# Navigation and Maneuver Planning Results from the autoNGC CAPSTONE Flight Test

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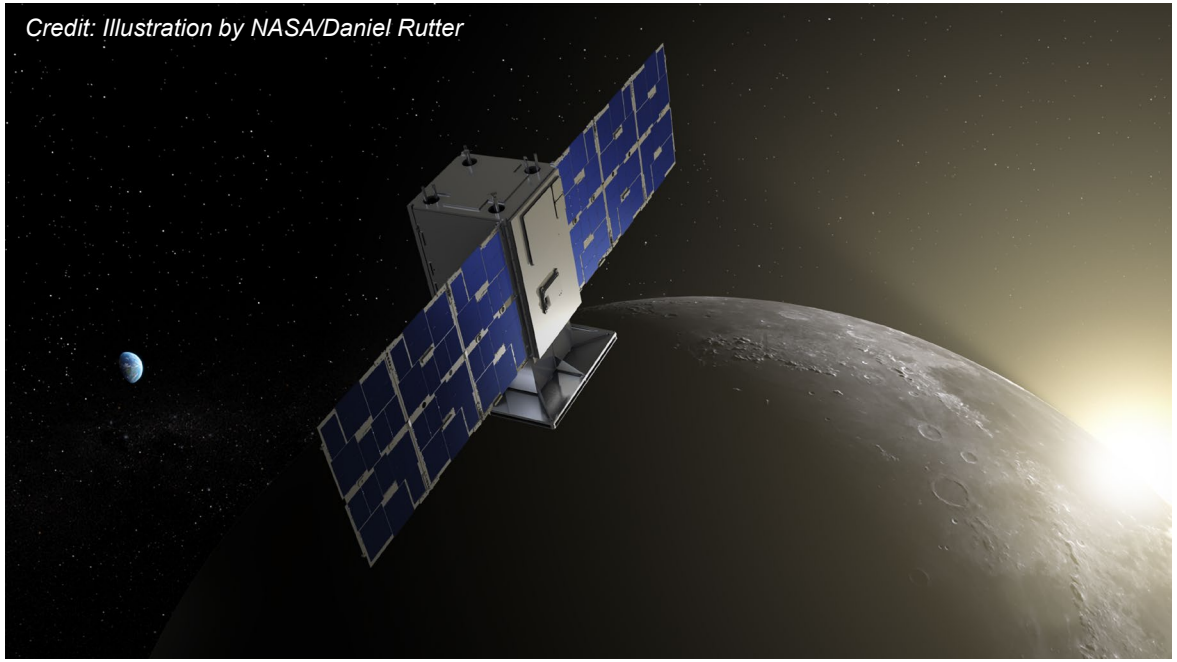
# Introduction

CAPSTONE Spacecraft in Lunar Orbit

*Credit: Illustration by NASA/Daniel Rutter*

# Introduction – autoNGC Motivation & Background

- Drivers for Onboard GN&C Autonomy
  - Reduce reliance on over-subscribed ground assets and costly ground operations
  - Enable new mission capabilities:
    - Low-latency mission operations
    - In-situ planning and execution
    - Complex missions at far distances, for example, Touch-and-Go (TAG) Guidance for small body sample return
    - Distributed Systems Missions (DSMs)

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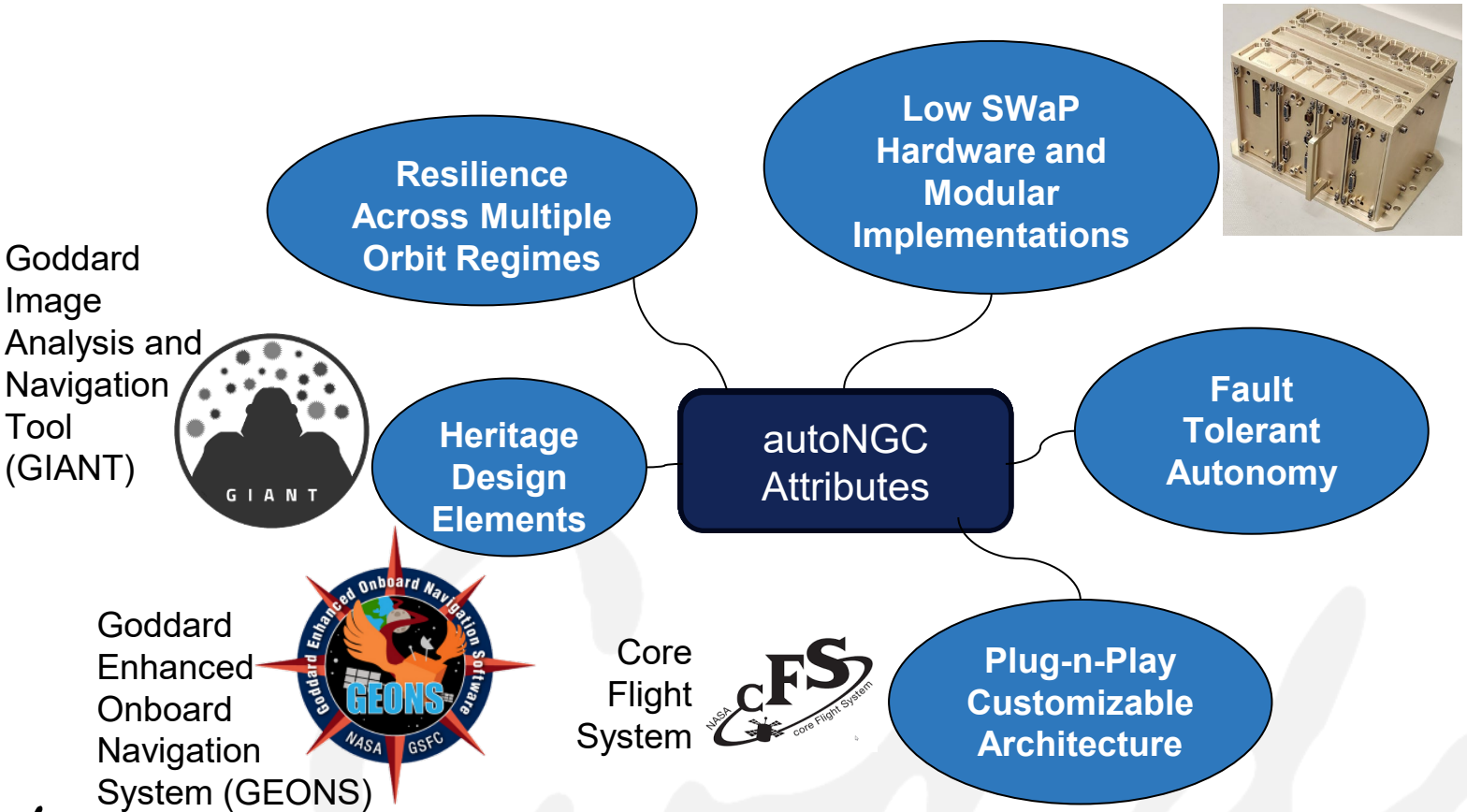
# Introduction – autoNGC Background

- autoNGC is an onboard software application suite, built on the core Flight System (cFS), and flight hardware that performs **real-time autonomous** spacecraft **navigation, guidance, and control** (NGC).

