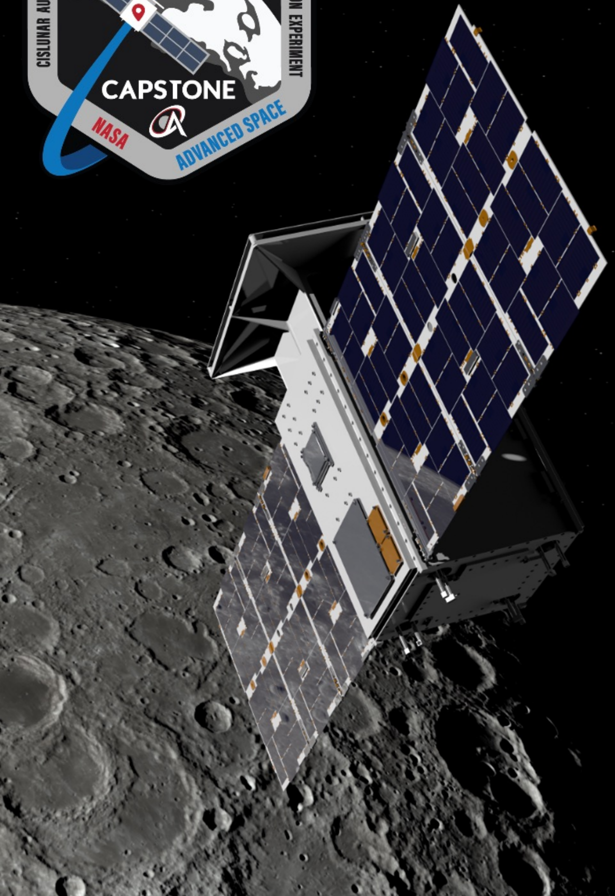

Using CAPSTONE's Mission Extension to Navigate the Future of Cislunar Technology

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Delivering Innovation to Orbit™

CAPSTONE Mission Objectives

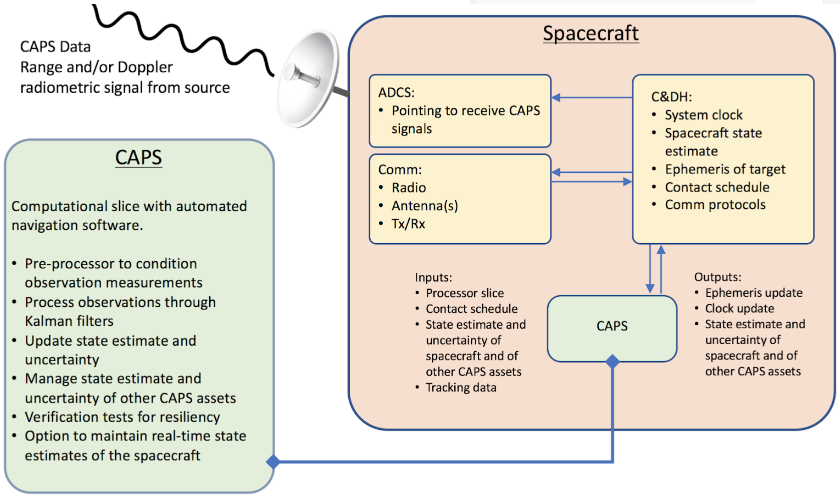
- **C**islunar **A**utonomous **P**ositioning **S**ystem **T**echnology **O**perations and **N**avigation **E**xperiment
- Validate and demonstrate NRHO/three-body Earth-Moon Operations
  - Same orbit Gateway will be operating in
  - Mitigate technical risks of NRHO operations and validate navigation and station keeping analysis and simulation
- Pathfinder – learn quickly to inform fundamental lunar exploration requirements and Gateway planning activities
- Demonstrate and Accelerate Infusion of the **C**islunar **A**utonomous **P**ositioning **S**ystem (CAPS)

Operations Summary

- CAPSTONE has been successfully operating in the NRHO for 30 months
  - Encompasses 142 completed NRHO revolutions
  - 42 Orbital Maintenance Maneuvers
- All Operational Objectives Completed
- CAPSTONE has ~50% of its fuel remaining (100 m/s)
- Currently in extended mission phase with funding through 2025
- Planned disposal is heliocentric
- Demonstrated Navigation and Autonomy
  - CAPS Crosslink
  - CAPS One-Way
  - Neural Nets for Easy Planning (NNEP)
  - Horizon-based Optical Navigation (HOpNav)

