TECHNICAL CONCEPT OF A EUROPEAN LASER ALTIMETER FOR PLANETARY EXPLORATION

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Abstract

In the past year, our team has developed an alternative concept for a high-performance Laser Altimeter for Planetary Exploration (LAPE) for a Mercury mission with parameters similar to the BepiColombo Mercury Planetary Orbiter mission. The instrument must be capable to operate in a harsh thermal environment. Its mass is required to be less than 10kg and the power consumption less than 20W. In order to avoid excessive thermal loading and to keep the weight down we have chosen to study the applicability of a small receiver telescope with 15cm aperture. The key features of this alternative altimeter concept are a high repetition rate microlaser and single photon detection by gated "Geigermode" APDs. The cw-operation of the pump laser diodes of the microlaser avoids power switching and also makes bulky capacitor banks unnecessary. These features lower the operation risk and mass requirements substantially. However, due to the high shot repetition rate the data processing becomes more complex and requires special provisions for binning and averaging of the data. The basic performance of our concept has been evaluated by simulation. This paper outlines critical aspects of the altimeter design and discusses some of the simulation results.

Introduction

Laser altimeters have become useful tools for planetary exploration as has been convincingly demonstrated by e.g., the MOLA (Mars Orbiting Laser Altimeter) instrument on Mars Global Surveyor [1]. The Mercury Laser Altimeter MLA [3] has been launched on board NASA's Messenger mission in the summer of 2004. Another laser altimeter is part of the strawman payload of the ESA cornerstone mission BepiColombo which is scheduled for launch to Mercury in 2012 [2]. The general concept of a laser altimeter is shown in figure 1. A solid state pulse laser (L) generates short laser pulses of approximately 1 ns pulse width and transmits them via a small optical telescope. A high bandwidth optical detector such as a PIN-diode records the moment of laser fire and logs it with respect to a high precision time-scale. After traveling between 400 and 1600 km the laser pulse hits the ground on Mercury and a proportion of around 20% is reflected [5]. When returning back to the spacecraft another optical telescope picks up the remaining light of the laser pulse and focuses it onto a highly sensitive photo detector (D). Sharp spectral and spatial filtering is applied in order to keep the noise background and the thermal load low. This moment of detection again is timed by the onboard event timer and the range (d) of an individual measurement taken at the epoch of the start event is determined by evaluating the time of flight as $d=c\cdot t/2$. In order to reduce the measured raw ranges to a meaningful altitude above ground, it is necessary to correct these raw range measurements for internal delays caused by the time of transit of the electrical signals inside the altimeter instrument. Furthermore one has to reduce the range measurement to a geometrical point of reference at the spacecraft. The difference Δt between stop and start epoch valid for the moment of laser fire t_0 is then converted to a range measurement according to:

$$h(t_0) = x(t_0) - \frac{1}{2}c(\Delta t(t_0) - d)\,,$$

where $x(t_0)$ is the orbital position of the satellite, c the vacuum velocity of light and d accounts for constant internal signal delays in order to reference the range measurements to the center of mass of the satellite. The mission requirement for the precision of the altitude measurements is less than 1.5 m. A prerequisite of the altimeter operation is a good control of the satellite orientation in “Pitch” and “Roll”, as well as a stable nadir telescope pointing and a precise orbit determination. The post-processing error must be substantially smaller than the measurement resolution. For this paper’s discussion a sufficient knowledge of the satellites reference point is assumed.

