Moonraker: De-Risking Lunar Landing Sites with High Resolution LiDAR

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Abstract—With renewed international interest in returning humanity to the Moon, safely landing robotic and crewed landers on the rough lunar surface has become a critical challenge. Hazards such as boulders, small craters, and steep slopes can easily compromise a lander, yet are unresolvable in current elevation maps. The Moonraker mission addresses this gap by deploying a mapping LiDAR instrument aboard a small satellite in a 50 km polar lunar orbit. The payload will operate in two modes: a wide-area 1X mode which will produce 4 m ground sample distance (GSD) topographic maps of both polar regions, and a high-resolution 13.33X mode which will deliver 0.3 m GSD scans of candidate landing sites. Moonraker's LiDAR data products will also be used for a variety of other scientific and exploration purposes, such as identifying deposits of water ice, measuring surface roughness, and studying surface features such as ancient volcanoes and impact craters. The spacecraft is built on SFL's DAUNTLESS-L platform, a heritage-based bus adapted for the demanding lunar environment. A Ka-band high-gain antenna (HGA) enables direct data downlink to KSAT's Lunar Network at up to 200 Mbps. Moonraker is about to begin a Phase A study funded by the European Space Agency (ESA) within the Small Missions for Exploration initiative. This paper describes the mission architecture, technology, and current development status of the Moonraker mission.

Keywords—small satellite, Moon, lunar, ESA, LiDAR, topography, mapping, de-risk, landing site, exploration.

1. INTRODUCTION

The resurgence of international lunar exploration, driven in large part by NASA's Artemis programme and the Commercial Lunar Payload Services (CLPS) initiative, has created an urgent need for high-resolution topographic data of the lunar surface. The lunar South Pole is of particular interest: it hosts permanently shadowed regions (PSRs) believed to contain water ice deposits, and long-duration sunlit ridges suitable for solar power generation. Yet this terrain is also among the most rugged on the Moon, presenting severe hazards to any lander.

Today's best topographic data comes from NASA's Lunar Reconnaissance Orbiter (LRO), which carries the Lunar Orbiter Laser Altimeter (LOLA) instrument. While LOLA has been transformative in our understanding of lunar topography, its digital elevation models (DEMs) of the polar regions have resolutions of approximately 20 m/pixel, and many grid cells are interpolated from single data points [1]. This is insufficient to reliably identify and de-risk landing sites, where small boulders, craters, and slopes could cause a lander to tip over, as occurred with Intuitive Machines' Odysseus and Athena landers, as well as JAXA's SLIM lander [2,3].

The Moonraker mission is designed to close this gap. It will deploy a high-performance mapping LiDAR from a small satellite in a lunar polar orbit, generating DEMs of the polar regions at 4 m GSD for wide-area coverage and 0.3 m GSD for individual landing site characterisation. Moonraker is about to begin a Phase A study funded by the European Space Agency (ESA) within the Small Missions for Exploration initiative, following its selection under the "Destination the Moon" call. The Moonraker consortium consists of six partner organisations: NUVIEW GmbH (prime, LiDAR payload), SFL Missions Inc. (spacecraft bus and system integration), Lunar Outpost EU (payload thermal control and MBSE), DLR Institute of Planetary Research (data processing and DEM generation), AEM Antennas Inc. (High Gain Antenna, or HGA), and KSAT (ground station network).

2. SCIENTIFIC RATIONALE

The primary mission objective is to support safe exploration of the Moon by providing the highest-resolution topographic maps of the lunar polar regions to date. Beyond exploration, however, the dataset will enable a broad range of scientific investigations, including the characterisation of PSRs and their potential volatile deposits (including water ice) [4], the study of illumination conditions for energy harvesting in permanently sun-lit locations [5], and the investigation of surface roughness as a proxy for space weathering and ice stability [6,7].

Moonraker's altimetry will also contribute to planetary geodesy. The high-density point cloud, accumulated over the mission lifetime, will refine the lunar rotational axis orientation, constrain libration amplitudes, and potentially detect tidal deformation of the lunar surface on the 27-day cycle. These measurements bear on the rheology of the lunar interior and the long-term evolution of the Earth–Moon system. At the geologic level, the data will support studies of impact cratering rates, crustal deformation, mass-wasting dynamics, and regolith evolution. In summary, Moonraker will provide a uniquely capable dataset for both human exploration support and fundamental lunar science.

