

# Low SWaP Onboard Satellite Navigation, Guidance, and Control Technology

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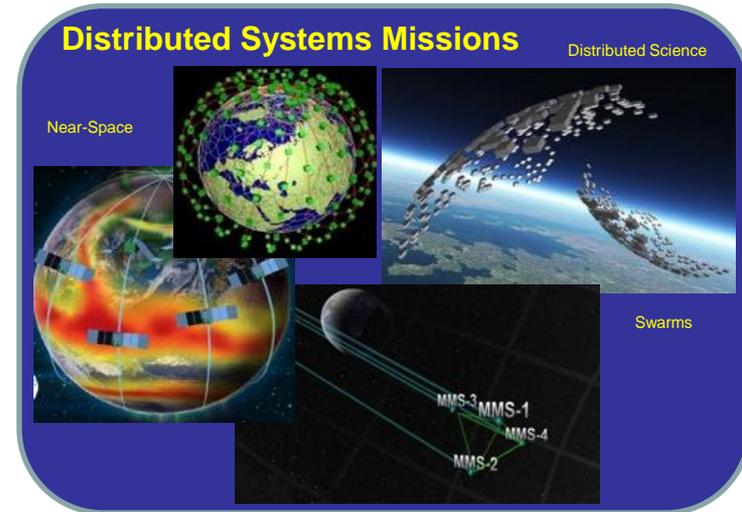


# Agenda

- Needs, goals, and objectives of autonomous Navigation, Guidance, and Control (autoNGC)
- Representative software and hardware design
- Hardware-in-the-Loop (HWIL) test bed
- Upcoming capabilities

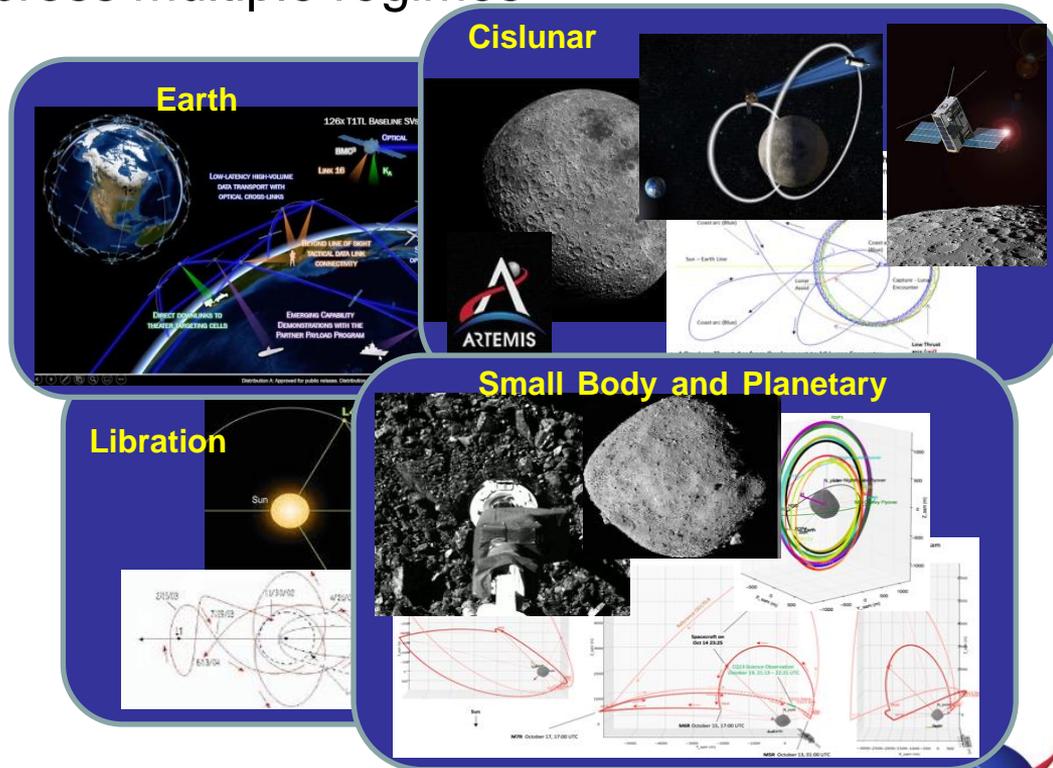
# Needs for autoNGC

- Reduced ground reliance on over-subscribed ground assets for navigation, guidance, and control (NGC) functions
- Enable new mission capabilities
  - Low latency mission operations
  - Complex missions at far distances
  - In-situ planning and execution
  - Distributed Systems Missions (DSMs)
  - Flexibility to dynamically re-assign assets to alternate orbits



