Mars Science Lander GN&C Design for Entry, Descent, and Landing

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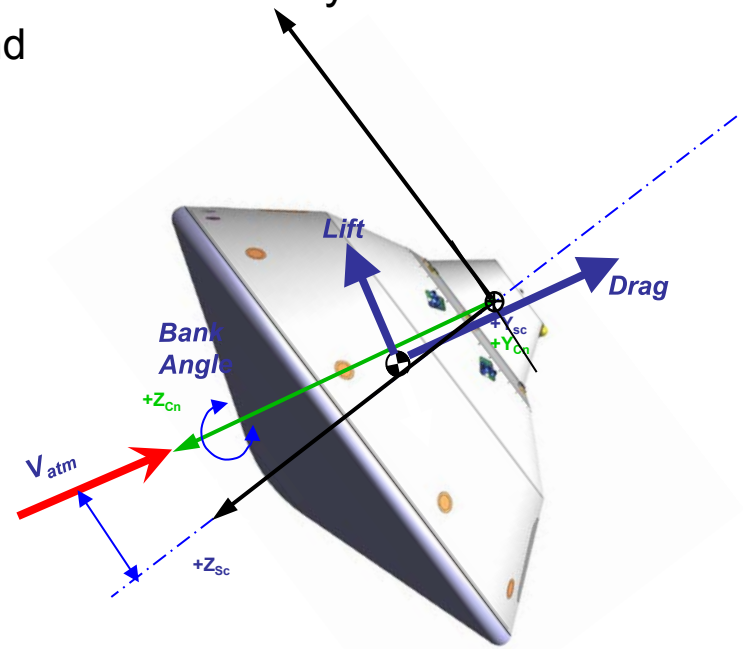
MSL EDL/GN&C Challenge

EDL Challenge

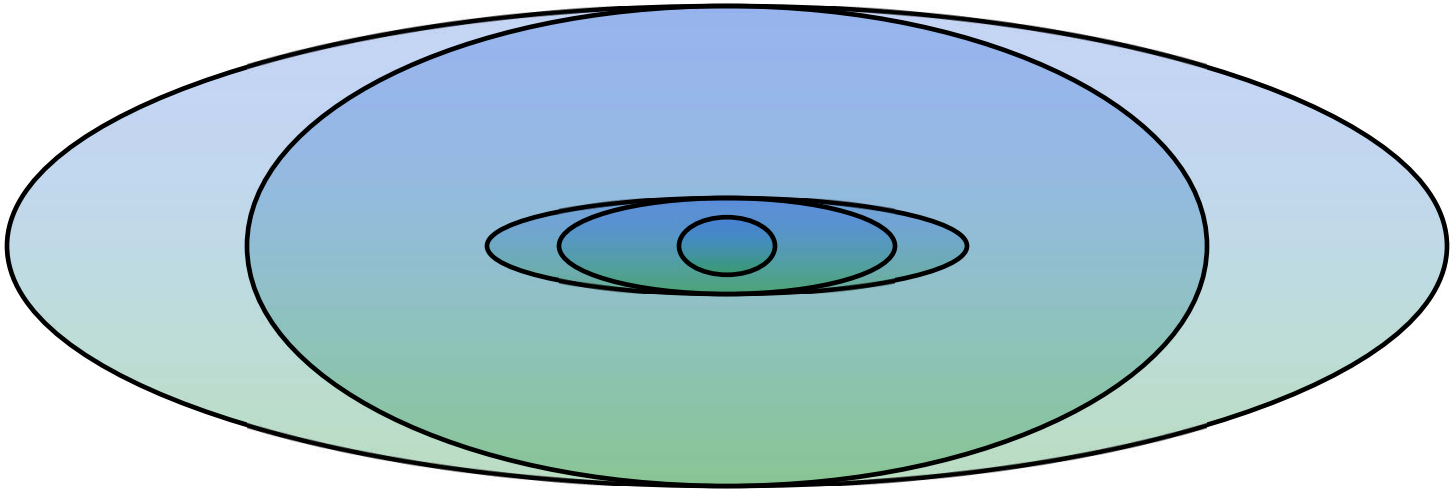
- Improve accessibility to landing sites of high scientific value by:
  - Increasing Landing Site Elevation capability, and
  - Reducing Landing Ellipse size



Response

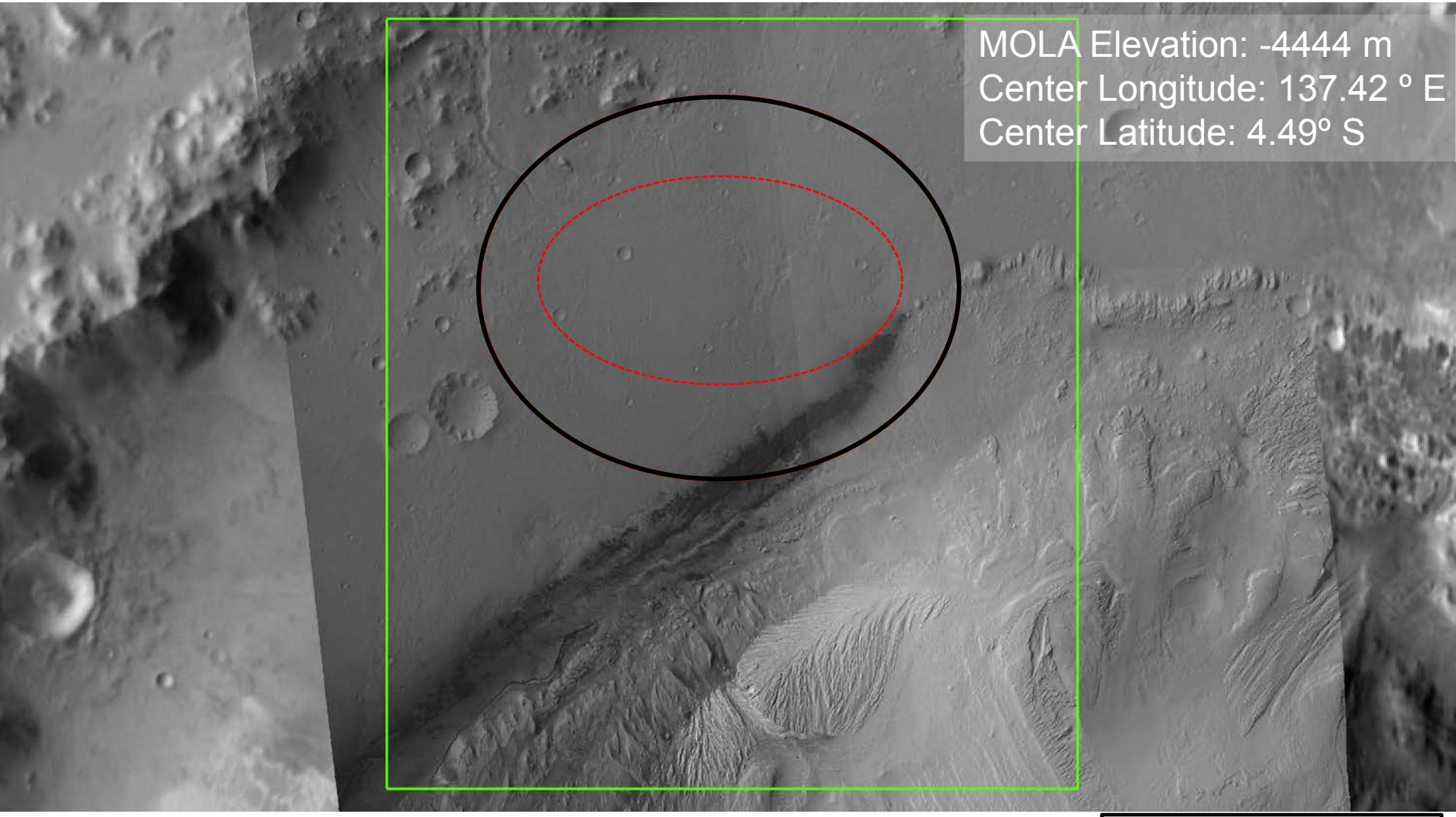
- Lifted-Guided Entry
  - Angle-of-Attack = 15-20 degrees (L/D = ~0.25)
  - 3-Axis RCS Attitude Control
    - Exo-Atmospheric Phase prior to Entry
      - Spin-Down from 2rpm Spin-Stabilize Cruise Phase
      - Turn to Entry Attitude
    - Stabilize Plant through regions of Static and Dynamic Aerodynamic Instability
    - Bank/Roll Control to direct Lift
  - Apollo Entry-Guidance Algorithm
    - Range and Cross-Range Control

	Viking	MPF	MER	PHX	MSL
Landing Ellipse	300 km x 100 km	200 km x 100 km	100 x 20 km (LSW 3)	70 x 20 km (shortly before landing)	20 x 14 (us now)



