NASA project

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Introduction

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Contents

1 High level specifications

The radiation and mass, power and volume budget are listed in table 1 and table 2.

Table 1: Overview of radiation limitations

Radiation	
Total Integrated Dose in Silicon behind 100 mil Al spherical shell	500 krad

Table 2: Requirements for mass, power and volume

Mass, Power & Volume Budget	
Optical Head	<5 kg
Inside vault	<1 kg
Max cable length between optical head and electronics	2 m
Power	<50 W

The Lidar sensor features two operation modes: the Altimetry Mode, and the Hazard Detection Mode.

1.1 Altimetry Mode

Altimetry Mode is the first phase of the landing. During the Altimetry Mode, the Lidar sensor has to provide the altitude of the sensor in relationship to the surface op Europa. The requirements for the Altimetry Mode are listed in table 3

Table 3: Requirements for Altimetry Mode

Altimetry Mode	Threshold	Goal
Max acquisition Slant Range	5 km	8 km
Range Accuracy (3-sigma)	1%	0.10%
Update Rate	0.1 Hz	1 Hz

1.2 Hazard Detection Mode

During the Hazard Detection Mode a 3d map of the surface of Europa must be created around the landing place. The Hazard Mode is operational when the sensor is close enough to the surface of Europa. The requirements for the Hazard Detection Mode can be found in table 4

Table 4: Requirements for Hazard Detection Mode

Hazard Detection Mode	Threshold	Goal
Max range (altitude)	400 m	500 m
Min Operational Range (altitude)	5 m	1 m
Range Accurcay (3-sigma on final 3D map)	10 cm	5 cm
Ground Sample Distance (per pixel on 3D map)	10 cm	5 cm
Ground Area Coverage at max altitude	100 m x 100 m	125 m x 125 m
Time for 3D map creation	1 s	1 s

2 System engineering level design

In this section a system engineering level design is constructed that meets the performance requirements stated in section 1. Section 2.1 shall provide an overview of the system, section 2.2 shall list the assumptions made, and section 2.3 shall elaborate on trade-offs and design decisions.

2.1 Overview

A schematic overview of the sensor is shown in fig. 1.

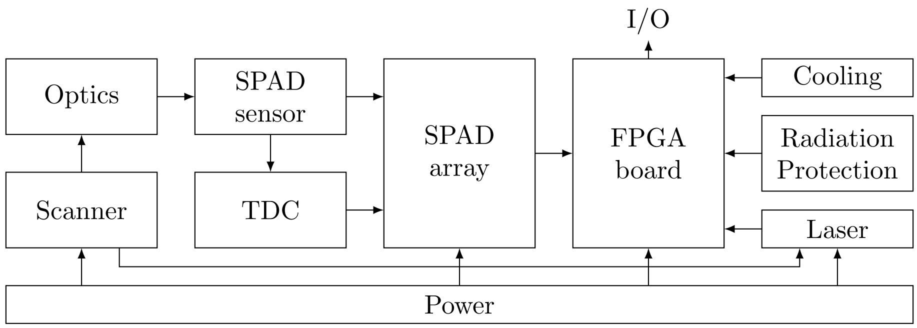

Figure 1: Schematic overview

Laser: The laser must send short pulses but powerful pulses at a predefined frequency, to transmit photons that can be detected by the SPAD Sensor. A critical requirement for the laser is the amount of photons it is able to transmit as a function of time, within the budget and technical limitations.

SPAD Sensor: The Single Photon Avalange Diode (SPAD) is responsible for generating a digital pulse when hit by a photon. A circuit build around the SPAD must ensure that the sPAD is quenched as quickly as possible to minimize the deadline. A critical requirement for the SPAD is a small jitter to maximize the accuracy of the sensor.

TDC: The Time Interval to Digital Converter (TDC) is connected to the laser and the SPAD Sensor. The TDC must measure the time difference between the transmission of teh laser and the receiving at the SPAD sensor. This measurement requires an accuracy of tens of picoseconds to meet the accuracy requirements.

Scanner: The scanner handles the scanning motion that is needed to accumulate the entire picture. Different scanning motions can introduce undesired jitter and heavily influency the amount of SPAD Sensors that are needed on teh SPAD Array.

