SINGLE PHOTON COUNTING LASER ALTIMETRY FOR PLANETARY EXPLORATION: DEVELOPMENT AND VALIDATION WITH APPLICATION FOR DEEP SPACE MISSIONS

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Why Laser Altimetry matters

Laser altimeters turn precise engineering measurements into planetary science discoveries.

Laser altimeters provide:

- Global and regional surface topography
- Tidal deformation measurements
- Constraints on internal structure and subsurface oceans
- Surface slopes and landing-site characterization
- Independent measurements in illuminated and shadowed regions

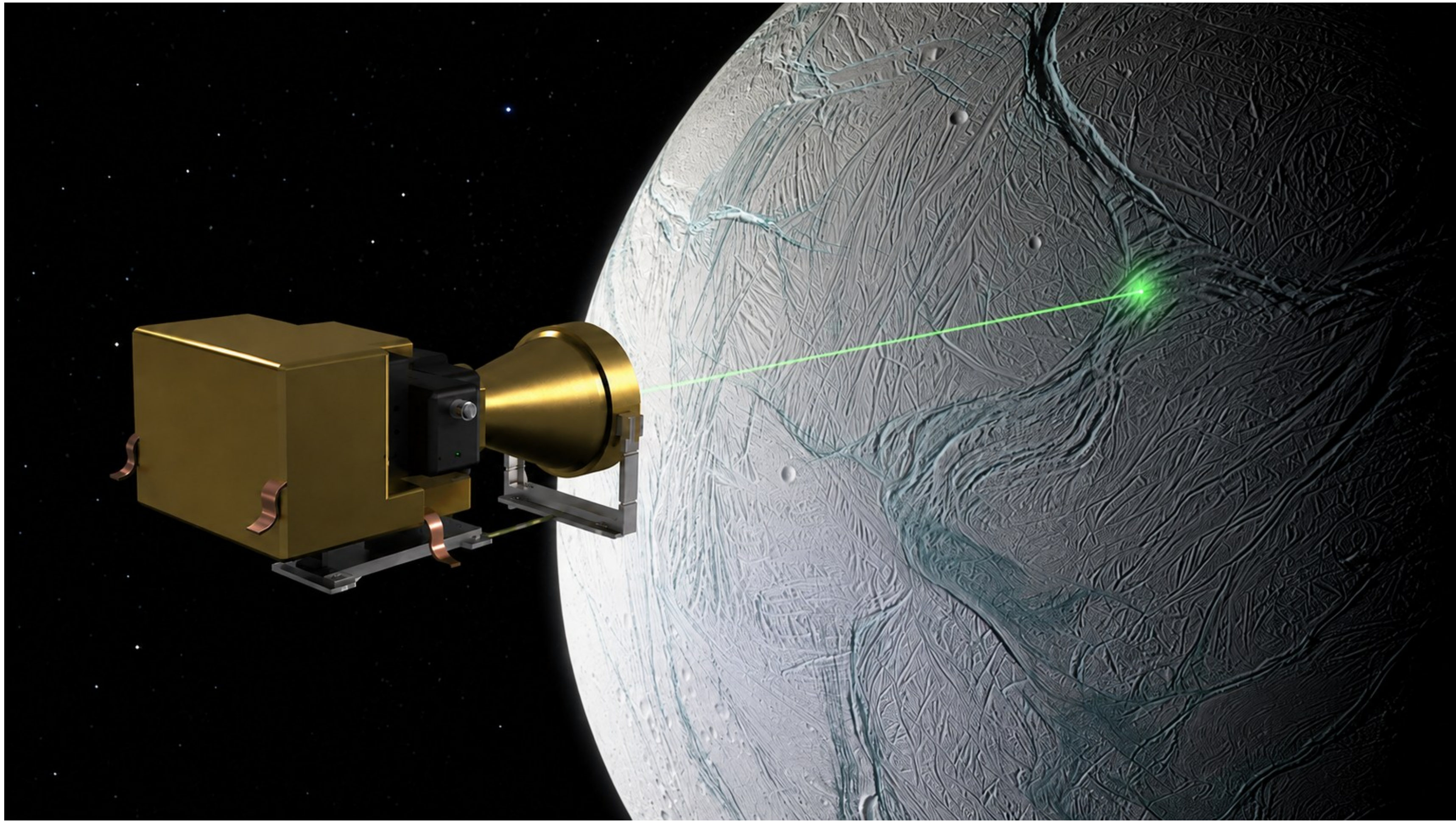


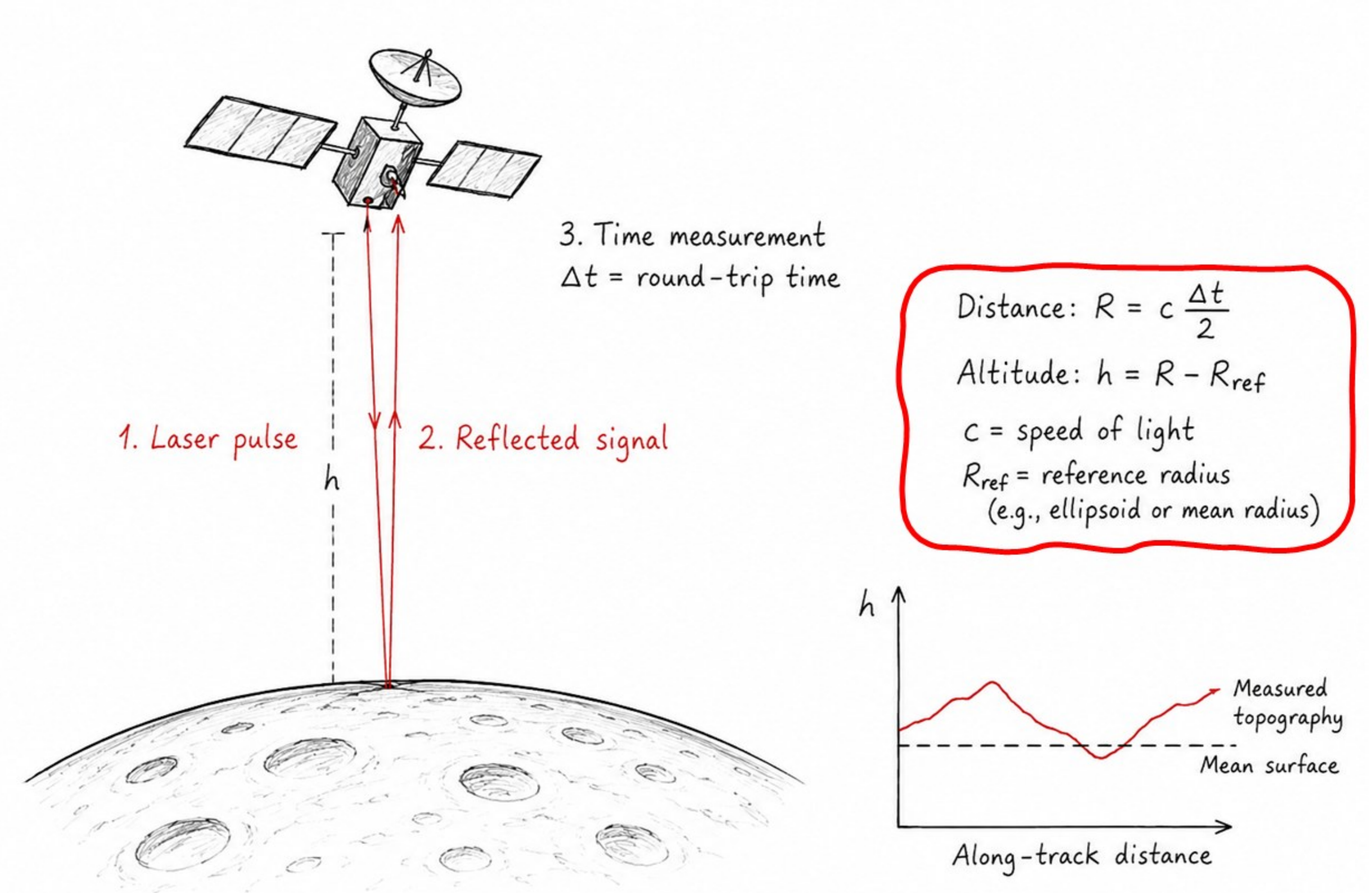
Illustration of a laser altimeter in orbit around Enceladus.
Credit: AI generated from NASA's Cassini spacecraft on Oct. 9, 2008 NASA/JPL/Space Science Institute

