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# LM LINUSS™ - Lockheed Martin In-space Upgrade Servicing System

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**ABSTRACT**

The LM LINUSS system is a pair of LM 50™ 12U CubeSats – each about the size of a four-slice toaster – designed to demonstrate how small satellites can serve an essential role in sustaining critical space architectures in any orbit. Developed using internal funding, the LM LINUSS system performed multiple demonstrations in Geosynchronous Earth Orbit (GEO). The LM LINUSS mission is to validate essential maneuvering capabilities for Lockheed Martin's (LM) future space upgrade and servicing missions, as well as to showcase miniaturized Space Domain Awareness capabilities. The LM LINUSS mission also demonstrated mature new onboard high-performance processing by Innoflight; low-toxicity propulsion by VACCO; inertial measurement units, machine vision, 3-D printed components and SmartSat™ (transformational on-orbit software upgrade architecture) technologies by LM. Part of Lockheed Martin's LM50 family of smallsats, both LM LINUSS spacecraft – measuring roughly 8x8x12 inches – are the collaborative integration of the company's mission electro-optical payload deck with a next-generation 12U bus from Tyvak Nano-Satellite Systems, a Terran Orbital Company. On orbit performance data from 1Q2023 is presented.

## 1.0 INTRODUCTION

The LM LINUSS mission was launched on USSF-44 on November 1, 2022 and deployed from the LDPE-2 secondary payload system on January 6$^{th}$ and 9$^{th}$ 2023[1]. The LM LINUSS mission is a technology demonstration funded internally by LM, composed of two LM 50™ 12U CubeSats[2]. While on-orbit, the system demonstrated rendezvous and proximity operations (RPO) as conceptually illustrated in Figure 1. The focus of this RPO demonstration campaign was to validate essential maneuvering capabilities for future space upgrade and servicing missions.

The LM LINUSS program was a collaboration between LM, the USG and subcontractor community (see Acknowledgements) made possible by a Cooperative Research and Development Agreement (CRADA).

**Figure 1: Conceptual LM LINUSS RPO[3]**

At its inception in 2017, the LM team embraced a Class D mindset by being enabled to take calculated risks and invest in low TRL technologies that were key to enabling the mission. As a collaboration of multiple small satellite companies, responsibilities were setup that enabled best-of-breed technologies. Terran was responsible for providing the redundant Avionics, Electrical Power Systems (EPS), Star Trackers, Reaction Wheels, and C&DH software, 12U CubeSat dispensers,[4] and overall integration of the space vehicle. VACCO provided a micro-propulsion system. Innoflight provided a radio and on-board processor. LM provided the RPO imaging suite, the vision processing unit, LM50 inertial measurement unit (IMU), Guidance Navigation and Control (GNC) software, computer vision (CV) software, avionics simulation in the loop (ASIL) environments, and operations. Together, the first generation LM50-LM LINUSS platform was created that enables >20 m/s of delta-V, 6-DOF concurrent attitude and trajectory control, an imaging suite capable of far-field acquisition (>500 km) through proximity operations, and closed loop GNC utilized as a steppingstone for future space servicing missions.[5]

During the demonstration, one of the LM LINUSS CubeSats acted as the designated servicing vehicle, navigating towards the second CubeSat, which represented the resident space object (RSO). As the mock servicing vehicle approached the RSO, on-board guidance algorithms made final real-time adjustments to complete its rendezvous operations. Its culminating success was declared when the CubeSats maneuvered in a proximity of one another that demonstrated high confidence in conducting future on-orbit servicing missions for customers.[3]

In addition to an RPO campaign in support of future space upgrades, the 12U CubeSats also accomplished additional technology demonstrations while on-orbit:

- Performed RPO missions with increasing amounts of autonomy.
- Leveraged LM's Horizon™ 2.0 command and control (C2) software and advanced RPO mission planning software.[6]
- Implemented a secure cloud-based architecture for mission telemetry, tracking and control, linked to the Swedish Space Corporation worldwide infrastructure of ground entry points (GEPs).[7]
- Showcased the company's advanced SmartSat™ software.[8]

The spacecraft pushed the limits of bus density, payload accommodation and on-orbit processing for the CubeSat community, enabling revolutionary mission capabilities in the future.[9] Part of Lockheed Martin's LM50 smallsat family, the LM LINUSS program was a collaborative integration of the company's mission electro-optical payload deck with a next-generation bus from Terran Orbital Corporation. The LM LINUSS mission and other LM pathfinders are helping create a more sustainable future, safely adding mission life and more.

