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Kalman Filter based Positioning for Integrity in Lunar Applications

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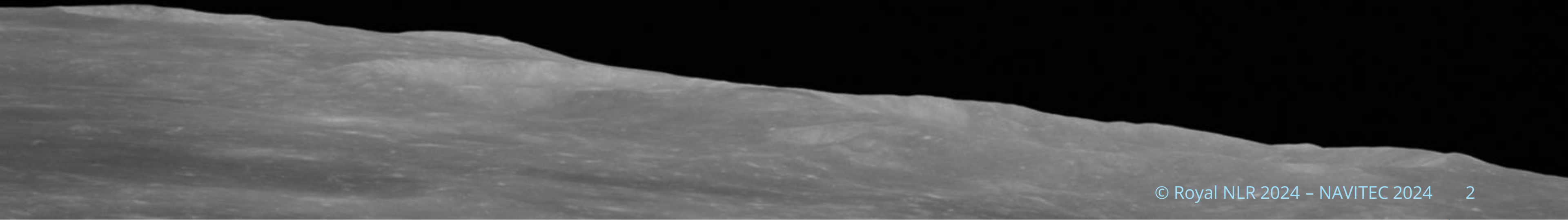
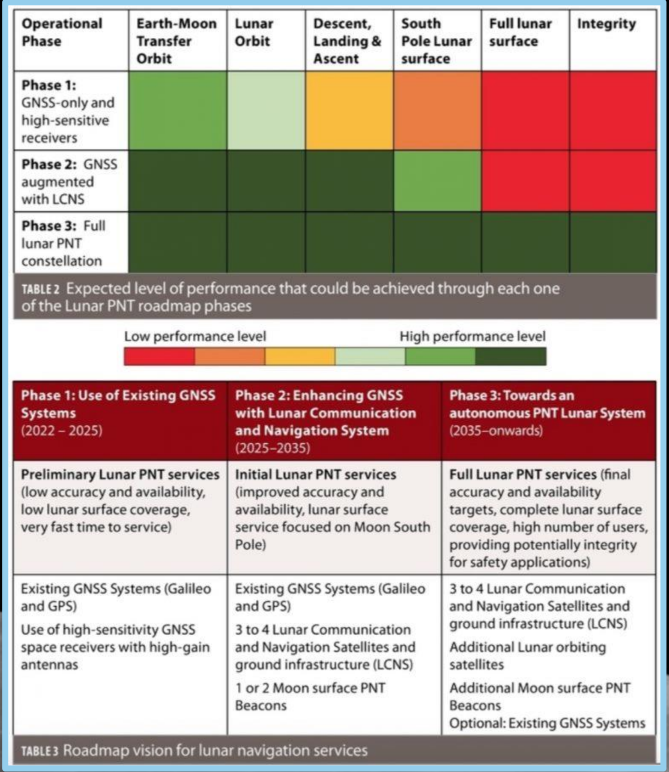
Content

- Integrity for Lunar navigation
- Simulation methodology
- Simulation results
- Conclusions



Introduction

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

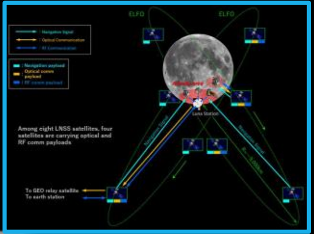
TABLE 3 Roadmap vision for lunar navigation services

Schönfeldt et al, "*Across the Lunar Landscape – Exploration with GNSS Technology*", Inside GNSS, 2020

