

Moonraker: The Moon with High Resolution LiDAR

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Abstract

With the Artemis missions planning to land astronauts on the lunar South Pole, there is a need for high GSD elevation maps of this region. The Moonraker mission will use a mapping LiDAR instrument to improve the state-of-the-art of lunar topographic maps, allowing mission planners to identify and de-risk landing sites for future missions. The Moonraker small satellite will operate at a 50 km altitude polar lunar orbit. Its LiDAR payload will have a 1X zoom mode and an 8X zoom mode. The instrument's 1X mode will generate wide-area 3D maps of the Moon's polar regions (60°S-90°S and 60°N-90°N) with 4 m GSD. The 8X mode will be used to scan individual landing sites at 0.5 m GSD, enabling small hazards such as boulders and craters to be identified. The data will be downlinked directly to Earth and processed into digital elevation mod-els (DEMs). 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. Moonraker is in a pre-phase A study, funded by the European Space Agency's Small Missions for Exploration initiative.

Introduction

With the recent resurgence of interest in lunar exploration, there is a growing need for higher resolution elevation maps of the Moon. A better understanding of the topography of the South Pole is especially critical, since this region is a prime target for Artemis landers, CLPS missions, and others [1]. However, unlike the mid-latitude regions ex-plored by Apollo, the terrain near the South Pole is extremely rough. This presents a challenge for mission planners who need to select landing sites near targets of explora-tion (e.g. deep craters and tall mountains) but must prioritize lander safety. Today's best topographical data comes from NASA's Lunar Reconnaissance Orbiter (LRO), but this data has significant gaps and insufficient resolution to de-risk landing sites [2].

The Moonraker mission will use a mapping LiDAR instrument to improve the state-of-the-art of lunar topographical maps, allowing mission planners to identify and de-risk landing sites

for future lunar lander missions. The Moonraker small satellite will fly in a 50 km altitude polar orbit around the Moon. It is equipped with a light detection and ranging (LiDAR) payload, which will have a 1X zoom mode and an 8X zoom mode. The instrument's 1X mode will generate wide-area 3D maps of the Moon's polar regions (60°S-90°S and 60°N-90°N) with 4 m ground sample distance (GSD) to aid mission planners in landing site selection. The 8X mode will be used to scan individual landing sites at 0.5 m GSD, enabling small hazards such as boulders and craters to be identified. The data will be downlinked directly to Earth and processed into digital elevation mod-els (DEMs) of the lunar surface. The LiDAR data products will also be used for a varie-ty of other scientific and exploration purposes, including scanning permanently shad-owed regions for water ice, identifying permanently sun-lit regions, and improving the geodetic and geologic data-sets of the Moon from previous missions.

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Moonraker is currently in a pre-phase A study funded by the European Space Agency (ESA), following its selection within the frame of the Small Missions for Exploration. This new initiative from the Human & Robotic Exploration (HRE) Directorate started with “Destination the Moon”. The Moonraker consortium consists of six companies and institutions. NUVIEW GmbH is the prime and responsible for the LiDAR payload. The Space Flight Laboratory (SFL) is responsible for the spacecraft bus and system integration. Lunar Outpost EU is responsible for the payload thermal control system (TCS) and coordinating the model-based system engineering (MBSE) efforts. DLR's Institute of Space Research will process the LiDAR data and develop the DEMs. AEM Antennas Inc. will provide the mission's high gain antenna (HGA). And finally, KSAT will be responsible for the ground stations with their Lunar Network.

Scientific Objectives

The polar areas of the Moon are of high interest to the science and exploration communities as low solar angles in these heavily cratered regions lead to permanently shadowed regions (PSR) in topographic lows, e.g. impact crater floors, next to areas that receive sun light over very long periods of time, e.g. crater rims or mountain ridges [3-6]. Whereas the PSRs are expected to contain volatile deposits usable as resources, potentially including water ice [7-14], the long-term sunlit areas allow for continuous generation of solar power usable for maintenance of lunar bases and operations on the surface, e.g., [4]. For these reasons, the lunar polar areas are very attractive landing sites for future exploration. However, in contrast to the much smoother Apollo landing sites, these areas are located in the lunar highlands, and contain extremely rough terrains including large slopes and boulders and are thus much more challenging targets for landed elements. To mitigate the risk of hazards and to clearly identify sun-lit areas usable for reliable power generation, the elevation maps need to be more accurate than the ones generated from current data-sets. The present data-products of the lunar poles based on the Lunar Orbiter Laser Altimeter (LOLA) onboard the Lunar Reconnaissance Orbiter (LRO) [3,5] are insufficient to reliably avoid hazards and to mitigate risks for humans landing on the Moon. Digital terrain models of the South Pole region currently have resolutions of 20 m/pixel [3,4]. However, many grid cells are interpolated or only determined by single data points.

