Lunar Relay Onboard Navigation Performance and Effects on Lander Descent to Surface

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Outline

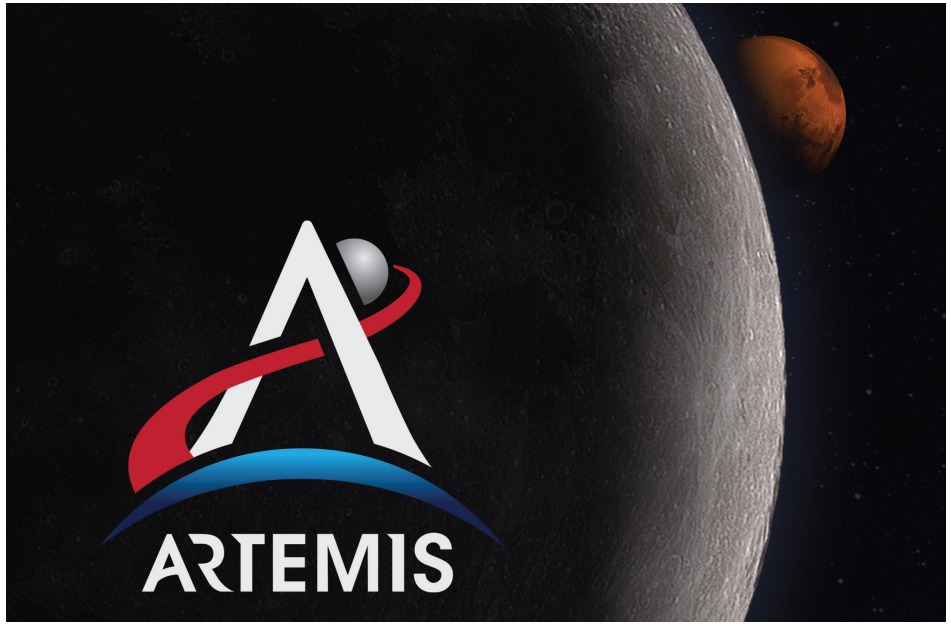
- Introduction
- Measurement Types
- Simulation Setup
- LNN Self-OD Results
- Descent OD Results
- Conclusion

Introduction

Lunar Navigation Background

- Given the variety of upcoming Lunar missions, including Artemis, a navigation infrastructure at the Moon is needed

- Relying solely on Earth based communications constrains Lunar missions
  - Limited navigation accuracy, dependent on shared Earth based resources like the Deep Space Network (DSN)

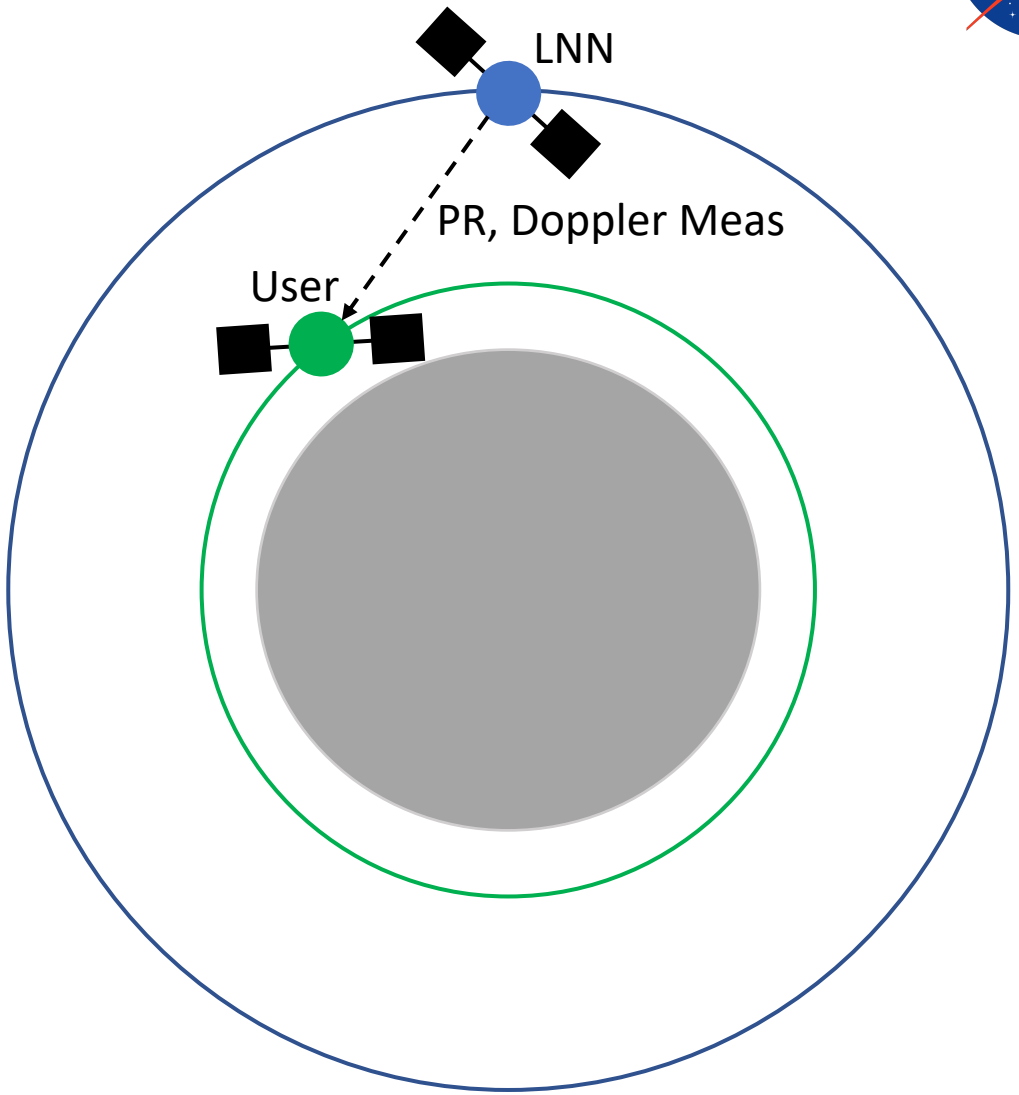


LunaNet

- LunaNet is a proposed Lunar communications and navigation infrastructure consisting of satellites called nodes (Israel et al.)
  - Referred to as Lunar Navigation Nodes (LNN) in this work

- Each node provides several services
  1. **Position, navigation and timing (PNT)**
  2. Data transfer
  3. Scientific Utilization

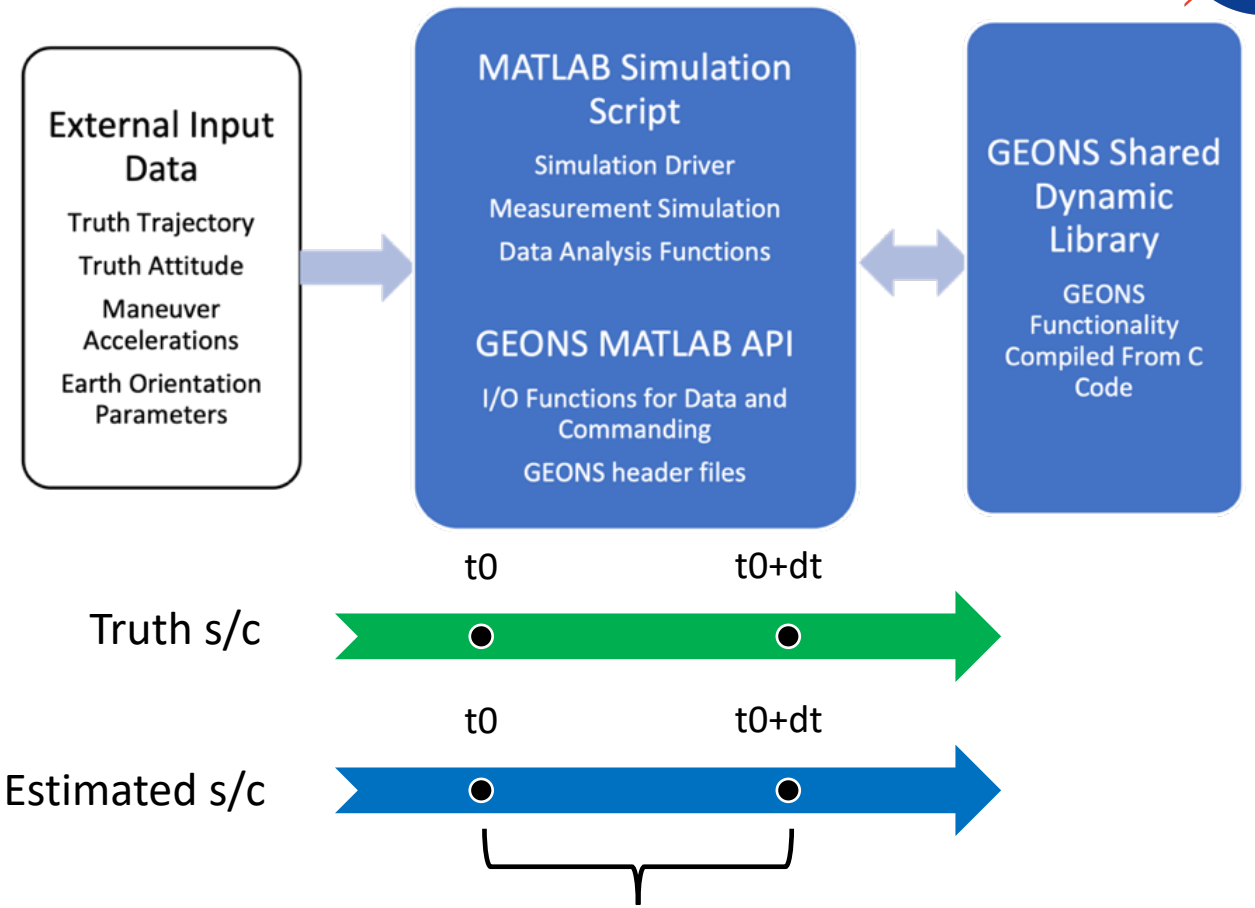
- Reference signal link between LNN and user allows for Pseudorange (PR) and Doppler measurements



