National Aeronautics and Space Administration

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SPACE LAUNCH SYSTEM

Application of GPS to Enable Launch Vehicle Upper Stage Heliocentric Disposal

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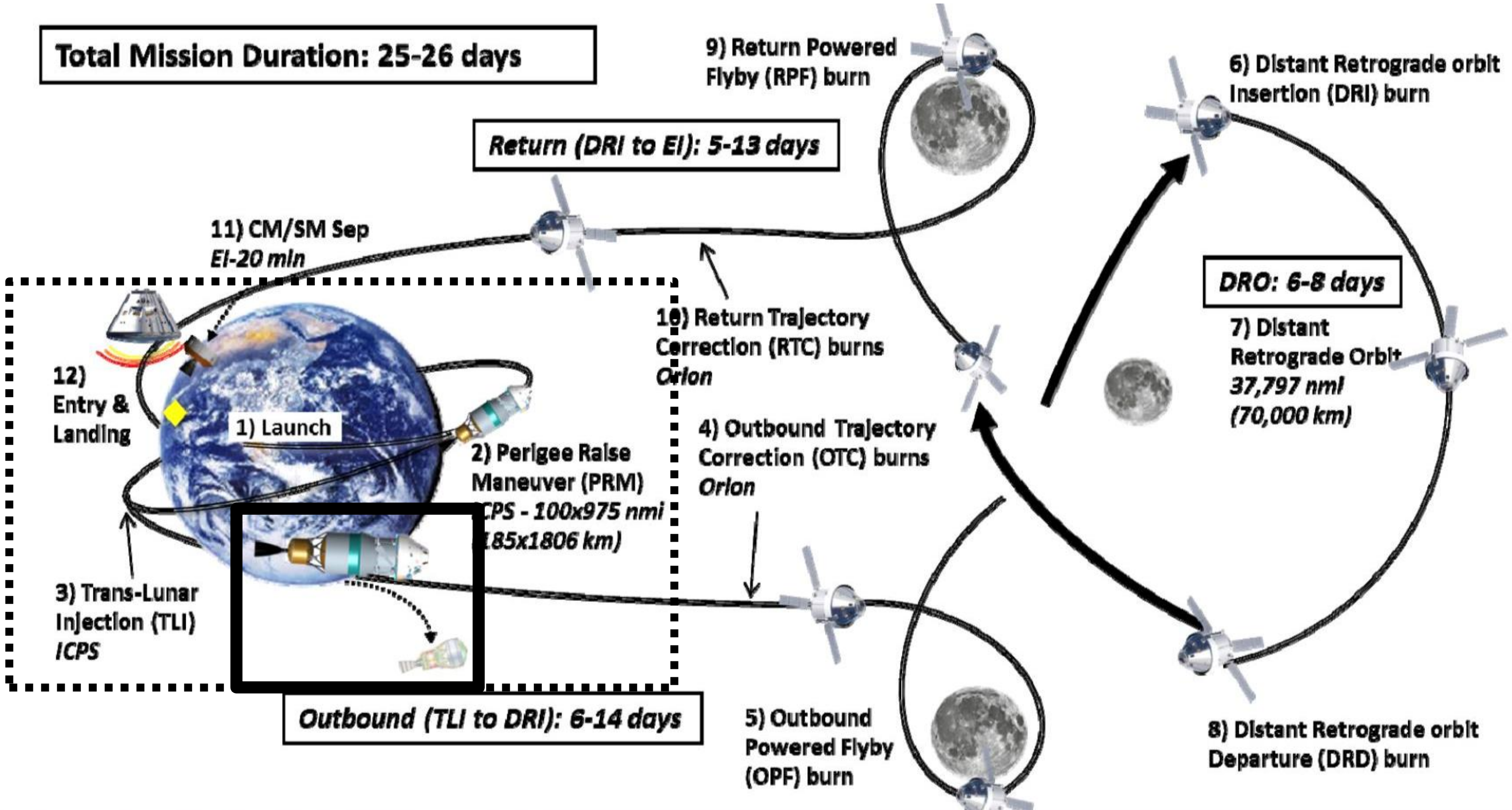
Overview

- **Exploration Mission-1**
- **Space Launch System Block 1 Vehicle**
- **Core Stage**
  - 2 5-segment SRBs
  - 4 RS-25 engines
  - 70 metric ton lift capability
- **Upper Stage**
  - ULA DCSS-derived ICPS
  - 1 RL-10 engine