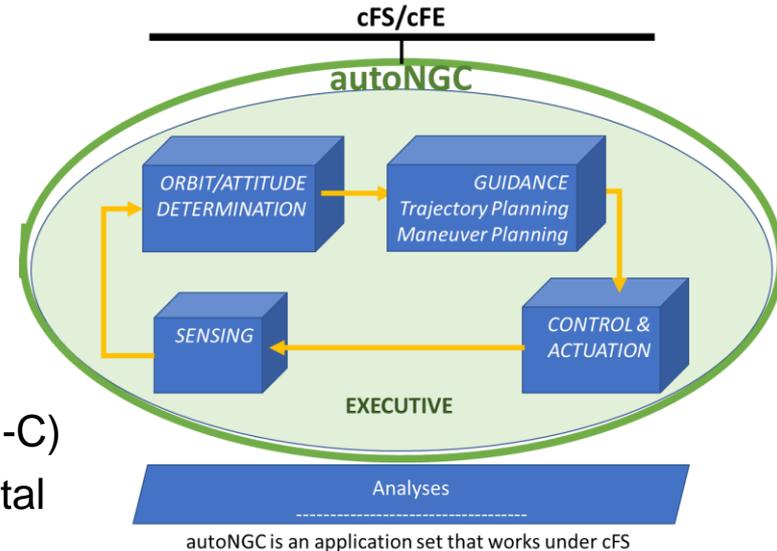
# Goals of autoNGC

- Resilient navigation solutions across multiple regimes
- Reduced mission cost and risk
  - Lower operations cost through onboard autonomy
  - Lower NRE cost over time
    - Utilize a common software bus and framework with a library of customizable capabilities
    - Lower risk by not having to develop NGC flight software from scratch
    - Flight software and hardware separately customizable



# Objectives of autoNGC

- An **onboard software application suite** built on the core Flight System (cFS) and **flight hardware solution** that performs real-time autonomous spacecraft navigation, guidance and control
  - Autonomous onboard navigation and timing
  - Autonomous onboard guidance and control - executive decision/control for spacecraft maneuvers
  - Fault tolerant
  - Low size, weight/mass, power, and cost (SWaP-C)
  - Multi-mission extensibility – DSMs, multiple orbital regimes, customizable (plug-n-play)
  - Class B flight software (per NASA Procedural Requirement 7150.2)



# Core Flight System (cFS)

- Goddard-developed software platform and project-independent reusable software framework and a set of open source reusable software applications
- Undergoing Class A certification for human spaceflight for the Lunar Gateway

## Concepts and Standards

### Core Flight Executive (cFE)

- Layered Architecture
- Standard Middleware/Bus
- Standard Application Programmer Interface for core services