3. MISSION OVERVIEW

3.1 Orbit and Transfer

Moonraker will be launched into a direct lunar transfer trajectory, reaching the Moon after an approximate 5-day transit. A lunar orbit insertion (LOI) manoeuvre of will capture the spacecraft into a highly elliptical polar orbit (perilune 200 km, apolune 8600 km), followed by a sequence of five perilune lowering manoeuvres to achieve the nominal science orbit. Before reaching the science orbit, Moonraker will pause in a

140×50 km quasi-frozen orbit to undergo payload commissioning without the pressure of frequent orbit correction maneuvers.

The nominal science orbit is a near-circular, 50 km altitude polar orbit at approximately 90° inclination. This inclination enables the poles to be imaged directly, while this altitude balances LiDAR link margin against ground track density and orbital perturbation magnitude. The lunar gravity field produces altitude variations of up to ±25 km from the nominal. Station-keeping manoeuvres are therefore performed every sidereal period (≈27.3 days) using the monopropellant primary thruster system. The total delta-V budget is 1453 m/s, accommodating LOI, orbit lowering, station-keeping over the mission lifetime, and de-orbit at end of mission. De-orbit requires only 12 m/s from the 50 km operational orbit; the impact location will be selected to avoid scientifically sensitive regions.

3.2 Ground Segment

The Moonraker ground segment architecture is shown in Fig. 1. Target requests from the user community are filtered and prioritised by DLR's science team, who forward a fixed number of monthly requests to NUVIEW's Payload Control Center (PCC). The PCC computes daily payload command sequences for both LiDAR zoom levels, which are forwarded to SFL's Mission Control Center (MCC). The MCC combines payload commands with spacecraft telecommands and routes them through KSAT's Network Operations Center (NOC) for uplink via KSAT's Lunar Network. The Lunar Network comprises three 20-metre antennas located in Australia, Spain, and the Western USA, providing continuous 24-hour lunar coverage.

Payload data and spacecraft telemetry are downlinked through the same KSAT ground stations. Ranging and Doppler measurements taken during contact windows keep the onboard clock synchronised with UTC. The MCC processes spacecraft telemetry and provides spacecraft state information to the PCC, where it is fused with raw LiDAR measurements during pre-processing to associate precise position and attitude data with each altimetry point. The pre-processed data is forwarded to DLR's Data Processing Center (DPC) for conversion into 1X and 13.33X zoom DEMs. Finished products will be released to ESA for public distribution, while NUVIEW's commercial platform will offer enhanced versions with additional analytics.

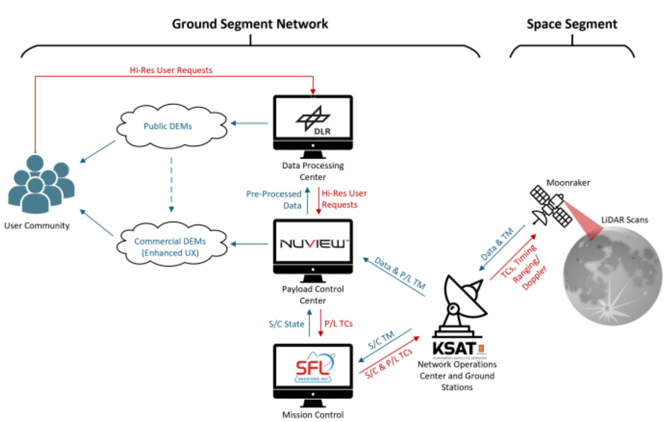

Fig. 1 – Moonraker System Architecture

3.3 Mission Timeline

With a baseline launch date of Q2 2030, Moonraker will complete payload commissioning within the first weeks of lunar orbit operations. Wide-area polar mapping (60°N–90°N and 60°S–90°S) at 4 m GSD can be completed within the first year at a nominal 30% payload duty cycle. With a planned three-year mission lifetime, there is substantial margin for contingencies, repeat coverage, and extended mapping beyond the polar regions.

Once the main mission objectives are satisfied, Moonraker could be moved into a quasi-frozen orbit for extended mission operations. This would help to ration the remaining propellant, enabling Moonraker to continue to map more of the lunar surface—and de-risk more future landing sites—well beyond the planned 3 year mission duration.

