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)
- Spacecraft Adapter Jettisoned Fairings (SAJ)

Orion
<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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<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>
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<td>AA-2</td>
<td>Orion Abort Test Booster</td>
<td>No</td>
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<td>Under development</td>
<td>Less than 3 minutes</td>
<td>Stratosphere</td>
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<td>26–40 days</td>
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<td>2 years</td>
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Current CFS Projects in Development/Test

**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.

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

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

3 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

4 ENTER EARTH ORBIT
Perform the perigees 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 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 OUTBOUND POWERED FLY-BY
Results in DRO insertion; 62 miles from the Moon

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

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

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

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

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

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

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. Crew and Orion Capsule Recovery
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. Entry and Landing

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
**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.
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 Flight Software Architecture

- **Executive Services**
- **Event Services**
- **Table Services**
- **CFS Configurable Applications**
- **Mission Specific I/O Apps**
- **cFE Core Services**
- **Software Bus**
- **Time Services**
- **Executive Services**
- **Event Services**

### Key Components:

- **Telemetry Output** (40 Hz)
- **Command Ingest** (10 Hz)
- **Telemetry Output** (40 Hz)
- **Command Ingest** (10 Hz)
- **Housekeeping** (10 Hz)
- **Scheduler / Sync** (40 Hz)

### Interfaces:

- **1553**
- **DFI** Framed CCSDS 1.28 Mbps (combined)
- **Ethernet**

### Additional Services:

- **Inter-task Message Router (SW Bus – Publish/Subscribe)**
- **Launch Abort System**
- **Pyros, ATB discrete signals**
- **SSRs, Avionics temps, voltage, etc.**
- **LAS I/O (40 Hz)**
- **A IO (40 Hz)**
- **D IO (40 Hz)**
- **SIGI IO (40 Hz)**
- **EDR IO (40 Hz)**

### Encoder Details:

- Manchester Encoded RS-422

### Data Rates:

- **1 Hz**
- **40 Hz**
- **2553**

### Discrete Signals:

- **Pyros, ATB discrete signals**
- **Launch Abort System**
- **GNC 40 Hz**
- **GNC 1 Hz**
- **GNC 40 Hz**
- **GNC 1 Hz**
- **EDR RS-422**
- **Telemetry Output Serial (40 Hz)**
- **Telemetry Output Serial (40 Hz)**
- **Command Ingest (50 Hz)**
- **Housekeeping (50 Hz)**
- **Scheduler / Sync (40 Hz)**
- **Telemetry Output (40 Hz)**
- **Command Ingest (50 Hz)**
- **Launch Abort System**
- **Pyros, ATB discrete signals**
- **SSRs, Avionics temps, voltage, etc.**
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

Moon radius (SVD) = 659.5229 pixels

Moon center (SVD): row = 1160.1663 pixels

Moon center (SVD): column = 1473.042 pixels
Loss of Comm Navigation

Orion Lunar Return Navigation: Lost Comm

Orion Multi-Purpose Crew Exploration Vehicle

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
19,800 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 (EI-5.5 hours)

Burn Targeting (Flyby-57.5 hours)

Burn Targeting (EI-20.5 hours)

Return Powered Flyby Maneuver

4 GPS Satellite Visibility
EI-15 minutes
Inertial Velocity = 8.87 km/s
Altitude = 3,185 km

TDRSS Constellation

GPS Constellation

Entry Interface
Flight Path Angle = 5.86°
Inertial Velocity = 11 km/s

Service Module Separation
EI-30min

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.n.holt@nasa.gov
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
OpNav Application Software Architecture

OpNav within CFS Layered Framework

- **OpNav App**
- **cFE (core Flight Executive) Services**
- **Operating System Abstraction Layer (OSAL)**
- **Platform Specific Package (PSP)**

- **CFS Reuse Apps**
- **Other Mission Specific CFS Apps**

- **OpNav within CFS Layered Framework**

**OpNav Application Software**

- **OpNav FileData**
  - File System Imagery
  - File System Mass Storage Video, Still Imagery
  - Data Storage (DS)

**CFS Application Framework (32-bit)**

- **Inter-task Message Router**
  - (Software Bus – Publish/Subscribe)

**OpNav Core Services**

- **OpNav Reuse Apps**
- **Other Mission Specific CFS Apps**

**OpNav**

- **(1 Hz)**

**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**

**Data To/From Ground**

**OpNav Application Software Framework**

- **Pixelink Camera Drivers, I/O Apps (64-bit)**
- **GoPro App**
- **Camera Controller App**
- **Stored Command (SC)**
- **Software Bus**
- **Time Services**
- **Executive Services**
- **Table Services**

**OpNav FileData**

- **File System Imagery**
- **File System Mass Storage Video, Still Imagery**
- **Data Storage (DS)**

**Camera Controller App**

- **GoPro App**
- **House-Keeping (HK)**
- **Scheduler (Sch)**
- **CFDP - File Transfer**
- **FileManager (FM)**

**OpNav within CFS Layered Framework**

- **Application Layer App**
- **OpNav App**
- **CFS Core Services**
- **CFS Reuse Apps**
- **Other Mission Specific CFS Apps**

**Pixelink Camera**

- **OpNav Camera**
- **FileSystem**
- **Imagery**
- **CFDP - File Transfer**
- **FileManager (FM)**

**Video System (VID) Apps**

- **GoPro**
- **OpNav**
- **OpNav within CFS Layered Framework**

**OpNav App & Data**

- **OpNav Core Services**
- **CFS Reuse Apps**
- **Video System (VID) Apps**

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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

Earth J2000

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

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<tr>
<th>Item</th>
<th>BFS</th>
<th>Primary FSW</th>
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<tr>
<td><strong>Hardware and Operating System</strong></td>
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<tr>
<td>CPU</td>
<td>LEON 3</td>
<td>PPC-750</td>
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<td>Operating System / compiler</td>
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<td>Rhapsody, DOORS</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

VPU
Backup Flight Software
VxWorks, CFS, Leon3

ACU

DU

Onboard Data Network (time triggered)

Utility Network

CC (opnav)

Primary FSW Integrity
ARINC653 OS, PPC 750

VMC
FCM
FCM
DCM
CCM

VMC
FCM
FCM
DCM
CCM

ACU

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

- **TIME SERVICES**
  - **CFE (CCSDS Command & Data)**
  - **Table Services**
  - **Software Bus**

- **EXECUTIVE SERVICES**
  - **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**

- **SOFTWARE BUS**
  - **gnc apps**
  - **BEX (BFS Executive) 40 Hz**
  - **MP (Manual Piloting) 40 Hz**
  - **MC (Manual Commanding & Routing) 10 Hz**
  - **CFS Software Bus**

- **FILE SYSTEM**
  - **HK (Housekeeping)**
  - **LC (Limit Checker) (EM-1 only)**
  - **SCB (Stored Command - Sequencer) (40Hz)**

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

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

- **CFS Core Services**
  - **CFS Framework & apps**
  - **VPU and CC/VID**

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

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

- **Multi-Discipline Cmd Sequences**
  - **Table Services**
  - **Excutive Services**
  - **Software Bus**
  - **cfe**

- **BFS Libraries**
  - **bfs shared libs**
    - **bfs shared libs**
      - **IOlib**
      - **cpplib**
      - **CFSlib**
      - **ODNlib**

- **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?