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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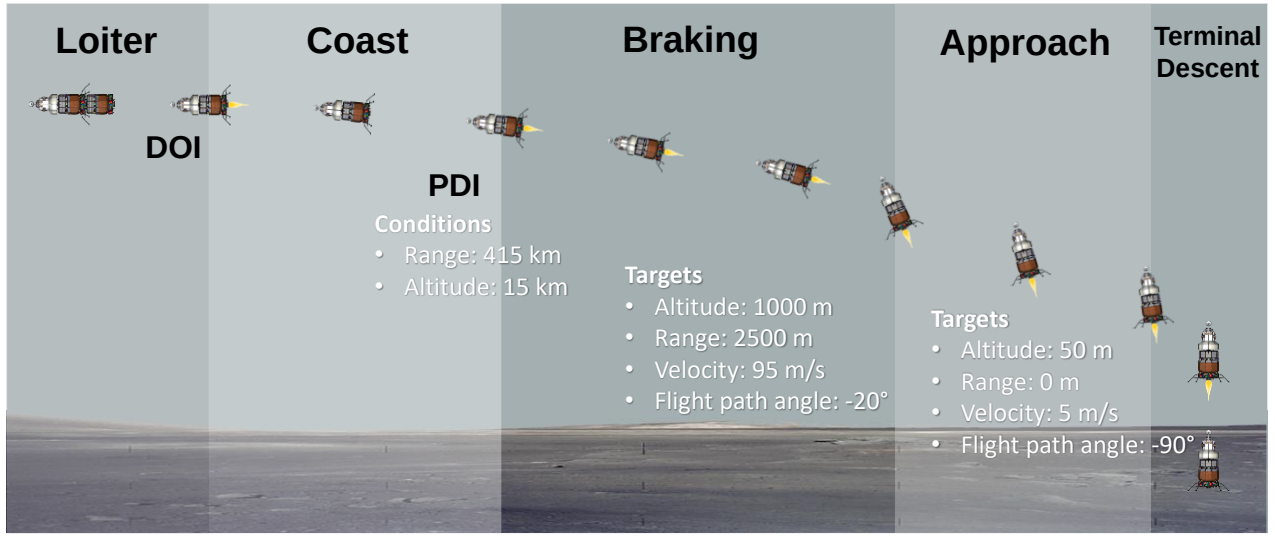
Introduction

- **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 assess 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
- **POST2-based SPLICE simulation framework updated with navigation sensors running in-the-loop**

Vehicle & Concept of Operations

- **Artemis government reference two-element Lunar lander**
  - Ascent element & descent element
  - ~48 t prior to DOI
  - 3x 8000 lbf throttleable main engines with TVC
- **Simulation begins ~15 min prior to DOI**
  - Handoff from 3-rev loiter orbit provided by 3DOF end-to-end simulation (NRHO to touchdown)

