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

European Service Module (ESM)

Crew Module Adapter (CMA)

Crew Module (CM)

Launch Abort System (LAS)

Orion

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

Current CFS Projects in Development/Test
Exploration Mission 1 Overview

EXPLORATION MISSION-1

The first uncrewed, integrated flight test of NASA’s Orion spacecraft and Space Launch System rocket, launching from a modernized Kennedy spaceport.

LAUNCH
SLS and Orion lift off from pad 39B at Kennedy Space Center

JETTISSON ROCKET BOOSTERS
Solid rocket boosters separate

EARTH ORBIT
Systems check and solar panel adjustments

TRANS LUNAR INJECTION (TLI) BURN
Burn lasts for approximately 20 minutes

INTERIM CRYOGENIC PROPSLION STAGE (ICPS) SEPARATION
The ICPS provides enough thrust to circularize orbit and commit Orion to TLI

3 JETTISSON LAUNCH ABORT SYSTEM & CORE STAGE SEPARATION
The LAS is no longer needed, Orion could safely abort at anytime; core stage separation and engine shut down

4 ENTER EARTH ORBIT
Perform the perigee raise maneuver

5 EARTH ORBIT
Systems check and solar panel adjustments

6 TRANS LUNAR INJECTION (TLI) BURN
Burn lasts for approximately 20 minutes

7 INTERIM CRYOGENIC PROPSLION STAGE (ICPS) SEPARATION
The ICPS provides enough thrust to circularize orbit and commit Orion to TLI

8 OUTBOUND TRANSIT
Requires several attitude maneuvers and Optical Navigation Checkout

9 OUTBOUND TRAJECTORY CORRECTION (OTC)
As necessary adjust trajectory for Lunar insertion to DRO

10 RETURN TRANSIT
Return Trajectory Correction burn prep; travel time 6-10 days

11 ORBIT INSERTION
Enter Distant Retrograde Orbit for next 6-10 days

12 DISTANT RETROGRADE ORBIT (DRO)
Burn maneuver and solar panel adjustment; 37,000 miles from the surface of the Moon

13 RETURN TRANSITION BURN
Precision Trajectory Burn aiming for Earth’s atmosphere

14 RETURN POWER FLY-BY (RPF)
RPF burn prep and return coast to Earth initiated

15 FINAL RETURN TRANSITION (RTC)
Precision targeting for Earth entry

16 CUBESATS DEPLOY
ICPS deploys 13 CubeSats total

17 SPLASHDOWN
Pacific Ocean landing within view of the U.S. Navy recovery ships

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)

1. Crew Module (CM) / Service Module (SM) separation
2. Perigee Raise Maneuver (PRM) by Interim Cryogenic Propulsion Stage (ICPS) into 100x975 nmi orbit
3. Trans-Lunar Outbound: 4 days with Outbound Trajectory Corrections (OTC) by Orion Aux Engines
4. Trans-Earth Return: 4 days Return Trajectory Corrections (RTC) by Orion Aux Engines
5. Apogee Raise Burn to High Earth Orbit with 24 hour period for Systems Checkout followed by ICPS separation from Orion
6. Crew and Orion Capsule Recovery
7. Orion Trans-Lunar Injection (TLI) by Orion Orbital Maneuvering System (OMS)
8. Lunar Fly-by 4,800 nmi
9. ICPS Disposal to Heliocentric orbit

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
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 Pad Abort Test
AA-2 Flight Test Vehicle
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.
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
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.
Loss of Comm Navigation

Orion Lunar Return Navigation: Lost Comm

- RTC-1: Flyby-167 hours, 76,500 km from Earth
- RTC-2: Flyby-58 hours, 84,000 km from Moon
- RTC-3: Flyby-6 hours
- RTC-4: EI-110 hours, Flyby+18 hours, 371,500 km from Earth
- Burn Targeting (Flyby-5.5 hours)
- Burn Targeting (Flyby-5.5 hours)
- RTC-5: EI-21 hours, 188,000 km from Earth
- RTC-6: EI-5 hours, 69,000 km from Earth
- Entry Interface: Flight Path Angle = -5.86°, Inertial Velocity = 11 km/s
- GPS Constellation
- TDRSS Constellation
- Return Powered Flyby Maneuver
- Optical Navigation Image Processing

ACRONYMS
- RTCC: Return Trajectory Correction
- TDRSS: Tracking & Data Relay Satellite System
- GPS: Global Positioning System
- EI: Entry Interface

LEGEND
- Onboard Burn Targeting
- Translational Maneuver
- Mission Events
- External Nav Systems
- Optical Nav Tracking Arc

Orion Multi-Purpose Crew Exploration Vehicle

Moon’s Orbit

Orion Orbit

National Aeronautics and Space Administration
NASA

NASA POC: Greg Holt
greg.n.holt@nasa.gov
MPCV Camera Locations

Orion Vehicle Camera System
Locations and Nomenclature

Star Tracker 2
Star Tracker 1
with RCS Plume Shield
OpNav Camera

SAW Cam 4
(SA4 Stbd Upper)

SAW Cam 1
(SA1 Port Upper)

SAW Cam 2
(SA2 Port Lower)

