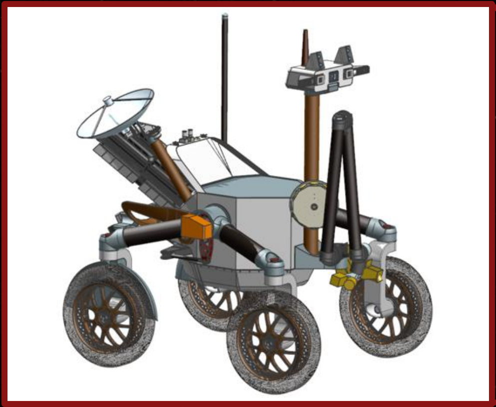
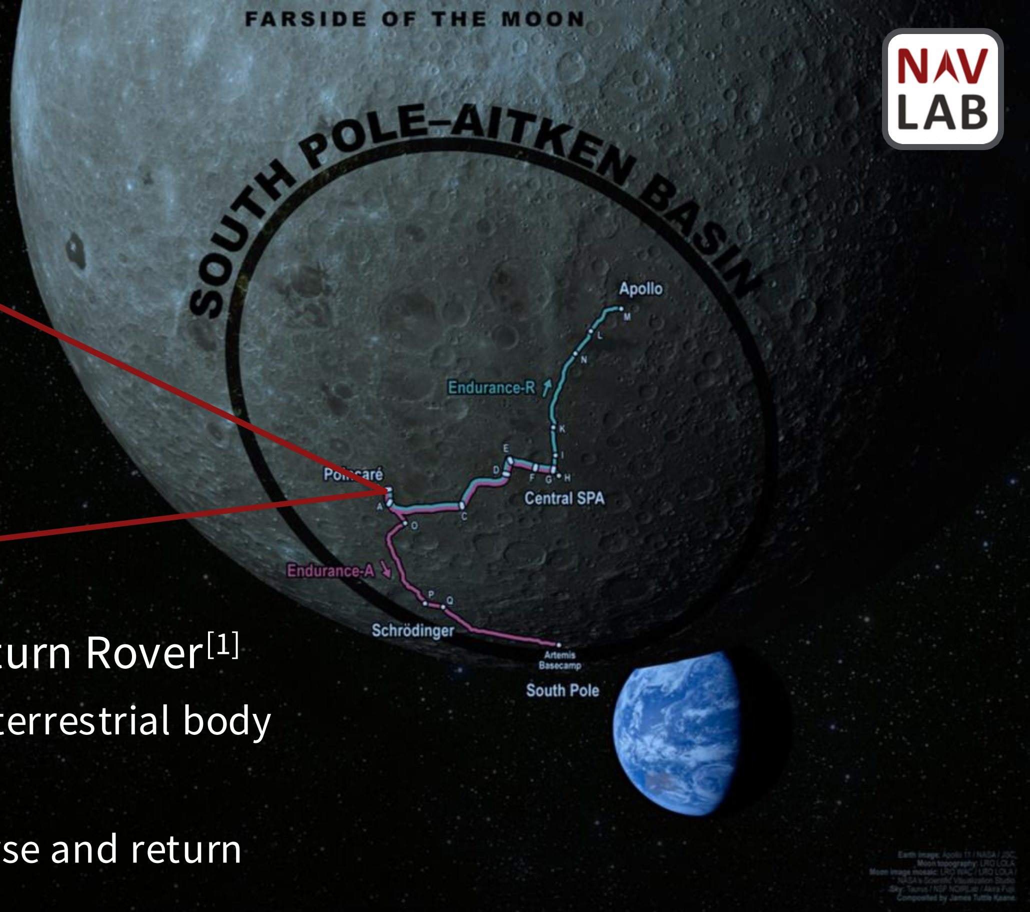
Single-Satellite Lunar Navigation via Doppler Shift Observables for the NASA Endurance Mission

KAILA M. Y. COIMBRA, MARTA CORTINOVIS, TARA MINA, AND GRACE GAO

NASA Endurance Mission





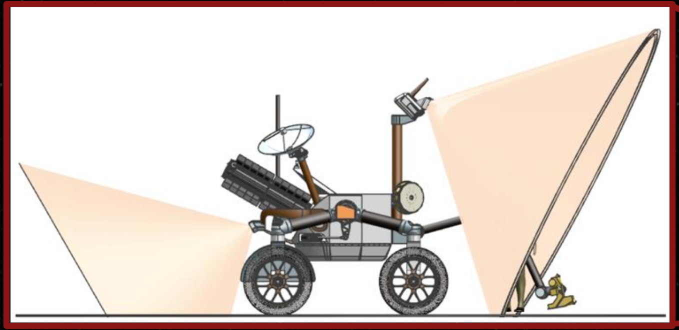
Lunar SPA Basin Traverse and Sample Return Rover[1]

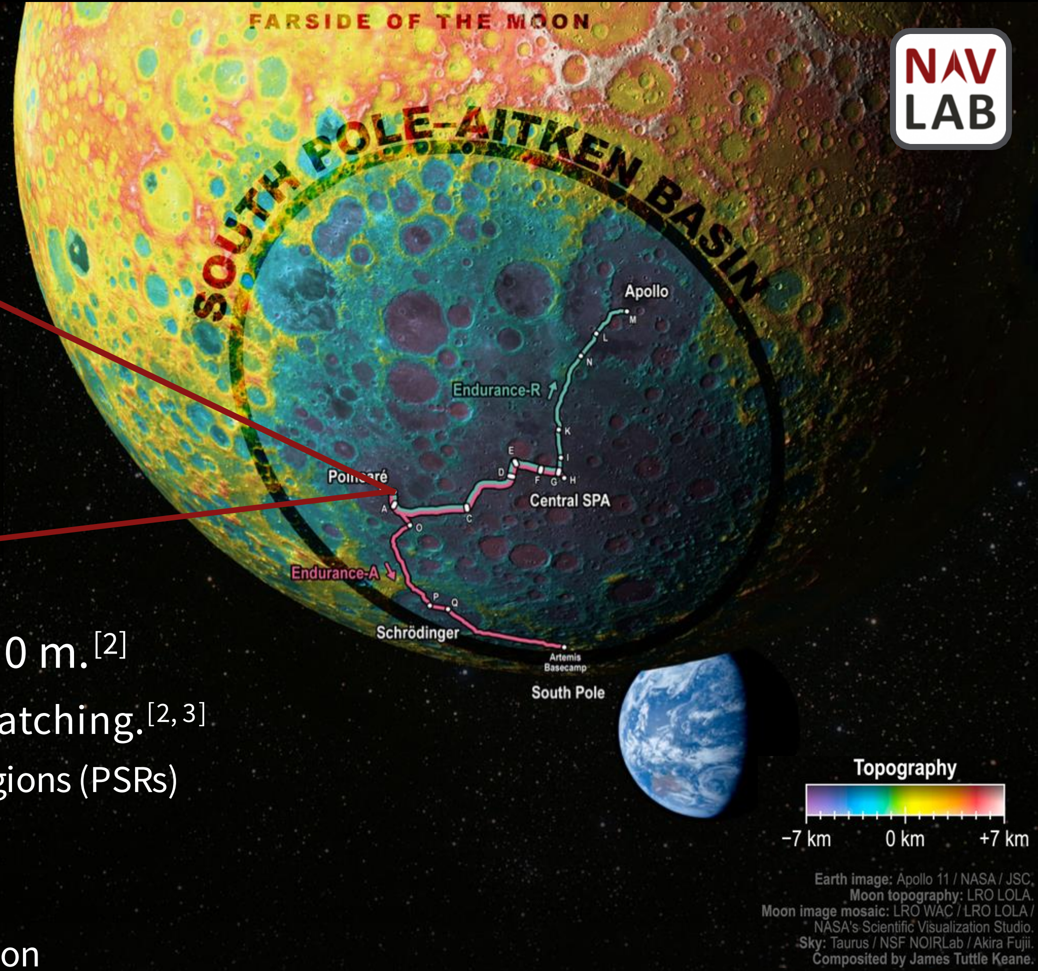
- First rover to traverse 2000 km on an extraterrestrial body
- *Launch*: ~2030s
- *Mission*: Collect 12 samples along its traverse and return samples to Artemis astronauts

[1] Keane et al., 2022

NASA Endurance Mission

Front and rear navigation cameras FOVs shown[1]





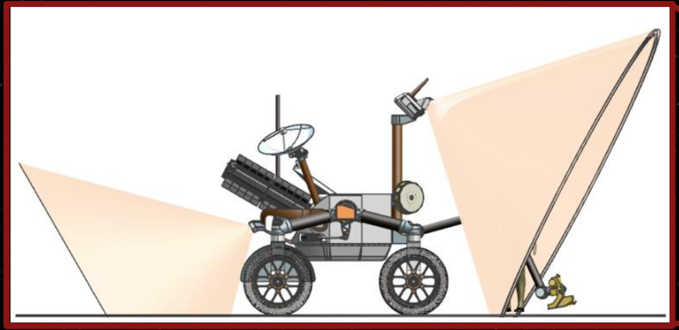
Global localization errors must remain ≤10 m.[2]

