PL&HA
Precision Landing and Hazard Avoidance

SPLICE
Safe and Precise Landing –
Integrated Capabilities Evolution

STMD Game Changing Development Program

Precision Landing Performance of a Human-Scale Lunar Lander Using a Generalized Simulation Framework

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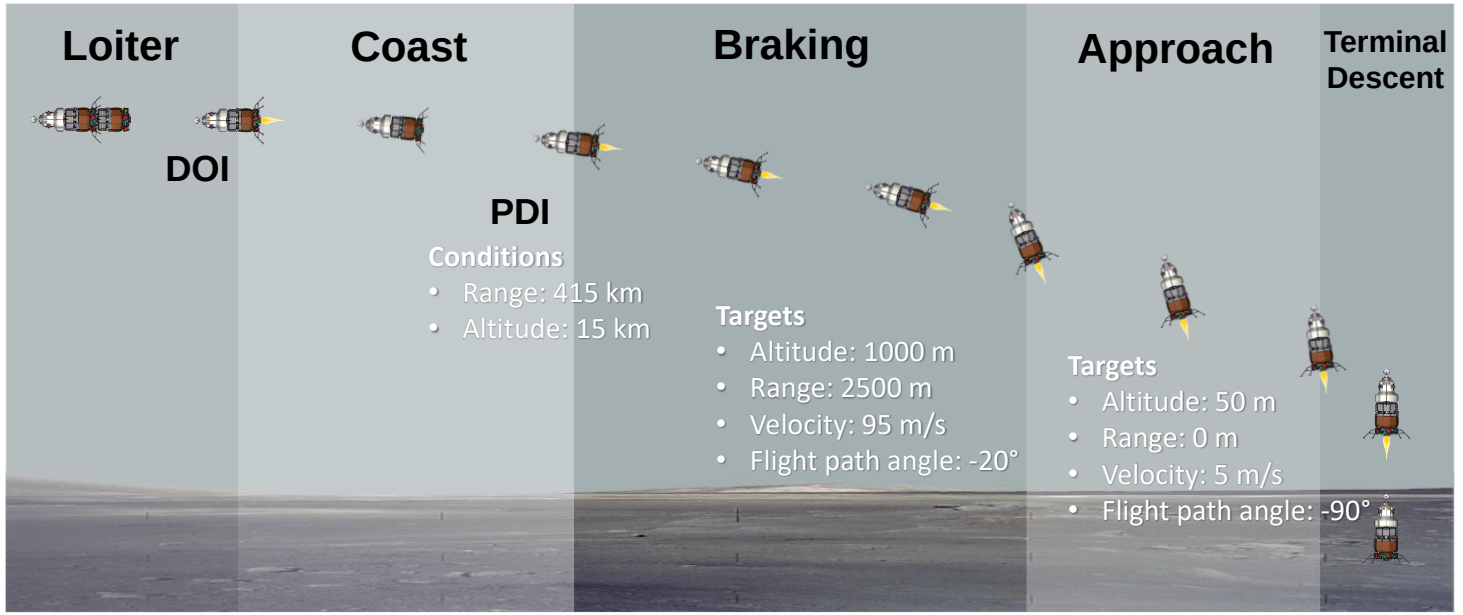
Introduction

- **Safe & precise crewed landing landings at the Moon and Mars with require evaluation of, and advances in, GN&C technologies**
- **Safe and Precise Landing Integrated Capabilities Evolution (SPLICE) project assesses these technologies and their performance effects**
  - Focus on deorbit/entry, descent, and landing (DDL/EDL)
  - 6DOF integrated performance simulations
  - Modeling of GN&C systems with varying levels of quality and fidelity
- **SPLICE simulation framework updated with navigation sensors running in-the-loop (POST2)**



