SCOTT: A time and amplitude digitizer ASIC for PMT signal processing

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Abstract

SCOTT is an ASIC designed for the readout electronics of photomultiplier tubes developed for KM3NeT, the cubic-kilometer scale neutrino telescope in Mediterranean Sea. To digitize the PMT signals, the multi-time-over-threshold technique is used with up to 16 adjustable thresholds. Digital outputs of discriminators feed a circular sampling memory and a "first in first out" digital memory. A specific study has shown that five specifically chosen thresholds are suited to reach the required timing accuracy. A dedicated method based on the duration of the signal over a given threshold allows an equivalent timing precision at any charge. To verify that the KM3NeT requirements are fullfilled, this method is applied on PMT signals digitized by SCOTT.

Keywords: Neutrino detection, KM3NeT, PMT, PMT signal processing, Time-over-threshold, ASIC

1. Introduction

The KM3NeT consortium [?] is currently preparing for the construction of a cubic-kilometer scale neutrino telescope in the Mediterranean Sea. The charge current interaction of a muon neutrino produces a muon. The Cerenkov light emitted by the muon while crossing the telescope is detected by a 3-dimensional array of photomultiplier tubes (PMTs). The time and charge of the PMT signals allow the direction and energy reconstruction of the muon track.

To achieve the required muon angular resolution of 0.1°, it was shown that the PMT pulse from a single photon must be measured with a timing precision better than 2 ns RMS [?] and a charge estimate in the dynamic range up to 100 photoelectrons (pe) [? ?].

An custom analogue-to-digital data processing ASIC was developed based on the time over threshold (TOT) technique to read out the PMT signals. This ASIC, named SCOTT, has to address the high counting rate environmental background signals [?] while keeping good performance on the single photoelectron pulse. A specific method, based on the time over threshold, has been developed to retrieve the pulse time and charge from the ASIC output data. The method has been implemented and fully tested.

The principle of data processing of the SCOTT ASIC with its technical details and performances are described in the following section. Then the algorithm development and data analysis for PMT signal processing are presented. The performances of the ASIC reading a PMT are presented in the last section.

2. The SCOTT ASIC

2.1. Original data processing

The SCOTT ASIC original concept of data processing uses a double sampling strategy. The analogue PMT signal is input in parallel to several channels, sampled first in amplitude in a discriminator and then in time in a digital memory (Fig. ??). The output is a digital waveform of which the amplitude accuracy depends on the number of used channels while the time accuracy is a function of the frequency of the sampling clock.

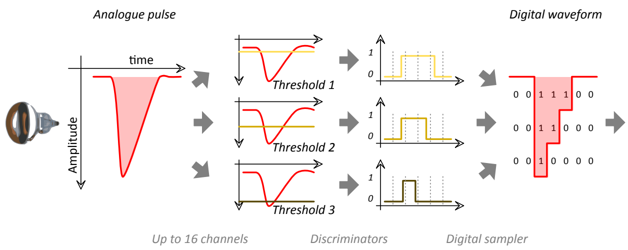

Figure 1: Principle of SCOTT ASIC data processing. The analogue signal is sampled first in amplitude then in time.

2.2. ASIC architecture

The SCOTT ASIC is built in AMS BiCmos 0.35 μm process technology. It is a data driven multi-channel circuit including sixteen channels with independent inputs (Fig. ??). Each channel is divided in 3 sub-circuits: one asynchronous stage and two synchronous systems.

The first sub-circuit is an analogue comparator composed of a switch network, a differential discriminator and a 10-bit

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digital to analogue converter (DAC). The switch network is optionally used to route one analogue input signal up to eight discriminators inside the ASIC. The DACs are differential with a resistor string architecture [?] to guarantee their monotonicity. They can be individually programmed through a slow control interface compatible with the serial to parallel (SPI) protocol. Any of the sixteen channels, or a combination of them, can be used as a trigger condition.

In the second sub-circuit, the digital outputs of discriminators are sent to a 32 cell circular digital memory. The sampling frequency is controlled by a delay locked loop (DLL) which produces an equal delay between the 32 clock commands. With a nominal input clock frequency at 50 MHz, the time interval between delayed clock is 20 ns/16 = 1.25 ns. The circular memory is divided into two subsets working alternatively with one subset in writing phase while the second subset is connected to a "first in first out" (FIFO) digital memory. The subsets are divided into 16 cells, or "time slices" of 20 ns. If at least one cell of data matches the trigger condition, all 16 time slices are stored. After one clock cycle, the subsets are inverted and the newly written cells are connected to the FIFO whereas the 16 cells already read out switch to the writing phase. In order to synchronize the data for post-processing reconstruction, a 16-bit time stamp provided by an internal clock counter is added to each time slice.

