The Use of Standards on the LADEE Mission

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The Lunar Atmosphere Dust Environment Explorer (LADEE)[i] was a small explorer class mission that launched Sept 7, 2013 and successfully de-orbited and impacted the moon's surface on April 17, 2014. The spacecraft was the first to launch from a Minotaur 5 and was the first deep space mission to launch from the Wallops flight facility. Figure 1 shows the famous image of a frog unlucky enough to be launched from the facility at the same time as LADEE. The science mission for the spacecraft was to determine the density, composition and variability of the lunar exosphere. In addition, it performed a first-of-a-kind demonstration of laser-based communications from deep space that exhibited a record downlink rate of 622Mbps from the moon. In order to perform the lunar dust surveys, the spacecraft was placed in a retrograde equatorial orbit with periapsis between 20 and 60 km. The mission was granted an extension in which final science surveys were performed at altitudes as low as 2 km over the moon's surface.

The cadence for spacecraft operations was demanding: the moon's highly inhomogeneous gravity field distorted the orbit, the regular maneuvers were subject to strict payload-induced pointing requirements, and there were periodic attitude changes to keep the spacecraft thermally safe. This led to a need for high reliability in the operation of the spacecraft while obeying strict budget and schedule guidelines.

To minimize fabrication and design costs, the "modular common bus" spacecraft was designed with common structural components that could be connected together to form the spacecraft. As seen in Figure 2, LADEE was formed of four such modules:

- Two "Extension Modules" encasing the propulsion system,
- The "Bus Module" hosting the radiator assembly where the avionics, the Lunar Dust Experiment (LDEX), and the Ultra Violet Spectrometer (UVS) were located,
- The "Payload Module" which hosted the Neutral Mass Spectrometer (NMS), and the and the Lunar Laser Communications Device (LLCD).

For further details on the mission and spacecraft, please see Hine, Spremo, Turner and Caffrey[ii].

The philosophy for the flight software development was complementary to the physical construction, in that it proceeded with a low-cost rapidly prototyped product-line effort. An emphasis was placed on the "best-practices" use of layered, modular software architecture with strong re-use of Government Off-The-Shelf (GOTS) and Commercial Off-The-Shelf (COTS) components. Guidance, Navigation and Controls (GN&C) engineers utilized model-based methods (Mathworks Simulink) to develop high-level spacecraft control functions. Software engineers then "auto-coded" the models to the "C" programming language for integration with the rest of the software layers. This minimized the opportunity for communication and transcription errors between algorithm designers and qualified software developers. The model based-methodology also enhanced early prototyping of requirements, enabled validation and verification during early stages of development and provided a common platform for

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communication between subsystems, software engineers and stakeholders.

The overall layered architecture for the onboard flight software is shown in Figure 3. The applications auto-coded out from Simulink modules are shown in yellow, with each control application being coded as a separate object. These were automatically integrated with the Core Flight Executive (cFE) and Core Flight System (cFS)[iii] (blue) using a hand-coded "Simulink Interface Layer". Other hand-code developed for the project included memory scrub, telemetry, command and hardware input/out drivers shown in green. The real time operating system used here was VxWorks.

When development of the onboard flight software (OFSW) for the LADEE mission started in 2008 the applicable NASA procedural requirements for software development and software assurance were NASA Procedural Requirement (NPR) 7150.2A and the NASA Software Assurance Standard NASA-STD-8739.8. These documents provide the minimum set of requirements that projects must perform for all phases of software development. The software requirements in NPR 7150.2A were developed by the NASA Office of the Chief Engineer's Software Working Group, and the NPR included the requirement that Class B software (that is, software responsible for the successful operation of a robotic spacecraft) "be acquired, developed and maintained by an organization with a non-expired CMMI-DEV rating as measured by a Software Engineering Institute authorized lead appraiser". Since the LADEE flight software was classified as Class B, the project participated in several CMMI appraisals during the course of the mission that resulted in the project's home division at NASA Ames successfully achieving the required CMMI Maturity Level 2 rating in 2010 and again in 2013. NPR 7150.2B and the accompanying Software Engineering Handbook also incorporate other industry-wide standards. Applicable IEEE standards that are referenced include:

- IEEE Standard for Configuration Management in Systems and Software Engineering, IEEE 828-2012
- ISO/IEC/IEEE 24765 Systems and software engineering-Vocabulary
- IEEE 1028, IEEE Standard for Software Reviews and Audits
- IEEE 1012, IEEE Standard for Software Verification and Validation

Each of the requirements in NPR 7150.2B is governed by its applicability according to software classification and is accompanied in the NASA Software Engineering Handbook (https://swehb.nasa.gov/display/7150/Book+B.+7150+Requirements+Guidance) by its rationale, guidance, tailoring for small projects, resources and lessons learned. The Handbook's "resources" section makes explicit the influence of outside standards for each of the requirements of NPR 7150.2B. Links are also provided that enable authorized NASA users access to the NASA Standards and Technical Assistance Resource Tool (START). START provides access to technical standards from specifically contracted Standards Developing Organizations (SDOs), such as IEEE.

