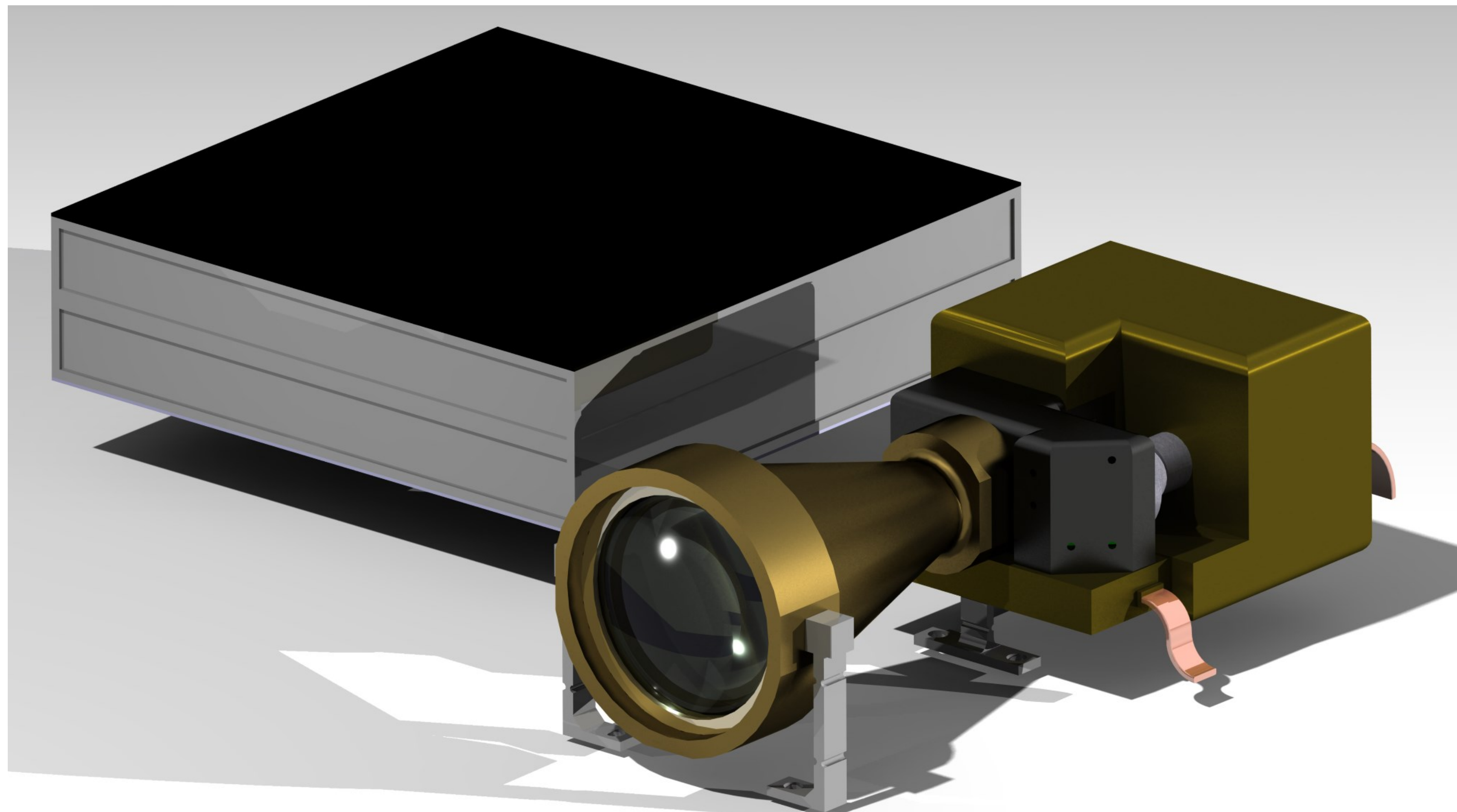


Development and Validation of a Single-Photon Counting Laser Altimeter

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Rendering of the single-photon counting laser altimeter demonstrator 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.