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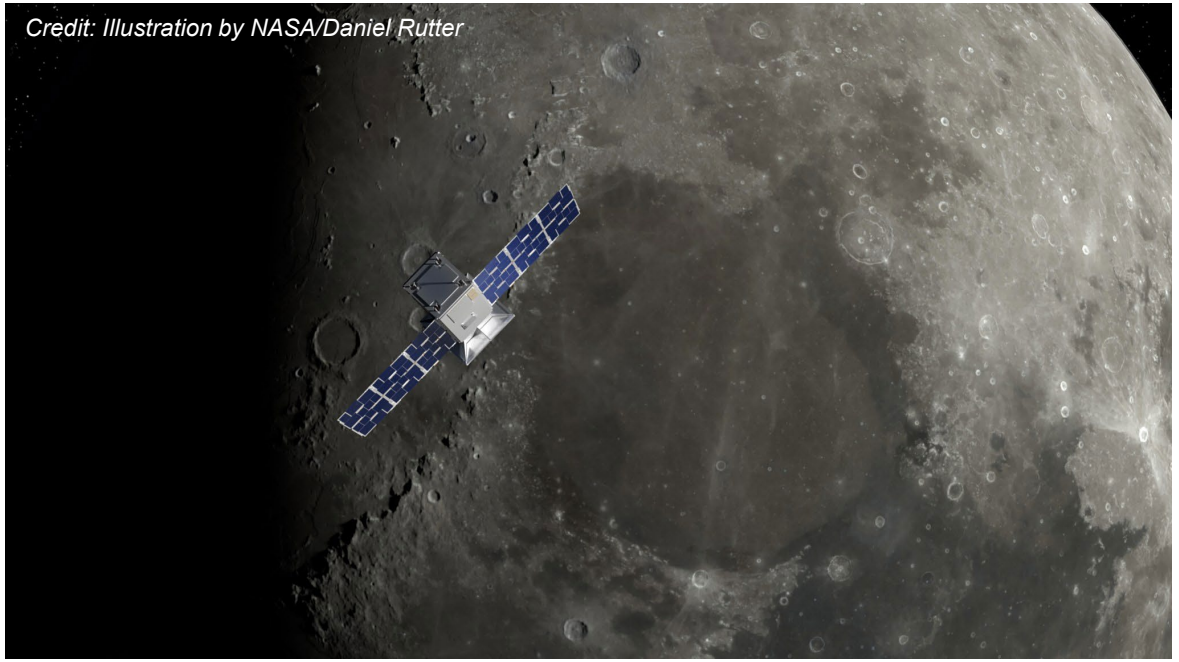
# Introduction – CAPSTONE Mission

- CAPSTONE Mission
  - 12U CubeSat launched in 2022.
  - Developed by Advanced Space, Terran Orbital, and other partners.
  - Served as a pathfinder for the Gateway space station.
  - Demonstrated new navigation and communication technologies.
  - Completed its primary mission objectives in 2023 and now operates in an extended mission phase.
  - Operates as a technology demonstration testbed.

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# Introduction – autoNGC CAPSTONE Flight Test

- **The objective of the autoNGC experiment was to mature to TRL 7 several of its onboard lunar navigation and guidance capabilities using CAPSTONE sensors and hardware.**

| | autoNGC Experiments | Flight Test |
|---|---|---|
| Crawl | 2-way DSN Doppler and PN range – near real-time onboard processing | Jan 2026 |
| | ADCS and Accelerometer processing during and after maneuvers | |
| Walk | Optical navigation with star tracker: Limb-based (Moon, Earth) and celestial (other bodies) | Apr 2026 |
| Run | 1-way forward DSN Doppler (modified) | Feb 2026 |
| | Onboard Maneuver Planning using GSFC app | |

- **The success criteria of the autoNGC experiments**
  - ☑ Onboard navigation performance achieved on the flight test is within the expected tolerance of the ground test predictions accounting for all deviations between ground and flight tests
  - ☑ Onboard maneuver plans are verified on the ground to achieve the desired NRHO station keeping objectives
- **The CAPSTONE flight test was a steppingstone towards achieving long-term autoNGC goals.**

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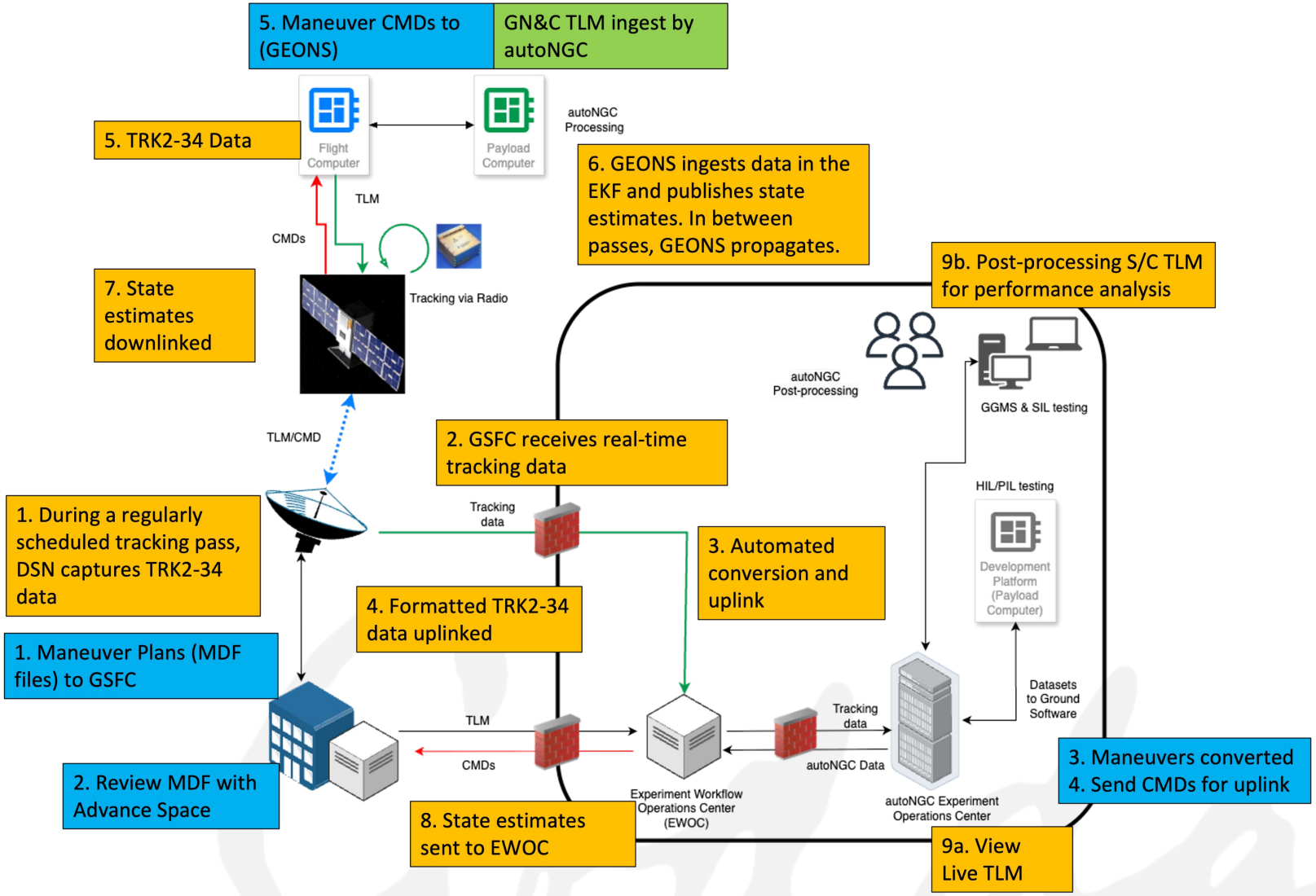
# Experiment Overview – Flight Operations