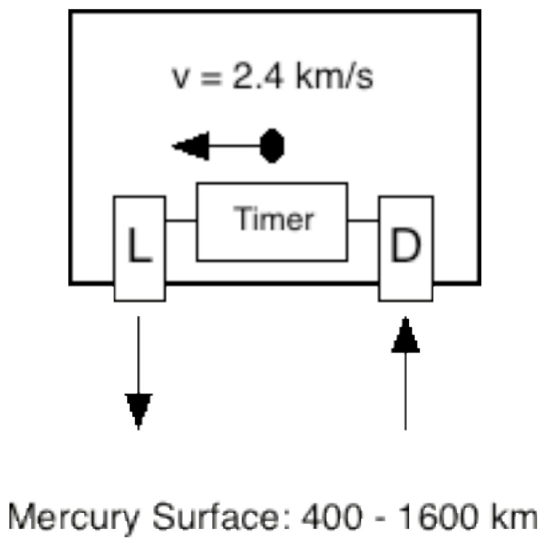

Figure 1: Schematic diagram of an altimeter on a spacecraft. Only the transmitting pulse laser (L), the detector with receive telescope (D) and control electronics including the event timer (Timer) are indicated.

Conventional altimeter concept: In previous altimeter missions in Earth and Mars orbit, such as LITE and MOLA telescopes with apertures larger than 0.5 m have been used. Together with a pulse energy of more than 20 mJ at a repetition rate of 10 Hz, this produces a comfortable link budget margin. Even under the application of detectors with moderate quantum efficiency, echoes are obtained at almost every shot. This allows to carry out measurement of the time of flight as well as to use the variations in the pulse width as a terrain slope indicator. For a mission to the innermost planet the application of a large telescope aperture is critical because of the hostile environmental conditions, in particular the excessive solar heat influx. MLA has four telescopes with 12.5cm aperture [3]. The recently proposed BepiColombo Laser Altimeter BELA foresees a telescope with 25cm aperture [4].

Alternative altimeter concept: In this paper, we report on a study of an alternative altimeter concept, which may have the potential of achieving the mission goals by going from a strict conventional multi-photon return pulse requirement to a statistical single photon detection scheme. At the same time the instrument is much more compact and the requirements for power and weight are greatly reduced. Instead of using high power Nd:YAG pulse lasers we consider a high repetition microlaser working at a pulse repetition rate of about 20 kHz at an energy level of around 10 μJ[1]. Because of the moderate demands on the range resolution of 1.5 meter, the pulse width is not critical and may be chosen to be around 2 ns. In comparison to high power pulse lasers with low repetition rate, microlasers do not require water cooling and are much smaller and lighter than conventional Nd:YAG systems. Since the microlasers of interest are cw- pumped, there is the considerable advantage of a reduced risk of laser failure. In order to match the high repetition rate and the low energy of the transmitter, corresponding changes to the detector system are necessary. Avalanche photo diodes (APD) operated in the Geiger mode [6] reach quantum efficiences well in excess of 50% and have demonstrated their suitability for extreme sensitive single photon detection in Lunar Laser Ranging [7]. Since they are solid state devices they require less space and work under convenient operating voltages in contrast to a photomultiplier. In order to satisfy the 1.5 m range resolution requirement the altimeter is equipped with a direct counting clock operated at a frequency of 350 MHz. The time-scale in the form of a frequency reference and 1 pulse per second (pps) signal is presumably provided by the interface bus of the spacecraft and is therefore considered as given here. The noise reduction, averaging of data points and slope detection is done in the onboard unit of the altimeter in real time as the spacecraft carries out the measurements. The preprocessed data are then transmitted back to Earth. Suitable averaging and data format definitions have to ensure that the maximum data rate of 500 bps is not exceeded.

The entire alternative altimeter concept is based on a differently arranged trade-off. We avoid large apertures, high mass, and high risk of failure by utilizing higher receiver sensitivity, single photon counting and a statistical data processing approach. This is achieved through a substantially higher repetition rate of the data taking cycle. Simply speaking, we are looking at hardware of lower complexity at the expense of more sophisticated software requirements. The concept study offers interesting perspectives for future planetary missions to Mercury or beyond. Nevertheless, the full development of such an instrument is a complex undertaking. Because the schedule for the development of instruments for BepiColombo is very tight and funding is limited we have not proposed this alternative altimeter for the BepiColombo payload.

