Characterization of Silicon PhotoMultipliers for the Cherenkov Telescope Array

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Dixitque Deus fiat lux et facta est lux. (Genesis 1,3)
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Abstract

The Cherenkov Telescope Array (CTA) project is capable of detecting very high energy cosmic gamma-rays from 10 TeV to 100 TeV. For the Small Sized Telescopes within the CTA project, a Compact High Energy Camera (CHEC) equipped with an arrays of photosensitive Silicon PhotoMultipliers (SiPMs) will be used. This thesis worked on setting up an experiment to characterize the performance and to determine the suitable SiPM among the two commercially available products: S12572-50C from Hamamatsu and C30742-66 from Excelitas. Specifically, measurements on dark photon count, optical crosstalk probability and absolute Photon Detection Efficiency (PDE) were performed and compared across the parameter space of over-voltage and wavelength. It was found out that the Excelitas SiPM has lower darkcount and optical crosstalk. For dark count rate, the Hamamatsu SiPM detected between 0.313 and 0.658 thermal photons in the range of (1.72, 3.72) Volt over-voltage, and for Excelitas, the count is between 0.296 and 0.534 in the range of (2.2, 4.2) Volt overvoltage. In the same overvoltage range, Hamamatsu’s crosstalk probability is between 21% and 61% and Excelitas’ is between 26% and 55%. In terms of detection efficiency, except at 454nm where the PDEs are comparable, the detection efficiency of Excelitas is approximately 60% that of Hamamatsu at 389nm, 586nm and 740nm. We concluded that the Hamamatsu SiPM is the better choice for the Compact High Energy Camera in the Cherenkov Telescope Array.
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Nomenclature

Roman Symbols

\( eV \) electron Volt (\( 10^{-19} \text{ Joule} \))
\( J \) Differential Flux
\( P \) Probability

Greek Symbols

\( \beta \) spectral index
\( \gamma \) gamma ray
\( \phi \) flux
\( \mu \) average number of photons detected
\( \Omega \) solid angle
\( \pi \) pion

Superscripts

\( j \) superscript index

Subscripts

\( 0 \) subscript index

Other Symbols

\( \oint \) integration around a curve \( \gamma \)

Acronyms

\( CTA \) Cherenkov Telescope Array
DFE  Differential Flux Equation

HEAP  High Energy AstroParticle Physics

LST  Large-Sized Telescope

MST  Medium-Sized Telescope

PDE  Photon Detection Efficiency

pe  photon-equivalent

SiPM  Silicon PhotoMultiplier

SST  Small-Sized Telescope

VHE  Very High Energy
Chapter 1

Introduction

"The strongest affection and utmost zeal should, I think, promote the studies concerned with the most beautiful objects. This is the discipline that deals with the universe’s divine revolutions, the stars’ motions, sizes, distances, risings and settings... for what is more beautiful than heaven?" Nicolaus Copernicus

The sky has always been mankind’s source of aspiration. For millennium astronomers looked upon the movements of heavenly bodies, wondering what divine secrets they might reveal to us about the cosmos and about human’s very own existence in the vast universe. The light we see from the sun, the moon and the stars are emissaries that carry generous information about their origins. As the course of history progresses, we learn how to understand more deeply their messages, and technological advancement allows us to open more windows beyond the visible light spectrum to welcome more exotic messengers who enrich our understanding of the universe.

One of the recently discovered messengers are very high energy cosmic rays. They are extremely energetic in nature, creating a violent impact against the Earth’s atmosphere upon their arrival. The debris from the collision continue to cascade a chain reaction, creating what is commonly referred to as an "air shower" that consists of several billions particles hurdling towards the Earth’s surface. Fortunately, such violent guests seem not to visit us very often and pose no threat to life on Earth. On average, the event rate is approximately one cosmic ray of this type per square kilometer area per year. Unfortunately, for Science, it means we have to either wait for a very long period or build a very large facility to study them. Given the limited lifespan of a human being, the latter option comes as the logical choice. The Cherenkov Telescope Array (CTA) will be the largest telescope array built thus far for this purpose.

The Cherenkov in CTA is the short form of Cherenkov radiation and requires
a special mention in this introduction. It is named after the Soviet scientist Pavel Cherenkov who received the Nobel Prize in 1958 for his discovery of the phenomenon. In short, the phenomenon is a shock-wave created when charged particles move faster than the speed of light *in the local medium*, similar to a sonic boom when an aircraft or a bullet breaks the sound barrier when travelling at supersonic speed. Traditionally, Cherenkov radiation is detected using a PhotoMultiplier Tube (PMT) that is capable of multiplying the faint photon signal several million times. However, recent development in semiconductor technologies permits the use of a special class of silicon devices capable of similar or even better performances relative to PMTs. These silicon devices are named Silicon PhotoMultipliers (SiPMs) and are state-of-the-art photon detectors. An apt analogy of this technological transition is the replacement of Cathode Ray Tube (CRT) TV by modern LED TVs. SiPMs have been used widely in medical applications but it is the first time that they are employed for large scale astronomy purposes, and the choice of suitable SiPMs is crucial and requires in-depth characterizations. As the industry is catching up, there are currently several companies offering SiPMs for CTA with similar performances, and it is yet clear which choice to make among these vendors.

This thesis makes progress in developing experimental setup and characterizing performances of several potential SiPM candidates which will be used in the ∼70 Small Sized Telescope (SST) cameras within CTA. The written part is organized as follows. The Introduction chapter provides the context and motivation for the work carried out in this thesis. Chapter 2 provides a survey on the theories and principles behind HEAP, CTA and SiPM. Chapter 3 involves the techniques and experimental setup to characterize performances of the SiPMs. Chapter 4 discusses the findings during the work. Chapter 5 summarizes the finding and provides suggestions for the suitable SiPM as well as for further studies.
Chapter 2

Cosmic Ray, CTA and SiPM

"Pray remember that I leave you all my theory complete,
Lacking only certain data for your adding, as is meet."
Sarah Williams

2.1 Cosmic Ray Physics

In 1912 V. Hess discovered during his famous balloon flights an increase of ionization radiation at higher altitude in the Earth’s atmosphere. He then concluded that there was radiation penetrating the atmosphere from the outer space, which earned him the Nobel Prize in 1936. Since then, the study of cosmic rays (high energy radiation originating from the outer space) has played an important role in astrophysics and astronomy. With the increase in sensitivity of the instruments, scientists have been able to study a wide spectrum of cosmic rays. Figure 2.1 below describes the (differential) energy spectrum of cosmic rays arriving on Earth.

A remarkable property of this spectrum is that, above $E = 10^{11}$ eV, it follows a broken power law relation across several orders of magnitude according to the following equation $^1$:

$$ J(E) = \frac{d^2\phi(E)}{dEd\Omega} \sim \left( \frac{E}{eV} \right)^{-\beta} $$

Here $\beta$ is the spectral index of the spectrum, corresponding to the slope of the red line on figure 2.1. Note that the plot’s scales are logarithmic. The power

\(^1\)the notation is explained in more details in the nomenclature section
law is broken since $\beta$ changes with the energy range. Between $E = 10^{15}$ eV and $E = 10^{16}$ eV (the "knee" region) the slope stiffens from $\sim 2.7$ to $\sim 3.1$. Around $E = 10^{18}$ eV (the "ankle" region) the slope returns to the earlier value of $\sim 2.7$. Beyond $E = 5.10^{19}$ eV $\sim 8$ Joule the spectrum is heavily suppressed, and this limit is referred to as the Greisen Zatsepin Kuzmin (GZK) cutoff. For a reference, the designed proton collision energy (center of mass frame) at the Large Hadron Collider at CERN is 15 TeV ($\sim 10^{13}$ eV), nearly a million times less energetic than cosmic rays at the ankle region. What sources or process capable of accelerating such high energy particles? How did they arrive on Earth? What can they tell us about the medium that they have travelled through? What caused the cutoff? These are the several questions that the field of Cosmic Ray Physics seeks to answer.

A special domain of Cosmic Ray Physics is Very High Energy Gamma Ray (VHE\(\gamma\)) Astronomy, which concerns $\gamma$ radiation with $E > 10$ GeV. Unlike the vis-
ible photons normally observed through an optical telescope, VHE\(\gamma\) are not produced by thermal processes. They are theorized to be produced by non-thermal processes such as synchrotron radiation, Bremsstrahlung, inverse Compton scattering, neutral pion decay, etc. The list of possible sources capable of producing such effects is extensive, including more exotic ones such as super massive black-holes, accretion discs, supernovae, etc. A short description of these processes can be found in Rossiter [2015]. By studying VHE\(\gamma\), it is possible to trace back their sources and creation processes, and possibly to discover new physics beyond the Standard Model.

One of the challenges in VHE\(\gamma\) Astronomy is that electromagnetic waves, with the exception of visible light and radio waves, are unable to penetrate through the Earth’s atmosphere. The energy of the original \(\gamma\) radiation goes into the production of secondary particles after the initial impact in the following process. The incoming \(\gamma\)-ray photon first undergoes pair production in the vicinity of the nucleus of an atmospheric molecule. This electron-positron pair is extremely energetic and immediately undergo Bremsstrahlung (‘braking radiation’). The produced radiation is itself still extremely energetic, with many of the photons then undergoing further pair production. A cascade of charged particles thus follows, and due to the extreme energy, some particles are able to travel faster than the speed of light in the Earth’s atmosphere, producing a flash of Cherenkov radiation lasting between 5 and 20 ns. The Cherenkov radiation produces a widespread cone of light (\(\sim\)100 m radius at ground level) 2.2. As such, Earth-bound experiments usually study VHE\(\gamma\) indirectly via reconstruction of air-shower from detectors’ optical signals. Reconstruction methods are beyond the scope of this thesis, but interested readers are invited to read more in et al. [1996]. The next part of this thesis will focus on the instrumentation aspect of VHE\(\gamma\) Astronomy.