SPAD Array: The SPAD Array integrates the SPAD Sensors on a chip and connects them to the TDC's. The layout of the SPAD Array is closely rtelated to the scanning motion that is used in the scanner.

Optics: The optics must tranfer as much of the incomming photons as possible to the sensitive area on the SPAD Sensors. The Optics part also implements a bandpass filter around the target frequency.

FPGA Board: The FPGA Board controls the sensor. It is responsible for accumulating and interpreting the measurements from the TDC's, and controlling the Scanner and Laser.

Cooling: The cooling has to keep the temperature of the FPGA chip under a threshold temperature.

Radiation Protection: The Radiation Protection shields sensitive parts of the sensor from radiation. The most sensitive part of the system is expected to be the FPGA Board, based on experience.

Power: The power block has to supply the scanner, SPAD Array, FPGA Board, and the laser with the required power. The power block has to operate within the specified power budget.

2.2 Assumptions

This section will list the assumption that are made throughout the design.

Reflectivity of surface Europa: It is assumed that out of all light that hit's Europa, 35% is reflected in a perfectly diffuse manner. The rest of the light is either reflected in a specular way that will not hit the sensor, or absorbed by the ice on the surface of Europa. This assumption is made in order to avoid the added complexity when using a more elaborate model.

Wavelength laser: The wavelength of light emitted by the laser is assumed to be 850 nm. This wavelength is a typcial choice for Silicon SPAD's.

Bandpass filter:A bandpass filter will be used o filter background noise. This filter is assumed to be a bandpass filter with a center frequency of 850 nm and a FWHM of 10 nm.The minimum transmission of the filter is 50%. These values are directly taken from the "*850nm, 10nm FWHM, 12.5mm Mounted Diameter*" product made by Edmund Optics and sold for 75 $.

Jitter of SPAD Sensor: The jitter of the SPAD Sensor, or Full Width Half Max (FWHM) is assumed to be 100 ps. This value is a typical FWHM for state of the art Silicon SPAD's.

Jitter of TDC: The jitter of the TDC's is assumed to be insignificant when compared to the jitter of 100 ps caused by the SPAD Sensors. Experience with previous designs show that TDC jitter is generally a very small contributor to overall jitter.

Accuracy of TDC: The accuracy of the TDC is assumed to be 50 ps, and therefore well within the accuracy requirements. The accuracy should be 5 cm. Using eq. (1), the desired accuracy is 333 ps.

$$t = \frac{2x}{c} \tag{1}$$

where x is the accuracy in distance, and $c \approx 3 \cdot 10^8$ the speed of light. The factor two is present because the light travels the distance twice.

Sunlight: It is assumed that the light from the sun that is reflected of Europa is the only signifant contributor to background noise. No other sources of light will be considered.

Photon Detection Probability: It is assumed that the PDP of the SPADs is 35%.

Effective area on chip: It is assumed that 5% of the SPAD Array can be used to receive photons. This assumption is based on current gen Silicon SPAD's.

What should I choose here? Swisspad or LinoSPAD? (confused)

Signal to Noise Background Ratio: It is assumed that a Signal to Noise Background Ratio (SNBR) of 0 dB will be sufficient for the sensor. This value is based on previous research on Silicon SPADs.

Laser efficiency: It is assumed that the laser has an efficiency of 10%.

Surface of SPAD: It is assumed that the surface of a single SPAD is $20 \times 20\,\mu m^2$.

2.3 Trade-offs and Methodology

This section will list the trade-offs that can be found in the system. Each trade-off will be analysed, and based on that, a decision will be made.

2.3.1 High Frequency vs Low Frequency pulses

The pulse frequency is limited by the roundtrip time of the transmitted photons. The roundtrip time can be calculated using eq. (2)

$$t_{round} = \frac{2r}{c} \tag{2}$$

where $c \approx 3 \cdot 10^8$ is the speed of light, and r the altitude of the sensor. The maximum pulse frequency can then be calculated using eq. (3)

$$f_{pulse} = \frac{1}{t_{round}} = \frac{c}{2r} \tag{3}$$

The maximum altitude are different for the Altimetry and Hazard Detection mode. The maximum pulse frequency of both modes is shown in table 5.

