Single-Satellite Doppler-Based Localization for Lunar Rovers in Motion

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Need for Absolute Localization

CADRE, 2026[1]

FLEX, 2026[2]

LUPEX, 2028[3]

Endurance (concept), 2030[4]

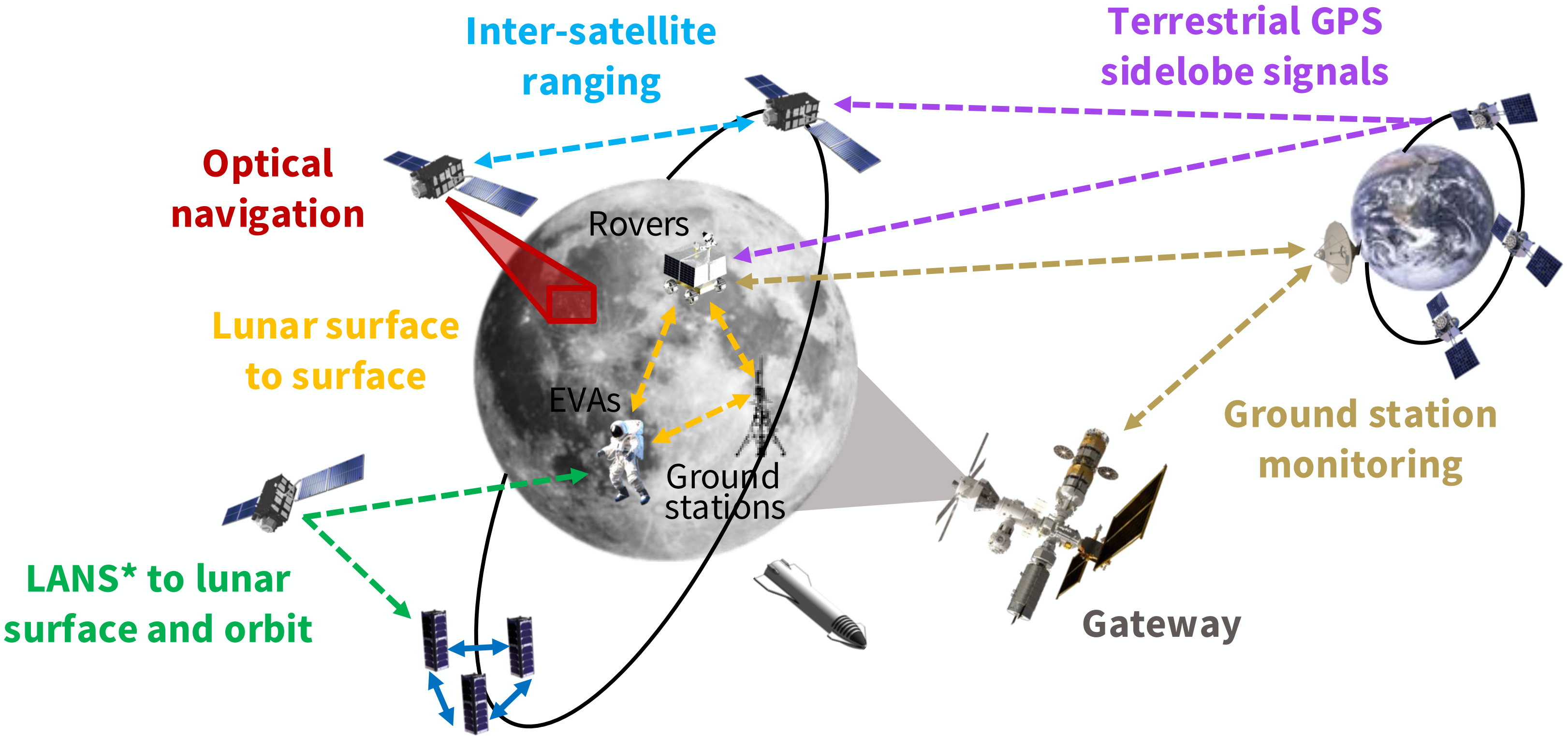
Sample collection rovers must geotag samples with high accuracy.

→

Precise absolute localization of lunar rovers is essential.

[1] NASA, 2023
[2] Astrolab, 2023
[3] JAXA, n.d.
[4] Keane et al., 2022

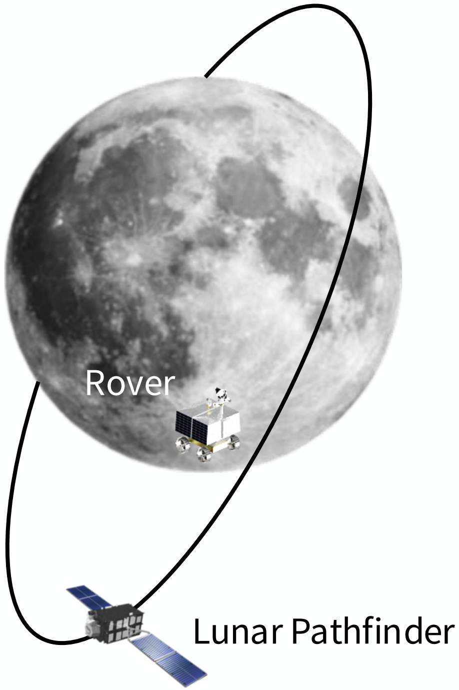
The Upcoming Lunar PNT Landscape

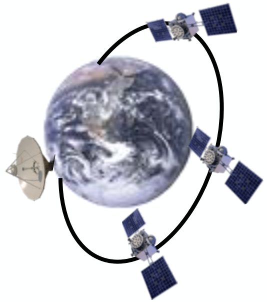


*LANS (Lunar Augmented Navigation Service) will provide GNSS-like capabilities.

Referenced Schier, 2022.

