Onboard Autonomy with autoNGC

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Autonomous Navigation

- NASA GSFC has been developing autonomous navigation, guidance, and control (autoNGC) technology that addresses many of the NASA STMD shortfalls
  - 1557: Position, Navigation, and Timing (PNT) for In-Orbit and Surface Applications
  - 1531: Autonomous Guidance and Navigation for Deep Space Missions
  - 1559: Deep Space Autonomous Navigation
  - 1431: Access Beyond LEO for Small Spacecraft
  - 1432: Rendezvous, Proximity Operations, and Debris Remediation using Small Spacecraft
- autoNGC is an enabler for future missions including Moon-to-Mars

What is autoNGC?

*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)*

Where am I?

How do I get to where I want to go?

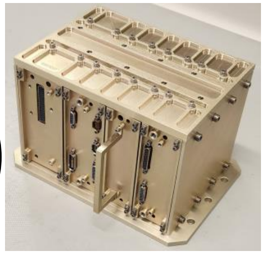
How do I stay on the planned path?

Why autoNGC?

- Reduces reliance on over-subscribed ground assets and costly ground operations
- Enables new mission capabilities
  - *Low latency mission operations*
  - *Complex missions at far distances, e.g., Touch-and-Go (TAG) Guidance*
  - *In-situ planning and execution*
  - *Distributed Systems Missions (DSMs)*
  - *Dynamic replanning/reallocation of orbital assets*

autoNGC Attributes

- **Resilience Across Multiple Orbit Regimes**
- **Low size, weight, and power (SWaP) Hardware and Modular Implementations**
- **Fault Tolerant Autonomy**
- **Plug-n-Play Customizable Architecture**
- **Heritage Design Elements**



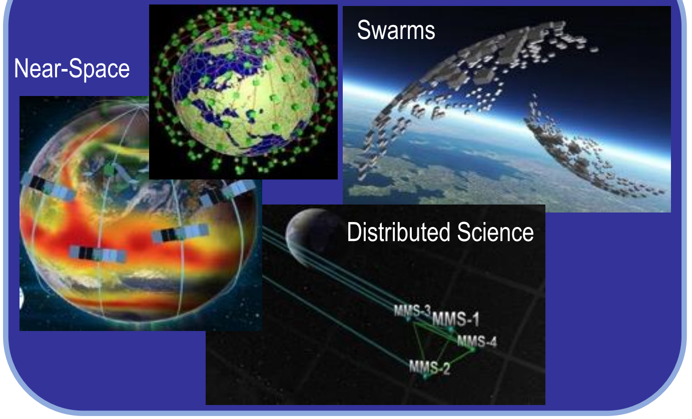
Goddard Image Analysis and Navigation Tool (GIANT)

Goddard Enhanced Onboard Navigation System (GEONS)

