Brian Peters *received his B.S in Electrical Engineering from Ohio University in 2019 and is currently pursuing his M.S. in Electrical Engineering at Ohio University. He completed an internship at NASA Ames Research Center in 2020 where he was involved with the development of LAPS. He is currently a research assistant at Ohio University's Avionics Engineering Center.*

Introducing the Lunar Autonomous PNT System (LAPS) Simulator

Benjamin Hagenau, Brian Peters, Roland Burton,

Kelley Hashemi, Nicholas Cramer

NASA Ames Research Center

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Introduction

- Increasing volume of Lunar missions creates increased need for Lunar PNT services
- **Terrestrial GNSS**-based solutions for Lunar users impose significant power and mass requirements, and may not be suitable for low-cost missions
- Dedicated **Lunar GNSS** may be too expensive, considering the relatively small number of end users
- **LAPS** aims to leverage existing science and exploration assets for PNT services in a distributed, decentralized manner

LAPS Concept of Operations

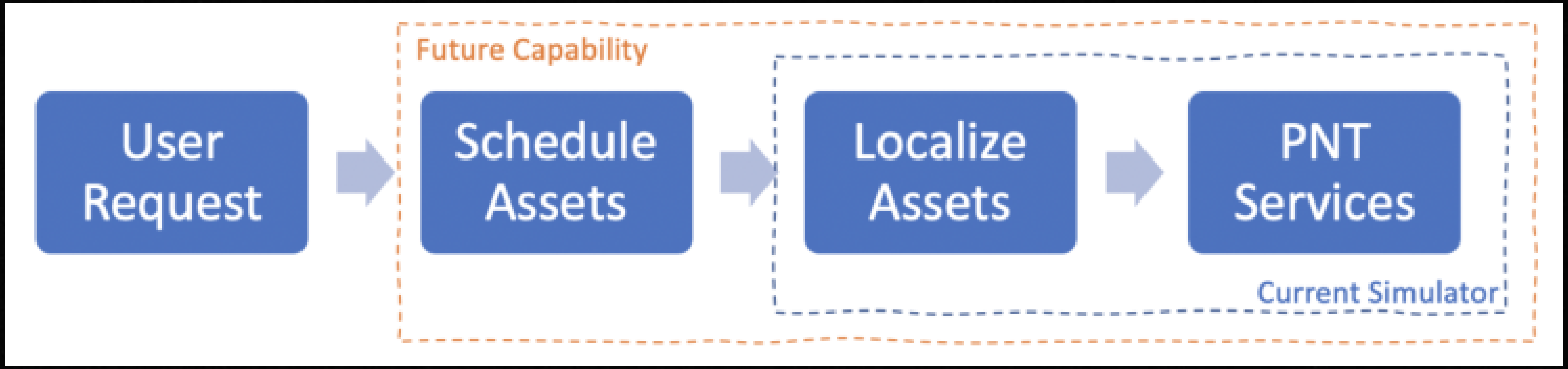


Figure: LAPS Concept of Operations

- Non-dedicated, heterogeneous swarm assets
- Distributed swarm asset localization

Credit: NASA Image and Video Library

The LAPS Simulator

- Modularly designed software simulation
- GMAT is used to propagate asset orbits and generate truth data
  - Truth data is imported in MATLAB via CCSDS-OEM formatted ephemeris, allowing the use of other orbit propagators
- Asset and user localization is simulated, producing PNT quality of service metrics
  - Metrics provide essential feedback to aid in the refinement of LAPS algorithms and architecture
- Simulator modules will be used as prototypes for flight software modules

