Flight Software for the LADEE Mission

Aerospace Control and Guidance Systems Committee Meeting #116

Howard Cannon
NASA Ames Research Center
Howard.N.Cannon@nasa.gov

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Lunar Atmosphere and Dust Environment Explorer

Objective
- Measure Lunar Dust
- Examine the Lunar atmosphere

Key parameters
- Launched in September 2013
- Science Data Acquisition: 146 days
- Lunar Impact April 18,2014

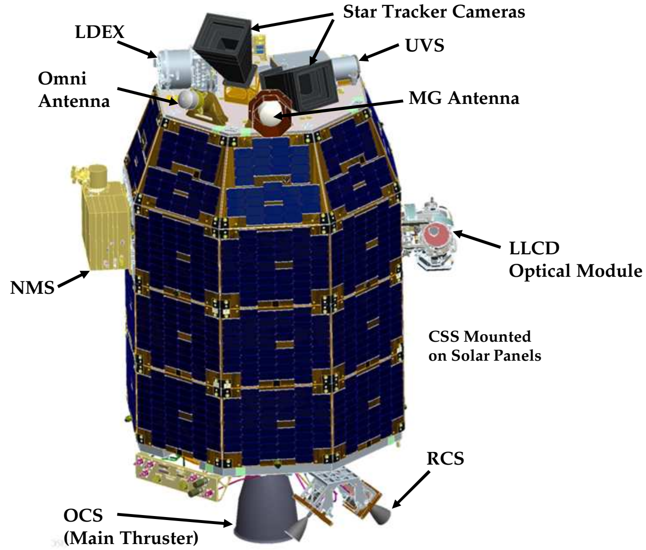
Spacecraft
- Type: Small Orbiter - Category II, Enhanced Class D
- Provider: ARC/GSFC

Instruments
- Science Instruments: NMS, UVS, and LDEX
- Technology Payload: Lunar Laser Communications Demo