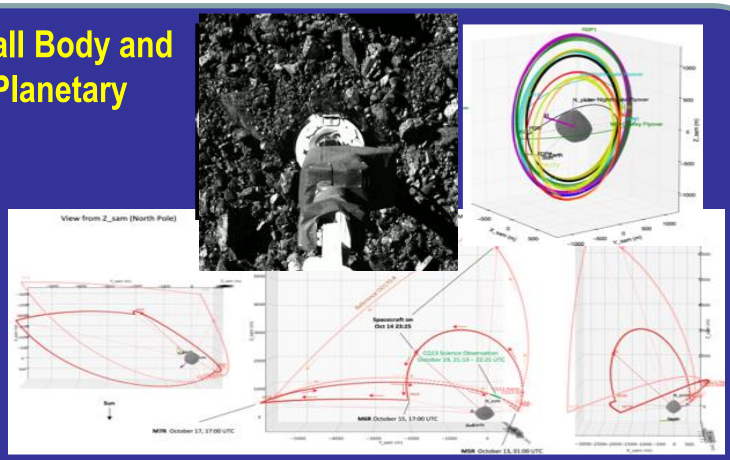
Core Flight System

autoNGC Supports Multiple Orbit Regimes and Mission Types

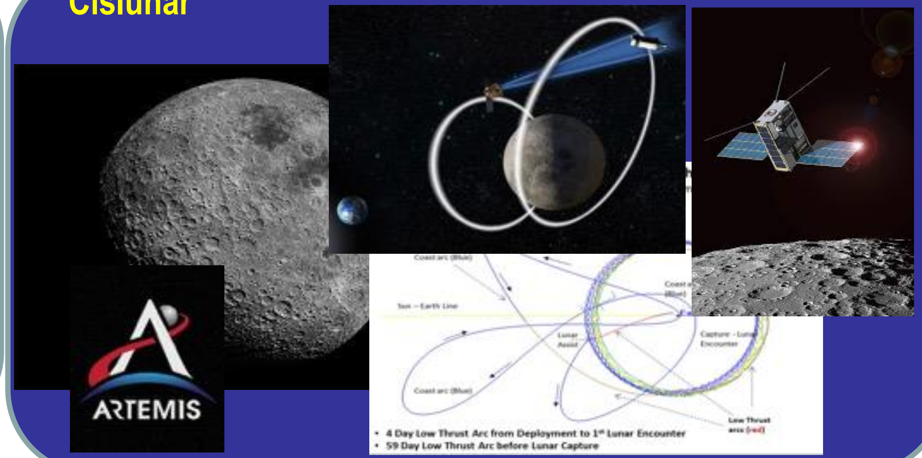
Distributed Systems Missions

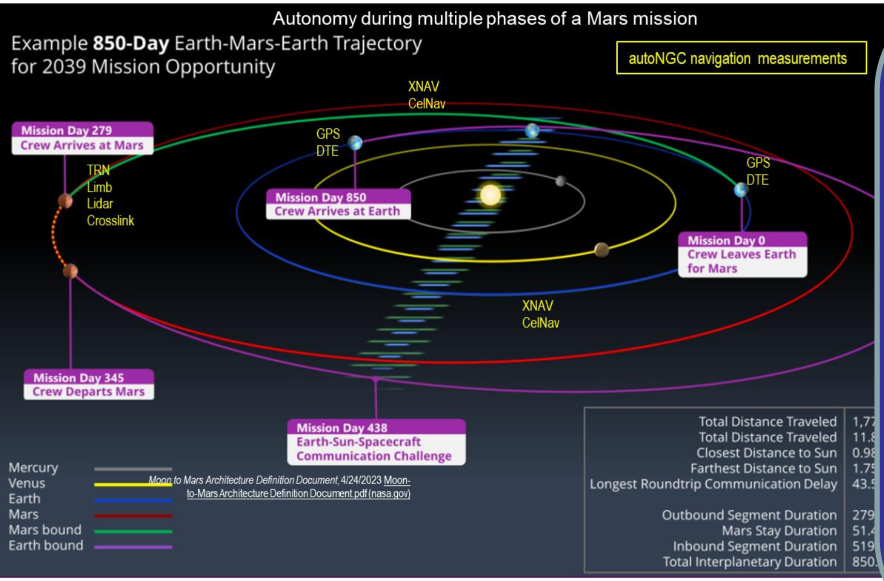


Small Body and Planetary

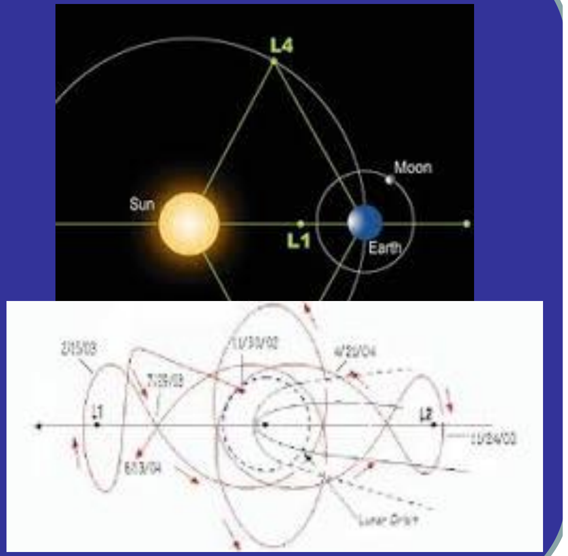


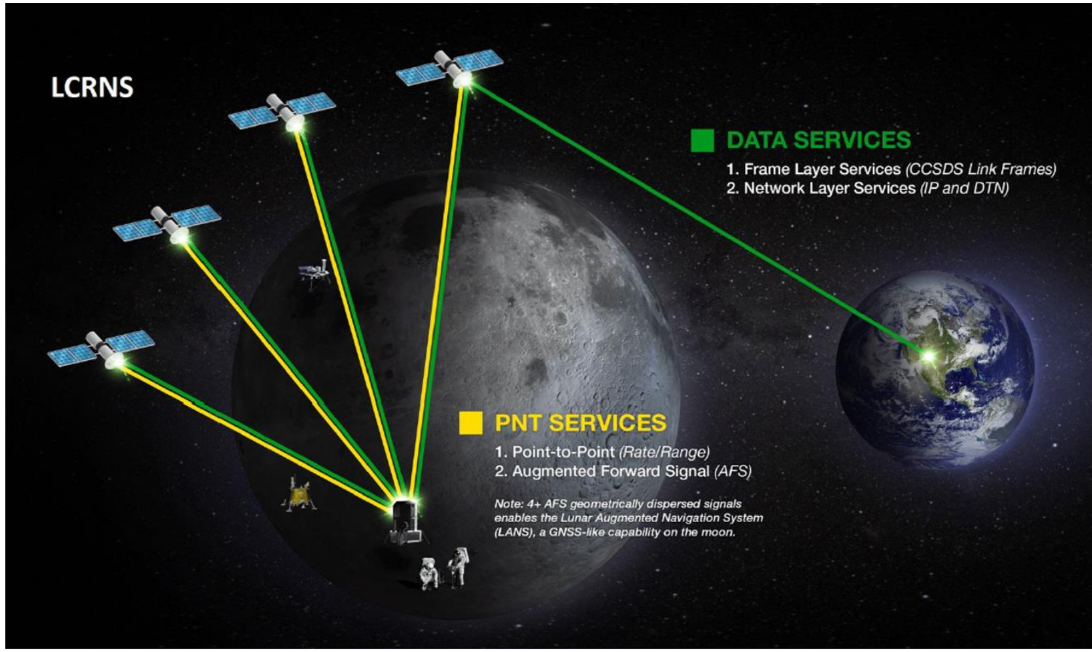
Cislunar



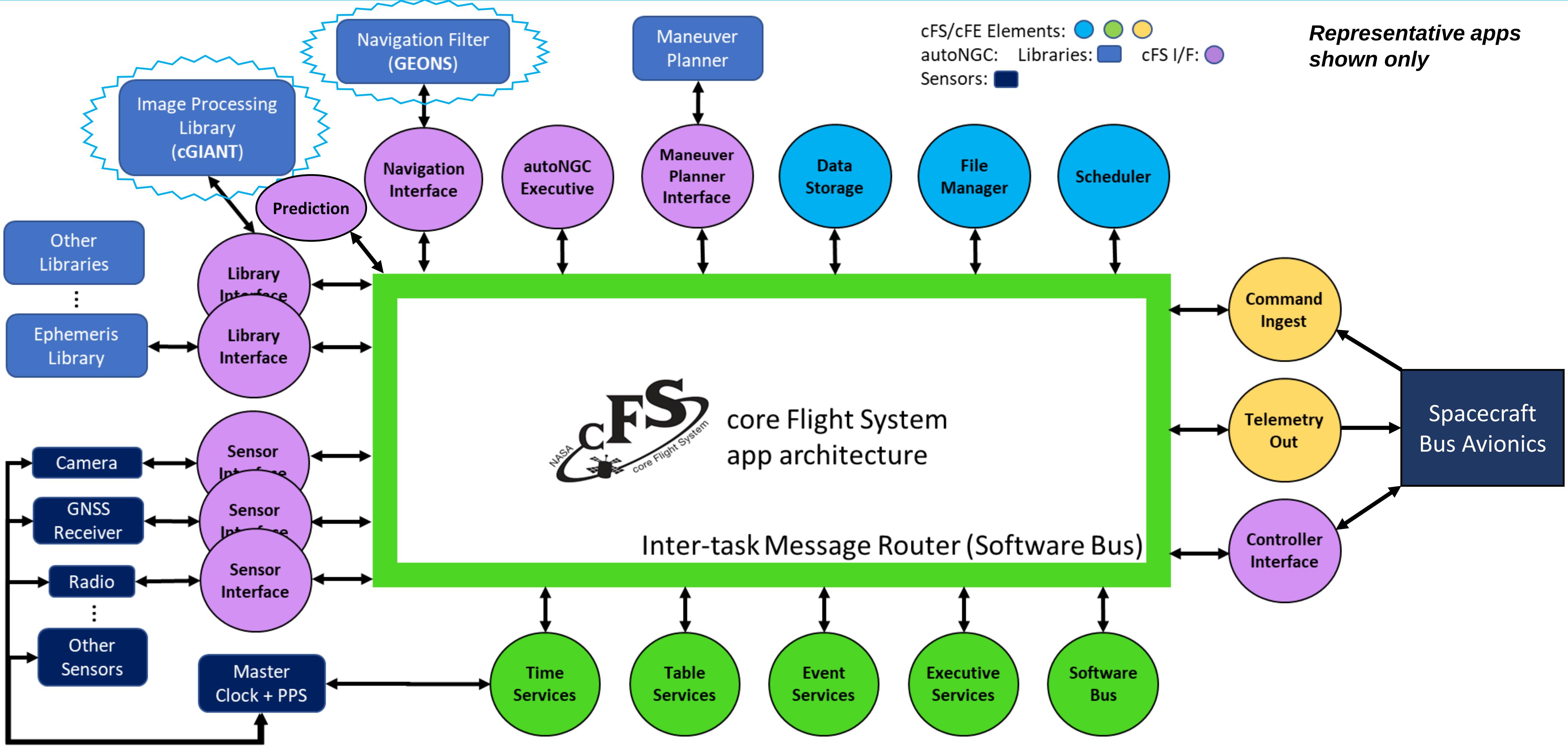


Libration





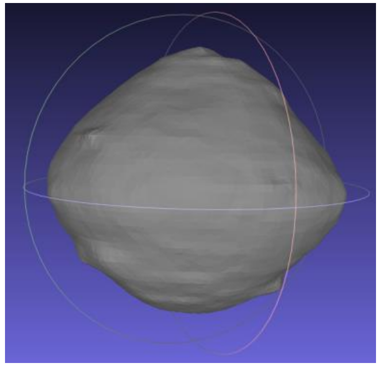
autoNGC Flight Software on cFS Architecture



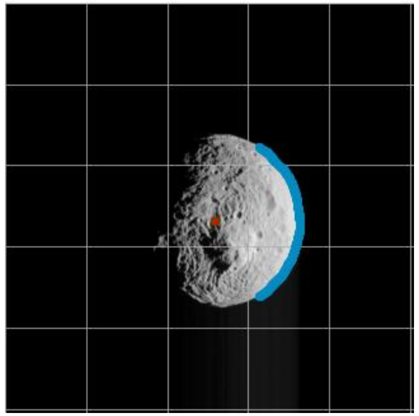
cFS Goddard Image Analysis and Navigation Tool (cGIANT)

- cFS app that performs autonomous onboard image processing for precision optical navigation (OpNav) without ground-in-the-loop delays
- State-of-the-art algorithms with ground heritage on OSIRIS-REx
- Enables navigation relative to bodies whose trajectories and shapes are not well known

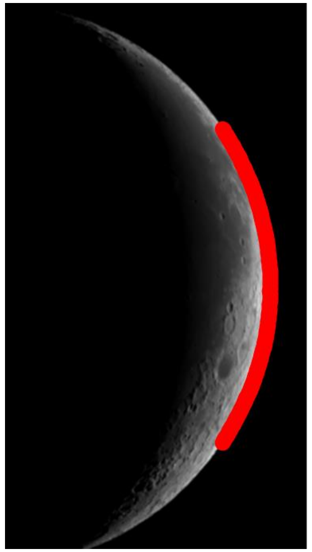
- Sub-pixel level measurements of
  - Center-finding line-of-sight
  - Limb-based line-of-sight and range to target
  - Surface feature navigation for known surfaces
  - Precision attitude estimation using star fields
  - Celestial navigation
  - Autonomous limb-based shape modeling