What’s Available for Early-Stage Rover Missions





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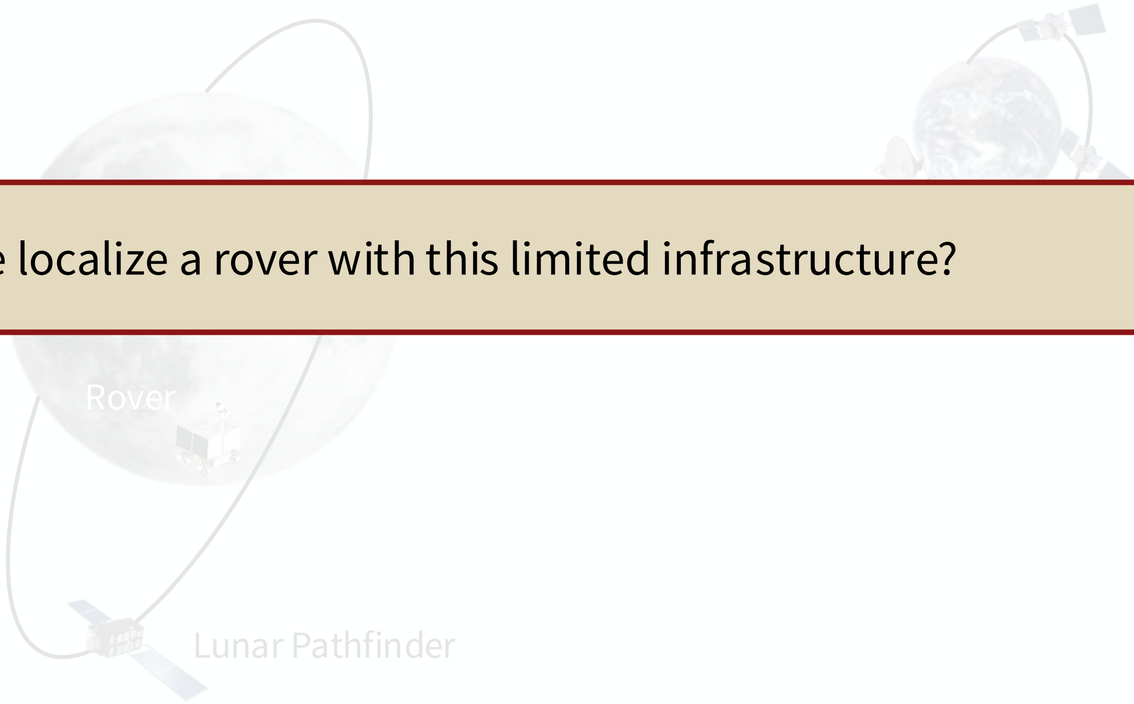

How can we localize a rover with this limited infrastructure?

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Single-Satellite Localization for Stationary Rover[5]

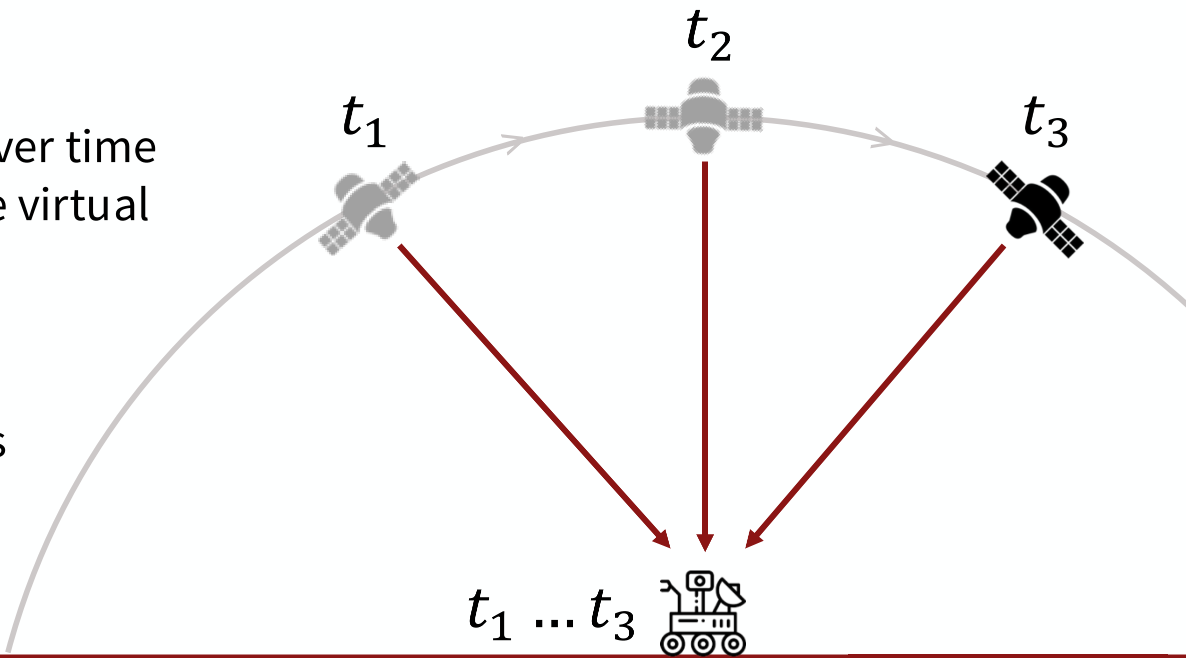
Align with the *expected infrastructure* for early-stage lunar rover missions.