2.2 CTA

The instrument used to detect the Cherenkov radiation usually comprises of a large segmented mirror reflecting the Cherenkov light onto an array of photosensors, reminiscent of a conventional telescope (see left figure, 2.3). The sensors are coupled to fast electronic readouts which amplify, digitize and record the pattern of the shower. Usually, Cherenkov telescopes come in an array, with a distance of 70 to 120 meters apart so that the energy threshold (the peak sensitivity) of the telescope can be lowered and the effective area can be increased. The shower reconstruction and background rejection offered by an array of telescopes can provide a significant improvement in sensitivity and energy resolution as compared to a single telescope. This advantage can be seen through the trend of increasing number of telescopes within an array over the year: MAGIC (2004, 2 telescopes),
Figure 2.2: Detection of VHE\textgreek{\gamma} using the Cherenkov technique. From left to right: A primary $\gamma$ initiates an airshower with secondary particles. A light cone of Cherenkov light is produced from ultrarelativistic particles in the atmosphere. Cherenkov photons are then recorded on the camera pixel. Different images recorded by the telescopes are then used to reconstruct the origin of the airshower. Figure taken from Rossiter [2015].

VERITAS (2007, 4 telescopes), HESS (2012, 5 telescopes). Since its construction, HESS has identified more than 90 sources of TeV $\gamma$-rays, establishing the effectiveness of the Cherenkov method in HEAP.

CTA is built to bring VHE\textgreek{\gamma} Astronomy to the next level. The project is a huge leap in terms of number of telescopes: the baseline design consists of 8 Large-Sized Telescope (LST), 40 Medium-Sized Telescope (MST) and 70 Small-Sized Telescope (SST). The project consists of two arrays. The first one is located at the Northern Hemisphere (La Palma, Canary Island) with an emphasis on the study of extragalactic objects at the lowest possible energies. The second array is located at the Southern Hemisphere, covering the full energy range and concentrate on galactic sources. The distribution of these telescopes within CTA is provided in table 2.1. In addition, the science program of CTA goes beyond high energy astrophysics into cosmology and fundamental physics. Due to its scale and complexity, CTA is divided into several sub-consortia. This thesis is a part of the Gamma-ray Cherenkov Telescope (GCT) consortium, which proposes to build SSTs for CTA in the Southern Arrary. The GCTs are envisioned to cover the energy range from 1 to 300 TeV.

The GCT is of Schwarzschild-Couder (SC) optical design, using primary and secondary mirrors to focus Cherenkov light on to the Compact High Energy Camera (CHEC) located at the curved focal surface, as seen in 2.3. According to
Table 2.1: Distribution of telescopes within CTA. CTA [2016]

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CTA’s requirements, SSTs are intended to be widely spread over large fields of view so as to detect the highest energy gamma-rays, which are typically bright but relatively rare. As such, detection at single-photon level with small dead time is crucial for an efficient detection. More specifically, the CHEC component is designed so as to be able to record flashes of faint Cherenkov light lasting from a few to a hundred nanoseconds. To meet these requirements, CHEC must have a low-cost design but with high-data-quality capable of providing full waveform information for every camera pixel in every event in the whole array.

Currently two prototypes of CHEC have been built. Each camera is fitted with 32x64 pixel photosensor modules. Signal from these sensors will be fed to an amplifier, followed by a digitizer Application-Specific Integrated Circuit (ASIC) module named TARGET. Camera trigger decisions are then made using the backplane printed circuit board (PCB) with programmable algorithms on a Field Programmable Gate Array (FPGA). The key difference between these two camera is the choice of photosensors. The first prototype (CHEC-M) is based on multi-anode photomultipliers and the second one (CHEC-S) will be based on silicon photomultipliers. The photosensors used in CHEC-S are central for this thesis, and the next section will describe and explain the unique qualities making them a good fit for the whole array of SST.

2.3 Silicon PhotoMultiplier

As the previous section explained the needs for high quality photosensor capable of single-photon resolution, this section presents an introduction to the functional principles of these state-of-the-art devices. Traditionally, photosensors in HEAP experiments such as IceCube, KM3NET are Photo Multiplier Tubes (PMTs). Notably, PMTs were used as neutrino detectors in the Super-Kamiokande Observatory in Japan, confirming the oscillation of neutrino and thereby winning the Nobel Prize in Physics 2015. However, PMT is a difficult device to work with, especially in terms of safety. In 2001, a PMT imploded and caused a chain reac-
Figure 2.3: GCT and CHEC. From left to right: Design of GCT with CHEC located between the secondary and primary mirrors. Note that the primary mirror design will be different in the final construction of CTA. The CHEC camera components illustrating the modular design with several photosensors. Figure modified from CTA [2015].

In 2012, the explosion of the reactor building of the detection chamber that destroyed 7000 of the 11000 PMTs in Super-Kamiokande, delaying its operation for several months. In addition, PMTs operate at high voltage (∼kV), are bulky and subjected to magnetic fields. Recent advance in semiconductor materials allows the use of photodiodes as alternatives for PMTs. Hundreds to thousands of photodiodes are connected in parallel in one single silicon substrate, and the commonly referred to as Silicon Photo Multiplier. Sometimes SiPM is referred as Geiger-mode Avalanche PhotoDiode (GAPD) or Multi-Pixel Photon Counter (MPPC), emphasizing its operating principles. A comparison between SiPM and PMT is shown in figure 2.4.

Figure 2.4: Physical comparison between PMT and SiPM. Left: side view. Right: front view. The PMT is from the ZEUS experiment, 13cm long and 4cm in diameter. The SiPM is from Philips, has dimension of 3.26 cm × 3.26 cm consisting of 400000 individual photodiodes, with individual cells being 59.4 µm × 32µm. Figure taken from Rossiter [2015].

In principles, an SiPM can be seen as a special silicon “solar-cell” device: an incident photon generates an electron-hole pair inside the silicon semiconducting
material, which in turns create an electric current that can be detected and quantified. Both devices are wavelength-dependent, and employ ”efficiency” as the prime parameter to evaluate the performance. However, the distinguishing feature among the two is that the SiPM requires input power while the solar-cell produces output power. In other words, an SiPM needs a potential difference to operate while a solar-cell operates by creating a potential difference. This required potential difference is crucial and will be mentioned several times in the remaining parts of this thesis.

2.3.1 Photon Detection

As a photon travels through silicon, there is a probability that it will be absorbed by an electron if the photon’s energy \( E \) is greater than the band gap energy \( E_g \) of Silicon (\( \sim 1.1 \text{ eV at } T = 300 \text{ K } \sim \lambda = 1127 \text{ nm} \)), creating an electron-hole (e-h) pair. One created, the e-h pair must be separated in order to generate electric current flow. One way of achieving this is to use pn junction.

A pn junction is created when a positively doped semiconductor is brought into contact with a negatively doped semiconductor. Negative charge carriers (electrons) will diffuse into the p-doped region, and vice versa. The holes and electrons thus drift away from each other at the pn interface. They leave a depletion zone close to the junction with positive and negative ions. The electric field generated by the ions counteracts the diffusion process, creating an equilibrium. Figure 2.5 describes qualitatively the distribution of charge density at equilibrium. Note that the depletion region is called ”space charge region” in the figure.

When the junction is positively biased (a negative potential on the n region and positive potential on the p region), the depletion region shrinks, and if the bias voltage is high enough, electrons from the n region will gain enough energy to cross the positive layer in the depletion region and current will flow. Conversely, when a reversed bias is applied to the junction, the depletion region widens thus prevents any current flow. As such, pn junctions operate as diodes, only allowing current flow in one direction.

Now, when an e-h pair is created in the depletion region, the field inside the depletion region will separate the charge carriers. According to the blue potential line in Figure 2.5, the electron will move ”downhill” towards the p region and the hole will drift towards the n region, thus creating a photo current. It is crucial that the e-h separation due to incident photon takes place inside the depletion region, otherwise recombination will happen and the information about the photon is lost. Different wavelengths get absorbed differently in the semiconducting material, making performance of their performances wavelength-dependent. In general it is desirable that the depletion region should be as large as possible to be able to
absorbed the incident photon but not too large to prevent charge recombination of the e-h pair. This paradoxical requirement can be achieved by sandwiching an undoped region (sometimes called "intrinsic region") between the heavily doped n+ and p+ regions. This is the operating principles of PIN (p-on-i-on-n) diode, as depicted in Figure 2.6.

PIN diodes are widely used in photodetection which high detection efficiency due to their good absorption properties. However, they have two shortcomings making them unsuitable for applications in Cherenkov light detection. Firstly, they have no intrinsic gain: the energy of the output electrical current is equal to or less than the energy of the absorbed photons. The lack of intrinsic amplification means that PIN diode requires an external signal amplifier to detect faint Cherenkov signal, making it less competitive to PMT, which has an internal gain of $\sim 10^6$. The lack of internal amplification means that PIN diodes usually have slow readout, having have to wait until charges are built up above certain detectable threshold. Secondly, PIN diodes are single devices. During the reading from the incident photon, the diode loses its ability to distinguish the original photon signal from the next photon signal (should additional "hit" occurs afterwards). As a result, it is difficult to achieve single-photon resolution with PIN diodes, making energy reconstruction of the incident photons challenging.

SiPMs are designed to overcome these shortcomings of PIN diodes. Firstly, a bias voltage is applied to the diode to provide the e-h pair with additional energy to increase the signal output strength. Secondly, the diodes are miniaturized and
put in parallel to reduce individual diode’s ”dead time” during readout. The two improvements will be explained shortly in more details.

E-h pairs are charged particles and can be accelerated by an electric field, which can be achieved by putting a large amount of dopants in the appropriate region. For illustration purposes, let us consider the modification to the depiction of the PIN diode in figure 2.6 by adding several layers of doped and heavily doped material in Figure 2.7. After the e-h pair creation, the electron is accelerated towards the p region due to the intense electric field from the positive dopants. If the electron’s kinetic energy is large enough (above the bandgap energy), it will be able to create an additional e-h pair by colliding with another electron. This phenomena is called impact ionization. The newly created e-h pair, in turns, can generate additional e-h pairs, creating an avalanche effect. This leads to an internal amplification of signals, typically ∼20 times with respect to those of a PIN diode.

