Development of a Lunar Mission Operations Center for the NASA JPL Lunar Flashlight Mission

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With advancements in small satellite technology being seen, these low cost, small form factor systems are being considered for interplanetary missions. NASA's Jet Propulsion Laboratory's (JPL) mission, Lunar Flashlight is a 6U CubeSat which aims to orbit the Lunar South pole and detect craters for water ice. This mission is a technology demonstration which hopes to prove the viability of low cost CubeSats for interplanetary missions. This low resource model for satellites extends to its mission operations as well. Georgia Institute of Technology's Space System Design Laboratory has been contracted to perform mission operations for Lunar Flashlight. The operations team was able to develop and expand the capabilities Georgia Tech Mission Operations Center (MOC) to support this Lunar mission. Hardware integration was established to connect various operations machines to each other and the Deep Space Network. Interfaces were defined between the operations team and external parties including the Mission Design and Navigation team at JPL. Using the certified MOC, the operations team was also successfully able to perform and complete their first operational readiness test which simulated the first phase of the Lunar Flashlight mission.

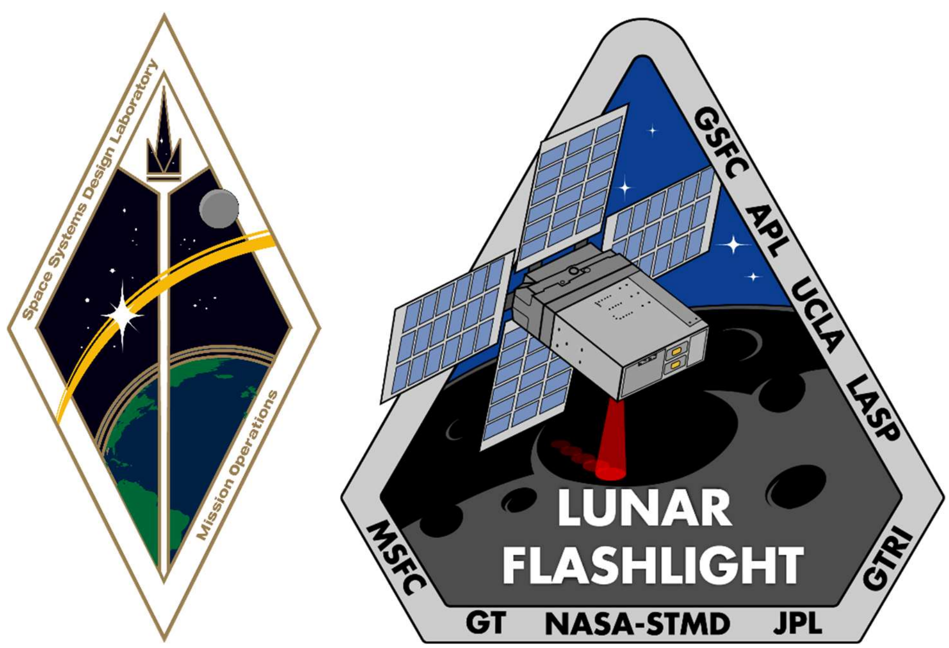

Figure 1. Space Systems Design Laboratory Mission Operations, and Lunar Flashlight Mission Patches

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I. Acronyms

ADCS	=	Attitude Determination and Control System
AMMOS	=	Advanced Multimission Operation System
AMPCS	=	AMMOS Multimission Data Processing and Control System
APID	=	Application Process ID
DSN	=	Deep Space Network
EVR	=	Event Response Record
GDS	=	Ground Data Segment
I&T	=	Integration and Test
IM-1	=	Intuitive Machines 1
IRIS	=	Communications System used on Lunar Flashlight
JPL	=	Jet Propulsion Laboratory
LEOP	=	Launch and Early Operations
LFL	=	Lunar Flashlight
LOI	=	Lunar Orbital Insertion
MDNAV	=	Mission Design and Navigation
MET	=	Mission Events Timeline
MMPAT	=	Multi-Mission Power Analysis Tool
MOC	=	Mission Operations Center
MOP	=	Mission Operations Plan
MOS	=	Mission Operations System
MPP	=	Mission Planning Procedures
MPSE	=	Mission Planning and Sequence Editor
MSFC	=	Marshall Space Flight Center
NRHO	=	Near Rectilinear Halo Orbit
OICD	=	Operational Interface Control Document
ORR	=	Operational Readiness Review
ORT	=	Operational Readiness Test
OTM	=	Orbital Trim Maneuver
RDP	=	Realtime Dynamics Processor
SCLINK	=	Spacecraft Link
SLE	=	Spacecraft Link Engineer
SOC	=	Science Operations Center
SSDL	=	Space System Design Laboratory
STMD	=	Space Technology Mission Directorate
TCM	=	Trajectory Correction Maneuver
TLM	=	Telemetry
UART	=	Universal Asynchronous Receiver-Transmitter
V&V	=	Verification and Validation
VM	=	Virtual Machine
XACT	=	ADCS used on Lunar Flashlight

II. Introduction

With CubeSats becoming more affordable and more prolific in the space exploration industry, people have begun to consider their role in interplanetary exploration. NASA's Jet Propulsion Laboratory (JPL) was the first to embark on this endeavor with their Mars Cube One (MarCO) mission. This was a technology demonstration mission which aimed to show the capabilities of CubeSat technology for interplanetary missions. The MarCO mission had two 6U CubeSats which performed a flyby of Mars in order to provide a communications relay for NASA's InSight landing. This mission was overall a success despite many anomalies along the way. It paved the path for other CubeSats which are being developed to explore another celestial body, including the Moon. One such CubeSat is Lunar Flashlight.

While system requirements, mission design, and engineering development are all important factors in satellite missions, one of the most important elements for any space mission is operations. Mission operations is the phase which involves commanding, monitoring, operating, and performing activities with a spacecraft once it has launched. It is crucial to have a well-designed and prepared Mission Operations System (MOS) in place before launch to ensure a smooth mission. Most interplanetary missions require large MOS infrastructure to support them. However, CubeSat missions are commonly low budget and have fewer resources (human personnel, infrastructure, etc.) compared to flagship interplanetary missions like Mars 2020. This creates some unique challenges when it comes to developing an operation system with the lower resources for interplanetary CubeSats.

The Georgia Tech Space Systems Design Laboratory (SSDL) was contracted by JPL to be the main Mission Operations Center (MOC) for Lunar Flashlight. The operations team was given system requirements which dictated the expected capabilities for the MOC. Prior to this contract, the SSDL MOC had been set up to operate Low Earth orbiting CubeSats which were developed by the lab. This paper details the process the operations team went through in expanding the capabilities of the MOC to support an interplanetary mission. It provides an overview of the various mission system elements, the development and certification of the MOC, interfaces with external stakeholders, and Operational Readiness Tests. It also shows how this development was implemented for Lunar Flashlight and can be used as a reference for other interplanetary CubeSat missions.

III. Lunar Flashlight Mission Overview

Lunar Flashlight (LFL) is a technology demonstration mission within the Small Spacecraft Technology program under NASA's Space Technology Mission Directorate (STMD). LFL is a 6U CubeSat designed to orbit the Moon in a Near Rectilinear Halo Orbit (NRHO) with a perilune over the Lunar south pole. This orbit will allow Flashlight to perform low altitude passes over craters in the south pole and use a Laser Reflectometer to detect any water ice. As a technology demonstration mission, Lunar Flashlight's mission objectives include demonstrating: 1) the use of NASA's new green monopropellant called ASCENT, 2) the capability of CubeSats for exploring planetary bodies such as the Moon, demonstrating the use of laser spectroscopy in differentiating water ice and lunar regolith, and mapping water ice locations around the south pole.

Lunar Flashlight is scheduled to launch in early 2023 on the Intuitive Machines-1 (IM-1) mission aboard a Falcon 9 rocket. The Concept of Operations is separated into five mission phases as seen in Figure 2. The mission starts with Launch and Early Operations (LEOP), where the spacecraft launches, and a system checkout is performed. During LEOP, multiple Trajectory Correction Maneuvers (TCMs) are performed where the spacecraft uses its propulsion system to thrust and correct its course. The spacecraft then performs a flyby of the Moon and begins its 4-month cruise phase where it travels to the L2 Lagrange point before traveling back towards the Moon. The next critical event is Lunar Orbital Insertion (LOI) where the spacecraft performs a large burn to slow down so the Moon's gravity will capture it into the desired science orbit. This starts the science phase, where it orbits near the lunar south pole every 6 days, collecting science data at the perilune. During these orbits a series of Orbital Trim Maneuvers (OTMs) are performed to correct the trajectory. After 60 days, the spacecraft performs a disposal burn.