Table 5: Pulse frequency for both modes

Pulse Frequency	Altimetry	Hazard Detection
Maximum altitude	$8\,km$	$500\,m$
Roundtrip time	$53.3\,\mu s$	$3.33\,\mu s$
Pulse frequency	$18.75\,kHz$	$300\,kHz$

In order to increase the frequency, it is intersting to see what happens if the frequency is increased. The TDC measures the time between the last outgoing pulse and the incomming pulse. This means that the performed measurement t_{TDC} can be calculated using eq. (4).

$$t_{TDC} = ToF \mod T_{pulse} \tag{4}$$

$$ToF = t_{TDC} + k \cdot T_{pulse} \qquad k \in \mathbb{N} \tag{5}$$

where t_{TDC} is the measurement of the TDC, ToF the time of flight, and T_{pulse} the time period of the laser pulses. The returned answer is related to ToF as shown in eq. (5). The precision of the measurement is maintained, but on a larger scale the information is lost.

To solve this problem one can make measurements in two different frequencies. The idea is also applied in TDCs (Name of technique?), where two ring oscillators with different frequencies are used to amplify the range of the TDC. A similar idea can be applied here, but instead of using two oscillators, the time is devided in half, and in the first half the laser sends pulses in frequency f_1, and in the second half pulses with frequncy f_2. These two different measurements can first be used to determine the large scale ToF, and then the measurements can be combined to get a high accuracy to accompany that.

As a proof of concept. This idea is applied to the Altimetry Mode. It is assumed that a difference of $5\,ns$ between λ_1 and λ_2 is sufficient. Now using a maximum ToF one can calculate that optimal two frequencies, such that $f1_{>}f_2$ and f_2 as high as possible.

$$\frac{50\mu}{5n} = 10660 \tag{6}$$
$$\sqrt{\frac{50\mu}{5n}} \approx 103 \tag{7}$$

Now two coprime numbers in $\mathbb{N}$ around 103 are 103 and 104. The resulting frequencies are

$$T_1 = 103 \cdot 5n = 515n \tag{8}$$
$$T_2 = 104 \cdot 5n = 520n \tag{9}$$
$$f_1 = \frac{1}{T_1} = 1.9417\,MHz \tag{10}$$
$$f_2 = \frac{1}{T_1} = 1.9231\,MHz \tag{11}$$
$$\tag{12}$$

The pulse frequency increases by a factor 100. A matlab plot of the resulting system is shown in fig. 2, where the measurement values of the TDC are plotted against the ToF.

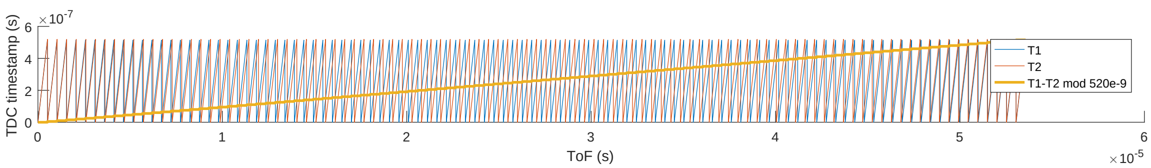

Figure 2: Matlab plot of TDC measurements vs ToF

The ToF can be calculated using eq. (14).

$$t_{1-2} = (t_1 - t_2) \mod T_2 \tag{13}$$
$$ToF = \frac{t_{1-2}}{T_2 - T_1} T_1 + \frac{t_1 + t_2 - t_{1-2}}{2} \tag{14}$$

2.3.2 Optics

The receiver optics guide the photons that arrive at the device. The main task of the receiver optics is to lose as little incoming photons as possible.

The most basic approach is a single lens with an aperture. Loss of photons is determined by the absorption of the lens, the f-number (size of the aperture), and active area on the chip. The active area on the chip, the percentage that can receive light, is assumed to be $\approx 5\%$.