Typically, the chain reaction will stop after all the holes have reached the cathode. To shorten the dead time of the diode, a reverse bias $V_{\text{bias}}$ is applied to the terminals of the diode (positive potential on the anode and negative potential on the cathode, thus the electric field is pointing towards the bottom of the page in figure 2.7) to accelerate the movement of the holes towards the cathode. However, beyond a certain bias voltage, an interesting phenomenon starts to take place: the (reverse) bias voltage becomes so strong that the holes can gain enough kinetic...
energy to impact on other ions thereby creating an avalanche. The avalanche induces a sudden current flow, temporarily breaking down the diode until the current is quenched using external circuitry to restore the space-charge region. As such, this critical bias voltage is termed breakdown voltage $V_{\text{bd}}$. When an SiPM operates below $V_{\text{bd}}$, it is said to operate in proportional mode, whereas above $V_{\text{bd}}$, the diode enters Geiger-Avalanche mode, reminiscent of the operating principles of Geiger radiation counter. For this reason, a device of this type is known by the name Geiger Avalanche Photo Diode (GAPD). The voltage above $V_{\text{bd}}$ is defined as overvoltage ($V_{\text{ov}}$), following the simple mathematical expression:

$$V_{\text{ov}} \equiv V_{\text{bias}} - V_{\text{bd}}$$ (2.2)

Operating SiPMs above $V_{\text{bd}}$ provides two additional benefits. Firstly, the internal amplification becomes comparable with PMTs using only a voltage that is $\sim 100$ times smaller. Naturally, higher $V_{\text{ov}}$ correlates with better amplification and hence better signal. Secondly, the delay time between photon absorption and photocurrent generation is shortened to few nanosecond, making SiPMs extremely fast devices. However, operating SiPM in Geiger mode also comes with several disadvantages. Firstly, it is possible that an e-h pair is created due to thermal processes within the SiPM and generates signals that are indistinguishable from photon-incident events. This is known as “dark noise” due to the fact that SiPMs can produce signal even when there is no incident photon. The dark
noise is an intrinsic property of SiPM, which must be characterized and subtracted away during operation. For this reason, SiPMs are criticized as being noisy devices. In this respect, high $V_{oc}$ correlates with higher chances of thermal signal, increasing the dark noise and reducing signal quality. Secondly, the external circuitry (typically a quenching resistor connected in series with the diode) must be able to quench the photocurrent with sufficient speed to reduce deadtime during readout. This complicates the fabrication process and increases the device cost. Typically, a $3 \text{ mm} \times 3 \text{ mm}$ device can cost up to several hundreds euros. However, as the fabrication processes in semiconductor technology continues to develop, it is expected that the cost of SiPMs will go down in the future.

Besides the thermal noise, there are also two types of intrinsic noise that degrade further SiPM signal quality: optical crosstalk and afterpulsing. Optical crosstalk is caused by the generation of a photon inside the SiPM which generate signals identical to the signals from external radiation. The cause for this photon generation is still under investigation. Figure 2.8 shows the emitted light intensity of a Hamamatsu SiPM in the dark, demonstrating that the SiPM can itself act as a source of photons, which can potentially cause crosstalk phenomenon. The camera shutter was opened for 300 seconds to collect as much as possible light emitted from the SiPM. The image is then overlaid with a photo of the same SiPM. Unlike crosstalk, afterpulsing refers to the generation of cell breakdowns that is not due to incident photon or thermal e-h pair. The cause of afterpulsing is even less understood than the cause of crosstalk. In general, afterpulsing is thought to be caused by the trapping of charge carriers due to impurities in the SiPM material. In this thesis, only optical crosstalk will be discussed.

So far, this thesis has employed the terms GAPD and SiPM interchangeably. However, technically, an SiPM is an array of thousands of cells connected in parallel. Each cell, in turns, is made of a GAPD and a quenching resistor connected in series. A typical layout of an SiPM can be found in figure 2.9, together with a simplified equivalent circuit diagram. A cell breakdown happens when an avalanche, either due to thermal processes or due to an incident photon, takes place inside the GAPD. If a cell breaks down, the SiPM will generate a standard signal called 1 photon-equivalent (1pe). Connecting cells in parallel ensures that the signal is proportional to the number of breakdowns, making SiPM a very linear device as long as the number of incident photons is below the number of cells inside the SiPM. This linearity of SiPM will be explored further in the next section to provide a framework to evaluate the performance of an SiPM.

2.3.2 Photon Counting

In order to understand how to characterize the performance of an SiPM, we first need to examine a typical signal of an SiPM, as shown in Figure 2.10. The figure
contains 4 photon signals, each characterized by a sharp voltage dip followed by a gentler recovering slope. The sharp dip corresponds to a breakdown event with a sudden drop in the potential across the terminal due to photo current generation. As seen on the figure, the time it takes for the avalanche to develop is typically on the order of a few nanoseconds. The pulse height correlates with the number of photons impinging on the SiPM. After the avalanche stops, it takes roughly a hundred nanoseconds for the quench resistor to quench the photo current, restoring the space-charge region.

As mentioned earlier, the signals from a photon impinging on the SiPM and from a thermal event are indistinguishable. However, using a special statistical technique, it is possible to count exactly how many photons are due to incident photons and how many are due to thermal processes. Let us take a look at the following oscilloscope readout in figure 2.11 containing $5 \times 10^4$ signals retained on the screen using the persistency mode. The SiPM was under illumination of an LED with wavelength 450nm pulsing at 1 MHz. The trigger for oscilloscope reading is synchronized with the pulses of the LED.

In this figure, the horizontal red line is the baseline level, basically representing the voltage measurements when there is no cell breakdown. The pulses in the middle of the readout are SiPM pulses. The lowest pulses occurred more often, as seen with a relatively high intensity in red. The second lowest pulses occurred less
Figure 2.9: Typical layout of an SiPM. From left to right: S10362-11-100C Hamamatsu SiPM with 100 cells. A simplified equivalent circuitry of an SiPM with only 8 cells connected in parallel. Each cell consists of a GAPD and a quenching resistor $R_q$. Modified from Stephan [2014].

often, even more so with subsequent ones. Besides, we also notice other random pulses with varying peak height (purple lines) with no correlation. These are SiPM pulses due to stochastic breakdown from thermal processes. In addition, there is one crucial observation: the peak height are roughly proportional to the lowest peak height.

By measuring the peak height of every voltage trace and then subsequently putting them into a histogram, we obtain a "peak height spectrum". Peak height spectrum provides several useful information about the performance of the SiPM. The peak height spectrum of Figure 2.11 is produced in figure 2.12. In this plot, most of the voltage traces contain a small "peak", corresponding to the random peak due to electrical noise ("white nose") of the system. (Note that the y-axis is on the logarithmic scale). The peaks due to white noise are known as "pedestal" peak for they contain no breakdown event. Subsequent peaks are actual SiPM peaks due to 1pe, 2pe, 3pe etc events. It is possible to perform a Guassian distribution fit on these pe peaks to categorize the events as due to 1, 2, 3, etc cells breakdown.

Now, let us first assume an ideal SiPM with no thermal breakdown. Assuming further that, given an LED light pulse $X$ with a fixed pulsing frequency and intensity, there exists a probability that it will cause a given integer number of
cell breakdowns (x) occurring in a fixed time interval. These events should occur with a known average rate (\( \mu \)) and independently of the time since the last event. These events are then Poissonian and follow the probability mass distribution function:

\[
P_\mu(X = x) = \frac{\mu^x}{x!} e^{-\mu}
\]  

(2.3)

Thus, if we would like to know the probability that the light pulse causes no cell breakdown (x = 0), the equation simplifies to:

\[
P_\mu(X = x = 0) = \frac{\mu^0}{0!} e^{-\mu} = e^{-\mu}
\]  

(2.4)
Figure 2.11: Oscilloscope screen with $5 \times 10^4$ voltage traces superimposed in persistent mode. The color intensity relates the frequency of the voltage traces, from low (purple) to high (red). In this example, the two most probable SiPM responses are no cell breakdown (red horizontal line) and 1 cell breakdown (red pulses) at the center of the screen. There are also random purple pulses due to cell breakdowns from stochastic thermal events. The oscilloscope readout was taken during this thesis with a Hamamatsu S12572-50C device being biased at 66.5 Volt.

On the other hand, from the histogram, we know that the average probability for no cell breakdown is simply the ratio of number of pedestal events $N_{ped}$ and the total number of events $N_{tot}$:

$$P(x = 0) = \frac{N_{ped}}{N_{total}}$$  \hspace{1cm} (2.5)

Equating the two equations and solving for $\mu$, we get:

$$e^{-\mu} = \frac{N_{ped}}{N_{total}} \Rightarrow \mu = -\ln\left(\frac{N_{ped}}{N_{total}}\right)$$  \hspace{1cm} (2.6)

Thus by counting how many events are pedestal events and then applying equation 2.6, we are able to count the average number of cell breakdown ($\mu$) due to photon-equivalent events. Now, let us include the number of cell breakdowns due
Figure 2.12: Peak height spectrum of signals shown in figure 2.11. The first peak corresponds to the pedestal events where the peak height is relatively small. Subsequent peaks are peaks of the voltage trace with one or more cell breakdowns. The distances between peaks are proportional to each other, illustrating the linear property of an SiPM. The positions of each peaks are found using Gaussian function, plotted with the dashed lines up to $3\sigma$

to thermal processes, which is assumed to be constant during the measurement regardless of the presence of light source. With the same analysis, we can obtain the average rate of cell breakdowns in the absence of light, which will subsequently be subtracted away from the measurement with light:

$$
\mu_{\text{SiPM}} = \mu_{\text{light}} - \mu_{\text{dark}} = - \ln\left(\frac{N_{\text{ped}}}{N_{\text{total}}}\right)_{\text{light}} - \left[ - \ln\left(\frac{N_{\text{ped}}}{N_{\text{total}}}\right)_{\text{dark}} \right] \\
$$ (2.7)

Physically, $\mu_{\text{SiPM}}$ gives us the number of photons impinging on the SiPM which cause a breakdown in the diode. The values of $\mu_{\text{SiPM}}$ depends on the type of light source being used, its intensity, SiPM bias voltage, wavelength, the area of the SiPM surface being illuminated and the structure of the SiPM itself. In other words, $\mu_{\text{SiPM}}$ can be seen as the number of photons that the SiPM has detected under these experimental conditions. For the work carried out in this thesis, $\mu_{\text{SiPM}}$ is typically between 0.1 and 3.
In addition, the peak height spectrum in the dark also allows us to determine the crosstalk probability. If we assume that, in the absence of external light source, cell breakdowns beyond the 1pe level are solely caused by optical crosstalk. In other words, in the peak height spectrum, all events beyond the 1pe peaks $N_{pe\geq2}$ are assumed to be caused by optical crosstalk. Thus, the probability of optical crosstalk $P_{OXT}$ is given by:

$$P_{OXT} = \frac{N_{pe\geq2}}{N_{total} - N_{ped}}$$  \hfill (2.8)

By counting the number of pedestal events and the number of events beyond the 1pe level, we are able to obtain the $P_{OXT}$ of the SiPM. This method has a limitation: the experiment must be carried out in absolute darkness, otherwise photons leaked into the setup will be mistaken as crosstalk events.

