Flight Team Development in Support of LCROSS – a Class D Mission

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The LCROSS (Lunar Crater Observation and Sensing Satellite) project presented many challenges to the preparation for mission operations. A class D mission under NASA's risk tolerance scale, LCROSS was governed by a $79 million cost cap, followed a 29 month schedule from "authority to proceed" to flight readiness, and was NASA Ames Research Center's first flight mission after many years of pursuing other strategic goals. This paper describes how LCROSS prepared its flight team by deeply involving its operators in spacecraft and ground system design, implementation and test; leveraging collaborations with strategic partners; and conducting a spiral test and rehearsal program synchronized with the ground-up development of the ground system and spacecraft.

I. Introduction

LCROSS developed its flight team under particularly challenging conditions: the project had a small budget and a fast-paced development schedule, a unique and difficult mission and, owing to a 7-year gap since the last time ARC had led a mission, little available operations experience or infrastructure on which to base its flight. LCROSS assembled a diverse staff with varying degrees of operational experience, and transformed it into a capable operations team that performed well in nominal and emergency conditions. The remainder of Section I summarizes the conditions under which LCROSS team development began.

A. LCROSS Project

LCROSS was conceived as an economical approach to determining the nature of hydrogen observed in permanently shadowed craters at the lunar poles. LCROSS was selected in April 2006, under the Lunar Precursor Robotic Program (LPRP) of NASA's Exploration Systems Mission Directorate (ESMD), as a secondary payload to be launched with the Lunar Reconnaissance Orbiter (LRO)[1]. Under the earliest possible launch date of October 28, 2008, LCROSS was obligated to meet a 29 month development schedule from ATP through launch readiness††. The LCROSS project was constrained to a $79 million cost cap. The project's tight budget and fast-paced schedule

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provided a strong impetus for utilizing a small staff in creative ways to accomplish the huge body of work required to prepare for flight while managing risk.

To ease the budget and schedule challenges, NASA designated LCROSS as "Class D" under its risk tolerance scale. This classification allowed the project to accept greater risk relative to higher-profile, big-budget missions, and shaped the development strategy and operational approach. However, the definition of Class D was not well-documented, nor did it have a strong precedence in prior NASA missions. Hence, the LCROSS project team had to work out how the classification translated into actual programmatic, engineering and operational practice, in coordination with NASA ARC, the program office and NASA headquarters. Importantly, it had to balance the need to reduce cost and save time against the natural tendency to pursue the reliability standards of bigger-budget missions.

Figure 1. Flight Team in the Mission Operations Control Room (MOCR). *The MOCR seated seven operators and was the focal point for execution and monitoring operations during the mission.*

B. The Mission

The non-routine character of the LCROSS mission strongly influenced the makeup of the flight team and the design of operational practices. It was the first to operate with a Centaur upper stage far beyond launch. It comprised many unique event types (e.g. trajectory corrections, several types of science calibrations, lunar flyby, Centaur separation, lunar impact) and required extensive in-flight re-planning. It involved two periods of intense activity (launch week, lunar impact), separated by over three months of relative calm. LCROSS's success hinged on a single event – impact - at the very end of the mission; many other events were also time-critical. Class D programs take greater risks in spacecraft development (e.g. streamlined testing), but undetected problems often manifest themselves in flight, favoring an adept flight team, or a spacecraft with a foolproof "safe mode" and plenty of time to analyze and recover from problems. Portions of the LCROSS timeline were not tolerant to such delays. Despite these challenges, the LCROSS mission was short, and presented no option for an extended mission.

C. Initial State of Mission Operations

The LCROSS mission operations campaign was the first NASA ARC had led since the Lunar Prospector (LP) mission, which ended in 1999[2]. In the intervening years, ARC supported Space Shuttle payload operations and, concurrent with LCROSS, was preparing to support science operations for the Kepler mission[3]. However, neither was directly relevant to LCROSS. At its inception, LCROSS was provided with rooms and networks, but the majority of the ground system was undefined. Another consequence of the gap in flight missions was the small number of experienced operations staff available to LCROSS. Barring hiring operators from outside ARC, many team members had to be selected from other arenas of ARC business, and trained to be flight operators. Also, there was no pervasive operations culture upon which to found LCROSS operational practices.

With this introduction, Section II describes how team development advanced in parallel with GDS and spacecraft development, and Sections III and IV cover how we composed our team and developed our operational practices. Training, both formal and opportunistic, is covered in Sections V and VI. Section VII provides a brief overview of LCROSS flight experience and team performance, from the human perspective, as a complement to descriptions of our experience with the spacecraft[4-6]. We point to our most valued lessons and consider the value of our approach for future missions in Section VIII.

II. Team Development Process

With little operational culture to draw from, the Mission Operations System (MOS) team had to define everything about how it would operate: its composition, its facilities, its general operational practices (e.g. voice loop protocols, Deep Space Network interaction, telemetry data archival, anomaly resolution processes) and LCROSS-specific practices (e.g. mission plan, team roles and responsibilities, team interactions and data transfers, command product generation and verification, procedures, flight rules, etc). It also needed to invent and execute a team training plan that would prepare its operators for flight.

Upon the selection of LCROSS, NASA ARC initiated a mission operations facilities and ground systems restoration effort. Hence, the MOS, GDS, and spacecraft developments proceeded in parallel. The MOS was responsible for defining requirements for generic and mission-specific tools and operations facilities. The implementation of mission-generic elements was handled under project-external ARC funding. Details of the ground systems development are described in Hunt et al. (Ref 7).

