Development of testing procedures for the optical and electronic components of the IceAct Air Cherenkov Telescopes

Yuriy Popovych

MASTER THESIS IN PHYSICS
submitted to the
FACULTY OF MATHEMATICS COMPUTER SCIENCE AND NATURAL SCIENCES
RWTH AACHEN UNIVERSITY

written at
DEPARTMENT OF PHYSICS
III. PHYSIKALISCHES INSTITUT B

First Referee: Prof. Dr. Christopher Wiebusch
Second Referee: Prof. Dr. Thomas Bretz

November 2020
Abstract

To enhance the performance of the IceCube Neutrino Observatory, one uses several surface extensions including IceAct which consists of an array of compact Air-Cherenkov telescopes. To satisfy its function as a veto-detector for IceCube the IceAct array will have to include many more telescopes than there are currently in operation. Ensuring a correct and stable operation under the harsh weather condition at South Pole the future deployed telescopes will require to be tested and characterized in a straight and reliable way. This work focuses on the testing procedures of the TARGET-C Data-Acquisition system and the SiPM camera used for current and future IceAct telescopes. Measurements on triggering, datataking and the signal propagation through TARGET are performed. Critical steps are identified to establish a full functionality process between DAQ and camera. Like this, a full testing routine is worked out to be used on telescopes for future deployment.
## Contents

<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Contents</strong></td>
<td>i</td>
</tr>
<tr>
<td><strong>1 Introduction</strong></td>
<td>1</td>
</tr>
<tr>
<td><strong>2 Cosmic Rays and their detection</strong></td>
<td>2</td>
</tr>
<tr>
<td>2.1 The Cosmic Ray Spectrum</td>
<td>2</td>
</tr>
<tr>
<td>2.2 Extensive Air Showers</td>
<td>3</td>
</tr>
<tr>
<td>2.3 Cherenkov Effect</td>
<td>4</td>
</tr>
<tr>
<td>2.4 Photomultipliers</td>
<td>6</td>
</tr>
<tr>
<td>2.5 Imaging Air-Cherenkov Telescopes</td>
<td>7</td>
</tr>
<tr>
<td><strong>3 The Detector</strong></td>
<td>9</td>
</tr>
<tr>
<td>3.1 The IceCube Neutrino Observatory</td>
<td>9</td>
</tr>
<tr>
<td>3.2 Surface Extensions</td>
<td>10</td>
</tr>
<tr>
<td><strong>4 IceAct</strong></td>
<td>12</td>
</tr>
<tr>
<td>4.1 General Setup and mechanical construction</td>
<td>12</td>
</tr>
<tr>
<td>4.2 IceAct Camera</td>
<td>13</td>
</tr>
<tr>
<td>4.3 The TARGET-C DAQ</td>
<td>14</td>
</tr>
<tr>
<td>4.3.1 Shaper</td>
<td>15</td>
</tr>
<tr>
<td>4.3.2 Triggering with T5TEA</td>
<td>16</td>
</tr>
<tr>
<td>4.3.3 Readout and Digitization</td>
<td>17</td>
</tr>
<tr>
<td><strong>5 General experimental Setup</strong></td>
<td>19</td>
</tr>
<tr>
<td>5.1 TARGET Adapter Board</td>
<td>19</td>
</tr>
<tr>
<td>5.2 Splitter Board</td>
<td>20</td>
</tr>
<tr>
<td>5.3 Darkbox for Camera Tests</td>
<td>21</td>
</tr>
<tr>
<td><strong>6 Trigger Calibration</strong></td>
<td>23</td>
</tr>
<tr>
<td>6.1 Input Signal</td>
<td>23</td>
</tr>
<tr>
<td>6.2 Trigger Baseline and electrical Noise</td>
<td>25</td>
</tr>
<tr>
<td>6.3 Scan with Input Signal</td>
<td>26</td>
</tr>
<tr>
<td>6.4 Trigger on Multiple Channels</td>
<td>30</td>
</tr>
<tr>
<td>6.5 Different threshold parameters</td>
<td>33</td>
</tr>
<tr>
<td>6.6 Summary</td>
<td>34</td>
</tr>
<tr>
<td><strong>7 Datataking and Digitization</strong></td>
<td>36</td>
</tr>
<tr>
<td>7.1 Pedestal Correction</td>
<td>36</td>
</tr>
<tr>
<td>7.2 Temperature Stability</td>
<td>38</td>
</tr>
</tbody>
</table>
Chapter 1

Introduction

To explore the universe and get to know more about distant galaxies one studies high-energy Cosmic Rays which arrive on Earth every second. These cosmic particles travel through the universe and undergo different processes of acceleration and deflection. By reconstructing the energy and direction of the cosmic rays one tries to find and understand their sources.

For this matter neutrinos are especially interesting particles. Because of their neutral charge and small mass resulting in very weak interactions, they nearly do not get influenced by different acceleration and deflection mechanisms at all. By reconstructing an intergalactic neutrino’s trajectory one could backtrack it to its source and get to know more about neutrino sources this way.

A prominent example for a large scale neutrino detector is the IceCube Neutrino Observatory [1], located at the geographic South Pole. It makes use of the antarctic ice as a medium for the Cherenkov effect to perform indirect detection of neutrinos.

To enhance the particle detection further, there are several additional surface extensions including IceAct. IceAct consists of an array of small, compact IACTs (Imaging Air Cherenkov Telescopes) monitoring the night sky scanning for Cosmic Primary particles. A distant goal of this project is to create an anti-coincidence trigger between IceCube and IceAct to filter IceCube events triggered by atmospheric neutrinos.

Currently, there are two IceAct telescopes in operation with four more already in production. For these telescopes as well as for future telescopes, testing routines have to be established for the hardware to undergo a characterization of the different parts.

This thesis focuses on developing testing routines for the optical camera to detect the Cherenkov light, as well as for the electronic components to ensure stable and reliable data taking, processing and the signal propagation through the data acquisition system. To be able to apply these tests on several telescopes under similar conditions, it is crucial to understand the processes within the hardware and identify challenging steps. Like this, instruments of high quality can be deployed to South Pole increasing the amount of quality data to be taken with them.
Chapter 2

Cosmic Rays and their detection

Cosmic Rays (CR) consist mostly of protons of energies up to $10^{20}$ eV [2]. They interact with our atmosphere and produce different secondary particles (also referred to as „Air Showers“). These particles can be detected and characterized by different kinds of detectors trying to answer the main question of Astroparticle Physics: „Where do Cosmic Rays come from?“.

2.1 The Cosmic Ray Spectrum

The Cosmic Ray Energy Spectrum (Fig. 2.1.1) shows the energy dependence of the flux of primary cosmic rays $\Phi(E)$. The spectrum can be well described by a power law $\Phi(E) \sim E^{-\alpha}$ with several features:

- At about $10^{15}$ eV the „knee“ is located. Until the knee, the spectrum can be described as
  \[ \Phi(E) \sim E^{-\alpha} \quad \alpha = 2.68[3]. \]  
  (2.1.1)

- Above the knee, the CR flux starts decreasing faster until the „ankle“ at about $10^{19}$ eV. Between knee and ankle we also can use a power spectrum with a different exponent.
  \[ \Phi(E) \sim E^{-\alpha} \quad \alpha = 3.1[3] \]  
  (2.1.2)

- Above very high energies of about $4 \cdot 10^{19}$ eV, the spectrum has a sudden cutoff and the CR flux decreases to almost zero. A possible explanation is the so called Greisen-Zatsepin-Kuzumin(GZK)-Effect [4], valid for cosmic particle from sources far away. A proton above energies of $E_{GZK} \approx 5 \cdot 10^{19}$ eV propagating through the universe can interact with a photon of the Cosmic-Microwave-Background(CMB) to produce a $\Delta^+$ hadron.
  \[ p^+ + \gamma_{CMB} \rightarrow \Delta^+ \rightarrow \pi^0 + p^+ \]  
  (2.1.3)

For traveling distances high enough, where the probability for an interaction with a CMB-photon is practically one, primary cosmic particle loose their energy exceeding $E_{GZK}$, because of this interaction. This results in the so called „GZK-cutoff“.[3, 4]
Because of the strong decrease in the flux, direct detection methods can only be used for energies below $\sim 10^{14}$ eV [6]. To detect primary CR particles balloon experiments or orbital detectors are used.

For higher energies one detects the secondary particles produced by air showers (see chapter 2.2) in our atmosphere using ground based experiments like Auger, KASCADE, as well as IceTop and IceAct.[6, 7]

### 2.2 Extensive Air Showers

To observe the CR Spectrum for high energies with ground based experiments one has to study air showers.

An Air Shower starts, when a primary CR particle (like a proton) interacts with our atmosphere. Produced particles from this interaction trigger a chain-reaction by interacting again with the atmosphere broadening the shower further until the shower maximum is reached (indicated by a certain average energy per particle). Then the shower narrows down again.

One way to describe these air showers is the „Heitler Model“[8] which works for electro-
magnetic showers. An electromagnetic shower (illustrated in fig. 2.2.1 (a) ) starts with e.g. a photon which produces $e^+e^-$ by pair production. Eventually, the charged particles emit additional photons which then produce $e^+e^-$ pairs again. One assumes that the energy of the primary particles is evenly split between the secondary particles. The average energy per particle after a distance $d$ can be described as:

$$E(d) = \frac{E_0}{2d/d_0}. \quad (2.2.1)$$

with $d_0 = \lambda_{EM} \cdot \ln(2)$ and $\lambda_{EM} = 36 \text{ g} \cdot \text{cm}^{-2}$ as the electromagnetic interaction length [9]. The shower reaches its maximum when the energy loss is equally dominated by ionization and bremsstrahlung. This particle energy for photons can be calculated as $E = 85 \text{ MeV}$. [8]

From hadronic showers (see fig. 2.2.1 (b)), one gets the following additional hadronic interactions [6]

$$p + N \rightarrow \pi^\pm, \pi^0, K^\pm, K^0, p, n, \cdots. \quad (2.2.2)$$

With further decays of these secondary hadronic particles:

$$\pi^0 \rightarrow \gamma\gamma, \quad \pi^+ \rightarrow \mu^+ + \nu_{\mu}, \quad \pi^- \rightarrow \mu^- + \bar{\nu}_{\mu} \quad (2.2.3)$$

The hadronic decays initiate new electromagnetic air showers, so air showers initiated by a proton consist of a hadronic and an electromagnetic part. Also, the pion and muon decays produce atmospheric neutrinos which can be detected in neutrino detectors together with cosmic neutrinos. [10]

Figure 2.2.1: Schematic views of (a) an electromagnetic cascade and (b) a hadronic shower. (Taken from [8])

### 2.3 Cherenkov Effect

Another observed effect of CR particles with matter is the emission of Cherenkov light.

A charged particle moving through a medium with a refractive index $n > 1$ having a velocity $v > \frac{c}{n}$ exceeding the velocity of light in this medium emits so called "Cherenkov light"[11]. The shape of the emitted light is a cone in the direction of the propagation of the particle with an opening angle of $\Theta_C$ with

$$\cos \Theta_C = \frac{1}{\beta \cdot n} \quad (2.3.1)$$
where $\beta = \frac{v}{c_0}$ with $c_0$ being the speed of light in vacuum. [11]

The Cherenkov Effect can be explained by using Huygens’ principle of elementary waves: A charged particle induces electromagnetic waves. For $v < \frac{c_0}{n}$ these waves propagate faster than the particle, so no radiation is emitted (see fig. 2.3.1a). For $v > \frac{c_0}{n}$ the particle itself is faster, so that the induced elementary waves add up to one wavefront (see fig. 2.3.1b). This emission of Cherenkov light can be seen as the optical analogue to a sonic boom. [12]

Figure 2.3.1: Cherenkov Effect explained with Huygens’ principle. (Taken from [13])

Furthermore, the number of emitted Cherenkov photons per unit length can be described with the Frank-Tamm formula [14]:

$$\frac{d^2N}{dx d\lambda} = 2\pi \alpha q \frac{1}{\lambda^2} \left(1 - \frac{1}{n^2(\lambda)\beta^2}\right)$$  \hspace{1cm} (2.3.2)

with the fine structure constant $\alpha$, the particle charge $q$ and the wavelength dependent refraction index $n(\lambda)$. The Cherenkov spectrum is shown in fig. 2.3.2.

Figure 2.3.2: Spectrum of Cherenkov light measured at the altitude of the HEGRA IACT system, 2200m above sea level, LaPalma. (Adapted from [15])
Chapter 2. Cosmic Rays and their detection

We can see the peak for $\lambda \sim 340$ nm which is in the blue wavelength region.

2.4 Photomultipliers

To detect Cherenkov light one can use different types of so called Photomultipliers.

The working principle of Photomultiplier Tubes (PMTs) is illustrated in fig. 2.4.1. Light enters a vacuum tube and hits a photocathode. Following the photoelectric effect, photoelectrons are emitted from the cathode. Inside the vacuum tube there is a high voltage electric field which accelerates the emitted photoelectrons and focuses them onto the first dynode. Hitting the dynode, more photoelectrons are emitted and accelerated again towards the next dynode and so on. At the end of this process, one gets an amplification in the magnitude of $\sim 10^6$ [16]. Therefore, even signals from single photons can get amplified strong enough producing a measurable electric signal. [16, 17]

![PMT Diagram](image)

Figure 2.4.1: Construction and working principle of a PMT. (Taken from [17])

Silicon Photomultipliers (SiPMs) use the property of silicon of absorbing a wide wavelength range of photon and transferring its energy to a bound electron [18]. An absorbed photon in silicon creates an electron-hole pair which results in an electric field, if a reversed bias voltage is applied. This way, the charge carriers are accelerated towards the anode and cathode. For an electric field above a certain strength (overvoltage), the charge carriers can create secondary charge pairs which trigger an ionizing cascade. It results in a macroscopic current flow and in an operation mode comparable to a Geiger-Counter. Like in a Geiger-Counter the output can be only binary this way, so it would not be possible to detect the number on incoming photons. To overcome this issue one builds a SiPM cell out of many „microcells“ (see fig. 2.4.2a). Each microcell produces an output signal, if a photon is absorbed, and is then blocked for a certain time. The output of the SiPM is the sum over all hit microcells (see fig. 2.4.2b). The amplitude of the output is quantized in the voltage which is produced by one detected photoelectron (1PE). [18, 19]
Chapter 2. Cosmic Rays and their detection

(a) Electric circuit of one SiPM consisting of multiple microcells. The signal from an absorbed photon results in a voltage drop across the resistor which prevents further events until a certain recovery time passes and the voltage recharges.

(b) SiPM output signal. The rise time is determined by avalanche formation inside the microcells and the transit time between microcell and output. The recovery time is indicated by the decay time of the pulse which results from the capacitance and resistance of each microcell, as well as the number of microcells.

Figure 2.4.2: Simplified electric circuit (a) and signal output (b) of a SiPM. (Taken from [19])

Even without incoming light SiPMs show output signals mostly generated by thermal photons. The rate, at which a signal of 1PE is measured, is called „Dark Count Rate“. It depends on the overvoltage and temperature. During an avalanche, the accelerated charge carriers can emit photons which can trigger another avalanche in a neighboring microcell. This process is referred to as „crosstalk“. Therefore, even multiple PE can be measured without incoming light with the corresponding rate decreasing exponentially with the number of PE. [19]

SiPMs have microcell densities between 100 and several 1000 per mm$^2$, which enable small construction of these detectors. Furthermore, their supply voltage lies below 100 V (roughly between 20 and 30 V) which is much less than is needed for PMTs (several kV). [19, 20] Additionally SiPMs, in contrast to PMTs, cannot be damaged by an overexposure to light. All these properties allow good use of SiPMs as individual pixels in Air-Cherenkov Telescopes.

2.5 Imaging Air-Cherenkov Telescopes

To detect Cherenkov light produced by secondary CR-particles and reconstruct the air shower, large Imaging Air-Cherenkov Telescopes (IACTs) are using big mirrors up to 17 m in diameter to focus the incoming Cherenkov light on a camera with light sensors. With the big mirrors angular resolutions up to 0.07° can be achieved. Examples for large IACTs are HESS [21], MAGIC [22], VERITAS [23] and FACT [24].

Another way to increase the angular resolution is to combine observations from different
IACTs of the same air shower. Using formula 2.3.1 with a refractive index \( n \approx 1.0003 \) for air, one gets an opening angle of \( \sim 1^\circ \). Taking an altitude of about 10 km, where the shower starts, the Cherenkov cone on the ground has a diameter of about 240 m (see fig. 2.5.1). So two telescopes with a distance up to 240 m would be able to observe the same event and perform a so-called „stereo observation“.