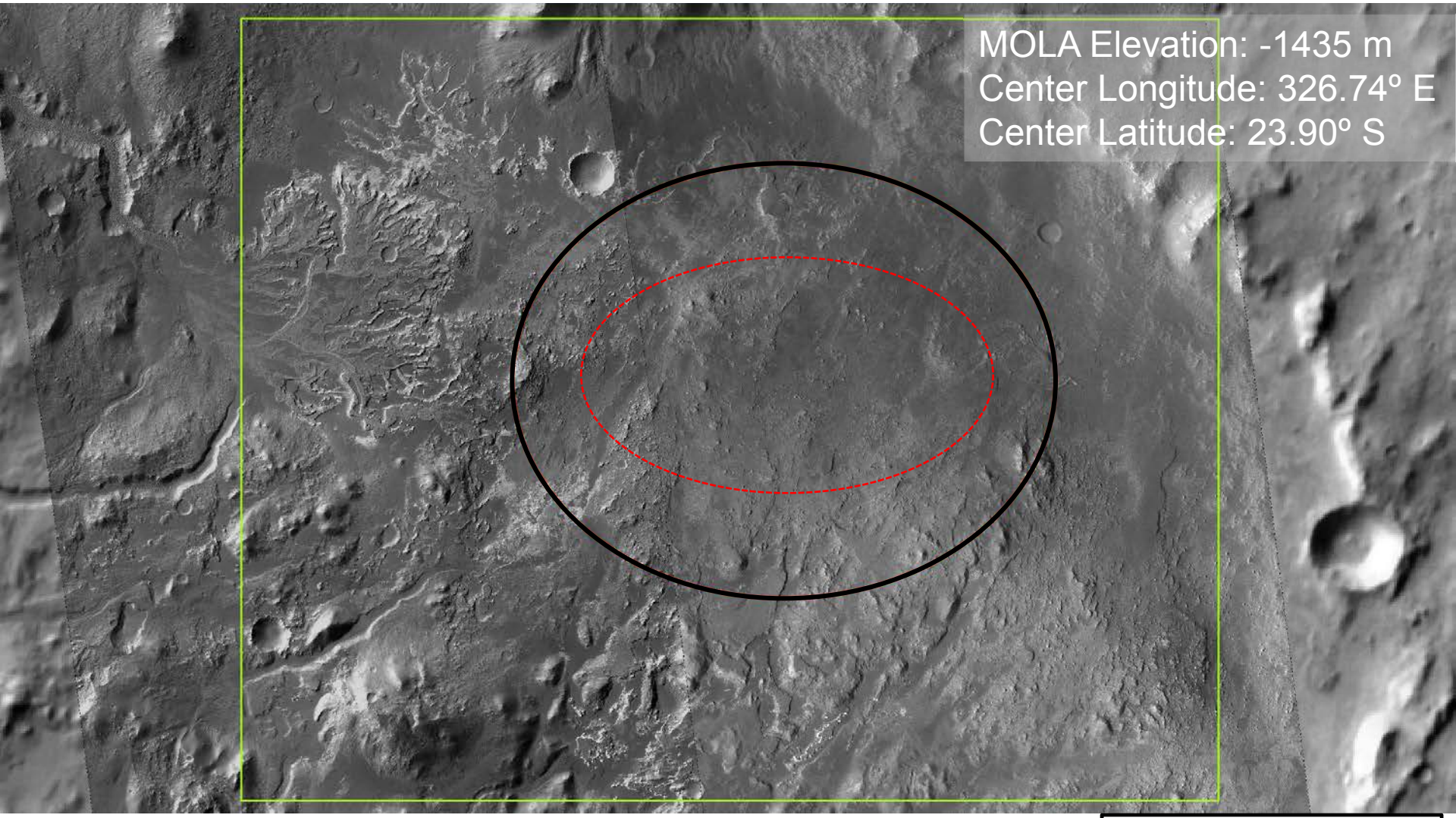
To scale, 2.5 in = 100 km

Gale



= 20km x 25km Ref. Ellipse
= 99% Ellipse Performance

Eberswalde

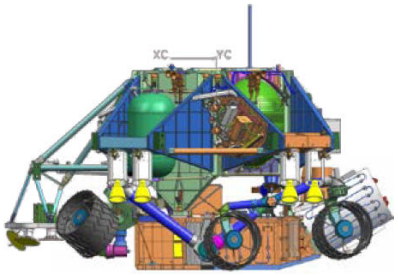


= 20km x 25km Ref. Ellipse
= 99% Ellipse Performance

MSL EDL/GN&C Challenge

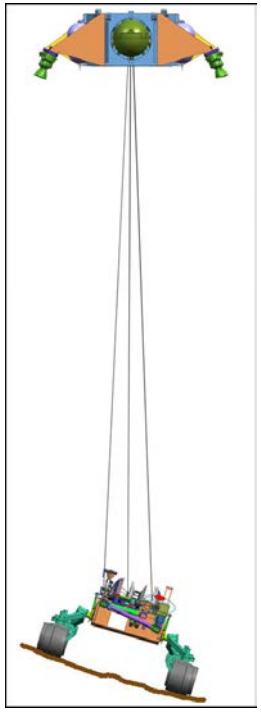
EDL Challenge

- Land a 950Kg Rover over terrain with:
  - < 30 degree slopes, and
  - < 1.2 meter rocks



Response

- 6-Axis Powered-Descent + SkyCrane
  - Parachute terminal velocity
    - Vertical = 65 to 100 m/sec
    - Horizontal = 0 to 40 m/sec
  - Powered-Descent Start Altitude
    - 1.5 to 2 km
  - Rover touchdown velocity
    - Vertical = 0.75 m/sec, +/- 0.1m/sec (3-sigma)
    - Horizontal = 0 m/sec, +/- 0.5 m/sec (3-sigma)
  - Descent Stage touchdown velocity
    - Vertical = 0.75 m/sec, +/- 0.1 m/sec (3-sigma)
    - Horizontal = 0 m/sec, +/- 0.1 m/sec (3-sigma)



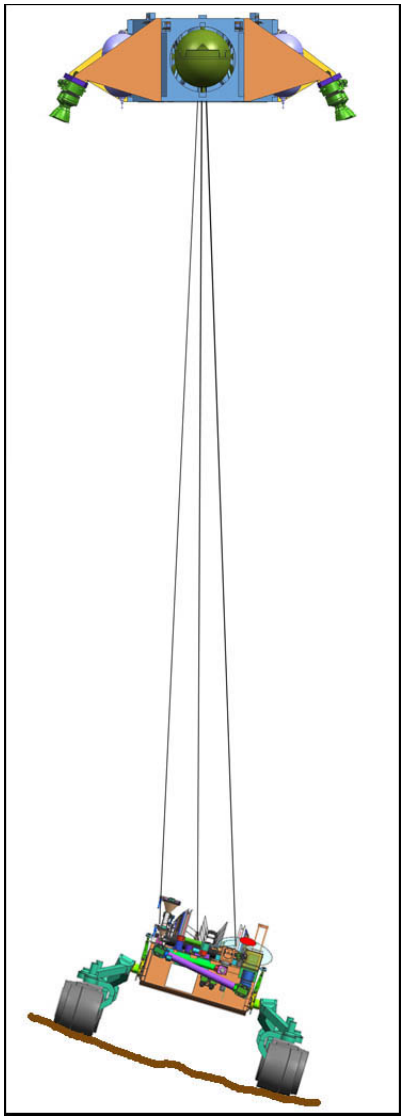
Advantages of the SkyCrane at Touchdown

- Two-body architecture and rocket plumes distance to the ground enables continued GN&C operation during touchdown event

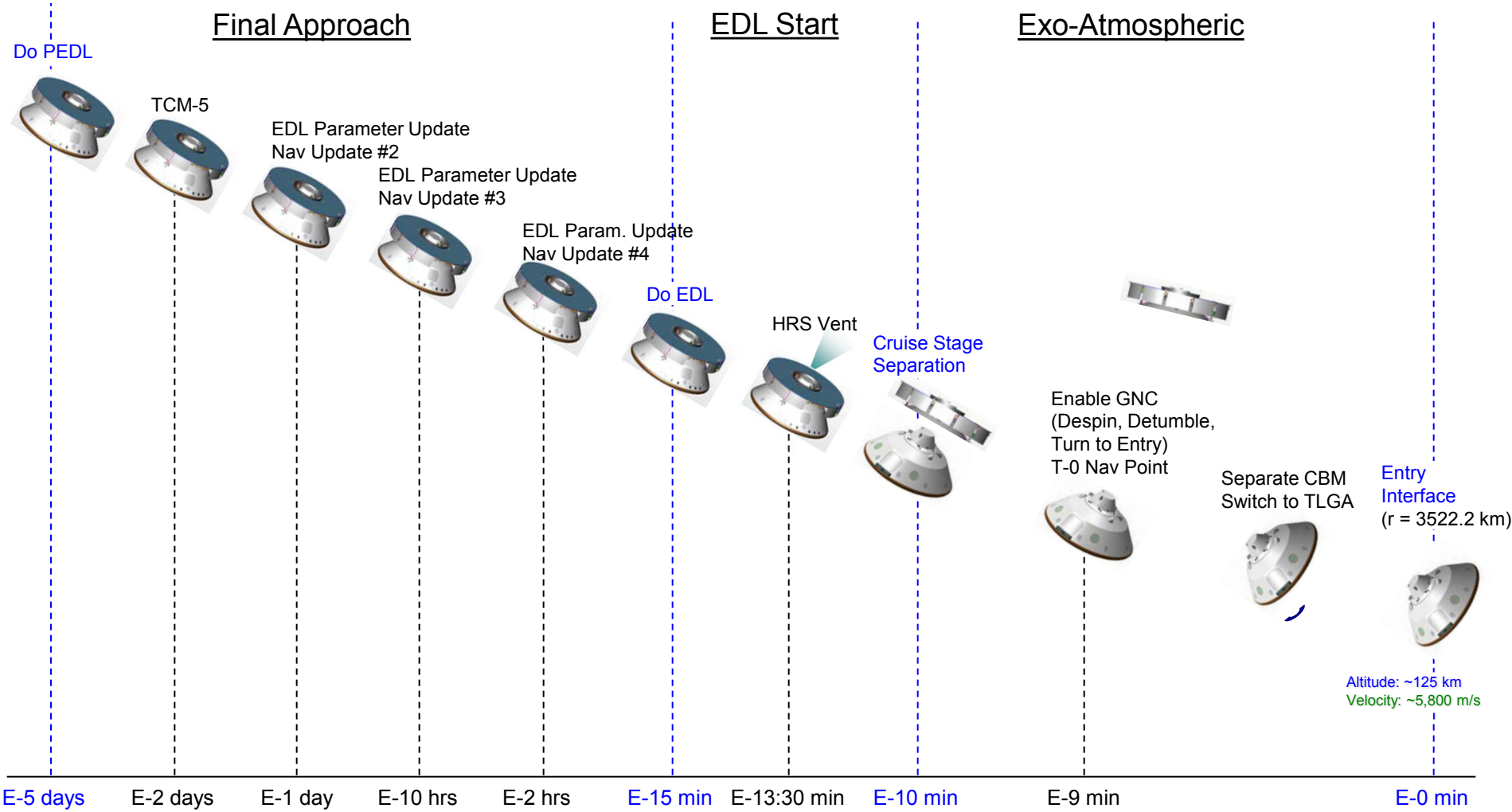
- **GN&C is part of the Touchdown System**

- The Descent Stage softly offloads the rover on the Mars surface
  - Reduces touchdown loads
  - Improves touchdown stability
  - Can land on mobility
    - No need for specialized touchdown gear
    - Solves rover egress problem