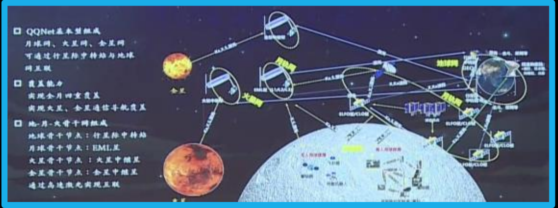
NASA LCRNS

ESA LCNS

JAXA LNSS



CNSA Queqiao



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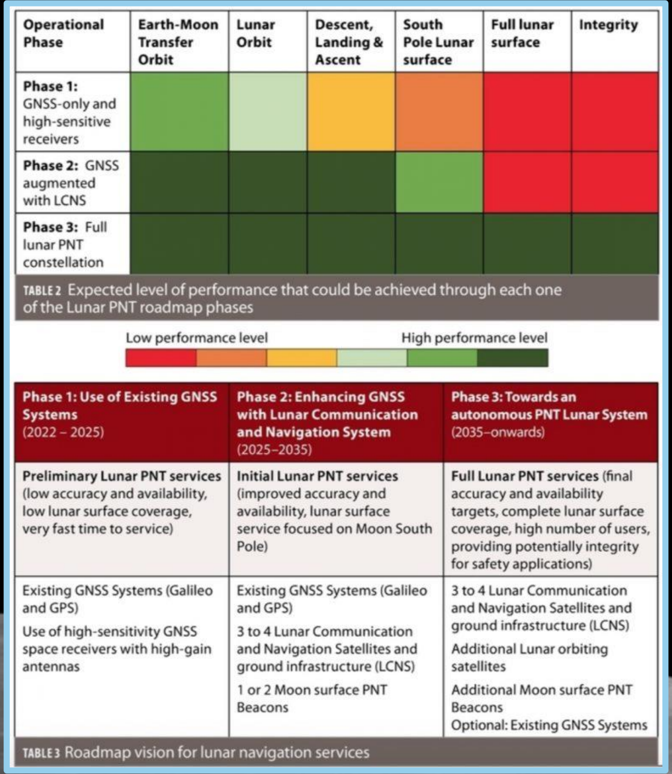

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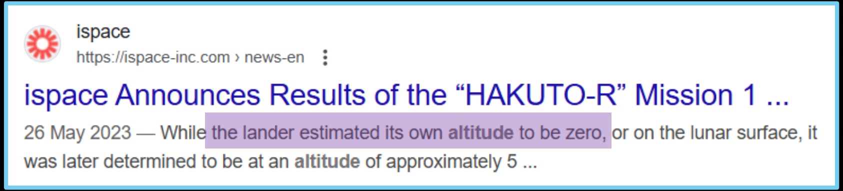


ispace
https://ispace-inc.com › news-en

ispace Announces Results of the "HAKUTO-R" Mission 1 ...

26 May 2023 — While the lander estimated its own altitude to be zero, or on the lunar surface, it was later determined to be at an altitude of approximately 5 ...

SpaceNews
https://spacenews.com › im-1-lunar-lander-tipped-over-...

IM-1 lunar lander tipped over on its side

23 Feb 2024 — The Intuitive Machines Nova-C lunar lander likely tipped over when touching down on the moon Feb. 22 and is now resting on its side.

He suggested that was caused by the lander coming down faster than expected.

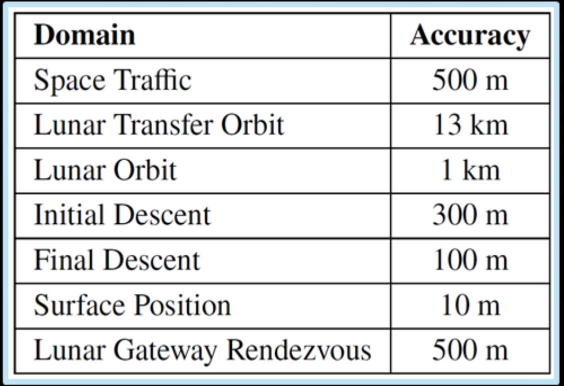
Why integrity?

- Mission and sensor reliability
- Astronaut safety
- High risks, low failure acceptance
- Increasing autonomy
- Navigating in space is a challenge!

Navigation Integrity should be treated as a critical component of (deep) space mission.