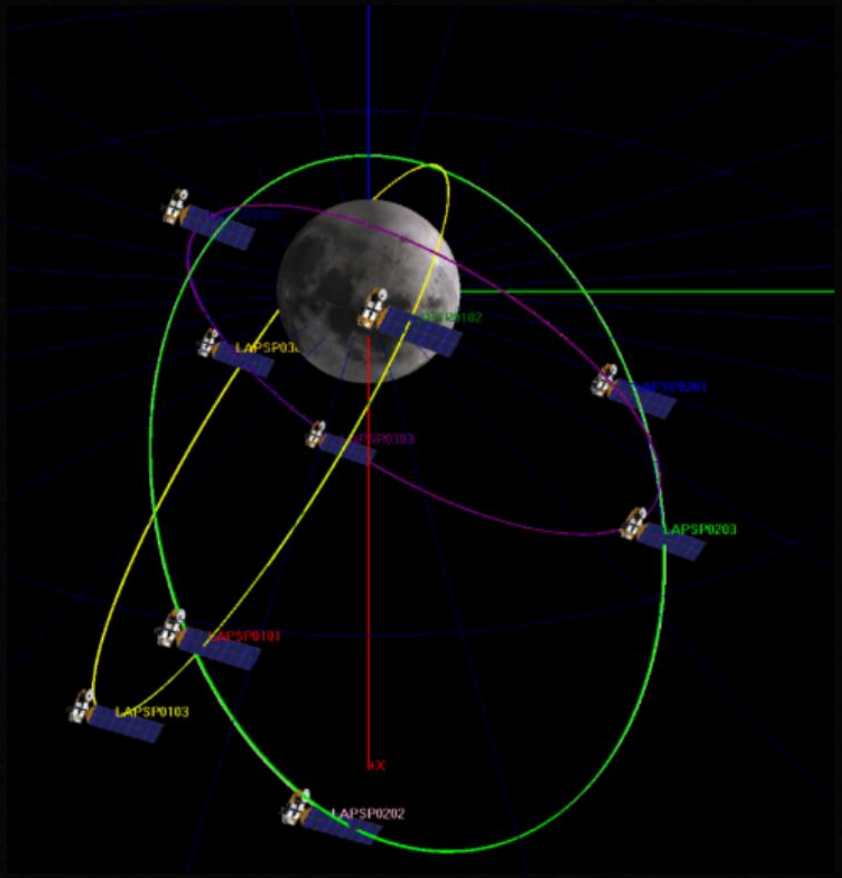
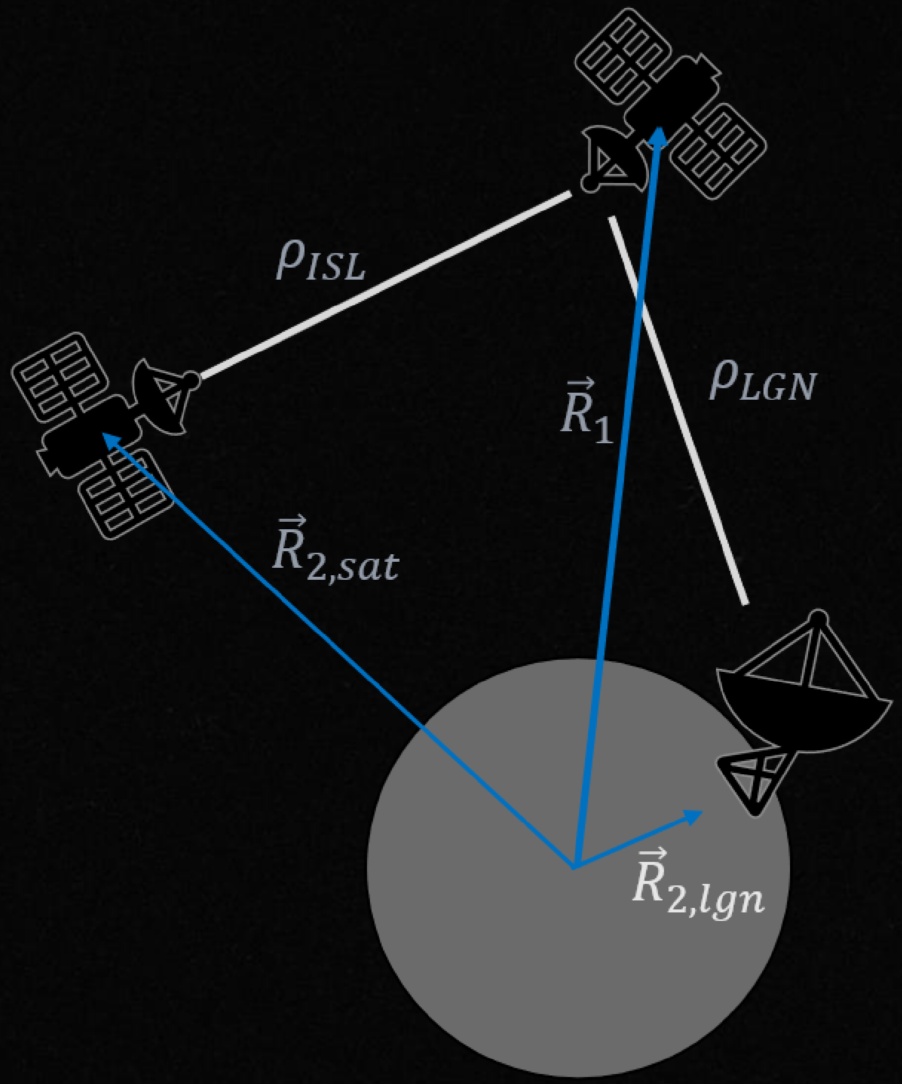


