National Aeronautics and Space Administration

Guidance and Navigation Design Trades for the Lunar Pallet Lander

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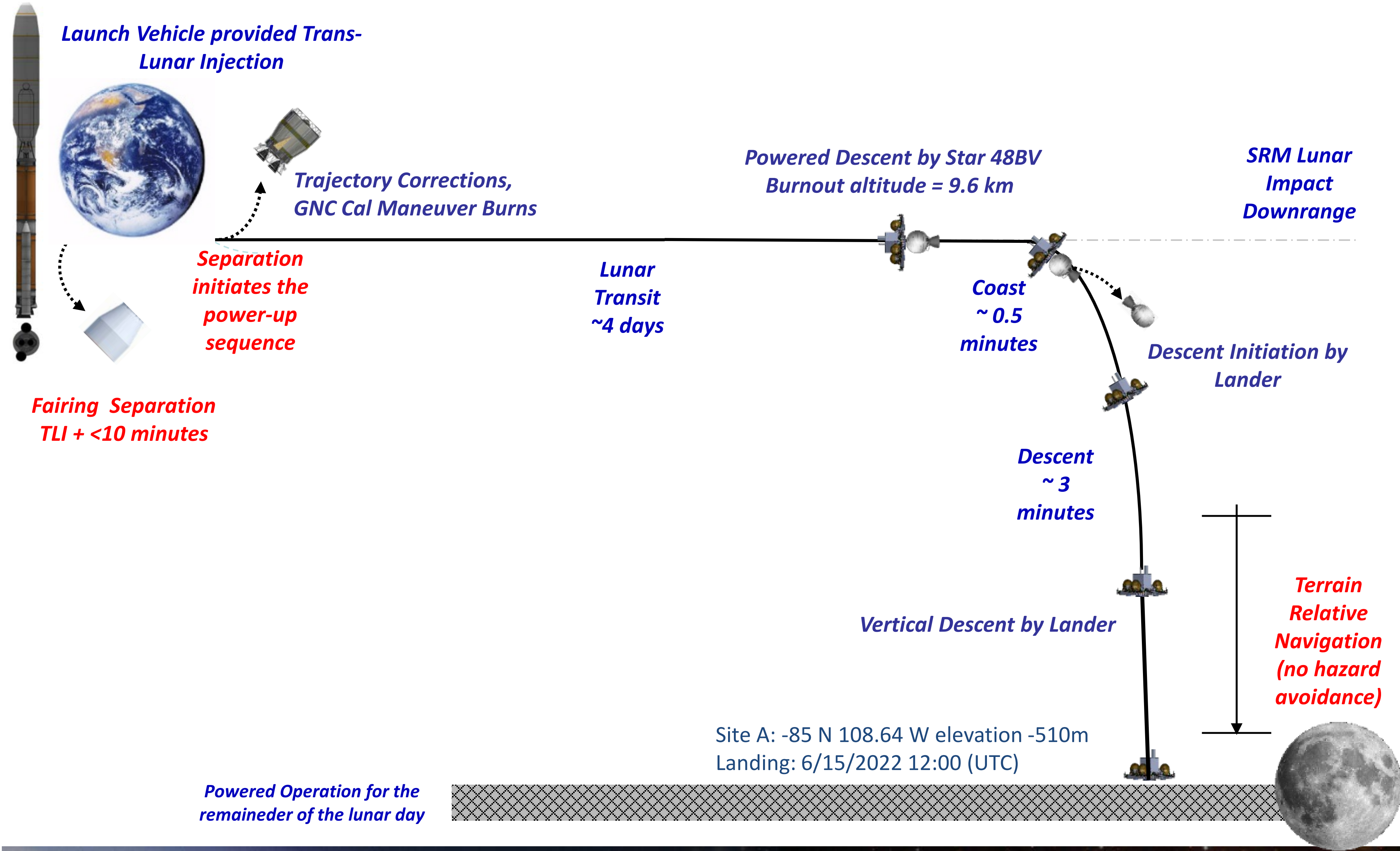
Overview

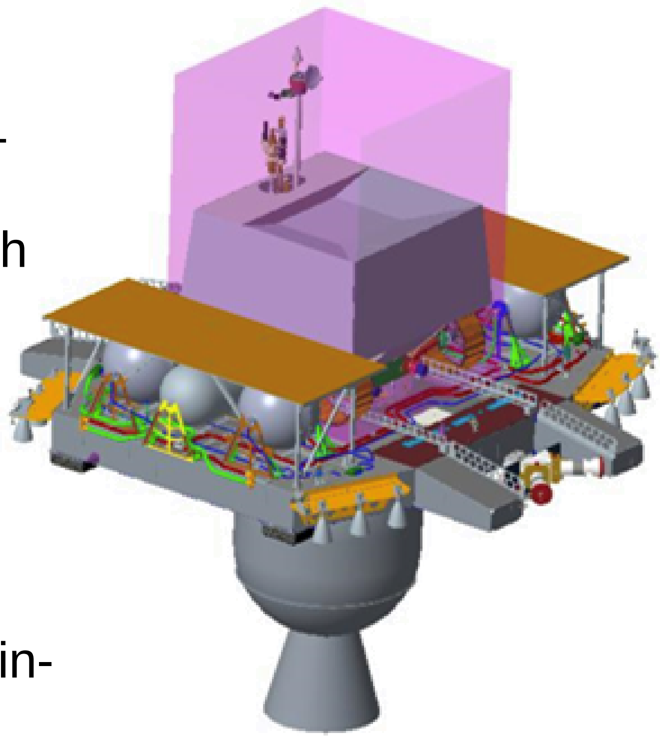
- Mission Concept and Design
- Vehicle GNC System Overview
- Simulation Architecture
- Descent Guidance Development
- Navigation System Design and Trades
- Future Work and Next Steps

Mission Overview



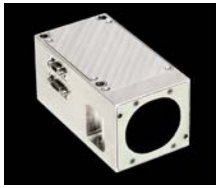
Mission Concept and Design

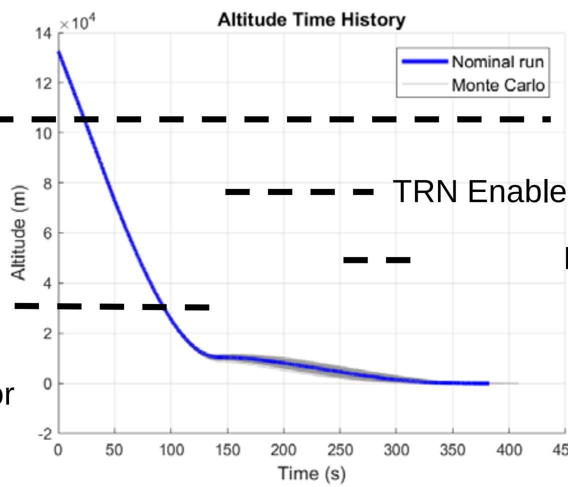
- Objective: Land a 300kg payload on the Lunar surface with high precision relative to target
- System Requirements
  - 100m lateral landing accuracy (knowledge + truth)
  - 2 m/s maximum velocity at touchdown (each axis)
  - Final attitude within 5 degrees of desired
  - 2 deg/s angular rate at touchdown
- Other Assumptions
  - Not including hazard avoidance
  - Landing site being selected based on trajectory optimization and minimize lack of in-situ hazards
- Key Enablers for Meeting Requirements
  - Terrain Relative Navigation
  - Navigation Doppler LIDAR



