



Accelerating
the future
of aerospace



Integrity Monitoring Strategies For LCNS Users

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ESA Moonlight Roadmap

Operational Phase	Earth-Moon Transfer Orbit	Lunar Orbit	Descent, Landing & Ascent	South Pole Lunar surface	Full lunar surface	Integrity
Phase 1: GNSS-only and high-sensitive receivers						
Phase 2: GNSS augmented with LCNS						
Phase 3: Full lunar PNT constellation						

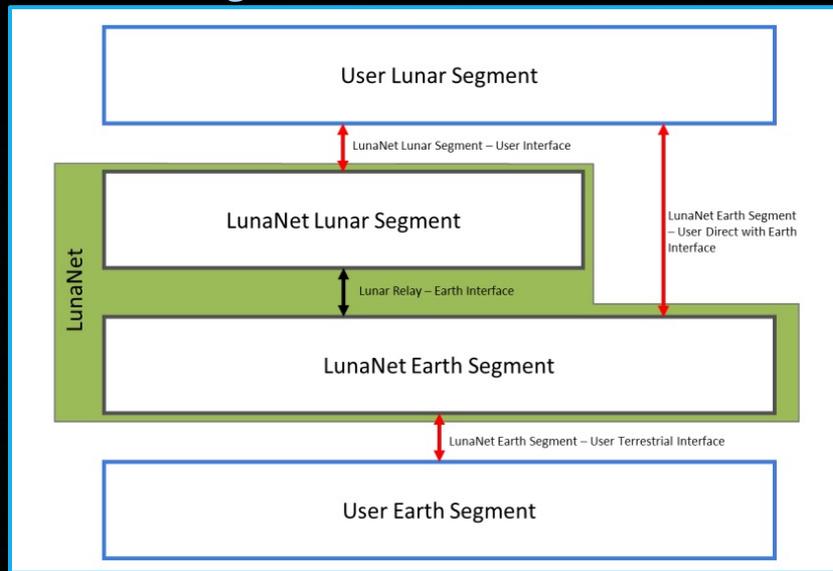
TABLE 2 Expected level of performance that could be achieved through each one of the Lunar PNT roadmap phases

Low performance level High performance level

Phase 1: Use of Existing GNSS Systems (2022 – 2025)	Phase 2: Enhancing GNSS with Lunar Communication and Navigation System (2025–2035)	Phase 3: Towards an autonomous PNT Lunar System (2035–onwards)
Preliminary Lunar PNT services (low accuracy and availability, low lunar surface coverage, very fast time to service)	Initial Lunar PNT services (improved accuracy and availability, lunar surface service focused on Moon South Pole)	Full Lunar PNT services (final accuracy and availability targets, complete lunar surface coverage, high number of users, providing potentially integrity for safety applications)
Existing GNSS Systems (Galileo and GPS) Use of high-sensitivity GNSS space receivers with high-gain antennas	Existing GNSS Systems (Galileo and GPS) 3 to 4 Lunar Communication and Navigation Satellites and ground infrastructure (LCNS) 1 or 2 Moon surface PNT Beacons	3 to 4 Lunar Communication and Navigation Satellites and ground infrastructure (LCNS) Additional Lunar orbiting satellites Additional Moon surface PNT Beacons Optional: Existing GNSS Systems

