National Aeronautics and Space Administration

Guidance, Navigation, and Control for NASA Lunar Pallet Lander

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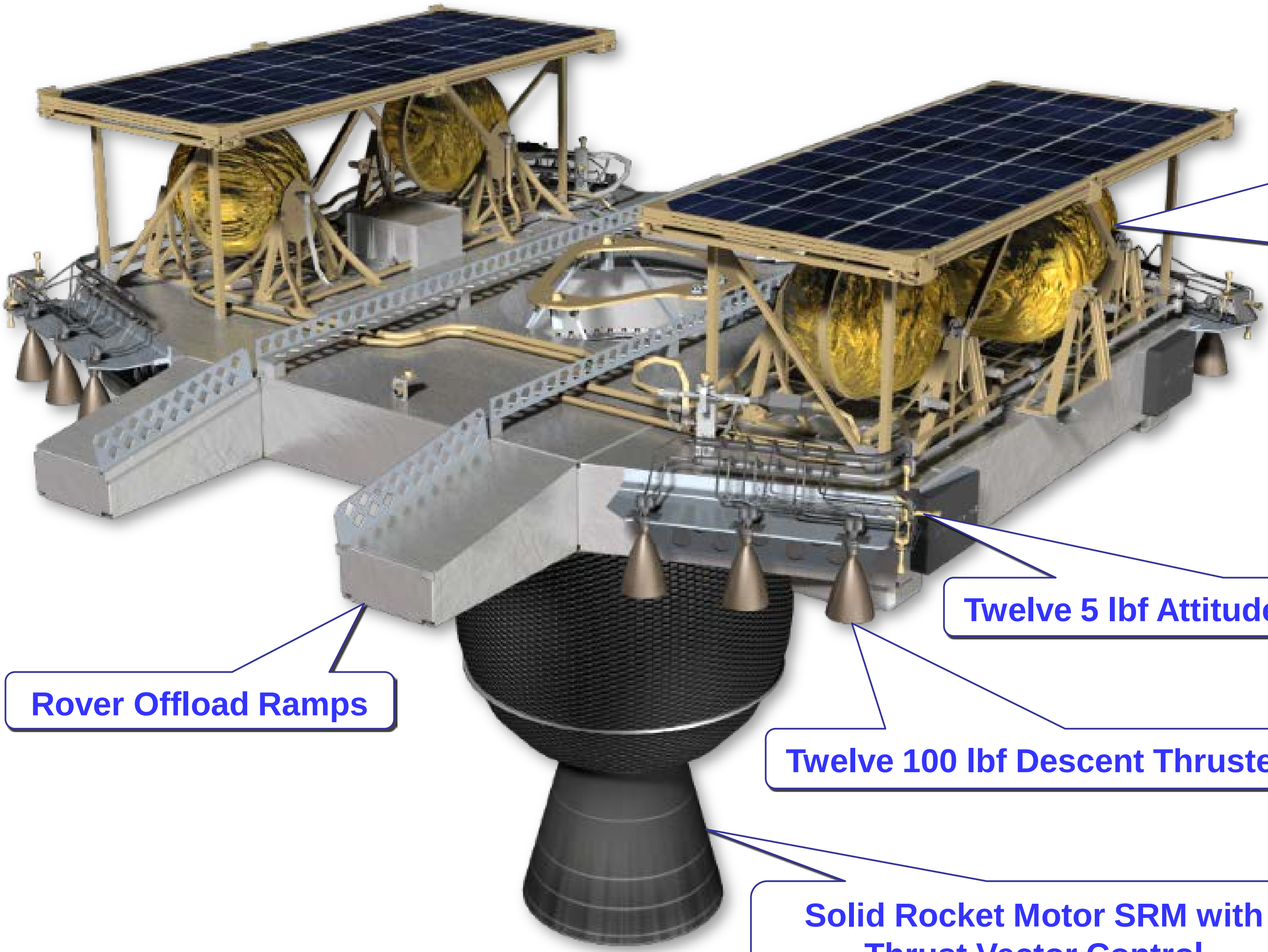
Overview

- Mission Concept
- Mission Requirements and Navigation Sensor Selection
- Vehicle Guidance Navigation and Control Overview
- Simulation Architecture
- Vehicle Landing Performance
- Future Work and Next Steps

Lunar Pallet Lander



Hypergolic Bipropellant: Monomethyl hydrazine and 25%Nitric Oxide or MON25

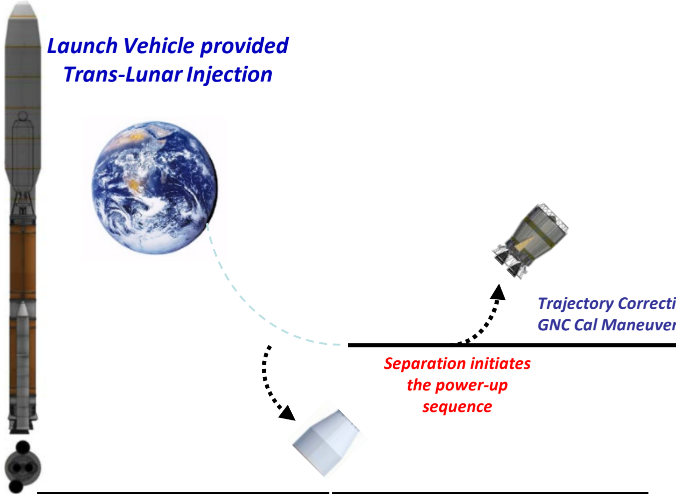
Twelve 5 lbf Attitude Thrusters (On/Off)

Rover Offload Ramps

Twelve 100 lbf Descent Thrusters (On/Off)