Navigation Key Assumptions

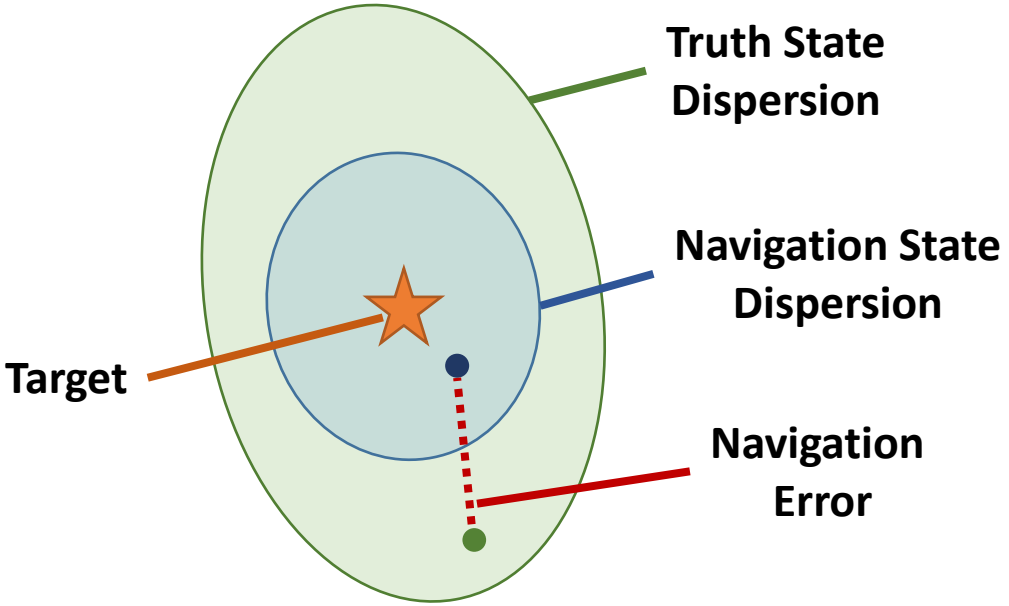
Loiter	Deorbit	Coast	Braking Phase	Approach Phase	Vertical Descent
IMU					
Star Tracker		Star Tracker			
DSN					
TRN					
NDL					

- **All sensors are mounted perfectly to the rigid body with known alignments (i.e., no sensor-to-body frame misalignments)**
- **Filter process noise includes IMU-related noise only**
- **Deep Space Network (DSN) update is treated as a filter re-initialization rather than a measurement**
  - DSN state measurement and associated covariance replaces current filter state and covariance

- **Inertial Measurement Unit (IMU)**
  - Generalized strapdown model
  - Scale factors, biases, internal misalignments, random walk/drift
- **Star Tracker**
  - Low-fidelity model (corrupted truth values)
- **Terrain-Relative Navigation (TRN) Camera**
  - Medium-fidelity model
  - Feature matching algorithm with state estimation
- **Navigational Doppler LIDAR (NDL)**
  - Tri-beam system (beams intersect terrain digital elevation model)
  - Error model accounts for modulation period and bandwidth, beam wavelength, frequency, and pointing knowledge

Performance Metrics

- **Navigation error**
  - Describes overall behavior of navigation system
- **Landing precision**
  - Describes how well integrated vehicle lands near pre-designated target
  - 100 m or better in a 99%-tile sense is desired
- **Success rate**
  - Describes percentage of 8,000 Monte Carlo samples that achieve a safe landing:
    - Horizontal velocity of less than or equal to 1.0 m/s
    - Vertical velocity of less than 3.0 m/s
    - Angle off vertical of less than 3°
    - Max angular rate about any axis of less than 0.5°/s
  - Success rate of 99% or better is desired