### cFS Applications

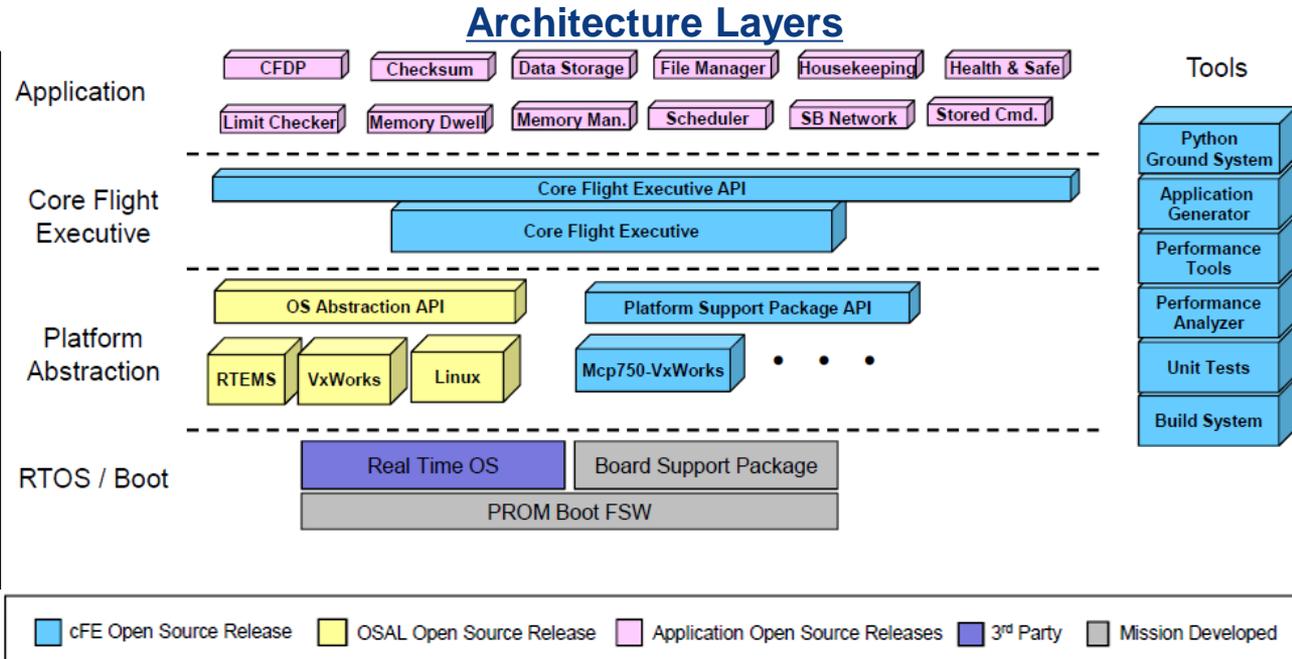
- Plug and Play Reusable Applications
- Command & Telemetry Database