Solid Rocket Motor SRM with Thrust Vector Control

Mission Overview

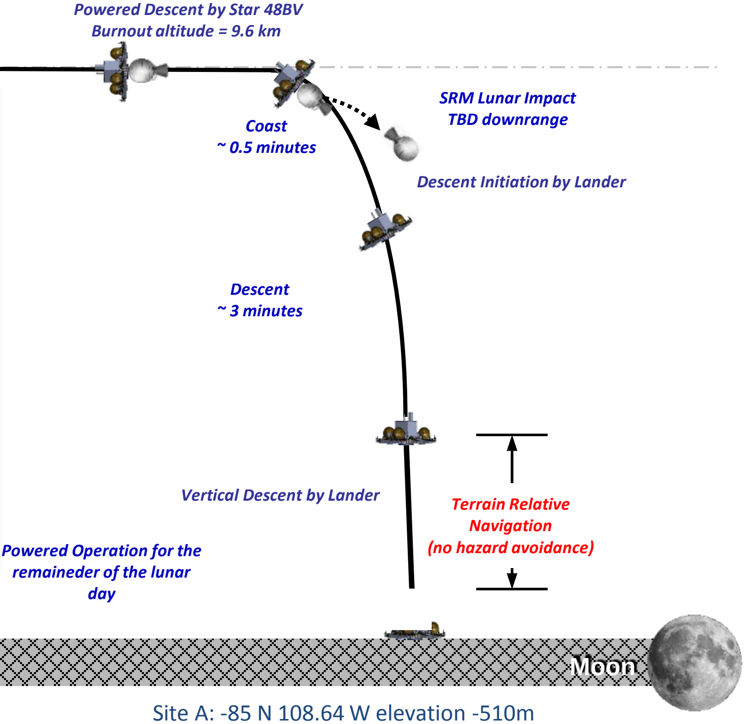


Launch Vehicle provided Trans-Lunar Injection

Separation initiates the power-up sequence

Trajectory Corrections, GNC Cal Maneuver Burns

Lunar Transit ~4 days



Powered Descent by Star 48BV Burnout altitude = 9.6 km

Coast ~ 0.5 minutes

SRM Lunar Impact TBD downrange

Descent Initiation by Lander

Descent ~ 3 minutes

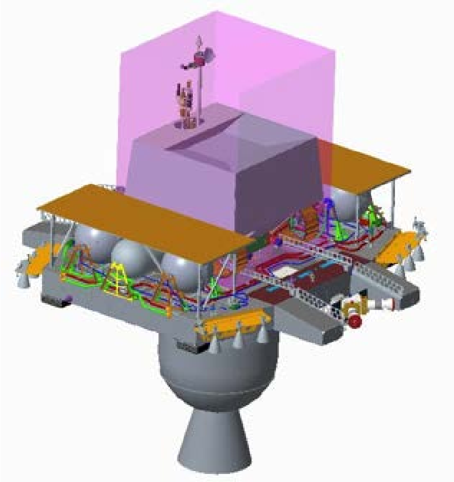
Vertical Descent by Lander

Terrain Relative Navigation (no hazard avoidance)

Powered Operation for the remaineder of the lunar day

Site A: -85 N 108.64 W elevation -510m
Landing: 6/15/2022 12:00 (UTC)

Flight Phase	Delta-V (m/s)
After separation from ELV	
+440-N descent thruster	25 (TCMs)
+22 N ACS thruster (10%)	2.5
SRM Operation	
+SRM operation	2390 (Braking Burn)
+22-N ACS thruster (25% Duty)	0.24
Vertical Descent by Lander	
+440-N descent thruster	411 (Liquid Descent)
+22-N ACS thruster (10%)	41
+440-N descent thruster (redirect budget)	21



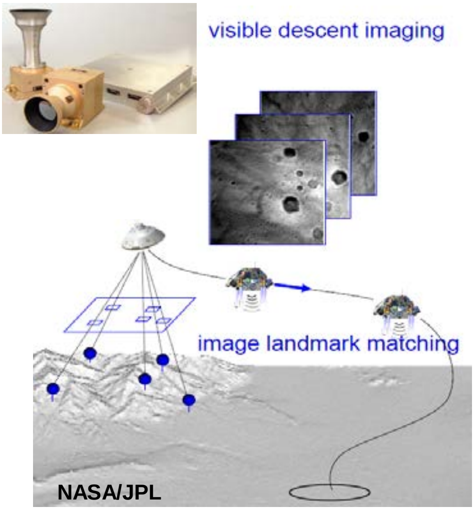
Lander Notes:

1. 37.6 kg Flight Performance Reserve of usable propellant load is added at the end
2. TVC assumed SRM
3. Altitudes above average lunar radius

Driving Requirements & Sensor Selection

- **Touchdown position and velocity requirements drive GNC sensor selection**
- **<u>Precision landing requirement of 100 meters</u>**
  - To achieve the above precision landing, good measurement of position and velocity are needed:
  - Terrain Relative Navigation (TRN) position sensor is used, which takes images of lunar surface during descent and updates lander location within < ~10m accuracy
  - Navigation Doppler Lidar (NDL) altimeter and velocity sensor for high accuracy altitude and 3-axis velocity measurements with ~0.17 cm/s velocity error
- **Touchdown requirements of 2m/s maximum vertical & horizontal velocities**
  - To meet this requirement, analysis shows that the NDL and a medium grade IMU suffice

Terrain Relative Navigation



NASA- Navigation Doppler Lidar

Candidate sensor

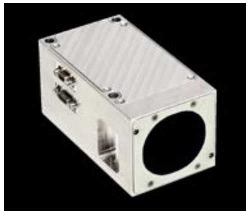
Driving Requirements & Sensor Selection

Attitude and Attitude Rate Requirements:

- **Max vertical attitude at touchdown of 5 deg**
- **Max angular rate at touchdown of 2 deg/s**
- **Max attitude error at touchdown +/-10 deg**
  - Sun pointing or Communications pointing
- **Sun pointing during cruise +/-10 deg**

- The above requirements can be met with medium grade IMU, Star Trackers, and Sun Sensors

