National Aeronautics and Space Administration

LUNAR COMMUNICATION RELAY AND NAVIGATION SYSTEMS

Autonomous Navigation of a Lunar Relay Using GNSS and Other Measurements

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Exploration & SPACE Communications

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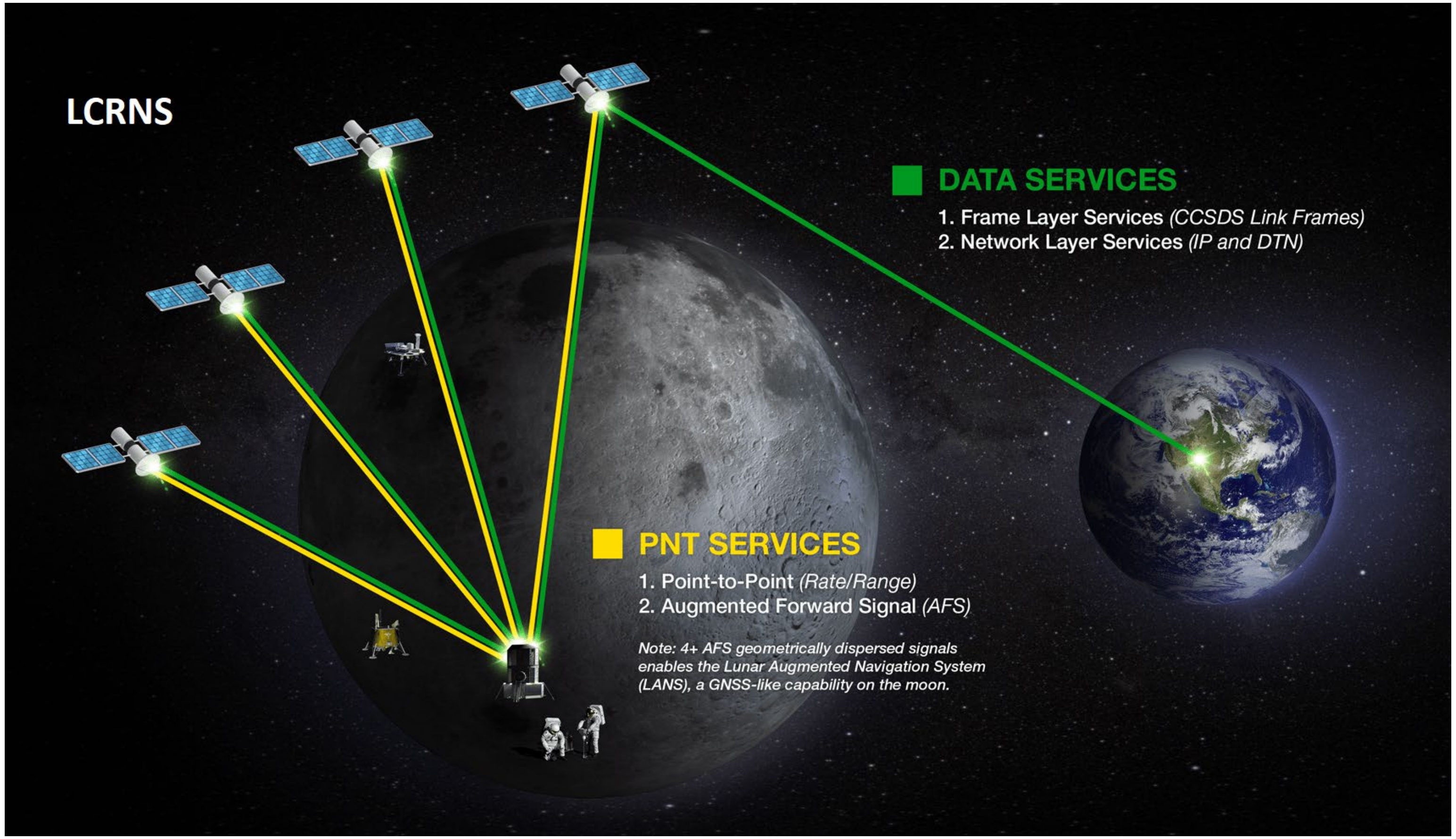


Introduction

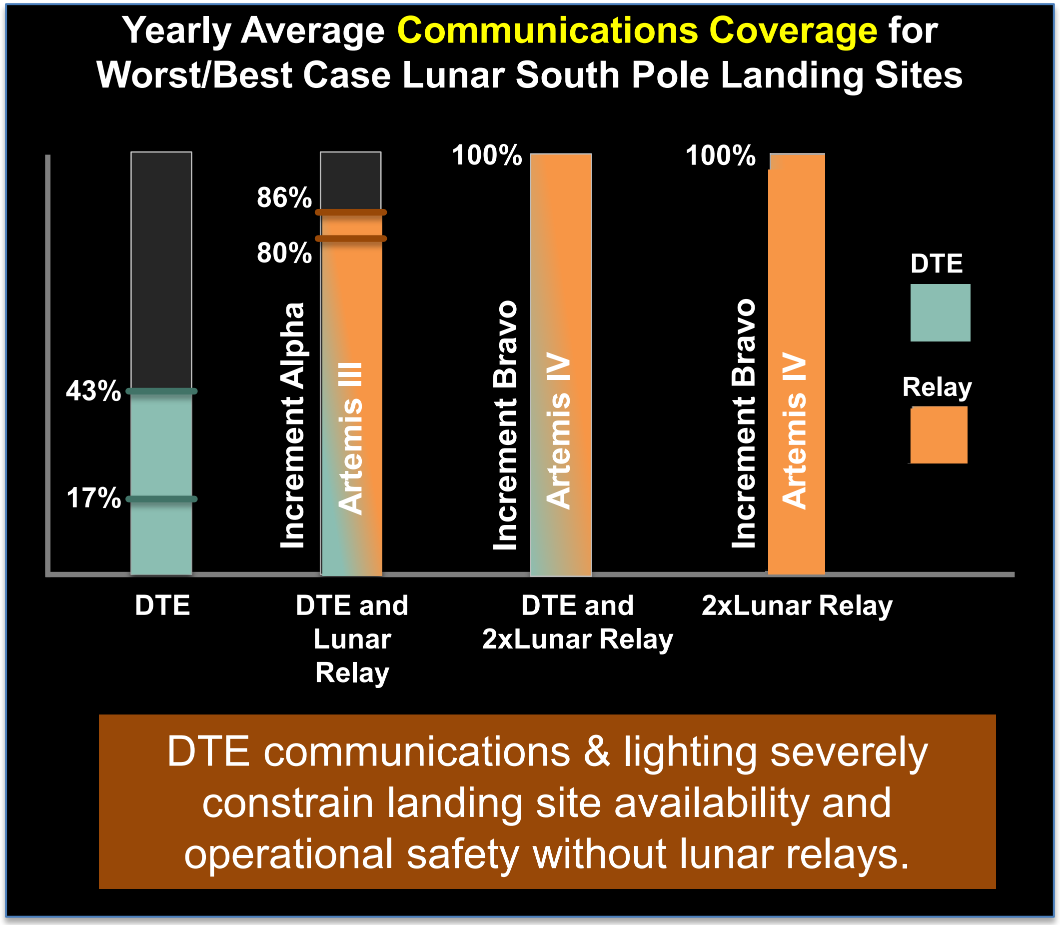
LCRNS Introduction

[Moon to Mars Objectives](#) define agency-level exploration objectives

- **Lunar Infrastructure Goal:** Create an interoperable global lunar utilization infrastructure where U.S. industry and international partners can maintain continuous robotic and human presence on the lunar surface for a robust lunar economy without NASA as the sole user, while accomplishing science objectives and testing for Mars.

Lunar Communications Relay and Navigation Systems (LCRNS)

- **Objective:** Enable an interoperable commercial lunar communications and navigation-orbiting infrastructure that meets NASA's needs, represents a sustainable, long-term approach to human and robotic exploration, and embodies an extensible solution for Moon and Mars.



