Comments on CAEN Application Note AN2502
C. J. Martoff, for Ph. 4796
July, 2017

These are notes meant to fill in the blanks and flesh out the partial explanations given in CAEN Application Note AN2502, SiPM Characterization.

The CAEN system this note describes is a very high-tech item with complex internal functions and a lot of engineering behind it. In half an hour or so, a technician could be taught to "just use it" to make repetitive measurements (for example, for quality control in an SiPM foundry). However, as physicists we need to understand at least the signal processing and overall performance characteristics of the system in some depth, without delving into the actual electronic design of the components. This is a bit of a tall order, due to the aforementioned complexity of the CAEN system. There's a lot of stuff to understand. A big part of gaining such "understanding" is to learn some of the jargon used by electronic engineers to describe these systems. I hope the following notes will accomplish this.

1. SiPM Fill Factor and PDE

The two Hamamatsu devices both cover silicon wafers 1 x 1 mm in size. The 25c divides the square mm into an array of 40 x 40 = 1600 sensitive "cells" (individual light detectors called "avalanche photodiodes") while the 100C has only 10 x 10 = 100 cells. To allow each cell to be electrically and functionally independent, there must be a certain border area or space between cells which is insensitive to light. The term "fill factor" refers to the fraction of the 1 x 1 mm area which is actually covered by sensitive photodiode rather than border space. The manufacturing process and physical characteristics of silicon require that the border areas be about a micron or two wide. So the active cells of the 25C are about 23 or 24 microns wide, separated from their neighbors by a micron or two of dead (insensitive) space. Taking 23 microns for an example, this gives a "fill factor" of about 23x23/25x25 = 84% for the 25C vs. 98x98/100x100 = 94% for the 100C. (Karla- see if Hamamatsu tells you the actual numbers to put in here.) So the 25C has less sensitive area and hence a lower PDE.

2. SiPM Dynamic Range

Understanding the dynamic range difference is a bit more subtle. Each cell of the SiPM is an avalanche photodiode. These devices just give a saturated signal of fixed height when they absorb any number of photons. You can't tell if a cell was hit by one photon or ten photons, it just gives the same pulse if it was hit at all. The way the SiPM is able to "count photons" is actually by counting hit cells.

Now, the term "dynamic range" refers to the range of input signals for which a system gives an output linearly proportional to the input. If the input exceeds the dynamic range, the output no longer tracks the input. The output is said to be "saturated". In this case, the input signal dynamic range is the range of numbers of photons arriving in a flash of light over which a linear increase in the output signal occurs as the number of photons in the flash increases.

For the 25C, we will start missing output pulse height due to multiple photons hitting a single cell when the input signal contains some substantial fraction of 1600 photons/mm^2

(one per cell). The 100C starts missing output signal due to multiple hits per cell already for signals of some fraction of 100 photons/mm^2. So the 25C has a higher dynamic range.

3. System Gains

There are at least three different "gains" in this system.

The physics of the avalanche process in each avalanche photodiode cell produces a macroscopic pulse of electrical charge from a single photoelectron. The ratio between the output pulse charge and the charge of one electron I will call G_{SiPM}. This gain is of the order of 10^6 according to the Hamamatsu data sheets.

The PSAU takes this charge pulse and uses transistors to amplify it further. This gain I will call G_{PSAU} and it is the subject of Fig. 2. Just to confuse you, G_{PSAU} is measured not as a charge ratio (a pure number) but in "dB", which is just 20 times the $\log_{10}$ the charge amplification ratio. So a gain of 40 dB means a charge amplification factor of 100.

Finally there is the "ADC channel conversion factor" discussed on page 3 with Equation [1]. This will be discussed below.

Like the SiPM, any amplifier also has a finite dynamic range. Often the dynamic range of an amplifier can be understood based on the maximum output signal size the thing can put out. For example, an op-amp amplifier cannot put out signals larger than the power supply voltage. So the dynamic range is limited to the range of input signals that produce output signals smaller than this.

To measure any gain, we must have a way to apply input signals of known size, and measure the resulting output. If we don't need the absolute value of the gain, but only want to know the dynamic range of the amplifier at its output, we can use input signals of unknown but constant size and measure while increasing the gain until saturation sets in. Or we can look at the output signals at constant gain, while increasing the input level by known factors.

From Fig. 2, the onset of saturation in the PSAU is softer, causing the curves to acquire a negative second derivative (departure from linearity in the form of a downward concavity)as the gain and the output signal size become larger. To my eyeball, the 40 dB curve is the lowest gain to show appreciable saturation, turning downward around .04 pC output charge. The behavior at higher gains is a bit strange, with nonlinearity appearing already at .03 pC for 44 dB and becoming more severe above .08 pC. This behavior is mainly due to the complicated effect that output signal height saturation has on the integrated charge in a pulse.