GEONS Simulation

- The Goddard Enhanced Onboard Navigation System (GEONS) software was utilized through a MATLAB API to conduct Monte Carlo (MC) Orbit Determination (OD) analyses

- Simulation processes one-way measurements to estimate spacecraft state



1. Propagate
2. Simulate measurements
3. Process with EKF, updated estimated trajectory state, compare to truth at each timestep

Analysis Steps

1. Determine LNN relay state and clock estimation accuracy using different combinations of one-way measurements and onboard clocks

2. Using LNN relay state and clock errors, assess impact on Lunar lander using LNN measurements and compare versus other measurement types

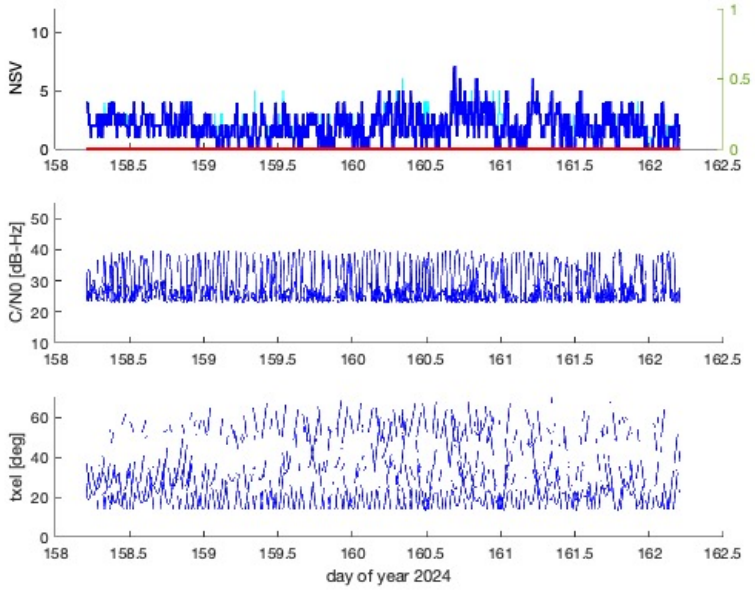
Measurement Types

Weak-Signal GPS Tracking

- Though originally designed for terrestrial and LEO applications, GPS based navigation has been extended to higher altitudes
- MMS mission has used GPS data up to 29.34 RE from Earth, or 50% of Lunar distance (Miller et al.)
- LuGRE mission will soon use GPS data at the moon, but no mission data available yet (Schlenker et al.)
- GGMS uses MMS flight data to model GPS signal degradation versus distance to extend modeling to Lunar distances
- GGMS also uses ACE mission data to compute the GPS antenna transmit patterns based on the azimuth/elevation of the GPS transmitter

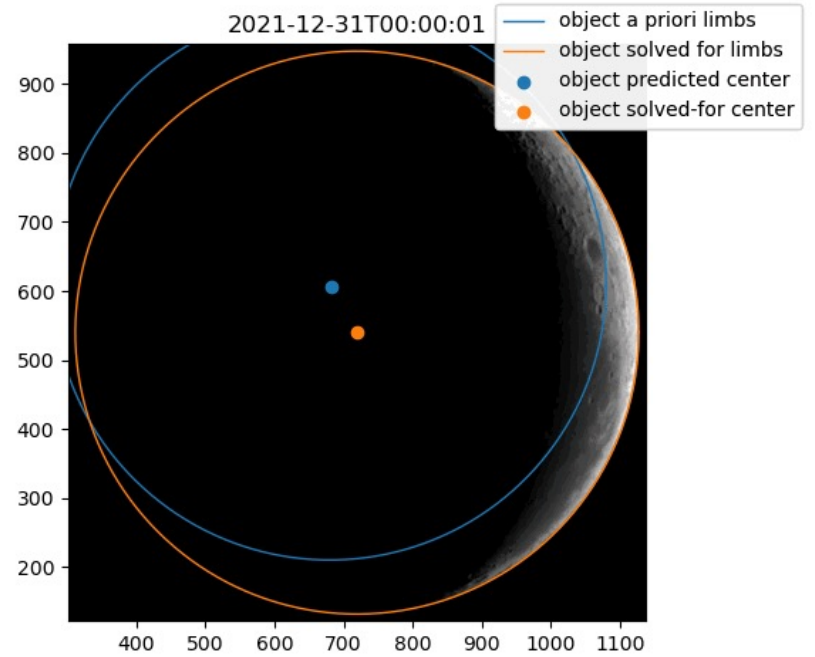


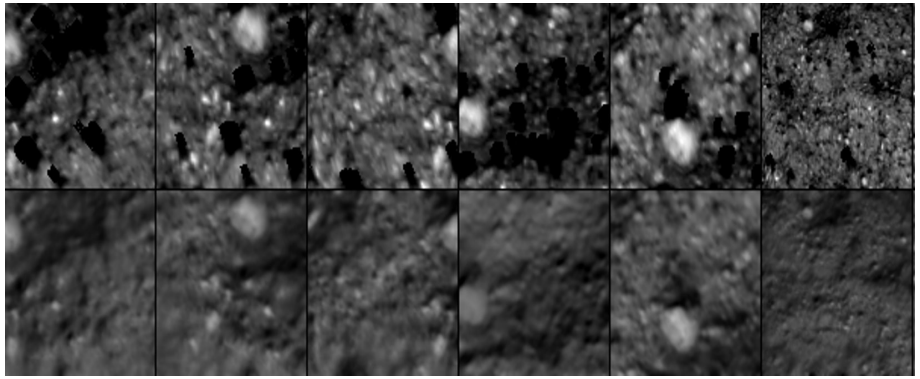




Optical Navigation (OpNav)

- OpNav measurements are extracted by matching an image of a body or feature with a template or model of that body or feature
- GGMS can simulate two types
  1. Center-finding (CF) measurements (top)
  2. Terrain relative navigation (TRN) measurements (bottom)
- CF Observables are relative to center of figure of body, TRN are relative to series of landmarks on surface of body