Figure 2.5.1: Shower detection by IACTs on ground. (Taken from [25])

The Air-Cherenkov light shows an elliptic shape in the camera image. By performing stereo observations (see fig. 2.5.2) one sees the air-shower from different angles. It results in ellipses pointing in different directions depending on the relative position of telescope to the shower. Combining the measurements from both telescopes enables to reconstruct the position of the shower. Using multiple telescopes increases the performance and accuracy of the reconstruction. [26]

Figure 2.5.2: Sketch of a stereo observation of a 300 GeV \( \gamma \)-ray coming from a 1 TeV primary proton. (Taken from [26])
Chapter 3

The Detector

3.1 The IceCube Neutrino Observatory

The IceCube Neutrino Observatory (see fig. 3.1.1) is currently the biggest neutrino detector on earth located at the geographic South Pole. It consists of an in ice detector array deployed between 1450 m and 2450 m below the surface. In the detection volume of about one cubic kilometer 86 vertical strings with 60 DOMs (Digital Optical Modules) with 17 m vertical spacing each are located. Each DOM consists of a PMT as the detection area at the bottom part, as well as electronics for data acquisition and triggering at the top part (see fig. 3.1.2). [27]
Chapter 3. The Detector

An incoming Muon neutrino $\nu_\mu$ interacts with the ice molecules producing a muon $\mu$. This high-energy $\mu$ emits Cherenkov light which can be detected by the PMTs inside the DOMs. Based on the photon number, position and timing information of the DOMs, we can reconstruct the energy and trajectory of the $\mu$ which gives us information about the corresponding $\nu_\mu$. [28]

Figure 3.1.2: Sketch of an IceCube in ice DOM. [29]

Within a radius of 125 m around the center, 15 DeepCore stings are located. They feature 50 DOMs per string with 7 m vertical spacing between 2100 m and 2450 m below the surface which is considered to the region with the clearest ice. These DeepCore DOMs contain PMTs with a clearly higher quantum efficiency than the „normal“ DOMs resulting in them being more light sensitive enabling to perform analyses of neutrino energies down to $E_\nu \approx 10 \text{ GeV}$ while the lower threshold using the normal DOMs is mostly $50 - 100 \text{ GeV}$. [30]

The next stage in the IceCube project will be an Upgrade deployed during the Antarctic winter 2022/2023. It will include seven new strings located in the central area with about 700 new optical and acoustic modules having a vertical spacing of 3 m. Besides the mDOMs (which could be seen as the successor of the DOMs), there are also pDOMs, DEggs, WOMs (Wavelength-shifting Optical Modules) and others. This Upgrade will most most like lower the threshold even further to a few GeV. [31]

3.2 Surface Extensions

For extended studies as well as for cross calibration there are several additional surface detectors to enhance the functionality of IceCube.

One of them is IceTop which consists of 162 ice-filled tanks arranged in 81 stations. Each tank contains two different DOMs. These tanks are sensitive to primary cosmic rays in the „knee“ region of the cosmic ray spectrum. They detect secondary cosmic ray particles from air.
showers using the Cherenkov effect in the ice. IceTop has been used to study PeV gamma rays, as well as radiation effects of solar flares. It can be also used as a partial veto for atmospheric neutrinos. [27]

The other surface extension, IceAct (see fig. 3.2.1), consists of up-to-date two compact IACTs with 61 pixel cameras. They use the Air-Cherenkov Effect to detect high energy cosmic rays. IceAct can be used to study the composition of Cosmic Rays as well as to perform a cross calibration between IceCube, IceTop and IceAct. The two IceAct telescopes have a distance of about 220 m and can perform stereo observations this way. For the future it is planned to deploy a whole array of IceActs so they can operate beside IceTop as an additional veto detector for IceCube (see chapter 4 for more information on IceAct). [33]
Chapter 4

IceAct

IceAct consists of small, compact and cheap IACTs, optimized for the harsh weather conditions on the South Pole, that are integrated in the IceCube datataking structure. Their main three scopes are:

- Cross calibration with IceCube and IceTop [34].
- Measuring the composition of cosmic rays, with the possibility to detect of gamma rays [35].
- Functionality as an effective neutrino veto detector, to reduce background of IceCube and lower the detection threshold (distant goal for the future) [34].

A big advantage of IceAct is the low construction cost of below 10000$ per telescope. Hence, IceAct telescopes could be mass-produced cost efficiently which would make a telescope array affordable. This chapter describes the main components of an IceAct telescope tested and characterized in this thesis.

4.1 General Setup and mechanical construction

The housing of a telescope is a cylindrical 52.1 cm long tube with a diameter of 62 cm made out of fiber glass (see fig. 4.1.1 for sketch). To provide a compact design IceAct uses a Orafol SC943 Fresnel lens mounted on top of the tube, to focus the incoming Cherenkov light. This lens has a diameter of 549.7 mm, a focal length of 502.1 mm for $\lambda = 546$ nm and a thickness of 2 mm. The lens is covered by a glass plate with an integrated heating structure between lens and glass to prevent accumulation of snow and frost. On the other end of the housing a 61-pixel SiPM-camera is located to detect the Cherenkov light, focused by the lens (see chapter 4.2 for more information). The camera is connected to the Data-Acquisition-System (DAQ), located beneath the tube, which is responsible for triggering, datataking, as well as for the power supply of the camera (see chapter 4.3 for further information). [36]
Currently, there are two IceAct telescopes in operation at South Pole. One is located on the roof of the IceCube Lab (ICL) (referred to as the "roof telescope"). The other one is about 220 m away (referred to as the "field telescope"). Since antarctic summer 2019/2020 both telescopes are equipped with the same camera and the same TARGET-C DAQ. Therefore, they produce comparable data and enable stereo observations of cosmic air showers. \[34\]

### 4.2 IceAct Camera

The IceAct camera (see fig. 4.2.1) consists of 64 6x6mm SensL-J-Series SiPMs \[20\]. 61 of them form a hexagonal structure of 134.8 mm diameter on which the light is focused. To increase the effective area, so called "Winston cones" are glued to each of the 61 pixels. They focus the light from a hexagonal pixel area to the quadratic SiPM (see fig. 4.2.2) (for more information on Winston cones and characterization of different kinds see \[37\]). The remaining three SiPMs are not mounted with Winston cones. They were used to monitor the night-sky-background and the electric noise. For future cameras only 61 SiPMs will be used \[38\].
4.3 The TARGET-C DAQ

„TeV Array Readout with GSa/s sampling and Event Trigger“ (TARGET) [40] provides electronics for readout, triggering and power supplying of the SiPMs of the IceAct camera. It has 64 channels to readout data of 64 SiPMs. The module is equipped with 8 Application-Specific Integrated Circuits (ASICs) controllable by a Field Programmable Gate Array (FPGA), four of which are used for data readout with a sampling frequency of 1 GSa/s (TARGET ASICs) and the other four are used for triggering (T5TEA ASICs). [41]

The hardware of the module is located on three PCBs (see fig. 4.3.1). The bottom board is called „Primary Board“. It contains two TARGET and two T5TEA ASICs for channels 0-31, as well as hardware for shaping and amplification for these channels (see chapter 4.3.1). On the right-hand side it has a connector for data transfer from the corresponding SiPMs. Additionally the FPGA is located on the Primary Board, together with a connector for programming. On the left-hand side, there is a connector to the adapter board which enables a connection between module and computer.

The middle board is the „Auxillary Board“ (AUX Board). It contains TARGET and T5TEA ASICs and shaper and amplifier electronics for channels 32-63, as well as the data transfer connector to the camera.

The top board, also called „Power Board“, controls the power supply of the SiPMs and provides power for the shaper and amplifier on the two lower boards. One the right-hand side it has
a connector to transmit the SiPM voltage, as well as a low voltage connector to supply the preamplifier on the camera PCB.

![Figure 4.3.1: TARGET-C module for IceAct.](image)

The main components of the module will be explained in detail in the following sections.

### 4.3.1 Shaper

The output signals of the SiPMs feature a fall time of about 100 ns [20]. To prevent a pile-up of consecutive incoming signals, one wants to shorten the output signal without losing important information. For this purpose a hardware shaper is used in the module.

![Figure 4.3.2: Electric circuit of the Hardware Shaper of TARGET-C module.](image)

The electrical circuit of the shaper, illustrated in fig 4.3.2, can be separated in four parts (from left to right):
First amplification (blue): First, the negative input signal of the preamplifier with the tail is amplified by a factor of \( \sim 3 \) with a saturation of about 1.3 V input voltage.

Shaping (orange): This part is the actual shaping process. It consists of a parallel resistor and capacitor forming a high-pass filter. The inverted SiPM input pulse becomes the symmetrical Gaussian shaped pulse, where the width strongly depends on the rise time of the input pulse. Because of the filtering characteristics, the amplitude gets smaller (see chapter 8.1.5b).

Second amplification (green): Now a second amplification of a factor \( \sim 4 \) is performed on the shaped pulse. The amplified signal is then inverted, so it becomes a positive Gaussian pulse.

Output and DC-offset (red): Finally, the signal can be measured at every channel. The output signal gets an additional, adjustable DC-offset which is individual for every output channel (for further Information see chapter 7.1). The amplitude of the signal does not change in this step.

A comparison between the shape of an input and output waveform of the shaper can be seen in fig. 4.3.3.

\[\text{(a) Input SiPM pulse} \quad \quad \quad \text{(b) Shaped output pulse without DC-offset on channel 16}\]

Figure 4.3.3: Comparison between input SiPM pulse of 123 mV amplitude and shaped output pulse after the final stage.

The saturation of each of the two amplification stages has a different effect on the shape of the output signal which is discussed in chapter 8.1.

4.3.2 Triggering with T5TEA

The „Target 5 Trigger Extension Asic“ (T5TEA) takes care of the triggering and adjusting of a threshold and a trigger baseline. Triggering is performed on the shaped and amplified input pulse with negative amplitude (see fig. 4.3.4). The T5TEA produces a trigger whenever a certain adjustable threshold with a certain adjustable trigger baseline is crossed from high to low. The shaped pulse should first be above the threshold line, then cross this line to reach a minimum to produce a trigger signal. [42]
The four T5TEA ASICs manage the triggering on 16 channels (SiPMs) each. Therefore the channels are organized into so-called “Superpixels” or “Trigger Groups”. Each Superpixel combines four channels which correspond to four neighboring camera pixels. The numbering of belonging channels to each Superpixel follows the numbering of the channels. Trigger group 0 contains channel 0-3, group 1 channel 4-7, etc. until group 15 which consists of channel 60-63. The signal, on which triggering is performed, equals the sum of the signals from the four channels in this trigger group. Therefore, a trigger becomes more likely, if multiple pixels are hit which lessens the probability of a false trigger due to high noise of one single pixel. \[44\]

The two adjustable parameters which have the most influence of the trigger performance are “Thresh” and “PMTref4”. Thresh sets the comparison voltage which the summed up signal is compared to and thereby sets directly the height of the threshold line. PMTref4 on the other hand sets up the reference voltage for the analogue sum of the four channels. Like this, it shifts the signal itself closer to the threshold line and can thereby be seen as shifting the trigger baseline. Both parameters are controlled by 12-bit Digital-to-Analogue-Converters (DACs), so integer values between 0 and 4095 can be adjusted. \[40, 45\]

The highest possible trigger rate is \(\sim 50\) MHz. However, the real event rate is limited by the readout and digitization speed which results in way fewer stored events. Detailed information on the readout ASICs is given in the next section. \[40, 45\]

### 4.3.3 Readout and Digitization

The four TARGET ASICs (see fig. 4.3.5) provide sampling and storing of shaped and amplified input waveforms. Each ASIC handles 16 channels in numbering order (ASIC 0 from channel 0-15, ASIC 1 or channel 16-31, ect.). Each channel consists of a sampling and a storage array. The sampling array consists for 64 cells corresponding to 64 unique capacitors. These cells are divided into two blocks, 32 cells each operating in a ping-pong fashion \[46\]. One block of 32 cells samples the data sequentially while the other 32 cells writes them into the storage array. After half a cycle the roles are switched. The storage array itself consists of 16384 cells per channel resulting in a storage time of 16 \(\mu\)s per waveform and a event rate of \(\sim 16.6\) kHz \[45\]. For use in practice together with a single telescope (like for IceAct) one only uses 4096 of the storage cells to lower the digitization time.
The digitization is done by the use of Wilkinson Analogue-to-Digital-Converters (ADCs) [40, 46]. For every sample a capacitor is charged creating a linear voltage charge curve (called „Wilkinson Ramp“) while at the same time a 12-bit counter starts running. The voltage of the storage cell is compared to the voltage of the ramp. If those voltages are equal the counter stops and returns the current value. This is the value of the voltage in the storage cell in the unit of ADC-Counts. The digitized output waveform can hereby have integer values between 0 and 4095 ADC-Counts. To compensate for the storage time one can use the FPGA to adjust the time at which the signal is digitized (called „Trigger Delay“). Using a Trigger Delay of $\sim 440$ ns enables the shaped signal to be in the digitization window [45].

Figure 4.3.5: **Block diagram of one TARGET5 ASIC.** TARGET5 is one of the previous TARGET models. The operation of TARGET C does not differ significantly from TARGET5. (Taken from [46])

The output waveforms have an adjustable length between $32 - 448$ ns. To prevent an underflow of the ADC for negative pulses, a DC-offset voltage is added to the signal before digitization. To correct for it, a pedestal correction is necessary (see chapter 7.1). [40, 44]
Chapter 5

General experimental Setup

This chapter explains the general measurement setup for testing the TARGET module and the IceAct camera going over the most important components.

5.1 TARGET Adapter Board

To communicate with TARGET via network, an Adapter Board (see fig. 5.1.1) is connected to the Primary Board of TARGET-C. It supplies the module with a DC voltage of 12 V coming from a Velleman LABPS23023 DC power supply [47]. In operation the module takes a current of $\sim 1.25 \text{ A}$ without a connected camera and a current of $\sim 1.65 \text{ A}$ with a camera connected.

To transmit trigger information to the module and digitized output waveforms to the computer, the board has a Avago connector for multimode fiber. It is connected to a tp-link MC220L Media Converter [48] via fiber which is connected to the computer via Ethernet.

![TARGET Adapter boards](image)

Figure 5.1.1: TARGET Adapter boards.

There are two Adapter Boards that can be used for different purposes. The one in fig. 5.1.1a can be used for an external trigger using a SMA(SubMiniature version A)-connector. Another SMA connector on the board can be used to read out the trigger signal. An issue of this board
is the absence of a bias voltage generator to supply the SiPMs. So one has to use the HV SMA connector to inject the High Voltage externally. The other Adapter Board (see fig 5.1.1b) has an integrated HV generator. In exchange there are no SMA connectors for triggering. Instead trigger in- and output goes via the RJ-45 connector. The first board is more of use to test the TARGET module while the other board can be better used for camera tests.

## 5.2 Splitter Board

While testing the TARGET module, one wants to test all 64 channels simultaneously. To send an input pulse to several channels two Splitter (or Multiplexer) Boards designed at the Erlangen Centre for Astroparticle Physics (ECAP) are used. One board can be connected either to the Primary or the AUX Board by the same connector the camera has for data output. It gets the input, generated by a RIGOL DG5072 Function Generator [49], via two SMA connectors. The input signal from one connector is split onto 16 channels and proceeds to the output connector. One board is powered by ±5 V coming from two XP DNR60 power supplies [50]. To turn single channels on and off the Multiplexer Board is connected to an adapter PCB which is mounted on a DFRobot Bluno MEGA [51] (a variant of the Arduino MEGA) micro controller (see fig. 5.2.1). One has 32 digital output pins either being on or off which correspond to 32 channels on the TARGET module.

For communication with the Arduino, the software „Firmata Express“[52] is flashed onto it. It enables the usage of Arduino commands directly in python using the pymata4 package [53]. In this way, the single channels can be turned on and off with the same script which is responsible for communication with the TARGET module.

One can turn te pins on the Arduino on and off. See Appendix A.1 for the mapping between pins and channels.
The whole experimental setup is shown in fig. 5.2.2.

Figure 5.2.2: Photo of full setup to test the TARGET-C module.

5.3 Darkbox for Camera Tests

The setup for camera tests is shown in fig. 5.3.1.

Figure 5.3.1: Top-down view on the Camera test setup inside a light isolated black box.
Chapter 5. General experimental Setup

To prevent unnecessary light entering the SiPMs, the camera tests are performed inside a darkened black box. To avert reflections inside the setup, light areas on the bottom and on the sides are covered by black fabric. The camera is placed on one end of the box being fixed by a 3D printed structure pointing the detection area to the opposite side. To prevent light entering ever further the Winston cones are additionally covered by a black sheet (see fig. 5.3.2). The camera is connected to the TARGET DAQ by three Connector Boards each of them connecting to one of the TARGET boards (see fig. 5.3.3). On the backside the camera has a low voltage connector to connect with TARGET for supplying the preamplifier.

A light source is given by a pulser developed by Dr. Martin Rongen [54] using a 850 nm diode. It can produce short pulses of $\sim 100$ ps length. The pulsed light enters an „Integrating (Ulbricht-)Sphere“ [55] which then outputs homogeneous light. This pulses can be used to check of homogeneous illumination of the camera pixels.
Chapter 6

Trigger Calibration

Triggering is managed by the T5TEA of the TARGET-C. The trigger decision is made for each trigger group consisting of four channels, where the trigger runs over the sum of the four shaped signals and can be set up by the two parameters „PMTref4“, which shifts the trigger baseline, and „Thresh“, which shifts the threshold line, in DAC counts. To set up a reasonable trigger threshold for standard telescope operation as well as for the calibration of the SiPMs one needs to know to which voltage the set up threshold corresponds.

In this chapter a DAC to voltage threshold calibration is performed and the influence of each channel on the trigger decision for the corresponding trigger group is studied.

6.1 Input Signal

In normal telescope operation, the input signal of the DAQ equals the output signal of the preamplifier on the camera board which is an amplified, inverted SiPM pulse. To test and characterize the DAQ independently of the camera one injects a simulated preamplifier signal which has the same shape as the amplified and inverted SiPM pulse (referred to as „PreAmp pulse“).

The pulse first goes through the Splitter Board (see chapter 5.2) which can potentially change the shape and amplitude of the signal. To investigate one compares the output signal on the function generator with the signal at the output of the multiplexer using a RIGOL DS1054Z oscilloscope [56] (see fig. 6.1.1).
Chapter 6. Trigger Calibration

Figure 6.1.1: **Comparison between output signal from function generator and output from multiplexer.** We can see a clear change in the amplitude. The rise time after the multiplexer also becomes a little bit larger.

The Splitter Board performs an attenuation on the signal (see fig 6.1.1a). Scaling the Splitter Board output signal to the same peak height as the signal from the function generator reveals a slightly change in the rise and fall time of the pulse, which is not that significant.