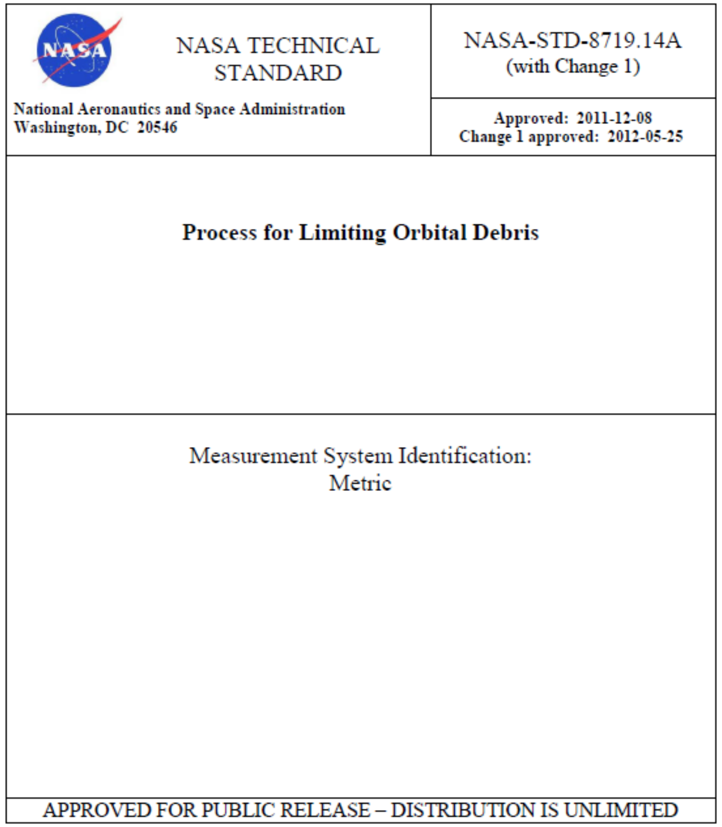


EM-1 Mission Profile Considerations

- **Demonstrates initial SLS vehicle performance**
- **Provides for challenging, extended (3 week) test of uncrewed Orion systems in the deep space environment**
- **Demonstrates ability to enter, operate in, and exit DRO**

Need for Upper Stage Disposal

- **NASA-STD-8719.14A**
  - Inter-agency agreement
  - Limit creation of new orbital debris to reduce risks to future missions
  - Has led to powered re-entry/lifetime requirements for orbital satellites
  - Requires long-lifetime state propagation to assess risk of re-impact with existing assets
- **Requirement to dispose of upper stage to have minimal impact to Earth-Moon space**
  - Reduce risk of potential re-contact with payload (Orion and secondary payloads)
- **Vehicle-level requirement must be assessed with integrated design**
  - Core and upper stage performance
  - Guidance capability and targeting
- **Options for stage disposal**
  - Intentional breakup
  - Lunar Impact
  - Direct heliocentric burn
  - Heliocentric via Lunar Fly-by
- **Earth-Moon geometry plays large role in difficulty of maneuver**


NASA TECHNICAL STANDARD

National Aeronautics and Space Administration
Washington, DC 20546

NASA-STD-8719.14A
(with Change 1)