For LADEE FSW, the standards infused each of the process areas, but the influence was particularly evident in the Software Quality and Validation and Verification areas. As advised by the standards, the test reporting system incorporated unit testing, integrated testing, scenarios for science operations, maneuvers and fault management testing and implemented full bi-directional traceability between requirements, designs, models/code, test scripts and test artifacts. We performed testing in many different fidelities ranging from Workstation Simulations (WSIM) to Processor In the Loop (PIL) to full Hardware In the Loop (HIL). One particularly powerful test system was the "Travelling Road Show" in which we would load the flight software on an Engineering Development Unit (EDU) and test interfaces on-site with our payloads and other hardware. We applied custom Simulink Model Advisor checks to ensure compliance with our modeling standards and performed static analysis of all hand and automatically generated code. We used a formal inspection program to drive out defects in requirements, designs, code/models and associated test scripts.

Despite all of these efforts, a small number of software defects that "escaped" the software V&V and the spacecraft I&T cycles into flight. One area of difficulty was misinterpretation of Interface Control Documents (ICDs). For instance, right after activation of the spacecraft, the fault management system shut down all reaction wheels of the spacecraft. It turns out that a flag that we had interpreted as an error flag was instead a warning flag. After careful re-reading of the ICD, an update was made to the fault management table to ignore the flag, and the spacecraft's attitude system returned to normal. The star tracker system also exhibited emergent behavior, issuing delayed state estimates the closer we got to "Big Bright Objects" such as the earth and the moon. This unanticipated behavior required two separate uploads of new state estimation software to ignore the delayed and corrupted state estimates from the star tracker. We also had one unanticipated reboot of the spacecraft at the end of LLCD operations. It was determined that we had used a task lock instead of an interrupt lock inside of an interrupt service layer called from the high-speed lasercom interface. For the next mission, we will add this item as a specific question for our formal inspection program.

In the end, the LADEE mission was a great success. The mission accomplished 188 days in orbit with approximately 200% of planned science data returned at altitudes as low as 2km. The spacecraft endured a lunar eclipse that it had not been designed to survive. We utilized our star tracker in an unplanned and unusual way, taking close-up pictures of the lunar surface. The Lunar Reconnaissance Orbiter (LRO) imaged us in orbit (http://lroc.sese.asu.edu/posts/736). We uploaded a complete new build of the flight software that corrected all of the known defects and completed the final month of orbital maintenance maneuvers, science operations and survived the eclipse with no further software defects found. LADEE was successfully deorbited and impacted the moon on the eastern rim of Sundman V crater on April 18, 2014. Our final resting place, currently just in sight of earth, was confirmed by post-impact images from LRO (http://lroc.sese.asu.edu/posts/822).