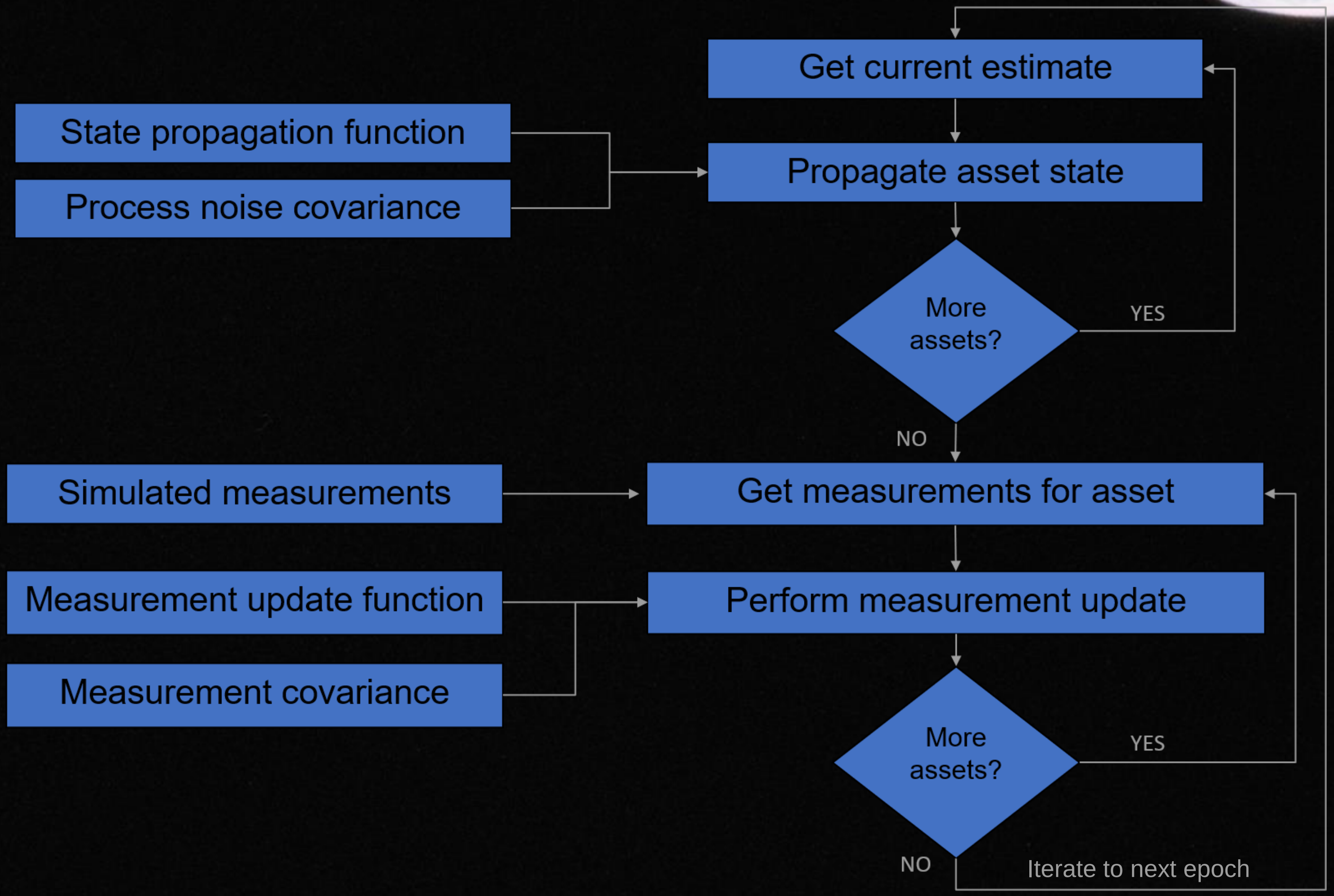
Figure: LAPS assets modelled in GMAT

Measurement Modelling



- Assets localize with respect to neighboring nodes, using a distributed EKF (DEKF) and inter-satellite link measurements (ρ_{ISL})
- Pseudorange measurement error is modelled by additive white Gaussian noise summed with the true range between the assets
- Anchor nodes ensure all swarm asset states remain observable, and state estimation errors remain bounded