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# Onboard Navigation

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# Onboard Navigation – Concept of Operations

## Sample autoNGC CAPSTONE Flight Experiment Contact Schedule

| | Mo | Tu | We | Th | Fr | Sa | Su | Mo | Tu | We | Th | Fr | Sa | Su | Mo | Tu | We | Th | Fr | Sa | Su | Mo (HOL) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 1/26/2026 | 1/27/2026 | 1/28/2026 | 1/29/2026 | 1/30/2026 | 1/31/2026 | 2/1/2026 | 2/2/2026 | 2/3/2026 | 2/4/2026 | 2/5/2026 | 2/6/2026 | 2/7/2026 | 2/8/2026 | 2/9/2026 | 2/10/2026 | 2/11/2026 | 2/12/2026 | 2/13/2026 | 2/14/2026 | 2/15/2026 | 2/16/2026 |
| DOY | 26 | 27 | 28 | 29 | 30 | 31 | 32 | 33 | 34 | 35 | 36 | 37 | 38 | 39 | 40 | 41 | 42 | 43 | 44 | 45 | 46 | 47 |
| Flight | FLT-Crawl | FLT-Crawl | FLT-Crawl | FLT-Crawl | FLT-Crawl | FLT-Crawl | FLT-Crawl | FLT-Craw | FLT-Crawl | FLT-Craw | FLT-Crawl | FLT-Craw | FLT-Crawl | FLT-Crawl | FLT-Crawl | FLT-Crawl | FLT-Crawl | FLT-Crawl | FLT-Crawl | FLT-Crawl | FLT-Crawl | |
| OMM (EST/EDT) | | | 178 14:00 | | | | | | ~~179 22:55~~ | | | | | | | | ~~180 08:00~~ | | | | | |
| MAM | | 178 | | | | | | ~~179~~ | | | | | | | | | | | | | | ~~181~~ |
| MDF CMD | | | 178 | | | | | | ~~179~~ | | | | | | | | | | | | | ~~181~~ |
| Range to Moon (km) | 52374 | 66795 | 70536 | 64242 | 46568 | 7573 | 42623 | 62380 | 70360 | 68450 | 56424 | 30867 | 26681 | 54458 | 68007 | 71815 | 66630 | 51464 | 20400 | 35672 | 58744 | 69400 |
| SPE<120 deg (EST/EDT) | XXXXXXXX | XXXXXXXX | XXXXXXXX | XXXXXXXX | XXXXXXXX | XXXXXXXX | XXXXXXXX | XXXXXXX | XXXXXXXX | XXXXXXX | XXXXXXXX | XXXXXXX | XXXXXXXX | XXXXXXXX | XXXXXXXX | XXXXXXXX | XXXXXXXX | 8:06 | | | | |
| DSS-17 (EST/EDT) 6 | | | | | | | | | | | | | ~~05:30-09:15~~ | | | | ~~07:00-10:45~~ | ~~08:00-12:00~~ | | ~~10:20-14:20~~ | | |
| DSS-24 (EST/EDT) 7 | | | | | | | | | | | | | | | | | | | | | | |
| DSS-25 (EST/EDT) 1 | | | 00:30-02:45 | | | | | | 01:05-04:50 | | 01:50-05:35 | | | | | | | | | | | |
| DSS-26 (EST/EDT) 8 | | | | | | 04:10-07:30 | 02:50-06:35 | | | | | | | | | | | | | | | |
| DSS-34 (EST/EDT) 9 | | | | | | | | | | | | | | 07:40-10:40 | | | 09:30-10:15 | | | | | |
| DSS-35 (EST/EDT) 2 | | | | | | | | | | | | | | | 08:05-09:40 | | | | 12:00-14:00 | 14:30-16:35 | | 19:05-20:05 |
| DSS-36 (EST/EDT) 10 | | | | | | | | | | | | | | | | | | | | | | |
| DSS-54 (EST/EDT) 13 | | | | | | | | | | | | | | | | | | | | | | |
| DSS-55 (EST/EDT) 14 | 12:40-16:25 | | 13:00-16:45 | | | | | | 21:55-01:40 | | | | 20:45-23:05 | | | | | | 03:10-04:10 | | | |
| DSS-56 (EST/EDT) 15 | | ~~18:00-20:15~~ | | | | | | | | | | | | | | | | | | | | |

- Onboard filtering of 2-way DSN measurements (PN range and Doppler) uplinked from the ground in near real-time to estimate the position and velocity of CAPSTONE.
  - Near real-time updates of the onboard navigation state from the 2-way measurements allows faster and more resilient autonomous operations
- Onboard processing of spacecraft ADCS and accelerometer data during and after maneuvers.
  - Orbit maintenance maneuvers can be measured using the onboard accelerometer.
  - Accelerometer data can help navigation recover faster after a maneuver.

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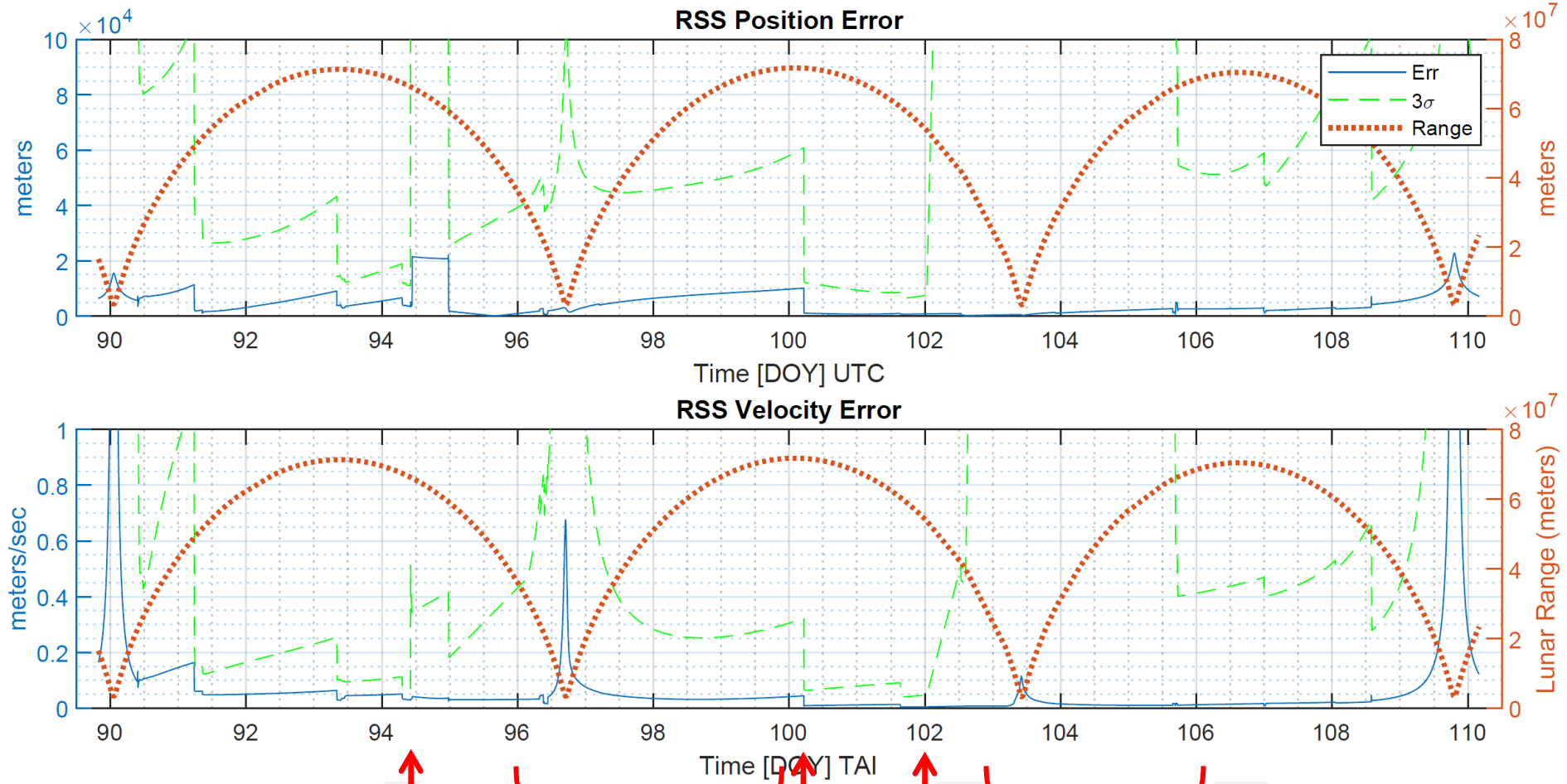
# Onboard Navigation – Results and Analysis