2.4 Summary

In this chapter, we started with the properties and open questions about cosmic rays, especially those with very high energy. Next, we discussed the Cherenkov technique to detect (VHE$\gamma$) rays, motivating the need to build a large array of telescopes to increase sensitivity. The thesis then described the GCT telescope with its CHEC camera that will be used in CTA. The thesis then provided theoretical backgrounds on the Silicon sensors, demonstrating the reasons why these sensors are suitable candidates for the cameras that will be used in 70 SST telescopes in the CTA. Finally, the thesis provided a mathematical method that can be used to count exactly how many photons have been detected by the photosensor, providing a technique to compute the photon detection efficiency of the device.

The next chapter will describe the experimental test setup that characterizes and compares performances of SiPM samples obtained from different companies.
Chapter 3
Experimental Setup

"Science never solves a problem without creating ten more.”
George Bernard Shaw

3.1 Principles

At the beginning of this thesis, there were SiPM samples from 4 different manufacturers that could potentially be used for CTA: Philips, Hamamatsu, SensL and Excelitas. Shortly afterwards, previous thesis work concluded that the Philips SiPM sample was not suitable for CTA’s purposes due to slow electronic readout. Out of the remaining 3, the natural question to ask then is: which samples should be eliminated next? Putting aside the cost issue, a general answer should be the sample with low detection efficiency and high noise. As mentioned in the previous chapter, these qualities depend on the wavelength and operating voltage. As such, this thesis chose wavelength $\lambda$ and overvoltage $V_{ov}$ to be the free variables to evaluate and compare performances of different SiPMs. The experiment was still on-going when this thesis was written, and the writing part only reports the comparison between Hamamatsu and Excelitas SiPMs. It should also be noted that there are secondary SiPM qualities that should be taken into consideration: low operating voltage (costs less energy) and ability to produce a clean peak height spectrum (facilitates calibration processes and background rejection).

There are two possible methods to compare the Photon Detection Efficiency (PDE): absolute and relative, which are both considered in this thesis. Both methods have advantages and disadvantages:

- **Absolute PDE** means the number of detected photons is compared against the number of detected photons using a referent calibrated photosensor de-
vice (Thorlab Silicon PIN Diode FDS1010 in this thesis). The advantage of absolute PDE measurement is that the result is a single absolute number in percentage that is intuitive to understand. For example, given a device with 25% absolute PDE, one can unambiguously conclude that out of 4 photons impinging on the SiPM surface, the device only detects 1 on average. In addition, the datasheet from manufacturers always quotes absolute PDE as the parameter. The disadvantage is that absolute PDE measurements rely on the data from the calibrated device, which itself requires additional comparison against another device. In other words, it’s turtles all the way down. Additionally, absolute PDE measurement requires longer experiment time.

• **Relative PDE** means the number of detected photons is compared directly among 2 SiPMs, eliminating the need for an absolute referent photosensor. Getting rid of the intermediate steps speeds up the experiments and provides a straightforward comparison among SiPMs. Additionally, since both photosensors are measured at the same time, the ambient parameters (temperature, light-tightness) are identical, providing a more controlled experimental conditions. However, relative PDE is less intuitive in the case of a large variety of different SiPMs, especially when results from different research groups are cross-checked with each other. Besides, error propagation among relative PDE measurements is harder to rectify. Besides, the energy reconstruction of air showers needs an absolute value of detected photons.

In any case, it is possible to directly translate absolute PDE to relative PDE via a conversion ratio. As such, under a controlled experiment condition, both measurements should reach the same conclusion. Getting this conversion ratio is also an interesting exercise. In this thesis, the absolute PDE measurements were carried out by the author while the relative ones were done by a bachelor student working under the supervision of the author A.Pol [2016]. The principles for the experimental setups for both are almost identical, shown in figure 3.1.

The idea behind the experiment is to illuminate identically the photosensors with a (pulsed) light source and then compare the number of detected photons. A beam of light enters the integrating sphere and is reflected several times inside the sphere and exits evenly at the 2 ports with mounted photosensors. Additionally, since different sensors have different active area, an aperture with known radius is placed in front of the photosensors in order to normalize the illuminated area. By applying formula 2.7 the number of detected photons can be calculated and compared against the value from the referenced sensor (for absolute PDE) or against another SiPM (for relative PDE). The wavelength of the incoming light beam and the bias voltage will be varied to survey possible operating scenarios of the controllable parameter space of \((\lambda, V_{ov})\).
Figure 3.1: Principles of the experimental setup. Incoming light beam enters the integrating sphere (black circle), undergoes multiple scattering reflections and finally illuminates equally 2 ports with mounted photosensors. The aperture is used to ensure that only a small area of the SiPM is exposed. The schematic is used for the absolute PDE measurement. For relative PDE measurement, the calibrated photodiode on port 1 is replace with an SiPM with aperture similar to the one on port 2. Figure taken from A.Tadday [2010]

The schematic and actual photo of the experiment setup are shown in Figure 3.2 below. Except for the wavelength scan, the whole setup was automated via Python, from controlling bias voltage to collecting raw data and finally plotting peak height spectrum. The experiment typically took place at room temperature, which typically varied ± 1°C. The temperatures were recorded but not controlled.

3.2 Equipments

This section provides information on various equipments used in the thesis and can be skipped during the first reading.

3.2.1 Light Sources

Two different light sources were used in this thesis, which are shown in figure 3.3.

3.2.1.1 CHEC Flasher

For the relative PDE measurement, this thesis used one of the 4 flasher units used in the GCT camera. The flasher houses 10 Bivar UV3TZ-400-15 LEDs that
have a peak wavelength at 400 nm and can produce light pulses with Full-Width-Half-Maximum (FWHM) in the order of 4 ns. Each LED can be turned on/off via USB serial command interface. In this thesis, a Python module was written to relay the command during the experiment. The photo of the flasher unit is shown in Figure 3.3a below. The diffuser was not used in this thesis.

3.2.1.2 Nijmegen Light Source

For the wavelength scan, a light source with different wavelengths was needed. This thesis used a light source with different LEDs developed at Nijmegen. The light source also includes filter wheels that can reduce the number of photons impinging on the photosensors (Figure 3.3b). In this experiment, a 20% filter wheel was used to allow only \( \sim 20\% \) of the light intensity from the LEDs.

3.2.2 Pulse Generator

The pulse generator is Agilent 33522A Signal Generator (Figure 3.4) capable of generating square pulses that generate trigger pulses for the flasher LED and trigger data acquisition. It has two synchronized outputs routed to the CHEC flasher and to the oscilloscope. During this thesis, it was found out that square waveforms are not desirable: the fast switching of the pulses created distortions of SiPM readout, possibly due to mismatched impedance among various electronic components. It was discovered that the mismatch was mitigated by using a trapezoidal waveform with a gentler slope (Figure 3.5).

3.2.3 THORLABS IS200-4 Integrating Sphere

The IS200-4 Integrating Sphere is a general purpose integrating sphere that spreads evenly the incoming light by multiple reflections over the entire sphere surface. The ports for incoming light, SiPM and PIN diode are mutually orthogonal to each other to ensure that the light has been reflected multiple times before arriving at the sensors.

3.2.4 Calibrated Reference Sensor

The reference sensor in this thesis is THORLABS FDS1010-CAL - Calibrated Si Photodiode with 10mm x 10mm active area.
3.2.5 SiPMs, Nikhef-made bias boards and apertures

The SiPM samples from different vendors are given in the Table 3.8 below with parameters quoted from the data sheet. In order to bias the SiPMs and to collect data, several custom-made Printed Circuit Boards (PCB) were needed. These bias boards were made at Nikhef and contain passive electronic circuitry necessary to bias the SiPMs. Each board can be mounted onto the integrating sphere using THORLABS SM1CP2M endcaps. Each endcap was milled out in the center to accommodate the SiPM. An aperture was placed in front of the SiPM to ensure that all SiPMs had the same exposed area. Figure 3.9 shows the boards, SiPMs and apertures in the experiment.

3.2.6 Signal Amplifiers

In order to amplify the SiPM signal sufficiently above the resolution of the oscilloscope, a signal amplifier was needed. This thesis used signal amplifiers from 2 different manufacturers: Mini-Circuits ZFL-500 Series and Texas Instrument LMH6629 Evaluation Board. These amplifiers sit between the SiPM bias board and the oscilloscope, and several amplifiers can be connected in series to further increase the amplification. Figure 3.10 shows the two amplifiers.

3.2.7 Oscilloscope

The SiPM signal was collected using an oscilloscope. The oscilloscope used in this thesis is an HDO4034 Lecroy oscilloscope capable of 12-bits ADCs and display signals up to 1 GHz. The oscilloscope is connected to the computer via LAN interface, and the data readout is obtained using cVXI11 Python module. For each voltage trace, the oscilloscope records the voltage trace and provides the voltage difference between the peak and the base line level. The list of peak height values is then recorded in a .txt file. Figure 3.11 shows a photo of the oscilloscope’s screen during one of the measurements.

3.2.8 Picoammeter

An ammeter is needed to measure the photocurrent of the PIN diode (reference sensor). Given that this thesis measures energy at the single-photon level, a device capable of measuring current at pico-Ampere was needed. The Keithley 6485 Picoammeter in Figure 3.12 was chosen, which can measure currents from 20fA to 20mA, at speeds up to 1000 readings per second. The picoammeter communicates with the computer via GPIB interface, and a Python script was written to remotely control the picoammeter and collect photocurrent readings.
3.2.9 Power Supplies

For absolute PDE measurement, the AIM-TTI INSTRUMENTS PLH120P power supply was used to bias the SiPM. This power supply is capable of producing 120V and 750mA current. For relative PDE measurement, the AIM-TTI INSTRUMENTS MX100TP was used to bias the additional SiPM. This power supply is capable of producing 70V and 6A current. Both power supplies are connected to LAN interface and can be programmed via Python (using the Python socket module) to adjust the voltage. Figure 3.13 shows images of the power supplies from the manufacturer’s website.