### *Paper Outline*

This paper discusses the LM LINUSS mission, within the context of mission lessons learned (2.0), overview of LM50-LM LINUSS (3.0), and our roadmap of docking adapters for future demonstrations (4.0). We conclude with a short discussion of our RPO testbed dubbed the Space Operations and Simulation Center (SOSC) (5.0).

## 2.0 MISSION SUCCESSES AND LESSONS LEARNED

The LM LINUSS mission accelerated the learning curve for the LM team and our technology partners. Striving for and operating through the GEO space environment provided an incredibly challenging learning laboratory.

### *Overall Success*

The day that SV1 was dispensed was a culmination of years of hardware work by a team of dedicated engineers. Many of the developers were also designated as the operators, which would prove valuable as mission challenges required creative CONOPs and on-orbit software mitigations. Within minutes of being dispensed, the end-to-end communication system worked as designed, enabling critical commands to be sent to the vehicle for safe recovery. Subsequent days of checkout and calibration demonstrated a healthy vehicle with all components demonstrating its functionality (excepting a star tracker PPS). Three days later, the second vehicle was dispensed. The well-rehearsed ops team was able to recover the vehicle and upload a new GNC application within four hours, with complete checkout and commissioning happening within the subsequent two days. The team continued with operating two vehicles in a ping-pong type cadence as additional imager alignments and far-field acquisition operations began. The team also captured images of the Earth to demonstrate the ability to complete celestial alignments as illustrated in Figure 2.

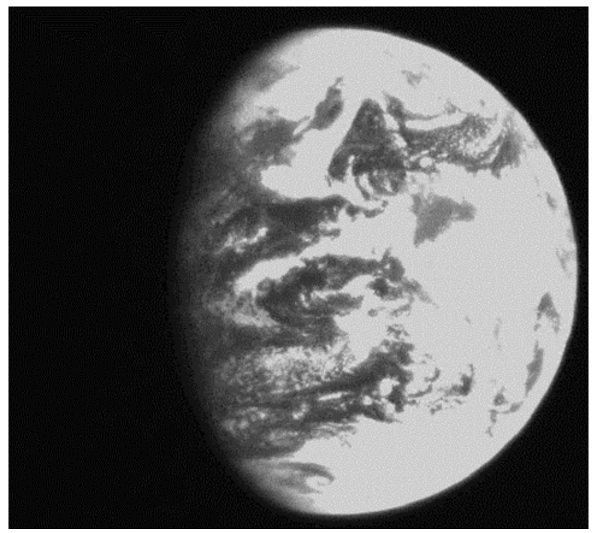

**Figure 2: WFOV Earth Image**

### *Demonstrated Hardware Capabilities*

Achieving Technology Readiness Level 9 (TRL9) for the inaugural 12U hardware baseline was an important consideration, but was in reality a means to an end for demonstrating overall mission capability. The pair of 12U LM LINUSS vehicles successfully demonstrated and operated for five months at the time of writing. As discussed, the LM LINUSS system was designed for a Class-D mission assurance level for one year of operations, with a predicted reliability as shown in Table 1. Future LM LINUSS systems have already been upgraded to a Class-C mission assurance level with a three-to-five-year qualified mission life requirements.

