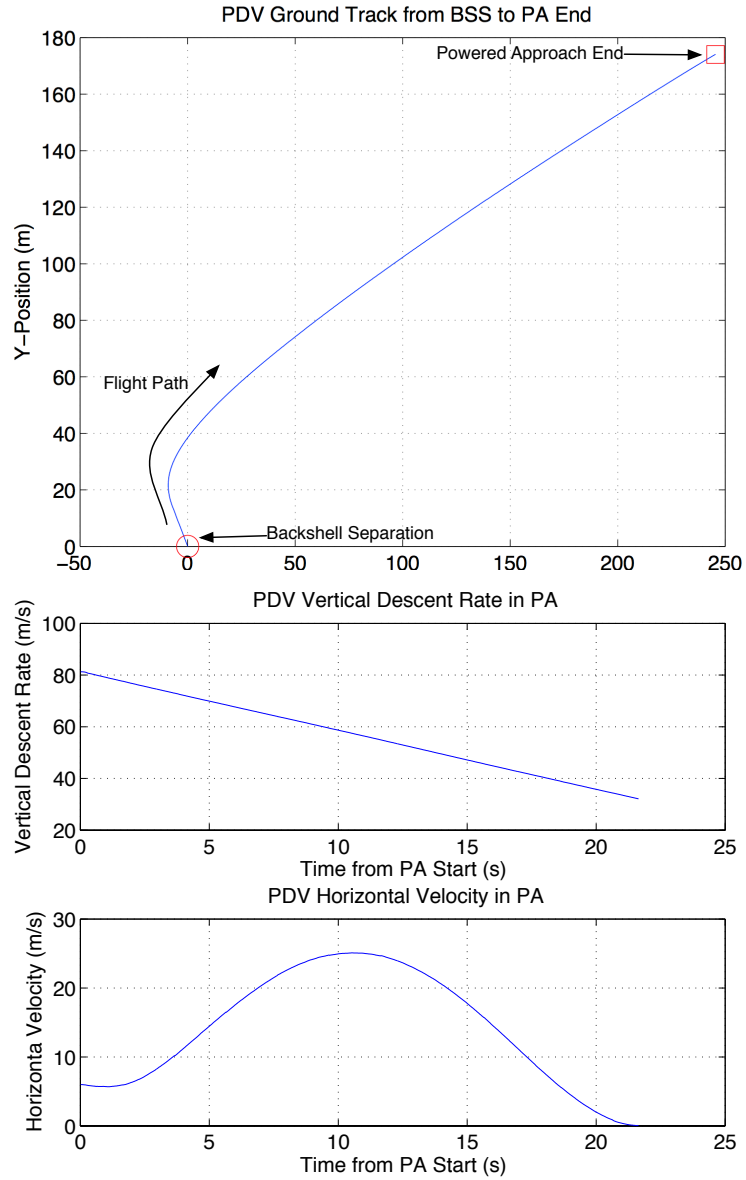




- Powered Approach
  - Starting conditions were almost right on the mean of pre-flight predictions in both altitude and velocity
  - Off-vertical angle during Powered Approach also in the heart of the pre-flight predictions

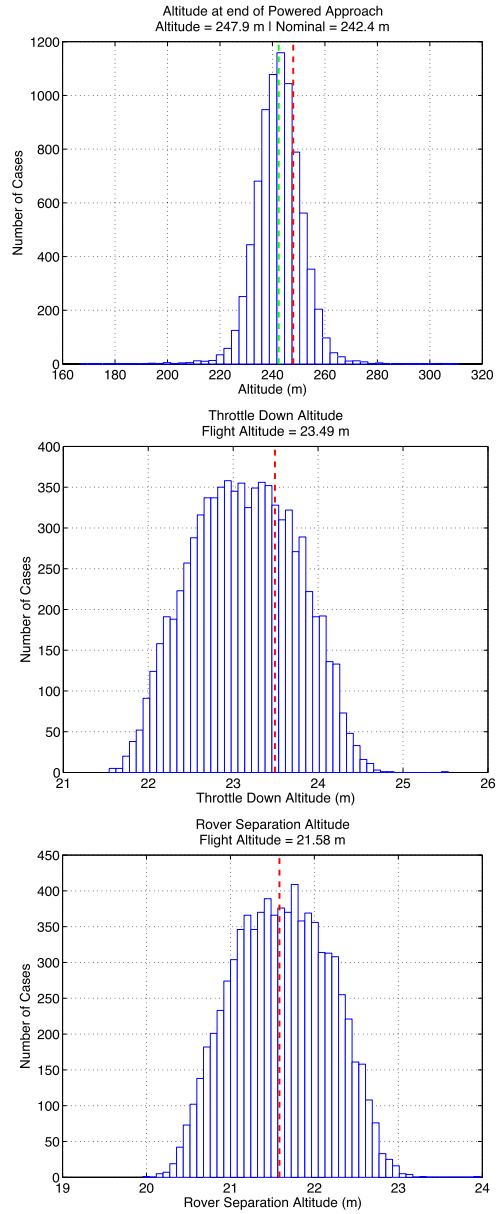
Divert

- Part of powered approach is to execute a 300m divert perpedicular to flight path
  - Avoids contact with backshell/parachute on the surface
- Flight path shows proper execution of divert in both distance and direction
- Velocity profile also shows execution of the divert as well as linear deceleration to 32 m/s vertical descent