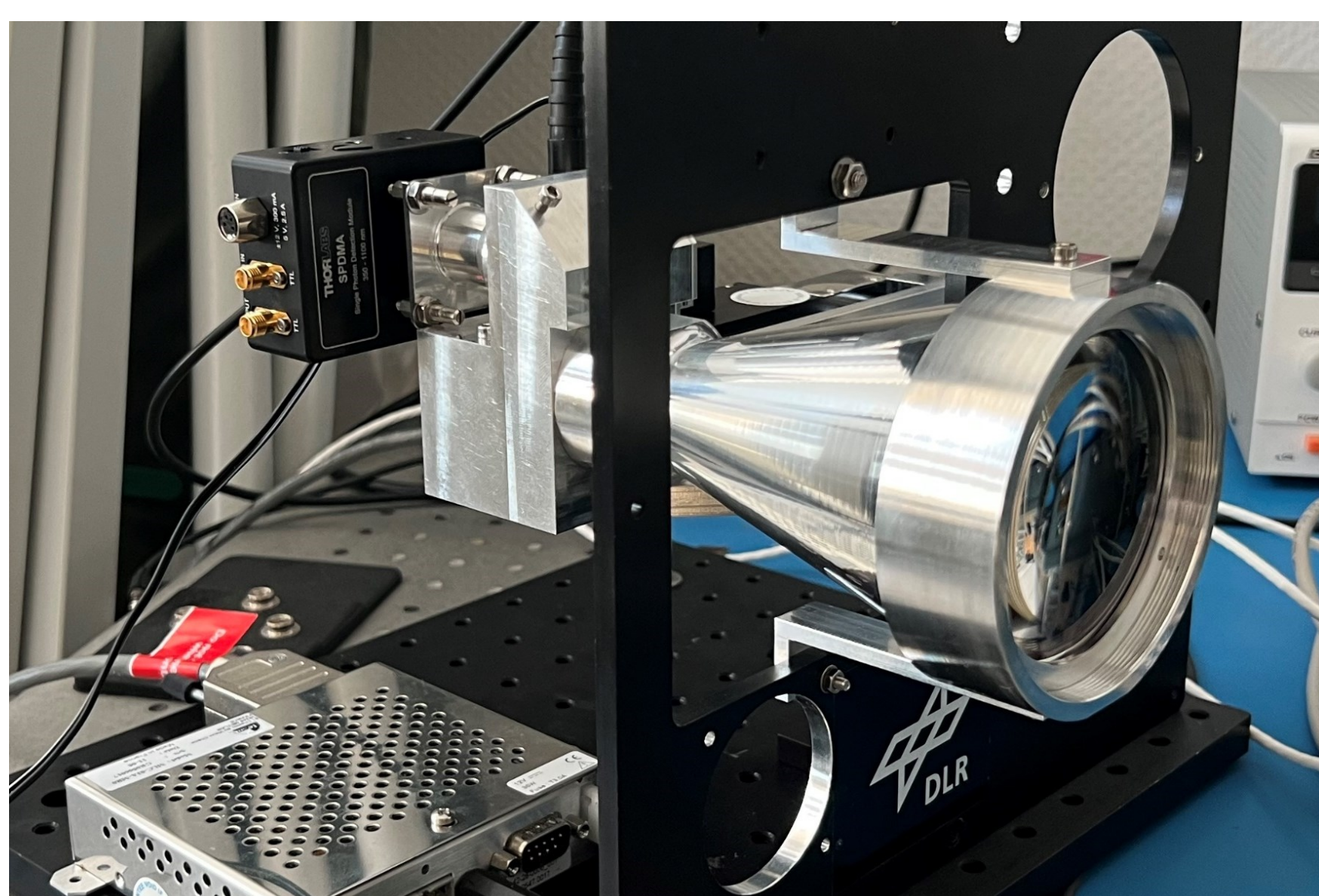
ABSTRACT

Single-photon laser altimetry enables high-sensitivity ranging with very low optical power, making it attractive for small satellites and planetary missions. However, the technique introduces challenges such as detector noise, timing uncertainty, and first-photon bias. We present the development and validation of a compact single-photon laser altimeter demonstrator. The system was tested through laboratory characterization, airborne campaigns, and measurements on a calibration track with surveyed targets.