LAPS DEKF Framework



Credit: NASA Image and Video Library

User Localization

- Algorithms similar to GNSS least-squares approach
- Separately configurable user clock bias model
- Least squares weighting model based on each asset's state covariance matrix

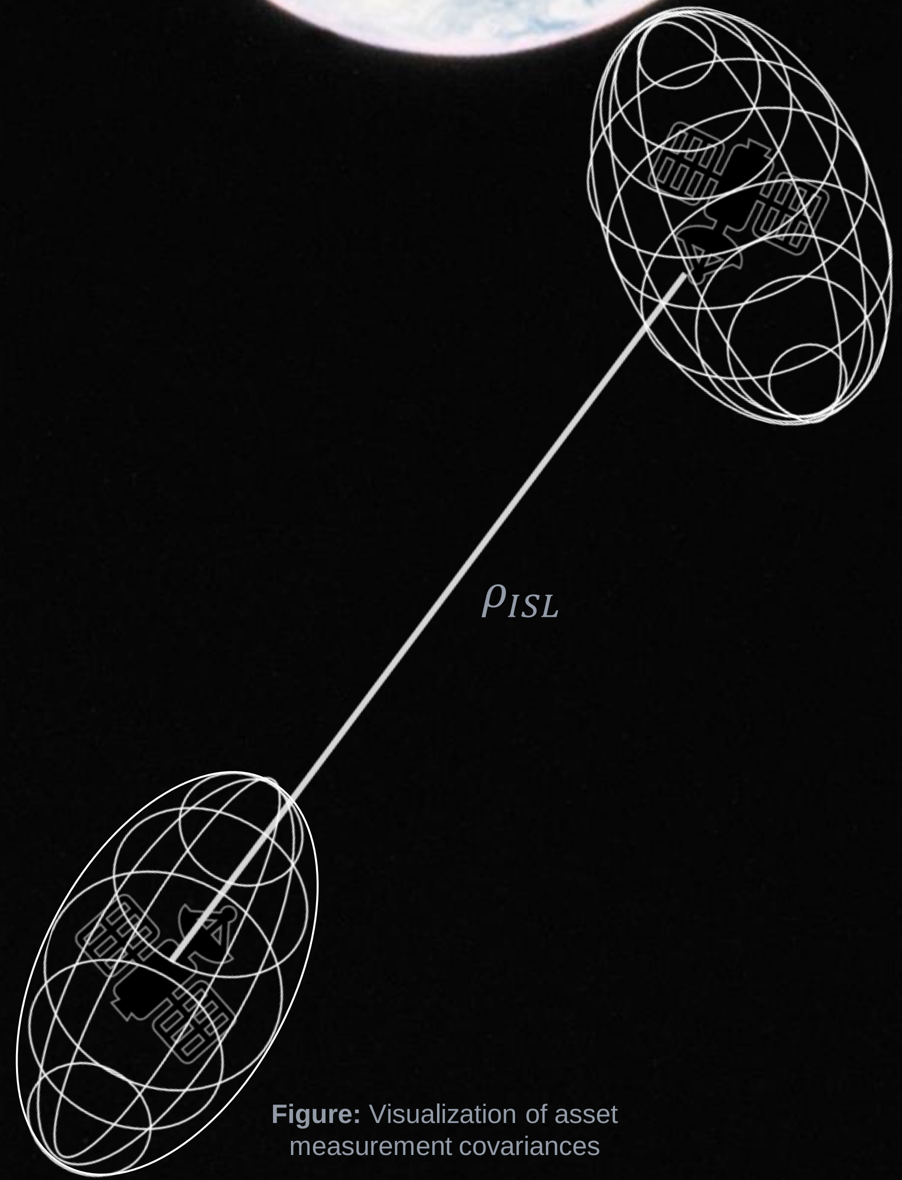