### Library & CM

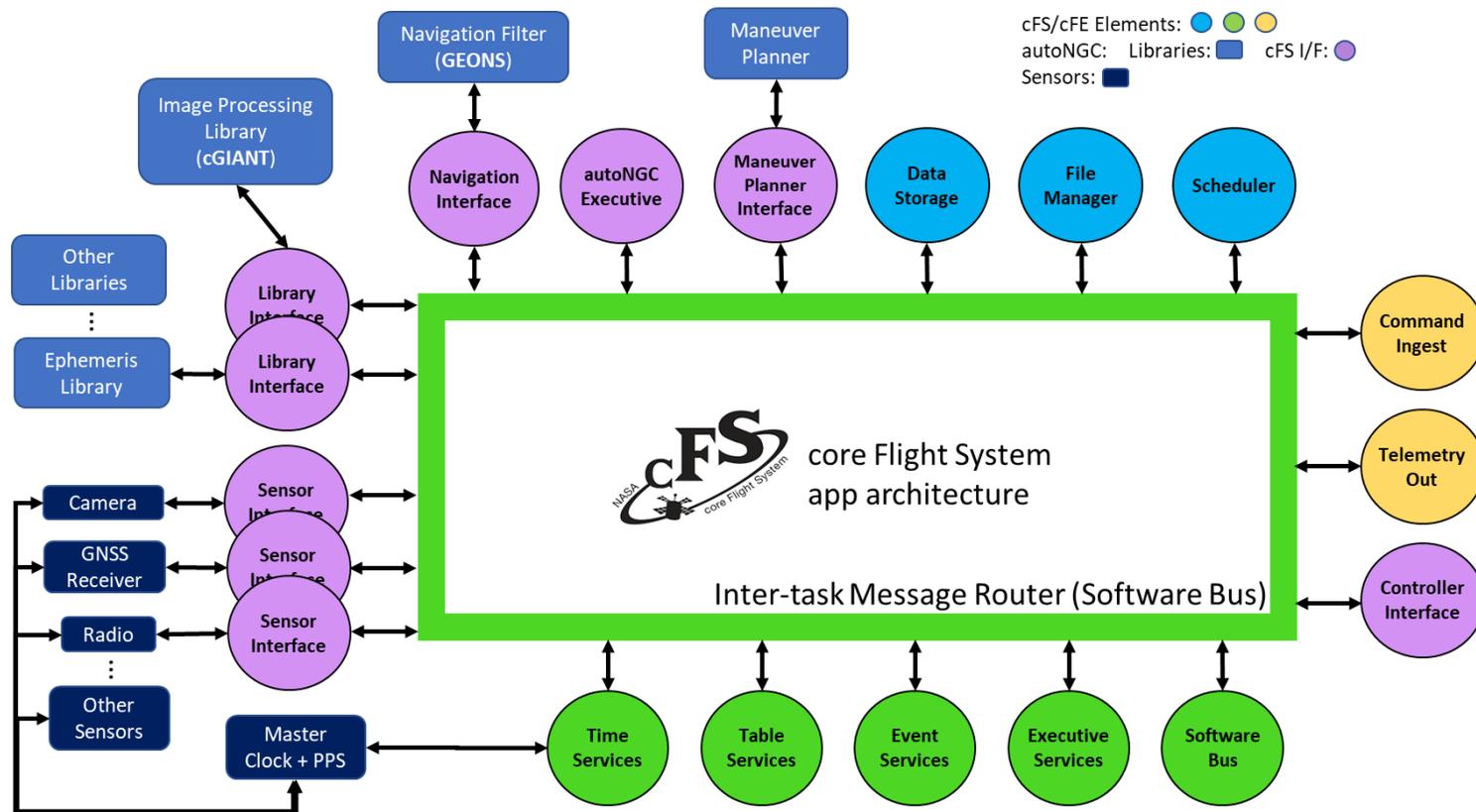
- Reuse Requirements Management
- Reuse Standards
- Reuse Repository