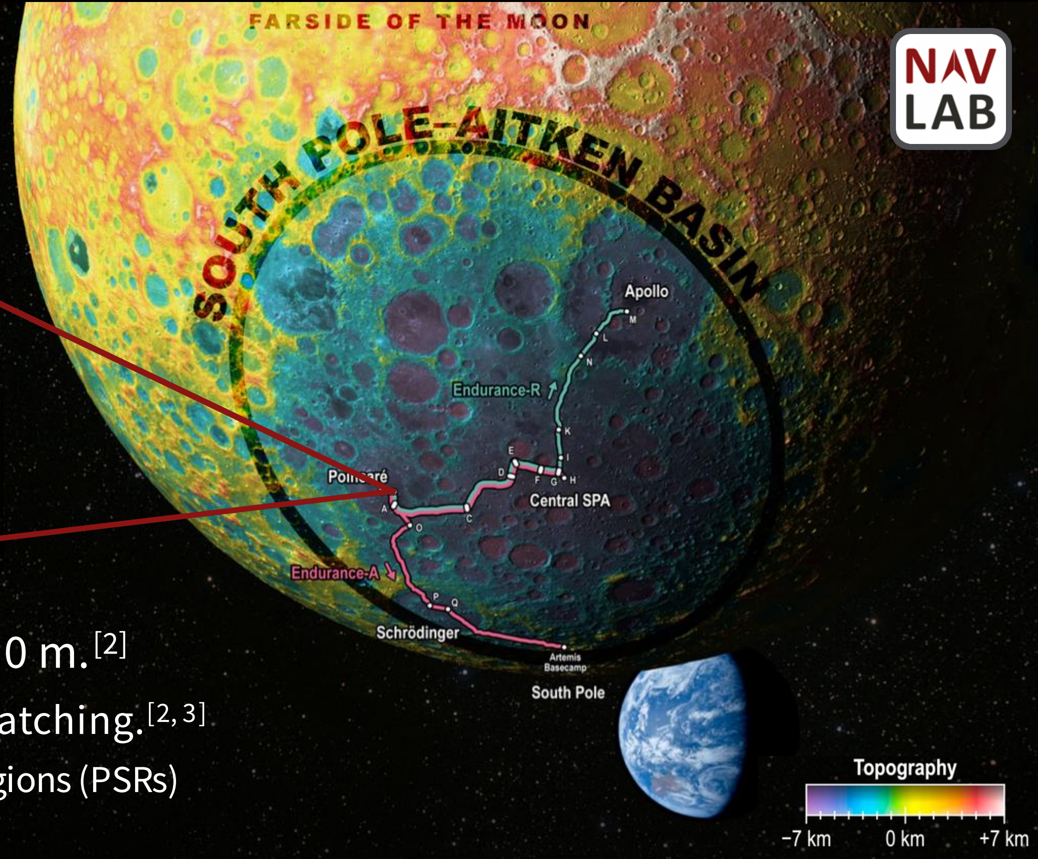
- NASA is considering autonomous crater matching.[2, 3]
  - Limited visibility in permanently shadowed regions (PSRs)
  - Computationally expensive
  - Memory intensive
  - Dependent on the quality of the maps' resolution

[1] Keane et al., 2022
[2] Cauligi et al., 2023
[3] Daftry et al., 2023

NASA Endurance Mission

Front and rear navigation cameras FOVs shown[1]





Global localization errors must remain ≤10 m.[2]

- NASA is considering autonomous crater matching.[2, 3]
  - Limited visibility in permanently shadowed regions (PSRs)
  - Computationally expensive

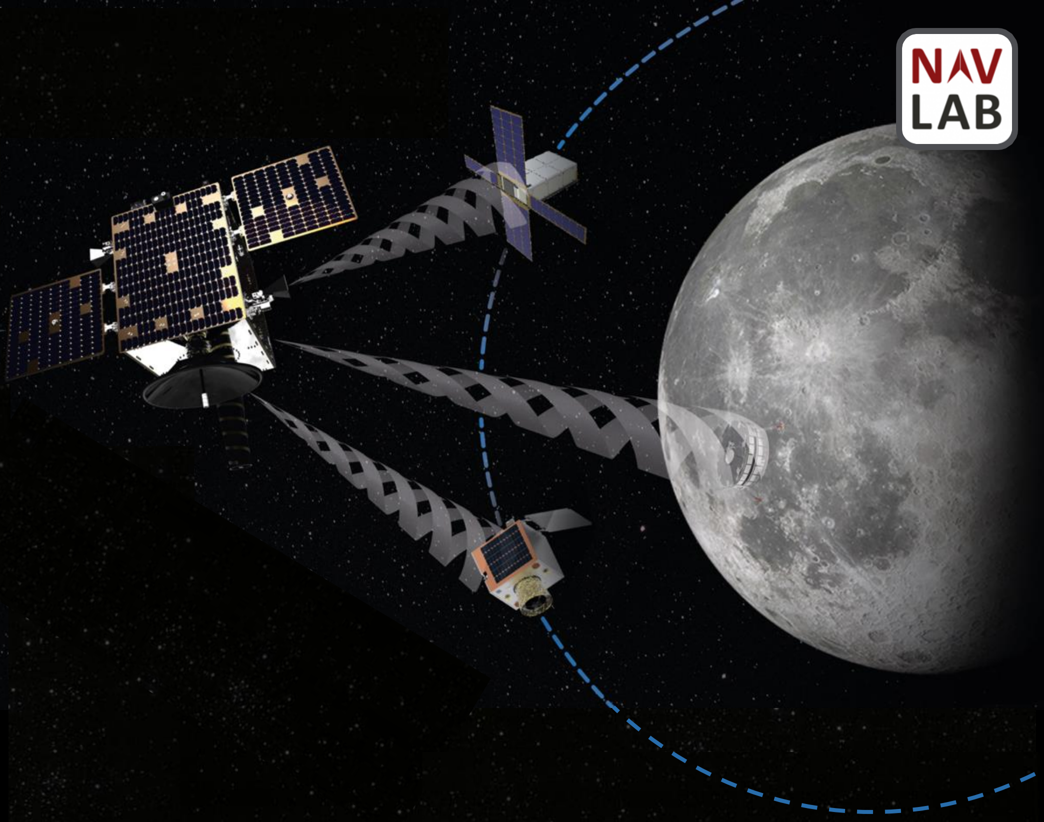
What existing resources can we utilize for localization?

[1] Keane et al., 2022
[2] Cauligi et al., 2023
[3] Daftry et al., 2023

SSTL Lunar Pathfinder

Data Relay Satellite in ELFO[4]

- *Service*: ~2025 - 2033
- *Mission*: Provide communication services to any lunar asset

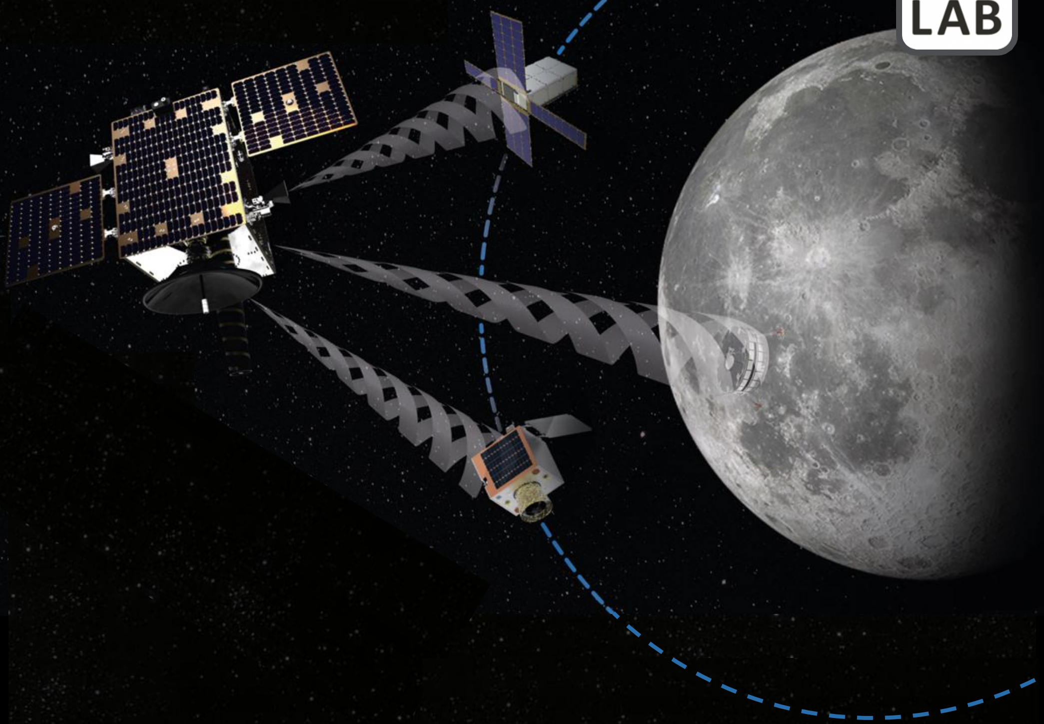


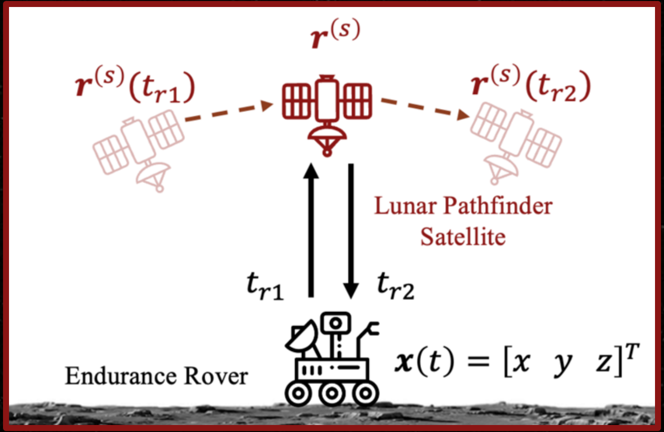
[4] SSTL, 2022

SSTL Lunar Pathfinder

Data Relay Satellite in ELFO[4]

- *Service*: ~2025 - 2033
- *Mission*: Provide communication services to any lunar asset





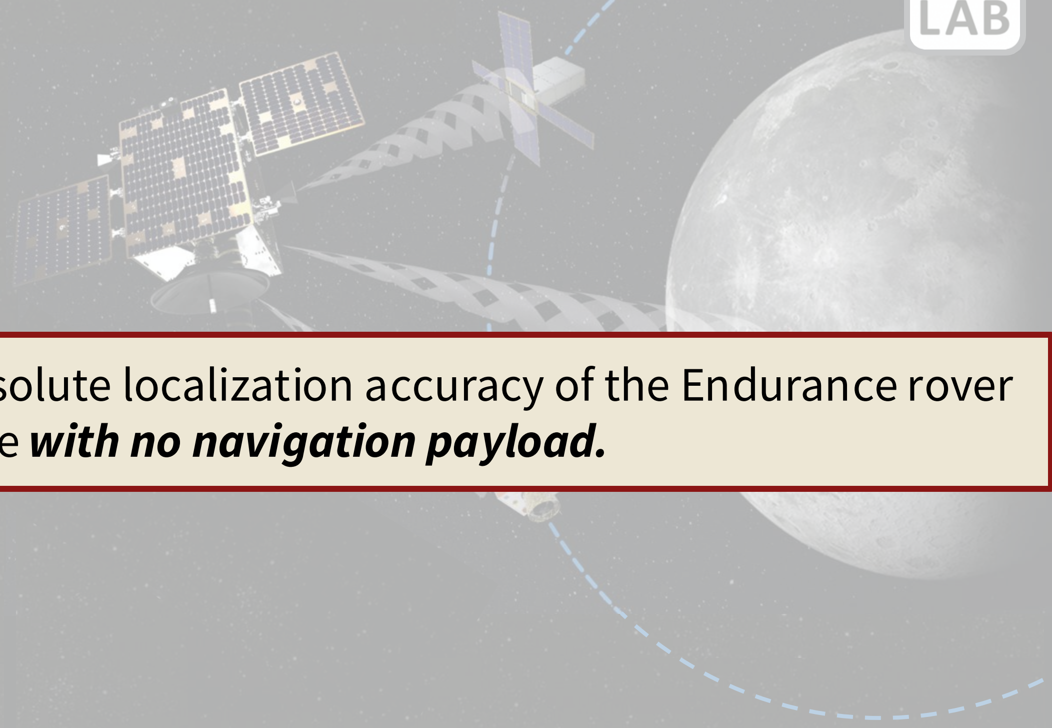
Prior work assessed the absolute localization accuracy using two-way ranging measurements.[5]