To characterize the attenuation of the Multiplexer Board we send in PreAmp pulses with different amplitudes and measure the multiplexer output voltage. The peak height is determined by the minimum of the waveform and the error is estimated from the fluctuation of the peak height seen on the oscilloscope (see fig. 6.1.2).

Figure 6.1.2: **Linear fit between input and output peak height of multiplexer board.** $\chi^2/dof = 12.8/11$ For telescope operation one expect mostly signals of lower voltage and this work will mostly use events of amplitudes below 1 V. Hence, the fit is more focused on low voltages and gets worse for larger peak heights.

24
One can observe a linear correlation between input and output voltage of the splitter board. From a linear fit, one gets the gain of the multiplexer with

\[ G = 0.816 \pm 0.003. \]  

(6.1.1)

In the residues, we can see the fit getting worse for higher signals which results from the large number of points for small voltages. This was chosen, since throughout this thesis mostly smaller waveforms will be used.

### 6.2 Trigger Baseline and electrical Noise

Before we proceed to calibrate the threshold we first want to locate the trigger baseline for each superpixel and look at the noise of it. For this one performs a threshold scan without any external signal entering the DAQ. The threshold value „Thresh“ is set to a constant of 2000. For each of the 16 trigger groups the value for „PMTref4“ (later referenced as PMTref) is changed in steps of one and the trigger is enabled. For a duration of 0.2 s the number of triggered events are counted. From this number of events the events rate can be calculated for each value of PMTref. The results can be seen in fig. 6.2.1.

![Threshold scan of all Trigger Groups without signal](image)

Figure 6.2.1: **Threshold scan of all Trigger Groups without signal.** Each group is indicated by a different color. For some groups one can see small single lines just after the curve drops to zero. These come from some random events in 0.2 s measurement time (because of the randomly distributed noise).

For every group the most part of the scan returns no triggers except a small area with a sharp peak reaching rates up to 26 MHz. The peak position indicates the position of the trigger baseline while the peak width describes the corresponding noise. This can be illustrated by imaging a threshold line which goes from the top to the bottom. The noise is distributed symmetrical around the baseline. Because there is no signal, mostly nothing will cross this line until it get close enough to the baseline. First, one only gets single events from the small part
of the noise which is high enough. But the rate increases the closer the threshold line gets to the baseline. Being directly on the baseline yields the most events. Going more down decreases the number of events until one has no triggers. The position of the baseline can be changed either by changing the other threshold DAC value “Thresh” to alter the threshold for the whole group or by shifting the DC-offset of the single channels$^1$.

To determine the peak width and hereby the noise level one takes the width of the part where the rate exceeds 950 Hz. This condition is chosen, because for the threshold calibration a frequency of 950 Hz is used and so rates below it cannot be distinguished between noise or signal rate. The results are shown in fig. 6.2.2.

![Histogram of noise peak width for each Trigger Group](image)

Figure 6.2.2: Histogram of noise peak width for each Trigger Group. Because of the DAC values, of PMTref the values for the width are discrete.

The peak width returns values between 12 and 14 DAC Counts which means that the baseline noise for each trigger group behaves similarly. To transfer this value into a voltage, a DAC to voltage threshold calibration has to be done which will follow in the next sections.

### 6.3 Scan with Input Signal

Now we perform this threshold scan for input SiPM pulses. The measurement settings stay the same, as for the scan of the baseline: a constant value for “Thresh” of 2000 with varying PMTref in steps of 1 DAC Count and a measurement time of 0.2 s per PMTref value. The inverted SiPM pulse see in fig. 6.1.1 is injected in the TARGET module via the Splitter Board with a

---

$^1$To calibrate and use the trigger it is not necessary to have the trigger baseline at the same value for PMTref. As long as one knows the peak position, one can correct is accordingly in the calibration function (see following sections). Furthermore the DAC of each trigger group works slightly differently, so having the baseline at the same value for the threshold would not guarantee it being at the same voltage.
frequency of 950 Hz. The resulting threshold scan and the corresponding shaped waveform on which triggering happened is shown in fig. 6.3.1.

![Threshold scan and corresponding output waveform for group 2 at 31 mV input voltage.](image)

(a) Threshold scan for trigger group 2. For PMTref values not shown in this plot no triggers were measured.

(b) Shaped waveform used for trigger decision on channel 9 (belonging to trigger group 2)

Figure 6.3.1: Threshold scan and corresponding output waveform for group 2 at 31 mV input voltage. For this measurement the signal was injected only in one of the four channels belonging to the trigger group. So the trigger decision only includes the signal on channel 9.

The shape of the triggerscan (fig. 6.3.1a) can be explained by looking at the shaped and amplified waveform the trigger decision was made on (fig. 6.3.1b). For low values of PMTref (which correspond to a positive high threshold voltage) the threshold line is above the baseline and no triggers are measured. Eventually the threshold line touches the overshoot which can be seen in the waveform starting at about 50 ns after the SiPM peak. So the trigger rate gradually increases. Because the overshoot is produced by the input signal, one can see a very small plateau in the triggerscan at about the frequency of 950 Hz. It is not really clearly visible, because it is only a little bit above the noise of the baseline.

When the noise of the baseline is reached one can see the sharp peak around the baseline in the triggerscan which was already discussed in the last chapter. After the peak the rate falls down to 950 Hz and stays constant for some time before it decreases to zero at some point. This point indicates the peak height of the waveform. The PMTref value of the point at which the threshold scan goes down to zero corresponds to the peak voltage of the input SiPM pulse. For higher input amplitudes also PMTref increases, so performing the threshold scan for PreAmp pulses of different voltages will result in a calibration curve between voltage and PMTref DAC Counts.

One can see that the event rate does not fall down to zero instantly, but there is a fall-down region over several PMTref DAC Counts. This is because of the uncertainty of the input peak height coming from noise. Assuming Gaussian distributed noise the fall down part of the curve can be described by an error function, where the PMTref value for the fall down point is included in the fit parameters. The fitted function can be parametrized as

\[
f(x; b, c) = a \cdot erf(-b \cdot (x - c)) + d = 475 \cdot erf(-b \cdot (x - c)) + 475
\]  

(6.3.1)

The amplitude \(a\) indicates half of the vertical width of the curve. We measure values between 0 and 950, so \(a = 950/2 = 475\). A normal error function is symmetrical around the x-axis, so to make it go between 0 and 950 one has to shift it by \(d = 950/2 = 475\) on the y-axis. The fit parameter \(b\) describes the x-axis width of the curve (so basically how many points lay between
950 and 0) and $c$ indicates the shift on the x-axis which is the PMTref value we are looking for. An example fit can be seen in fig. 6.3.2.

![Error function fit at fall down flank for group 2 at 31 mV input voltage.](image)

For the fit all points between 0 and 950 Hz are used, sometimes together with some points with rate=950 Hz or rate=0 Hz. The errors on the rate follow a binomial distribution with $\text{Var}(n) = np(1-p)$ with $p = n/N, N = 950$. For $n = 950$ or $n = 0$, $p = 0.5/950$ was used.

This process is now repeated for different input amplitudes on all trigger groups. The signal is injected only to the second channel of each trigger group, so channel 1 for trigger group 0, channel 5 for trigger group 1, etc. Like this, one can be sure that the trigger decision was made on only one channel. The curve can be seen in fig. 6.3.3.

![Calibration curve for PMTref triggerscan for group 1.](image)

Figure 6.3.3: Calibration curve for PMTref triggerscan for group 1. On the y-axis you see the distance between the baseline and the fall down flank in units of PMTref DAC counts.

We can see a seemingly linear correlation at the beginning for input signals until $\sim 50$ mV and a saturation which happens after that. For telescope operation, as well as for calibration
of the SiPMs one wants to characterize the trigger very precisely for low voltages. To collect as many events as possible, one wants to set a low threshold which is just above the noise level. So we perform a linear fit at the first points with low input voltage (see fig. 6.3.4).

![Linear fit for low input voltages of triggerscan for group 1.](image)

**Figure 6.3.4:** Linear fit for low input voltages of triggerscan for group 1. $\chi^2$/dof = 11.62/7. The y-axis is already corrected with the gain of the Splitter Board from fig. 6.1.2. The errors on the input voltage results from the accuracy of the oscilloscope which is $3 - 4\%$ of the full scale.

For this particular example, this results in a slope $m$ and a y-axis offset $b$ following values

$$m = (0.167 \pm 0.002) \text{ mV/DAC Counts} \quad b = (0.60 \pm 0.09) \text{ mV} \quad (6.3.2)$$

One gets a y-axis offset not equal zero, but it is in a neglectable magnitude\(^2\). Comparing the fit parameters of all trigger groups with each other (see fig. 6.3.5) one can find values between 0.17 and 0.21 mV/DAC Counts for the slope and values between $-0.6$ and 0.8 mV for the y-axis offset. Because there are only 16 values, we cannot really characterize the distribution here, but one can say that there are no trigger group behaving clearly differently.

\(^2\)One sees that the y-axis offset is not exactly zero within the error margin. But looking at the residuals, we recognize that the offset is within the fluctuations of the points around the fit (and is even smaller than the error on the datapoint of high amplitudes.)
Chapter 6. Trigger Calibration

Figure 6.3.5: Distribution of linear fit parameters for all trigger groups. The error made because of the offset is neglectable. One cannot see one specific group behaving significantly different from the others.

We have characterized the trigger, if only one channel per group contributes to the trigger decision. Now one wants to study the behavior when multiple channels belonging to one trigger group see the same pulse.

6.4 Trigger on Multiple Channels

To look at the influence of multiple channels on the trigger decision we send the same PreAmp pulse with the same amplitude to several channels belonging to the same trigger group and first compare the shape of the whole curve (see fig. 6.4.1).

Figure 6.4.1: Comparison of triggerscans for a different number of channels with input pulse belonging to trigger group 1. The order of turning the channels on was: 5,4,6,7

One notices a similar shape for every curve, but scaled differently with a different saturation point. To compare these four curves qualitatively one again performs a linear fit for input voltages until \( \sim 50 \text{ mV} \) (see fig. 6.4.2).
(a) Input signal on 1 channel (channel 9). (b) Input signal on 2 channels (channel 9,8). \( \chi^2/\text{dof} = 4.68/7 \) \( \chi^2/\text{dof} = 4.42/7 \)

(c) Input signal on 3 channels (channel 9,8,10). \( \chi^2/\text{dof} = 9.93/7 \)

(d) Input signal on 4 channels (channel 9,8,10,11). \( \chi^2/\text{dof} = 7.92/7 \)

From the fits one gets following parameters for the slope and the y-axis offset.

<table>
<thead>
<tr>
<th>Channels with signal input</th>
<th>slope [mV/DAC Counts]</th>
<th>y-axis offset [mV]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.196 ± 0.003</td>
<td>-0.04 ± 0.10</td>
</tr>
<tr>
<td>2</td>
<td>0.0913 ± 0.0008</td>
<td>0.25 ± 0.06</td>
</tr>
<tr>
<td>3</td>
<td>0.0598 ± 0.0008</td>
<td>0.37 ± 0.09</td>
</tr>
<tr>
<td>4</td>
<td>0.0447 ± 0.0006</td>
<td>0.31 ± 0.09</td>
</tr>
</tbody>
</table>

Table 6.4.1: Fit parameters from linear fit of triggerscans with different number of input channels of trigger group 2. According to the working principle of T5TEA one would expect the value for slope-(number of channels) to be constant.

To check the prediction of the T5TEA working principle, that each channel contributes 1/4
to the trigger, we take the slope for 1 input channel and calculate which slopes we would expect for more input channels, based on this value. The results are shown in tab. 6.4.2.

<table>
<thead>
<tr>
<th>Channels</th>
<th>slope [mV/DAC Counts]</th>
<th>expected slope [mV/DAC Counts]</th>
<th>deviation</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.196 ± 0.003</td>
<td>0.196 ± 0.003</td>
<td>-</td>
</tr>
<tr>
<td>2</td>
<td>0.0913 ± 0.0008</td>
<td>0.0965 ± 0.0015</td>
<td>0.0052 mV/DAC Counts → 3σ</td>
</tr>
<tr>
<td>3</td>
<td>0.0598 ± 0.0008</td>
<td>0.0653 ± 0.0010</td>
<td>0.0055 mV/DAC Counts → 4σ</td>
</tr>
<tr>
<td>4</td>
<td>0.0447 ± 0.0006</td>
<td>0.0490 ± 0.0008</td>
<td>0.0043 mV/DAC Counts → 4σ</td>
</tr>
</tbody>
</table>

Table 6.4.2: Deviation between measured and expected slopes for different numbers of input channels belonging to trigger group 2. The expected slope is calculated by dividing the slope for one channel by the the number of input channels. The given number of σ intervals is in integer values rounded up. The deviation for 3 and 4 channels is only slightly above 3σ. This results in a relative deviation of ~ 5%.

One possible reason for the deviation between the measured and expected slope could be a fluctuation between the slope of the four single involved channels. To check on this matter one should compare the slopes of the four single channels, as well as different channel combinations.

To check the contribution of each channel to the trigger decision one performs trigger scans for each of the four single channels belonging to the same trigger group. A comparison of the linear fit parameters for low input voltages can be seen in fig. 6.4.3.

![Comparison of slope](image1)

![Comparison of y-axis offset](image2)

Figure 6.4.3: Comparison of linear fit parameters from trigger scans between the four single input channels belonging to trigger group 2. The errors are illustrated by the red lines. One can see that the fluctuation between the channels exceeds the error margin, so the different contribution from the channels are able to explain the effect from tab. 6.4.2.

The biggest fluctuation for the slope within one trigger group is 0.0072 mV/DAC Counts which lies within a 2σ interval. Like this, one could explain 0.0036 mV/DAC Counts of the deviation for 2 input channels, 0.0024 mV/DAC Counts of the deviation for 3 input channels and 0.0018 mV/DAC Counts of the deviation for 4 input channels.
Using the information from fig. 6.4.2 the effective error on the slope can be estimated as about twice the error from the fit itself. Therefore, we get deviations for multiple channels of up to $2\sigma$.

### 6.5 Different threshold parameters

Until now all trigger scans were done by changing only the parameter „PMTref“ while leaving the other one „Thresh“ constant. Now we want to study the influence of both parameters by changing either one of them while leaving the other one constant and compare the resulting curves of the trigger scans.

At first, we do a threshold scan without an input signal to compare the shape of the baseline peak. For the scans one parameter is varied while the other one is set to a constant value of 2000. The comparison can be seen in fig. 6.5.1.

![Comparison of raw scans](image)

Figure 6.5.1: Comparison of trigger scans with varying PMTref and Thresh without an input signal for trigger group 13. The scans over both parameters share the same x-axis, so it shows Thresh for the blue and PMTref for the orange curve. One can see that both curves have the same shape, but a different scaling factor.

One identifies a similar shape for both curves except a scaling fact of $\sim 13$. It takes about 13 times more Thresh DAC Counts than PMTref DAC Counts to scan over the we perform the same comparison with an input signal to one channel belonging to the corresponding trigger group (see fig. 6.5.2).
Chapter 6. Trigger Calibration

Figure 6.5.2: Comparison of trigger scans with varying PMTref and Thresh with an input signal of 9 mV on channel 53, belonging to trigger group 13. Additionally to the conclusion from the comparison of the noise scans one can see that the curve is inverted on the x-axis. So the (imaginary) threshold line goes from low to high. We can see the scaling factor of $\sim 13$ again. The deviation at the borders could result from the fact that the precision of PMTref does not allow a finer sampling of the rise and fall region than one sample, so it seems wider for the Thresh scan.

It can be concluded that changing both of the threshold parameters results in the same curve for the threshold scan besides a scaling factor of $\sim 13$ and an inversion around the trigger baseline. Using this information it is possible to set a precise threshold by using PMTref as a rough and Thresh as a fine setting. Furthermore we confirmed that the threshold can be set up similarly either by shifting the threshold line (Thresh) or the trigger baseline (PMTref) without resulting in different systematics, seen in the trigger scan.

6.6 Summary

In this chapter the triggering of the TARGET-C module was characterized and calibrated. We studied the position and width of the trigger baseline of every trigger group to see that the width is similar for every group while the position varies.

To calibrate the DAC of the threshold setting, we used PreAmp pulses of different amplitudes and determined the DAC value where the number of counted triggers falls down to zero. From this a linear correlation between DAC counts and voltage can be concluded which is valid for small input voltages up to $\sim 50$ mV. The magnitude of the y-axis offset does not have a significant influence on the calibration curve. Using those information, we derive following transfer function to set up the correct value for PMTref given a threshold voltage $U$:

$$\text{PMTref}[\text{DAC Counts}] = \frac{U[\text{mV}]}{m[\text{mV/DAC Counts}]} + \text{PMTref}_0[\text{DAC Counts}]$$ (6.6.1)

$m$ is the determined slope from the linear fit of the input voltage with respect to the fall down PMTref value and PMTref$_0$ is the position of the trigger baseline in units of PMTref DAC Counts. The parameter "Thresh" was kept at a constant value of 2000. Changing this value additionally to PMTref would result in the possibility of adjusting the trigger threshold more
precisely, because increasing PMTref by one DAC Count equals increasing Thresh by about 13 DAC Counts. So we conclude that one can either change the threshold line or shift the trigger baseline to set up the threshold.

The trigger decision is made on the sum of the four channels, belonging to the same trigger groups. This can be seen by comparing the slopes resulting from the DAC to voltage calibration curves while injecting the signal to a different number of channels belonging to the same trigger group. Taking into account the fluctuation between the calibration curves of single input channels of the same trigger group the expected slopes for multiple input channels can be calculated. The measurement with multiple input channels match the expectations, taken from single channel measurements with $2\sigma$ intervals. To investigate on this matter one could take measurements with more variations in the future, like comparing different combination of multiple input channels, belonging to the same trigger group. Furthermore, one can include the variation of Thresh additionally to the scan using only PMTref to determine the DAC value where the number of triggers falls down to zero as precisely as possible. Another important subject of future studies would be the temperature dependency of the trigger behavior, especially when taking into account the difference between the temperature in the laboratory and at the South Pole.