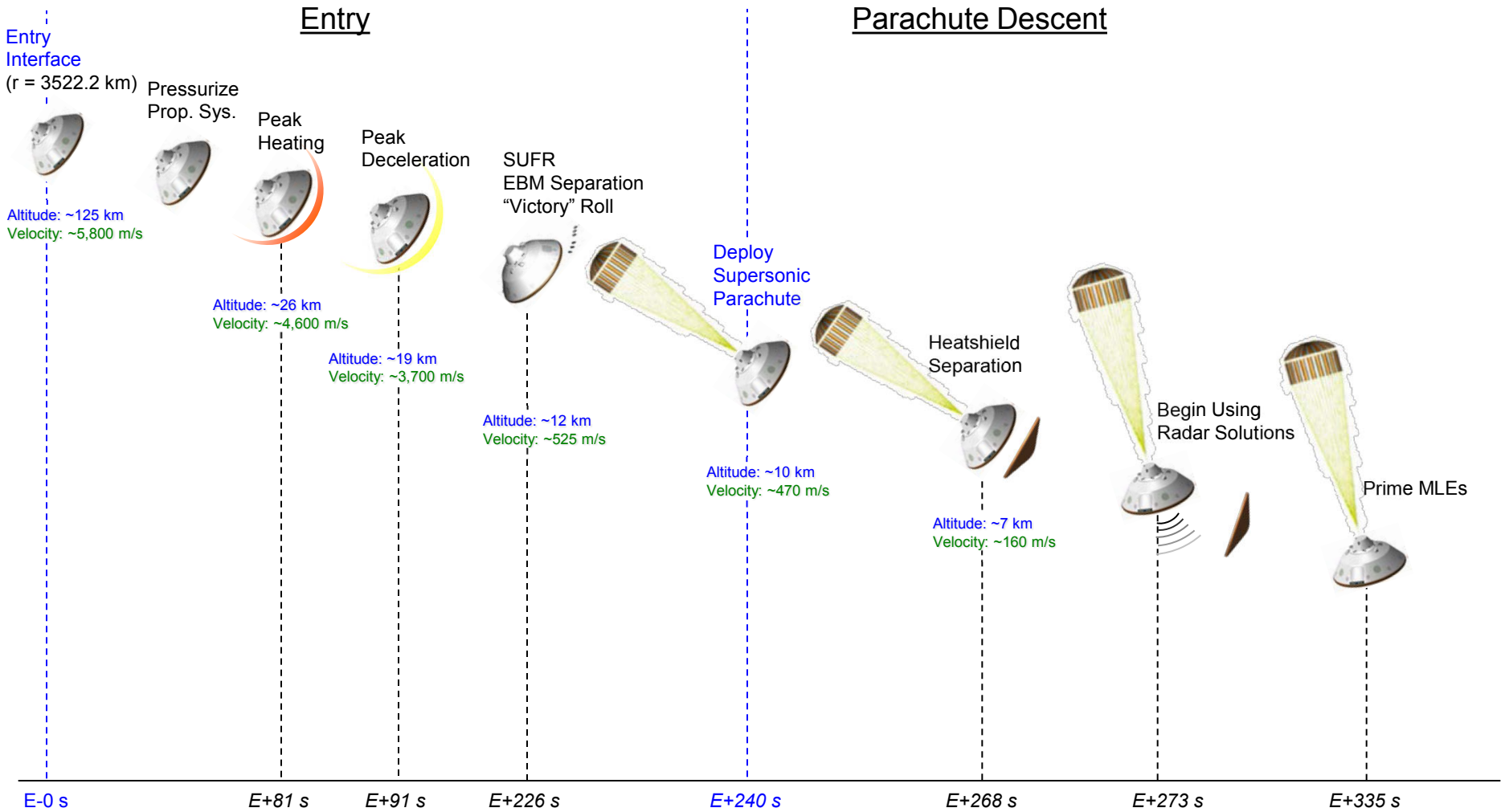
- Minimum touchdown vertical velocity is limited by fuel
  - Driven by altitude knowledge errors