Navigation requirements and scenarios

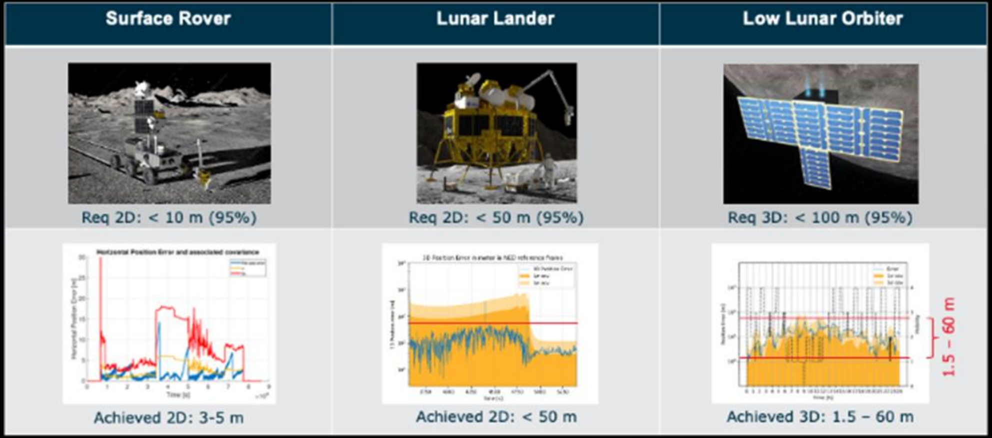
Navigation Requirements



Domain	Accuracy
Space Traffic	500 m
Lunar Transfer Orbit	13 km
Lunar Orbit	1 km
Initial Descent	300 m
Final Descent	100 m
Surface Position	10 m
Lunar Gateway Rendezvous	500 m

Critchley-Marrows, J. J.,Wu, X., and Cairns, I. H. (2023). An architecture for a visual-based pnt alternative. Acta Astronautica, 210:601–609.