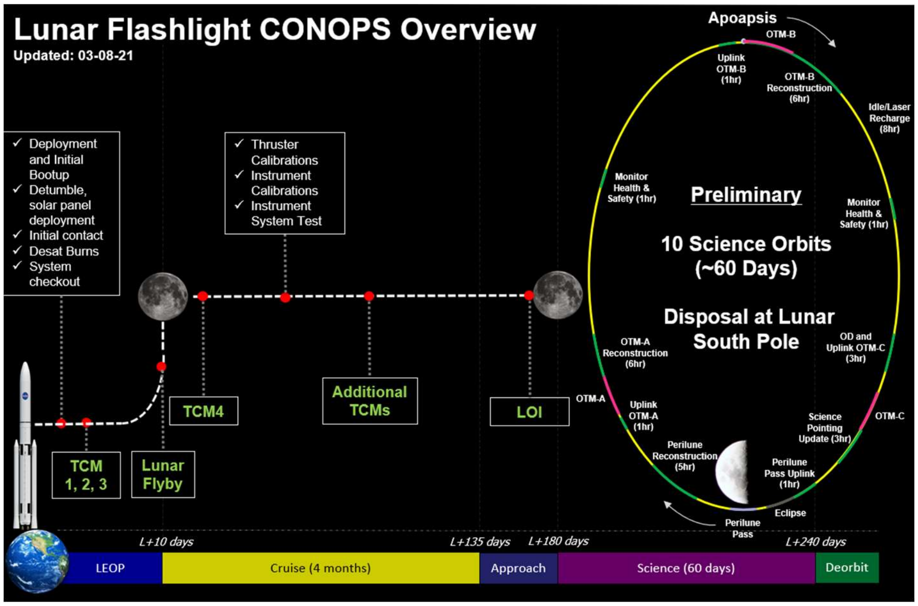

Figure 2. Lunar Flashlight Concept of Operations

Lunar Flashlight is made up of six major subsystems which will be referenced in this paper. Figure 3 shows the breakdown of these subsystems. LFL uses the Sphinx flight computer (developed by JPL for the MarCO mission). For communications, it uses the IRIS radio system (developed by JPL) with multiple patch antennas. The attitude determination and control system (ADCS) is provided by the Blue Canyon Technologies XACT system. This system uses various sensor inputs from the spacecraft (including inertial measurement units, sun sensors, and star trackers) to compute its attitude. It can also respond to perturbations and commands to change its attitude. The payload system (developed by JPL) includes a laser and reflectometer which can detect the reflected beam. The Lunar Flashlight Propulsion System (LFPS) was developed by Marshall Spaceflight Center (MSFC) in conjunction with the Glenn Lightsey Research group at Georgia Tech. It is made up of four 100 mN Thrusters. Lastly, the electrical power system (developed by JPL) contains four solar panels along with a control board and lithium-ion batteries.

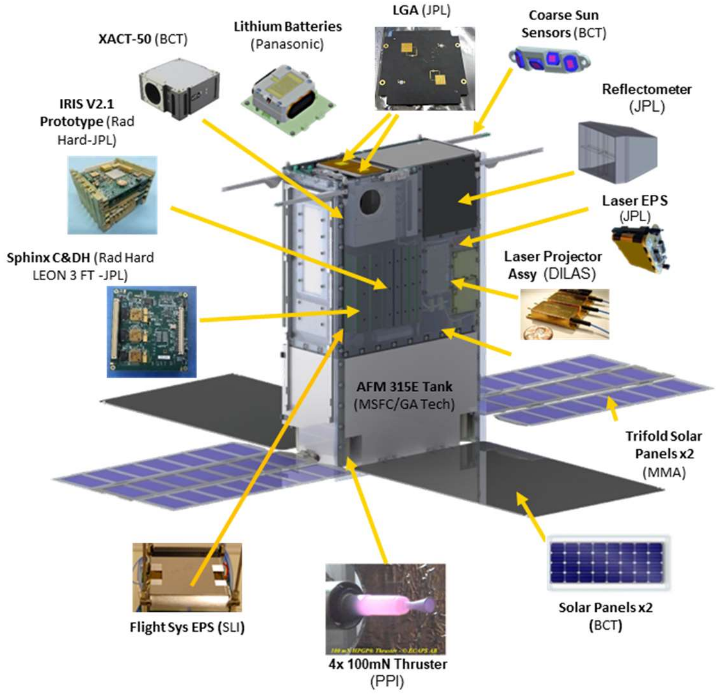

Figure 3. Lunar Flashlight subsystems

IV. Mission Operations System Elements

The Lunar Flashlight Mission Operations System (MOS) has multiple elements and organizations that interact with each other through defined interfaces. Figure 4 shows a simplified view of the organizations and elements that comprise the MOS. At the center is the Georgia Tech Mission Operations Center (GT MOC) which houses the mission operators, operations computers/virtual machines, LFL Testbed, and databases. The GT MOC communicates with the LFL satellite through the NASA Deep Space Network (DSN). The Science Operations Center for this mission is managed by University of California Los Angeles (UCLA). JPL provides engineering support to the MOC. Additionally, the Mission Design and Navigation (MDNAV) team at JPL provide the navigation support for the mission. Lastly Marshall Space Flight Center (MSFC) completes the MOS by providing propulsion system expertise to the team. MSFC and JPL are the subject matter experts for the spacecraft subsystems. All of these elements interact with each other in order to support Lunar Flashlight operations. The following sections will describe the various components of the GT MOC including data flow, operational roles, operations hardware, and operations software.

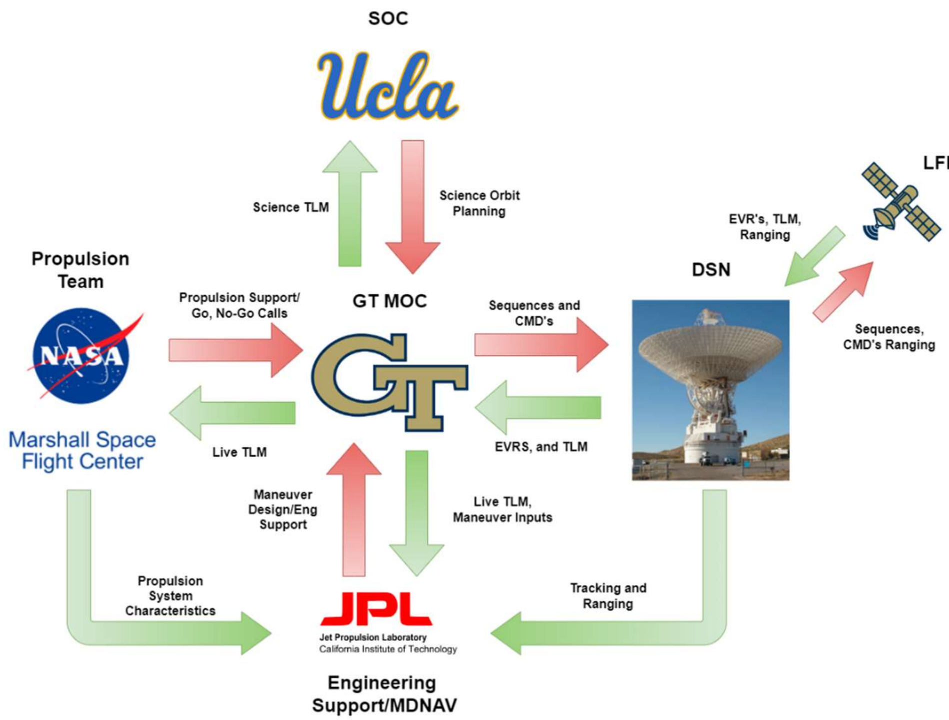

Figure 4. MOS Elements and Organizations

A. Operational Data Flow

Operating Lunar Flashlight requires managing large amounts of data in multiple formats. The Figure 5 shows how data is managed throughout the MOC and how it interacts with the elements. The various elements are separated by Institution, Human roles, Computing, and Hardware. Data is split into two main streams: Downlinked Telemetry and Uplinked Commands.

