# Core Flight Software projects on Orion Multi-Purpose Crew Vehicle

Flight Software Workshop

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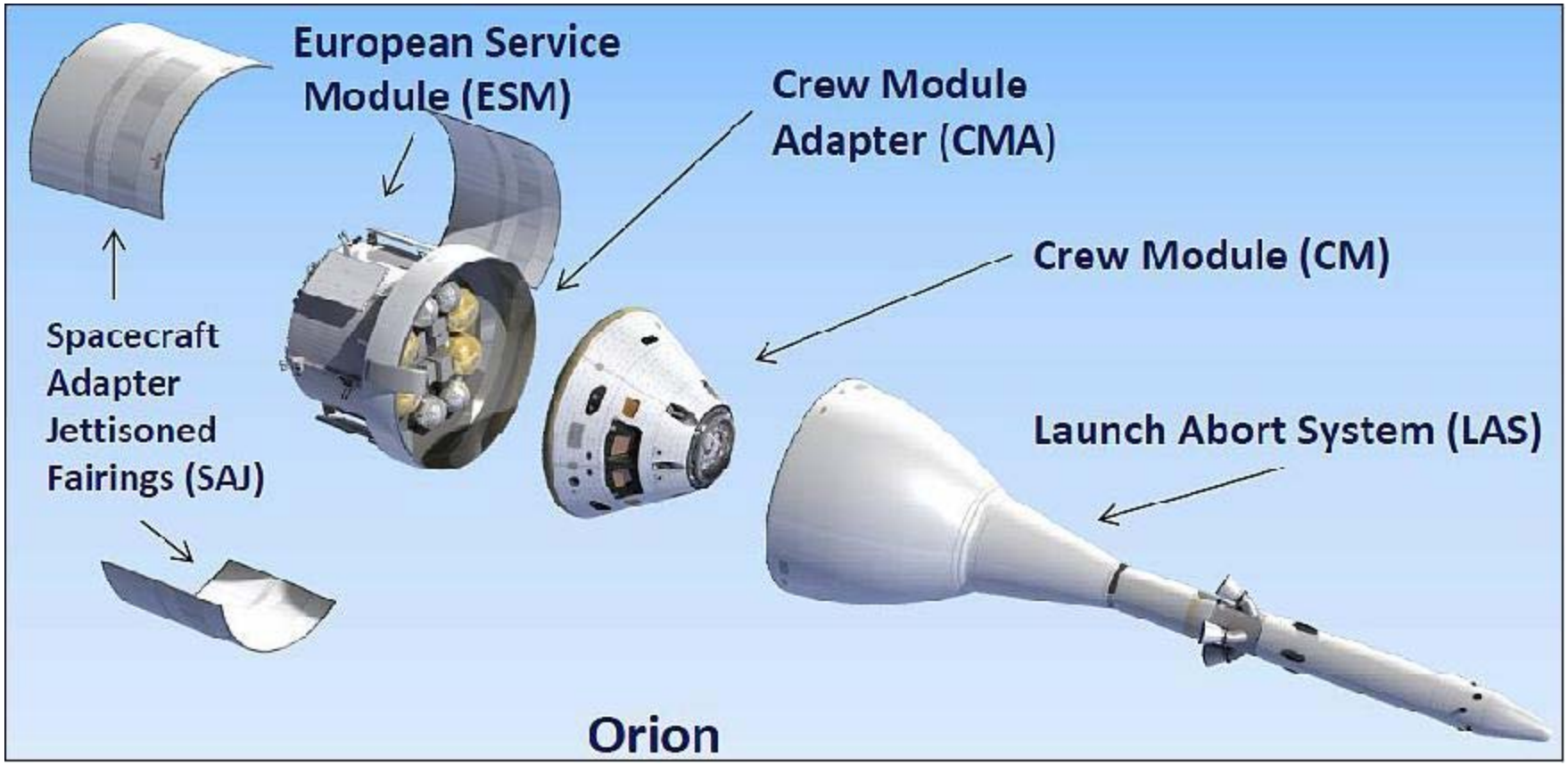
# Outline

- Orion Program Overview
- CFS Projects on Orion
  - Orion Ascent Abort 2 Flight Test
  - Optical Navigation Software
  - Backup Flight Software

# Orion Vehicle

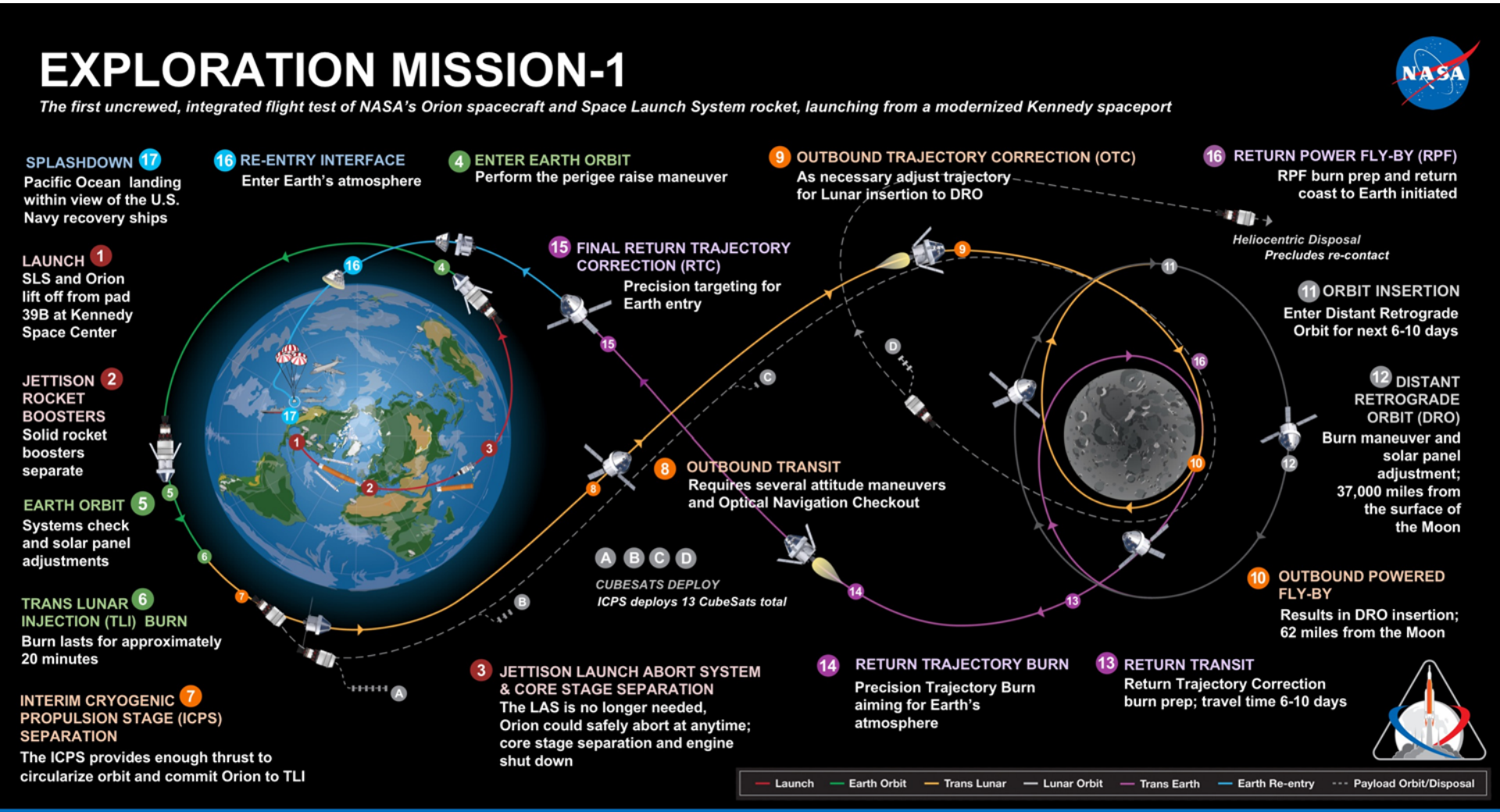


# Orion Program Mission Schedule (Wikipedia)

| Mission | Acronym | Rocket | Crewed | Launch date | Status | Duration | Destination |
|---|---|---|---|---|---|---|---|
| Pad Abort 1 | PA-1 | Orion LAS | No | May 6, 2010 | Success | 95 seconds | Troposphere |
| Exploration Flight Test 1 | EFT-1 | Delta IV Heavy | No | December 5, 2014 | Success | 4 hours, 24 minutes, two orbits | High Earth orbit |
| Ascent Abort Test 2 | AA-2 | Orion Abort Test Booster | No | April 2019 | Under development | Less than 3 minutes | Stratosphere |
| Exploration Mission 1 | EM-1 | SLS Block 1 Crew | No | 2020 | Under development | 26–40 days | Lunar orbit |
| Exploration Mission 2 | EM-2 | SLS Block 1B Crew | Yes | 2023 | Under development | 3–21 days | Multi TLI free-return flight |
| Exploration Mission 3 | EM-3 | SLS Block 1B Crew | Yes | Between 2023 and 2024 | Planned | 16–26 days | Gateway station |
| Exploration Mission 4 | EM-4 | SLS Block 1B Crew | Yes | 2025 | Planned | 26–42 days | Gateway station |
| Exploration Mission 5 | EM-5 | SLS Block 1B Crew | Yes | 2026 | Planned | 26–42 days | Gateway station |
| Exploration Mission 7 | EM-7 | SLS Block 1B Crew | Yes | 2027 | Planned | 191–221 days | Gateway station |
| Exploration Mission 9 | EM-9 | SLS Block 2 Crew | Yes | 2029 | Planned | 1 Year | Lunar orbit |
| Exploration Mission 11 | EM-11 | SLS Block 2A Crew | Yes | 2033 | Planned | 2 years | Martian orbit |