Moonlight scenarios

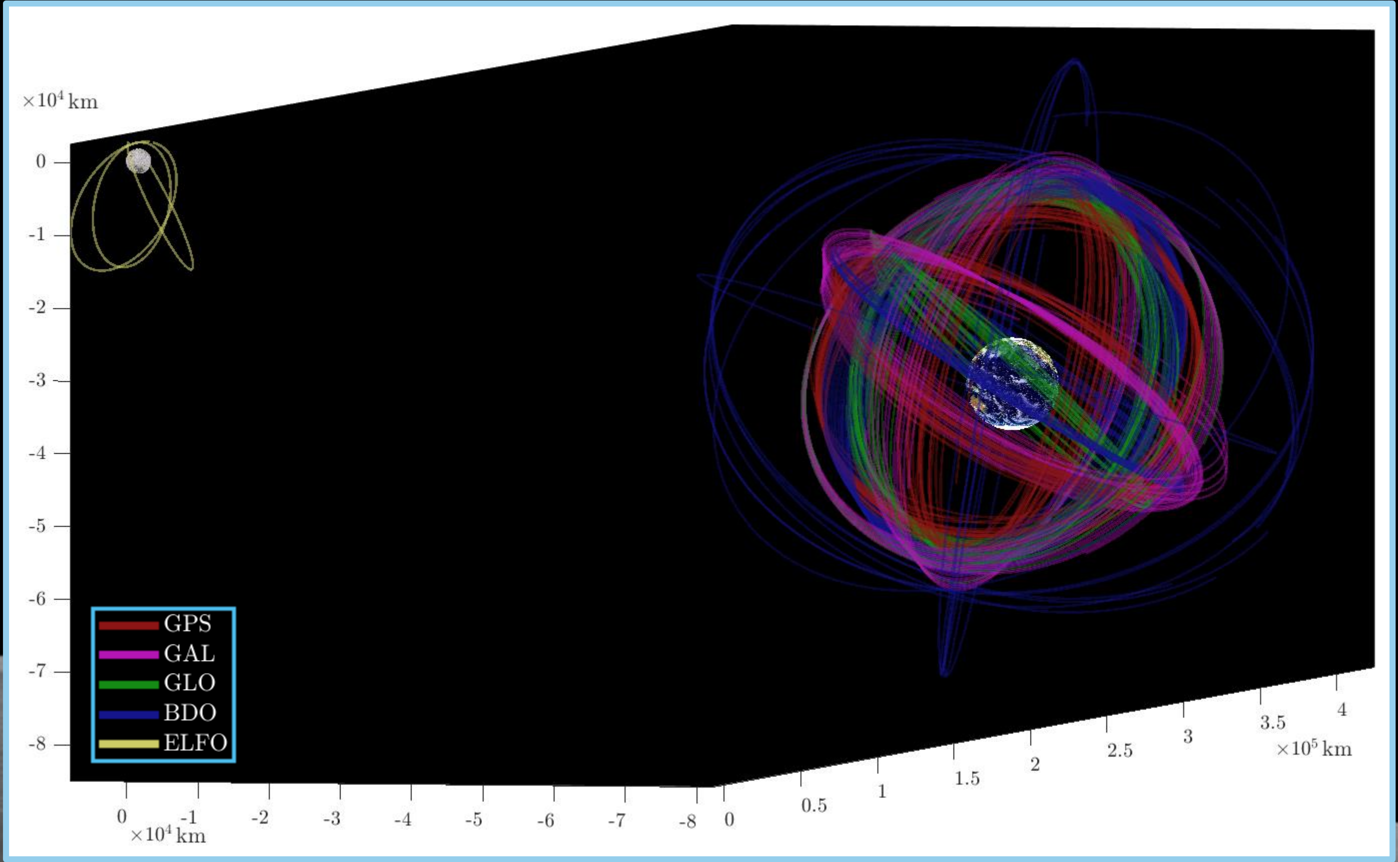


Surface Rover	Lunar Lander	Low Lunar Orbiter
Req 2D: < 10 m (95%)	Req 2D: < 50 m (95%)	Req 3D: < 100 m (95%)
Achieved 2D: 3-5 m	Achieved 2D: < 50 m	Achieved 3D: 1.5 – 60 m

Simulation scenarios considered:

- 4 LCNS satellites (or 1 LCNS, 1 LNSS and 2 LCRNS)
- NaviMoon GNSS receiver
- NovaMoon / Argonaut local beacon