Approved: 2011-12-08
Change 1 approved: 2012-05-25

Process for Limiting Orbital Debris

Measurement System Identification:
Metric

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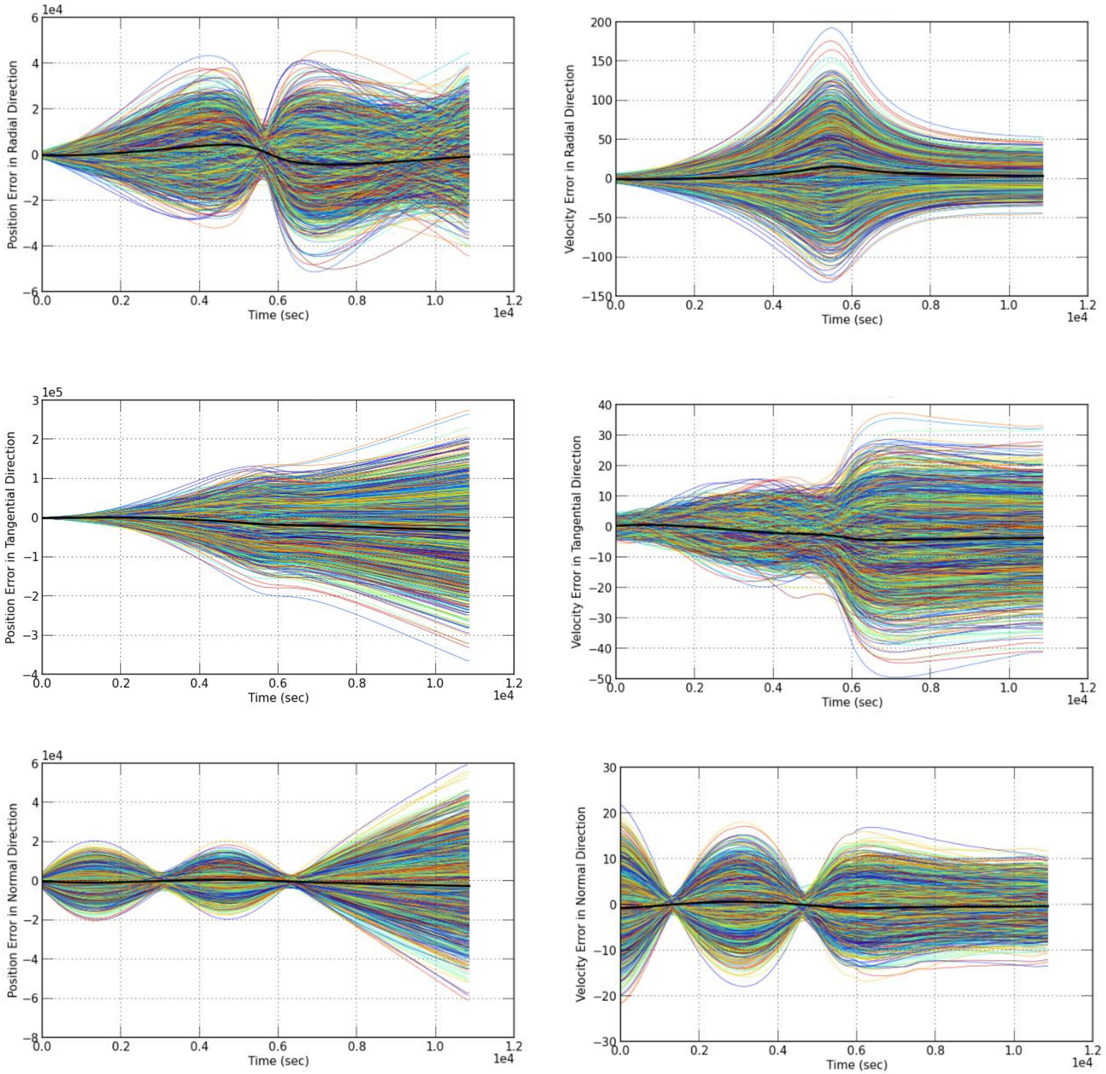
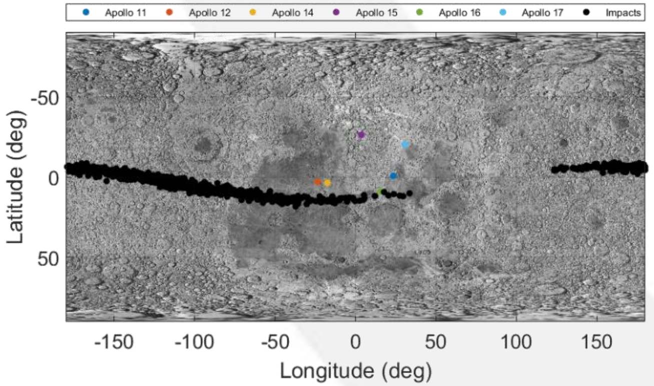
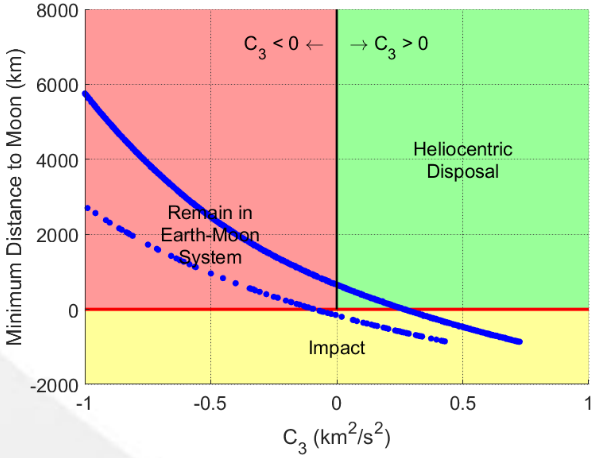
This NASA-STD is primarily designed to limit the creation of new orbital debris and, therefore, to limit the risk to other current and future space missions.