3.2.10 Arduino UNO with Temperature Sensor

The digital temperature sensor used in this thesis is DS18S20s series from Dallas semiconductor. The sensor needs a microcontroller board (Arduino UNO) to power and read the temperature via 1-wire communication protocol. Arduino then flushes the reading to the computer via USB serial communication. A Python script was written to record the serial message, filter out unnecessary information and write the temperature in a .txt file for future reference. Figure 3.14 shows the temperature sensor and the Arduino microcontroller.
Figure 3.2: Experimental setup for *absolute* PDE measurement. Top: schematic based on the experiment principles in Figure 3.1. Bottom: Photo of actual setup. The box was closed during the experiments. The LED flasher has a fixed wavelength at $\lambda = 400\text{nm}$. For the wavelength scan, a different light source was used. Figure taken from Stephan [2016].
(a) CHEC flasher with 10 LEDs producing light pulses at $\lambda = 400$nm. The diffuser and the mechanical holder were not used in this thesis. Instead, the LEDs and the green PCB were housed in a metal enclosure attached to the left side of the darkbox as seen in Figure 3.2. Figure taken from CTA [2015].

(b) Light source from Radboud University Nijmegen with LEDs at different wavelengths $\lambda = 320,390,455,590,740$ nm. The box also uses its own trigger pulse generator with 1MHz pulsing frequency. The box was closed during the experiment to prevent ambient light from leaking into the system.

Figure 3.3: Light sources used in this thesis. Left: CHEC flasher used for *relative* PDE measurements. Right: Nijmegen Mobile Light source for *absolute* PDE measurement. The box was closed during the experiment.

Figure 3.4: Agilent 33522A Signal Generator used to generate signal pulses for LED flasher and to trigger oscilloscope reading. Figure taken from Keysight.
Figure 3.5: Effect of pulse shape on the SiPM’s baseline noise level. The top thin lines are the shapes of the pulses created by the pulse generator. The widths of the pulses are 150ns in both cases. The bottom thick lines are the baseline noise level.

Figure 3.6: THORLAB φ 2” IS200-4 Integrating Sphere in Black Anodized Aluminum Housing. Figure taken from Thorlabs.
Figure 3.7: THORLAB FDS1010-CAL reference sensor with apertures. The aperture on the left provides full illumination area while the aperture on the right was used to normalize the exposure area with the SiPM.

<table>
<thead>
<tr>
<th></th>
<th>Hanamatsu</th>
<th>Excelitas</th>
</tr>
</thead>
<tbody>
<tr>
<td>Active area (mm²)</td>
<td>3x3</td>
<td>6x6</td>
</tr>
<tr>
<td>Fill factor (%)</td>
<td>62</td>
<td>40</td>
</tr>
<tr>
<td>Cell pitch (µm)</td>
<td>50</td>
<td>50</td>
</tr>
<tr>
<td>Typical dark count (kcps)</td>
<td>1000</td>
<td>5400</td>
</tr>
<tr>
<td>Dark count per mm² (kcps)</td>
<td>111</td>
<td>150</td>
</tr>
<tr>
<td>Typical gain</td>
<td>1.25-10⁶</td>
<td>1.5-10⁶</td>
</tr>
<tr>
<td>Number of pixels</td>
<td>3600</td>
<td>14400</td>
</tr>
<tr>
<td>Number of pixels per mm²</td>
<td>400</td>
<td>400</td>
</tr>
<tr>
<td>Typical breakdown voltage (V)</td>
<td>65</td>
<td>95</td>
</tr>
<tr>
<td>Typical overvoltage (V)</td>
<td>2.6</td>
<td>5</td>
</tr>
</tbody>
</table>

Figure 3.8: Table of SiPMs tested in this thesis, together data from quoted from the datasheet. Taken from A.Pol [2016]
(a) Back side of the bias boards showing the PCBs.

(b) Front side of the bias boards showing the mounting holes for the apertures and the SiPMs in the middle.

Figure 3.9: Bias boards with PCBs (green), THORLABS adaptors (black), apertures (bronze) and SiPMs (red squares). From left to right: Hamamatsu, Excelitas and SensL SiPMs. These apertures are assumed to have the same opening area as the PIN diode’s aperture on the right in Figure 3.7

(a) Texas Instrument LMH6629 Evaluation Board. Figure taken from Texas.

(b) Mini-Circuits ZFL-500 Series. Figure taken from Artison.

Figure 3.10: Signal amplifiers used in this thesis
Figure 3.11: HDO4034 Lecroy recording SiPM signal pulses.

Figure 3.12: Keithley 6485 Picoammeter to record photocurrent from the referent sensor. Figure taken from Tektronix.
Figure 3.13: Power Supplies to bias the SiPMs

(a) PLH120P Power Supply for *absolute* PDE measurements. Figure taken from RS.

(b) MX100TP Power Supply for *relative* PDE. Figure taken from Aim-TTi.

Figure 3.14: Temperature monitoring system for the experiment

(a) Dallas DS18S20 temperature sensor. Figure taken from Dallas.

(b) Arduino UNO Microcontroller with wiring for the Dallas temperature sensor.
Chapter 4

Results and Discussions

"Its just two numbers that divide
And the meaning they contain.
But they reveal what senses hide
And make a hidden order plain.”
van Schalkwijk

4.1 Dark Phenomena

4.1.1 Signal Comparison

To facilitate calibration and photon counting, the peaks of the peak height spectrum should be distinct and well-separated from the white electronic noise. The statistical uncertainty in photon counting arises from not knowing exactly the location of the peaks, as seen by the Gaussian-like spread of the pe peaks in the peak height spectrum. On the other hand, the systematic uncertainty arises from the experimenter’s decision whether to count an event as a pedestal event or a pe event. For the analysis in this thesis, the choice is taken to be 1/2 pe level (1/2 the distance between the pedestal peak and 1st pe peak).

A dimensionless parameter to quantify signal quality is the ratio of the 1 standard deviations of the Gaussian fit of the 1st pe peak over the 1/2 pe level obtained from $10^4$ voltage traces:

$$\rho(V_{ov}, \lambda)\bigg|_{n=10^4} = \frac{\sigma_{1pe}}{1/2V_{1pe}}$$

(4.1)

In general, $\rho(V_{ov}, \lambda)$ is a measure of the spread of the pe level relative to the
gain properties of the SiPM. The smaller $\rho(V_{\text{ov}}, \lambda)$ is, the better photon resolution we get. For practical purposes in this thesis, $n$ is kept at $n = 10^4$, which takes approximately 10 minutes to collect data and produce a peak height spectrum. Thus, given a fixed number of measurements, $\rho$ is the first quantity that characterizes the signal-to-noise ratio: the smaller $\rho$ is, the larger the distance between the peak and the baseline noise level is. Figure 4.1 shows signals with low $\rho$ value (left) and high $\rho$ value (right).

![Figure 4.1: Signal quality comparison between Hamamatsu (left) and Excelitas (right).](image)

(a) Oscilloscope screen for a low $\rho$ SiPM (Hamamatsu)  
(b) Oscilloscope screen shot for a high $\rho$ SiPM (Excelitas)  
(c) Well-localized and separated peaks. Pedestal events are clearly separated from pe events by the blue line $V = 1/2V_{1\text{pe}}$.  
(d) Fuzzy and cluttered peaks. Pedestal events are ill separated from pe events by the blue line $V = 1/2V_{1\text{pe}}$.  

Figure 4.1: Signal quality comparison between Hamamatsu (left) and Excelitas (right). On the left column, the pe events are clearly separated from the noise level and do not fluctuate significantly, which result in a sharp peak height spectrum. On the right column, the first pe events are almost drown in the noise, thus the peak height spectrum contains large uncertainties. The width of the blue vertical band is $2\sigma$ of the 1st pe peak, while the width of the red vertical band is $1/2V_{1\text{pe}}$.

An interesting point worthy of discussion is that Excelitas (device on the right) has a slightly higher gain: the half-pe level is at 950 mV whereas it is only 836 mV for Hamamatsu (on the left). It can be interpreted that the Excelitas SiPM
produces stronger signals in this particular situation. However, the strength of the signal alone does not guarantee better signal quality, as we have to take into account the systematic noise. Clearly in this case the Excelitas has larger systematic fluctuation noise that overshadows the signal strength thereby degrading the resolution power.

Let us now take a deeper look into the effects of $\rho$ on the uncertainty of $\mu$ (number of photons impinging on the SiPM). For the analysis in this thesis, an event that has peak height less than $V = 1/2V_{1pe}$ will be counted as a pedestal event. However, this factor 1/2 is rather arbitrary: it represents the experimenter’s systematic choice in defining what an pe event is. In fact, it can be argued that the 1/2 factor could instead be 1/4 or 3/4 depending on how strict the requirements are. For this reason, the $V = 1/4V_{1pe}$ and $V = 3/4V_{1pe}$ produce an upper (and lower) bounds on the value of $\mu$, respectively. $\sigma$, on the other hand, represents the stochastic variation of the signal. The smaller $\rho$ is, the more accurate and precise results we have. For concreteness, both errors of the two measurements in Figure 4.1 are given in Table 4.1 below:

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Definition</th>
<th>Hamamatsu</th>
<th>Excelitas</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\sigma$</td>
<td>standard deviation of 1st pe peak</td>
<td>0.274</td>
<td>0.359</td>
</tr>
<tr>
<td>$1/2V_{1pe}$</td>
<td>1/2 pe level</td>
<td>0.836</td>
<td>0.950</td>
</tr>
<tr>
<td>$\rho$</td>
<td>$\sigma/(1/2V_{1pe})$</td>
<td>0.327</td>
<td>0.378</td>
</tr>
<tr>
<td>$\mu</td>
<td><em>{1/2V</em>{1pe}}$</td>
<td>$\ln\left(\left(n &lt; 1/2V_{1pe}\right)/10000\right)$</td>
<td>4.88</td>
</tr>
<tr>
<td>$\Delta_{\text{choice}}(\mu)$</td>
<td>$\mu</td>
<td><em>{1/2V</em>{1pe}} - \mu</td>
<td><em>{1/4V</em>{1pe}} - \mu</td>
</tr>
<tr>
<td>$\Delta_{\text{stochastic}}(\mu)$</td>
<td>$\mu</td>
<td><em>{1/2V</em>{1pe}} - \sigma - [\mu</td>
<td><em>{1/2V</em>{1pe}} + \sigma]$</td>
</tr>
</tbody>
</table>

Table 4.1: Effect of $\rho$ on the uncertainty of photon counting. With Hamamatsu SiPM, we are able to perform more accurate and precise measurements, as seen by the relatively low $\Delta_{\text{stochastic}}$. $\rho$ thus correlates with the resolution on photon counting.