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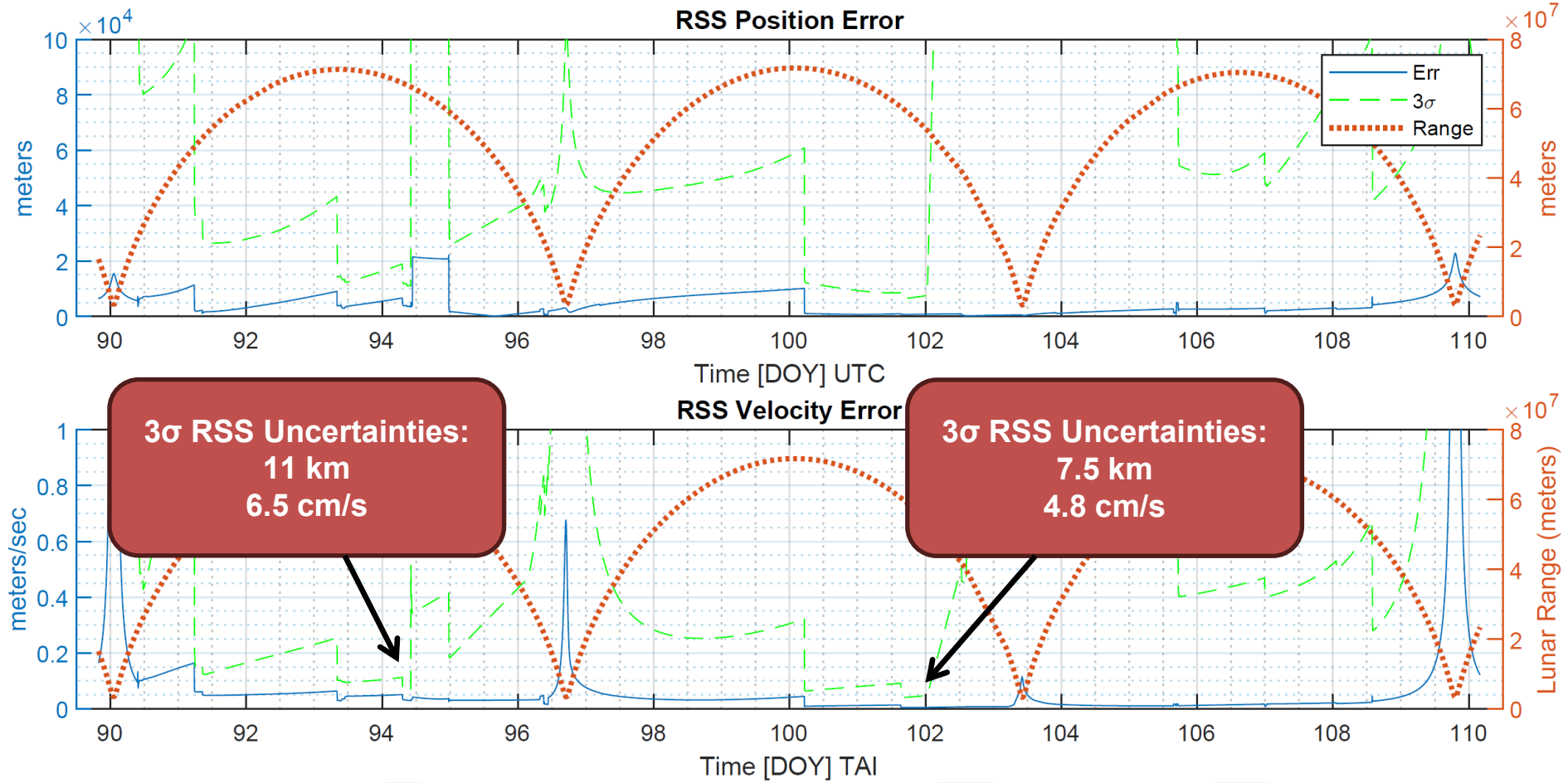