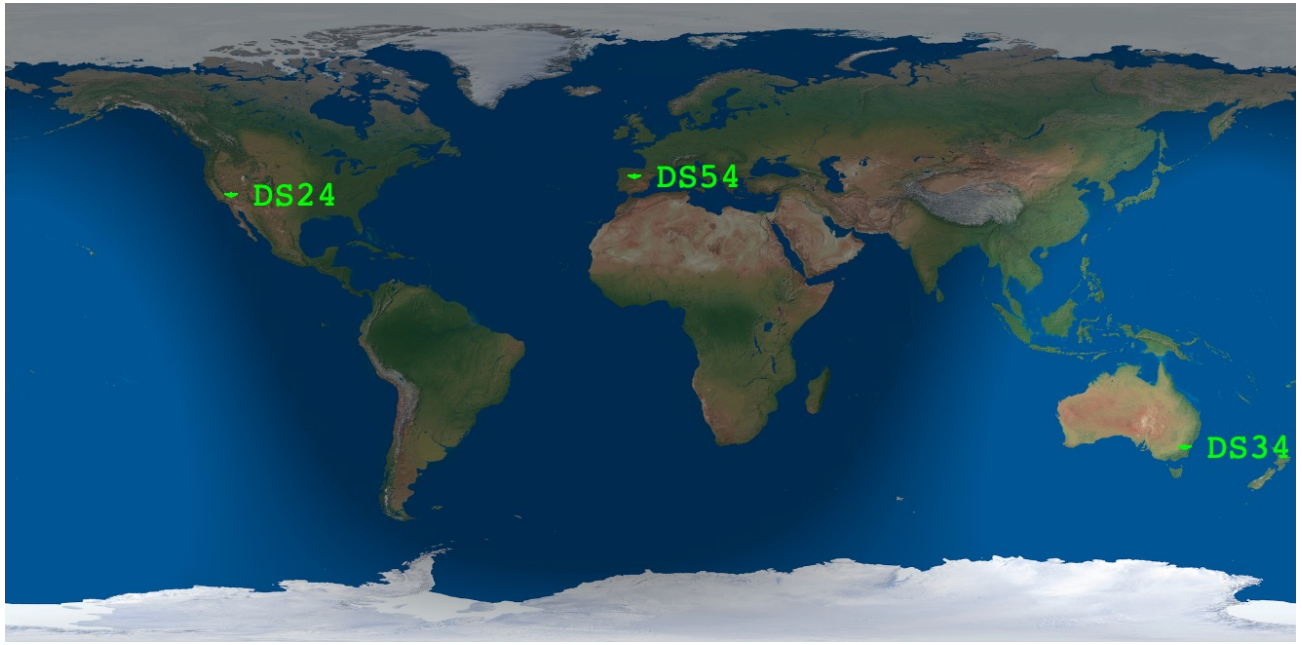




(Gnam et al.)

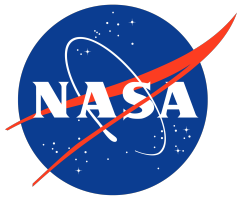
Ground Network (GN) Measurements

- Used one-way measurements from Deep Space Network (DSN) sites in simulation
  - DS24 (Goldstone)
  - DS34 (Canberra)
  - DS54 (Madrid)



LNN Reference Signal Measurements

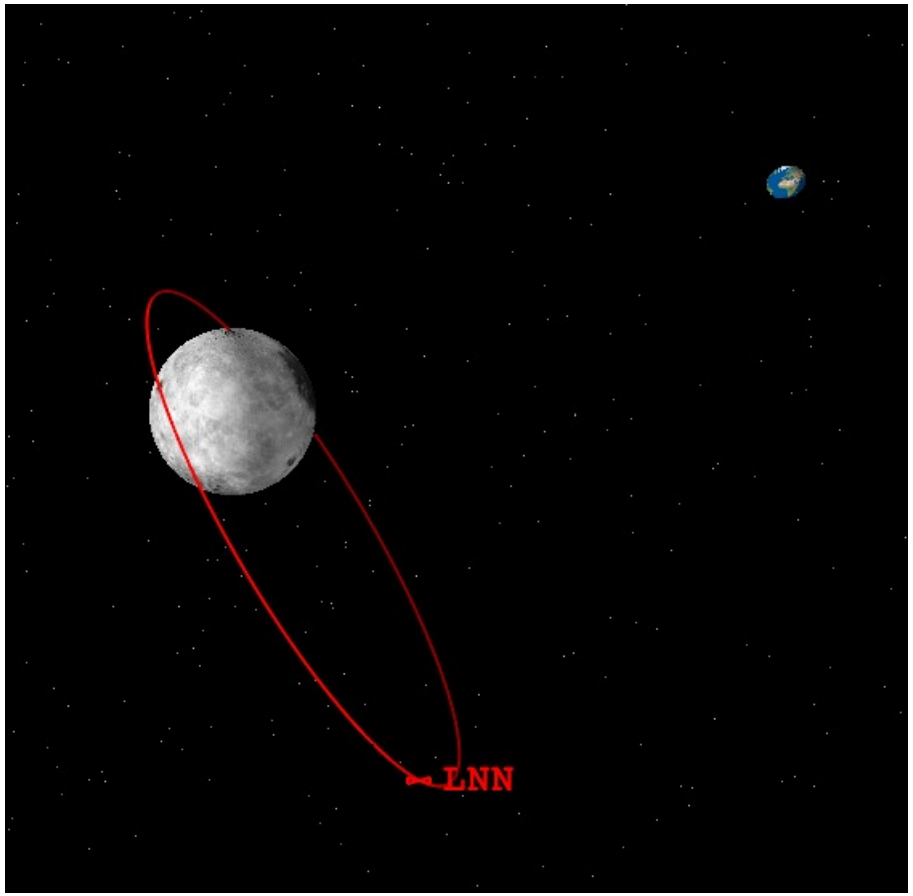
- Reference signals transmitted by LNNs allow for users to measure PR and Doppler
- Modeled as crosslink (Xlink) measurements in GEONS
- LNN state and clock errors can degrade quality of provided measurements



Simulation Setup

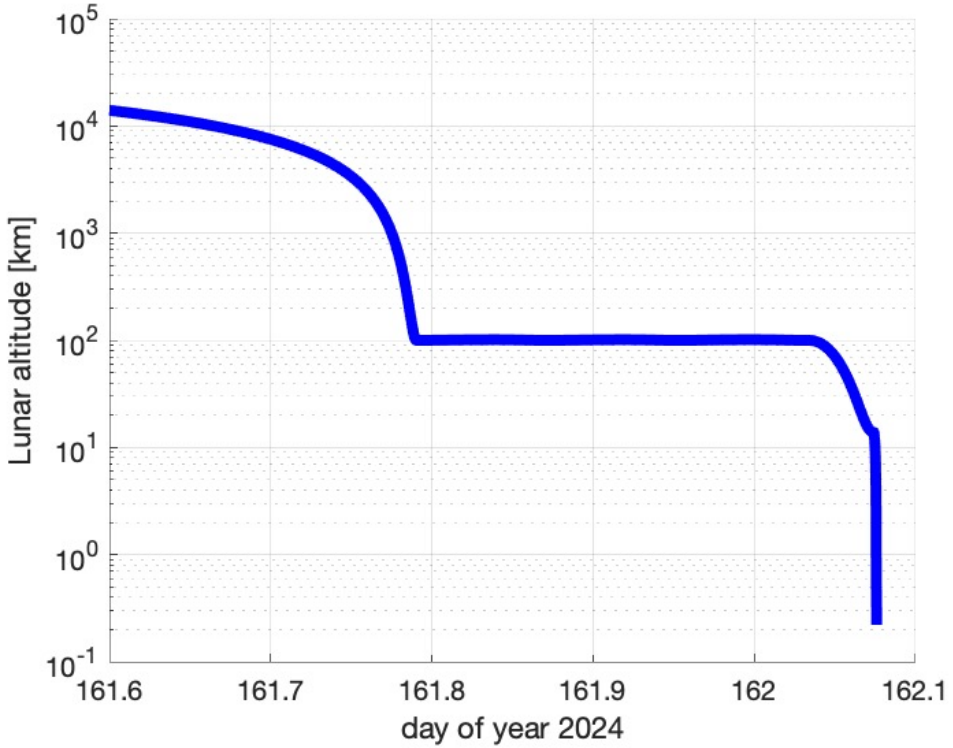
LNN Relay Orbit

- Many orbits are being considered for the LNN relays and no one orbit scheme is mandated
- To reduce scope this study only looked at one orbit, a frozen orbit with a 12-hour orbital period
- Orbit provides coverage 60-80% of the time for users between 45-90 degrees latitude south



Descent Trajectory

- Descent trajectory was created to meet constraints provided by NASA for a potential HLS trajectory
- Mission Chronology
    1. Depart a near-rectilinear halo orbit (NRHO) with a maneuver at Apoapsis and target a 100x100 km low Lunar orbit (LLO)
    2. Attain LLO (Lunar Orbit Insertion (LOI)) and perform three revolutions
    3. Reduce LLO altitude from 100 km to 15 km
    4. Perform departure burn from 15 km altitude
    5. Perform a series of maneuvers targeting a landing at the Lunar south pole



Measurement Noise - GPS

Link Parameter	Value
Antenna Noise Temperature T_a	34 K
System Noise Temperature T_{sys}	132 K
Implementation Loss R_{loss}	1.7 dB
Polarization Loss L_{pol}	1 dB
Block II/IIA P_T (max EIRP)	17.9 dBW (31.6 dBW)
Block IIR P_T (max EIRP)	17.3 dBW (29.2 dBW)
Block IIRM P_T (max EIRP)	18.8 dBW (32.1 dBW)
Block IIF P_T (max EIRP)	16.2 dBW (29.5 dBW)

$$\frac{C}{N_0} = P_T + G_T(\phi,\theta) - 20\log\left(\frac{4\pi}{\lambda_{L1}}\right) + G_R(\phi,\theta) - L_{pol} - 10\log(kT_{sys}) - R_{loss}$$