The FIFO, the third sub-circuit, has a depth of 32 time slices corresponding to a maximum of 640 ns continuous waveform with the nominal clock frequency. It has a double port architecture with a readout clock optionally different from the sampling clock. Data loss can occur due to the limited size of the FIFO and to the Poisson distributed arrival time of the photons. The depth of 32 time slices was chosen to reduce the data loss to approximately 1% for Poisson distributed input rate with a 1 MHz average using three thresholds leveled at the signal amplitude produced by a single photon. During the readout of the FIFO, a zero suppression process is applied. It consists in sending exclusively the channels which have a recorded signal.

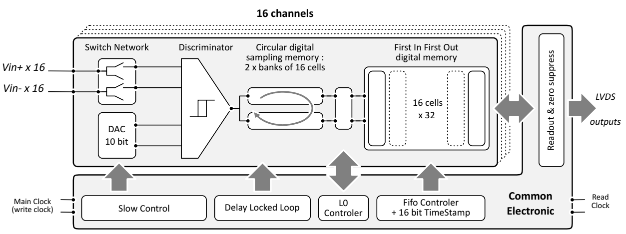

Figure 2: Top schematic of the SCOTT ASIC.

2.3. ASIC performances

The ASIC has been tested in laboratory with a HP 8111A pattern generator and a 10-in PMT. The performance of the SCOTT ASIC is detailed in [?]. The main parameters are summarized in table **??**. The expected performances are achieved for most of the measurements. Only, the measured discriminator offset is higher than expected (1 mV RMS). In practice, it can be easily compensated by calibration.

Table 1: Main SCOTT ASIC measured parameters.

Circuit	Parameter	Measure	
Discriminator	Bandwidth[a]	180	MHz
	Noise	<0.7	mV RMS
	Offset	<4.9	mV RMS
	Dynamic Range[b]	3	V
DAC	INL	<0.5	LSB
	DNL	<0.5	LSB
	LSB	2.85	mV
ASIC	Timing resolution	800	ps RMS
	Power	250	mW

[a] Worst case scenario using the internal switch network

[b] Differential

The ASIC SCOTT digitizes PMT signals via amplitude and time sampling. In the case of the 10-in. PMT option [?], the main parameters required for the muon track reconstruction are the pulse time and the pulse charge. In the following section, using a set of PMT pulses digitized with an oscilloscope, two algorithms developed to retrieve the pulse time and charge are described. One is based on a parametric function to fit the pulse shape. It is used to determine the level and number of thresholds necessary to meet the KM3NeT requirements. The second is a simpler estimation based on relation to the duration over the thresholds.

3. Time & Charge reconstruction and determination of the thresholds

A set of 10000 pulses were sampled with a 2.5 GHz oscilloscope. An ANTARES optical module [?], housing a Hamamatsu R7081-20 10-in. PMT was placed in a black box and illuminated with a LED. The one photoelectron amplitude was measured with the PMT dark noise at 40 mV with a charge of 8 pC corresponding to a gain of 5×10^7. With the variable LED power, pulses with amplitude from 40 mV to 3 V were recorded.

3.1. Pulse shape parametrization

The fast rising and slower descending slopes of the PMT pulse shape can be parametrized by the following function:

$$a(t) = \hat{A}\ (\frac{t-\hat{t}}{t_R}+1)^{\alpha}\ e^{-\frac{t-\hat{t}}{t_R}\alpha} \times H(\hat{t}-t_R) \quad (1)$$

where H is the Heaviside function and t_R is a defined rise time. The maximum amplitude $\hat{A}$ is reached at $t = \hat{t}$. An example of a pulse fitted with Eq. **??** is presented in Fig. **??**.

This parametrization is used to determine the minimum number and level of thresholds necessary to retrieve the pulse function . The pulse time is chosen to be the peak time ($\hat{t}$) and the charge is the integral of the function over 50 ns. The pulse time

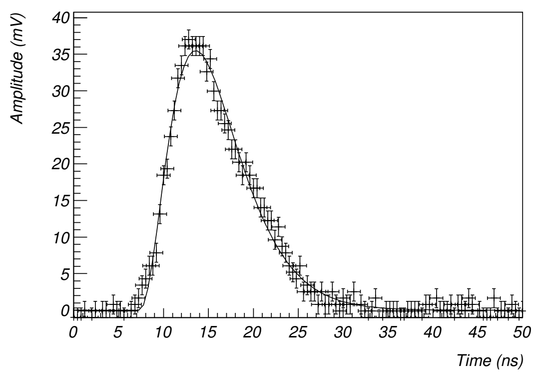

Figure 3: Example of a 10" PMT pulse fitted with the Eq. ??.