LCROSS adopted an iterative, "spiral" approach to both MOS and GDS development, recognizing that requirements would need to be refined through repeated, gradually more realistic testing. Training occurred on a gradually-developing ground system target, sometimes with serious limitations in capability, until late in the development schedule when all elements were in place. MOS process definitions were refined gradually through collaboration and repeated simulations. LCROSS borrowed relevant, previously-successful operational practices wherever possible, as long as they fit within the lean LCROSS model. Given the team's experience mix, it took specific inspiration from Lunar Prospector, the Mars Exploration Rover (MER) mission, Space Shuttle and International Space Station (ISS) operations, commercial communications satellite operations, prior Northrop Grumman (NG) missions, and even from ARC wind tunnel operational practices.

III. Composing the Team

Team composition was driven by two factors: the mission timeline (see section I.B) and the distributed expertise of the LCROSS team. Given the unique, non-routine character of the mission, the MOS had to cover a full range of operational disciplines. It needed to be lean enough to support long-term low-intensity operations, yet scale up for brief periods to support time- and mission-critical, high-intensity periods. The short mission meant that LCROSS could realistically maintain a single, lean team for the duration. To independently cover most operations, the MOS composed a small core team at NASA ARC, supplemented with maneuver design and navigation expertise from GSFC and JPL, and two systems engineers from NG. For the most intensive periods and for anomalies, an extended team of engineers from NG provided instant subsystem depth, reducing the risk of missing a critical event.

A. The Core Team at ARC

A core team of ARC employees filled many of the primary MOS roles (see Figure 2): planning and command generation (Scientists, Mission & Maneuver Design Engineers, a Link Analyst, a Command Sequencing Engineer, Engineering Analysts, and Simulator Engineers), event execution (Flight Directors, Flight Controllers, Systems Engineers, a Payload Engineer, and a Telemetry Data Engineer), and management (Mission Ops. Manager).

Budget limitations dictated a small and efficient MOS staff. In most cases the head count was barely enough to cover the shift schedule (1-2 people per role), and did not allow for backup operators. Given a particular mix of skill and experience, some staff members were assigned to more than one role. Furthermore, LCROSS could not afford the luxury of employing independent MOS and GDS development teams - many operators on the team began work on LCROSS as GDS developers and later inherited additional responsibilities as mission operators.

NASA ARC flight team members came from a diverse set of backgrounds. Some served in other mission operations roles, including in support of Lunar Prospector, Gravity Probe B, and other orbital science missions; the Mars Exploration Rover mission; Space Shuttle and International Space Station operations; and commercial satellite missions. Others were employed as engineers in support of space and defense-related engineering projects. A number of staff once led or supported wind tunnel operations at NASA ARC, and many had been researchers or software developers in the fields of autonomous systems, artificial intelligence and robotics. Regardless of background, all team members were highly technically competent in their respective fields, and all were very excited and motivated by the prospect of supporting operations for a lunar impact mission.

B. External Team Members

LCROSS partnered with other organizations to bolster ARC experience in key areas, to create a reserve capacity for key mission phases, and to support spacecraft anomalies, should they occur. Due to the particular LCROSS challenge of precise lunar impact targeting, ARC augmented its own expertise in trajectory design and maneuver planning by partnering with the Jet Propulsion Laboratory (JPL) (small forces modeling and precision orbit estimation expertise) and NASA Goddard Space Flight Center (GSFC) (complementary trajectory design and maneuver planning capabilities). JPL also provided a small team for Deep Space Network (DSN) scheduling.

The MOS needed to possess deep spacecraft systems and subsystems expertise to assess spacecraft performance throughout the mission, and to diagnose and remedy anomalous spacecraft behavior, as necessary. LCROSS employed only two ARC spacecraft engineers - the Project Systems Engineer and his deputy - to oversee spacecraft development at NG. Both were ultimately assigned as Systems Engineers on the flight team. To create a deeper

engineering team on short notice, a natural approach was to assign NG spacecraft engineers (leading design, integration and test) as part-time operators. It was unlikely that LCROSS could build a team with similar depth of knowledge in such a short time, and many at NG were excited at the prospect of participating in operations. Two NG sectors were involved in LCROSS development and later in the MOS (again, see Figure 2): Aerospace Systems (NGAS) in Redondo Beach, CA, and Technical Services (NGTS) in Lanham, MD. Despite the clear benefits, this approach presented a number of additional challenges:

1) LCROSS would have to devote budgetary resources to train these engineers (through classes, tests and rehearsals, etc), many of whom were not experienced in operations.
2) Because these engineers also served in leading roles in LCROSS spacecraft development, they were unlikely to be able to support all operational training activities (concurrent with spacecraft testing).
3) The spacecraft engineering team needed facilities and equipment to allow them to interact in real time with telemetry. To co-locate them at ARC would entail a substantial increase in operational floor space, an enormous travel budget, and a significant travel burden on each of the participants (with high attrition likely). A distributed solution would require the build-up of dedicated remote operations rooms at each of the NG facilities, and would introduce the difficulties of distributed team coordination during rehearsals and flight.
4) The LCROSS project could not afford to employ the full set of spacecraft engineers full-time for the entire flight phase. Part-time involvement required that engineers work on other projects. During flight, without management support and careful staff planning, these engineers were at risk of being fully claimed by other NG projects.