After having characterized the trigger, we want to study the process of datataking, where we want to characterize the shaper and the digitization of the TARGET-C module.
Chapter 7

Datataking and Digitization

After the trigger calibration we want to take a closer look on the output waveforms. To reach the goal of knowing the output signal of the camera, which equals the input signal of the TARGET, one has to understand the signal propagation inside the module. The first step consists of calibrating the digitized output signal and correcting several hardware effects.

This chapter focuses on the signal processing especially at the output part, which includes calibrating the ADC and correcting the digitization cell effects and offsets.

7.1 Pedestal Correction

A simplified sketch of the signal propagation of an input pulse through the TARGET hardware can be seen in fig. 7.1.1.

Like already explained in chapter 4.3, a DC-offset voltage, which is always larger than zero,
is added to the shaped pulse before the storage and digitization happens. The offset voltage can be adjusted by a 12-bit DAC for every channel individually using the parameter $V_{\text{ped}}$. Because the offset is not influenced by the shaper this way, one can calibrate the ADC using different offsets without having to take the gain of the shaper into account (see following sections). Using the knowledge from this calibration and the fact that the output is know in absolute units of mV, one can extract information on the effect of the shaper. Having a fully calibrated ADC and knowing the real output voltage this way, concludes that the changes in the amplitude of the pulse between in- and output are resulting from the shaper (including amplifications and shaping itself). Using this, the gain of the shaper can be characterized (AC-Correction, see also chapter 8). One should note that the shaping procedure consists of a frequency filter, so the shape of the output signal and the gain of the shaper are highly dependent on the shape of the input pulse, especially its rising time.

Examples of raw waveforms without offset correction (r0-files) can be seen in fig. 7.1.2.

![Waveform Examples](image)

(a) 74 mV PreAmp input pulse.  
(b) Noise without input signal.

Figure 7.1.2: **Raw waveforms without offset correction for $V_{\text{ped}} = 1200$.** The values on the y-axis are integer values between 0 and 4095. We can see a baseline offset of about 1350 ADC Counts, as well as large fluctuation and systematic dips. These result from cell effects of the storage array.

We can see a systematic dip in every 32th sample. This is caused by the fact that every 32th sampling array has a slightly different performance [45]. Taking another event would show the same structure, but shifted, because the waveform then starts with a different cell.

To correct the DC-offset and eliminate the effects from the storage cells we perform a so-called **pedestal correction** which basically consists of subtracting a pedestal file from the raw r0 file. To create a pedestal, one first needs several events without any input signal, where only the noise can be seen (like in fig. 7.1.2b). The pedestal file is created by averaging over all (noise-) events for each of the 4096 storage cells. For waveforms with 128 samples used in this thesis not more than 128 storage cells can be hit per event\(^1\). To ensure that every cell is hit often enough while having enough statistics a so-called „HardSync“-Trigger is used\(^2\). It sets the

---

\(^1\)The cell number does not increase linearly with the sample number. After some samples the cell number jumps up, increases, then jumps back. More information on this in section 7.3.2

\(^2\)The other possibility would have been to set up a normal internal trigger on noise level. Besides the already mentioned argument of longer measurement time, one would also create a certain bias in the data by triggering on noise.
time between two triggers high enough for the storage array to run through all 4096 cells, so the next triggered event would start with the same storage cell [44]. Like this, every triggered event always hits the same cells. This results in a fixed trigger of $\sim 450$ Hz. To change the hit cells, one can change the "TriggerDelay" parameter in steps of 32 ns. This is done 128 times with a 0.2 s long measurement between. This ensures for every cell to be hit more than 100 time in less than a minute.

Now, we create the pedestal file with averaged values for each cell, for every channel. The pedestal value for each cell on a certain channel is then subtracted from every sample in the signal file with the same cell number (or cell ID) on the same channel. Like this, the cell effect seen as dips in the r0 waveforms would cancel out and we get a pedestal corrected (r1) file with the baseline at zero\(^3\) (seen in fig. 7.1.3).

![Image of waveform](image1.png)

(a) 74 mV PreAmp input pulse.

![Image of waveform](image2.png)

(b) Noise without input signal.

Figure 7.1.3: **Pedestal corrected waveform for $V_{\text{ped}} = 1200$.** Because of the averaging one does not have integer values of ADC Counts anymore and negative values down to $\sim -700$ ADC Counts are possible. We cannot see the systematic dips anymore, but we still have cell dependent ADC Counts which slightly differ.

The pedestal correction eliminates the systematic dips seen before and shifts the baseline to zero. But the different performance of the storage cells still remains, so in the next steps we want to do an absolute calibration for the ADC Counts to take out the cell dependency.

## 7.2 Temperature Stability

During operation the module heats up to temperatures of 60$^\circ$C which could change the electrical properties of the different elements to influence the output signal. To study the magnitude of this effect, we monitor the temperature on the Primary Board before and during datataking. The change of the temperature and its influence on the baseline can be seen in fig. 7.2.1.

\(^3\)To get a baseline at zero, the signal and the pedestal run must have the same DC-offset (= same value for $V_{\text{ped}}$). Otherwise the baseline would be at the height of the difference between the two $V_{\text{ped}}$. 
Figure 7.2.1: Temperature change and baseline shift of channel without input signal over time without external cooling. The mean of the baseline is calculated by averaging every (pedestal corrected) event over all samples. To simulate an external trigger a PreAmp input signal with a frequency of 1 kHz was sent to channel 43 (Trigger Group 11) while channel 52 (Trigger Group 13) was read out. Every second a datapoint for the temperature was recorded. The main increase in temperature happens in the first 5 minutes which is an increase by \(\sim 12^\circ C\). This can also be seen in the baseline shift. In the first 5 minutes we get a decrease of the baseline of \(\sim 15\) ADC Counts. This is clearly above the noise level and will make a significant effect on the output signal. To keep the temperature as stable as possible and to prevent overheating of the electronics external cooling of the module using a room fan is introduced. Additionally a heat-up-time of 10 minutes is used\(^4\). The temperature change before and during datataking is shown in fig. 7.2.2.

Figure 7.2.2: Temperature change on Primary Board before and during datataking with external cooling using a fan. The temperature stabilizes much quicker compared to without cooling and is significantly lower (only \(\sim 10^\circ C\) above room temperature) preventing over heating of the module. During datataking one sees \(\sigma_{\text{Temp}} = 0.09^\circ C\).

\(^4\)The module is running, but the trigger is disabled.
We see a very low fluctuation in the temperature during datataking and can also conclude from fig. 7.2.2a that the temperature stabilizes already after 5 minutes of heat-up-time. Further, following fig. 7.2.3 we do not see a systematic shift exceeding the noise in the baseline anymore.

![Figure 7.2.3: Baseline shift of channel 52 without input signal with external cooling using a fan.](image)

We cannot see the systematic drift from before anymore. We only get a statistic fluctuation with $\sigma = 0.35$ ADC Counts which can be shown to be smaller than the baseline noise of one single event (see section 7.3.2).

From this section, we can conclude that to ensure a stable temperature during operation that does not influence our signal output, we need to perform active cooling of the module using a room fan. Still, one sees a strong increase at the beginning. To eliminate the effect from this increase on the baseline and minimize systematic temperature changes during datataking, we always wait 10 minutes after connecting to the module and before starting the datataking. This is done for all following measurements in the following sections.

### 7.3 Calibration of DC-offset

As mentioned in chapter 7.1, we want to calibrate the ADC without including effects from the shaper by using the DC-offset adjusted by the parameter $V_{\text{ped}}$. The goal is to get a calibration curve between output voltage and ADC Counts. Because the DC-offset is set up in DAC Counts, one has to perform this calibration in two steps:

- The offset voltage can be measured directly using measurement points for every channel on the two boards. Changing the $V_{\text{ped}}$ value on the whole range and measuring the voltage results in a calibration curve between voltage and DAC Counts (see section 7.3.1).

- For different $V_{\text{ped}}$ DAC values, we record a pedestal r0 file which would have a differently shifted baseline every time (with fluctuations between storage cells). Localizing the baseline in units of ADC Counts would result in a calibration curve between DAC Counts and ADC Counts for each storage cell in every channel (see section 7.3.2).
Combining the two calibration curves creates a calibration curve between voltage and ADC Counts for every channel with a storage cell dependency coming from the DAC to ADC curve. Applying this curve to the output signal takes out the storage cell dependency which simplifies the pulse height extraction for the analysis of the shaper (see chapter 8). Furthermore, this calibration is not signal dependent, because the shaper is not used here.

7.3.1 DAC to voltage

The offset voltage can be measured on the measuring points on the Primary (Channel 0-31) and on the AUX (Channel 32-63) Board shown in fig. 7.3.1. The AUX Board can be accessed from the top by removing the Power Board while voltage of the Primary Board channels can be measured from below the module.

![Image of Primary and AUX Boards](image)

(a) Primary Board (view from below)  (b) AUX Board (view from top)

Figure 7.3.1: Measurement points of channels for offset voltage. The channels are numbered from right to left (or from left to right, if you look from below). The Power Board can be removed while measuring the offset, because it is only needed to power the shaper.

The offset voltage is taken with a Fluke 8845A multimeter [57]. $V_{ped}$ is changed alternately in steps of 1 and 49 (except for the beginning), so the values would be 0, 1, 49, 50, 99, 100, 149, 150, 199, · · · 4095 (which is the highest possible value). For each DAC value one takes four voltage values successively to average over. Mostly the more dominant error comes from the precision of the multimeter which is 0.0035% of the value $+0.0005\%$ of the measuring range which is either 1 V or 10 V in our case [57]. The resulting calibration curves for all channels can be seen in fig. 7.3.2.
Chapter 7. Datataking and Digitization

Figure 7.3.2: DAC Counts to voltage calibration curves for DC-offset on all channels. The errors are from 0.012–0.130 mV, therefore they cannot be seen in the plot. One can identify a linear part in the curve between 1000 and 3000 DAC Counts, but we require to use the whole range for the calibration.

The calibration curves of all channels seem to have the same shape and are overall quite close to each other. We want to check the level of fluctuation between them and look out for possible systematics. For this a “mean calibration curve“ is determined by averaging the datapoints for each $V_{\text{ped}}$ over all channels. Then we calculated residues by subtracting this mean curve from the single curve of each channel. The result for one example channel is shown in fig. 7.3.3.

Figure 7.3.3: Residues from mean calibration curve of channel 52 for the DAC to voltage calibration of DC-offset. The curve for channel 52 was measured four times to ensure that the seen effects are not just random fluctuations.
The residues show clear jumps for DAC values close to 1000, 2000 and 3000. This effect can be also seen on other channels shown in fig. 7.3.4.

Figure 7.3.4: Residues from mean calibration curve of different channels for the DAC to voltage calibration of DC-offset. One clearly sees again the jumps at $V_{\text{ped}}$ values of powers of 2. We also see that the deviation from the mean is much higher than the error margin.

Again we can see the jumps at 1000, 2000 and 3000 DAC Counts and on some channels even at about 500 DAC Counts (see fig. 7.3.4b, 7.3.4c) and sometimes at $\sim$ 250 DAC Counts (see fig. 7.3.4d).

These jumps are a feature of the R2R Ladder DAC\(^5\) which is used for TARGET [44]. DAC values of power 2 -1 (because counting starts at 0) resemble every needed bit to be at 1 (e.g. a DAC value of $3 = 4 - 1 = 2^2 - 1$ requires all 2 bits to be at 1.). Switching to the next DAC Count would require to set all bits to 0 and add a new bit with value 1. For the circuit of the DAC it would mean turning off all active resistors and turning on one single new one. The resulting analogue voltage would only depend on this one resistor which maximizes effects coming from the tolerance on the resistance. Furthermore the new voltage results from this DAC value is much less correlated to the last value, as the last values were. Like this we see jumps at DAC values of 256, 512, 1024 and 2058. This effect increases with higher DAC Counts and higher resulting voltages, so the jumps at 10-bit and 11-bit can be seen in almost every

\(^5\)A Ladder DAC consists of a network resistors which can be turned on and off resembling single bits and so DAC Counts. More detailed information can be found in Appendix B.1.
channel. The third big jump is at 3072. Here we have 11 bits at 1 from which 10 are turned off at once. Because of the high voltage one can see the effect also there, even though the jump is smaller as it is at 2048.

From the residues we identified and explained the features of the DAC for $V_{\text{ped}}$. Additionally, it can be noted that the deviation from the mean calibration curve is much higher than the error margin on the single points, so the error made by averaging over all channels would be too large. That is why the ADC calibration will be performed with an individual calibration curve for every channel.

### 7.3.2 DAC to ADC

To perform the DAC to ADC Counts calibration, we record pedestal r0 data files like described in chapter 7.1 with different DC-offsets (meaning different DAC values for $V_{\text{ped}}$). The DAC values are chosen by using the DAC to voltage calibration curves from section 7.3.1. We chose 42 voltages to cover the whole curve and calculate the corresponding DAC value for $V_{\text{ped}}$ for each channel by performing linear interpolations between neighboring datapoints. Like this we get a different DAC value for every channel, but it ensures them all being at the same offset voltage.

Like we already saw in chapter 7.1 each storage cell, and so each sample in the waveform has a slightly different performance, so we want to determine calibration curves for every storage cell on every channel. First we take a look on the changing of the cell IDs within a waveform (see fig. 7.3.5).

![Single waveform](a) Single waveform  

![Multiple events compared](b) Multiple events compared

Figure 7.3.5: **Change of cell IDs throughout the waveforms for pedestal r0 file on channel 16.** In this case no HardSync trigger was used, but an external one. One can see that the cell ID does not increase linearly, but has jumps up and down every 31 samples.

To determine the DC-offset in units of ADC Counts, all samples of all waveforms are sorted by their cell IDs. Looking at the distribution of ADC Counts per cell comparing with the distribution over all samples of all cells one realizes in becoming clearly more narrow (see fig. 7.3.6).

---

6Using only pedestal corrected waveforms (like in real datataking) make this action unnecessary, because the pedestal file would correct for the different offset voltages anyway. But it makes a difference when using the r0 files.
(a) Distribution of all samples, 
\( \sigma = 65.6 \) ADC Counts

(b) Distribution of samples belonging to storage cell 0, \( \sigma = 2.6 \) ADC Counts

Figure 7.3.6: Distribution of baseline ADC Counts of pedestal file for \( V_{\text{ped}} = 1200 \) on channel 52. An external trigger was used rather than the Hardsync trigger, to show the distributions. We see that the distribution of all samples has two peaks, one between 1000-1100 ADC Counts and the other at 1300-1400 ADC Counts. The smaller peak resembles the dips seen in the waveform which were about at the same level. One cannot see this structure in the distribution for cell 0 where also \( \sigma \) is much smaller. So we can clearly see the cell effects.

The height of the baseline \( B \) for \( V_{\text{ped}} \) of cell 0 on channel 16 would then be

\[
B = (1382.2 \pm 2.6) \text{ ADC Counts} \quad (7.3.1)
\]

Determining the baseline for every cell, for 42 different \( V_{\text{ped}} \) values covering the whole range, will result in the DAC to ADC Counts calibration curves for every cell seen in fig. 7.3.7. It can be then combined with the DAC to voltage curve to get a calibration between ADC Counts and voltage.

Figure 7.3.7: DAC to ADC Counts calibration curves for all storage cells on channel 16. The curve is similar to the DAC to voltage curve with saturations at the beginning and the end and a linear part between. Furthermore we see that the curves for all cells have the same shape.
7.3.3 Applying the ADC Calibration

The used DAC values in fig. 7.3.7 were calculated by selecting the voltage first. So the only thing one has to do to get the ADC Counts to voltage calibration curve, is to exchange these channel specific DAC values with the general voltage values we got from the DAC to voltage calibration curve. The resulting ADC calibration curves for each cell can be seen in fig. 7.3.8.

![ADC Calibration curves for all cells on different channels.](image)

Figure 7.3.8: ADC Calibration curves for all cells on different channels. We see the same shape on all cells and both channels\(^7\). The curve has a divergence for small and large ADC Counts. So one should set up an offset voltage which is above 750 mV (this is the case for \(V_{\text{ped}} = 1200\)). Regarding the saturation for high voltages, see chapter 8.

The application of the ADC calibration curve (also called „Transfer Function“) is handled by the TARGET Software package, developed by the CTA working group. The function to generate the Transfer Function file needs several r0 files using different offset voltages, but for each file the voltage should be equal on all channels (the files we used to create the DAC to ADC calibration curve). The function takes the paths of these files and the corresponding offset voltages, which are derived from the DAC to voltage curve, as arguments\(^8\). Additionally you need to give the pedestal file which should be recorded with a fixed offset voltage\(^9\). In our case this voltage is 781 mV which corresponds to DAC values around 1200. The output Transfer Function-file can then be given as an additional argument to the pedestal correction function\(^10\) which then outputs a pedestal corrected and ADC calibrated data file.

The comparison between before and after the ADC calibration is illustrated in fig. 7.3.9.

---

\(^7\)The curves for channel 52 do not include the last point which strongly deviates from the rest. This is a technical issue concerning the channels on the AUX board which isn’t much of concern for this work. See Appendix B.2 for further information.

\(^8\)One writes all the paths for each file together with the corresponding voltage into a txt-file (each line contains one path and the voltage) giving it the function as an argument. It is necessary for the voltages to be in rising order.

\(^9\)The same offset that will be also used for the real datataking.

\(^10\)Which should be performed with the same pedestal file that was used generating the Transfer Function.
Chapter 7. Datataking and Digitization

Figure 7.3.9: Comparison between a waveform before and after ADC calibration with a PreAmp input pulse of 42 mV on channel 52. We notice almost the same shape of both curves. Corrected cell effects are not visible in this plot. For this one needs to quantitatively analyze multiple events (see next chapter).

