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FACULTY OF SCIENCE
JOINT LABORATORY OF OPTICS

BACHELOR THESIS

Calibration and monitoring of astroparticle
telescopes



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DECLARATION

I hereby declare that I elaborated this bachelor thesis independently under the supervision of Ing. Ladislav Chytka, Ph.D., using only information sources referred in the Literature chapter.

In Olomouc November 21, 2021

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Introduction

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Chapter 1

Astroparticle detection

More than 100 years have passed since Victor Franz Hess first encountered cosmic radiation. Since those times the techniques and methods of detection have been strongly improved. We have moved up from elevating electroscopes by balloons to observe growing electric charge to specialized techniques, which allows us to measure particles' energies, trajectories, etc.

1.1 Cosmic rays and particles

Cosmic rays is a term for radiation and energetic particles striking earth atmosphere with an origin in space sources (neutron stars, supernovas, black holes, etc). We divide them into two major groups - primary and secondary. Primary cosmic rays are the original cosmic particles, which strike the Earth's atmosphere. Secondary cosmic rays (also referred as showers) are particles, which have origin in particle interaction between primary cosmic rays and the atmosphere.

1.1.1 Primary cosmic rays

Primary cosmic rays consist of protons (95%), helium nuclei (4%), electrons and other heavy nuclei (up to iron). However, only the energetic rays make their way to the atmosphere. The Earth's magnetic field affects their trajectories and prevents the low-energetic (less than 100 MeV) particles from arriving to the atmosphere [5].

Part of primary cosmic rays are also Ultra-high energy cosmic rays (UHECRs), which we refer in the next chapter.

Neutrinos are also a part of cosmic radiation, but their interaction with matter is very rare, so they are very hard to detect. The special underwater detectors are developed to detect some of them.

1.1.2 Secondary cosmic rays

Secondary cosmic rays are created by interaction of high-energetic particles of primary component with air's nucleis, such as nitrogen. They consist of low-energetic and high-energetic muons, gamma photons, electrons and positrons. Most of muons travel up to the earth's surface although their half-life is only about 2.2 microseconds before they decay into electrons. Due to their high relativistic speeds, their half-life is increased for external observers.

1.2 Ultra-high energy cosmic rays (UHECRs)

UHECRs are particles with energies from 10^{18} to 10^{20} eV, which is much more than particles created on Cern's Large hadron colider (LHC) with energies about 10^{13} . Due to their high energies, the trajectory remains nearly unchanged by space magnetic fields [7].

UHECRs' origin is yet unknown, but it is supposed and experimentally proved that they come from outside of the Milky Way. Some theoretical physicists expects, that the one possible source of UHECRs acceleration are the starburst galaxies. One of the UHECR possible candidate is proton.

In many particle physics experiments, some form of calorimeter is used to determine the particles' energy and direction. In case of UHECRs, the air molecules of atmosphere have the function of calorimeter. When the UHECR interacts with atmospheric nuclei, the cascade of particles is induced. This cascade concists of three main components: electromagnetic, hadronic and muonic. It is also refered as extensive air shower (EAS).

In case of ultra-high energy proton striking an air molecule, kaons, baryons, nuclear fragments and mostly pions are created. Together, they are refered as hadronic component. The pions with short lifetime decay into electromagnetic sub-shower. The behaviour of pions with longer lifetime is energy-dependent. At higher energies they reinteract with atmospheric nuclei and feed hadronic and electromagnetic component. At lower energies they decay into muonic component with muonic neutrinos. The muons with short lifetime decay into electrons and positrons with neutrinos, which joins the electromagnetic cascade, while the others reach the Earth's surface carrying the energy, which we are unable to detect. The UHECR's cascade scheme could be seen on picture 1.1.

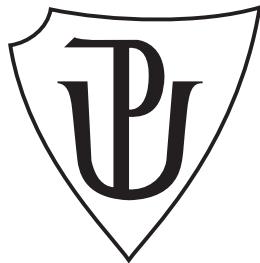


Figure 1.1: UHECR's cascade, taken from nevimco ??.

The electromagnetic cascade consisting of electron, positrons, gama photons carries the most of UHECR's original energy. With increasing depth, the cascade develops by decaying the photons into electron and positron pairs, which again emit photons and this process repeats. The cascade develops until the the energy treshold is reached, where the ionization is higher than the radiation losses. ??.

One of the main parameters of electromagnetic cascade is X_{max} - the point along the shower axis, where is the maximum of deposited energy.

1.3 UHECRs detection techniques

Nowadays there are three main proven techniques to detect UHERCs - air fluorescence, surface particle detection and Cherenkov light detection.