4. The digitizer and Firmware integration

To really specify what the device does, the name used by CAEN for their "Digitizer' should really be 'Waveform Digitizer". A waveform digitizer is a fairly complex device that produces a digital record (a list of numbers) representing the shape and size of an input waveform vs. time. To do this requires the following internal operations:

- Accept an analog signal (continuously variable voltage vs. time signal) from the SP5600 and send this signal to ground through a resistance R_{in}.
- Generate an internal "clock" signal (a train of pulses repeating at a precise time separation, in this case 4 ns, for 250 million samples per second [MSPS]) to use as the time base for the waveform digitization. The rate of this signal is called the "sampling

rate" of the waveform digitizer, often [incorrectly] specified in Hz. The DT5720A has a sampling rate of 250 MSPS (Mega Samples Per Second) or 250 MHz. The time between clock pulses is often referred to as the "time bin".

- At each "tick" of the clock, sample the input waveform voltage and convert its amplitude into a binary number ("digitize it") with a fixed number of binary bits. The number of bits is called the "depth" or often [incorrectly] the "digitizer resolution". The 12-bit depth of the CAEN system is the most common today. Very fast (clock rates >1 GSPS) or very cheap digitizers may be limited to 8 bits, and some high precision devices have 14 or 16 bits.
- Record the resulting binary number in time order by transferring it into a digital memory.
- Be ready for the next clock tick to repeat the sampling and digitization, storing the next digital value in the next memory location.

Present-day digital oscilloscopes are waveform digitizers with a display.

5. ADC Channel Conversion Factor ("conversion gain")

First thing to note: there is a big fat problem with Equation [1] as written. The LHS says ADC Channel/Coulomb, but the RHS contains a factor (V/R)Δt, which has units of Coulombs. The "Coulombs" appears in the denominator on the LHS but in the numerator on the RHS, which cannot be right.

In the text after this equation, conversion gains are quoted in units fC/ADC (fC = femtoCoulomb = 10^{-15} Coulomb $\sim$ 6,500 electrons). Of course this is really the **inverse** of the gain, since it expresses input/output rather than output/input. But this inverse nomenclature is unfortunately customary for digitizers. Equation [1] RHS does give "gains" with these units.

Bottom line: LHS of Equation [1] should be written as Coulomb/ADC channel, not ADC channel/Coulomb.

Now, what **is** this "conversion gain"? The "gain" associated with a digitizer is not a pure number (a ratio) like it is for a voltage amplifier. This gain tells the relationship between the output digitized number and something characterizing the input signal size. The output digitized number is often referred to as the "ADC channel" because these numbers are sometimes displayed as a probability distribution histogram in which these numbers are the x- (or "channel")-axis value.

Most engineers and most data sheets would characterize the input signal as a voltage. That's what the ADC actually measures and converts. So the gain would have units of output/input = (ADC channels)/Volt. But for reasons best known to them, the CAEN engineers instead characterize the input signal in terms of **charge**. The charge represented by one single output of the ADC is just the input current times the digitization period (the "time bin", = 4 ns here). Obviously current * time = charge, so it does make sense to represent the input signal in this way.

The input current is $\mathbf{I} = \mathbf{V}/\mathbf{R}_{IN}$ where **V** is the voltage amplitude of the signal developed at the ADC input when the avalanche current **I** from the SiPM is sent to ground[1] through

[1]It should be noted that if there were any other resistors **R'** to ground between the SiPM cathode and

the input impedance of the digitizer $\mathbf{R}_{IN} = 50\Omega$ (you should know what input impedance is from Ph. 4301).

Not only that, but as noted above the CAEN engineers actually quote the inverse of the conversion gain. Therefore the CAEN engineers' quote digitizer gain in units Coulomb/ADC channel rather than ADC channel/Volt.

The physical quantity of interest in a pulse from an SiPM is the total charge in the pulse, not the charge in a single time bin. The digitizer includes software to compute the total charge in an input pulse by just adding together the charges represented by all the time bins within the pulse.

Now we can rearrange Equation [1] and understand it as a product of three factors:

1. The range of charges the digitizer can see within its input dynamic range. This is $\mathbf{I}_{max}*\Delta t = \mathbf{V}_{pp}/\mathbf{R}_{IN}*\Delta t$. $\mathbf{V}_{pp}$ comes in because the digitizer is set up to accept signals of $\pm$ 1 V for an input dynamic range $\mathbf{V}_{pp} = 2$ V.

2. (One over) the total number of ADC channels that can be output by a digitizer with depth Nbits (= 12 in this case). This is just the number of distinct digital number outputs, which are numbers ranging from Nbits of zeroes to Nbits of 1's. Some thought reveals that this number is 2^{Nbits}.