Keywords: single-photon counting lidar, laser altimetry, calibration, first-photon bias, filtering, flight campaign

System Design

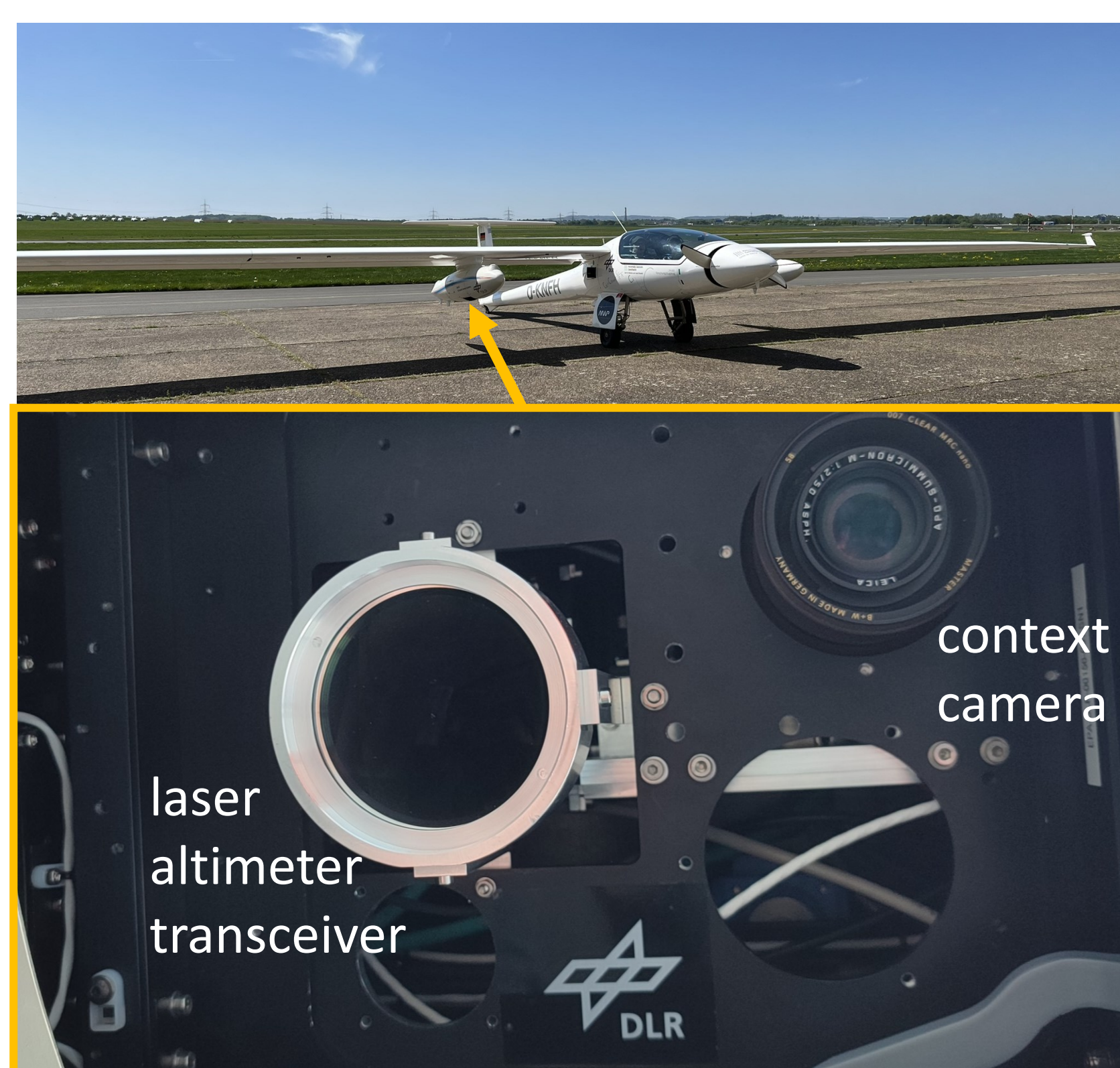
The demonstrator consists of a transmitter, receiver, detector, and timing electronics. The transmitter uses a 532 nm microchip laser with 0.5 μ J pulse energy and a repetition rate of 200–400 Hz. The receiver includes an 8 cm telescope with a 0.15 nm narrowband filter. Photon detection is performed with a SPAD detector (>50% PDE, <1 kHz DCR) with a dead time of 20 ns. Signal timing is recorded using an oscilloscope with $\sim$ 800 ps resolution.



Laboratory setup of the single-photon counting laser altimeter demonstrator showing the receiver telescope, SPAD detector module, and opto-mechanical mounting structure used for system testing and calibration.

Airborne Demonstration

Airborne measurements were conducted using a motorglider at altitudes of 300–2500 m and speeds of $\sim$ 50 m/s. The campaign recorded 149 profiles, corresponding to $\sim$ 1.19 million laser shots and $\sim$ 260 km of total profile length across water, vegetation, and urban surfaces.