A shape model of Bennu built autonomously using cGIANT



Limb observations of Vesta extracted using cGIANT



Moon limb observations extracted using cGIANT

Goddard Enhanced Onboard Navigation System (GEONS)

- Performs navigation for 1+ user satellites or surface assets, individually or simultaneously, estimating absolute and relative orbital states, clock errors, and additional parameters
- UD-factorized extended Kalman Filter, $4^{th}/8^{th}$ order RK integrator, realistic process noise models for onboard real-time navigation – 20+ years flight heritage
- Currently supporting: Terra, MMS, GPM, NICER/SEXTANT

- Measurement types:
  - Nominal and weak signal GNSS, WAAS
  - 1-way forward DSN/GN/TDRSS
  - 2-way DSN/GN
  - Crosslink
  - Celestial object bearing angles
  - Terrain Relative Navigation
  - Limb/Centroiding
  - Accelerometer
  - X-ray pulsar
  - Horizon matching
  - Visual odometry

- Dynamics models
  - High fidelity gravity potential and relativistic corrections
  - Solar system bodies
  - Harris-Priester atmospheric density
  - SRP with spherical or multi-plate
  - Eclipses
  - Measured acceleration
  - Impulsive and continuous thrust maneuvers
- Ground processing and analysis capability

DSN: Deep Space Network
GN: Ground Network
GNSS: Global Navigation Satellite System
TDRSS: Tracking and Date Relay Satellite System
WAAS: Wide Area Augmentation System

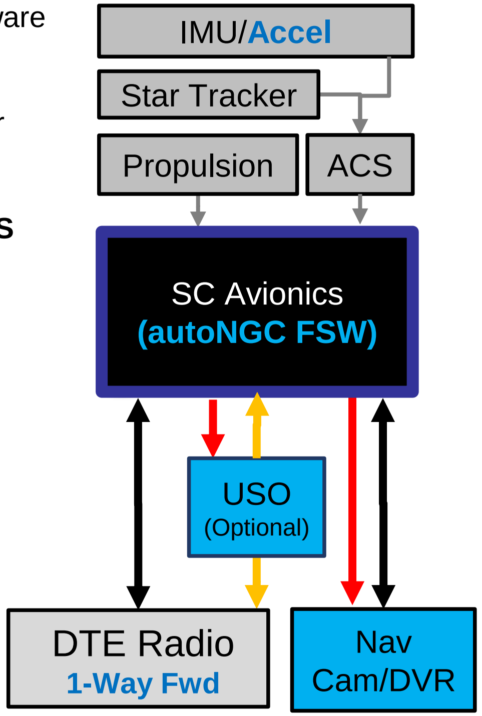
Implementation Options

(Optical Nav, Direct to Earth (DTE) Radio, Accelerometer Example)

All options are highly customizable

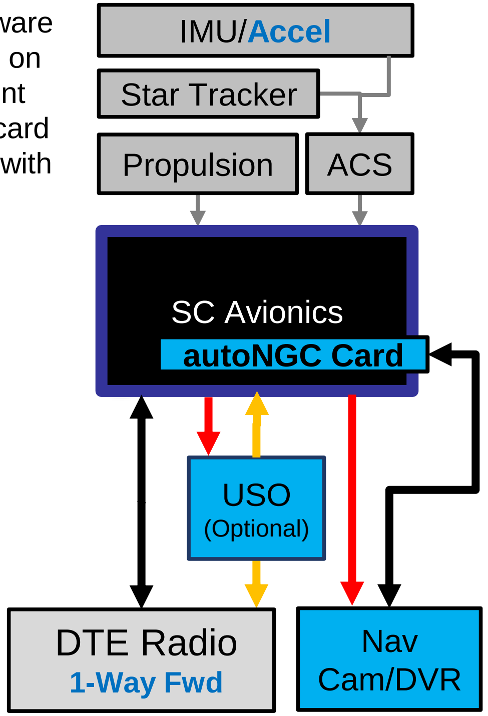
autoNGC Flight Software Only

Flight software hosted on spacecraft avionics (or payload) processor running **cFS**



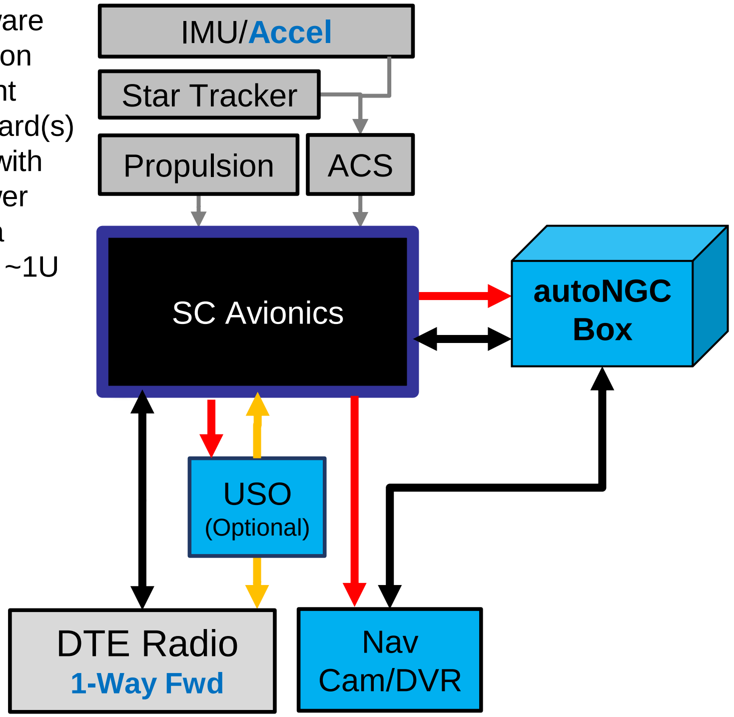
autoNGC Processor Card

Flight software embedded on build-to-print autoNGC card integrated with spacecraft avionics



autoNGC Box

Flight software embedded on build-to-print autoNGC card(s) integrated with IO and power cards into a standalone ~1U box



