Trigger Studies of TARGET-7:
A Proposed Front End Electronics Solution for the Cherenkov Telescope Array

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Abstract
Gamma ray observations provide a wealth of information that astrophysicists can use to learn about the most energetic physical phenomena. The Cherenkov Telescope Array will be the largest and most powerful ground based gamma-ray observatory ever constructed when it is completed in 2020. Integral in the electronics systems that will be used by CTA telescopes are the front end electronics which serve to sample and digitize the data as well as generate level-zero trigger signals. TARGET-7 is a proposed solution for the front end electronics of some CTA telescope prototypes and this paper details the characterization of its trigger response in terms of trigger threshold and trigger noise. The studies presented in this paper reveal that the minimum trigger threshold is around 40 mV and the trigger noise is roughly 15 mV, whilst CTA’s requirements translate to approximately 10 mV and 1 – 2 mV, respectively. Further, it is demonstrated that the high minimum trigger threshold and large noise are due to a coupling between the sampling and triggering functions that are intrinsic to the design of TARGET-7.
1 Introduction

The light that humans can see is just a very small subset of the full electromagnetic spectrum. From the low energy regime of radio waves all the way up to the highest energies of gamma rays, light delivers information from distant objects and tells us about the nature of the Universe. Gamma rays, which are emitted by the most energetic processes in the Universe, have historically been challenging to detect. Since no gamma rays can penetrate through the Earth’s atmosphere, direct detection of these high energy particles of light can only be accomplished via space based telescopes such as the Fermi Gamma Ray Space Telescope. Unfortunately, these space based gamma ray telescopes don’t detect many very high energy gamma rays because so few of them hit within the relatively small size of the telescope. Though direct detection of high energy gamma rays from the ground cannot be accomplished, they can be detected from the showers of charged particles they produce when they collide with the atmosphere and cause pair production. The charged particles in the showers have so much energy that they actually travel faster than the speed of light in air, and as a result they emit a cone of light which is called Cherenkov light. In addition to other techniques, gamma rays can be indirectly detected via Cherenkov light using imaging atmospheric Cherenkov telescopes (IACT) which give the best point spread function (PSF) and have the highest sensitivity to sub-TeV gamma rays. The principle under which IACTs operate is presented in Figure 1.1:

![Figure 1.1: The process by which gamma rays are detected using IACT arrays: an incoming high energy gamma ray strikes the Earth's atmosphere and causes pair production leading to showers of charged particles that travel faster than the local speed of light and thus emit cones of Cherenkov light which then hits arrays of telescopes on the ground.](image)

As shown in Figure 1.1, the Cherenkov light cone will spread out before hitting the array of telescopes in an elliptical shape (or circular if the shower comes from directly overhead). Additionally, the flashes of Cherenkov light are somewhat rare, faint relative to the night sky background light, and last only a very short amount of time (on the order of nanoseconds). Given these factors, the camera system and electronics must be very specially designed and implemented for detection and quantification to be accomplished.

The light directed into the camera from the telescope will first hit a photo-detector, which converts the light into an electric signal. Specifically, photo-multipliers are typically used for the photo-detectors because they have suitably fast response times (~ns) and their high gain and low noise boost the faint signal. The electric signal then travels through a pre-amplifier, which boosts the signal further. Next, the signal will enter the front end electronics (FEE), which have two primary responsibilities: sampling and digitizing the data as well as sending a trigger signal (if necessary). On the data side, the signal is first sampled at a high frequency so that the instrument is sensitive to the extremely short duration flashes of Cherenkov light. After being sampled, the signal is digitized on demand using an analog-to-digital converter (ADC). The trigger signal from the FEE is a component that is used in the construction of a more sophisticated trigger pattern that can ultimately initiate the read out and recording of data.

