Measurements of the 277 nm photon detection efficiency of the OnSemi MicroFJ-60035 silicon photomultiplier

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Abstract. The article describes a method for absolute calibration of the photon detection efficiency of the OnSemi/SensL MicroFJ-60035 silicon photomultiplier by the Newport Power/Energy Meter 841-PE with the 883-UV photodiode sensor head, and the PicoQuant PLS-270 fast diode source of 277 nm ultraviolet emission. The dependences of the power of the detected emission and the number of ultraviolet photons on the distance to the source were obtained. The photon detection efficiency of the silicon photomultiplier was measured to be approximately 8% compared to the 9.6% level claimed by the manufacturer. It was also shown that, within the experimental setup, absorption of the 277 nm emission at paths in the air shorter than 1 m is not significant, and the angular distribution of the emission source is homogeneous. The obtained three-dimensional calibration surface of the dependence of the irradiance on the distance to the detector and the source intensity will be employed for development of a novel camera of the TAIGA-IACT telescope array.

1. Introduction
The TAIGA Cherenkov gamma-ray observatory is currently under development in the Tunka Valley in Buryatia, Russia [1]. The observatory includes the TAIGA-IACT Cherenkov telescopes, built on vacuum photomultipliers. The progress of silicon photomultipliers (SiPMs) allows one to create systems that are superior to vacuum photomultipliers in a number of important parameters [2]. A new SiPM-based detection cluster for cameras of the TAIGA-IACT telescope array is being developed at the Ioffe Institute. The cluster will be sensitive to Cherenkov emission in both visible (300-600 nm) and near ultraviolet (250-300 nm) ranges. In order to test and calibrate the developed cluster, a dedicated test bench has been created.

2. The test bench and the experiment
The pulsed ultraviolet source PicoQuant PLS-270 emits 600 ps wide pulses of 277 nm radiation, which pass through the black rubber bellow and hit the detector. The detector can be either a Newport Power/Energy Meter 841-PE with a 883-UV photodiode sensor head or an OnSemi/SensL MicroFJ-60035 silicon photomultiplier. It is important to note that the radiation source is used without lenses or filters, and the OD3 attenuator is removed from the sensor head.

The black rubber bellow creates a light-insulated volume excluding any influence of external light on the measurements. It also allows for an easy change of the distance between the source and the detector, and its ribbed structure reduces the effect of radiation reflection from the walls (compared to a smooth pipe).
The employed power meter allows one to measure 30 seconds-averaged power with accuracy better than 2%. The pulse amplitudes at the output of the SiPM detector were automatically read out by a 2 GHz oscilloscope LeCroy WR 620Zi. A distinctive feature of the MicroFJ 60035 SiPM is the presence of a fast output, which allows one to obtain signals of a few nanosecond lengths. To read out such a short signal, a slightly modified variant of the scheme described in [3] was applied. The temperature regime was steady (+31.0 ± 0.5 °С).

Figure 1 shows the scheme and the shape of the output signal. The noisy region after the pulse corresponds to typical reflection pattern of the electric signal from the oscilloscope high impedance input (AC1M). However this does not significantly affect the pulse shape due to its short duration (4 ns FWHM) and can be decreased by balancing the input impedance of the oscilloscope and the wave resistance of the transmission line.

![Figure 1. The preamplifier circuit for the tested SiPM (left panel), and a typical output signal of 4 ns FWHM (right panel).](image)

At the Geiger mode, as a single photon hits one of SiPM microcells, it produces an avalanche, which generates an electric signal at the SiPM output. As all the microcells of a particular SiPM are sufficiently identical, the electrical signal from each of the triggered microcells will be the same. Hence the amplitude of the signal from multiple simultaneously triggered microcells will be proportional to their number. The amplitude of the single cell signal can be determined via measurements of the dark count pulses, and for the circuit described above (Figure 1) it is 6 ± 0.5 mV. Consequently, with the assumption that only one photon hits one SiPM microcell it is possible to calculate the total number of detected photons by dividing the amplitude of the output signal by the amplitude of the single microcell signal. Further on, we will treat this value as the number of photoelectrons.

There is a wavelength-dependent probability that an incoming photon would trigger an avalanche (“produces a photoelectron”) in one of the SiPM microcells. That probability is called the Photon Detection Efficiency (PDE) of the SiPM.

3. Calibration of the Photon Detection Efficiency

In the first place, the dependence of the radiation power on the distance between the source and the 883-UV detector was obtained (Figure 2). With known geometric dimensions of the detecting surface (ø10 mm) and the photon energy, the irradiance of the detecting surface can be calculated in units of photons per mm² via the following formula:

$$E_e = \frac{W}{E_1 \cdot F \cdot S}$$
where $E_e$ is the irradiance, $W$ is the radiation power, $E_1$ is the energy of a single 277 nm photon, $F$ is the frequency of radiation pulses (5 MHz in this experiment), and $S$ is the area of the detecting surface.

![Figure 2](image.png)

**Figure 2.** The dependence of the measured radiation power on the distance between the source and the 883-UV detector in units of power and irradiance.