How a Laser Altimeter works

- a laser pulse is fired toward the surface
- the surface reflects the pulse back
- the round-trip travel time is measured
- distance is calculated from the speed of light
- millions of repeated measurements build a global 3D topographic map of a planetary surface

Link Budget Equation:

$$N_{\mathrm{det}} = \frac{E_{\mathrm{L}}\lambda}{hc} \cdot \frac{\rho}{\pi} \cdot \frac{A_{\mathrm{Rx}}}{R^2} \cdot \cos\theta \cdot T_{\mathrm{atm}}^2 \cdot \eta_{\mathrm{opt}} \cdot \eta_{\mathrm{det}}$$



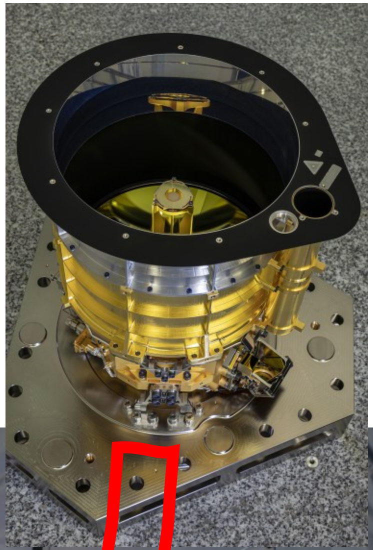
Credit: AI generated from sketch

Classical Laser Altimeters - Heritage

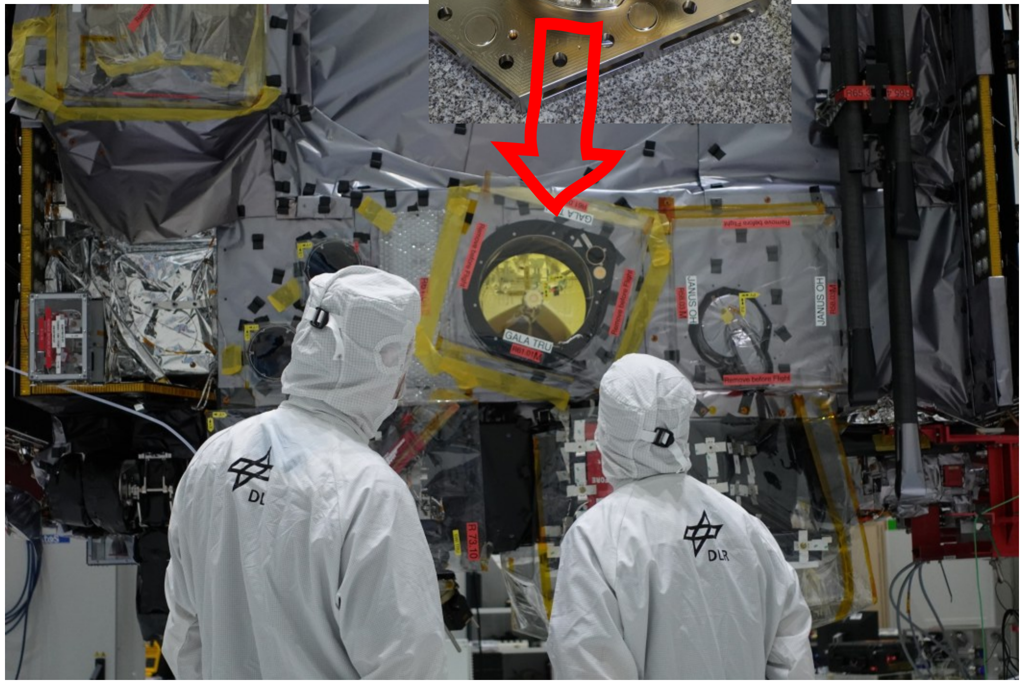
GALA

Launch date:
14 April 2023

GALA: 25 kg, 50 W



GALA TRU
Credits: Hensoldt

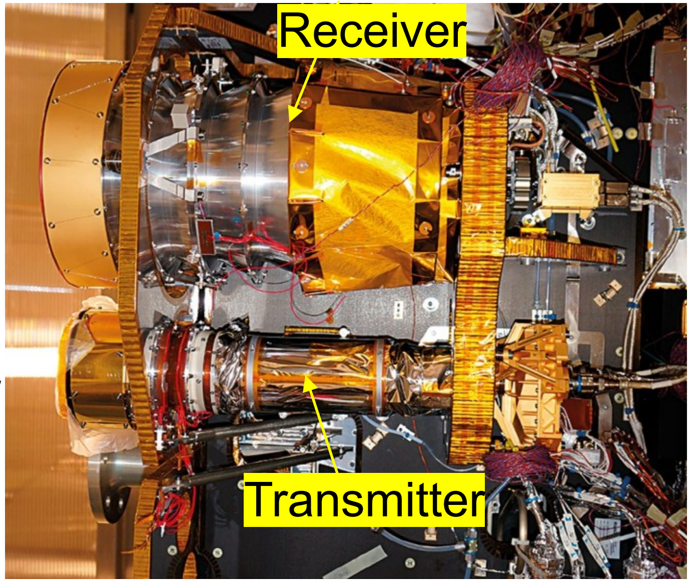


GALA integrated on S/C Credits: DLR

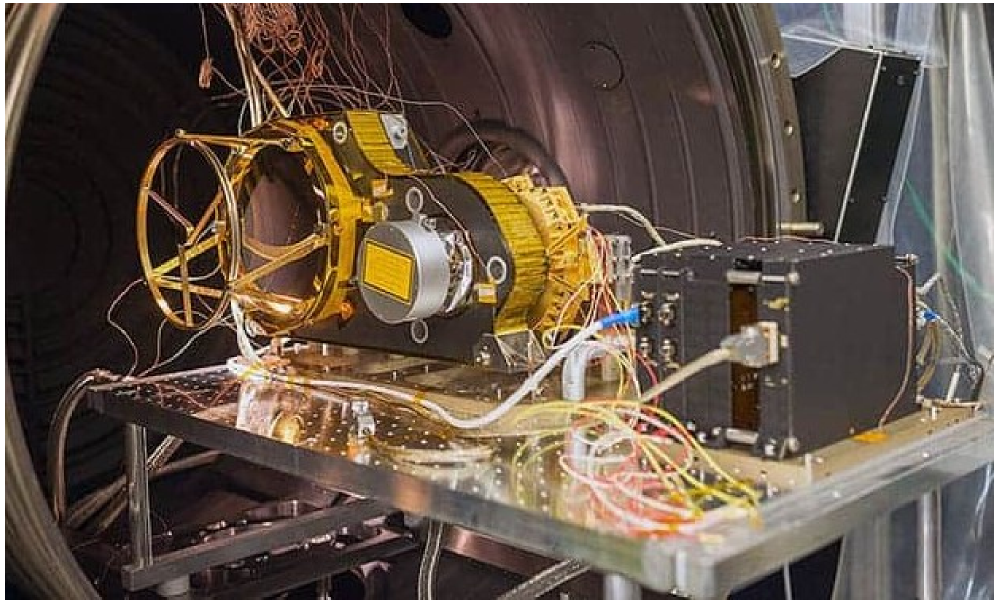
BELA

Launch date:
20 Oct 2018

BELA: 15 kg, 43 W



BELA on S/C
Credits: DLR



BELA during testing Credits: University of Bern

The Remaining Capability Gap

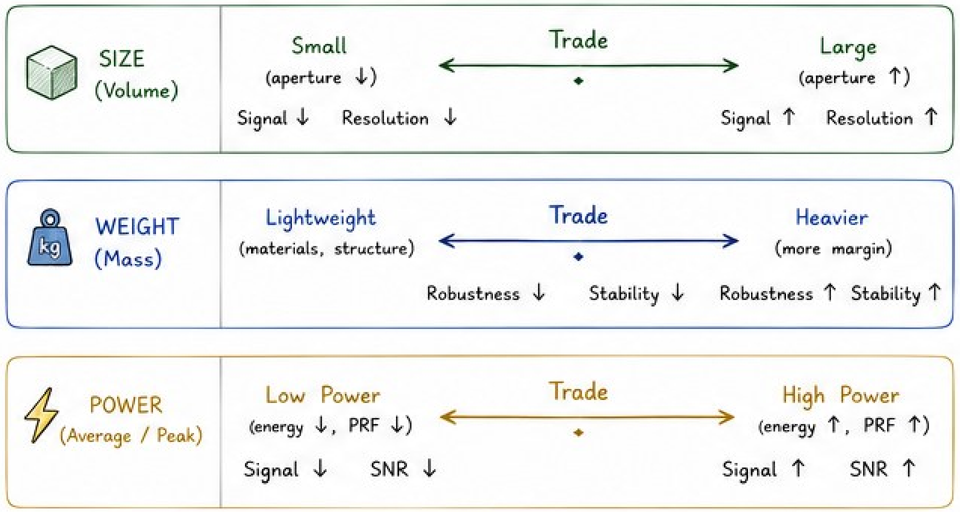