Figure: Visualization of asset measurement covariances

Credit: NASA Image and Video Library

Test Case: Low Latitude Swarm

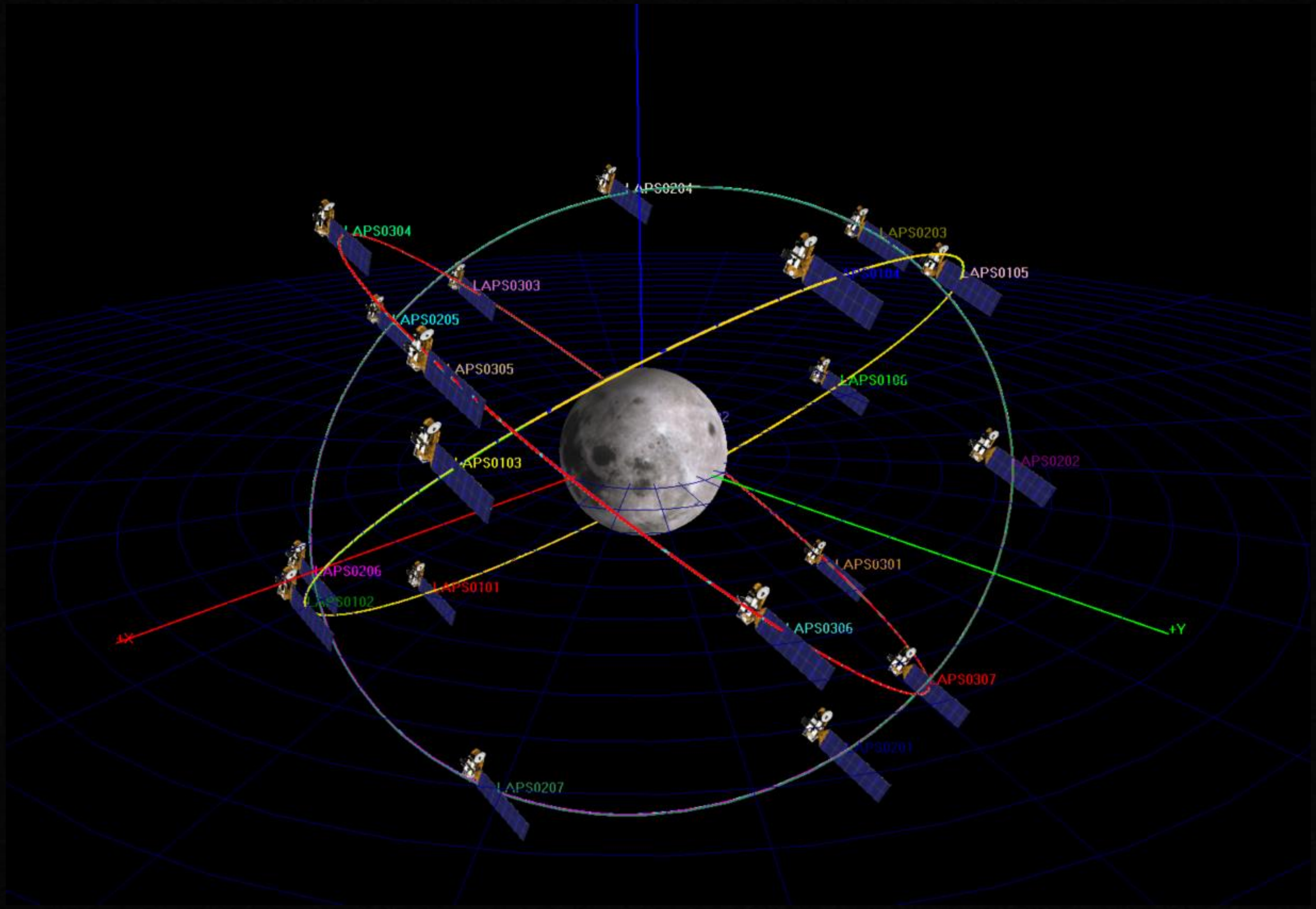


Figure: GMAT view of low latitude swarm

No. of orbital planes	3
Assets per plane	7
Inclination	39.71°
Eccentricity	0.001
Semi-major axis (km)	7298.6