Candidate sensor:
Northrup Grumman LN200S IMU
~.07 deg/sqrthr angle random walk

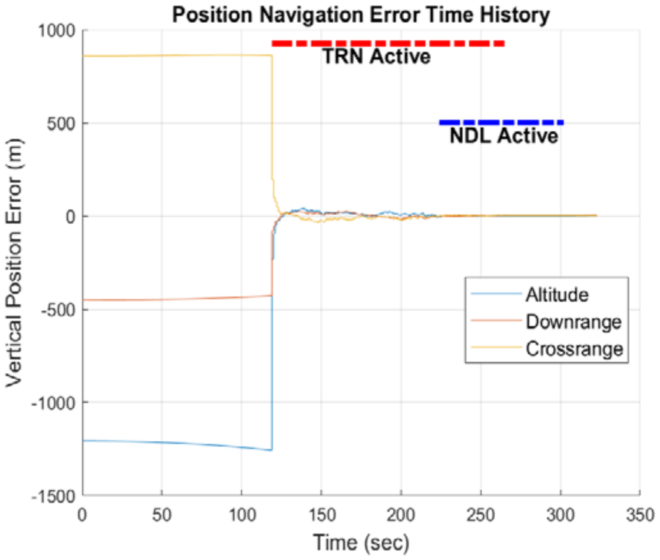


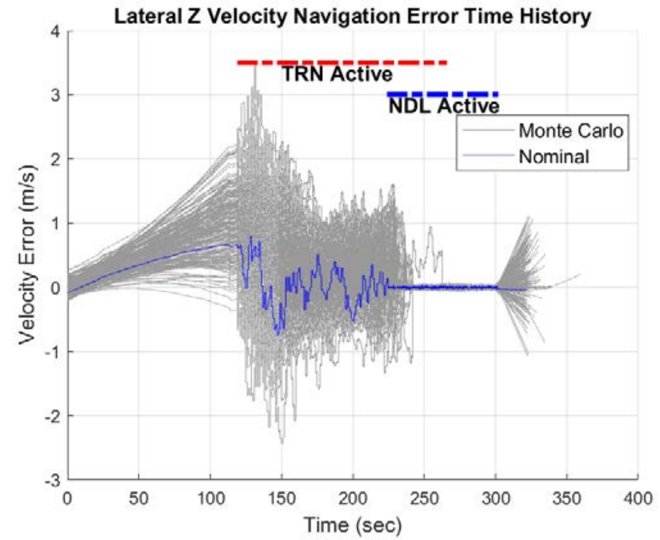
Candidate sensor:
2-NST Blue Canyon Star Tracker
Cross-boresight Accuracy 6 arcsec, 1-sigma
Around-boresight Accuracy 40 arcsec, 1-sigma

Candidate sensor:
6xNewSpace Fine Digital Sun Sensor
.1deg accuracy with 140deg FOV

Precision Landing Requirement

- Precision landing has never been attempted in space
  - For this mission precision landing means landing within 100 meters (3σ) of a prescribed target
  - Mars 2020 will employ *autonomous* TRN for the first time (primarily for hazard avoidance)
- Previous lunar missions targeted large, flat areas which are largely devoid of hazards
  - Most science missions, however, want to land near craters and outcrops
- Without lunar GPS, precision landing requires **Terrain Relative Navigation (TRN)**
- TRN measures position by correlating images taken by an on-board camera with stored imagery of the lunar/planetary surface
- Combining TRN with NDL significantly improves the Navigation knowledge to achieve precision and soft landing





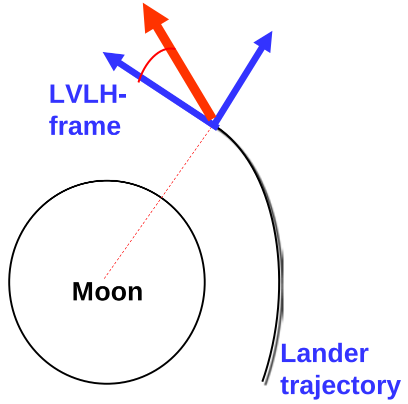
Guidance

- SRM burn, uses a fixed pitch angle w.r.t. LVLH is used,
  - Based on a ***Moon Entry Descent Algorithm by Ellen M. Braden – NASA/JSC/EG5***
  - Employs a predictor-corrector, predicts vehicle location down to descent and landing
  - Uses an estimated SRM thrust profile based on PMBT
  - Attempts to ensure a good initial state for liquid burn
  - Can be ran during pre-SRM coast to calculate initial LVLH pitch angle
- Liquid Descent, several guidances are currently traded
  - Apollo (baseline), Tunable Apollo, and Quadratic guidances
    - With quadratic formulation of the commanded acceleration

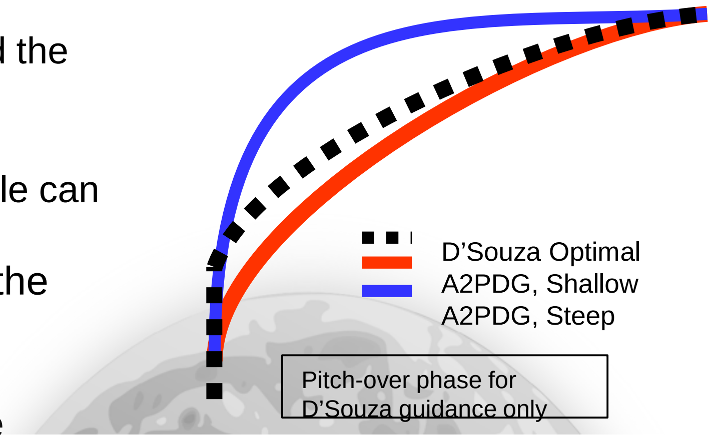
$$a_c = c_0 + c_1 t_{go} + c_2 {t_{go}}^2$$

    - Differences lie in the commanded acceleration coefficients and the targets
    - All target a final position, velocity, and acceleration vector
    - By targeting acceleration, the desired final attitude of the vehicle can be specified
  - The Minimum Acceleration (D'Souza) guidance only targets the final position and velocity vectors
    - The final attitude of the vehicle cannot be specified
    - A pitch-over maneuver is needed for the vehicle to achieve the desired final attitude

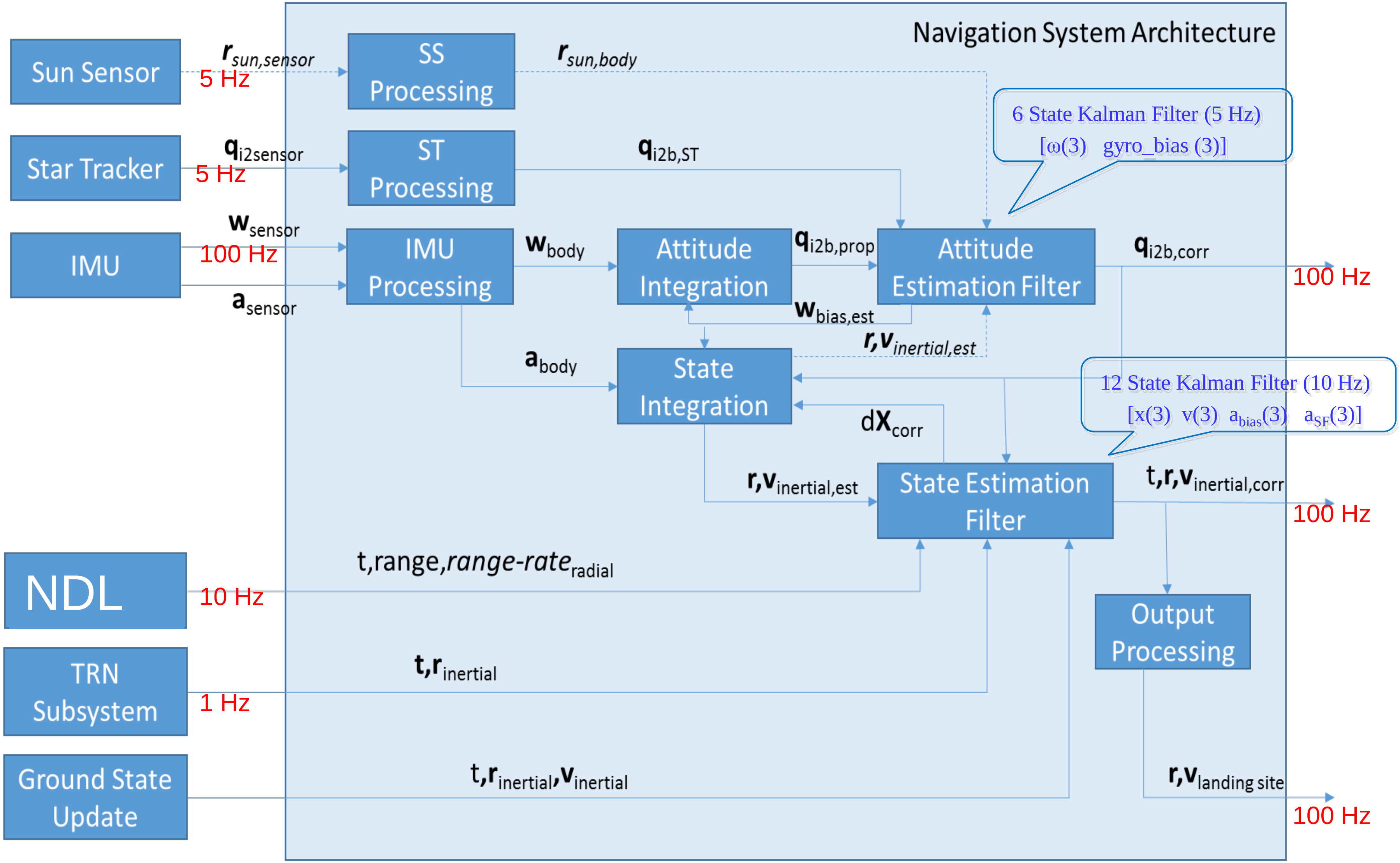
Solid Breaking Burn at Constant LVLH -Pitch