[4] SSTL, 2022
[5] Cortinovis et al., 2024

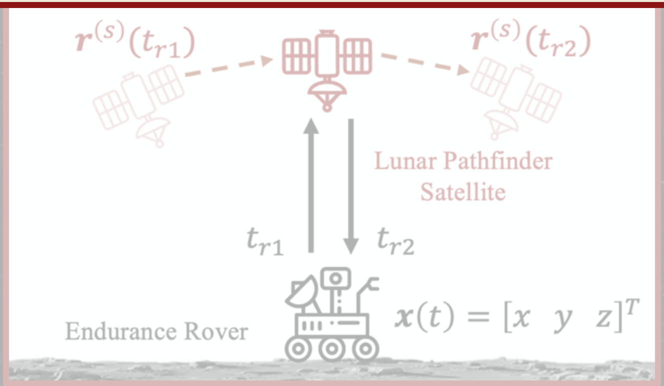
SSTL Lunar Pathfinder

Data Relay Satellite in ELFO[4]

- *Service*: ~2025 - 2033
- *Mission*: Provide communication services to any lunar asset



In this work, we assess the achievable absolute localization accuracy of the Endurance rover using a single satellite ***with no navigation payload.***

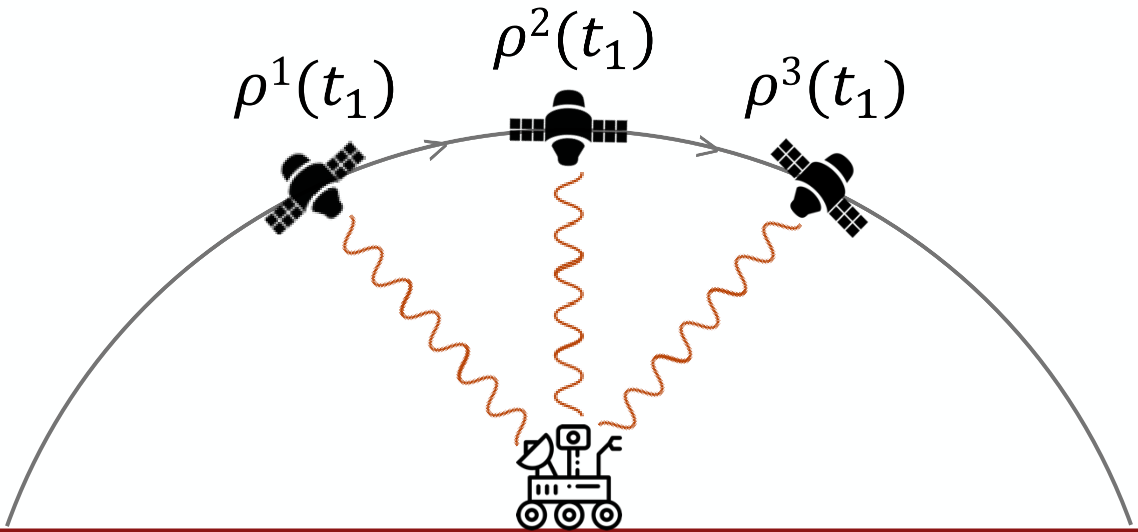


Prior work assessed the absolute localization accuracy using two-way ranging measurements.[5]

[4] SSTL, 2022
[5] Cortinovis, et al., 2024

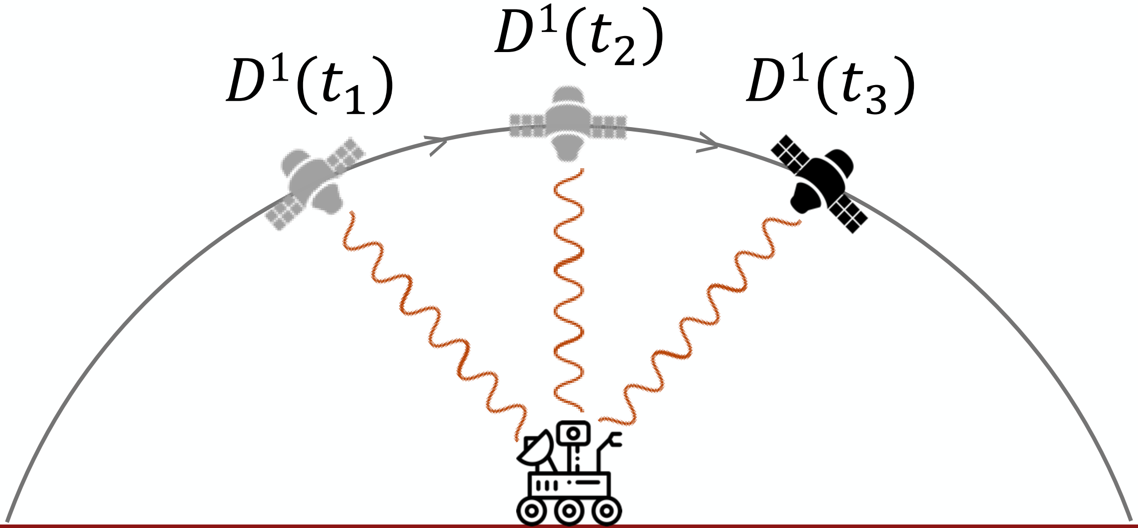
Traditional Scenario

1. ***Multiple satellites*** – instantaneous localization (with at least 4 satellites)
2. ***Navigation payload*** – obtain pseudorange measurements for trilateration



Our Scenario

1. ***Single satellite*** – accumulate measurements over time
2. ***No navigation payload*** – use Doppler shift observables to obtain pseudorange rate measurements



Contribution

Measurement Modeling and Filtering

- Simulate and filter realistic measurements from the Lunar Pathfinder's communication signal to obtain a positioning fix.

State Estimation Performance

- Compare the trend in positioning errors over time when the rover is placed at different locations on the Moon.

Sensitivity Analysis

- Evaluate the convergence time to achieve sub-10-m level positioning under various levels of clock and ephemeris error uncertainty.

Contribution

Measurement Modeling and Filtering

- Simulate and filter realistic measurements from the Lunar Pathfinder's communication signal to obtain a positioning fix.

State Estimation Performance

- Compare the trend in positioning errors over time when the rover is placed at different locations on the Moon.

Sensitivity Analysis

- Evaluate the convergence time to achieve sub-10-m level positioning under various levels of clock and ephemeris error uncertainty.

Doppler Shift Measurement Model

NAV LAB

Application

Collect Doppler shift measurements.

$$D = f_{\text{received}} - f_{\text{source}}$$

Calculate the observed pseudorange rates.

$$\dot{\rho}_{\text{obs}} = -\frac{cD}{f_{\text{source}}}$$

[6] Misra and Enge, 2012

Doppler Shift Measurement Model

Application

Collect Doppler shift measurements.

$$D = f_{\text{received}} - f_{\text{source}}$$

Calculate the observed pseudorange rates.

$$\dot{\rho}_{\text{obs}} = -\frac{cD}{f_{\text{source}}}$$

Simulation

Difference in the rover's and the satellite's clock drifts

$$\dot{\rho}_{\text{obs}} = \mathbf{v}_{\mathbf{sat}}^{(t)} \cdot \frac{\mathbf{x}_{\mathbf{sat}}^{(t)} - \mathbf{x}_{\mathbf{rov}}}{\left\| \mathbf{x}_{\mathbf{sat}}^{(t)} - \mathbf{x}_{\mathbf{rov}} \right\|} + c\left(\dot{\delta t}_{\text{sat}} - \dot{\delta t}_{\text{rov}}\right) + \epsilon_{\dot{\rho}}\,, \quad \epsilon_{\dot{\rho}} \sim \mathcal{N}(0, \sigma_{\dot{\rho}}^2)$$

Projection of the satellite's velocity onto the line-of-sight vector

Error in pseudorange rate measurements

[6] Misra and Enge, 2012

Measurement Error Model

$$\dot{\rho}_{\text{obs}} = \mathbf{v}_{\mathbf{sat}}^{(t)} \cdot \frac{\mathbf{x}_{\mathbf{sat}}^{(t)} - \mathbf{x}_{\mathbf{rov}}}{\left\| \mathbf{x}_{\mathbf{sat}}^{(t)} - \mathbf{x}_{\mathbf{rov}} \right\|} + c\left(\dot{\delta t}_{\text{sat}} - \dot{\delta t}_{\text{rov}}\right) + \epsilon_{\dot{\rho}}\,, \quad \epsilon_{\dot{\rho}} \sim \mathcal{N}(0, \sigma_{\dot{\rho}}^2)$$

Pseudorange rate error:

- Thermal noise contribution of the phase locked loop (PLL)
- Contribution from the frequency error of the rover's clock

$$\sigma_{\dot{\rho}}^2 = \sigma_{\text{PLL}}^2 + \sigma_{\text{clock}}^2$$

Total measurement error:

- Used for the weighting matrix in the measurement filtering to prioritize the measurements with less variance

$$\sigma_{\text{tot}}^2 = \sigma_{\text{eph,vel}}^2 + \sigma_{\dot{\rho}}^2$$

[6] Misra and Enge, 2012

State Estimation Framework

NAV LAB

Weighted Batch Filter

Accumulate the simulated measurements over time.

→

Solve non-linear weighted least squares problem to ***minimize the measurement residual*** iteratively using Gauss-Newton method.

$$\delta y = \dot{\rho}_{\text{obs}} - \dot{\rho}_{\text{pred}}$$

→

Obtain the rover's state estimate.

State Estimation Framework

NAV LAB

Weighted Batch Filter

Accumulate the simulated measurements over time.

Solve non-linear weighted least squares problem to ***minimize the measurement residual*** iteratively using Gauss-Newton method.

$$\delta y = \dot{\rho}_{\text{obs}} - \dot{\rho}_{\text{pred}}$$

Obtain the rover's state estimate.

The **EKF** does not retain a good history of previous measurements, which is key for this single-satellite scenario. Therefore, we choose to use the **weighted batch filter** as the state estimation algorithm for this scenario.

State Estimation Framework

NAV LAB

Weighted Batch Filter

Accumulate the simulated measurements over time.