7.4 Summary

In this chapter the basic concepts of datataking with the TARGET-C module and signal processing in the steps of storing and digitizing were studied.

The thermal drift of the components of TARGET was analyzed and the effect it has on the resulting waveform. There is a phase of strong temperature increase in the first 5 minutes after connecting to the module. In this time the baseline of the waveform decreases by up to 15 ADC Counts continuing with seeable fluctuations after it. Applying external cooling using a fan shortens the starting temperature increase and enables a much more stable temperature curve. Furthermore, the temperature increases only up to $\sim 35^\circ$C, not 60$^\circ$C this way. So the module is far less likely to overheat. To enable a stable temperature during datataking one waits 10 minutes after connecting to the module before datataking starts.

The pedestal correction was introduced to correct for the DC-offset in the output waveform. In the r0 waveforms one can clearly see the different performance of the storage cells, so the pedestal correction has to be done for each cell individually. Comparing the baseline sample distribution for one and for all cells one sees it becoming much more narrow while looking at only one cell which confirms the storage cell effect once more.

Even after the pedestal correction the different performance of the cells still remains. To take out the cell effect and calibrate the ADC Counts, we performed and ADC calibration which consists of two steps using the adjustable DC-offset $V_{\text{ped}}$:

- Creating a DAC to voltage calibration curve by measuring the offset voltage on each channel.
- Creating a DAC to ADC Counts calibration curve by recording pedestal files for different DAC values of $V_{\text{ped}}$.

This results in an ADC to voltage calibration curve for each storage cell on each channel. These curves are similar for each cell having a linear part in the middle with divergences at the start and the end. To avoid effect from the divergence at the start the offset voltage should be set high enough (something above 750 mV). This curve can then be applied to the raw waveform using the TARGET software, so the signal will be in absolute units of voltage without any cell effects.

After having a look at the baseline of the output signal and had only taken the processing after the shaper into account, we now want to analyze the shaper itself by using PreAmp signals.
Chapter 8

Characterization of the Shaper

Based on the results of the digitization of TARGET and the calibration of the ADC, we now want to investigate the properties of the shaper. The shaper consists of two amplification steps with a high pass filter between them. Both amplifiers have a different saturation voltage which influence the output waveform differently. Furthermore, the filtering of the high-pass makes the shape and amplitude of the output strongly dependent on the input waveform (so will the resulting gain). Injecting an input signal and comparing it with the output using the information from the ADC calibration would ensure that the changes can only result from the shaper itself.

This chapter characterizes the shaper by analyzing the signal processing in every step on amplification and shaping and determine the gain of the shaper as a whole (also referred to as „AC-Correction“). Additionally one will check the effect of the ADC calibration on the output pulses by comparing the pulse heights and cell effects before and after the ADC calibration.

8.1 Signal processing steps

First we want to study each of the shaping and amplification steps mentioned in section 4.3.1. The input signal is measured on the output of the splitter board and the final output signal can be seen on the same measurement points that were used to measure of the offset voltage\(^1\). To measure the other two stages a pole-zero resistor located on the bottom of the Primary Board (see fig. 8.1.1) is used. Both sides feature a different stage (after first amplification and after shaping)[38].

\(^1\)Like already mentioned in chapter 4.3 the top Power board has to stay mounted to supply the shaper. So only the channels on the Primary Board are easily accessible for this measurement.
Figure 8.1.1: **Pole Zero resistors on the bottom of Primary Board.** Measuring the right side of the resistors over ground will show the signal after the fist amplifier, the left side shows the signal after the high-pass (but before the second amplification).

The comparison between a waveform after different stages within the shaper can be seen in fig. 8.1.2.

Figure 8.1.2: **Comparison of waveform processing through the TARGET shaper, measured by an oscilloscope using a probe.** The channel output is measured on channel 0. Because the trigger on the oscilloscope had to be set differently for every stage, the signal is shifted on the x-axis differently every time. To see all signals simultaneously for better comparison the waveforms were shifted manually.

We now want to study the saturation behavior and the gain for each of those stages. For this we save waveforms with different input amplitudes after each of the four stages and compare their peak heights. These were determined by taking the minimum (or the maximum for the
channel output) of the waveform considering the accuracy of the oscilloscope.

First we look at the saturation of the first amplification stage shown in fig. 8.1.3.

![Diagram showing saturation of first amplification stage](image1)

**Figure 8.1.3:** Change of amplitude between input and signal after the first amplification using an PreAmp input pulse. The blue line connects the red datapoints with error bars. We see a seemingly linear correlation with a saturation starting at 1300 – 1400 mV input voltage.

One can see a linear correlation with a clear saturation for high input voltages. The effect of this saturation on the channel output waveform can be seen in fig. 8.1.4.

![Diagram showing saturated first amplifier output and channel output](image2)

**Figure 8.1.4:** Saturated first amplifier output and resulting channel output for 2.17 V input amplitude. The saturation on the first amplification flattens the peak while the channel output produces rectangle shaped structure after the shaped peak.

---

For the channel output the baseline was corrected first by subtraction the median of the waveform. The baseline is corrected to zero (within the noise level) this way, because the shaped pulse is fairly short, so there are enough samples featuring the baseline.
The saturation of the first amplifier causes the shaped channel output pulse to gain a rectangle structure as well as an undershoot after it. The width of the rectangle increases with the input amplitude.

Looking at the curve at the High-Pass (see fig. 8.1.5a) no saturation effects can be seen which is to be expected, because the single components of a frequency filter do not have such characteristics. We can still see a linear correlation for all datapoints, but not while comparing high-pass and channel output, where the curve flattens at the end (see fig. 8.1.5b). This is likely caused by the saturation of the second amplifier.

![Figure 8.1.5: Comparison between Input vs. High-Pass output and High-Pass output vs. channel output](image)

(a) Change of amplitude between input and signal output of High-Pass  
(b) Change of amplitude between High-Pass and channel output

Figure 8.1.5: Comparison between Input vs. High-Pass output and High-Pass output vs. channel output. While the High-Pass output follows a linear correlation, the curve for the channel output flattens at the end which suggests some saturation effects.

At input amplitudes of about 2.3 V we see saturation effects for the output pulses of the Splitter Board (see fig. 8.1.6) which takes us the possibility to study the behavior of the shaper for higher input pulses. Nevertheless, the highest amplitude measured on the channel output (which is not expected to increase any more) is $\sim 2.18$ V. Adding the 781 mV offset voltages up to 2.96 V is possible. It is clearly above the maximum voltage the ADC can be calibrated for. This could result in saturation effects unique to the digitized, ADC calibrated waveforms which will be further discussed in chapter 8.4. The input to channel output curve can be seen in fig. 8.1.7.
Chapter 8. Characterization of the Shaper

Figure 8.1.6: **Saturated waveform from Splitter Board output.** Amplitude=2.3 V

Figure 8.1.7: **Comparison between input amplitude and channel output.** The channel output had an amplitude of 2.18 V when the saturation of the splitter started.

Now we want to determine the gain of every amplification and shaping step by performing linear fits to the comparisons of the amplitudes of two consecutive steps. Only the points before the saturation effects are taken into account. The results can be seen in fig. 8.1.8.

(a) Input to first Amplifier, $\chi^2/dof = 10.7/15$

(b) First Amplifier to High-Pass, $\chi^2/dof = 9.0/6$
Chapter 8. Characterization of the Shaper

Figure 8.1.8: **Linear fits to determine the gain of the single elements of the TARGET shaper.** The values for the channel output are first baseline corrected. The errors result from the accuracy of the oscilloscope.

The gain of every step as well as the gain over all elements are well described by a linear function. The gains for each step and the other determined properties of the shaper are summarized in tab. 8.1.1.

<table>
<thead>
<tr>
<th>Element</th>
<th>Function</th>
<th>Gain</th>
<th>Saturation</th>
</tr>
</thead>
<tbody>
<tr>
<td>First Amplifier</td>
<td>Amplification</td>
<td>3.28 ± 0.07</td>
<td>$\sim -1.3 - (-1.4)$ V Input, $\sim -4.7$ V Output</td>
</tr>
<tr>
<td>High Pass</td>
<td>Shaping, resulting in attenuation</td>
<td>0.100 ± 0.005</td>
<td>not possible</td>
</tr>
<tr>
<td>Second Amplifier and Output</td>
<td>Amplification, inverting, adding offset</td>
<td>4.32 ± 0.13</td>
<td>$\sim -0.5$ V input, $\sim 2.19$ V output</td>
</tr>
<tr>
<td>Whole Shaper</td>
<td>Shaping, amplifying, inverting, adding offset</td>
<td>1.42 ± 0.03</td>
<td>$\sim -1.3 - (-1.4)$ V input (slope decreases not completely flat), $\sim 2.19$ V output</td>
</tr>
</tbody>
</table>

**Table 8.1.1:** Function, gain and saturation behavior of each element of the shaper and of the shaper itself. The offset coming from the linear gain fits was zero within a 2σ range. Adding the DC-offset, the channel output exceeds the calibration range for the ADC.

Our next step is to analyze the digitized output waveforms and compare the performance of the different channels.

### 8.2 Pulse height extraction

For normal telescope operation only the digitized TARGET output waveforms are analyzed. For the reconstruction of the energy the pulse height is important, so one has to find an automatic, dependable and precise way to determine the peak heights. We want to compare the performance of several methods.
The IceAct online analysis, performed at the South Pole and developed by Johannes Schäfer from ECAP, performs a Gaussian fit on the TARGET output pulse to determine the arrival time and pulse height\(^3\). For a precise determination of the peak height it is important to reconstruct the top of the peak with the best possible quality, rather than parametrize the whole waveform. So only the samples above half the maximum value are included in the fit. The fitted function is

\[
f(x; a, \mu, \sigma) = \frac{a}{\sqrt{2\pi\sigma^2}} \cdot e^{-\frac{(x-\mu)^2}{2\sigma^2}}
\]  

which equals a not normalized Gaussian with the peak height \(amp = a/(\sqrt{2\pi\sigma^2})\). A Gaussian fit for an example waveform can be seen in fig. 8.2.1.

![Gaussian fit on TARGET output waveform on channel 52 with 109 mV input amplitude.](image)

**Figure 8.2.1:** Gaussian fit on TARGET output waveform on channel 52 with 109 mV input amplitude. Peak height: \(amp = 146\) mV, Peak position: \(\mu = 38\) ns. The starting parameter for \(\mu\) was chosen based on the position of the maximum.

Based on the Gaussian fit there are now two possibilities to get the peak height:

- Taking it directly from the fit parameter \(a\) with \(amp = a/(\sqrt{2\pi\sigma^2})\)
- Using the peak position \(\mu\) from the fit and choosing the datapoint of the corresponding sample as the peak height.

To compare these two methods we take a look at the distribution of those values for several waveforms and compare the corresponding standard deviations (see fig. 8.2.2).

---

\(^3\)Before doing so a Butter low-pass filter is applied on the waveform to reduce the noise. We do no do it here, because now we are only dealing with the electrical noise of the TARGET which is considerably low compared to the noise of the SiPMs.
(a) Peak height from fit, \( amp = (147.7 \pm 2.8) \text{ mV} \) (b) Peak height from data, \( amp = (148.1 \pm 4.1) \text{ mV} \)

Figure 8.2.2: Distributions of peak heights coming from two different methods of peak height extraction using Gaussian fits on channel 52 for 109 mV input voltage. Both distributions look similar, like a Gaussian distribution with a little asymmetry to the right side. Both peak height values are equal within a 1\( \sigma \) range, but the method using the peak height from the fit has a clearly smaller error.

Another possible method for pulse height extraction is used in the analysis on FACT. One takes the maximum of the waveform together with its two neighboring samples. A parabola is calculated through the logarithm of these three points and the peak height and position is taken from the maximum of this parabola. The logarithm of a Gaussian equals a square polynomial, so this method should yield results comparable to the methods using Gaussian fits. Additionally the algorithm can determine the trigger point using the derivative of the parabola (which is not used here). The method is working fine for high pulses (see fig. 8.2.3a) while it has issues for smaller pulses, where the maximum is not always at the center of the peak (see fig. 8.2.3b). A big advantage of this method is the fact that it consists of a simple calculation lowering the computing time. Up to 50000 events per second can processed this way on a single CPU while only \( \sim 900 \) Gaussian fits can be done in this time. The peak height distribution using this method is shown in fig. 8.2.4.
Figure 8.2.3: **Comparison between a more and a less suitable parabola calculation for peak height extraction on channel 52.** We see that for small signals the maximum is not always at the center of the peak. This effects results in a shift of the peak position and influences the calculated peak height. Similar problems occur for saturated waveforms.

The last method discussed here would be to take the maximum of the waveform and get the peak position from the corresponding sample. The main advantage of this method is that it works without issues for pulses above noise level, even for saturated pulses\(^4\). On the other hand, it is very sensitive to random spikes in the waveform. The corresponding peak height distribution is shown in fig. 8.2.5.

![Graph](image)

**Figure 8.2.4:** **Peak height distribution for the parabola method on channel 52 with 109 mV input voltage.** \(amp = (152.0 \pm 4.0)\) mV. The distribution seems like a Gaussian distribution with a little asymmetry to the right side.

**Figure 8.2.5:** **Peak height distribution for using the maximum of the waveform on channel 52 with 109 mV input voltage.** \(amp = (151.7 \pm 3.9)\) mV. The spikes result from the quantification effect caused by the method of using only one specific sample of the waveform.

Comparing these four methods for different input voltages (in this case 45 mV, 74 mV, 109 mV and 146 mV) yields the same results, we saw before: The distributions look similar and the de-

\(^4\)It will not reconstruct the real pulse height, but it will clearly show the saturation while the other methods will mostly fail.
Chapter 8. Characterization of the Shaper

determined peak height values are equal within a 1 σ range, while the method using the amplitude from the Gaussian fit has the lowest uncertainty (see fig. 8.2.6 and tab. 8.2.1). So using this method for the pulse height extraction will get the most accurate results.

![Figure 8.2.6: Comparison of mean and standard deviation (std) of determined peak heights on channel 52 using different peak height extraction methods. The bars are centered around the value for the input voltage on the x-axis. We see that the standard deviation for the method using the amplitude from the Gaussian fit is consistently the lowest.](image)

<table>
<thead>
<tr>
<th>Input amplitude [mV]</th>
<th>Gauss fit amplitude [mV]</th>
<th>Gauss fit data [mV]</th>
<th>Parabola [mV]</th>
<th>Maximum [mV]</th>
</tr>
</thead>
<tbody>
<tr>
<td>45</td>
<td>67.5 ± 2.4</td>
<td>67.6 ± 3.9</td>
<td>70.4 ± 3.8</td>
<td>70.1 ± 3.7</td>
</tr>
<tr>
<td>74</td>
<td>96.5 ± 2.4</td>
<td>97.0 ± 3.9</td>
<td>99.7 ± 3.8</td>
<td>99.4 ± 3.5</td>
</tr>
<tr>
<td>109</td>
<td>147.7 ± 2.8</td>
<td>148.1 ± 4.1</td>
<td>152.1 ± 4.0</td>
<td>151.7 ± 3.9</td>
</tr>
<tr>
<td>146</td>
<td>202.1 ± 3.0</td>
<td>202.2 ± 4.5</td>
<td>203.8 ± 4.5</td>
<td>203.4 ± 4.4</td>
</tr>
</tbody>
</table>

Table 8.2.1: Mean and std of peak height for different pulse height extraction methods for different input voltages on channel 52. We see that the peak heights for all methods are equal within the error margin. These measurements were done before, without the Splitter Board, where the input voltage could not be measured precisely at the input of the TARGET, but only at the output of the function generator. That is why the input voltage does not include the attenuation of the Splitter, so the gain is smaller.

Using the results of the optimal pulse height extraction method, we now will use it to determine the gain of the shaper using the digitized output pulses.

### 8.3 Cell effects on pulse height

Being able to extract the pulse height precisely one takes another look on the cell effects on the waveform. After the cell effects on the baseline were studied in chapter 7.3, we want to look at the cell effects on the peak heights and the resulting peak height distributions from it. For this we compare the distributions before and after the ADC calibration to additionally check, if the calibration removes the cell effects.
8.3.1 Before ADC Calibration

To analyze the cell dependency for the peak height one needs to sort the peaks accordingly. The peak position and so the corresponding sample and storage cell are determined by the fit parameter $\mu$ from the Gaussian fit. The distribution of the peak position can be seen in fig. 8.3.1.

![Distribution of peak position samples on channel 52, determined by a Gaussian fit at 109 mV input voltage.](image)

Figure 8.3.1: Distribution of peak position samples on channel 52, determined by a Gaussian fit at 109 mV input voltage. It is discrete, because we are interested in the corresponding storage cell rather than the precise time. The distribution mostly covers the same two samples which is to be expected, because of a fixed trigger threshold.

Before sorting all the peak heights by storage cell, we are interested in the peak height distribution over all cells. One, once again, compares the amplitude from the Gaussian fit with the datapoint at the peak position (see fig. 8.3.2).
Chapter 8. Characterization of the Shaper

(a) Peak height from Gaussian fit amplitude, \(\text{amp} = (528 \pm 11)\) ADC Counts

(b) Peak height from Gaussian fit datapoint, \(\text{amp} = (530 \pm 23)\) ADC Counts

Figure 8.3.2: \textbf{Comparison between peak height distributions before ADC Calibration on channel 52 for different peak height extraction methods using Gaussian fits.} For the method using the datapoint we see a second small peak similar to the features of the baseline studied in chapter 7.3.