CoAx

Spacewire

Power

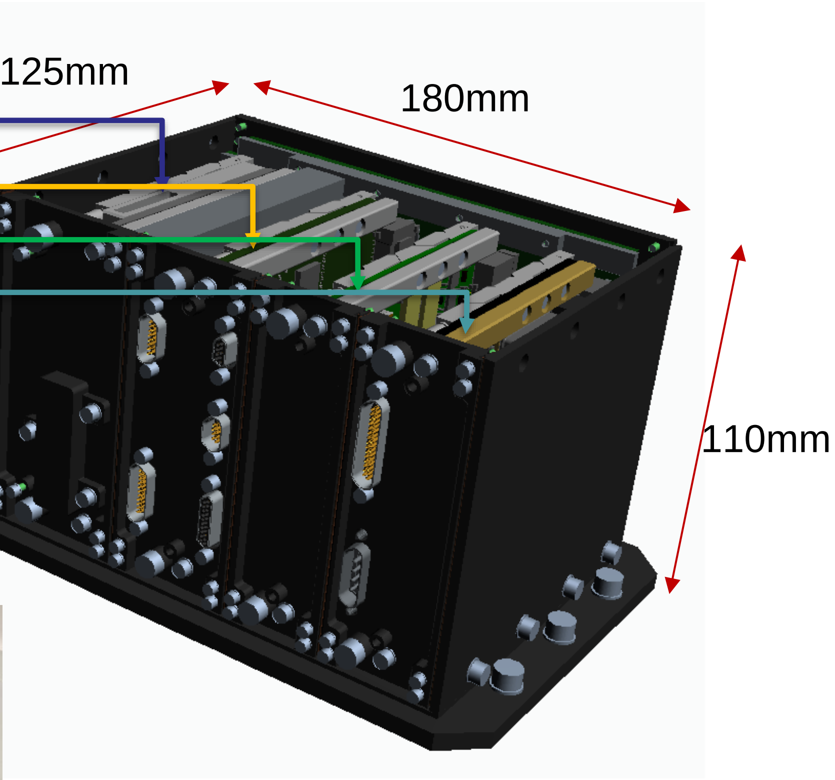
A Hardware Implementation for Lunar Navigation

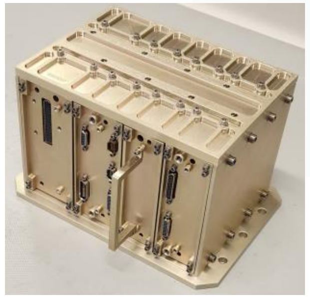
CubeSat Card Specification (CS)²

Box Components:

- **Two Processor Card Implementation**
  - Primary Processor Card
    - *Xilinx Kintex UltraScale with RISC-V Software Processor*
    - *2GB DDR3 SDRAM (x72 wide for ECC) / 2x 16GB NAND Flash*
  - Secondary Processor Card
    - *Xilinx Zynq with Dual ARM Cortex-A9*
    - *1GB DDR / 4GB NAND Flash*
- **Low Voltage Power Card (LVPC)**
  - 28V Input, 6x internal switched services of 3.3V, 5.0V or 12V power rails, Voltage and Current Monitoring
- **Configurable IO Card**
  - 12 Buffered Differential Transmitters (LVDS or RS422)
  - 12 Buffered Differential Receivers (LVDS or RS422)
  - 16 Buffered Single Ended Lines
  - 32 Un-Buffered Signals – Routed as Differential Pairs
- **Backplane**
  - Power Distribution, 8-Channel Temperature Monitoring, and Point-to-point topology for high-speed data interfaces

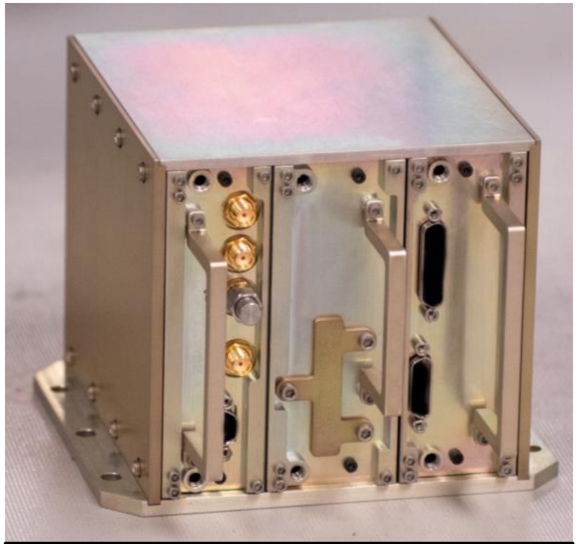
Mass	< 2.5 kg
Power	10 W (Nominal), 15 W (Peak)





NavCube3-mini (NC3m) GNSS Receiver

- Low-SWaP GNSS receiver for all orbit regimes, especially cislunar/lunar space
  - High sensitivity receiver with fast acquisition
  - GPS L1C/A and L2C (or L1C/A and L5) currently available
  - Galileo E1 and E5a in development
  - On-orbit upgradable, FPGA-based radiation tolerant
  - Currently at TRL6 (L1C/A and L2C)
- Includes Goddard's onboard navigation filter software: Goddard Enhanced Onboard Navigation System (GEONS)
  - Enables high-altitude operation with sparse visibility and poor geometry
- Builds on the flight proven (TRL9), high altitude, Magnetospheric Multiscale (MMS) Mission Navigator GPS receiver