LCRNS PNT Instrument (LPI)

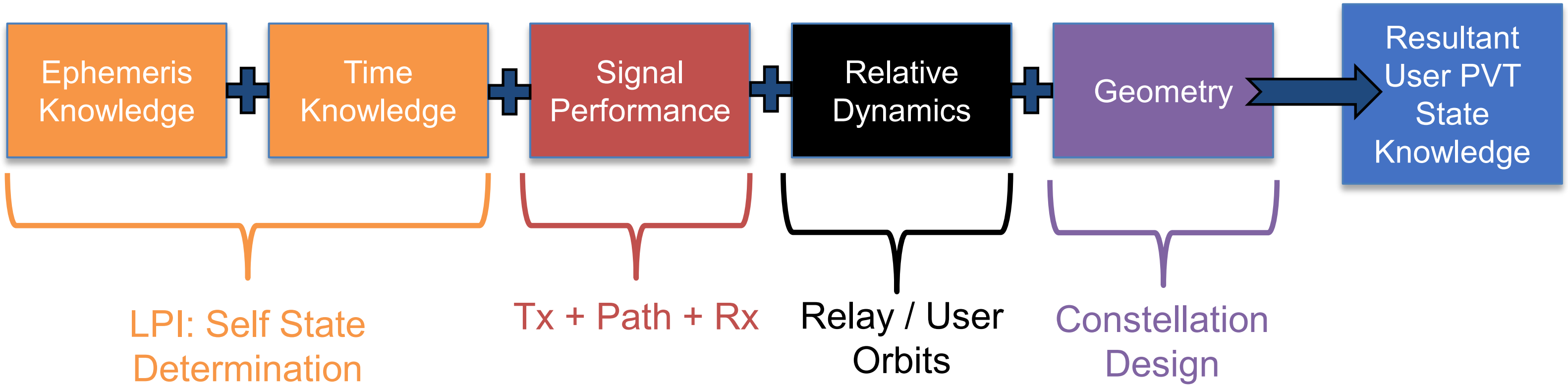
Sample lunar user need: LCRNS.3.0570 Table 3-10 Representative User Scenario PNT Performance Requirements

	Lander/Orbiter - Low Lunar Orbit	Lander - Prior to De-Orbit Insertion	Powered Descent Initiation to Landing	General Surface
Position Knowledge (m) (3-sigma value)	100	100	25 radius[1]	± 10 absolute; < 10 relative[2]
Velocity Knowledge (m/s) (3-sigma value)	0.01	0.05	0.1 3D[3]	N/A[4]
Time to First Fix (s) - Time Delay to meet Knowledge	3600	-1200[5]	-900[6]	600
Time Delay to meet Knowledge Update (s)	30	1	1[7]	1
Time Knowledge (ms)	0.10	0.10	0.10	0.10

NOTE: All values are specified relative to the (TBS) lunar reference frame.

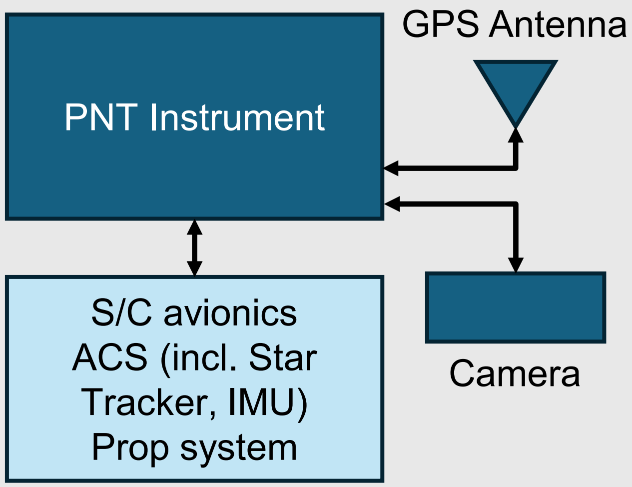
[1] Assumes lander includes Hazard Detection/Avoidance system; requirement is per axis until landing at which point it is the RSS of the lateral directions as represented by radius from landing target.
[2] Relative to another surface asset or feature; requirement is not fully allocated to the Lunar Relay, however radiometrics from Lunar Relay contribute to relative knowledge solution.
[3] 3D means per axis.
[4] Assumes path ill-defined and velocity results from differencing of previous and current position measurement.
[5] Not time to first fix, but rather is time prior to Descent Orbit Insertion when knowledge requirement must be met.
[6] Not time to first fix, but rather is time prior to PDI assuming a maximum of 30 minutes to achieve the PVT performance.
[7] Update rate using radiometrics; also assumes landing is supplemented with IMU, camera and/or LiDAR, not wholly reliant on radiometrics; map update may be provided as part of the messaging service.

User performance depends on a combination of factors:



LCRNS PNT Instrument

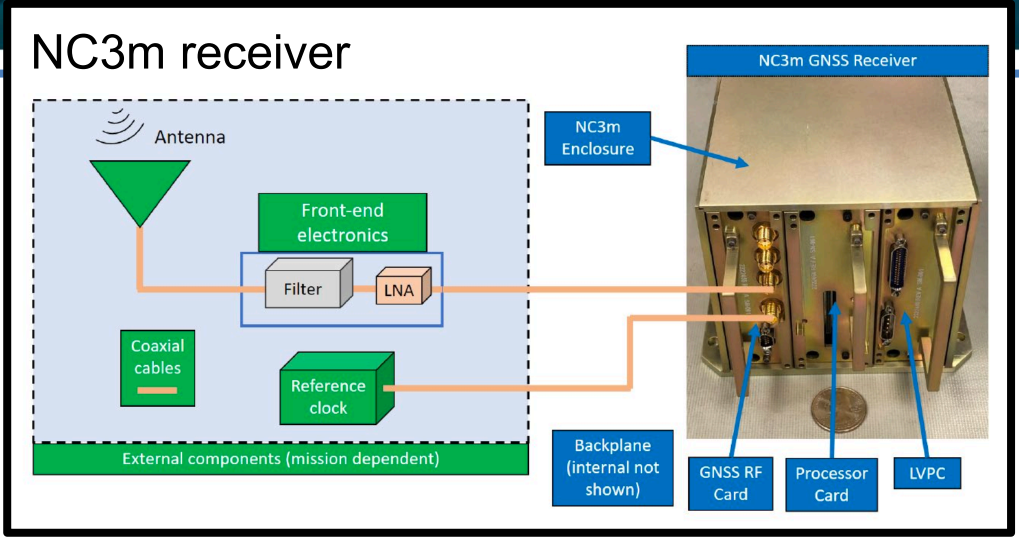
- Payload under development at NASA Goddard
- Ingests a variety of measurement types (e.g., GPS, images)
- Estimates and propagates the host spacecraft state (position, velocity, and time) with sufficient accuracy for the delivery of PNT services to users in cislunar space.

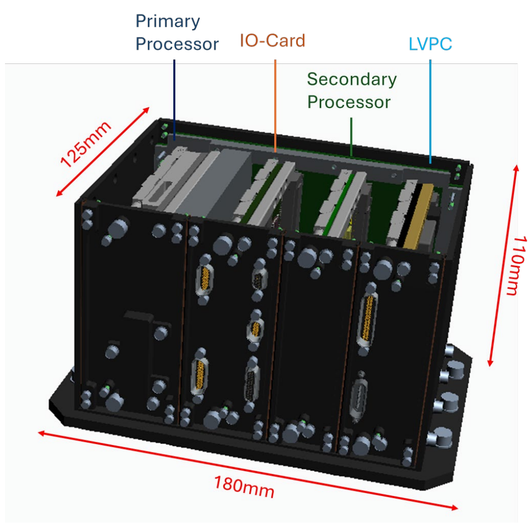


LCRNS LPI (cont.)

