Single Photon Counting Laser Altimetry for Planetary Exploration: Development and Validation with Application for Deep Space Missions

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This work investigates the feasibility of single-photon avalanche diode (SPAD) matrix–based laser altimetry as a low size, weight, and power (SWaP) solution for future planetary missions, including lunar applications and the European Space Agency L4 mission to Enceladus. These missions require centimeter-level ranging accuracy to enable high-resolution topographic mapping and the detection of tidal surface deformation, providing key constraints on subsurface ocean structure and internal dynamics. Achieving such performance under deep-space conditions remains challenging for conventional avalanche photodiode (APD)-based systems due to their comparatively high resource demands.

The scientific and technical motivation builds on recent advances in laser altimetry from instruments such as the BepiColombo Laser Altimeter[1] and the Ganymede Laser Altimeter[2] aboard JUICE. These systems are designed to achieve vertical accuracies better than 10 cm and enable global topographic mapping as well as the detection of tidal deformation signals. However, a capability gap persists at meter-scale lateral resolution combined with centimeter-level vertical precision, limiting detailed surface process studies and landing site characterization. Addressing this gap is a key driver for next-generation altimetry concepts.

A central precursor to this work is the single-photon counting laser altimeter (S3LA[3]), studied at DLR (Figure 1). Airborne and laboratory demonstrations showed that SPAD-based altimetry can achieve decimeter to centimeter-level ranging precision with very low pulse energies (~0.5 µJ), enabling compact and energy-efficient instrument architectures. In particular, airborne campaigns achieved 10–15 cm precision and demonstrated the viability of single-photon altimetry under dynamic conditions. At the same time, these studies identified key limitations of SPAD detection, including first-photon timing bias, sensitivity to background noise (dark counts, stray light) and the absence of waveform information for direct surface characterization.

To overcome these limitations, this project develops a SPAD matrix–based laser altimeter breadboard using commercial off-the-shelf components with full event logging. In contrast to conventional approaches based on coincidence detection or fixed range gating, the system records time-resolved photon statistics across multiple pixels, enabling advanced post-processing. Statistical correction models and Bayesian filtering techniques are applied to mitigate first-photon bias and improve signal-to-background discrimination in conditions with little signal photons (Figure 2). Previous results demonstrate that systematic timing errors can be reduced from several centimeters to sub-centimeter levels using such approaches.

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[1] N. Thomas et al. The BepiColombo Laser Altimeter. Space Sci Rev 217, 25 (2021). https://doi.org/10.1007/s11214-021-00794-y.
[2] H. Hussmann et al. The Ganymede Laser Altimeter (GALA) on the Jupiter Icy moons Explorer (JUICE) Mission. Space Sci Rev 221, 33 (2025). https://doi.org/10.1007/s11214-025-01149-7.
[3] Werner, S. C. and the The SER3NE Team: SER3NE - A small orbiter mission to the Moon, EGU General Assembly 2025, Vienna, Austria, 27 Apr–2 May 2025, EGU25-8239, https://doi.org/10.5194/egusphere-egu25-8239, 2025.

The study combines theoretical and experimental investigations. A detailed link budget analysis accounts for surface reflectivity and orbital geometry representative of deep-space missions such as Enceladus. Laboratory experiments focus on noise suppression and robust signal extraction, including outlier rejection and probabilistic filtering. A key objective is to exploit the spatial and temporal statistics of SPAD matrix data to retrieve not only range but also surface properties such as albedo, slope, and roughness.

System validation is performed through airborne testing on a motor glider, enabling performance assessment under dynamic conditions. Building on S3LA heritage, the results demonstrate improved ranging precision and enhanced surface characterization capability, advancing the system toward Technology Readiness Level 5. This work establishes a validated, end-to-end concept for SPAD-based laser altimetry and provides a scalable pathway toward high-precision, low-SWaP instruments, directly supporting future flight payloads for the ESA L4 mission and other planetary exploration missions.

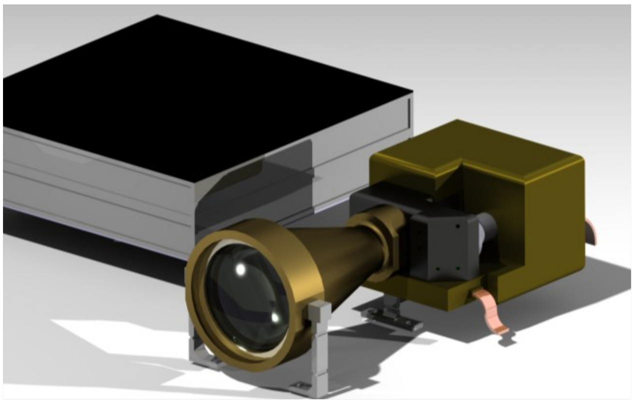

Figure 1: Rendering of the single-photon counting laser altimeter proposed for the SER3NE mission showing the transmitter–receiver optical assembly with telescope optics and the integrated electronics unit. The compact design enables deployment on airborne platforms and supports future miniaturized spaceborne implementations.

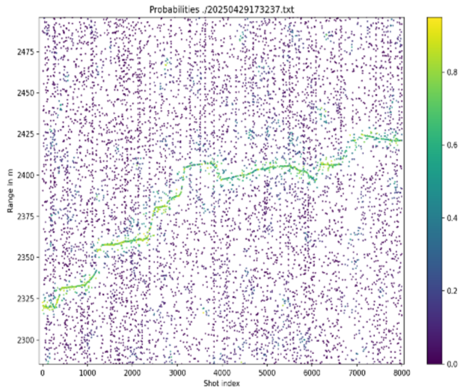

Figure 2: Example results from an airborne measurement profile. The diagram shows detected signal photon events plotted versus shot index and range, with color indicating detection probability (analysis method: patent pending).