Baseline GNC Sensor Suite

- DSN update prior to SRB burn
- Northrup Grumman LN200S IMU
  - .07 deg/sqrthr angle random walk
- 2-NST Blue Canyon Star Tracker
  - Cross-boresight Accuracy 6 arcsec, 1-sigma
  - Around-boresight Accuracy 40 arcsec, 1-sigma
- NewSpace Fine Digital Sun Sensor
  - .1deg accuracy with 140deg FOV
- Navigation Doppler Lidar (NDL)
  - TRL needs to increase
  - Excellent performance (1.7 cm/s velocity error)
- Malin ECAM L50 System for TRN
  - New camera system with global shutter for Mars 2020





IMU Enabled

TRN Enabled

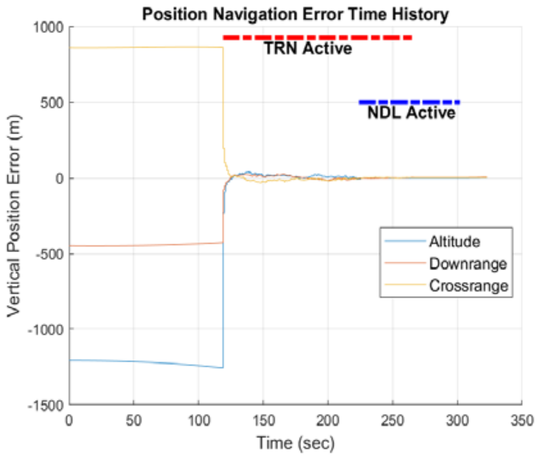
NDL Enabled

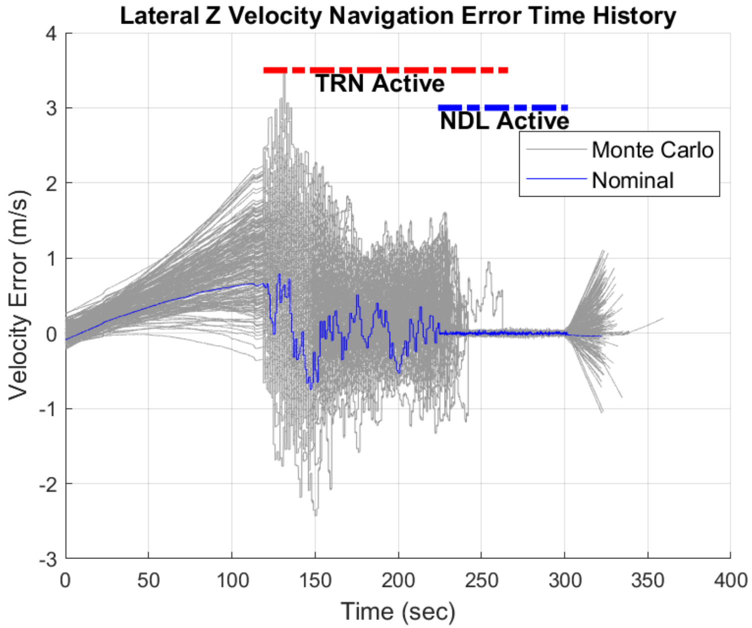
Star Tracker and Sun Sensor

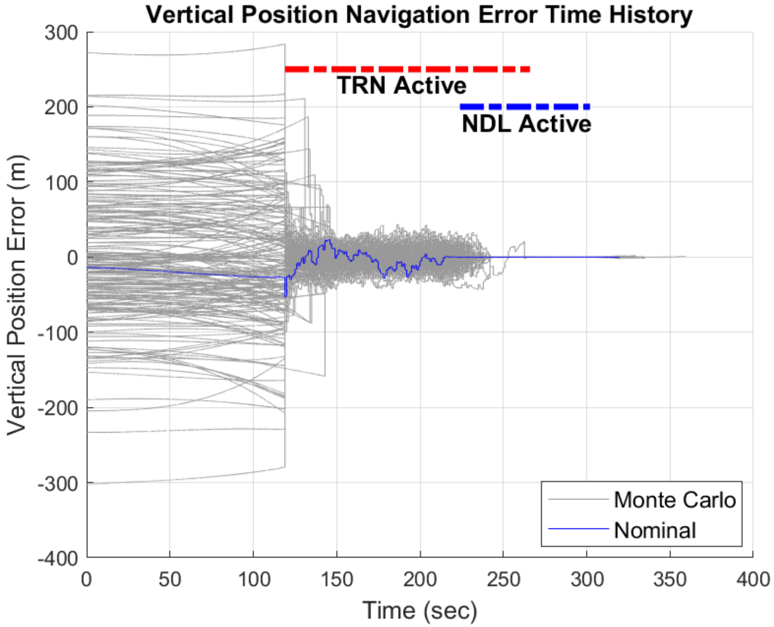
Note: Camera & TRN electronics will be chosen by the TRN provider

Baseline Performance

- Vehicle meets high level mission requirements with baseline design
- Baseline sensor suite + Apollo-based lander guidance
- Iterating mission, vehicle, sensor design through ongoing trades