SAW Cam 3
(SA3 Stbd Lower)

Star Tracker & OpNav Camera Locations

Star Tracker 2
OpNav Camera
Star Tracker 1 with RCS Plume Shield

SAW Cam 2

CMA Cam 3

CMA Cam 1

SAW Cam 3

OpNav Cam

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

Orion Structural Coordinate System

X_{struct}

Z_{struct}

Y_{struct}
Orion EM-1 OpNav Pass Visualization

OpNav Passes

- spacecraft outbound
- spacecraft inbound
- moon
- earth

Different Ways to Visualize EM-1 DRO

Earth/Moon, 2 Body Rotating Pulsating

Both coordinate frames show the same EM-1 trajectory (opening of launch period)
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
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

<table>
<thead>
<tr>
<th>Item</th>
<th>BFS</th>
<th>Primary FSW</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Hardware and Operating System</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>CPU</td>
<td>LEON 3</td>
<td>PPC-750</td>
</tr>
<tr>
<td>Operating System / compiler</td>
<td>VxWorks</td>
<td>Green Hills Integrity</td>
</tr>
<tr>
<td>Framework</td>
<td>CFS Framework</td>
<td>ARINC653</td>
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<tr>
<td><strong>Development Tools / Language</strong></td>
<td></td>
<td></td>
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<tr>
<td>Algorithm Implementation</td>
<td>Hand-Coded</td>
<td>Auto-generated C++</td>
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<tr>
<td>Development Environment(s)</td>
<td>Eclipse, VxWorks Workbench</td>
<td>Rhapsody/Green Hills</td>
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<tr>
<td>Programming Language(s)</td>
<td>C or C++</td>
<td>C++</td>
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<td><strong>Software, Documentation, and Data Configuration Management</strong></td>
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<tr>
<td>Data Management</td>
<td>CCDD -&gt; ODS</td>
<td>ODS</td>
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<tr>
<td>In-Flight Reconfiguration</td>
<td>CFE tables</td>
<td>SLDB</td>
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<td>Documentation Storage</td>
<td>NASA SharePoint, Windchill</td>
<td>Windchill</td>
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<td>Requirements Linkage</td>
<td>Excel, DOORS</td>
<td>Rhapsody, DOORS</td>
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<td>CM</td>
<td>Git -&gt; Perforce</td>
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<td>Rhapsody, DOORS</td>
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<td><strong>Integration, Test, and Simulation</strong></td>
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<td>Unit Test Framework (UTF)</td>
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<td>Code Coverage</td>
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<td>Static/Standards Analysis</td>
<td>ucc code check, cpp check</td>
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<td>Code Review</td>
<td>Gitlab, Crucible / Code Collaborator</td>
<td>Crucible/Code Collaborator</td>
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<td>RAMTARES, CFS Test Framework, OrionSim</td>
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<td>C – NASA, C++ - Orion SDP</td>
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<td>NPR 7150.2, Primary SDP</td>
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</table>
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

Primary FSW
Integrity ARINC653 OS, PPC 750

Onboard Data Network (time triggered)

Utility Network

VPU
Backup Flight Software
VxWorks, CFS, Leon3
EM-2 Backup Flight Software Architecture within VPU’s CFS Framework (Planning Purposes)

- **Time Services**
- **Executive Services**
- **Software Bus**
- **File System**

**CFS Software Bus**

- **PRP (Prop Mon & Mgmt)**: 20 Hz
- **SOL - Solar Arrays & Pwr Mon & Ctrl**: 1 Hz
- **NAV (Navigation)**: 40 Hz
- **GCE (Entry Guid & Ctrl)**: 40 Hz
- **GSM (SM Guidance)**: 40 Hz
- **CSM (SM Control)**: 40 Hz

**Data To/From ODN**

**VPUD Mission Specific Applications**
- EM1 BFS Apps/Sequences

**BFS Libraries**
- **bfs shared libs**
  - **GNCLib** (Common GNC)
  - **BFSLib** (C++, C? Lib)
  - **BIF BFS I/F Lib**

**MULTIDISIPLINARY**
- Custom App (BFS & VPU requirements)
- BFS condition & hazard monitoring
- Mode change events
- Sequence Triggering
- Possible refactor BEX from EM-1

**VPUD Mission Specific Applications**
- **VPUD Mission Specific Applications**
  - **EM1 BFS Apps/Sequences**
  - **BFS Config sequences**
  - **CM RCS prop pressurize**
  - **Functions of EVE (EM-1’s EVE App refactored possibly)**
  - **Possible Incorporate BEX from EM-1**

**VPU and CC/VID**

**Partial List of CFS Core Services**
- **MP (Manual Piloting)**: 40 Hz
- **MC (Manual Commanding & Routing)**: 1 Hz

**BFS Condition & Hazard Monitoring**

**MULTIDISIPLINARY**
- **Mode change events**
- **Sequence Triggering**

**VPUD Mission Specific Applications**
- **EM1 BFS Apps/Sequences**
- **BFS Config sequences**
- **CM RCS prop pressurize**
- **Functions of EVE (EM-1’s EVE App refactored possibly)**
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Questions?