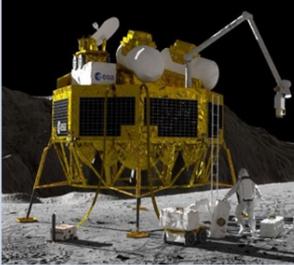
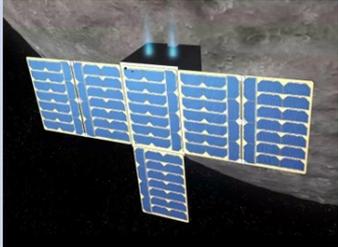
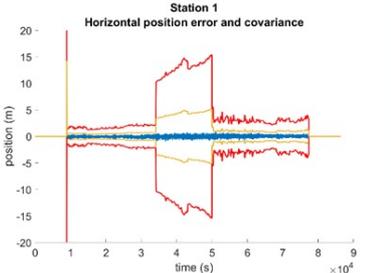
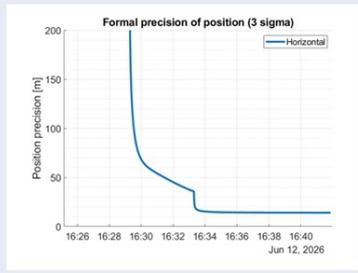
TABLE 3 Roadmap vision for lunar navigation services

LunaNet Segments



Lunanet interoperability specification v5

Navigation Performance Requirements

Surface Rover	Lunar Lander	Lunar Orbiter
		
<div data-bbox="92 600 483 873"> <p>Station 1 Horizontal position error and covariance</p>  </div> <div data-bbox="502 600 637 764"> <p>Target <10m</p>  </div> <div data-bbox="492 786 618 873"> <p>Using LCNS + DEM and IMU</p> </div>	<div data-bbox="685 600 1043 873"> <p>Formal precision of position (3 sigma)</p>  </div> <div data-bbox="1062 600 1217 764"> <p>Target <50m</p>  </div> <div data-bbox="1062 786 1197 873"> <p>Using LCNS + altimeter and IMU</p> </div>	<ul style="list-style-type: none"> • Target for Moonlight <ul style="list-style-type: none"> • 3D position accuracy < 100m (95th percentile) • 3D velocity accuracy < 1 m/s (95th percentile) • Timing accuracy < 15 ms (95th percentile) <p>Using LCNS + reduced dynamical model</p>
<p>Ref: Navigation Performance of a Lunar Surface Rover Using LCNS Positioning Assuming Realistic ODTs Performances, ENC 2023</p>	<p>Ref: Positioning and Velocity Performance Levels for a Lunar Lander using a Dedicated Lunar Communication and Navigation System, Navigation Journal 2022</p>	

User / Autonomous

- ✓ Tailored to user needs and sensor suite
- ✓ Protects against local faults
- Doesn't scale
- Consumes valuable computing resources
- Difficult to detect certain 'wide' or system faults.

Hybrid

System / Augmentation

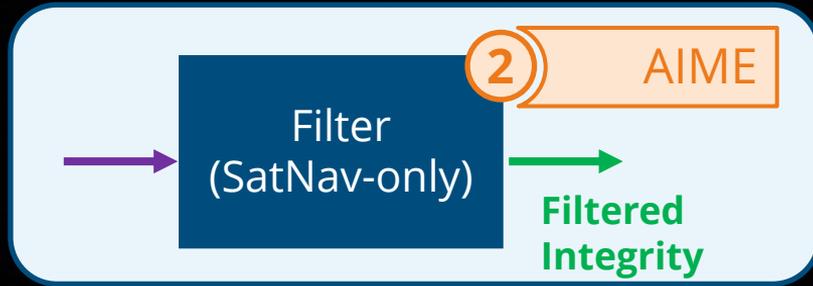
- ✓ Provides protection for wide range of users (scalable)
- ✓ Relative low impact on user processing
- ✓ Can detect system faults
- Doesn't protect against local faults
- Not optimized for user sensor suite
- System complexity and costs