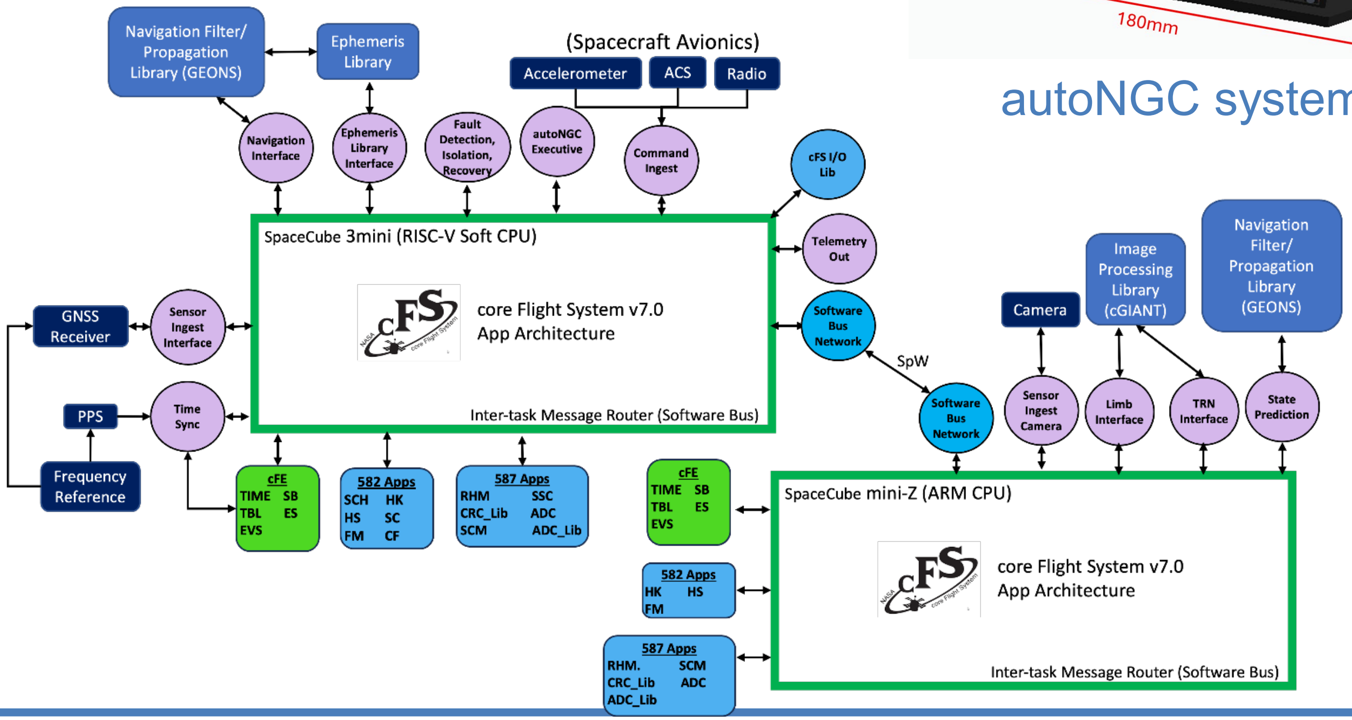
LCRNS PNT Instrument consists of:

- Weak signal GNSS receiver
  - NavCube3-mini (**NC3m**) GNSS receiver is a low size, weight, and power (SWaP), multi-frequency, multi-GNSS receiver designed and built at NASA GSFC
- Onboard navigation system
  - The autonomous Navigation, Guidance, and Control (**autoNGC**) subsystem includes flight software built on the core Flight System (cFS)
  - Goddard Enhanced Onboard Navigation System (GEONS)
  - cFS Goddard Image Analysis and Navigation Tool (cGIANT)
- Clock subsystem
  - Chip Scale Atomic Clock (CSAC) or Ultra-stable Oscillator (USO) and pulse per second (PPS) source





autoNGC system



LCRNS Study Overview

Monte Carlo analysis is conducted to examine the sensitivity of different parameters:

- GPS receiver sensitivity
- Measurement combinations (e.g., with and without GPS TDCP-Doppler, with and without TRN)
- Clock performance

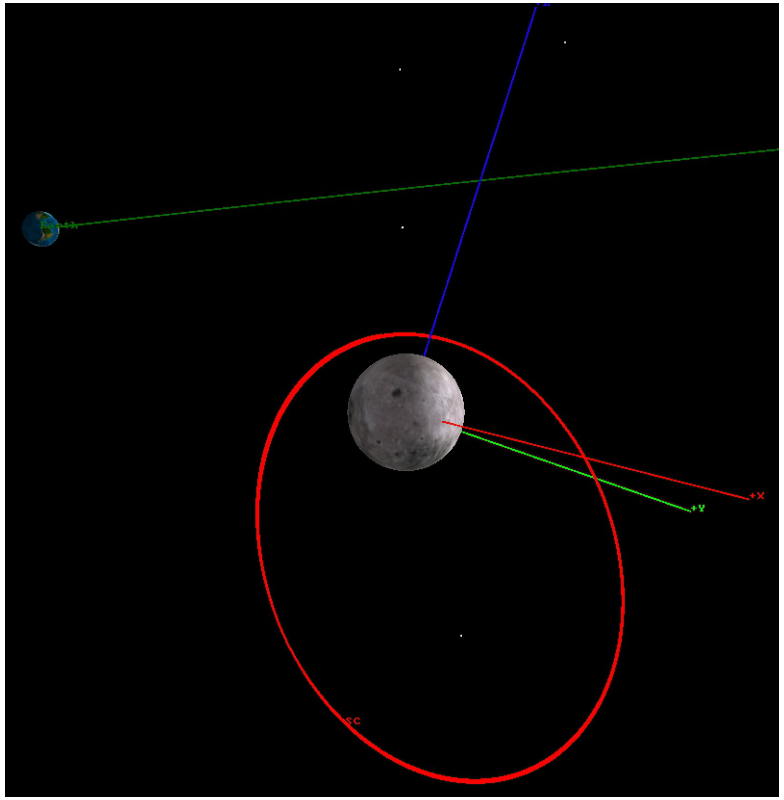
Orbit

- Pseudo-frozen elliptical orbit
- Period: 13.19 hours
- Apolune over lunar south pole

Simulation parameters

- Four-day span
- Extended Kalman Filter (EKF) state estimates every 10 sec
- 100 Monte Carlo runs per instrument configuration

Note: This study only examines part of the solution required for LCRNS to deliver PNT services. A relay provider will need to account for all contributions to PVT error, including on-board delays, antenna displacements, and propagation and representation errors for future times when ephemeris and time estimate products are made available to users and deemed valid.



Epoch	May 27, 2024, 12:16:34 UTC
Initial semi-major axis	6541.4 km
Initial inclination relative to Moon orbital plane	56.2°
Eccentricity	0.6
Initial true anomaly	0°

LCRNS Filter parameters

GEONS uses a factorized EKF to estimate the spacecraft state and other dynamical model parameters in real time from onboard sensor measurements