4. LIDAR PAYLOAD

4.1 Payload Architecture

The Moonraker LiDAR is a bespoke mapping instrument developed by NUVIEW GmbH. It uses a pulsed near-infrared (≈1 µm) tapered-gain fibre laser to illuminate the lunar surface and measure the round-trip time of individual photon returns, building up a three-dimensional point cloud that is post-processed into DEMs. The instrument operates in two distinct zoom modes, selectable in flight, which differ in beam divergence, telescope aperture, and scanning geometry. Key payload parameters are summarised in Table 1.

TABLE 1. MOONRAKER LIDAR PAYLOAD METRICS AND DESIGN PARAMETERS

PARAMETER	VALUE
Mass	90.5 kg
Average Power	241.9 W
Peak Power	482 W
Duty Cycle per Orbit	30%
1X Data Generation Rate (compressed)	21.7 Mbps
Data Generated per Orbit (compressed)	5.1 GB
Onboard Data Storage	256 GB
Range Accuracy	≤ 1 m
Vertical Precision	≤ 5 cm
1X Zoom Cell Size	4 m
13.33X Zoom Cell Size	0.3 m
Points per Cell	2
1X Zoom Swath Width × Length (max)	1 × 3275 km
13.33X Zoom Tile Size	425 × 425 m

4.2 Laser and Transmitter

The fibre laser delivers a pulse repetition frequency (PRF) of 26–360 kHz, a pulse duration of 0.25–2 ns, and an average optical output power of 1–52 W (nominal 28 W). All laser parameters are adjustable via telecommand, allowing in-flight optimisation of range precision, data rate, and thermal load depending on the scan mode in use.

Transmitter optics consist of a refractive beam expander that sets the beam divergence to achieve the desired footprint size on the lunar surface. A fast-scanning mirror (FSM) controls the lateral position of the transmitted beam. A selectable diffractive optical element (DOE) switches the transmit system between the 1X and 13.33X zoom modes, adapting the beam divergence and spot size accordingly. A 3rd position on the DOE introduces a calibration mode which transmits fiducial markers onto the lunar surface, enabling operators to calibrate the alignment between the transmit and receive optics.

4.3 Receiver Optics and Detectors

The payload includes two independent receive telescopes—one for each zoom mode. The 1X zoom telescope has a 78 mm aperture, matched to the 4 m GSD requirement at 50 km altitude. The 13.33X zoom telescope has a 300 mm aperture to support the 0.3 m GSD requirement. The 1X telescope uses a refractive optical design, while the 13.33X uses a reflective Cassegrain design. On the 1X zoom optical path, a dichroic beamsplitter separates the incoming photon flux: near-infrared photons are directed to a Geiger-mode avalanche photodiode (GmAPD) camera for ranging, while visible photons are routed to a time-delay integration (TDI) camera to provide co-registered panchromatic context imagery. The 13.33X zoom path leads directly to the GmAPD. A selector mirror enables switching between the 1X and 13.33X light paths. FSMs on both paths actively steer the incoming beam onto the 128×32 pixel GmAPD sensor array, enabling whisk-broom scan patterns which increase the LiDAR swath on the lunar surface.

A CAD model of the payload is shown in Fig. 2. All optical assemblies are mounted to a stiff optical bench that also carries the spacecraft's inertial measurement unit (IMU) and star trackers. Co-locating these sensors on the optical bench minimises thermo-mechanical misalignment between the navigation sensors and the LiDAR optical axis, which is critical for accurate geo-referencing of the altimetry data.