Solve non-linear weighted least squares problem to ***minimize the measurement residual*** iteratively using Gauss-Newton method.

$$\delta y = \dot{\rho}_{\mathrm{obs}} - \dot{\rho}_{\mathrm{pred}}$$

Obtain the rover's state estimate.

Satellite ephemeris errors are modeled as a **zero-mean Gaussian noise model.**

$$\begin{cases} \epsilon_{\mathrm{eph,pos}} \sim \mathcal{N}(0, \sigma^2_{\mathrm{eph,pos}_{xyz}} I_3) \\ \epsilon_{\mathrm{eph,vel}} \sim \mathcal{N}(0, \sigma^2_{\mathrm{eph,vel}_{xyz}} I_3) \end{cases}$$

Contribution

NAV LAB

Measurement Modeling and Filtering

We designed a batch filter framework to perform localization on the lunar surface using a single satellite with no navigation payload.

State Estimation Performance

- Compare the trend in positioning errors over time when the rover is placed at different locations on the Moon.

Sensitivity Analysis

- Evaluate the convergence time to achieve sub-10-m level positioning under various levels of clock and ephemeris error uncertainty.

Contribution

Measurement Modeling and Filtering

We designed a batch filter framework to perform localization on the lunar surface using a single satellite with no navigation payload.

State Estimation Performance

- Compare the trend in positioning errors over time when the rover is placed at different locations on the Moon.

Sensitivity Analysis

- Evaluate the convergence time to achieve sub-10-m level positioning under various levels of clock and ephemeris error uncertainty.

Error Modeling Parameters

We use LCRNS's SISE specification for 1-way forward Doppler reference signals[7] as a lower bound.

Error	Value
SISE Position	13.43 m (3σ)
SISE Velocity	1.2 mm/s (3σ) @ 10 s

Ephemeris Errors to Test	
Position σ [m]	Velocity σ [mm/s]
4.48	0.40
10.00	1.00
20.00	2.00
30.00	3.00
40.00	4.00
50.00	5.00

SISE contributions include:

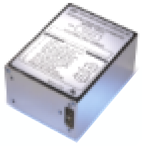
- Relay on-board state knowledge
- Signal integrity and on-board path delays
- Predicted relay states conveyed to users
- States and time representation

SISE contributions do not include phase noise by the user system.

[7] NASA, 2022

Rover Clock Candidates

NAV LAB

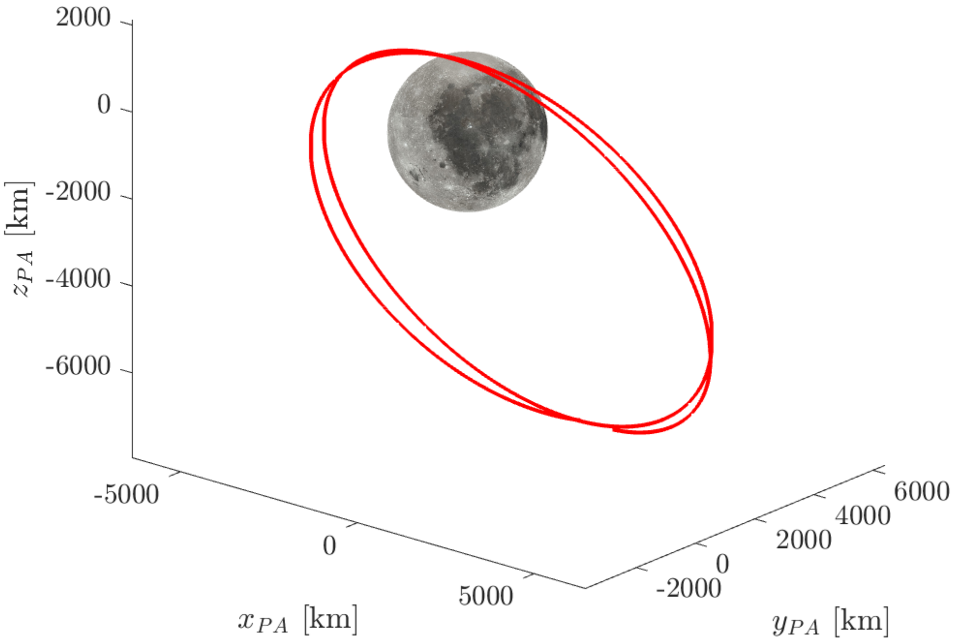
	Clock Type	Size [cm^3]	Weight [kg]	Power [W]	TDEV per day [μs]
	Microchip CSAC	17	0.035	0.12	1.5
	Microchip MAC	50	0.086	5	0.17
	SRS PRS 10	155	0.6	14.4	0.07
	Excelitas RAFS	1645	6.35	39	0.0048

[8] Schmittberger et al., 2020
[9] Bhamidipati et al., 2022

Experimental Set Up

Lunar Pathfinder's Orbital Elements[4]	
Semi-major axis	5740 km
Eccentricity	0.58
Inclination	54.856 °
RAAN	0 °
Argument of the Periapsis	86.322 °
Mean Anomaly	180 °

Simulation Parameters	
ELFO orbital period[4]	10.84 hours
Initial epoch	2030/10/01 00:00:00 UTC
Total simulation length	2 orbits



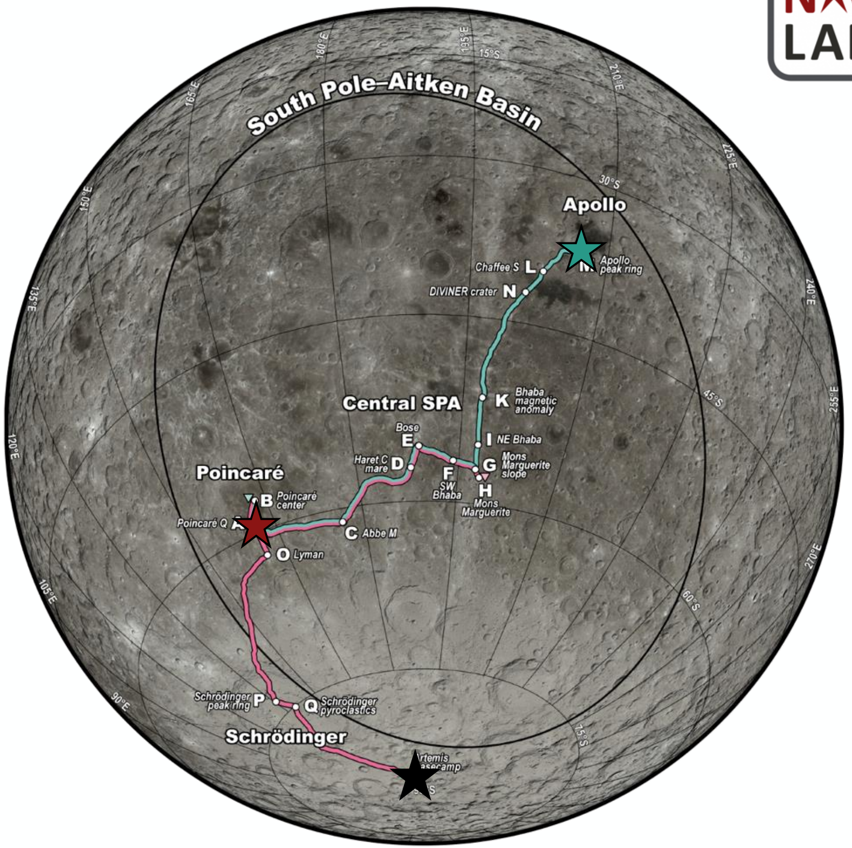
Two orbital periods of the Lunar Pathfinder in the fixed Moon Principal Axis frame of reference

[4] SSTL, 2022

Experimental Set Up

Location[1]	Latitude	Longitude
Poincaré Q★	-59.12448°	161.05104°
Apollo Peak Ring★	-37.7115°	-153.0430°
Artemis Basecamp★	-90°	0°

Comm Signal & Simulation Parameters	
S-band frequency[4]	2050 Hz
EIRP @ HPBW[4]	26.5 dBW @ 7.1°
Initial rover position error	100 m σ (3D)
Measurement sampling rate	1 Hz
Filter update interval	180 seconds
Number of Monte Carlo runs	100

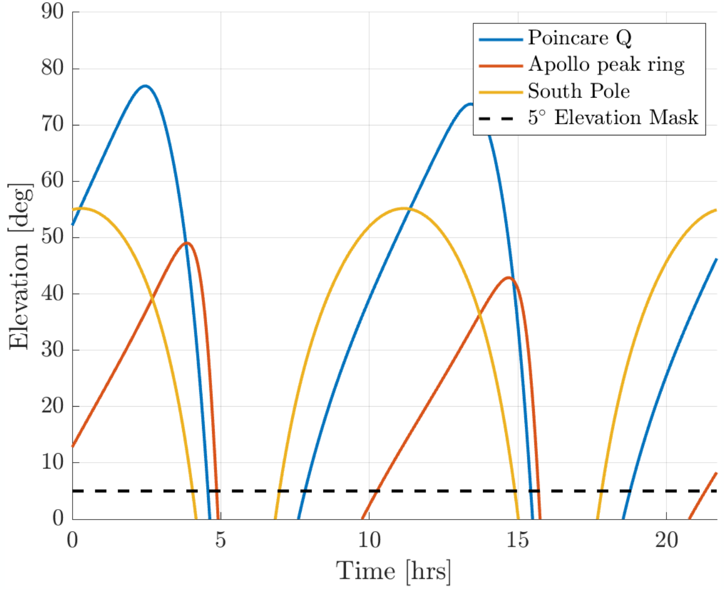


Map of the rover's long-range traverse[1]