Liquid Descent



Navigation Architecture



Navigation System Architecture

Sun Sensor

$\boldsymbol{r}_{sun,sensor}$

5 Hz

SS Processing

$\boldsymbol{r}_{sun,body}$

Star Tracker

$\mathbf{q}_{\text{i2sensor}}$

5 Hz

ST Processing

$\mathbf{q}_{\text{i2b,ST}}$

6 State Kalman Filter (5 Hz)
[ω(3) gyro_bias (3)]

IMU

$\mathbf{w}_{\text{sensor}}$

100 Hz

$\mathbf{a}_{\text{sensor}}$

IMU Processing

$\mathbf{w}_{\text{body}}$

Attitude Integration

$\mathbf{q}_{\text{i2b,prop}}$

$\mathbf{w}_{\text{bias,est}}$

Attitude Estimation Filter

$\mathbf{q}_{\text{i2b,corr}}$

100 Hz

$\boldsymbol{r,v}_{inertial,est}$

$\mathbf{a}_{\text{body}}$

State Integration

12 State Kalman Filter (10 Hz)
[x(3) v(3) a_{bias}(3) a_{SF}(3)]

$\mathrm{d}\mathbf{X}_{\text{corr}}$

$\mathbf{r,v}_{\text{inertial,est}}$

State Estimation Filter

$\mathbf{t,r,v}_{\text{inertial,corr}}$

100 Hz

NDL

10 Hz

t,range,*range-rate*$_{\text{radial}}$

Output Processing

TRN Subsystem

1 Hz

$\mathbf{t,r}_{\text{inertial}}$

Ground State Update

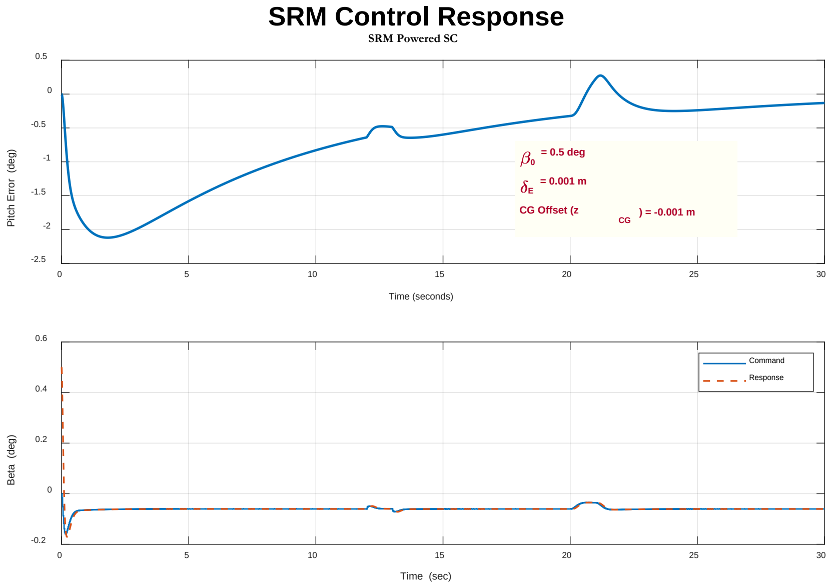
$\mathbf{t,r}_{\text{inertial}},\mathbf{v}_{\text{inertial}}$