IACT arrays have the advantage over space based gamma ray telescopes in that they can be used to observe high energy gamma rays (>100’s of GeV) due to their large effective collection areas. Additionally, they are easier to
maintain and modify simply because they are on the the ground and not in space. Several IACT experiments are already in existence such as VERITAS, MAGIC, and HESS, but not none are as sensitive as the proposed Cherenkov Telescope Array (CTA) will be [3]. CTA will be composed of two sites each containing 50 to 100 telescopes, one in the Northern hemisphere and one in the Southern hemisphere, thus allowing for full sky coverage.

The scientific goals of CTA address deep questions in physics and astrophysics, and the data collected will certainly lead to new insight and understanding of the Universe. Specifically, CTA should be able to detect sources of very high energy gamma rays which will allow for cosmic ray acceleration and propagation to be better understood. Additionally, CTA will be able to collect data on active galactic nuclei (AGN), which are some of the most distant and powerful sources in the sky and which can be analyzed to probe the extragalactic background light which is related to the star-formation history of the Universe [4]. CTA may even be able to detect gamma rays predicted to be produced by dark matter annihilation, which would be a groundbreaking discovery. Beyond all of the specifics, CTA will also be superior to current ground based gamma ray observatories in terms of sensitivity, energy range, and angular resolution. Construction is expected to be completed by 2020.

The SLAC National Accelerator Laboratory is heavily involved in the development of a proposed FEE solution for use with the cameras for the prototypes of some CTA telescopes. This solution, the TeV Array Readout with GSa/s sampling and Event Trigger generation 7 (TARGET-7) is an application specific integrated circuit (ASIC) that was specifically designed for CTA to be a highly efficient, cost effective, compact, and reliable solution for the FEE needs [1]. Additionally TARGET-7 enables the use of smaller and more tightly packed pixels which allow for the camera to have a sharper point spread function (PSF). As is suggested by it’s name, TARGET-7 is designed to perform all of the FEE functions, which have been traditionally been performed using several components. This paper will present the methods and findings of studies into the triggering behavior of TARGET-7 that were conducted by the author at SLAC during the summer of 2014.

The following sections of the paper will serve to detail the concept and characterization of triggering. Additionally, TARGET-7 will be discussed in depth with specific emphasis placed on the parameters and configurations that were used in the experimentation. Next, the methods of testing that were utilized will be presented along with the results. The paper will be concluded with a discussion pertaining to the impact of the results.

2 FEE TRIGGERING

Ideally, triggering at the FEE level is characterized by a single parameter, which is the trigger threshold as is presented in Figure 2.1 by the red line. The trigger threshold is defined as a level above which an input signal will initiate a trigger signal and below which an input signal will not initiate a trigger signal. Due to statistical fluctuations, the trigger threshold will have some ‘width’ to it as is represented by the blue line in the same Figure. This ‘width’ is referred to as the trigger noise and it has the effect of spreading the threshold out, so in practice the triggering behavior is characterized by both the trigger threshold and the trigger noise.

![Figure 2.1: An ideal trigger threshold is shown in red, while a more realistic trigger threshold is shown in blue, with width of the trigger noise marked in green.](image-url)
3 TARGET-7

As was discussed in the Introduction, TARGET-7 is a proposed FEE solution designed for some CTA telescope prototypes. Given that it was designed to perform all of the FEE functions, TARGET-7 must be able to sample at a high rate (GSa/s) and digitize the data, as well as send a trigger signal at the appropriate time. The triggering functionality is a critical component of the FEE for an IACT system and thus significant effort was expended to test and characterize the trigger of TARGET-7 in order to verify if it would be suitable to accomplish the scientific objectives of CTA, which require that the trigger threshold be tune-able to compensate for different sky background conditions, but that it be possible to have a threshold of as low as 2.5 photo-electrons (∼10 mV for TARGET-7) and that the trigger noise be less than one photo-electron (∼1–2 mV).