Integrity System **Observables:**

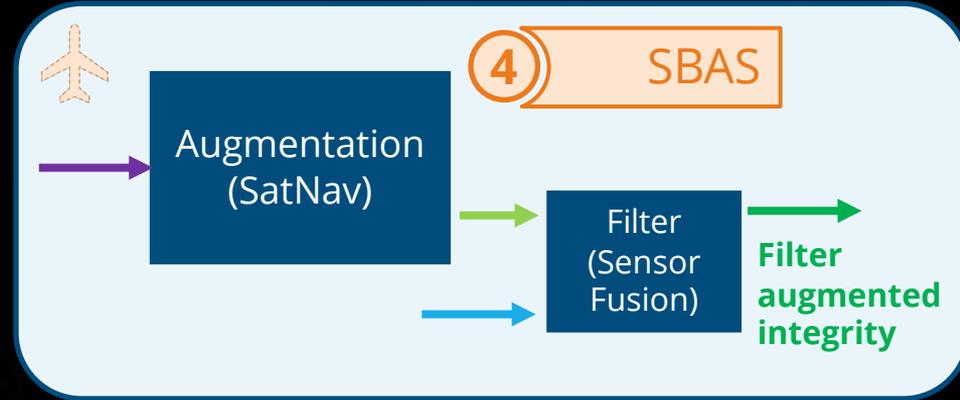
- GNSS
- Moonlight LCNS & LunaNet
- On-board sensors
- ...

Integrity Monitoring Strategies

User / Autonomous



System / Augmentation



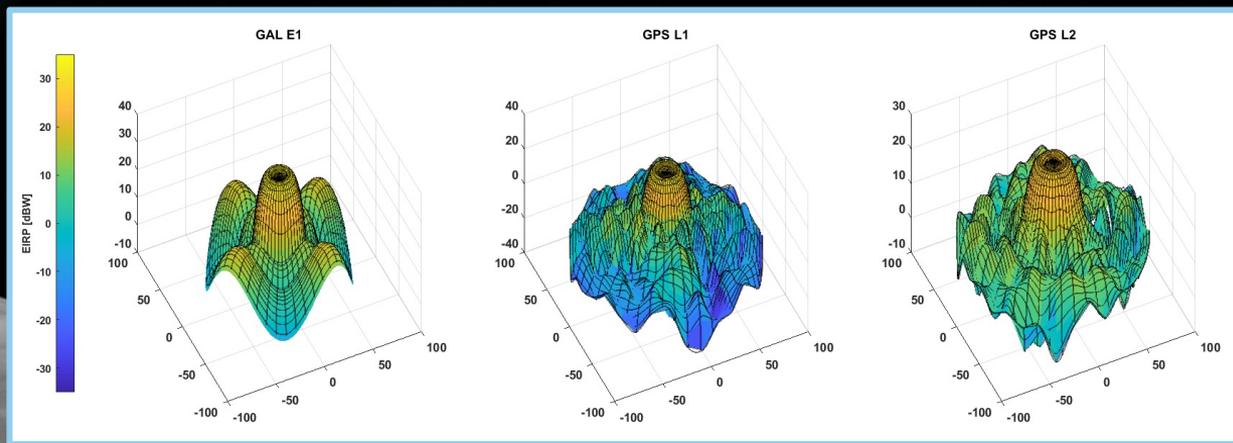
Some (preliminary) results of these different methods and implementations will be presented in the following slides.



Ephemeris Decoding

Nav. Message	Demodulation Threshold [dB-Hz]	Demodulation Duration [s]	Ephemeris Validity [h]
I/NAV	27.7	30	4
F/NAV	20.7	50	4
LNAV	26.5	48	4
CNAV	26.1	24	4