Design considerations

Before the design considerations for this alternative approach are discussed, we are summarizing important mission characteristics (see table 1):

Table 1: Laser Altimeter Operation Characteristics

Parameter	Value	Specification/Comment
Mercury Properties		
Albedo	0.2	mean value at the Laser wavelength
Distance to sun	68.5 / 104 Mio km	perihelion / aphelion
Observing conditions		

[1] Recently a compact microlaser with an extra amplifier stage capable of approximately 100μJ pulse energy was considered feasible.

S/C Distance to surface	400 / 1500 km	periherm / apoherm
S/C Speed w.r.t. Ground	2.6 / 1.35 km/s	periherm / apoherm
Operation		
Laser Spot Diameter	40 / 150 m	periherm / apoherm
Shot-to-Shot Spacing	0.16 / 0.084 m	periherm / apoherm
Single Shot Detect. Prob.	0.0188 / 0.0012	periherm / apoherm
Typical Integration Time	0.1 / 0.5	periherm / apoherm
Int. Detection Probability	0.9 / 0.2	periherm / apoherm
Maximum Data Rata	500 bps	
Heat / Solar Flux		
Solar Irradiance at Mercury Surface	14490 / 6290 W/m^2	periherm / apoherm
Planet's Black Body Surface Temperature	630 / 575 K	periherm / apoherm
VIS Flux	2.7 W	VIS flux encountering the optics *)
	0.05 W	Vis flux entering the optics *)
IR Flux	10.8 W	IR flux encountering the optics *)
	3.2 W	IR flux entering the optics *)

*) worst case: Mercury at perihelion, spacecraft at periherm

Figure 2 shows a block diagram of the altimeter design. The central function block is the orbit reference. It provides time and spacecraft position. Based on this information the microlaser is fired. The epoch of the generated laser pulse is recorded by an event timer. An afocal beam expander is used to fill the full aperture of a small (3cm diameter) coelestat.

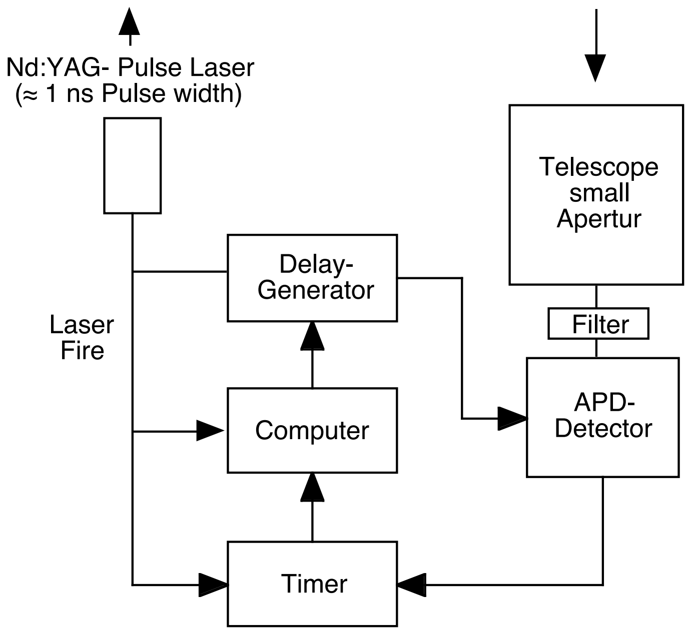

Figure 2: General block diagram of a laser altimeter

This mirror can be adjusted to compensate for velocity aberration, should this be necessary. The reflected pulse from the Mercury surface is captured by a 15 cm aperture receive telescope in Cassegrain configuration. Both telescopes are operated near the diffraction limit.