Current CFS Projects in Development/Test

# Exploration Mission 1 Overview

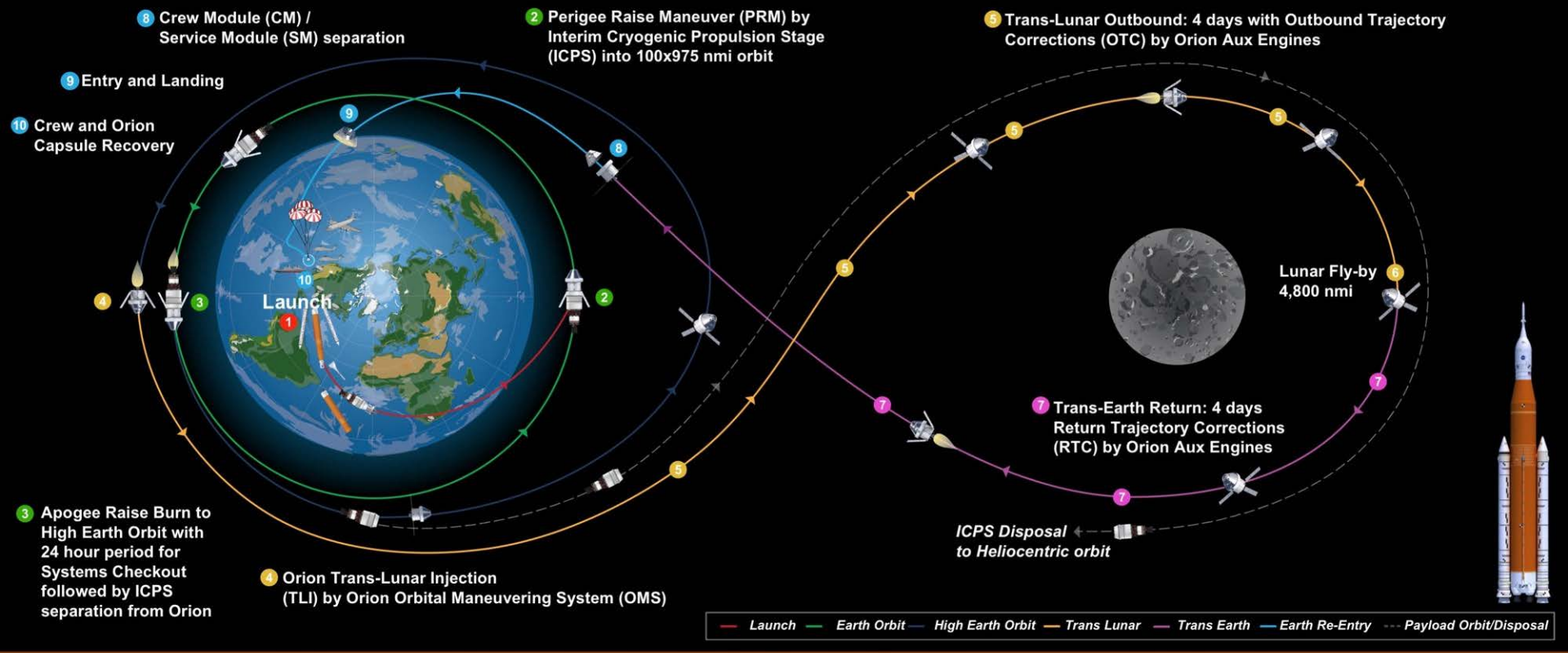



**Total distance traveled: 1.3 million miles – Mission duration: 25.5 days – Re-entry speed: 24,500 mph (Mach 32) – 13 CubeSats deployed**

# Exploration Mission 2 Overview

## EXPLORATION MISSION-2

Crewed Hybrid Free Return Trajectory, demonstrating crewed flight and spacecraft systems performance beyond Low Earth Orbit (LEO)




*SLS Configuration (Block 1) with Human Rated ICPS | 22x975 nmi (40.7x1806 km) insertion orbit | 28.5 deg inclination*

4 astronauts | Total distance traveled: 1,090,320 km – Mission duration: 9 Days – Re-entry speed: 24,500 mph (Mach 32)

# CFS Projects On Orion

- CFS Projects on Orion Missions
  - Orion Ascent Abort 2 Flight Test
    - CFS Framework for Primary Flight Software
    - Hardware: AiTech SP0 processor
    - Operating System: VxWorks
  - Orion Exploration Mission 1 & 2
    - Vision Processing Unit (VPU)
      - Backup Flight Software
        - » EM-1: Entry phase, EM-2 & beyond: All Flight Phases
      - Hardware: Sparc LEON 3
      - Operating System: VxWorks
    - Camera controllers Units – Crew Module & Crew Module Adapter
      - Camera controlling software (still image & motion video)
      - Optical Navigation Software
      - Hardware: Intel NUC
      - Operating System: Ubuntu-64

# AA-2 Project Introduction

Ascent Abort 2 (AA-2) Flight Test

- AA-2 is a Development Flight Test for the Multi Purpose Crew Vehicle (MPCV) Program
- Single launch planned for April 2019 from Space Launch Complex 46
- AA-2 will test the LAS under flight-like conditions to help certify the system for crewed missions
- AA-2 uses a surrogate low cost, less complex booster and Crew Module

AA-2 Avionics & Software

- Designing to use COTS avionics wherever possible
- Dual string design using cFE/CFS on VxWorks
- Reuse of ANTARES Trick Simulation
- CFS wrapped GNC Matlab/Simulink Autocode from mainline MPCV

Apollo Pad Abort Test

Apollo Ascent Abort Test (Little Joe II Booster)

Orion

Orion Pad Abort Test

AA-2 Flight Test Vehicle

# AA-2 Flight Test Profile

**Event Description**

**1** ATB ignites.
Vehicle departs on eastward trajectory.
ATB boosts the FTA to the test condition.

**2** Test Condition is reached
ATB sends signals to the FTA
CM triggers the abort event.
CM ignites the LAS AM and ACM
CM separates from SR
LAS propels CM away from ATB.

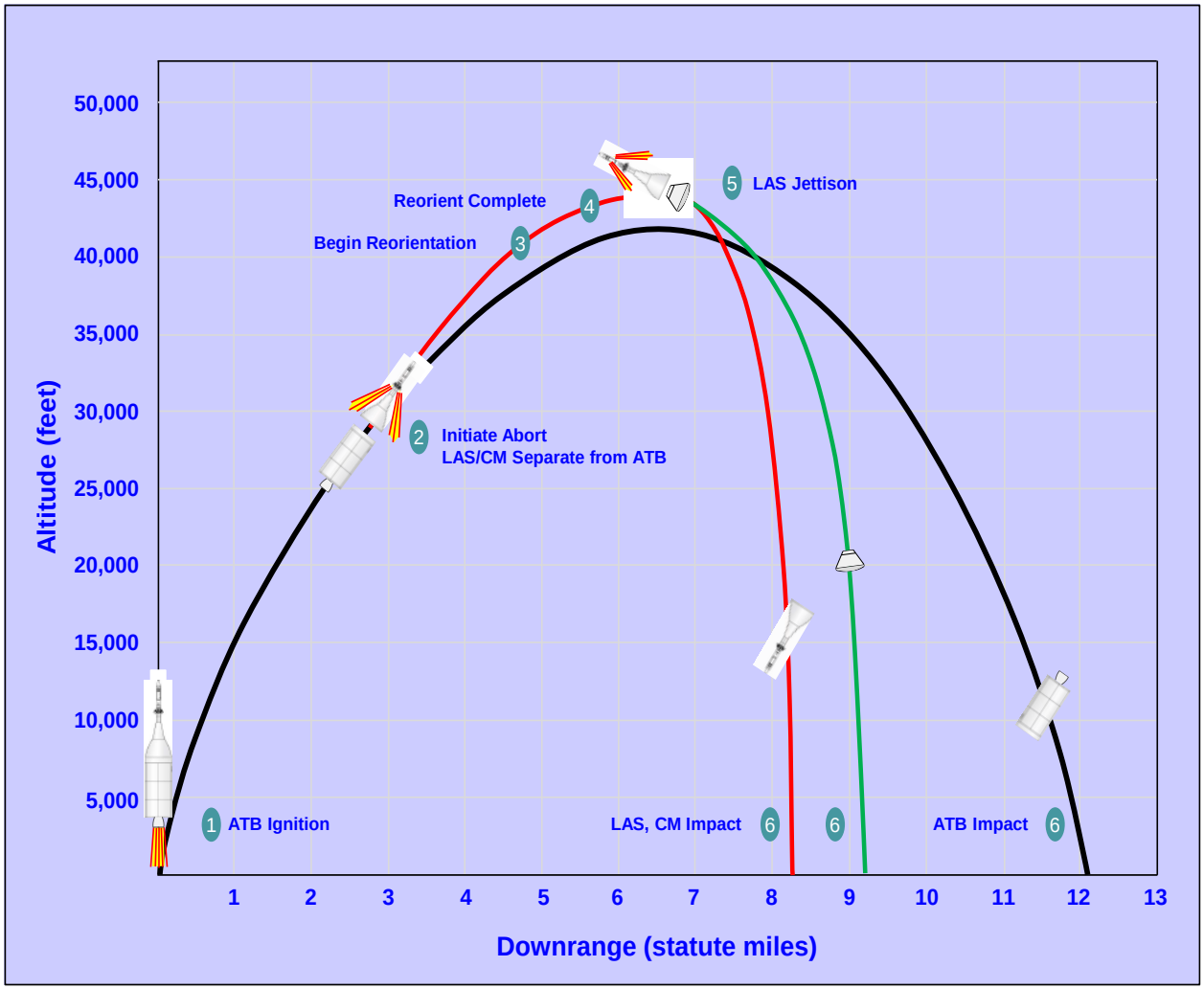
**3** LAS AM burns out.
CM/LAS continue coasting to apogee.
While coasting,
ACM reorients CM heat-shield forward.