Radiation Patterns



Autonomous Integrity Monitoring

1) Standalone SatNav: ARAIM – legacy and widely accepted

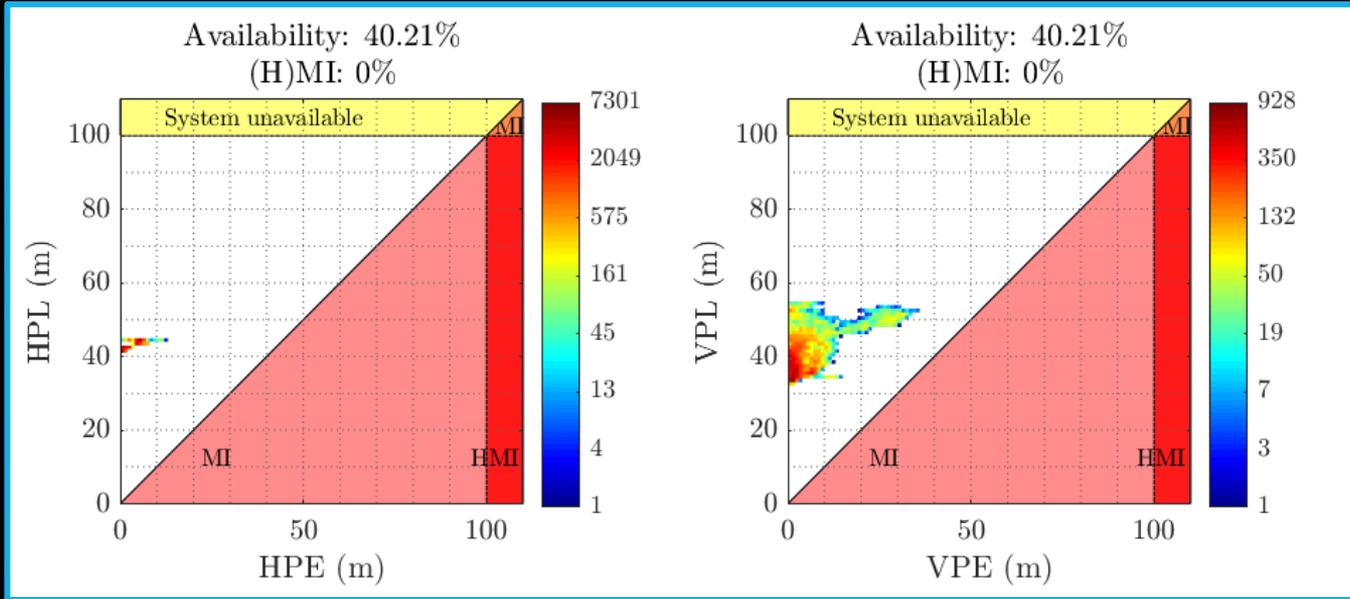


(a) Horizontal Protection Levels						(b) Vertical Protection Levels					
P_{HMI}	1e-4	1e-5	1e-6	1e-7		P_{HMI}	1e-4	1e-5	1e-6	1e-7	
P_{LCNS}	1e-5	1e-5	1e-5	1e-6	1e-5	P_{LCNS}	1e-5	1e-5	1e-5	1e-6	1e-5
$MIN.[m]$	67	117	2861	2928	3317	MIN	62	80	231	237	281
50%[m]	115	198	7896	7917	9029	50%	107	141	618	622	725
1 σ [m]	137	262	9436	9482	10765	1 σ	123	163	815	842	960
2 σ [m]	8247	10077	22833	26655	27418	2 σ	749	923	2230	2618	2726

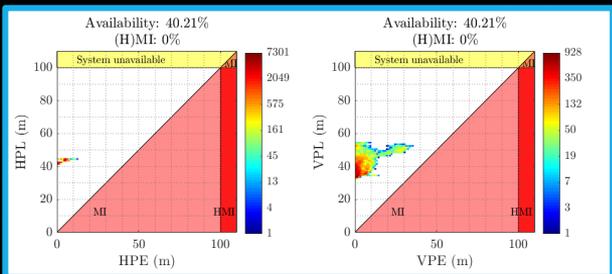
- Anticipated levels: might be feasible for less stringent operations such as orbital coasting, but not for descent and surface operations.
- **Aviation levels: not feasible**