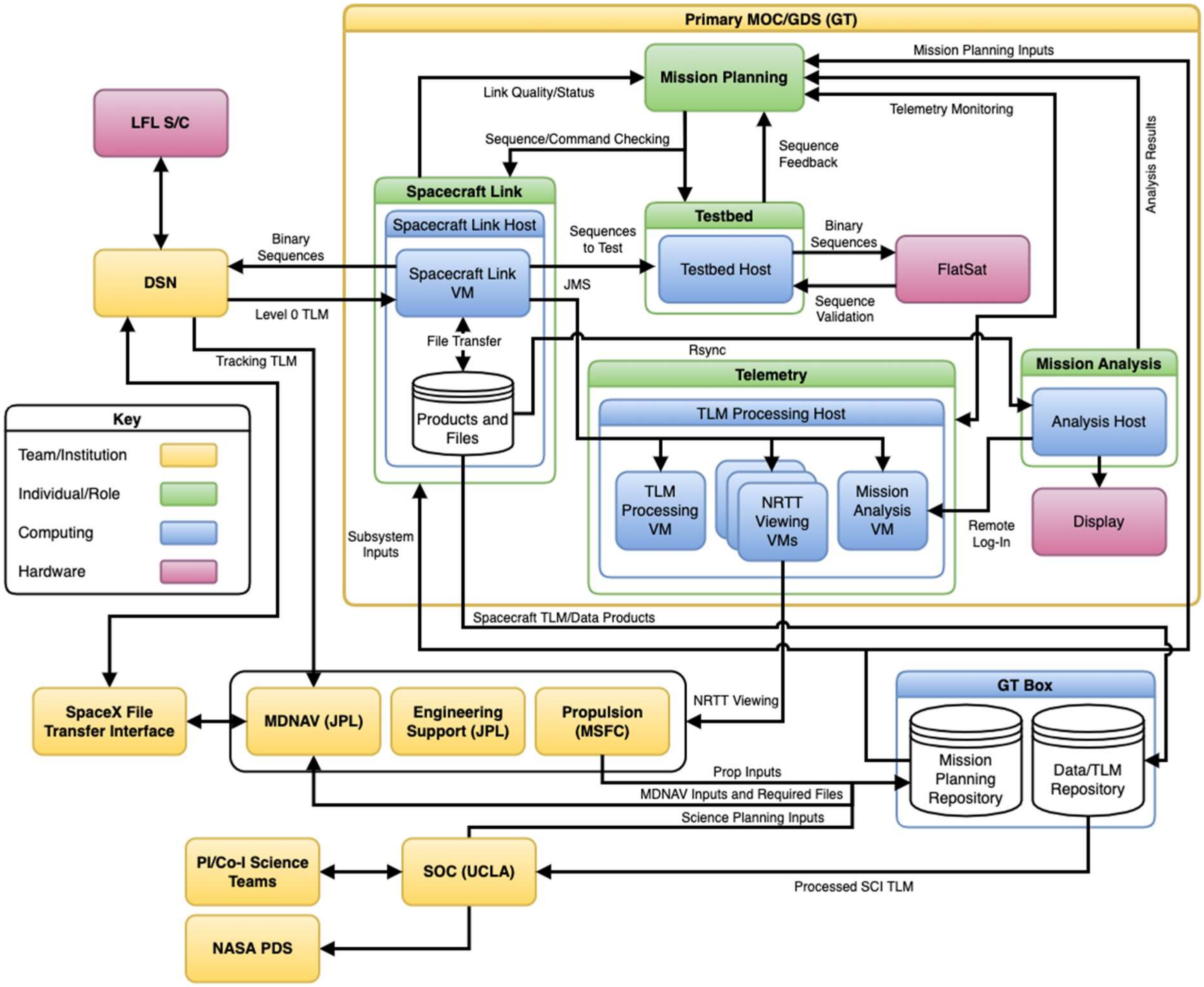

Figure 5. MOC Data Flow

1. Downlinked Telemetry

Beginning with the spacecraft, all raw telemetry coming from the satellite is classified as Level 0 telemetry. This is raw binary data that is unprocessed or filtered. For Lunar Flashlight this data comes in the form of Channel Telemetry, telemetry recorded by the various subsystems and sensors packaged into channels and packets, and Event Verification Records or EVRS. EVRS are flight software responses to onboard events like warnings, faults, confirmation of commands, etc. As mentioned previously, the GT MOC is connected to the spacecraft via the DSN. Level 0 TLM is radiated over RF to the DSN, which then sends the telemetry to the MOC over a network connection.

Inside the MOC, there are four major computing machines called hosts for operation. These include the Spacecraft Link (SCLINK), Testbed, Telemetry, and Mission Analysis. SCLINK, Telemetry, and Testbed host machines contain virtual machines which run AMPCS, the JPL operations software utilized for this mission. Using virtual machines (VM) instead of the host computer is preferable since this prevents operations from being tied to a single piece of hardware. If the host machine fails, the VM can easily be ported over to another computer. AMPCS will be discussed in detail in Section III C. Staffing the MOC are the following 5 operator roles:

1. Mission Planner
2. Spacecraft Link Engineer (SLE)
3. Testbed Engineer
4. Telemetry Engineer
5. Mission Analyst

Details of each role will be described in section III B.

Level 0 Telemetry first arrives to the Spacecraft Link host which contains the Primary Ops VM and is staffed by the Spacecraft Link Engineer. This computer is in charge of processing all the data going to and coming from the DSN. The SLE will use this machine for all commanding of the Lunar Flashlight spacecraft. Telemetry is also initially processed by AMPCS into the various telemetry channels. This initially processed Level 1 telemetry is saved on a local database on the SCLINK computer and is also sent in a stream to the Telemetry Host.

The Telemetry Host staffed by the Telemetry engineer, is where all live telemetry is monitored and distributed to various external parties. The telemetry host contains six VM's. The TLM master VM is where the TLM engineer performs telemetry checks. The remaining VM's display focused subsystem telemetry for subsystem engineers from JPL to view live. These include ADCS, Propulsion, Science, and Navigation. Members of these teams can connect remotely to view live TLM pertaining to them.

Level 1 Telemetry is also stored on Box, an online storage repository. Telemetry is backed up on Box at the end of every contact. Here teams can access the data from any previous contact. The science operations team pulls data from this database to post process scientific analysis for ongoing research.

2. Uplinked Commands

The MOC uses 2 main methods to respond to this downlinked telemetry sent by the satellite. These include immediate commands and binary sequences. Immediate commands are individual flight software commands which are sent in real time by the Spacecraft Operator and executed once received. These commands can also be packaged into groups which will also execute immediately in sequence. Binary sequences are commands compiled into a package that includes timing information. These commands will run with relative timing between each other or run at an absolute time. Both types of commands are sent to the DSN as binary data which gets radiated to the spacecraft.

Binary sequences are generated before live operations during the mission planning phase. These sequences are initially tested on the Lunar Flashlight Testbed before being uplinked to the spacecraft. The LFL Testbed, seen in Figure 6, contains many similar components as the flight unit including the same flight software. It is able to emulate the response and actions of the flight unit closely. When sequences are sent to the Testbed Host, the Testbed engineer runs them in order to validate the expected response. This ensures sequences do not harm the spacecraft or the mission activities before they are uplinked to the flight unit. Sequences approved by the Mission Planner are transferred back to the SCLINK host where they can be uplinked to the spacecraft using AMPCS.

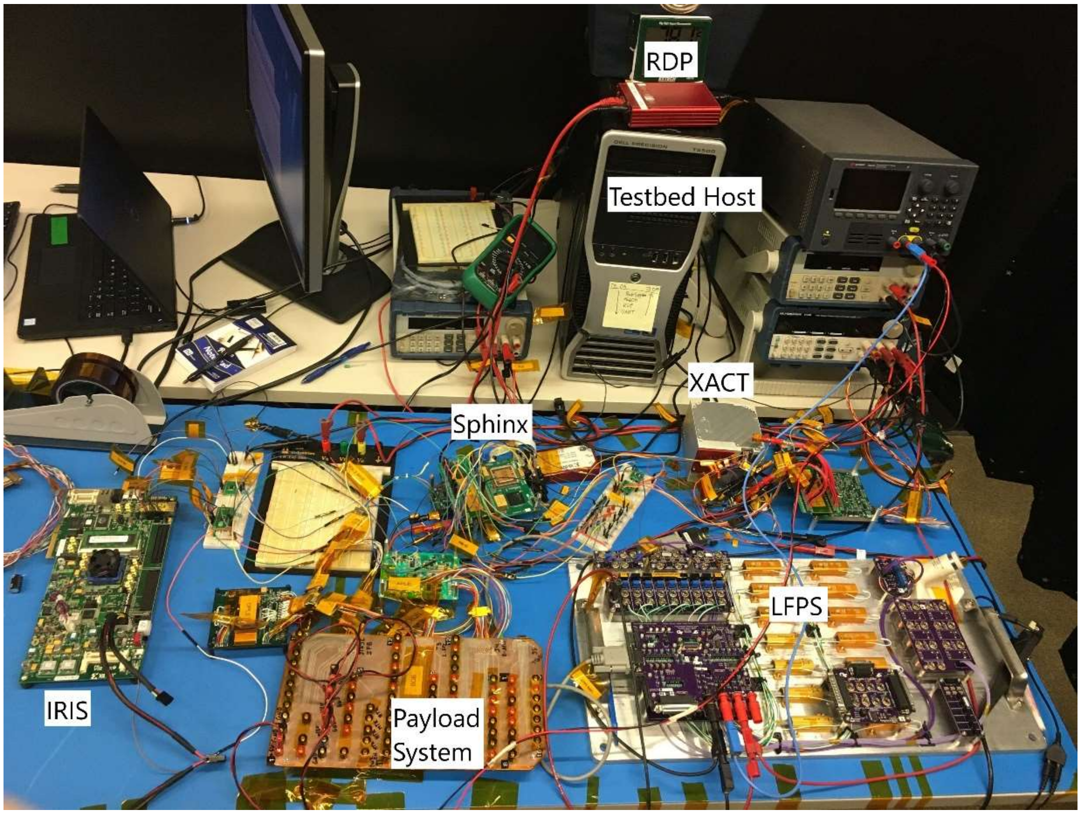

Figure 6. Lunar Flashlight Testbed

B. Operational Roles

A key component of operations is the mission operators themselves which staff the consoles and perform activities on the spacecraft. There are two different levels of LFL operators. Level 1 operators include Mission Analyst, Spacecraft Link Engineer, and Testbed Engineer. Level 2 operators include the Telemetry Engineer, and Mission Analyst. Level 1 operators fill a more complex role compared to Level 2 operators.