In order to investigate this trigger behavior, a variety of parameters of TARGET-7 were studied. These parameters will be detailed in the following section. Additionally, Section 3.2 will discuss the TARGET-7 evaluation board which made up an integral part of the apparatus with which measurements were taken. In reading these following sections, the reader should be aware that TARGET-7 has 16 parallel input channels arranged in 4 groups of 4. Each of these groups is capable of initiating a trigger based on the analog sum of the signal in the channels within that group. Additionally, a trigger signal can be sent based on the sum of all 16 channels.

3.1 TARGET-7 Triggering Parameters

The trigger response of TARGET-7 is affected by the voltages which control various mechanisms within the triggering circuit. Figure 3.1 presents the basic circuit configuration that controls the triggering of TARGET-7:

As can be seen in the schematic presented in Figure 3.1, the incoming AC signal is offset by a DC voltage denoted as Vped (ranging from 0 to 3 V) which makes it positive everywhere, thereby avoiding signal loss due to the fact that the ADC used in TARGET-7 only digitizes positive voltages. The signal then passes through a two-stage amplifier, where the offset of the first and second stage amplifiers are given by Vofs1 & Vofs2, respectively. The signal is then passed into a summing amplifier that takes the sum of the 4 channels within a group. The reference voltage of this summing amplifier is given by PMTref4. Then the signal passes through a comparator whose threshold for triggering is Thresh. Vped is set at the chip level, while PMTref4 and Thresh are group specific, and Vofs1 & Vofs2 are channel specific. Shown also in Figure 3.1 are three voltage measurement points denoted as Node A, Node B, and Node C whose use will be detailed in Section 4.2.1.
3.2 TARGET-7 EVALUATION BOARD

The TARGET-7 evaluation board that was utilized consisted of the TARGET-7 chip and a field programmable gate array (FPGA) responsible for controlling the chip and providing additional features. The evaluation board also provided connectivity so that a voltage source, function generator, and computer could be connected. The evaluation board and the connectivity afforded by it are presented in Figure 3.2:

![TARGET-7 evaluation board](image)

Figure 3.2: Annotated photograph of a TARGET-7 evaluation board. In clockwise order from the top left: Power Supply Connection, Connection J6, FPGA, TARGET-7 chip, a grounding point, Ch 7, and the ethernet connection

As can be seen in Figure 3.2, channel 7 is clearly indicated. The connection directly to the left of it is for channel 0, and these were the only channels with connectors on the evaluation board that was used. Channel 7 was used to input signals from the function generator for all of the trigger studies that were conducted because it offered a direct connection, while channel 0 was also connected also to the pre-amp.

4 METHODS & RESULTS

4.1 APPARATUS

The primary apparatus used to take measurements and conduct the investigation consisted of the TARGET-7 evaluation board, a function generator, a power supply, and a computer.

The function generator used was an Agilent 33250A Function/Arbitrary Waveform Generator. It was configured to supply pulses to TARGET with an 8 ns width, 5 ns edge, and a 0 V baseline. Other parameters such as the pulse height and the pulse frequency were varied based upon the specific investigation being conducted and will thus be detailed as necessary.

The power supply used was a BK Precision 1687 Switching Mode DC Regulated Power Supply. Its output was fixed at 5.01 V for all investigations that were conducted.

The computer utilized was running the Mac OS X operating system and was equipped with the Python programming language for data collection and analysis. Measurements were taken using Python scripts on this computer.
Prior to conducting any investigation, the evaluation board was configured. In the configuration process, the power supply is power-cycled and then a Python script is run to initialize the board and set pertinent TARGET-7 parameters. The power supply and computer were connected to the evaluation board in the locations specified in Figure 3.2. All trigger studies were conducted using the TARGET-7 evaluation board SN #06 via channel 7 with CMP_VSS physically grounded and firmware version eva1_T7_0x6_05.mcs.