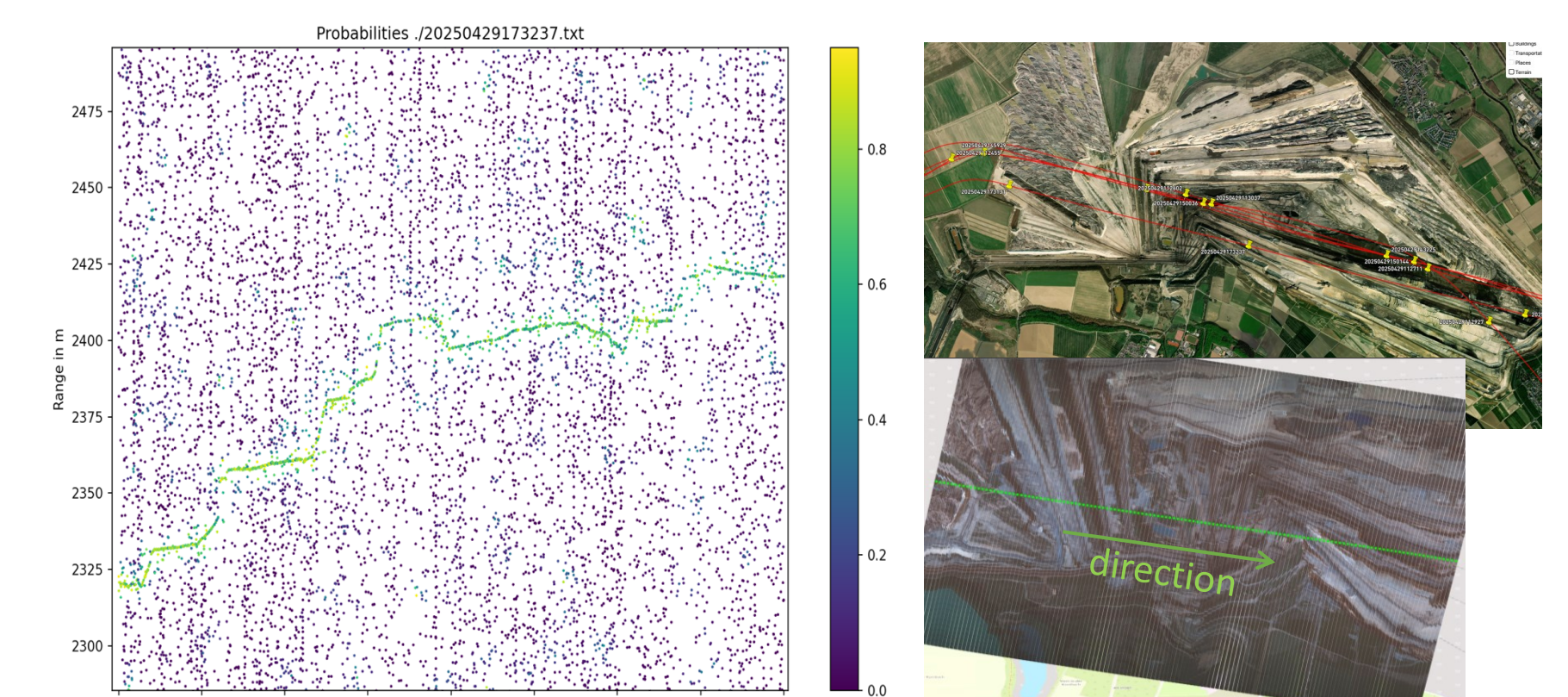
Airborne measurement platform used for the flight campaigns. Top: motorglider aircraft (Stemme S10) used for data acquisition. Bottom: single-photon counting laser altimeter instrument mounted in the airborne payload rack prior to installation.