Results: DEKF Performance

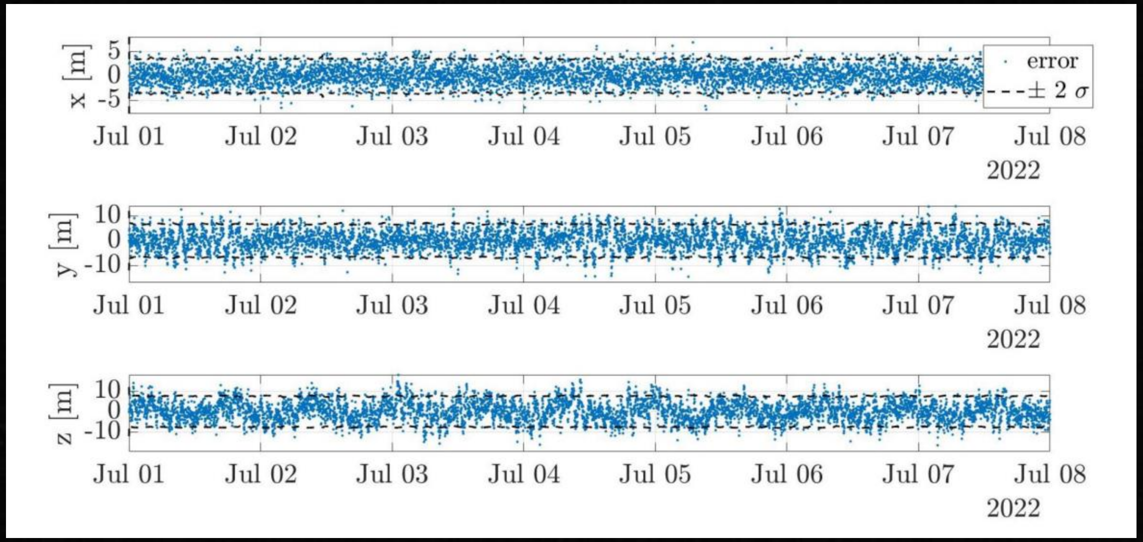


Figure 1: Position estimate error for representative asset with 22 anchor nodes
X-axis: orbit radial, Y-axis: along-track, Z-axis: orbit normal

Number of Anchor Nodes	**22**	**8**
CEKF Mean Error (m)	2.7	3.6
CEKF Max. Error (m)	12.3	14.1
DEKF Mean Error (m)	3.2	6.7
DEKF Max. Error (m)	13.2	25.3

Table: DEKF/CEKF performance with respect to number of anchor nodes

- Variance of inter-satellite pseudoranges assumed to be $10 m^2$
- Pseudoranges measured every 100 s

