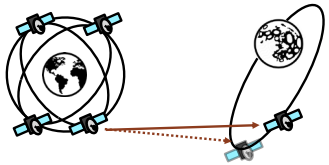
Designing Lunar Navigation Satellite Systems

PROF. GRACE X. GAO

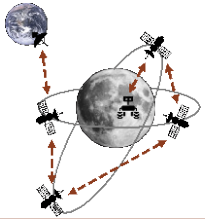
Designing Lunar Navigation Satellite Systems

NAV LAB

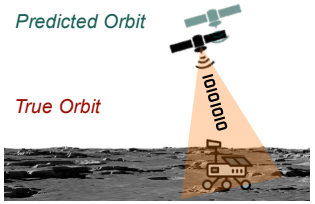
1. Using GNSS for Time and Orbit Determination



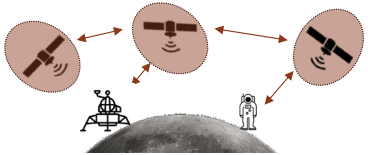
2. System Design and Tradeoff Studies



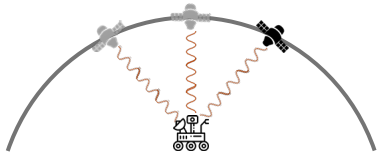
3. Ephemeris and Code Design



4. Using Crosslinks for Scheduling and Integrity

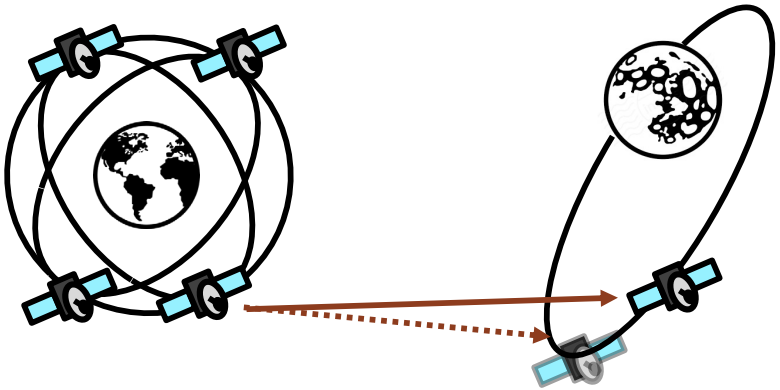


5. Intermediate step with 1-2 satellites



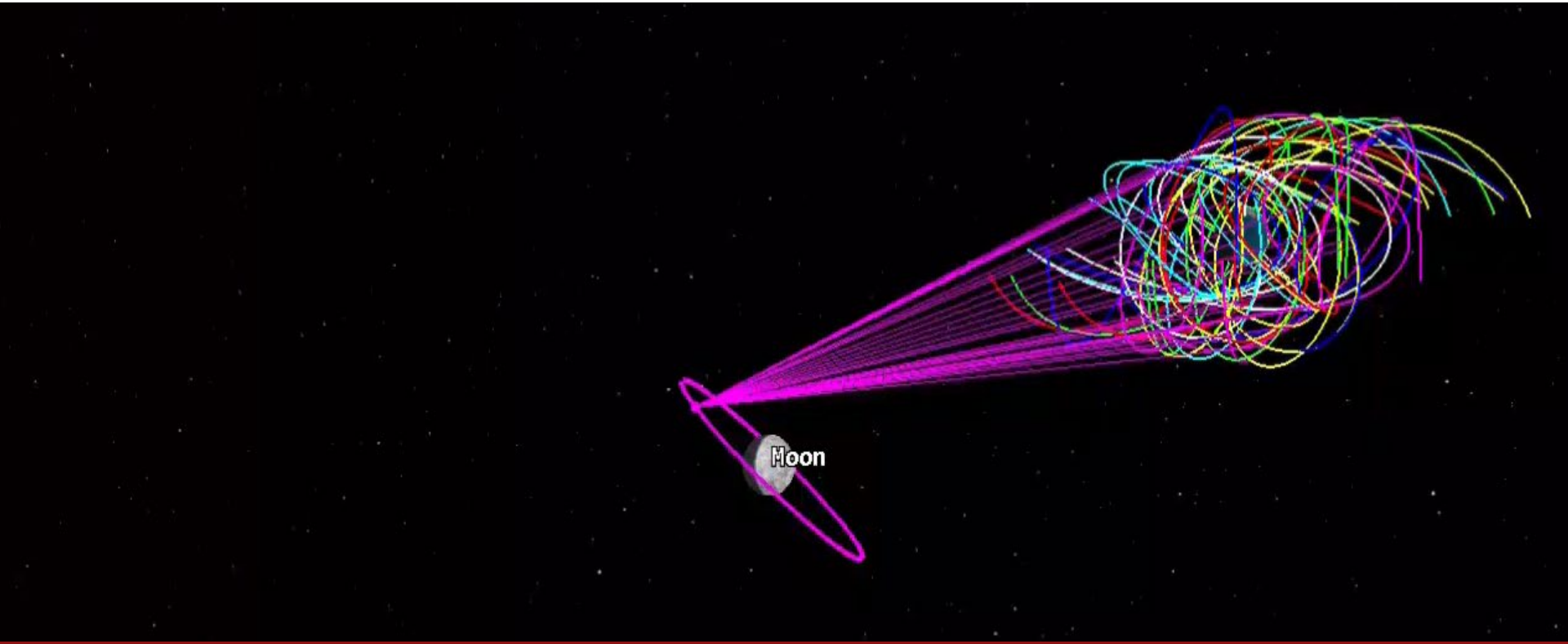
6. LuPNT: an Open-Source Simulator

1. Using GNSS for Time and Orbit Determination



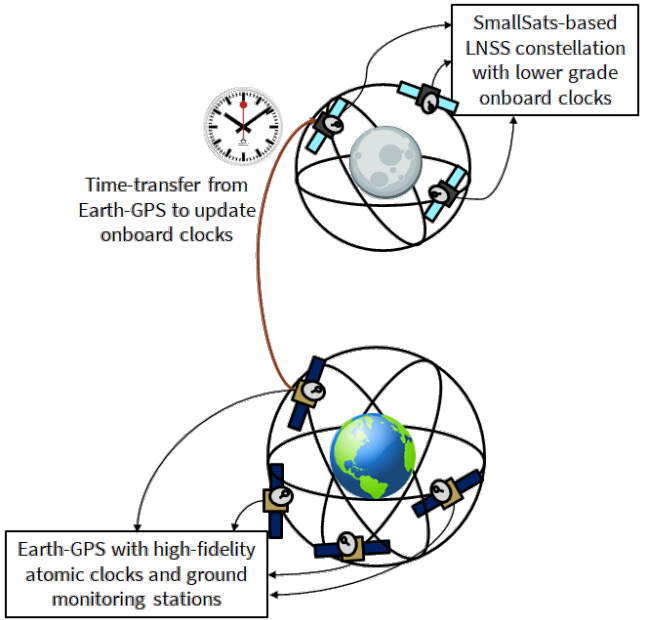
- Iiyama, Bhamidipati and Gao, ION Navigation Journal 2024
- Iiyama and Gao, ION GNSS+ 2023
- Iiyama, Bhamidipati and Gao, IEEE Aerospace Conf. 2023
- Iiyama, Bhamidipati and Gao, ION ITM 2023
- Bhamidipati, Mina and Gao, ION Navigation Journal 2022