### Integration Development Environment

- Configuration Tool for Mission Users
- Development Tools



# autoNGC Flight Software on cFS Architecture

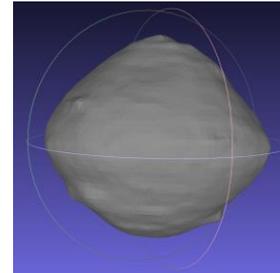


# cFS Goddard Image Analysis and Navigation Tool (cGIANT)

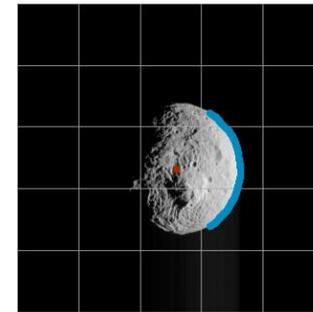
- cFS app that performs autonomous onboard image processing for precision optical navigation (OpNav) without ground-in-the-loop delays
- State-of-the-art algorithms with ground heritage on OSIRIS-REx
- Enables navigation relative to bodies whose trajectories and shapes are not well known



- 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)

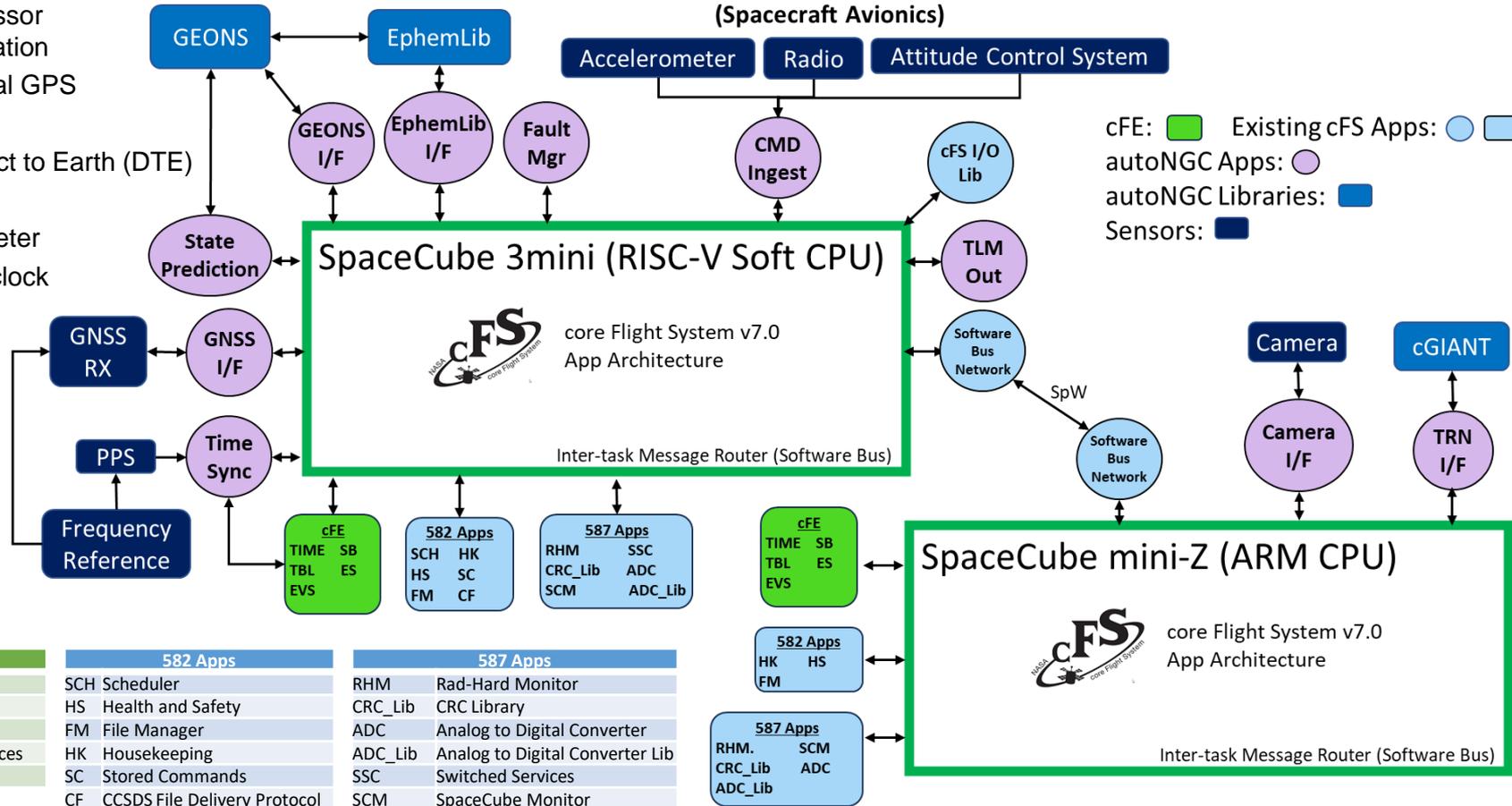
- Performs navigation for 1+ user satellites or surface assets, individually or simultaneously, estimating absolute and relative orbital states, clock errors, and additional parameters
- UD-factorized extended Kalman Filter, 4<sup>th</sup>/8<sup>th</sup> order RK integrator, realistic process noise models 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 TDRSS/DSN/GN
  - 2-way DSN/GN
  - Crosslink
  - Celestial object bearing angles
  - Terrain Relative Navigation
  - Limb/Centroiding
  - Accelerometer
  - X-ray pulsar
- 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

# A Lunar Navigation Implementation

- Two processor implementation
- Weak signal GPS
- TRN
- 1-way Direct to Earth (DTE)
- 2-way DTE
- Accelerometer
- Rubidium clock