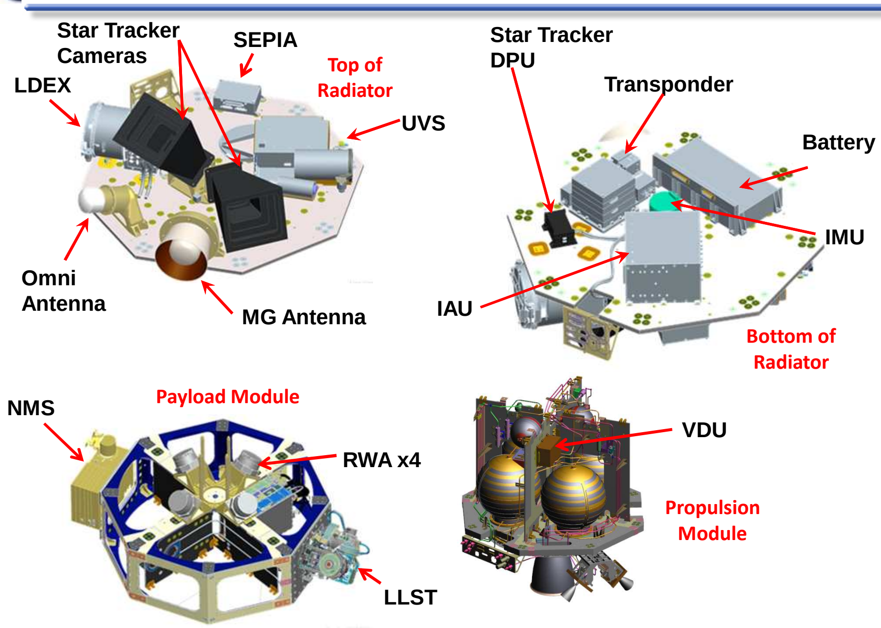
Launch Vehicle: Minotaur V

Launch Site: Wallops Flight Facility

Spacecraft Components - External



Spacecraft Components - Internal

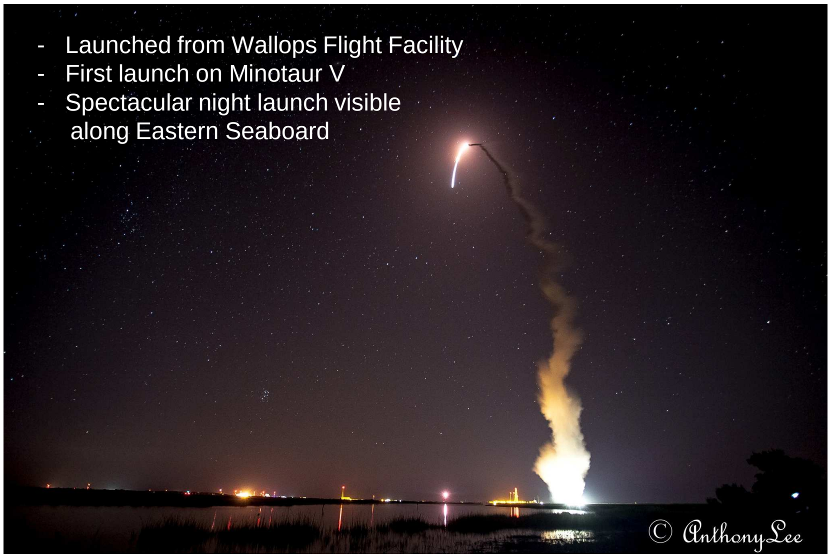


LADEE in Flight Configuration

LADEE Encapsulation

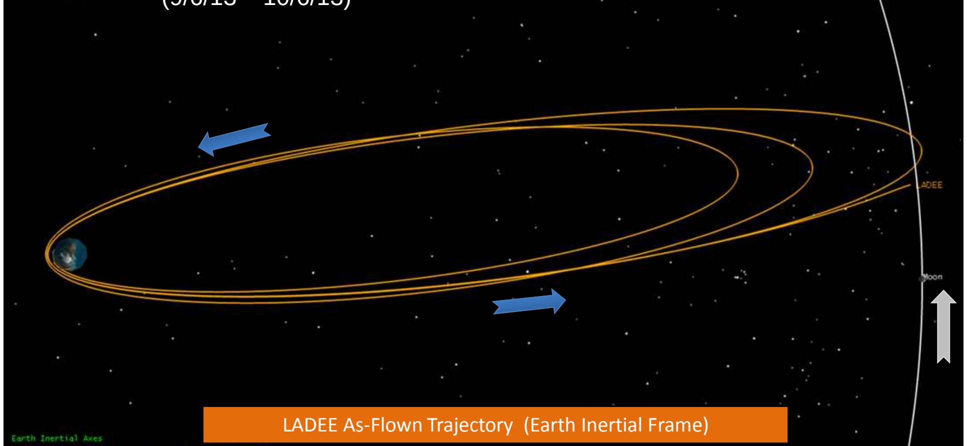
LADEE Launch – 9/7/2013

- Launched from Wallops Flight Facility
- First launch on Minotaur V
- Spectacular night launch visible along Eastern Seaboard



LADEE's Journey to the Moon

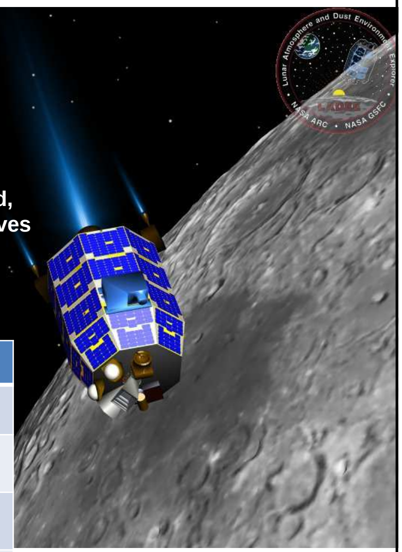
- Earth "Phasing Loop" trajectory approach used to account for uncertainty in launch vehicle performance
- Three and a half loops performed over the course of 29 days (9/6/13 – 10/6/13)



LADEE As-Flown Trajectory (Earth Inertial Frame)