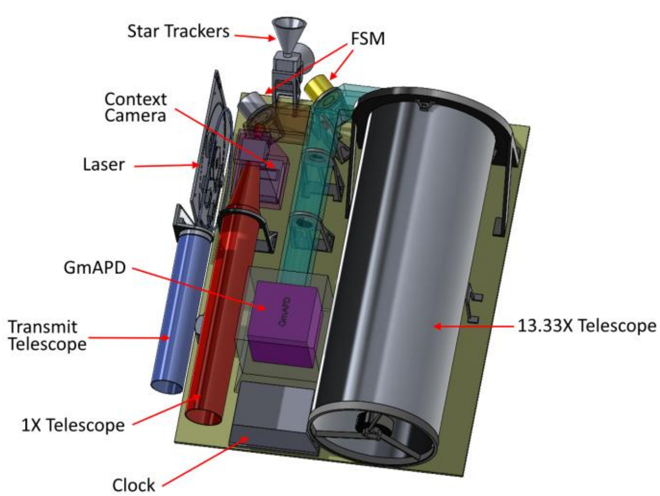

Fig. 2 – Moonraker LiDAR Payload CAD Model

4.4 Payload Thermal Control

Payload thermal management is handled by Lunar Outpost EU using a zonal approach that creates distinct temperature regions for individual components with differing thermal requirements. Three dedicated radiators manage heat rejection: a cold radiator for the GmAPD detector, a dedicated laser radiator, and a main radiator thermally coupled to the payload enclosure. A 4th radiator is used for the platform avionics. A phase-change material (PCM) container is inserted into the laser heat-rejection path to buffer and slowly dissipate the pulsed thermal load from the laser diodes, thermally stabilising critical components and reducing heater power demand during operations. Multi-layer insulation (MLI) surrounds the payload enclosure. Heater lines, commanded by the payload, keep the payload within operational temperature limits during nominal operations. Survival heater lines, commanded by the spacecraft bus, maintain component temperatures within non-operational limits during the lunar transfer and any payload-off periods.

5. 13.33X RECEIVE TELESCOPE RE-DESIGN

5.1 Re-Design Rationale

During the Moonraker Pre-Phase A study, the 13.33X zoom telescope was originally designed as an 8X zoom refractive telescope with a 150 mm aperture and a 5 m effective focal length (EFL). This yielded a 0.5 m GSD for the landing site scans. Between project phases, however, ESA requested a re-design of the optics to support 0.25-0.3 cm GSD landing site scans, based on a landing hazard requirement for their Argonaut lunar lander. A full re-assessment of the zoom optics and a sensitivity analysis of the telescope design on key mission parameters was therefore conducted.

5.2 Telescope Type Trade Study

A structured trade study was used to compare alternative telescope designs with the following optical baseline: 0.25 m GSD imagery, a 250 mm aperture, a 10 m EFL, and an angular resolution of 5 µrad. Three concepts were selected: a refractive design, a reflective Cassegrain design, and an off-axis Three Mirror Anastigmat (TMA) telescope. Critical design criteria were selected and weighted, including (in order of importance) technical risk, mass and volume, Field of Regard (FoR), cost, complexity, compatibility with a context camera, and Rx efficiency.

- The refractive design came in 3rd place with a score of 138/320. It had a good FoR, low alignment complexity, and good Rx efficiency. However, it scored low on all other criteria, with the highest mass and volume of the three.
- The off-axis TMA design came in 2nd place with a score of 166/320. It had low alignment complexity and high Rx efficiency, but scored moderately on most other criteria, and very low on cost and design complexity.
- The Cassegrain design came in 1st with a score of 182/320. It had a low mass and low complexity, and moderate cost, FoR, and Rx efficiency. It was selected as the architecture for the 13.33X zoom telescope.

5.3 Sensitivity Analysis

A sensitivity analysis was conducted to estimate the impact of changing the telescope size on a variety of mission parameters. Two independent variables were adjusted: GSD (which is related to EFL) and the primary aperture (PA) diameter (which itself is tied to the Ensquared Energy, EE, value, a parameter which determines the sharpness of the imagery). Parametric equations were developed to relate these variables to the following mission parameters: telescope mass and volume, telescope price, payload mass, spacecraft wet mass, and launch price (Ariane 6).

Figures 3-6 show the results of this analysis. All curves demonstrate the same characteristic shape, with most change driven by primary aperture size rather than GSD (i.e. EFL). However, there is clearly an inflection point at 0.3 GSD: values below this point result in rapid changes to the mission parameters compared to values above it. This indicates that a GSD of 0.3 is optimal for the Moonraker system. Furthermore, a PA of 0.3 m was selected as it provides the best EE and image quality without exceeding mass, volume, and price constraints (lower PA's, while reducing mission impacts, would result in worse image quality).