- Bhamidipati, Mina, Sanchez and Gao, ION GNSS+ 2022
- Sanchez and Gao, ION GNSS+ 2022
- Bhamidipati, Iiyama, Mina and Gao, IEEE Aerospace Conf. 2022

Utilizing GNSS Signals

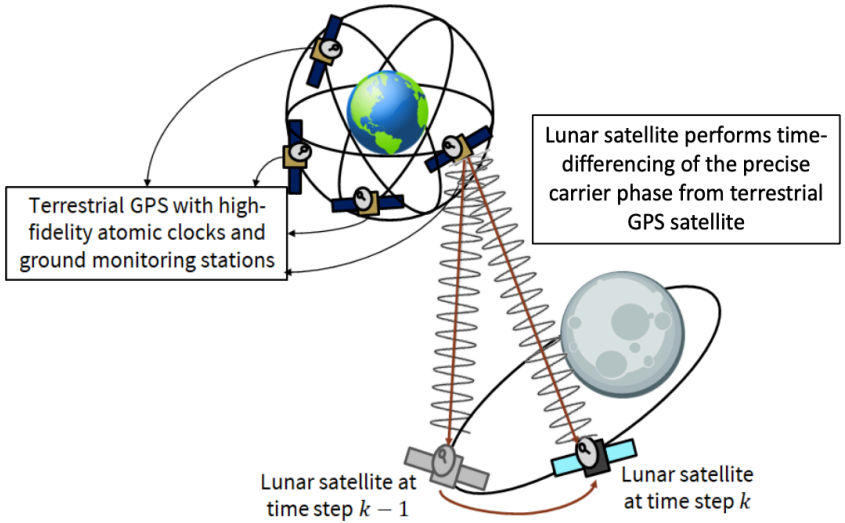


Utilizing GNSS Signals

Lunar Satellite Clock Correction: Time-Transfer from GNSS



Orbital Determination: GNSS Time Differenced Carrier Phase (TDCP)



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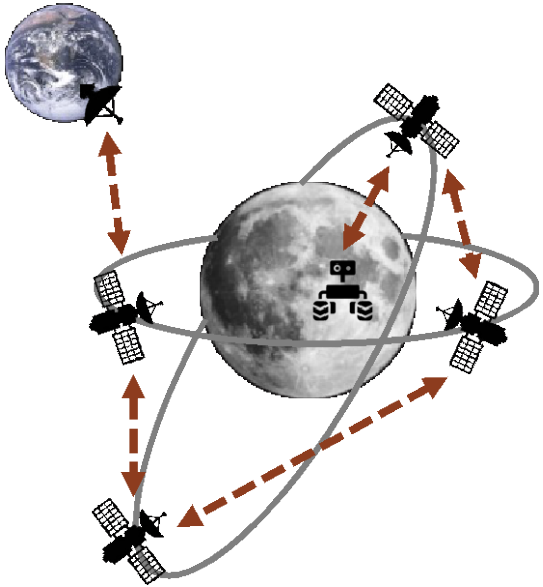
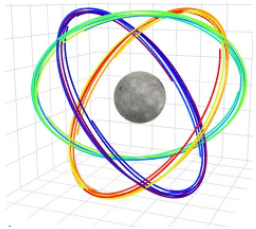
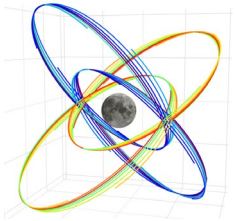


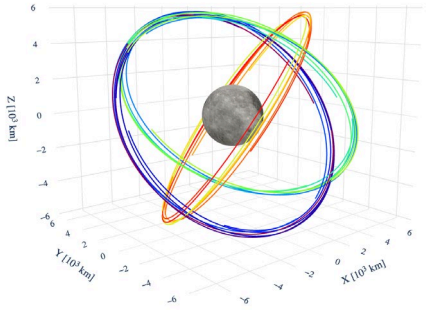
- Bhamidipati, Mina and Gao, ION Navigation Journal 2023
- Bhamidipati, Mina and Gao, ION Navigation Journal 2023 (2)
- Bhamidipati, Mina and Gao, ION Navigation Journal 2022
- Bhamidipati, Mina, Sanchez and Gao, ION GNSS+ 2022
- Sanchez and Gao, ION GNSS+ 2022
- Bhamidipati, Iiyama, Mina and Gao, IEEE Aerospace Conf. 2022
- Bhamidipati, Mina and Gao, ION ITM 2022
- Bhamidipati, Mina and Gao, ION GNSS+ 2021