Lunar Orbit Insertion Burn #1: 10/6/2013

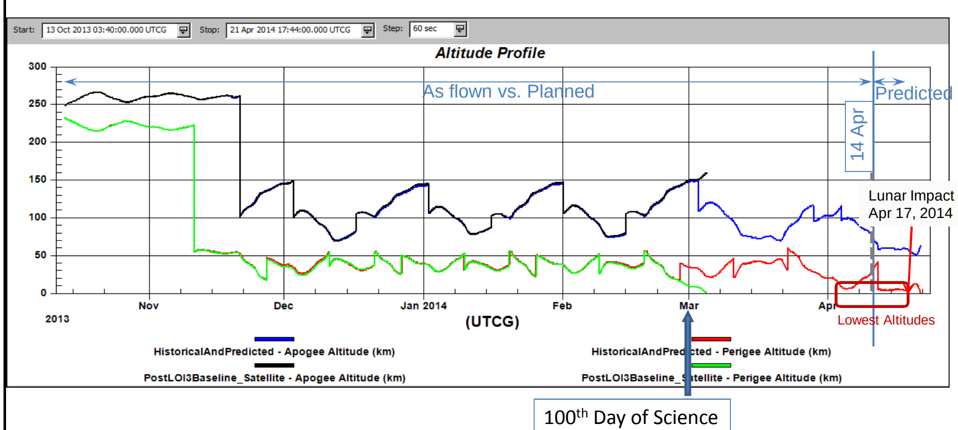
LADEE Classical Orbit Elements
Time (UTCG): 6 Oct 2013 10:57:23.000
Semi-major Axis (km): -6318.236831
Eccentricity: 1.365392
Inclination (deg): 138.458
RAAN (deg): 156.296
Arg of Perigee (deg): 353.798
True Anomaly (deg): 18.736
Mean Anomaly (deg): 18.736



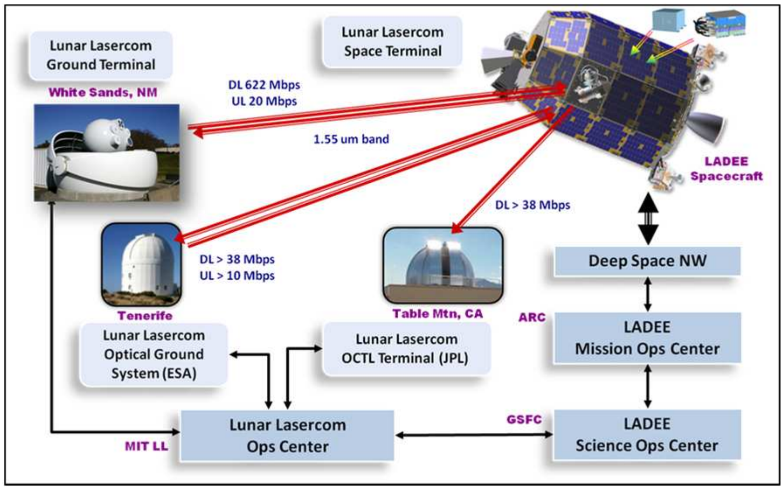
- **LOI-1 Burn was critical – if unsuccessful or delayed, could have resulted in not meeting science objectives**
- **Final approach out of view from earth**
- **Start burn within 5 minutes of coming into view**
- **Burn duration approximately 3 minutes**

Delay	Impact to Mission
5 min	Mission still meets most science objectives.
10 min	Mission meets many science objectives, but doesn't achieve full success.
15 min	Mission meets only minimum science objectives.
20+ min	Mission doesn't meet science objectives.