The final design of the 13.33X telescope is a reflective Cassegrain with a 300 mm aperture, an EFL of 8.33 m, a GSD of 0.3 m, and an EE of >66%. The system is neither detector-limited nor optics limited at this stage, similar to most Earth Observation optics. This design point is shown by a green diamond in Figures 3-6.

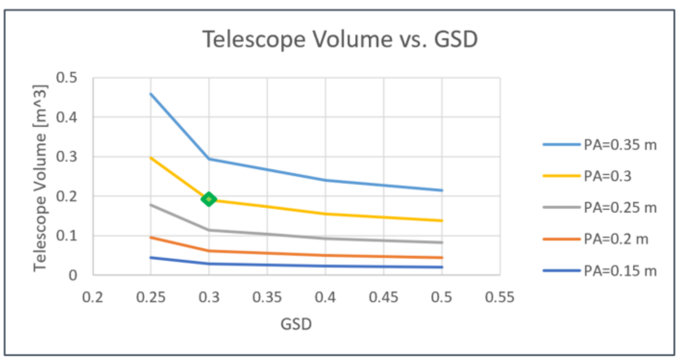

Fig. 3 – Telescope volume vs. GSD

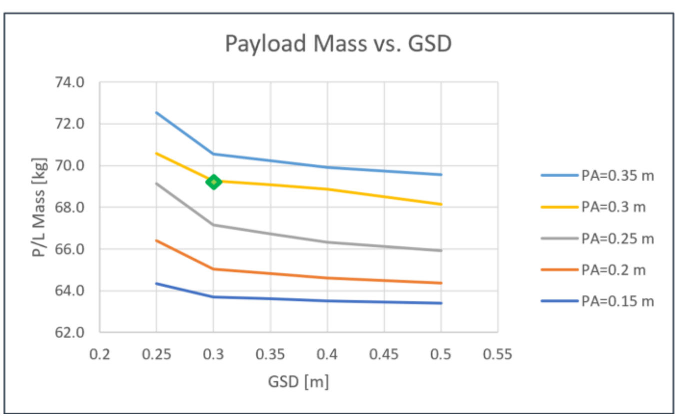

Fig. 4 – Payload Mass vs. GSD

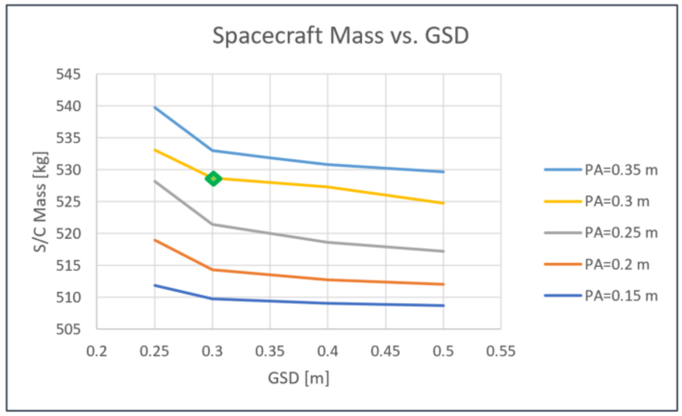

Fig. 5 – Spacecraft Wet Mass vs. GSD

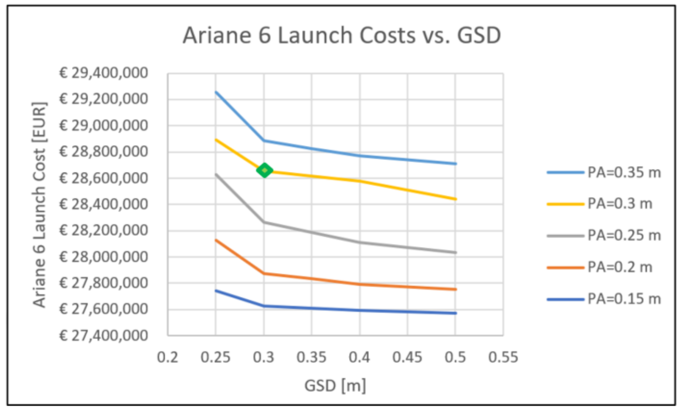

Fig. 6 – Ariane 6 Launch Costs vs. GSD

5.4 Orbit Altitude Sensitivity

Another means of improving the GSD is by lowering the orbital altitude of the spacecraft. The mean altitude of Moonraker was baselined at 50 km (with gravitational perturbations leading to a 25 km perilune and a 75 km apolune prior to each orbit correction maneuver). A second sensitivity analysis was conducted to study the impacts of lowering mean orbital altitude on various mission parameters. The results are shown in Figures 7-10 below. The new 13.33X telescope baseline (0.3 m PA, 8.33 m EFL) was used in all cases.