NC3m GNSS Receiver

- *Size: WxDxH: 5.0"x5.0"x4.0"*
- *Mass: 1.5 kg*
- *Power: <13 W*

Current Status:

- NC3m achieve TRL6 in summer of 2022
- A US patent awarded for this technology (August 2022)
- NC3m is baselined for LEO mission and lunar technology demonstration in 2026

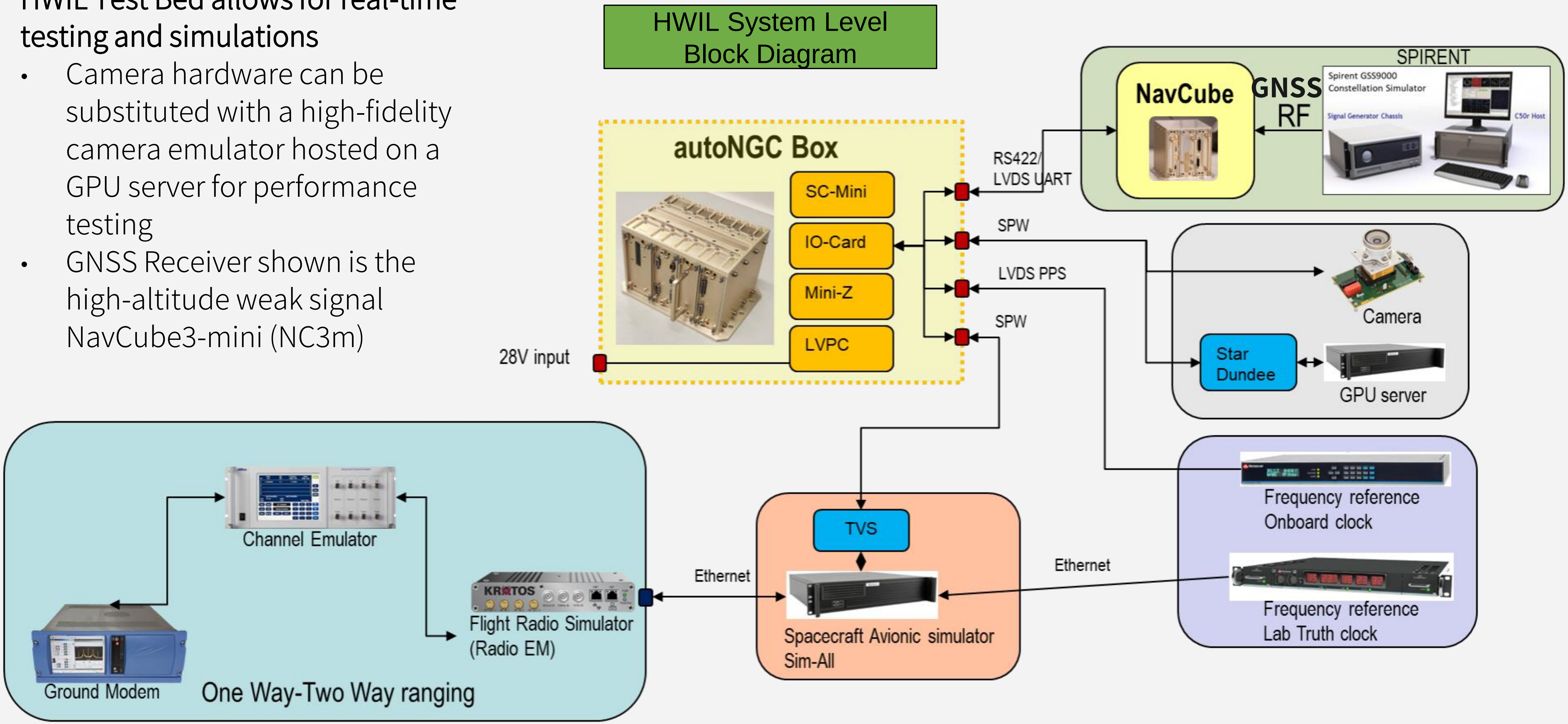
autoNGC Test Facility

- Located at NASA Goddard
- Focused on high-fidelity autoNGC simulations for TRL advancement
- Includes high-fidelity simulators for a variety of navigation sensors
  - GPS Simulation
  - Camera/Image simulation
  - Rubidium-based atomic clock
  - High resolution phase and frequency offset generator
  - Radiometric
  - Ground station
- Includes computing hardware to test on flight-like hardware
  - Development boards
  - Computing hardware ETUs

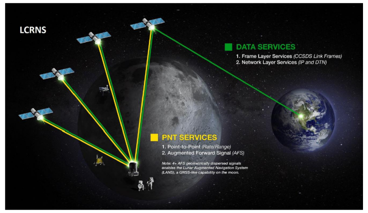
Hardware-in-the-Loop (HWIL) Test Bed

HWIL Test Bed allows for real-time testing and simulations

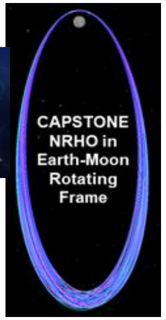
- Camera hardware can be substituted with a high-fidelity camera emulator hosted on a GPU server for performance testing
- GNSS Receiver shown is the high-altitude weak signal NavCube3-mini (NC3m)