C. Team Collaboration during Development and Test Phases

A key to MOS success was its tight integration and culture of open communications across organizations. Small team size enhanced the MOS's ability to communicate and to remain focused and coordinated. All organizations demonstrated full commitment to the LCROSS project. Of critical importance, management at all participating organizations successfully established an atmosphere of collaboration, without barriers. Inter-organizational relationships were not strictly bounded by contract limitations. NG openly voiced problems encountered during spacecraft development, and they involved ARC at every stage in working through these obstacles. As full-fledged MOS team members, NG engineers regularly reviewed and steered the development of spacecraft operational procedures at ARC. By participating in procedure development and training exercises, they could also better understand the operational effects of spacecraft design decisions. As described in Section VI, ARC MOS engineers were also included in key aspects of spacecraft development and test, further solidifying this collaborative bond. Finally, tight cross-organizational team integration allowed external participants to communicate effectively. For example, the JPL Navigation team worked closely with NG attitude control engineers to develop models of the perturbation effects of thruster-based control modes on the trajectory. Through this body of interactions, and because of the tone set by management early in the project, the MOS (and the project at large) became a cohesive unit concerned principally with mission success, despite political and organizational boundaries.

In balance, a distributed MOS presented challenges. Though the team was well-integrated across organizational lines, communications breakdowns sometimes occurred due to physical separation. With the bulk of the team at ARC, informal discussions there occasionally unintentionally excluded external partners. Even full-team teleconferences suffered from poor audio quality and acoustics or occasionally poor network or graphics-sharing software performance. We recognized the importance of effective distributed team coordination early in the MOS development, and reflected that both in MOS operational processes and in the GDS design (see section IV.B).

IV. Development of Operational Practices

LCROSS operational practices were built on standard models of space operations, tailored to the LCROSS mission plan. The most fundamental of these practices are expressed in the choice of team organizational roles, described in the previous section. How these team members operated together is the subject of this section. The full set of practices is too large to describe in detail here, but the following sections highlight some of the salient features of LCROSS practice.

A. Workflow and Shift Scheduling

LCROSS operated under a cyclical workflow model with four phases: Planning, Command Generation and Verification, Execution, and Assessment. The first two phases were particularly important for LCROSS, in which

plans and command sequences depended heavily on the outcome of previous events. Depending on the operation, a full cycle lasted anywhere from 7 to 48 hours:

1) Planning: During this phase, the Maneuver Design team designed trajectory correction maneuvers and spacecraft attitude changes to meet the requirements of impact targeting, science instrument calibrations, communications, and other activities, while minimizing propellant consumption and satisfying operational constraints. Systems Engineers designated housekeeping activities to be executed, and the Science Team and Payload Engineers designed payload observation sequences, as applicable. Link Schedulers coordinated DSN contact periods for LCROSS, and Link Analysts predicted link performance for future contacts based on past experience. Planning phase culminated in an Activity Selection Review, during which the team reviewed maneuver designs and selected and ordered the supporting activities to be undertaken during a future contact. The resulting fully-ordered list of activities and their associated parameters was called an Activity Plan. The Maneuver Design Engineers operated in multiple overlapping shifts during peak activity periods; all others supporting this phase operated in a single shift.
2) Command Generation and Verification: During this phase, the Command Sequencing Engineer converted the Activity Plan into a Command Plan, combining onboard command sequences and ground-based commanding procedures. This process was partially automated to minimize human error, but was sufficiently flexible to enable in-flight modifications. The Engineering Analyst and Simulation Engineer verified the correctness and safety of the command products using a combination of analysis (e.g. rudimentary automated flight rule checking) and simulation. This phase concluded with the Command Approval Meeting, during which the team reviewed all Command Plan elements and associated analysis and simulation results before providing final approval to proceed. The minimal team supporting this phase comprised a single shift of activity, immediately following Planning Phase.
3) Execution: In this phase, the MOS enacted the Command Plan. All execution was conducted by the team in near real-time (with speed-of-light delays of seconds). The Flight Controller coordinated DSN ground stations and performed all commanding. Systems and Payload Engineers monitored spacecraft and payload telemetry, and made real-time recommendations. The Telemetry Data Engineer coordinated, packaged, and archived telemetry. A Flight Director orchestrated the team and was the lead authority for nominal operations. During 24-hour operations, the Execution team was divided into two shifts, A and B, each staffed with operators for every core role. Often one shift actively monitored the spacecraft during Planning and Command Generation phases, and the other performed Execution. Single Execution shifts conducted the operations for isolated DSN passes. Science team operators augmented the standard Execution team for events focused on science data collection.
4) Assessment: This phase ran in parallel with Execution phase and persisted while the team estimated the trajectory, characterized orbit perturbations and evaluated burn performance (Navigation), analyzed engineering telemetry (spacecraft and payload engineers), and analyzed science data (Science Team) to infer spacecraft health status and to determine the degree of success for maneuvers and science activities. This information was fed back into the next Planning phase, and to status briefings for project stakeholders.

Day-to-day operations were led by the Flight Director on duty. The Mission Operations Manager ensured that the flight team adhered to accepted operational practices, helped coordinate anomaly responses, and was the primary communicator between the flight team and project management and LCROSS stakeholders.

B. Facilities, Physical Distribution, and Team Communications

The organization of LCROSS facilities was strongly influenced by the workflow design and team distribution. Operations were centered at ARC, and utilized three primary rooms, all of which were built up and equipped in stages during LCROSS development (for technical details on facility and GDS design, please consult Ref 5). Mission Operations Control Room (MOCR; see Figure 2) activities focused on Execution and Assessment Phases. The MOCR was a self-contained facility that accommodated a core set of seven operators with telemetry and command workstations and primary and backup telemetry and commanding data systems. The Science Operations Center (SOC) was the room from which the Science Team evaluated science instrument data streaming in real-time from the spacecraft during science events, coordinated the ground telescope observation campaign at lunar impact, and performed some post-event science data analysis. The SOC was physically isolated from the MOCR to allow science and engineering-oriented activities to proceed in parallel without disturbance to either team. The Mission Support Room (MSR) was the venue for the Planning and Command Generation and Verification Phases, and portions of Assessment Phase. It was the center for off-line activities: maneuver planning, development and test of command products, and discussion of engineering issues (including anomaly resolution). The MSR was separated from the MOCR and SOC to allow discussions and coordination in parallel with real-time and science activities.