4.2 Trigger Studies

As discussed in Section 2, the triggering functionality is characterized by the trigger threshold and noise. In turn, the trigger threshold and noise are probed by studying the trigger efficiency $\epsilon$ and its associated uncertainty $\sigma_\epsilon$ as a function of the input pulse amplitude. The trigger efficiency is computed according to Equation 4.1 where $N_{\text{trig}}$ is the number of pulses read out through the FPGA and $N_{\text{input}}$ is the number of pulses given as an input to TARGET-7:

$$\epsilon = \frac{N_{\text{trig}}}{N_{\text{input}}}$$ (4.1)

$N_{\text{trig}}$ is a parameter that is read-out from the FPGA and $N_{\text{input}}$ is simply the product of the elapsed time $t$ and the frequency at which the function generator supplied pulses to TARGET-7. Using Bernoulli statistics, $\sigma_\epsilon$ is given simply by the following Equation 2:

$$\sigma_\epsilon = \sqrt{\frac{\epsilon(1-\epsilon)}{N_{\text{input}}}}$$ (4.2)

By plotting each efficiency as a function of the input pulse amplitude and fitting a function $\epsilon(z)$ of the form presented in Equation 4.3 to the points, an ‘efficiency curve’ can be found.

$$\epsilon(z) = \frac{1}{2} \left[ \frac{2}{\sqrt{\pi}} \int_{0}^{\frac{z-\mu}{\sigma}} e^{-t^2} \, dt + 1 \right]$$ (4.3)

From fitting this function, the triggering threshold voltage $\mu$ and noise $\sigma$ can be determined as the values that yield the best fit to the data using a $\chi^2$ minimization. An example efficiency curve generated from collected data is presented in Figure 4.1.

Figure 4.1: An efficiency curve generated from data. Note that the parameters Thresh and PMTref4 are expressed in hexadecimal form.

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1 the interval of time in which trigger signals were sent

2 In cases where $\epsilon$ evaluates to either 0 or 1 using Equation 4.1 the following approximations are used: $\epsilon = \frac{N_{\text{trig}}+1/3}{N_{\text{input}}+2/3}$ & $\sigma_\epsilon = \sqrt{\frac{\epsilon(1-\epsilon)}{N_{\text{input}}+2}}$. 
With the goal of characterizing the triggering behavior of TARGET-7, several tasks were completed which will be detailed in the following subsections.

4.2.1 Optimization of \(V_{ped}, V_{ofs1}, \text{and } V_{ofs2}\)

As detailed in Section 3.1, there are many free parameters that can have an effect on the triggering behavior of TARGET-7. Scanning through all of these simultaneously, while possible, would be time consuming and the results would be overly complicated. Thus, another method was employed to fix some of these parameters, namely \(V_{ped}, V_{ofs1}, \text{and } V_{ofs2}\), to optimal values for the purposes of scanning the remaining parameters. The methodology employed to optimize the parameters will now be detailed.

First, a \(V_{ped}\) value was selected. In truth, \(V_{ped}\) is not a free parameter because it must be chosen such that it pushes the input signal into the linear region of the ADC transfer function, however within this linear range there is some freedom. From experience with TARGET-7, 900 mV was selected as the initial \(V_{ped}\) value because it satisfies this condition.

Next, a Python script was utilized to tune \(V_{ofs1}\) and \(V_{ofs2}\) such that the channel specific voltages within each group at Node A matched as closely as possible, and the same for the channel specific voltages within each group at Node B (Nodes are as discussed in Section 3.1 and are presented in Figure 3.1). From experience, the value for \(V_{ofs1}\) corresponding to the first channel of a group was set to 1500, and the corresponding \(V_{ofs2}\) was set to 2048. Matching the voltages at Node A and Node B, respectively for each channel within a group ensures that the amplification factor is the same for each channel within a group, and thus that those channels will be equally weighted when entering the summing amplifier. The script performed this optimization over a specified range of \(V_{ped}\) values centered at 900 mV for each of the four channel groups. For each group, the script generated an output text file containing the channel specific values of \(V_{ofs1}, V_{ofs2}, \text{Node A, and Node B,}\) as well as the parameter \(\text{Node C}\) for each step in the specified range of \(V_{ped}\) values.