2) Standalone SatNav: AIME – Sliding window residual monitor

4 LCNS

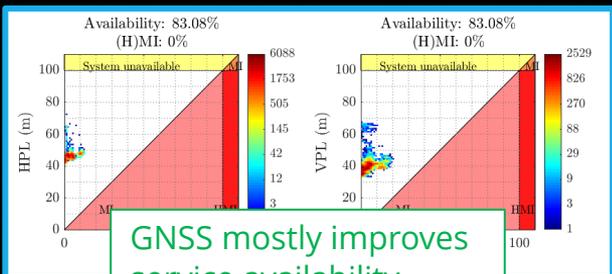
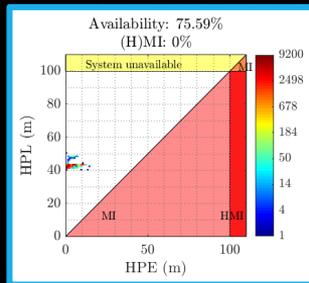


Novamoon allows for tighter integrity bounds and improved availability



4 LCNS

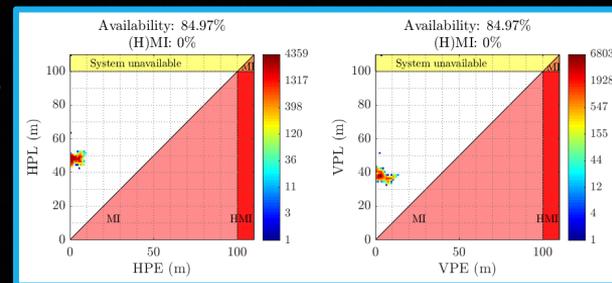
4 LCNS + Beacon (NovaMoon)



4 LCNS + GAL

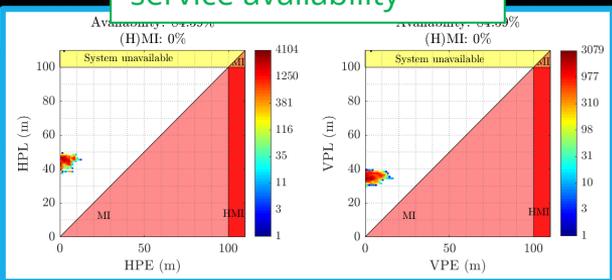
4 LCNS + GAL + GPS + Beacon

GNSS mostly improves service availability

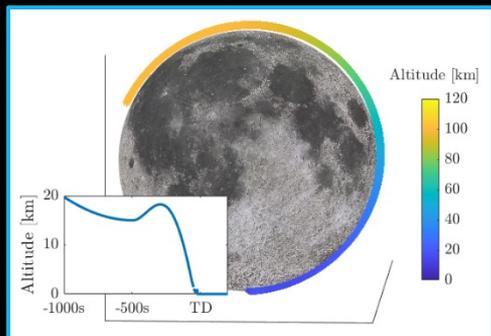


4 LCNS + GAL + GPS

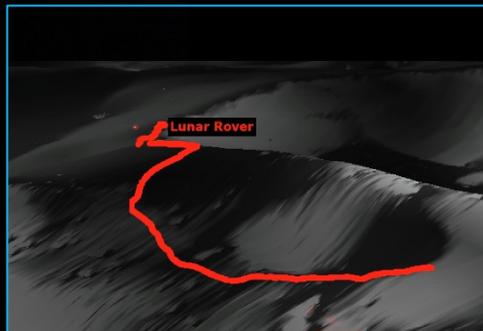
- ✓ better protection against poor geometries than snapshot ARAIM
- ✓ Benefit of GNSS mostly in service availability