Cislunar Autonomous Positioning System (CAPS)

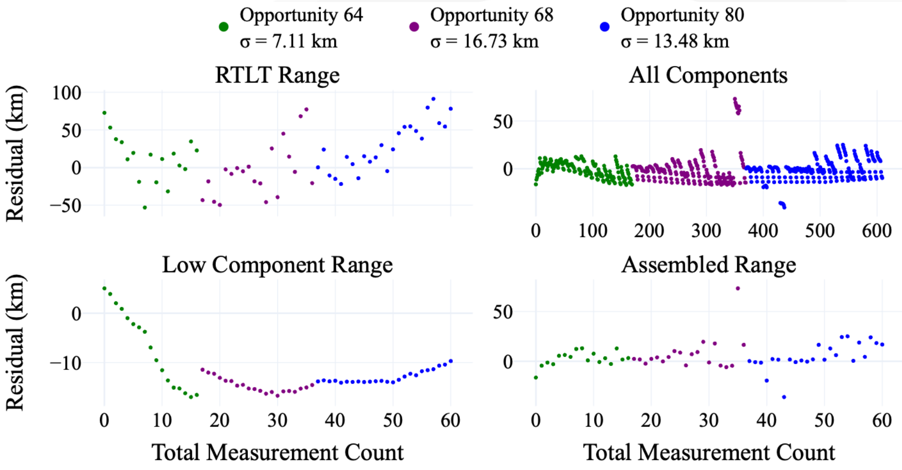
- CAPS was originally developed as a navigation algorithm that enables a spacecraft to estimate its state via a crosslink with another spacecraft
- CAPSTONE has demonstrated CAPS in flight via a crosslink with the Lunar Reconnaissance Orbiter (LRO)
- During CAPSTONE development, a partnership was formed with JPL to demonstrate one-way navigation with CAPSTONE/CAPS
- There are two separate CAPS technology demonstrations planned on CAPSTONE
  - Demonstrate crosslink navigation with LRO
  - Demonstrate one-way (uplink) navigation

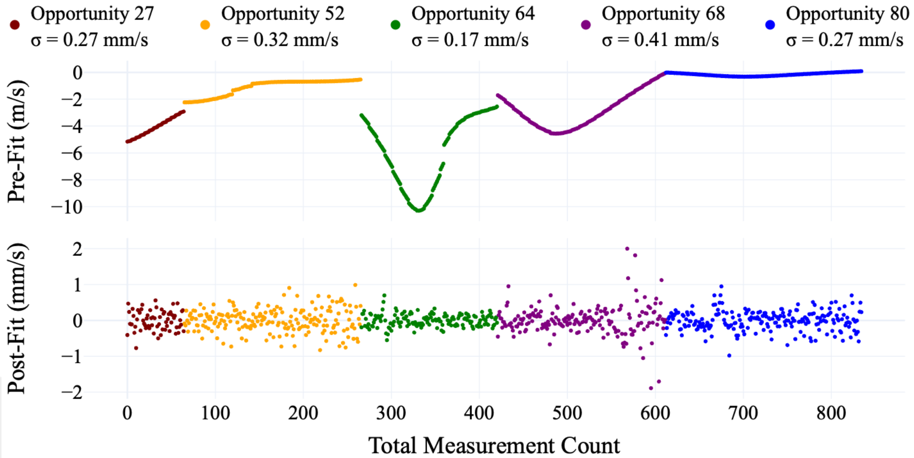


Navigation Observables

Sequential Ranging Assembly (SRA)