Constellation Design for Full Coverage

We consider 2 types of symmetrical constellations

	 Walker Constellation (18 sats required)	 ELFO Constellation (24 sats required)
Orbit Type	Circular	Elliptical
Stability	Moderate	Very Stable
Global coverage	Excellent	Moderate
Pole visibility	Moderate	Excellent

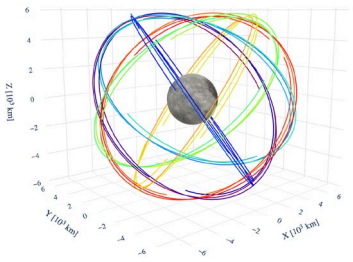
3-plane configuration (6 sats each)



Minimum altitude:
4300 - 4500km

Best Inclination:
≈ 55 deg

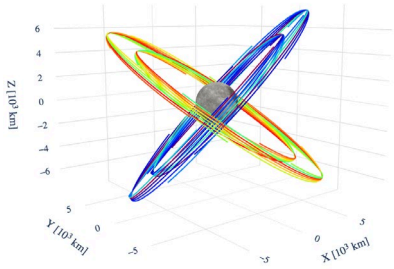
6-plane configuration (3 sats each)



Minimum altitude:
6500 - 6700 km

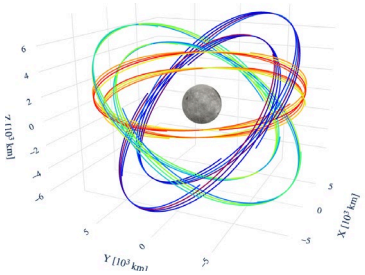
Best Inclination:
≈ 55 deg

4-plane configuration (6 sat each)



Minimum
semi-major axis:
8000 - 9000 km
Best Inclination:
40 deg

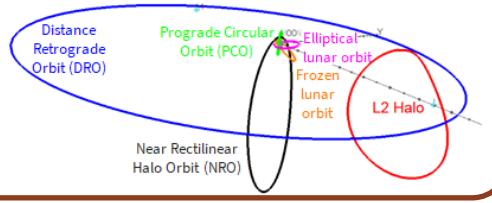
6-plane configuration (4 sat each)



Minimum
semi-major axis:
7000 - 8000 km
Best Inclination:
40 deg

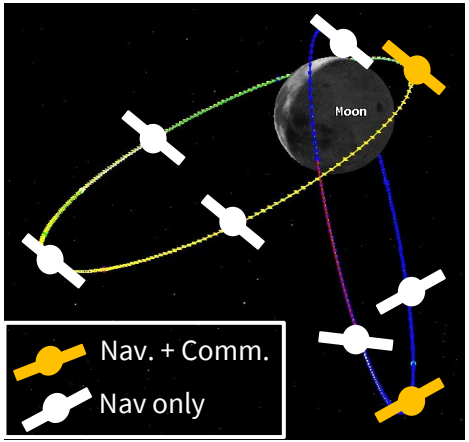
Trade-off Studies and Case Studies

Orbit choices:

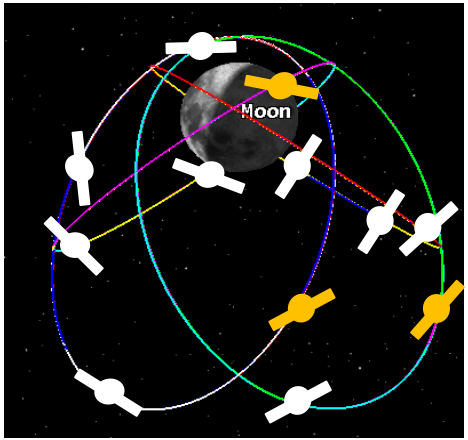


Clock choices:

