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 Program Mission Schedule (Wikipedia)

<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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<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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<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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<td>EM-1</td>
<td>SLS Block 1 Crew</td>
<td>No</td>
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<td>Under development</td>
<td>26–40 days</td>
<td>Lunar orbit</td>
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<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>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>EM-4</td>
<td>SLS Block 1B Crew</td>
<td>Yes</td>
<td>2025</td>
<td>Planned</td>
<td>26–42 days</td>
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<td>EM-5</td>
<td>SLS Block 1B Crew</td>
<td>Yes</td>
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<td>26–42 days</td>
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<td>EM-7</td>
<td>SLS Block 1B Crew</td>
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<td>191–221 days</td>
<td>Gateway station</td>
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<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>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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</tbody>
</table>

**Current CFS Projects in Development/Test**
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

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

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

JETTISON ROCKET BOOSTERS 2
Solid rocket boosters separate

EARTH ORBIT 5
Systems check and solar panel adjustments

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

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

ENTER EARTH ORBIT 4
Perform the perigee raise maneuver

RE-ENTRY INTERFACE 16
Enter Earth’s atmosphere

OUTBOUND TRANSIT 8
Requires several attitude maneuvers and Optical Navigation Checkout

OUTBOUND TRAJECTORY CORRECTION (RTC) 9
Precision targeting for Earth entry

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

FINAL RETURN TRAJECTORY CORRECTION (RTC) 15
Precision targeting for Earth entry

CUBESATS DEPLOY 12
ICPS deploys 13 CubeSats total

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

RETURN TRANSIT 13
Return Trajectory Correction burn prep; travel time 6-10 days

RETURN POWER FLY-BY (RPF) 16
RPF burn prep and return coast to Earth initiated

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

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

OUTBOUND POWERED FLY-BY 10
Results in DRO insertion; 62 miles from the Moon

RETURN TRAJECTORY BURN 14
Precision Trajectory Burn aiming for Earth’s atmosphere

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

1553 Bus
Ethernet & RS422 Busses
CM & LAS Interface, RS422 & Discrete Pyro

Flight Computer 1
PCU, Battery
Flight Computer 2
PCU, Battery

SIGI
PDU
DFI
EDR

LAS
Pyros
AA-2 Flight Software Architecture

- **Command Ingest** (10 Hz)
- **Telemetry Output** (40 Hz)
- **Executive Services**
- **Event Services**
- **Table Services**
- **Mission Specific Apps**
- **cFE Core Services**
- **CFS Configurable Applications**

- **SSRs, Avionics temps, voltage, etc.**
- **Pyros, ATB discrete signals**
- **Launch Abort System**
- **Telemetry Output Serial (40 Hz)**
- **Telemetry Output (40 Hz)**
- **Command Ingest (50 Hz)**
- **House-Keeping (50 Hz)**
- **Scheduler / Sync (40 Hz)**

- **Inter-task Message Router (SW Bus – Publish/Subscribe)**
  - **Ethernet**
  - Framed CCSDS 1.28 Mbps (combined)
  - RS-422 (two channels)

- **SISI**
- **EDR**
- **A IO (40 Hz)**
- **D IO (40 Hz)**
- **LAS I/O (40 Hz)**
- **Pyros, ATB discrete signals**
- **Manchester Encoded RS-422**
- **GNC 40 Hz (40 Hz)**
- **GNC 1 Hz (1 Hz)**
- **Automated Flight Manager (AFM) (40 Hz)**
- **Ethernet**
- **Software Bus**
- **Time Services**
- **Executive Services**
- **Event Services**
- **Table Services**
Optical Navigation (OpNav) Application Software

- 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

Orion Multi-Purpose Crew Exploration Vehicle

National Aeronautics and Space Administration

Orion Moon’s Orbit

Loss of Comm

RTC-1
Flyby-167 hours
76,500 km from Earth

RTC-4
EI-110 hours
Flyby+18 hours

RTC-3
Flyby-6 hours

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

RTC-4
EI-110 hours
Flyby+18 hours
371,500 km from Earth

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

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

Burn Targeting (Flyby-57.5 hours)

Burn Targeting (EI-15 minutes)
Inertial Velocity = 8.87 km/s
Altitude = 3.185 km

4 GPS Satellite Visibility

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

TDRSS Constellation

Entry Interface

Service Module Separation
EI-30min

Return Powered Flyby Maneuver

Optical Navigation Image Processing

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

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

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

Orion Vehicle Camera System
Locations and Nomenclature

Axe in Orion Structural Coordinate System

SAW Cam 4
(SA4 Stbd Upper)

SAW Cam 1
(SA1 Port Upper)

SAW Cam 2
(SA2 Port Lower)

SAW Cam 3
(SA3 Stbd Lower)

+Y 270°

-+ 0°

190°

180°

160°

130°

60°

SAY Panel 3
110°

CMA Cam 1

CMA Cam 2

CMA Cam 3

OpNav

OpNav Camera

Star Tracker 2

Star Tracker 1 with RCS Plume Shield

SAW Cam 2

SAW Cam 3

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

Described Herein

Optical Camera
OpNav Application Software Architecture

OpNav within CFS Layered Framework

Other Mission Specific CFS Apps

OpNav App

CFS Reuse Apps

cFE (core Flight Executive) Services

Operating System Abstraction Layer (OSAL)

Platform Specific Package (PSP)

OpNav Application Software

OpNav (1 Hz)

File To/from Ground

External I/O Apps:
DEM telem
DEM cmd
UDP I/O (via Data Util Network)
VEPC I/O (via RS-422)

Data To/from Vehicle Systems

OpNav App & Data
CFS Core Services
CFS Reuse Apps
Video System (VID) Apps
Orion EM-1 OpNav Pass Visualization

Different Ways to Visualize EM-1 DRO

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>
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<td></td>
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<tr>
<td>CPU</td>
<td>LEON 3</td>
<td>PPC-750</td>
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<tr>
<td>Operating System / compiler</td>
<td>VxWorks</td>
<td>Green Hills Integrity</td>
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<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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<td>Development Environment(s)</td>
<td>Eclipse, VxWorks Workbench</td>
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<td>Programming Language(s)</td>
<td>C or C++</td>
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<td><strong>Software, Documentation, and Data Configuration Management</strong></td>
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<td>Data Management</td>
<td>CCDD -&gt; ODS</td>
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<td>In-Flight Reconfiguration</td>
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<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>Git -&gt; Perforce</td>
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<td>Rhapsody, DOORS</td>
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<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>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

Primary FSW Integrity
ARINC653 OS, PPC 750

VPU
Backup Flight Software
VxWorks, CFS, Leon3

ACU
DU

Onboard Data Network (time triggered)

Utility Network

CC (opnav)
Questions?