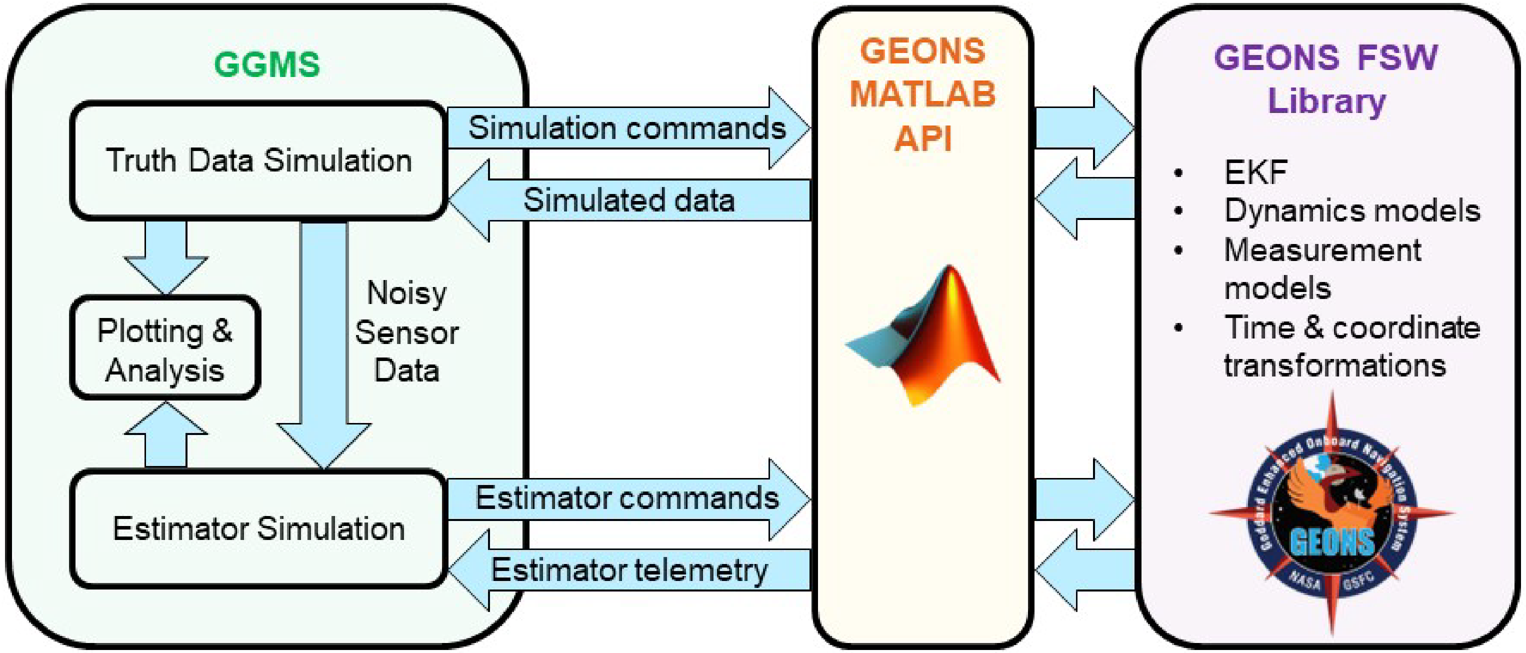
Estimated state vector

- Spacecraft position, velocity,
- Solar radiation pressure coefficient (SRP)
- Clock bias, drift, and drift rate

Covariance propagation

- Velocity and clock process noise models adjusted to provide predicted covariance consistent with estimation errors
- Velocity process noise model dynamics higher at perilune
- Clock process noise model per clock Hadamard variances

Parameter	Value
Dry mass	273.85 kg
SRP model	Spherical
SRP area	4.767 m^2
Coefficient of Reflectance	1.2
Solar flux	1367 W/m^2
Reference distance for solar flux	Sun-Earth average distance
Lunar gravitational model	GRGM 900C
Lunar gravitational degree	100 (truth), 18 (filter)
Lunar gravitational order	100 (truth), 18 (filter)
Propagator	RungeKutta4
Orientation of Moon body frame	DE421
Planetary ephemeris	DE421
Earth Orientation Parameters	IERS Bulletin A from 5/30/24 (truth and filter)



Measurement Models

Global Positioning System (GPS)

- Constellation state from broadcast ephemeris
- Transmit properties of satellites modeled using GPS Antenna Characterization Experiment (GPS ACE) data, publicly released GPS transmit patterns, and calibration from Magnetospheric Multiscale (MMS) mission flight data
- GPS Doppler is computed by differencing two carrier phase observables at two different times and dividing the result by the time difference (10 sec in this sim)
  - This gives an average Doppler observable over the differencing interval with the high precision of carrier phase observables and units of cycles/s or Hertz; Time Differenced Carrier Phase Doppler (TDCP-Doppler)

Terrain Relative Navigation (TRN)

- TRN involves the correlation of onboard navigation maps, rendered on-board using the current state estimate and digital terrain models (DTMs) of the surface, with real time images from an onboard navigation camera
- Bearing measurements simulated to five surface landmarks per image, one image per minute
  - Zero mean Gaussian noise with 2-pixel standard deviation for a 40-degree field of view, 4 mega pixel camera
  - Landmarks assumed uniformly distributed on the surface of the Moon; five visible landmarks selected per image

Simulation Results

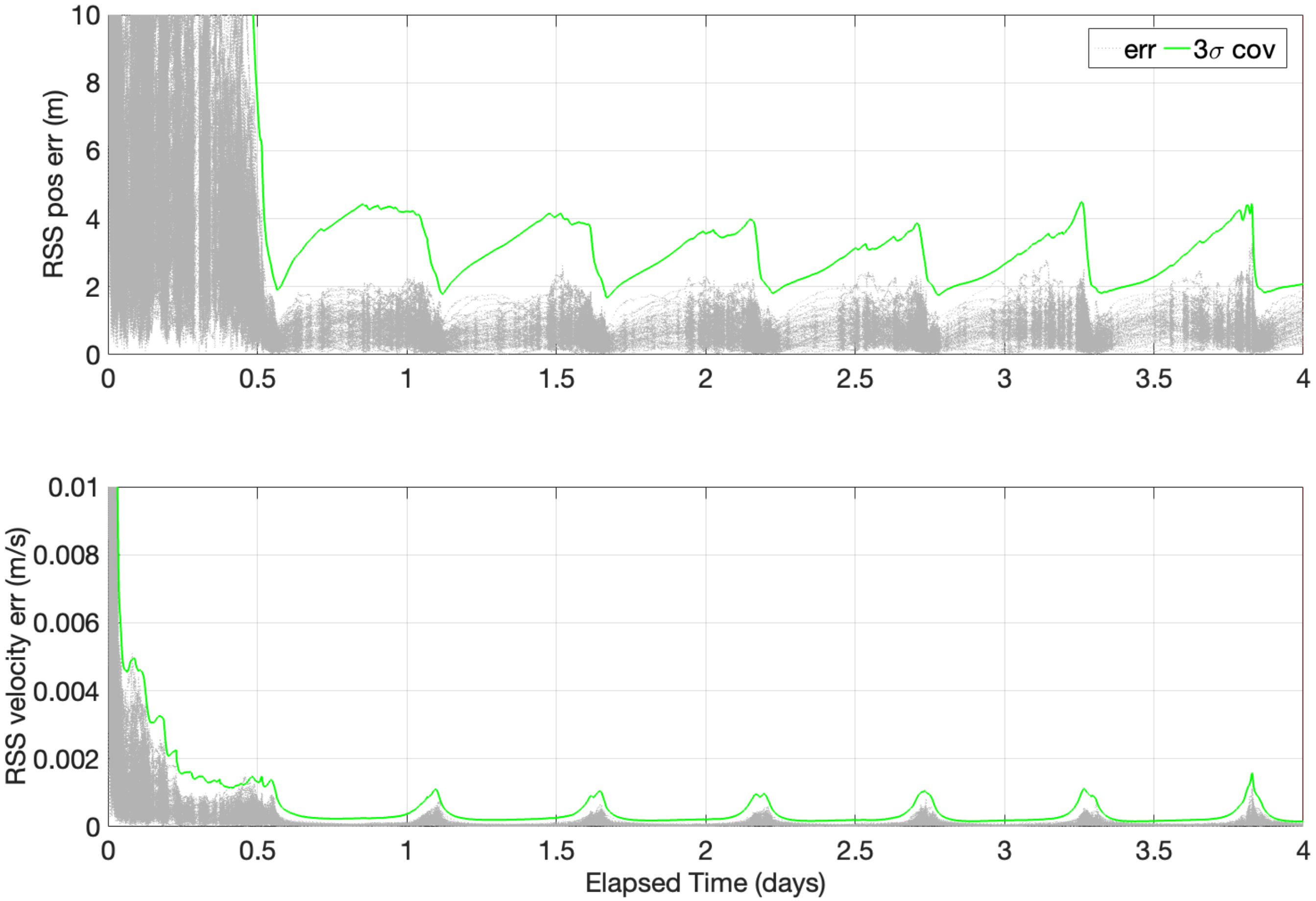
LCRNS Baseline Configuration

Baseline case

- GPS pseudorange, GPS TDCP-Doppler, receiver acquisition/tracking threshold of 23 dB-Hz, CSAC