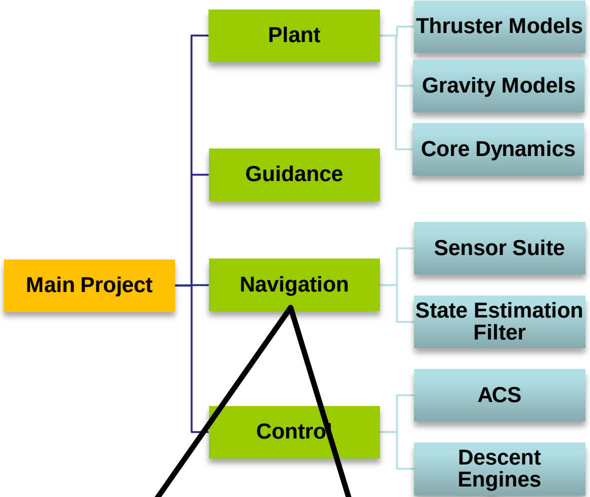


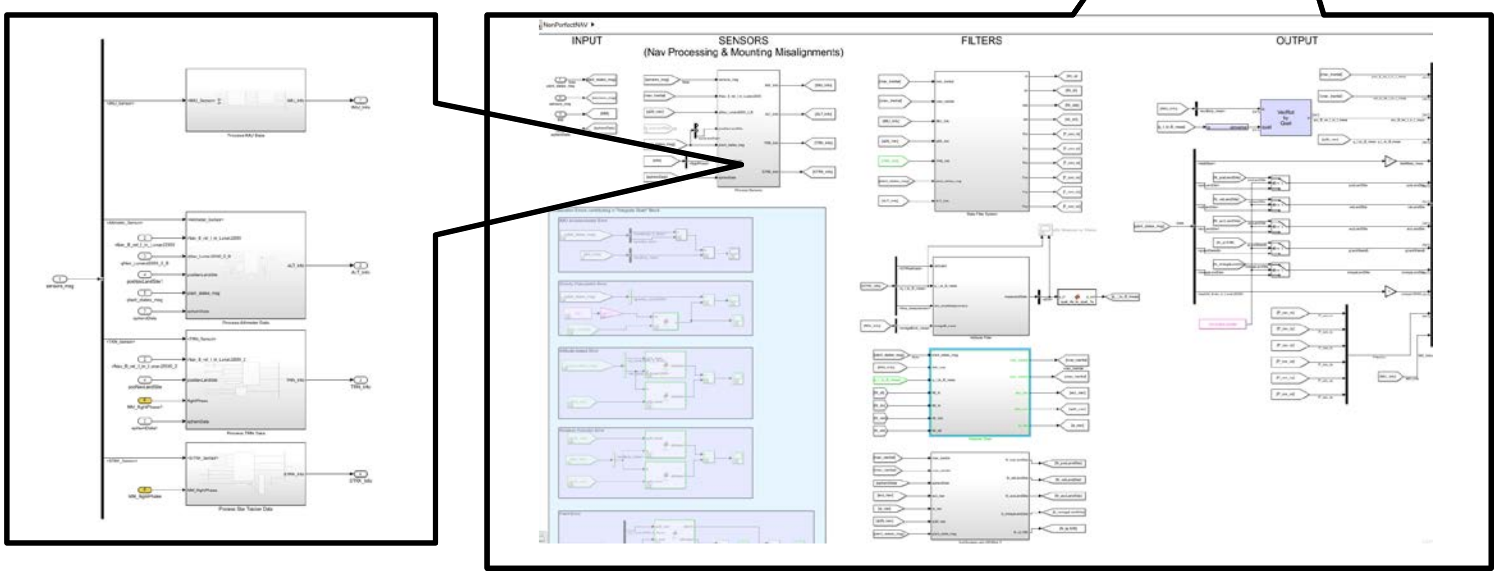




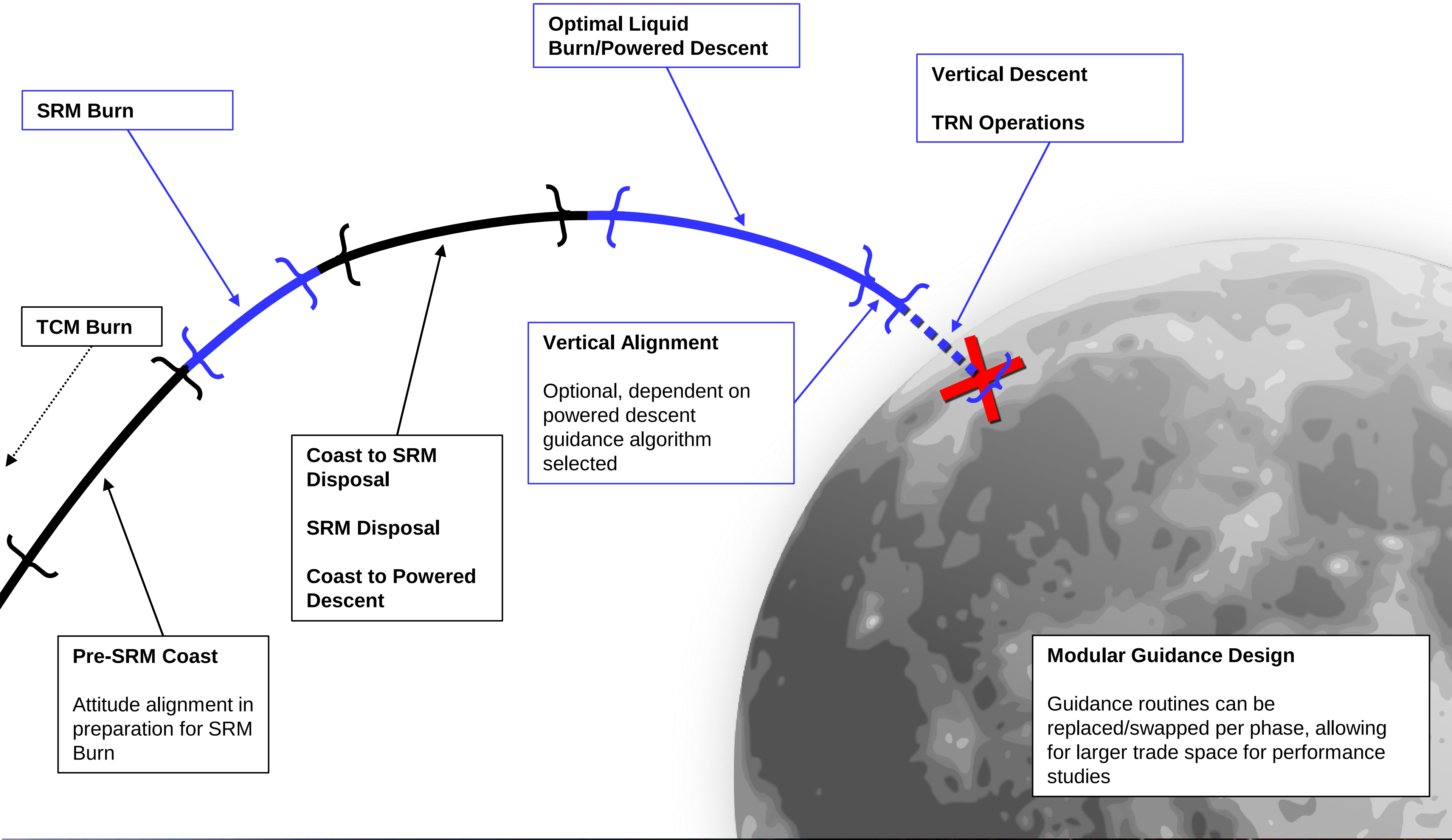
Lander Simulation Architecture

- **G**eneric **LA**nder **S**imulation in **S**imscape
  - Integrated 6DOF simulation
  - MATLAB/SimScape
  - Independent Guidance and Navigation sub-models
  - Intent to deliver GNC algorithms as autocode to FSW
  - “Perfect Nav” mode for guidance and control development
  - Algorithms embedded within m-blocks where possible
- Standalone Navigation Capability
  - Use of reference trajectory to run dispersed Monte Carlo 6DOF analysis
  - Variance-based Sensitivity Analysis
  - Multidimensional trade study capability
  - Utilizes MATLAB’s Parallel Toolkit for execution