Disposal Capability with Pure-Inertial Systems

- **State of the art inertial systems used through ascent and in-space operations***
- **Large state uncertainty at time of disposal maneuver**
  - Inertial navigation over long period of time
  - Single optimized orbital targets calculated well before launch as function of launch time
- **Inertial Navigation and targets optimized for heliocentric trajectory post-swingby**
  - Probability of Lunar impact: ~42%
  - Probability of Heliocentric disposal: ~48%
- **Dispersion at the moon exceeds Lunar diameter**
- **Inertial-only navigation insufficient to allow for adequate robustness in stage disposal**





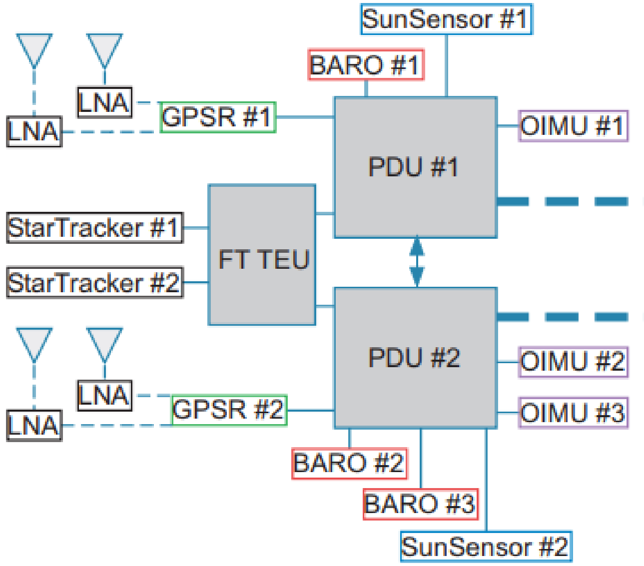


*assessed using notional error budget from similar systems

Design Space for Potential Options

- **State update from ground**
  - Additional requirements on communication system (upload and transponder)
- **State update from payload (if interface)**
  - Complications and latency in interface definition
  - Limited data throughput between elements in stack
  - High accuracy navigation solution due to expanded sensor suite
- **Algorithms to improve on-orbit propagation**
  - On-orbit calibration of sensors with external measurements
  - Neglect accelerometers during orbital cruise in inertial navigation
  - Expanded gravity models (higher order, additional bodies)
  - In-orbit target generation (optimization based on state knowledge)
- **Incorporate GPS into upper stage**
  - Complications with integrating new hardware onto COTS stage
  - Orbital environments at high altitude
  - Limited time for receiver development and integration
- **Reduce time in orbit/time to disposal maneuver**
  - Time for checkouts vs. inertial drift

MPCV Navigation Architecture



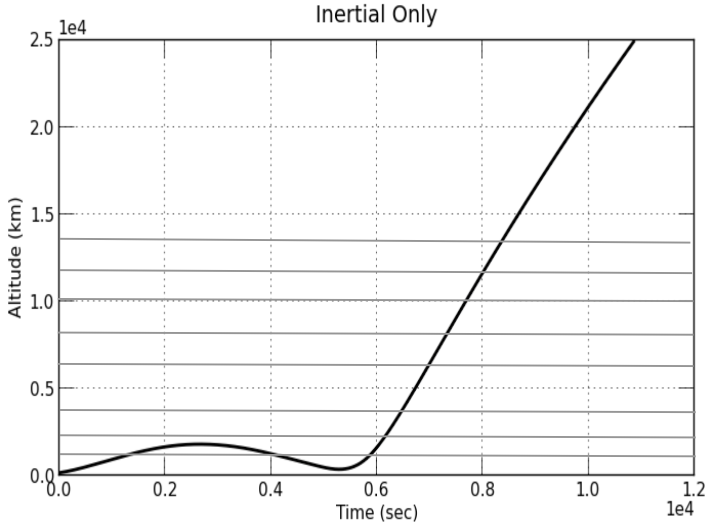
NASA/Holt

NASA/JPL

GPS Integration Algorithms Used

- **Generic GPS Receiver Model**
  - Errors modeled as 1-sigma values based on constellation capability
  - Modeled as ECEF measurements of position, velocity, time
  - Neglecting moment arm effects at GPS sensor
- **Inertial navigation using reference sensor error budget**
  - Trapezoidal integration with 100Hz DV and DΘ
- **15 State Loosely-Coupled Filter**
  - Position, velocity, and attitude updates
  - Accelerometer bias and gyroscope bias estimation
  - Increase of Velocity Error Process Noise during orbital maneuvers
  - Covariance Propagation at 50Hz, 1Hz updates
- **Modeling GPS outage at fixed altitudes for each Monte Carlo set**
  - Inertial-only, 1000km, 2000km, 4000km, 6000km, 8000km, 10,000km, 12,000km, 14,000km
  - Disposal maneuver well into lunar-bound trajectory with high altitude rates