Results

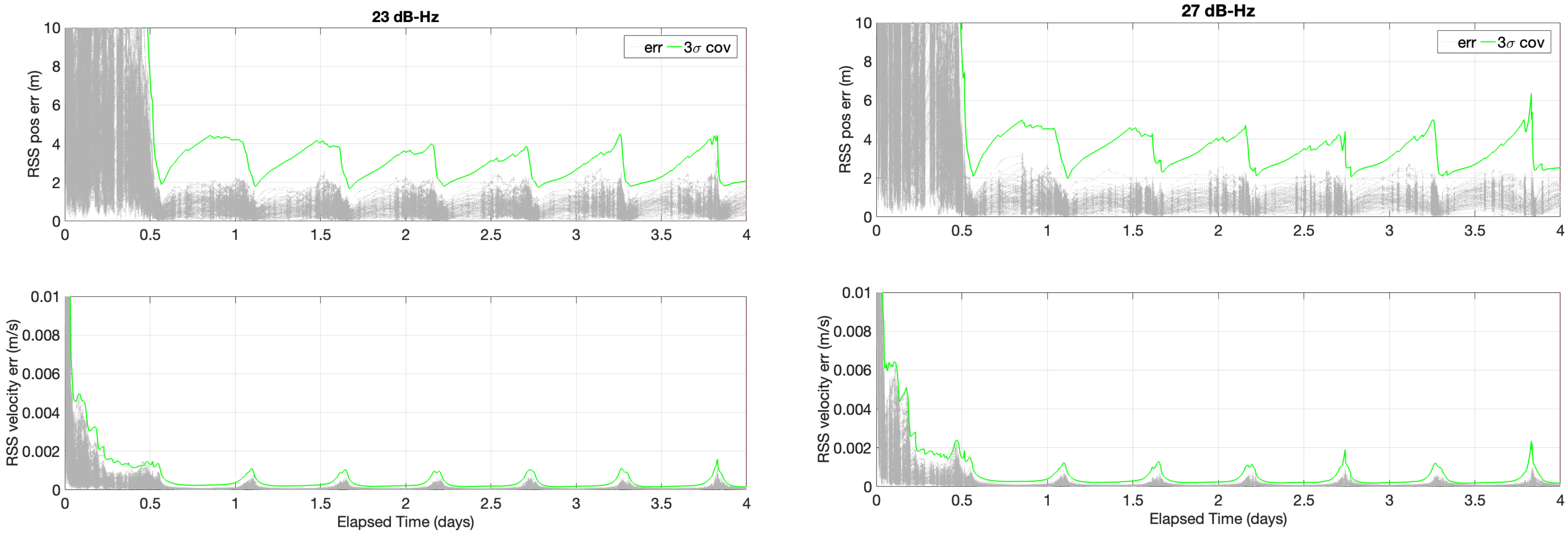
- Root-sum-square (RSS) position error (top) and velocity error (bottom)
- Errors for each of the 100 Monte Carlo cases are plotted in grey
- Formal error is plotted in green
  - 3x the square root of the diagonals of the 100 Monte Carlo covariances
  - this approximates a 99.7-percentile of the RSS errors according to the formal filter covariance
- After the initial convergence of the filter, errors oscillate throughout each orbit
  - Position errors highest at apolune, velocity at perilune



Receiver Sensitivity

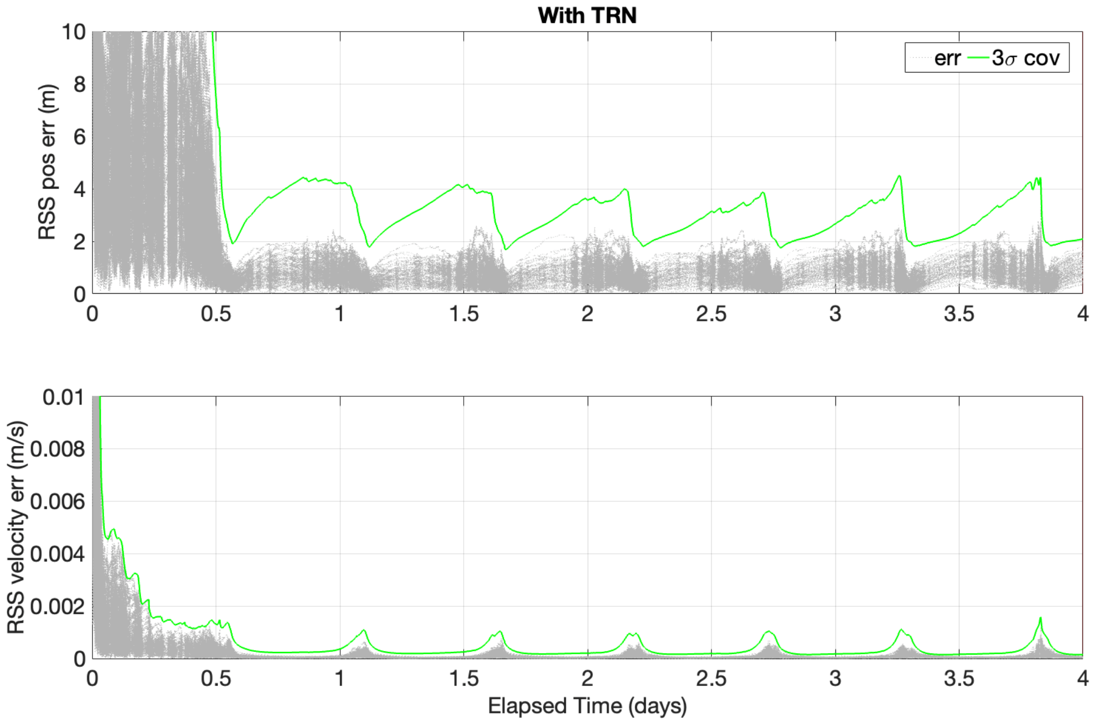
Comparison of baseline case (left) and case with a less sensitive GPS receiver (right), i.e., acquisition/tracking threshold degraded from 23 dB-Hz to 27 dB-Hz

- Number of GPS signals above 23 dB-Hz in this lunar orbit is only slightly greater than the number above 27 dB-Hz; resulting position and velocity errors are largely unchanged



Comparison of baseline case (left) and case with TRN measurements added (right)