Takeaways

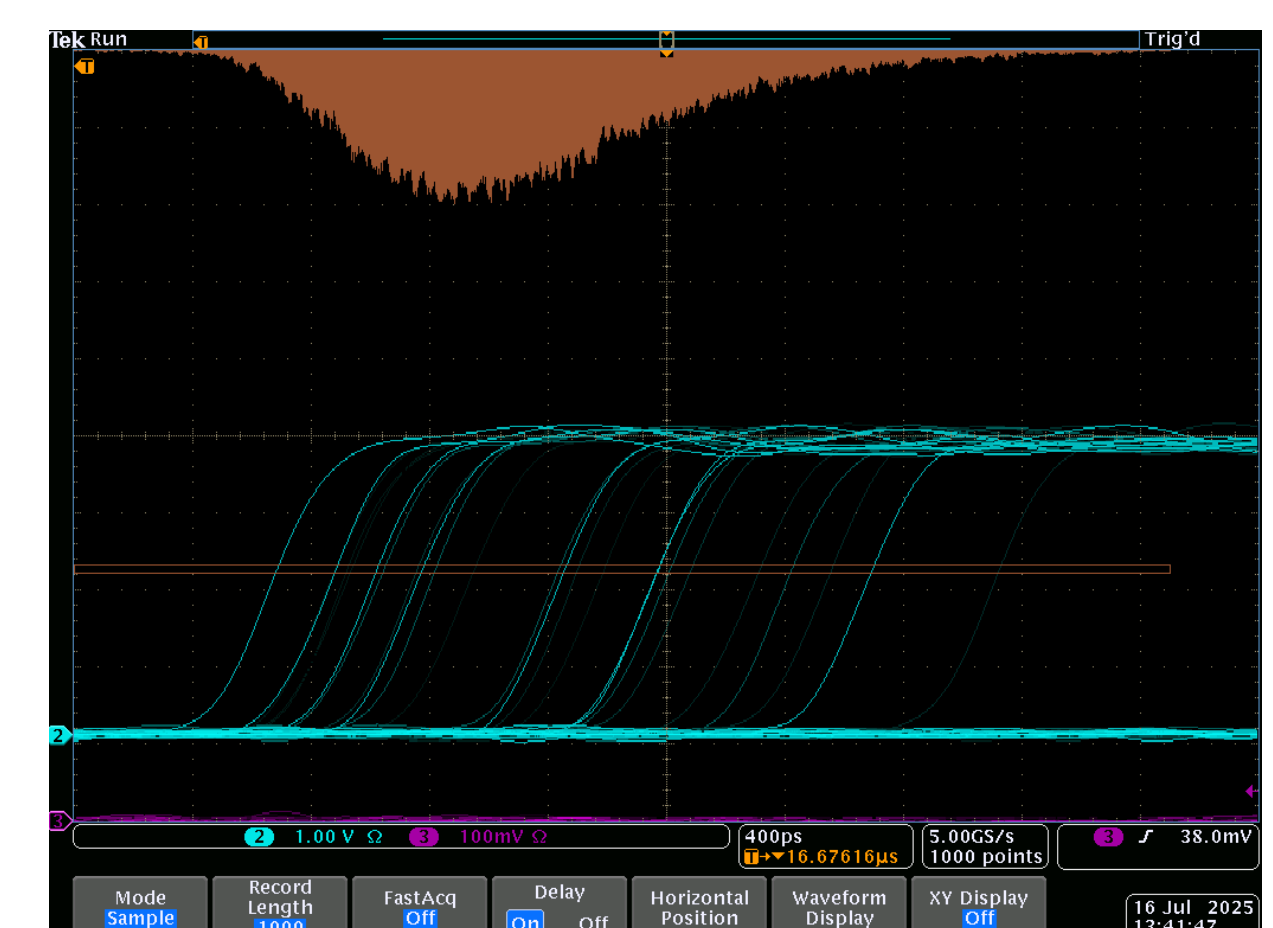
- First-photon bias reduced from $\sim$ 5 cm to <1 cm using an SNR-dependent statistical correction model
- Airborne precision of 10 - 15 cm demonstrated with only 0.5 μ J laser pulse energy
- A dedicated calibration track enables absolute validation of single-photon altimetry performance