3. A factor of $1/\mathbf{G}_{PSAU}$. This is needed to make the conversion gain refer to charge **from the SiPM itself**. If the PSAU amplifies the SiPM current by a factor before the digitizer sees it, we need to divide out this factor to get a gain that refers to the actual SiPM charge rather than the amplified charge. To partly compensate for the different SIPM avalanche gains of the 25C vs. 100C SiPM devices, the CAEN engineers choose to quote the digitizer gain using different user-selected G_{PSAU} values for the two different SiPM detectors. The instructor does not approve of this either but you need to understand it to understand this equation.

The product of these factors (charge range)/(G_{PSAU} * ADC channels) gives the CAEN engineers' version of the conversion gain in fC/ADC channel.

Note that Equation [1] assumes that the digitizer responds completely linearly throughout its entire dynamic range. This assumption could be checked with a precision pulser.

6. SiPM avalanche Gains $\mathbf{G}_{SiPM}$

In the next paragraph, without any introduction, the application note launches into a discussion of the SiPM avalanche gains and how to measure them. This discussion glosses over several important points. We calculated above the digitizer gain for a single time bin. However, Figures 6 and 7 don't show data for single time bins, but rather the integrated charge (sum of individual time bin charges) within the user-determined pulse widths ("gates") of 160(88)ns respectively. The data are shown as frequency histograms of these

---

the digitizer input, the actual SiPM charge vs. time would have to be scaled to account for the current division between these other resistors and the digitizer input resistance. This might be the case for example in a high energy physics experiment involving long cables between the SiPM and the digitizer(s), in which case a resistor **R'** to ground near the SiPM itself is needed to avoid stretching out the signal in time by integrating it onto the cable capacitance. The signal is then said to be "double terminated" and the digitizer input impedance only sees a fraction **R/(R + R')** of the SiPM current and charge.

integrated charges. Because the system is assumed to be (and actually is reasonably) linear throughout, the conversion gain for these integrated charges is **the same** as for an individual time bin.

How to measure $\mathbf{G}_{SiPM}$? Well, several facts about the system allow us to do this quite easily. First, it can be shown that the series of weird spikes in Figures 6 and 7 corresponds to simultaneous avalanches in N = 1, 2, 3, ... cells of the SiPM array, in other words detection of N = 1, 2, 3 photons, each producing a single-photoelectron avalanche. Since the avalanche gains of all the cells are very close to identical, the charge produced from N simultaneous photoelectrons is just Ne * $\mathbf{G}_{SiPM}$. So the spacing between adjacent spikes corresponds to a charge difference e * $\mathbf{G}_{SiPM}$ Coulombs. But we know the conversion gain of the digitizer. So if we count the number of ADC channels separating adjacent spikes, we can convert it into the corresponding observed charge difference. This difference is e * $\mathbf{G}_{SiPM}$ Coulombs and we know $e = 1.6{\times}10^{-19}$ Coulombs, so we have just measured $\mathbf{G}_{SiPM}$.

Apparently the SiPM has no problem distinguishing simultaneous absorption of say 7 vs. 8 photons. But the light pulser setting used to produce these histograms was fixed, i.e. all the light flashes were supposedly identical in amplitude. Why then are the distributions of pulse charges histogrammed in Figures 6 and 7 so broad, apparently showing peaks ranging from one to more than 15 photoelectrons? The answer is that the light flashes in this case are more or less identical in amplitude, but the detections of individual photons are statistically independent probabilistic events. The number of detections occurring in a given flash is therefore governed by (Poisson) counting statistics, as we discussed in the first lab exercise in this course. It is an interesting exercise to show that the frequencies for N = 1, 2, 3... photoelectrons obtainable from Figures 6 and 7 (or using the "PSAU Staircase" tab as in Figure 13) are actually well fitted by a Poisson distribution.

7. SiPM Dark Count Rate (DCR)

Every sensitive light detector has a dark count rate- it gives output pulses even when absolutely no light falls on it. Usually, this is mostly due to thermal emission of photoelectrons from the sensitive region of the detector.

It should be noted that the DCR of the SiPMs shown in Figures 16 and 17 are of the order of 10^5-10^6 counts per second per mm^2 of sensitive area. This is very high and is the main limitation in the use of SiPMs for low level light detection. A good photomultiplier tube operated at room temperature can have a DCR of less than one count per second per mm^2. It's pretty hopeless to do single photon counting with room temperature SiPMs at the present level of development. However, the DCR is getting lower with every new generation of SiPM devices.

Since it is mostly due to thermal emission, the DCR of SiPMs can be reduced tremendously by cooling them, particularly to temperatures below -175° C. This adds significant complexity, but it has been shown to allow SiPM DCR's of less than or equal to that of good PMTs operated at room temperature.