**4** CM/LAS reorientation is completed.

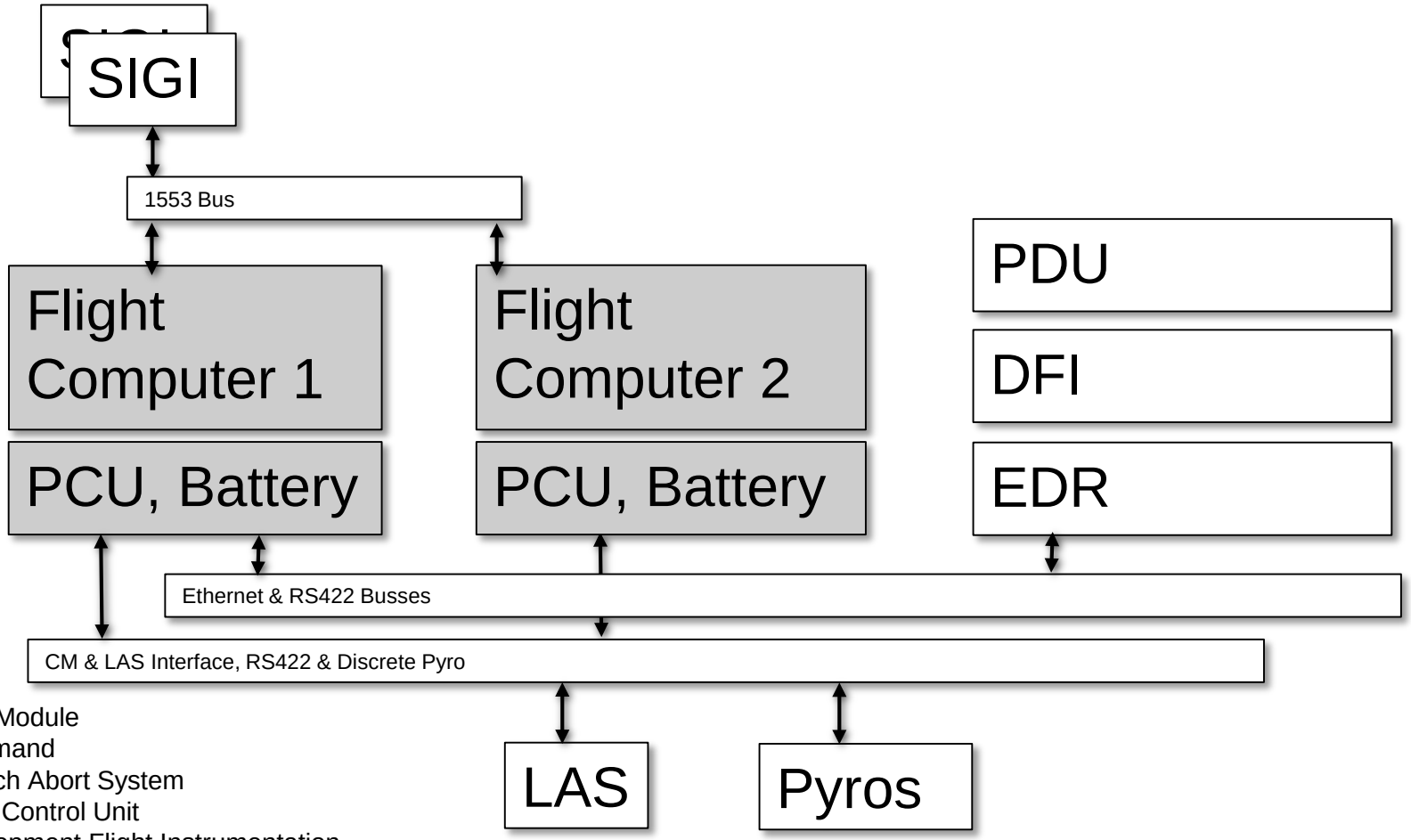
**5** CM ignites LAS JM
CM separates the LAS from the CM
LAS is jettisoned away from the CM.

**6** ATB, LAS, and CM free-fall into the ocean.
Flight Test is completed.

No planned recovery. Will depose
of items that are hazards to marine navigation

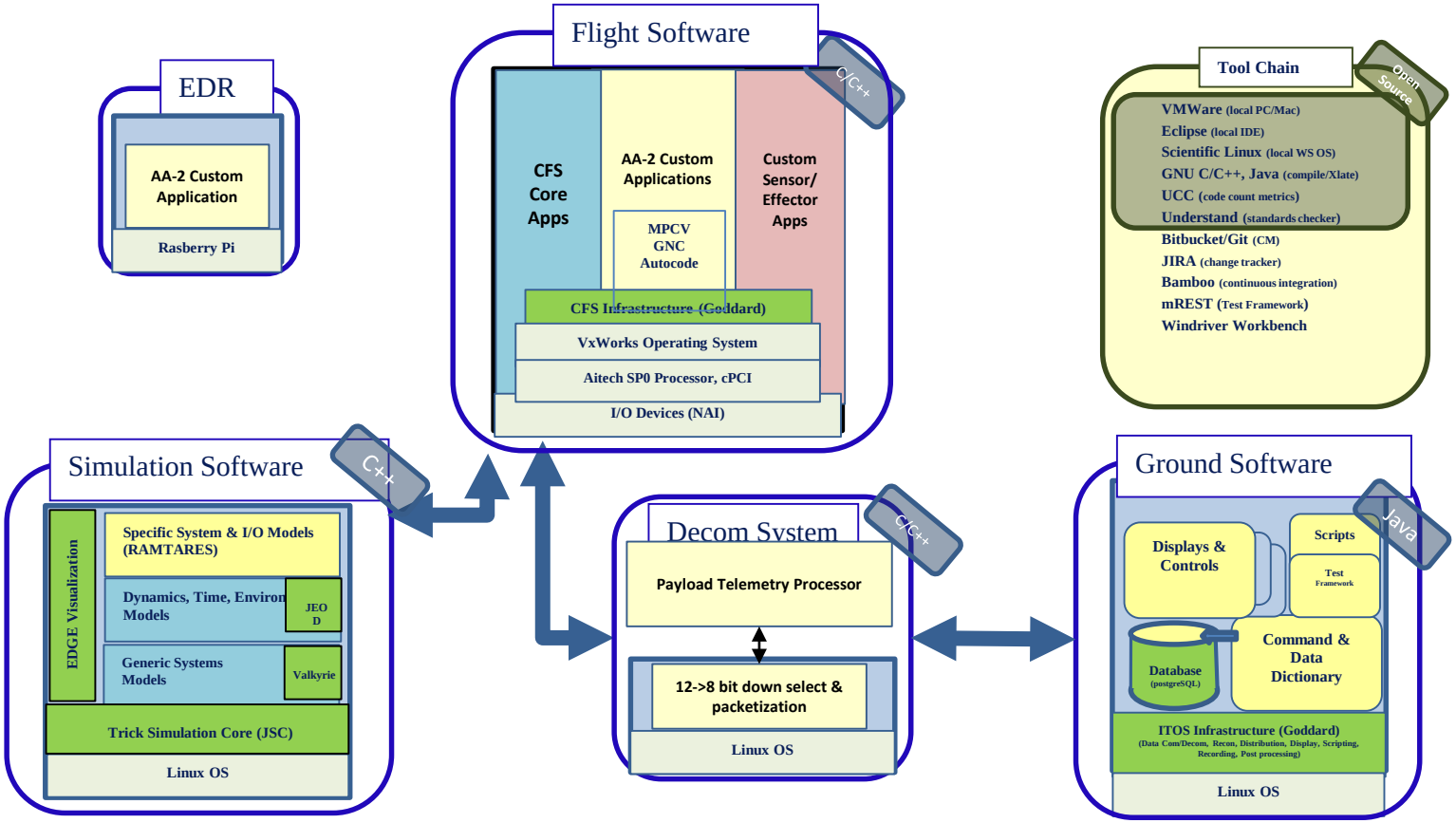


# High-Level AA-2 Avionics Architecture

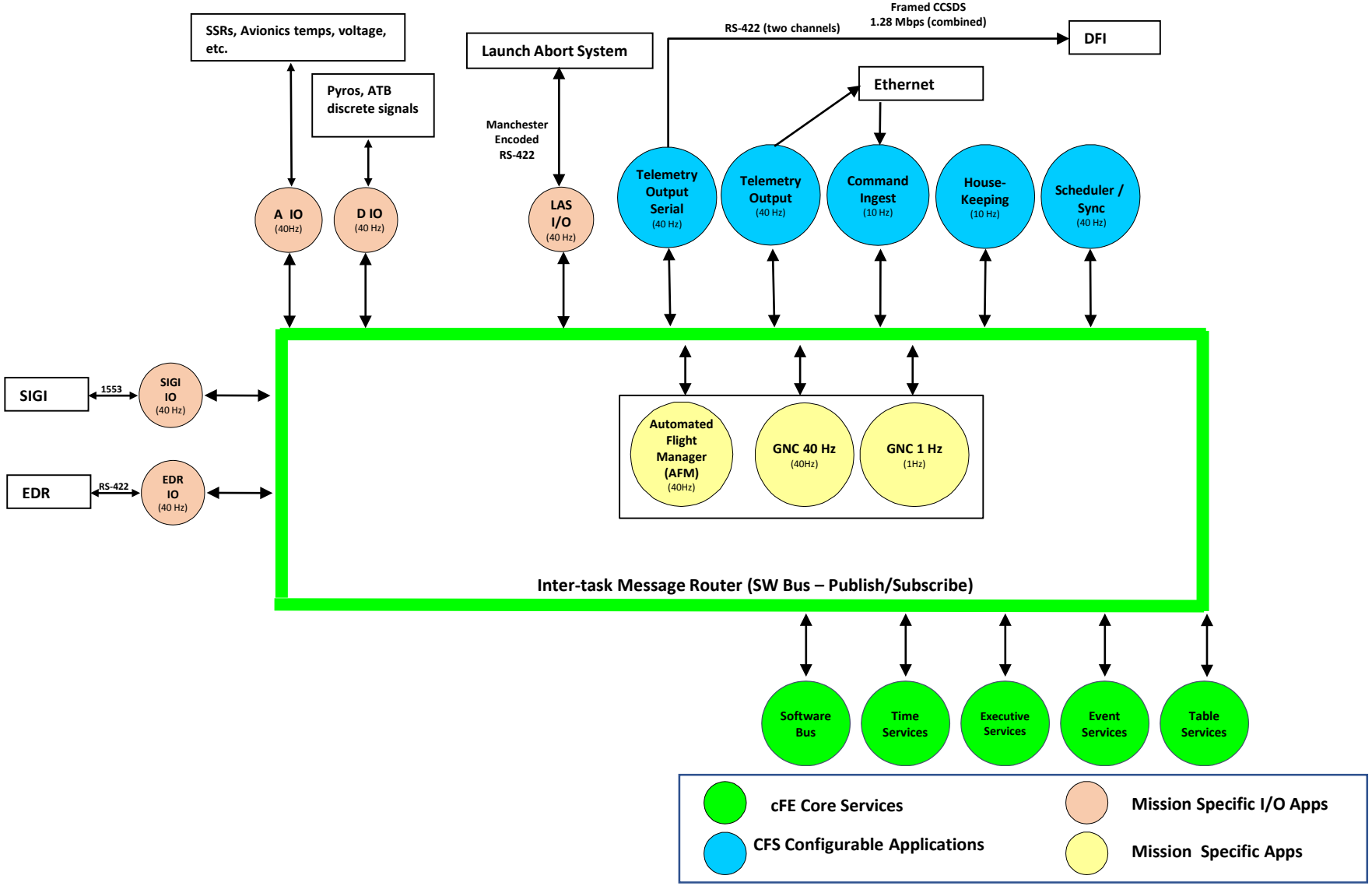



CM – Crew Module
Cmd - Command
LAS – Launch Abort System
PCU – Pyro Control Unit
DFI – Development Flight Instrumentation
SIGI – Space Integrated GPS/INS
GPS – Global Positioning System
INS – Inertial Navigation System
Tlm - Telemetry
PDU – Power Distribution Unit

# AA-2 Top Level Software Block Diagram



# AA-2 Flight Software Architecture



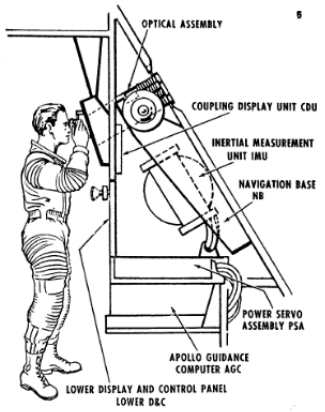
# Optical Navigation Project Overview - Background