For the group containing channel 7, which was used for all input signals, the Node B channel voltages as well as the Node C voltage are plotted with respect to \(V_{ped}\). Figure 4.2 is representative of such a plot and was actually used for Group 1.

Figure 4.2: Tuning voltage plot for Group 1 (Ch 4 - 7). Note how tightly all of the Node B voltages fit together, this is a sign that the optimization worked properly. Note also the vertical black line marking the crossing of the Node B voltages with the Node C voltage, at 892 mV in this case (not 900 mV).
As can be seen in Figure 4.2, by the location of the crossing of the Node B voltage with the Node C voltage, the optimized parameters favored 892 mV instead of the 900 mV value for Vped that was initially set. Thus, in this specific case the optimized value for Vped was considered to be 892 mV, and in general the optimized value was considered to be wherever the crossing occurred because at this crossing, signals of either polarity can trigger within the dynamic range of the summing amplifier and the comparator.

The optimized values for Vofs1 and Vofs2 for each channel were found by then going back to the output of the Python script and looking at the pertinent values associated with the optimized value for Vped. After obtaining these, the optimization process is considered complete. Table 4.1 presents the optimized parameters that were found using the above method.

| Ch | 1   | 2   | 3   | 4   | 5   | 6   | 7   | 8   | 9   | 10  | 11  | 12  | 13  | 14  | 15  | 16  |
|----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|
| Vofs1 | 1500 | 1506 | 1506 | 1493 | 1500 | 1503 | 1512 | 1505 | 1500 | 1500 | 1482 | 1500 | 1474 | 1497 |
| Vofs2 | 2048 | 2054 | 2061 | 2093 | 2048 | 2054 | 2066 | 2068 | 2048 | 2063 | 2060 | 2062 | 2048 | 2105 | 2069 | 2085 |
| Vped | 892 mV |

Table 4.1: Table presenting the optimized parameters of Vped, Vofs1, & Vofs2 found according to the method described in Section 4.2.1

4.2.2 TRIGGER THRESHOLD AND NOISE DEPENDENCE ON PMTREF4 AND THRESH

The trigger performance was characterized by scanning through Thresh and PMTref4 space to determine the trigger threshold and noise at a given point in this space. This scan was implemented by using a Python script to vary the pulse amplitude of the function generator and then find the efficiency and its associated uncertainty according to Equations 4.1 & 4.2 at each pulse amplitude for a given point in Thresh and PMTref4 space. From these efficiency measurements, the threshold and noise were found by fitting Equation 4.3 as was discussed in Section 4.2. This process was then repeated for each point within a specified grid composed of Thresh and PMTref4 as the axes, resulting in a threshold and noise value for each point within the grid. Many scans were performed in various regions of Thresh and PMTref4 space, and the most concise and significant result is presented below, preceded by the scan configurations:

Vped: 892 mV
Pulse Amplitude: 6 - 80 mV, increment of 2 mV
Vofs1 & Vofs2: Given in Table 4.1

Thresh: 800 to 1150, increment of 25
PMTref4: 1775 to 1975, increment of 8

8
As can be seen in the plots presented in Figure 4.3, the minimum observed trigger threshold was around 40 mV, and the minimum observed trigger noise was roughly 12 mV. However, the trigger noise associated with the values of PMTref4 and Thresh that yielded the lowest trigger thresholds is roughly 15 mV. Thus in terms of both of the characterization parameters, TARGET-7 does not seem to perform to the specifications required by CTA.