<u>Level 1 Operators</u>

1. Mission Planner

The Mission Planner plans, organizes, and prepares for upcoming operations. This person is in charge of creating the Mission Events Timeline (MET) which outlines the major events that occur during the contact. They are the liaison between the MOC and the other teams including SOC, JPL, and MDNAV. Activity requests and other mission planning inputs from these teams are processed to coordinate the events of a contact. They review operations procedures and flight checklists before each mission. During live operations, they serve as the director of operations. They monitor the activities of the SLE and approve any command/sequence sent to the spacecraft.

2. Spacecraft Link Engineer

The SLE manages the communications link between the MOC and the spacecraft through the DSN. This person establishes the link to the DSN and communicate with DSN operators during the contact. They are also in charge of commanding/controlling the spacecraft. They execute mission activities according to the MET with approval from the Mission Planner and convert text sequences to binary sequence files for uplink. Additionally, they monitor anomalies, faults, and EVR's sent back by the spacecraft.

3. Testbed Engineer

The Testbed engineer operates the LFL testbed to verify and validate commands/sequences before they are sent to the spacecraft. This person provides feedback to the mission planner and report any anomalies which may arise.

Level 2 Operators

4. Telemetry Engineer

The Telemetry Engineer monitors spacecraft health through telemetry checks and manages live telemetry viewing for supporting teams. This person creates custom telemetry displays in AMPCS for each team so that they have a focused look at their respective subsystem. TLM engineer also plays back telemetry that is recorded between DSN contacts to check spacecraft health during this period. The telemetry engineer also makes sure telemetry is uploaded to BOX at the end of contacts.

5. Mission Analyst

The Mission Analyst interprets telemetry, performs limit checks, and completes trend analysis. This person uses various tools to perform analyses including MMPAT (Multi-Mission Power Analysis Tool) for power modeling, and Tball for ADCS modeling. They also fill the role of ADCS engineer for the mission. This involves modeling the spacecraft attitude and generating data products for MDNAV to aid navigation (detailed in Section V).

C. Operations Software

Lunar Flashlight uses the AMMOS Multimission Data Processing and Control System (AMPCS) product as its operations software. AMMOS is the Advanced Multimission Operation System, which was built by JPL, and is the backbone for AMPCS. AMPCS provides multiple services necessary for operations. AMPCS is able to process the data uplink and downlink between the MOC and the DSN.

Lunar Flashlight has 937 different telemetry channels. These channels are organized into 15 groups, called Application Process IDs or APIDs. Lunar Flashlight will downlink telemetry as APIDs at different rates. AMPCS is able to parse APIDs in order to extract individual telemetry channels to display. AMPCS has a user interface which allows viewing of the telemetry on monitor screens and can be customized to show specific channels or plot data. Custom monitors are created for each operational role in order to help operators focus their information. AMPCS is also able to process EVRs and color code them for ease of identification. Figure 7 shows an AMPCS viewing window which has plotted telemetry from the attitude control system called the XACT. This window also includes EVRs and tabularized XACT data.

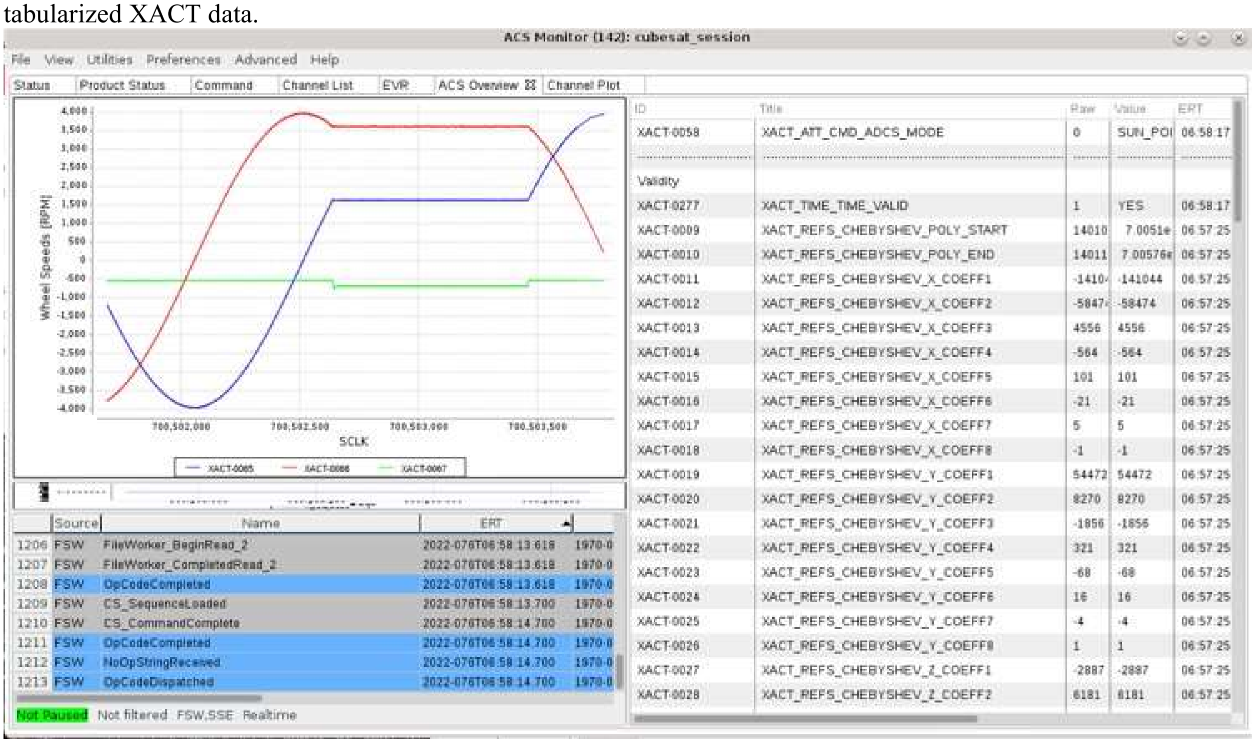

Figure 7. Sample AMPCS viewing window showing ADCS Telemetry

AMPCS also provides an easy system for sending commands. Immediate commands can be built using the AMPCS command builder or loaded as a text file. Sequences can be generated using a program called Mission Planning and Sequencing Editor (MPSE). This program allows users to format sequences properly and convert them into Binary Sequence Files for uplink. Binary sequences are uplinked/executed through an immediate command.

V. MOC Development and Certification

The Lunar Flashlight mission operations system development and certification was completed concurrently with operator training and certification. This development can be broken down into three major phases:

1. Phase I: GDS and Basic Operations training
2. Phase II: Interface development and operator role training
3. Phase III: Operational Readiness Tests.

At the end of each phase there is a certification checkpoint which verifies the completion of the phase. This development timeline can be seen in Figure 8.

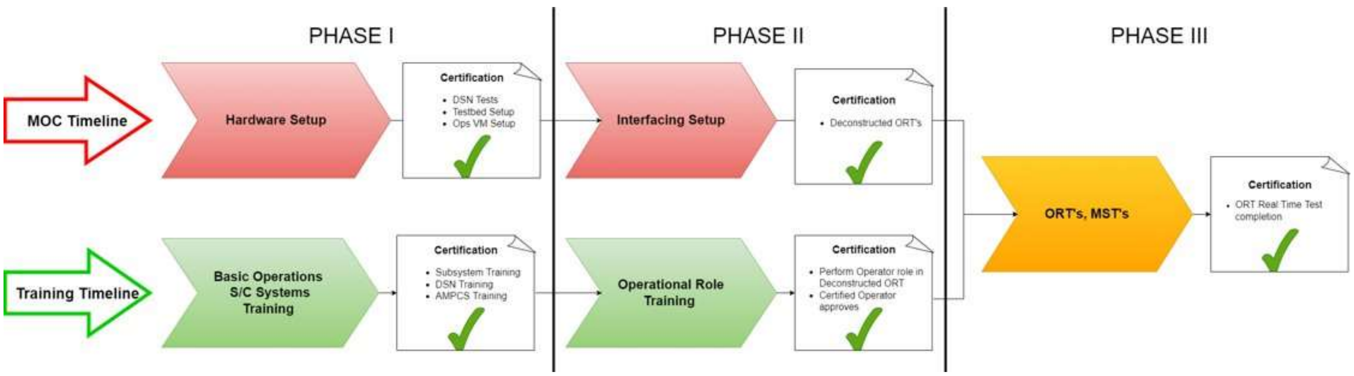

Figure 8. Development and Training Timeline for the GT MOC

1. Phase I

The first phase of development involves the initial Ground Data System (GDS) setup of the MOC. During this phase, the four primary host machines were procured and AMPCS installed. The networking behind the scenes was setup as well including creating operations VMs on each host and connecting them through the JPL network. Once this was complete, connection between the MOC and the DSN was established. The MOC went through a series of DSN connection tests where the SCLINK computer binds to each DSN station through the SLE Proxy and simulates data downlink. Sample telemetry was flowed from the station to the SCLINK where it was displayed in AMPCS. Commands were also sent from the MOC to the DSN to verify uplink control. The DSN does not radiate any of the commands, however the DSN operators acknowledge they have received the command strings. Figure 9 is a screen capture from the DSN Now website which shows station 25 is connected to the Lunar Flashlight MOC and flowing data. Certification of the MOC development included successful connection tests with all 15 DSN stations, setup of LF Testbed, and setup of operations hosts/VM's.