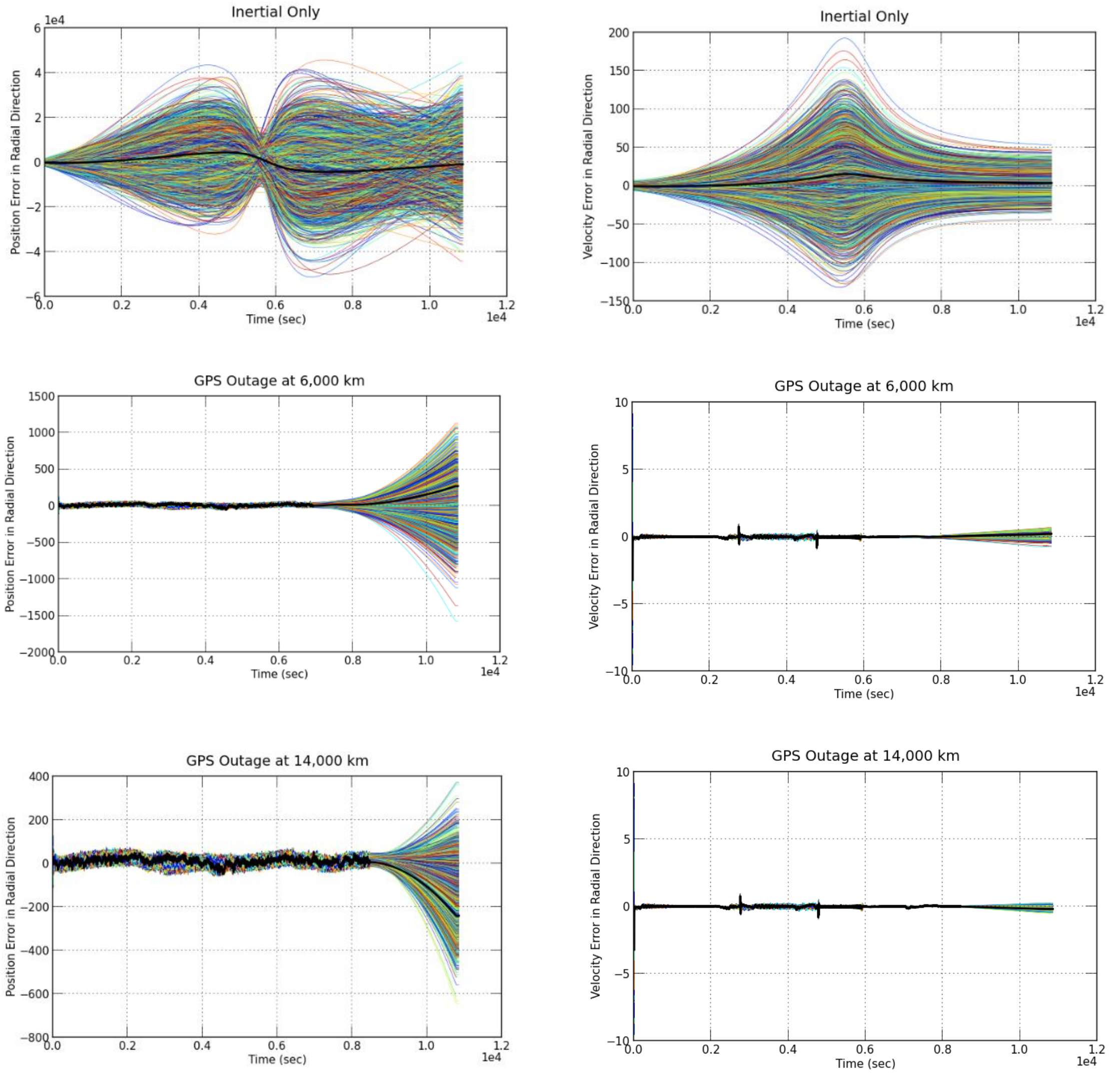
$$\bar{x} = \begin{bmatrix} \bar{r}_{err} \\ \bar{v}_{err} \\ \bar{\varphi}_{err} \\ \bar{b}_a \\ \bar{b}_g \end{bmatrix}$$