Altitude Errors

- As Powered Flight Progressed, Altitude errors were well-behaved and decreasing
- First on-board look at error is at CV start
  - Ideal Alt = 242.4 m
  - In-Flight = 247.9 m
  - System sized to accommodate up to 100 m
- By Rover Separation, error was 0.3 m
  - Further analysis pending rover IMU post-processing
  - First look shows by touchdown, error was less than 0.2 m (not discussed in paper)



CV 242 m AGL
5.5m error

ThDwn 23 m AGL
0.5m error

RSep 21.3 m AGL
0.3m error

Touchdown

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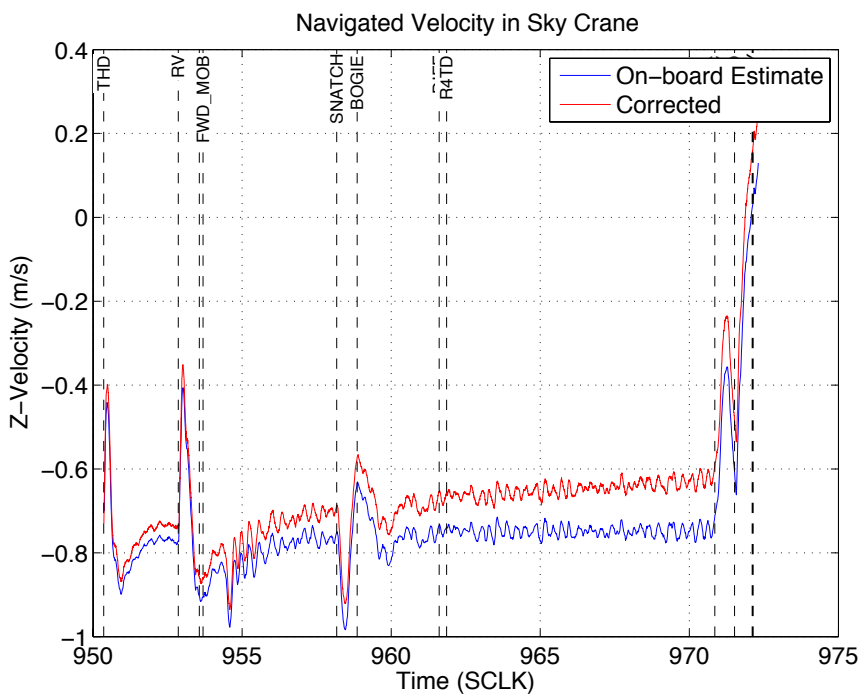
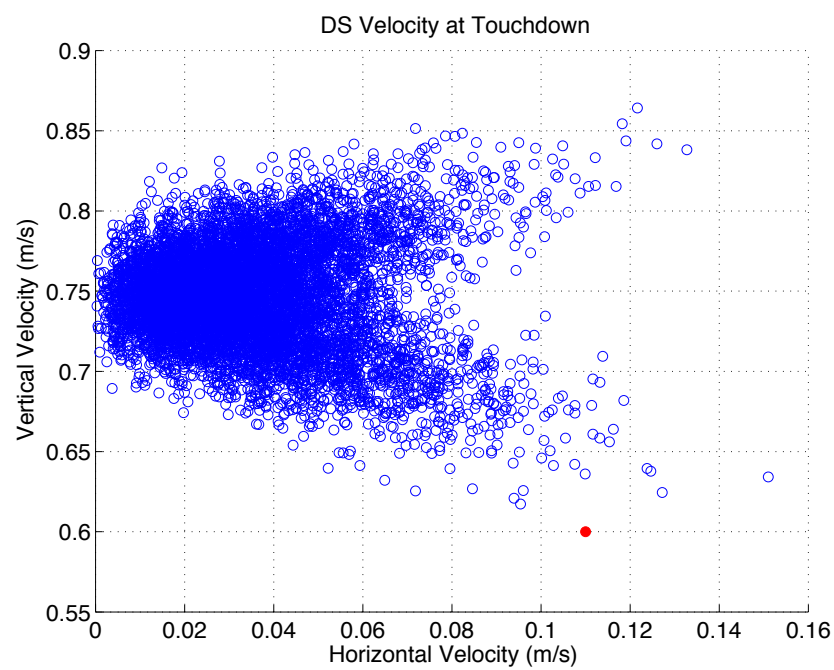
- Touchdown Conditions as measured on-board in error due to a gravity model deficiency in on-board Nav Filter
  - Only affected navigation after rover separation
  - Resulted in system descending slower than expected
  - Ref: Serrichio and San Martin paper in this conference
- Touchdown occurred well within Rover capabilities (0.85 m/s vertical, 0.5 m/s horizontal)