One can observe that fig. 8.3.2b shows a feature similar to that in the distribution of the baseline from chapter 7.3 which indicates a clear cell effect. The distribution from fig. 8.3.2a on the other hand does not have structures like that and looks very similar to the distribution after the ADC calibration. The reason for it most likely lies in the method the peak height is determined. Using one specific sample to determine the peak height results in the cell effects being very dominant, because we effectively compare the same value on different cells (just like for the baseline in chapter 7.3). Getting the peak height from the amplitude causes it not being dependent on one specific sample and one specific cell, but more on the whole structure throughout different cells (with different performance). Like this, the cell effects would be less dominant and one gets a significantly smaller error.

Now we want to compare the distribution of the peak height of all cells with the average peak heights for each cell. For this the peak heights from fig. 8.3.2b are sorted by the storage cell belonging to the sample of the peak position. The distribution of the mean peak heights and the corresponding standard deviation per cell are shown in fig. 8.3.3.
Figure 8.3.3: Distribution of mean and standard deviation of peak heights per storage cell on channel 52 with 109 mV input voltage. The peak height was determined by using the datapoint of the sample of the peak position determined by a Gaussian fit. In the distribution for the mean peak heights we see again the feature from before, confirming that the seen cell effect results from several cells with different performances.

Looking at the distribution of the standard deviation per cell one realizes that the standard deviation for every storage cell is significantly lower than the std over all events confirming the cell effects. Furthermore we see that the std of ∼ 11 ADC Counts resulting from the peak height extraction using the amplitude from the Gaussian fit is conformable with the the standard deviation distribution per cell. So one can further conclude that this method mostly corrects for cell effects.

In the next section the peak heights per cell after the ADC calibration are studied to investigate the change in the cell effects.

### 8.3.2 After ADC Calibration

Now we repeat the same procedure with the ADC calibrated waveform and determine the peak heights from Gaussian fits in units of mV.

The distributions for the peak height over all storage cells were already shown in fig. 8.2.2. Comparing the distribution coming from using the peak height from the data sample we do not see the structure featuring a small peak on the left anymore which indicated cell related effects.

Sorting the peak heights by cell and calculating the mean and standard deviation per cell we get distributions shown in fig. 8.3.4.
(a) Mean peak height per cell, $amp = (150 \pm 3) \, \text{mV}$

(b) Standard deviation of peak height per cell, $\text{mean}=2.5 \, \text{mV}$

Figure 8.3.4: Distribution of mean and standard deviation of peak heights of ADC calibrated waveforms per storage cell on channel 52 with 109 mV input voltage. Like in the distribution for all cells, we do not see the cell effects anymore. Furthermore the std of the mean distribution is close to the mean std value and is included in the std distribution.

The standard deviation from the distribution of the mean peak heights per cell of 3 mV is now included in the distribution of the standard deviation values per cell. Furthermore it is pretty close to the mean of the std distribution (2.5 mV).

Generally, we can conclude that the ADC calibration corrects for the cells effects in the distribution of the peak heights. The standard deviation over all cells is not very different from the standard deviation over single cells. But still, extracting the peak height from the amplitude of the Gaussian fit yields more accurate results which, once again, confirms this method as the most suitable for analyzing the peak height for our purposes.

### 8.4 AC-Correction for digitized waveforms

After having determined the gain of the shaper using direct voltage measurements, we now want to do it using the digitized output waveforms (which relates closer with the real telescope operation). Like already done in section 8.1, PreAmp pulses of different amplitudes are sent through the TARGET. The peak heights of the digitized and ADC calibrated output waveforms are determined by the methods discussed in section 8.2 and can be compared to the input amplitudes (see fig. 8.4.1). In this way, the gain of the whole shaper is determined. It is only valid for this specific pulse form, because of the high-pass component.
Chapter 8. Characterization of the Shaper

Figure 8.4.1: Output vs. Input peak height of PreAmp pulses through the TARGET using different peak height extraction methods. The errors on the output result from the distribution of peak heights while the errors on the input correspond to the accuracy of the oscilloscope. The curve follows a linear relation with saturation behavior at the end.

For both shown channels one sees a saturation behavior starting at about 1000 mV input amplitude. It is earlier that we would expect from the studies measuring the voltage directly. Furthermore, we see especially for channel 52 that the errors for several pulse height extraction methods get significantly larger. To investigate on this further, we take a look at waveforms in the saturation region (see fig. 8.4.2).

In the waveforms, we see the rectangular structure we already observed in section 8.1 resulting from the saturation behavior of the first amplification step. Further, we note that the peak itself is cut off. We did not observe this effect on the channel output voltage, so this should result from the digitization. There could be two possible reasons:

- The peak is cut off at a signal height of 1460 mV. Adding the 781 mV DC-offset, we get...
a total voltage of 2241 mV which is about the highest voltage the ADC can be calibrated for (see chapter 7.3). So the ADC calibration would saturate for higher values.

- The voltage could also be too high for the ADC to even digitize. The Wilkinson ADC ramp goes until a certain value (which should be the voltage for 4095 ADC Counts). If the actual value exceeds the maximum of the ramp, no ADC value can be assigned to this voltage. The ADC will then most likely return the maximum possible value of 4095 ADC Counts\(^5\).

To check which one of the two possibilities is actually the case here, we take a look on the waveform before the ADC calibration shown in fig. 8.4.3.

![Waveform](image1)

**Figure 8.4.3: Saturated waveforms before ADC calibration on channel 16 with 1.1 V input voltage.** We do not see the spike from before anymore. The cut off peak is not that clear anymore, but one still can see a flat structure at the top.

Looking at the not ADC calibrated waveforms, one realizes that the earlier seen cut off is not that clear anymore. From this, we can conclude that the ADC calibration is partly responsible for it. Like this, the ADC calibrated output data can only be used, if the peak height with added DC-offset does not exceed the range of the ADC calibration which basically equals the range of adjustment of the DC-offset voltage. But additionally we can still recognize a little flat structure the r1 and r0 waveforms which could indicate a saturation of the ADC itself. However, this assumption is contradicted by the fact that the r0-waveform does not reach its maximum value of 4095 ADC Counts, but only goes up to 3991 ADC Counts (taking all events into account). So this feature has likely a different origin.

To determine the gain of the whole shaper, the peak extraction method using the amplitude from the Gaussian fit, which was proven to be the most accurate one, is applied. We use all datapoints before the saturation, which are all points except the last one. A linear fit between input and output peak height is performed to determine the gain \(G\) from the slope and the y-axis offset \(b\) (see fig. 8.4.4).

---

\(^5\)Another issue that could occur is an overflow of the ADC resulting from the Wilkinson-Ramp being too wide. For further information see Appendix B.2.
Figure 8.4.4: **Linear fit for AC-Correction using digitized output waveforms on two example channels.** The peak height was determined using the amplitude from a Gaussian fit. The gain $G$ is similar for both channels, but not equal within the error margin. The offset for both channels is zero within a $1\sigma$-interval.

Doing the linear fit for every channel and comparing their gains results in a distribution seen in fig. 8.4.5. The gains of the channels spread between 1.5 and 1.6 with a uncertainty of $\approx 0.017$ between them which is about the error on the gain of a single channel. Nevertheless, this distribution does not really agree the the gain taken from the voltage measurement which touches the channel distribution only within an $2\sigma$-interval.

Figure 8.4.5: **Distribution of AC-Correction gains per channel using digitized waveforms and comparison between gain from the measurement of the analogue signal.** The error resulting from the distribution over all channels is similar to the error on the gain from a single channel. The gain value from the analogue measurement agrees with the channel distribution within a $2\sigma$-interval which is a relative deviation of $\sim 5\%$. Only one gain (for one example channel) was determined from the voltage measurement. So the plot shows the width of the error with the mean in the middle.
8.5 Summary

In this chapter, the Shaper of TARGET and its different elements were analyzed. For this, PreAmp pulses were used which are expected to be produced by the preamplifier of the camera during telescope operation.

To characterize each element (First Amplifier, High-Pass, Second Amplifier and Output) separately, we measured the output voltage on each of those elements directly while injecting PreAmp input pulses of different amplitudes. For the different signal stages, we get the following characteristics:

- The first amplifier amplifies the negative signal by a factor of $\sim 3.3$.
- The High-Pass is responsible for the Shaping itself. It shapes the input pulse depending on its rise time. In this case the used PreAmp pulses the shaping results in a gain of 0.1.
- The second amplifier and output amplifies the shaped signal by a factor of $\sim 4.3$ and inverts it to make the pulse positive. Additionally a channel specific DC-offset is added to the pulse. This pulse will be then digitized and will be seen in the output of the TARGET software.

The main saturation effect that was observed here was caused by the first amplifier which saturates at input amplitudes starting at $1.3 - 1.4$ V. In the channel output, this effect can be seen by a rectangular structure coming after the shaped pulse. Furthermore, the output signal only increases slightly after this point is reached.

To analyze the shaper using the digitized waveforms different peak height extraction methods were introduced. It was proven that the method determining the peak height from the amplitude of a fitted Gaussian yielded the most accurate results. Another advantage of this method is the low storage cell dependency, caused by the fact that multiple samples are used to determine the peak height rather than only one. So even while using the not ADC calibrated output, this method can determine the peak height accurately without producing cell structures seen in the peak height distribution.

Determining the gain of whole shaper using the peak height from the Gaussian fit amplitude and comparing it to the result from the voltage measurement (see tab. 8.5.1) one sees the gains for each channel distributed between 1.5 and 1.6 with errors on single values of $\sim 0.015$. The error resulting from the distribution of the mean values of the gain is very similar which concludes that the fluctuation between the channels is fairly small. But the channel distribution does not match the gain value from the voltage measurement completely. It would take at least $2\sigma$–intervals for the two values to match. Furthermore, one discovered that the saturation effect coming from the first amplifier already starts at $\sim 1.0$ V input amplitude rather than $\sim 1.3$ V. These two issues could be studied in a future, more detailed work.
<table>
<thead>
<tr>
<th></th>
<th>Gain</th>
<th>Accuracy</th>
<th>Saturation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Voltage measurements</td>
<td>1.42</td>
<td>0.03</td>
<td>(\sim 1.3 - 1.4) V input</td>
</tr>
<tr>
<td>Digitized waveforms</td>
<td>1.5–1.6 mean: 1.53</td>
<td>single channel: (\sim 0.015) mean distribution per channel: (\sim 0.017)</td>
<td>(\sim 1.0) V input</td>
</tr>
</tbody>
</table>

Table 8.5.1: **Comparison of TAREGT shaper properties using the measured voltage or using digitized output waveforms.** The accuracy is given in the same units as the gain (dimensionless). One sees that the fluctuation between the channels is low, but that the average gain from the digitized data does not completely match the results taken from voltage measurements.

Based on the main signal processing properties of the TARGET and having calibrated the trigger and digitization, one will proceed to investigate the IceAct camera.
Chapter 9

Camera Tests

Each of the 64 channels of the TARGET DAQ corresponds to a SiPM on the camera. The signal processing inside TARGET starts with the input of an amplified SiPM output pulse. This SiPM pulse results from photons entering the detector and generating an output voltage which heights is quantified based on the number of incoming photons. To reconstruct the measured air shower one needs to know the number of detected photons. Further, it has to be ensured that all the camera pixels have the same performance (or to know the performance differences exactly) to be able to analyze the shape seen on the camera properly.

Using the knowledge about TARGET from the previous chapters, one wants to to characterize the camera by analyzing the TARGET output caused by the camera input.

9.1 SiPM Bias Voltage

The supply voltage for the SiPMs is set up for each trigger group of four channels using a 8-bit DAC. The set up SiPM bias voltage can be measured on the 16 measurement points located at right side on top of the Power Board\(^1\) (see fig. 9.1.1).

![Measurement points for SiPM bias voltage](image)

Figure 9.1.1: **Measurement points for SiPM bias voltage.** Top view of the Power Board of TARGET. The metallic barrier on the edges can be used as ground.

\(^1\)The mapping of the trigger groups in the TARGET software does not correspond to the order of the points or to the Test Point(TP) numbering written on the board. See Appendix A.2 for the correct mapping.
The bias voltage can be set up in DAC Counts between 0 and 255. To calibrate these DAC Counts one uses the same procedure as in section 7.3.1: The voltage on the measurement points is measured with a multimeter while changing the DAC Counts value to create a DAC to voltage calibration curve. The resulting curves can be seen in fig. 9.1.2.

![Figure 9.1.2: DAC to voltage calibration curves for SiPM bias voltage of all 16 trigger groups. DAC steps of 1 were used. The curves have very slight curvature but cannot be estimated by a linear relation.](image)

We see that bias voltages between $\sim 26$ V and $\sim 32.5$ V can be set up using the integrated DAC. By measuring the voltage for every possible DAC Counts, a lookup table can be created for every trigger group to set up the SiPM voltage as precise as possible.

Finally, one wants to take a look at the differences between the curves of different trigger channels. For this matter, a mean curve is created by averaging the voltage for each DAC Count over all channels and plotting residues for every curve (see fig. 9.1.3).
Chapter 9. Camera Tests

Figure 9.1.3: Residues from mean calibration curve from DAC to voltage calibration of SiPM bias voltage. It can be noted that the deviation from the mean calibration curve is up to 0.2 V.

We notice that the largest observed deviation from the mean curve is $\sim 200$ mV. Using 6 V overvoltage [20] results in a fluctuation of more than 3%. We see that the calibration curve is similar for all Superpixels, but because of the not negligible fluctuation, one uses a different lookup-table for each Trigger group to set up the SiPM bias voltage.

According to [20] the operation voltage for the used SiPMs is between 25.2 and 30.7 V. Using a high bias voltage increases the gain and hereby make small pulses to be better recognizable (but on the other hand it increases the Dark Count). Therefore, a bias voltage of 30 V is used for all pixels for the next measurements. This corresponds to DAC values around 80 DAC Counts.

9.2 SiPM Dark Count

Setting up the SiPM bias voltage to 30 V, we now want to analyze the output of the camera.

The first thing that was not taken into account while testing the DAQ are the effects coming from the preamplifier on the camera board. Before looking at the noise of the SiPMs itself, the noise of the preamplifiers (which there is one for every SiPM) is determined. This is done by performing a threshold scan analogue to chapter 6 with varying PMTref and constant Thresh of 2000. The SiPM bias voltage is turned off by disconnecting the Power Board with the camera. Using the results from chapter 6 the x-axis can be calibrated to get the noise level in units of voltage rather than DAC Counts (see fig. 9.2.1).
Figure 9.2.1: **Triggerscan for PreAmp noise for trigger group 2** compared with trigger scan for electrical TARGET noise. The calibration was performed by using the trigger calibration results, where the signal was injected on one channel per trigger groups. So the voltage equals the summed up PreAmp noise of four channels.

One can see that the curve for the PreAmp noise has the same symmetrical shape as the curve for the baseline noise of TARGET, but is wider. Further it has its peak at the same position, so the preamplifier does not cause a baseline shift. Comparing the widths of the PreAmp peaks, we get the distribution shown in fig. 9.2.2.

Figure 9.2.2: **Distribution of the noise width per trigger group from the preamplifier on the camera board.** The width is defined as the distance on the x-axis for trigger rates higher than 20 Hz.

So one can conclude that the noise width coming from the preamplifier is between 12.5 and 16.5 mV per trigger group. To get the noise of the preamplifier per channel (per SiPM) we divide this value by 4 which results in noise width of $3.1 - 4.1$ mV.
Now, one takes a look at the Dark Count Noise of the SiPMs. Even without light the SiPM would measure single photons with a certain frequency dependent on the temperature, the so called Dark Rate. To ensure reasonable datataking of the telescopes, it is important to set the trigger threshold high enough, so the telescope does not trigger on the SiPM noise. Further, one is interested in how high the SiPM signal should be (how many PE) to differentiate it from the Dark Count. A rough estimate for the threshold in units of PE $N_{PE}$ can be done using following formula (see [58] for a more precise calculation):

$$f_{\text{thresh}} = f_{\text{Dark}} \cdot (P_{\text{cross}})^{N_{\text{PE}}-1}$$  \hspace{1cm} (9.2.1)

with the rate above the threshold $f_{\text{thresh}}$, the Dark Count Rate $f_{\text{Dark}}$ and the crosstalk probability $P_{\text{cross}}$. According to [20] the Dark Count Rate on 6x6 mm$^2$ at 6 V overvoltage is 5.4 MHz and the crosstalk probability is 25% resulting in a threshold of $\sim 10$ PE to get a rate bellow 20 Hz.

To get further into this, a threshold scan is performed with turned on SiPMs (with a camera connected to the Power Board) with SiPM bias voltages of 30 V. To prevent any light from entering the detector, the camera is placed inside the light isolated black box and is additionally covered with black material. The resulting curve from the threshold scan can be seen in fig. 9.2.3.

Figure 9.2.3: Triggerscan for Dark Count Noise for trigger group 2 compared with triggerscan for TARGET and PreAmp noise. The peak of the SiPM is shifted by $5 - 8$ DAC Counts in the positive direction. One can see a jump at 2058 DAC Counts. This results from a feature of the DAC already discussed in section 7.3.1.

Unlike the curves for the preamplifier and TARGET noise, this curve is not symmetrical, but has an asymmetry to the right side which equals a negative PreAmp output pulse (meaning a positive SiPM output pulse). The difference from the PreAmp curve on the left side is very small which suggests that the noise on the positive side results only from the PreAmp. Further, according to formula 9.2.1 the Dark Count should have an exponential dependence of the number of PE which can be seen as a line in the logarithmic plot. But one would expect to see the single PE as plateaus in the threshold scan which is not the case here. That is, because we look at the sum of four SiPMs which make the PreAmp noise larger than one PE. Further, the gain of each SiPM is slightly different. Overlapping these four different distributions results in no structures being recognizable. To see the plateaus in the threshold scan, one would have
to turn off three of the four SiPMs belonging to the Trigger Group.