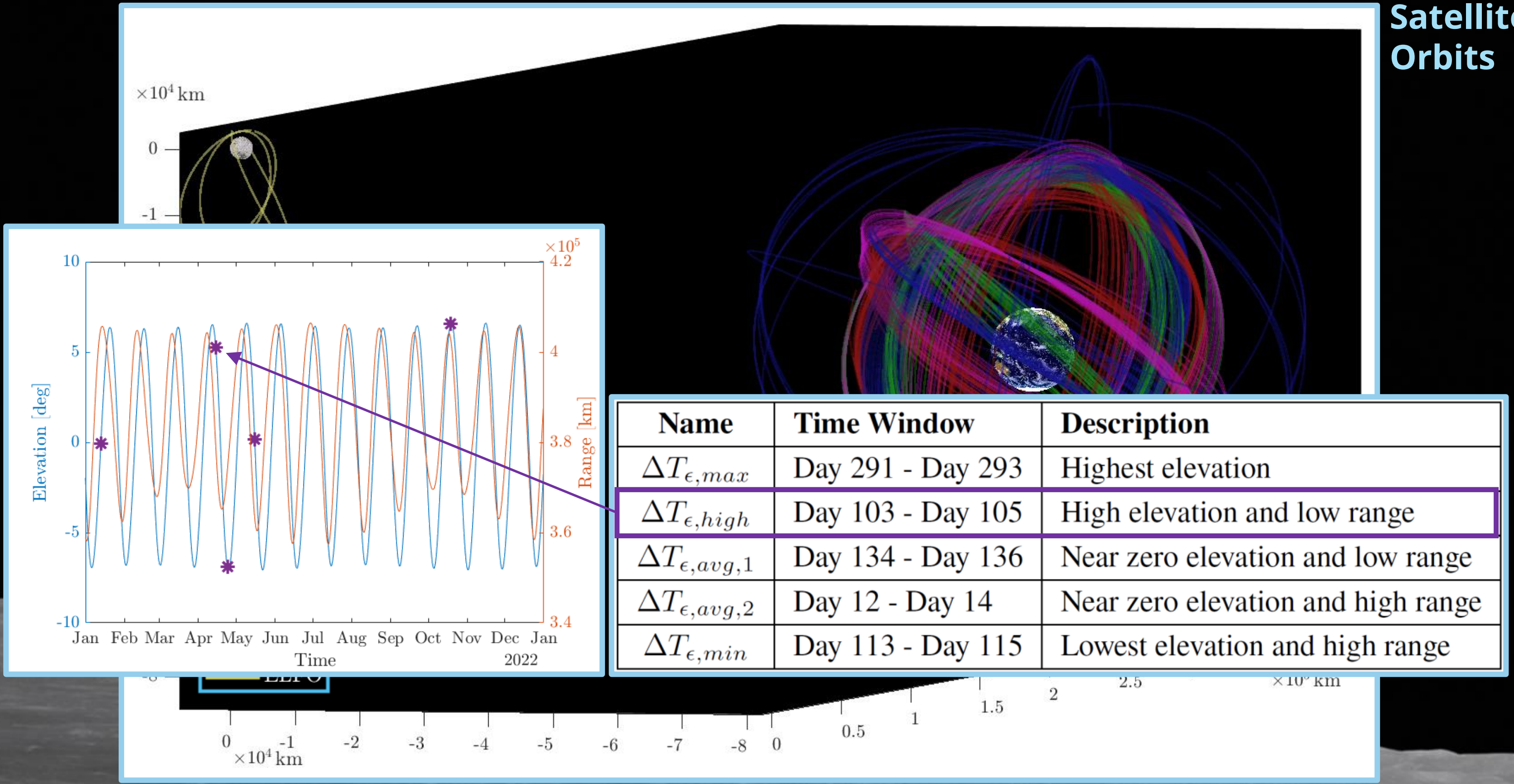
Satellite orbits and simulation windows



Satellite Orbits

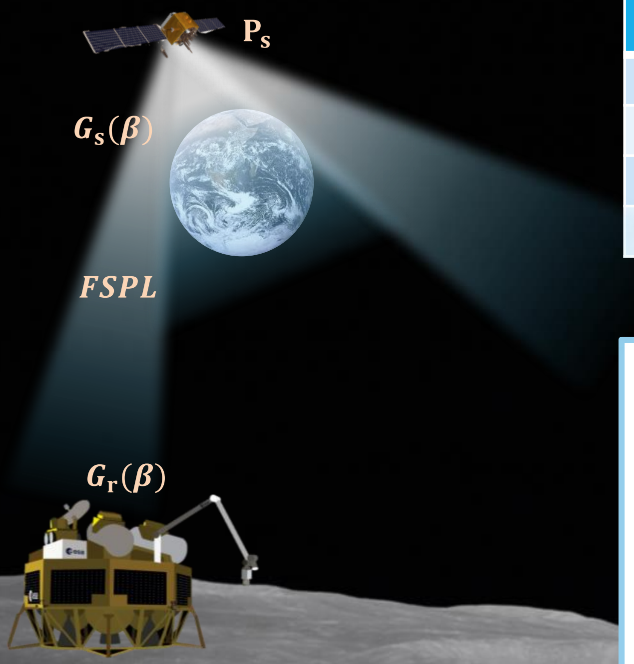
Satellite orbits and simulation windows

Satellite Orbits



Name	Time Window	Description
$\Delta T_{\epsilon,max}$	Day 291 - Day 293	Highest elevation
$\Delta T_{\epsilon,high}$	Day 103 - Day 105	High elevation and low range
$\Delta T_{\epsilon,avg,1}$	Day 134 - Day 136	Near zero elevation and low range
$\Delta T_{\epsilon,avg,2}$	Day 12 - Day 14	Near zero elevation and high range
$\Delta T_{\epsilon,min}$	Day 113 - Day 115	Lowest elevation and high range