Flyaway

- Flyaway Controller executed on the motor controller in the DS (Rover had been in control to this point)
  - Simple rate-only controller
  - Executed a simple “turn and burn” for 6s to throw the DS to a safe impact distance
  - Required > 150 m; Predicted ~500 m; Achieved 650 m

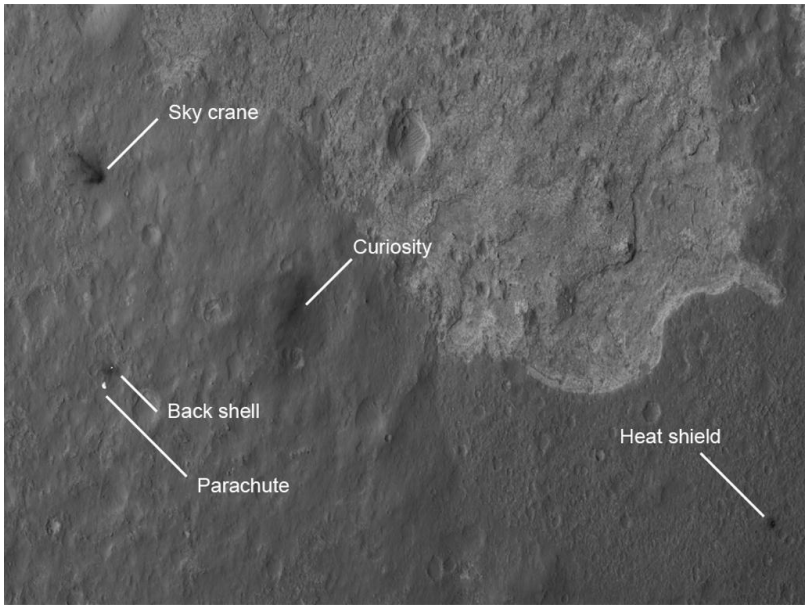
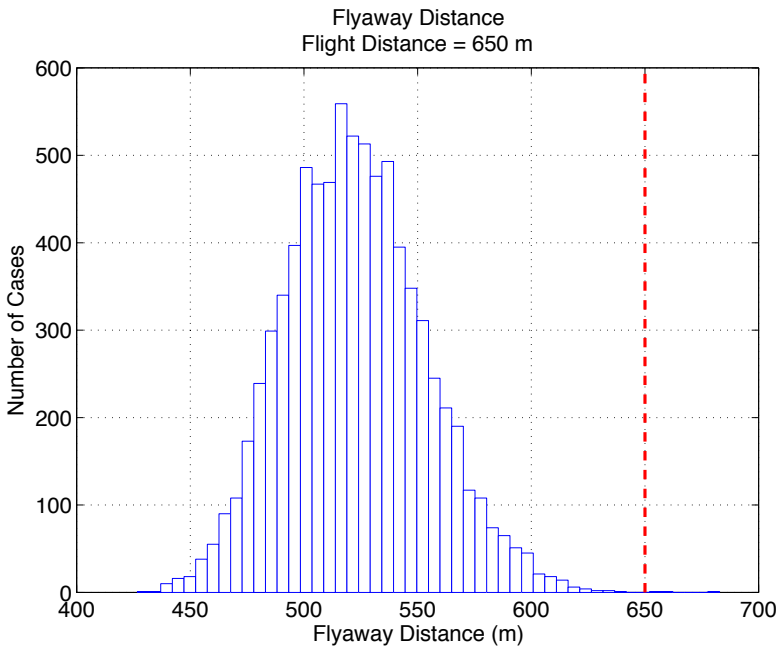


Image Credit: NASA/JPL-Caltech/Univ. of Arizona



Conclusions

- Powered Flight portion of the MSL Entry Descent and Landing Sequence is perhaps the most daring and complex to date in the Mars exploration program
- The system behaved as expected
  - No major surprises
  - In-flight performance matches pre-flight predictions extremely well
    - Exceeds pre-flight predictions in some cases
- Detailed analysis of Sky Crane is still work to go, but all indications are that it performed as expected

- Questions?