4.3 HIGH TRIGGER THRESHOLD & NOISE INVESTIGATION

A possible cause for the high trigger threshold and noise would be an undesired interaction between the sampling and triggering functions of TARGET-7 given their physical proximity as outlined in Figure 3.1 (they are on the same substrate). This possibility was investigated by using two different configurations that removed sampling, and conducting similar scans in PMTref4 and Thresh space. The configurations and results are presented in the following subsection:

4.3.1 TRIGGER THRESHOLD AND NOISE DEPENDENCE ON PMTref4 AND Thresh WITH ALTERNATE CONFIGURATIONS

Sampling on TARGET-7 is driven by an external clock on the FPGA. Thus the first alternate configuration to be tested, which will be referred to as Sampling Off, was where the sampling clock on the FPGA was disabled. After configuring the evaluation board as discussed in Section 4.1 with the exception of disabling the sampling clock on the FPGA, an optimization of Vped, Vofs1, & Vofs2 was carried out according to the methodology described in Section 4.2.1. The resulting optimized parameters are presented in Table 4.2.
Table 4.2: Table presenting the optimized parameters of $V_{ped}$, $V_{ofs1}$, & $V_{ofs2}$ found according to the method described in Section 4.2.1 for the Sampling Off configuration. As expected, the values are nearly identical to those in Table 4.1.

Having configured the evaluation board to be in Sampling Off mode and optimized the parameters as discussed above, a scan was conducted similar to that presented in Section 4.2.2. The particular configurations and results are presented below:

- **$V_{ped}$**: 891 mV
- **Pulse Amplitude**: 6 - 80 mV, increment of 2 mV
- **Thresh**: 800 to 1150, increment of 25
- **PMTref4**: 1775 to 1975, increment of 8
- **$V_{ofs1}$ & $V_{ofs2}$**: Given in Table 4.2

![Plot of trigger threshold](image1)

![Plot of trigger noise](image2)

(a) Plot of trigger threshold on a color scale as a function of Thresh and PMTref4.

(b) Plot of trigger noise on a color scale as a function of Thresh and PMTref4.

Figure 4.4: Plots of trigger threshold (Fig. 4.4a) and trigger noise (Fig. 4.4b) resulting from scans with the evaluation board configured in Sampling Off mode.

As can be observed in the plots presented in Figure 4.4, the triggering threshold and noise are lower in the Sampling Off configuration. The minimum observed trigger threshold was roughly 16 mV with a noise of roughly 2 mV. These results suggest a possible connection between the sampling and triggering functions of TARGET-7. In order to investigate this connection, another configuration was utilized where the sampling clock on the FPGA was left on but the timing parameters of TARGET-7 were purposely misconfigured to disable sampling. This configuration
will be referred to as Sampling Disabled. After configuring the evaluation board to introduce this state, an optimization of $V_{ped}$, $V_{ofs1}$, & $V_{ofs2}$ was carried out according to the methodology described in Section 4.2.1. The resulting optimized parameters are presented in Table 4.3.

| Ch | 1  | 2  | 3  | 4  | 5  | 6  | 7  | 8  | 9  | 10 | 11 | 12 | 13 | 14 | 15 | 16 |
|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|
| $V_{ofs1}$ | 1500 | 1505 | 1506 | 1492 | 1500 | 1504 | 1512 | 1505 | 1500 | 1500 | 1500 | 1482 | 1500 | 1500 | 1474 | 1496 |
| $V_{ofs2}$ | 2048 | 2048 | 2054 | 2087 | 2048 | 2057 | 2066 | 2067 | 2048 | 2063 | 2059 | 2062 | 2048 | 2107 | 2072 | 2088 |
| $V_{ped}$ | 891 mV |

Table 4.3: Table presenting the optimized parameters of $V_{ped}$, $V_{ofs1}$, & $V_{ofs2}$ found according to the method described in Section 4.2.1 for the Sampling Disabled configuration.