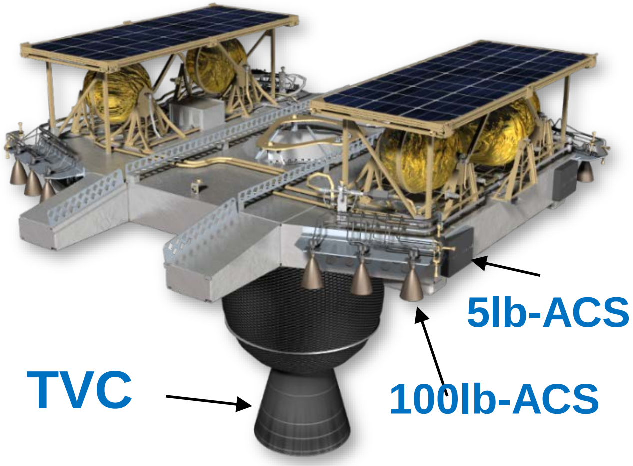
$\mathbf{r,v}_{\text{landing site}}$

100 Hz

SRM - Control

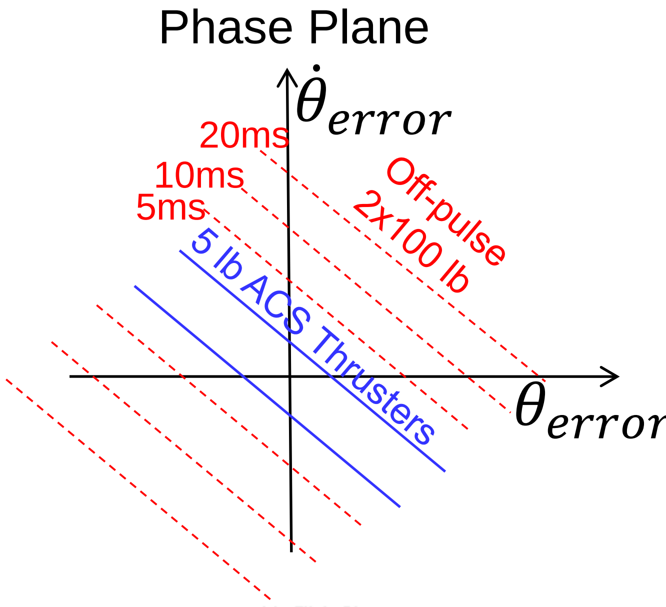
- Control operates at 50Hz
- SRM stage uses thrust vector control
  - Proportional Integral Derivative (PID) linear control law
  - Roll control via the Attitude Control System (5lb-ACS)
  - SRM is sized for the specific mission/landing site

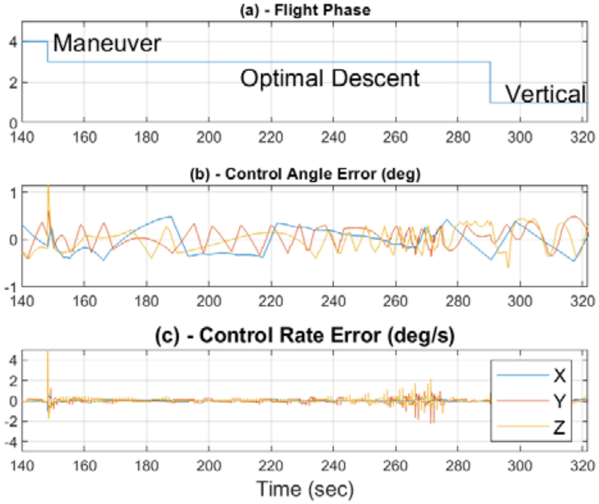




Pulsed Liquid Engine Control

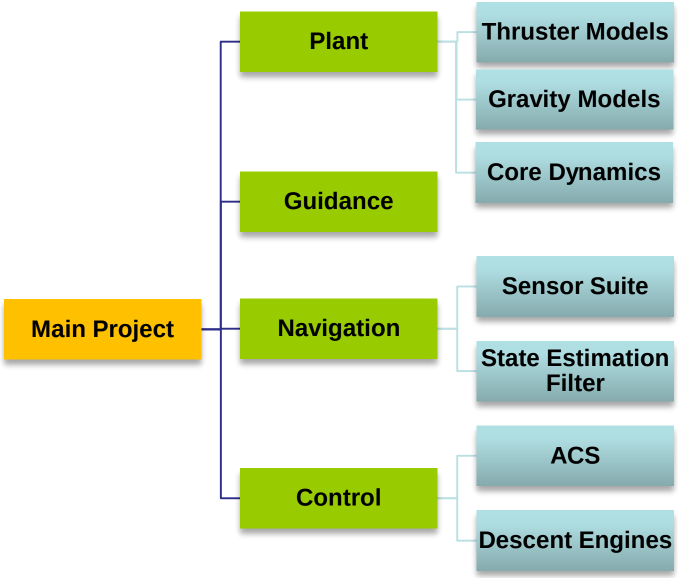
- Descent Engines (DE):12 x100 lb
  - Pulsed On/Off to minimize axial velocity error
  - “*Water Hammer*” effects:
    - All engines On/Off simultaneously causes hi-pressure waves on propellant lines and valves
    - Mitigate through staggering the number of DE engines turned On/Off and at a given time
- Attitude Control System (ACS) Engines: 12 x 5 lb
  - Phase-Plane control: On/Off pulsing if attitude or rate error is outside “deadbands”
  - “*Off-Pulsing*” - Augment ACS control authority by turning *Off* pairs of DE engines:
    - To counter large torques e.g. due to C.G. offsets
    - Off-Pulsing requires fast-acting propulsion system/valves performance, ~5ms On/Off cycles
    - Off-Pulsing for 5, 10, or 20ms depending on magnitude of control error/disturbance torque



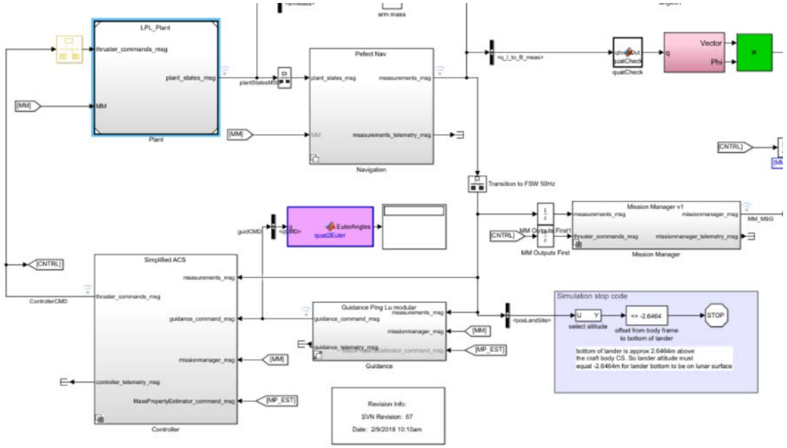


Generic LAnder Simulation in Simulink (GLASS)

- Lunar Pallet Lander is modeled in the Generic LAnder Simulation in Simulink (GLASS) developed by MSFC
  - Uses Mathworks Simscape Multibody dynamics tool for spacecraft and planetary bodies
  - GLASS is used to develop and autocode GNC software in C language
  - Uses Simulink Projects for high modularity and version control capability
  - Highly focused on Model Based Design approach
  - Interfaces with Core Flight Software cFS
- Using GLASS a 200-Case Monte Carlo dispersed analyses has been conducted to evaluate the lander soft touchdown performance
- Dispersed mass properties, propulsion performance, and sensor error parameters