Descent Guidance - Phases of Flight



Descent Guidance Options & Algorithms

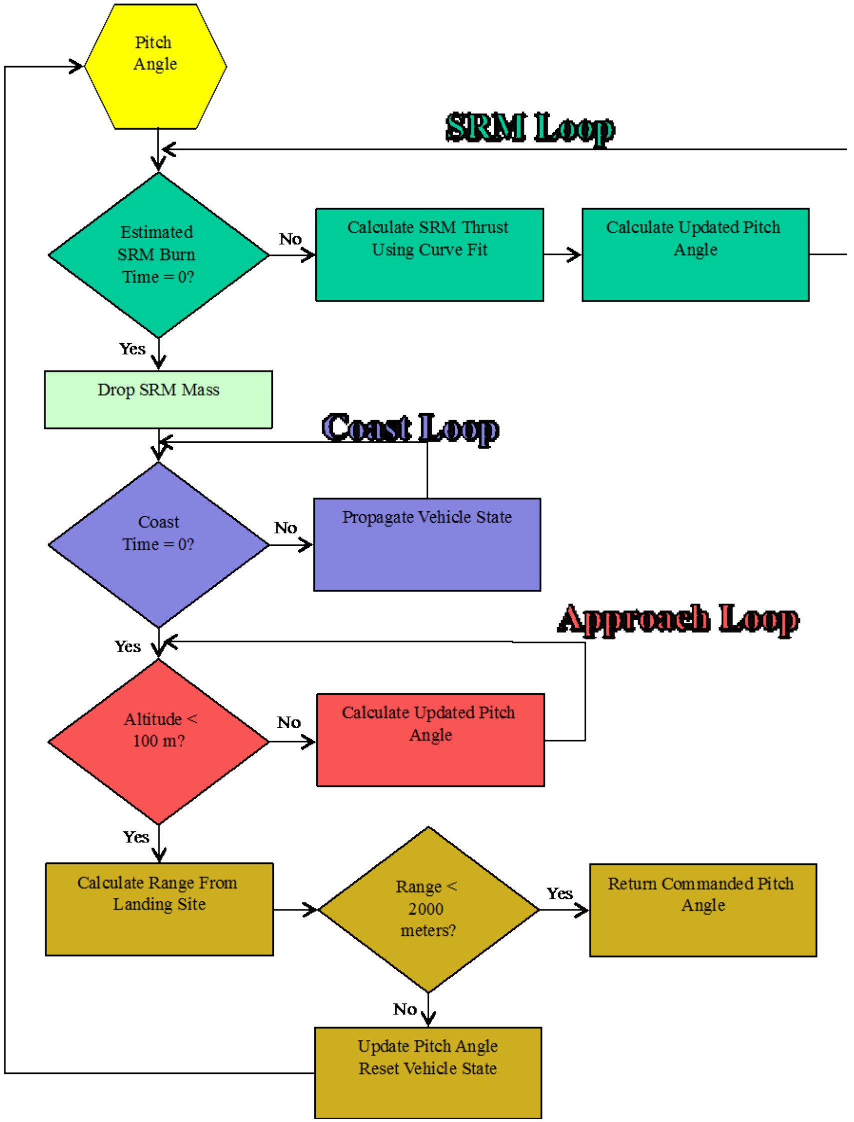
Phase of Flight	Guidance Routine Options
Pre-SRM Coast	• **LVLH Hold** – adjusts attitude to pre-determined LVLH pitch angle • **MEDeA Predictor** – runs MEDeA descent algorithm (described later), predicts starting LVLH pitch angle
SRM Burn	• **LVLH Hold** – holds pre-determined LVLH pitch angle through duration of burn • **MEDeA** – closed-loop SRM guidance for adjusting commanded LVLH pitch angle throughout burn
Post-SRM Coast	• **Fixed-Time Coast** • **MEDeA Post-SRM Coast** – attempts to adjust coast time to avoid excessive liquid fuel consumption during powered descent
Powered Descent	• **D'Souza** – Optimal closed-loop feedback guidance law, t_{go} calculated by solving analytical quartic equation • **A2PDG** – Augmented Apollo Powered Descent Guidance, tunable closed-loop steering law that ranges from E-guidance (linear acceleration profile) to Apollo Guidance (quadratic acceleration profile)
Vertical Alignment	Optional mode to pitch vehicle vertically, required if using D'Souza's optimal powered descent law
Vertical Descent	Linear velocity ramp-down, then linear position-velocity controller logic

SRM Burn Guidance - MEDeA

Moon Entry Descent Algorithm

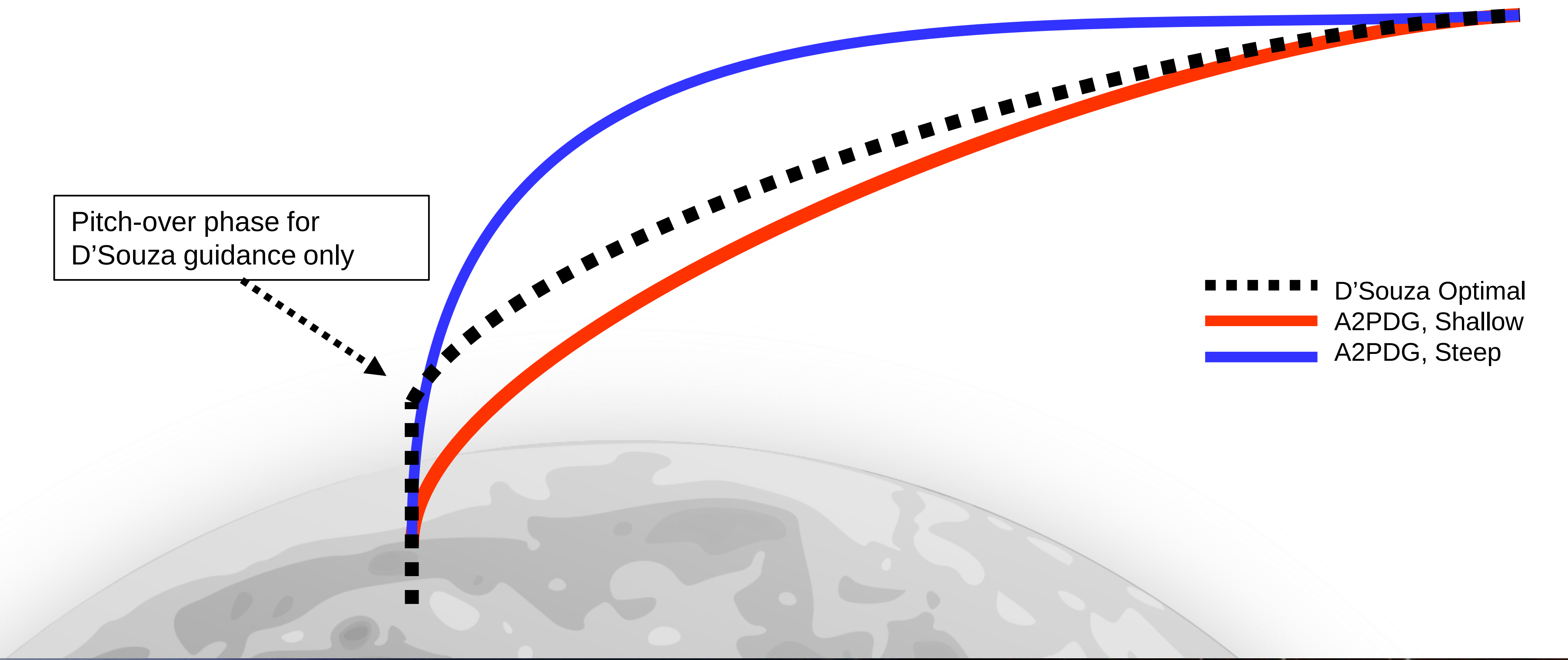
Ellen M. Braden – NASA/JSC/EG5

- MEDeA employs a predictor-corrector SRM loop, predicts vehicle location down to descent and landing
- Uses an estimated SRM thrust profile based on PMBT
  - 7th order polynomial and a linear thrust ramp down after a specified time
  - Two sets of polynomials used for “cold” or “hot” PMBT
- Attempts to ensure a good initial state for liquid burn
- Can be run during pre-SRM coast to calculate initial desired LVLH pitch angle
- Future study: compare Monte Carlo performance to standard LVLH-fixed pitch angle for SRM Burn