To determine the width of the Dark Counts Noise one determines the width of the Dark Count curve and subtracts the width of the PreAmp curve to determine the additional noise coming from the SiPMs. The distribution for all trigger groups can be seen in fig. 9.2.4.

![Distribution of width of Dark Count Noise for each Trigger Group.](image)

Figure 9.2.4: Distribution of width of Dark Count Noise for each Trigger Group. The width is again determined by the part with a trigger rate $> 20$ Hz. The used camera did not have bias connectors for trigger groups 8,9,10, so there are only 13 except of 16 entries.

We get widths of $45 - 65 \text{ mV}$ per trigger group which results in widths of $11.3 - 16.3 \text{ mV}$ for one SiPM. Assuming one PE equals $\sim 4 \text{ mV}$ [44] this would be more than 4 PE per SiPM. To ensure that no channel triggers on noise the set up threshold should be about $80 \text{ mV}$ which equals 20 PE. To judge this result one should note that the Dark Count Rate is temperature dependent, so it would be much lower for the low temperatures at South Pole. But an additional effect during real operation not taken into effect yet is the additional noise coming from the Night Sky Background which is much higher.

### 9.3 Camera Events and Waveforms

The calibration of the camera is a non-trivial process which will not be studied completely in this thesis. Nevertheless, we want to take a look at the output waveforms caused by triggered camera events.

After having determined the SiPM bias voltage and the required threshold to be above the SiPM Dark Count, we set up a threshold value within the Dark Count Noise, but above the PreAmp noise and look at the height and shape of some output waveform on the channels (see fig. 9.3.1).
(a) Channel 8, \( amp = 40.5 \text{ mV} \approx 10 \text{ PE} \), \( \sigma = 4.2 \text{ mV} \).

(b) Channel 52, \( amp = 46.0 \text{ mV} \approx 11 \text{ PE} \), \( \sigma = 3.5 \text{ mV} \).

Figure 9.3.1: Example waveforms with Gaussian fit triggered by Dark Count of SiPMs with 30 V bias voltage. To show waveforms which are clearly above the noise level one chose the trigger higher than 1 PE. Besides the clearly smaller pulse width compared with the TARGET only measurement, one can also see a clear undershoot after the peak which could not be observed during the TARGET calibrations.

Comparing these pulse shape with output pulse during the TARGET calibration measurements one notices that the pulse became much slimmer. Now, we have pulse widths of 3–4.5 ns while in the previous chapters, they were more like 8–9 ns. To explain this change of a factor larger than 2 one compares the direct output of the PreAmp with the TARGET input used in the previous chapters (see fig. 9.3.2).

Figure 9.3.2: Comparison between PreAmp output and TARGET input used for TARGET calibration. The PreAmp output and the Splitter output were measured by an oscilloscope while the FuncGen output is the function given to the function generator.

We see small changes between the rise times, especially while looking at the output of the Splitter Board which suggests influence on the signal shape coming from the function generator.
But the change in the rise is too small to explain a factor of 2 in the output signal width.

Another function test for the camera we gonna perform at the end is the Muon test. For this, the covered camera is placed face up inside the black box. The threshold for all channels is set clearly above the Dark Noise so that the trigger rate should be zero. Atmospheric muons penetrate the blackbox and the camera cover without much of an energy loss. Muons with energies high enough would emit Cherenkov light within the Winston cones which would be then detected by the SiPMs. The amount of light produced by such an event will be high enough to be clearly detectable. Some of the events can be seen in fig. 9.3.3.

![Image of Muon Events](image)

Figure 9.3.3: Camera images of some muon events with high Threshold\(^2\). An additional image cleaning was performed on the images which sets the peak height of every pixel which is bellow 50 mV to zero so the hit pixels are highlighted especially.

Events, where only one pixel is hit (see fig. 9.3.3a), result from vertical incoming muons. The Cherenkov cone would hit only the one SiPM below the Winston cone where the Cherenkov

\(^2\)All channels belonging to the same Superpixel/Trigger Group are located close to each other on the camera. See Appendix A.3 for the mapping of the pixels.
light was emitted. For muons arriving at a certain angle, multiple neighboring Winston cones are hit (see fig. 9.3.3b) and the emitted light enters several SiPMs. For very horizontal incoming muons even more than two pixels can be hit in a straight line (see fig. 9.3.3d).

Finally, one wants to compare the peak heights of single and multiple pixels events. Therefore, we look at the distribution of average peak height for events with one pixel hit and events where multiple pixels were involved (see fig. 9.3.4).

![Graphs](image.png)

(a) Distribution for single pixel hits, mean=494 mV

(b) Distribution for multiple pixel hits, mean=271 mV

Figure 9.3.4: Distributions of average peak heights for muon events with one or with multiple pixel hits. The hit pixels were determined by having a peak height higher than 50 mV.

One can see that single pixel events tend to have a much larger peak height than the multiple pixel events. The average multiple pixel distribution peaks around 200–300 mV (mean=271 mV) while single pixel height are more around 500 mV (mean=494 mV). This is to expected, because vertical incoming muons would emit their whole Cherenkov cone in the one SiPM while for diagonally incoming muons multiple SiPMs would share the Cherenkov photons, even though the muons had similar energy resulting in a similar number of emitted Cherenkov photons. This observation confirms once again that the seen events result most likely from muons and not from other unknown perturbing effects.

### 9.4 Future Tests and Measurements

In this chapter the rough functionality of the camera was tested and preparations were made for future work.

We calibrated the DAC for the SiPM bias voltage and used this information to set up the bias voltage of every channel to 30 V which results in a high gain.

Further, the noise of the preamplifiers on the camera board and the Dark Count Noise of the SiPMs were measured. The Dark Counts Noise was determined to be 11.3–16.3 mV per

---

3There are also cases of multiple pixel events having a higher amplitude which results from a higher energetic muon
SiPM for room temperature. To get a better image of the real performance of the sensors at South Pole one needs to study this matter for different temperatures.

Finally, the camera was used to detect atmospheric muons by using the Winston cones as a medium for Cherenkov light. We saw camera patterns, we would expect from muon events. This way, it could be confirmed that the triggering system is working and that the SiPMs can detect Cherenkov light. But to interpret the information taken from the waveforms, several additional studies have to be done.

First, the measured peak height voltages can be compared to each other, but to reconstruct the shower one needs to know the number of emitted Cherenkov photons which is not known exactly yet. For this, one will have to a charge calibration to know what voltage equals one Cherenkov photon (1PE). This is done by setting the trigger pretty much exactly to the expected value for 1 PE and recording the dark count waveforms. Creating a histogram of the pulse heights (or pulse areas) extracted from the waveforms would reveal the voltages for 1, 2, 3, ect. PE in form of peaks.

Another issue is the different detection efficiency of the SiPMs. To compare it, one would use a light pulse (from our pulser) of homogeneous light directed at the camera. If one can ensure that the camera is hit by the same number of photons everywhere, we can compare the output pulse heights to calculate the detection efficiency for every pixel. Seeing a difference between the SiPMs would require to correct for it accordingly.

Besides the pulse height, we are also interested in the arrival time. For this it is important to find out what the time delay between arrival of the photon and the recorded trigger time is. This can be done by triggering the telescope using an external trigger coming from the light source. With known traveling distance of the photon one would see the trigger delay in the output waveform.

After all this test and calibration measurements for the camera one should additionally perform a full working test using the whole telescope including the lens and the housing.
Chapter 10

Conclusion and Outlook

In this thesis, test and calibration measurement were performed on the TARGET-C DAQ and the 61-pixel IceAct camera. Like this, a testing routine could be established addressing several issues that will have to be studied in more detail in the future.

The trigger threshold for IceAct can be set up with TARGET by either shifting the threshold line itself or by shifting the trigger baseline for each trigger group. It could be proven that both methods have the same effect on the threshold beside a scaling factor. Further, the noise of the baseline was studied using a threshold scan which revealed that the noise is very similar on each trigger group. To calibrate the threshold set up in DAC Counts to a real threshold voltage we used an output signal of the preamplifier on the camera board of different amplitudes. The DAC value, where the measured trigger rate falls down to zero equals the corresponding input voltage (including amplification procedures happening inside the module). One realized that there is a linear correlation between the threshold DAC count and the input voltage for inputs up to $\sim 50$ mV per channel. Doing threshold scans for a different number of input channels belonging to the same trigger group confirmed that the trigger decision is made on the sum over all four channels belonging to the corresponding trigger group (taken the fluctuation between single channel measurements into account). Because the noise measure of one trigger group equals the summed noise over four SiPMs, we are able to set up a precise trigger for voltages up to 200 mV which should overcome the SiPM Dark Count Noise and the noise resulting from the Night Sky Background and enable normal telescope operation this way. If a higher trigger threshold is necessary, it would be still possible to create a look-up table for higher threshold voltages.

To test the TARGET under laboratory conditions one should keep the temperature change in mind. The modules heats up to 60$^\circ$C during operation which influences the output. One could observe a baseline drift of up to 20 ADC Counts within 10 minutes of measurement time. So to ensure a stable measurement it is necessary to apply external cooling to the module. A simple room fan is enough to keep the temperature quite stable at 30 – 35$^\circ$C. Taking about 5 minutes as a warm-up time for the module ensures the drift to be not seeable and the fluctuations in the baseline to be minimal.

We also performed a calibration of the ADC of TARGET which is done in two steps. First, the DAC setting up the DC-offset voltage is calibrated by measuring this voltage on the measurement points of each channel. Because the calibration curves for each channel are different, one has to record 64 curves by hand. For future testing of multiple modules this process will
have to be automatized. In the second step the information from the DAC calibration is used to set the offset to the same voltage on every channel. For different voltages, a pedestal is taken which then can be used to perform a calibration between DAC and ADC Counts. Combining both steps results in an ADC Counts to voltage calibration curve which is slightly different for every storage cell of the ADC. The resulting transfer function can be applied to the output waveforms. Because no specific input signal was used to calculate the transfer function, this calibration is always valid independent on the input signal.

In the process of analyzing the shaper using PreAmp pulses, the signal output and function of each element could be studied. During a measurement of the analogue output signal one could see that each element possesses a linear gain and sometimes a saturation at some point. The most obvious effect was the saturation of the first amplifier at input voltage of $1.3 - 1.4 \text{ V}$ which changes the output behavior of the final channel output. Using input voltages below the saturation results in a gain of $\sim 1.42$ for the whole shaper for PreAmp pulses.

The shaper was also studied using the digitized output pulses. To extract the pulse heights in an optimal way, several methods were compared. It was concluded that the method using the amplitude from the Gaussian fit yields the best results. Especially, it is not influenced by storage cell effects. Comparing the peak height distribution resulting from different methods before the ADC calibration, we can see a structure consisting of 2 peaks which is caused by the different performance of every 32th cell. After the ADC calibration the structure changes into one big Gaussian peak. Using the Gaussian amplitude for the peak height extraction gives us this distribution even before the ADC calibration which enables us extracting peak heights precisely even without needing the information of the ADC calibration. Using this best extraction method one can determine the gain of the shaper being a bit different from the measurement using the DC-offset calibration. Further, we see the saturation of the first shaper happening earlier, already at $1.0 \text{ V}$. This effect can be partly explained by the limited range of the ADC calibration which is only valid up to $\sim 2.3 \text{ V}$ including the DC-offset. But even looking the raw waveforms, one can see cut off pulses even though the maximum ADC Count was not reached. This investigation was also done using the case of a PreAmp pulse with a fixed rise and fall time. Because of the High-Pass element the performance will most likely change for different input pulses. So the pulse shape dependency of the shaper is another issue to be studied in the future.

To perform a reliable camera calibration we desire a high gain of the SiPM which is realized by a high SiPM bias voltage. After performing a DAC calibration for it, we set it to $30 \text{ V}$. Using a calibrated threshold scan the noise of the preamplifier on the camera board and the Dark Noise of the SiPMs were determined. One noticed the absence of plateaus in the scan which should indicate the threshold for 1, 2, 3, ect. PE. This was caused by having all four SiPMs of the Trigger groups being turned on. Turning only one SiPM on would results in less PreAmp noise and will most likely let us see the desired structures. Setting the threshold clearly above the Dark Noise a functionality test of the camera was performed by muon emitting Cherenkov light inside the Winston cones which is then detected by the SiPMs. One could observe different camera patterns resulting most likely from muons arriving under different angles resulting in a different number of pixels to be hit. However, to reconstruct the shower correctly one needs to know the number of detected Cherenkov photons.

Several tests for the camera are still to be performed yet for the camera to be fully operational. To calibrate the number of detected photons one first needs a rough estimate of the
voltage for 1 PE (that could be taken from the threshold scan). The trigger is then set to 1 PE and the resulting peaks in the waveforms (being in the magnitude of several single PE) can be used to plot a spectrum where the voltages for single PEs can be taken from. Additionally, it is necessary to determine the detection efficiency for every pixel to be able to get consistent data during operation at South Pole. And finally, to be able to determine the arrival time one needs to determine the delay between the Cherenkov photons arriving and the triggering. After the camera is fully calibrated a full test, using a whole telescope with lens and housing is needed. There one has to take an additional source of noise into account, the Night Sky Background. During all this test one should keep in mind the temperature difference between lab and South Pole which results in different performance of the elements.

This thesis showed us the complexity of the electronics used for IceAct which are yet to be fully understood. The detailed analysis of each testing step enables the developed of automatized routines with focus on the critical steps. Like this, a large number of constructed IceAct telescopes can be tested reliably under the same conditions. Striving to characterize the whole signal processing withing the telescope, a full simulation chain is currently being implemented including a full hardware simulation of TARGET. The quality of this simulation would most likely profit from a real measurements set of the simulated hardware. Ensuring better testing conditions upgrades the quality of operation, datataking and analysis which would lead to enhancing the data quality of IceCube and thus, allowing for even deeper studies of Neutrino Physics.
Appendix A

Mappings of channels

A.1 Arduino pins to Channels

The splitter board is connected to the digital output pins 22-53 on the Bluno MEGA, where each pins corresponds to one channel on TARGET. The multiplexer board has two SMA connectors each of them sending the input signal to 16 of the 32 channels. The „outer connector“ is more close to border while the „inner connector“ is more close to the connector to the multiplexer adapter board. The mapping between the pins and channels and the information which of the two input connectors are needed for that channel can be found in tab. A.1.1 and tab. A.1.2.

<table>
<thead>
<tr>
<th>Channel</th>
<th>Arduino Pin</th>
<th>Channel</th>
<th>Arduino Pin</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>outer connector</td>
<td></td>
<td>inner connector</td>
</tr>
<tr>
<td>0</td>
<td>34</td>
<td>5</td>
<td>27</td>
</tr>
<tr>
<td>1</td>
<td>31</td>
<td>6</td>
<td>26</td>
</tr>
<tr>
<td>2</td>
<td>30</td>
<td>8</td>
<td>28</td>
</tr>
<tr>
<td>3</td>
<td>32</td>
<td>10</td>
<td>29</td>
</tr>
<tr>
<td>4</td>
<td>33</td>
<td>11</td>
<td>23</td>
</tr>
<tr>
<td>7</td>
<td>37</td>
<td>13</td>
<td>25</td>
</tr>
<tr>
<td>9</td>
<td>35</td>
<td>14</td>
<td>24</td>
</tr>
<tr>
<td>12</td>
<td>36</td>
<td>15</td>
<td>22</td>
</tr>
<tr>
<td>17</td>
<td>39</td>
<td>16</td>
<td>53</td>
</tr>
<tr>
<td>22</td>
<td>40</td>
<td>18</td>
<td>50</td>
</tr>
<tr>
<td>24</td>
<td>38</td>
<td>19</td>
<td>51</td>
</tr>
<tr>
<td>27</td>
<td>42</td>
<td>20</td>
<td>52</td>
</tr>
<tr>
<td>28</td>
<td>43</td>
<td>21</td>
<td>46</td>
</tr>
<tr>
<td>29</td>
<td>44</td>
<td>23</td>
<td>47</td>
</tr>
<tr>
<td>30</td>
<td>45</td>
<td>25</td>
<td>49</td>
</tr>
<tr>
<td>31</td>
<td>41</td>
<td>26</td>
<td>48</td>
</tr>
</tbody>
</table>

Table A.1.1: Arduino digital output pins to TARGET channel mapping on Primary Board.
Appendix A. Mappings of channels

<table>
<thead>
<tr>
<th>Channel</th>
<th>Arduino Pin</th>
<th>Channel</th>
<th>Arduino Pin</th>
</tr>
</thead>
<tbody>
<tr>
<td>outer connector</td>
<td></td>
<td>inner connector</td>
<td></td>
</tr>
<tr>
<td>32</td>
<td>33</td>
<td>33</td>
<td>26</td>
</tr>
<tr>
<td>34</td>
<td>32</td>
<td>36</td>
<td>27</td>
</tr>
<tr>
<td>35</td>
<td>30</td>
<td>39</td>
<td>23</td>
</tr>
<tr>
<td>37</td>
<td>36</td>
<td>40</td>
<td>28</td>
</tr>
<tr>
<td>38</td>
<td>31</td>
<td>41</td>
<td>25</td>
</tr>
<tr>
<td>44</td>
<td>34</td>
<td>42</td>
<td>29</td>
</tr>
<tr>
<td>45</td>
<td>35</td>
<td>43</td>
<td>24</td>
</tr>
<tr>
<td>46</td>
<td>37</td>
<td>47</td>
<td>22</td>
</tr>
<tr>
<td>49</td>
<td>40</td>
<td>48</td>
<td>52</td>
</tr>
<tr>
<td>51</td>
<td>42</td>
<td>50</td>
<td>50</td>
</tr>
<tr>
<td>52</td>
<td>38</td>
<td>53</td>
<td>53</td>
</tr>
<tr>
<td>54</td>
<td>41</td>
<td>56</td>
<td>51</td>
</tr>
<tr>
<td>55</td>
<td>39</td>
<td>57</td>
<td>46</td>
</tr>
<tr>
<td>61</td>
<td>43</td>
<td>58</td>
<td>47</td>
</tr>
<tr>
<td>62</td>
<td>44</td>
<td>59</td>
<td>48</td>
</tr>
<tr>
<td>63</td>
<td>45</td>
<td>60</td>
<td>49</td>
</tr>
</tbody>
</table>

Table A.1.2: Arduino digital output pin to TARGET channel mapping on AUX Board.