Using the optimized parameters as presented in Table 4.3 with the Sampling Disabled evaluation board configuration a scan in PMTref4 and Thresh space was conducted. The results are presented as follows, preceded by the specific configurations of the scan:

$V_{ped}$: 891 mV
Pulse Amplitude: 6 - 80 mV, increment of 2 mV
$V_{ofs1}$ & $V_{ofs2}$: Given in Table 4.3
Thresh: 800 to 1150, increment of 25
PMTref4: 1775 to 1975, increment of 8

![Plot of trigger threshold on a color scale as a function of Thresh and PMTref4.](image)

(a) Plot of trigger threshold on a color scale as a function of Thresh and PMTref4.

![Plot of trigger noise on a color scale as a function of Thresh and PMTref4.](image)

(b) Plot of trigger noise on a color scale as a function of Thresh and PMTref4.

Figure 4.5: Plots of trigger threshold (Fig. 4.5a) and trigger noise (Fig. 4.5b) resulting from scans with the evaluation board configured in Sampling Disabled mode.

From the plots presented in Figure 4.5, it can be observed that the minimum observed trigger threshold was on the order of 11 mV with a minimum trigger noise of around 1 to 2 mV. This result again suggests a connection between
the sampling and triggering functions of TARGET-7 because the trigger threshold and noise both decrease when the sampling is disabled, whether it be by turning off the sampling clock (Sampling Off) or disabling sampling on the ASIC itself (Sampling Disabled). This connection was investigated further, and the methods and results of this investigation are presented in the following subsection.

4.3.2 Trigger Threshold and Noise Dependence on Sampling Clock Phase

The relation between the triggering and sampling of TARGET-7 was further investigated by scanning through the phases of the sampling clock to determine the trigger threshold and noise as a function of sampling clock phase. Connection J6 on the evaluation board (as presented in Figure 3.2) outputs a signal at 119.1 Hz that is synchronized with the sampling clock on the FPGA. This signal was connected to the function generator so that pulses could be sent to TARGET-7 that were synchronized with the sampling clock. By varying the delay after receiving the synchronization signal before sending a pulse, the phases of the sampling clock could effectively be probed. It was desired to see two full periods of the sampling clock phase, and thus integer delays from 0 to 127 ns were utilized. The scan was performed using a Python script to find the efficiency and its associated uncertainty according to Equations 4.1 & 4.2 at each specified pulse amplitude for a given trigger delay. From the efficiency measurements, the threshold and noise were found by fitting the function presented in Equation 4.3 to the data as was discussed in Section 4.2. This process was then repeated for all of the trigger delays corresponding to the sampling clock phases over two periods. Scans were performed over the specified interval of trigger delays for the Sampling On and Sampling Disabled evaluation board settings. The Sampling Off evaluation board setting could not be tested because the sampling clock was off. The results from the scans will be presented, preceded by the scan configurations in the following bullet points:

- **Sampling On**:
  
  - Vped: 892 mV
  - Pulse Amplitude: 2 - 100 mV, increment of 2 mV
  - Vofs1 & Vofs2: Given in Table 4.1
  - Thresh: 800
  - PMTref4: 1875
  - Trigger Delay: 0 - 127 ns, increment of 1 ns
  - Trigger Threshold: 50.79 mV
  - Trigger Noise: 16.20 mV

  (a) Plot of trigger threshold with respect to sampling clock phase.
  (b) Plot of trigger noise with respect to sampling clock phase.

  Figure 4.6: Plots of trigger threshold (Fig. 4.6a) and trigger noise (Fig. 4.6b) resulting from scans with the evaluation board configured in Sampling On mode.

- **Sampling Disabled**:
  
  - Vped: 891 mV
  - Pulse Amplitude: 10 - 100 mV, increment of 2 mV
  - Vofs1 & Vofs2: Given in Table 4.3
  - Thresh: 850
  - PMTref4: 1871
  - Trigger Delay: 0 - 127 ns, increment of 1 ns
  - Trigger Threshold: 50.13 mV
  - Trigger Noise: 2.42 mV

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3 the sampling clock period is 64 ns
Examining Figure 4.6a, it is observed that in the Sampling On configuration the trigger threshold varies periodically by approximately 60 mV, while the Sampling Disabled configuration shows variations that are relatively small. These results are conclusive in their indication of a coupling between sampling and triggering in TARGET-7. Specifically, it can be noted from Figure 4.6b, that the trigger noise at any given phase of the sampling clock tends to be under 4 mV, however the large variation of trigger threshold based on the sampling clock phase causes the trigger noise in the normal configuration to be larger, on the order of 15 mV as observed.