Link Parameter	Value
T_c	9.7752e-07 s
B_{dll}	1.0 Hz
d	1.0 chip
T	20.0 ms

$$\sigma = cT_c\sqrt{\frac{B_{dll}d}{2\frac{C}{N_0}}\left(1+\frac{2}{(2-d)T\frac{C}{N_0}}\right)}$$

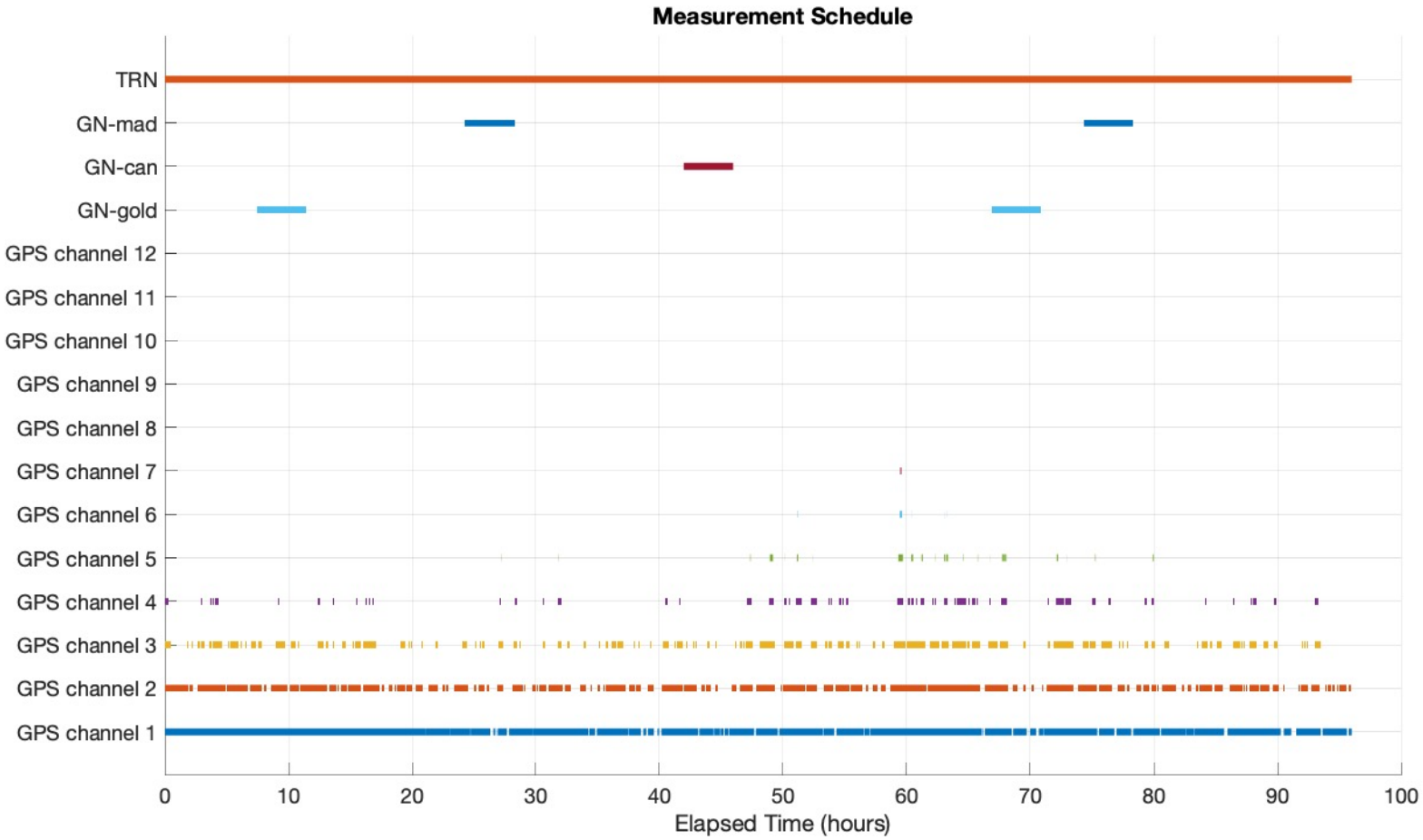
Measurement Noise – GN, OpNav, LNN

GN Parameter	Value
DSN Frequency	X-band
PR 1-σ Noise	0.32 m
PR 1-σ Bias	15 m
Doppler 1-σ Noise	0.1 $\frac{mm}{s}$
Doppler 1-σ Bias	0 $\frac{mm}{s}$
Measurement Update Period	10 seconds
LNN Meas Schedule	One 4-hour Pass Per Day
Lander Meas Schedule	Constant Coverage

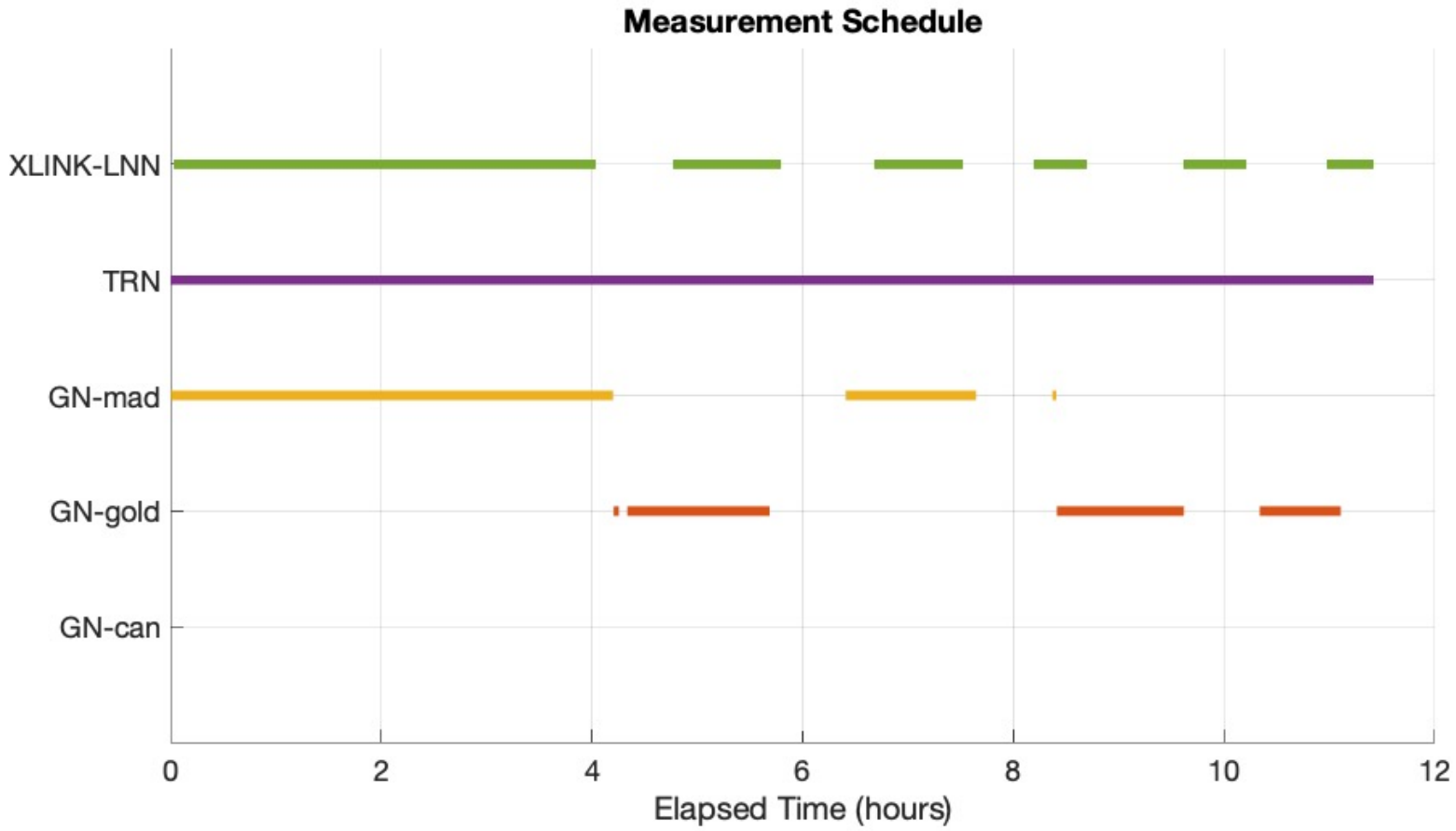
OpNav Parameter	Value
CF Operating Range	> 300 km
CF Bearing 1-σ Noise	1 pixel
CF Bearing 1-σ Bias	0 pixels
CF Range 1-σ Noise	0.02% of range to Lunar surface
TRN Max Number of Landmarks	6
TRN Operating Range	0 - 300 km
TRN Bearing 1-σ Noise	3 pixels
TRN Bearing 1-σ Bias	0.5 pixels
Measurement Update Period	60 seconds