From the definition, $\rho$ is inversely proportional to $V_{1pe}$ and one might be able get better photon counting resolution by operating at higher voltage. As such, it is not always fair to compare directly $\rho$’s at any particular bias voltage. Instead, Figure 4.2 below shows the ratio of $\rho(\text{Excelitas})$ over $\rho(\text{Hamamatsu})$ across a voltage range. In this figure, the ratio is always greater than 1, which implies that Excelitas has worse photon resolution than Hamamatsu most of the times. Additionally, Hamamatsu SiPM behaves as expected: increasing bias voltage leads to higher (relative) photon resolution. Excelitas, however, is not able to improve photon resolution beyond a certain threshold (approximately in
the region between 96.5V and 97V). From the plot, it is clear to conclude that Hamamatsu provides better signal quality.

![Figure 4.2: Relative photon resolution of Excelitas over Hamamatsu as a function of bias voltage. Red means Hamamatsu is significantly better while dark blue means Hamamatsu and Excelitas have comparable resolution power.](image)

**4.1.2 Breakdown Voltage and Gain Comparison**

From the theoretical discussion, the breakdown voltage is the minimum bias voltage above the noise level at which an avalanche can place to generate the SiPM pulse signal. The higher above the breakdown voltage the bias voltage is, the larger the pulse height we get due to the fact that the photocurrent is proportional to the field. Conversely, when the bias is at the breakdown voltage, the pulse heights (difference between the peak heights and the baseline noise level) are zero. Exploiting this fact, we simply plot the pulse heights of the 1st, 2nd, 3rd peak etc peaks of the peak height spectrum as a function of bias voltage and find their intersection point. This is illustrated in Figure 4.3. Hamamatsu has lower breakdown voltage and is therefore a more desirable device, since it costs less energy to bias the device into avalanche mode.

From the plot, it is clear that the pedestal peaks (due to electronics noise) are not coupled to the bias voltage and remain constant across the bias voltage
range. The positions of the pe peaks, on the other hand, vary linearly with the bias voltage. As such, to a good approximation, the slope of the red line (1st pe) correlates with the gain per overvoltage. The linear fit for Hamamatsu gives slope $= 1.11 \times 10^{-3}$ while the linear fit for Excelitas gives slope $= 0.88 \times 10^{-3}$. As such, Hamamatsu is a more desirable device since it is able to provide higher gain per energy input.

### 4.1.3 Dark Noise Comparison

Recall that an SiPM can generate photon signals even in the absence of light due to thermal processes that generate electron-hole pairs within the device. This phenomenon makes SiPMs "noisy" devices, and a better SiPM should have low dark count. The dark count of each SiPM is obtained by performing photon counting on the peak height spectrum in the dark using the Poissonian statistics formula discussed earlier in this thesis:

$$
\mu_{\text{dark}}(V_{\text{ov}}) = -\ln \left( \frac{N_{\text{ped}}}{N_{\text{total}}} \right)
$$

Physically, $\mu_{\text{dark}}$ can be called "detected pseudo thermal photon" since it represents the number of detected photons from the thermal processes inside the device. For PDE measurements, $\mu_{\text{dark}}$ should be subtracted away to correct for this phenomenon. It should be noted that Excelitas device is 4 times as large as Hamamatsu, so each dark count value should be divided by 4 to normalize.
with respect to the active area. The plot of the dark count of Hamamatsu and Excelitas as a function of overvoltage is given in Figure 4.4a below. Also, the contour plot of their ratios of dark counts is shown in Figure 4.4b.

(a) Dark counts of SiPMs. Hamamatsu (blue data points) has higher dark count. The asymmetrical vertical error bars are defined according to $\Delta_{\text{stochastic}}(\mu)$ described Table 4.1 while the horizontal error bars are the 0.1V uncertainty of the power supply unit.

(b) Contour plot of relative dark photon counts. The diagonal solid line in the middle is where $\mu_{\text{dark}}(\text{Excelitas}) = \mu_{\text{dark}}(\text{Hamamatsu})$. Blue means Excelitas has lower dark photon count and hence is more quiet.

Figure 4.4: Dark photon counts of 2 SiPMs, showing that Excelitas is a more quiet device with low dark photon count relative to Hamamatsu when both devices are biased at low overvoltage.

Again, the dark photon count increases with the overvoltage due to the fact that there are more chances for cell breakdowns due to thermal processes with the increase in the potential across the cells. The general trend is that the Excelitas SiPM is more quiet, but from Figure 4.4a, it is possible for Excelitas to become noisier than Hamamatsu if Hamamatsu is biased at lower voltage and Excelitas is biased as higher voltage. As such, it is not always objective to compare the dark photon counts at any particular overvoltage. The contour plot in Figure 4.4b captures a more complete picture of the relative dark photon counts of two devices.

4.1.4 Optical Cross Talk Comparison

Recall that optical crosstalk is caused by the generation of a photon inside the SiPM which caused additional cell breakdowns. Assume that, in the absence of external light sources, cell breakdowns beyond the 1 pe level are solely caused by optical crosstalk, then the probability of optical crosstalk $P_{\text{OXT}}$ is given by:
\[
P_{\text{OXT}} = \frac{N_{\text{pe} \geq 2}}{N_{\text{total}} - N_{\text{ped}}} = 1 - \frac{N_{\text{1pe}}}{N_{\text{tot}} - N_{\text{ped}}}
\] (4.3)

Results from the calculation of \(P_{\text{OXT}}\) are presented in Figure 4.5, which give us similar conclusion as in the case of \(\mu_{\text{dark}}\): Excelitas is more desirable than Hamamatsu when both devices are biased at low overvoltage, but the situation can be reversed when Excelitas is operating at high overvoltage and Hamamatsu at low voltage.

To summarize Section 4.1 Dark Phenomena, we have seen that Hamamatsu produces higher signal quality and requires lower voltage to operate, but Excelitas appears to be a better device in terms of noise. However, the crucial observation is that SiPM noise is overvoltage dependent. Operating at low overvoltage will reduce noise, but it means that the device’s detection efficiency will also be reduced since the photosensor will detect fewer Cherenkov photons at lower overvoltage. We will therefore need to examine how the 2 devices fare against each other when it comes to light detection.
4.2 Light Phenomena

4.2.1 PIN Diode Photon Counting

One way of characterizing the performance of SiPM when being exposed to light is to compare the number of photons the SiPM detected against the number of photons detected by a calibrated photosensor. However, unlike the SiPM, the reference sensor (PIN diode used in this thesis) does not produce peak height spectra. Instead, the difference in photocurrent $\Delta I = I_{\text{light}} - I_{\text{dark}}$ collected at the output of the sensor is directly proportional to the number of photons impinging on the PIN diode $\mu_{\text{PIN}}$ per unit of time:

$$\Delta I = \mu_{\text{PIN}} \times (QE \times q \times f) \quad (4.4)$$

where $f$ is the frequency of the light pulse (1MHz in this experiment), $q$ is the elementary charge, and $QE$ is the PIN diode’s quantum efficiency (the probability that an incident photon will generate an electron-hole pair). Essentially, PDE is a measure of QE and must be obtained from the manufacturer’s calibrated data. In this thesis, Mr. Feynman’s tower of turtles stops at the PDE of the PIN diode. Normally, in the data sheet, QE is given implicitly in terms of the PIN diode’s responsivity in the unit of A/W (charge produced per unit energy of incoming photon):

$$\eta \equiv QE \frac{q}{hc/\lambda} \quad (4.5)$$

where $h$ is the Planck’s constant and $c$ is the speed of light in the vacuum. Solving for QE in equation 4.5 to put into equation 4.4 and subsequently solving for $\mu_{\text{PIN}}$, we obtain a formula to calculate the number of photons (per light pulse) impinging on the SiPM:

$$\mu_{\text{PIN}} = \frac{I_{\text{light}} - I_{\text{dark}}}{\eta \times hc/\lambda \times f} \quad (4.6)$$

The denominator of equation 4.6 is fixed for a particular light source, while the numerator is the difference of current measured from the PIN diode during the experiment. To get $I$, typically 5000 readings were taken from the picoammeter and the mean current was obtained using a Gaussian fit on the histogram. Figure 4.6 below shows a typical photon counting results from the PIN diode.

The current detected by the PIN diode is not constant. This is due to the fact that the generation of electron-hole pairs is a quantum process. However,
Figure 4.6: Distribution of the current readings from the PIN diode under pulsed LED illumination. The mean of the Gaussian fit is $I_{\text{light}}$. Note that $\mu$ in the plot denotes the mean current reading and not the number of detected photons.

as the number of measurements increases, the mean of the current will tend to the true value. According to the distribution of the current readings in Figure 4.6, the uncertainty is approximately 3.5% of the mean value. More details on current readings of the PIN diode can be found in Appendix A (5)

4.2.2 Absolute PDE

When both SiPM and PIN diode are illuminated identically at the openings of the integrating sphere, the absolute PDE then follows the equation:

$$PDE \equiv \frac{\mu_{\text{SiPM}}}{\mu_{\text{PIN}}} = \frac{\mu_{\text{SiPM,light}} - \mu_{\text{SiPM,dark}}}{\mu_{\text{PIN}}}$$ (4.7)

However, since different photosensors have different active areas, apertures were put in front of the sensors to control the exposure area. The PDE is then divided by a normalizing geometrical factor, denoted as $R$ according to the following the equation:

$$R \equiv \frac{\mu_{\text{PIN with PIN aperture}}}{\mu_{\text{PIN with SiPM aperture}}}$$ (4.8)
To get R for the absolute PDE measurement, the PIN diode was first illuminated with the left aperture in Figure 3.7 (full illumination). This aperture was then removed and the right aperture in Figure 3.7 with similar opening area to the SiPM aperture was placed in front of the PIN diode. For PDE measurement with Hamamatsu SiPM, $R = 28.5 \pm 6$ and for Excelitas, $R = 26.6 \pm 3.6$.