- Optical Navigation (OpNav) Application Software
  - NASA/JSC/Engineering Directorate Government Furnished Equipment (GFE) software project authorized October 2016, delivered April 2018
  - Orion (EM-1, EM-2) software producing navigation data for onboard GNC flight control in the event of loss of communication with ground
    - Determines position and range of spacecraft based on optical image recognition of either earth or moon from images taken by dedicated fixed-mounted camera (Pixelink) on bottom of Orion Command Module
    - Self calibrates images onboard prior to navigation use by imaging starfields, high accuracy required
  - Functions as Orion backup navigation sensor in the event of comm loss
    - Orion requires nav updates from ground, if comm is lost, poses LOC/LOM risk during entry
    - Provides autonomous navigation updates upon Loss of Comm
    - Class A Safety-Critical Software
  - For EM-1, images taken every 30s during approximately 8, 2-hour “passes”
    - Dedicated “calibration passes” image star field to determine camera distortion & orientation
    - Dedicated “imaging passes” image earth or moon to derive navigation solution
    - Function validated on “outbound leg” to moon for EM-1, evaluated as a DTO for this phase
    - Activated on the “inbound” from moon for loss-of-comm
      - Solution fed to Orion FCM-GNC and downlinked
  - Located in Camera Controller (CC) unit on Orion EM-1 vehicle, Linux computer running the Core Flight Software (CFS) framework

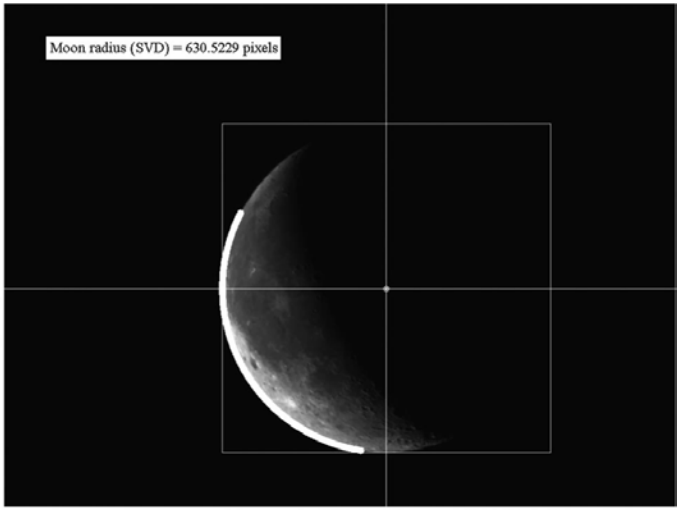
# How Optical Navigation Works

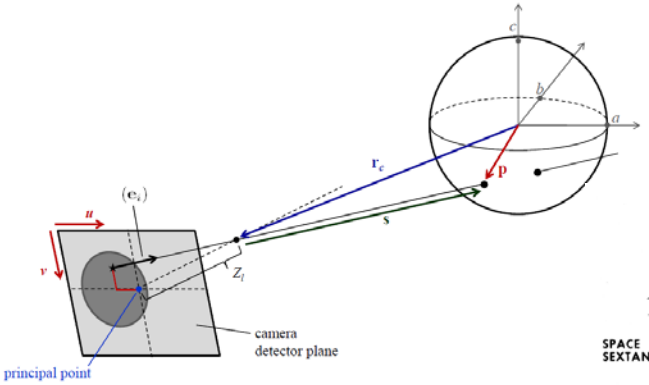
- Still images of Moon or Earth are processed to find apparent angular diameter and centroid in camera focal plane
- Raw data is transformed into range and bearing angle measurements using planetary data and precise star tracker inertial attitude
- Measurements are sent to the main flight computer's Kalman filter to update the onboard state vector
- Images are collected over an arc (~2hrs) to converge the state and estimate velocity
- The same basic technique was used by Apollo to satisfy loss-of-comm, but Apollo used manual crew sightings with sextant instead of autonomously processing optical imagery