### *Demonstrated GNC Capabilities*

In support of future on-orbit upgrade and servicing missions, the LM Guidance, Navigation and Control (GNC) Software within a common LM enterprise framework was rigorously tested, including multiple rapid on-orbit GNC software updates (in one case within four hours of deployment on SV2). The vehicle included

LM's CoreSim based suite of inertial navigation, attitude guidance, and attitude control capabilities. Additionally, it included a relative navigation filter that could ingest both 2-DOF bearing measurements and 3-DOF (including range) measurements from computer vision. Hills Guidance was utilized to autonomously compute onboard the trajectory waypoint burns to maintain mission planned forced motion circumnavigations (FMCs). Unexpected thermal challenges on the vehicle resulted in the creative use of attitude guidance modes to ensure that only certain space vehicle panels would see solar flux. Additionally, the flexibility of the onboard optimal jet selection was utilized to mitigate plenum pressure leaks through unique turn-and-burn sequences.

**Table 1: System Reliability by Month**

| Months | 1-Vehicle | 2-Vehciles |
|---|---|---|
| 1 | 0.929 | 0.995 |
| 2 | 0.860 | 0.980 |
| 3 | 0.792 | 0.957 |
| 4 | 0.726 | 0.925 |
| 5 | 0.663 | 0.886 |
| 6 | 0.603 | 0.842 |
| 7 | 0.546 | 0.794 |
| 8 | 0.493 | 0.743 |
| 9 | 0.443 | 0.690 |
| 10 | 0.397 | 0.637 |
| 11 | 0.355 | 0.584 |
| 12 | 0.317 | 0.533 |

### *Demonstrated Ground Capabilities*

Most fundamentally, robust ground operations, using the Horizon 2.0 (H20) Cloud-based Telemetry, Tracking and Control (TT&C) software, coupled with LM's RPO planning toolsets, showed to be extremely reliable and deterministic throughout the mission. As mentioned previously, the Swedish Space Corporation GEP Integration with secure websocket interface to LM's cloud was demonstrated. Most importantly, the LM and SSC ground infrastructures facilitated concurrent operations of two LM50 vehicles with single operational crew.

Additionally, inertial OD based on RF Ranging was successfully demonstrated. Our RPO planning software successfully supported planning and mission constraint checks, attitude profiles, inertial burns, phasing burns, and terminal guidance planning and execution.

### *Demonstrated Computer Vision (CV)*

LM's CV system, powered by an onboard high-performance vision processing system, enabled the demonstration of multiple capabilities, including GEO image collection, unresolved centroid collections, and stellar calibration of a multi-visible imager suite. The LM LINUSS platform imager suite supports mission demands from far field acquisition through proximity operations for future space servicing capabilities. This includes both 3-DOF measurement generation utilizing stereo centroiding, spare stereo, and stadiometric-based measurements, as well as full 6-DOF pose measurement generation.

During far field acquisition, unresolved centroids are downlinked to the ground. A ground relative navigation filter not only estimates inertial positions based on RF ranging measurements but utilizes this bearing measurement for additional crosstrack observability to help solve for the initial relative state utilized by the onboard relnav filter. The ground tool can complete additional processing such as stellar correction and rejection, track formulation from non-inertial RSOs, and correlation to objects available in the satellite catalog. This helps to ensure that proper identification is made in congested regions of the GEO belt.

### *Operational Lessons Learned*

LM worked closely with our USG stakeholders to prioritize safety of flight for commercial space upgrade and servicing operations. As stated in the CRADA, the USG reserved the right to approve all LM LINUSS operational plans prior to implementation, with a focus on ensuring safety of flight and avoiding situations that would violate RPO and/or other USG policy. LM also worked with NOAA and the FCC to get licensing approvals for limited imaging (could only collect resolved imagery of the other LM LINUSS vehicle and the Earth) and RF frequency approvals. We also had to coordinate in advance an end-of-life mission execution plan for safe and responsible disposal.

Although LM developed multiple hardware-in-the-loop (HWIL) simulation capability (including avionics and scene generation) and used the SOSC extensively, these were not developed early enough to be fully leveraged with more lengthy rehearsals. Funding and people resource constraints constantly had to be traded before, during and after the launch campaign, leading to learning lessons post-deployment that should have been discovered and resolved before launch.