Powered Descent Guidance

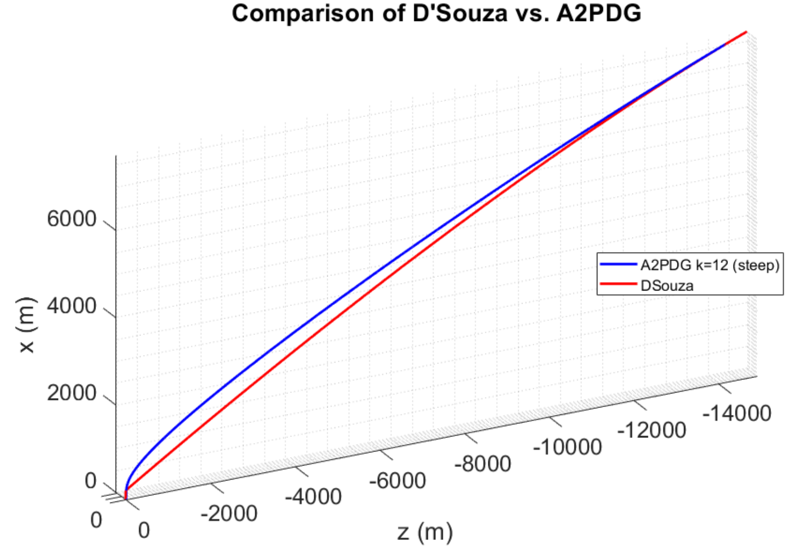
- **D’Souza’s optimal powered descent leaves vehicle non-vertical at end of powered descent**
  – Vertical alignment phase is required after achieving desired target
  – Initial trade studies show ~10kg less propellant required versus A2PDG
  – **Targets**: 200m above surface, -2 m/s along vertical axis
- **A2PDG, in whole range of tunable options, leaves vehicle vertical w.r.t. landing site**
  – Tuning parameter allows for more steep/shallow powered descent profile
  – Slightly less efficient w.r.t. propellant
  – **Targets**: 100m above survace, -15m/s along vertical axis



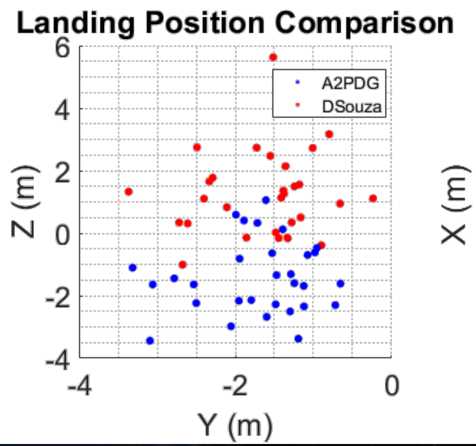
Terminal Descent Performance

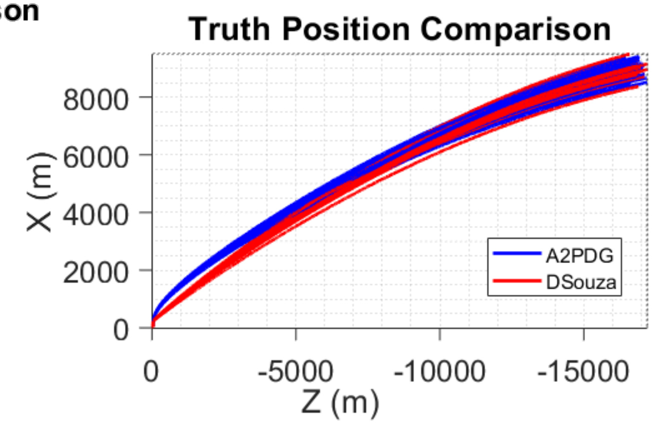
- Comparing Terminal Guidance Algorithms
- Both land with similar accuracy, but different flight profiles
  - Allows for increased mission flexibility
  - Extended time for future detection of hazards
  - Stable vertical descent
  - Fuel efficiency
- Dispersed performance similar to notional
  - All cases meet lateral landing requirements