Lunar Lander



Lunar Rover



Static User

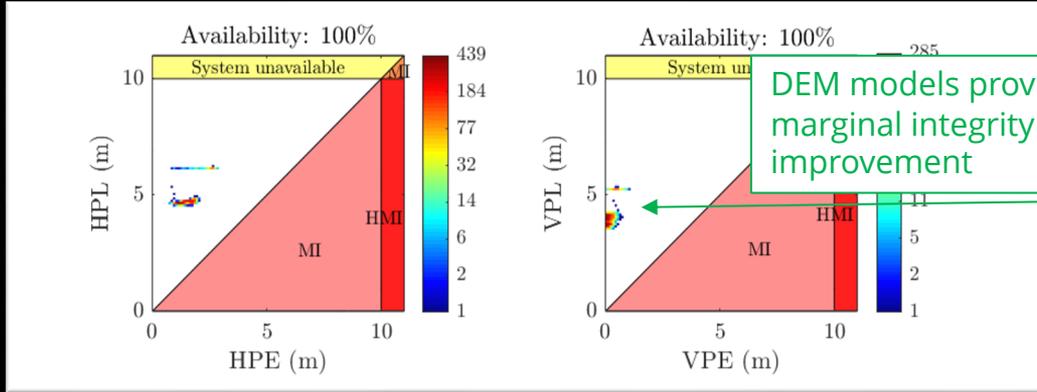


- 4 LCNS
- IMU
- Altimeter <5000m

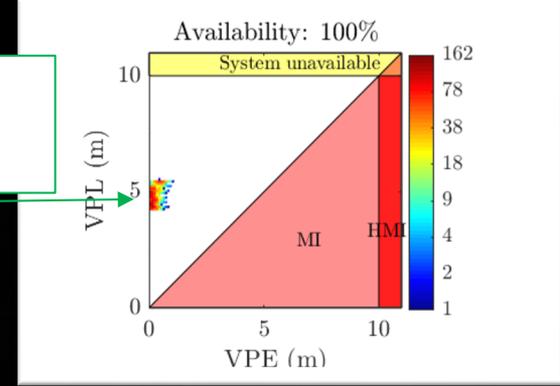
- 4 LCNS
- DEM models
 - Vertical constraint

- 4 LCNS
- Vertical constraint

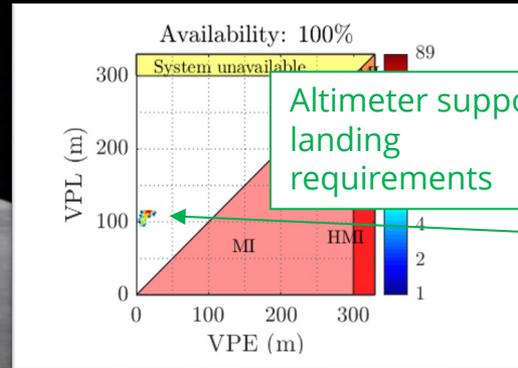
Rover: 4 Moonlight LCNS (Ops. Window)



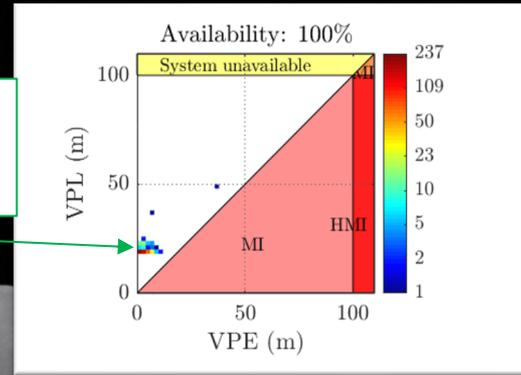
Static: 4 Moonlight LCNS (Ops. Window)