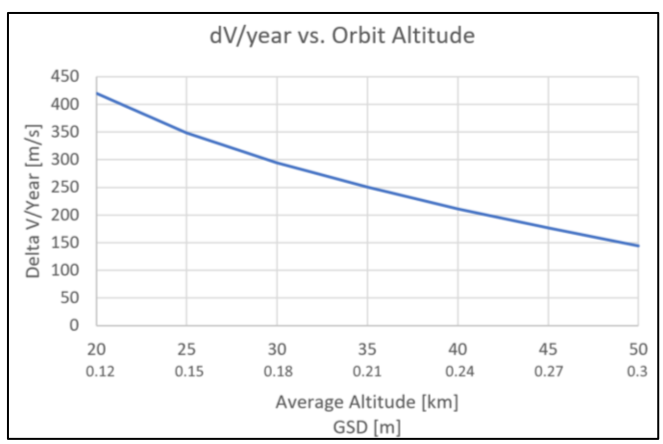

Fig. 7 – dV/Year vs. Orbit Altitude (GSD)

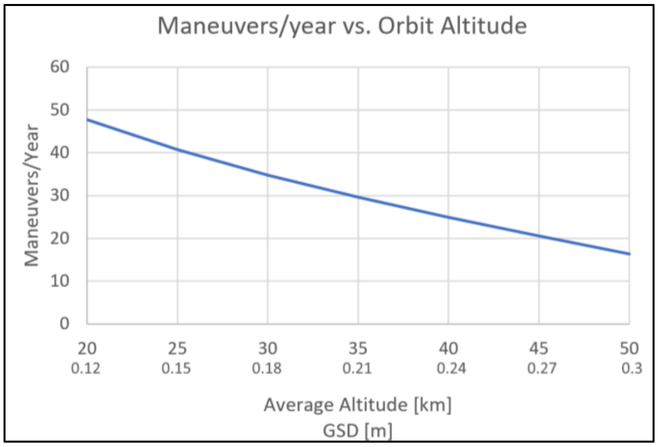

Fig. 8 – Maneuvers/Year vs. Orbit Altitude (GSD)

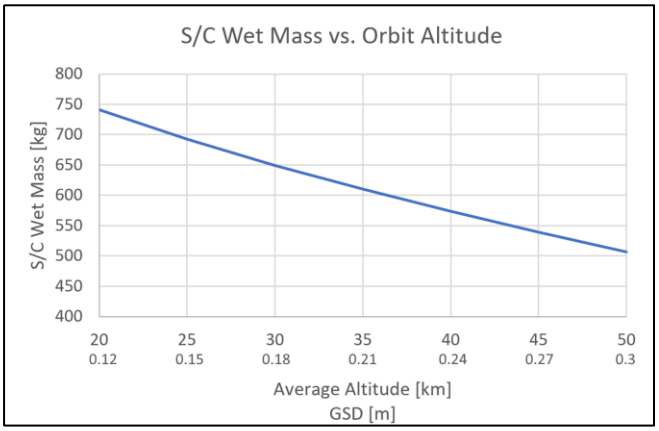

Fig. 9 – Spacecraft Wet Mass vs. Orbit Altitude (GSD)

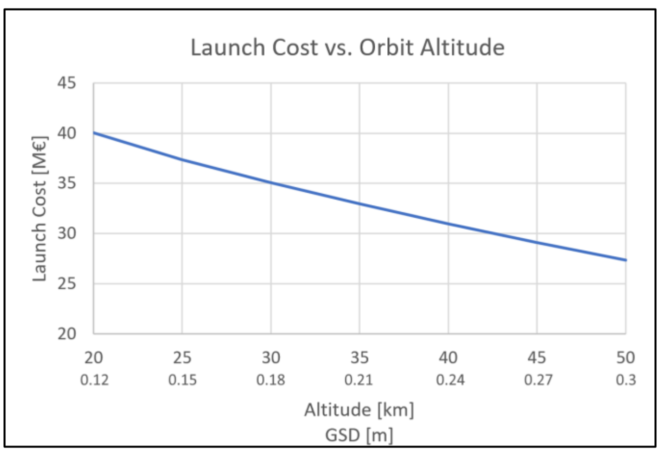

Fig. 10 – Launch Cost (Ariane 6) vs. Orbit Altitude (GSD)