Perfect Navigation

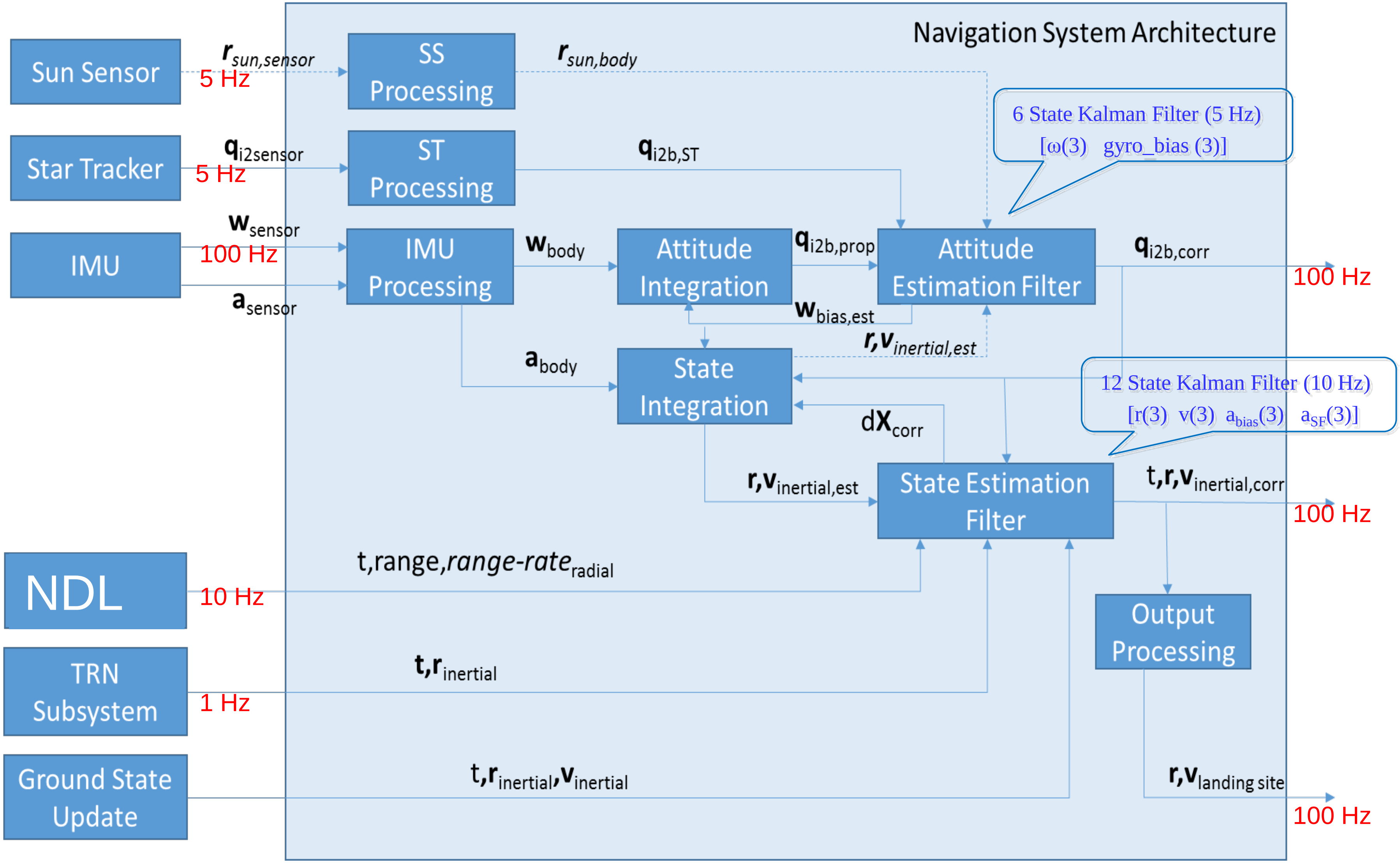


With IMU Errors



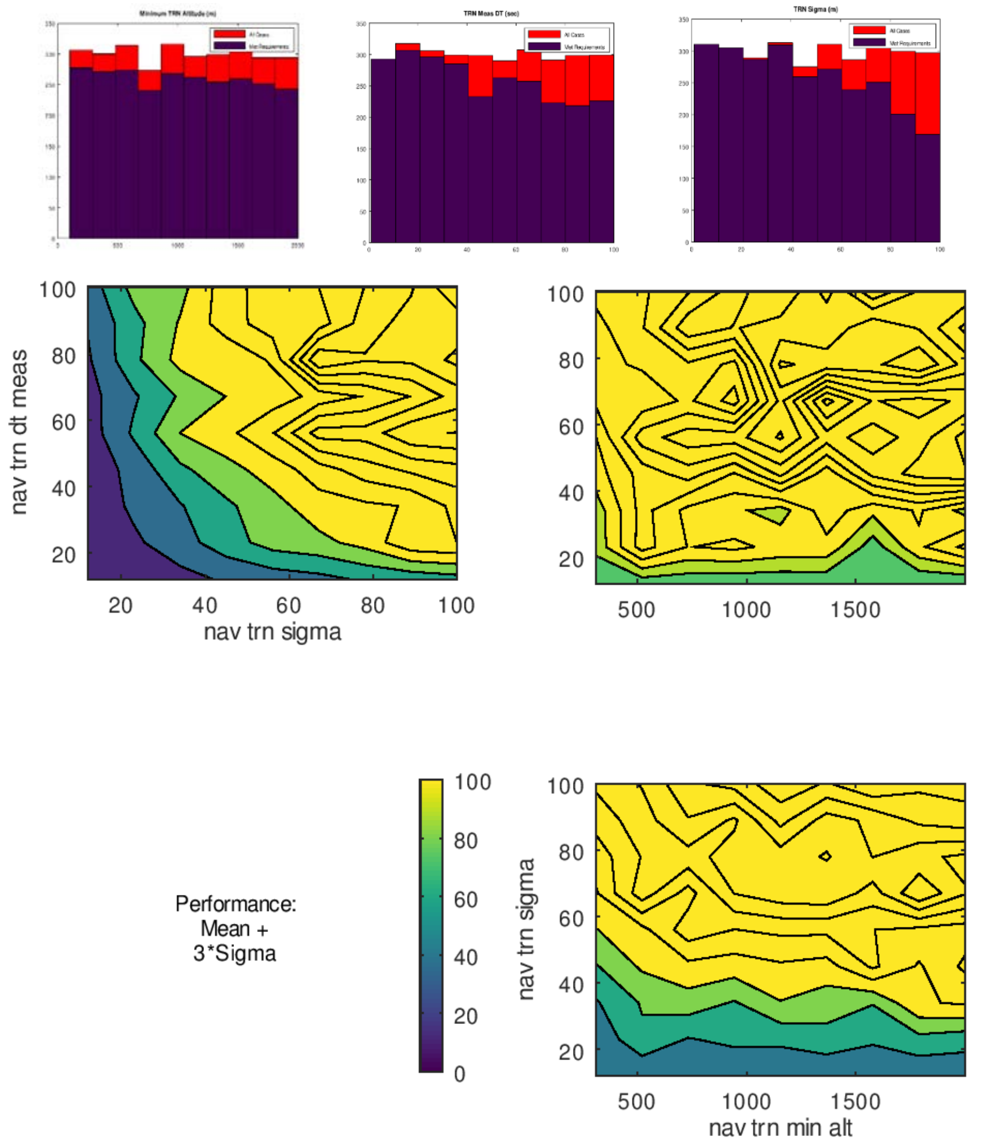


Navigation Architecture



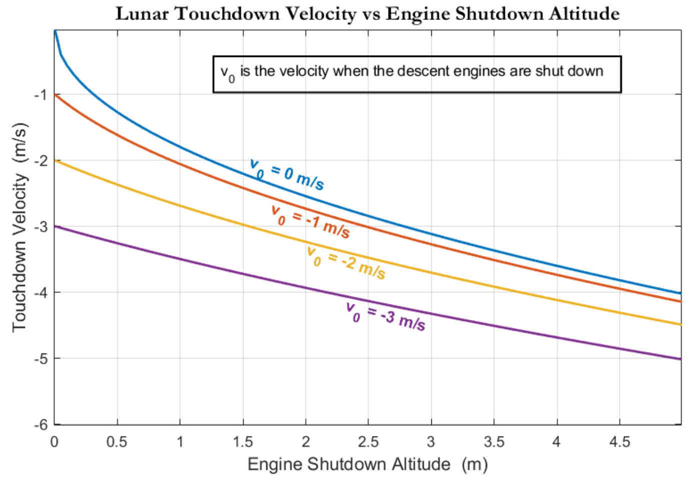
TRN Requirements Development

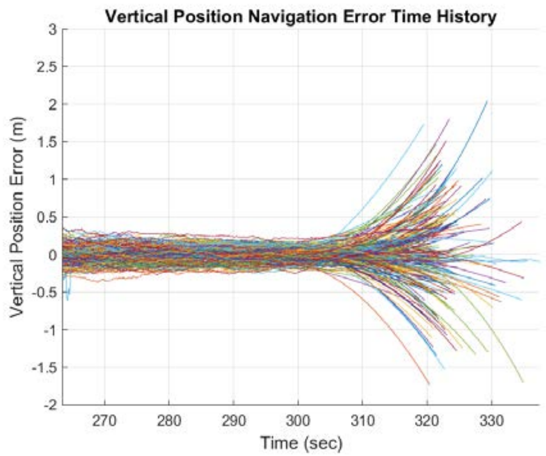
- Implementation approach to TRN being developed as part of PDR
  - In-house development, purchase a COTS systems, external development
- Treating TRN as black-box development to vehicle
  - Define input/output interface
  - Required performance metrics over flight
- Monte Carlo approach to requirements development
  - Navigation-system only
  - Other systems as-baseline
  - Comparing minimum operating altitude, update rate, and allowable error (1-sigma)



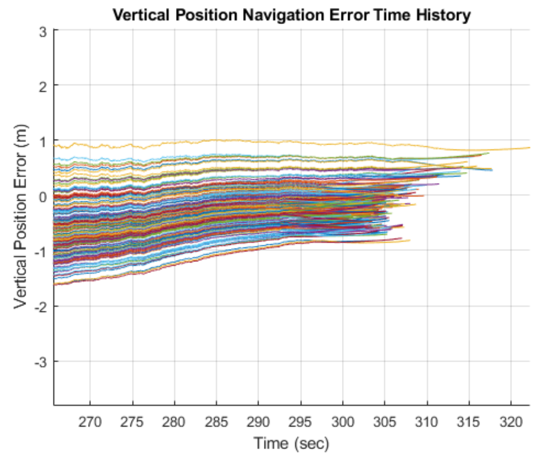
Altitude Knowledge Immediately Prior to Landing

- Used to determine when to shutdown engines
  - Too early, the vehicle hits the ground too hard
  - Too late, the engine plume will impinge badly
- Touchdown sensors currently not included
- Limited use of altimeter at low altitudes due to potential blowback and impingement
- Improving IMU reduces error growth at end of flight at cost of additional mass and cost