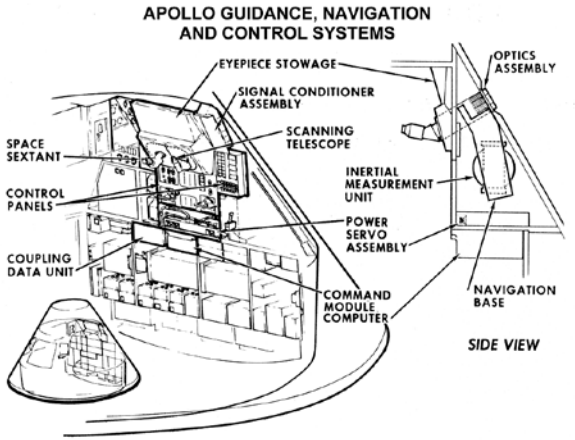
## Apollo Space Sextant



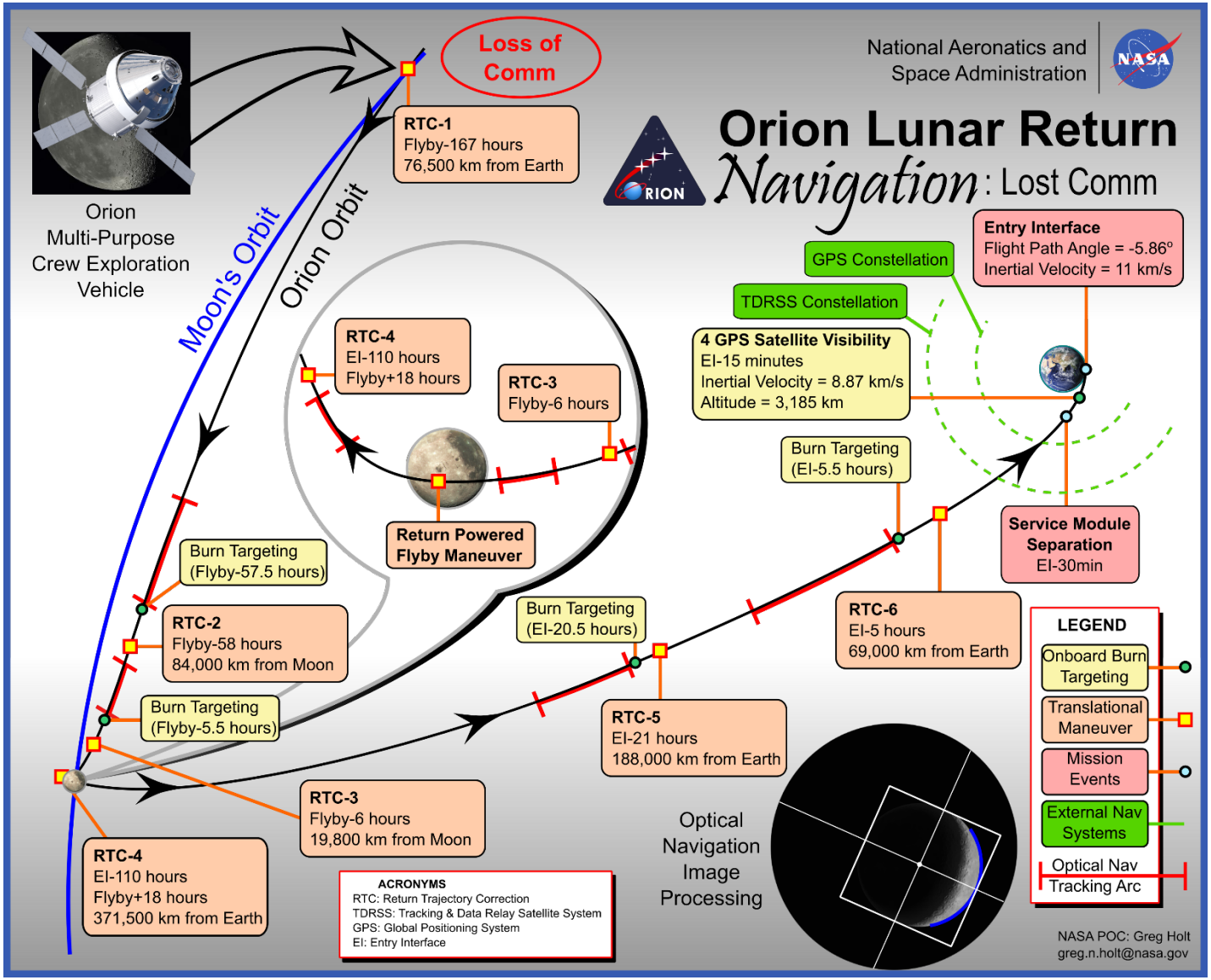

LOCATION OF GUIDANCE AND NAVIGATION EQUIPMENT IN SPACECRAFT GN-9005



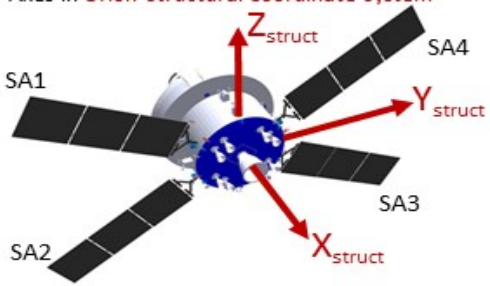
# Loss of Comm Navigation



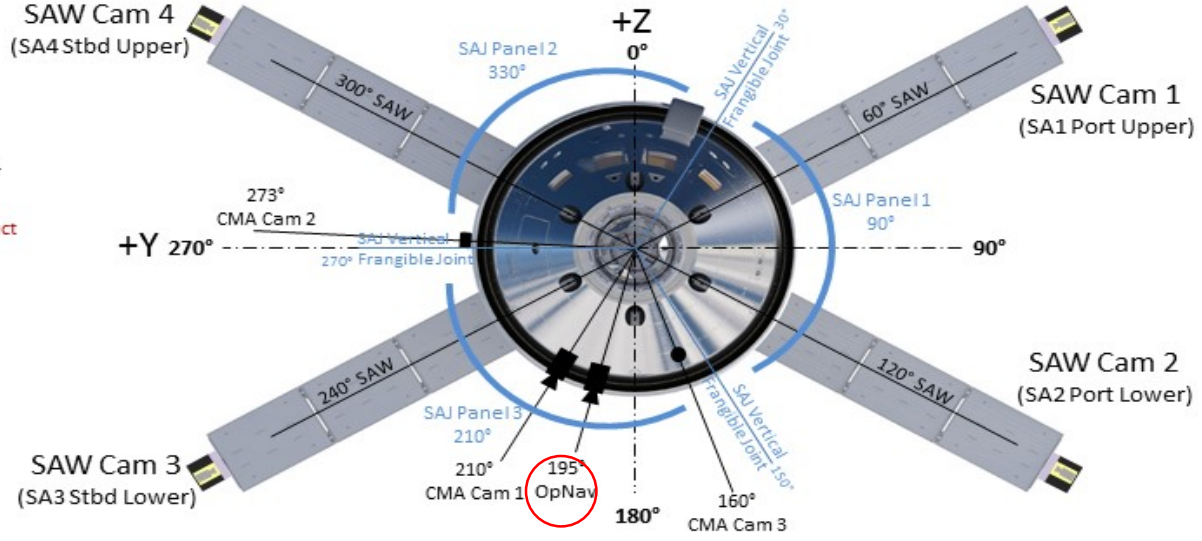
# MPCV Camera Locations

**Orion Vehicle Camera System**
Locations and Nomenclature

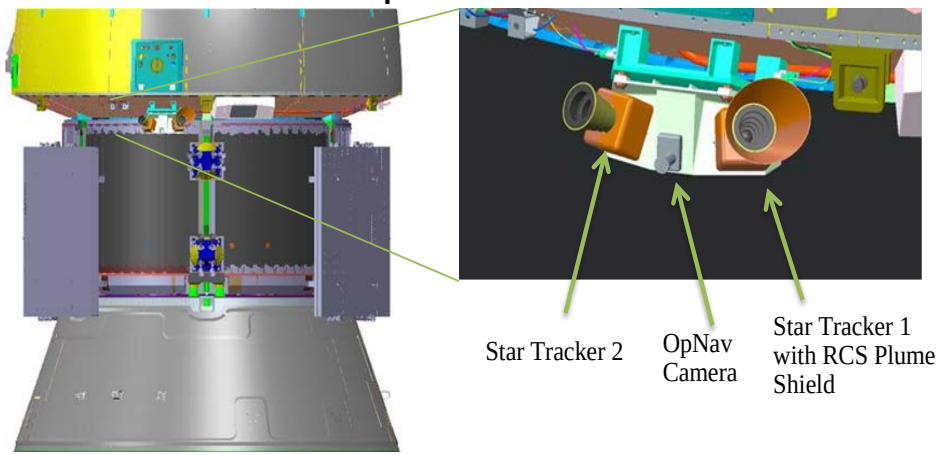
Axes in Orion Structural Coordinate System

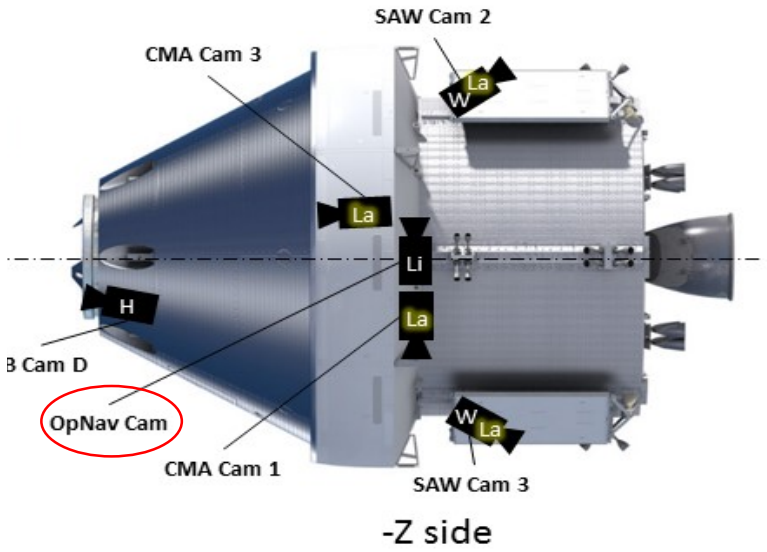



La = LED illuminators (**active**)
Li = LED illuminators (**inactive**)
W = WiFi wireless
H = High speed