Event Timeline 1/3



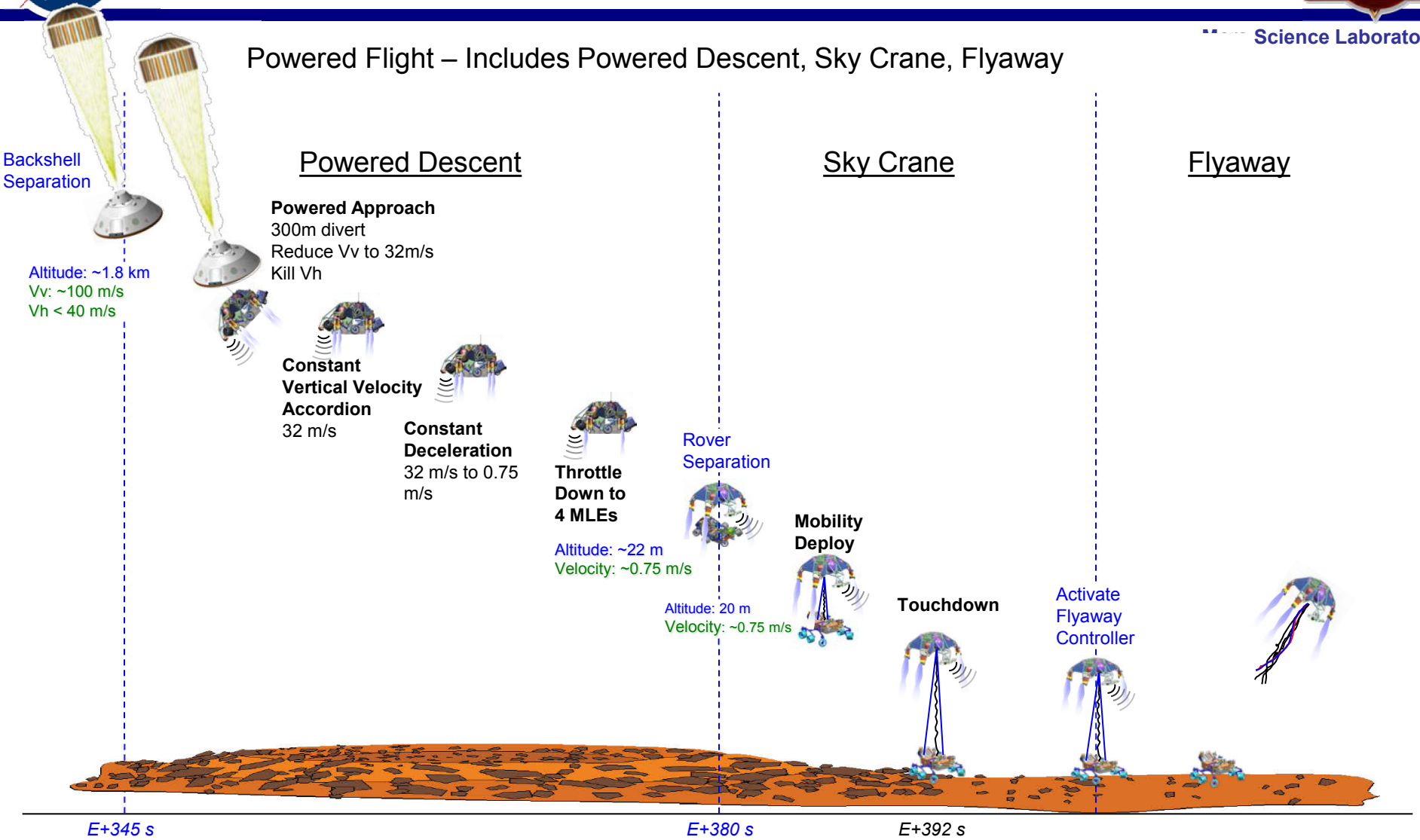
Event Timeline 2/3



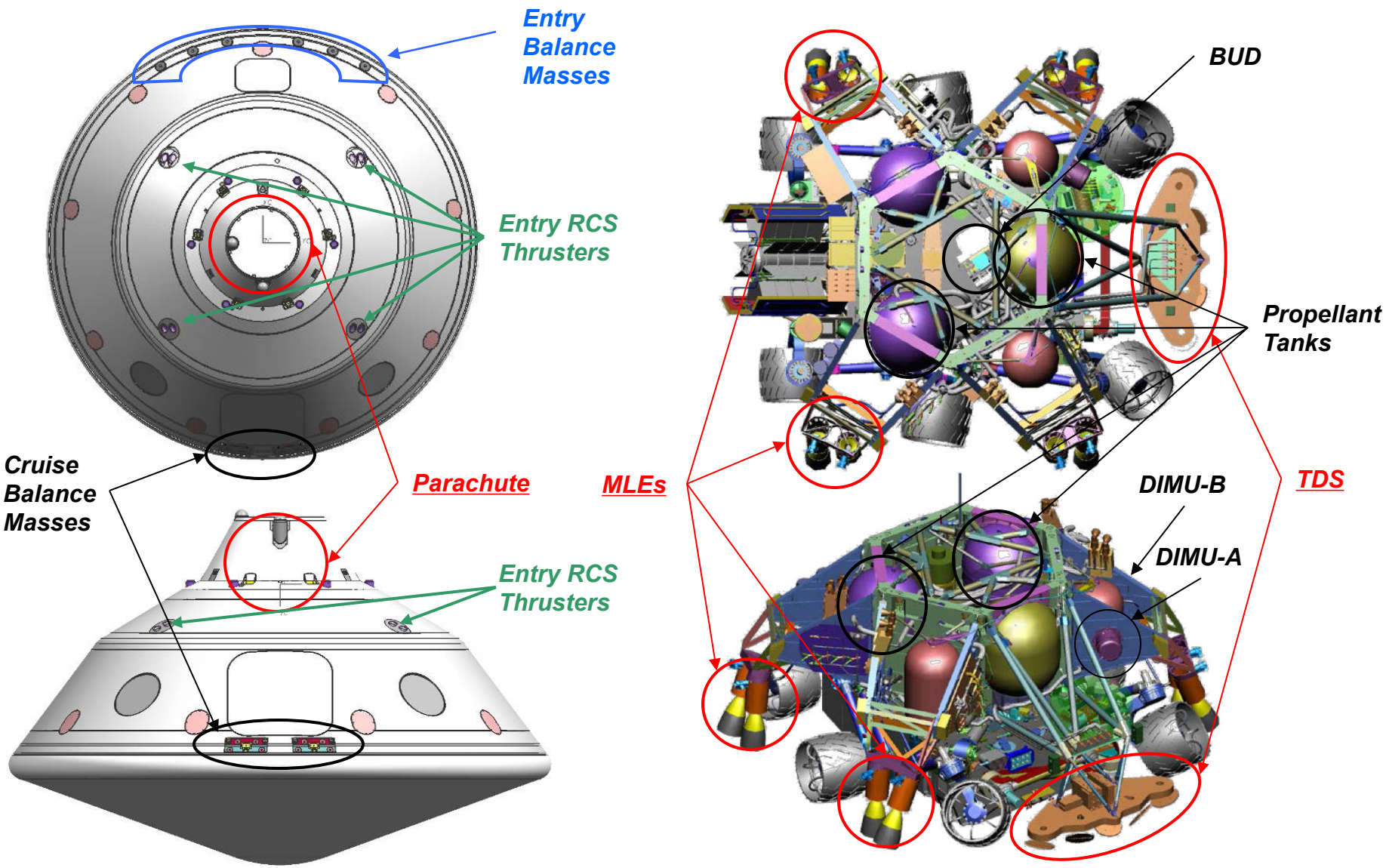
Event Timeline 3/3

Mars Science Laboratory

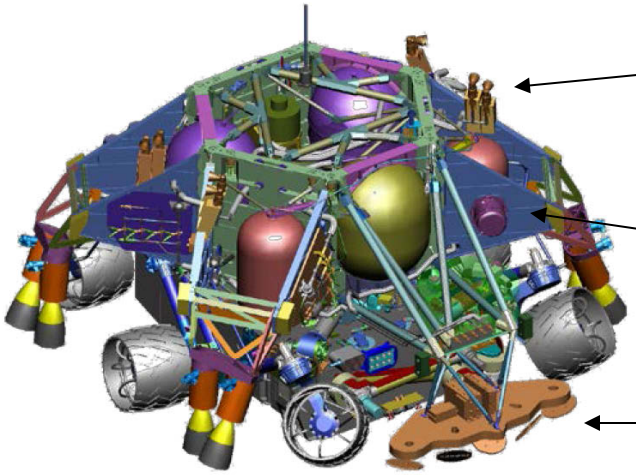
Powered Flight – Includes Powered Descent, Sky Crane, Flyaway



Key EDL Hardware



Descent Stage Configuration

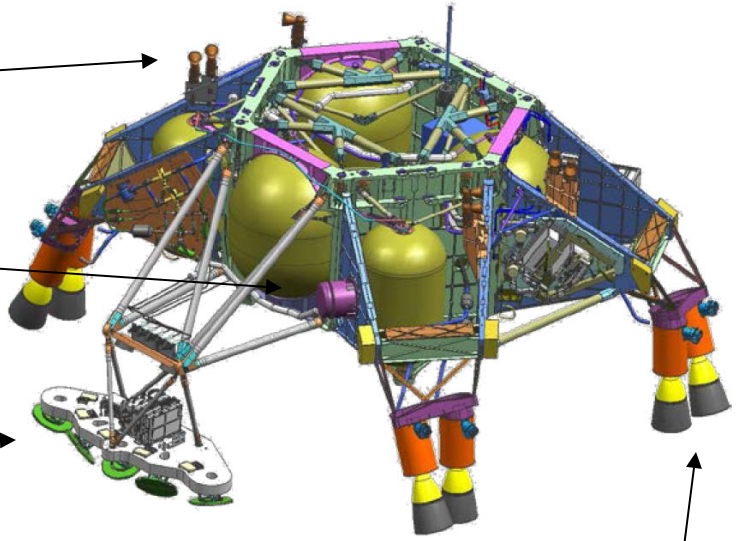


Descent Stage
Entry Configuration

Entry RCS 8x

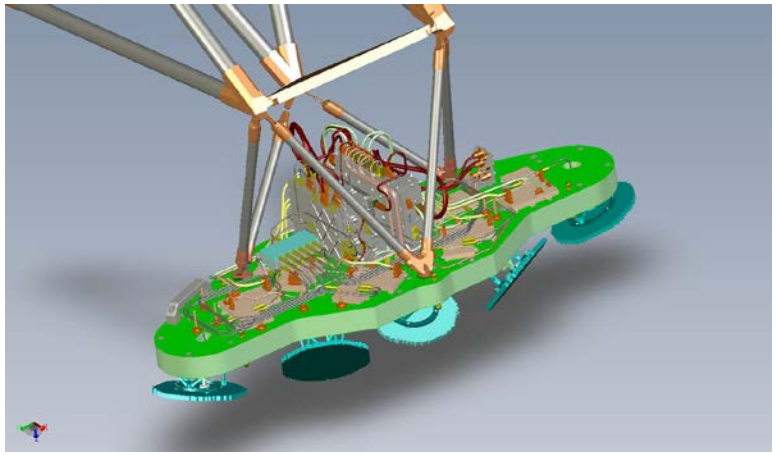
Descent IMU
(DIMU) 2x

Terminal
Descent
Sensor
(TDS) 1x



Descent Stage
Skycrane Configuration

Mars
Landing
Engines
(MLEs) 8x



Terminal Descent Sensor (TDS)

IMU

- 2 IMUs (primary and backup)
  - Honeywell MIMU
- It provides 3 axis position and attitude knowledge in the form of:
  - Accumulated angle for each DIMU axis.
  - Accumulated sensed acceleration for each DIMU axis.
- Operation:
  - One IMU operational at a time.
  - IMU selection done before EDL.

DIMU (MIMU)

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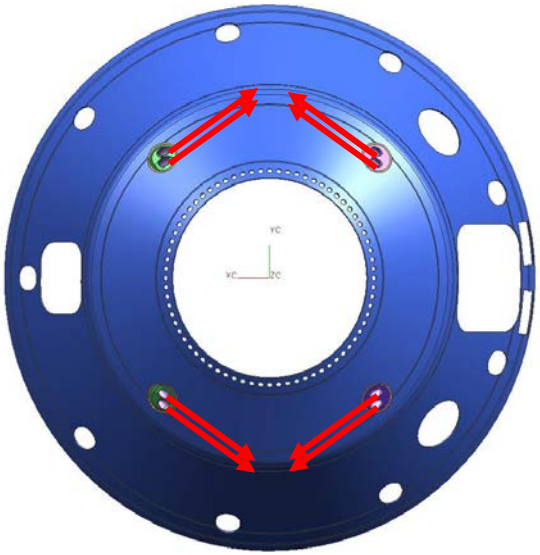
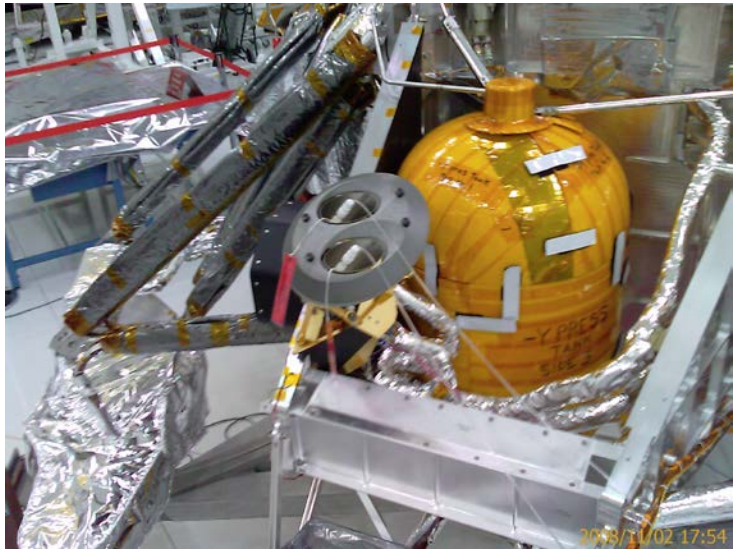
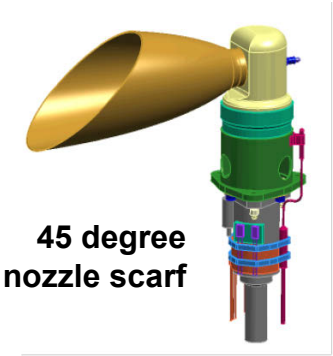
RCS

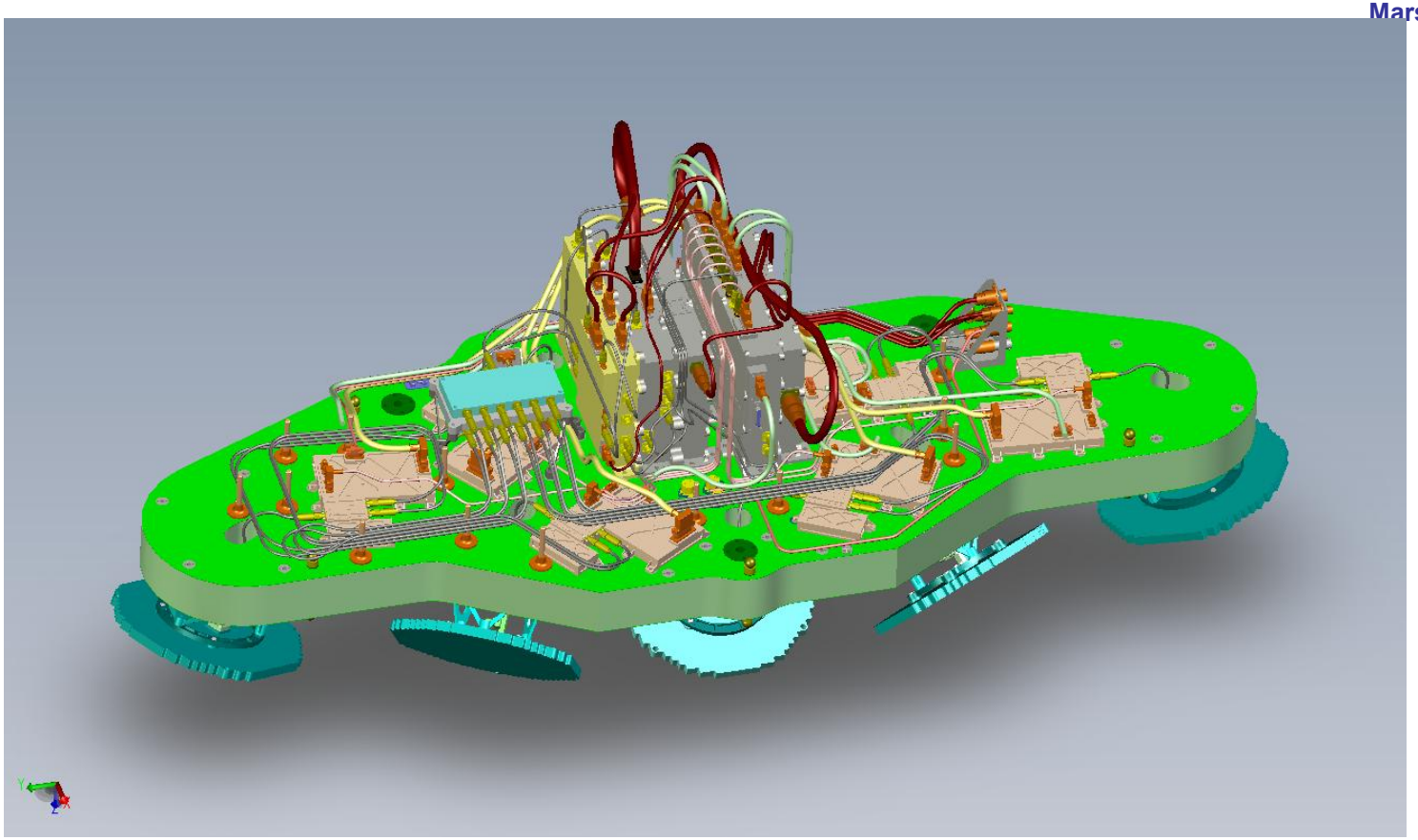
- **Used for Entry and Parachute Descent only**
- **Monopropellant propulsive system**
  - Blowdown operation during exo-atmospheric phase (~150 N)
  - Pressurized during entry phase (~250 N)
  - 8 RCS thrusters in pairs.
  - RCS configuration re-re-designed to minimize aero-RCS interactions.
- **Operation**: Commanded at 64 Hz