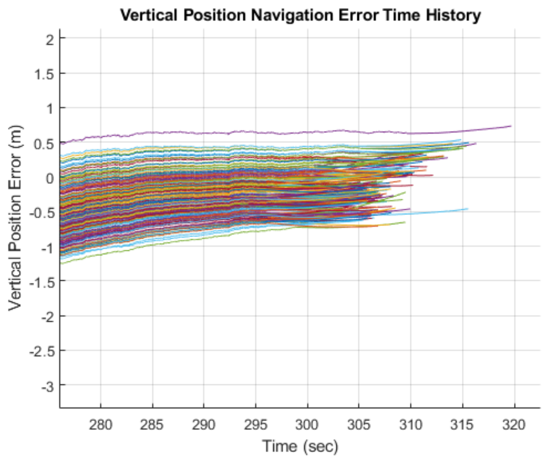




LN200S



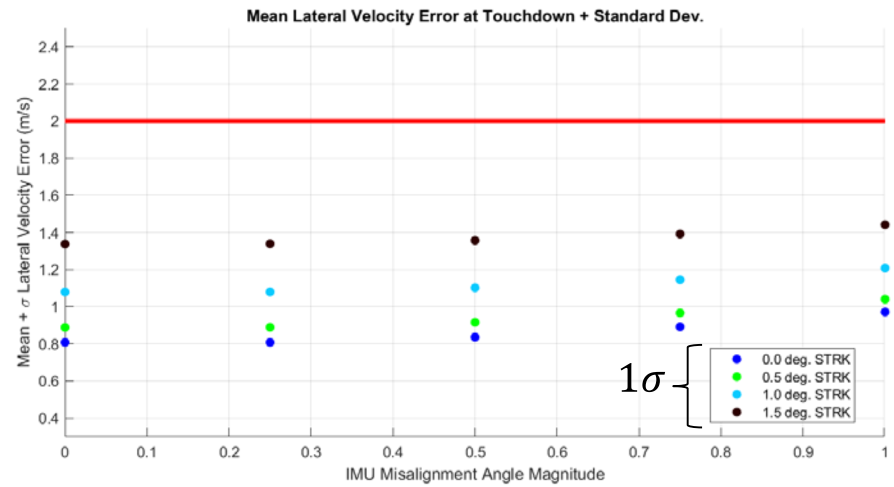
Medium Quality

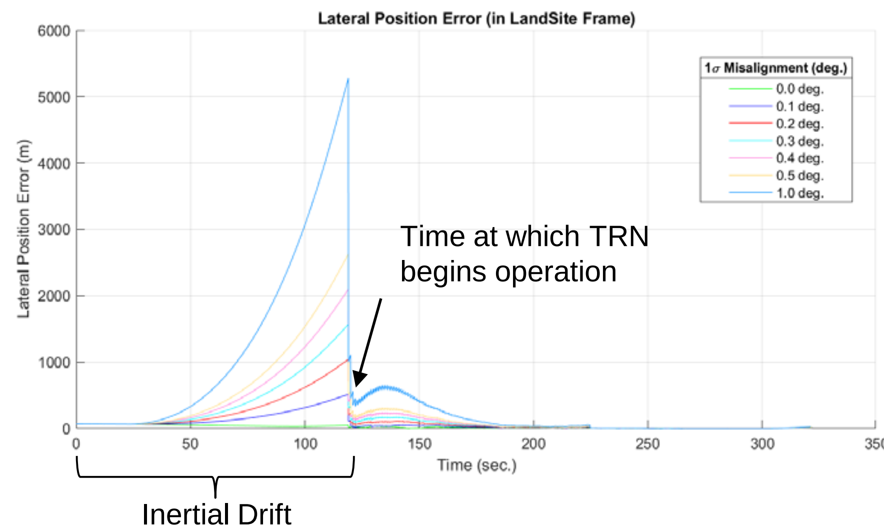


High Quality

IMU + Star Tracker Misalignment Study

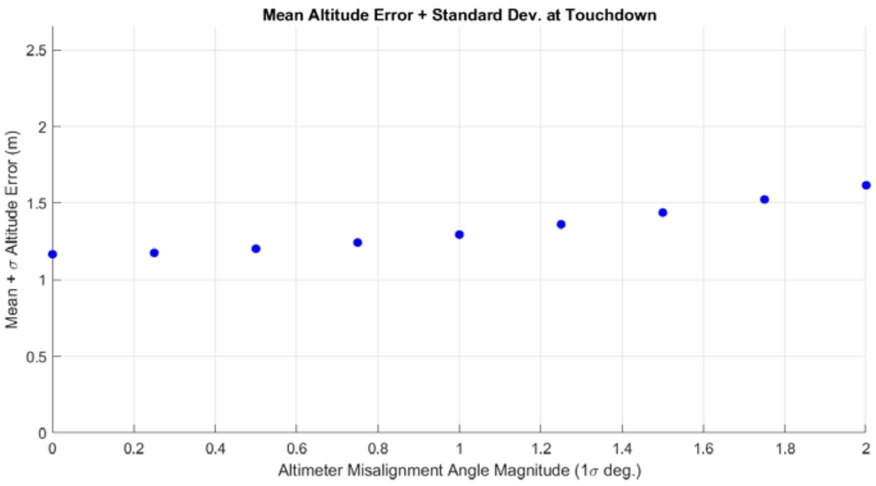
- Monte Carlo approach to sensor misalignment study
  - Navigation-system only
  - Other sensors perfectly aligned
  - Compared IMU & Star Tracker misalignment (1-sigma) with Navigation errors (mean + 1-sigma)
- Results
  - Lateral touchdown velocity error was most affected touchdown error (top right) relative to requirement
  - All errors had large drifts proportional to misalignment errors prior to TRN on time
- External measurements reduce sensitivity to raw inertial measurements while operational
  - See sensitivities once go-inertial at lower altitudes

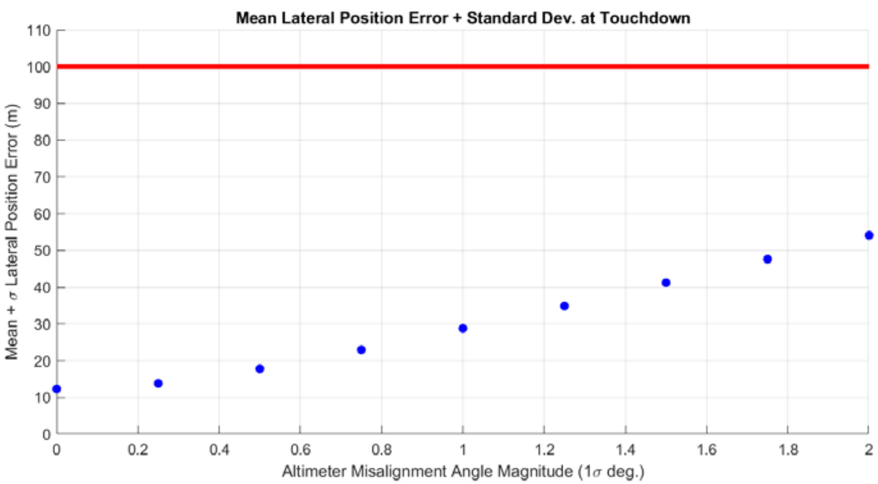




NDL Altimeter Misalignment Study

- Monte Carlo approach to sensor misalignment study
  - Navigation-system only
  - Other sensors perfectly aligned
  - Compared NDL Altimeter misalignment (1-sigma) with navigation errors (mean + 1-sigma).
- Results
  - Touchdown altitude errors grow slowly with increasing misalignment at ~0.25 m/deg.
  - Touchdown lateral position errors grow at ~20 m/deg.
- Improvements in touchdown altitude error are needed
- Desirable to have navigation altitude errors ≤0.5m