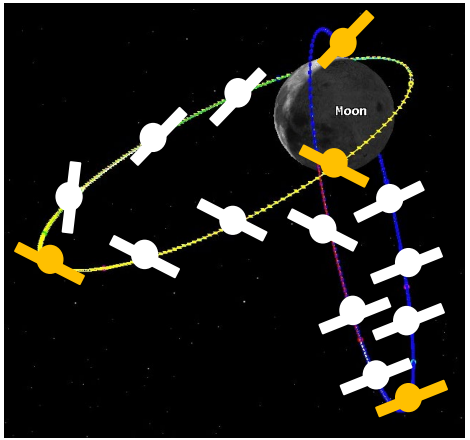
CASE-A: 6 nav-only SVs, 2 nav+comm SVs



CASE-B: 9 nav-only SVs, 3 nav+comm SVs



CASE-C: 12 nav-only SVs, 4 nav+comm SVs



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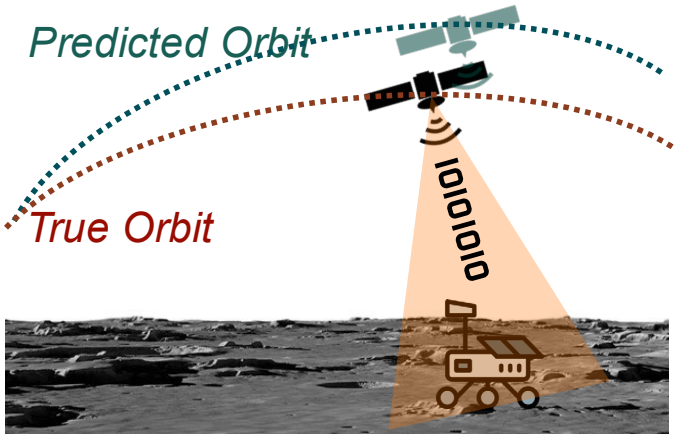
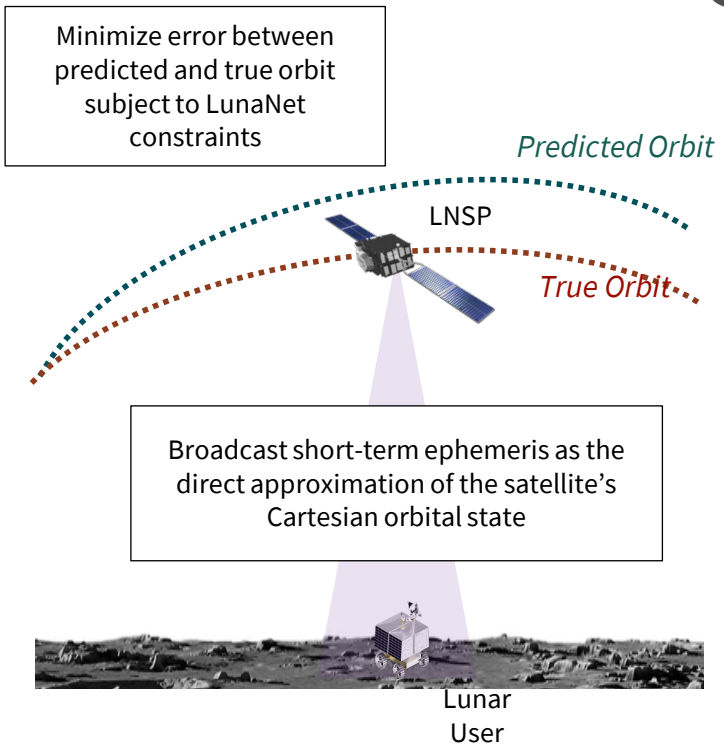





- Cortinovis, Iiyama and Gao, *ION Navigation Journal 2024*
- Cortinovis, Iiyama and Gao, *ION GNSS+ 2023*
- Yang, Mina, Boyd and Gao, *ION GNSS+ 2024*
- Yang, Mina and Gao, *EURASIP Journal on Advances in Signal Processing, 2024*
- Yang, Mina, and Gao, *ION ITM 2024*
- Yang, Mina, and Gao, *IEEE ICASSP 2023*
- Yang, Mina, and Gao, *ION GNSS+ 2023*
- Mina, Yang and Gao, *ION GNSS+ 2023*

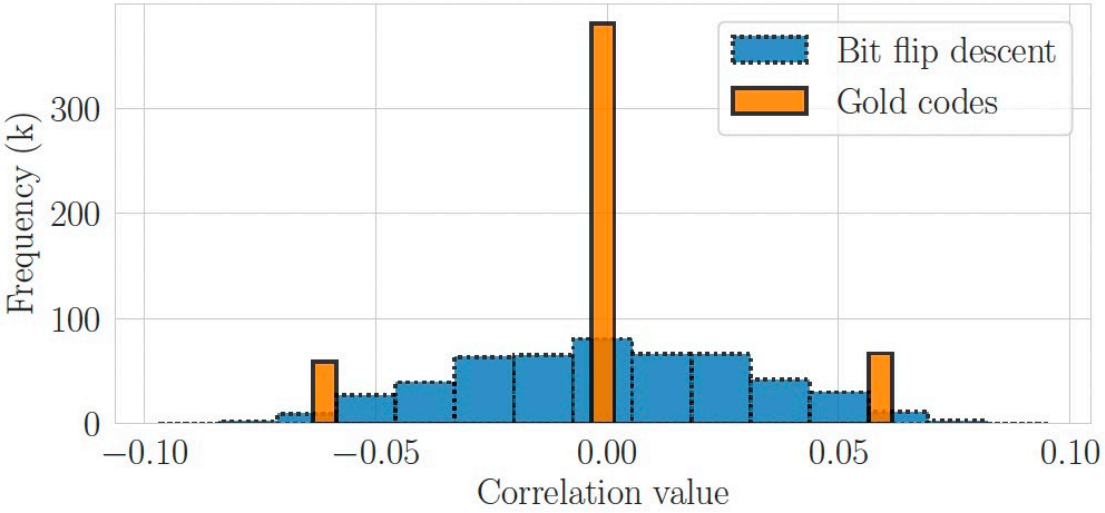
Ephemeris Design

- **Constrained convex optimization**
- **Cartesian-based model** vs Orbital Parameterization Model
- Tradeoff among **precision**, **duration**, and **broadcast data volume**
- Compliant parameterizations with Polynomial and Chebyshev models
- Decreased message length with Chebyshev model