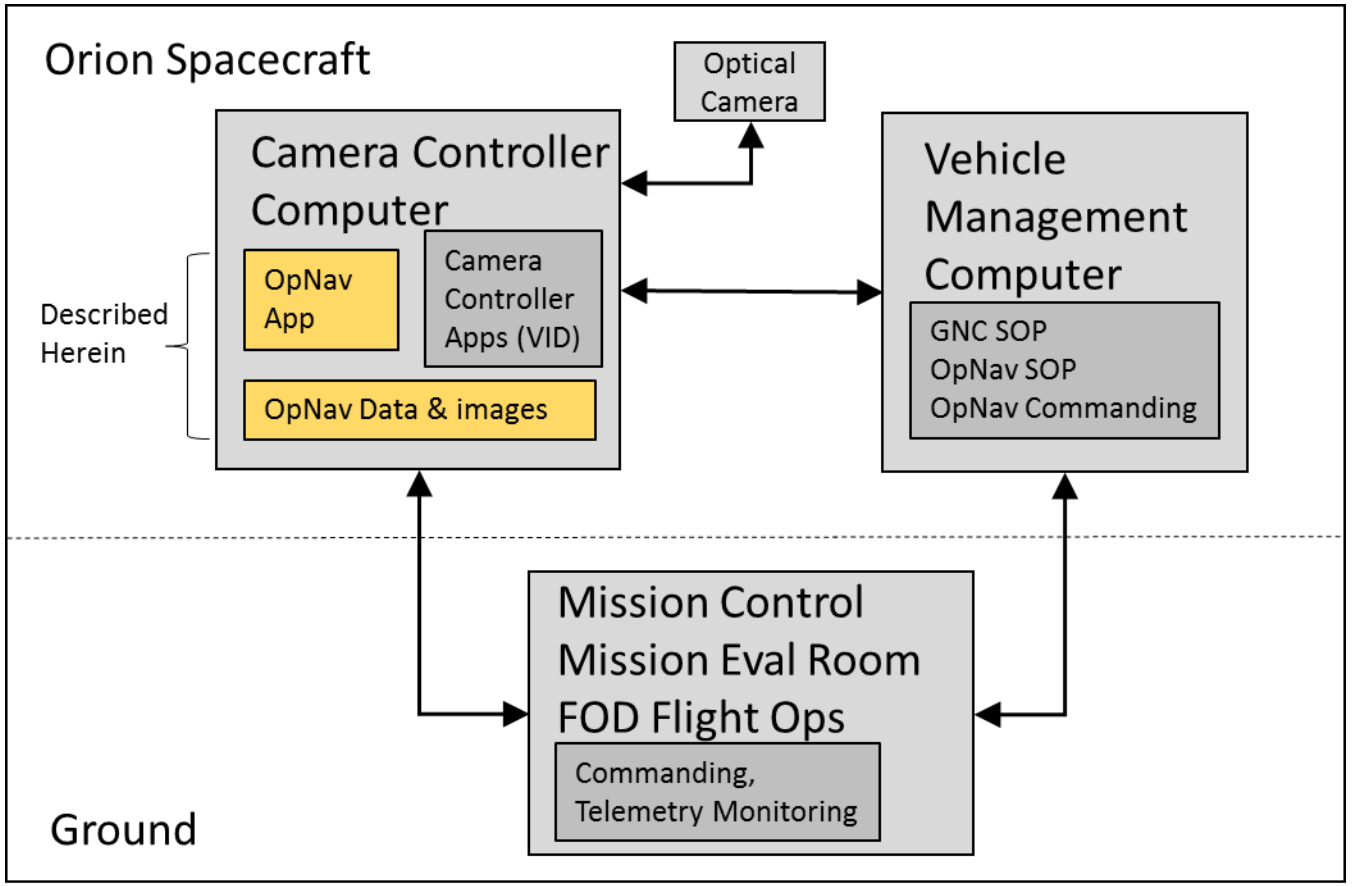

## Star Tracker & OpNav Camera Locations



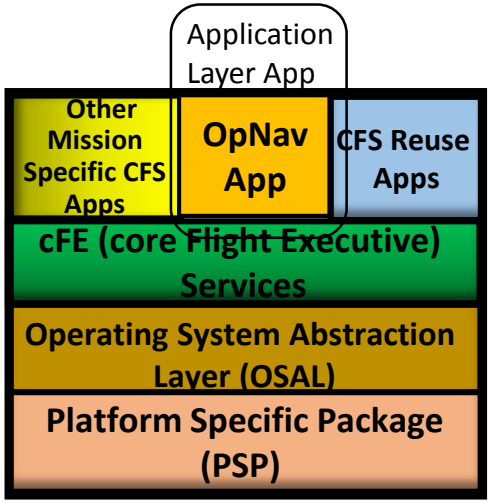

-Z side

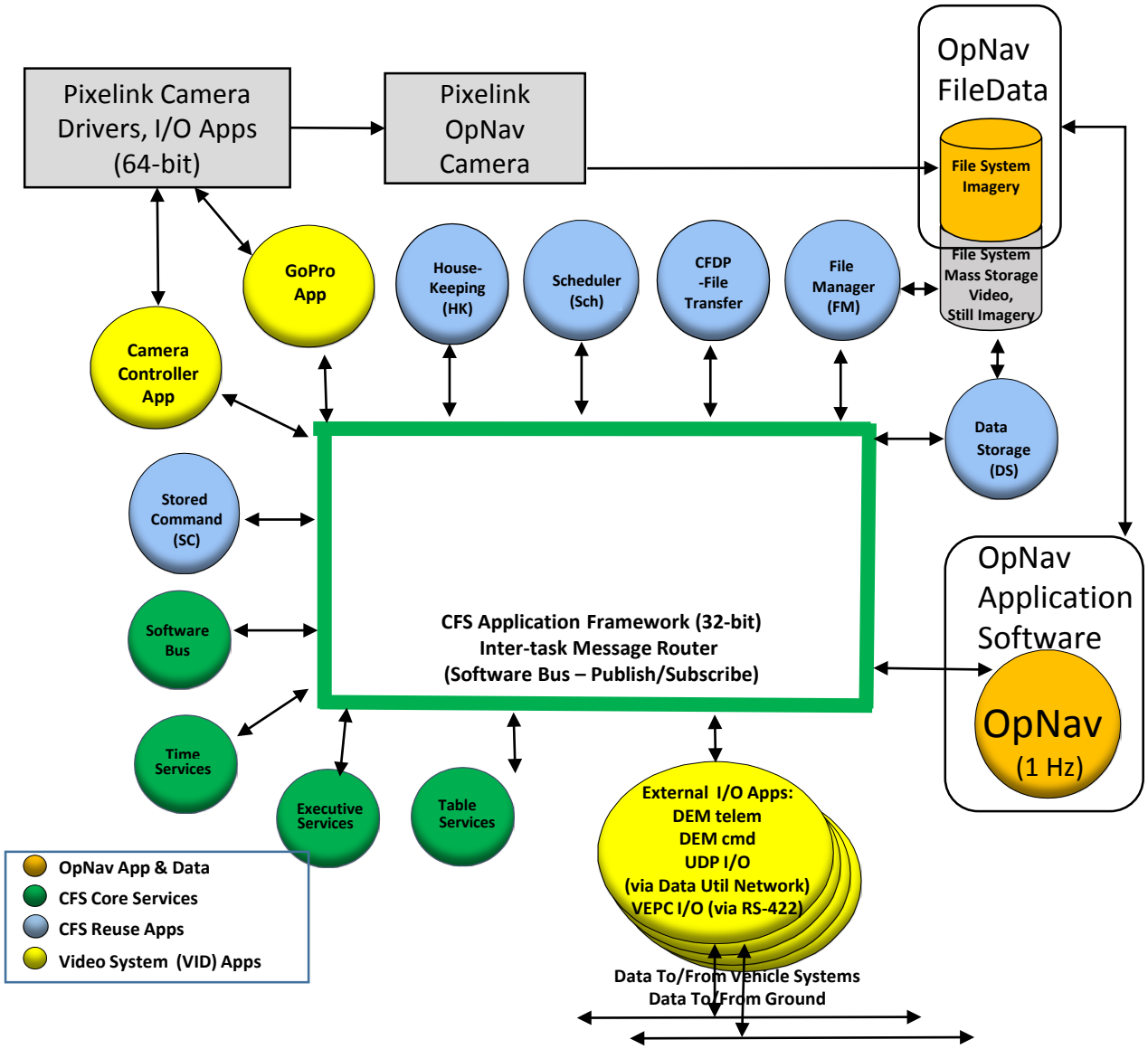
# OpNav System Architecture



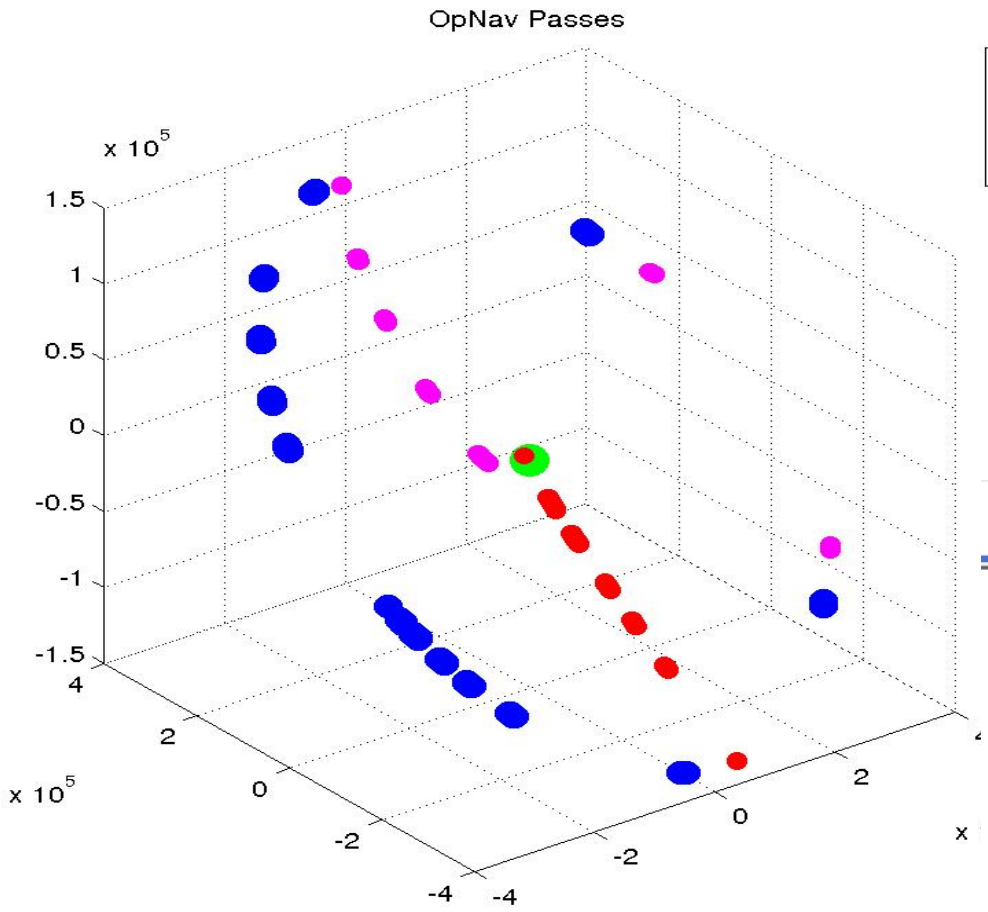
# OpNav Application Software Architecture