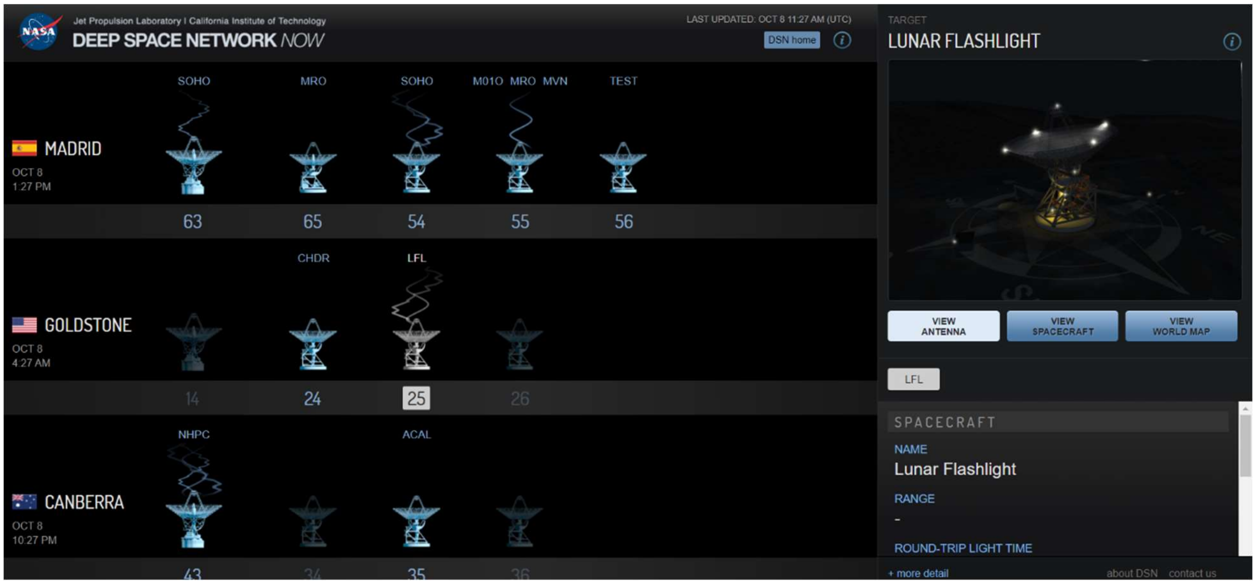

Figure 9. NASA DSN Now Website showing Lunar Flashlight being tracked by Station 25

This phase also involves the development of important preliminary operations documents. The first written and approved document was the Mission Operations Plan (MOP). This document outlines the mission phases, information about the spacecraft, ground data system, project team, and external interfaces. It includes an overview of operational plans, processes, and procedures which will be implemented by the MOS. This document summarizes all aspects of mission operations for Lunar Flashlight with references to additional documentation which describe components in more detail.

The next document developed is the MOS/GDS Verification and Validation (V&V) Plan. This document outlines how it will be verified that the MOS/GDS meets the system requirements, as well as validate that it meets the overall mission/project requirements. This document includes a V&V matrix which tracks the completion of each V&V requirement. These requirements include success criteria, estimated completion date, and proof of completion.

The next document is the MOS/GDS Training and certification plan. This document outlines the process of training and certifying new mission operators. It includes the development timeline and certification of the MOC as well.

Another document is the Mission Operations Center Integration and Test (I&T) Plan. This document outlines the process to integrate the MOC with the Ground Data Segment (GDS). This involves details about hardware and networking through the MOC. Along with information on connecting to the DSN.

Lastly the final document in Phase I is the Mission Planning Procedure (MPP). This document details the review process of mission planning inputs/activity requests from stakeholders are reviewed in order to plan contacts and generate sequences. The Mission Planning flow diagram can be seen in Figure 10.

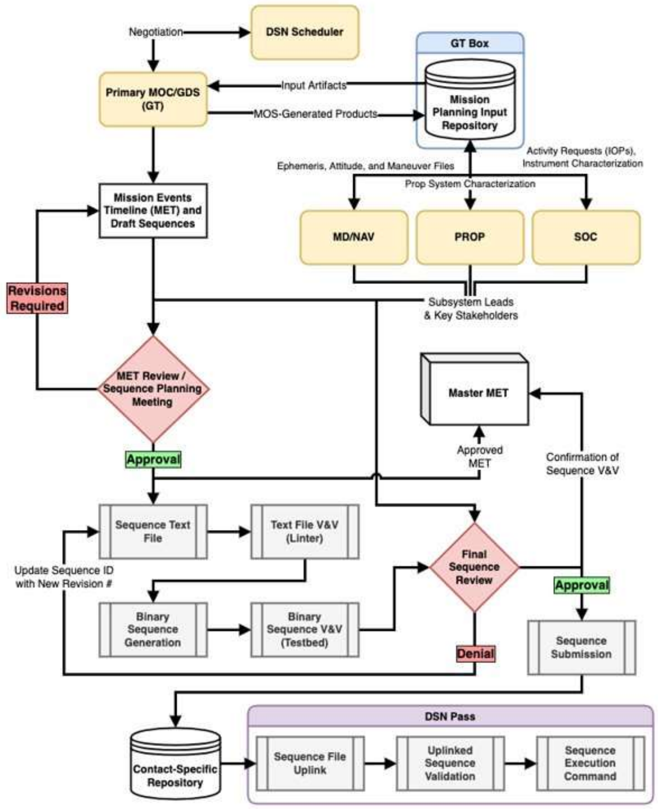

Figure 10. Mission Planning flow diagram

Operators during this phase receive basic operations training. Training involves learning mission operations procedures and functional architecture through the MOP and MPP. JPL has provided training material for operators for JPL interfaces. The training includes instruction on how the DSN operates, how to use AMPCS for operations, and a Lunar Flashlight subsystem overview (provided by subsystem leads). Successful completion of these trainings certifies operators. Upon completing the training, operators will have a good understanding of how various interfaces of the MOS/GDS connect with each other, along with basic operations procedures.

2. Phase II

The second phase of MOS/GDS development focuses on completing interfaces between elements. This involves establishing a connection between all the operations hosts and VM's as per the data flow diagram in Figure 5. Each arrow on this diagram is another connection which must be setup and tested. The testing of these connections is called a Thread Test. The list of thread tests for lunar flashlight can be seen in Table 1.

Table 1. Thread Tests required to certify the MOC

Lunar Flashlight Thread Tests
Bind to DSN
Send Binary Sequences to DSN
Send Binary Sequences to Testbed Host
Test sending sequences to Primary Ops VM from Box
Uplink sequences to FlatSat
Create and verify command sequence
Demonstrate live telemetry viewing
Push telemetry from database to Box
Populate Open MCT Displays with Telemetry
Populate Chill Monitor sessions with Telemetry
Subsystem checkout and report
Check flight rules for command sequence
Spacecraft activity reconstruction

Completion of these thread tests allows the operations team to perform full systems tests known as deconstructed Operational Readiness Tests or deconstructed ORTs. These tests allow the MOS to simulate operations for large mission phases, mimicking an actual flight scenario. Each day a contact from this phase is simulated. ORTs are further discussed in Section VI. Successful completion of all thread tests and start of Deconstructed ORTs certifies MOC for Phase II.

The MOC interfaces with multiple different mission stakeholders as mentioned in Section III. These other teams include the MDNAV, JPL engineering, Marshall Flight Center, and the Science Operations Center. The MOC exchanges multiple data products used for mission planning between the various interfaces. During Phase II, Operational Interface Control Documents (OICDs) are created to define this exchange and includes information such as file formats, product contents, file persistence, and mission planning process. One of the largest interfaces is with the MDNAV team. This process is detailed further in Section V.

Mission Operators train for each of the five operational roles during this phase. This is accomplished through the deconstructed ORTs. During these tests, new operators shadow certified operators as they perform operations. This gives them the opportunity to observe and understand the role each operator plays in the system. For Level 2 Operator roles, TLM engineer and Mission Analyst, trainees will be able to fill these roles during the ORT with the certified operator shadowing them. If the certified operator is satisfied with their performance, they will sign off and approved them for the role. Level 1 operator certification is done in Phase III.

3. Phase III

The last phase of MOS development includes Operational Readiness Tests. During these tests the MOS will perform operations for a mission phase in a flight like situation. During Phase III, ORTs are performed in real time meaning that contacts are not broken up over a period of multiple days unlike the deconstructed tests. Further details about the differences between deconstructed and real time ORTs are mentioned in Section V. ORTs are the most important test of MOS/GDS development since they will exercise every component of operations. Procedures, sequences, and plans are developed in this phase in order to prepare for ORTs. These documents will be updated based on the results of the ORT and will eventually turn into flight documentation.

During this phase, trainees will shadow certified operators in order to learn the roles of Level 2 operators. Certified mission operators for each role will provide on demand training for them by following this process:

1. Trainees will shadow mission operators and watch them perform their roles during ORTs.
    a. This gives the trainee a chance to ask questions and learn about the role in practice
2. When the operator thinks the trainee is ready, they will let the Trainee sit in the operator's seat and shadow them as they perform the role

    a. The certified operator will monitor them
    b. The certified operator will verify each step the trainee takes
3. When the certified operator is satisfied by the trainee's performance, they will sign off and approve them for the role.