1.3.1 Air fluorescence

The electrons and positrons from electromagnetic cascade excite nitrogen molecules, which then deexcite and emit fluorescence light in UV spectre with two main wavelengths 337 and 357 nm. The intensity of this light is directly proportional to the calorimetric energy of the shower.

However, the intensity of this light is very low, and thus the measurements must be done in dark nights with no light smog. Even a low intensity of external sources could lead to detection of false events or worse - the unwanted light could damage the very sensitive equipment.

The detection equipment are mostly the superreflective UV mirrors which focus part of the UV shower into the PMT or into the camera based on PMTs. It is necessary to have atmospheric monitoring system (temperature, humidity, pressure etc.) along with the detection part, because the fluorescence is highly dependent on these conditions.

The main advantage of fluorescence detection is the fact, that by measuring and integrating the light profile we are able to calculate the total calorimetric energy. However, corrections

The FAST telescope, on which we focus in this thesis, is considered to be a fluorescence telescope.

1.3.2 Surface particle detection

Surface particle detection is a method, which is based on detecting individual particles from EAS. There are two proven surface techniques to detect EAS - by scintillators or water Cherenkov detectors. To detect the EAS full geometric distribution, the huge surface needs to be covered by surface detectors.

Compared to fluorescence detection method, the surface detectors don't require the dark night and any light exposure is not a threat for them.

1.3.3 Cherenkov light detection

1.3.4 Hybrid detection

1.4 UHECRs observatories

1.4.1 Pierre Auger observatory

1.4.2 Telescope array project

Chapter 2

FAST telescope

The Fluorescence detector Array of Single-pixel Telescopes (FAST) is an international project of fluorescence telescope sensitive to UHECRs.

Until today there are four prototypes in active service. Three of them are situated in Black Rock Mesa site of the Telescope Array experiment in central Utah and one in Argentina near Pierre Auger Observatory.

The main goal of FAST project is to develop a cheap fluorescence telescope, which could be used in future to cover the wide surface area. This new oncoming fluorescence telescope array should be able to fully reconstruct the geometry of UHECRs induced UV shower by combining the information from telescopes, which has encountered an event at the same time.

2.1 FAST detection and operation scheme

Main detection part of telescope consists of superreflective UV mirrors and photomultipliers.

2.2 Protection hut

The entire telescope along with monitoring systems and other instruments is situated in a hut with remote shutter, where it is protected from negative metrological phenomena, such as rain or fast wind, but also from dust and aerosols. Exposure of mirrors to any of this phenomena could lead to reduction of their reflectivity. It is also necessary to monitor and protect PMTs from unwanted light sources. Even a low-intensity sources could decrease PMT's service life.



Figure 2.1: FAST telescope's hut in Argentina.

2.3 Remote control and monitoring

In case of Argentina prototype, the telescope's systems are connected to Pierre Auger network and through it, the telescope could be controlled and monitored over the internet.

Testing measurements, sometimes referred as shifts, are performed in the night. Their main purpose is to acquire data, which could be later analyzed and compared with data from Los Leones part of Pierre Auger, which has the similar FoV as Argentine FAST. The testing measurements require an operator to look after the telescope systems. An operator's duty is to power on and off the DAQ, PMTs' voltage sources, perform calibration, open and close the shutter and mainly check for failures and negative phenomena. To do that, operator could access webcam (2.2), meteostation with thermometers, humidity, wind and light sensors and the Allsky camera (2.3).



Figure 2.2: FAST telescope with closed shutter from webcam.



Figure 2.3: View from Allsky camera installed atop the hut. It gives the information of sky quality by comparing visible stars with theoretical star map.

2.4

Chapter 3

Calibration of astroparticle detectors

Calibration is a process, which we perform to obtain relationships between measured values by tested device and values given by used ethalon. These relationships may be specified by calibration constants, functions or by other mathematical relations. The tested devices could be also calibrated relatively to each other.

In case of astroparticle detection, we mostly need to , ,

3.1 Absolute calibration

3.2 Relative calibration

3.3 FAST calibration

FAST telescope calibration techniques are yet under development. It is necessary to calibrate PMTs both in absolute and relative way, but also the entire telescope as optoelectronical system with mirrors and PMTs.

3.3.1 Flasher

As was mentioned before, the FAST telescope is equipped with UV LED flasher, which is used to generate light pulses. Calibration by flasher is performed during every shift - two times at the beginning and two times at the end. One time with opened shutter and one time with closed shutter.

3.3.2 YAP pulser

3.3.3 Homogenous light source

There is

Chapter 4

Instrumentalization and measurement preparation

To perform all of neccesary measurements we need to use various types of optical and electronical equipment.

4.1 Integration sphere

The Integration sphere (IS) is a special optical equipment, which can be used either as extended uniform light source (EULS) or with spectrometer in determining the material reflectance. In our experiments we use general purpose Labsphere (Fig. 4.1).