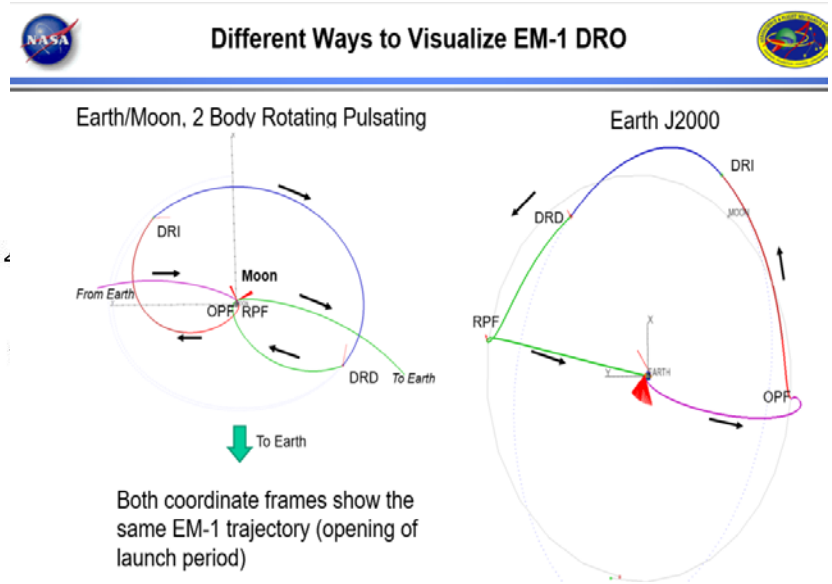
OpNav within CFS Layered Framework



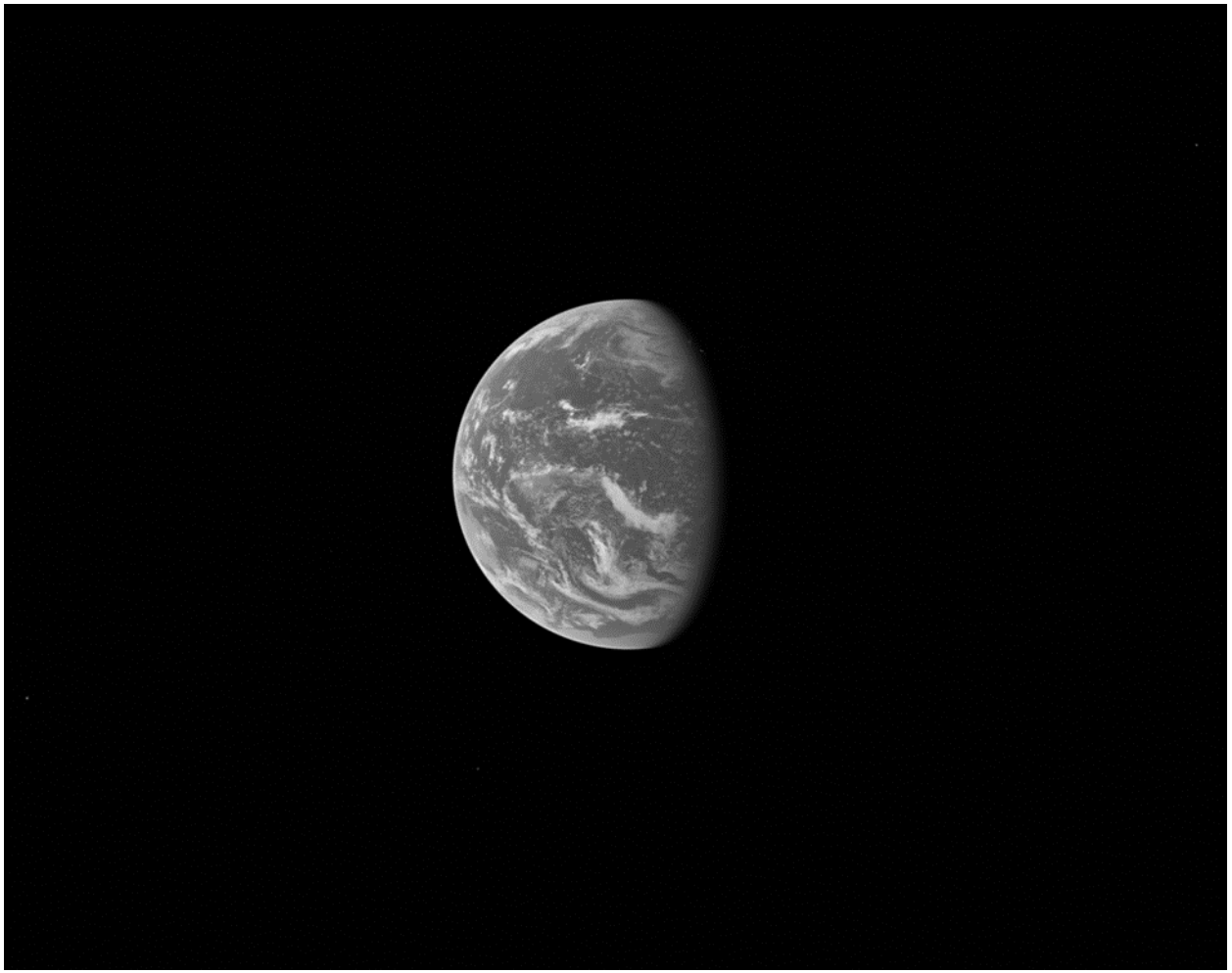



# Orion EM-1 OpNav Pass Visualization

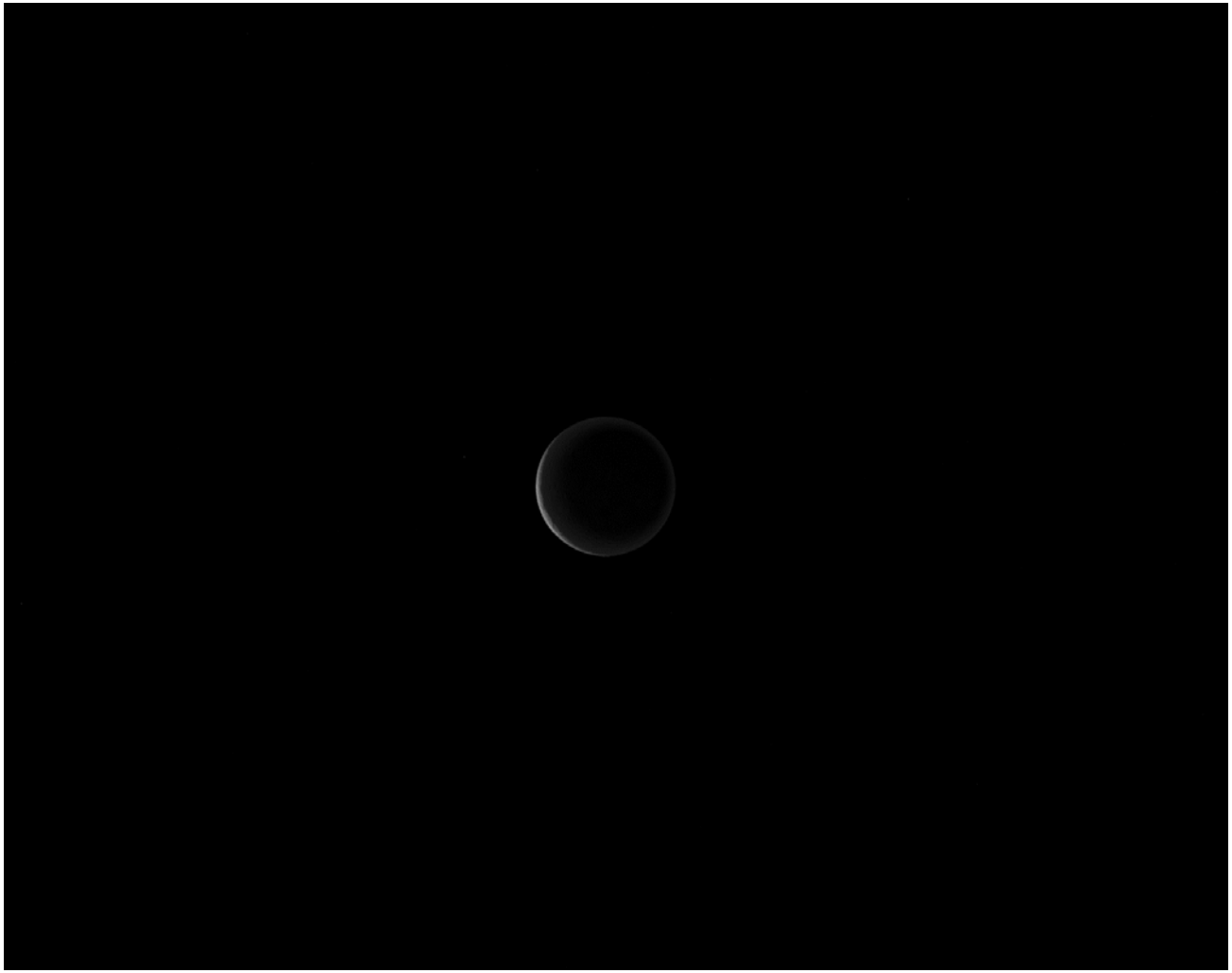


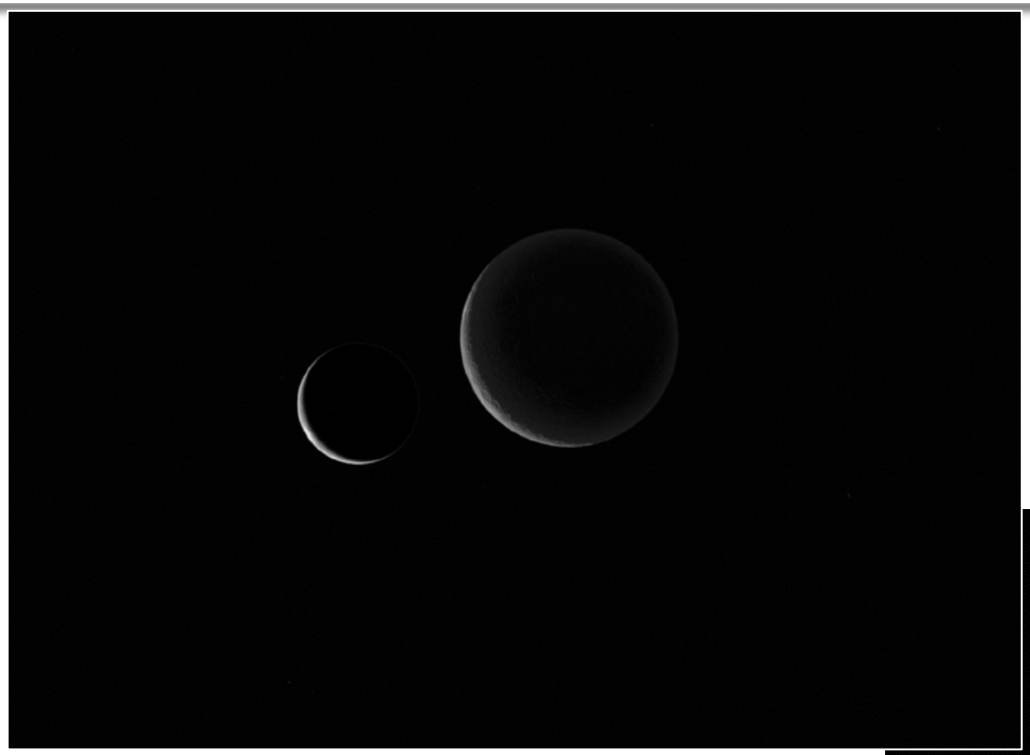
# Practice Earth Pass Sample Image, Trajectory Time 39065