During operations, maintaining inertial and relative state knowledge, "blob wrangling," centroid collects, continuous thermal management, management of propulsion leaks, getting consistent star tracker measurements, and replanning coming out of comm blackouts presented continual challenges. Operational workarounds were developed for many situations.

Other real-world considerations, such as competing for GEP resources, limited comm windows, unexpected thermal constraints, measurement limitations impacting converged filter states, eclipse season, and staff burnout, had to be constantly managed by the leadership team to ensure success of the demonstration.

## 3.0 LM50-LM LINUSS OVERVIEW

The LM LINUSS mission provided the first demo of the LM50-LM LINUSS class of satellites. Drawing on LM's extensive experience working RPO spacecraft, including Orion and OSIRIS-REX, the LM50-LM LINUSS platform provides a tailorable form factor architecture for performing space servicing missions in multiple orbits. One of the keys to the LM LINUSS mission success was the tight integration of all spacecraft subsystems and an extensive simulation environment.

Carried on in the LM50-LM LINUSS platform architecture shown in Figure 3, the LM LINUSS spacecraft were designed from the ground up as tightly integrated systems. This was necessary to ensure proper performance during high precision RPO measurements and maneuvers. It was especially important to tightly integrate the RPOD GNC flight software with low-level bus functions to minimize latency within the system. This integration was key to both on-ground simulation and on-orbit mission execution. The tight integration of the spacecraft required multiple levels of interfaces and requirements to be collaborated on by all organizations on the LM LINUSS mission team. This systems engineering provides a foundation for applying core LM50-LM LINUSS technologies to multiple bus sizes to enable a wide variety of satellite servicing missions.

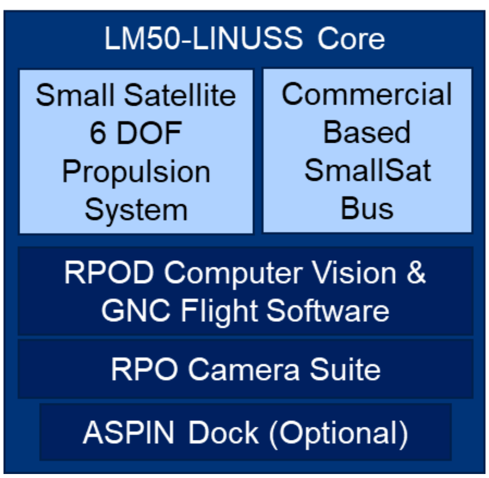


**Figure 3: Architecture block diagram of LM50-LM LINUSS core showing necessary integration of both RPO camera suite and flight software to ensure success of highly dependent subsystems.**

To accomplish the LM LINUSS mission, and future space servicing objectives, LM has developed a high fidelity, faster than real-time simulation, for the purposes of Monte Carlo simulations to perform verification by analysis of the integrated LM50-LM LINUSS platform. The same simulation truth models, inclusive of environments and hardware models, is ported to a real-time environment called the Avionics Simulation in the Loop (ASIL). This affordable environment utilizes an EDU set of avionics with the simulator providing flight equivalent (RS-422) interfaces to the Terran Orbital C&DH and GNC software. Concurrently, a scene generation system (SGS), anchored in on-orbit and SOSC based image collects, renders image-realistic scenes that emulate the images received by the vision processor. This digital twin capability has proven valuable for formal software qualification as well as for operational rehearsals prior to flight.

## 4.0 ASPIN FAMILY OF DOCKING ADAPTERS

Although the LM LINUSS system did not include any on-orbit docking port technology for the first demonstration, LM released an open-source, non-proprietary interface standard to support on-orbit docking in 2022[10]. The Mission Augmentation Port (MAP)[11] interface standard supports industry application to on-orbit servicing and mission augmentation. The MAP standard provides a mechanical interface design for docking spacecraft to one another. Equipping satellites with docking adapters offers a novel way to add new mission capabilities to a platform after launch. LM's own Augmentation System Port Interface (ASPIN) is designed to be compliant with the MAP standard. The ASPIN adapter provides electrical and data interface between a host spacecraft and a satellite augmentation vehicle (SAV). With this technology, it is now possible to upgrade operational spacecraft at the speed of technology and provide built-in servicing infrastructure for spacecraft on orbit.