![Figure 4.7: PDE of SiPMs in the ($V_{ov}, \lambda$).](image)

(a) Excelitas. The device has wider uncertainty from the estimation of the $1/2 V_{1pe}$. (b) Hamamatsu. The device has wider uncertainty from the estimation of the geometrical factor R ratio.

Figures 4.7 shows the PDEs for Hamamatsu and Excelitas in the ($V_{ov}, \lambda$) parameter space. With Hamamatsu, we are able to get more precise measurements, as seen by the smaller spread of the uncertainty lines. For Excelitas, the uncertainty is dominated by the uncertainty of choosing the $1/2 V_{1pe}$. This is expected, as Excelitas has worse signal quality and the peak height spectra are fuzzy. This uncertainty is intrinsic to the SiPM and unless the company is able to produce better devices, it is not possible to reduce this uncertainty. For Hamamatsu, the uncertainty is dominated by the geometrical factor R ratio, which varies up to $\pm 17\%$ of the measured values. The $1/2 V_{1pe}$ uncertainty is hardly visible in the right plot. Therefore, further experiment should be conducted to reduce this systematic uncertainty. The large aperture (full illumination) of the PIN diode are not necessary as it was seen that the PIN diode was able to detect photons even with the same aperture as the SiPM’s aperture. For future experiment, the aperture on the right of Figure 3.7 should be used, and R will assumed to be 1 in most of the cases.

For each wavelength (same color), the PDE of Hamamatsu does not increase significantly over the bias voltage. This can be explained by the fact that the overvoltage range in this experiment is already within the recommended operating overvoltage ($\sim 2.4V$) from the manufacturer. Excelitas, on the other hand, seems
to continue to increase, as the overvoltage range is below the recommended value (∼5V) from the manufacturer. This is interesting, since according to Figure 4.5, Excelitas already has more than 50% optical crosstalk before reaching 5V overvoltage. In other words, Excelitas can achieve high detection efficiency at the expense of noise.

Overall, Hamamatsu has higher detection efficiency, as seen by the relative heights at each wavelength between the 2 plots. An exception can be made at 454 nm (blue light) where Excelitas seems to have higher detection efficiency. However, since the uncertainty of Excelitas is rather high, its claim of higher PDE can be challenged. Additionally, if we restrict ourselves to the low crosstalk region (low overvoltage) the PDEs at 454 nm are comparable.

Another anomaly in the result is that at 586 nm (yellow), the PDE dropped significantly. The reason for this was yet understood and requires further investigation, but one possible explanation is that the measurements were not accurate at low PDE levels. Essentially, the SiPMs become insensitive to incoming light to produce reliable statistics. This explanation is reasonable if we compare it with the next wavelength (740 nm in red). The PDEs at these 2 wavelengths are very close to zero, which means that both SiPMs detected nothing but noise. If this assumption holds true, there are few suggestions for further experiments in this range. One is to increase the light intensity at the SiPM by removing the aperture, and the second is to not filter the SiPM with the 20% filter wheel from the Nijmegen mobile test setup.

### 4.2.3 PDE Comparison

Having obtained the PDEs in the parameter space, the next step in the analysis is to find out under which operating conditions one SiPM is performing better than the other. For each wavelength, a contour plot of $PDE_{Excelitas}/PDE_{Hamamatsu}$ over the overvoltage range is plotted, together with the 30% $POXT$ limit. The plots for 4 wavelengths at 389, 454, 586 and 740nm are shown in Figure 4.8 below. The uncertainty is not taken into account in the contour plot.

A general trend can be immediately seen: except at 454nm (Figure 4.8b, top right), the remaining contour plots are mostly blue in color without the diagonal line where $PDE_{Excelitas} = PDE_{Excelitas}$. It means that the ratio of $PDE_{Excelitas}/PDE_{Hamamatsu}$ is less than 1 in these cases, which clearly favors Hamamatsu as a device with higher detection efficiency. Even at low PDE wavelengths (586 and 740nm), Hamamatsu was able to detect photons, even though the measurements were not reliable.

The conclusion becomes even stronger if we restrict ourselves to the conservative region where the optical crosstalk is less than 30% for both devices (lower left corners of the contour plots). In these regions at 399, 454 and 740nm, Excel-
(a) 389nm: Excelitas always has lower PDE than Hamamatsu.

(b) 454nm: Excelitas has comparable PDE with Hamamatsu. The diagonal line is where $PDE_{\text{Excelitas}} = PDE_{\text{Hamamatsu}}$.

(c) 586nm: Excelitas always has lower PDE than Hamamatsu

(d) 740nm: Excelitas always has lower PDE than Hamamatsu

Figure 4.8: Contour plots for relative PDE of Excelitas and Hamamatsu across 4 different wavelengths. The x-axis is the overvoltage of Hamamatsu, and the y-axis is the overvoltage of Excelitas. The color at each point scales with the ratio of $\frac{PDE_{\text{Hamamatsu}}}{PDE_{\text{Excelitas}}}$. Blue color means $PDE_{\text{Excelitas}} < PDE_{\text{Hamamatsu}}$. The red horizontal and vertical lines are the 30% $P_{\text{OXT}}$ crosstalk probability thresholds.
celitas’ PDE is between 40% and 60% of Hamamatsu’s PDE. An exception can be made if one only wants to detect light specifically at 454nm, where the PDE of two devices are comparable with each other. Even so, if we look closely at the conservative region, Excelitas requires slightly higher overvoltage to surpass Hamamatsu. However, higher overvoltage comes at the cost of increasing noises, which is not desirable. As such, with the most conservative criteria based on high PDE and low noise, Hamamatsu proves to be a more superior device.

4.3 Relative PDE Measurements Comparison

![Figure 4.9: Comparison between relative (left) and absolute (right) PDE measurements near 400nm.](image)

To check for consistency of the absolute PDE measurements (SiPM and PIN diode mounted on the integrating sphere), the results are compare against the relative PDE measurements (2 SiPMs on the Integrating Sphere). The contour plots for both experiments with 400nm wavelength are shown below in Figure 4.9.

In this plot, the results for the relative measurement are shown on the left subplot. The color shows the ratio of $\mu_{\text{SiPM}}$ (number of detected photons at each overvoltage). The subplot on the right, on the other hand, shows the ratio of absolute PDEs (number of detected photons relative to the PIN diode calibrated photosensor) at each overvoltage. Assuming that the behavior of the PIN diode calibrated photosensor does not change throughout the experiment, the two results should agree with each other.
There are several differences that are immediately seen. Firstly, in the case of absolute PDE measurement, the conservative 30% $P_{OXT}$ limit is lower: 2.2V (2.7V) versus 2.56V (2.93V) for ($V_{Hamamatsu}, V_{Excelitas}$). This is due to the fact that the setup during the absolute PDE measurement was less light-tight than the one in the relative measurement. Photons leaked into the setup were interpreted as crosstalk photons, which explained why the devices reach high crosstalk even at lower overvoltage. Secondly, it appears that, within the 30% $P_{OXT}$ conservative region, Excelitas has slightly higher relative PDE in the left plot ($4.9a$), as seen by the presence of cyan color. The discrepancy can be explained by the large systematic uncertainty of the $R$ (aperture correction ratio) in the absolute PDE measurement. Lastly, the line where $PDE_{Excelitas} = PDE_{Excelitas}$ is not present in the left plot. This is due to the fact that the contour plot on the right stops at 4.2 V for Excelitas. Together with the large uncertainty of the aperture correction ratio, it is likely that the line will be observed when Excelitas is biased at higher voltage. In other words, it is possible for Excelitas to have comparable PDE with Hamamatsu when Excelitas is biased at high voltage. However, since the crosstalk noise is too high at this overvoltage, this operational condition is not recommended for operation and will not be relevant for the discussion.

As far as relative PDE is concerned, the claim that Hamamatsu is a better device for photon detection around the peak of the Cherenkov spectrum still stands. In the conservative region where $P_{OXT} < 30\%$ for both devices, Excelitas always has lower PDE.

4.4 Data Sheet Comparison

4.4.1 PDE with respect to wavelength

SiPM samples came with data sheets specifying the device’s PDEs with respect to wavelengths. The data were extracted and plotted in the Figure 4.10. Qualitatively, from the data sheet alone, it is clear that Hamamatsu outperforms Excelitas in the violet region (first 2 bars). Now, comparing with the experimental results, this conclusion is confirmed to be in agreement with data given in figure 4.8a, which says that Excelitas’ PDE is $PDE_{Excelitas} \sim 60\% PDE_{Hamamatsu}$ at 400nm. As the wavelength increases to $\sim$ 450nm (cyan) Hamamatsu becomes comparable with Excelitas. Towards the infrared, Hamamatsu has higher PDEs than Excelitas, which is confirmed with Figures 4.8c and 4.8d (second row).

Next, we examine the highest PDE values of 2 SiPMs and compare them with the data from the manufacturers. Figure 4.11 shows the PDE as a function of wavelength for both devices, together with their uncertainties.

The PDEs obtained from the experiment fell short with the value quoted by
Figure 4.10: PDE as a function of incoming wavelength of Hamamatsu (left at 2.6V $V_{ov}$) and Excelitas (right at 5V $V_{ov}$) according to the data sheet from the manufacturers. The height of each bar is the PDE, the color is the color of the incoming wavelength, and the opacity of the bar scales linearly with the overvoltage.

The data sheet, even when uncertainties are included. For Excelitas, this can be explained by the fact that the experiment was carried out below the recommended operating overvoltage (5V). It is likely that when the overvoltage increases, experimental results will be in better agreement with the data sheet. Hamamatsu, on the other hand, was already operating beyond the 2.6V overvoltage recommended by the manufacturer. Interestingly, except for the anomaly at 586nm, all the measured PDE are approximately 65% of the quoted data from the manufacturer, which could be explained by a yet-known systematic error during the experiment.

4.4.2 PDE with respect to overvoltage

Additionally, the data sheets also specify the device’s PDEs with respect to overvoltage. The data were extracted and produced in the Figure 4.12. Unlike the previous case with the wavelength sweep, it is not possible to compare directly PDE from Figure 4.12 because both devices were measured with different wavelengths. However, it is possible to fit empirically the data with a simple exponential decay function to extrapolate the maximum PDE according to the following equation:
(a) Excelitas experimental results and PDE at 5V according to the data sheet.