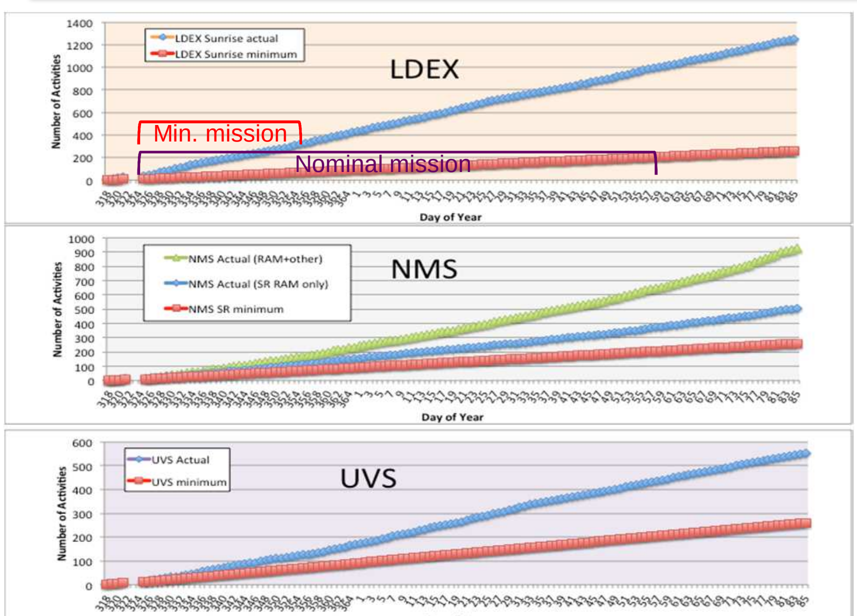
Lunar Orbit



Lunar LaserComm Demonstration



LADEE L1 Science Requirements



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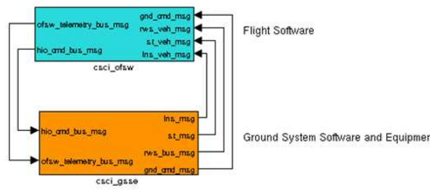
LADEE Flight Software Overview

- Scope
  - Onboard Flight Software (Class B)
  - Support Software and Simulators (Class C)
  - Non-Safety Critical (launch powered off)
- Key Features
  - Attitude Control (RW & Thrusters)
  - Power & Battery Management
  - Thermal Management
  - Safe Mode Control
  - Command & Data Handling


LADEE



Low Cost Approach:

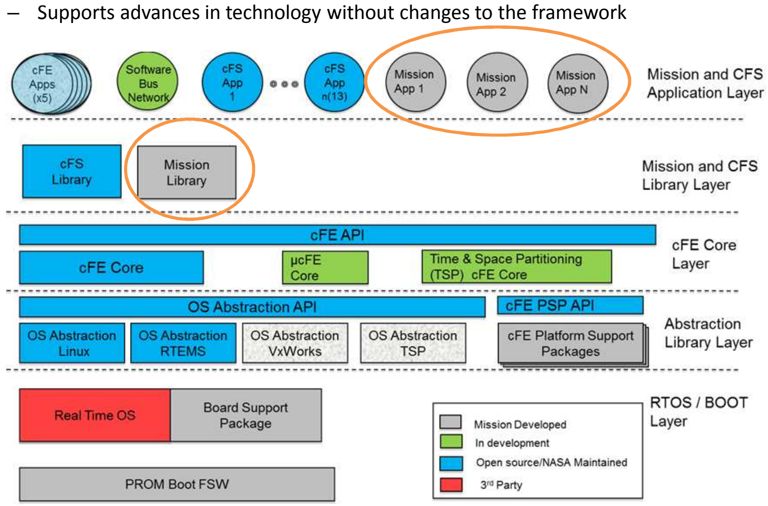
- Leverage Heritage Software
  - GSFC OSAL, cFE, cFS, ITOS
  - Broad Reach Drivers, VxWorks
  - Mathworks Matlab/Simulink & associated toolboxes
- Development Approach
  - Model Based Development Paradigm (prototyped process using a “Hover Test Vehicle”)
  - 5 Incremental Software Builds, 2 Major Releases before launch, 1 Minor Release after launch.

Use of Core Flight System

- Low Cost Mission and fixed schedule demanded low cost flight software development leveraging COTS/GOTS/MOTS.
- The Core Flight System (cFS) is a platform-independent, mission-independent, reusable Flight Software environment (Product Line)
  - core Flight Executive (cFE)
  - Operating System Abstraction Layer (OSAL)
  - CFS Applications (cFE-compliant)
  - All of the above were developed and managed by Flight Software Branch GSFC Div. 582

cFS Key Features

- Layered architecture
  - Reusable components
  - Platform Independent
  - Supports advances in technology without changes to the framework



cFS Core Services

Executive Services
- Manages the software system

Software Bus Services
- Provides publish/subscribe software bus messaging interface

Time Services
- Provides spacecraft time

Event Services
- Provides interface for sending, filtering, and logging event messages

Table Services
- Provides interface to manage table images

The cFS core layer is the system glue. It provides the common software functions that are needed by all missions.