Figure 4.1: General purpose Labsphere.

The IS inner surface consist of white optical diffusive material (BaSO_4 and Poly-tetrafluoroethylene). The IS also contains several circular apertures, which are called input/output ports. They can be used to mount detectors or optical sources or left free to let light flux enter or exit IS.

The inner surface is part where light intergration happens. The effect which takes place here is known as Lambertian scattering. After one spot of inner surface is hit by a ray, the energy should be uniformly radially distributed. In output port this produces a homogenous light source. The homogeneity decreases with increasing number and sizes of input/output ports.

Using optical source with IS requires baffle to prevent source's light flux or its part to exit IS without integration.

More deeper explanation of IS working principles and characterization of optical properties of the identical IS, which we use, can be found in [3].

For our pusrpeses, in case of FAST calibration, we use IS as EULS in UV spectre. In case of testing optical calibration source, we don't even care about homegenity. The

reason why we use IS in this case is that it focuses the entire optical power of the source into output ports, where our detectors are mounted, and blocks any other external light source, which could affect our detectors.

4.2 Photomultiplier tube

Photomultiplier tube (PMT) is considered to be a high voltage optoelectronical part. It allows us to measure very low intensity optical signals. PMT is also characterized by high amplification, low noise and stability. It has many variants of usage. It can be used either as detector of optical signal (pulse or continual) for chosen wavelength or as a radiation detector. We can construct a counter or a multichannel analyzer by mounting an appropriate scintillator on the window of the PMT. The general theory of PMTs is described in more detail in [4, 6].

4.2.1 Operating principle

PMT consists of 6 main elements, which can be seen on scheme 4.2.



Figure 4.2: Photomultiplier tube scheme.



Figure 4.3: XP2262 PMT used for our measurements.

The input photon with sufficient energy, which strikes the PMT's photocathode, excites photocathode's electron. This electron then follows electrostatic field to the first dynode of the electron multiplier, where it induces secondary emission of more electrons. These electrons are then attracted by the next dynode, where the emission process repeats. After few times of multiplying electron number over dynodes, the electrons are then collected by the anode, which is situated on the end of the electron multiplier. The anode output current is then converted to voltage signal by appropriate load resistor or by operational amplifier current-to-voltage circuit.

As all other laboratory instruments, which are based on accelerating electrons, such as electron microscopes, the photomultiplier's main parts must be kept in vacuum. To maintain vacuum, the photomultiplier is surrounded by special glass envelope. To

avoid mechanical damage of the glass envelope, the entire photomultiplier is situated in a plastic tube.

One of the basic adjustable characteristic of PMT is its gain. The gain is defined as:

$$G = \frac{I_a}{I_p}, \quad (4.1)$$

where I_a is the anode current and I_p is the input photocurrent from the photocathode.

In case of ideal, noiseless PMT, we can adjust gain by varying the supply voltage. By varying supply voltage we can adjust gain according to an equation:

$$\frac{G_2}{G_1} = \left(\frac{V_2}{V_1}\right)^{\alpha N}, \quad (4.2)$$

where G_2 and G_1 are gains at supply voltages V_2 and V_1 . α is coefficient given by dynode material and N is the number of dynodes.

Other effects, such as temperature, may also vary PMT's gain, and it is necessary to keep them on constant value or measure them and involve them in the final evaluation of data.

For proper functionality of the PMT, the charge and current linearity should be considered. Charge linearity is the ratio of the number of incident photons to the number of electrons collected at the anode. Current linearity express the proportionality between incident light flux and anode current. Ideal PMT is always linear, but the real PMT may vary from linearity due to drifts, space charges, instability of voltage divider etc. These effect can lead up to saturation of the PMT. In saturation, increasing the input light flux leaves the anode current mostly unchanged.

Window

The photocathode is superimposed by glass window, whose main purpose is to admit light of certain wavelengths. Glass materials are characterized by the spectral sensitivity to wavelengths. For transparency in UV spectre, it is advised to use borosilicate or fused silica glasses.

Photocathode

The photocathode is the only light-sensitive part of PMT. It transfers the light flux into the electric current.

One of its main parameters is quantum efficiency. It is referred as ratio of emitted photoelectrons to the number of incident photons expressed as a percentage. It is generally less than 35 %. For measurement, the more practical parameter is cathode radiant sensitivity. It is the ratio of photocathode current to an incident light power, which is expressed in mA/W.

Photocathode material must be sensitive to certain wavelengths, which we want to detect with the PMT, and must have sufficient quantum efficiency. Preferred materials are usually alkali antimonides.

Electron multiplier

The electron multiplier consists of dynodes and one anode. Dynodes are electrodes, which produce more electrons through secondary emission. To maintain electrostatic

field between dynodes, each of dynodes is held on different potential. This is achieved by using the voltage divider. Every resistor in the divider sets the potential of one diode according to its resistivity.