(b) Hamamatsu experimental results and PDE at 2.6 according to the data sheet.

(c) Excelitas data sheet compared with highest PDEs from the experiment.

(d) Hamamatsu data sheet compared with highest PDEs from the experiment.

Figure 4.11: Data sheet PDE comparison between PDEs in the wavelength range of Excelitas (left) and Hamamatsu (right). Top row contains all the data including the data from the manufacturers. Bottom row contains highest PDE measured at each wavelength and the data from the manufacturer.
Figure 4.12: PDE as a function of overvoltage for Excelitas at 440nm (back) and Hamamatsu at 408 nm (front) according to the data sheet from the manufacturers. The height of each bar is the PDE, the color is the color of the incoming wavelength.

\[
PDE = Y_0 - \frac{V_0}{K} (1 - e^{-K \times V_{ov}})
\]  

(4.9)

In this equation, K is the saturation rate with respect to the overvoltage \( V_{ov} \), and \( Y_0 - \frac{V_0}{K} \) is the theoretical maximum PDE. The results of the fit for Excelitas and Hamamatsu are shown in Figure 4.13.

From the fit, we predict that the maximum PDE for Hamamatsu is approximately 45.36% and 37.49% for Excelitas. Hamamatsu has higher saturation rate (K), which means that it has a limited dynamic range with respect to operating voltage. Consequently, it also implies that the device is more sensitive to the environment: a slight change in the breakdown voltage can quickly lead to unnecessary saturation of PDE thus requires more frequent calibration. Excelitas, on the other hand, has wider dynamic range and is therefore more robust and does not require frequent calibration.

Next, we compare the prediction against the experimental data as shown in Figure 4.14.
Figure 4.14: Data sheet PDE comparison between PDEs in the overvoltage range of Excelitas (left) and Hamamatsu (right). Top row contains all the data including the data from manufacturer. Bottom row contains PDE measured near 440nm (Excelitas) and 400nm (Hamamatsu) and the data from the manufacturer.
For Hamamatsu, the measurements do not fit well with the data sheet. We fit the data with the equation 4.9, which yields theoretical maximum PDE at around 26%, which is, again, approximately 60% of the expected data from the data sheet. Therefore, we strongly believe that there is one unidentified systematic error that reduced the PDE of Hamamatsu by 60%. However, given that the results of relative measurements agree with absolute measurements, it is also unclear whether this systematic error comes from the measurements of the data sheet or from the experimental setup in this thesis. For Excelitas, the experimental results seem to agree with the data sheet, taking into account the error bars and the wavelength difference (data sheet was measured at 440nm while the thesis measured at 454nm).
Chapter 5
Conclusions and Outlooks

The study of air showers by means of Cherenkov telescopes is a powerful technique that opens new windows in the field of High Energy Astroparticle Physics. With the success of predecessor telescopes such as H.E.S.S. and VERITAS, CTA aims to bring the field to the next level with the construction of 2 telescope arrays that consist of \( \sim 100 \) telescopes in total. 70 of these telescopes are Small-Size Telescopes capable of detecting particles in the 100 TeV range. The camera sensors for SST telescopes are novel silicon semiconductors with single photon detection capability, referred in this thesis as Silicon PhotoMultipiers - SiPMs. These SiPMs offer several advantages as compared to the traditional PhotoMultiplier Tubes (PMTs) used in Cherenkov light detection, including lower operational voltage and mass production potential.

This thesis made progress in developing an experimental setup which can be used to compare SiPM samples from different manufacturers. It was found out that Excelitas S12572-50C samples are less desirable than Hamamatsu C30742-66 for the following reasons:

- **Signal quality:** Excelitas has lower signal quality as seen by the fuzzy and not well-separated peak heights spectrum.

- **Operational voltage:** Hamamatsu has lower breakdown voltage at room temperature: 64.8 Volt against 93.3 Volt for Excelitas.

- **PDE with crosstalk:** in terms of PDE, especially at the peak wavelength of the Cherenkov light spectrum \((\lambda = 400\text{nm})\), Hamamatsu outperforms Excelitas within the conservative regions where optical crosstalk is less than 30%. The absolute PDE result at 400nm agrees with the relative PDE measurement done in a separate study with different setup.

In terms of experimental setup, there are 2 issues that need to be addressed:
• \textit{Controlling the geometrical correction ratio R}: R contributes to 17\% of the systematic uncertainty. In the future, the full illumination aperture of the PIN diode is no longer necessary and R is assumed to be 1 to get rid of this systematic uncertainty.

• \textit{Discrepancies between experiment data and data provided by Hamamatsu data sheet}: The PDEs of Hamamatsu measured in this thesis were only 60\% of what the data sheet claims. However, it does not change the conclusion that Hamamatsu is a better device for the purpose of the Cherenkov Telescope Array.

Nonetheless, the thesis also finds several areas where Excelitas proves to be a better device. Firstly, Excelitas is a more robust device with low dark count rate and optical crosstalk. Secondly, it is also comparable with Hamamatsu specifically at 450nm. As such, for projects that require photon detection with specific wavelength at 450nm, Excelitas can be a better choice of photosensor. As the semiconductor technology is developing at a fast speed, it might be the case there will be better Excelitas samples being introduced in the coming months until the final construction of the 70 SST telescopes in Chile. In the case new samples are introduced, this thesis, especially the data, will serve as a guide for setting up the experiment that compares and verify the claim that the manufacturer indeed improves their products.
Appendix 1: Photon counting with the PIN diode

The Keithley 6485 is able to collect current reading from the referent sensor PIN diode at different speed. The data taking speed is usually quoted in terms of Number-of-Power-Line-Cycles (NPLCs). One NPLC corresponds to 0.02 second integrating time between two measurements (1/50Hz, assuming European Standard Power Line Frequency). Higher NPLC is recommended for measurement, as the noise induced by the alternating current will be averaged out. We first examine the distribution of the current readings using various integer NPLC, as shown in Figure 1:

The measured current follows a Gaussian distribution. The means are similar, but the width of the Gaussian decreases with higher NPLC, thus confirming that waiting longer between two measurements indeed improves the precision of the measurement. The situation changes slightly when non-integer number of NPLCs are used instead, as shown in Figure 2:

The sharp Gaussian peaks are the same measurement results in Figure 1 with integer NPLCs while the non-integer ones are significantly more widespread with symmetrical cutoff at large current, which is possibly due to the accumulated alternating current during the readout. As such, we conclude that only integer number NPLCs should be used in this thesis. However, high NPLC also means longer waiting time, as Figure 3 below shows a contour plot of the waiting time in the (NPLC, number of events) parameter space:

As expected, the time taken to complete the measurements increases with both NPLC and number of data points taken. For the experiments in this thesis, we choose NPLC to be 2 to be compatible with the measurement of the SiPM pulses from the oscilloscope.
Figure 1: Distribution of measured currents with various NPLCs (only integer NPLCs).
Figure 2: Distribution of measured currents with various NPLCs (including non-integer NPLCs). The sharp peaks at the center are integer NPLC while the wide-spread histograms are non-integer NPLC.

Figure 3: Contour plot of waiting time as a function of NPLC and number of events measured.
Appendix 2: Relative PDE of HAMAMATSU and EXCELITAS

Below are enlarged plots for the relative PDEs of Hamamatsu and Excelitas across 4 different wavelengths.

Figure 4: Relative PDE at 389nm.
Figure 5: Relative PDE at 454nm.

Figure 6: Relative PDE at 586nm.
Figure 7: Relative PDE at 740nm.
Appendix 3: Linearity of Hamamatsu PDE

We have seen that SiPMs are linear devices: the peak heights of photon-equivalent event are multiples of each other, allowing us to determine how many photons have impinged on the SiPM. The gain is also linear with respect to the bias voltage, as seen by the fact that the distance between peaks varies linearly with the overvoltage, which we have used to determine the breakdown voltage. Additional, SiPMs also behave linearly with respect to the number of photons impinging on the device, as long as they are operating in the low-light condition.

The linearity of SiPM with respect to the light intensity is called dynamic range: when there are few photons impinging on the SiPM, the device will be able to detect signal. However, as the number of photon increases (up to the order of the number of cells within one SiPM), the device will no longer be able to capture signal from all the photons since the cells are busy most of the time and are unable to detect additional photons. This phenomenon was tested in this thesis using Nijmegen test setup with filter wheels, as described in earlier chapter.

At each wavelength and overvoltage, various combinations of filters were placed between the LED and the optical fiber that coupled the light into the integrating sphere. These filters allowed 0.2%, 0.4%, 1%, 2%, 5%, 20% LED intensity to be coupled into the Integrating Sphere. The numbers of photons detected by the SiPMs and PIN diode are produced in Figure 8.

In this figure, $\mu_{\text{PIN}}$ is the number of photons impinging on the PIN diode, which is assumed to be the same as the number of photons detected by the SiPM multiplied the PDE. It is seen that the number of detected photons for by the SiPM varies linearly with the number of photons impinging on the device. The slope of the line is no other than the absolute PDE (20.5% in this case). The measurements at very low flux (near the origin) are not reliable, considering that
both sensors detected some noises at this level, while the right most data point had been collected several weeks before the rest. The linearity of data points shows the consistency of the experiment in this thesis, in the sense that both $\mu_{\text{SiPM}}$ and $\Delta_{\text{SiPM}}$ yield the same PDE despite the time difference between the measurements. It also shows the consistent performance of Hamamatsu, since the PDE of the device should not be dependent on the light flux intensity as long it is operating in the low flux region (where the number of photons impinging on the device is less than the number of cells). Figure 9 shows similar conclusion from a separate study with an SiPM with 100 cells.

Notice that, in figure 9, the deviation from the linearity occurs when the number of detected photons by the SiPM is approximately 1/2 of the total number of cells in the SiPM. Given that Hamamatsu SiPM samples in this thesis has 3600
Figure 9: Dynamic Range of SiPM with 100 cells showing the linearity region (red) and the saturation region at the end of the device’s dynamic range. Figure taken from T.Kowalew [2013].

cells and it only detects at most 2.3 photons, any deviation from the linearity in Figure 8 is solely due to the uncertainty coming from the anomaly at the very low flux region (≤ than 1 photons). As a suggestion for the future studies, if one wish to scan the whole dynamic range of the SiPM to observe the saturation region, the light intensity should be increased by 3 order of magnitude (1000 times).
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