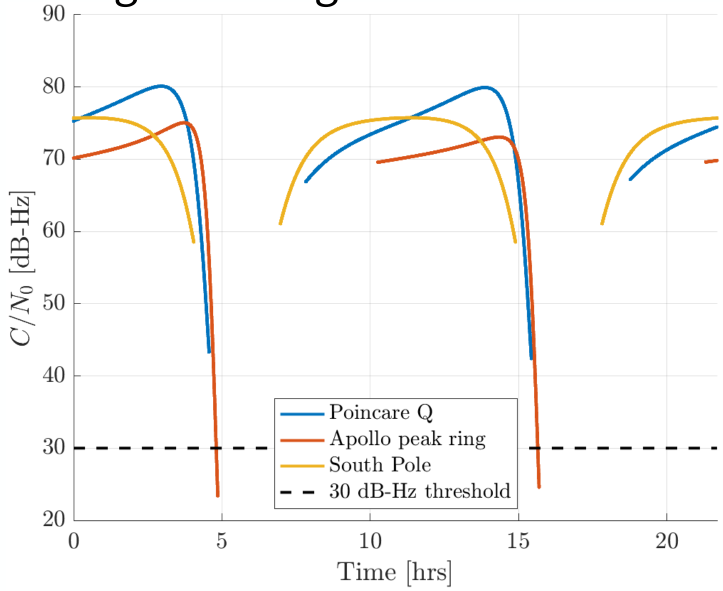
[1] Keane et al., 2022
[4] SSTL, 2022

Signal Availability

Elevation mask > 5°



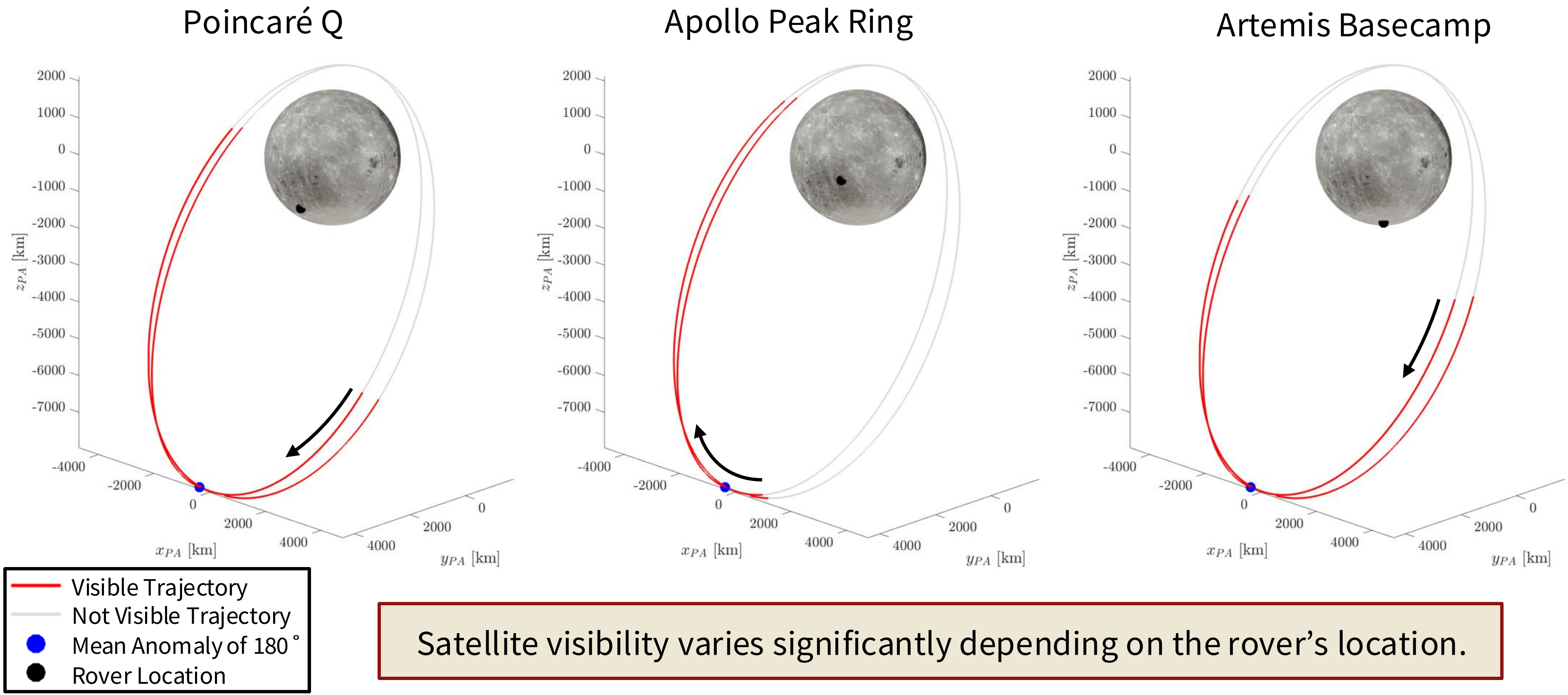
Signal strength > 30 dB-Hz[10, 11]



The union of the two requirements result in an occultation period of 2.9 hours for the Artemis Basecamp, 3.3 hours for Poincaré Q, and 5.5 hours for the Apollo Peak Ring.

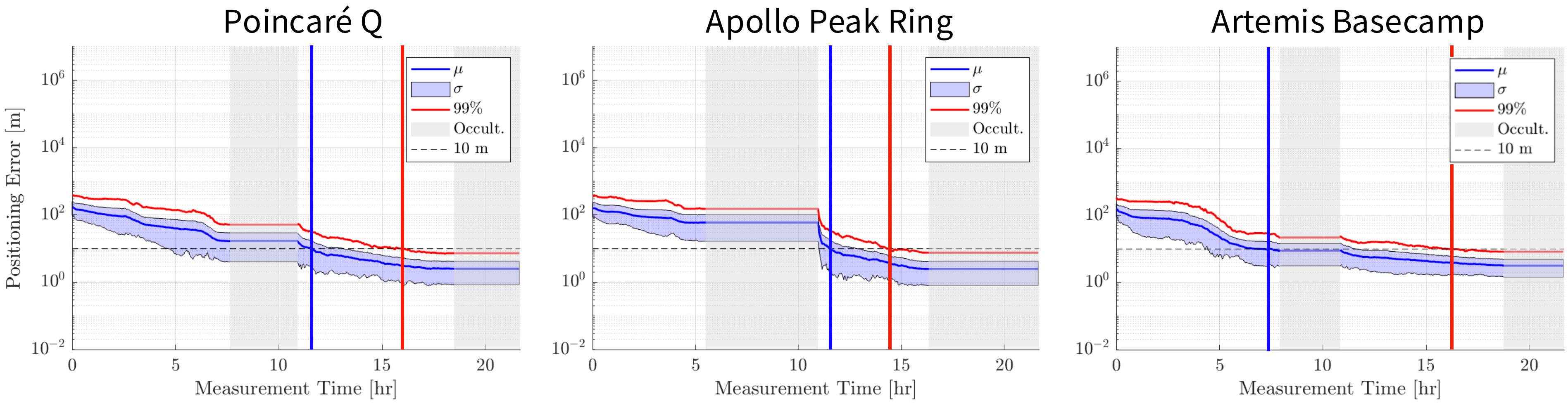
[10] Nardin et al., 2023
[11] Melman et al., 2022

Satellite Visibility

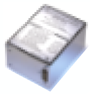


Satellite visibility varies significantly depending on the rover's location.

State Estimation Performance



Location	Mean [hr]	99% error [hr]
Poincaré Q	11.6	16.0
Apollo Peak Ring	11.5	14.4
Artemis Basecamp	7.5	16.4

Clock Type: SRS PRS 10 

Satellite Ephemeris Errors: Per LCRNS's SISE specification

Contribution

Measurement Modeling and Filtering

We designed a batch filter framework to perform localization on the lunar surface using a single satellite with no navigation payload.

State Estimation Performance

We demonstrated that our method was able to achieve sub-10-m localization within two orbital periods of the Lunar Pathfinder.

Sensitivity Analysis

- Evaluate the convergence time to achieve sub-10-m level positioning under various levels of clock and ephemeris error uncertainty.

Contribution

NAV LAB

Measurement Modeling and Filtering

We designed a batch filter framework to perform localization on the lunar surface using a single satellite with no navigation payload.

State Estimation Performance

We demonstrated that our method was able to achieve sub-10-m localization within two orbital periods of the Lunar Pathfinder.

Sensitivity Analysis

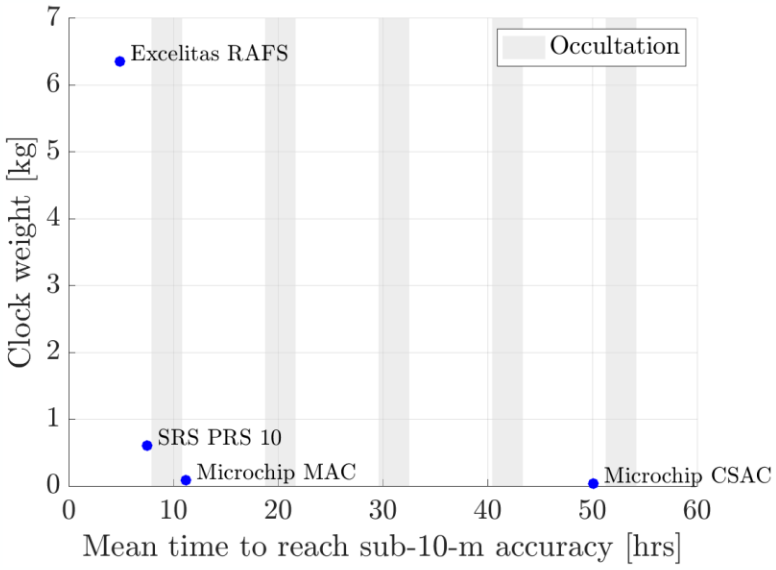
- Evaluate the convergence time to achieve sub-10-m level positioning under various levels of clock and ephemeris error uncertainty.

Sensitivity Study on Clock Errors

Location: Artemis Basecamp

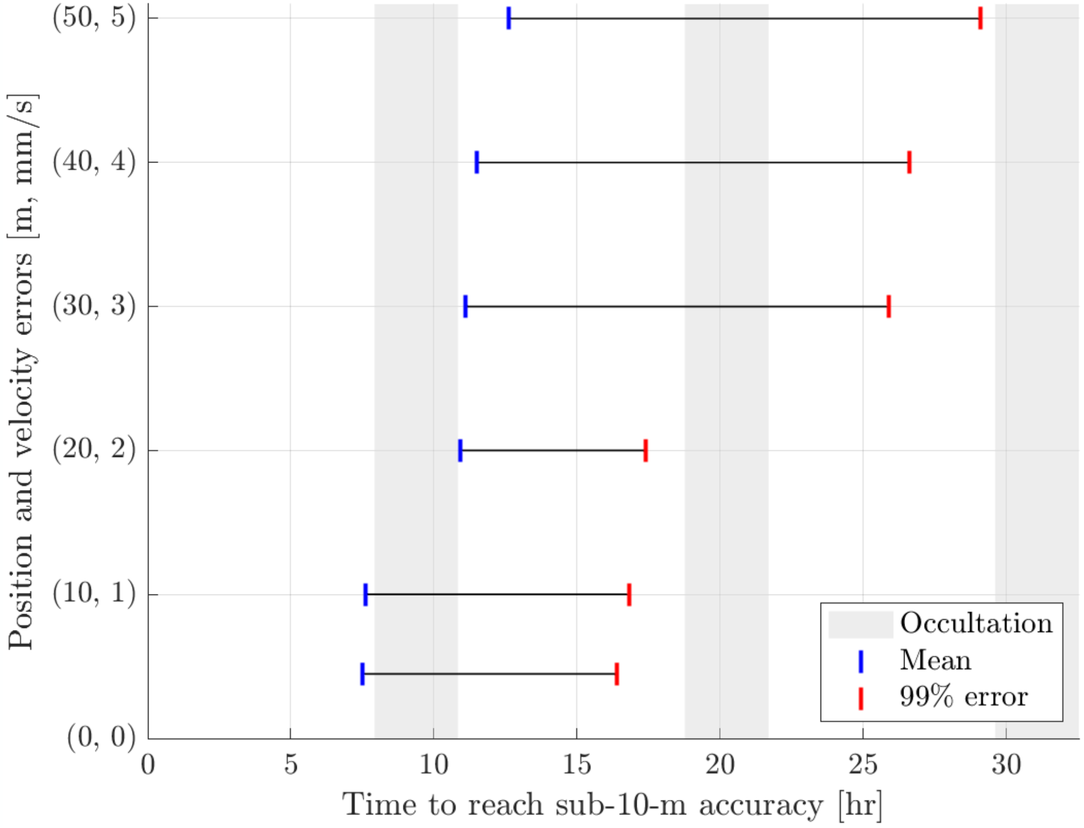
Satellite Ephemeris Errors: Per LCRNS's SISE specification