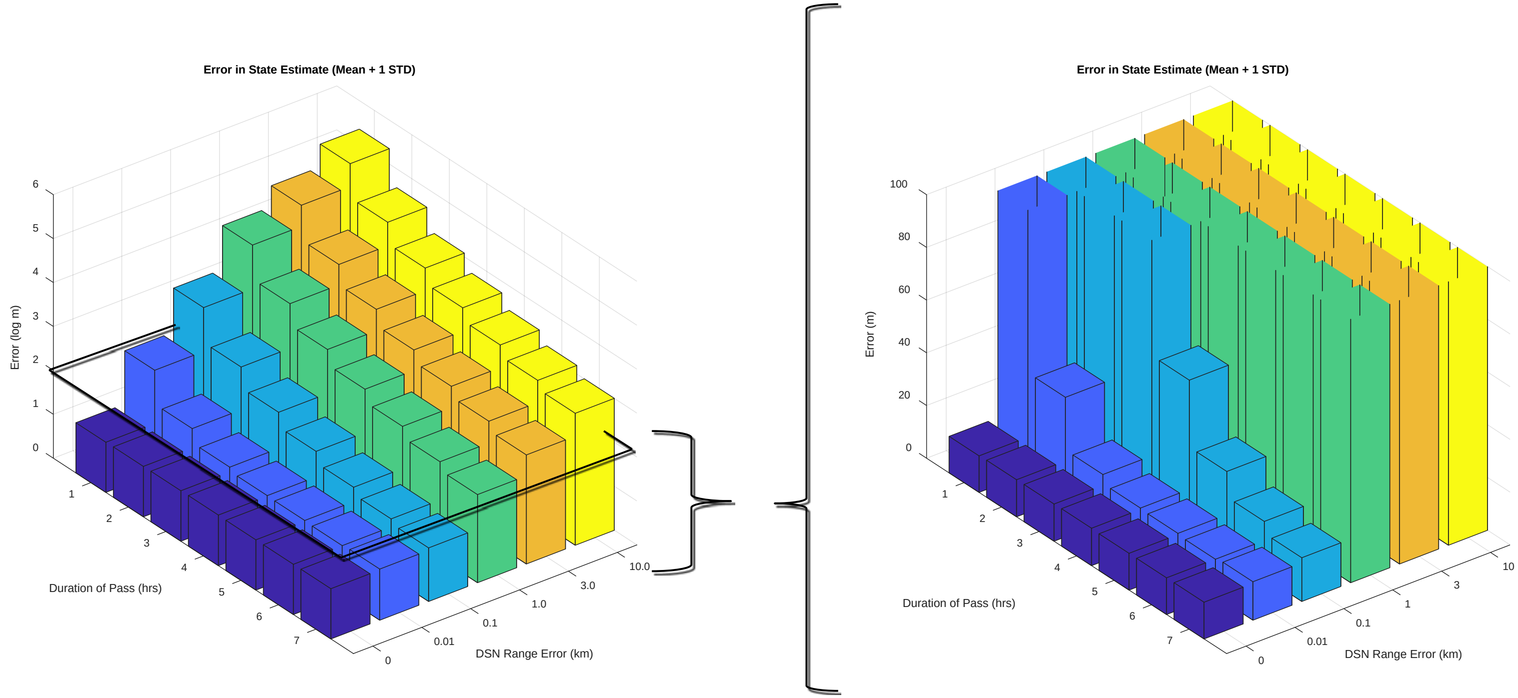


Landing Verification

- Requirement of LPL mission to demonstrate high accuracy landing
  - Need to land within 100m of required target
  - Characterization of navigation state uncertainty through simulation provides initial estimate
- Multiple methods to verify landing accuracy
  - Star Tracker + inclinometer
    - Attitude, local gravity, time provide state estimate
  - Photography
    - Downward looking imagery prior to touchdown to map to high resolution maps
  - Laser Ranging using reflector on vehicle
    - Track pulse of signals and measure TOF
  - Radiometric Ranging using DSN
- Focus of this work on assessing feasibility of DSN-based ranging and duration of measurement
  - Limited operational time on lunar surface post landing

Simulated DSN Capability

- Assessing capability to use DSN observations to verify landing location
  - Assume static on spherical surface, nonlinear least squares to estimate position in Lunar-Centered frame
  - Traded sigma on ranging measurements and total observation time
- Performance with no errors limited by random bias per sim (10m)
  - Can be improved by adding a bias estimation term
- State Determination Accuracy (100m) can be achieved within operational constraints
  - Within 2 hours with 10 m ranging uncertainty (1-sigma)
  - Within 4 hours with 100 m ranging uncertainty (1-sigma)
  - Difficult to get 1km measurements to have errors much lower than one order of magnitude

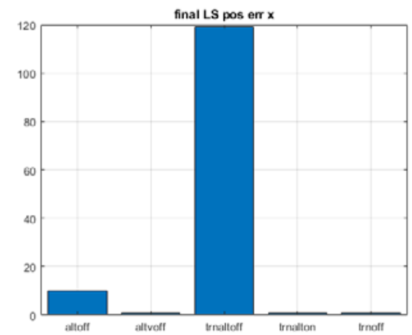


Navigation Takeaways

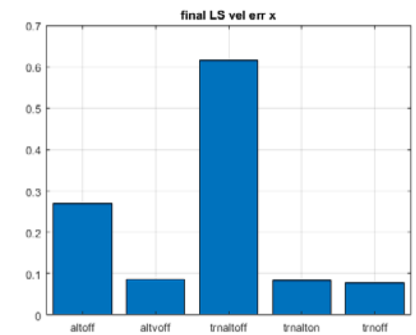
- TRN essential to position knowledge and guidance
- NDL critical to maintaining velocity knowledge at lower altitudes
- Higher grade Accelerometers greatly reduce navigation uncertainty
  - May need for engine cut-off initiation
- Still can have ~ 1 m uncertainty at landing (vertical knowledge)
  - Much better behaved with higher grade sensors
  - Filter improvements can be made with altimeter measurement ingestion to further improve accuracy
- Next steps:
  - Process/Assess navigation errors at 30m, 10m, and at 1m true altitude
  - Tune filter with higher grade IMU to reduce altitude noise further
  - Continue to assess bias estimation during cruise for accelerometers
  - Consider additional low altitude-focused altimeter

Vertical Uncertainty

Position (m)

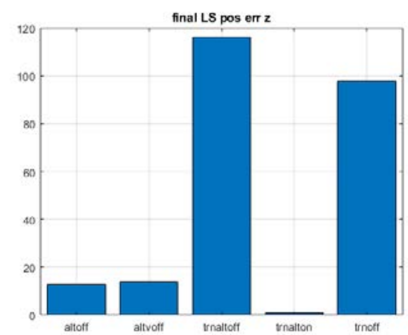


Velocity (m)

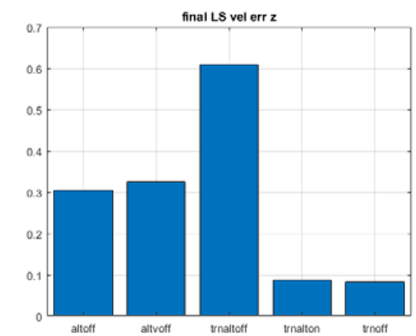


Lateral Uncertainty

Position (m)



Velocity (m)



Future Work and Next Steps

- Finalization of TRN requirements
  - Program selection of development approach
- Sensor requirements verification
  - Verify velocity constraint at landing
  - Finalization of mounting alignment requirements
- Continue to trade Guidance algorithms for improved vehicle performance and terminal descent
- Working towards Spring PDR
  - Program transitioning between Mission Directorates
  - Development of final system requirements
- Sensor selection
  - Re-evaluating IMU options for cost-savings, performance enhancements
  - Finalizing options for meeting touchdown velocity requirements

Thank you

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Naaem Ahmad, Jason Everett, Kyle Miller (NASA/MSFC),

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Any questions?