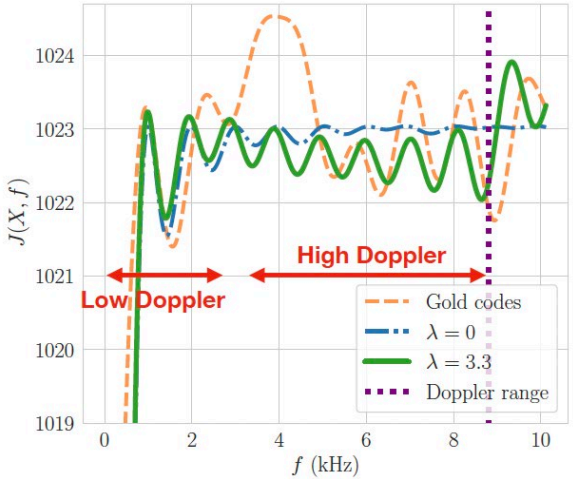


Pseudo-Random Noise (PRN) Code Design

Improved correlation properties

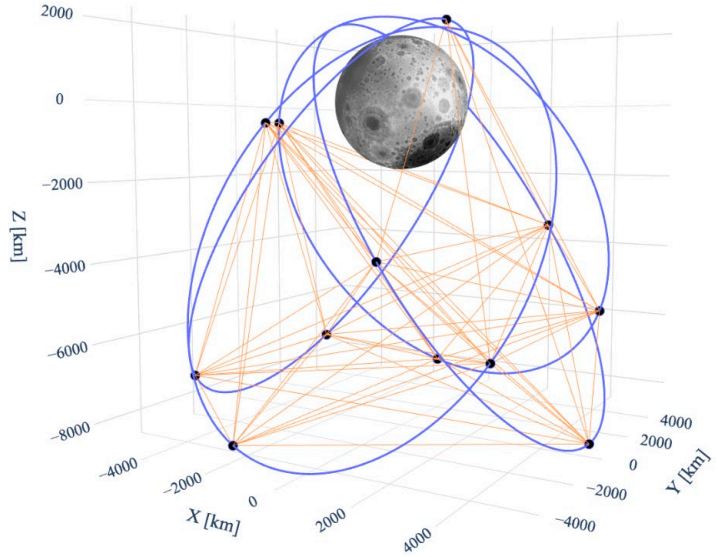


Considering Doppler effect



$n = 31,\ T = 1023$

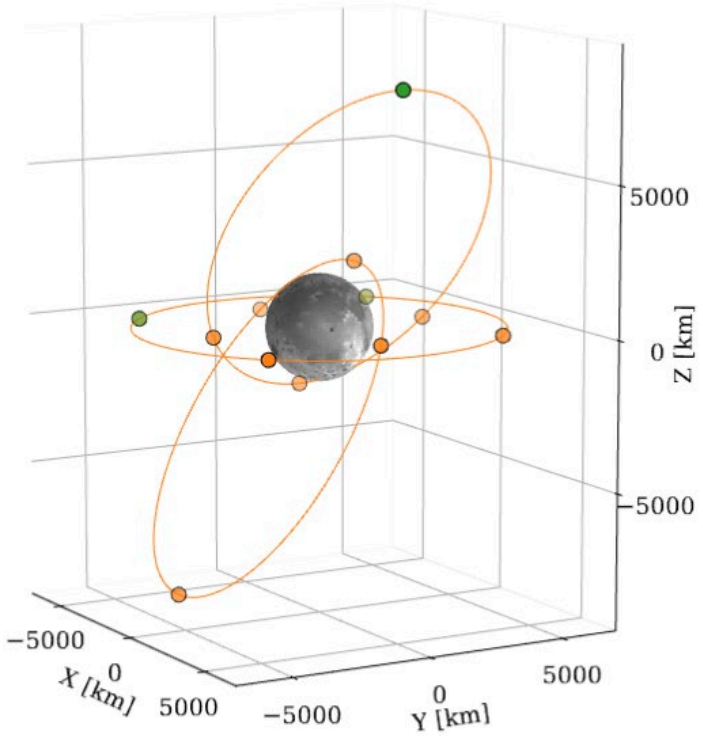
4. Using Crosslinks for Scheduling and Integrity





- Casadesus Vila and Gao, *ION GNSS+ 2024*
- Iiyama, Neamati and Gao, *ION GNSS+ 2024*
- Iiyama, Casadesus Vila and Gao, *IEEE Aerospace Conf. 2024*

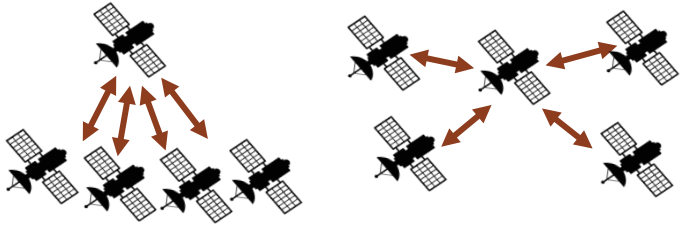
Crosslink Scheduling & Distributed PNT



For Orbital Determination and Time Synchronization: (ODTS):

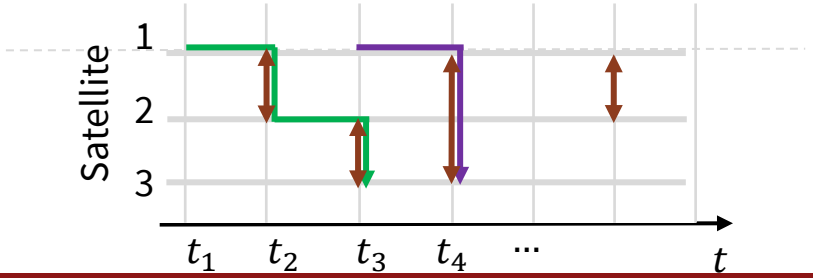
Worse schedule **Better schedule**

DOP

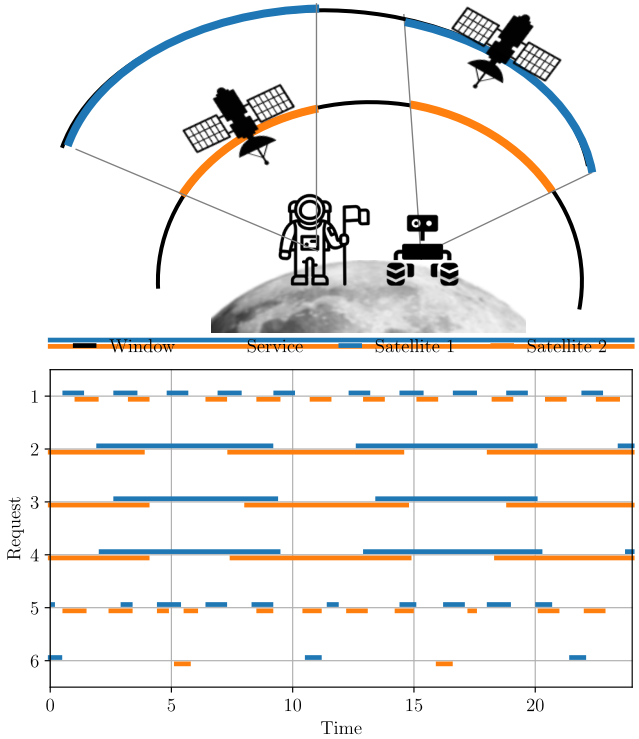


For communication:

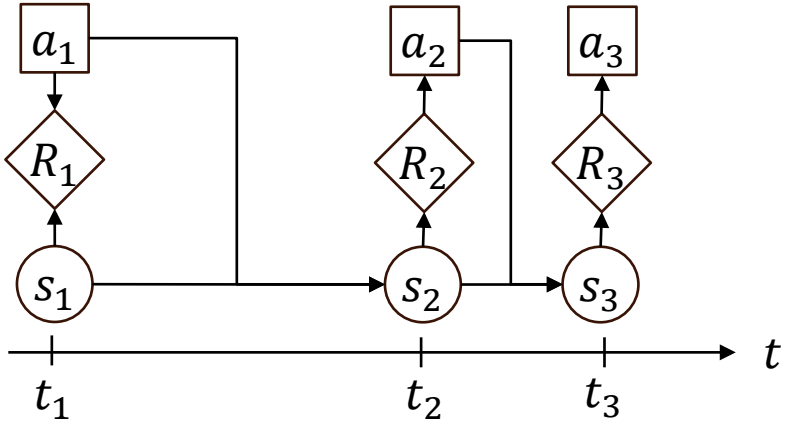
Link schedule



Service Scheduling using Markov Design Processes



Semi-MDP (SMDP): non-uniform time step



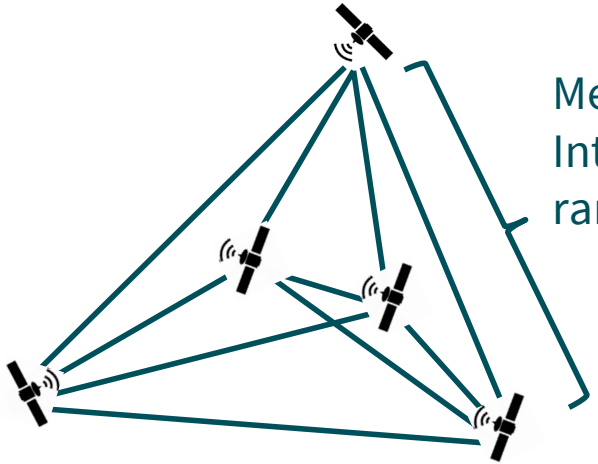
Fault Detection using Rigid Graphs

We propose an **onboard satellite fault detection** algorithm
that uses a **rigid graphs** constructed from a set of **inter-satellite ranges**

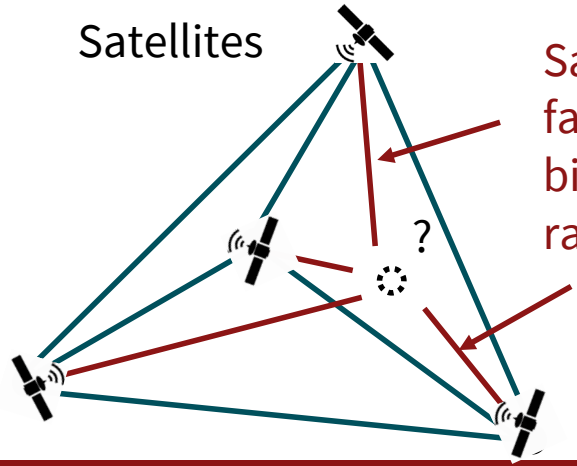
We construct a “rigid” graph, which cannot be deformed

→

We detect faults when the given set of ranges is not realizable in 3D space

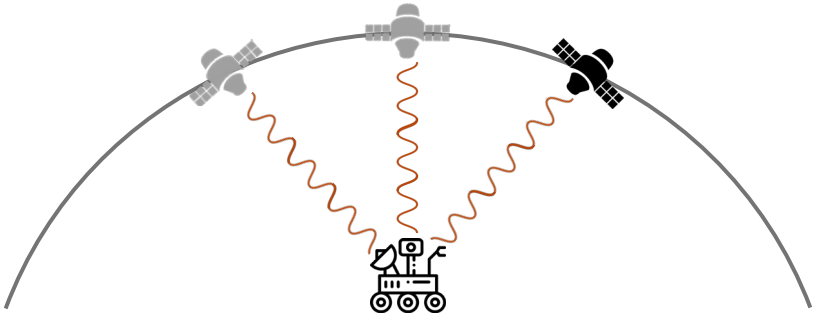


Measured Inter-satellite ranges



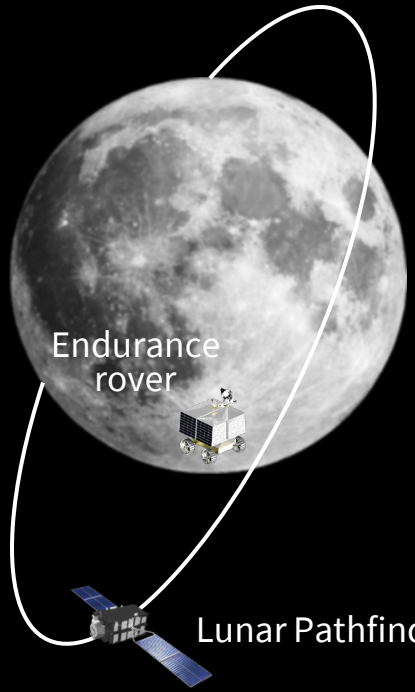
Satellite clock faults generate biases in measured ranges

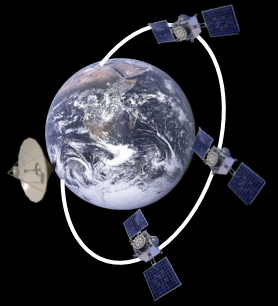
5. Intermediate step with 1-2 satellites