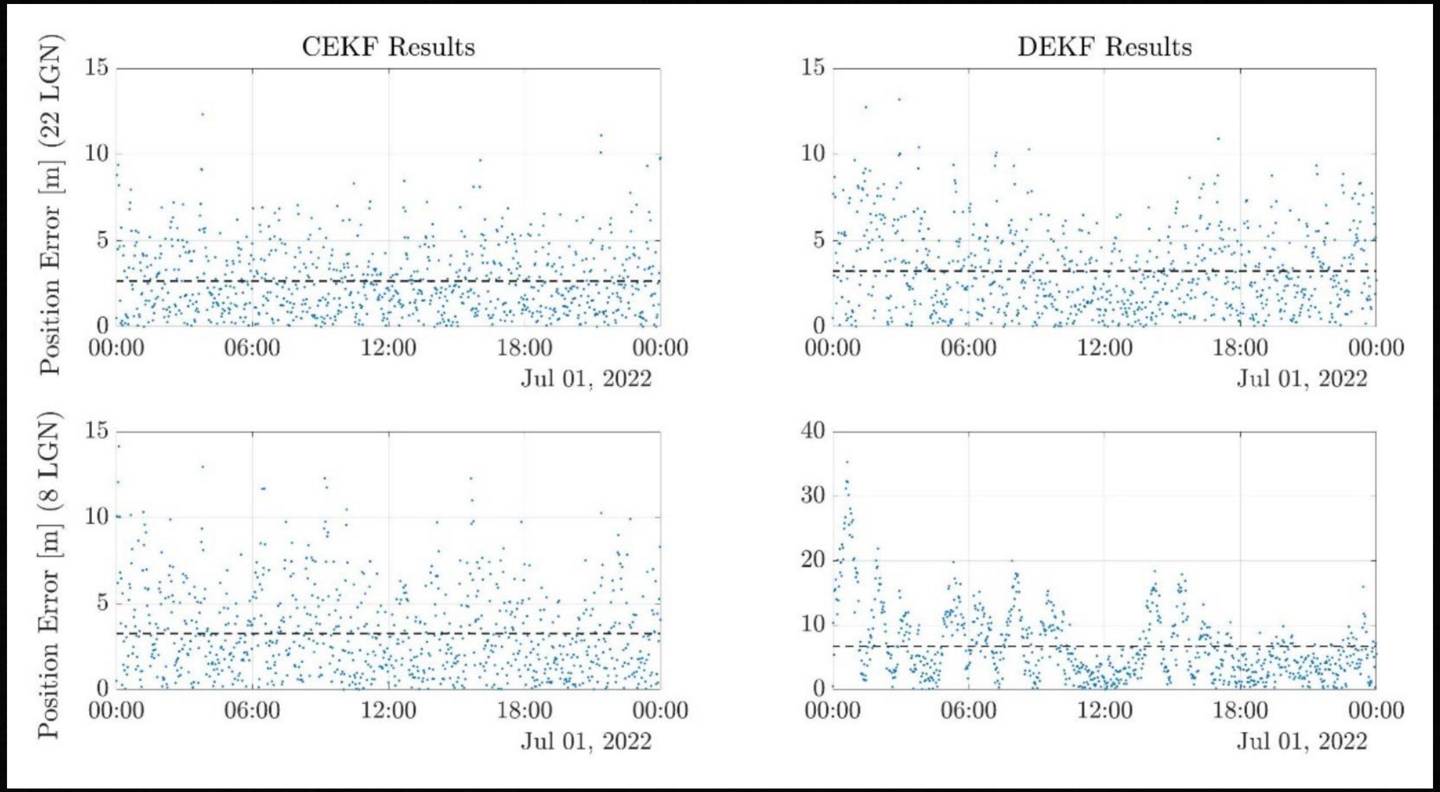


Figure 2: DEKF/CEKF estimate RMS error for representative asset
blue points: RMS error at each epoch, dashed lines: mean estimate error

