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
<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>
</tr>
</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, 2 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</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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<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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<tr>
<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>
<td>2026</td>
<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>
<td>Yes</td>
<td>2027</td>
<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

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

2. JETTISON ROCKET BOOSTERS
Solid rocket boosters separate

3. EARTH ORBIT
Systems check and solar panel adjustments

4. ENTER EARTH ORBIT
Perform the perigee raise maneuver

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

6. JETTISON 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

7. INTERIM CRYOGENIC PROPULSION 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 POWER FLY-BY
RPF burn prep and return coast to Earth initiated

14. RETURN POWERED FLY-BY
Results in DRO insertion; 62 miles from the Moon

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

16. CUBESATS DEPLOY
ICPS deploys 13 CubeSats total

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
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. Apogee Raise Burn to High Earth Orbit with 24 hour period for Systems Checkout followed by ICPS separation from Orion
5. Orion Trans-Lunar Injection (TLI) by Orion Orbital Maneuvering System (OMS)
6. Trans-Earth Return: 4 days Return Trajectory Corrections (RTC) by Orion Aux Engines
7. Lunar Fly-by 4,800 nmi

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 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 Ignition**
   
   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.
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-4
El-110 hours
Flyby+18 hours

RTC-2
Flyby-58 hours
84,000 km from Moon

RTC-3
Flyby-6 hours

RTC-5
El-21 hours
188,000 km from Earth

RTC-6
El-5 hours
69,000 km from Earth

Burn Targeting
(Flitby-57.5 hours)

Burn Targeting
(Flitby-5.5 hours)

ACRONYMS
RTC: Return Trajectory Correction
TDRSS: Tracking & Data Relay Satellite System
GPS: Global Positioning System
El: Entry Interface

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

GPS Constellation
Flight Path Angle = -5.86°
Inertial Velocity = 11 km/s

TDRSS Constellation

Entry Interface

Service Module Separation
El-30mun

Optical Navigation Image Processing

LEGEND

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

Orion Vehicle Camera System
Locations and Nomenclature

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

Orion Structural Coordinate System

X_{struct}

Y_{struct}

Z_{struct}

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

SAJ Panel 1
90°

SAJ Panel 2
270°

SAJ Panel 3
110°

SAJ Panel 4
195°

SAJ Panel 5
160°

270° Frangible Joint

SAJ Vertical Stiffeners

SAJ Vertical Stiffeners
OpNav System Architecture

Orion Spacecraft

- Camera Controller Computer
  - OpNav App
  - Camera Controller Apps (VID)
  - OpNav Data & images

- Vehicle Management Computer
  - GNC SOP
  - OpNav SOP
  - OpNav Commanding

Ground

- Mission Control
- Mission Eval Room
- FOD Flight Ops
  - Commanding, Telemetry Monitoring

Optical Camera

Described Herein
Orion EM-1 OpNav Pass Visualization

OpNav Passes

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>
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<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>
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<tr>
<td>Framework</td>
<td>CFS Framework</td>
<td>ARINC653</td>
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<tr>
<td><strong>Development Tools / Language</strong></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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<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>
<td>Perforce</td>
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<td>Documentation Tools</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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<tr>
<td>Unit Test Framework (UTF)</td>
<td>GoogleTest &amp; UTAssert</td>
<td>LDRA</td>
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<td>Code Coverage</td>
<td>gcov (Linux and VxWorks)</td>
<td>LDRA</td>
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<td>Static/Standards Analysis</td>
<td>ucc code check, cpp check</td>
<td>Klockwork</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>Simulation / Test</td>
<td>RAMTARES, CFS Test Framework, OrionSim</td>
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<td><strong>Development Process / Standards</strong></td>
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<td>Coding Standards</td>
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<td>Software Development Process Addendum</td>
<td>NPR 7150.2B, BFS SDP Addendum</td>
<td>NPR 7150.2, Primary SDP</td>
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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
VxWorks, CFS, Leon3
ARINC653 OS, PPC 750
EM-2 Backup Flight Software Architecture within VPU’s CFS Framework (Planning Purposes)

**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**
- **CFS Core Services**
- **CFS Reuse Apps**
- **BFS-Mission Specific Apps/Sequences**
- **VPUD MIssion Specific Applications**

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

**VPUD Apps**
- **DemCmd**
- **DemTlm**
- **Diag**
- **SBNx**
- **UDP**
- **VHC**
- **Cmt**
- **Odl**

**BFS App/Sequences**
- **MM (Limit-Checker) (EM-1 only)**
- **LCB (BFS Limit Checker) (hazards)**: 40 Hz
- **LCB (BFS Limit Checker) (hazards)**: 1 Hz
- **BEX (BFS Executive)**: 40 Hz
- **ECS (Environment Ctrl & Suits)**: 10 Hz
- **MP (Manual Piloting)**: 40 Hz
- **MC (Manual Commanding & Routing)**: 1 Hz

**Time Services**
- **cfe**
- **Table Services**
- **Executive Services**

**File System**
- **vpuud**
- **vpuud apps**
- **Vpud libs**

**Fat File System**
- **BFS-Mission Specific Apps/Sequences**

**Multi-Disciplinary**
- 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**
- **BFS-Mission Specific Apps/Sequences**
- **EM1 BFS Apps/Sequences**

**VPUU and CC/VID**
- **CFS Framework & Apps**
- **VPUU and CC/VID**

**VF Library**
- **BFSLib (C++, C? Lib)**
- **BIF**
- **GNCLib (Common GNC)**

**CFS Core Services**
- **CFS Framework & Apps**
- **VPUU and CC/VID**

**CFS Reuse Apps**
- **CFS Reuse Apps**
- **VPUD MIssion Specific Applications**
- **BFS-Mission Specific Apps/Sequences**

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

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

**Multi-Disciplinary**
- Modified SC for higher rate time response, sub second times
- Multi-Discipline Cmd Sequences (RelTime & AbsTime):
  - Ascent Sequences
  - Entry Sequences
  - Config heaters
  - Config pressurization
  - Manual Burn Attitude
- BFS Config sequences
- CM RCS prop pressurize
- Functions of EVE (EM-1’s EVE App refactored possibly)
- Possible Incorporate BEX from EM-1

L. Prokop 1/7/2019
Questions?