A 1 or 2 nm wide spectral filter with an additional coating for solar heat flux reduction at the front end of the receiving telescope minimizes the amount of unwanted radiation substantially and therefore reduces the heat influx. A spatial filter at the Cassegrain focus lowers the background light input and limits the receiver field of view to about 5 seconds of arc. Additional spectral filtering reduces the unwanted background light even further. Based on the precision of the orbit reference the microprocessor unit provides a range gate of 2 μs corresponding to 300 m tolerance for the range. Since the entire concept is based on the single photon detection mode, we detect far less than one photo-electron (p_e) per shot, on average $p_e \sim 0.005$. Neglecting the contribution from background light far less than one echo per gate is expected. However in the presence of background light we may well have the case of more than one photo-electron per gate. Since the detector and timing system can handle only one event per gate, we also have to consider the case of the loss of valid returns due to the detector dead-time.

For that purpose the concept is using a high repetition rate of 20 kHz and a statistical approach by binning dead-time corrected data of 2000 shots. This allows us to obtain one final measurement at 260 m intervals (periherm) and 675 m (apoherm and longer averaging), while the spot-size of the collimated laser beam on the ground is 40 m at periherm (400 km) and goes up to 150 m for an altitude of 1600 km.

Avalanche photodiodes operated in the Geiger- mode are currently the most sensitive type of detectors for photon counting applications [7]. Depending on the type of solid state diode a quantum efficiency of more than 50% can be achieved. The Geiger- mode is characterized by gating the bias voltage of a reverse operated avalanche photo-diode well above the breakdown voltage [8]. As a consequence however this results in the detection of one event per gate. A rather short gate length of around 10 μs is a practical maximum, unless cryogenic cooling is employed. In case of a high background noise level the duration of the gate must be reduced further.

Handling as much as 20 000 shots per second is a considerable demand for the timing device, which therefore must be as simple as possible. For this purpose a direct counting Epoch timer with a clock rate as high as 350 MHz, corresponding to a range resolution of 2.9 ns per clock cycle is sufficient. This is well within the range resolution requirement of 1.5 m and avoids the necessity of complicated interpolator hardware.

Simulations

Based on the above outlined severe mission constraints we have built a simulation suite in order to analyze the properties of the photon counting approach. This suite allows the investigation of the impact of variations in the parameters of various altimeter components. Figure 3 shows an example of such a simulated range measurement.

The simulation with an integration time of 0.1 s per frame is based on an orbit height of 800 km above the Mercury surface, a microlaser with 2 μJ pulse energy and a repetition rate of 16 kHz. A telescope aperture of 15 cm with a system transmission efficiency of 50% and a detector quantum efficiency of 60% was chosen. Since the signal to noise ratio (SNR) is barely exceeding a value of 2, not all averaged frames will obtain an ad hoc valid range measurement. However suitable post-processing strategies are expected to allow echo identifications at a SNR worse than this example. This possible improvement is considered as an extra option and was not taken as a baseline for the altimeter design. Because the SNR at higher altitudes will always be very low, we have looked at the probability of detecting a return as a function of integration time. Three situations were of particular interest:

- maximum peak detection scheme
- simple range prediction based on previous return identifications
- a less conservative but still highly realistic parameter ensemble

The parameter sets for these simulation runs are summarized in table 2 and correspond to a worst case scenario with the satellite at apogee.

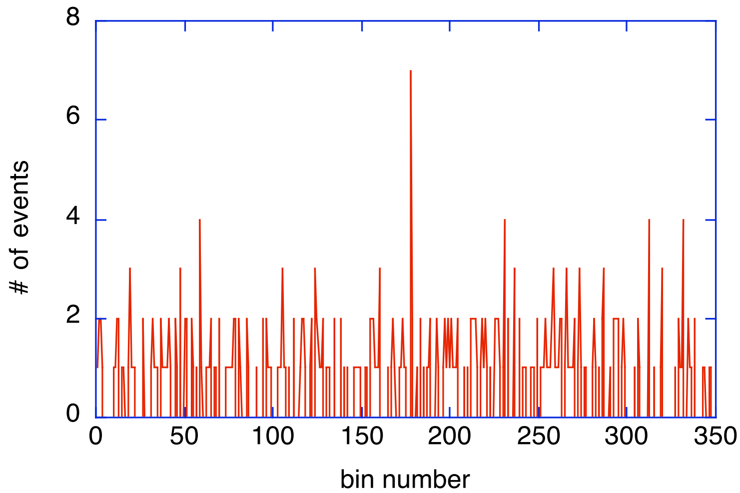

Figure 3: Example of a simulated altimeter range measurement at a distance of 800 km, obtained after 0.1 second of integration.