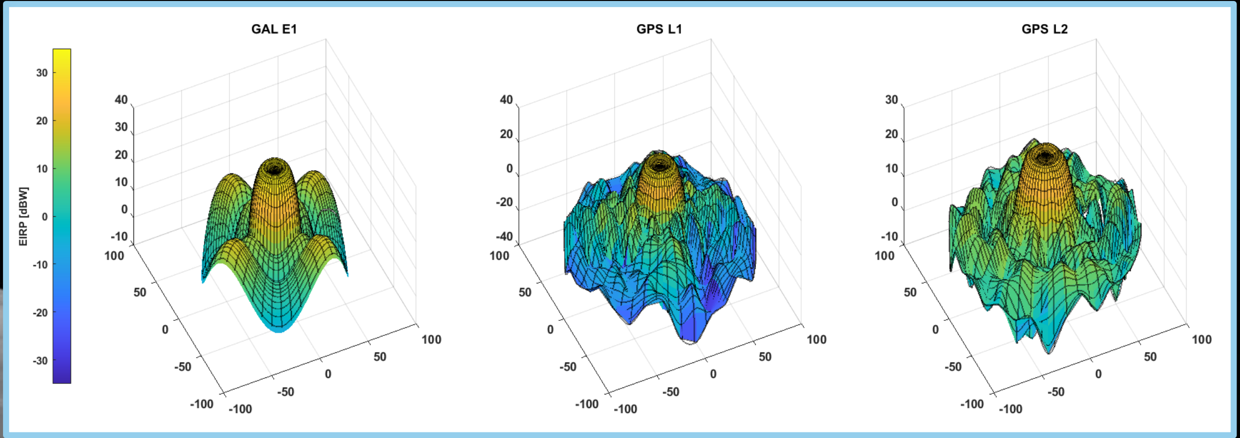
Processing methodology



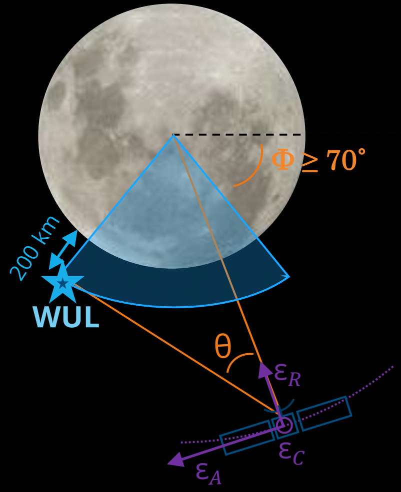
Ephemeris Decoding

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

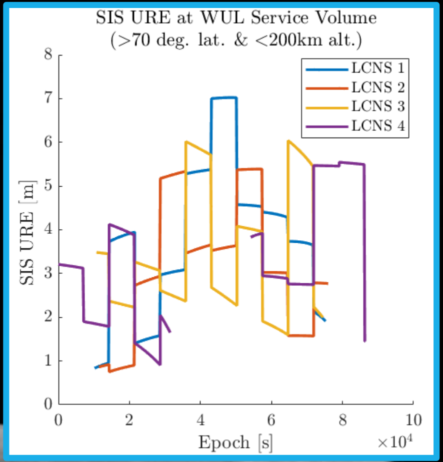


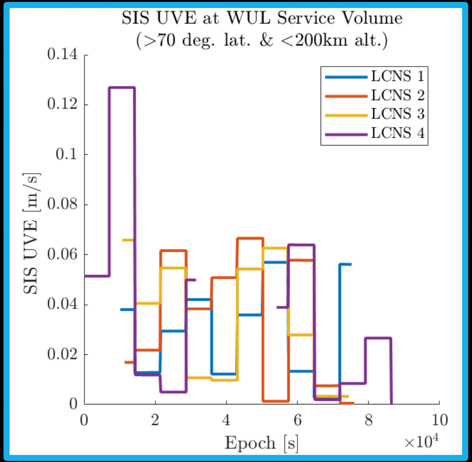
LCNS Performance Analysis



$$\text{SIS−URE}_{WUL} = \max_{\theta\in[0,\theta_{max}]}\left(\epsilon_R\cos\theta + \sqrt{\epsilon_A^2+\epsilon_C^2}\,\sin\theta + |\Delta t_s|c\right)$$

$$\text{SIS−UVE}_{WUL} = \max_{\theta\in[0,\theta_{max}]}\left(\dot{\epsilon}_R\cos\theta + \sqrt{\dot{\epsilon}_A^{\,2}+\dot{\epsilon}_C^{\,2}}\,\sin\theta + |\dot{\Delta t}_s|c\right)$$


SIS URE at WUL Service Volume
(>70 deg. lat. & <200km alt.)


SIS UVE at WUL Service Volume
(>70 deg. lat. & <200km alt.)

$$URA = q_{99.7}(\text{SIS−URE}_{WUL})$$

$$UVA = q_{99.7}(\text{SIS−UVE}_{WUL})$$

Integrity Monitor

Poor geometry

- Most satellites in small cone

Significantly impacts solution separation approach
-> residual monitor more suitable