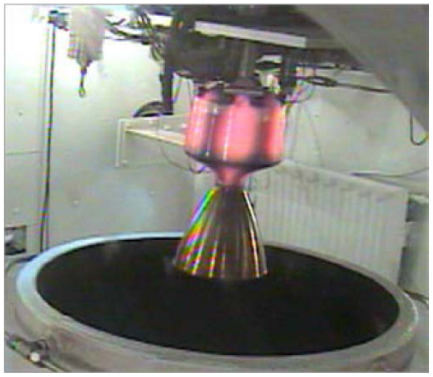


Terminal Descent Sensor



- **The Radar Terminal Descent Sensor produces line of sight range and velocity measurements on 6 independent narrow (~3.5 deg) beams**
  - **Single antenna per beam, with 3 beams canted 20° off nadir, 2 beams canted 50° off nadir, and 1 nadir beam**
  - **Ka-band (35.75 GHz) center frequency**
  - **Pulse doppler radar design**

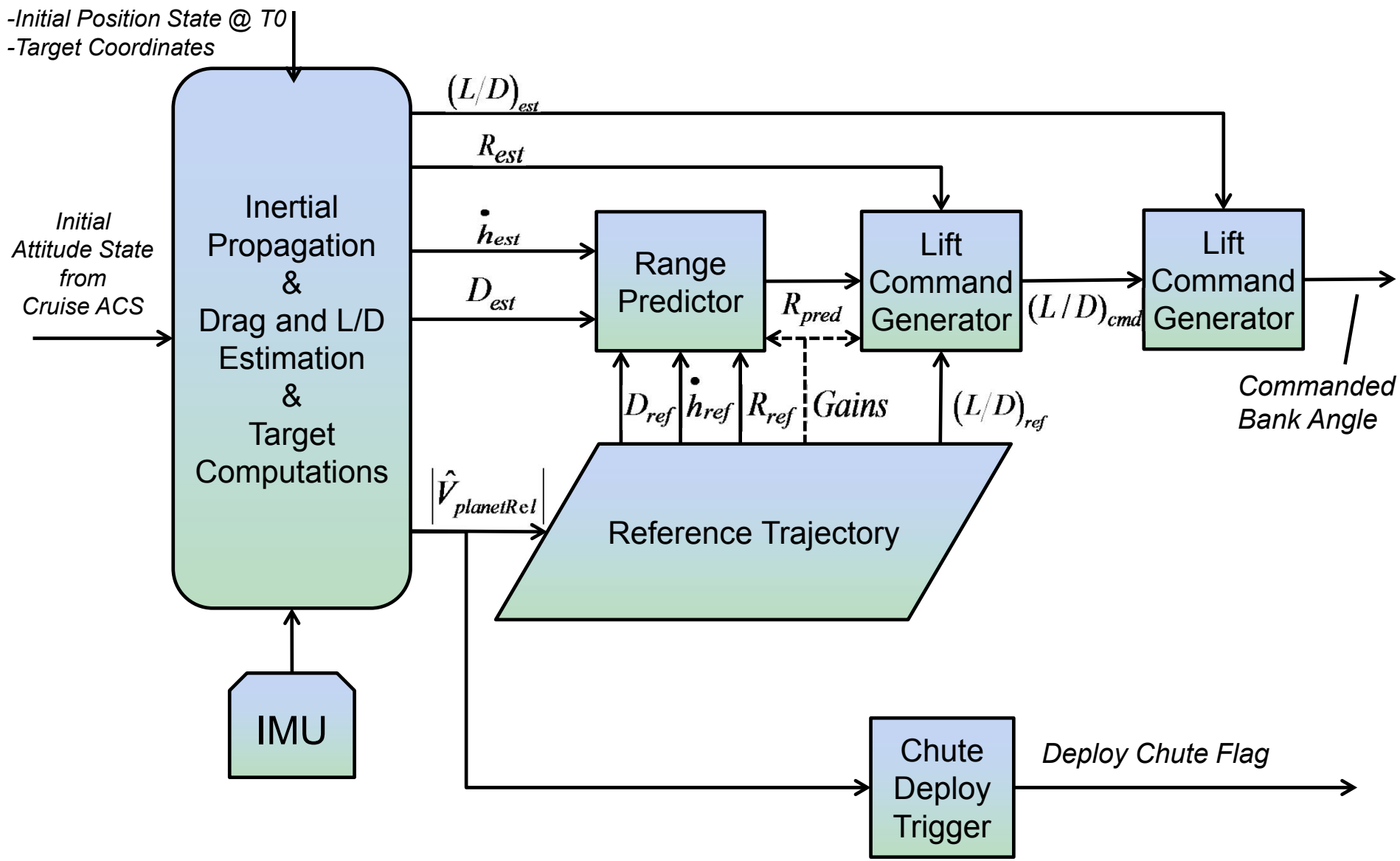
Key MLE Features



- MLE design based on Viking descent thruster design
  - Updated catalyst bed retention design and updated materials
  - New cavitating Throttle Valve Assembly (TVA) makes flow independent of downstream pressure drop
- Key performance characteristics
  - Delivered thrust at maximum throttle setting ≥ 3060 N / engine at 600 psia inlet pressure
  - Nominal throttle range 400 N to 3060 N
  - Minimum specific impulse is a function of thrust level:
    - 221 lbf-s/lbm @ 3060 N
    - 213 lbf-s/lbm @ 1500 N
  - MLEs are capable of operating at “near shutdown” (about 1% of maximum flow):
    - Following initial ignition (prior to warm up)
    - From the start of the sky crane phase to the end of flyaway
    - There is no fully closed position of the throttle valve
- Bandwidth (TVA + reactor) = ~15 Hz
- Accuracy = 5%

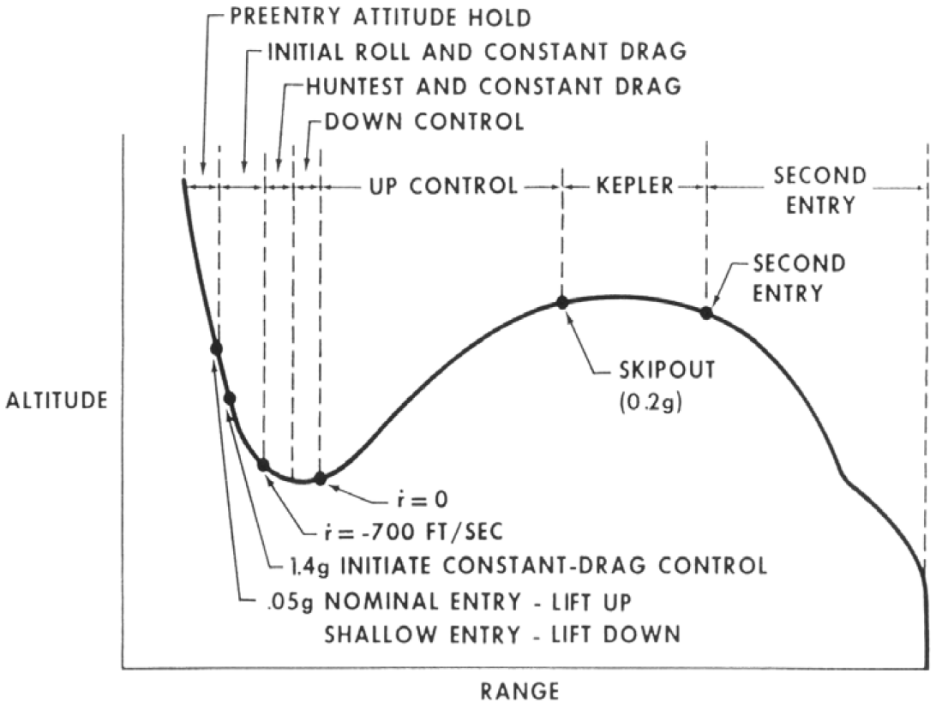
Flight Descent Stage and Rover

Range Entry Guidance



Ranging control Implementation

Heritage Apollo Entry profile



Only the second entry phase logic is used for Mars.

K_3 is an "L/D over-control" gain to adjust the level of aggressiveness in the convergence of predicted range to the actual range.