Based on this analysis, to reduce the GSD on the 13.33X telescope from 30 cm to 24 cm via mean altitude adjustments (i.e. moving from 50 km → 40 km), the mission parameters would change as follows:

- dV/Year: 144 m/s → 211 m/s (+46.5%)
- Maneuvers/Year: 16 → 25 (+52.5%)
- S/C Wet Mass: 506 kg → 574 kg (+13.3%)
- Launch Costs (Ariane 6): 27M€ → 31M€ (+13.3%)

6. PAYLOAD OPERATIONS

6.1 Wide-Area 1X Scanning

Wide-area mapping uses the 1X zoom mode in a push-broom configuration, with the spacecraft's orbital motion providing the along-track dimension and the FSM sweeping back-and-forth in the cross-track direction. The swath width is 1 km, and a single pass can capture up to 3275 km in length at 4 m GSD. Adjacent swaths are planned with approximately 10% overlap to support cross-track co-registration. The spacecraft will steer up to 20° off-nadir between orbits to ensure progressive and complete coverage of both polar regions (60°N–90°N and 60°S–90°S). A 30% payload duty cycle (≈34 minutes per orbit) is sufficient to complete the full polar mapping campaign within 1 year of nominal operations.

6.2 High-Resolution 13.33X Scanning

High-resolution landing-site scans use the 13.33X zoom mode in a whisk-broom configuration. The FSM rasters the beam across the target tile during a single orbital pass, producing a 425×425 m tile at 0.3 m GSD without requiring body-steering of the spacecraft. Targets are a combination of sites pre-selected before launch and sites identified from Moonraker's own 1X zoom data during operations. Both zoom modes can be executed within the same orbital pass, allowing efficient use of the 34-minute duty cycle.

6.3 Data Volume and Downlink

The LiDAR generates compressed data at 21.7 Mbps (including a 25% margin); the TDI visible camera adds 2.06 Mbps. Over a single orbit, this produces approximately 5588 MB of 1X zoom data, 15.4 MB of 13.33X zoom data, and 524 MB of visible imagery—roughly 6.1 GB per orbit in total. The Ka-band HGA downlinks at up to 200 Mbps, requiring approximately 56 minutes of ground contact per day to clear the daily data volume. With 256 GB of onboard storage, Moonraker can accumulate up to 41 orbits of data before the storage is full, providing resilience against ground contact gaps.

7. SPACECRAFT

7.1 Platform

Moonraker uses SFL Missions Inc.'s DAUNTLESS-L platform—a lunar adaptation of the flight-proven DAUNTLESS bus. The platform is designed for spacecraft with a total wet mass up to 600 kg and uses a four-point release launch interface. Heritage subsystems are used for command and data handling, power management, navigation, and attitude control, with hardware selection and sizing driven by the specific power, pointing, propulsion, and data-throughput requirements of the Moonraker mission. The spacecraft in its deployed configuration is shown in Fig. 3. Spacecraft performance characteristics are summarised in Table 2.

TABLE 2. MOONRAKER SPACECRAFT PERFORMANCE METRICS

PARAMETER	VALUE
Spacecraft Dry Mass	287 kg
Propellant Mass (Monoprop + Cold Gas)	213 + 6 kg

Spacecraft Wet Mass	506 kg
Stowed Dimensions	1.35 × 1.10 × 1.39 m
Deployed Dimensions	1.35 × 1.10 × 5.49 m
Peak Power Generation (EoL)	697 W
TC&M Uplink / Downlink	Up to 2 Mbps
Payload Data Downlink	Up to 200 Mbps
Attitude Determination (1σ)	7.9 arcsec
Attitude Control (1σ)	9.6 arcsec
Peak Slew Rate	0.4 °/s
Delta-V Budget	1453 m/s
Design Life	5 years