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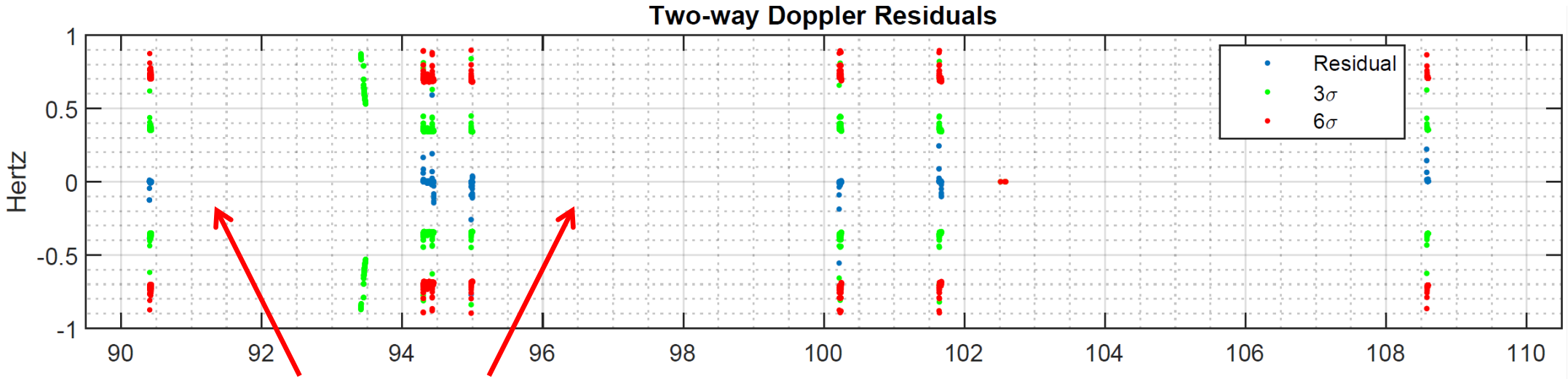
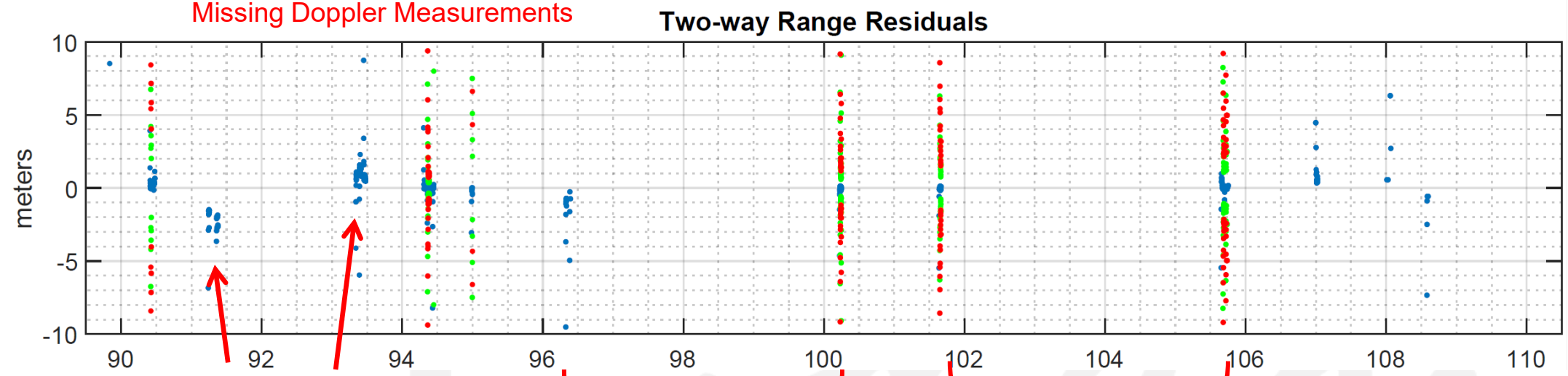
# Onboard Navigation – Results and Analysis




Missing Doppler Measurements




Dropped Ramp Records

Gap in tracking due to Artemis 2

Gap in tracking due to ground software anomaly

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# Onboard Maneuver Planning

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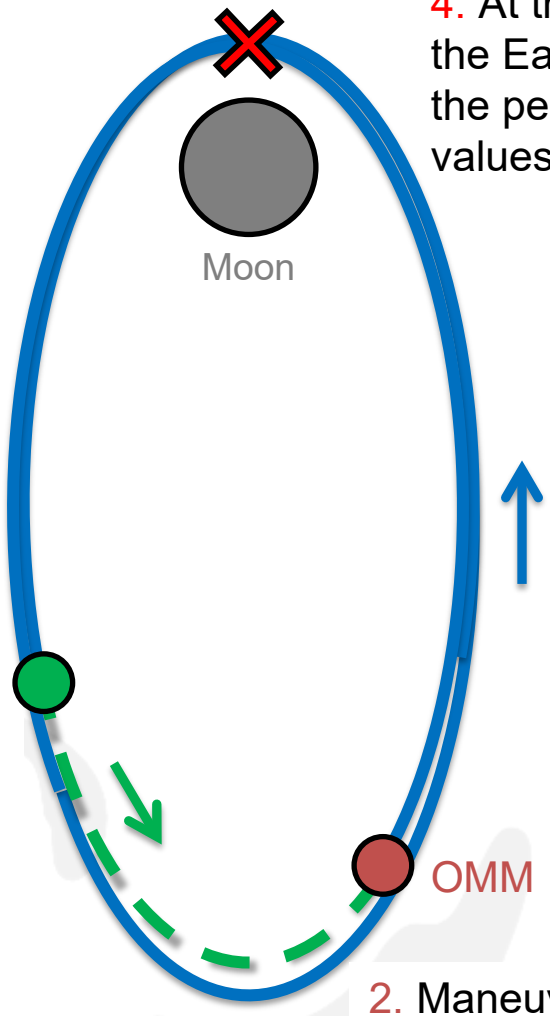
# Onboard Maneuver Planning – Concept of Operations




4. At the target perilune, the $V_x$ component of the Earth-Moon rotating frame velocity and the perilune epoch are constrained to match values from a reference NRHO.

3. The targeting algorithm propagates from the OMM to 6.5 revolutions “downstream”.

1. Command is sent from the ground that causes the onboard estimate to be sent to the maneuver planning app. This command also contains targeting problem settings.

2. Maneuver planner propagates from the DCO time to the scheduled time of the Orbital Maintenance Maneuver (OMM) as defined by the CAPSTONE operations team.

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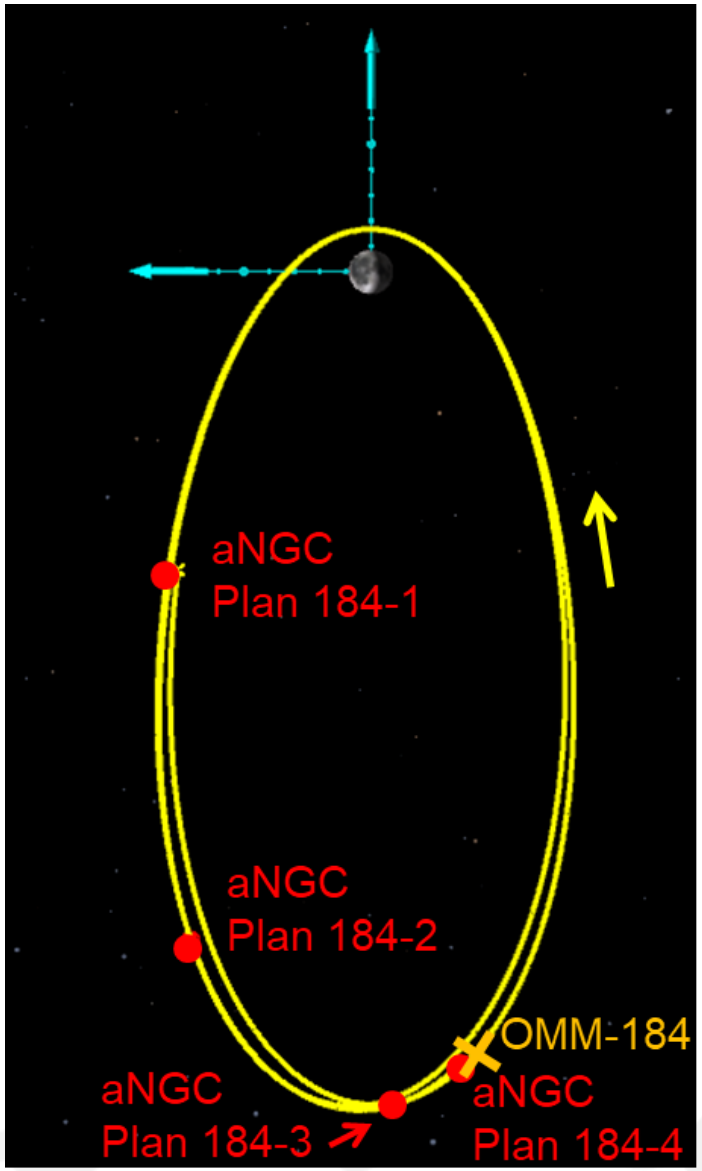
# Onboard Maneuver Planning – Results and Analysis