cFS Applications

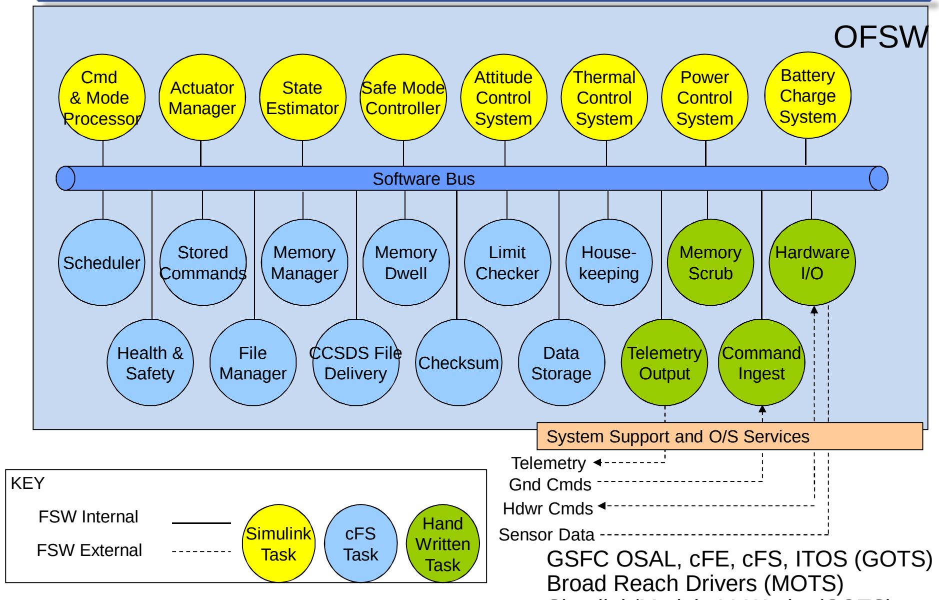
Application	Function
CF/CFDP	Transfers/receives file data to/from the ground
Checksum	Performs data integrity checking of memory, tables and files
Command Ingest Lab	Accepts CCSDS telecommand packets over a UDP/IP port
Data Storage	Records housekeeping, engineering and science data onboard for downlink
File Manager	Interfaces to the ground for managing files
Housekeeping	Collects and re-packages telemetry from other applications.
Health and Safety	Ensures that critical tasks check-in, services watchdog, detects CPU hogging, and calculates CPU utilization
Limit Checker	Provides the capability to monitor values and take action when exceed threshold
Memory Dwell	Allows ground to telemeter the contents of memory locations. Useful for debugging
Memory Manager	Provides the ability to load and dump memory.
Software Bus Network	Passes Software Bus messages over Ethernet
Scheduler	Schedules onboard activities via (e.g. HK requests)
Scheduler Lab	Simple activity scheduler with a one second resolution
Stored Command	Onboard Commands Sequencer (absolute and relative).
Telemetry Output Lab	Sends CCSDS telemetry packets over a UDP/IP port

cFS Open Source

- cFE open Internet access at http://sourceforge.net/projects/coreflightexec/
  - Source code
  - Requirements and user guides
  - Tools
- OSAL open Internet access at http://sourceforge.net/projects/osal/
  - Source code
  - Requirements and user guides
  - Tools
- cFS application suite is also available on sourceforge
- For more information, contact:

Dave McComas
NASA GSFC/Code 582 Flight Software Branch
Dave.C.McComas@nasa.gov

LADEE FSW Architecture



GSFC OSAL, cFE, cFS, ITOS (GOTS)
Broad Reach Drivers (MOTS)
Simulink/Matlab, VxWorks (COTS)