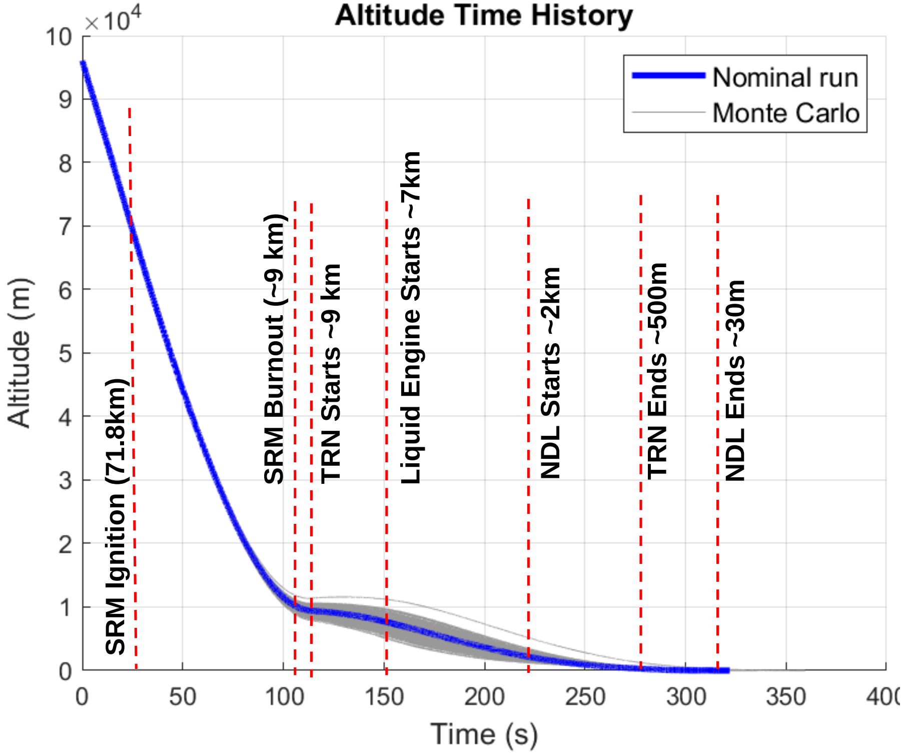
- Main Project
  - Plant
    - Thruster Models
    - Gravity Models
    - Core Dynamics
  - Guidance
  - Navigation
    - Sensor Suite
    - State Estimation Filter
  - Control
    - ACS
    - Descent Engines

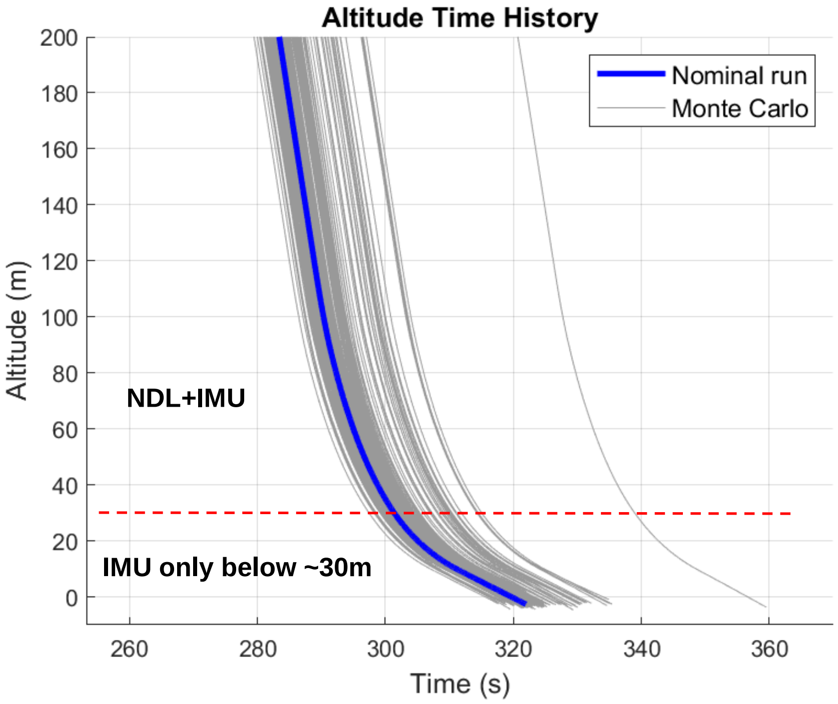


bottom of lander is approx 2.6464m above the craft body CS. So lander altitude must equal -2.6464m for lander bottom to be on lunar surface

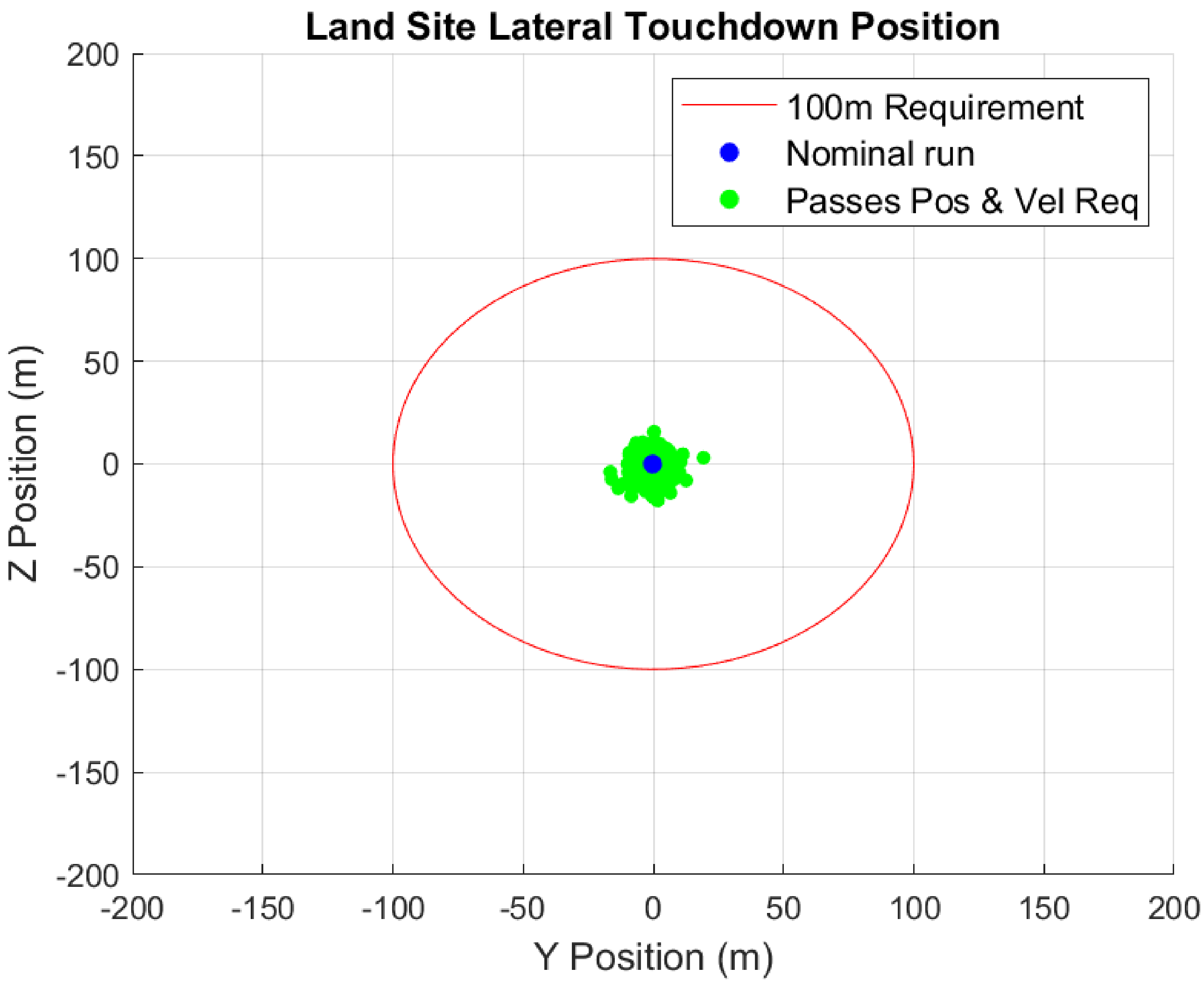
Revision Info:
SVN Revision: 67
Date: 2/9/2018 10:10am