- In this orbit, addition of TRN has little effect

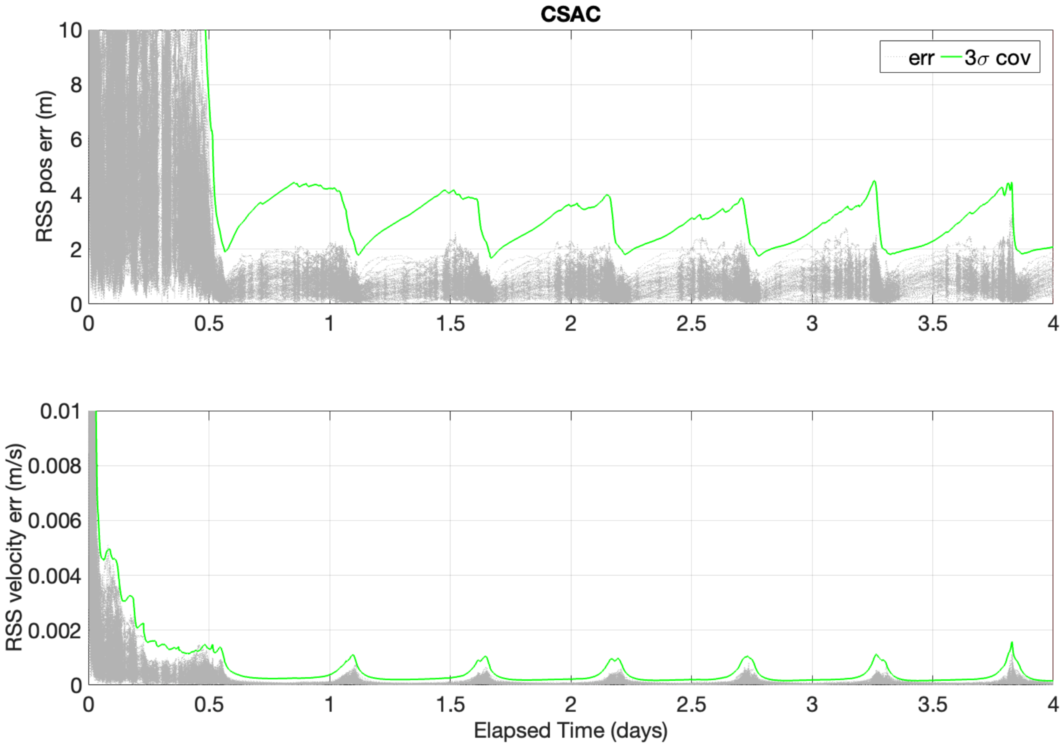


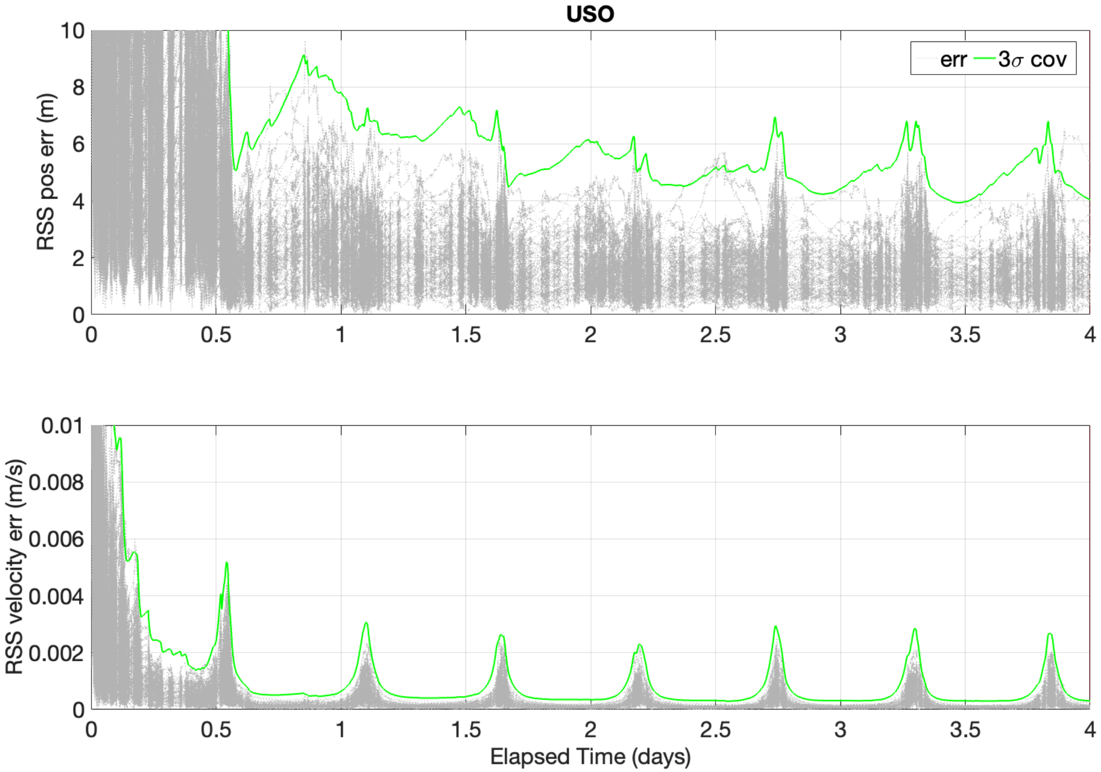
LCRNS Clock Model

Two clocks are considered: a CSAC and a USO

- Relativistic effects are not modeled
- Steady state errors are greater when USO used

		Clock State Time Variance q-values		
Clock Model	10 sec Allan Dev	q1	q2	q3
USO	3.30e-12	1.1e-22	1.4e-26	5.9e-75
CSAC	7.61e-12	5.8e-22	1.5e-29	1e-45

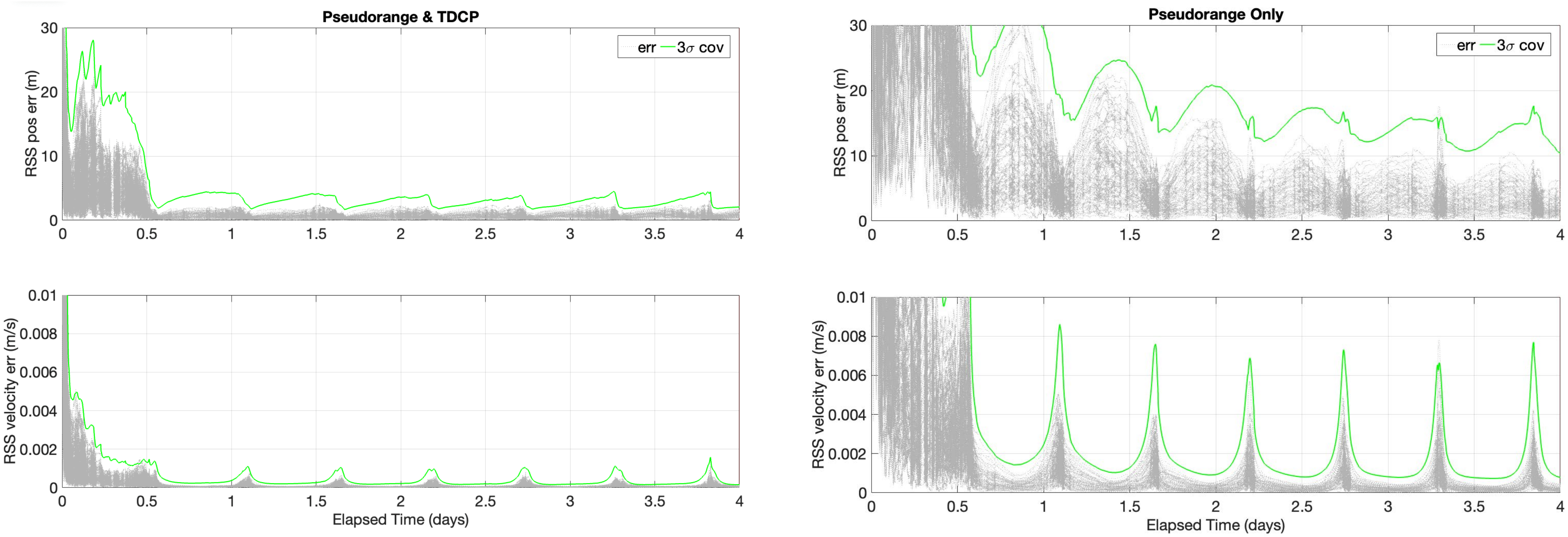




TDCP-Doppler

Comparison of baseline case (left) and a case with only GPS pseudorange (i.e., no TDCP-Doppler)

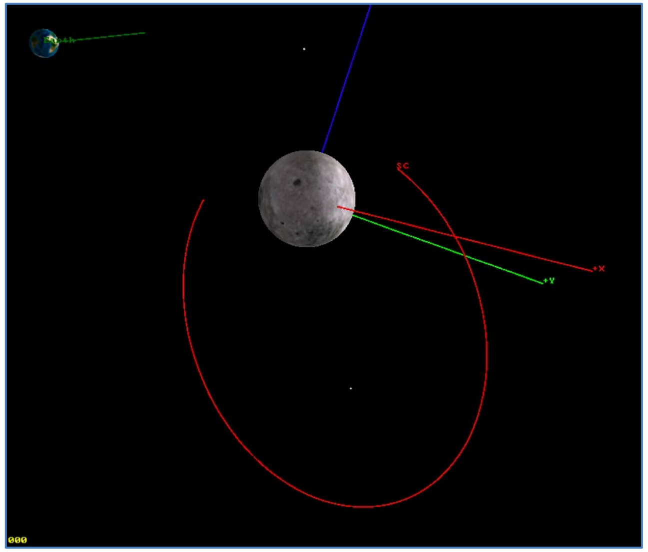
- Removal of TDC—Doppler significantly increases the convergence time and steady state errors for both position and velocity