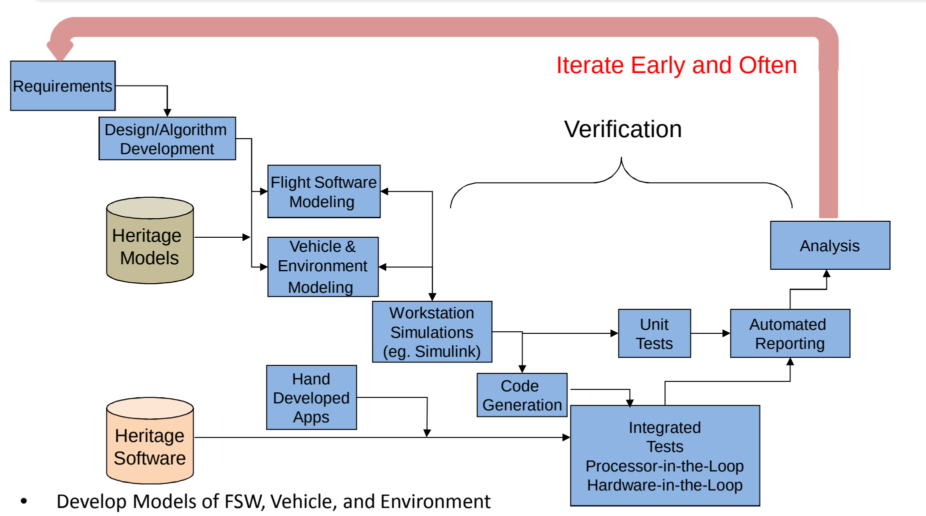
Simulink Application Summary

Application	Function
Command & Mode Processor (CMP)	Decodes and latches commands for other Simulink modules, and handles mode transitions.
Actuator Manager (ACT)	Manages which module talks to the thruster & reaction wheel hardware.
State Estimator (EST)	Estimates the attitude and rates of the spacecraft.
Safe Mode Control (SMC)	Controls the spacecraft orientation and rates while in Safe Mode and Rate Reduction Modes.
Attitude Control System (ACS)	Controls the spacecraft orientation and rates while in DeltaV, FinePoint, or DeltaH Modes.
Thermal Control System (TCS)	Turns heaters on and off based on set points.
Power Control System (PCS)	Turns electrical switches on and off as commanded. Provides current limit protection and load shedding.
Battery Charge System (BCS)	Monitors and Controls battery voltage.

Model Based Development

- Issues:
  - Low Cost Mission and fixed schedule demanded rapid, low cost flight software development process
  - Simulations needed for FSW Verification and Mission Operations development, training, and command verification.
- Solution:
  - Use model based development approach
    - Automatic conversion of Models to FSW allows development and testing of algorithms which then becomes Software. Avoids "throwing it over the fence to be coded".
  - Developed multiple simulators of varying degrees of fidelity (WSIM, PIL, HIL)
  - Developed Simulink Interface Layer
    - Allows immediate translation from models to Code allowing rapid turnaround
  - Developed an automated test harness for rapid turnaround of verification results
- Result:
  - Model Based Development coupled with "push button" code generation and testing was highly effective for rapid software development.
  - Models and Simulations used extensively in Mission Operations.
    - WSIM provided faster than real time capability for rapid command verification.
    - Processor in the Loop and Hardware in the Loop simulations provided high fidelity simulations for critical maneuver verification, Ops training, and debugging anomalies
    - Fully Coupled Simulations (Power, Thermal, Propulsion, Attitude Control) provided better insight for coupled problems.

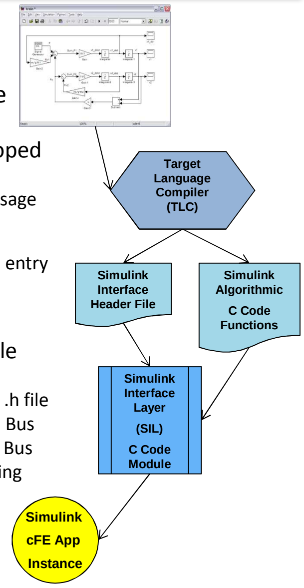
Iterative Development



- Develop Models of FSW, Vehicle, and Environment
- Automatically generate High-Level Control Software
- Integrate with hand-written and heritage software.
- Iterate while increasing fidelity of tests – Workstation Sim (WSIM), Processor-In-The-Loop (PIL), Hardware-in-the-Loop (HIL)
- Automated self-documenting tests providing traceability to requirements

Simulink Interface Layer (SIL)