Moonraker will fill that gap and will provide highly precise digital terrain models for landing sites and larger context areas. Moonraker will provide enhanced mapping of these regions and will significantly improve the density of topographic data points to characterize selected landing site candidate areas in more detail with the goal to minimize risks for human and robotic exploration. Studies will include elevation variation, slope distribution, boulder distribution within the selected areas across baselines as small as 0.5 m. Furthermore, Moonraker's data will enhance the knowledge of illumination and thermal conditions also on the basis of roughness studies. Surface roughness will provide crucial information in the search of ice deposits [12] in PSRs in which smooth terrain would indicate ice deposits, and lobate features on crater walls may indicate ice-assisted creep processes.

With its dense, highly precise height information collected over

a longer time span, Moonraker will provide the required data-set to determine the precise orientation of the lunar rotational axis which has implications on the physical properties at the surface, e.g. regarding time-variable thermal conditions. The expected data will also support the re-refinement of the libration amplitudes (small periodic changes in the Moon's spin rate) and phases in longitude and latitude, which depend on the lunar moments of inertia and therefore contain information on the deep lunar interior. By observing periodic changes in the degree-two shape, the tidal deformation on the main tidal cycle of 27 days could potentially be detected, depending on the actual amplitude, which is currently unknown but estimated to be on the order of a few tens of cm. This will provide constraints on the rheology and dissipation of the lunar interior, an important aspect regarding the long-term evolution of the Earth-Moon system.

The precise topographic information is an essential data-set to investigate geologic surface processes on the Moon, e.g., [13], and to understand the geologic context of potential landing sites, e.g., [14]. Moonraker data-sets will be used to:

- Improve our understanding of the magmatic history of the Moon.
- Enable topographic characterization of small lunar impact craters to constrain the recent impact cratering rate on the Moon and in the inner Solar System.
- Determine recent crustal deformation of the Moon and the implications for lunar tectonics and its thermal history.
- Study the dynamics of mass wasting events on the Moon, an important measurement to understand landslides on the Moon.
- Understand the evolution of lunar regolith texture and thickness. Correlation (or anti-correlation) of geologic units with surface roughness maps on different scales [13] and with albedo maps at the laser wavelength [15] will identify space weathering and surface erosion due to solar wind particles and the lunar radiation environment.

In summary, Moonraker will provide a detailed mapping of the lunar surface (1) to enable safe operations of astronauts at the selected landing sites of the Artemis missions (2) to characterize the terrain in precise digital elevation models for planning and carrying out operations at the lunar surface (3) to provide geodetic constraints on lunar shape, rotation and tidal deformation and (4) to investigate the geology of the Moon and processes that shaped the lunar surface, in particular in the polar regions.

The LiDAR Payload

The payload for Moonraker is a mapping LiDAR system that uses a near-infrared laser to perform altitude measurements, generating a point cloud of photon returns which are converted into digital elevation maps (DEMs) of the lunar surface during post-processing. Table 1 shows the payload metrics and design parameters.

Table 1: Moonraker Payload Metrics and Design Parameters

Parameter	Value
Mass	49.8 kg
Average Power	241.9 W
Peak Power	482 W
Duty Cycle per Orbit	30%
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
8X Zoom Cell Size	0.5 m
Points/Cell	2
1X Zoom Swath Width x Length (max)	1 x 3275 km
8X Zoom Tile Size	425 x 425 m

The LiDAR uses a tapered-gain fiber laser, with a wavelength near 1 micron. The laser has a pulse repetition frequency (PRF) of 26 - 360 kHz, a pulse length of 0.25 – 2 ns, and an average output optical power of 1-52 W (nominal 28 W). The laser's parameters can be adjusted in-flight via telecommands.

The transmitter optics use a refractive beam expander sized to achieve the desired beam divergence, while a fast-scanning mirror (FSM) will control the beam's path. A se-lectable diffractive optical element (DOE) will allow the transmit system to switch be-tween the 1X and 8X zoom modes.