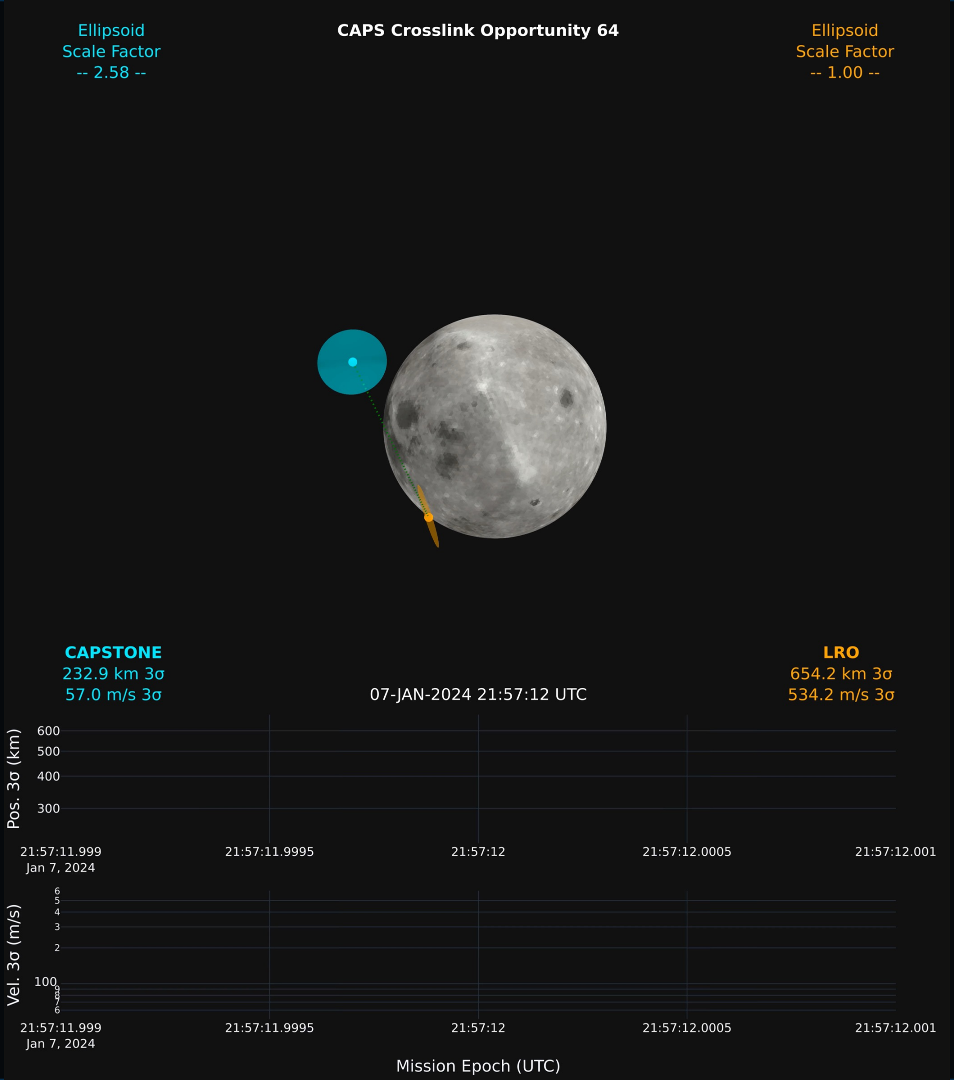
- Functionality suffered from lack of pre-flight radio characterization
  - Required In-flight calibration
  - Large non-gaussian noise → not used for OD
- Ranging Component Assembly process obscure and not well documented
  - Led to difficulty in proper implementation





Doppler (Range-Rate)

- Exceptional Performance
  - $\sigma_D = 0.3$ mm/sec (DSN: ~0.1 mm/sec)
  - Enables Doppler-only orbit determination
  - Lack of atmospheric effects offers low noise



CAPS Opportunity 64
January 7th, 2024

- 1 hour & 6 minutes – longest track
- Closest pass – 1,500 km link distance at close approach
- Lengthened Doppler Integration time
  - $T = 20$ sec $\rightarrow \sigma_{\dot{\rho}} = 0.17$ mm/sec
- CAPSTONE Timing Anomaly:
  - CAPSTONE’s clock off by ~180 sec.
  - Resulted in ~18 degrees off-pointing at close approach
  - Still maintained link due to small distance
- Performance:
  - CAPSTONE 3σ – 18.3 km, 4.1 m/sec
  - LRO 3σ – 18.5 km, 16.5 m/sec