| Maneuver Plan | Data Cutoff Epoch (UTC) | Delta-V |
|---|---|---|
| **OMM-182 — Scheduled for 2026 Feb 24 09:25:00 UTC** | | |
| Monte Plan | 2026 Feb 17 08:30:19 | 9.8 cm/s |
| aNGC Plan 182-1 | 2026 Feb 23 22:57:58 | 13.7 cm/s |
| **OMM-183 — Scheduled for 2026 Mar 02 09:55:00 UTC [Cancelled]** | | |
| Monte Plan | 2026 Feb 27 12:47:08 | 4.1 cm/s |
| aNGC Plan 183-1 | 2026 Feb 28 22:05:17 | 23.7712 cm/s |
| **OMM-184 — Scheduled for 2026 Mar 09 02:55:00 UTC** | | |
| Monte Plan | 2026 Mar 06 12:30:38 | 7.8 cm/s |
| aNGC Plan 184-1 | 2026 Mar 05 07:36:43 | 84.7 cm/s |
| aNGC Plan 184-2 | 2026 Mar 06 10:27:53 | 48.2 cm/s |
| aNGC Plan 184-3 | 2026 Mar 08 11:58:29 | 40.0 cm/s |
| aNGC Plan 184-4 | 2026 Mar 09 02:13:15 | 28.1 cm/s |
| **OMM-185 — Scheduled for 2026 Mar 15 18:25:00 UTC [Cancelled]** | | |
| Monte Plan | 2026 Mar 13 08:40:27 | 4.6 cm/s |
| autoNGC Plan 185-1 | 2026 Mar 10 04:55:57 | 27.0 cm/s |
| autoNGC Plan 185-2 | 2026 Mar 14 16:45:39 | 14.5 cm/s |

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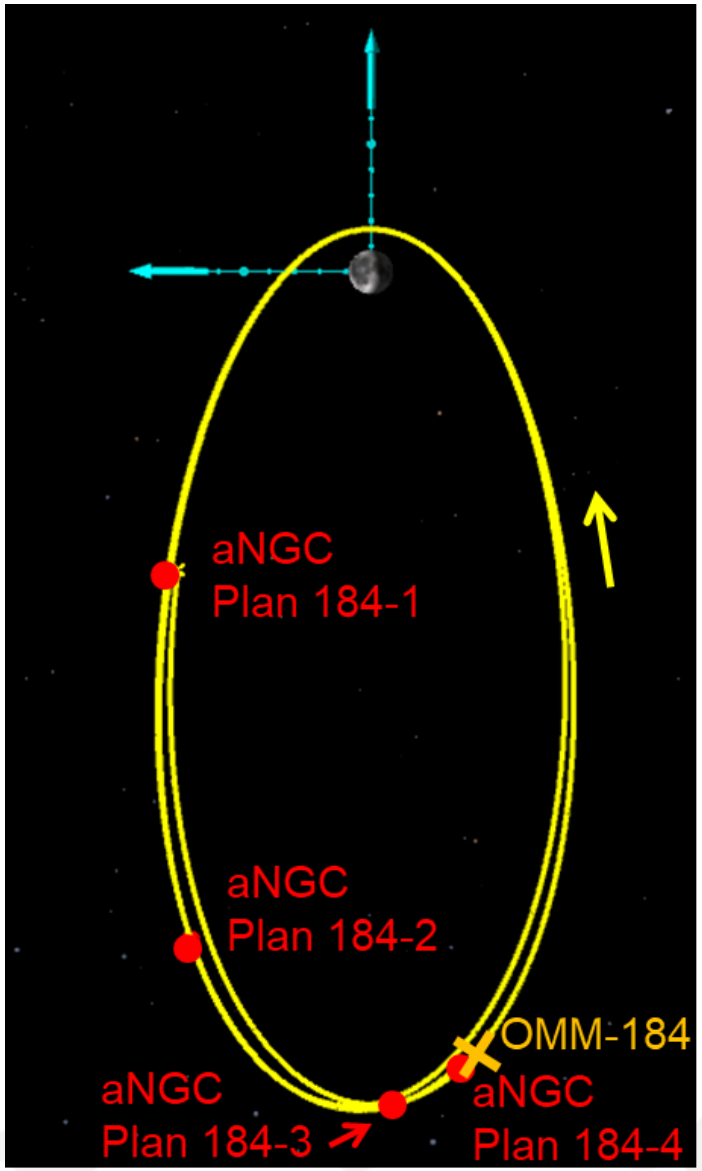
# Onboard Maneuver Planning – Results and Analysis

| Maneuver Plan Number & DCO Epoch | RSS Pos. Error | RSS Vel. Error | $\Delta v$ |
|---|---|---|---|
| **aNGC Plan 184-1** 2026 Mar 05 07:36:43 | 81.9 km | 107.4 cm/s | 84.7 cm/s |
| **aNGC Plan 184-2** 2026 Mar 06 10:27:53 | 28.9 km | 16.2 cm/s | 48.2 cm/s |
| **aNGC Plan 184-3** 2026 Mar 08 11:58:29 | 39.1 km | 15.7 cm/s | 40.0 cm/s |
| **aNGC Plan 184-4** 2026 Mar 09 02:13:15 | 24.7 km | 5.3 cm/s | 28.0 cm/s |

- The Advanced Space maneuver design process, conducted on the ground using Monte and SNOPT, had an uncertainty requirement at DCO of 10km and 10cm/s 3σ.
- Differences between autoNGC and Monte solutions are due to:
  - Estimation error
  - Optimal vs. feasible solutions
  - Differences in dynamical model and numerical integration

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# Concluding Remarks

- Flight Experiment Summary:
  - Demonstrated processing of two-way DWE and accelerometer measurements in an onboard real-time filter.
  - Achieved RSS position uncertainties of less than 10km in less than a week despite data quality challenges.
  - Resolved network connection issues leading to a reliable TRK-2-34 stream.
  - Computed four NRHO orbital maintenance maneuvers onboard using the onboard estimate.
  - Satisfied NRHO station-keeping constraints with onboard OMM and explored reasons for differences from OMM computed on the ground.
  - Advanced the TRL of the autoNGC flight software suite.

- Next Steps:
  - Mature and extend autoNGC capabilities through participation in CAPSTONE 2.
  - Continue partnerships with industry and other government agencies.

- Special thanks to Advanced Space and Terran Orbital! We are also grateful for the support of the ground systems teams at NASA Goddard along with the GEONS and cGIANT development teams.