The payload includes two receive telescopes, one for the 1X zoom mode and one for the 8X zoom mode. The telescopes use refractive optics, with the 1X telescope having a 78 mm aperture to provide the 4 m GSD and the 8X telescope having a 150 mm aperture for the 0.5 m GSD. A dichroic on the 1X zoom optical path splits the visible light into a time delay an integration (TDI) visible camera, while the near-infrared light is sent to a Geiger-mode avalanche photon detector (GmAPD) camera. The 8X zoom optical path leads directly to the GmAPD. FSMs on both optical paths guide incoming photons to the GmAPD's 128 x 32 pixel sensor.

The payload optics are mounted to a stiff optical bench to help minimize alignment er-rors between the transmit and receive optical paths. The spacecraft's inertial measure-ment unit (IMU) and star trackers are also mounted to the optical bench, ensuring that any mechanical and thermal misalignments between the sensors and the payload are minimized.

Payload thermal control includes a mixture of passive an active elements. Heat is reject-ed from the payload through three radiators: a cold radiator dedicated to the GmAPD, a dedicated laser radiator, and a "main" radiator thermally coupled to the payload enclo-sure. This approach was chosen to create distinct temperature zones, that meet the needs of individual payload components. A phase change material (PCM) container will be included on the laser heat rejection path to absorb and then slowly dissipate heat from the laser diodes. The PCM will thermally stabilize critical laser components and addi-tionally reduce the required heater power in operational mode. Multi-layer insulation (MLI) will be used to help insulate the payload. Heater lines, controlled by the bus, will actively warm the payload and help to maintain all units within operational tempera-tures. Survival heater lines will keep payload components within non-operational tem-peratures when the payload is powered OFF, e.g. during the transfer to the Moon.

Figure 1 shows the CAD model of the LiDAR payload.

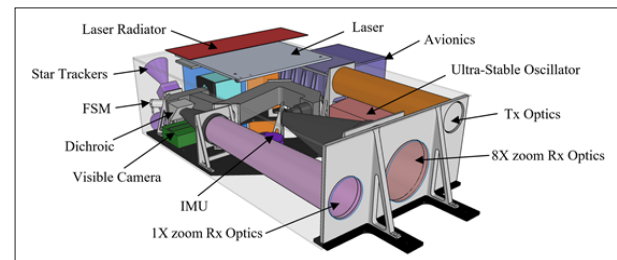


Figure 1: Moonraker Payload

Payload Operations

The mission has been sized to accommodate a 30% payload duty cycle, or ~34 minutes per orbit. Scans will include 1) wide-area scans of the lunar polar regions and 2) high-res scans of landing sites. Both 1X and 8X scans can be performed in a single orbit.

The 1X zoom wide-area scans will use a standard "push-broom" capture with a 1 km swath width and up to 3275 km in length at 4 m GSD (average). Neighboring swaths will maintain ~10% overlap to assist with co-registration of data. The platform will point off-nadir up to 20° will help ensure that new regions are scanned with every orbit. Moonraker will perform the wide-area scans of at least the two lunar polar regions (60°N to 90°N, and 60°S to 90°S).

The 8x zoom high-resolution scans will focus on landing sites already selected prior to Moonraker's launch and those selected from Moonraker's wide-area scans. The 8X zoom captures will rely on the FSMs to perform "whisk-broom" scans of the landing site, resulting in a 425 x 425 m tile scanned during a single orbital pass without body-steering the satellite.

The LiDAR will produce data at a rate of 21.7 Mbps, after compression/conditioning and a 25% margin are taken into account. The visible camera will produce data at a rate of 2.06 Mbps, with a 25% margin. Therefore during a single orbit, Moonraker will pro-duce approximately 5682 MB of 1X zoom data, 2.63 MB of 8X zoom data, and 524 MB of visible camera data, for a total of ~6.2 GB/orbit. With a download rate of ~200 Mbps from the Ka-band high gain antenna (HGA), Moonraker will spend approximately 56 min/day downlinking data to Earth.

With a 30% payload duty cycle, Moonraker will be capable of scanning both polar re-gions of the Moon in ~10 months. With a 3 year mission planned, there is plenty of op-erational margin for contingencies and extended operations to map more the Moon.