Single satellite

- Accumulate measurements over time (measurements from multiple virtual satellites)

No navigation payload

- Use Doppler shift observables

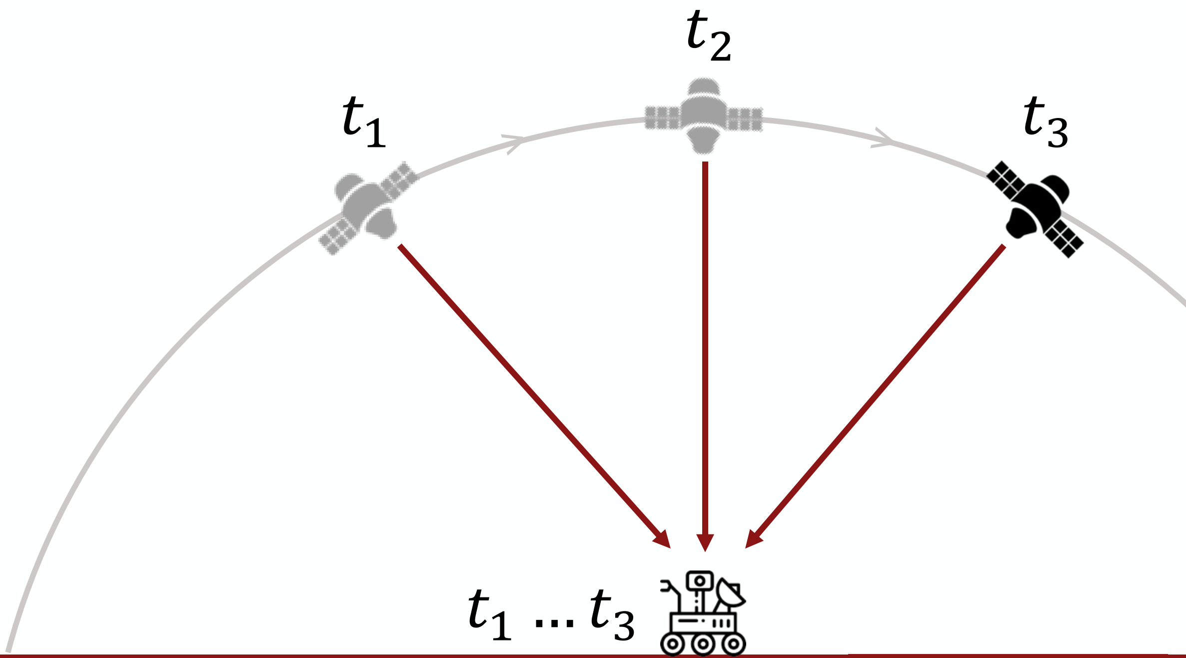


[5] Coimbra et al., 2024

Results from Stationary Rover Scenario[5]

Using a single satellite, the rover was able to localize to sub-10-m accuracy after 11.2 hours.

Drawback



[5] Coimbra et al., 2024

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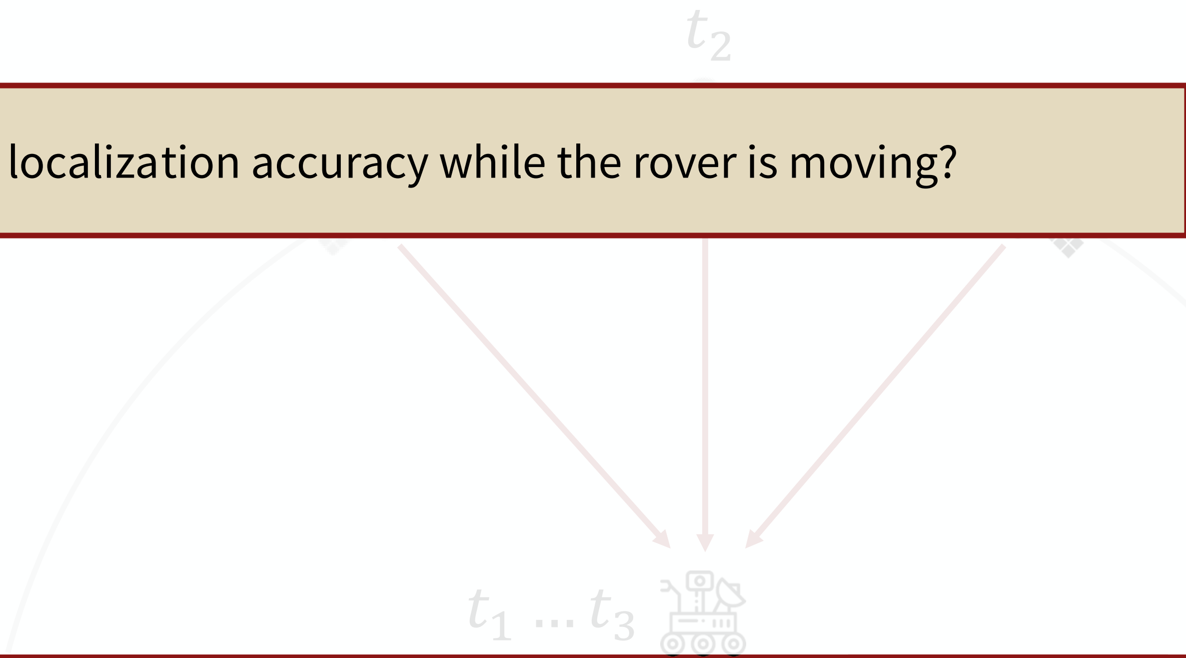

Can we still achieve good localization accuracy while the rover is moving?