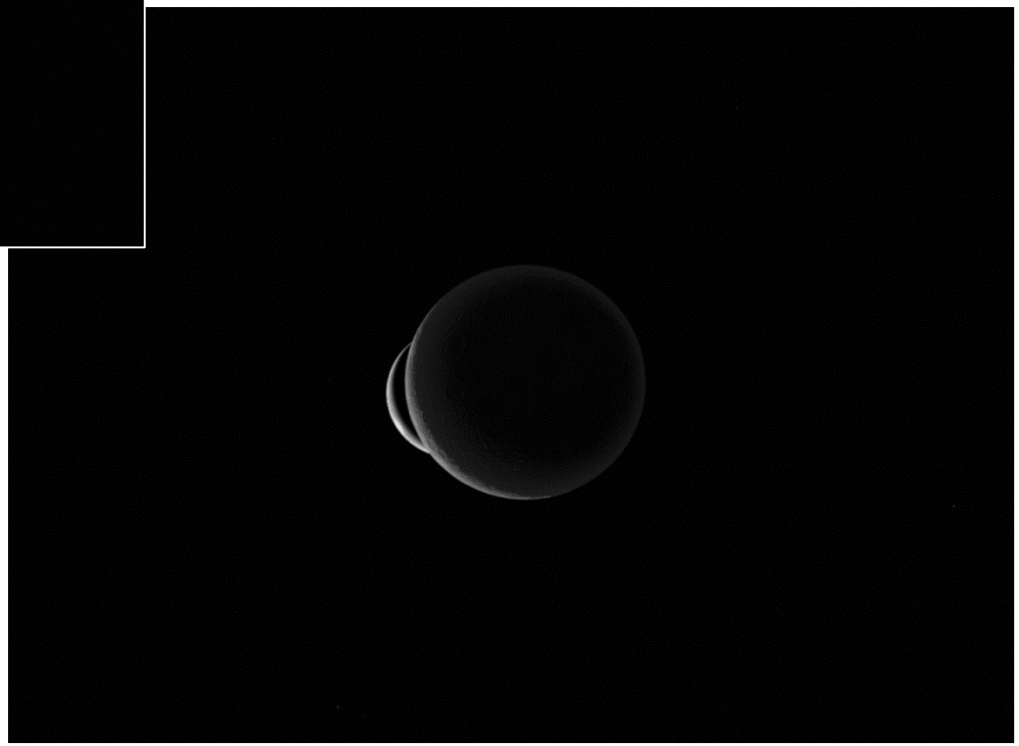


# 8.5.5 Cert 2 Backup Moon Pass Sample Image, Trajectory Time 415275

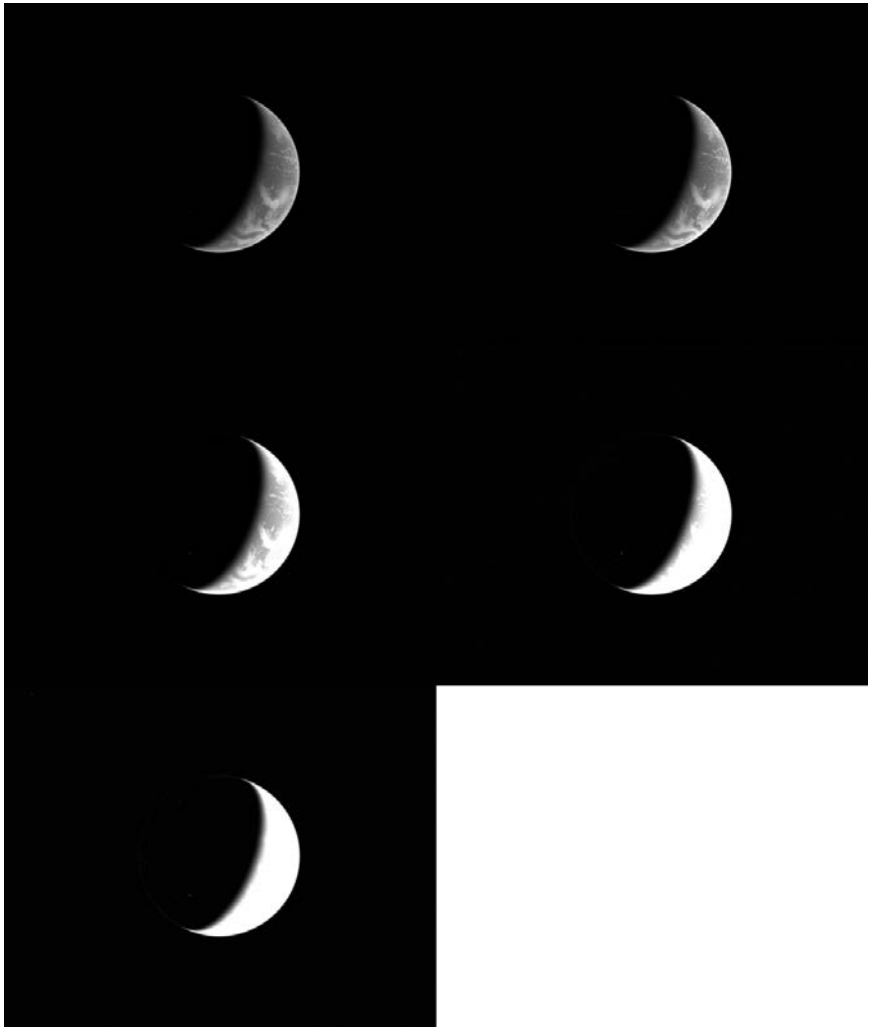


# Sample Off Nominal – Earth and Moon in Image during DRO





# Over-Underexposures (exposure bit) for each Pass



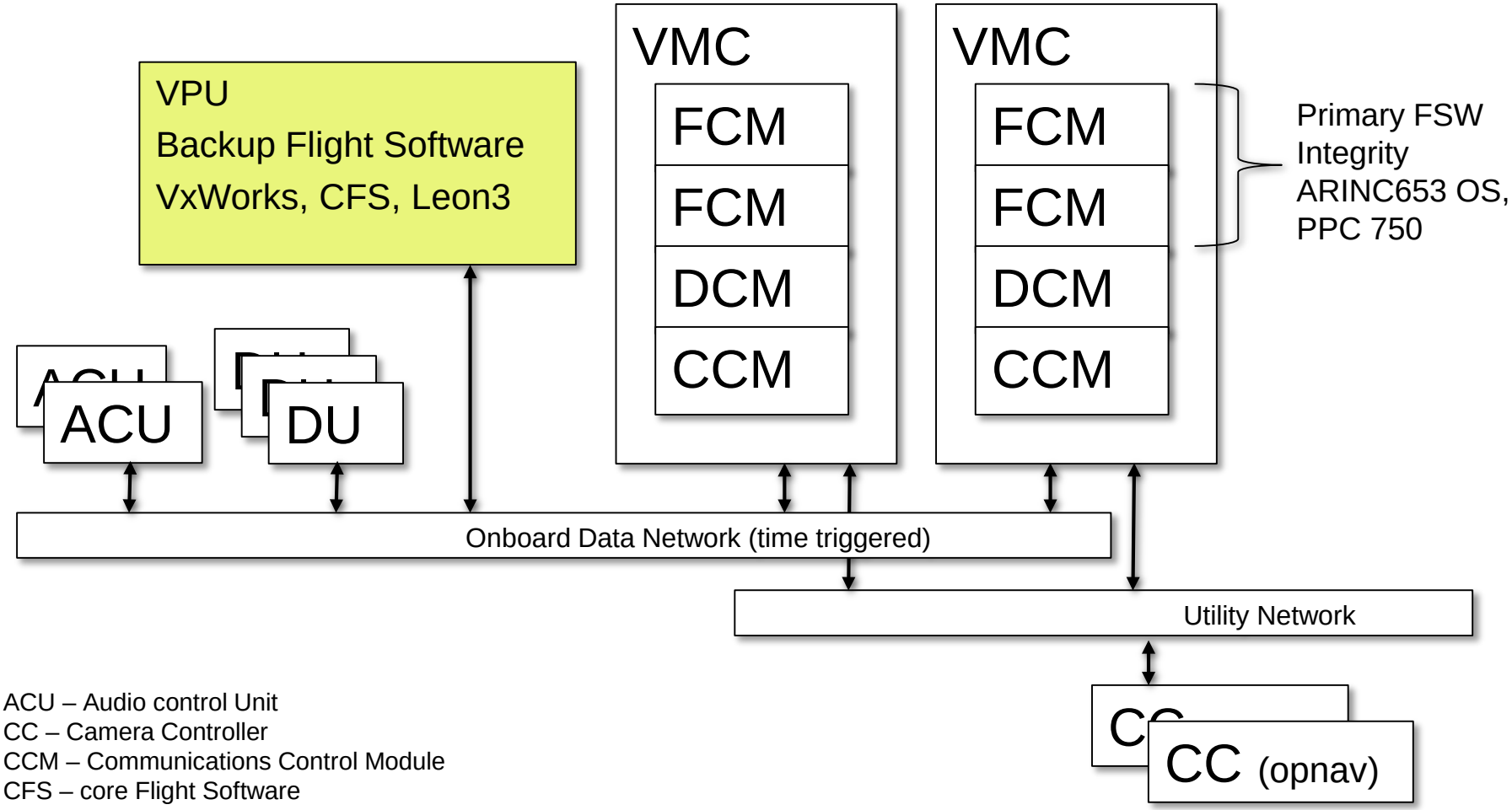
# Orion Backup Flight Software

- Human-rated spacecraft requires high degree of redundancy / fault tolerance
  - Redundant hardware systems (example:  quad-voting systems)
  - Redundant software systems
    - If primary software fails to operate, backup system is needed
    - Backup Flight Software (BFS) exists to mitigate the risk of software common cause failure in the primary flight system
      - Strive for dissimilarity in all life cycle phases, process, tools, platform, etc.
- Orion backup software
  - EM-1 BFS written to support backup during Entry
  - EM-2 BFS will be expanded to support all flight phases
    - EM-2 project started October 2018
      - Joint team with NASA and Lockheed-Martin (Orion prime contractor)
        - » Mix of C & C++ applications running within CFS framework
        - » LEON3 processor
        - » VxWorks OS
    - Reduced set of capabilities compared to primary, but can “take over” in event of a primary software failure
      - Complete dynamic flight events such as ascent, entry, and burn targeting
      - Maintain knowledge and control of vehicle attitude and state during quiescent flight phases
      - Maintain control of life support, power, and communication systems
      - Monitor and mitigate crew environmental hazards
      - Provide manual commanding and piloting capabilities to the crew

# Orion BFS vs. Primary Toolchain

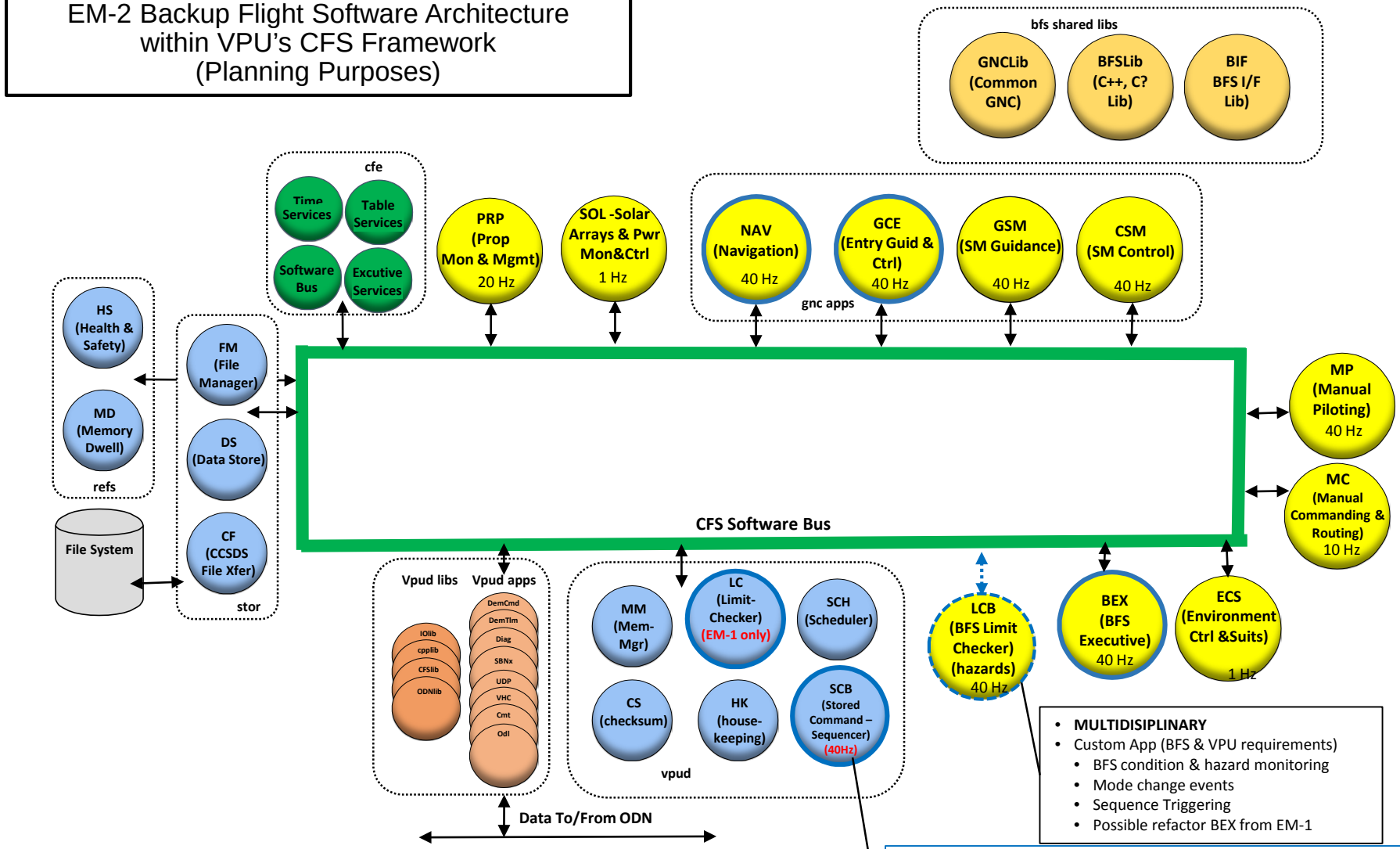
| Item | BFS | Primary FSW |
|---|---|---|
| Hardware and Operating System | | |
| CPU | LEON 3 | PPC-750 |
| Operating System / compiler | VxWorks | Green Hills Integrity |
| Framework | CFS Framework | ARINC653 |
| Development Tools / Language | | |
| Algorithm Implementation | Hand-Coded | Auto-generated C++ |
| Development Environment(s) | Eclipse, VxWorks Workbench | Rhapsody/Green Hills |
| Programming Language(s) | C or C++ | C++ |
| Software, Documentation, and Data Configuration Management | | |
| Data Management | CCDD -> ODS | ODS |
| In-Flight Reconfiguration | CFE tables | SLDB |
| Documentation Storage | NASA SharePoint, Windchill | Windchill |
| Requirements Linkage | Excel, DOORS | Rhapsody, DOORS |
| CM | Git -> Perforce | Perforce |
| Documentation Tools | Microsoft Office, Doxygen, DOORS, Windchill | Rhapsody, DOORS |
| Integration, Test, and Simulation | | |
| Unit Test Framework (UTF) | GoogleTest & UTAssert | LDRA |
| Code Coverage | gcov (Linux and VxWorks) | LDRA |
| Static/Standards Analysis | ucc code check, cpp check | Klockwork |
| Code Review | Gitlab, Crucible / Code Collaborator | Crucible/Code Collaborator |
| Simulation / Test | RAMTARES, CFS Test Framework, OrionSim | OrionSim |
| Development Process / Standards | | |
| Coding Standards | C – NASA, C++ - Orion SDP | Orion SDP |
| Software Development Process | NPR 7150.2B, BFS SDP Addendum | NPR 7150.2, Primary SDP |

# High-Level Orion Avionics Architecture




ACU – Audio control Unit
CC – Camera Controller
CCM – Communications Control Module
CFS – core Flight Software
DCM – Display Control Module
DU – Display Unit
FCM – Flight Control Module
FSW – Flight Software
ODN – Onboard Data Network
VMC – Vehicle Management Computer
VPU – Vision Processing Unit

# EM-2 Backup Flight Software Architecture within VPU's CFS Framework (Planning Purposes)



# Backup

- Questions?