When applying an integration time of 2 seconds the detection probability of the very conservative parameter set Case 1 approaches 80% while it is 20% at an interval width of 0.5 seconds, which will still give a reasonable resolution for adjacent data points along the ground-track of the satellite. Case 2 assumes more laser power, a slightly higher system transmission and detector quantum efficiency, but also a wider optical bandpass filter. Apart from the laser specifications, which seem a reasonable expectation, the system parameters are still assumed to be very moderate and therefore leave room for optimization.

Table 2: Parameter list as used in the simulation based on a modified program of [9]

Parameter	**Case 1**	**Case 2**	**Units**
Wavelength	0.532	0.532	µm
Pulse Energy	2.0	8.0	µJ
Pulse Length	1.0	1.0	ns
Laser Beam Divergence	100.0	100.0	µrad
Telescope Aperture Size	0.15	0.15	m
Receive Optics Transmission	0.5	0.6	
Pulse Repetition Rate	16	16	kHz
Detector Noise Rate	200	200	kHz
Detector Quantum Efficiency	0.6	0.7	
Range Gate Width	1.0	1.0	µs

Clock Frequency	350	350	MHz
Filter Bandwidth	0.1	0.15	nm
Range	1600	1600	km
Mercury Albedo	0.2	0.2	
Averaging Time	0.1 – 2.0	0.1 – 0.4	s
Sun Illumination	no	no	

Without any changes to the hardware parameters of the ranging system one can improve the detection rate by including a priori information in the histogram analysis. The middle line (1) in figure 4 illustrates this for a simple case. When the maximum search in the measured histogram does not give an unambiguous result, the largest peak around the range value of the previous unambiguously identified ground echo is chosen as the most probable result.

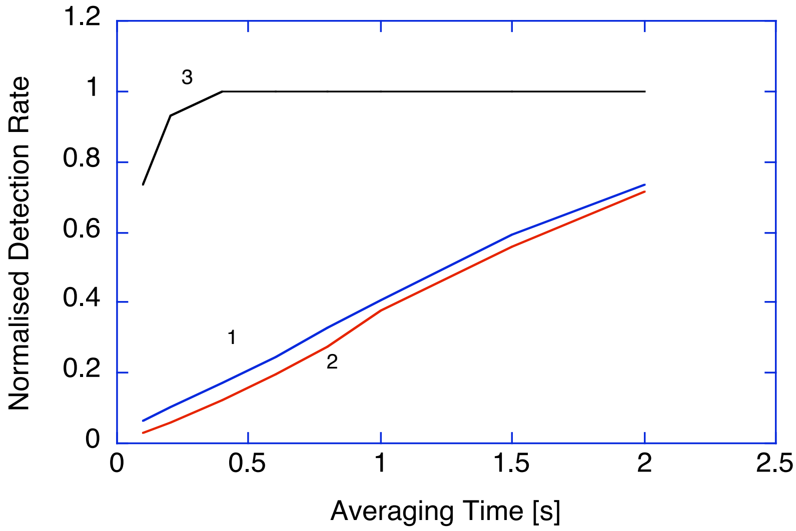

Figure 4: Normalized detection rate for the LAPE from an orbit height of 1600 km. A simple return prediction model (1) improves the return rate already noticeably over a plain range-gate evaluation (2). For the case of moderately improved parameters the detection rate improves as in curve (3).