Failure detection

$$s_{avg}^2 = y_{avg}^T V_{avg}^{-1} y_{avg}$$

$$T_d = \chi^{-2}(P_{fa}, \nu)$$

$$s_{avg}^2 \sim \chi^2(n)$$

Sliding window batch

$$\left\{\begin{array}{l} V_{avg}^{-1} = \displaystyle\sum_{i=k-m+1}^{k} V_i^{-1} \\ \mathrm{y_{avg}} = \left(\mathrm{V_{avg}^{-1}}\right)^{-1} \displaystyle\sum_{i=k-m+1}^{k} V_i^{-1} y_i \end{array}\right.$$

Filter design

$$\mathrm{H_k} = \left[\begin{array}{cccc} -\boldsymbol{u}_r^s & 0 & 1 & 0 \\ -\dfrac{\left(\dot{\boldsymbol{r}}_r^s - (\dot{\boldsymbol{r}}_r^s \boldsymbol{u}_r^s)\boldsymbol{u}_r^s\right)^T}{\boldsymbol{r}_r^s} & -\boldsymbol{u}_r^s & 0 & 1 \end{array}\right] \begin{array}{l} \textbf{range} \\ \textbf{rate} \end{array}$$

$$\mathrm{R_k} = \begin{bmatrix} \sigma_{DLL}^2 + URA^2 & 0 \\ 0 & \sigma_{FLL}^2 + UVA^2 \end{bmatrix}$$

$$\mathrm{V_k} = \mathrm{H_k P_k^- H_k + R}$$

Protection levels

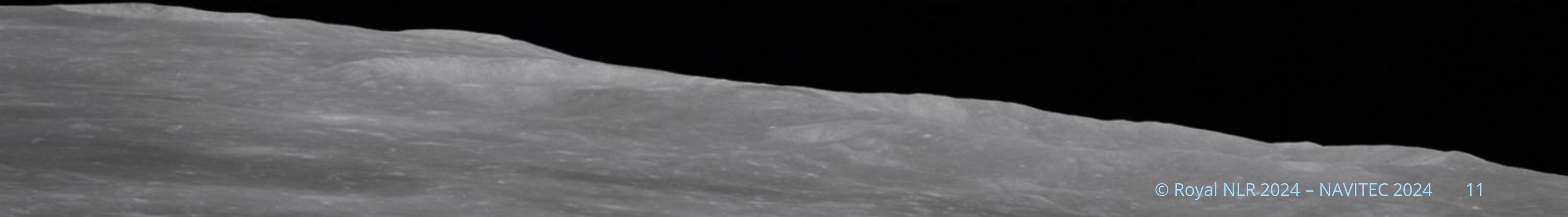
$$PL = SLOPE_{max}\sqrt{T_d} + k\sqrt{diag_3(P)}$$

$$k = \sqrt{2}\,\mathrm{erfc}^{-1}(P_{md})$$

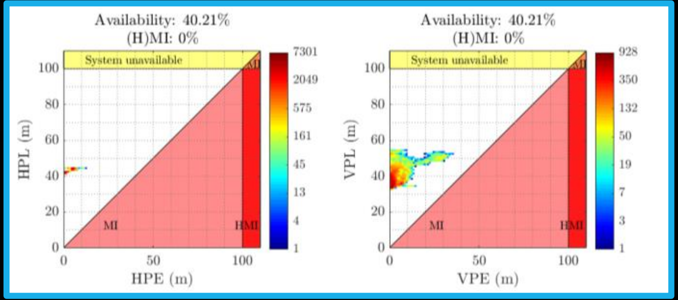
$$SLOPE_{max} = \sqrt{\lambda_{max}(K^T KS)}$$

Integrity Monitor

- Filter need to be reset when PDOP restores within thresholds
- Satellite exclusion should take into account the impact on PDOP
- 2-hour contingency period after exclusion (even false alarm) can have a big impact on availability.