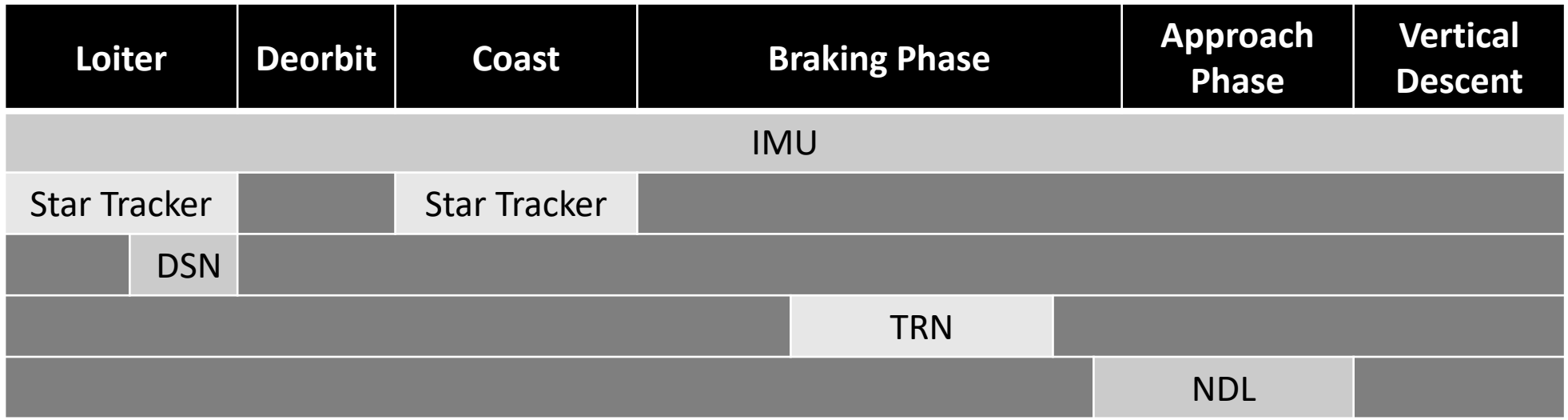


	Loiter	Deorbit	Coast	Powered Descent	Vertical Descent
Propulsion	RCS			Main Engines & RCS	
Guidance	Open-Loop			Apollo PDG	Vertical
Steering Law	Attitude Hold			Polynomial Acceleration Profile	Vertical
Roll Control	RCS				
Pitch/Yaw Control	RCS			TVC	
Roll Control Law	Phase-Plane				
Pitch/Yaw Control Law	Phase-Plane			PID + Allocator	

Navigation Sensors

- **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 DEM)
  - Error model accounts for modulation period and bandwidth, beam wavelength, frequency, and pointing knowledge

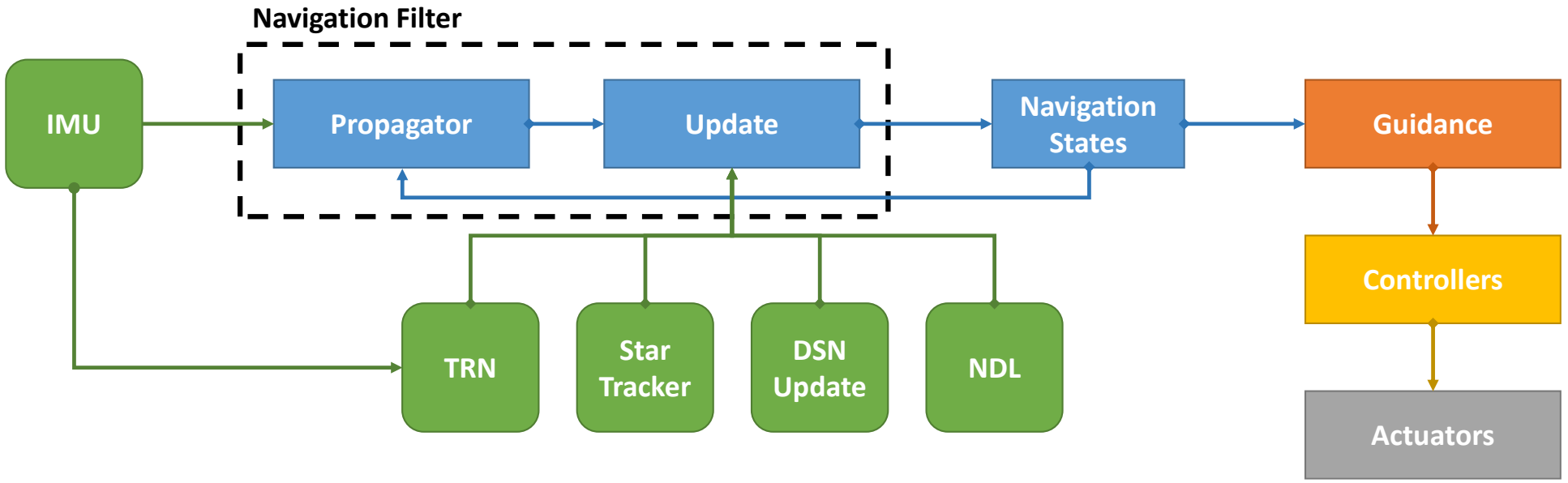
Navigation Key Assumptions



- **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**
- **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