NG assembled and maintained two Remote Operations Centers (ROCs), one at the NGAS facility in Redondo Beach, CA, and another at NGTS in Lanham, MD. These supported two roles. First, the NG ROC's acted as an extension of the MOCR, providing real-time oversight of subsystem and system behavior during Execution phases. Second, they supported Assessment as engineering extensions of the MSR for more detailed review and discussion of spacecraft behavior (both nominal and anomalous), with easy access to NG design and test repositories and factory support. Most of the subsystem engineering disciplines and the Systems Engineers operated from NGAS, while the subsystems engineers overseeing Avionics and Flight Software operated from NGTS.

The JPL Navigation and Link Scheduling teams operated from their own fully-equipped facilities, while GSFC Mission Design team partners supported the critical initial and final weeks of the mission from the MSR at ARC, but worked from their home facilities during the months of Cruise Phase.

A major challenge was enabling effective communications and situational awareness over this distributed team. Early tests proved that telemetry screens and voice loops were insufficient to keep the team informed and coordinated. The primary means of communications for Execution phase remained a multi-channel voice loop system that linked all operations consoles as well as operators at the launch site and the Deep Space Network. For meetings, (see section IV.A), the team collaborated via conference telephones and a secure shared-meeting system that allowed network-based distribution of graphical presentations. All team workstations were networked to a Mission Data Product Server that served as the central repository and transfer point for data products.

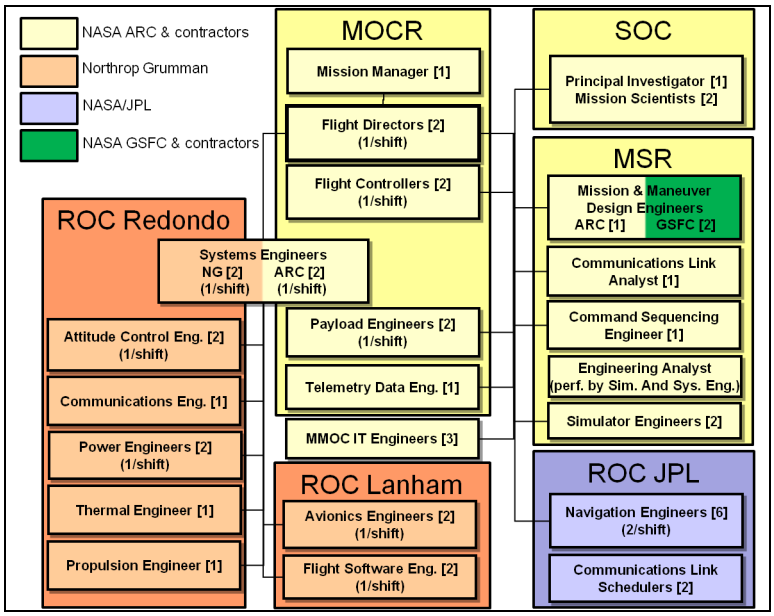

Figure 2. LCROSS Flight Team and Physical Distribution. *Small boxes represent the full set of flight team staff, while encompassing boxes represent facilities from which they most often worked. Planning and Command Generation & Verification Phases were concentrated in the MSR. Execution Phase was led by the MOCR, often with assistance from Systems Engineers at NG. Critical events were also supported by subsystems engineers, up to the full set of disciplines, depending on need. The SOC and Payload Engineers participated in all science/payload activities.*

For situational awareness, operators at all facilities were equipped with workstations to provide access to real-time telemetry. Workstations also mirrored the display of the single commanding workstation in the MOCR to enable viewing of commands as they were being issued to the spacecraft. A video distribution system and large overhead monitors enabled rooms at ARC to mirror workstation displays in other ARC rooms. For real-time operations, ARC distributed a graphical display of the current procedure step to all facilities, and also a real-time animation of the LCROSS spacecraft and trajectory that was linked to telemetry to depict the attitude state of the vehicle and fields-of-view of all sensors. ARC also provided software to graphically display the detailed LCROSS event timeline (DSN tracks, key events, shift schedules). The display updated in real-time to highlight current activities and to list the time since past events and time until future events.

C. Tight Integration of Science Team and Payload Engineers with MOS

LCROSS science operations were focused activities lasting up to one hour[‡‡] (but separated by hours, days or weeks), during which the science team collected image and spectroscopy data, assessed instrument performance, and adjusted instrument parameters on the fly. Over the course of development, the MOS came to recognize the importance of coordinating closely with the science and payload teams before and during flight. Without coordination, there was a significant risk that the MOS would not meet the needs of the science team during these events, and that the science operations concept would be inconsistent with the rest of operations.

[‡‡] Thermal constraints dictated that the LCROSS payload could not be powered on for more than one hour at a time.

Our effort to fully integrate the scientists and Payload Engineers into operations began through months of command and procedure development covering all science events. For Execution Phase, the Payload Engineer was assigned one of seven consoles in the MOCR and led the assessment of payload engineering performance during all payload activities. The SOC was equipped with science workstations networked to the MOS-wide telemetry data server, enabling scientists to view and assess science data seconds after capture on the spacecraft. Prior to execution, a science or payload representative became a required signatory for the approval of command products involving the payload. To keep real-time commanding authority consistent with other operations, Science Team members and the Payload Engineer made command requests (from a pre-arranged set) to the Flight Director verbally over the voice loop. The Flight Director quickly evaluated the criticality of science requests relative to other immediate ground-commanded tasks, and passed them on to the Flight Controller for radiation. This preserved a notion of centralized authority at the "big picture" level, albeit with some added delay. In cases where timing was especially critical, the MOS devised quick responses to specific science team requests. As flight approached, science and payload team members were integral participants in all science-oriented MOS tests and rehearsals.