5 DISCUSSION

In a ground based gamma ray observatory that makes use of IACTs such as CTA, the FEE are responsible for sampling and digitizing the data as well as sending trigger signals if necessary. TARGET-7 is a proposed FEE solution that has been specifically designed for some CTA telescope prototypes and this paper has presented the methods and results of studies that were conducted into characterizing the trigger response of TARGET-7 during the summer of 2014 at the SLAC National Accelerator Laboratory. Triggering was characterized by the trigger threshold and noise, which in the case of TARGET-7, CTA requires to be sensitive to as low as 10 mV and 1 to 2 mV, respectively. Under normal operating conditions, the lowest trigger threshold observed in the laboratory for TARGET-7 was on the order of 40 mV with a noise of 15 mV.

Investigation was conducted into the high trigger threshold and noise by trying two different configurations of TARGET-7 and the evaluation board. First, the sampling clock on the FPGA was disabled. Next, the sampling clock was left on, but the timing parameters of TARGET-7 were configured such that sampling was disabled. Table 5.1 shows the minimum observed threshold and noise for these configurations as well as the original one with sampling on.

<table>
<thead>
<tr>
<th>Mode</th>
<th>Minimum Threshold (mV)</th>
<th>Minimum Noise (mV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sampling On</td>
<td>40</td>
<td>15</td>
</tr>
<tr>
<td>Sampling Off</td>
<td>16</td>
<td>2</td>
</tr>
<tr>
<td>Sampling Disabled</td>
<td>11</td>
<td>1 − 2</td>
</tr>
</tbody>
</table>

Table 5.1: Table of the approximate minimum threshold and noise values that were observed for the three evaluation board configurations that were investigated.

The results presented in Table 5.1 clearly indicate that both metrics for characterizing the trigger response of TARGET-7 improved and approached the CTA requirements when the sampling function was removed. This result suggests some correlation between the triggering and sampling functions of TARGET-7. In order to investigate this correlation, the trigger threshold and noise were observed as a function of the phase of the sampling clock while...
TARGET-7 was operating under a standard configuration as well as when the sampling was disabled on the chip. Under normal operating conditions, the trigger threshold was found to vary periodically by as much as 60 mV, while there was negligible variation when the sampling was disabled. This result confirms the earlier assumption of a correlation between triggering and sampling in TARGET-7, namely that the trigger threshold depends heavily on the phase of the sampling clock. The large trigger noise is most likely due to the large variation in the trigger threshold as a function of sampling clock phase.

From the observations that were performed, a coupling between the triggering and sampling functions of TARGET-7 was found such that trigger threshold and noise are both unacceptably high for CTA while both functions are enabled. This likely results from the fact the sampling circuit and the triggering circuit both reside on the same substrate. Due to the fact that TARGET-7 must perform the sampling and triggering functions for it to be a viable FEE solution, TARGET-7 as is, will not be suitable for an application on a CTA telescope.

In order to preserve the established time line, TARGET-7 will be delivered for testing with a US CTA telescope prototype, but an upgrade and replacement is planned. Given that the cause of high trigger threshold and noise has been determined to be the coupling between triggering and sampling, the functions will be separated into two different ASICs. Though further testing will need to be conducted once the new ASICs are manufactured to characterize the trigger response, the trigger threshold and noise should in principle be able to be as low as the best results presented in Table 5.1 if the same components are used because the coupling between triggering and sampling will be removed.

6 ACKNOWLEDGMENTS

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REFERENCES