Results Summary

Steady state errors

- Selected timespan: 45 minutes after perilune in the 7th orbit to 45 minutes before the next perilune
  - Focuses on portion in view of lunar south pole
- 95th percentile of all Monte Carlo cases over selected timespan



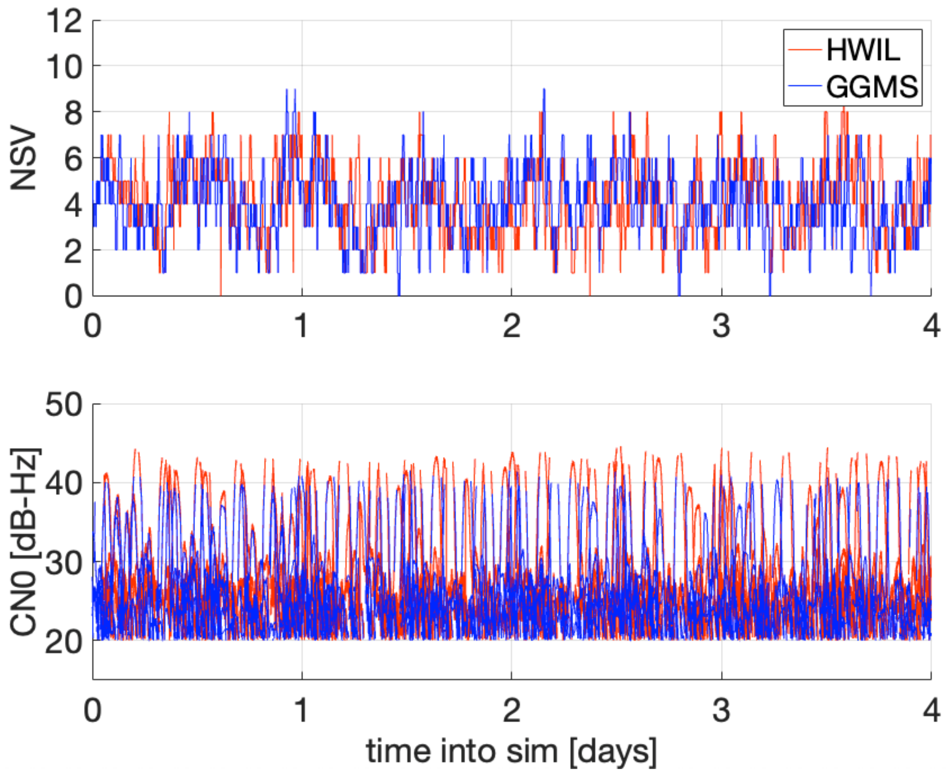
Results Figure	Measurements			Analysis Modeling Parameters		100-case Monte Carlo statistics – 7th orbit in view of lunar south pole				
	GPS pseudo-range	GPS TDCP-Doppler	TRN	GPS acq/trk threshold [dB-Hz]	Clock model	RSS position error [m] 95th percentile	Clock bias magnitude error [m] 95th percentile	RSS velocity error [mm/s] 95th percentile	Clock drift magnitude error [mm/s] 95th percentile	Clock drift rate magnitude error [mm/s^2] 95th percentile
4	X	X		23	CSAC	1.53	1.63	0.133	0.090	0.0038
5	X	X		27	CSAC	1.71	1.82	0.146	0.103	0.0038
6	X			23	CSAC	6.39	2.91	0.624	0.285	0.0040
7	X	X		23	USO	2.60	2.00	0.297	0.475	0.1397
8	X	X	X	23	CSAC	1.54	1.59	0.138	0.090	0.0043

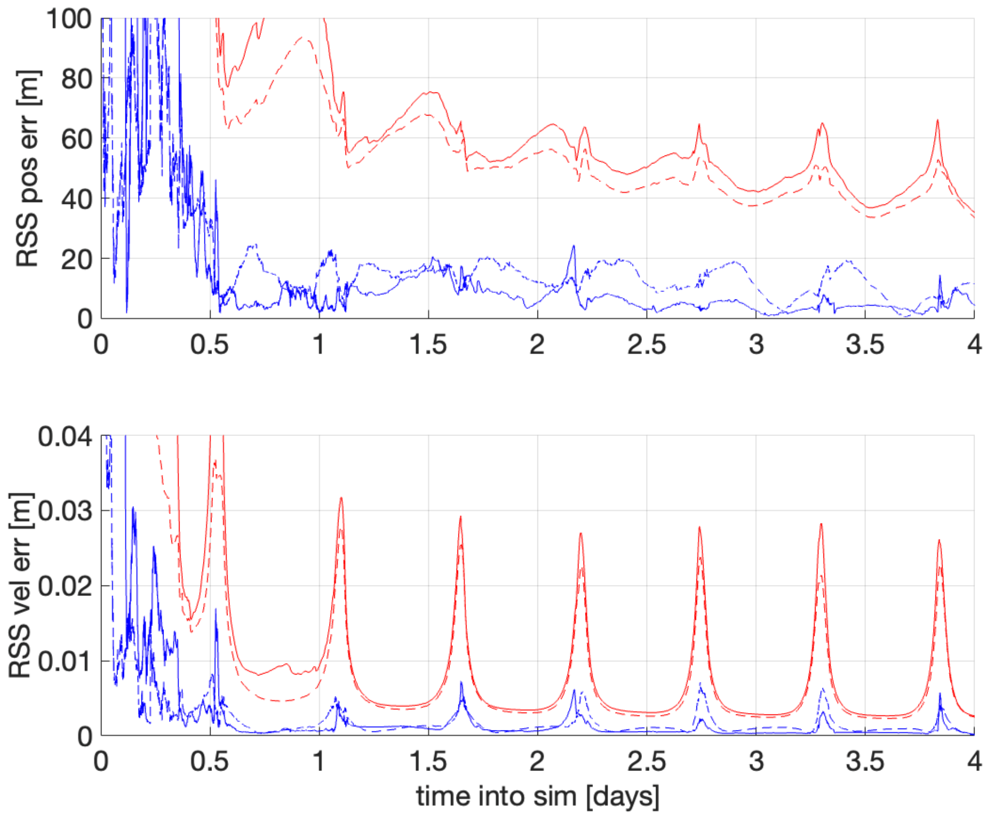
Simulation Validation

NC3m Hardware in the Loop (HWIL)

HWIL simulation performed with NC3m dev unit (and internal GEONS filter), USO, GPS pseudorange only