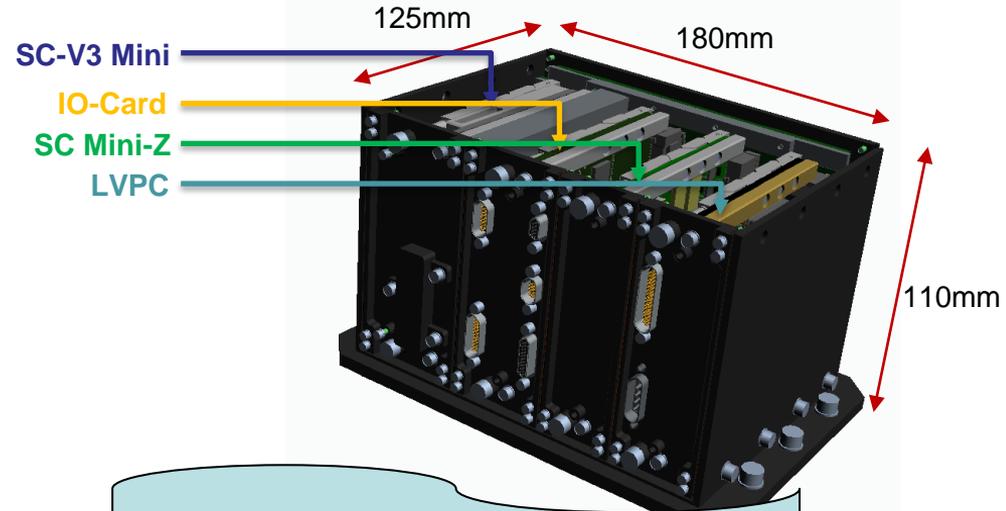
# A Hardware Design for Lunar Navigation

## CubeSat Card Specification (CS)<sup>2</sup>

### Box Components:

- **Two Processor Card Implementation**
  - **SpaceCube v3.0 Mini Processor Card**
    - Xilinx Kintex UltraScale with RISC-V Software Processor
    - 2GB DDR3 SDRAM (x72 wide for ECC) / 2x 16GB NAND Flash
  - **SpaceCube Mini-Z+ Processor Card**
    - Xilinx Zynq 7020 SoC 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 Transmitter (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 (Idle), 15 W (Nominal), 20 W (Peak)



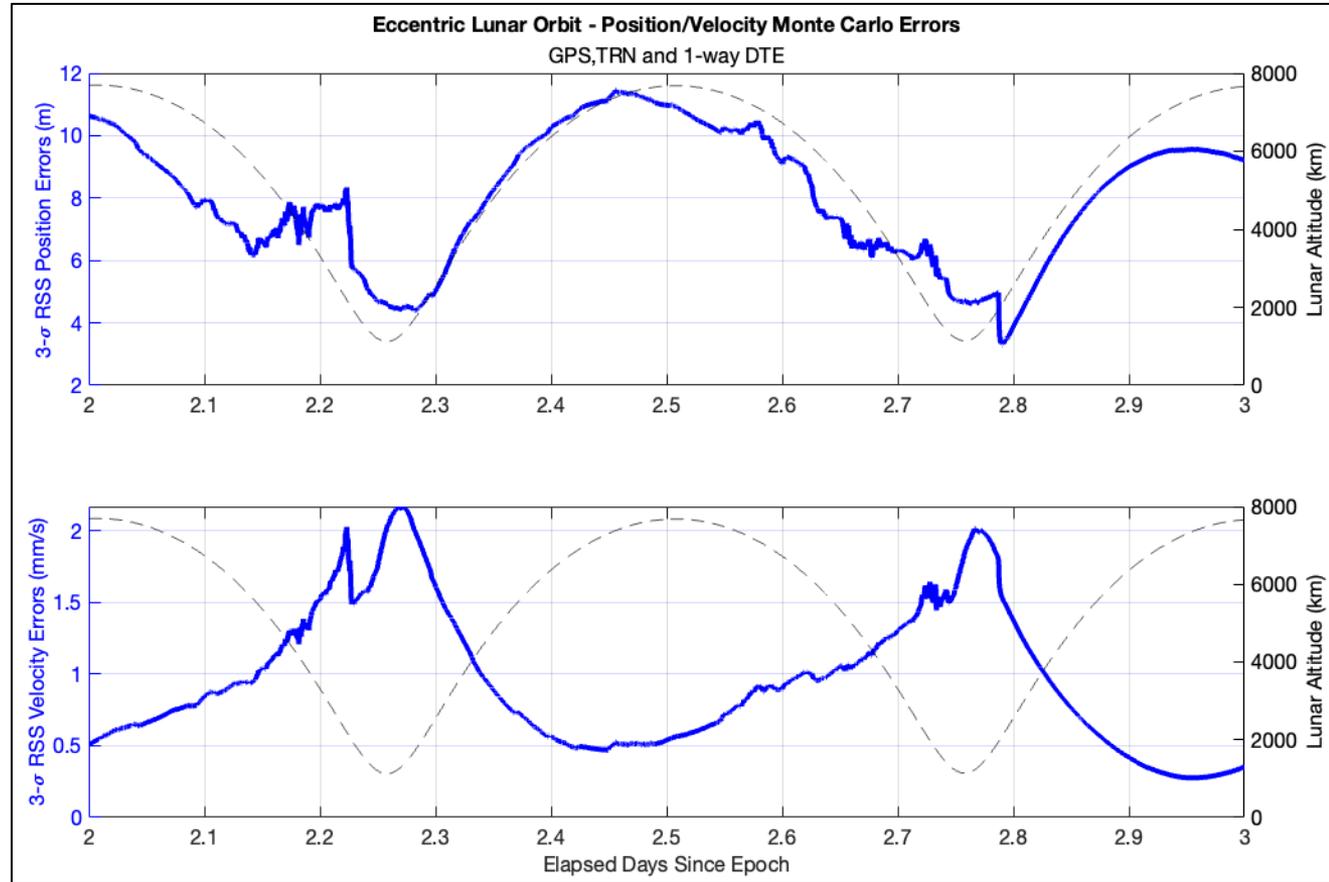
**In Development:** SpaceCube Mini-Z upgrade featuring a larger Zynq 7045 SoC and the addition of 187.5 GB rad-hard non-volatile memory for storing surface maps used in Terrain Relative Navigation (TRN).