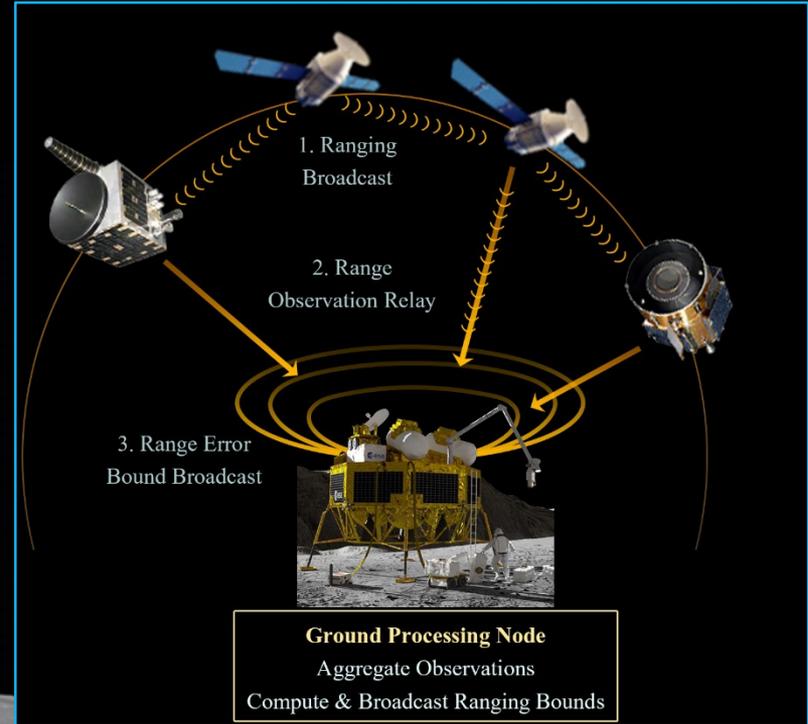
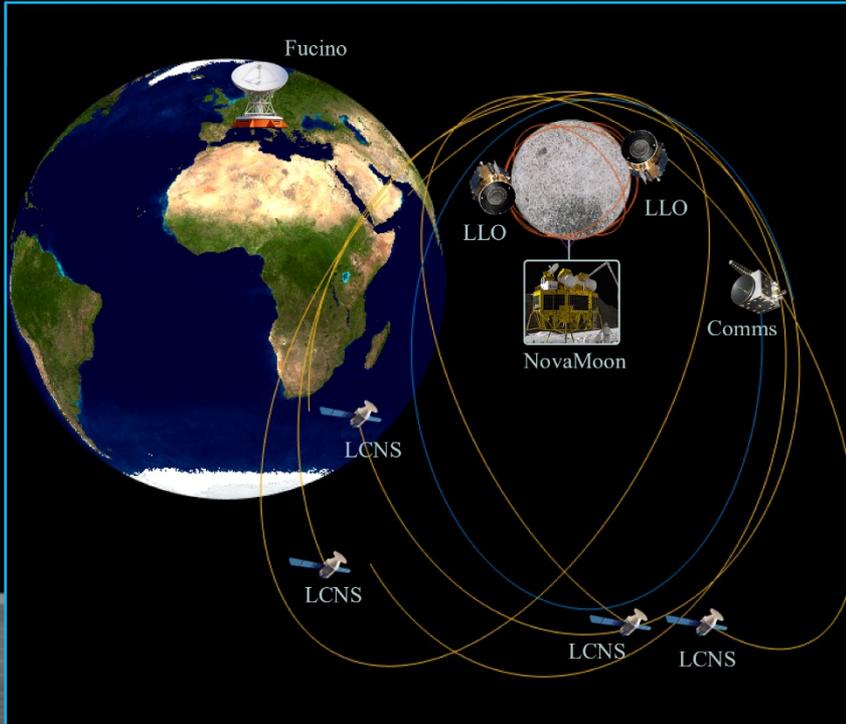
Lander - Initial Descent
4 Moonlight LCNS (Ops. Window)