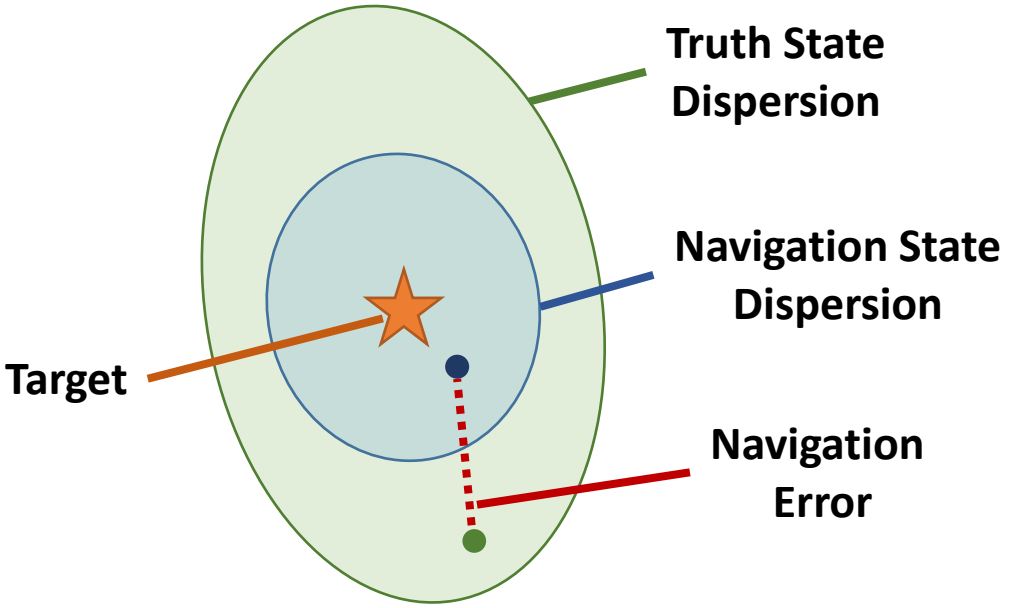
Simulation Framework

- POST2-based simulation with generalized GN&C models
- Provides users with method of building detailed simulations with “off-the-shelf” models that can represent a variety of systems
- Fast simulation run time (~10 min for 8000-run Monte Carlo) enables quick turnaround of trade studies



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 3σ sense is desired (99%-tile statistics also assessed)
  - Assume that inertial location of landing site is known perfectly and that the same location is used for GN&C targeting
- **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

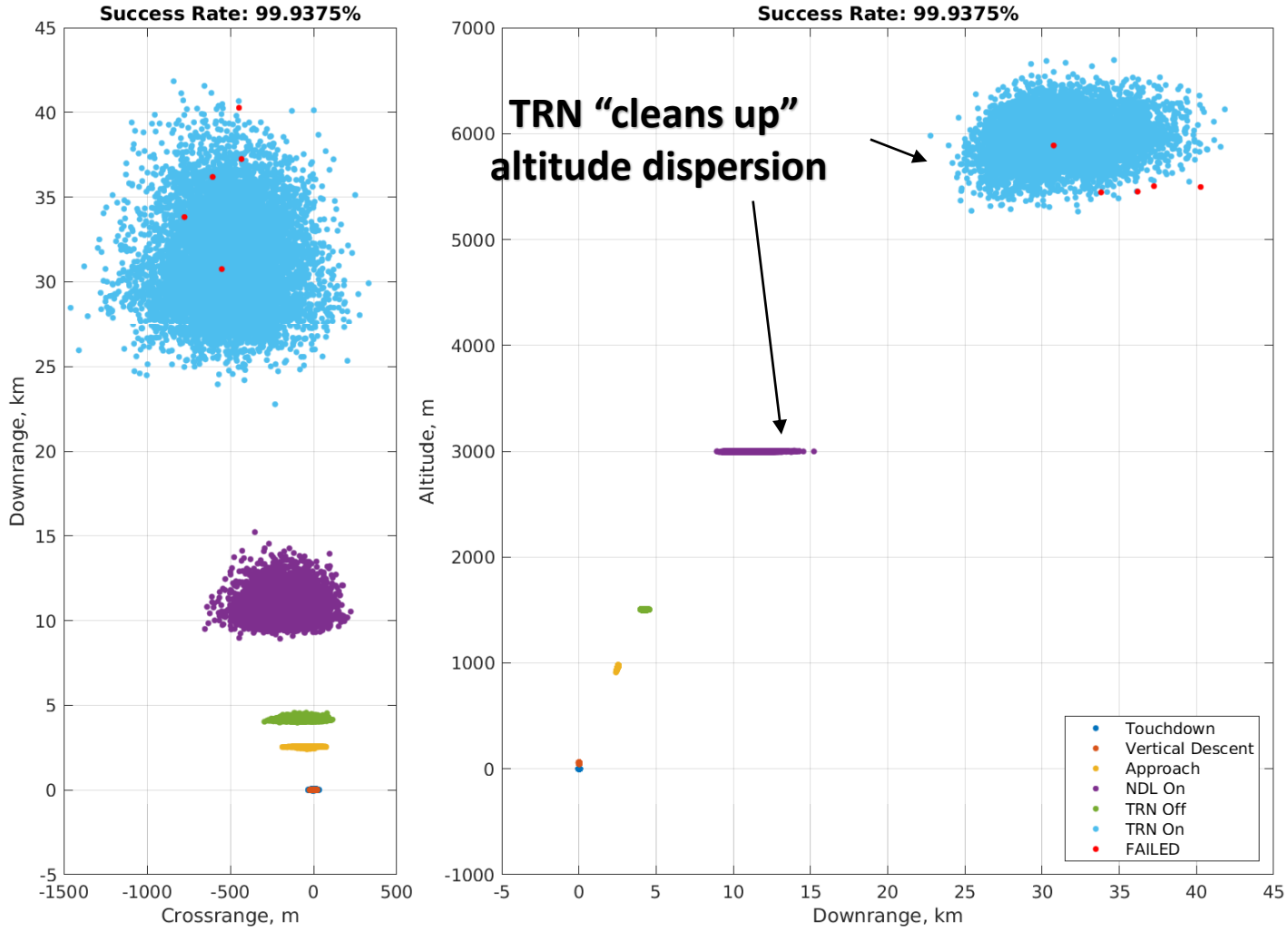
- Each trade is an 8000-sample Monte Carlo
- Trades chosen to explore effects of DSN measurement quality
- NDL and TRN sensors have detailed error models
- Star tracker and DSN models are of “low fidelity”