Second entry phase guidance equations:

Predicted range:

$$R_p = R_{ref} + \frac{\partial R}{\partial D}\left(D - D_{ref}\right) - \frac{\partial R}{\partial \dot{h}}(\dot{h} - \dot{h}_{ref})$$

Vertical L/D command:

$$\left(\frac{L}{D}\right)_C = \left(\frac{L}{D}\right)_{ref} + \frac{K_3\left(R - R_p\right)}{\partial R / \partial\left(L/D\right)}$$

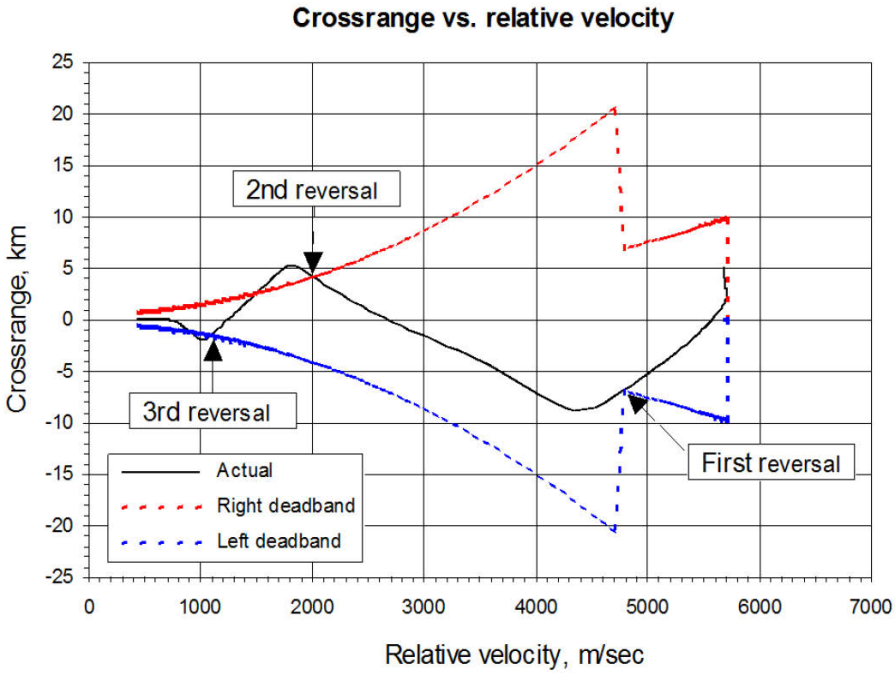
Bank angle command:

$$\phi_C = \cos^{-1}\left(\frac{L/D_C}{L/D}\right) * K2ROLL$$

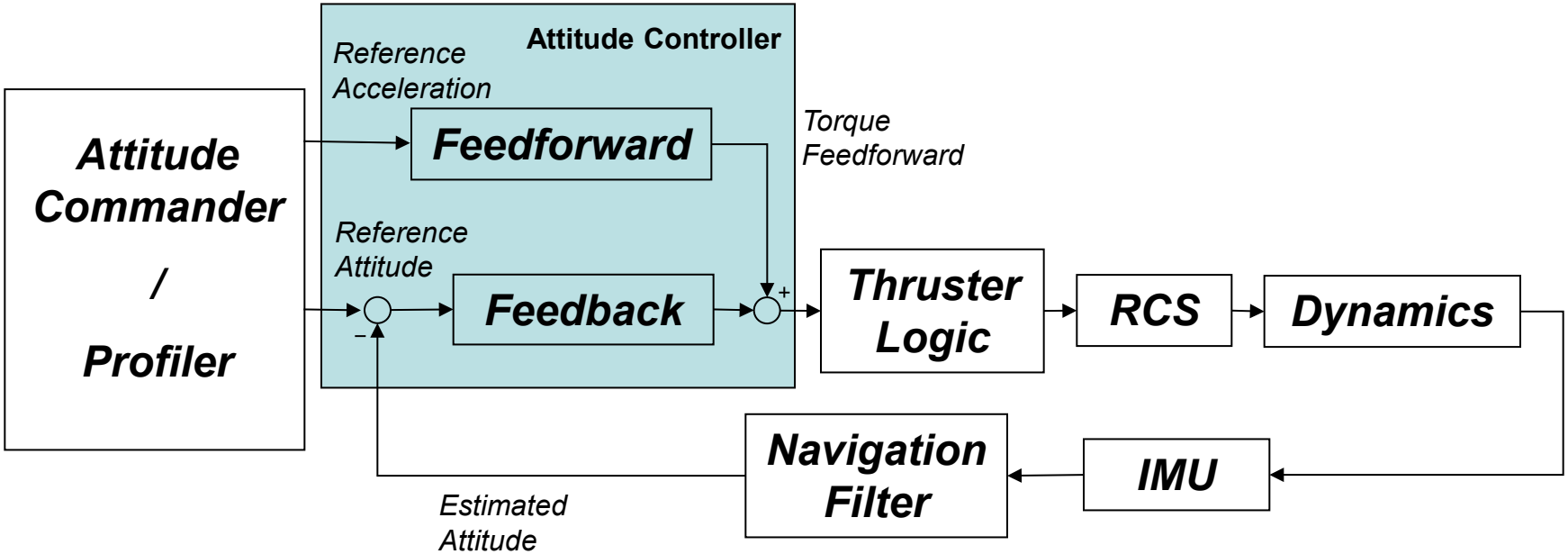
K2ROLL is the bank direction flag (+/- 1)

Lateral control

- Cross-range control is accomplished by bank reversals which are performed at corridor limits on the target out-of-plane central angle (LATANG).
  - Reversal triggers are quadratic functions of relative velocity.
  - A tighter dead-band is used prior to the first reversal to protect low L/D dispersed cases.
  - A minimum bank angle command of 15 deg is reserved in the direction toward the target.
- Ranging control effectiveness becomes significantly diminished at low velocities, but heading control effectiveness is maintained at lower velocities.
  - Bank angle commands are switched to a heading alignment controller for Vrel<1100 m/sec, to null final cross-range errors with proportional control.



Entry Attitude Controller Block Diagram



- Feedforward provides the torque needed to achieved the desired angular acceleration requested by the attitude profiler. Acceleration profile calculated by profiler once. Angle profile adjusted to follow current guidance command. Discrepancy between acceleration and angle profiles to be handled by feedback controller.

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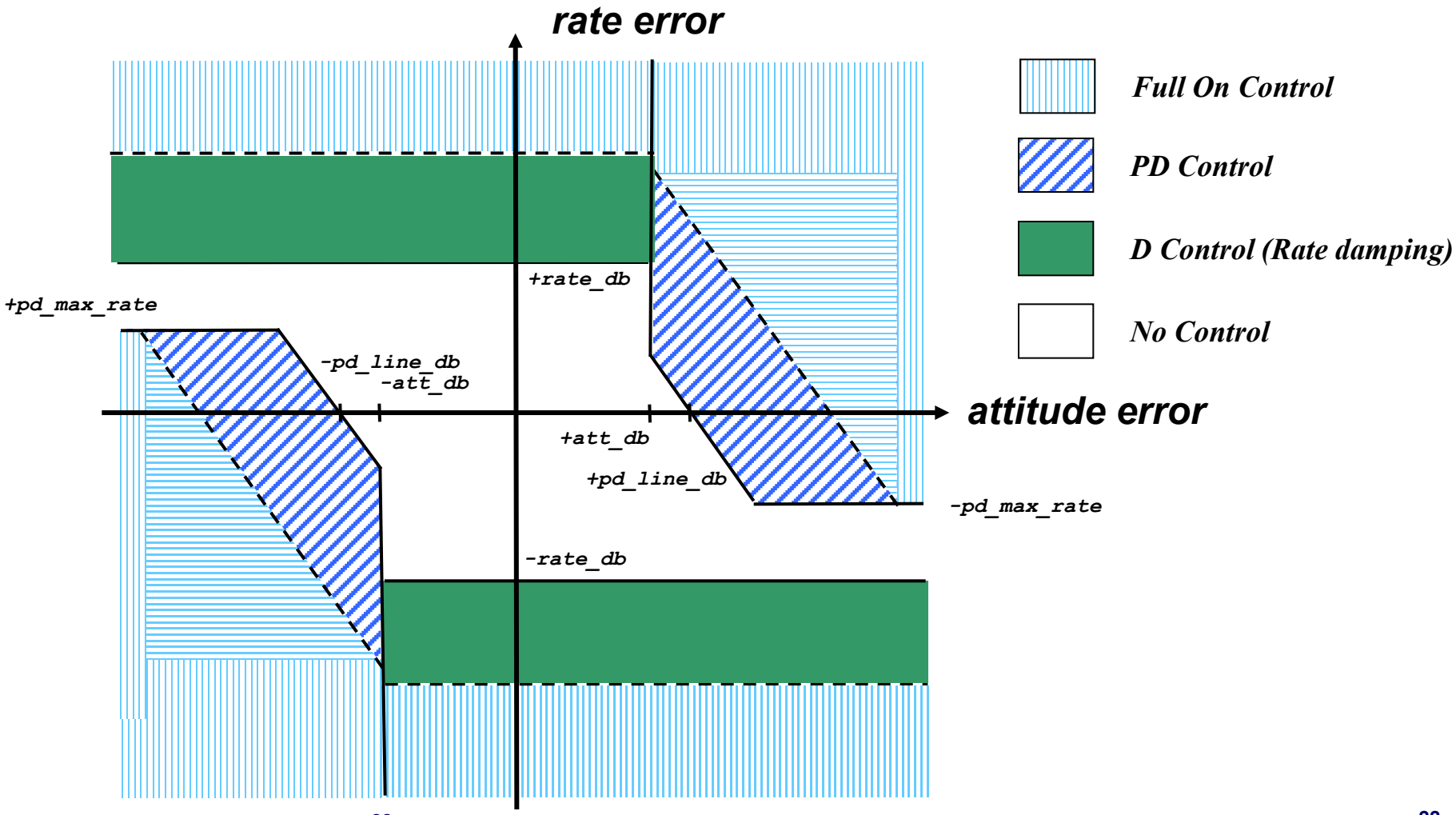
Feedback Design

- 3-axis PD/D controller (in control frame) with attitude and rate deadbands and switching lines to minimize fuel usage