LNN Parameter	Value
Broadcast Frequency	S-band
PR 1-σ Noise	0.32 m
PR 1-σ Bias	RSS of 0.65 m nominal plus LNN clock bias
Doppler 1-σ Noise	0.16 $\frac{mm}{s}$
Doppler 1-σ Bias	0 $\frac{mm}{s}$
Measurement Update Period	10 seconds
Lander Meas Schedule	Constant when in view

LNN Relay Measurement Schedule



Lander Measurement Schedule



Onboard Clock Model

- Onboard clock needed to process one-way measurements
- Looked at two different onboard clocks in this analysis
  - Rubidium Atomic Frequency Standard (RAFS)
  - Ultra-Stable Oscillator (USO)
- Clock stability can be characterized using the Hadamard deviation which is a function of parameters q_1, q_2, q_3 (Hutsell et al.)
- q_1, q_2, q_3 are fit to RAFS and USO stability data

Clock	q_1	q_2	q_3
RAFS	3.70e-24	1.87e-33	7.56e-59
USO	2.53e-23	4.22e-24	1.00e-38

Relay OD Simulation Setup

Force Modeling

Parameter	Truth Trajectory	Estimated Trajectory
Planetary Ephemeris	JPL DE421 [12]	JPL DE421
Solar System Gravity	Point Mass Sun, Earth, Venus, Mars, Jupiter, Saturn	Point Mass Sun, Earth, Venus, Mars, Jupiter, Saturn
Lunar Gravity Model	250x250 GRGM900C	100x100 GRGM900C
Solar Radiation Pressure	Mass = 273.85 kg Area = 4.76709 m^2 Cr = 1.2	Mass = 273.85 kg Area = 4.76709 m^2 Cr = 1.2

Parameters Varied with each of 100 MC runs

Parameter	Error Applied (1-σ)
Initial Position	10 km
Initial Velocity	10 $\frac{cm}{s}$
Initial Clock Bias	3,000 km (1 ms)
Initial Clock Bias Rate	3 $\frac{m}{s}$
Initial Clock Bias Acceleration	3e-07 $\frac{m}{s^2}$
Spacecraft Mass	0.91 kg
Spacecraft Area	0.16 m^2
Spacecraft Cr	0.1
GN PR Bias (per-pass)	15 m

Lander OD Simulation Setup

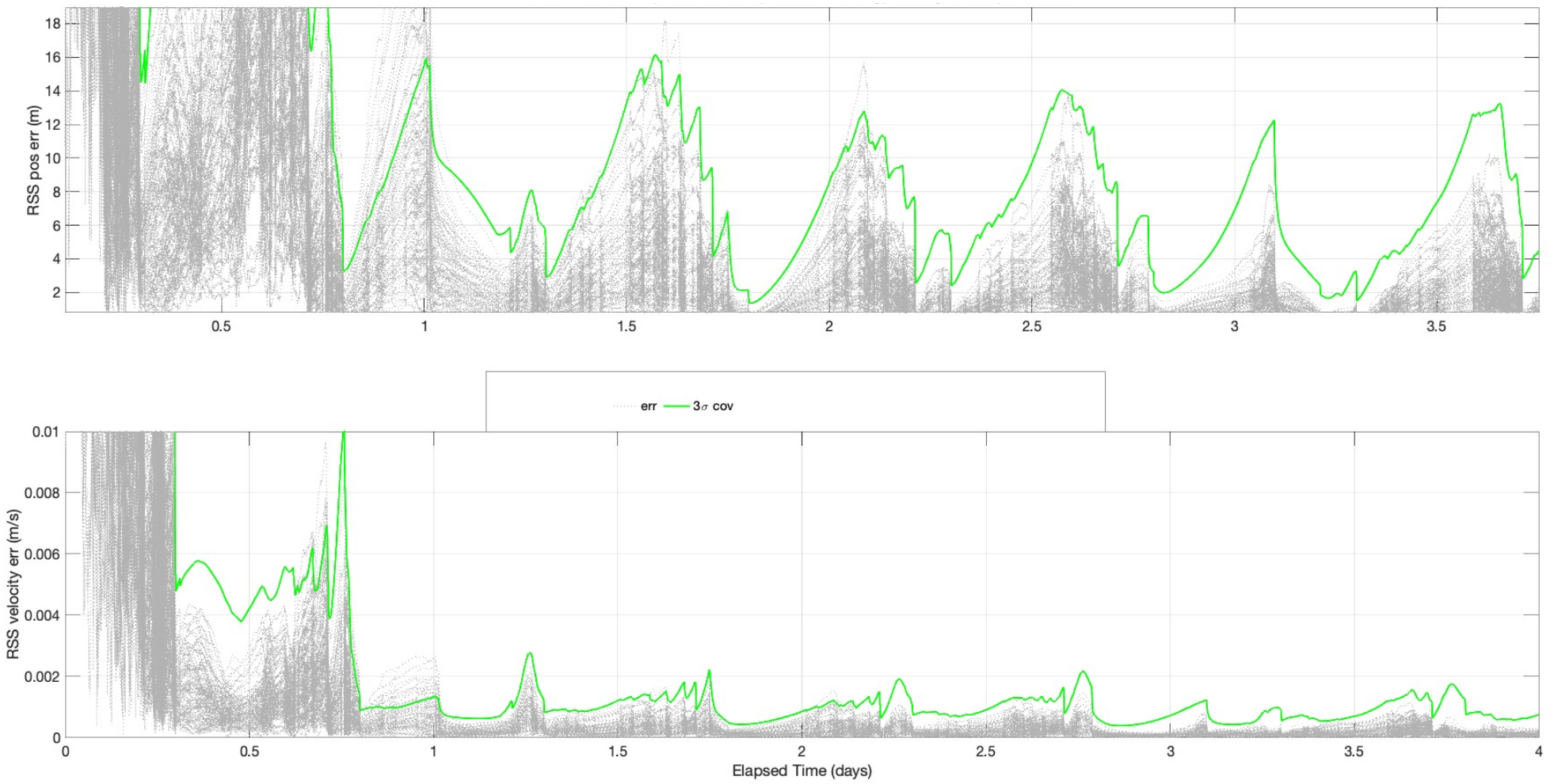
LNN Cases

Relay Self-OD Case	Clock	GPS Outages	Observables
LNNA	RAFS	None	OpNav CF, GPS, GN
LNNB	USO	None	OpNav CF, GPS, GN

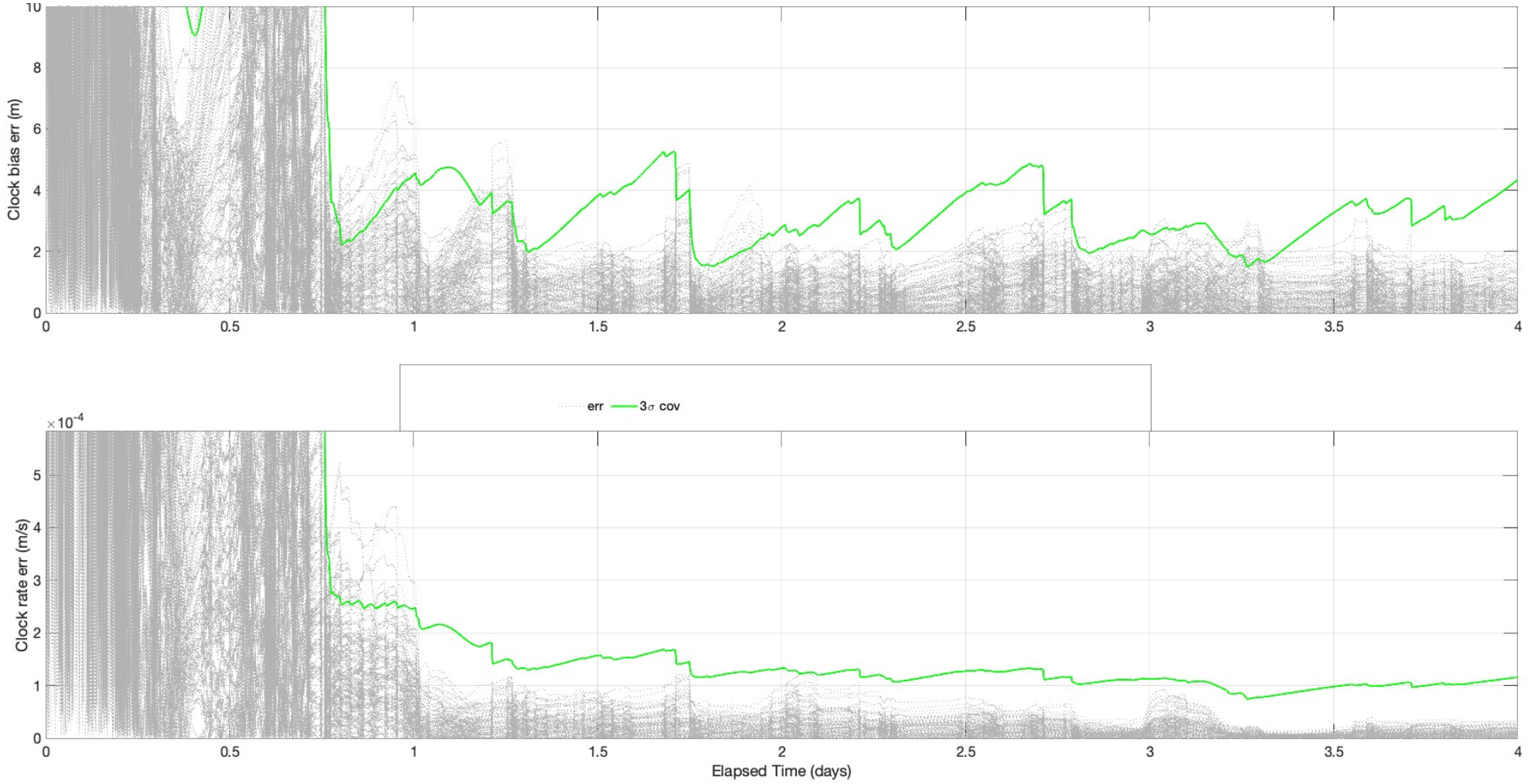
Parameters Varied with each of 100 MC runs