*Notional mission does not represent actual flight dates or final trajectory

Navigation Results

- **Seeded by results of Ascent Monte Carlo***
  - Requirements-based assessment of initial attitude solution
  - Dispersed sensor error terms per run
- **Simulation Events**
  - Trans-lunar injection by upper stage
  - Separation of payload
  - Ends at start of disposal maneuver
- **GPS filter comes online at start of in-space trajectory**
  - Pure inertial navigation over ascent
- **All scenarios had pure-inertial periods prior to disposal maneuver**
- **Primary inertial error sensitivities**
  - Gravity estimation due to position error
  - Numerical integration over long coast
  - Higher order sensor error terms and noise



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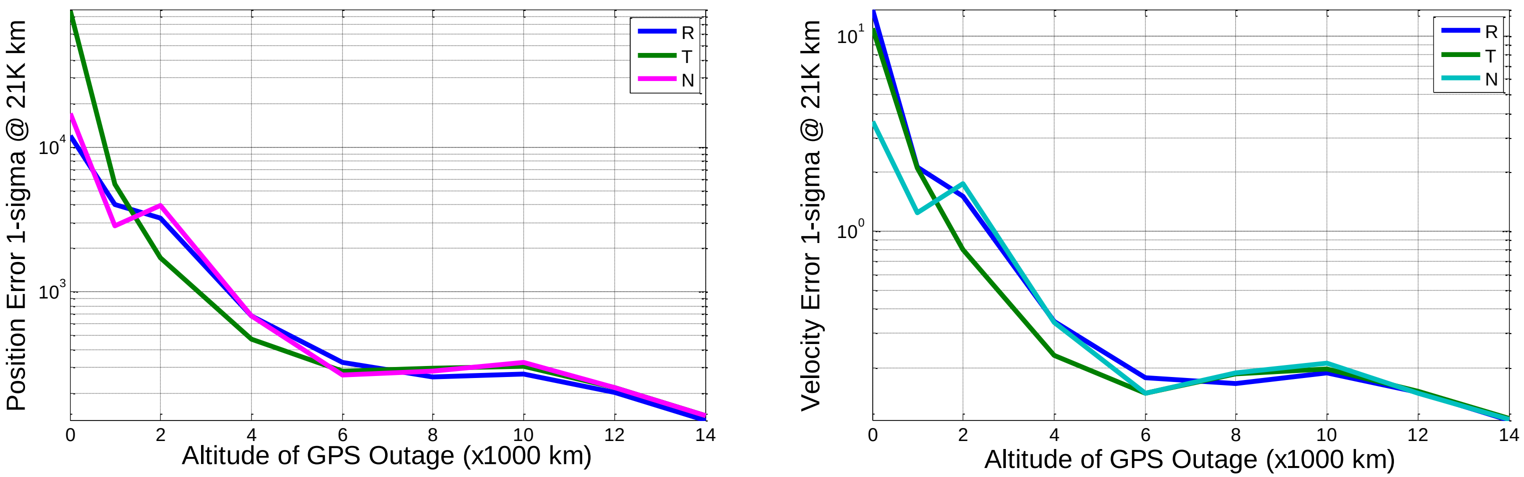
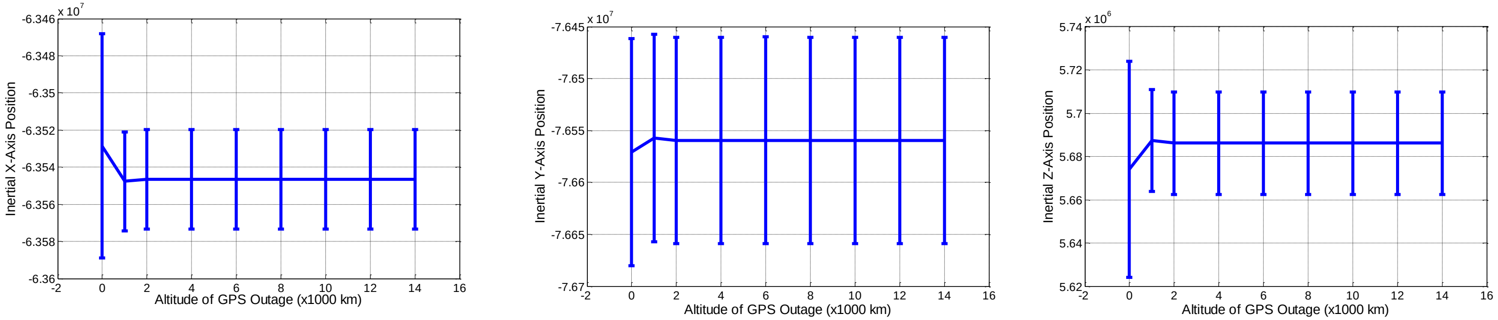
Dispersions of State vs. Knowledge of State at Disposal