Classical laser altimeters are powerful instruments for large distance ranging.

BUT high vertical precision is still linked to large instrument resources

Classical APD-based laser altimeters require many detected photons per pulse to reliably distinguish the surface echo from detector and background noise

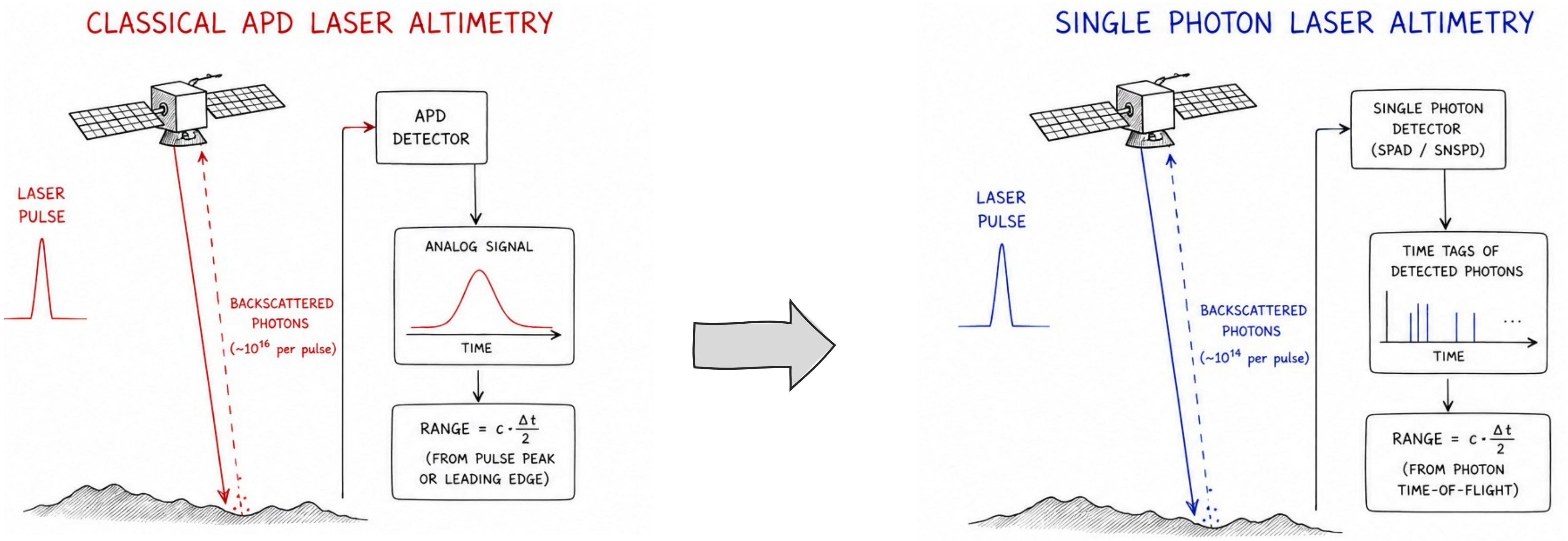
This results in:

- High laser pulse energy
- Large transmitter and receiver optics
- High electrical power and thermal dissipation
- Significant instrument mass and volume



The detection principle drives the overall instrument size, mass and power consumption. Small instruments need another approach.

Single-Photon Laser Altimetry

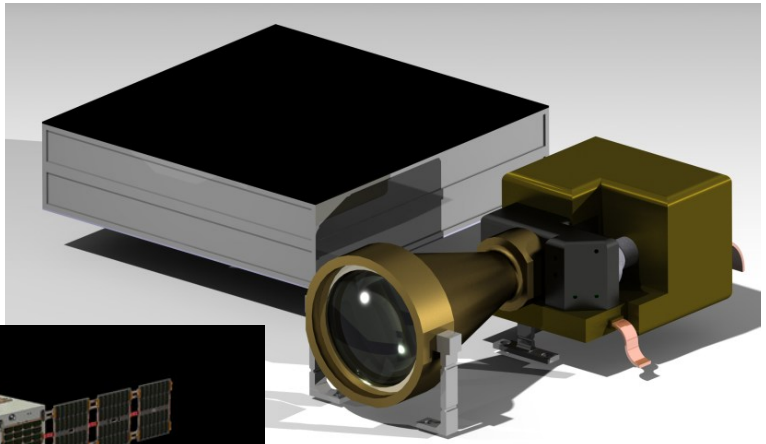


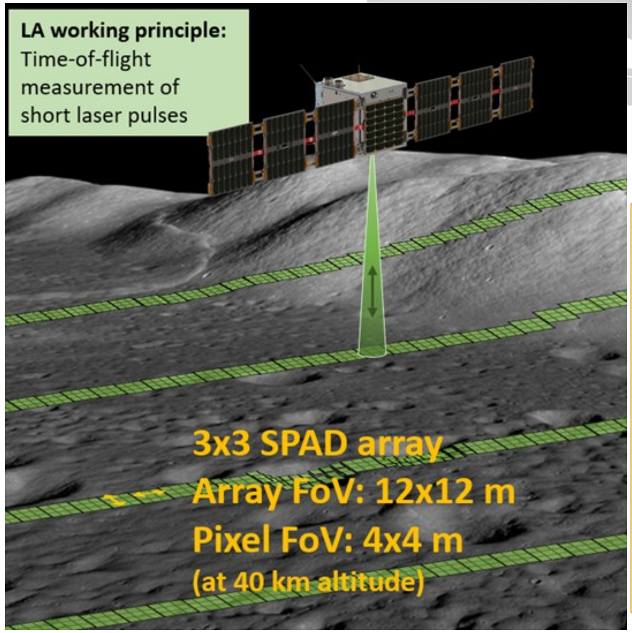
Credit: AI generated from sketch

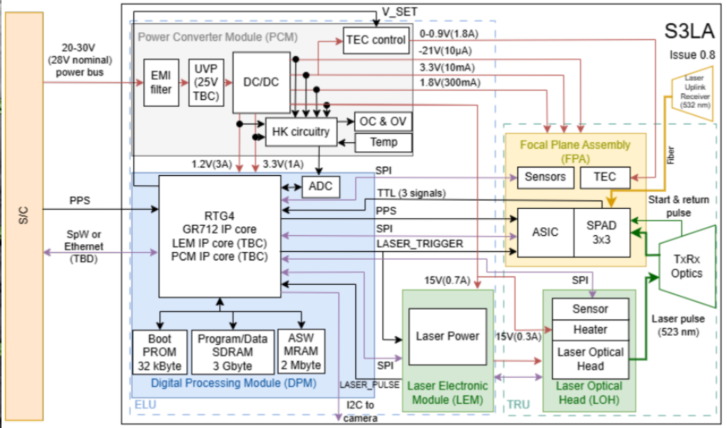
Classical APD altimetry	Single-photon altimetry
Strong echo required	Individual photons detected
High laser pulse energy	Low laser pulse energy
Relatively simple processing	Statistical processing required
Limited sensitivity	High sensitivity
Robust against background	Sensitive to background events