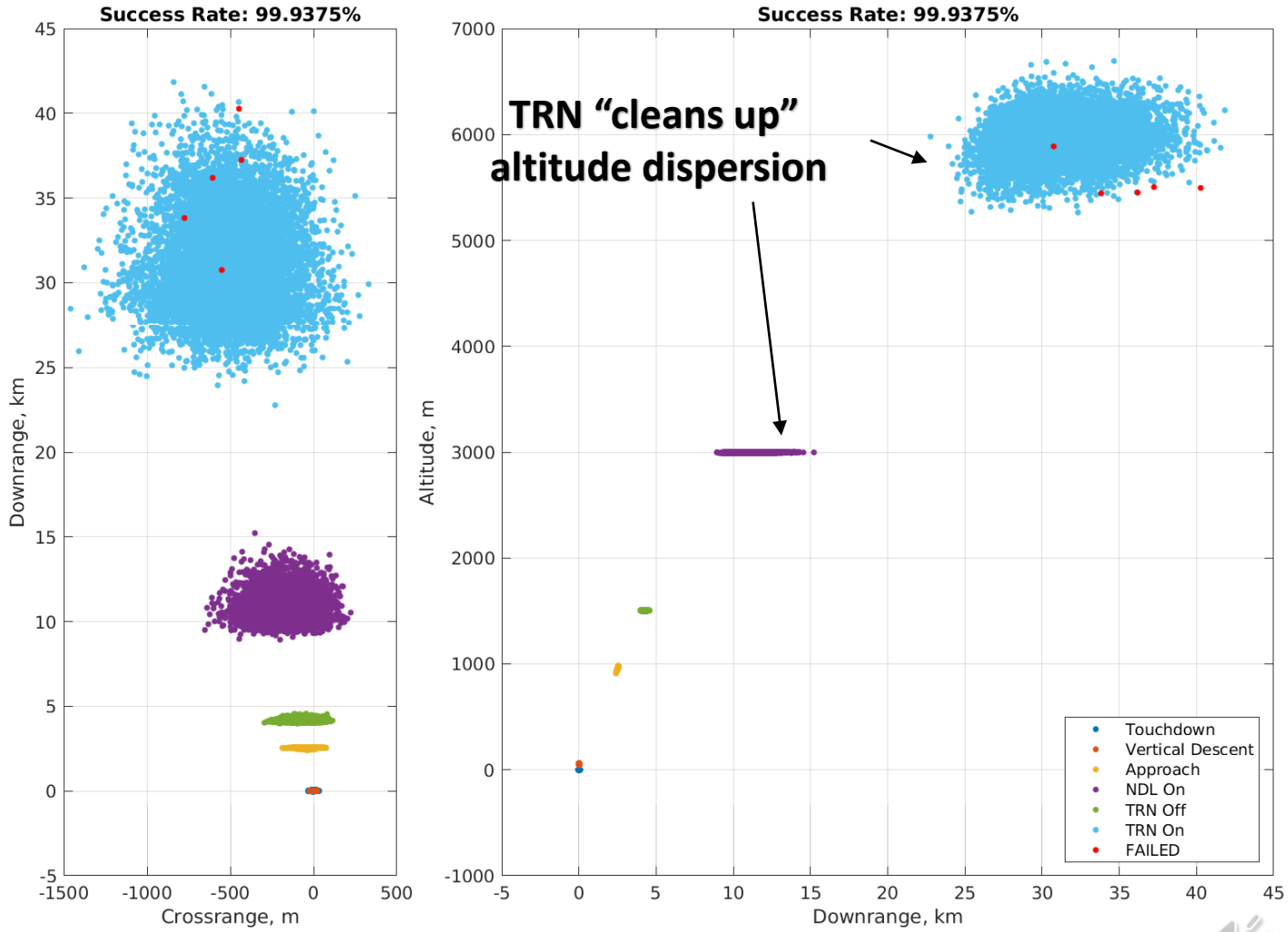
Trade Studies

	SPLICE	DSN 50%	DSN 10%	DSN Pos 10%
DSN Quality	High	R & V bias dispersions reduced by 50%	R & V bias dispersions reduced by 10x	R bias dispersions reduced by 10x
Comment	Baseline SPLICE specifications	Represents a more accurate state update	Represents near-perfect state knowledge	Sensitivity to position vs. velocity uncertainty

- **Each trade is an 8000-sample Monte Carlo (~10 min runtime)**
- **Trades chosen to explore effects of DSN measurement quality**
- **NDL and TRN sensors have detailed error models**
- **Star tracker and DSN models are of “low fidelity”**