Other more rigorous forms such as additional pulse width evaluation in the return histogram will improve the detection rate still further. This approach is based upon the assumption that the Mercury topography will spread the histogram peaks of the returns in a characteristic fashion and therefore helps to distinguish echoes from arbitrary noise events in the averaging process. In On top of that this approach provides additional information about the slope of the terrain. The drawback however is a dramatically reduced SNR when the pulse spreading becomes large.

For the poor case scenario "Case 1" in table 2 a sample dataset of the recovered ground-track is shown in figure 5. Since the averaging time has been set to 0.5 seconds, a little over 20% of the data contains identified ground returns. This corresponds to one range reading at roughly every 2.5 seconds. Since the space probe is assumed to be at apoherm the ground speed is at its minimum of approximately 1.4 km/s. A blow up of the front portion of the Mercury surface track of figure 5 is shown in figure 6. One can see that despite of all gaps a fair part of the echoes could still be recovered. At perigee the SNR is much more than one order of magnitude better and the averaging time can be reduced substantially to values as low as 0.2 seconds.

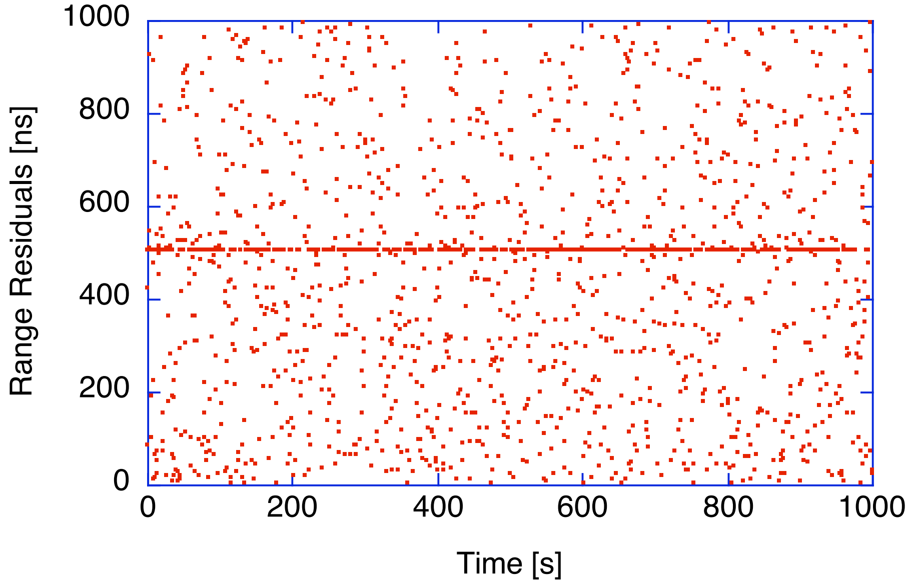

Figure 5: Simulated range residuals with a range resolution of 44 cm. The diagram shows an interval of 1000 seconds worth of data computed for a total range of 1600 km with a detection probability of around 20%.