S3LA Study for Moon Small Sat Mission SER3NE

- **Instrument concept S3LA for SER3NE (ESA Pre-Phase A study by the ESA within the Terra Novae E3P programme)**







Single-Photon Counting
- Highly sensitive detection
- Small laser and compact telescope
- Fully digital instrument

Key Components
- SPAD array with on-chip timing
- Combined transmit/receive optics
- High-performance FPGA

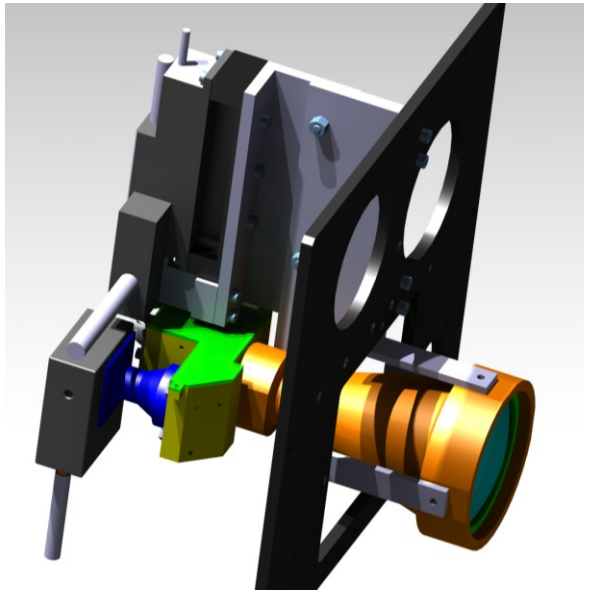
Demonstration in laboratory and flight tests (TRL 3–4)

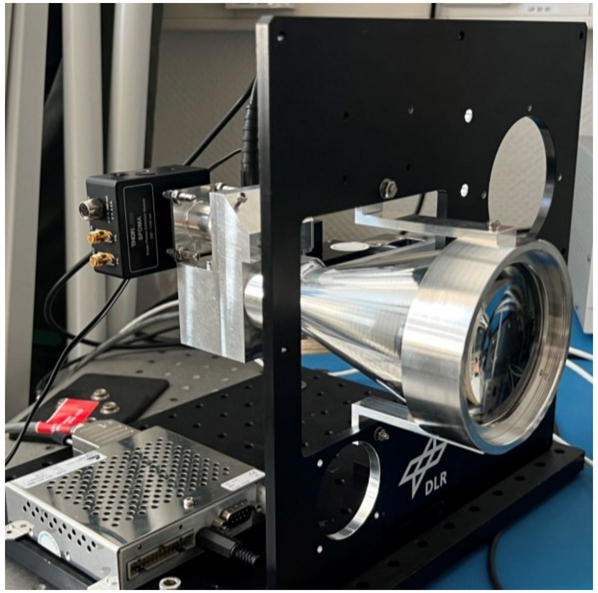
Preliminary Instrument Summary	
Parameter	**Baseline estimate**
Surface range	20–40 km
Pulse energy	0.5–2 mJ
Pulse rate	200–425 Hz
Telescope aperture	8 cm
Mass	3.6 kg
Power	20 W

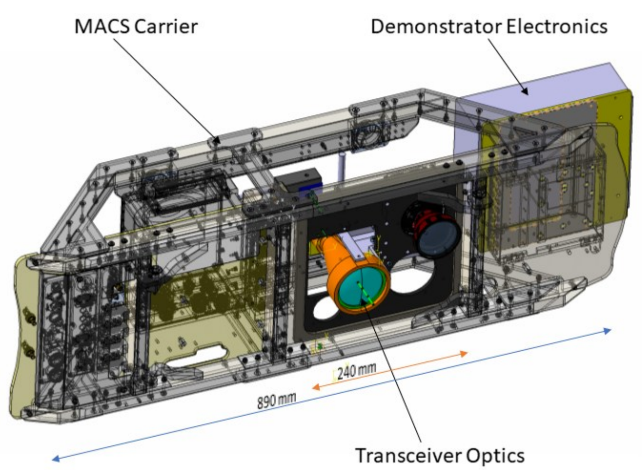
Demonstrator for Laboratory and Airborne Testing

- **Representative:** optics, wavelength, filter and detector sensitivity
- **Not representative:** single-pixel SPAD and oscilloscope-based timing
- **Objective:** validate the measurement and processing principles

  - combined Tx-Rx-Optics, aperture 8 cm
  - bandpass filter with narrow bandpass (0.15 nm)
  - microchip laser with more realistic parameters: 0.5 µJ, 200 Hz, 532 nm
  - 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 ~800 ps resolution







Lessons Learned from Demonstrator

Identified key limitations

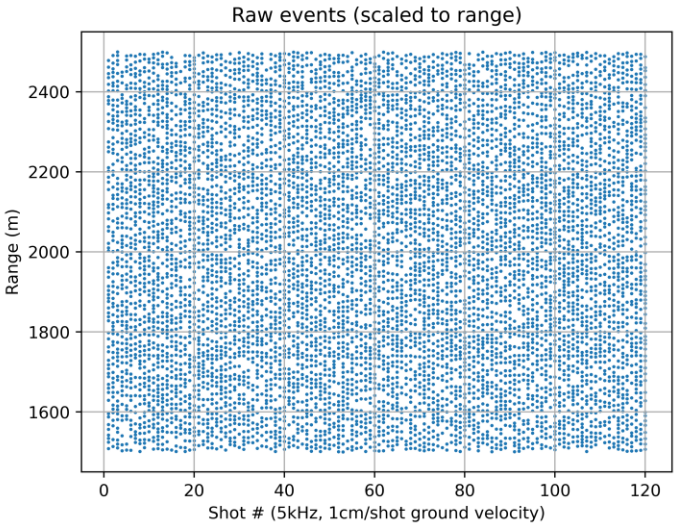
- first-photon detection introduces a systematic timing bias
- detector dark counts and stray light produce background events
- a single-pixel detector provides no spatial information
- single-photon measurements do not provide a conventional analogue waveform
- No immediate distinction between signal and noise

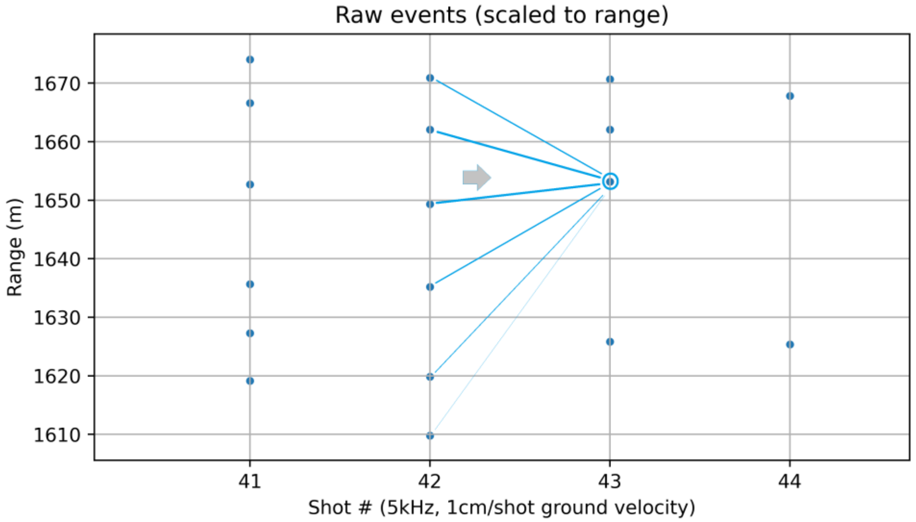
Robust single-photon altimetry therefore depends on event processing.
Hardware complexity is shifted to processing complexity.