The performance of a possible configuration is shown in table 6

Table 6: Parameters for a basic optical system

Basic Optics	
f-number	2
absorption	0.05
active area on chip	0.05
effective opacity	0.011875

Improvements

There are a couple of additions that can improve the performance of the optics. The performance of the optics is most affected by the active area on the chip, so in order to improve that, one can use microlenses. Microlenses focus light on a small area on the chip, and one is needed for every SPAD. Two types of microlenses will be considered: a spherical lens, and a square shaped lens. The presence of microlenses poses a limitation of the main lens. The f-number must be 8 or higher. A higher f-number means a smaller aperture and therefore more loss of energy. A way of dealing with this problem is to use a second lens instead. An overview of the available options is shown in fig. 3

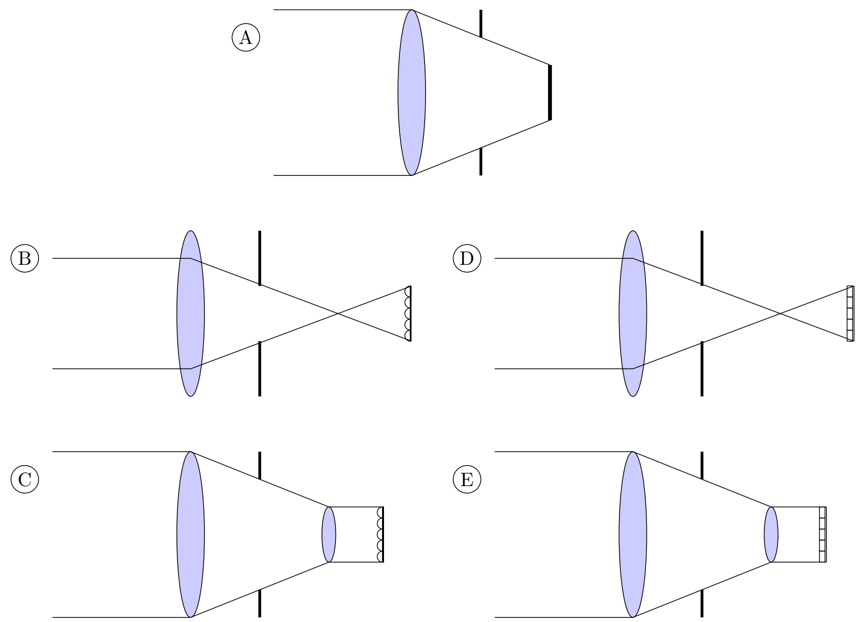

Figure 3: Overview of possible receiver optics implementations

A comparison between the different options is shown in table 7

Table 7: comparison of different optics solutions

Type	**A**	**B**	**C**	**D**	**E**
absorption 1^{st} lens	0.05	0.05	0.05	0.05	0.05
f-number	2	8	2	8	2
absorption 2^{nd} lens	0	0	0.05	0	0.05
active area on chip	0.05	0.55	0.55	0.65	0.65
effective opacity	0.011875	0.008164	0.124094	0.009648	0.146656

The comparison in table 7 shows that type **E** is the best option. This is the version with square microlenses, and a second lens to increase the maximum allowable aperture.

2.3.3 SPAD Array and Scanning Motion

The specifications state the dimensions and resolution of the image. The specifications are provided in table 8.

Table 8: Properties of ground image

image properties		
ground area coverage	15625	m^2
ground sample distance	0.05	m
total amount of pixels	6250000	$-$

Basic approach

The most straightforward pixel layout, is one where every pixel is represented by a single SPAD. The size of a SPAD with a quenching circuit is assumed to be $20 \times 2\,\mu m^2$. This results in a chip size of $5 \times 5\,cm^2$, which is very large for a chip. This also only accounts for the SPAD and the quenching electronics. The TDCs and other components need to be put elsewhere. The system is also inefficient, because only a limited number of transmitted photons arrives at the SPADs, the SPADs are mostly idle, or receiving background noise.

Scanning

To tackle this issue one can use scanning. Here a SPAD is responsible for multiple pixels. This has a couple of advantages. First of all, the idle time of the SPAD's goes down, which means that the SNR goes up. Second, the chip size can be a lot smaller. A clear negative is that a scanning motion must be made. Two types of scanning will be considered. The first one is a line of SPADs, and the second one a square of SPADs.