Credit: NASA Image and Video Library

Results: User Localization

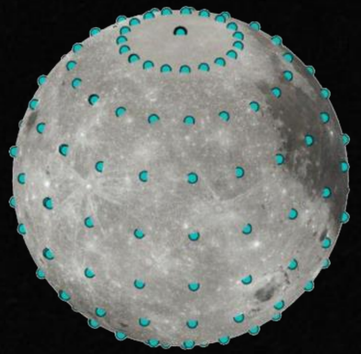


Figure 1: Simulated user positions on lunar surface

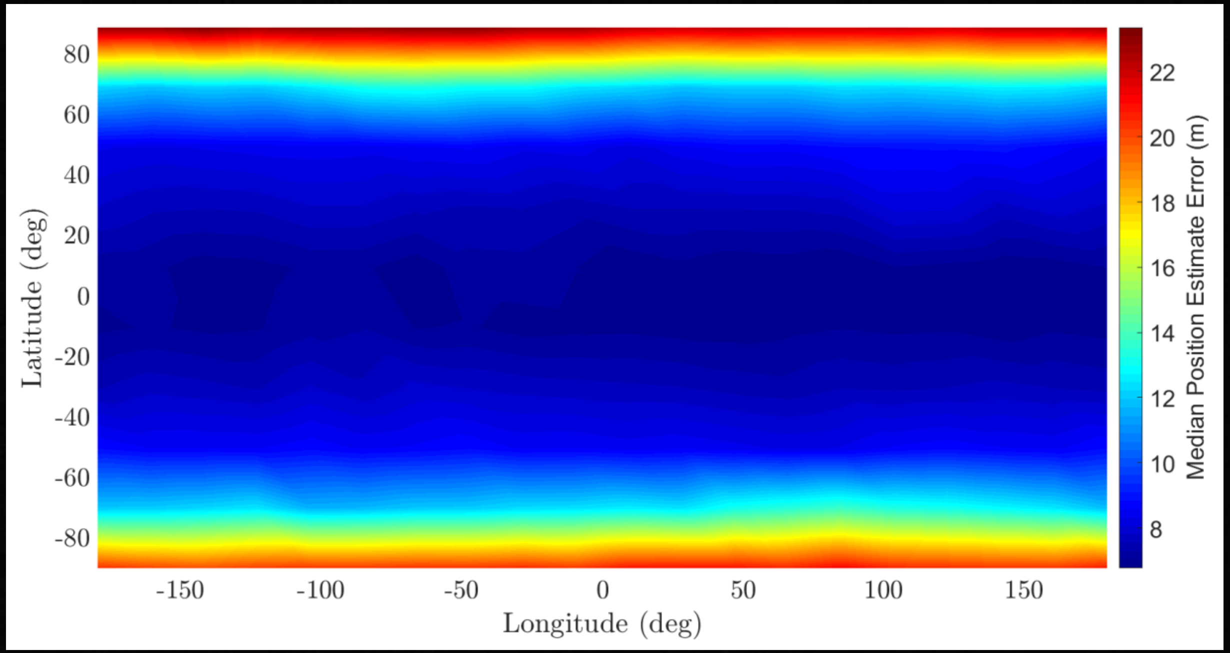


Figure 2: Heat map of user position estimate error over 1 lunar day

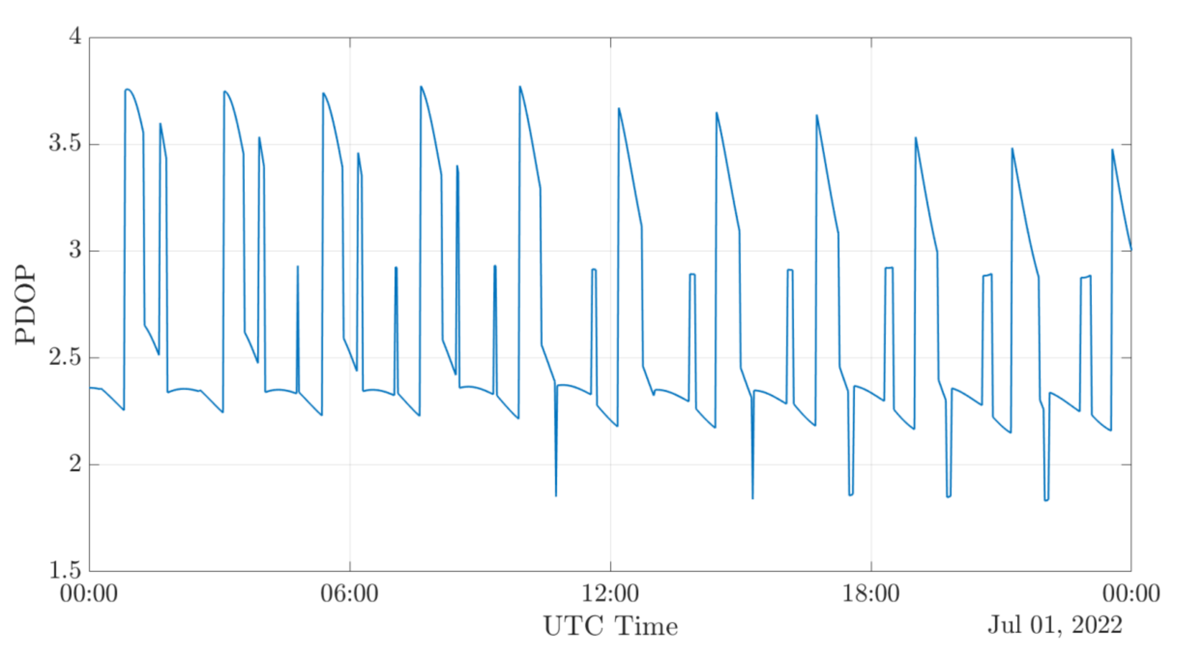


Figure 3: PDOP time history for user at 20° N, 90° W

- User clock error set at ~1.5 ms
- 15° visibility cutoff

Credit: NASA Image and Video Library

Conclusions and Future Work

- Provides key insights into crucial design considerations
  - Anchor node quantity and distribution
  - Swarm asset distribution
- The simulator will be expanded to encompass all phases of the LAPS CONOPs
  - Resource scheduling
  - Swarm networking
- Lunar PNT swarm hardware-in-the-loop demonstration

Credit: NASA Image and Video Library

Acknowledgements

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Questions?

Contact:

Brian Peters – bp908214@ohio.edu

Roland Burton – roland.burton@nasa.gov