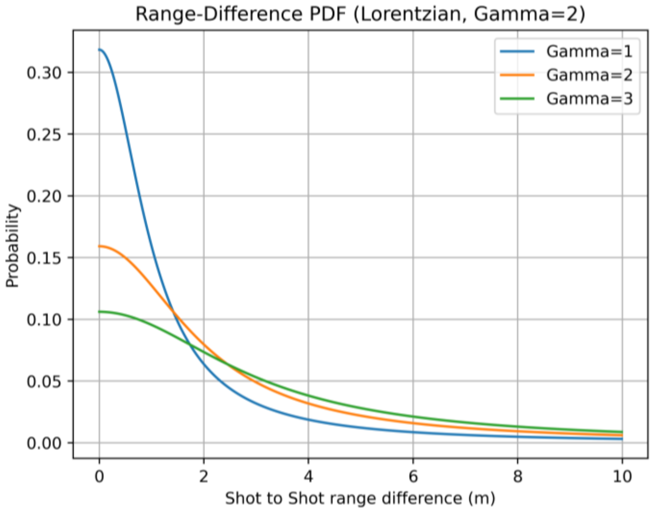
New algorithms on very noise data
Idea: Bayesian inference

Processing steps:

1. Record all photon events within the observation window
2. Assign an initial signal probability to each event
3. Apply a rough expected range and topography distribution
4. Update the probability using spatial and temporal consistency
5. Retrieve the most probable surface range for each individual shot

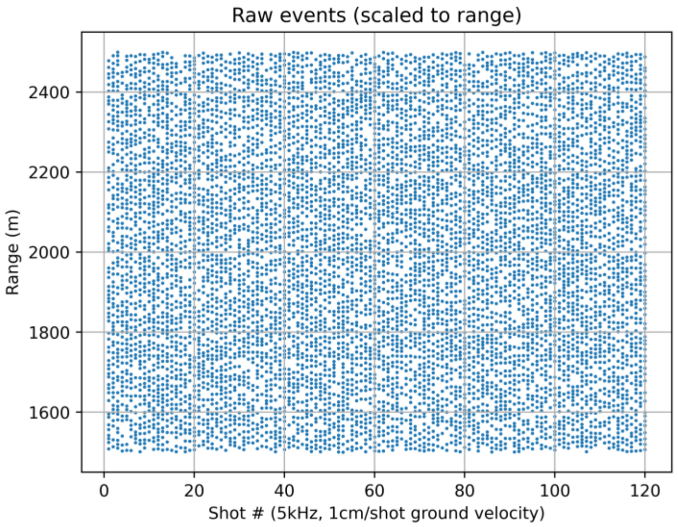


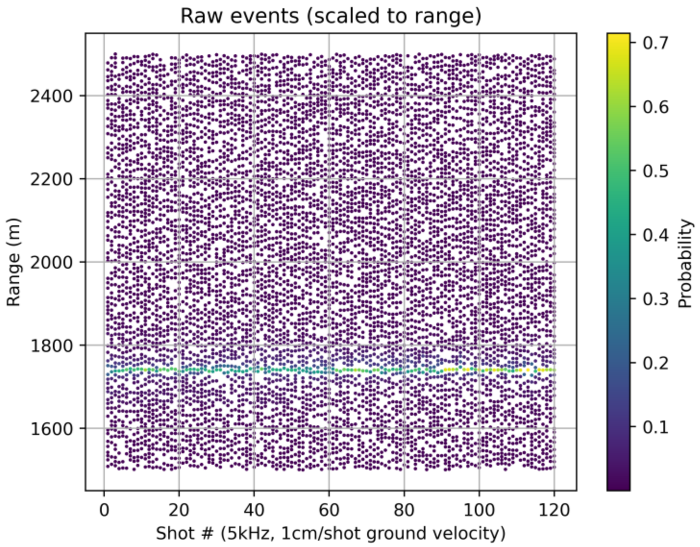


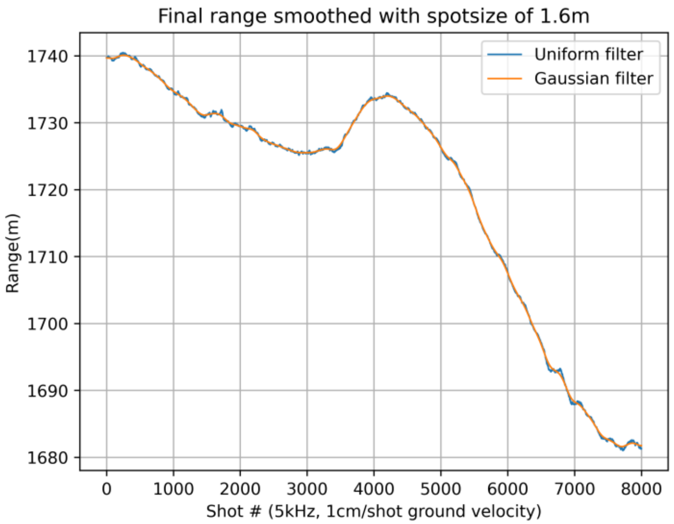


New algorithms on very noise data
Idea: Bayesian inference

The method provides:
- Outlier rejection
- Signal-to-background discrimination
- Shot-by-shot ranging
- Tracking of changing surface distance
- **Analysis method:** Patent pending



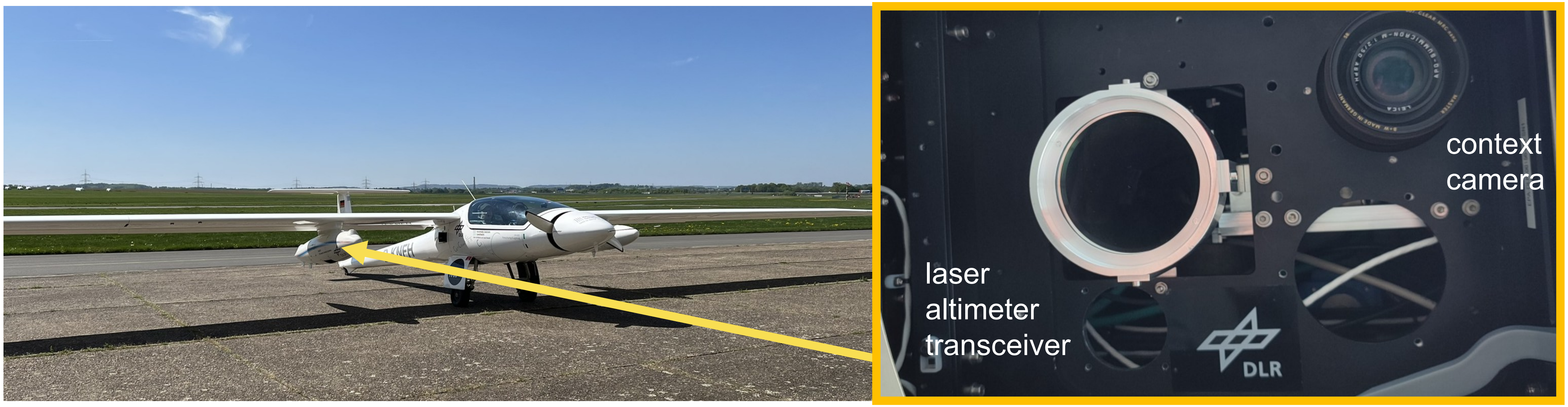




System validatin in Airborne Demonstration

Airborne measurements were performed using a motor glider.