[5] Coimbra et al., 2024

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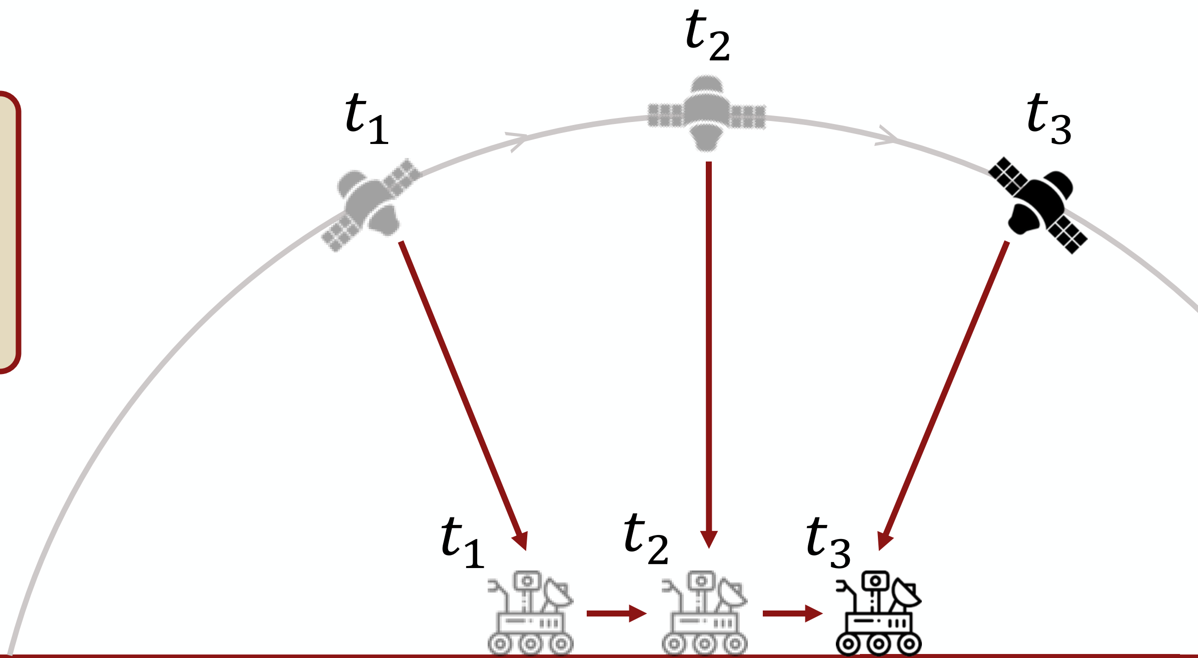
High-Level Approach

Assumption:

Rover motion model is known.

We can still leverage measurements from multiple virtual satellites as the rover is moving.

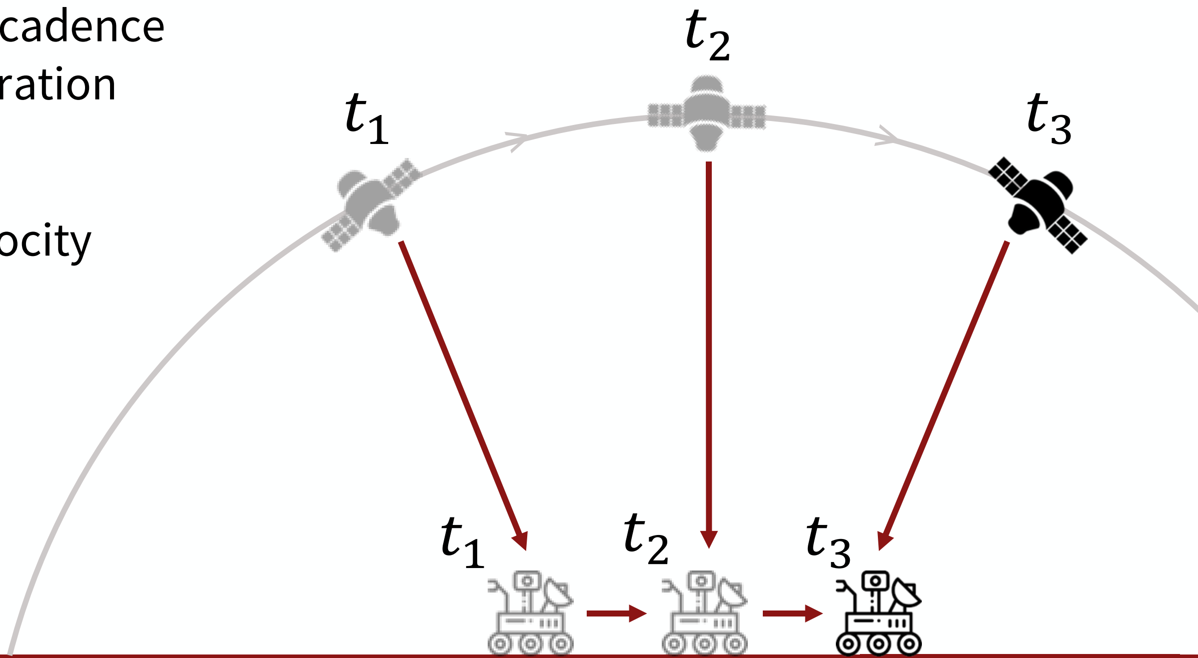


Contributions

1. Develop a localization filter for a ***moving*** rover using a single satellite without a navigation payload.

2. Simulate scheduled mission cadence based on a planned long-duration rover traverse.

3. Quantify the filter's rover velocity noise tolerance to maintain desired accuracy.



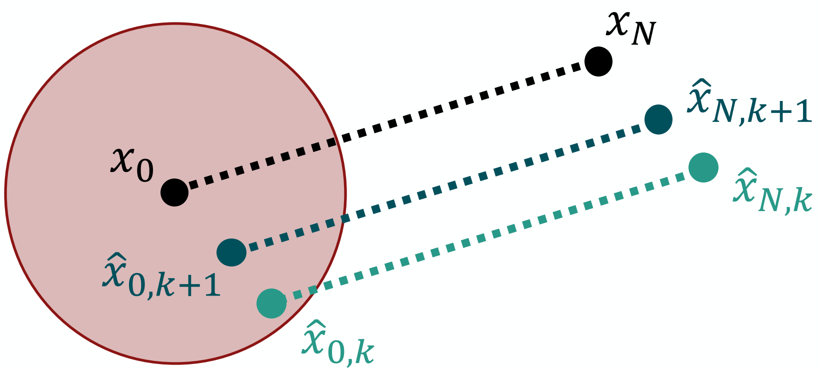
Weighted Batch Filter

- Rover has an erroneous initial position estimate.
- Assumes that the rover knows its velocity.
  - Precompute relative displacements from global start.
- Minimize the weighted Euclidean norm of residual.