A.2 SiPM bias voltage measurement points

The mapping of the measurement points for the SiPM bias voltage is not in the same order as the measurement point are positioned on the Power Board. The number of the channel also does not correspond to the numbering of the TP written on the board. The mapping can be seen in tab. A.2.1 while fig. A.2.1 shows the position of the measurement points.

Figure A.2.1: Positions of measurement points for SiPM bias voltage. View from top on Power Board.
<table>
<thead>
<tr>
<th>Channel/Trigger Group</th>
<th>TP</th>
<th>Position</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>1</td>
<td>12</td>
</tr>
<tr>
<td>1</td>
<td>2</td>
<td>15</td>
</tr>
<tr>
<td>2</td>
<td>4</td>
<td>14</td>
</tr>
<tr>
<td>3</td>
<td>3</td>
<td>13</td>
</tr>
<tr>
<td>4</td>
<td>13</td>
<td>11</td>
</tr>
<tr>
<td>5</td>
<td>10</td>
<td>4</td>
</tr>
<tr>
<td>6</td>
<td>14</td>
<td>10</td>
</tr>
<tr>
<td>7</td>
<td>9</td>
<td>6</td>
</tr>
<tr>
<td>8</td>
<td>12</td>
<td>5</td>
</tr>
<tr>
<td>9</td>
<td>16</td>
<td>8</td>
</tr>
<tr>
<td>10</td>
<td>15</td>
<td>9</td>
</tr>
<tr>
<td>11</td>
<td>11</td>
<td>7</td>
</tr>
<tr>
<td>12</td>
<td>5</td>
<td>3</td>
</tr>
<tr>
<td>13</td>
<td>7</td>
<td>2</td>
</tr>
<tr>
<td>14</td>
<td>6</td>
<td>1</td>
</tr>
<tr>
<td>15</td>
<td>8</td>
<td>0</td>
</tr>
</tbody>
</table>

Table A.2.1: Mapping of measurement points for SiPM bias voltage.

A.3 Camera Pixels

The pixel mapping of the camera and the corresponding Superpixels is illustrated in fig. A.3.1.

Figure A.3.1: Mapping of the pixels of the IceAct camera. Channels 44, 45 and 46 correspond to the SiPMs without a Winston cone, so the channels of Superpixel 11 are not neighboring. (Taken from [59])
Appendix B

Features of Hardware Elements

B.1 Ladder DAC

The DAC to set up the DC-offset voltage of TARGET is a R2R-Ladder DAC (see fig. B.1.1) [44]. This is a resistor network with resistances of $R$ and $2R$ where each bit is represented by a $2R$ resistor. A bit can either be connected to the reference voltage $V_{cc}$ (1) or to ground (0). The turning of and off of the bits influences the output voltage $V_{out}$ in the following way:

$$V_{out} = V_{cc} \cdot \frac{\text{Value}}{2^N}$$  \hspace{1cm} (B.1.1)

with the number of bits $N$ and the binary number of turned on bit converted to a decimal number Value. [60]

For bit values of $2^N - 1$ $N$ bits in a row are active. Switching to the next value $2^N$ results in all bits being switched off and one new bit to be switched on. Like this, $V_{out}$ is strongly dependent on the resistance of this one resistor having the tolerance on the resistance playing a major role. One sees a clear jump in the curve at this point which becomes clearer the higher the value is. In our case of a 12-bit DAC, we see the biggest jump at 2047 to 2048 where

![Scheme of a 4-bit R2R network.](image)
11 bit are turned off simultaneously. Similar things can be seen at 3071 to 3072 where 10 out of the 11 bits are turned off (even though this effect is smaller).

## B.2 Overflow of Wilkinson ADCs

The width of a Wilkinson Ramp is dependent on the value of the used capacitor. The capacitor is chosen, so the end of the ramp (the maximum voltage that can be digitized) equals the maximal possible ADC Counts (4095 in our case). Having a wrong capacitor built in results in the ramp having a smaller slope without changing the maximum ramp voltage (see fig. B.2.1).

![Figure B.2.1: Comparison of Wilkinson Ramps with different capacitors.](image-url)

Because the clock inside the ADC is independent on the capacitance, the ADC will reach its maximum value before the climbs up to the desired voltage. This will cause the ADC to start again at zero while the ramps continues to increase. Like this, voltages increasing 4095 ADC Counts will be digitized after subtracting 4095 ADC Counts from them. Examples can be seen in fig. B.2.2.
Figure B.2.2: **Examples of output waveform with ADC overflow observed on channel 52 of TARGET.** The shape looks like at some point the peak was cut off and continued at zero ADC Counts. These waveforms were observed before the corresponding capacitor was changed. So the measurement shown in this thesis were performed while using the correct capacitor.

This effect could first be observed on the channels of the AUX board resulting from a wrong capacitor. Even after changing this capacitor some overflow effects could have been observed for very high input voltage like the high DC-offset voltage for the ADC calibration. Because this was a very small effect which does not influence our results this much, the last point the the ADC calibration curves of channel 32-63 was taken out.
Acknowledgments

From my time at the institute I received many different kinds of impressions and undoubtedly, learned a lot of things. So there are some people I would like to give my thanks to.

I would like to thank Prof. Dr. Christopher Wiebusch for giving me the opportunity to take part in real scientific work and giving me a deep dive into the exciting world of science. This is a career path I will definitely pursue further.

I would also like to thank Merlin Schaufel, for supporting me with my thesis all the way and providing me with helpful advise in the best of his possibilities. Further, his corrections definitively improved my thesis a lot.

Then I am grateful to Prof. Dr. Thomas Bretz for listening to my problems in the meeting and providing me with many helpful advise, as well as being the second referee for my thesis.

I also would like to thank the whole Aachen IceCube working group for the nice conversations and for creating a very nice and relaxing working atmosphere, especially Erik Ganster for proofreading parts of my thesis and giving me constructive advise.

A very special thanks goes to Dr. Adrian Zink from ECAP. He provided me with lots of technical support for TARGET and was always available when I needed help. Without him this work would not be possible to this extent. Thanks a lot!

And finally, I want to thank all the people for supporting me throughout this whole time. Thanks to Franziska Tischbein and Simon Klütttermann for taking the time to proofread my thesis. Thanks a lot to Sukee for keeping me company in the office and for being a very nice conversation partner and friend. Thanks to all my dear friends: Marcel, Moritz, Lars, Simon, Lukas, Kai, Til, Nico and especially to my mother for proving me with tons of emotional support during this hard time!
# List of Figures

2.1.1 The differential energy spectrum of cosmic rays over eleven decades of energy . . 3  
2.2.1 Schematic views of (a) an electromagnetic cascade and (b) a hadronic shower. . 4  
2.3.1 Cherenkov Effect explained with Huygens’ principle. ................................. 5  
2.3.2 Spectrum of Cherenkov light measured at the altitude of the HEGRA IACT system, 2200m above sea level, LaPalma in arbitrary units. ......................... 5  
2.4.1 Construction and working principle of a PMT ............................................. 6  
2.4.2 Simplified electric circuit (a) and signal output (b) of a SiPM .......................... 7  
2.5.1 Shower detection by IACTs on ground ...................................................... 8  
2.5.2 Sketch of a stereo observation of a 300 GeV γ−ray coming from a 1 TeV primary proton ................................................................. 8  
3.1.1 IceCube Neutrino Observatory Setup. ...................................................... 9  
3.1.2 Sketch of an IceCube in ice DOM ............................................................. 10  
3.2.1 A photo of the IceAct demonstrator telescope ........................................ 11  
4.1.1 Drawing of the actual IceAct design ....................................................... 13  
4.2.1 Photo of IceAct Camera with glued Winston Cones ................................. 14  
4.2.2 Event recorded shortly after the First Light of the IceAct roof-telescope during the Antarctic winter 2019 ................................................................. 14  
4.3.1 TARGET-C module for IceAct ............................................................... 15  
4.3.2 Electric circuit of the Hardware Shaper of TARGET-C module ................... 15  
4.3.3 Comparison between input SiPM pulse of 123 mV amplitude and shaped output pulse after the final stage ......................................................... 16  
4.3.4 Illustration of a shaped, amplified input pulse which results in a trigger .......... 17  
4.3.5 Block diagram of one TARGET5 ASIC .................................................. 18  
5.1.1 TARGET Adapter Boards ................................................................. 19  
5.2.1 Splitter Board and Bluno MEGA to send pulses to all channels on TARET ... 20  
5.2.2 Photo of full setup to test the TARGET-C module .................................... 21  
5.3.1 Top-down view on the Camera test setup inside a light isolated black box .... 21  
5.3.2 Front view of camera mounted in the camera test setup ............................. 22  
5.3.3 Connector of Camera to DAQ ............................................................... 22  
6.1.1 Comparison between output signal from function generator and output from multiplexer .............................................................. 24  
6.1.2 Linear fit between input and output peak height of multiplexer board ......... 24  
6.2.1 Threshold scan of all Trigger Groups without signal ............................... 25  
6.2.2 Histogram of noise peak width for each Trigger Group ............................ 26
6.3.1 Triggerscan and corresponding output waveform for group 2 at 31 mV input voltage. ................................................................. 27
6.3.2 Error function fit at fall down flank for group 2 at 31 mV input voltage. ................................................................. 28
6.3.3 Calibration curve for PMTref triggerscan for group 1. ............................ 28
6.3.4 Linear fit for low input voltages of triggerscan for group 1. ................. 29
6.3.5 Distribution of linear fit parameters for all trigger groups. .................. 30
6.4.1 Comparison of triggerscans for a different number of channels with input pulse belonging to trigger group 1. ......................... 30
6.4.2 Linear fits for low input voltages for different numbers of channels with input pulses belonging to trigger group 2. .................. 31
6.4.3 Comparison of linear fit parameters from trigger scans between the four single input channels belonging to trigger group 2. ........ 31
6.5.1 Comparison of trigger scans with varying PMTref and Thresh without an input signal for trigger group 13. ............................. 32
6.5.2 Comparison of trigger scans with varying PMTref and Thresh with an input signal of 9 mV on channel 53, belonging to trigger group 13. 34
7.1.1 Simplified sketch of signal propagation through TARGET. ................. 36
7.1.2 Raw waveforms without offset correction for $V_{\text{ped}} = 1200$. .......... 37
7.1.3 Pedestal corrected waveform for $V_{\text{ped}} = 1200$. .......................... 38
7.2.1 Temperature change and baseline shift of channel without input signal over time without external cooling. ............................. 39
7.2.2 Temperature change on Primary Board before and during datataking with external cooling using a fan. ................................. 40
7.2.3 Baseline shift of channel 52 without input signal with external cooling using a fan. ................................................................. 41
7.3.1 Measurement points of channels for offset signal. .............................. 42
7.3.2 DAC Counts to voltage calibration curves for DC-offset on all channels. 43
7.3.3 Residues from mean calibration curve of channel 52 for the DAC to voltage calibration of DC-offset. ................................. 44
7.3.4 Residues from mean calibration curve of different channels for the DAC to voltage calibration of DC-offset. ........................... 45
7.3.5 Change of cell IDs throughout the waveforms for pedestal r0 file on channel 16. ................................................................. 46
7.3.6 Distribution of baseline ADC Counts of pedestal file for $V_{\text{ped}} = 1200$ on channel 52. ................................................................. 47
7.3.7 DAC to ADC Counts calibration curves for all storage cells on channel 16. ................................................................. 48
7.3.8 ADC Calibration curves for all cells on different channels. ................. 49
7.3.9 Comparison between a waveform before and after ADC calibration with a PreAmp input pulse of 42 mV on channel 52. ................................. 50
8.1.1 Pole Zero resistors on the bottom of Primary Board. ........................... 51
8.1.2 Comparison of waveform processing through the TARGET shaper, measured by an oscilloscope using a probe. .......................... 52
8.1.3 Change of amplitude between input and signal after the first amplification using an PreAmp input pulse. ................................. 53
8.1.4 Saturated first amplifier output and resulting channel output for 2.17 V input amplitude. ................................................................. 54
8.1.5 Comparison between Input vs. High-Pass output and High-Pass output vs. channel output. ................................................................. 55
8.1.6 Saturated waveform from Splitter Board output. ................................. 56
8.1.7 Comparison between input amplitude and channel output. .......... 53
8.1.8 Linear fits to determine the gain of the single elements of the TARGET shaper. .......... 54
8.2.1 Gaussian fit on TARGET output waveform on channel 52 with 109 mV input amplitude. .......... 55
8.2.2 Distributions of peak heights coming from two different methods of peak height extraction using Gaussian fits on channel 52 for 109 mV input voltage. .......... 56
8.2.3 Comparison between a more and a less suitable parabola calculation for peak height extraction on channel 52. .......... 57
8.2.4 Peak height distribution for the parabola method on channel 52 with 109 mV input voltage. .......... 57
8.2.5 Peak height distribution for using the maximum of the waveform on channel 52 with 109 mV input voltage. .......... 57
8.2.6 Comparison of mean and standard deviation (std) of determined peak heights on channel 52 using different peak height extraction methods. .......... 58
8.3.1 Distribution of peak position samples on channel 52, determined by a Gaussian fit at 109 mV input voltage. .......... 59
8.3.2 Comparison between peak height distributions before ADC Calibration on channel 52 for different peak height extraction methods using Gaussian fits. .......... 60
8.3.3 Distribution of mean and standard deviation of peak heights per storage cell on channel 52 with 109 mV input voltage. .......... 61
8.3.4 Distribution of mean and standard deviation of peak heights of ADC calibrated waveforms per storage cell on channel 52 with 109 mV input voltage. .......... 62
8.4.1 Output vs. Input peak height of PreAmp pulses through the TARGET using different peak height extraction methods. .......... 63
8.4.2 Saturated, digitized, ADC calibrated output waveforms on channel 16 for different input voltages. .......... 63
8.4.3 Saturated waveforms before ADC calibration on channel 16 with 1.1 V input voltage. .......... 64
8.4.4 Linear fit for AC-Correction using digitized output waveforms on two example channels. .......... 65
8.4.5 Distribution of AC-Correction gains per channel using digitized waveforms and comparison between gain from the measurement of the analogue signal. .......... 65
9.1.1 Measurement points for SiPM bias voltage. .......... 68
9.1.2 DAC to voltage calibration curves for SiPM bias voltage of all 16 trigger groups. .......... 69
9.1.3 Residues from mean calibration curve from DAC to voltage calibration of SiPM bias voltage. .......... 70
9.2.1 Triggerscan for PreAmp noise for trigger group 2 compared with trigger scan for electrical TARGET noise. .......... 71
9.2.2 Distribution of the noise width per trigger group from the preamplifier on the camera board. .......... 71
9.2.3 Triggerscan for Dark Count Noise for trigger group 2 compared with triggerscan for TARGET and PreAmp noise. .......... 72
9.2.4 Distribution of width of Dark Count Noise for each Trigger Group. .......... 73
9.3.1 Example waveforms with Gaussian fit triggered by Dark Count of SiPMs with 30 V bias voltage. .......... 74
9.3.2 Comparison between PreAmp output and TARGET input used for TARGET calibration. .......... 74
<table>
<thead>
<tr>
<th>Figure</th>
<th>Description</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>9.3.3</td>
<td>Camera images of some muon events with high Threshold.</td>
<td>75</td>
</tr>
<tr>
<td>9.3.4</td>
<td>Distributions of average peak heights for muon events with one or with multiple pixel hits.</td>
<td>76</td>
</tr>
<tr>
<td>A.2.1</td>
<td>Positions of measurement points for SiPM bias voltage.</td>
<td>82</td>
</tr>
<tr>
<td>A.3.1</td>
<td>Mapping of the pixels of the IceAct camera.</td>
<td>83</td>
</tr>
<tr>
<td>B.1.1</td>
<td>Scheme of a 4-bit R2R network.</td>
<td>84</td>
</tr>
<tr>
<td>B.2.1</td>
<td>Comparison of Wilkinson Ramps with different capacitors.</td>
<td>85</td>
</tr>
<tr>
<td>B.2.2</td>
<td>Examples of output waveform with ADC overflow observed on channel 52 of TARGET.</td>
<td>86</td>
</tr>
</tbody>
</table>
List of Tables

6.4.1 Fit parameters from linear fit of triggerscans with different number of input channels of trigger group 2. .................................................. 31
6.4.2 Deviation between measured and expected slopes for different numbers of input channels belonging to trigger group 2. ............................................. 32
8.1.1 Function, gain and saturation behavior of each element of the shaper and of the shaper itself. ................................................................. 54
8.2.1 Mean and std of peak height for different pulse height extraction methods for different input voltages on channel 52. .................................................. 58
8.5.1 Comparison of TAREGT shaper properties using the measured voltage or using digitized output waveforms. ......................................................... 67
A.1.1 Arduino digital output pins to TARGET channel mapping on Primary Board. .... 81
A.1.2 Arduino digital output pin to TARGET channel mapping on AUX Board. .......... 82
A.2.1 Mapping of measurement points for SiPM bias voltage. ................................. 83
Bibliography


[38] Personal Communication Merlin Schaufel (III. Physikalisches Institut B, RWTH Aachen University).


[44] Personal Communication Dr. Adrian Zink (Erlangen Centre for Astroparticle Physics).