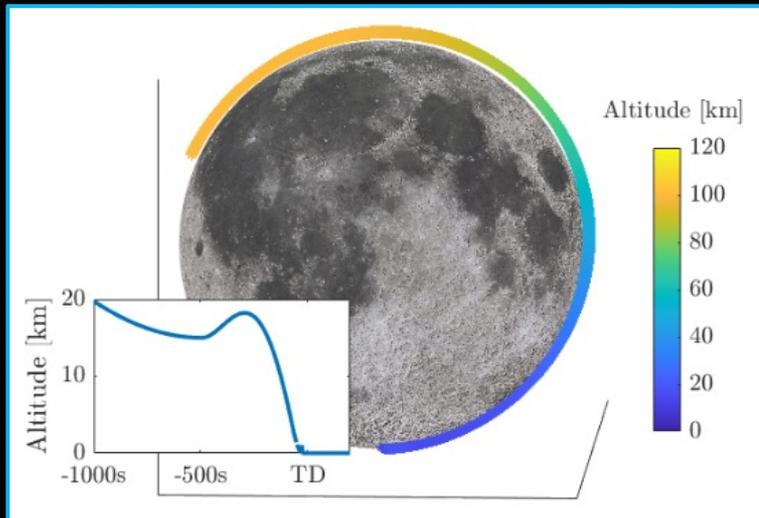
Lander - Final Descent
4 Moonlight LCNS (Ops. Window)



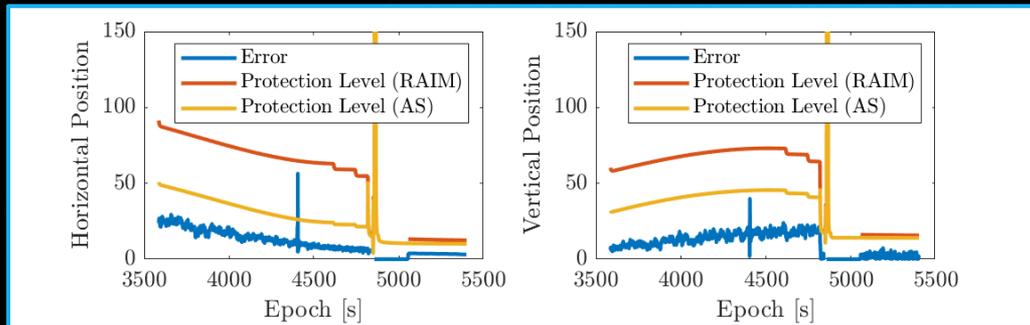
Augmented Integrity Monitoring



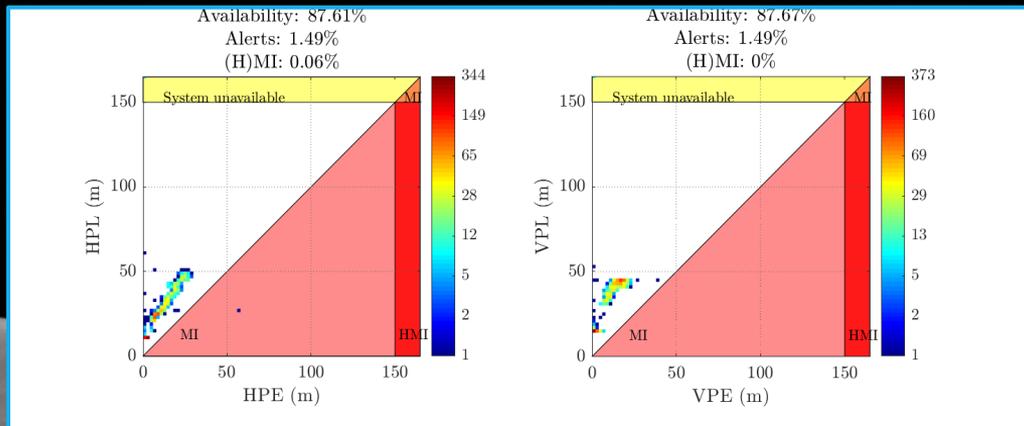
Lander Trajectory



Integrity Bounds during Landing



Stanford Plots



Conclusions

Studies are performed evaluating several navigation integrity frameworks

- GNSS-only allows for virtually no operational scenarios.
 - Combining GNSS with Moonlight LCNS provides marginal benefits due to poor geometry.
- Filtered approaches in combination with LCNS / LunaNet ranging providers can potentially provide integrity bounds meeting requirements
- A stepwise maturing integrity augmentation system could be a feasible way forward, reducing the user computation costs



Thank you for your attention!



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