- Flight altitude: approximately 300–2500 m
- Flight speed: approximately 50 m/s
- 149 measured profiles
- Approximately 1.2 million laser shots
- Approximately 260 km total profile length
- Measurements over water, vegetation, agricultural and urban surfaces



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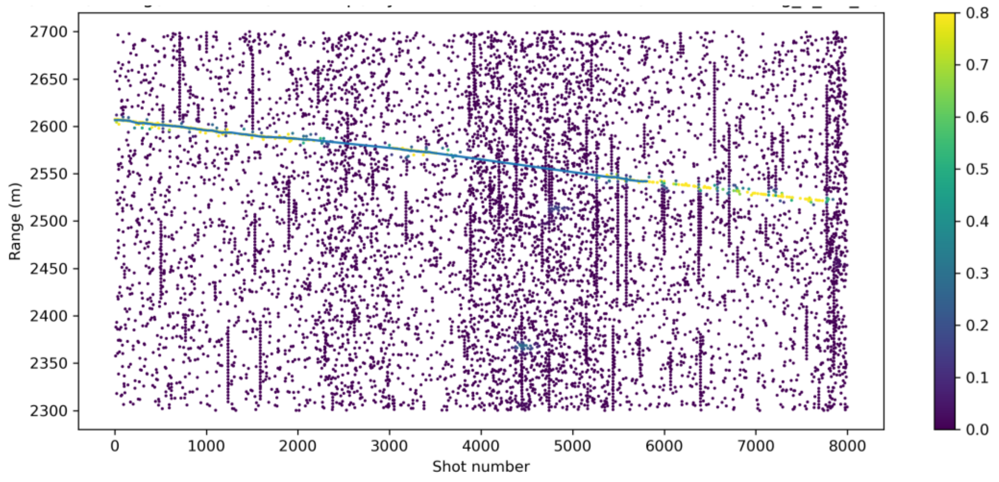
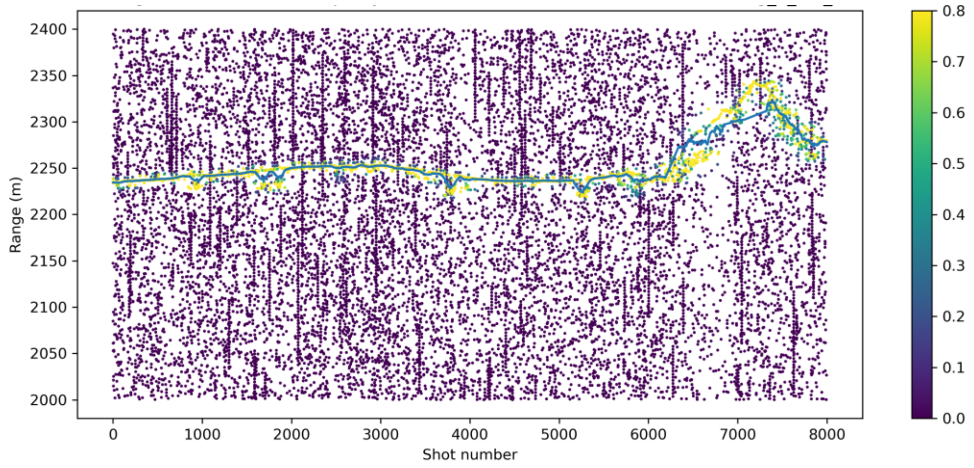
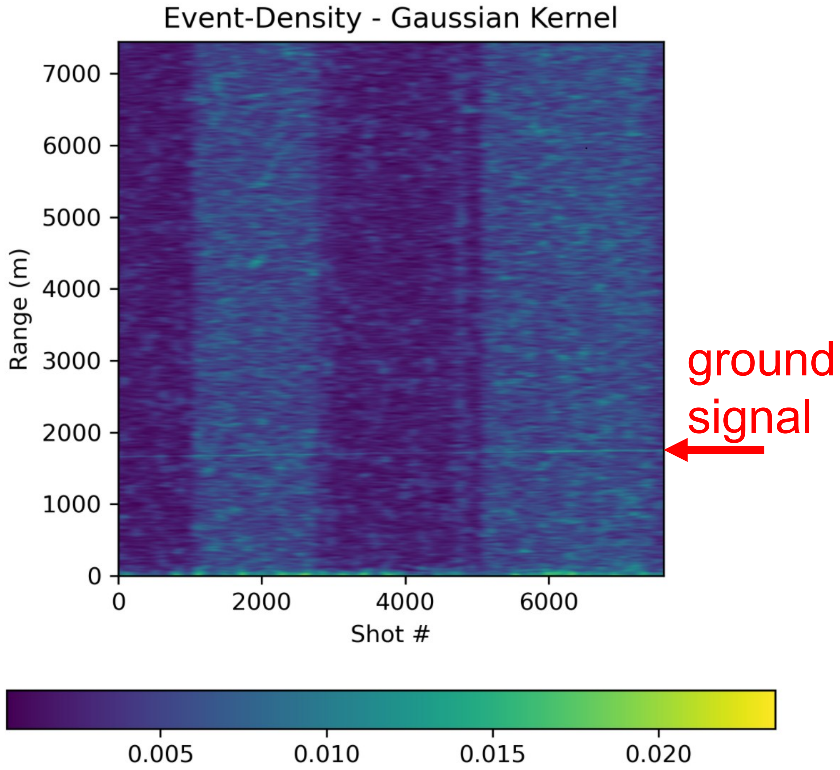
Flight Campaign Tracks