	Parameter	Dispersion (Normal)
Initial Conditions	• Body rates • Attitude • State Covariance	• 0.3°/s 3σ • 3.0° 3σ • 0.03° 3σ for angles, 0.03 km 3σ for altitudes
Propulsion	• Peak Thrust • Isp	• Scale factor: 1% 3σ • Scale factor: 1% 3σ
Mass	• Total Mass • Center of Gravity • Moments & Products of Inertia	• 250 kg 3σ • 0.05 / 0.01 / 0.01 m 3σ • 1% kg-m^2 3σ
IMU	• Accel & Gyro Misalignment, Bias, Scale Factor, Random Walk	• SPLICE High Quality
Star Tracker	• Misalignment • Boresight Noise	• 8 arcsec 3σ • 24 arcsec 3σ
DSN	• Position Bias • Velocity Bias	• 500 / 1000 / 200 m 3σ • 0.05 / 0.10 / 0.01 m/s 3σ
NDL	• NDL Error Model	• See paper
Optical TRN	• TRN Error Model	• See paper

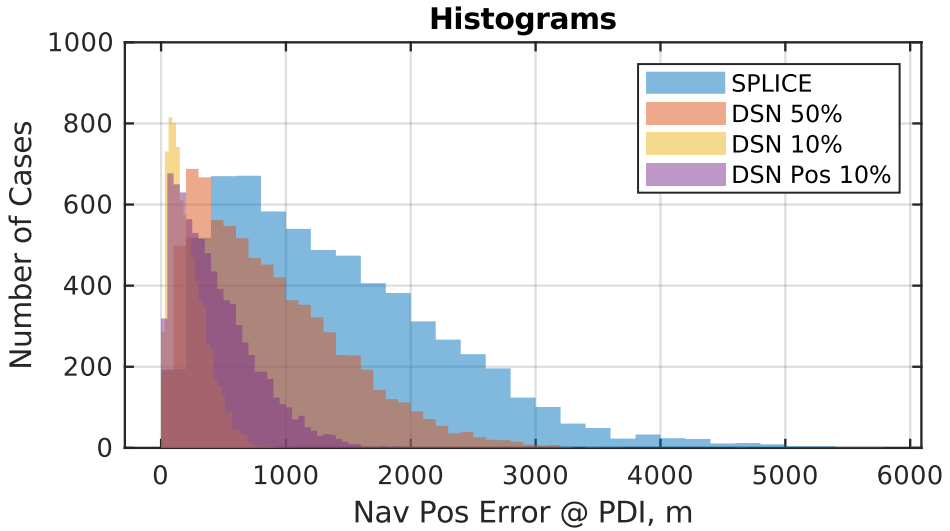
	SPLICE	DSN 50%	DSN 10%	DSN Pos 10%
DSN Quality	High	R & V bias dispersions reduced by 50%	R & V bias dispersions reduced by 90%	R bias dispersions reduced by 90%
Comment	Baseline SPLICE specifications	Represents a more accurate state update	Represents near-perfect state knowledge	Sensitivity to position vs. velocity uncertainty