Extrapolated Results - Simulation

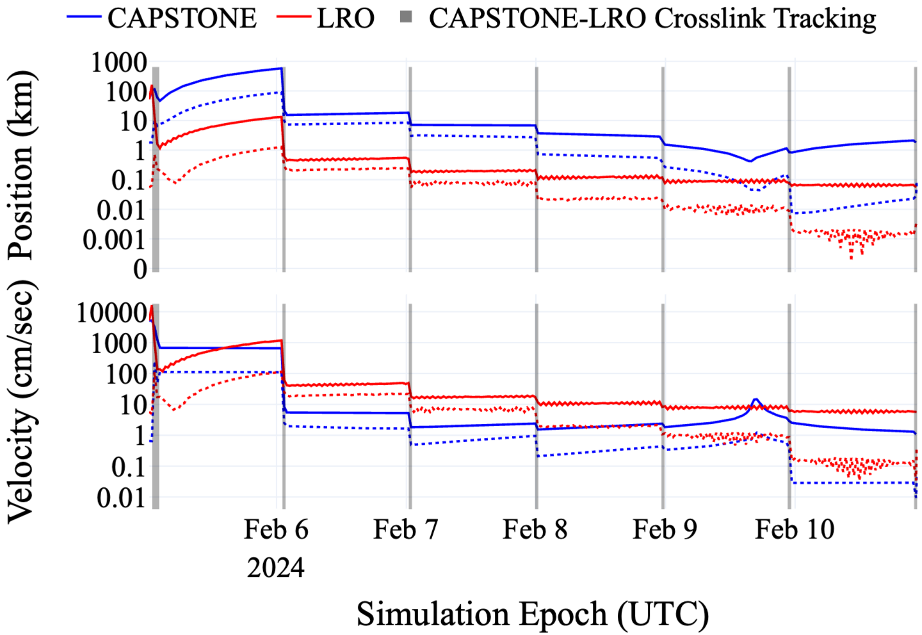
Implementation

- Extra truth propagation and tracking simulation aspects added
- CAPS ground filter fed simulated data
- SRP and Clocks considered instead of estimated

Assumptions

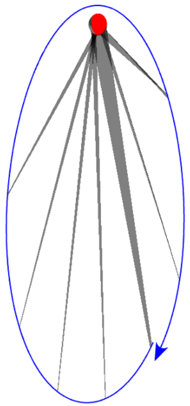
- No link distance constraint
- No geometry constraint
- Reliable Link (all arcs generate measurements)

Crosslink OD Simulation – 1 NRHO Revolution (6.5 Days)



Total Tracking Duration

03:24:39



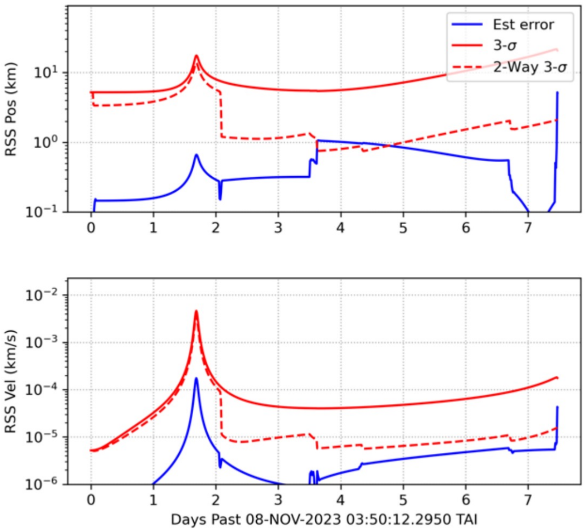
	CAPSTONE	LRO
	1.81 km 3σ	0.05 km 3σ
	1.07 cm/sec 3σ	5.70 cm/sec 3σ

Doppler	Range	Cadence
$\sigma = 0.3$ mm/s $T = 12$ sec.	$\sigma = 10$ m $T = 132$ sec.	~50 minutes Once/Day

Mission Requirements:
CAPSTONE: 10 km, 10 cm/s
LRO: 0.5 km RMS

One-Way Navigation Overview

- One-way "Beacon" navigation:
  - Deep Space Network broadcasts a constant carrier frequency modulated with a PRN code
  - Spacecraft demodulates carrier to obtain observables:
    - Doppler – received carrier freq. – expected carrier freq.
    - Range – Correlate PRN code to determine location of received signal in the code sequence, combine with Earth-Transmit Time (ETT) encoded in PRN sequence
  - Accurate frequency reference onboard critical to obtaining precise observables
    - CAPSTONE integrated a Chip Scale Atomic Clock
  - Observables processed in a traditional navigation filter to solve for spacecraft state



- Benefits:
  - One ground station can beacon to many spacecraft in the beam pattern
  - Spacecraft Autonomy – onboard processing permits spacecraft to solve for their navigation states without coherent two-way tracking time
- Results:
  - Measurement noise is ~one order of magnitude larger than two-way measurements
  - Generated OD solutions able to meet CAPSTONE's ground navigation requirements