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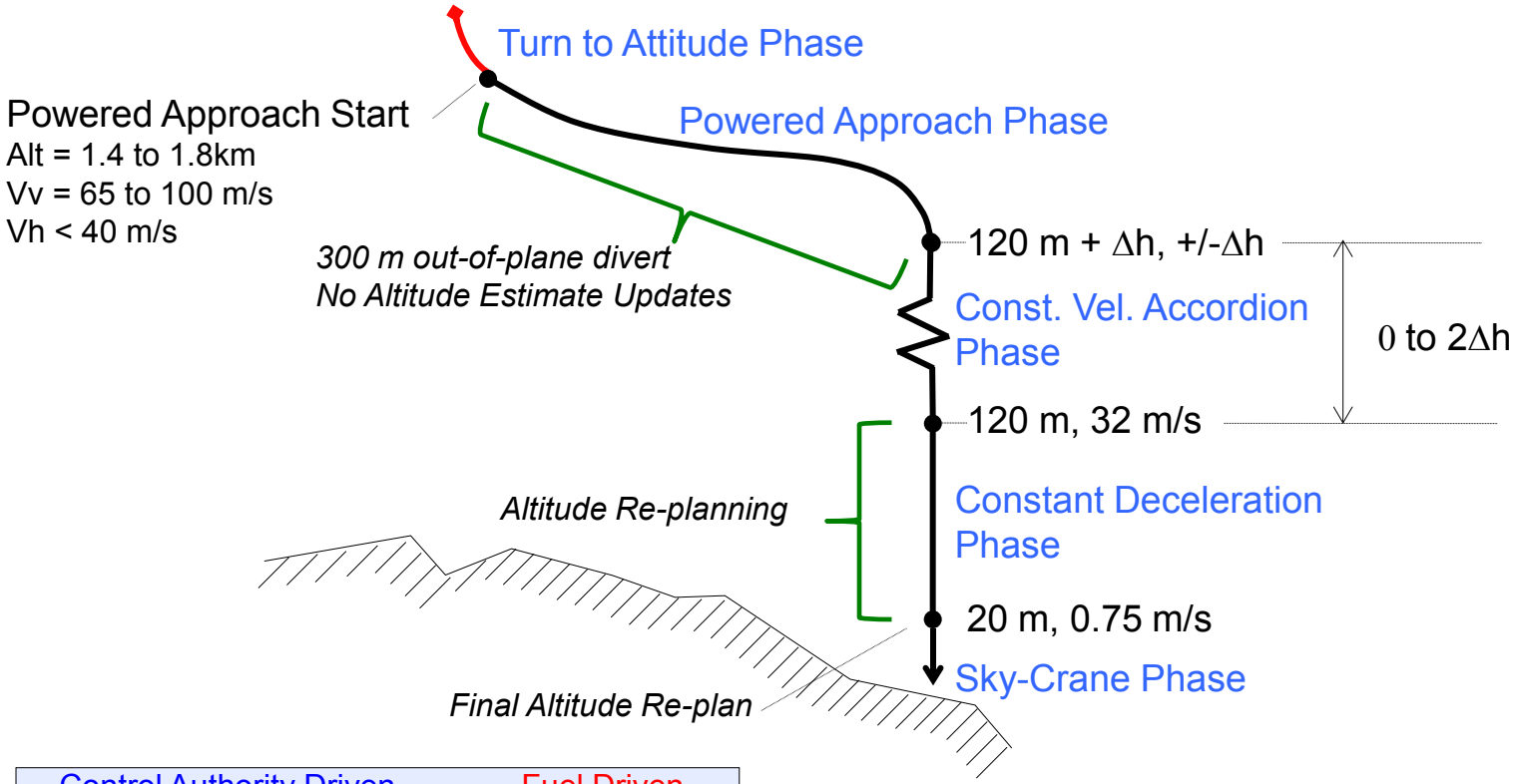
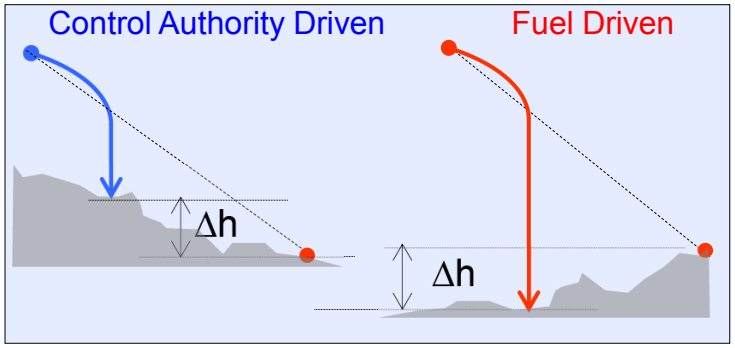
Terminal Descent Phases