Figure 1. Frog being "launched" at the same time as LADEE

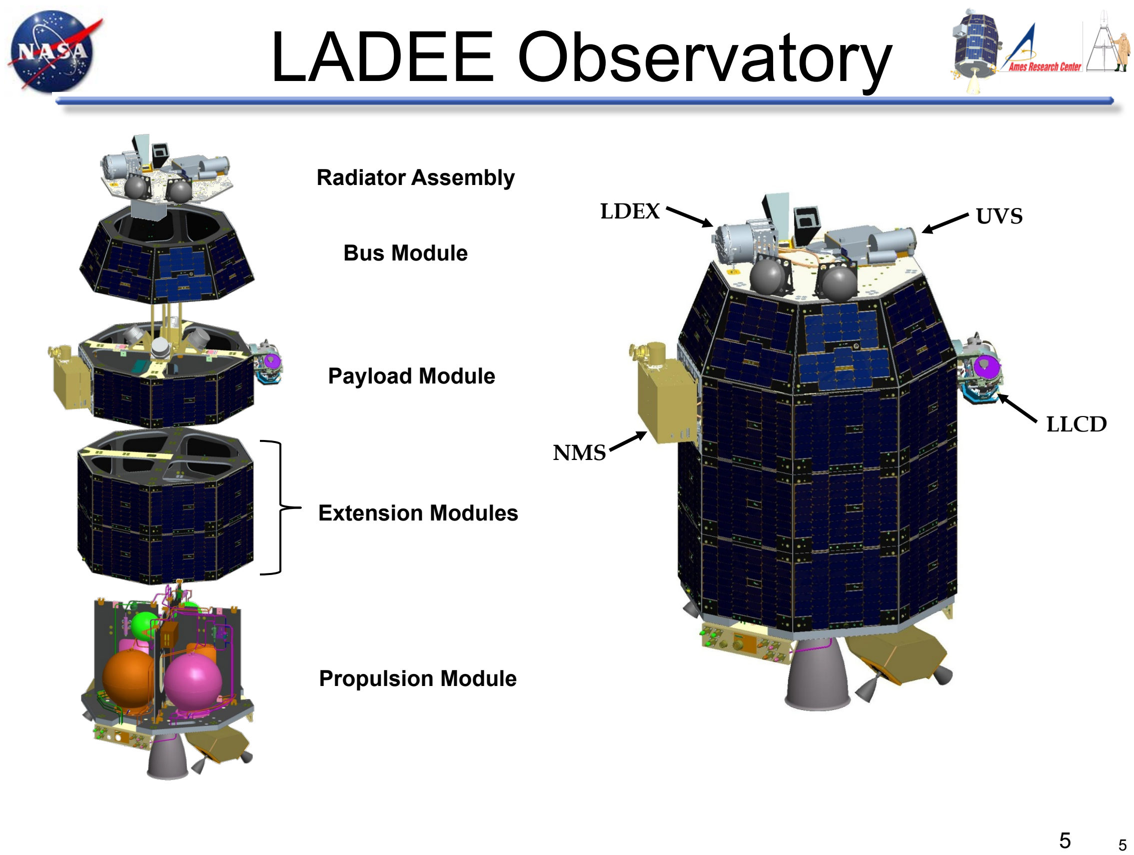

Figure 2. Picture of LADEE observatory, showing payloads and purpose of each assembly module.

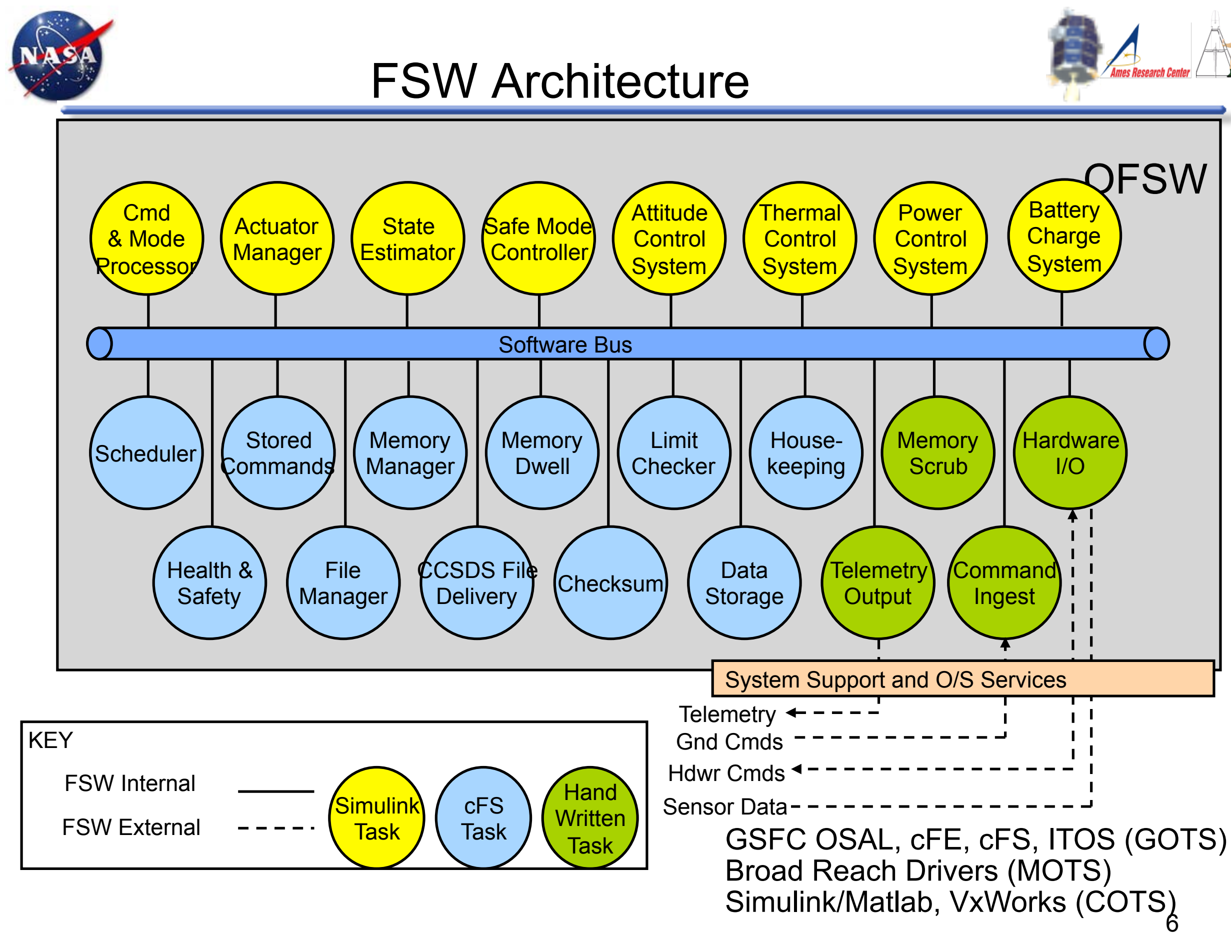

Figure 3. Layers of the Onboard Flight Software

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vii Wilmot, J. "Implications of Responsive Space on the Flight Software Architecture", 4th Responsive Space Conference, RS4-2006-600 3, April 2006.

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