Then the dependence of the number of SiPM-produced photoelectrons on the distance was obtained (Figure 3). With the known detector area (6.07×6.07 mm) and the microcell fill factor (75%), the irradiance of this detector can also be calculated in units of photoelectrons per mm$^2$.

Knowing both these dependencies, it is now possible to compare the irradiance of the 883-UV sensor head and the SiPM, the ratio of which corresponds to the PDE of the SiPM. The average PDE for the MicroFJ-60035 SiPM at 277 nm was measured to be $(8.01 \pm 1.25)\%$. The averaging was performed by 6 points illustrated on Figure 4. The measured PDE is about 17% less than the value stated by the manufacturer (9.6% at the overvoltage of 4.3 V). The temperature reduction of the breakdown voltage by 215 mV (at +31°C) was taken into account.

It is interesting to note the following unexpectedly discovered effect. Having several measurement points at different distances between the source and the detector, it is possible to plot a dependence of PDE on the distance, expecting no correlation between these two values. However, Figure 4 shows a weak relationship between the distance and the PDE, which slightly increases as the source approaches to the detector. A possible explanation for the observed pattern may be an increase of the SiPM crosstalk as the distance decreases.

The reason of the crosstalk is the emitting of the infrared (IR) photon when an avalanche is triggered. The infrared photon can hit an adjacent cell and trigger it, increasing the SiPM output signal. However a significant part of the IR photons go away to the direction perpendicular to the detector plane, i.e., in this case, towards the PLS-270 emitter. The surface of the emitter is metallic, so it can act as an efficient reflector of the IR photons back to the detector. In other words, at small distances between the source and the detector the signal is amplified due to an increase of the crosstalk effect from IR photons returned to the detector after reflection from the metal surface of the emitter. This increase can be illustrated by the leftmost point in Figure 3, which is somewhat higher than the fit corresponding to the quadratic regression of the flux with distance.
Figure 3. The dependence of the number of detected photons on the distance between the source and the SiPM detector in units of photoelectrons and irradiance.

Figure 4. The dependence of PDE on the distance between the source and the SiPM detector.

The fitting curve on Figure 4 is a smooth quadratic approximation of measured points. The increase of error bar sizes at bigger distances is caused by the decreasing number of photons detected by SiPM and the decreasing measured power of the radiation approaching to the limit of the sensitivity of the power meter.

4. Discussion
The experimental results presented above allow us to carry out a few conclusions. One of these results is a clear quadratic regression of the power and the number of photoelectrons in both detectors with increasing distance from the source (Figures 2 and 3), which means that absorption of the 277 nm ultraviolet emission by the +31 °C air at normal pressure and humidity at lengths less than 1 m is not significant. This agrees with an estimate of the optical depth of $< 10^{-3}$ even at 250 nm, where the absorption is most strong, performed in the same way as we did in [4] and based on the compilation of cross-sections of [5].

Another by-product is a measurement of the angular distribution of the PLS-270 emitter. During additional experiments, we were able to change the relative angular positions of the source and the
detector due to the flexible connection via the rubber bellow, and the dependence of the power on the angle was not observed, which means that the angular distribution of the source is close to homogenous in the studied range of angles (±20°). These observations were augmented by the measured dependence of the power on the distance, because while changing the distance we actually change the angular size of the detector visible from the photon emission point. Therefore, it is possible to obtain the angular distribution of the radiation power by subtracting measurements at different distances. In effect, we have one circular and several ring-shaped detectors (Figure 5). Taking into account the observed absence of absorption of the 277 nm UV light by the air, this method confirms the homogeneity of the angular distribution of the source at distances and angles probed during the experiment (81...305 mm, ±3°32').

One more result is the measurement of a three-dimensional calibration surface of the number of photons depending on the distance and the source intensity (Figure 6). This dependence will allow us to calibrate detectors of TAIGA-IACT camera at a given distance and intensity of the source.

**Figure 5.** The angular distribution of the radiant intensity as seen from the photon emitting point to the circular 883-UV detector at different distances.

**Figure 6.** The three-dimensional calibration surface of the irradiance depending on the distance and the source intensity.

5. **Conclusions**

In the course of a specifically designed experiment the average PDE of a MicroFJ-60035 SiPM at a wavelength of 277 nm has been measured as (8.01 ± 1.25)%, which is about 17% less than the value stated by the manufacturer − 9.6% at the overvoltage of 4.3 V. However, the 8% PDE is still high enough to employ the MicroFJ-60035 SiPMs in the novel detector clusters developed for the TAIGA-IACT Cherenkov telescope. It has been also found out that absorption of the 277 nm UV radiation at the spatial scales of the experiment (less than 1 m) is not significant, and the angular distribution of the PLS-270 radiation source is close to homogenous at angles ±3°32'. The three-dimensional calibration dependence of the number of photons per mm² on the distance and the intensity of the source has been measured, which is necessary for further development of SiPM-based detectors for TAIGA-IACT.

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