Additional Information:

<https://digitalcommons.usu.edu/smallsat/2020/all2020/136/>

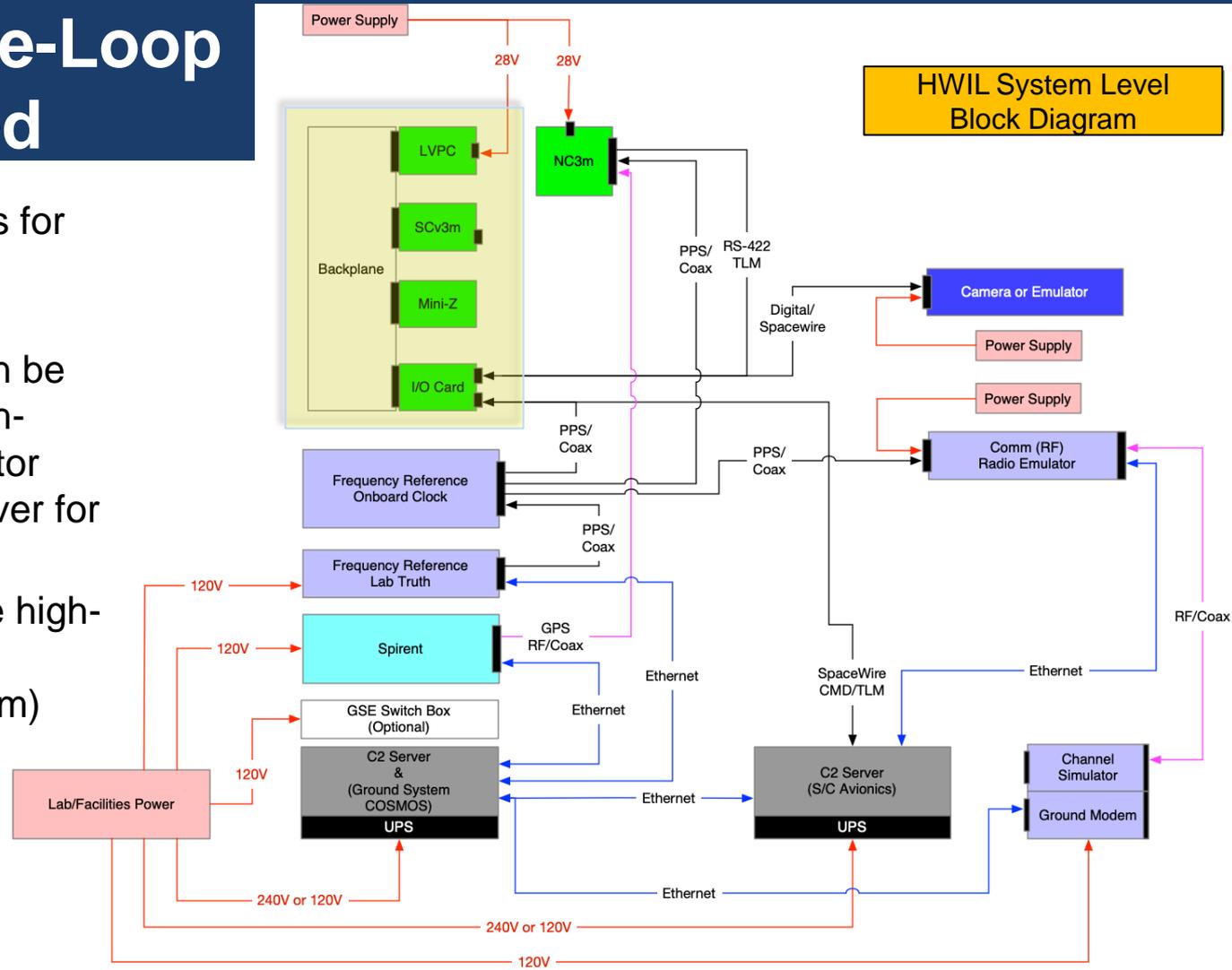
# Eccentric Lunar Orbit PNT Performance

- Measurements:
  - Weak signal GPS pseudo-range
  - 1-way forward DTE Range and Doppler
  - Terrain relative navigation (TRN)
- Rubidium atomic clock
- Position & velocity: 11 meters and 2 mm/s (3- $\sigma$ ) RSS
- Time knowledge <10 ns (3- $\sigma$ )



# 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 is the high-altitude weak signal NavCube3-mini (NC3m)



# Upcoming autoNGC Capabilities

- Additional measurement types
  - LiDAR
  - Celestial navigation
  - Cross-link range and Doppler
  - X-ray pulsar navigation
- Onboard autonomous trajectory correction
- Onboard NGC planning and scheduling software for coordination with payload execution
  - Station-keeping maneuver scheduling
  - Event driven response

# autoNGC Maneuver Planning

- Ongoing IRAD project implements a single shooting targeting algorithm as a cFS app that uses GEONS dynamical models and propagators.
- Maneuver planning scenarios studied include: stationkeeping, small body touch and go, lunar lander, and multi-spacecraft coordination.
- Researching alternate techniques for onboard maneuver planning including convex optimization, model predictive control, and AI/ML.
- Interested in collaborations:
  - In conversation with JSC about adapting the two level targeter (TLT) software run onboard Orion for compatibility with cFS.