V. Operational Training and Test Program

The LCROSS MOS training program included a combination of conventional and less conventional training methods. This section describes all of the more conventional approaches we used to ready ourselves for flight. In addition to attending class-based training, operators were encouraged to attend spacecraft design reviews, and were obligated to attend operations-oriented seminars and workshops focusing on specific spacecraft subsystems and mission events. System-wide tests and rehearsals were the cornerstone of operational training, and provided a basis for informal operator certification through MOS peer review.

A. Ground Data System Training

Training in the use of GDS tools (telemetry and commanding software, voice loops, link analysis, etc) was performed through formal classes taught by software vendors, through classes taught by MOS team members to the broader team, and via informal on-the-job practice. Some GDS software tools were custom-designed and implemented by the end-user, obviating the need for training. Partial-team and system-wide tests presented many opportunities to practice GDS tool usage.

B. Reviews, Workshops, and Seminars

An important part of training was to familiarize team members with the spacecraft design. The MOS recognized the value of spacecraft design reviews as training opportunities. LCROSS encouraged MOS attendance at early reviews, and required attendance at detailed subsystem Critical Design Audits presented by NG.

To complement training via spacecraft design reviews, the MOS held a series of Spacecraft Subsystem Workshops: Attitude Control, Avionics, Flight Software, Power, Propulsion, Communications, Autonomy and Fault Management (each conducted by the NG lead subsystem designer), and Payload (conducted by the Principal Investigator and lead payload software engineer). Each workshop lasted from four to eight hours and reviewed subsystem design, but emphasized operation and upkeep, including the use of primary relevant commands and telemetry, typical on-orbit behavior, troubleshooting and operational constraints. All ARC MOS members were required to attend these workshops.

A series of Operational Focus Workshops, led by the Lead Flight Director, provided in-depth reviews of operations for specific mission events at the system level. These reviewed the sequences of events, DSN utilization, geometric considerations, command sequences, operational procedures and constraints, the workflow covering the events, timelines and staffing. Workshops were held for Activation and Checkout; Cruise Phase Housekeeping; Cruise Phase Trajectory Correction Maneuvers; Star Field Calibration and Lunar Swingby; Earth Look Calibrations; and Separation and Lunar Impact. All MOS team members were required to attend these workshops.

In conjunction with the Operational Focus Workshops, the MOS conducted many workshops to develop and review command sequences for the same events. These meetings gathered spacecraft subsystem and systems-level expertise, Flight Directors and Flight Controllers, and for science-related activities, members of the science and payload team to communicate design requirements to the Activity Planning & Sequencing Lead, who implemented the sequences and, for parameterized activities, the tools used to generate sequences during flight.

C. MOS Operational Tests

With the concurrent development of the MOS, facilities, and GDS, MOS training was limited by the degree of availability of facilities and tools, as governed by the GDS development schedule. The LCROSS team recognized

two things: first, that MOS training could not wait until the facilities and GDS were fully deployed, and second, that the GDS team could not confidently deploy a quality product without intermediate validation testing by the MOS team. Hence, the MOS coordinated with the GDS development team to create a schedule of interleaved GDS releases and MOS operational tests that served as both training exercises and GDS requirement validation tests (see Figure 3). The GDS release schedule was designed to provide increasingly capable sets of hardware, software and command products that built logically upon previous releases, but that were usable in intermediate form to support MOS tests. MOS tests grew in sophistication and realism, starting with tests of contiguous "threads" of the operational workflow, and growing to system-wide tests closely approximating the operations for full mission events.

An LCROSS spacecraft simulator was a key GDS delivery in support of MOS tests. It combined a partial copy of LCROSS avionics hardware, a full copy of flight software, and a software-based dynamic simulator to simulate vehicle flight dynamics and the behavior of other spacecraft systems not represented in hardware (e.g. IRU, star tracker, power electronics and solar array, thruster modules). Importantly, the simulator was built partially from engineering test units used by NG to develop LCROSS flight software. Therefore, MOS simulation-based validation tests could not be conducted until the primary flight software delivery to NGAS. However, once transitioned, the LCROSS spacecraft simulator became a dedicated resource for GDS development (for command products) and for MOS tests (during which it represented the spacecraft). The simulator was critical to the success of LCROSS.

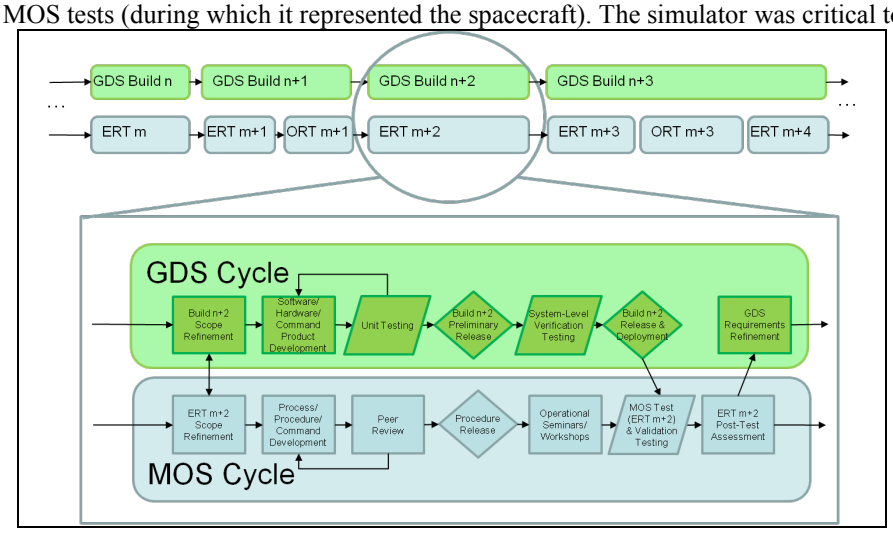

Figure 3. Interleaved GDS and MOS Development Cycles to Support Parallel Development. *GDS cycles provided increasing system-wide capabilities. MOS cycles focused on specific mission events and drove the development of event-specific GDS elements. Operationally-realistic MOS tests doubled as GDS requirements validation tests; results occasionally prompted the refinement of GDS requirements. In general, GDS releases served multiple MOS development cycles.*