Horizontal Line layout

In the horizontal line layout each SPAD is responsible for every point on a vertical line. The width of the chip remains the same at $5\,cm$, but the length is extremely short which besides production costs, leaves room for on board TDCs, that are directly attached to the SPADs. The Laser must be configured to send out a line, and the system must be capable of performing a vertical scanning motion. Also the lens must be configured to concentrate the incomming information on a line instead of a more square shaped form. The main problem of the scanning motion is that it should vary based on the altitude. This could cause uncertainty problems, especially at large speeds.

Square Layout

The second alternative uses the same approach as the basic approach, but now with less SPAD's. The ground image is devided into blocks that are scanned consecutively. The scanning motion is more complicated than both the basic, and horizontal line layout, but the main advantage is that the amount of SPAD's are free to choose for the designer.

Comparison

The first design with a SPAD for every pixel is not feasible. The size of the resulting chip would be to large, even in the most optimistic case, and the advantages for this design are mostly limited to the absence of the scanning motion. The Square layout is a better alternative in terms of chip design and efficiency, but the scanning motion is very complex, usign two axis, and cause a lot of extra jitter on the signal. The Horizontal Line Layout is the most promising layout of the three designs. It uses only one axis, which is the most reasonable of the two scanning motions, and also has the advantage of a smaller and more efficient chip design. For the following calculations, the assumption will be made that the SPAD Array is of size 2500×4 for a total of $N_{SPAD} = 10000$.

2.3.4 Background Noise

For the background noise, it is assumed that the sun is the dominant source. The sum is modelled as an ideal black body. The spectral irradiance of the sun can be calculated using eq. (15).

$$I_\lambda(\lambda, T) = \frac{2hc^2}{\lambda^5} \frac{1}{e^{\frac{hc}{\lambda kT}} - 1} \tag{15}$$

where $I_\lambda(v, t)$ is spectral irradiance with unit W/m^3.
h is the planck constant
c is the speed of light in vacuum
k is the Boltzman constant
λ is the wavelength of the electromagnetic radiation
T is the absolute temperature of the body
The spectral irradiance of the sun is calculated in table 9.

Table 9: Calculation of sun irradiation

Sun irradiation		
h	$6.63 \cdot 10^{-34}$	$J \cdot s$
c	$3.00 \cdot 10^{8}$	m/s
k	$1.38 \cdot 10^{-23}$	j/K
λ	850	nm
T	5780	K
I_λ	$1.51 \cdot 10^{13}$	W/m^3

The next step is to calculate the power emitted by the sun in the specified bandwidth, at the location of Europa. This is done by modelling sun as a point source, and then spreading that power over a sphere with a radius equal to the distance between the sun and Europa, as is done in eq. (16).

$$P_{sun} = I_{\text{sun}} B_\lambda S \frac{r_{\text{sun}}^2}{r_{\text{europa}}^2} \tag{16}$$

where I_{sun} is the spectral irradiance of the sun at the center frequency of the filter, B_λ is the bandwidth of the filter in meters, S the surface area of the target area on Europa, r_{sun} the of radius of the sun, and r_{europa} the distance between Europa and the sun. The effective radiance of the background noise at Europa is calculated in table 10 using eq. (16).

Table 10: Effective power that hits the target area on Europa

background power		
I_{lambda}	$1.51 \cdot 10^{13}$	W/m^3
B	10	nm
S	15625	m^2
r_{sun}	695700	m
r_{europa}	$8 \cdot 10^{8}$	m
P_B	0.179	W

2.3.5 Resolution

The maximum allowable $FWHM$ of the measurement is $333\,ps$ as shown in section 2.2. Using eq. (18) the maximum standard deviation is $\sigma = 141\,ps$.

$$FWHM = 2\sqrt{2\ln 2}\sigma \tag{17}$$

$$\sigma = \frac{FWHM}{2\sqrt{2\ln 2}} \tag{18}$$

The power of the background noise leaving the surface of interest at europa is calculated in section 2.3.4, and is $P_B = 0.179\,W$. However, this is the power at Europa. One can use eq. (20) to calculate the amount of power that hits the SPADs.

$$P'_B = \frac{P_B}{2\pi r^2} \cdot R_{europa} \cdot \pi D_l \cdot L_f L_l \tag{19}$$

$$= \frac{P_B R_{europa} D_l L_f L_l}{2r^2} \tag{20}$$

where P'_B is the background noise at the SPADs,
r the altitude of the sensor,
R_{europa} the reflectivity of Europa,
D_l the diameter of the lens,
L_f the opacity of the bandpass filter, and
L_l the effective opacity of the optics. This calculation is performed in table 11.