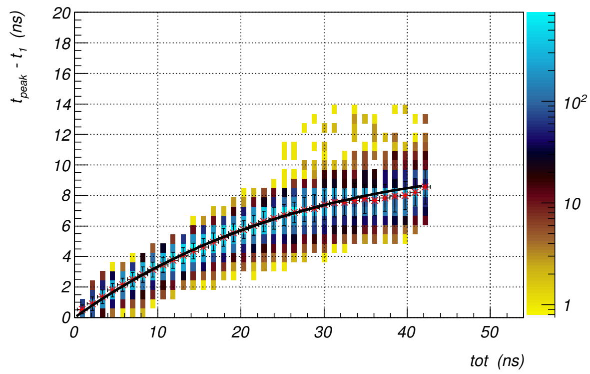

Figure 4: Distribution of the $t^{\text{tru}}_{\text{peak}} - t_1$ as a function of the TOT for many thresholds placed between 10 mV and 3 V. Red points are the mean values for each slice of TOT, the back line is a fit using Eq. ??

and charge from the set of pulses sampled at 2.5 GHz fitted with the Eq. ?? are taken as reference. The SCOTT concept of operation, as described in Section ??, is then applied to the same set of pulses, reducing the number of points to the crossing times at the given amplitude of each chosen threshold. These pulses are fitted again with Eq. ?? and the resulting time and charge compared to the reference ones. The number and level of thresholds are varied searching for the minimum number level optimized thresholds to fullfill the KM3NeT requirements.
Five thresholds with amplitudes given in Table ?? allow a precision in the determination of the pulse time better than 1 ns up to 50 pe, and a error less than 20% for the charge up to 60 pe.

Table 2: Amplitude of the 5 thresholds needed to reconstruct the PMT pulse's charge and time for the KM3NeT requirements.

threshold value(pe)	1/3	2/3	1	3	8

3.2. Time and charge determination with time over threshold

A faster implementation of time and charge determination is investigated based on the time-over-threshold (TOT).

The TOT is defined by the time difference between the pulse crossing times t_1 and t_2 at a given threshold amplitude a_n. Fig. ?? shows the correlation between the TOT of numerous thresholds placed between 10 mV (1/3 pe) to 3 V (75 pe) and the rise time respect to the threshold: $\hat{t} - t_1$. The relation, derived from Eq.?? with $a(t_1) = a(t_2)$ is:

$$\hat{t} - t_1 = (t_2 - t_0) \times \frac{1}{X} \left(1 - (1 + X)\, e^{-X}\right) \qquad (2)$$

where $X = t_R\, \Delta t$ and $\Delta t = t_2 - t_1$. The TOT estimated peak time ($t^{\text{rec}}_{\text{peak}}$) is compared to the reference one ($t^{\text{tru}}_{\text{peak}}$). The RMS resolution using all the 5 thresholds in Table ?? is 0.7 ns. A better estimate is found using only the highest crossed threshold bringing the time resolution at the order of 0.5 ns in the range up to 50 ns as shown Fig ??. With this method, the time is obtained without the need of the charge and in addition, the peak time is not sensitive to the walk effect, time shift relative to the charge when the time is measured directly at the crossing threshold.

The charge, defined by the integral of the PMT pulse, is estimated using sums of the rectangle area under the thresholds: $\Delta t_i \times (a_i - a_{i-1})$ and above the thresholds: $\Delta t_i \times (a_{i+1} - a_i)$. As the thresholds are not spaced by the same amplitude interval, a combination of sums of the two areas is used: $c_Q \times (Q_+ + Q_-)$, where Q_+ (Q_-) is the sum of areas above the thresholds (respectively, under the thresholds) and c_Q depends on the highest crossed threshold. At higher pulse amplitudes, when the highest defined threshold is crossed and its TOT is larger than 10 ns, the factor c_Q becomes linearly dependant on the TOT [?]. The pulse charges estimated using this TOT method (Q_{rec}) are compared to the reference ones (Q_{tru}). The error on the charge is $< 15\%$ up to 40 pe degrading $< 20\%$ in the range 40-60 pe, as shown Fig. ??.