Filtering and Signal Detection

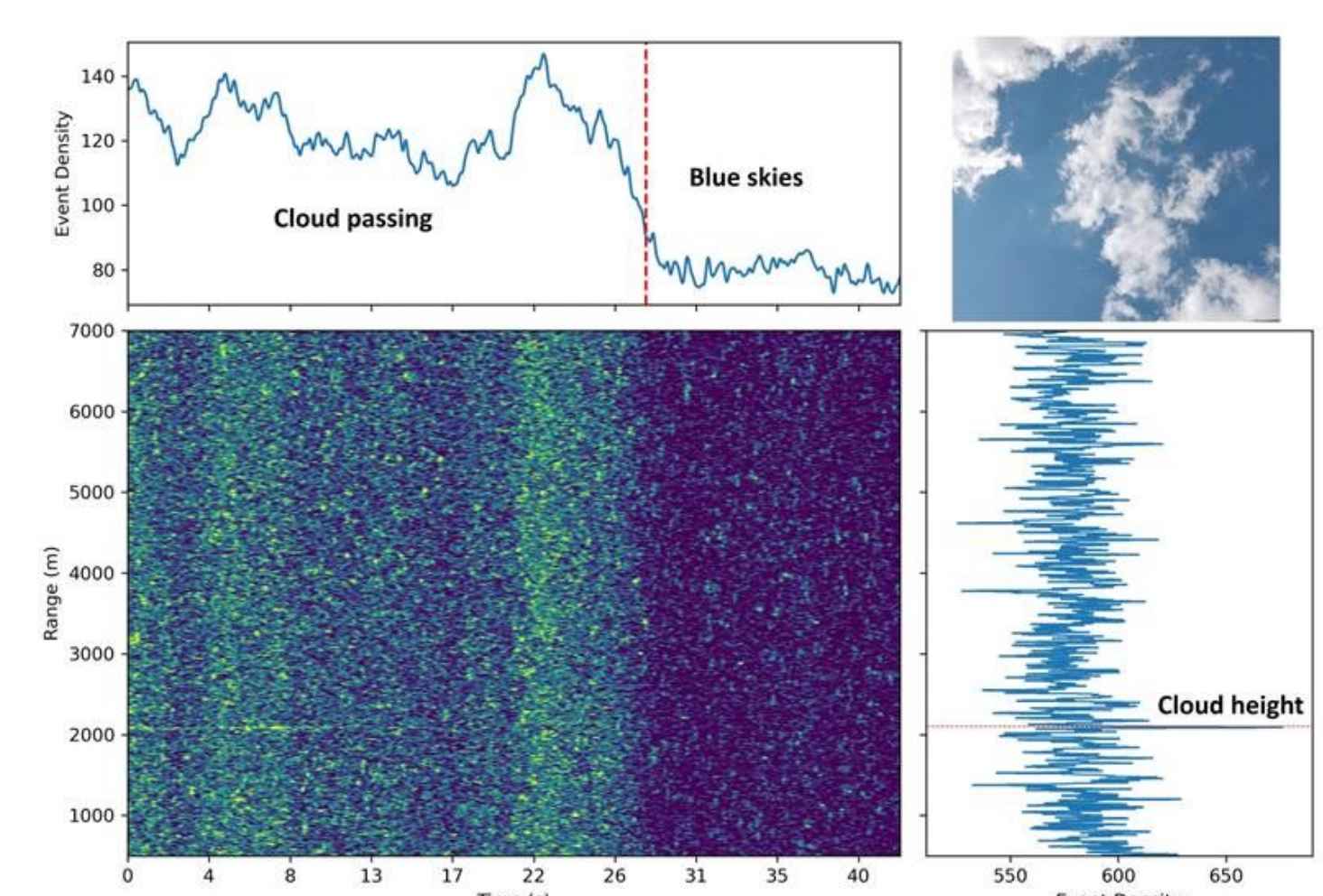
Single-photon detection introduces a systematic measurement bias because the earliest detected photon statistically arrives earlier than the actual pulse center. Under typical measurement conditions, the system detects about 1–10 signal photons per pulse, while background noise ranges from approximately 1–5 per μ s. If uncorrected, this effect leads to systematic errors in the estimated range.



Example results from an airborne measurement profile. left: detected signal photon events plotted versus shot index and range, with color indicating detection probability (analysis method: patent pending). right: corresponding flight track over the measurement area and context high resolution images.



Oscilloscope measurement of arriving SPAD signals from a fixed range target to analyze the first-photon bias of the system. This test was repeated for different ranges to study the resulting changes of the arrival bias probability distribution and non-systematic errors.



Example atmospheric measurement showing photon event density over time and range. The transition from cloud presence to clear sky is visible in the event density profile, allowing estimation of the cloud height from the detected photon distribution.

Conclusion and Outlook

A compact single-photon laser altimeter was validated through laboratory, airborne, and calibration experiments. A statistical correction model reduces the first-photon bias to centimeter level, enabling accurate ranging with very low signal photon counts. Airborne tests achieved $\sim$ 10 cm precision with 0.5 μ J laser pulses, demonstrating strong potential for future miniaturized spaceborne altimeters.