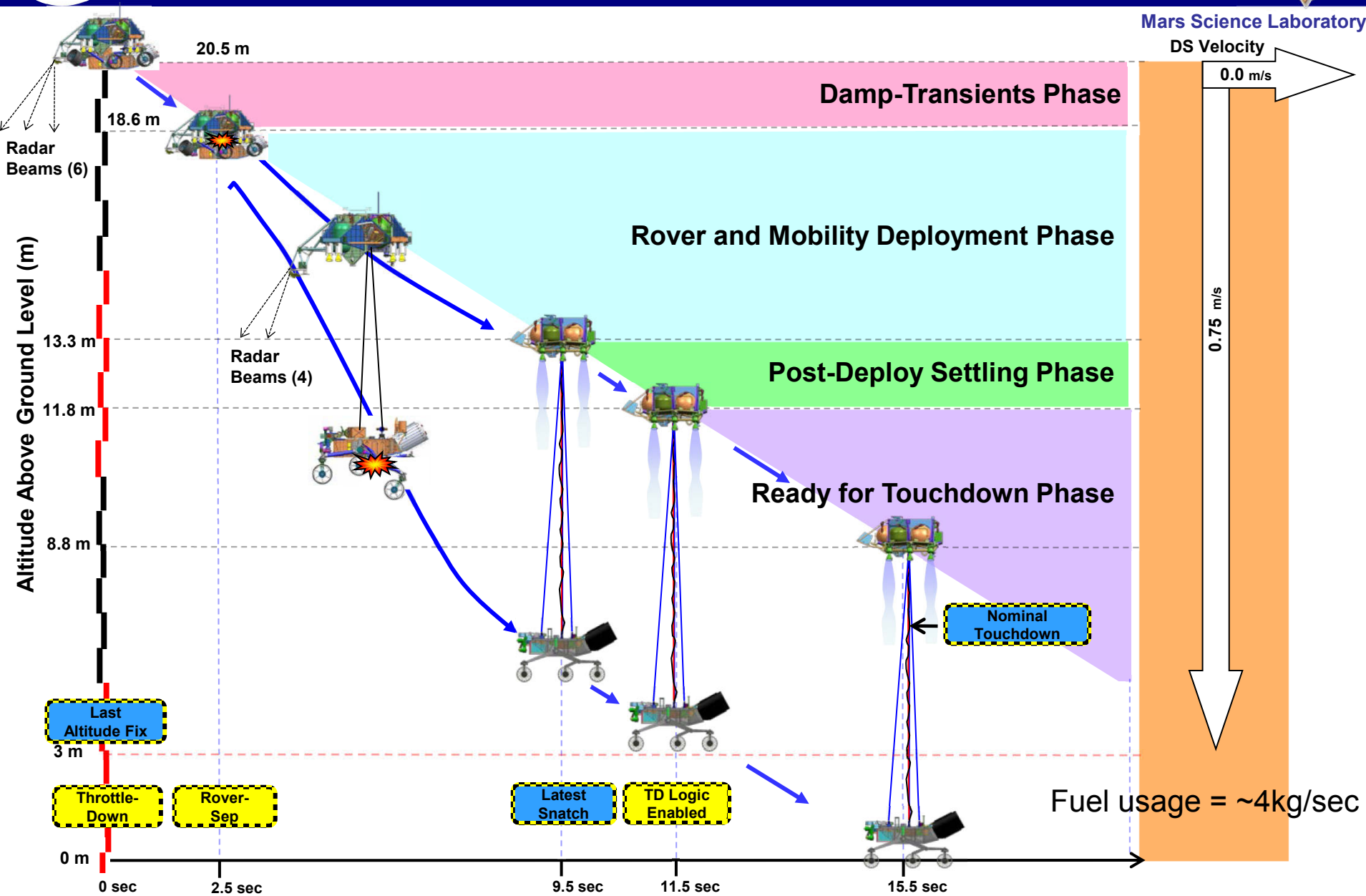
Altitude Knowledge Management



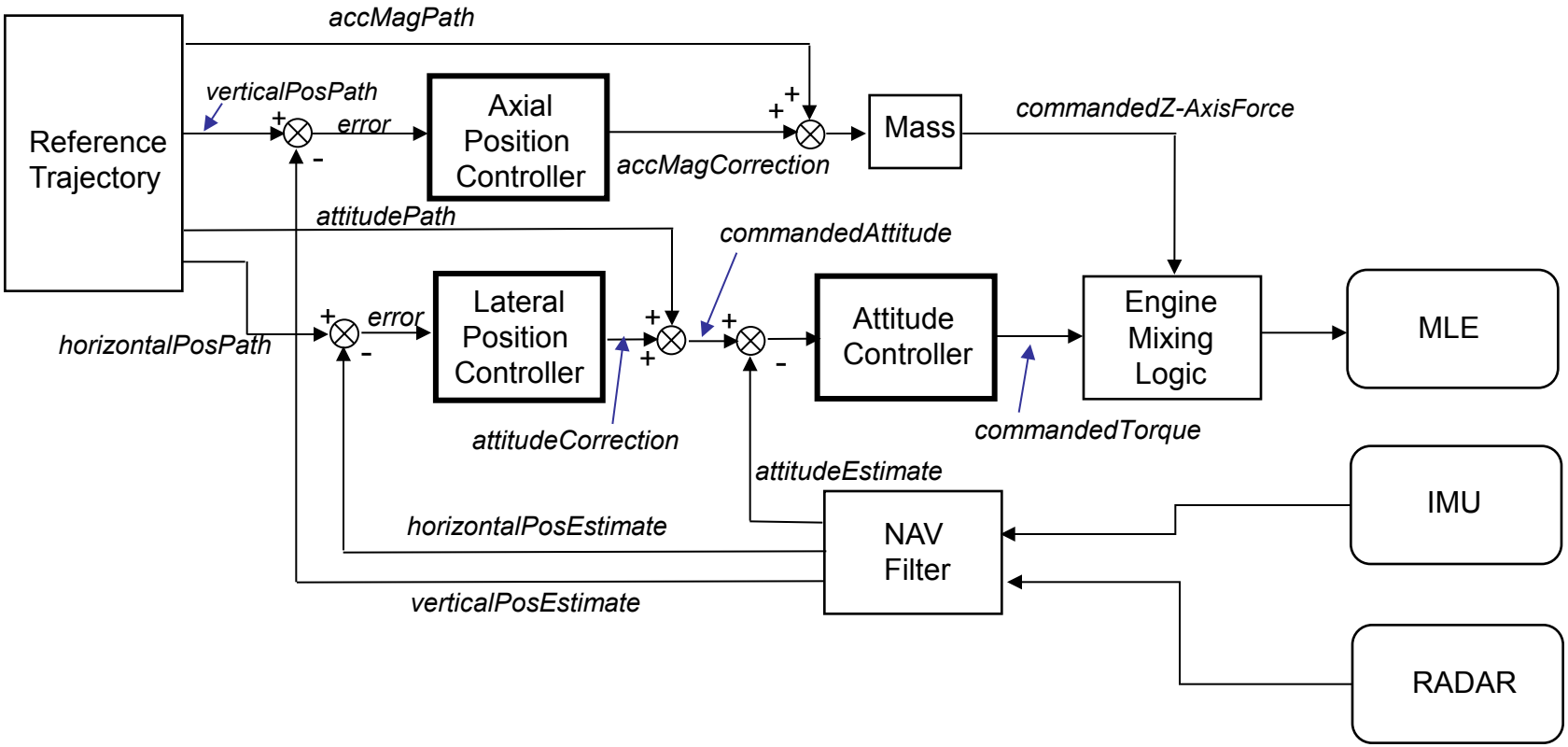


Δh = Altitude Uncertainty

Sky Crane Maneuver Description

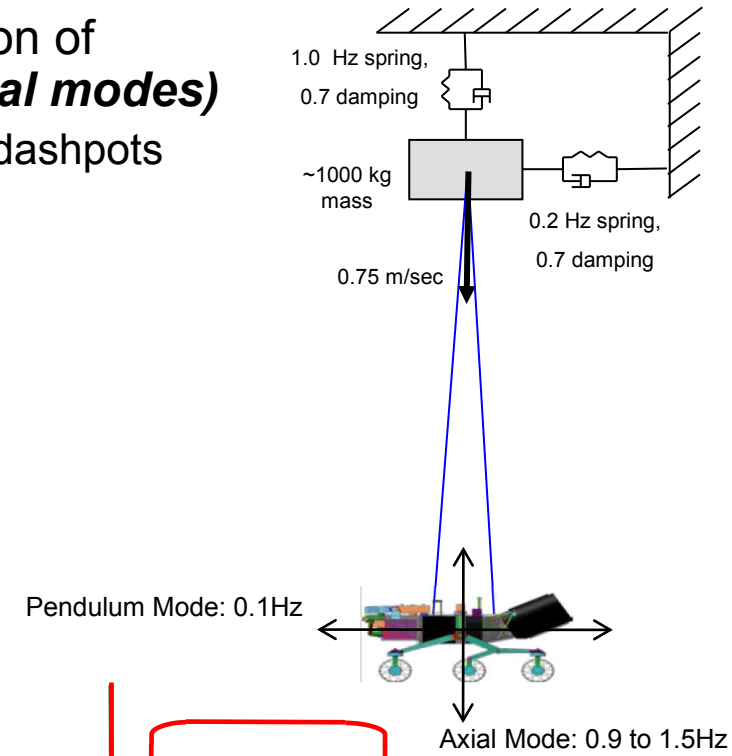


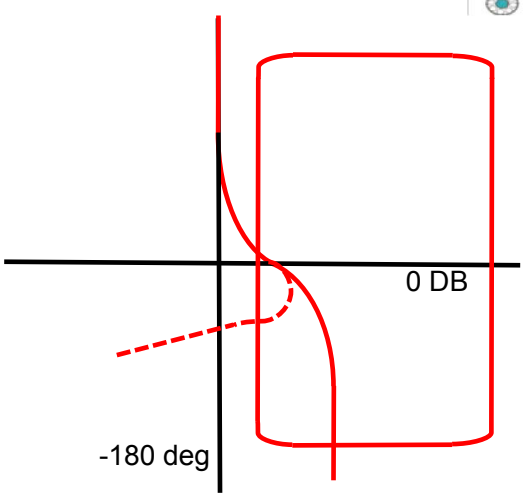
Powered Descent Control Block Diagram
Sky Crane Phase



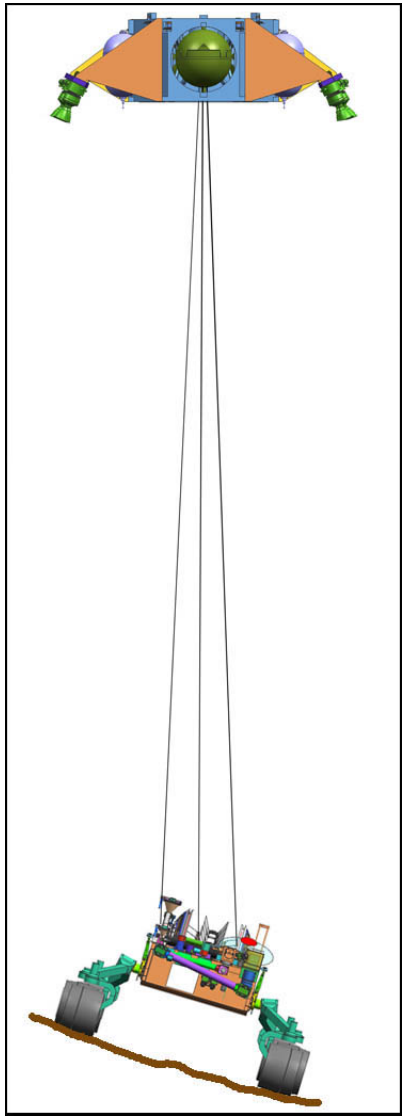
Control Design Design for Robustness

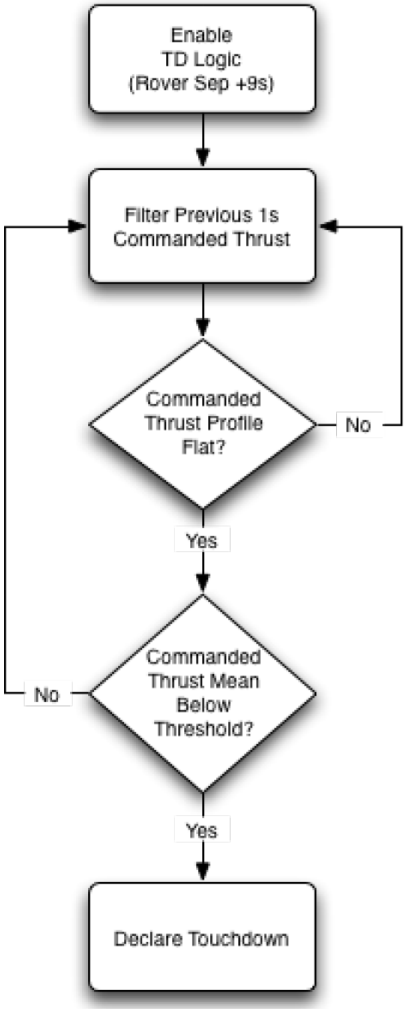
- Robust stability is achieved by phase stabilization of ***appendage modes (pendulum and bridle-axial modes)***
  - Make the control system behave as springs and dashpots
    - Collocated sensing (IMU) and control (MLE)
      - 16 Hz structure
    - High sampling rate and a single sample delay
      - 64 Hz sample rate
    - High bandwidth sensing and control
      - IMU bandwidth > 30 Hz
      - MLE bandwidth > 15 Hz
    - Attitude Control (Inner Loop) Bandwidth
      - ~ 1Hz
    - All modes below 5 Hz are phase stabilized
      - Fuel slosh modes < 2 Hz
      - Bridle mode axial 0.4 to 1 Hz
      - Pendulum mode < 0.2 Hz
      - System robust to uncertainty in mode
        - » Frequency
        - » Damping
- Structural modes are gain-stabilized
  - 8th order roll-off filter

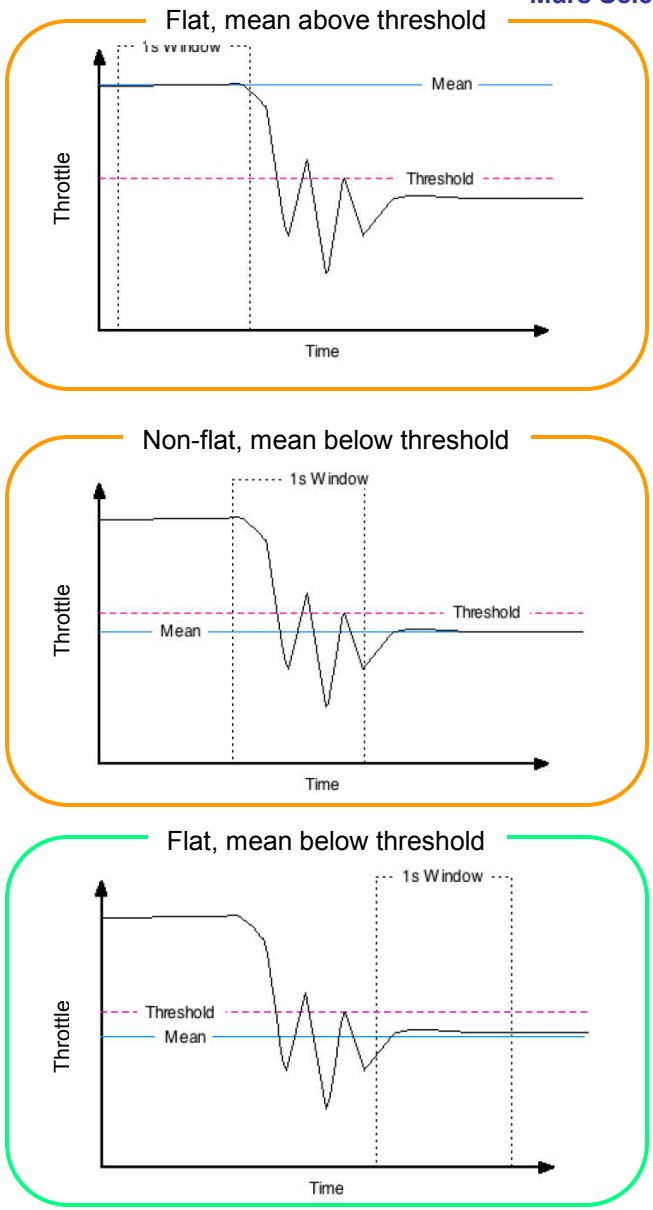




SkyCrane Touchdown Detection







Fly Away

- Descent Stage shall land at a distance > 100 meters from Rover
- Profiled-Closed-Loop pitch-rate profile
- Control law hosted in the Descent Stage MLE/TVA Motor Controller
  - Has access to MLE control
  - Added interface to IMU. Acts as a relay to the Rover Computer
- No explicit transfer of state data
  - Fly-away controller assumes that the Descent State state is
    - Zero velocity
    - Zero attitude rate
    - Aligned with vertical

Summary

- GN&C plays a major role in the MSL mission by
  - Reducing size of landing size ellipse
  - Enabling the super-soft landing of a large payload on hazardous terrain

- MSL GN&C will demonstrate and perform for the first time on Mars
  - Entry Guidance
  - SkyCrane Touchdown

References

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- Gurkirpal Singh, Alejandro M. San Martin, Edward C. Wong, “Guidance and Control Design for Powered Descent and Landing on Mars”, IEEE Aerospace Conference, 2007