Clock Type	Time to reach ≤ 10 m	
	Mean [hr]	99% error [hr]
Microchip CSAC	50.1	Did not converge within 65 hours
Microchip MAC	11.2	26.7
SRS PRS 10	7.5	16.4
Excelitas RAFS	4.9	11.1



The SRS PRS 10 and the Microchip MAC are promising clock candidates for the Endurance rover.

Sensitivity Study on Ephemeris Errors



Location: Artemis Basecamp

Clock Type: SRS PRS 10

The time for the 99% error to reach sub-10-m accuracy becomes substantially larger for ephemeris errors greater than 20 m in position and 2 mm/s in velocity.

Contribution

Measurement Modeling and Filtering

We designed a batch filter framework to perform localization on the lunar surface using a single satellite with no navigation payload.

State Estimation Performance

We demonstrated that our method was able to achieve sub-10-m localization within two orbital periods of the Lunar Pathfinder.

Sensitivity Analysis

We performed a sensitivity analysis on the rover's clock type and the satellite's ephemeris knowledge to better inform design decisions.

Summary of Contributions

Measurement Modeling and Filtering

We designed a batch filter framework to perform localization on the lunar surface using a single satellite with no navigation payload.

State Estimation Performance

We demonstrated that our method was able to achieve sub-10-m localization within two orbital periods of the Lunar Pathfinder.

Sensitivity Analysis

We performed a sensitivity analysis on the rover's clock type and the satellite's ephemeris knowledge to better inform design decisions.

Acknowledgements

Special thanks to the NAV Lab!

Single-Satellite Lunar Navigation via Doppler Shift Observables for the NASA Endurance Mission

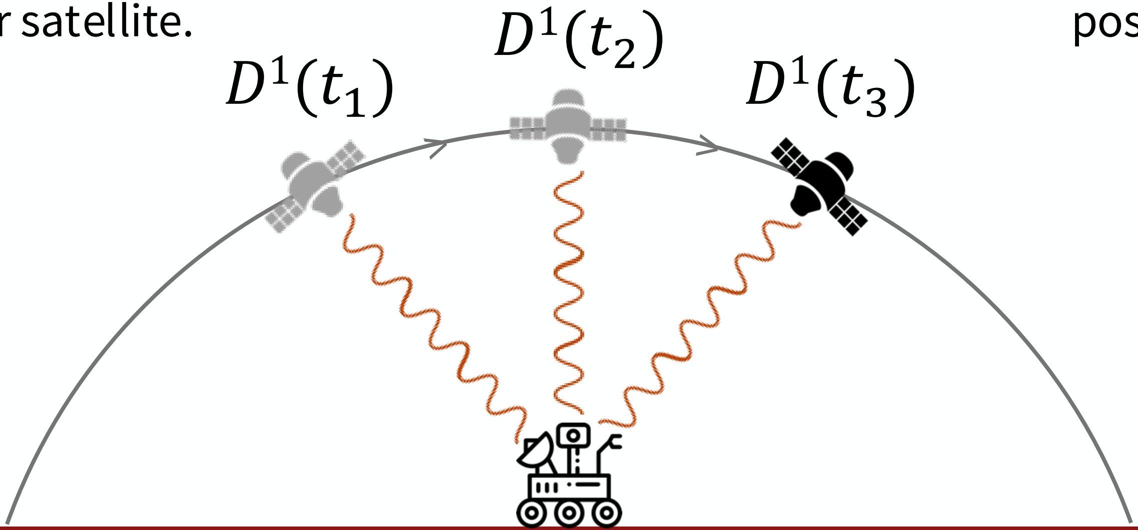
Back-Up Slides

Overview of the Proposed Work

Collect and retain multiple Doppler shift measurements over time.

Opportunistically leverage the communication signal of a singular lunar satellite.

Minimize the pseudorange rate residuals to obtain a positioning fix.



Implementation

Measurement Modeling and Filtering

- Simulate and filter realistic measurements from the Lunar Pathfinder's communication signal to obtain a positioning fix.

State Estimation Performance

- Compare the trend in positioning errors over time when the rover is placed at different locations on the Moon.

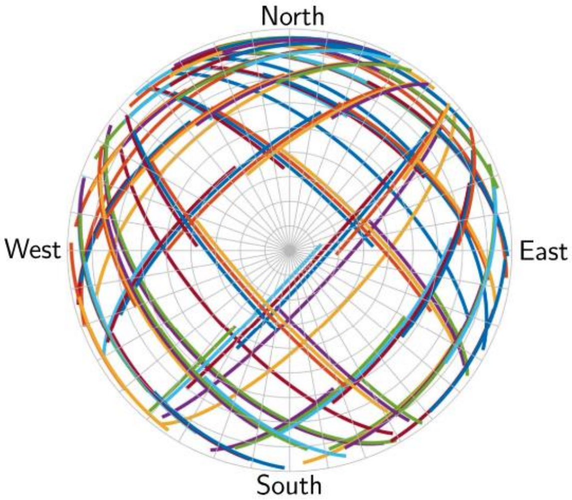
Sensitivity Analysis

- Evaluate the convergence time to achieve sub-10-m level positioning under various levels of clock and ephemeris error uncertainty.

Prior Works on Positioning with Doppler Observables

- TRANSIT employed Doppler measurements as the navigation observable.[6]
  - Achieved 5 m 3D positioning accuracy if the **receiver is stationary** for several days
  - Assumed that the **clock drift is constant** over the measurement window[12]

- Related works have opportunistically extracted navigation observables from large LEO constellations.[13, 14]
  - Achieved sub-5-m level positioning accuracy using the carrier Doppler shift of the downlink signals
  - Multi-satellite scenario enables the accumulation of multiple measurements **simultaneously**

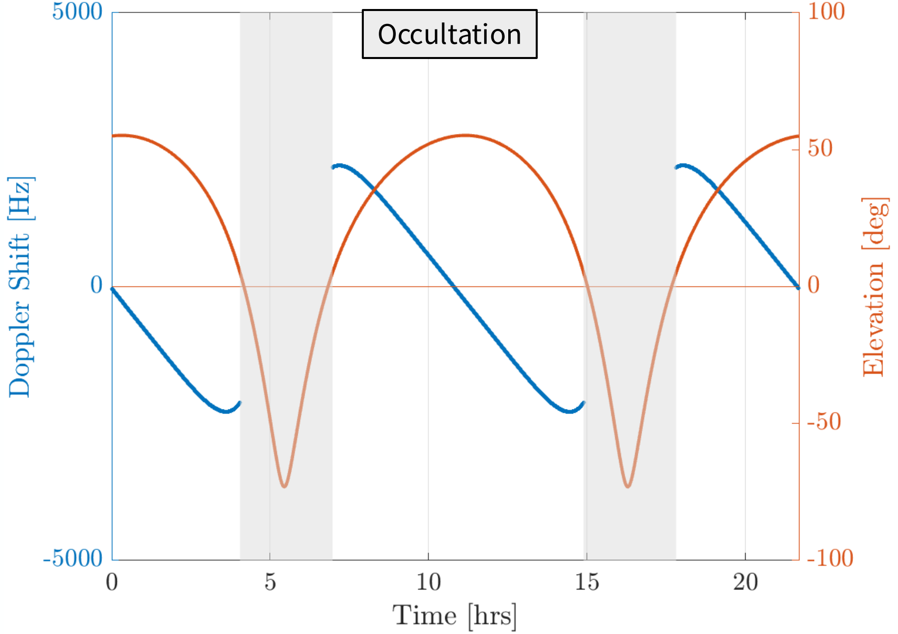


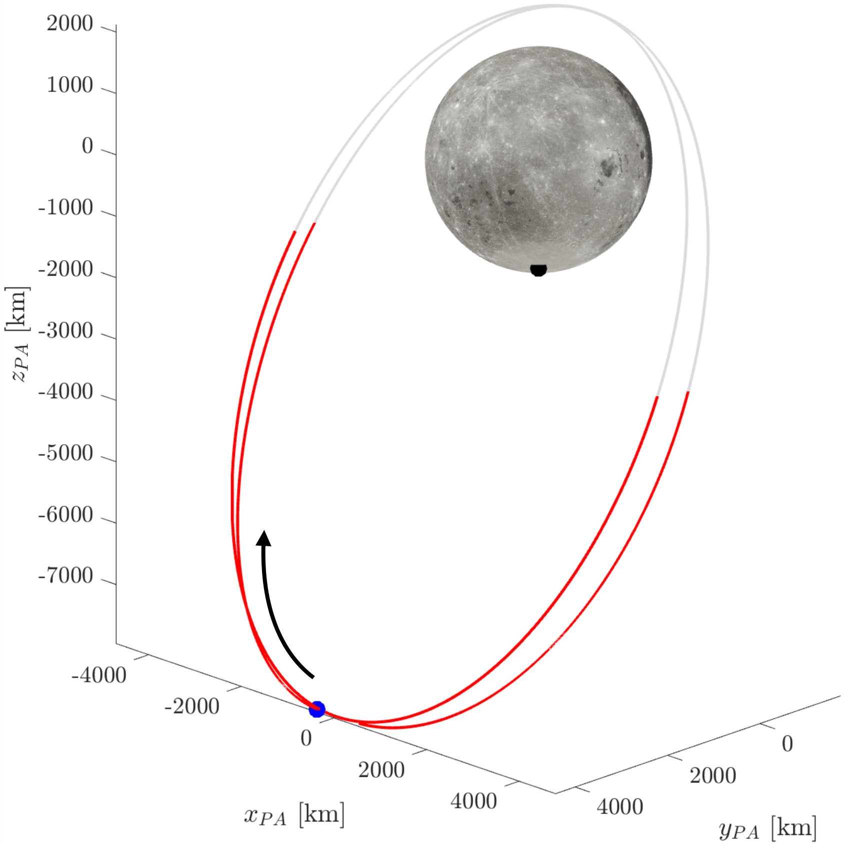
Skyplot of 103 SVs[15]