Current autoNGC Activities



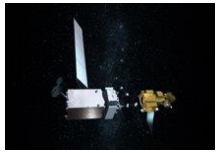
- **Lunar Communications Relay and Navigation Systems (LCRNS) PNT Instrument**
  - Provide autonomous onboard navigation using GPS pseudo-range and time-differenced carrier phase, terrain relative navigation (TRN), onboard state prediction
- **Cislunar Autonomous Positioning System Technology Operations and Navigation Experiment (CAPSTONE) Extended Mission**
  - Flight test various autoNGC capabilities to TRL7 in lunar near-rectilinear halo orbit (NRHO)
  - Demo onboard navigation using 2-way radiometric, 1-way forward radiometric, celestial navigation, and limb-based optical navigation; onboard maneuver planning for NRHO station keeping



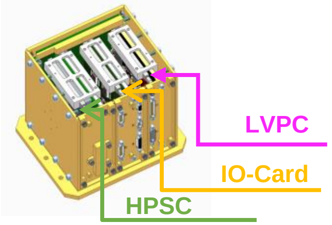
- **Starling 1.5 swarm technology demonstration**
  - Demo onboard GPS navigation, onboard state & uncertainty prediction for space traffic management, and onboard maneuver planning (**autoNGC's first flight May 2025**)

- **Touch-and-Go Guidance System (TGS) Field Test**
  - Test onboard navigation using TRN and LiDAR on a rocket at the Lunar Surface Proving Ground in Mojave Desert

- **Cislunar/NRHO rendezvous, proximity operations, and docking (RPOD) study**
  - Assess reuse of On-orbit Servicing, Assembly, and Manufacturing 1 (OSAM-1) technology for cislunar RPOD



- **Advanced avionics development**
  - Low SWaP box suitable for both surface and on-orbit use

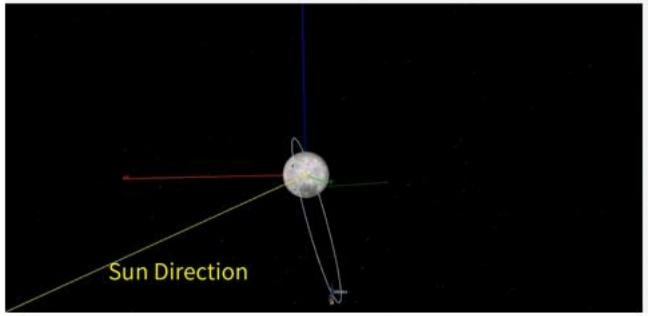


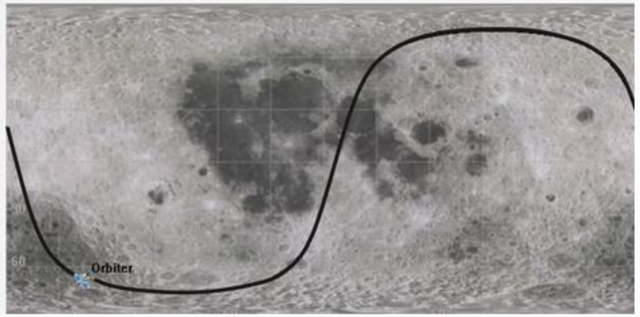
autoNGC 3-card box design
(CubeSat Size Standard)

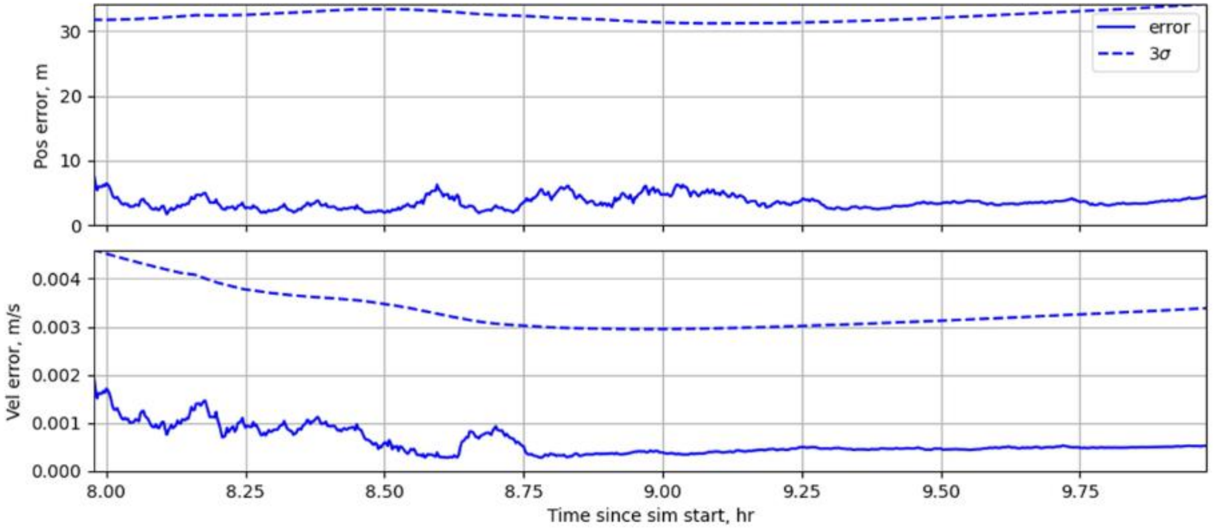
Lunar Orbit Navigation Scenario
Flight Software-in-the-Loop Demo
(Terrain Relative Navigation and Weak Signal GPS)