$$C = \|\underbrace{\underline{\dot{\rho}}}_{\text{Observed}} - \underbrace{\underline{\hat{\dot{\rho}}}_{k+1}}_{\text{Expected}}\|_W^2$$

$$W = \mathrm{diag}(\sigma_{tot,1}^{-2}, \ldots \sigma_{tot,N}^{-2})$$

$$\sigma_{tot}^2 = \underbrace{\sigma_t^2}_{\text{Thermal}} + \underbrace{\sigma_c^2}_{\text{Clock}} + \underbrace{\sigma_e^2}_{\text{Eph.}} + \underbrace{\sigma_v^2}_{\text{Rover velocity}}$$



- Update initial rover state.
- Propagate through to current time step using a growing, fixed-anchor batch.

Doppler Measurement Model

Doppler measurement

$$D = -\frac{\dot{\rho} f}{c}$$

Observed pseudorange rate

$$\dot{\rho} = \underbrace{(\underline{v}_s - \underline{v}_r) \cdot \frac{\underline{r}_s - \underline{r}_r}{\|\underline{r}_s - \underline{r}_r\|}}_{\text{True range rate}} + \underbrace{c\,(\dot{\delta t}_s - \dot{\delta t}_r)}_{\text{Rel. clock drift}} + \underbrace{\varepsilon_{\dot{\rho}}}_{\text{Noise}}$$

Zero-mean white Gaussian noise

$$\varepsilon_{\dot{\rho}} \sim \mathcal{N}(0, \underbrace{\sigma_t^2}_{\text{Thermal}} + \underbrace{\sigma_c^2}_{\text{Clock}})$$

Dubin's Car Model*

$$\dot{x} = \tilde{V}\cos\theta \qquad \tilde{V} = V + \varepsilon_v$$

$$\dot{y} = \tilde{V}\sin\theta \qquad \varepsilon_v \sim \mathcal{N}(0, \sigma_v^2)$$

$$\dot{\theta} = u$$

*Method is independent of rover motion model.

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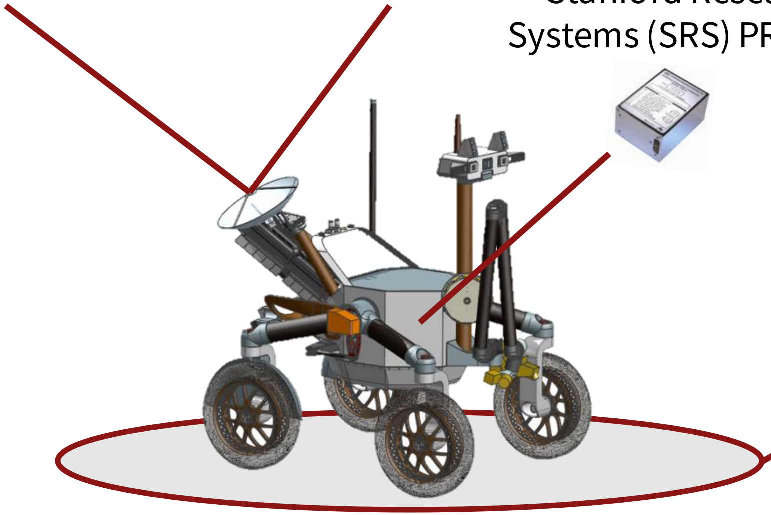
Rover Model

NASA Endurance Mission Concept[4]

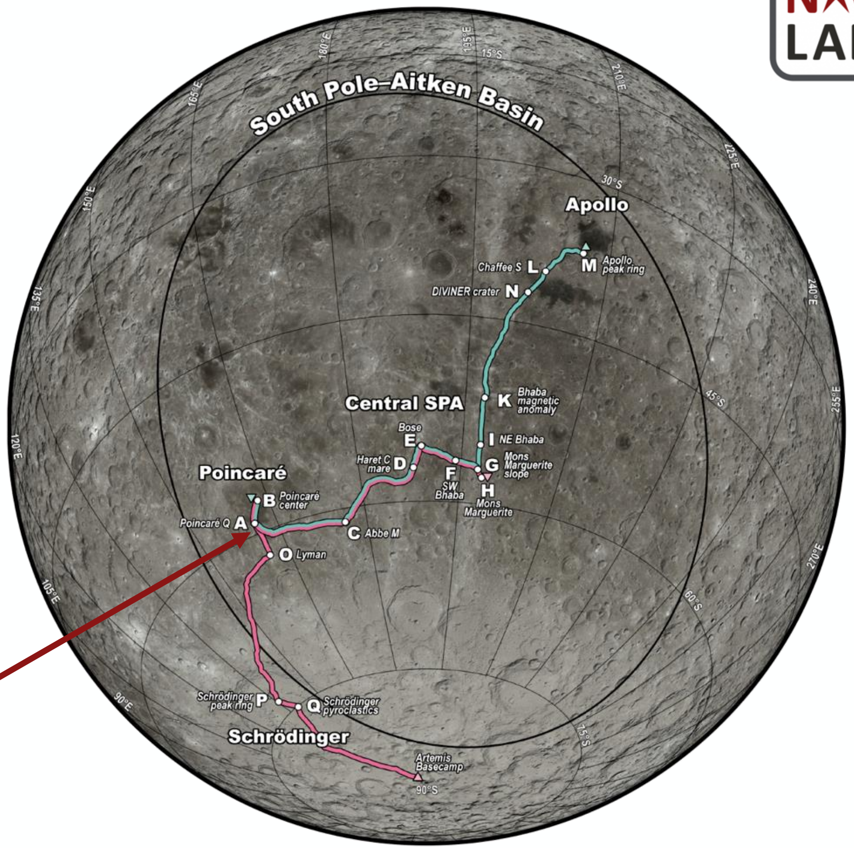
Sample return mission

75 cm high gain
omnidirectional antenna

Stanford Research
Systems (SRS) PRS 10[5]