Parameter	Error Applied (1-σ)
Initial Position	100 m
Initial Velocity	1 $\frac{mm}{s}$
Initial Clock Bias	10 m
Initial Clock Bias Rate	1e-10 $\frac{m}{s}$
Initial Clock Bias Acceleration	1e-15 $\frac{m}{s^2}$
Spacecraft Mass	0.96 kg
Spacecraft Area	1 m^2
Spacecraft Cr	0.1
GN PR Bias (per-pass)	15 m

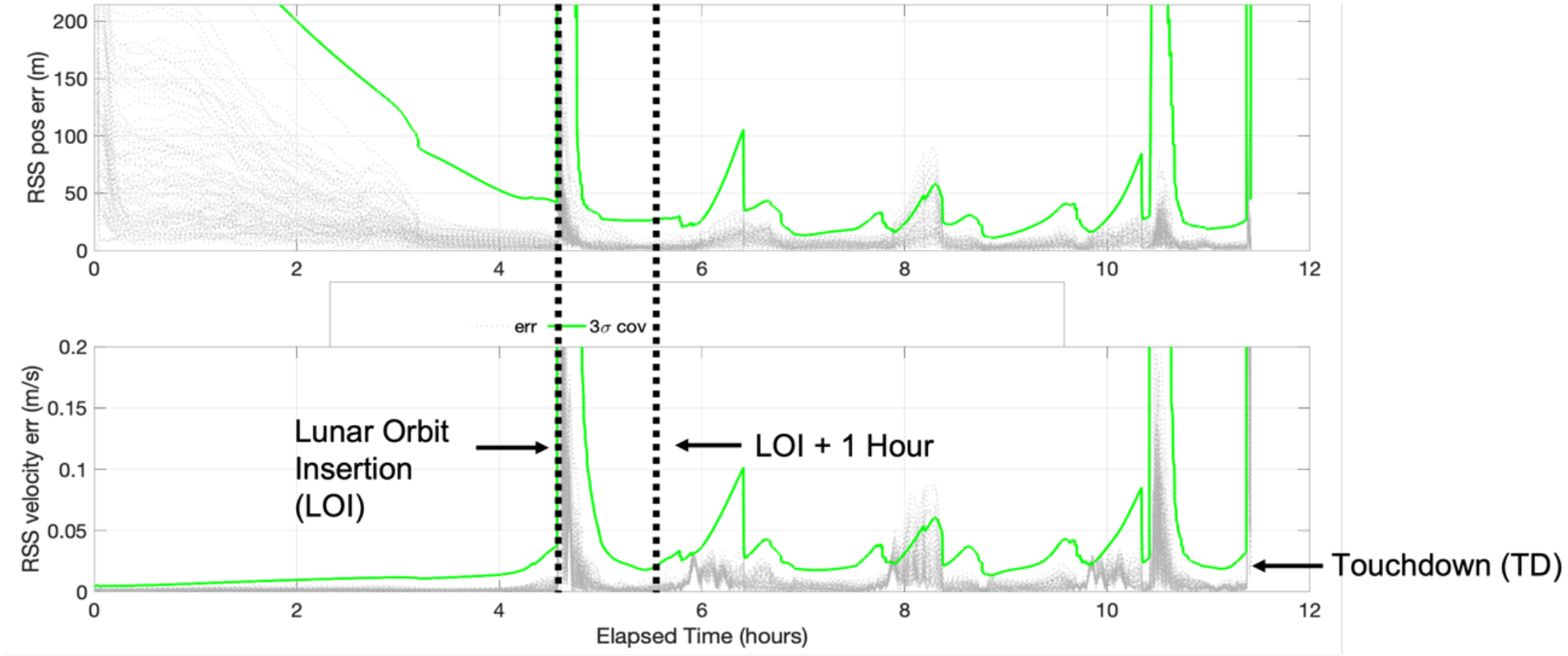
LNN MC State Errors – GN, CF, GPS with RAFS