- **State knowledge at Disposal Maneuver greatly improved due to GPS integration**
- **Consistent dispersions in actual state at disposal with GPS vs. without**
- **Dispersions of actual state primarily driven by TLI maneuver**
  - TLI guidance easily able to hit target within requirements with GPS-state knowledge
  - Insertion accuracy defined by guidance end conditions
  - Upper stage engine tail-off uncertainty has large impact
- **Attitude-only maneuvering between TLI and Disposal burns**

Navigation Uncertainty (1-sigma) in RTN



Mean State and Uncertainty (1-sigma) in Inertial Frame



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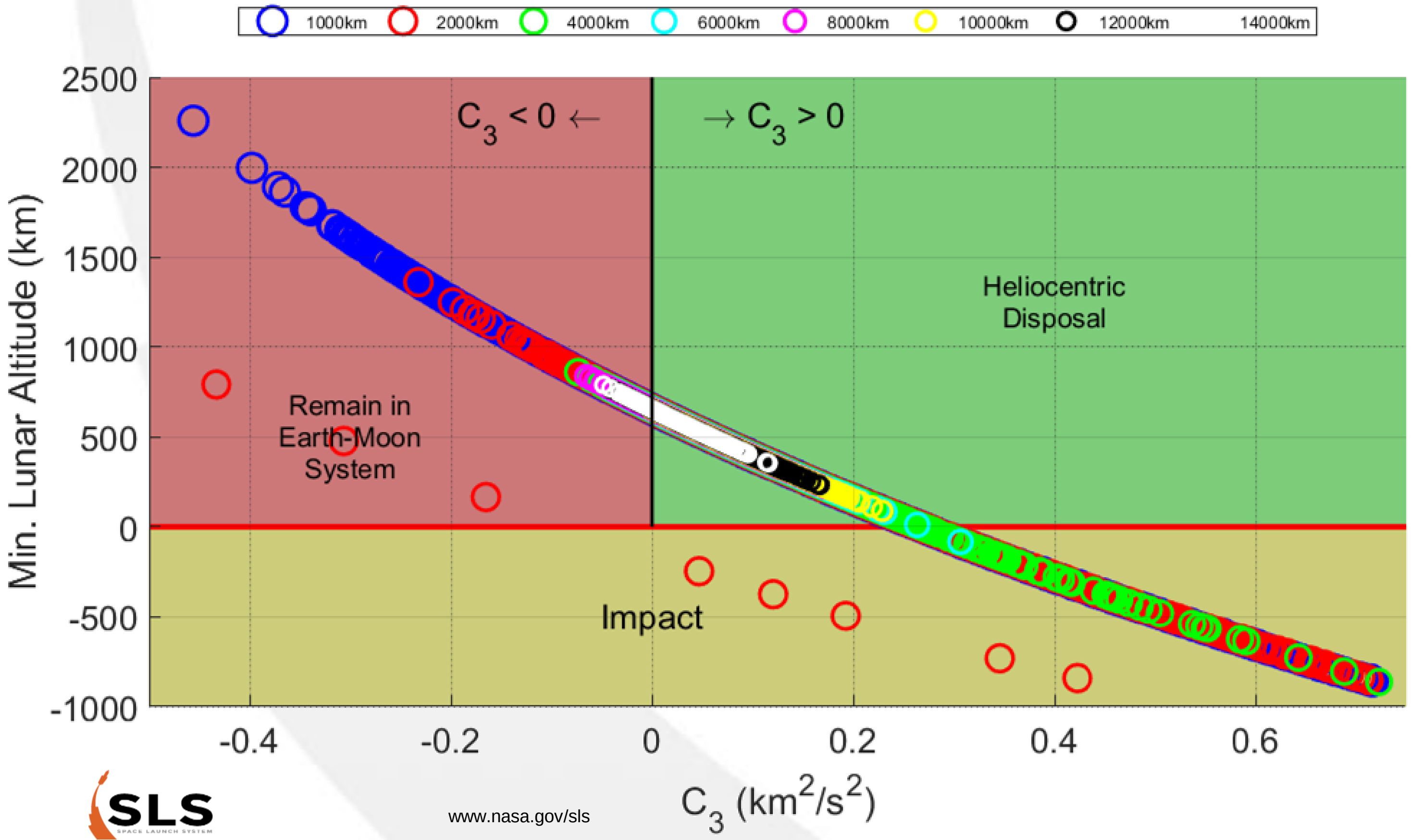
Disposal Success Probability