Completion of this process certifies new trainees as Level 2 mission operators, enabling them to take on the role of SLE, Testbed Engineer, and Mission Planner.

The Phase III certification for MOS/GDS development includes the completion of all planned ORTs (see Section V) and the Operational Readiness Review (ORR). The ORR is a large project review held by the JPL where the NASA program office reviews the operational readiness of the MOS. All aspects of operations are reviewed including but not limited to development of MOS infrastructure, operations procedures and documents, and performance on ORTs. If the MOS passes this test, then it is certified as ready to operate the Lunar Flashlight Spacecraft.

VI. Interface with MDNAV

MDNAV performs all the orbit determination and trajectory planning for the LFL mission. As mentioned in the Con Ops, Lunar Flashlight will perform multiple Delta V maneuvers including TCM's, OTM's, LOI. For each of these maneuvers, MDNAV and the operations team must exchange information in order to aid each other in the design, planning, and execution of the maneuver.

A. Data Products Exchanged

An overview of all the data products needed for maneuver design and planning can be seen in Table 2. A description of how these documents fit into the maneuver design process is detailed in Section V.B.

Table 2. Data Product Exchange Between MOC and MDNAV

Product	Team Delivering	Format	Description
Mission Events Timeline (MET)	MOC	pdf	Overview of mission events for each mission segment
Spacecraft Clock Kernel Spacecraft Event Time (SCLKSCET)	MOC	txt	Gives conversion from S/C clock to ET or UTC
SCLK Kernel	MOC	Spice Kernel	S/C clock conversion in Spice Kernel format
Maneuver Performance Data File (MPDF)	MOC	xml	Maneuver/thruster info for MPF
Maneuver Implementation File (MIF)	MOC	xml	OPS/SCT Implementation of Nav designed Man
C Kernel	MOC	Spice Kernel	Current satellite orientation
Reconstructed Small Forces File	MOC	xml	Reconstructed info on desats
Predicted Small Forces File	MOC	xml	Predicted info on desats
Spacecraft Ephemeris File (SPK BSP)	MDNAV	bsp	S/C trajectory in SPK format, delivered for all phases of mission
Spacecraft Ephemeris File (OEM)	MDNAV	txt	Launch/cruise trajectory in OEM format, delivered to SPIE for only first ~2 weeks of mission.
Chebyshev Polynomials	MDNAV	xml	S/C trajectory converted into Chebyshev polynomials for uplink
Maneuver Profile File (MPF)	MDNAV	xml	Predicted attitude of S/C
STUF File	MDNAV	xml	Contains information about trajectory and orbit parameters

B. Maneuver Design Process

Maneuver design is an iterative process which uses the various data products exchanged between MDNAV and MOC. The flowchart in Figure 11 outlines this process along with the exchange of documents. Initially, the MOC team provides information about the spacecraft mass/propulsion properties and the timeline of mission events through the MPDF and MET. The MOC team also provides the most recent attitude information through C Kernels and current clock information with the SCLKSCET file.

MDNAV uses this data to generate the trajectory for the vehicle, which is delivered as an ephemeris file and Chebyshev Polynomials File (polynomial approximations of the orbit). They design the maneuver and communicate the maneuver details to the MOC team through the MPF. This commences another iterative design loop. The MOC team uses the MPF to generate a preliminary maneuver sequence to be executed on the Testbed. The testing results inform any required changes to the maneuver design and are documented in the MIF. MDNAV then reviews the MIF and makes changes to the MPF accordingly. This process continues until a final maneuver sequence is generated.

As the maneuver significantly changes the state of the spacecraft, new mass and propulsion properties are computed and the MPDF is updated. Updates to the spacecraft attitude also require generation of C Kernels, which completes this process.

Mission events and attitude changes may also require the spacecraft to perform a desaturation maneuver. The MOC team creates a predicted SFF outlining details of this maneuver. Once the desaturation is performed, changes to the spacecraft state requires generation of new C Kernels along with updates to the MPDF. The reconstructed maneuver is relayed to MDNAV through the SFF Reconstructed file.

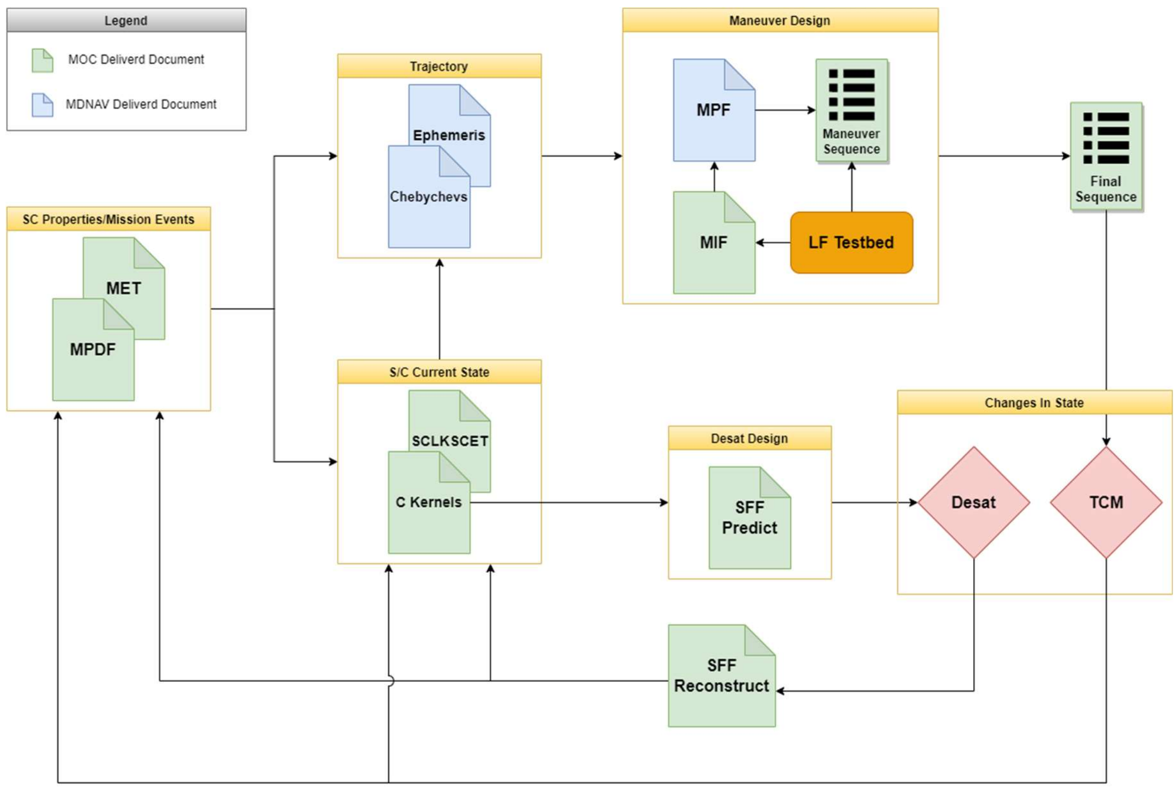

Figure 11. Maneuver Design Process and File Exchange

VII. Operational Readiness Tests

Operational readiness tests (ORTs) are an important part of developing a mission operations system. During an ORT, major mission events are simulated to test operations processes, hardware, interfaces, procedures, sequences, operator readiness, and operations tools. These essentially act as a dress rehearsal for the team. ORTs try to recreate as close to a flight like situation as possible. This means all teams in the MOS participate, including JPL, MDNAV, Propulsion, SOC and the DSN. ORTs can highlight any holes or areas of weakness in the MOS development that require rework before real operations begins.

Off nominal ORTs, , where anomalous events are introduced during test, are also be performed. A list of testable anomalies are created for this test. During the test, the JPL team will tell the testbed engineer to introduce these anomalies at random intervals without the rest of the operations team knowing. The operations team will have to react accordingly. These are beneficial in testing the anomaly/fault response procedure. They also test the operations team's ability to "react on the fly" and make critical decisions quickly in order to save the spacecraft.

The following sections go over the planned ORTs for Lunar Flashlight, what is involved in setting up these tests, and detail the events of ORT-1, which was performed on March 17th, 2022 by the operations team.

A. Lunar Flashlight ORT Schedule

The Lunar Flashlight Operations team have six ORTs planned before launch. These ORTs closely follow the mission phases listed in the concept of operations. Refer to Table 3 for the list of the planned ORTs. With an estimated launch window of January 2033, ORTs will be performed once a month up until the launch date. Previous ORTs may be repeated as needed in order to practice events and solidify operations procedures as well.

Table 3. Lunar Flashlight ORT Planned Schedule

ORT	Mission Events	Date
ORT-1	LEOP → TCM 1	3/17/2022
ORT-2	TCM-2	5/2/2022
ORT-3	Thruster Calibration	5/2022
ORT-4	Final TCM → LOI	6/2022
ORT-5	Instrument Operations → Perilune Pass	7/2022
ORT-6	Off Nominal LEOP → TCM 2	8/2022

B. ORT Setup

An ORT should mimic flight like conditions as closely as possible to test operations readiness. However, since the spacecraft is not operational, there are limitations that require workarounds. The following sections detail how the test is setup, how events are planned, and the execution of the tests.