- Higher level Flight Software Modules modeled in Simulink
- C-Software generated from Models using Real Time Workshop Embedded Coder
  - Template for Target Language Compiler (TLC) developed with Mathworks
    - Turns Specified Simulink Input/Output ports into cFE Message structures
      - I/O ports must be Simulink non-virtual buses
    - Creates C Header file that defines message interfaces and entry points
      - Specific Data Structures
      - Macros that identify key functions
  - Simulink Interface Layer (SIL) provides CFE compatible app functionality:
    - Uses message and entry point definitions from generated .h file
    - Input Messages – Subscribed to and recv'd from Software Bus
    - Output Messages – Registered and Published to Software Bus
    - Event Output – Custom Block with Trigger and Format String
    - Table Management – Mapped from tunable params
    - Housekeeping – General Meta-Data about App
  - Simulink Interface being made available in the CFS Community repository



Hardware Test Systems

WSIM **Workstation Simulations**	**Simulink on Windows, Mac, or Linux computers**	**•Models of GN&C, Prop, Power, & Thermal** **•Faster than Real Time** **•Used by FSW to generate and test algorithms.** **•Used by MOS for standard command uplink verification.**
PIL **Processor-in-the-Loop**	**PPC750 Processor(s) in Standalone chassis**	**•Includes all flight software functionality. Runs on 1 or 2 processors.** **•Run in real time** **•Multiple copies maintained by FSW as inexpensive system for real time software & fault management development.** **•Used by MOS for maneuver simulations**
HIL **Hardware-in-the-Loop**	**Avionics EDU with simulated vehicle hardware.**	**•Highest fidelity simulators includes hardware interfaces.** **•Run in real time.** **•Travelling Road Show used to test payload interfaces early in development cycle** **•Authoritative environment for verification of FSW requirements**

Automated Testing

- Need to verify the integrated flight software, not just the models.
  - 144 top level requirements to assess
- Test as we fly!
  - Telemetry is the normal indicator of the software health during flight so verify L4 requirements on the telemetry stream using same tool-chain as in flight.
  - Scenarios developed exercising each flight phase. Software response to identified fault conditions tested in Fault Management scenarios.
  - Assertions applied to telemetry stream and software artifacts to verify level 4s.
- Regression test cycle within one week.
  - Scenarios themselves take a "long weekend" to compute (in real time).
  - Reduction of 70 Gb of scenario data takes an additional day.
  - Automated test report for analysis

Automated Test Report

Summary Statistics.

```
There are 144 requirements to verify in this build out of a total
of 144 Level 4 requirements.
Number of TBRs: 0
Number of TBDs: 0
Number of tests that pass:  135
Number of tests that fail:  0
Number of Build requirements that partially pass: 9
Number of Build requirements that are tested but insufficient data to verify: 0
Number of Build requirements that have tests with execution errors: 0
Number of Requirements with stubbed tests: 0
Number of Uncategorized requirements: 0
Number of remaining requirements to verify in future builds:  0
```

ID Number	Requirement	Status
FSW-3	The FSW should be predictable in its operation.	PASS
FSW-5	The FSW implementations shall use standard metric units (kilogram [kg], meter [m], second [sec.], degrees centigrade [deg C], etc.) as the standard unit convention. Controlled use of hybrid units will be allowed per LADEE Systems Engineering Management Plan (Doc # C03.LADEE.SEMP).	PASS
FSW-6	The FSW shall define quaternions as vectors where the fourth element is the scalar value with a range >=0 and <=1.	PASS
FSW-10	The OFSW shall be designed for a minimum mission duration of 200 days.	PARTIAL

Conclusions

LADEE Mission Highly Successful

•Lowest science operations conducted under 2 Km over the moon's surface

•Successful Laser Communications demonstration: 622Mbs downlink rate. Very useful to be able to download a SDRAM partition in less than 2 minutes.

•Survived an eclipse!

•188 days of lunar orbit, with approximately 200% of planned science data returned to the earth. All science goals met.

LADEE Flight Software

•Delivered on time and within budget.

- Use of Heritage Software
- Model Based Development
- Automated Testing

•Software performed well throughout mission

- Flexibility in design allowed unanticipated use cases
- 2 software patches to account for emergent star tracker behavior
- 1 unanticipated reboot (Interrupt Handling)

Final Resting Place
April 18, 04:31 UTC
Orbit #2292
11.8407º latitude, -93.2521º longitude – visible from Earth between 5 and 9 days each lunar cycle
Mission Ops in communication and retrieving science data at impact