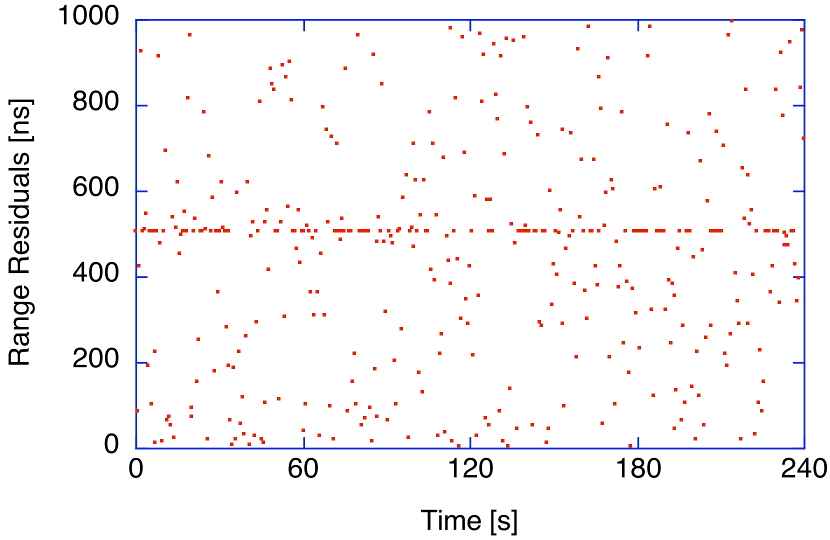

Figure 6: Blow up of the beginning of the diagram of figure 5. A section of the ground track corresponding to 4 minutes of the mission is shown.

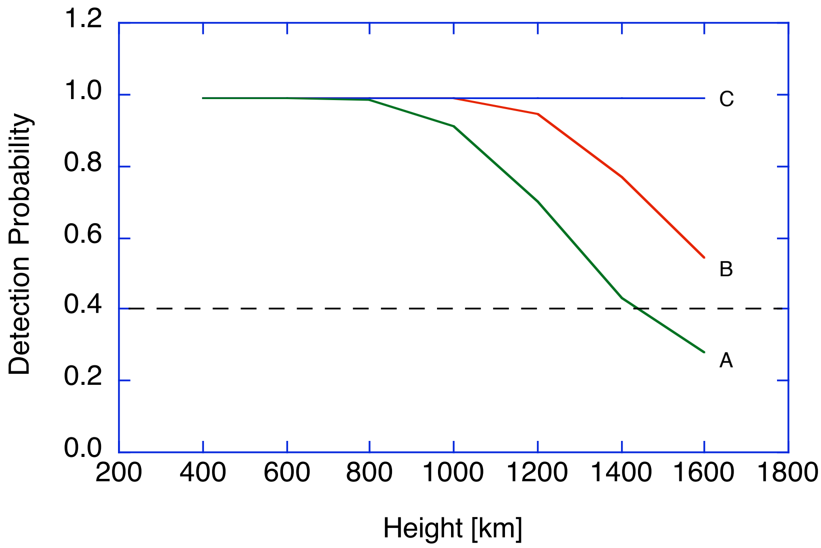

Figure 7: Detection Probability versus satellite height of one identified altimeter reading per time bin for 3 different parameter sets similar to table 2. The integration is 1 s and the laser energy was set to 2 µJ (A), 4 µJ (B) and 6 µJ (C).

Finally, it was investigated what detection probability as a function of range can be expected from a single photon counting altimeter. The laser beam energy of case 2 in table 2 was set to values of 2µJ (track A), 4 µJ (track B) and 6 µJ (track C). The corresponding integration time was 1 s for all 3 cases. Figure 7 shows that except for the last part of track A, the required detection is well in excess of 40%, which is an important mission requirement.

Conclusion

An alternative concept for a Mercury altimeter has been investigated. We have analyzed the potential of a single photon counting approach that will save mass, power, and volume. Instead of using a large and powerful pulse laser we have looked at a microlaser with a very high repetition rate. High receiver sensitivity and a statistical data evaluation technique allowed us to work in a different parameter regime of the link budget equation. Many aspects of the approach in this paper have been tested in the past in a different context, so that essentially only the high repetition rate of this altimeter concept is currently fully untested. Simulations show, that a fair number of mission requirements are well met by this concept, however there are also shortcomings and high risk aspects to be mentioned. Operations in daytime (target area illuminated by the sun) are not practical with the system parameters as used in this study. In particular a significant increase in laser power of more than a factor of 10 over the maximum values used in this work would be required to enable daylight operation. This seems feasible but is not yet demonstrated. Another issue is the reliable setting of a sufficiently wide range-gate under all mission conditions. A possible solution will increase the software complexity of this concept significantly.

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