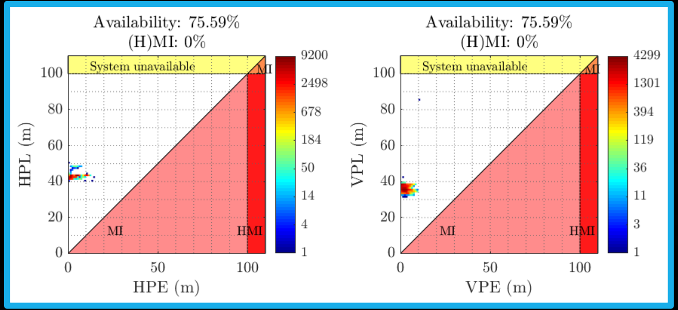


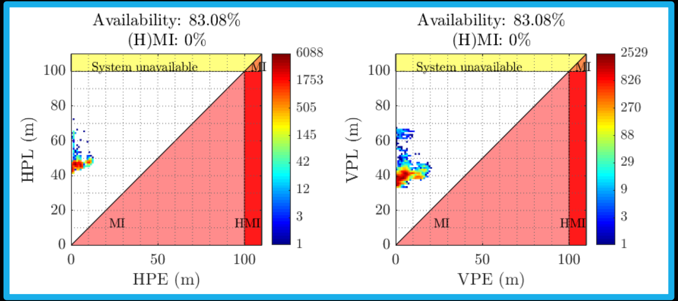
Integrity Availability on Lunar South Pole



4 LCNS

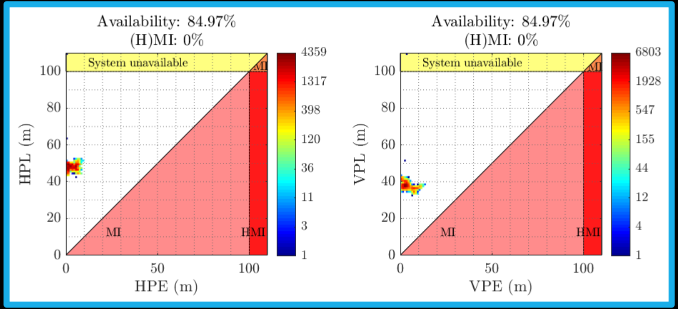
4 LCNS + Beacon

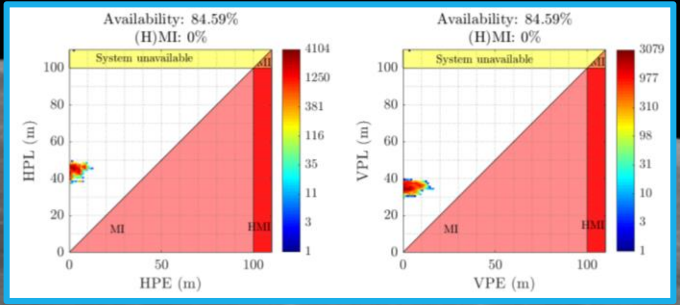




4 LCNS + GAL

4 LCNS + GAL + GPS + Beacon





4 LCNS + GAL + GPS

Note: LCNS orbits designed for Horizontal constraint HDOP<3.5 for >15h per day

Conclusions

EKF with sliding window integrity monitor is a promising approach for user-based integrity monitoring at the lunar surface

- Preferable over solution separation due to poor observability conditions
- EKF with LCNS can provide tight integrity bounds for orbiters
- Adding GNSS can help improving availability, but the impact on DOP should be carefully addressed
- Local beacons with ranging components can help further improve availability
- Further accuracy improvement and tight integrity bounds allowing for surface applications require additional sensor implementation (presented at ION PLANS 2025)

Questions?

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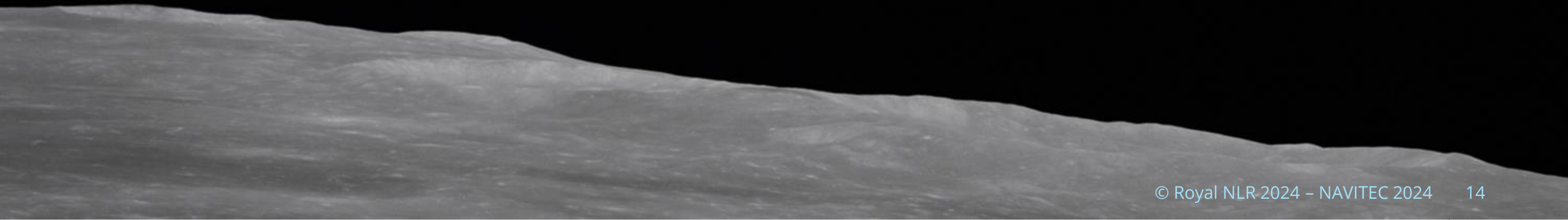

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Fully engaged

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