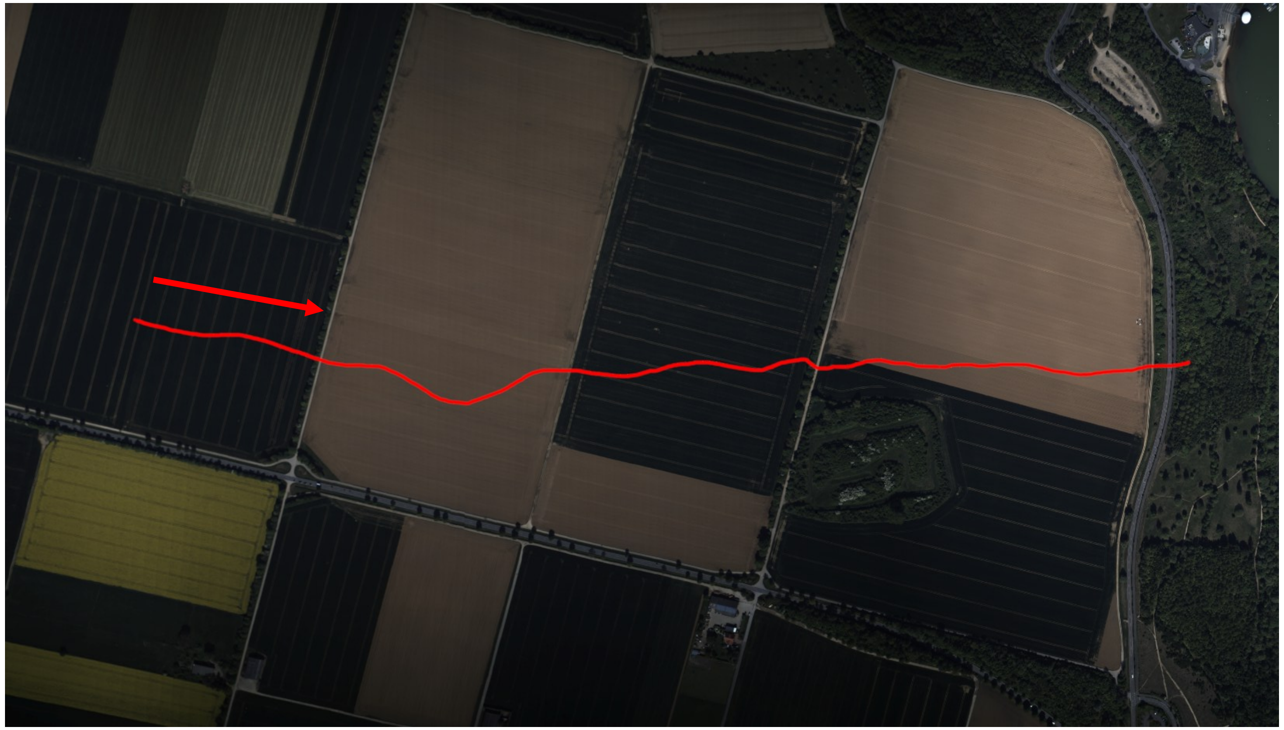




Flight Campaign Albedo Measurements

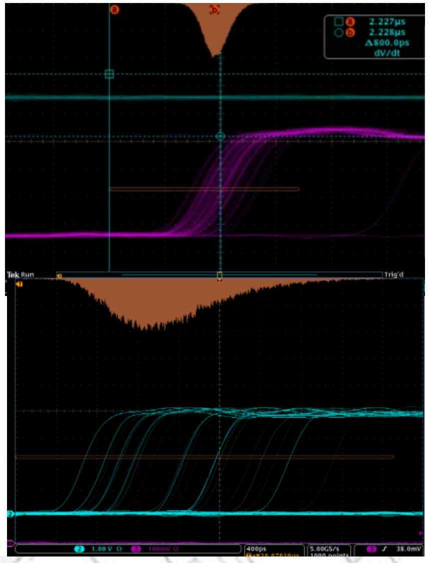
- Photon density changes with surface reflectance
- Surface transitions are visible in the event data
- Relative albedo can be derived after geometric correction





Demonstrator on the Landeskalibrierstrecke

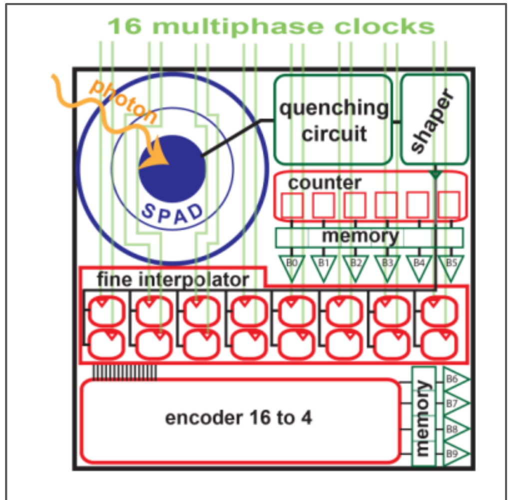
- calibration and testing facility
- measurements over calibrated baselines
  (~ 0.1 mm accuracy)
- characterization of systematic timing offsets
  (< 1 cm)
- signal-strength-dependent first-photon bias characterized
  (< 5 cm)
- absolute ranging calibration
  (~ 10 cm)



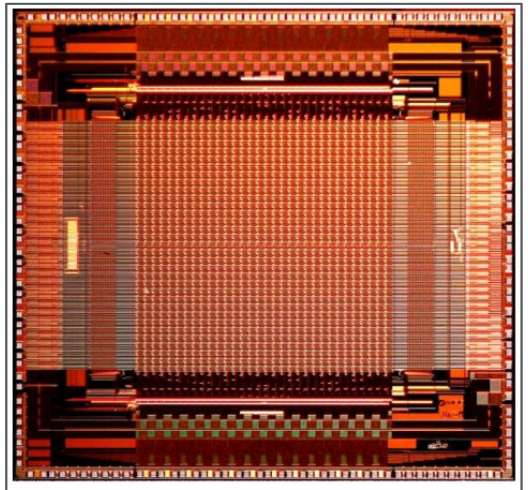
New SPAD Array Detectors

- multi-pixel SPAD matrix spatially resolves the laser footprint
- ungated or extended-gate operation
- all circuits close to the SPAD respectively on the die
- only digital output to the instrument electronics
- avoids harness with the weak analogue sensor signal

Example: 32x32 px SPAD array:



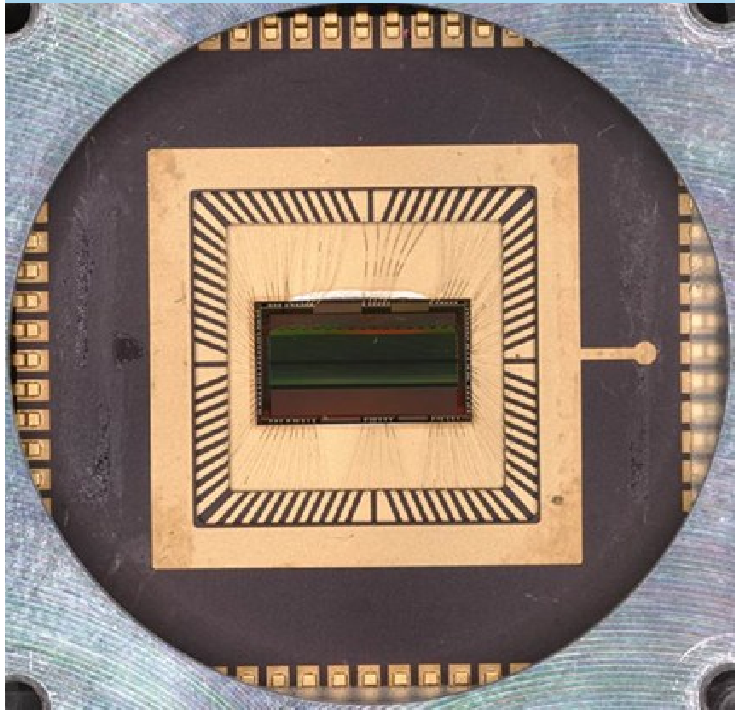
Pixel block diagram, with 30 μm SPAD and 10 bit TDC.



9. Micrograph of the 32 × 32 CMOS SPAD imager.

Pictures from 10.1109/JSTQE.2014.2342197

Detector array SPADeye2 used in DLR laboratory tests for single-photon detection (array 2 x 192 px)
from Fraunhofer IMS