  - Worked with Advanced Space via an SBIR.
  - Want to leverage the strengths of other institutions, like APL, through complementary IRADs and other avenues for cooperation.

# Summary

- autoNGC is an enabling technology for future space-borne missions
- Plug-n-play cFS architecture allows customization and insertion of new capabilities, even in flight
- Low SWaP design provides opportunity for onboard autonomy for a wide range of space mission types
- TRL 6 build of autoNGC software and hardware for autonomous navigation in lunar orbit targeted by Fall 2024
- Additional capabilities in both software and hardware continue to be developed
- Collaboration with other government agencies, industry, academia sought
- Flight demonstration opportunities sought



autoNGCSummarySheet.pdf

# BACKUP

# NavCube3-mini (NC3m) GNSS Receiver

- Low-SWaP multi-GNSS receiver, suitable for use in cis-lunar/lunar space
- Combined fast and weak signal acquisition; builds on flight-proven Navigator GPS receiver software and firmware on the GSFC Magnetospheric Multiscale (MMS) Mission
- Includes integrated Goddard Enhanced Onboard Navigation Systems (GEONS) navigation filter

- NC3m achieved TRL 6 in December 2022

## ➤ Other Attributes:

- On-orbit upgradable, FPGA-based radiation tolerant
- GPS L1C/A and L2C capability
- GPS L5 and Galileo E1 and E5a capabilities in development

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