Conclusion

- **Crosslink/One-way inertial navigation demonstrated at the Moon**
  - Proof-of-concept for CAPS – **provides a baseline** to improve upon
  - Promising results given opportunity restrictions and hardware difficulties
  - Simulations built **from the baseline** show promising autonomy capabilities necessary for reducing ground tracking
- **Technology Outlook**
  - CAPS Flight Software improvements in the works – Goals:
    - Offer a robust autonomy-enabled engineering implementation
    - NASA Core Flight System (cFS) application – deployment potential on a wide variety of cislunar missions and beyond
    - Add modular support for a wide variety of sensors for adaptability to different missions

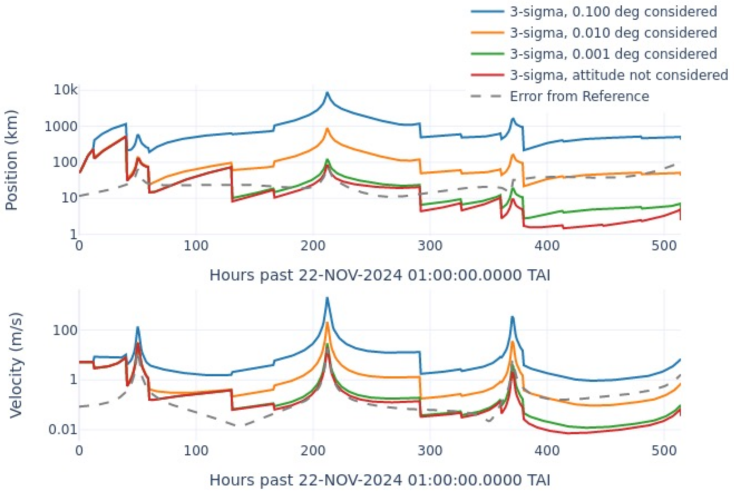
Overview of NNEP

Summary of the Technology

- Neural Networks for Easy Planning (NNEP) uses the powerful function approximation capabilities of neural networks (NNs) to enable real-time trajectory correction for spacecraft with electric or chemical propulsion.
- NN “learns” the relationship between state and control near a reference trajectory, then use the NN to optimally follow the reference path in the presence of uncertainty.
- Key benefits:
  - 1) the accuracy and optimality of running an onboard sophisticated program, and
  - 2) a low computational requirement similar to legacy linear control architectures.
- Results:
  - NNEP was trained on the ground and uploaded to the spacecraft to demonstrate OMM design
  - Onboard, NNEP ingested some ground navigation data and successfully replicated an OMM design

HOpNav

- Utilizing CAPSTONE's star trackers to demonstrate accuracy of Horizon-based Optical Navigation (HOpNav)
- Tools:
  - Goddard Image Analysis and Navigation Tool (GIANT)
    - Generates navigation observables from downlinked images
  - JPL's MONTE software toolkit
    - Used to process observables to generate a navigation solution
- 5 star tracker images were gathered over the course of a single orbit to analyze
- As expected, results are highly dependent on the attitude uncertainty
  - We see that specifying a general attitude uncertainty at $0.1°$ is necessary to capture the errors from the reference
  - Results seem to indicate $\sim 0.001°$ attitude solution uncertainty would meet CAPSTONE navigation requirement



CAPSTONE Today

- CAPSTONE was awarded a mission extension to continue operating through Dec 2025
- Working to demonstrate autonomy through CAPS and NNEP integration
  - CAPS one-way navigation solution feeds NNEP which will design OMMs
- Continue demonstrating horizon based optical navigation capabilities using lunar images
- Continuing to work with the Gateway team to demonstrate different operational scenarios
  - Currently studying how to better maintain proximity to the reference trajectory and the impacts/recovery of perturbations
- Utilizing CAPSTONE as a technology demonstration platform
  - Working with a number of government and commercial partners to demonstrate a variety of technologies in cislunar space
  - Focus is on Spacecraft Autonomy and Standards Based Interoperable Communications

(CAPSTONE)

Cislunar Autonomous Positioning System Technology, Operations, and Navigation Experiment

Demonstrating an innovative spacecraft-to-spacecraft navigation solution at the Moon from a near rectilinear halo orbit slated for Artemis' Gateway.

The CAPSTONE mission is managed by NASA's Small Spacecraft Technology Program. NASA's Advanced Exploration Systems funds the launch and supports mission operations. The mission is developed and operated by Advanced Space, LLC.