Early MOS tests were designed and conducted by the Flight Team Lead, who also held an operational role as Lead Flight Director. As tests became more complex, the MOS recognized that it needed a dedicated Test Conductor to design test scenarios and to orchestrate tests behind the scenes. The Test Conductor was selected for his extensive prior experience with mission operations and spacecraft systems engineering. Once trained in the specifics of the LCROSS mission and simulator operation, the Test Conductor could lead system-wide tests and independently judge the performance of the MOS team.

MOS tests of operational "threads" were called Thread Tests (TTs), and began with tests of telemetry receipt (telemetry decoding, distribution and display), commanding, and data product routing and archival, to name a few. Later TTs tested more significant threads, for example planning and command generation for trajectory correction maneuvers. In addition to supporting GDS validation tests, TTs helped train operators in the use of GDS tools, in the use of realistic basis data to create and deliver mission data products, and also to accustom them to segments of the MOS workflow.

With the availability of all ARC operations rooms and sufficient GDS readiness, the MOS introduced system-level Engineering Readiness Tests (ERTs) that brought a significant portion of the team together and tested the complete workflow in support of specific mission events. The primary goal of ERTs was to prove that all GDS elements and MOS procedures were ready to support specific mission events. Team readiness was secondary. Hence, ERTs allowed intermediate stops and starts, timeline stretching and compression, and event re-ordering to focus on the most important aspects of the test. ERTs sometimes exercised contingency execution paths, but always with advance warning. The MOS conducted 14 ERTs of one to three days each.

Once an ERT had proven out the GDS and MOS procedures for a particular event, the MOS conducted an Operational Readiness Test (ORT) for the same event. ORTs were like ERTs, except that they adhered more strictly to the mission timeline (duration and ordering), and focused on validating MOS processes and team readiness over

procedures and GDS tools. ORTs also tested contingency paths without warning the MOS team. Being able to correctly plan, execute and assess a mission event within the constraints of the mission timeline was a strong indication of operational readiness. The MOS conducted three ORTs, one for each of the three most critical periods.

Rehearsals were conducted as final training events before launch and also during flight. Unlike ORTs, rehearsals typically exercised two or more days of continuous operation (active and inactive periods), mimicking a segment of the mission timeline to the minute. The Test Conductor ran rehearsals with the highest possible fidelity, and the team was expected to exercise every MOS process exactly how it would in flight. Rehearsals also exercised ancillary support activities like planning catered meals for the team during critical periods of 24-hour operations, and securing and using on-site lodging for any operator living beyond a maximum range to avoid the dangers of driving after long shifts. The MOS conducted a First Week Rehearsal prior to launch covering launch through Lunar Swingby (six days in duration), and three rehearsals during flight covering the final trajectory correction maneuver, Centaur separation and lunar impact (1-2 days in duration). A significant result from rehearsals is that team members grew to fully appreciate the rigors of the mission timeline, and discovered their own strengths and weaknesses in adapting to unusual sleep and waking hours while supporting critical events. Furthermore, in 24-hour operations, with shifts on opposing sleep schedules, team members came to understand the importance of good communications during shift handovers, the only times in the schedule when the full team could interact.

VI. Opportunistic Training Through Development and Test

In addition to the more conventional training approaches, many of the MOS team enhanced their training through participation in spacecraft, payload, and GDS development and testing (see Figure 4). Many of these assignments were set up explicitly as training engagements, while in other cases, staff started as developers for the project, and evolved into operators. Active participation in the design, test, and review of the spacecraft and GDS was a far better training mechanism than classes and rehearsals alone. Dual responsibilities also had their share of disadvantages.

A. MOS Team in Spacecraft Development

The ARC Project Systems Engineer (PSE) and Deputy PSE were both assigned as lead Systems Engineers on the MOS. Furthermore, the MOS enlisted many NG spacecraft engineers to augment the core ARC team. The MOS benefitted from the inherent training each of these engineers acquired over more than two years of deep involvement and leadership of LCROSS design, construction and test. Maintaining the engineering team through the entire flight saved the project significantly in training time and coordination effort. The MOS trained these engineers in operational practices far more easily than it could have trained operators in the intricacies of LCROSS systems design and test results.

B. MOS Team in LCROSS/LRO Testing

To build greater ARC-internal expertise in LCROSS spacecraft designs and operation, the LCROSS project negotiated with Northrop Grumman to embed two team members into the spacecraft test flow. One served on-site at NASA GSFC as a technical liaison between the LRO and LCROSS projects, focusing on common hardware development and test. He also served at NGTS as an avionics and flight software test engineer during avionics unit testing and integrated “flatsat” testing. The second served on-site at NGAS as a liaison and interface between NASA ARC and NG systems engineers for science payload integration and S/C integration and test (I&T). He also served as an interface between the I&T team, split between NG and the launch facility, and the MOS at NASA ARC during the conductance of S/C end-to-end testing.