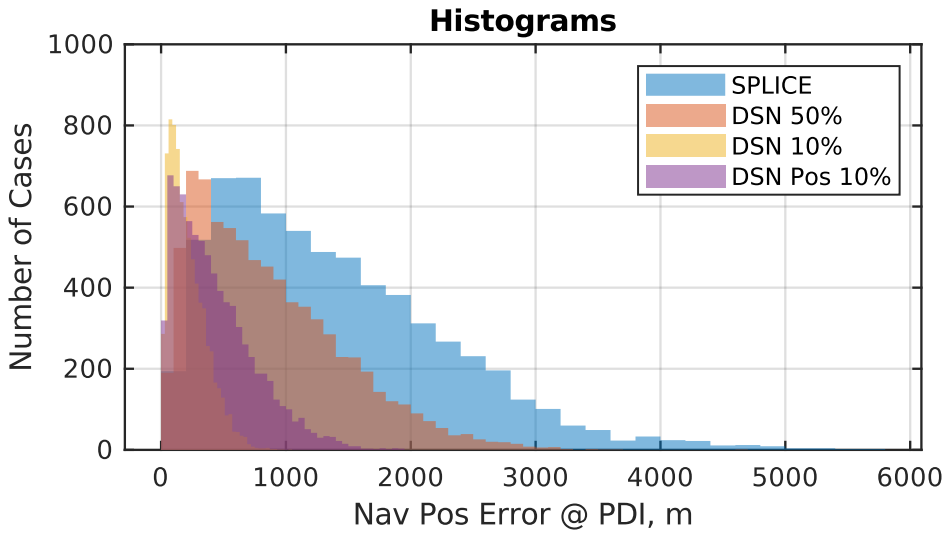
Results

- **DSN 10% trade**
  - Vehicle position in downrange-crossrange-altitude space relative to landing target
- **TRN On (cyan) and NDL On (purple) events triggered by navigated altitude**
  - TRN “cleans up” navigation errors

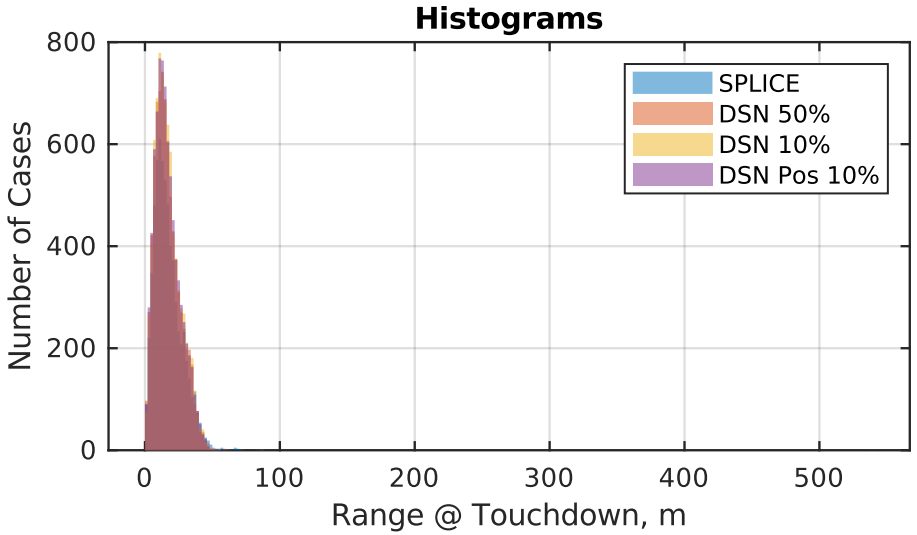


Results

- G&C can accommodate 1-2 km errors at PDI, but not 4+ km
- Landing precision is within requirement
- Success rate shows some trades do not ensure safe landing



	SPLICE	DSN 50%	DSN 10%	DSN Pos 10%
Nominal	3111.59	1527.26	260.26	710.08
Mean	1387.74	866.72	214.28	433.05
3-sigma	2742.06	1788.27	449.66	961.98
1.00 %-tile	123.72	68.77	16.76	23.84
99.00 %-tile	4217.77	2622.58	656.94	1392.9
Max Value	5657.97	4636.55	1043.68	1942.55
Min Value	24.35	12.77	2.91	3.53
Success	6412	7756	7997	7995
Percent	80.2	97	100	99.9



	SPLICE	DSN 50%	DSN 10%	DSN Pos 10%
Nominal	16.66	18.46	13.13	12.67
Mean	17.32	16.8	16.93	16.85
3-sigma	36.4	28.26	28.02	28.03
1.00 %-tile	1.66	1.84	2.09	1.88
99.00 %-tile	45.84	42.13	41.42	41.61
Max Value	539.19	72.25	86.61	57.24
Min Value	0.23	0.22	0.11	0.17
Success	6412	7756	7997	7995
Percent	80.2	97	100	99.9

Summary

- **Extensive updates to the POST2-based generalized SPLICE simulation framework**
  - Various navigation sensor engineering models have been improved and added
  - Vehicles can be modeled with closed-loop G&C and navigation running in-the-loop
  - Enable rapid investigation of a variety of vehicles and missions in an integrated performance sense
- **Future work**
  - Trade TRN sensor performance with DSN accuracy – can high altitude TRN buy back performance?
  - Refine sensor GR&As (include misalignments)