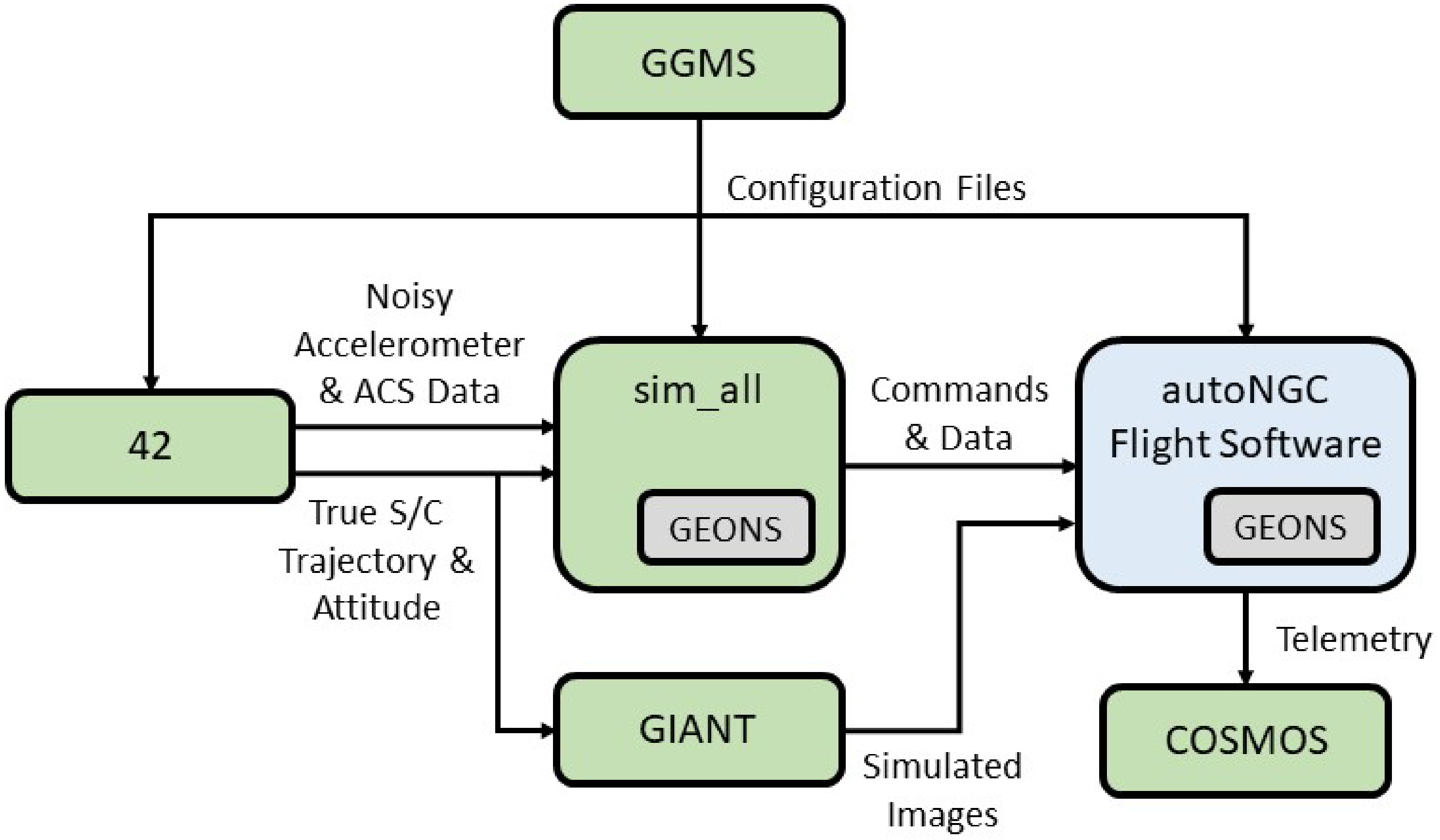
- Left: NC3m HWIL (red) and corresponding GGMS sim (blue) number of visible signals (top) and C/N_0 (bottom)
- Right: NC3m HWIL (solid) and identical GGMS run (dashed); formal errors (obtained from the filter covariance) are in red, estimation errors are in blue





autoNGC Software in the Loop (SIL)

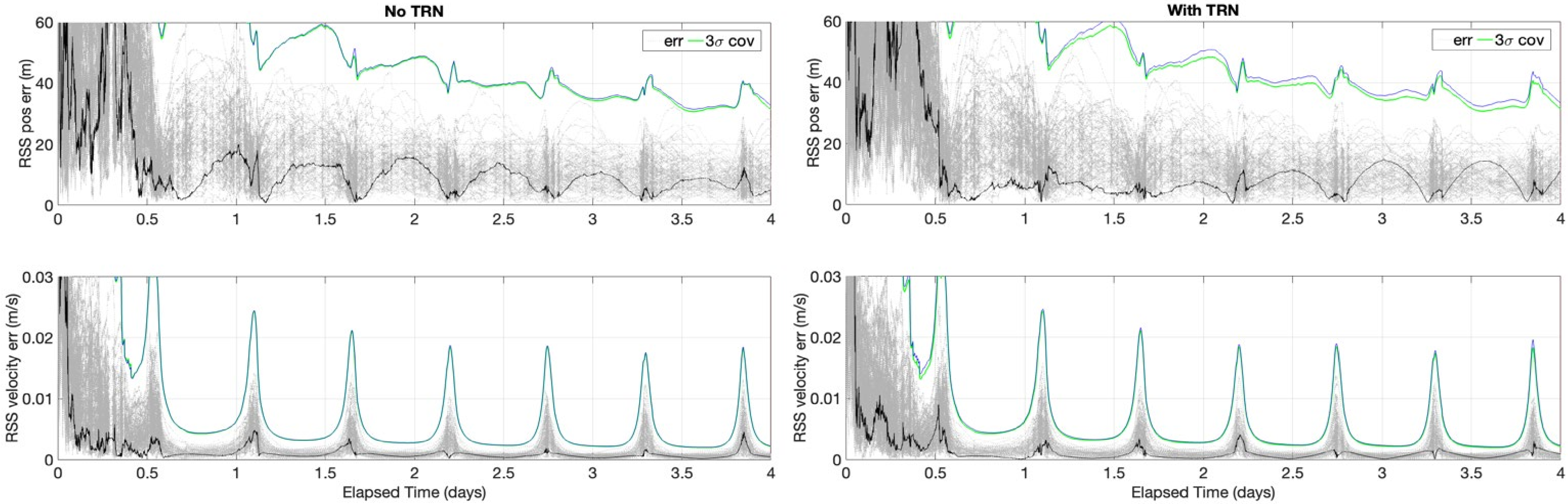
- Simulation software generates data, command, and telemetry packets consistent with what is expected to be received by the flight software in orbit
- Based on truth state, camera simulator renders a simulated image of the moon using ray tracing and sends a capture image command to the flight software
- Data is sent to and processed by the autoNGC flight software



autoNGC Software in the Loop (SIL)

SIL single run errors (black) and formal errors (blue) overlaid on 100 GGMS Monte Carlos (gray) and formal error (green) with only GPS pseudorange (left) and with the addition of TRN (right)

- TRN modeling in GGMS is representative of the real image processing in the SIL
- TRN did not significantly impact the filter formal error covariance, but it did slightly reduce the size of the estimation errors during convergence



Conclusions

Conclusions

Monte Carlo analysis is conducted to examine the sensitivity of different parameters

- Degradation of receiver acquisition/tracking threshold from 23 dB-Hz to 27 dB-Hz does not significantly increase the errors for scenario studied here
- Addition of TRN measurements does not reduce errors, however it:
  - Provides robustness and measurement redundancy benefit in this scenario
  - Expected to greatly benefit landers and potentially also scenarios in low lunar orbit
- Changing from a CSAC to a USO does degrade navigation performance, but not as much as removing GPS TDCP-Doppler measurements

Hardware in the loop (HWIL) and software in the loop (SIL) runs build confidence in the Monte Carlo results

Conclusions (cont.)

Position, velocity, and time estimation achieved in these simulations is excellent.

- No exact comparison, but consider:
  - Lunar Reconnaissance Orbiter (LRO) meets its 50-meter position requirement through daily 8- to 10-hour ground station tracking passes, an onboard altimeter, and extensive post-processing over several days of data
  - LCRNS Services Requirements Document (SRD) cites 100-meter position knowledge as a representative user need in low lunar orbit
  - Previous analysis of the Gateway orbit (a near-rectilinear halo orbit) showed maximum steady-state errors between 100 and 160 meters for DSN-based navigation and 20 to 50 meters for GPS-based navigation
- The LCRNS SRD cites 100-meter position knowledge as a representative user need in low lunar orbit
  - Recall that this study only examines part of the solution required for LCRNS to deliver PNT services, but LPI could be an enabling technology for onboard, real-time navigation at the Moon

LCRNS

Value of LPI

Lunar ecosystem will be expanding and evolving over the coming decade; **LPI will be an enabling technology**

- LPI enables:
  - Autonomous, onboard navigation
  - Orbit determination and prediction from a variety of measurement types, including terrain relative navigation (TRN) and GPS from lunar orbit
  - Distribution of lunar time
  - Provision of PNT services in Cislunar space
- LPI develops Agency capabilities
  - Low SWAP, weak signal GNSS receiver (NC3m)
  - Goddard Enhanced Onboard Navigation System (GEONS) (extended Kalman filter for onboard state estimation)
  - Onboard navigation processor (advancement of autoNGC)
- LPI improves NASA's understanding of the lunar environment and uncovers operational considerations
  - Criticality of Earth Orientation Parameters
  - Challenges of constellation maintenance in lunar orbits