Monte Carlo Results: Altitude

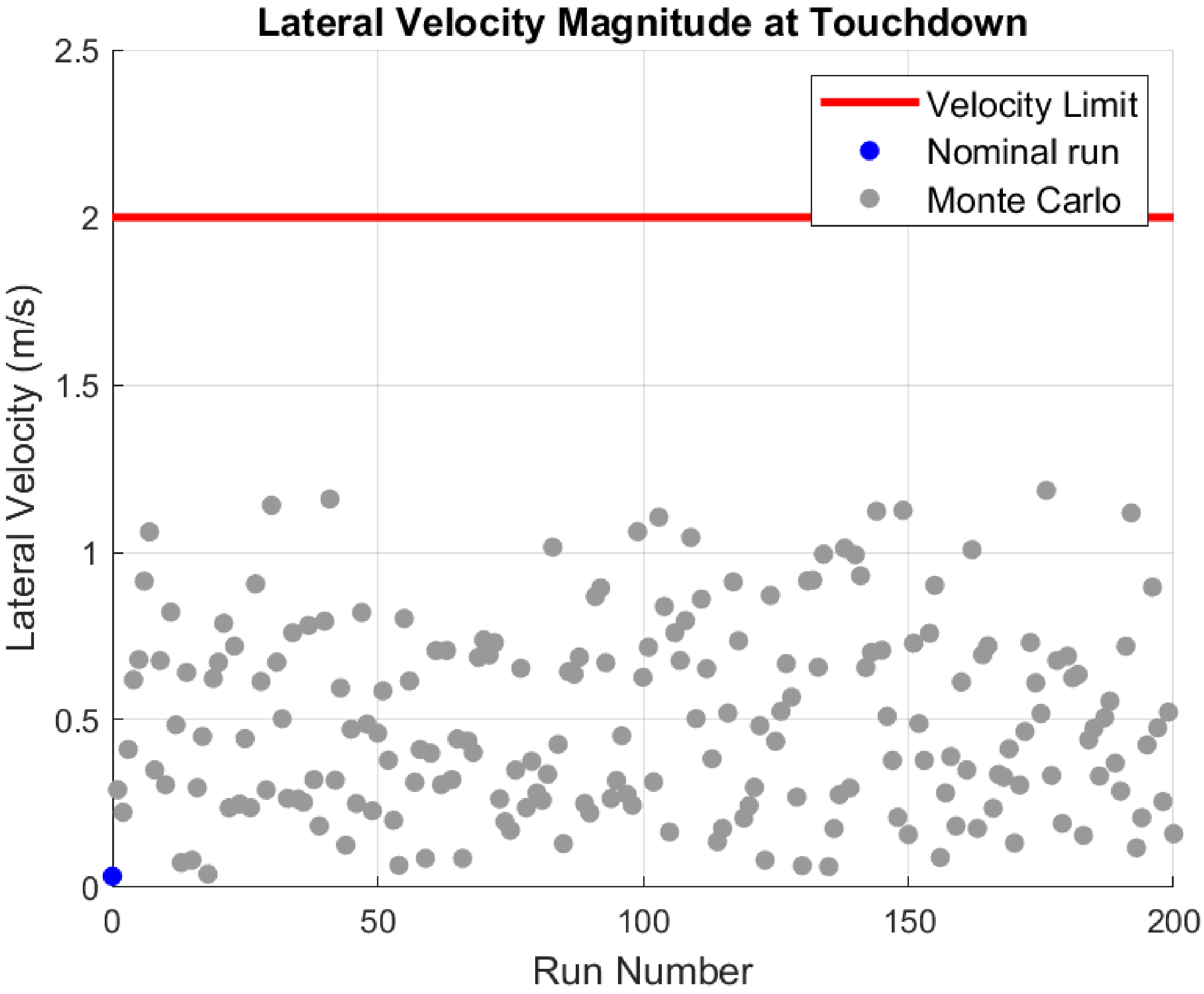




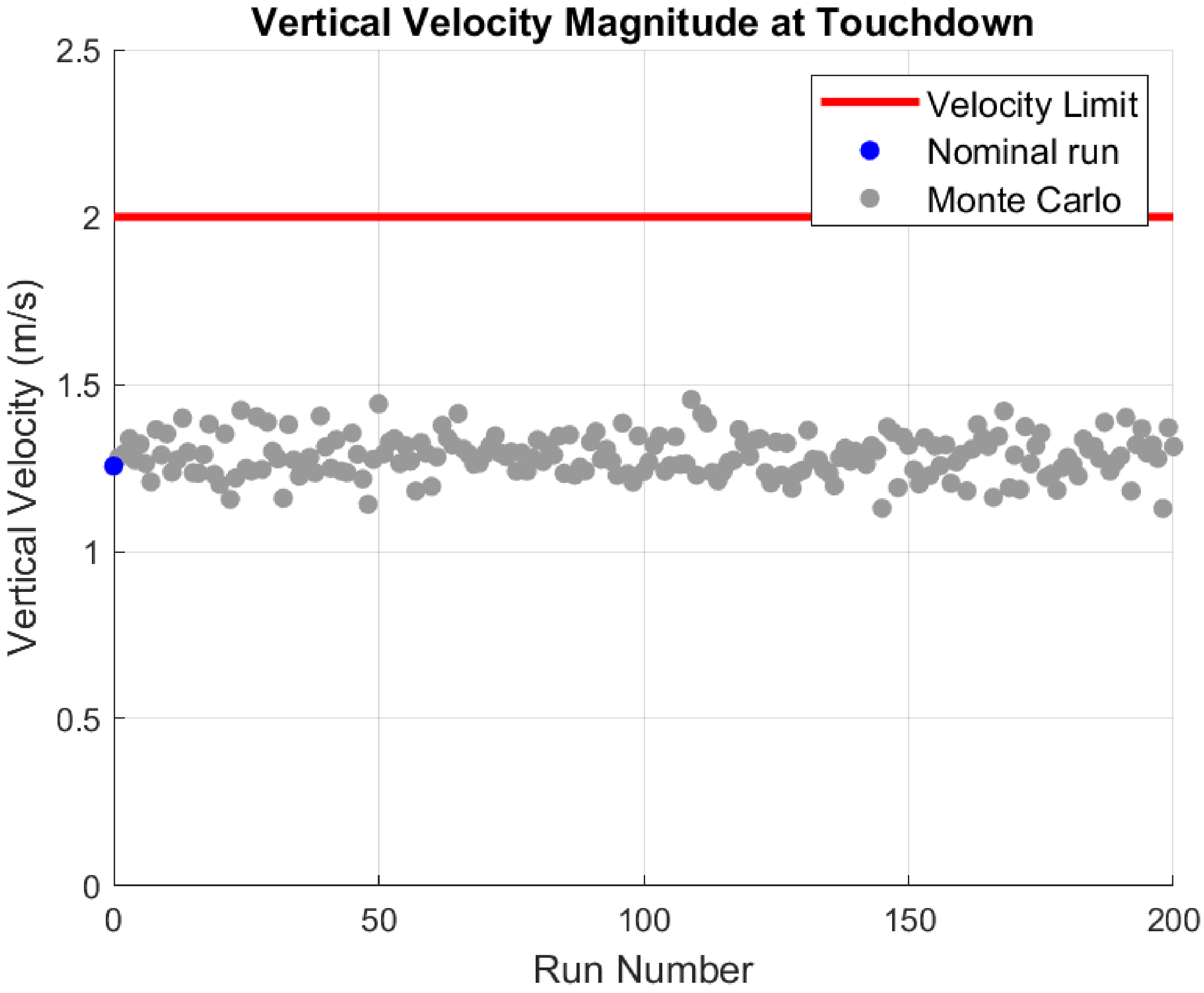
Lateral Position at Touchdown



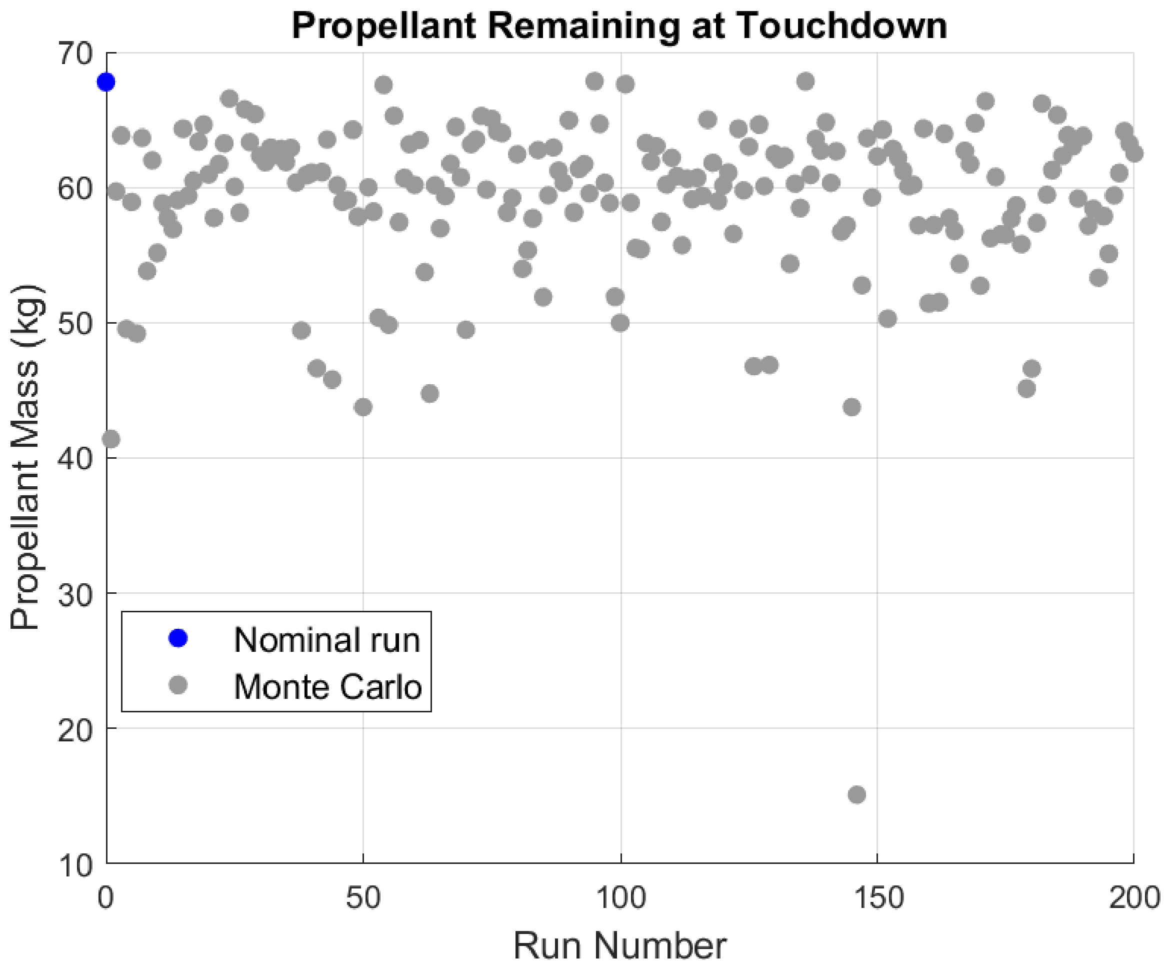
Lateral Velocity at Touchdown



Vertical Velocity at Touchdown



Usable Propellant Remaining



*26.9 kg of unusable propellant remaining onboard

Future Work

Working towards PDR in the Spring:

- Finalize TRN sensor requirements
- Finalize Nav. trades including lunar “touchdown” detection sensor selection
- Analyze Plume Surface Interaction effects
- Finish evaluation of different Guidance algorithms
- Evaluate alternative control algorithms
- Incorporate vehicle flexible body dynamics and mature propulsion models
- Include SRM separation analysis/effects
- Include Launch vehicle performance into dispersed analysis
- Finalize system-level requirements

Thank you

Thanks to...
Co-Authors:
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Any questions?