The Spacecraft Overview

Moonraker will use SFL's DAUNTLESS-L platform, a lunar version of the heritage DAUNTLESS platform. This lunar version is currently under development and will be available for Moon missions prior to the implementation phase for Moonraker. This plat-form is intended for spacecraft with a total mass up to 600 kg using a 4-point release system launch interface. The spacecraft will use a standard design with heritage compo-nents for command and data handling, power management, navigation, and attitude control. Certain subsystem hardware is sized/selected based on the power, pointing, propulsion, and data throughput requirements for the mission.

The moonraker mission will be equipped with AEM Antennas' multi-band Cassegrain High Gain Antenna (HGA) that supports both X-band and Ka-band communications directly to Earth. The antenna design incorporates a compact X-band and Ka-band feed network and fixed Cassegrain reflectors to reduce the overall antenna footprint. The main reflector is a 75 cm parabolic dish providing a gain of 32 dBi and 43 dBi at X-band and Ka-band respectively. A coaxial horn is implemented for the X-band receive and transmit functions while a concentrically placed smooth wall horn is used for Ka-band data downlink. Circular polarization is generated through polarizer components integrated with a novel coaxial asymmetric orthomode junction (OMJ) that reduces en-velope and mass.

The Moonraker spacecraft can be seen in Figure 2, and summary of the performance and characteristics for the proposed spacecraft is provided in Table 2 below.

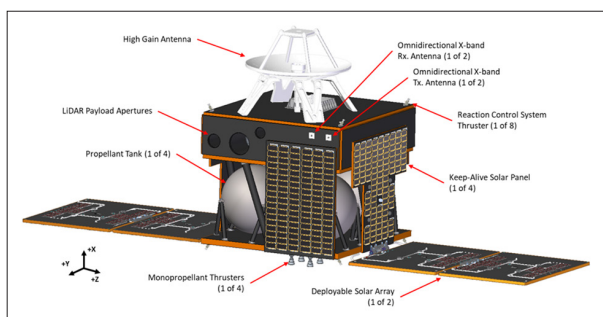


Figure 2: The Moonraker Spacecraft in its Deployed Configuration

Table 2: Moonraker Spacecraft Performance Metrics and Design Characteristics

Parameter	Value
Spacecraft Dry Mass	259 kg
Propellant Mass	Primary Propulsion Monopropellant: 213 kg Reaction Control System Cold Gas Propellant: 6 kg
Spacecraft Wet Mass	478 kg
Spacecraft Dimensions	Stowed: 1.35 m x 1.10 m x 1.39m Deployed: 1.35 m x 1.10 m x 5.49m
Peak Power Generation (end-of-life)	697 W
Primary Telemetry & Command Link	Uplink: Up to 2 Mbps (adjustable) Downlink: Up to 2 Mbps (adjustable)
Payload Data Downlink	Up to 200 Mbps (adjustable, limited by link budget)
Attitude Determination	7.9 arcsec (1 σ , nadir, not including static and thermal misalignments)
Attitude Control	9.6 arcsec (1 σ , nadir, not including static and thermal misalignments)
Delta-V	1453 m/s
Design Life	5 years
Power Generation	2 deployable solar arrays, 4 keep-alive panels
Communications	Telemetry & Command: X-band Payload Data Downlink: Ka-band

Attitude Determination	3-axis; 2x star tracker, 6x sun sensor, rate sensor
Attitude Control	3-axis; 4x reaction wheels, 8x reaction control thrust-ers
Navigation	Two-way Doppler and two-way ranging

Transfer Trajectory

Moonraker will use a direct lunar transfer where the launch vehicle places Moonraker into a lunar transfer orbit. The transfer will take 4-6 days, during which time trajectory correction maneuvers may be performed. The baseline trajectory begins on January 1, 2029 and the spacecraft reaches the Moon 5 days later. It will perform the lunar orbit insertion maneuver by applying 340 m/s of delta-V with a 25 minute burn time. This maneuver captures the spacecraft into a stable lunar polar orbit with a periapsis altitude of 200 km and an apoapsis altitude of 8600 km. Next, the spacecraft performs 5 succes-sive burns at its periapsis for 5.7 minutes per maneuver to circularize the orbit and complete the descent to a low lunar orbit.

Lunar Orbits

Prior to reaching it's nominal orbit, Moonraker will utilize a 140x50 km quasi-frozen orbit for payload commissioning. In this orbit, the variation of orbital elements follows a cyclic pattern every lunar sidereal period (approximately 27.3 days) with minimal drift. Once payload commissioning is complete, the orbit will be circularized.