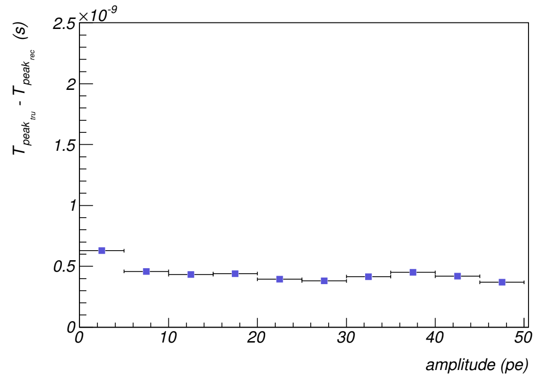

Figure 5: Contribution of the TOT method to the time resolution (RMS per bin of 5 pe), as a function of the amplitudes of the pulses.

4. Application of TOT method on SCOTT data

The two methods of pulse time and charge estimation described previously and the number and level of thresholds defined in Table ?? are applied to data taken with the SCOTT

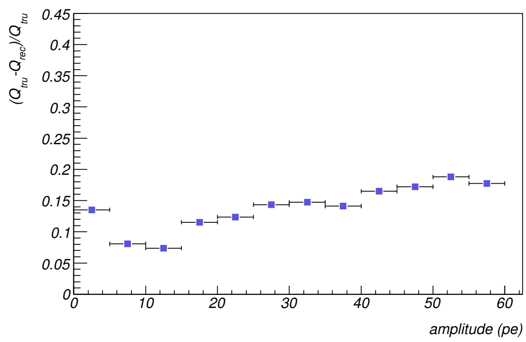

Figure 6: Contribution of the TOT method to the charge estimation: reduced error on the TOT reconstructed charge (RMS per bin of 5 pe), as a function of the amplitudes of the pulses.

ASIC reading a PMT. Data taking and results are presented hereafter.

An ANTARES 10-in. PMT is placed in a black box and illuminated with a LED. Pulses with amplitudes of 1 pe and 11 pe were processed with SCOTT. Five channels were used, set to the thresholds of Table **??**. Fig. **??** shows an example of a SCOTT output. An additional channel was used for the LED trigger, necessary for coincidences. Data taken with the same set up, were recorded with the oscilloscope for reference. The PMT gain is set to 3×10^7 producing a one photoelectron pulse at a 53 mV amplitude and 5 pC charge.

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0001111111111110000
0000111111111000000
0000011111110000000
0000001111000000000
00000001
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Figure 7: Example of the SCOTT ASIC output during the data taking of pulse at 11 pe. Each line corresponds to a threshold among the five defined ones, each 0 or 1 corresponds to 1.25 ns sampling.

The two methods presented in Section **??** are complementary. The fit of Eq. **??** is applied on a set of "training" pulses, which allows the parameters necessary for the TOT method to be determined. For the time determination, t_R is the only parameter needed for any thresholds, to be applied in Eq. **??**. For the charge, five values of c_Q, each corresponding to a threshold setting, plus one for the highest amplitude function of the TOT, have to be assessed. Results are presented in Table **??**.

Table 3: Mean and RMS (in brackets) of the charge distributions and RMS time resolutions for the pulses recorded with the oscilloscope, with the SCOTT ASIC using the function in equation **??** and the TOT method.

Measure	Method	1 pe	11 pe
Charge	Scope (Ref.)	5.3 (1.9)	66 (21)
[pC]	SCOTT Eq. **??**	5.1 (1.9)	70 (22)
	SCOTT TOT	5.2 (2.1)	63 (20)
Time	SCOTT Eq. **??**	1.9 ns	0.9 ns
[ns]	SCOTT TOT	1.9 ns	0.9 ns

5. Conclusion

A new analogue-to-signal converter ASIC has been designed for PMT readout based on the multi-time-over-threshold technique. It combines the features of an ADC with a TDC together with specific functionalities [**?**].

The flexible ASIC architecture is suited for multiple 3-in. or for single 10-in. PMTs. With a 10-in. PMT, it was shown that five thresholds placed between 0.3 pe and 8 pe are optimized for the KM3NeT requirements. The time-over-threshold information from the ASIC can be used to determine the pulse's charge and time. The contribution of the reconstruction to the charge resolution (20%) is below the PMT intrinsic charge resolution for any application (40% [**?**]). The peak time is derived from the last crossed threshold allowing a constant 0.5 ns resolution for charges up to 50 pe. With the 1.3 ns 10-in. PMT TTS [**?**] and the intrinsic ASIC time resolution (Table **??**), the overall timing resolution is found to be 1.9 ns at 1 pe.

The SCOTT ASIC, with it versatile data processing is suitable for any application requiring time precision, derandomization and non-linear amplitude discrimination.

Acknowledgement

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