What Future Laser Altimeter Instruments Need

Instrument

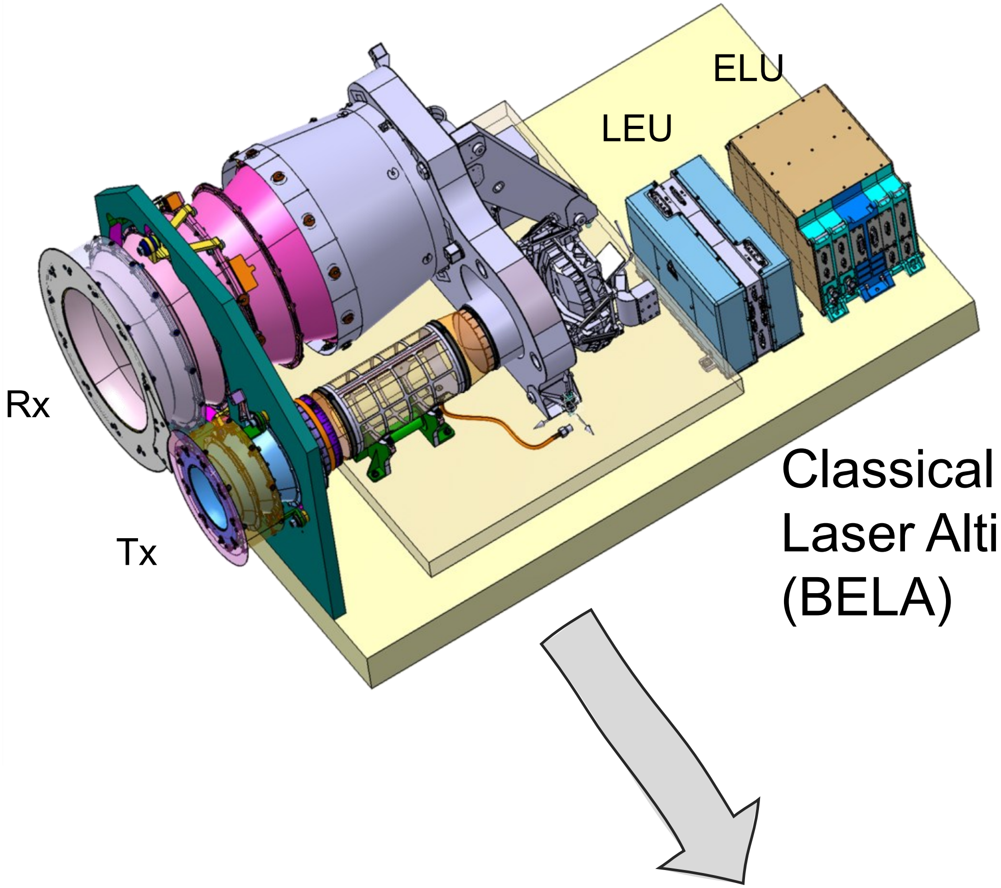
- Compact, low-power architecture
- Fully digital detector readout
- Radiation-tolerant onboard processing

Measurement

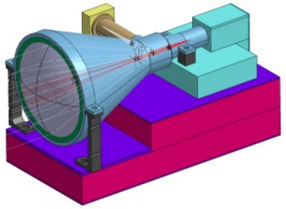
- Shot-by-shot event detection
- Fast range acquisition and tracking
- Spatially resolved photon statistics

Science

- Range, albedo, slope and roughness
- Multi-layer detection for clouds or plumes



Classical Laser Altimeter (BELA)

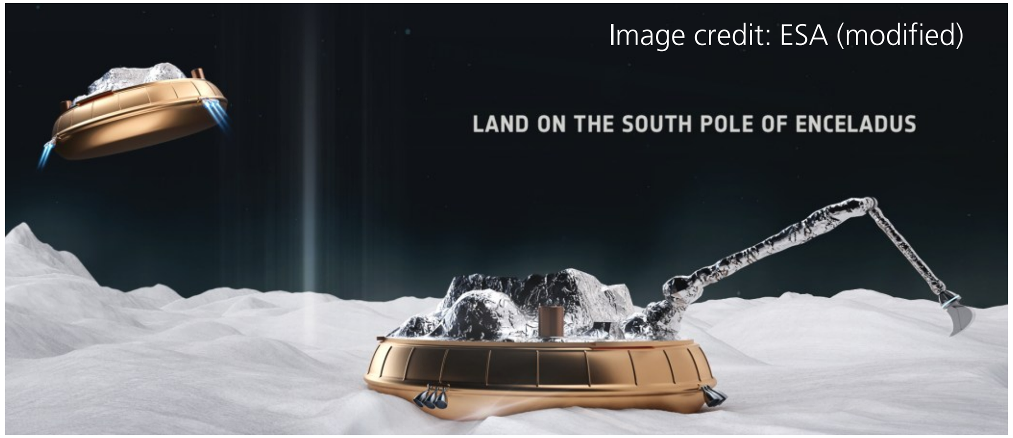


Miniaturized Laser Altimeter

Application to Enceladus

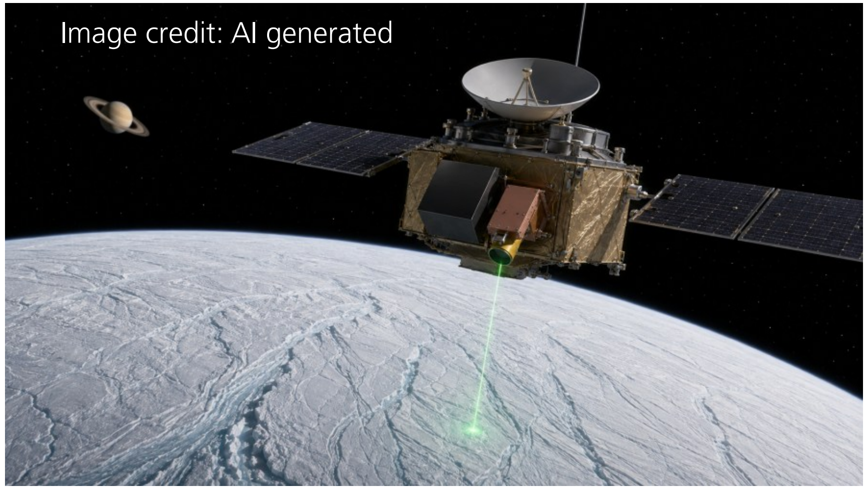
Proposal for ESA ITT „SURVEY AND FEASIBILITY STUDY OF OPTICAL TECHNOLOGIES FOR THE L4 ENCELADUS LANDER“

- **High-altitude mode:** 100–20 km, low-divergence laser and 5 × 5 SPAD pixels
- **Descent mode:** 600 m to <10 m, high-divergence laser and full 1000 × 1000 SPAD array
- Enables detection of hazards down to approximately 30 cm
- Dual lasers provide redundancy and support snow-depth measurements
- Compact design within an **8U envelope**



Preliminary Instrument SWaP Summary

Parameter	Baseline estimate
Mass, including 20% margin	**~7.7 kg**
Power, nominal mode (laser active)	**~27.8 W**
Total volume	**~7.2 L**



Application to Enceladus – Link Budget

- Dual-Mode Single-Photon Detection Laser Altimeter with SPAD array
- the high-altitude mode uses a **25-pixel region of interest** to maximize signal photons for long ranges
- during low-altitude mode, the complete a **1-megapixel SPAD array** is used for spatially resolved (down to ~ 30 cm) terrain and hazard measurements

Scenario	Range	Laser energy	Footprint	Detector pixels used	Detected signal photons/pulse/px *
High altitude	100 km	2 mJ	25 m	5 × 5 = 25 pixels	**~11**
High altitude	20 km	2 mJ	5 m	5 × 5 = 25 pixels	**~274**
Low altitude	600 m	2 mJ	0.17 m	1000 × 1000 = 1 MP	**~8**
Low altitude	100 m	2 mJ	0.05 m	1000 × 1000 = 1 MP	**~274**

*assumption is 80 mm dia. telescope

The Roadmap: From Demonstrator to Flight Model

Demonstrated here

- Single-photon ranging in laboratory and airborne campaigns ✓
- Bayesian signal extraction under high-background conditions ✓
- Absolute calibration of systematic offsets to below 10 cm ✓
- Albedo and multi-layer measurements ✓

Next development steps (and partly already heritage)

- Radiation-tolerant SPAD array with on-chip timing
- Flight-qualified laser and transceiver optics
- Onboard processing on a radiation-tolerant FPGA
- Integrated environmental qualification

Summary and Conclusion

- Single-photon ranging was validated in laboratory and airborne tests
- Bayesian processing enables robust ranging and characterization of weak signals
- Ungated detection mode features measurements of albedo, multi-surfaces, plumes, snow
- SPAD arrays provide spatially resolved, fully digital detection
- Link-budget results support a dual-mode altimeter for Enceladus

Single-photon detection, statistical processing and SPAD arrays provide a path from the airborne demonstrator to a compact deep-space laser altimeter.