Poincaré Q Waypoint
59.12448˚ S, 161.05104˚ E



Map of the rover's long-range traverse[4]

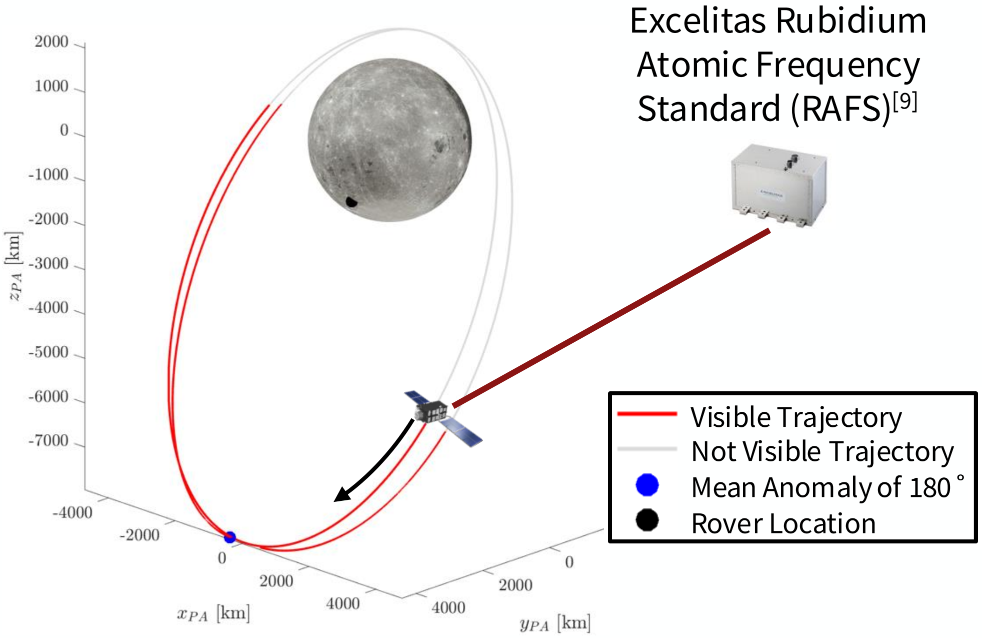
[4] Keane et al., 2022
[5] Coimbra et al., 2024

Satellite Model

ESA's Lunar Pathfinder[6]

Expected Launch Date: 2026

Orbital period: 10.84 hours



Orbital Elements[6]	
Semi-major axis	5740 km
Eccentricity	0.58
Inclination	54.856°
RAAN	0°
Argument of the Periapsis	86.322°
Mean Anomaly	80°

Satellite Visibility	
Definition[7, 8]	C/N_0 > 30 dB-Hz
	Elevation > 5°
1st Occultation	3.28 hours
2nd Occultation	3.36 hours

[6] SSTL, 2022
[7] Nardin et al., 2023
[8] Melman et al., 2022
[9] Coimbra et al., 2025

Simulation Parameters

Initial epoch	2030/10/01 00:00:00 UTC
Total simulation length	2 orbital periods (21.68 hours)
Initial rover position error	100 m σ (3D)
Measurement sampling rate	1 Hz
Filter update interval	180 seconds
Number of Monte Carlo runs	100

Define μ to be mean position error across all Monte Carlo runs.

Performance Metric:

$\mu \leq 10$ m is achieved before hitting the second occultation period (<18 hours).

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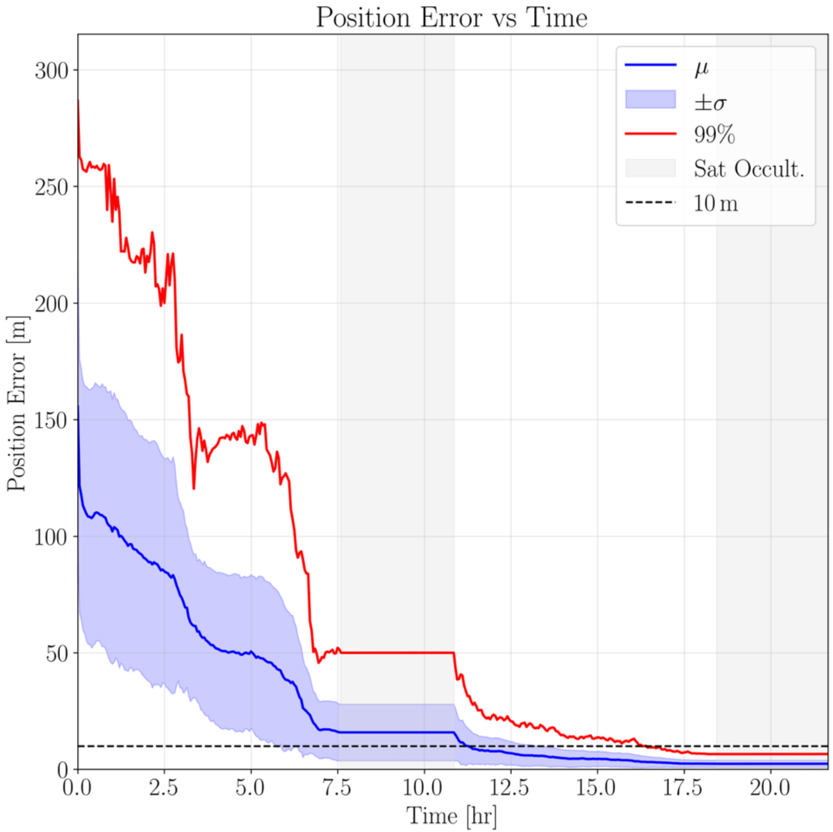
Benchmark: No Rover Velocity Noise

Scenario	Time to reach ≤10 m	
Stationary[5]	Mean	11.2 hours
	99th percentile	15.4 hours
Moving at Constant Speed	Mean	11.3 hours
	99th percentile	16.3 hours

1. The rover has a known motion model.
2. The rover is moving continuously.

Leverage planned mission dynamics to improve localization with imperfect motion knowledge.