1. Hardware/Networking Setup

The LF testbed is used to run the test, preventing wear and tear on the flight unit. The testbed contains several similar subsystems as the flight unit. Since it runs the same flight software version, it provides similar responses to commands and sends the same telemetry as the flight unit.

For the ORT, the testbed engineer's role is to set up and run the testbed as if it were the real satellite. The data stream from the testbed is redirected to the SCLINK computer. When the SLE starts the contact by launching AMPCS, they can connect directly to the testbed instead of to the DSN. Once the SLE connects, they receive the stream of TLM and EVRs. This same data stream is forwarded to the Telemetry Host as well, so the TLM engineer is able to perform their activities. This connection also allows the SLE to send commands directly to the testbed. This setup closely resembles the environment during real operations.

The testbed contains the same XACT attitude control system as used on the flight unit. XACT telemetry and commands are crucial to operations. Hence, it is important to have the XACT working in a flight like state during the ORT. The testbed does not have any of the attitude sensors connected. Instead, it is connected to the Real-time Dynamics Processor (RDP). The RDP can emulate the same sensor inputs it would expect to see in space. Using the COSMOS software (proprietary software from Ball Aerospace), the RDP can be given a setup script that provides a reference trajectory for the XACT to "follow", along with any initial body rates and quaternions. This allows the XACT to provide accurate TLM and respond to commands accordingly. The ops team can simulate launch conditions, TCMs, desaturation burns and slew maneuvers.

The Testbed does lack certain capabilities which would be found on the flight unit. One of these differences is the lack of an IRIS radio. Currently, the testbed does not have any control board to emulate the IRIS. As a result, IRIS commands do not work on the testbed. Instead, NO_OP_STRING commands are sent where the string argument is the original IRIS command. These commands generate an EVR which displays the IRIS command as a string so that operators can look through telemetry to know an IRIS command was meant to be sent.

Communication with the testbed is achieved through a UART protocol rather than radio frequency (RF) since there are no antennae on the testbed. UART poses certain limitations. For example, any files uplinked to the Testbed much be broken up into 300-byte chunks which are later concatenated together on the flight computer. This means the testbed uplink data rate is much slower than the RF data rates. Testbed components are also individually powered using power supplies which provide a constant voltage. On the spacecraft, subsystems are powered with a central electrical power system (EPS) which uses batteries and solar panels. The battery discharges throughout the mission therefore the input to the subsystems will be varied. As a result, the state of charge cannot be simulated during ORT's, and must be modeled separately. All these idiosyncrasies are be noted in order to understand where ORT scenarios diverge from an in-flight situation.

2. Mission Planning

ORT planning is critical to maintain the integrity of the test. Planning starts off by defining the Mission Events Timeline (MET) from the Con-Ops. Figure 12 below shows the Con-Ops timeline for the first 24 hours from deployment. The three areas highlighted in blue in the Telecom row are the times in which the MOC has 2-way contact (transmit and receive) with the spacecraft. The DSN does not enable 24-hour communication coverage for satellites. The DSN has plans to support over 70 missions as of July 8th 2020. Therefore, it can only provide a couple 1-2 hour contacts every day. Scheduling DSN passes around critical mission events is incorporated into mission planning.

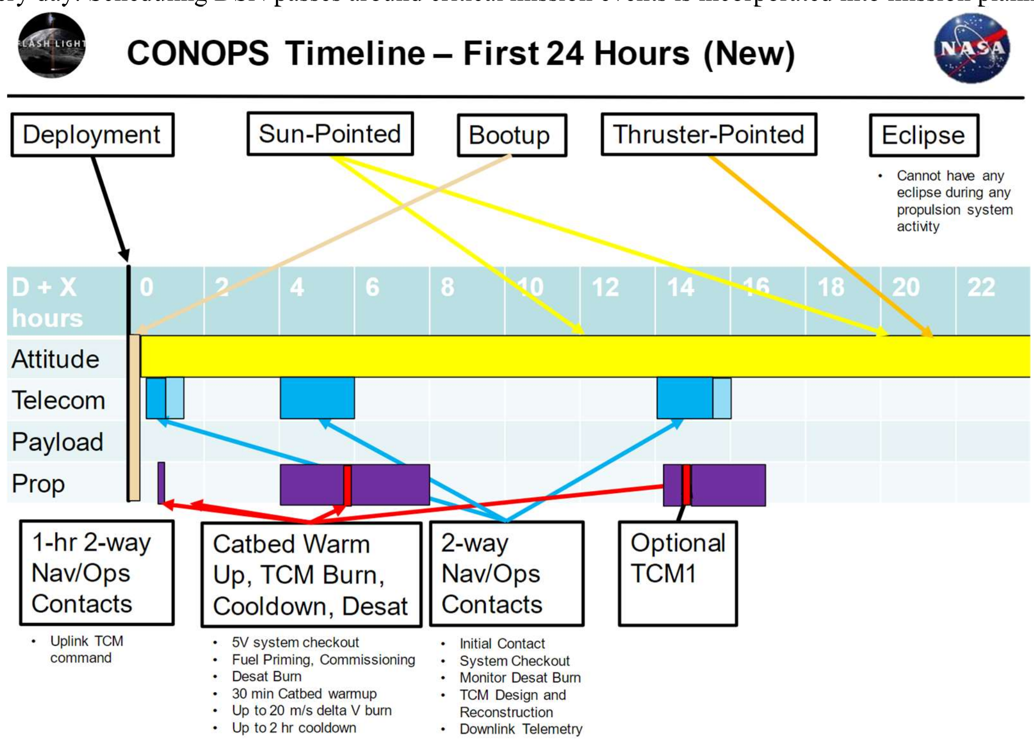

Figure 12. Concept of Operations for the first 24 hours of operations

During the mission planning phase, activities are planned for each contact. This includes sequences to be uploaded, TLM to downlink, and important mission events. This plan is then outlined in the MET with timestamps as seen in Figure 13. The MET will also include important activities which occur between contacts including data product deliveries, mission planning meetings, and data analysis. For the ORT, the flight version of the MET is modified to include ORT specific activities including setting up the testbed. The MET is used as a reference to develop procedures for each operator role. The mission planner will be following this document closely during the test.

Time from Deployment	Action	Description	Team	Notes
D+40 hrs	Start of Contact 6 Pre TCM2 Activities			
	Setup	Connect SCLINK to tesbed	S/C Link Engineer	
	Commanding	Send NO_OP_STRING	S/C Link Engineer	Verify contact and generate EVR for SCKLSCET Correction
	Commanding	Cancel Bridge sequence	S/C Link Engineer	
	Commanding	Enable Ranging	S/C Link Engineer	
	Downlink TLM	Downlink recorded TLM	MOS	Telemetry engineer and mission analyst dig deeper
	Downlink TLM	EVR's	MOS	Telemetry engineer and mission analyst dig deeper
	Uplink Sequence	Simulate Bridge Sequence 6-7 uplink time	S/C Link Engineer	Simulate the time it takes to uplink this sequence
	Uplink Sequence	Simulate TCM-2 Sequence uplink time	S/C Link Engineer	Simulate the time it takes to uplink this sequence
	Uplink Sequence	Simulate Bridge Sequence 8-9 uplink time	S/C Link Engineer	Simulate the time it takes to uplink this sequence
	Execute Sequence	Bridge Sequence 6-7	MOS	Bridge Sequence will include Putting IRIS in full duplex near the time of the next contact. All sequence executions have a few extra steps including onboard sequence verification and mission planner signoff
D+42 hrs	End of Contact 6			
	Setup	Disconnect from testbed host	S/C Link Engineer	
	Deliver Product	S/C Attitude File	GT G&C	
	Analysis	Final TCM-2 Design	MDNAV	
D+44 hrs	Deliver Product	MPF Final	MDNAV	
	Analysis	Test TCM-2 On Testbed	MOS	Simulate the time it takes to accomplish this
D+45	Deliver Product	MIF Final	MOS	
D+45	Deliver Product	TCM-2 Sequence	MOS	
D+46	Meeting	TCM-2 Decision	Project	
	Setup	Create final TCM 2 sequence	MOS	
	Uplink Sequence	TCM -2 Sequence	MOS	
	Analysis	NAV Check TCM-2 Design with OPM	MDNAV	
D+48 hrs	Start of Contact 7 (TCM 2)			

Figure 13. Sample Mission Events Timeline from ORT-2

3. *ORT Execution*

ORTs are run in two phases, deconstructed and real time. Initially, the operations team will perform a deconstructed version of the ORT. The test is split over multiple days with one contact performed each day. Time between contacts is not simulated. External teams such as MDNAV are not required to participate either. The testbed is powered off at the end of each run, and setup again the next day. The deconstructed run is used as a trial run for the operations team. They can verify procedures, test out hardware/networking connections, and test out software tools. Fixing minor bugs in the system as a result of this test will prevent disruptions to the simulation during the real time ORT. During the deconstructed run it is more important to test out all the planned activities than to adhere to time limits. Contacts can run longer than scheduled to finish the planned events. Results of this test might require changes to procedures, updates to tools, or even larger updates to mission planning.