- Coimbra and Gao, *IEEE Aerospace Conf. 2025*
- Coimbra, Cortinovis, Mina and Gao, *ION GNSS+ 2024*
- Cortinovis, Mina and Gao, *IEEE Aerospace Conf. 2024*

The Near-Term Lunar Landscape



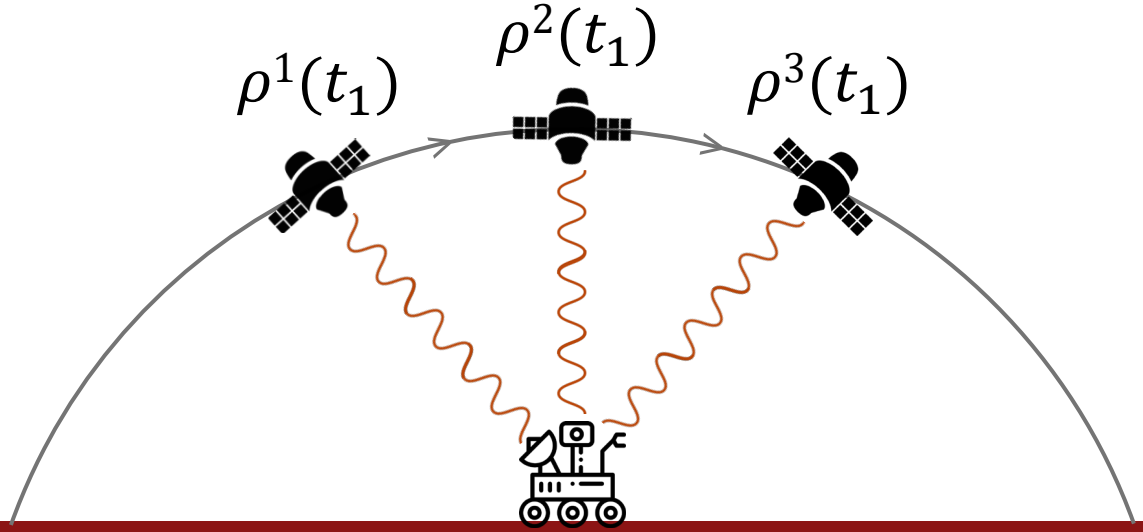


Lunar Pathfinder Satellite

- Data Relay Satellite
- in elliptical lunar frozen orbit (ELFO)
- *Service*: ~2025 - 2033

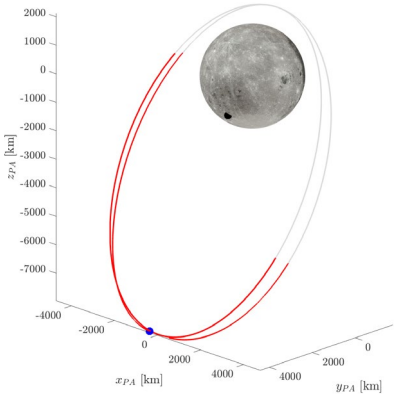
Desired Scenario with LunaNet

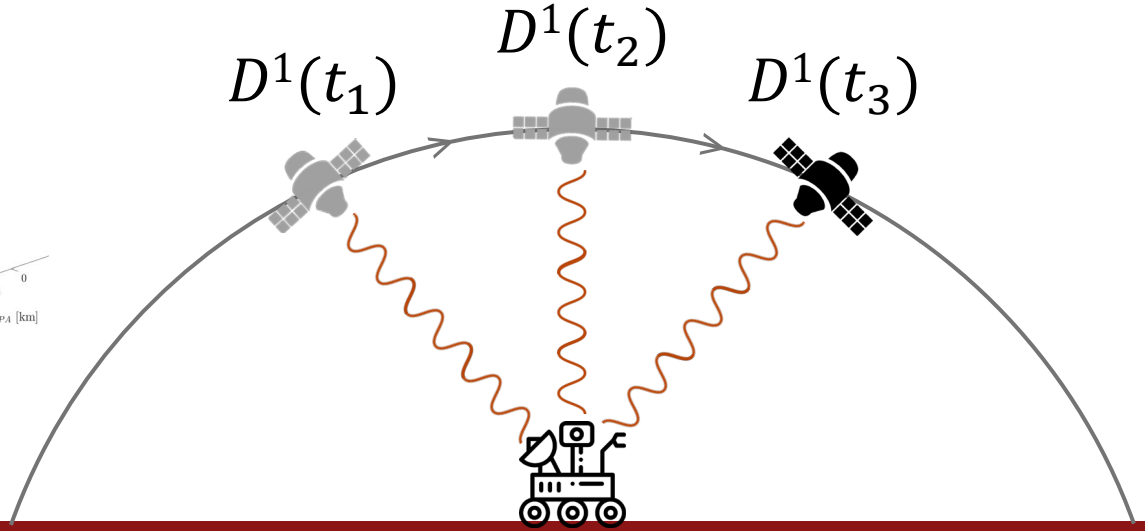
- ***Multiple satellites*** – instantaneous localization (with at least 4 satellites)
- ***Navigation payload*** – obtain pseudorange measurements for trilateration



Current Scenario

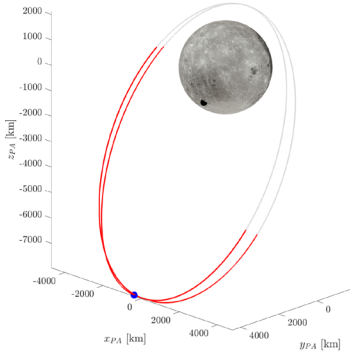
- ***Single satellite***
- ***No navigation payload***