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# Backup Slides

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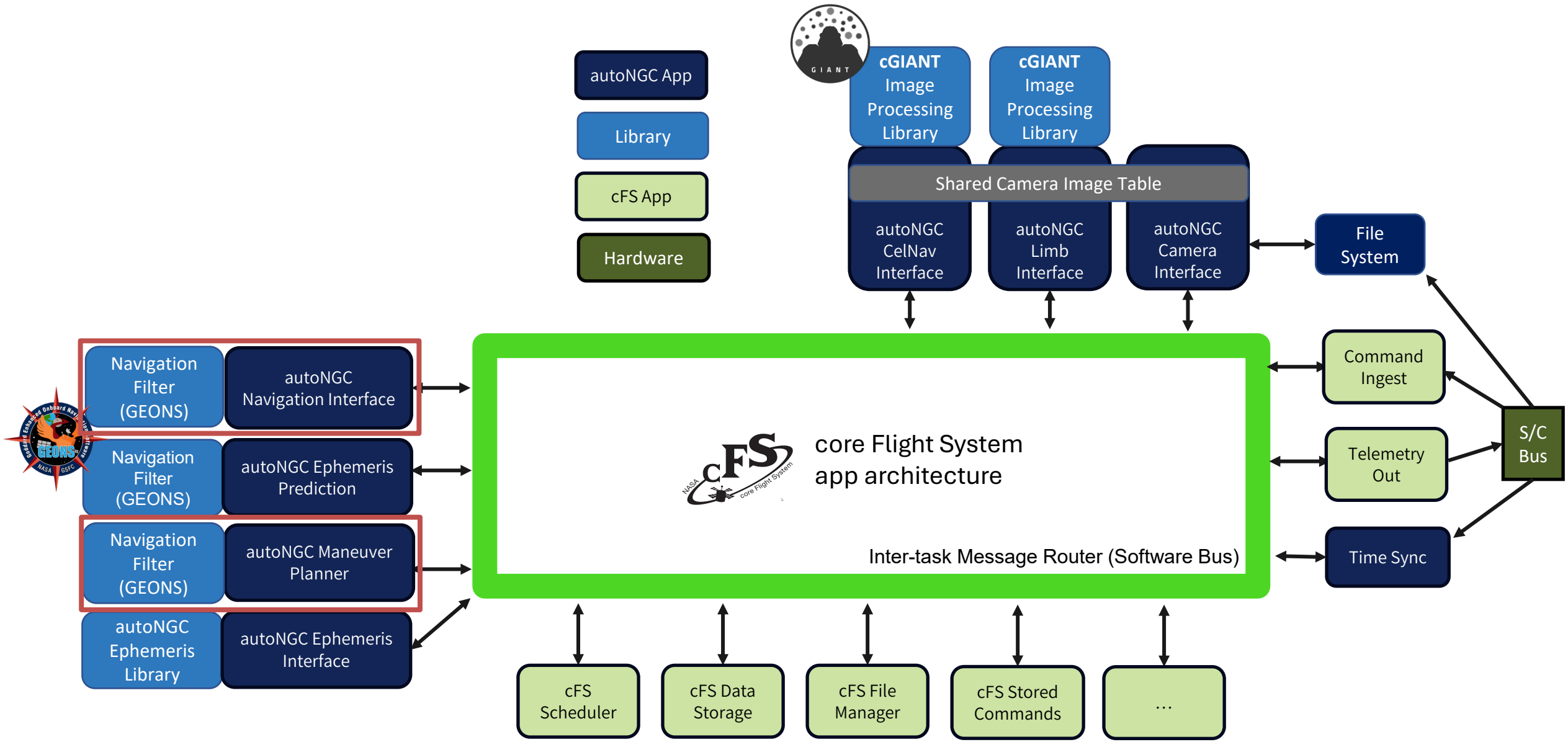
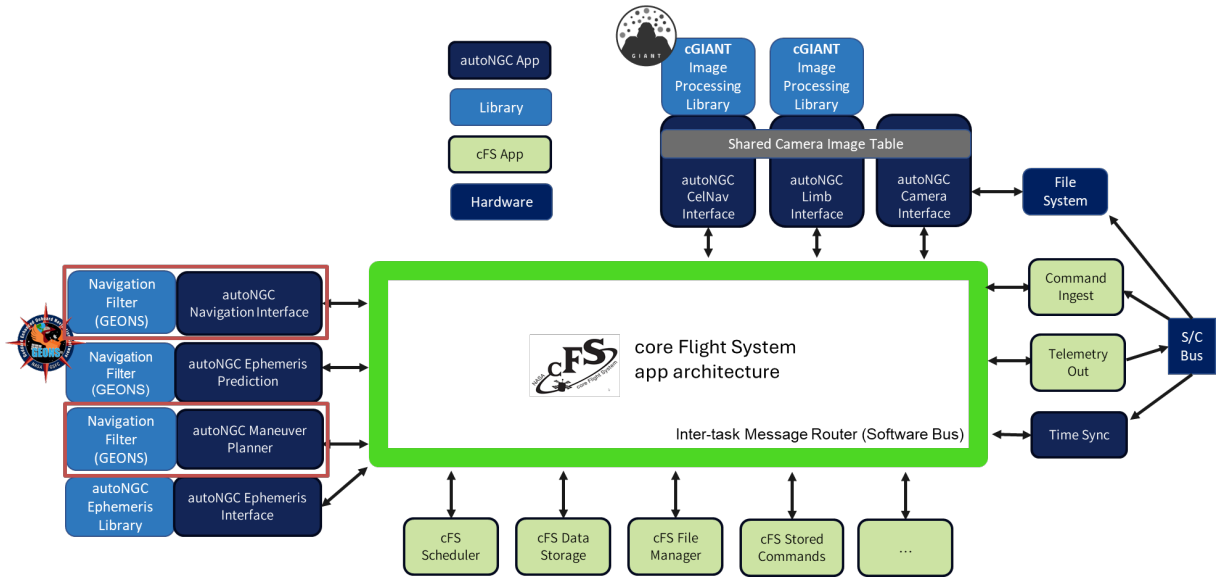
# Introduction – autoNGC Background



# Experiment Overview – Flight Software and Pre-Flight Testing




## Pre-Flight Software Test Campaign

GEONS Ground MATLAB Simulation → Software in-the-loop Testing → Processor in-the-loop Testing → DIGLET → CAPSTONE FlatSat → Flight Delivery and Uplink to Spacecraft

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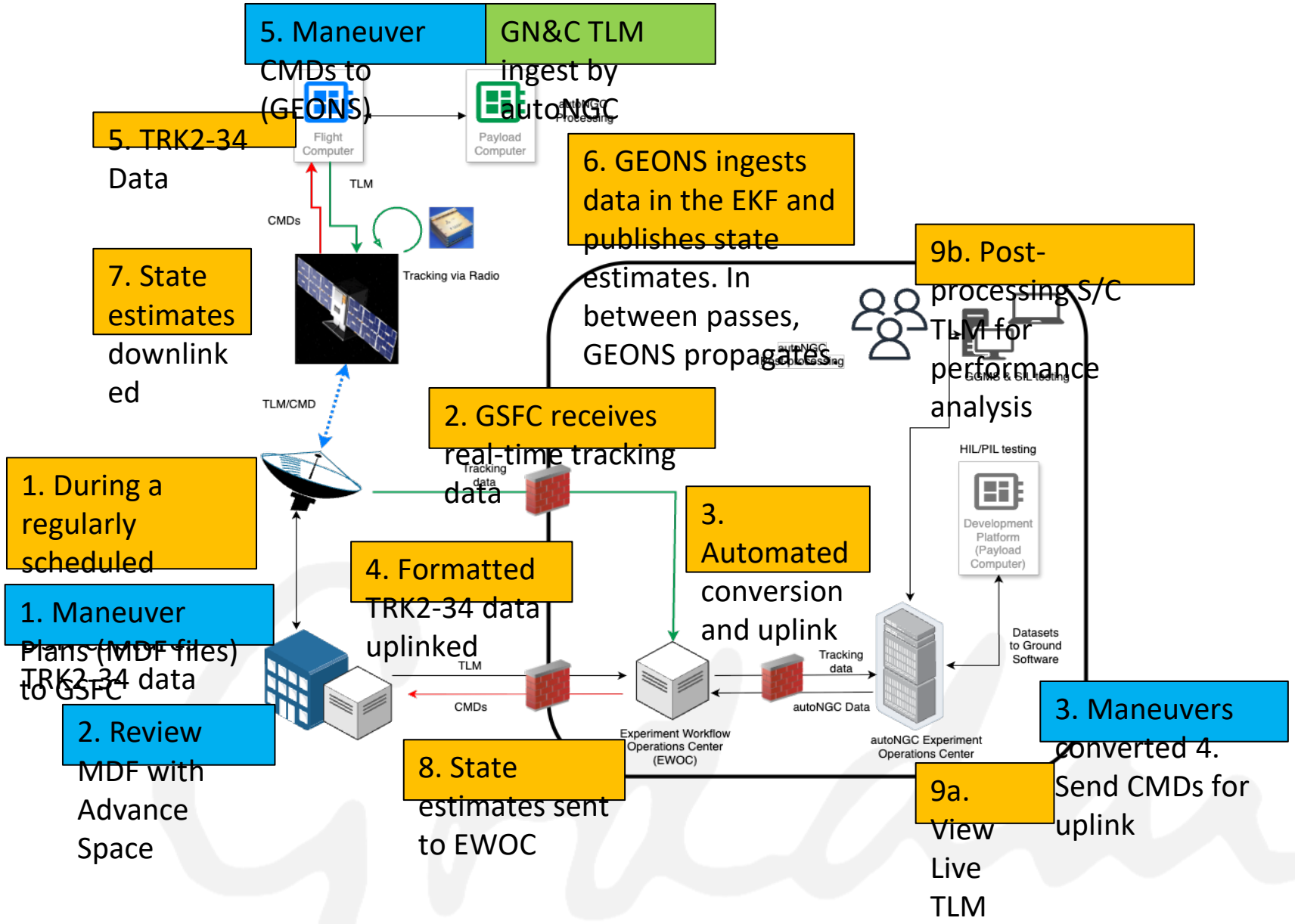
# Experiment Overview – Flight Operations