- **Inertial Navigation and targets optimized for heliocentric trajectory post-swingby**
  - Optimized for individual lower altitudes until requirement met, then fixed for high altitudes
  - Each individual case propagated with target set to ascertain disposal capability
- **Disposal Maneuver occurs at ~25000km altitude**
- **Disposal success (90% heliocentric) achieved with GPS to 4000km**



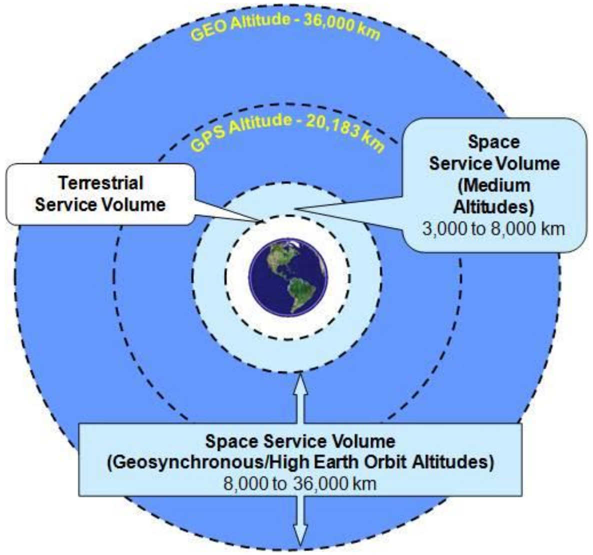
Monte Carlo Case	% Lunar Impact	% Heliocentric
No GPS	41.83	48.88
GPS Outage @ 1000km	28.29	60.17
GPS Outage @ 2000km	25.74	88.66
GPS Outage @ 4000km	03.85	96.30
GPS Outage @ 6000km	00.05	97.65
GPS Outage @ 8000km	00.00	91.85
GPS Outage @ 10000km	00.00	99.95
GPS Outage @ 12000km	00.00	98.45
GPS Outage @ 14000km	00.00	93.70

Conclusions and Design Considerations

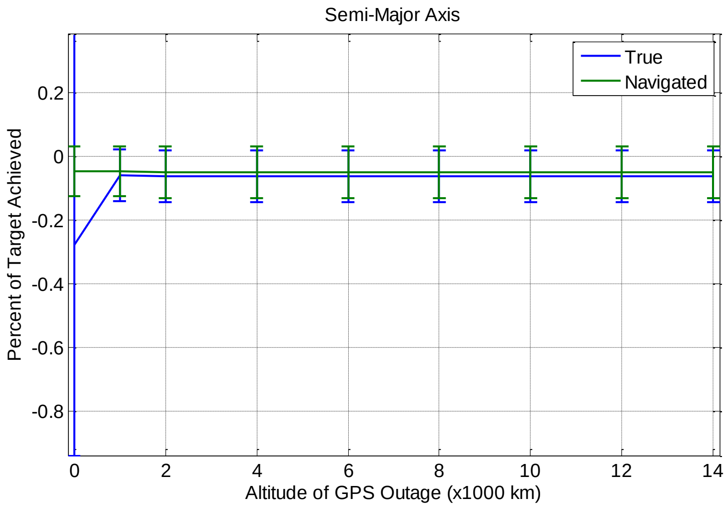
- **High altitude GPS enabled heliocentric disposal with burn in Earth orbit**

- **Design Considerations**
  - Algorithmic complexity
  - High-altitude operation
  - Integration of COTS unit into existing systems
  - Limited commercial options for high altitude operation
  - Performance definition of Service Volume
  - Large Earth-moon geometry sensitivity to process
- **Other options**
  - Include Heliocentric disposal as part of TLI maneuver
  - Further increase accuracy of in-space guidance
  - On-orbit autonomous targeting

Space Service Volume



SMA Achieved in TLI Maneuver



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Effect of Higher Altitude Capability

- With GPS solution at 4000km, able to meet disposal requirement
- Higher altitudes enable more robust/concentrated solutions