[6] Misra and Enge, 2012
[12] Kershner and Newton, 1962
[13] Psiaki, 2021
[14] Khairallah and Kassas, 2022

Doppler Shift Measurements: *Artemis Basecamp*

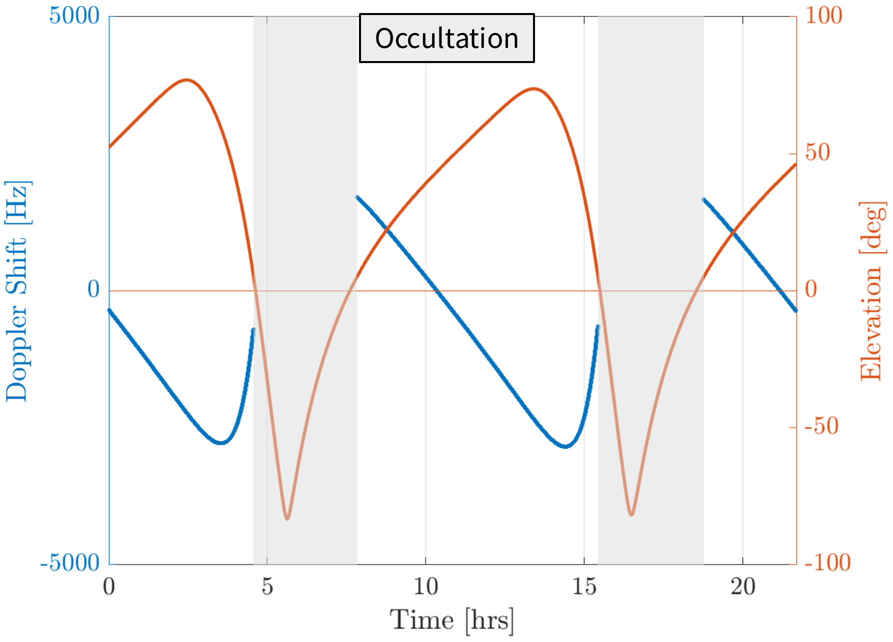
Signal availability and the respective Doppler shift measurements vary significantly depending on the rover's location.

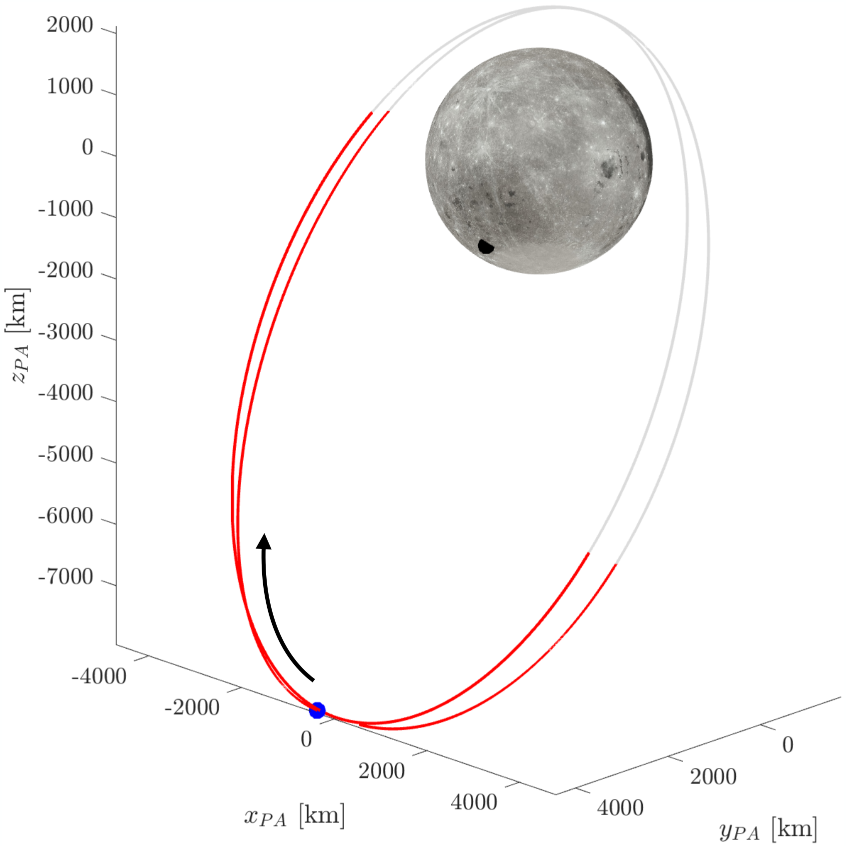




Doppler Shift Measurements: *Poincaré Q*

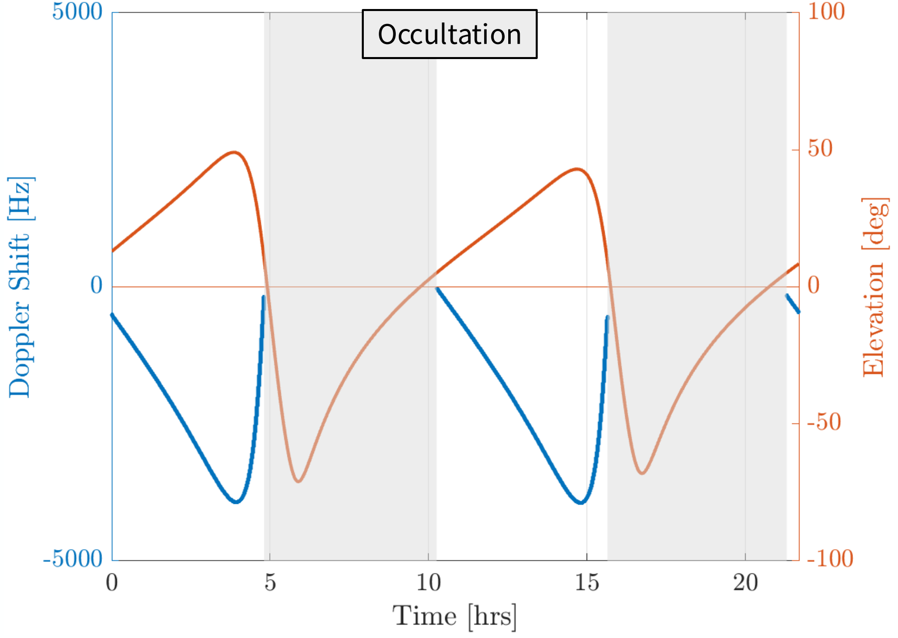
Signal availability and the respective Doppler shift measurements vary significantly depending on the rover's location.

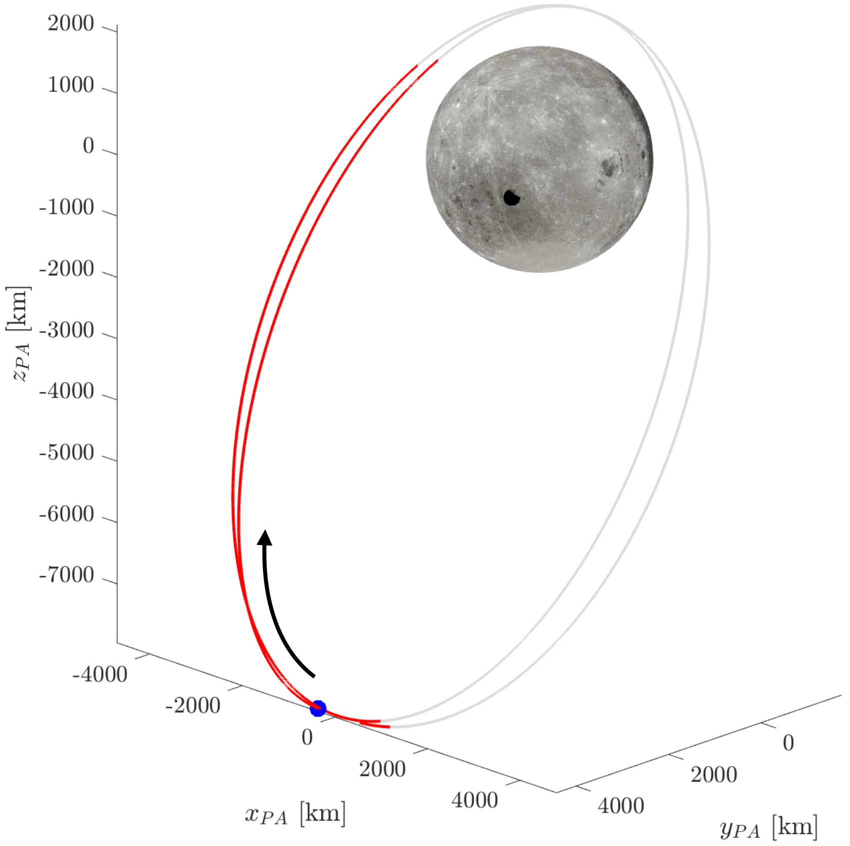




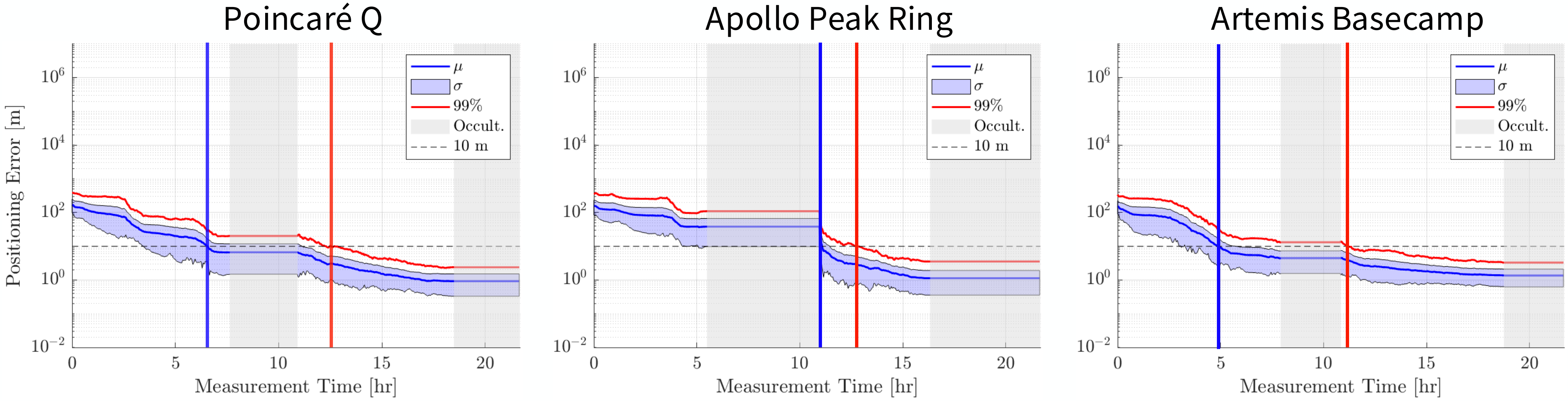
Doppler Shift Measurements: *Apollo Peak Ring*

Signal availability and the respective Doppler shift measurements vary significantly depending on the rover's location.