Moonraker's nominal orbit will be a circular, 50 km polar orbit at approximately 90° in-clination, enabling the LiDAR to scan the poles. However, lunar gravity field differs drastically compared to that of Earth. The mass distribution throughout the Moon is not as uniform, which leads to larger orbital perturbations, causing altitude variations of up to ± 25 km. These large perturbations necessitate the need for orbital station keeping maneuvers every sidereal period to ensure the spacecraft stays at its primary operational altitude range.

End of Mission

After mission completion Moonraker will be deorbited. Based on the 50 km operational orbit, it would only require 12 m/s of delta-V to cause the spacecraft to impact the Moon. The impact location of Moonraker will be selected to ensure it does not contami-nate any scientifically interesting locations.

System Architecture

The overall Moonraker system architecture is shown in Figure 3. The planning process will begin with the user community identifying high-resolution lunar targets. Requests will be filtered and prioritized by DLR, who will then transmit a fixed number of monthly target requests to NUVIEW's Payload Control Center (PCC). The PCC will compute the payload commands for both LiDAR zoom level scans on a daily basis. These commands will be forwarded to SFL's Mission Control Center (MCC) where they will be combined with spacecraft telecommands, and then sent to KSAT's Net-work Operations Center (NOC) for processing before being forwarded to the ground stations (GS) for uplink. KSAT's Lunar Network consists of 3x 20 meter antennas lo-cated in Australia, Spain, and Western USA,

providing 24h coverage of the Moon. KSAT's GS will upload the telecommands to Moonraker where they will be executed in a time-tagged queue. Telemetry data from the S/C and P/L and payload data will be downloaded to KSAT's ground stations. Simultaneously, ranging and Doppler measurements of the spacecraft will be taken, and the timing information will be sent to the onboard clock to keep it in sync with UTC. Spacecraft telemetry will be sent to the MCC, while payload telemetry will be sent to the PCC. The MCC will process the S/C telemetry and send S/C state information to the PCC. This will be combined with the LiDAR measurements during the pre-processing of the data such that the exact position and attitude of the spacecraft is provided for each LiDAR data point. This pre-processed data is passed on to DLR's Data Processing Center (DPC) where it is converted into both 1X and 8X zoom digital elevation models (DEMs). Free versions of the DEMs will be posted on a public server, while NUIVIEW's own platform will sell the DEMs with value-added features and an enhanced user experience.

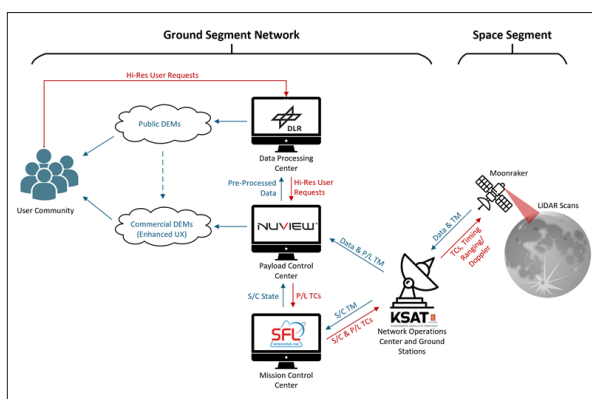


Figure 3: Moonraker System Architecture

Model-Based System Engineering Approach

The development of the Moonraker mission will be supported through MBSE through-out the entire project. The MBSE tool will serve as the main source of truth for requirements management and functional, physical and logical decomposition. Following a trade-off between 5 different software tools, Innoslate was selected as the MBSE tool, with the highest driving criteria being tool complexity, consortium collaboration, and cost.

The requirements were first incorporated in Excel, imported to Innoslate and decomposed into payload, bus and ground station network requirements. Relationships were added to the requirements to achieve traceability and identify the most influential requirements to guide the payload, bus and mission design. The model will be further developed while the project advances.

Summary And Conclusion

Moonraker has the potential to significantly improve the state of the art for lunar topography. DEMs produced from its LiDAR data will help identify and de-risk prospective landing sites for future lander missions, while scientific analysis of the data will yield insights into lunar geologic processes and history, surface characteristics, and aid in the search for water ice in permanently shadowed regions. Moonraker mission is currently in a pre-phase A study funded by ESA through the Small Missions for Exploration, a new initiative started with "Destination the Moon". The conceptual designs of the LiDAR payload, spacecraft bus, and ground segment are now completed, and the

Moonraker team will look to build upon these designs if selected for the next phase of this initiative.

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