The real time ORT will accurately simulate contact timing according to the MET. Once the test begins, the testbed is powered on and remains running until the end of the test. All external teams in the MOS will also participate to the extent they would during real operations. It is important to note that during the test, the operations team (SLE, Mission planner, Mission analyst, and TLM engineer) only receive the data stream of TLM and EVRs during the contact period. As soon as the contact period ends, port forwarding is disabled, and the data flow ends. Results of activities run at the end of a contact (i.e. TCMs) can only be viewed when the next contact starts. The operators are prevented from viewing the state of the testbed between contacts. Table 4 lists out all the major differences between the two types of tests.

Table 4. Differences between Deconstructed and Real Time ORT

Deconstructed ORT	Real Time ORT
Testbed Powered off between contacts	Testbed will run continuously for duration of the test
Frequent updates to onboard clock (SCLK)	Requires only initial update to the SCLK
New RDP setup script required for each contact	Only one RDP Setup Script is used
Time between contacts is extended	Flight like time between contacts
TCM review meeting not held	TCM review meeting held
JPL Monitoring not required; propulsion team Go/No Go not required	Requires JPL monitoring for prop activities and Go/No Go events

C. ORT-1: LEOP → TCM 1

The first ORT simulated initial deployment of the spacecraft up to the TCM-1 maneuver. This is the first 33 hours of the mission (D+0 to D+33). During this period there are 5 DSN contacts planned. The breakdown of the contacts can be seen in Table 5.

Table 5. ORT-1 Contact Breakdown

Contact	Time	Duration	Major Event
Deployment	D+0 hrs – D+0.5 hrs	30 minutes	Detumble, Initial SMS
Contact 1	D+0.5 hrs – D+1.5 hrs	1 hour	Subsystem Checkout
Contact 2	D+4 hrs – D+6 hrs	2 hours	Initial Prop Activities
Contact 3	D+14 hrs – D+16 hrs	2 hours	Backup Contact
Contact 4	D+24 hrs – D+25 hrs	1 hour	TCM-1
Contact 5	D+31 hrs – D+33 hrs	2 hours	TCM-1 Downlink

1. Contact 1: Subsystem Checkout

The focus of Contact 1 is to establish connection with the spacecraft for the first time and verify all subsystems are operating nominally. After deployment, the spacecraft turns on and runs the Initial Safe Mode Sequence (SMS). The spacecraft detumbles and goes to sun point mode. Successful deployment and safe mode sequence execution is verified during the contact. Required early operation sequences are uplinked, including standard safe mode sequence, prop SMS, and initial propulsion sequences. The major activity of this contact is a subsystem checkout where every subsystem is turned on and telemetry is monitored to verify nominal operation.

2. Contact 2: Initial Propulsion Activities

The focus of Contact 2 is to perform initial propulsion activities which include Fuel Priming, Commissioning, and a Desaturation maneuver. This will be the first time the propulsion system is activated. The prop system is checked out and then primed to be ready for the tests. The first test is fuel priming where inert gasses in the the thruster manifold and feed lines (initially filled with gas during integration) are expelled to create a vacuum. Then these lines are filled with propellant to prime the system. The next test is commissioning where the thrusters are fired. Every 10 seconds, the thrusters pulse for 50 milliseconds to verify proper functioning of the prop system. Lastly, a desaturation maneuver is performed to relieve momentum buildup in the reaction wheels caused by the detumble maneuver executed during deployment.

3. Contact 3: Backup Contact and Ranging

Contact 3 is primarily used as a back up contact in case any of the propulsion activities from Contact 2 are not completed. Given the number of activities planned in Contact 2, it is possible any anomalies during the contact might push some of the activities to Contact 3. Ranging mode will also be enabled on the IRIS radio to collect ranging data needed for MDNAV to improve their orbit determination.

4. Contact 4: TCM-1

During Contact 4, the TCM-1 maneuver is performed. The propulsion system is checked out, configured, and heated to prepare it for the maneuver. The whole project team is polled for a Go No-go decision before the sequence is executed. Once the sequence executes, due to power limitations, the IRIS radio is turned off which severs the communications link with the MOC, ending the contact.

5. Contact 5: TCM-1 Downlink

The objective of Contact 5 is to downlink the recorded telemetry from TCM-1 and enable IRIS ranging mode for orbit determination. The maneuver can be reconstructed, and its success is evaluated during this contact.

6. ORT -1 Test Results

ORT-1 was the first opportunity to test procedures, scripts, and tools that have been in development. During the deconstructed ORT there were multiple anomalies and matters to address. Much of the tooling was either in complete or in developmental stages which meant operations processes were manual and slow. This included telemetry checks, telemetry downlink, generating setup scripts for the RDP, and generating data products. Another issue was a lack of a sequence and procedure review before the ORT. Due to this oversight, there were multiple mistakes in the procedures, some of which led to anomalies on the spacecraft. Errors in sequences also triggered faults on the spacecraft which caused it to enter safe mode. A lack of sequence version control and uplink control meant older versions of some sequences were uploaded, leading to further faults. Another large issue arose with downlink speeds. Large volumes of telemetry data would be recorded between contacts to downlink. Limitations with UART downlink speeds meant not all telemetry channels were downlinked within a single contact. They would have to be downlinked in later contacts.

During the real time ORT, some of these problems were addressed. New tools made processes like generating setup scripts and downlinking telemetry more automated. Procedures were updated to reflect redlines, and a review was held one week in advance to go over sequences and procedures. However, new holes in the system were discovered during this ORT. A major procedural fault occurred during Contact 2 where the prop safe mode sequence needed to be truncated before being uplinked to the testbed. Instead of going through the process of rewriting the sequence and recompiling a binary file, the raw binary sequence was edited to save time. This caused the deletion of important footer bytes which invalidated the sequence. The sequence had to then be modified again the correct way which wasted a significant amount of time.

Sequence uplink on the testbed is done over a UART connection with limited data rate. Because of this, large sequences take much longer to upload compared to a flight like scenario. In flight uplink is done over RF which has a faster data rate. During Contact 2, the busiest contact, multiple large prop sequences were uplinked, which took longer than anticipated. In the end only, the fuel priming test was completed. Commissioning and Desaturation 1 were delayed to Contact 3.

There are other testbed idiosyncrasies which led to problems. The RDP connection cable is not firm, and it can sometimes come loose mid test which gives the XACT system invalid references and attitude causing a fault. File downlink was still an issue, however Contact 5 was used to catch up on downlinking all recorded telemetry. There were other minor anomalies including VM crashes. Time would be lost during contacts rebooting the host machine to solve this issue.

7. Lessons Learned from ORT -1

There were many valuable lessons learned from ORT-1. Gaps in the operations system were highlighted which helps the operations team know where more development is required. One area that needs development is automation tools. Alarms in AMPCS can be implemented for telemetry limit checks. AMPCS processes can be used to automatically parse recorded telemetry as it downlinks, allowing the telemetry engineer to verify the system was nominal during periods between contacts. It was also clear that the testing process needed to be improved to make portions of the simulation closer to a flight like scenario. One such process is file uplink. This can be changed by uploading sequences to the testbed prior to the ORT and instead simulating the time it would take to uplink over RF during the test.

Another important discovery from the ORT is that a downlink schedule will be required to track which telemetry channels will be downlinked during each contact. It is not possible to downlink all recorded telemetry APIDS during a single contact. Some contacts are more open for downlink activities than other. Therefore, a tool needs to be developed to track downlink progress and history. Priority schedules for each telemetry APID will be incorporated into mission planning since some packets are more important for certain contacts compared to others. For example, XACT and propulsion telemetry are prioritized for downlink after major propulsion maneuvers. It is also important to factor in when ranging is enabled. Downlink speeds can be reduced up to half the original rate when IRIS is in ranging mode.

Sequence and procedure reviews proved to be extremely valuable. Many mistakes were caught during these reviews which could have led to spacecraft faults if left unnoticed. Accidents were significantly reduced during the real time ORT by having this review a week prior to the test. However, procedures still need updates to include anomaly response (for when VMs crash or the RDP cuts out), and sequence modification procedure. These are all areas of development which will be worked on in the coming months before launch.

VIII. Conclusion

Through the processes and factors listed in this paper, the Georgia Tech Mission Operations team successfully developed the operations system for the Lunar Flashlight CubeSat. While this paper focuses on Lunar Flashlight, the general development process can be applied for any interplanetary CubeSat mission. Certain aspects of the system may differ including the external interfaces, operations software, or mission operator roles. However, the general aspects of the MOS will remain the same. Dataflow, hardware, software, and operators can all be expanded and modified to suit the specific requirements of the mission. Every mission will always require thread tests, documents, and procedures to interface with external parties, and ORTs to test the full system and find problems which require further development. The MOS for Lunar Flashlight has not yet been completed. In the coming months the operations team will further develop operations tools, procedures, and practices. They will test all of these in upcoming ORTs for later mission phases including LOI and science orbits. The results of these ORTs will help them better prepare for live operations. By the end they will be ready to operate the spacecraft when it launches and will become part of the next big phase of space exploration.

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Figure 14. Lunar Flashlight Team with LFL Spacecraft in the back on the clean bench.

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