As a result of their assignments, these operators became two of the most knowledgeable on the team in the detailed operation of the spacecraft. Both were assigned as primary Flight Controllers, the operators directly responsible for sending commands to, and acquiring telemetry from, the spacecraft. However, during their remote assignment over months during MOS development, the remainder of the team could not regularly call on their expertise and support of overflow work. Furthermore, these volunteers spent 11 and 16 months, respectively, displaced from home.

C. MOS Team Members as Developers of Onboard Command Sequences

In another collaboration between the MOS and NG, the MOS Command Sequencing Engineer (the operator in charge of implementing command sequences before and during flight) was assigned the responsibility of implementing the command sequences used by the spacecraft autonomy and fault management system for critical events, including initial spacecraft power-up and onboard fault responses. Working closely with NG systems

engineers who designed the command sequences, this team member became expert in using the command and telemetry databases, onboard command sequence authoring and compilation, and the basic operation of onboard subsystems.

D. MOS Team in LCROSS Payload Development

The Payload Flight Software Lead for the science payload evolved naturally into the primary Payload Engineer for flight. In his development role, he designed and implemented all supplementary flight code for the operation of the payload, implemented all instrument command sequences for science activities, and also designed and implemented software used by the science team to analyze imagery and to assess payload throughput. He also supported payload testing. No other experience could have prepared this person so thoroughly for the position of Payload Engineer.

One of the science team members served as Payload Test Engineer during development, and took a key role in science operations from the SOC during flight. Her detailed knowledge of payload test results benefitted her role as a mission scientist, and equipped her to help evaluate payload performance during science activities.

The only negative aspect of these arrangements was that when the timing of MOS test exercises conflicted with payload development and test activities, these two operators often had to prioritize their payload responsibilities.

E. MOS Team in GDS Development

Several MOS team members either oversaw GDS development or developed software tools for their respective MOS subsystems. For example, the GDS Development Lead, in charge of all LCROSS ground system development, became one of two Flight Directors. While larger teams might benefit from having dedicated software developers, the LCROSS MOS found distinct advantages in having its software end users also develop code. Most importantly, the problem of accurately communicating detailed requirements is obviated when the customer and the developer are one. This also goes for software training – the software developer is the most familiar with a tool's capabilities, limitations and idiosyncrasies. This is especially important in flight, when deep software knowledge could enable an operator to work around a bug that might otherwise interfere with the support of an important mission event. Other MOS team members served as GDS team members, but in capacities distinct from their operational roles, with little training advantage.

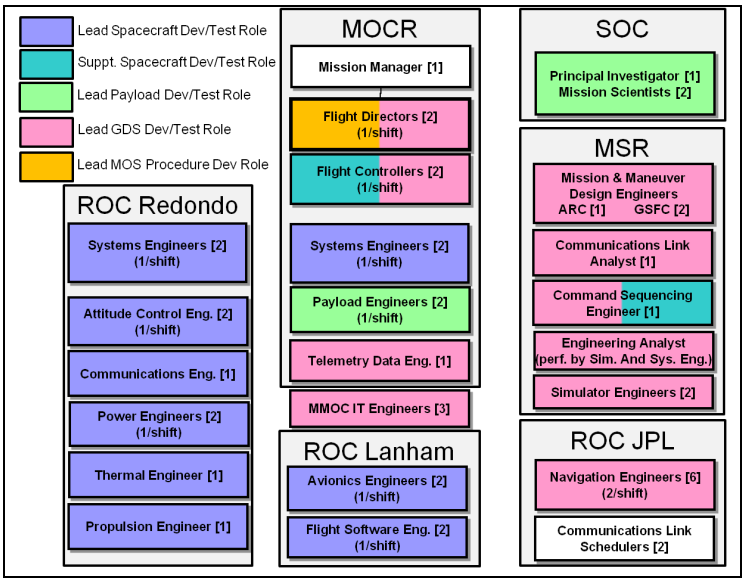

Figure 4. MOS Operator Roles in Development. *Most MOS staff played key roles in spacecraft, payload, GDS, or MOS procedure development. This simplified training, but contributed to a heavy workload and occasionally hindered simultaneous MOS and GDS development.*

Despite these advantages, having dually-tasked operators had its share of disadvantages. For one, when developer and operator are distinct individuals, the developer can perform unit-level testing, then pass the software to the operator to perform independent requirements verification testing. When one person serves in both roles, another operator, often less well-trained or even from a different discipline, must perform independent verification testing. Furthermore, peak pre-launch workloads often volleyed between the GDS and MOS teams according to the interleaved GDS and MOS test cycles. For those working on both teams, the workload was extremely difficult and afforded them little rest time. Also, because most of the MOS and GDS work was concurrent (e.g. software development and MOS rehearsal preparations), one task or the other often suffered.

These disadvantages continued in flight. LCROSS operators were, on average, more busy than anticipated (see section VII). Inevitably, GDS bug fixes and enhancements were developed during flight, but developer/operators were too consumed with flight duties to perform global GDS deployments. The team had to resort to less-formal point deployments for specific tools, complicating the GDS configuration management task.

VII. Summary of Team Performance in Flight

Arguably, the best measure of flight team preparation is its level of performance during its flight mission. This section provides a brief synopsis of LCROSS MOS performance during 112 days of flight.

Transfer Phase was six days of 24-hour operations, covering launch through lunar swingby, and the most challenging nominal segment of flight, save the pre-impact sequence. The MOS operated in two overlapping shifts of 13 hours, synchronized with major events. The MOS successfully performed all nominal events and responded to several in-flight spacecraft anomalies that forced significant operational changes from the baseline to maintain spacecraft health. On Day 3, during an experiment to test an anomaly mitigation strategy, a flight rule was inadvertently violated, causing the spacecraft to transition to its "safe mode". The error was attributed to a loss of situational awareness stemming from the departure from nominal operations. The processes for shift handovers and executing off-nominal commands were improved as a result, and the mistake had no lasting negative effect. By the end of Transfer Phase, the team was noticeably fatigued, particularly Shift B which had worked graveyard hours.