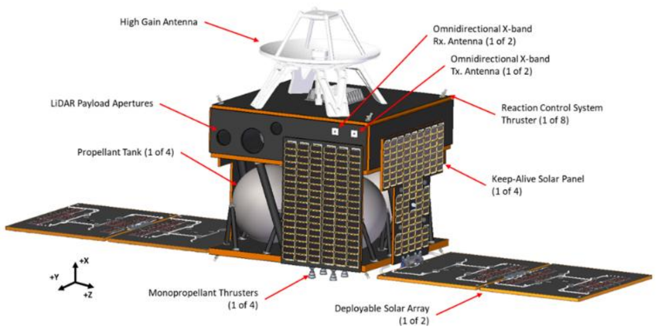

Fig. 11 – Moonraker Spacecraft in Deployed Configuration

7.2 Power

Power is generated by two deployable solar arrays, supplemented by four body-mounted keep-alive panels. End-of-life peak power generation is 697 W. Energy storage is provided by a 49.6 A·h battery pack on a 28 V unregulated bus. The payload's 30% duty cycle and PCM thermal buffer are key design drivers that allow the power system to be sized for average rather than peak load.

7.3 Communications

Telemetry and command operations use an X-band link at up to 2 Mbps (uplink and downlink). High-rate payload data is downlinked on a Ka-band link via AEM Antennas' multi-band Cassegrain HGA. The HGA features a 75 cm parabolic main reflector providing 32 dBi gain at X-band and 43 dBi at Ka-band. A coaxial X-band horn handles uplink and downlink for telemetry, while a concentric smooth-wall horn supports Ka-band data downlink. Circular polarisation is generated using a novel coaxial asymmetric orthomode junction (OMJ), reducing antenna envelope and mass. The compact fixed Cassegrain design minimises the HGA footprint on the spacecraft structure.

7.4 Attitude Determination and Control

The attitude determination subsystem uses two star trackers and six sun sensors, achieving 7.9 arcsec (1σ) attitude knowledge accuracy in the nadir-pointing mode. Control is provided by four reaction wheels, with eight cold-gas RCS thrusters used for momentum dumping and fine attitude manoeuvres. Attitude control accuracy is 9.6 arcsec (1σ). The star trackers and IMU are co-mounted with the payload on the optical bench, directly reducing the uncertainty introduced by structural flexure between the navigation sensors and the LiDAR boresight. Peak slew rate is 0.4°/s, sufficient to perform off-nadir pointing between swaths and to transition between scan modes within a single orbital pass.

8. MODEL-BASED SYSTEMS ENGINEERING

The Moonraker programme employs a model-based systems engineering (MBSE) approach throughout all development phases, managed by Lunar Outpost EU. MBSE serves as the single source of truth for requirements management and for the functional, physical, and logical decomposition of the mission. Following a structured trade-off among five candidate tools evaluated against criteria including tool complexity, consortium collaboration capabilities, and cost, Innoslate was selected as the MBSE platform.

Mission and system requirements were initially captured in a requirements spreadsheet, imported into Innoslate, and systematically decomposed into payload, spacecraft bus, and ground station network requirements. Traceability relationships were added to identify the most influential requirements and provide a structured basis for design decisions. The MBSE model will continue to evolve in parallel with the mission design as the programme progresses into subsequent phases.

9. SUMMARY AND CONCLUSIONS

The Moonraker mission offers a compelling combination of exploration utility and scientific value. By equipping a small satellite with a bespoke dual-mode mapping LiDAR in polar lunar orbit, Moonraker will produce the highest-resolution topographic maps of the lunar polar regions to date—4 m GSD for wide-area coverage and 0.3 m GSD for individual landing sites. These products will directly support the identification and de-risking of landing sites for ESA’s Argonaut lander, and NASA’s Artemis and CLPS missions, while also enabling a broad suite of lunar science investigations.

The mission builds on a heritage spacecraft platform from SFL, a high-performance antenna from AEM Antennas, and KSAT's established Lunar Network, minimising development risk. The LiDAR payload, developed by NUVIEW GmbH, represents a novel instrument optimised for photon-counting altimetry at the high pulse rates required for dense polar mapping. Moonraker is currently beginning a Phase A study under ESA's Small Missions for Exploration initiative.

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