Results

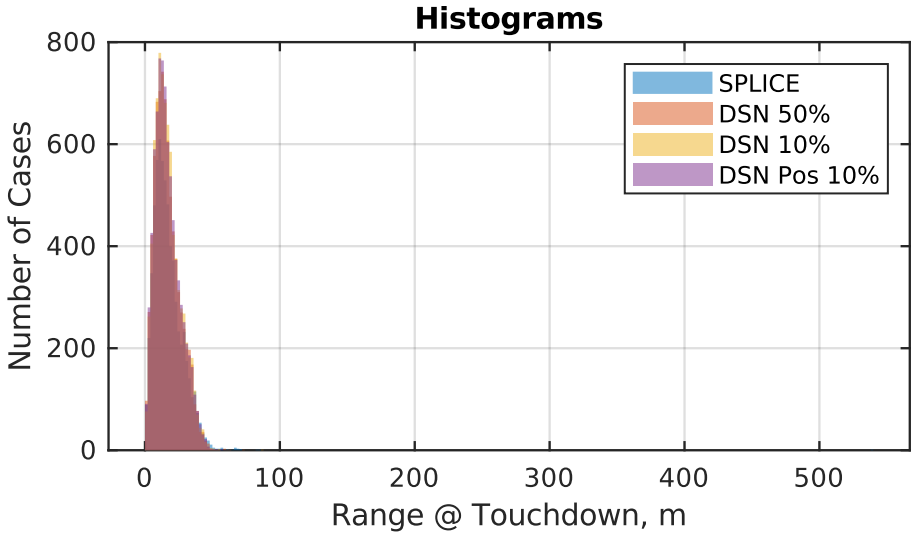
- **DSN 10% trade**
  - Vehicle position in downrange-crossrange-altitude space relative to landing target
- **TRN On (cyan) and NDL On (purple) events triggered by navigated altitude**
  - TRN “cleans up” navigation errors
- **Red dots correspond to five failed Monte Carlo samples in this trade**
  - Combination of low altitude and either excessive or insufficient velocity that contribute to insufficient control authority



- **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

Results: Navigation Error

	SPLICE			DSN 50%			DSN 10%			DSN Pos 10%		
	Pos (m)	Vel (m/s)	Att (deg)	Pos (m)	Vel (m/s)	Att (deg)	Pos (m)	Vel (m/s)	Att (deg)	Pos (m)	Vel (m/s)	Att (deg)
DOI	819	0.24	0.004	418	0.13	0.004	87	0.03	0.004	92	0.09	0.004
PDI	4218	3.69	0.003	2623	2.23	0.003	657	0.58	0.003	1393	1.21	0.003
TRN On	4638	4.10	0.006	2818	2.53	0.006	728	0.71	0.006	1584	1.42	0.006
TRN Off	8	0.15	0.068	8	0.14	0.067	8	0.14	0.067	8	0.14	0.067
Vertical Descent	18	0.07	0.296	15	0.03	0.071	15	0.03	0.068	15	0.03	0.069
Touchdown	20	0.20	0.295	15	0.16	0.065	15	0.15	0.064	15	0.15	0.064

- Effect of DSN update quality evident at DOI/TRN On
- Performance gains primarily in position accuracy
- TRN and NDL significantly reduce errors and keep them low
- Attitude errors are small (star tracker)

Summary & Conclusions

- **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
- **Overall navigation performance given design and analysis GR&As and a sufficiently accurate DSN measurements was satisfactory**
  - Better position accuracy can provide significant improvements in success rate
  - Must consider multiple metrics simultaneously – e.g., success rate and landing precision
- **Future work**
  - Trade TRN sensor performance with DSN accuracy – can high altitude TRN buy back performance?
  - Refine sensor GR&As (include misalignments)
  - Tune EKF to improve filter consistency

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