Cruise Phase, the bulk of time in flight, was more difficult than anticipated. Before launch, planning and training had focused on isolated Cruise Phase events. It had not sufficiently considered how the superposition of activities and unexpected changes in flight would affect the timeline and workload. The early part of Cruise was spent developing sustainable workarounds to anomalies discovered in Transfer. Due to late changes in the LCROSS launch date, DSN contacts were at highly variable times of day, and at variable intervals, making it difficult for the team to establish an operational rhythm. Results from earlier science events prompted the Science Team to modify and add to later payload calibrations, requiring in-flight re-designs of command products and procedures. Furthermore, efforts to remove ice from the Centaur upper stage were less effective than expected, prompting the team to design and execute two additional maneuvers for that purpose. On the second Earth revolution, a substantial spacecraft anomaly caused the MOS to divert from nominal operations for two weeks. The resulting effort to save remaining propellant and develop safeguards, all while supporting extra DSN passes, stretched the MOS team to its limit. Upon emerging from this taxing recovery period, the team finally progressed towards a more sustainable operational cadence. In the final weeks of the mission, rehearsals for Centaur separation and impact were interleaved with nominal operations, and the frequency of trajectory maneuvering increased in preparation for impact. Despite these challenges, the MOS performed with very few operational errors, none of which had measurable negative influence on mission outcome.

Impact Phase was executed nearly flawlessly. Over 27 hours, the MOS performed two full operational cycles to plan and execute Centaur separation and lunar impact. There were some voice loop communications problems in the final minutes of flight, attributed to shortcomings in training for real-time instrument commanding. These had some effect on data collected at the time of the Centaur impact, but with a negligible influence on overall science goals. LCROSS met all of its mission objectives.

VIII. Conclusions

What were the keys to the success of the LCROSS flight team? Perhaps most importantly, LCROSS benefitted tremendously from a pervasive spirit of cooperation and trust that crossed organizational boundaries. This improved communications at all levels, spawned additional collaborations, and caused people to devote extra time throughout the project to ensure mission success. From the MOS development perspective, securing full-time access to the LCROSS simulator was critically important. It provided the team with an accurate test platform in creating the hundreds of command products to support various mission events, and allowed the team to gain early, risk-free, and frequent experience in the operation of LCROSS.

Not surprisingly, frequent, repeated testing of the team under realistic conditions was invaluable. These tests exposed weaknesses throughout MOS development, enabling the team to refine its equipment, processes, procedures, and staffing schedules before launch. By launch, the team had "flown" each major event multiple times, and this significantly improved team confidence in flight. As an unintended consequence, MOS simulator-based tests were partially responsible for exposing two significant spacecraft bugs prior to launch (subsequently corrected). MOS testing, using MOS-developed flight command sequences, provided a level of realism that could not easily be achieved in standard spacecraft system-level verification tests.

Managing workload with a limited staff was a continual challenge for LCROSS. The development phase, entailing vast overtime hours, remained challenging up until launch. The flight schedule was busier and more irregular than anticipated, contributing further to team fatigue. For the most part, the team was getting sufficient sleep to avoid human error, but had little time off to tend to personal matters. Due to a lack of time and a small team, the MOS did not train a full set of backups for critical operational positions. Fortunately, the team did not falter on attendance or performance due to illness or accident. There were also an insufficient number of personnel to

compose a separate anomaly response team, and therefore day-to-day operations competed for time with anomaly investigations. However, the MOS responded effectively to a limited number of anomalous events concurrently with routine operations.

Distributed operations were largely successful. The MOS made substantial improvements to communications prior to launch, and operators from all disciplines made strong contributions to the team, despite being remotely situated. However, communications and situational awareness could have improved even more. Some basic problems (e.g. poor room acoustics) hampered communications between ARC and NG ROC's. Furthermore, we observed that the two roles played by the NG ROCs had mutually exclusive communications models. Supporting closely-coordinated procedure execution demanded quiet focus and attentive voice loop participation, whereas providing assessments of spacecraft performance benefitted from offline group discussion. Recognizing this conflict, we revised ROC protocols mid-flight to separate the two activities, with noticeable improvement.

Staff members that were dually-tasked as MOS operators and GDS developers were unable to fully satisfy the demands of both roles in flight. High-priority MOS tasks consumed most of operators' time, leaving no time to perform rigorous testing in support of a global GDS deployment. Instead, critical fixes were introduced on isolated workstations. A suggestion for future missions is to employ distinct GDS developers that double as backups for key operational roles.

Despite its success in supporting a single mission, it is debatable whether the LCROSS MOS development approach is sustainable over multiple missions. LCROSS succeeded, but this could not have happened without the extraordinary hours the team contributed from start to finish – a level of effort that is not easily repeated.

Appendix: Acronym List

ARC	NASA Ames Research Center	MSR	Mission Support Room (ARC)
ERT	engineering readiness test	NG	Northrop Grumman
GDS	ground data system	NGAS	- Aerospace Systems, Redondo Beach, CA
GSFC	NASA Goddard Space Flight Center	NGTS	- Technical Services, Lanham, MD
JPL	Jet Propulsion Laboratory	ORT	operational readiness test
LCROSS	Lunar CRater Observation and Sensing Satellite	ROC	Remote Operations Center
MOCR	Mission Operations Control Room (ARC)	SOC	Science Operations Center (ARC)
MOS	Mission Operations System	TT	thread test

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