[5] Coimbra et al., 2024

Concept of Operations for a Long Traverse Lunar Rover

[4]

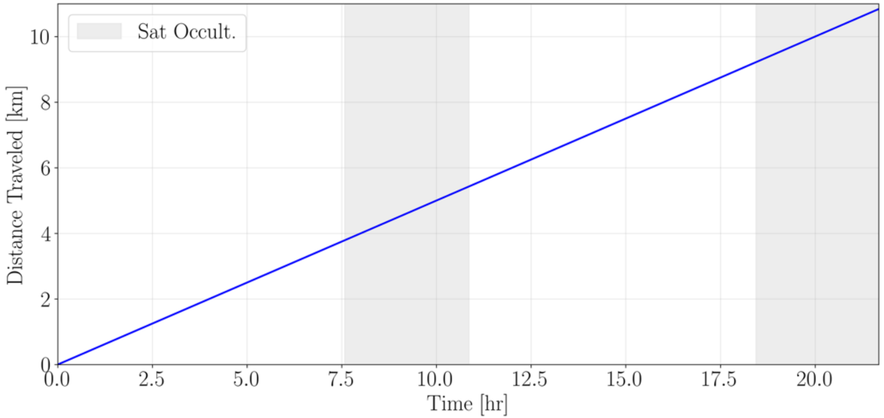
Total planned traverse: 2000 km

Average traverse speed: 0.5 km/hr (0.14 m/s)

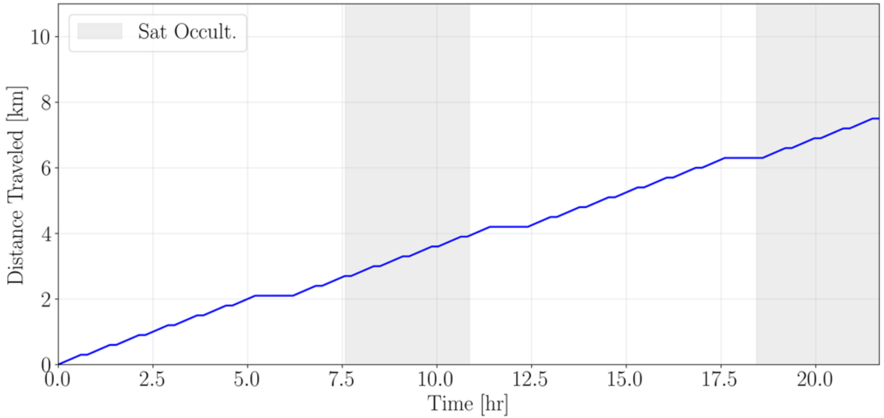
Stop-Go Rover Motion Model

- **Nominal:** Rover stops every 300 m for 10 min to image.
- **Mission stops:** Every 2 km for 1 hr.