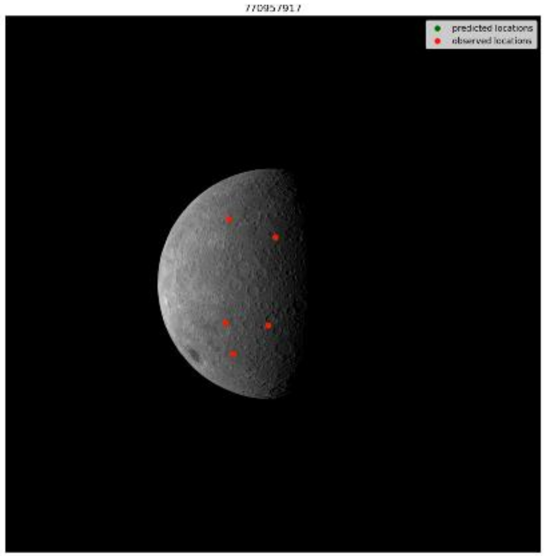
12-hour elliptical frozen orbit

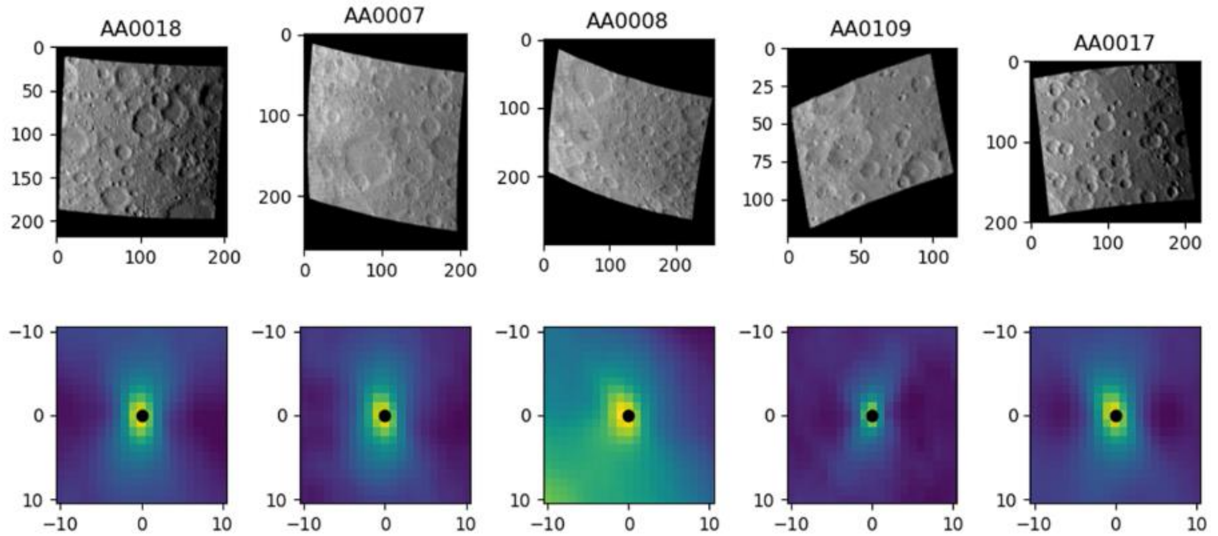
Semi-major axis: 6140 km
Eccentricity: 0.54
Inclination: 75 degrees
RAAN: 259 degrees
Argument of Periapsis: 78 degrees
True Anomaly: 178 degrees

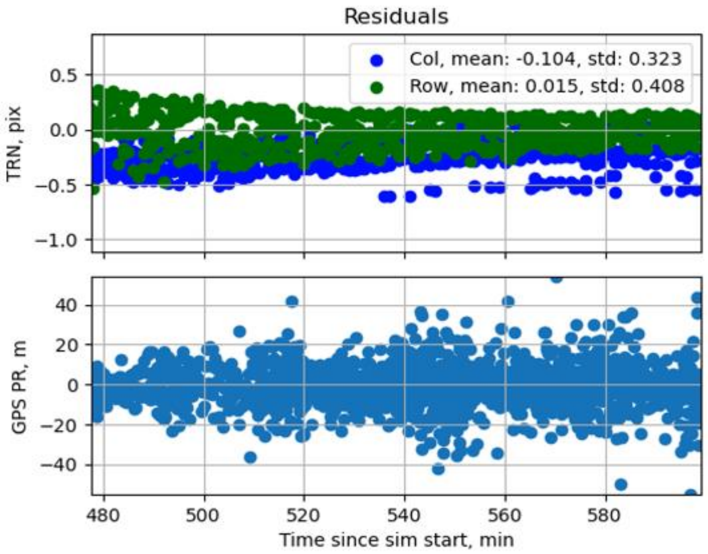












autoNGC

autoNGC Summary

- autoNGC provides onboard NGC autonomy – an enabler for future missions including Moon-to-Mars
- Addresses many of the NASA STMD shortfalls
  - 1557: Position, Navigation, and Timing (PNT) for In-Orbit and Surface Applications
  - 1531: Autonomous Guidance and Navigation for Deep Space Missions
  - 1559: Deep Space Autonomous Navigation
  - 1431: Access Beyond LEO for Small Spacecraft
  - 1432: Rendezvous, Proximity Operations, and Debris Remediation using Small Spacecraft
- Plug-n-play cFS architecture allows customization and insertion of new capabilities, even in flight, as exemplified on Starling and soon on CAPSTONE
- Low SWaP hardware design is suitable for a wide range of space mission types, including surface users
- Additional capabilities in both software and hardware continue to be developed
- High-fidelity hardware-in-the-loop testbed facility available for V&V
- Many of the autoNGC FSW apps and libraries, including cGIANT and GEONS, are available on the NASA Software Catalog for government purpose use