Future LM LINUSS demonstrations will demonstrate on-orbit docking and upgrades. For the small satellite (CubeSat) community, ASPIN-C was developed and completed a docking demonstration on the ground in the SOSC in Q1 2023, at the very same time that the LM LINUSS system was completing its demonstration on orbit. Previously, ASPIN-A was demonstrated Q1 2022. The MAP-C open source standard will be published Q3 2023.[10]

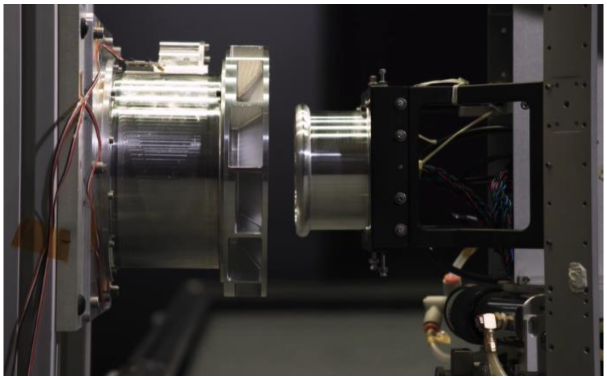

**Figure 4: ASPIN-C Docking Demo in the SOSC**

Similar to the way we can now update missions on orbit using SmartSat™ to push software updates or load new apps, LM recognizes the need to reconfigure hardware capabilities to meet evolving mission needs. That is where standards for docking come in: standardized docking interfaces allow satellite operators to unlock a new type of mission upgrades.[10]

Unlike previous space missions where cutting-edge technology begins to lose relevance immediately after launch, future missions will be able to be upgraded via on-orbit hardware and software upgrades. What LM is envisioning goes beyond "filling up the tank" to extend mission life. The company believes its work will add real mission capability in a sustainable, cost-effective way. [10]

## 5.0 SPACE OPERATIONS AND SIMULATION CENTER

The SOSC at the LM Waterton Campus in Littleton, Colorado is a dynamic test environment focused on Autonomous Rendezvous and Docking (AR&D) development testing and risk reduction activities. As mentioned previously, the SOSC was used extensively for developing the LM LINUSS system and ASPIN, and is available to the RPO R&D community upon request.[12]

The SOSC supports multiple program pursuits and accommodates testing Guidance, Navigation, and Control (GN&C) algorithms for relative navigation, hardware testing and characterization, as well as software and test process development. The SOSC consists of a high bay (60 meters long by 15.2 meters wide by 15.2 meters tall) with dual six degree-of-freedom (6-DOF) motion simulators and a single fixed base 6-DOF robot. The large testing area (maximum sensor-to-target effective range of 60 meters) allows for large-scale, flight-like simulations of proximity maneuvers and docking events. The facility also has two apertures for access to external extended-range outdoor target test operations. In addition, the facility contains four Mission Operations Centers (MOCs) with connectivity to dual high bay control rooms and a data/video interface room. The high bay is rated at Class 300,000 (0.5 m maximum particles/$m^3$) cleanliness and includes orbital lighting simulation capabilities.[12]


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## 6.0 SUMMARY AND CONCUSIONS

The LM LINUSS program was a successful demonstration of the key GNC and hardware capabilities required for future on-orbit docking demonstrations for the purpose of platform upgrades and servicing. We are developing our next on orbit demonstration and applying the lessons learned from this first mission. LM and the RPO community are continuing to develop safe and responsible behaviors for a future where on-orbit upgrades and servicing will be commonplace, within an ecosystem that will actively manage space debris as well.

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