Table 11: Calculation of noise power at SPADs

Effective noise power	**Altimetry**	**Hazard Detection**	
P_B	0.179	0.179	W
r	8	0.5	km
R_{europa}	0.35	0.35	$-$
D_l	0.05	0.05	m
L_f	0.5	0.5	$-$
L_l	0.146	0.146	$-$
P'_B	$1.7865 \cdot 10^{-12}$	$4.57345 \cdot 10^{-10}$	W

The next step is to calculate the number of background noise photons per second (PPS_B) that are detected by each SPAD. For that, one first needs to know the energy of a single photon E_{photon}. To calculate E_{photon} one can use eq. (21). The calculation of this is shown in table 12.

$$E_{photon} = \frac{hc}{\lambda} \tag{21}$$

Table 12: Calculation of photon energy

Energy of photon		
h	$6.63 \cdot 10^{-34}$	Js
c	$3.00 \cdot 10^{8}$	m/s
λ	850	nm
E_{photon}	$2.34 \cdot 10^{-19}$	J

The SPAD Array is assumed to be 2500×4 for a total of $N_{SPAD} = 10000$. Now to calculate the PPS_B for each SPAD one can use eq. (22)

$$PPS_B = \frac{P'_B \cdot PDP}{E_{photon} \cdot N_{SPAD}} \tag{22}$$

where PDP is the photon detection probability of the SPADs. This calculation is done in table 13

Table 13: Calculations of background photons per second

PPS for background photons	**Altimetry**	**Hazard Detection**	
P'_B	$5.69 \cdot 10^{-12}$	$1.46 \cdot ^{-9}$	W
E_{photon}	$2.34 \cdot 10^{-19}$	$2.34 \cdot 10^{-19}$	J
N_{SPAD}	10000	10000	–
PDP	0.35	0.35	–
PPS_B	267	$6.84 \cdot 10^4$	–

2.3.6 standard deviation shortcut

To calculate the standard deviation of the sum of multiple random variables that are independent and uncorrelated, one can use eq. (23)

$$\mathrm{Var}[aX + bY + cZ] = a^2\mathrm{Var}[X] + b^2\mathrm{Var}[Y] + c^2\mathrm{Var}[Z] \tag{23}$$

Next consider a situation where there are two random variable distributions. The first distribution is S, which is a normal distribution with $\mu_s = ToF$, where $ToF \in \{0, 50\mu\}$, and $\sigma_s = 100p$. The second distribution is N, which is a uniform distribution with $\mu_n = \frac{50\mu}{2}$ and $\sigma_n = \frac{50\mu}{\sqrt{12}}$.

$$\begin{aligned}
\mu_{mean} &= \frac{1}{110}\Big(\sum_{k=1}^{100}\mu_s + \sum_{l=1}^{10}\mu_n\Big) && (24)\\
&= \frac{100ToF + 10 * 25\mu}{110} && (25)\\
&= \frac{10}{11}ToF + 227.3n && (26)
\end{aligned}$$

$$\begin{aligned}
\mathrm{Var}_{mean} &= \mathrm{Var}\Big[\frac{1}{110}\Big(\sum_{k=1}^{100}S_k + \sum_{l=1}^{10}N_l\Big)\Big] && (27)\\
&= \frac{1}{110^2}\Big(\sum_{k=1}^{100}\mathrm{Var}[S] + \sum_{l=1}^{10}\mathrm{Var}[N]\Big) && (28)\\
&= \frac{1}{110^2}(100\sigma_s^2 + 10\sigma_n^2) && (29)\\
&= \frac{10^{-18} + 2.0833 \cdot 10^{-9}}{110^2} && (30)\\
&= 1.7218 \cdot 10^{-13} && (31)\\
\sigma_{mean} &= \sqrt{\mathrm{Var}_{mean}} && (32)\\
&= 414.94n && (33)
\end{aligned}$$