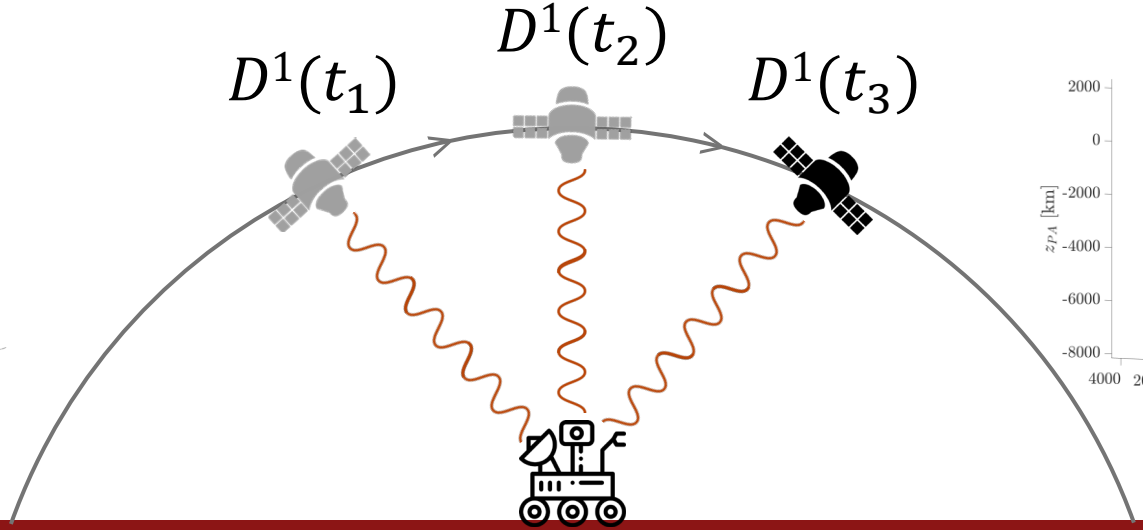


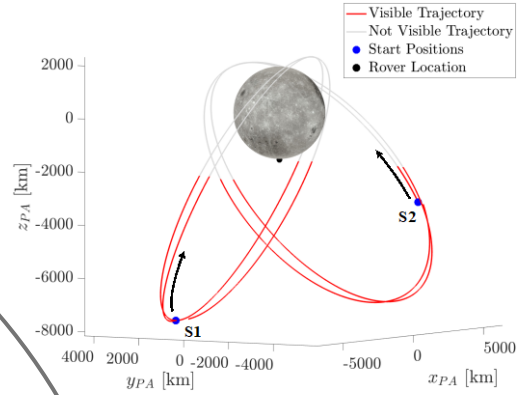


Key Ideas

- ***Single satellite*** – measurements over time -> multiple virtual satellites
- ***No navigation payload*** – use Doppler shift observables
- ***Adding a second satellite*** – Benefits and optimal SV placement







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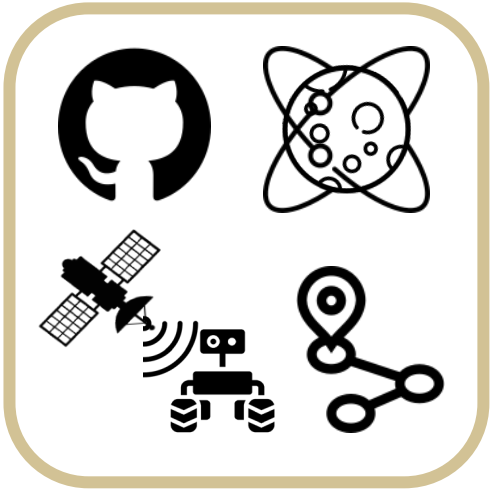
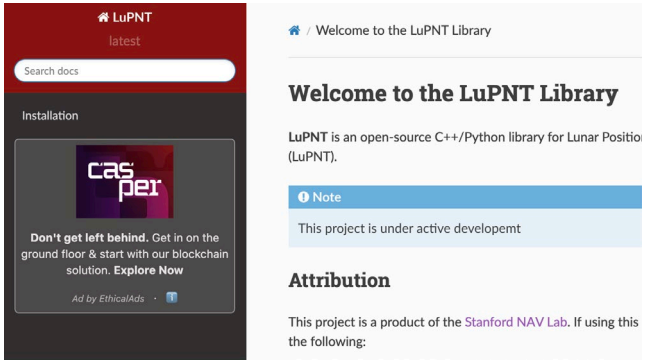


- Casadesus Vila, Iiyama and Gao, IEEE Aerospace Conf. 2025
- Casadesus Vila, Iiyama and Gao, ION GNSS+ 2023

Open-Source *LuPNT* Simulator



Module	# files	# lines
lupnt	75	10,800
pylupnt	25	3,200
projects	85	19,300
test	20	1,200
Total	**215**	**35,300**

~600 pages

Open-source simulator for lunar PNT services

GNSS measurement modeling at lunar region

Astrodynamics with automatic differentiation

Satellite-to-satellite measurements and communication

Modular and extensible to multiple research purposes

Summary of Our Research Efforts on Designing Lunar Navigation Satellite Systems

NAV LAB

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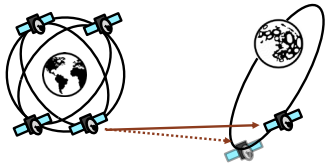

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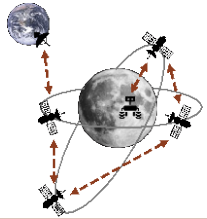

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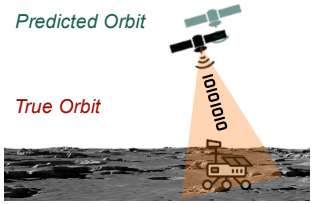

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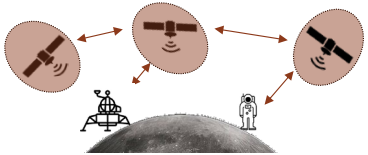

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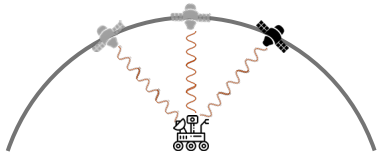

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Thank You!