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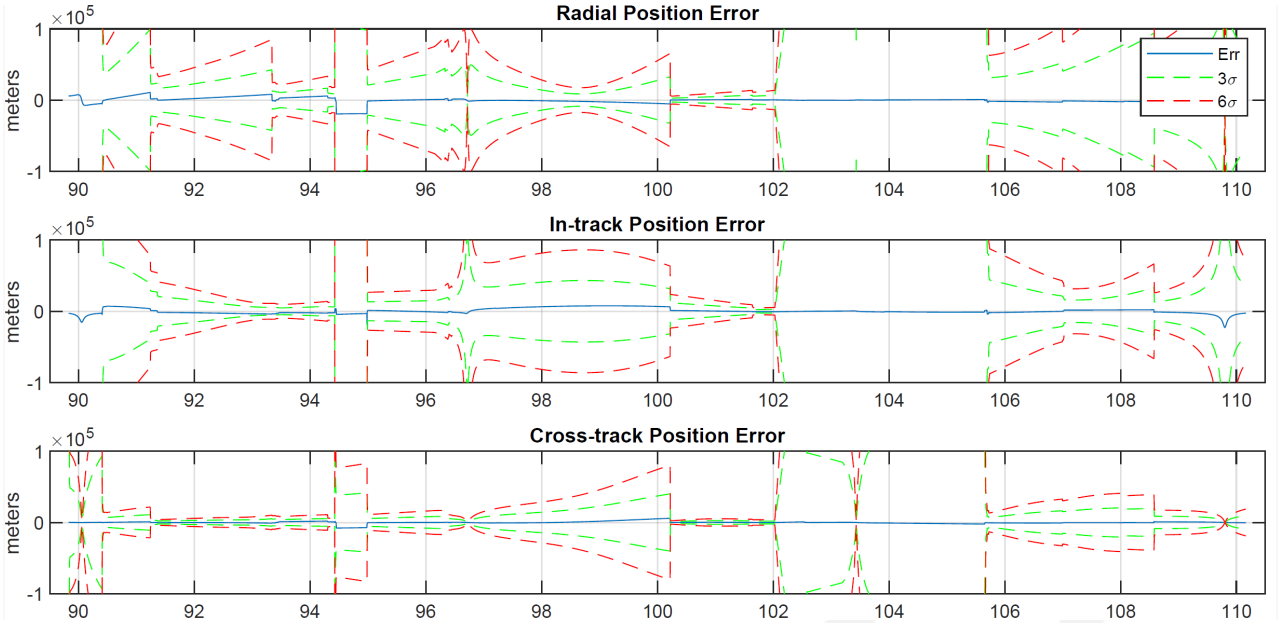
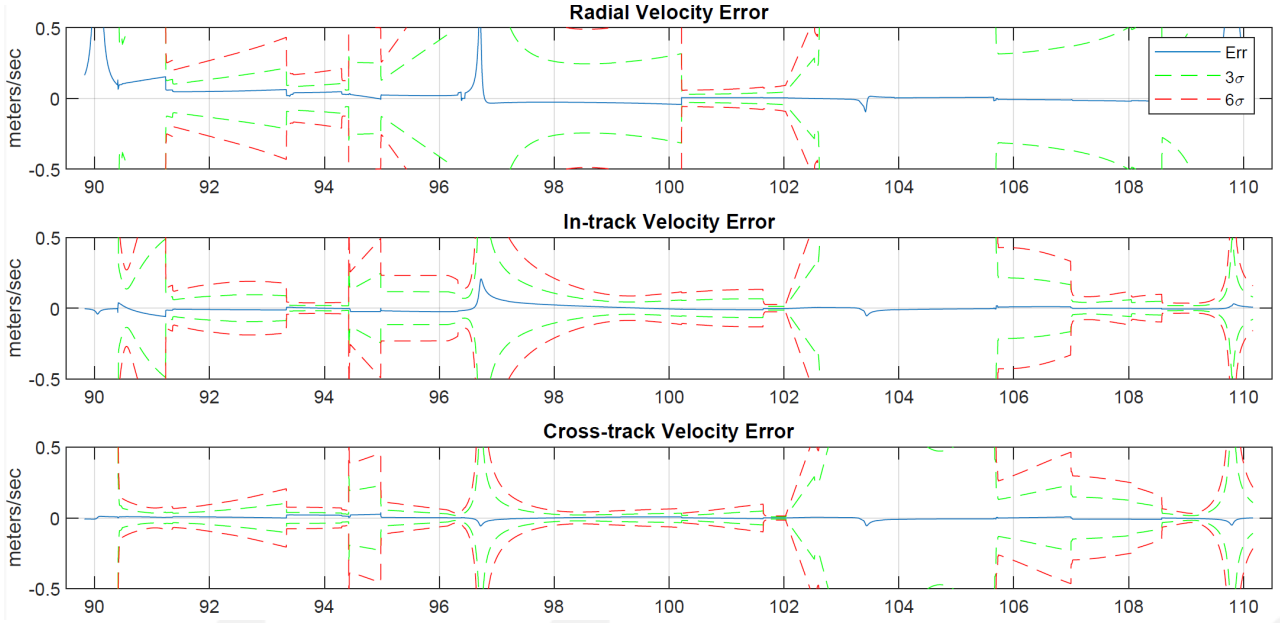
# Onboard Navigation – Results and Analysis

## Radial-Intrack-Crosstrack (RIC) Position Error and Uncertainty




## Radial-Intrack-Crosstrack (RIC) Velocity Error and Uncertainty

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# Onboard Maneuver Planning – Results and Analysis

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