LNN MC Clock Errors – GN, CF, GPS with RAFS

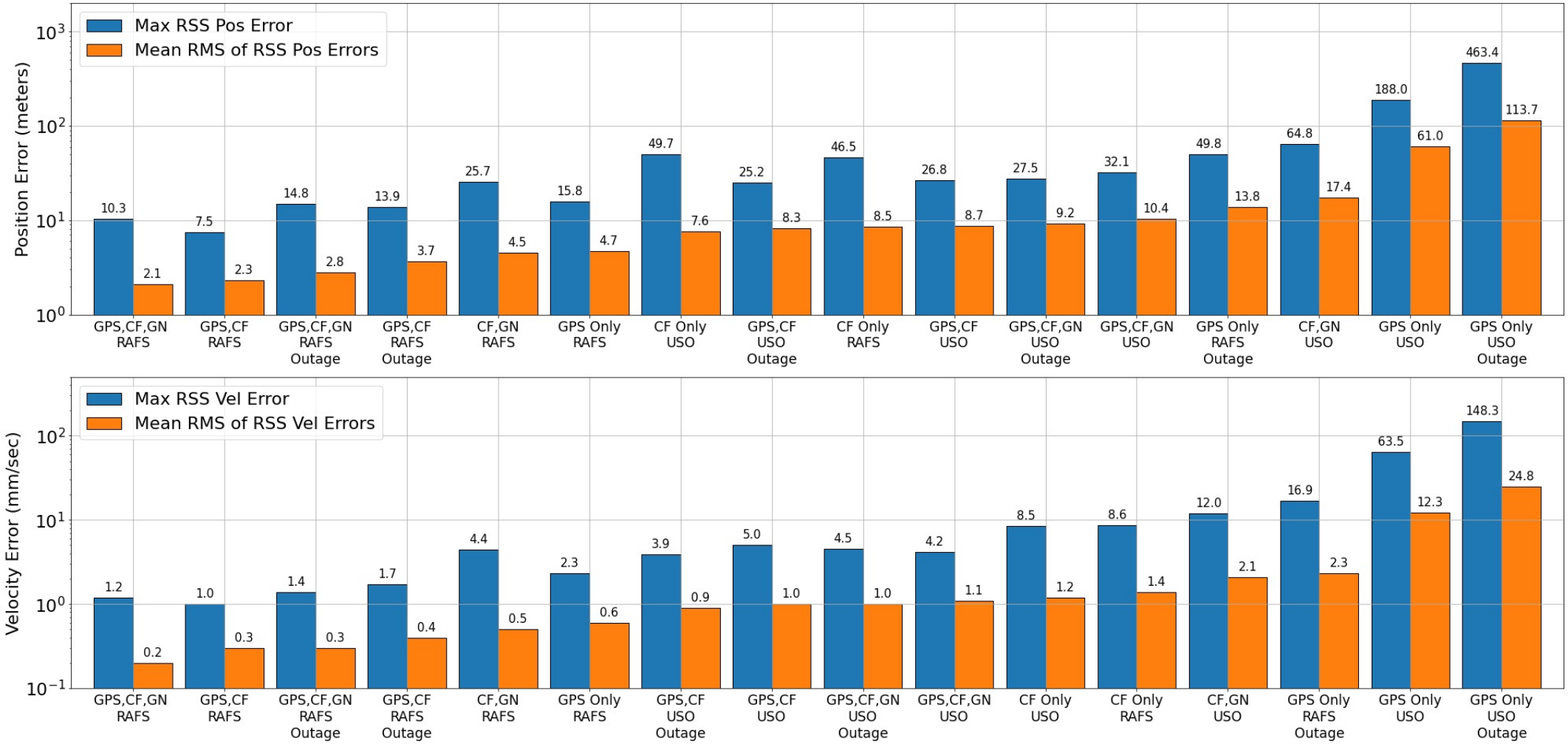


Descent MC State Errors – Xlink, GN, TRN LNNA

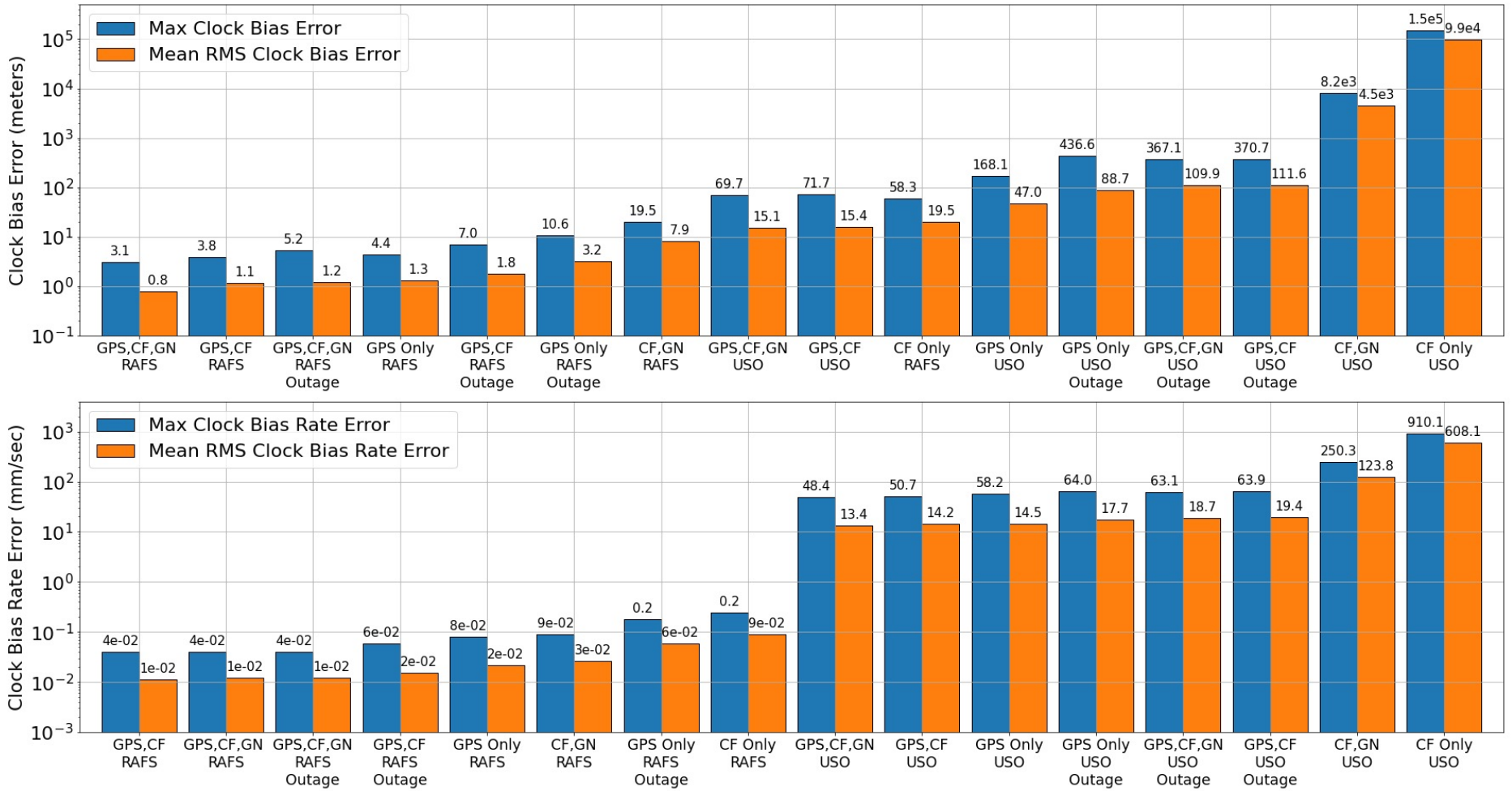


LNN Self-OD Results

LNN Self-OD
Position and Velocity Errors Over Last Orbit

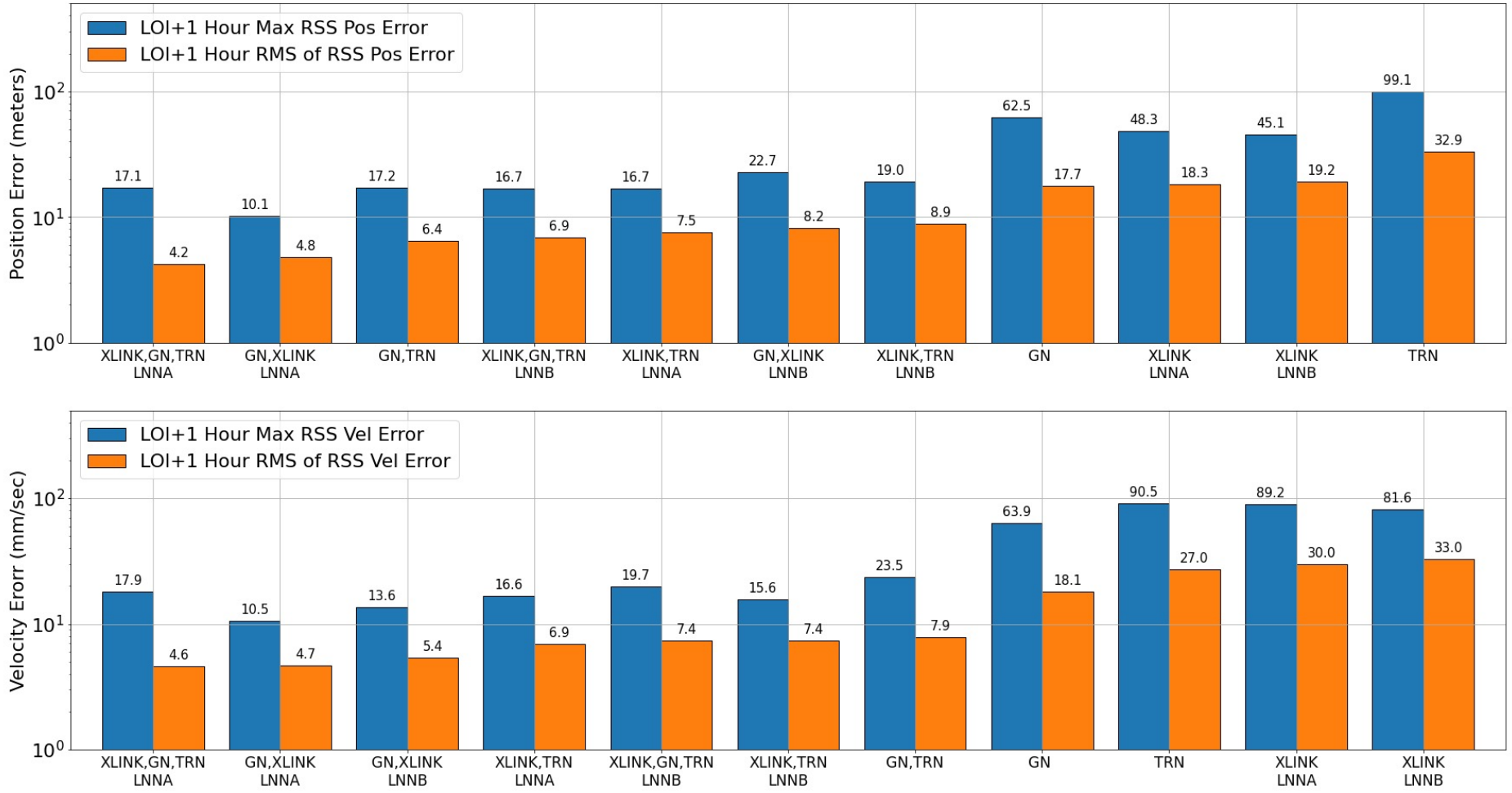


LNN Self-OD
Clock Bias and Rate Errors Over Last Orbit

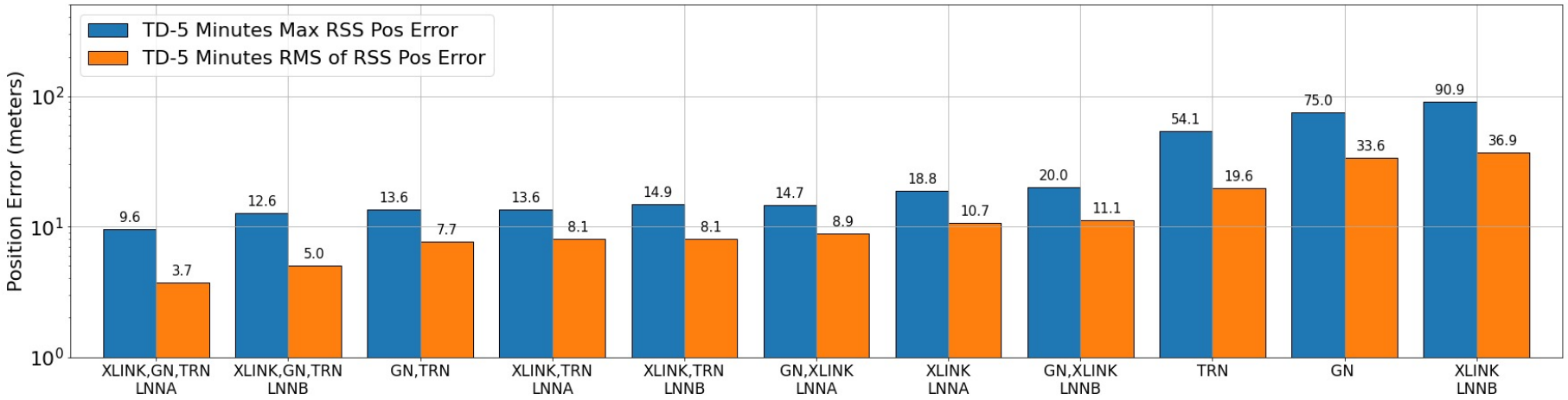


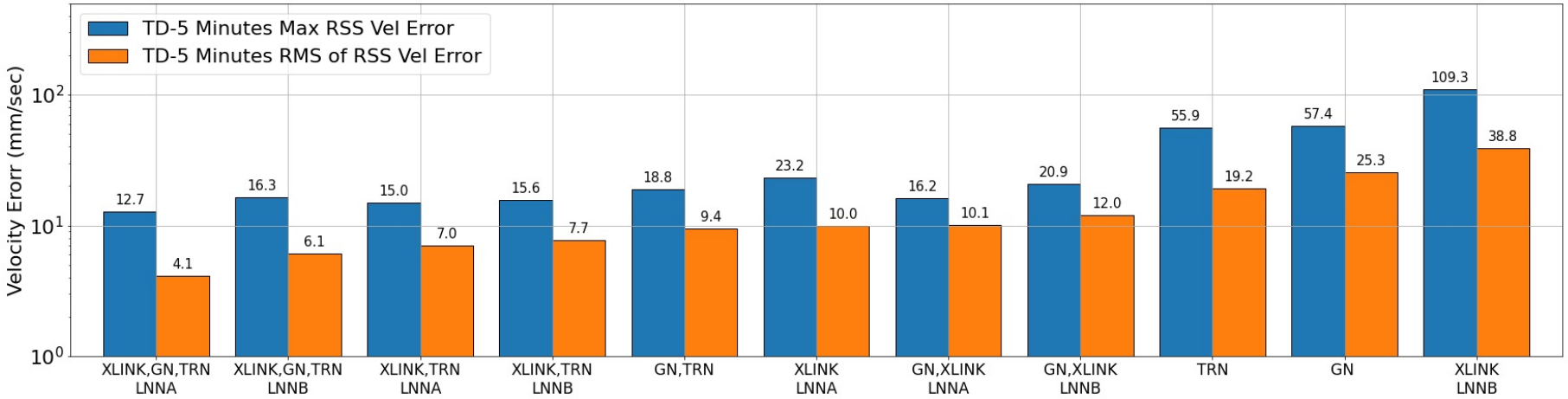
Descent OD Results

Descent MC State Errors
One Hour After LOI

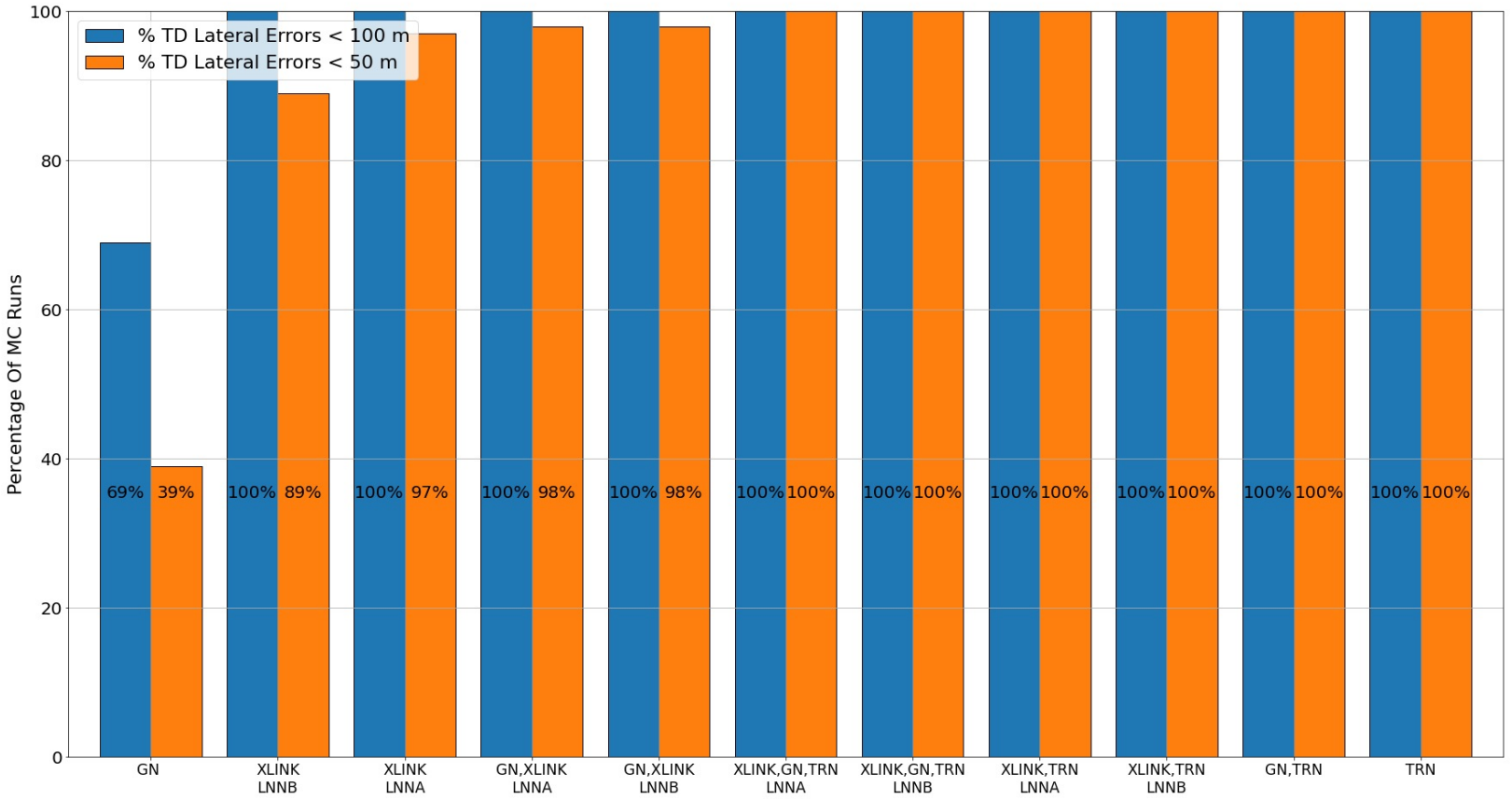


Descent MC State Errors
Five Minutes Before Touchdown





Descent MC - Percentage of Runs Within 100% and 50% of Landing Site



Conclusion

- Choice of LNN relay onboard clock has large effect on navigation and clock error estimation
- OpNav CF observables very useful for relay OD, especially during GPS outages, though does not inform clock estimation
- GPS measurements work well to estimate clock errors for relay OD
- LNN reference signal measurements provide best navigation results at one hour past LOI and five minutes before touchdown versus GN and TRN alone
- When LNN reference signal measurements combined with TRN or GN, errors at LOI and five minutes before touchdown are 5x lower than those measurements alone
- GN only is not sufficient for landing, TRN works quite well and LNN performance is slightly worse
- Future work will look at using TRN and GPS Doppler measurements for relay, lidar measurements for lander

References

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