Constant Speed



Stop-Go

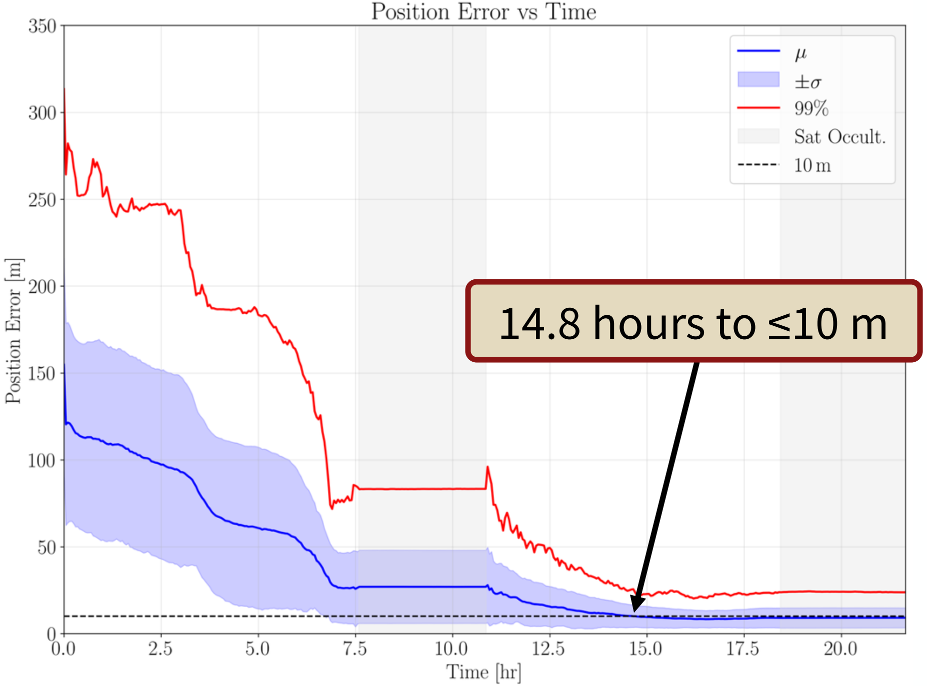


[4] Keane et al., 2022

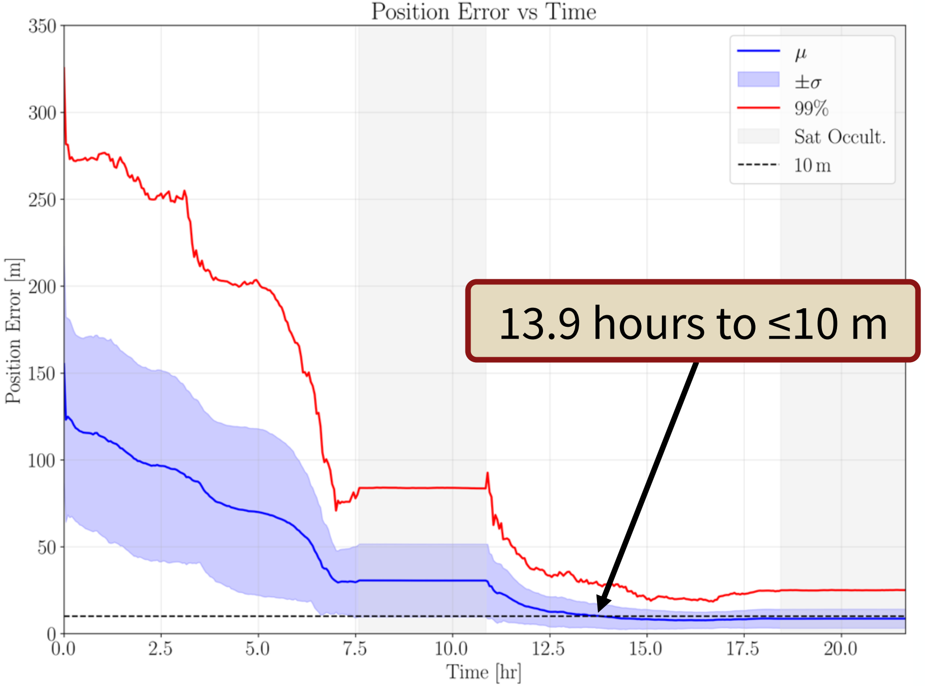
Comparing Performance for Different Motion Models

Applying 7.0 mm/s velocity noise (5% of the commanded velocity).

Constant Speed



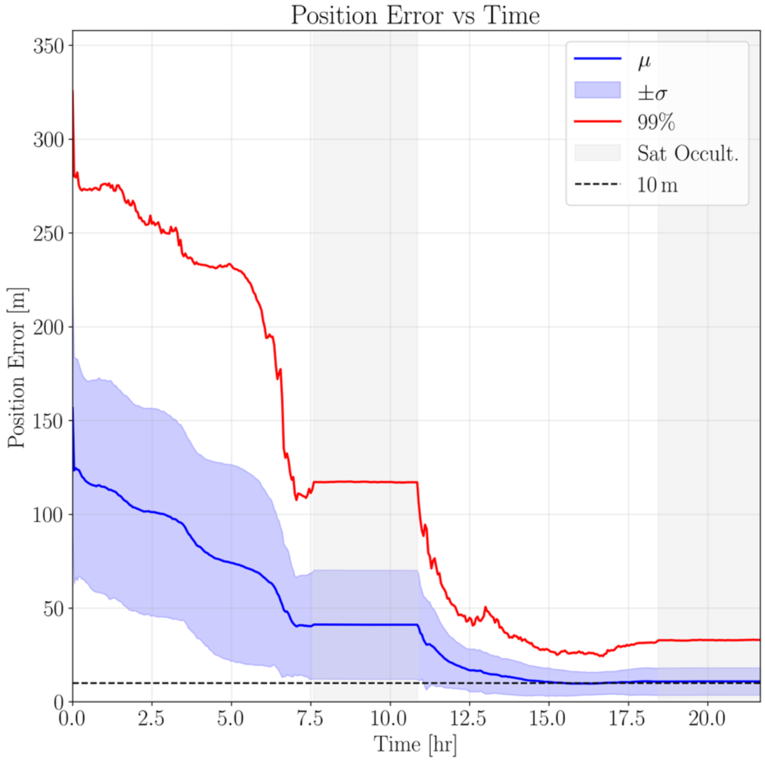
Stop-Go



Sensitivity Study on Rover Velocity Noise

Velocity Noise [mm/s]	% of commanded velocity	Mean time to reach ≤10 m [hr]
0.0	0.0%	11.2
6.0	4.3%	13.3
7.0	5.0%	13.9
8.0	5.8%	14.3
9.0	6.5%	14.9
10.0	7.2%	15.5
11.0	7.9%	>21.7

10.0 mm/s applied noise



Concluding Remarks

NAV LAB

Contributions

1. Develop a localization filter for a ***moving*** rover using a single satellite without a navigation payload.
2. Simulate scheduled mission cadence based on a planned long-duration rover traverse.
3. Quantify the filter's rover velocity noise tolerance to maintain desired accuracy.

Conclusions

1. Showed that the rover no longer needs to be stationary to localize.
2. Leveraged planned mission dynamics to improve localization under non-ideal conditions.
3. Achieved desired accuracy before 2^{nd} occultation with up to 7% added velocity noise.

Future Work

1. Improve model fidelity (e.g., time-correlated noise).
2. Stress test on more difficult rover motion paths (turns, varying speed).
3. Investigate the localization improvement with more than one satellite.

Acknowledgements

Knight-Hennessy Scholars
Stanford University

Graduate Research
Fellowship Program

Related ION GNSS+ 2025 Papers from NAV Lab

Session F1: K. Iiyama et al., "Constellation Design and Staged Deployment for the Lunar Navigation Satellite System."

Session F1: G. Casadesus Vila et al., "Lunar Surface Station to Support Lunar Positioning, Navigation, and Timing Services."

Session F3: K. Iiyama et al., "Plasmaspheric Delay Characterization and Comparison of Mitigation Methodologies for Lunar Terrestrial GNSS Receivers."

Session D6: A. Dai et al., "Full Stack Navigation, Mapping, and Planning for the Lunar Autonomy Challenge," **Adam Dai @ 2:58 PM on Friday, Holiday 2-3 (Second Floor).**

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