State Estimation Performance



Location	Mean [hr]	99% error [hr]
Poincaré Q	6.6	12.7
Apollo Peak Ring	11.1	12.8
Artemis Basecamp	4.9	11.1

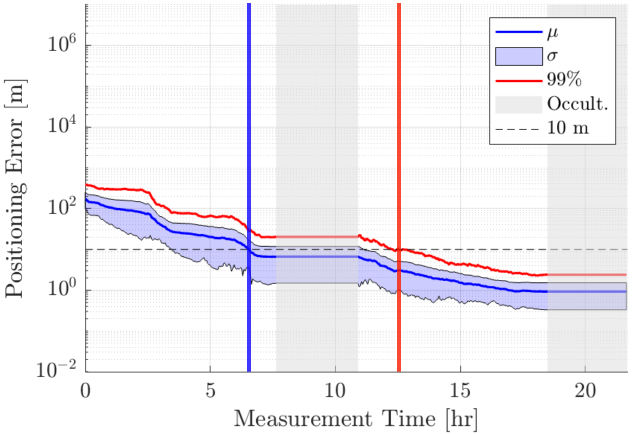
Clock Type: Excelitas RAFS 

Satellite Ephemeris Errors: Per LCRNS's SISE specification

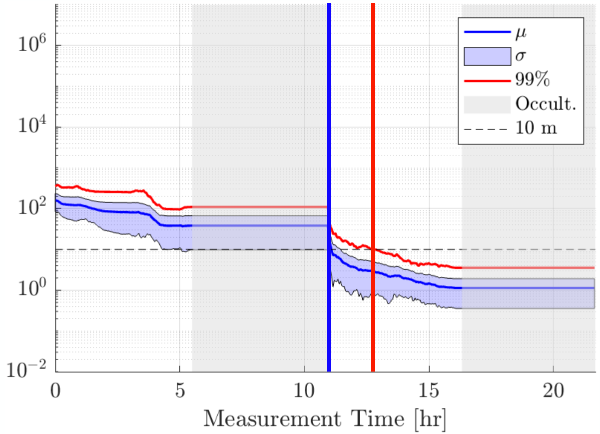
State Estimation Performance

NAV LAB

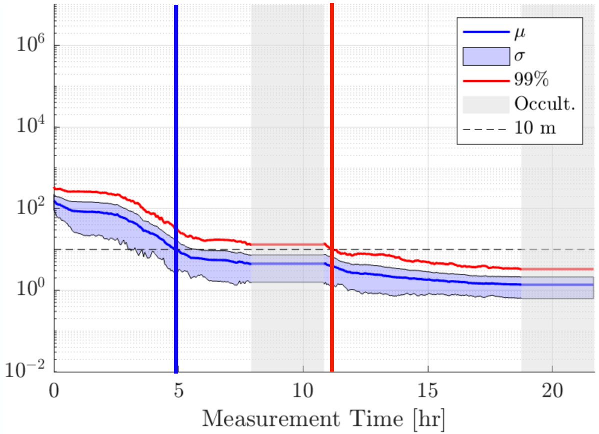
Poincaré Q



Apollo Peak Ring



Artemis Basecamp



In comparison to the SRS PRS 10

Location	Mean [hr]	99% error [hr]
Poincaré Q	5.0	3.3
Apollo Peak Ring	0.4	1.6
Artemis Basecamp	2.6	5.3

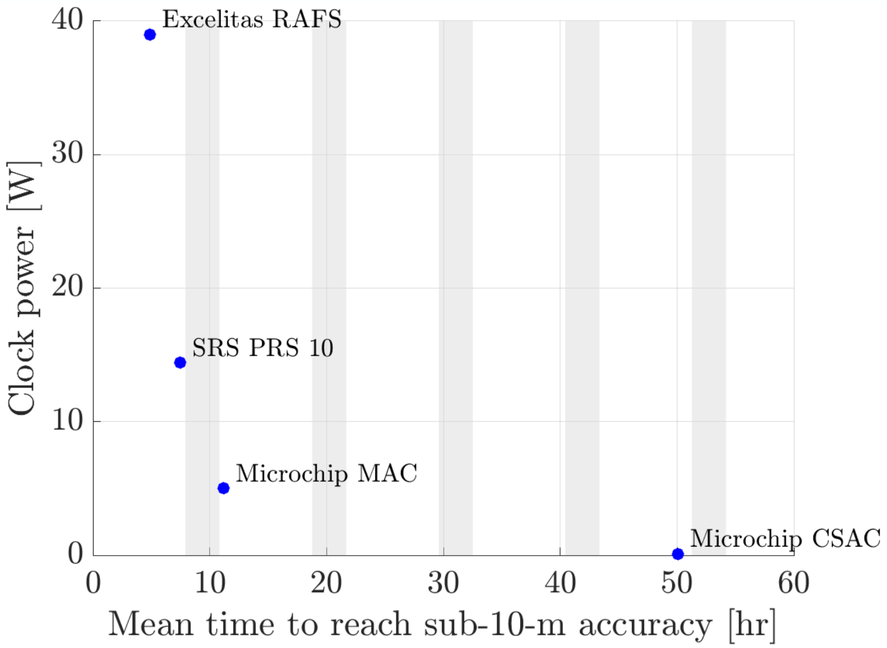
Clock Type: Excelitas RAFS 

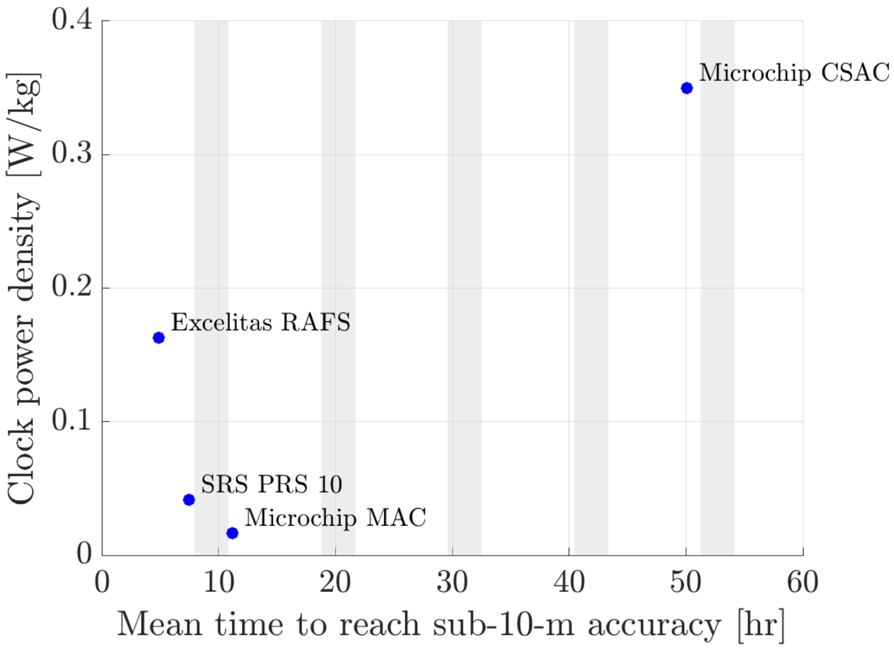
Satellite Ephemeris Errors: Per LCRNS's SISE specification

Sensitivity Study on Clock Errors

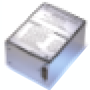
Location: Artemis Basecamp

Satellite Ephemeris Errors: Per LCRNS's SISE specification

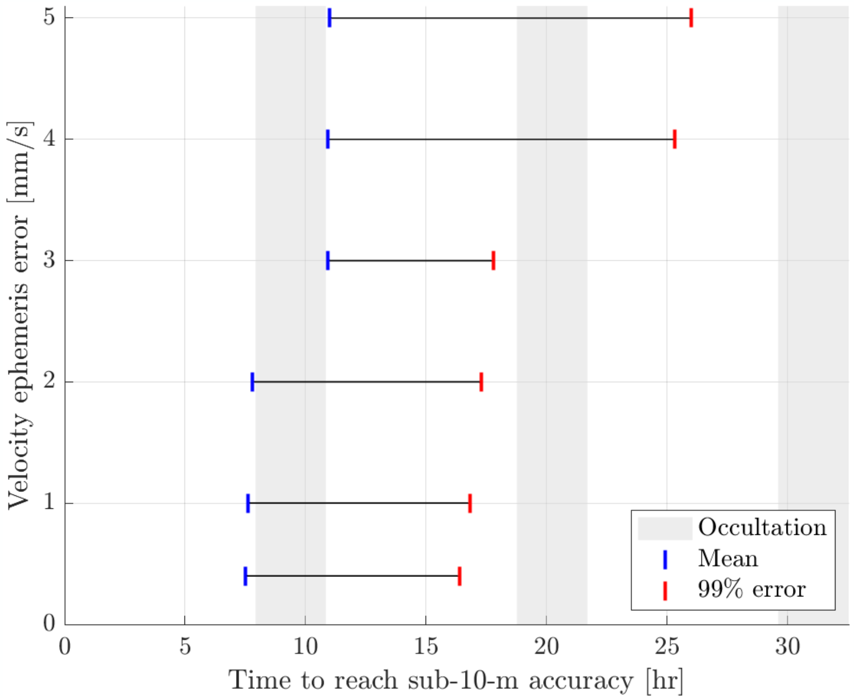




Sensitivity Study on Ephemeris Errors

Location: Artemis Basecamp, **Clock Type:** SRS PRS 10 

Constant SISE position error at 4.48 m



Constant SISE velocity error at 0.40 mm/s