All of the photoelectrons emitted by photocathode should be ideally collected by the first dynode. However, many of them could be diverted from their path to dynode due to various effects. The parameter, which characterizes this, is the collection efficiency. The Collection efficiency is a probability that photoelectron will strike area of the first dynode.

There are few types of dynodes arrangements. On the fig. 4.2 is the classic linear-focusing multiplier.

Voltage divider and voltage adjustement

Voltage divider could be a simple resistor serial network, which divide high input voltage between the dynodes.

It is neccessary to consider, that the multiplier current density increases in direction to the anode, so it tends to lessen the voltage between last dynode and anode. This phenomena can shake the potential levels across the entire multiplier. One way to reduce the impact on PMT's behaviour is to choose the proper resistor values of the divider.

The resistor values could same for all the dynodes, but for some applications it is better to have progresive voltage distribution, which increases from cathode to anode, or intermediate distribution with highest values on the beginning of the multiplier.

In some applications, where high anode current peaks are expected, the divider can be filled with reservoir capacitors, which prevent the temporaly charge exhaustion of the dynodes. In pulse mode, the unwanted oscillations on dynodes may occur, in that case, it is desirable to connect additional damping resistor to the divider.

Voltage supply should be stable during the PMT's operation. As was mention before, the PMT's gain is voltage dependent. To adjust sufficient gain, high voltage (thousands of volts) needs to be applied between photocathode and anode. The high voltage needs to be ramped on required level gradually to avoid negative consequences of transition and dark current effects, which can decrease the operating life of PMT. The same truth is for shutting down the PMT.

The high voltage could be applied to the PMT in negative or positive polarity. In case of positive polarity, the cathode is held at ground and anode on +HV. In case of negative polarity, the cathode is held at -HV and anode at ground.

4.2.2 Dark current

Dark current is anode current produced by photomultiplier in total darkness. It is considered to be a part of unwanted noise, causes errors in measurements and limits the detectivity of PMT. Dark current has origin in Ohmical leakage, thermionic and field emission or in radioactivity. Ohmical leakage is major part of dark current at low gain. With the increasing gain the thermionic emission prevails. At high gains the field emission becomes the major part.

Ohmical leakage

Insufficient insulation of electrodes, dynodes and all other parts which are under high voltage may lead to surface current over glass and tube. Dirt and humidity are in most cases the reason of Ohmical leakage.

Thermionic emission

Temperature causes emission of photocathode's electrons, which are at medium gains the major part of dark current. Due to this effect, some PMTs may need to be cooled during operation.

Field emission

At high gains the electrostatic field is so strong that it can rip the electrons out of the electrodes and accelerate them onto other surfaces, where they cause secondary emission. Field emission rapidly increases with supply voltage. In some literature it is also referred as cold emission.

Radioactivity

The radioactivity of PMT's components depends only on the material composition. In some applications, such as astroparticle detection, it is necessary to decrease radiation as possible. In astroparticle detection the radioactivity could be a source of false events. Only way to prevent this is to use materials with a very low concentration of radioactive isotopes.

4.2.3 Timing and response

Differences of photoelectrons' trajectories from the cathode to the first dynode lead into time distortion of signal. For example if we were able to produce delta-function pulse, the PMT would detect pulse with some response width time t_w . With respect to differences in electron trajectories and arrival times, the PMTs are divided into 3 types:

1. **Very-fast tubes** - photoelectrons arrive simultaneously, low collection efficiency.
2. **Fast tubes** - compromise between timing performance and collection efficiency
3. **General-purpose tubes** - simple optoelectronics, good collection efficiency, low timing performance

4.2.4 Operating life and degradation

The operating life of PMT is defined as the time required for anode sensitivity to be halved. If we neglect the outside effects, the operating life mainly depends on anode current. Degradation processes start to show themselves at currents higher than $10 \mu\text{A}$. Aging is accompanied by increasing or decreasing gain at stable voltage. Operating life of PMT is measured in thousands of operating hours.

By exposing PMT to bad conditions, such as humidity, mechanical stress, high temperatures or the high-intensity light, the PMT's operating life could be shortened much faster.

4.2.5 FAST's PMTs

4.2.6 Calibration

4.3 Silicon PM

4.4 Hardware for experiment control

4.4.1 Raspberry Pi

4.4.2 STM32 based microcontrollers

4.4.3 USB oscilloscope

4.4.4 PM16 optical Power meter

4.5 Sensors and other electronics components

4.5.1 MPU6050

4.5.2 servo motors

4.5.3 Dallas DS18B20 thermometer

Chapter 5

Calibration UV optical source

Blah blah we need it.

5.1 Karlsruhe UV source

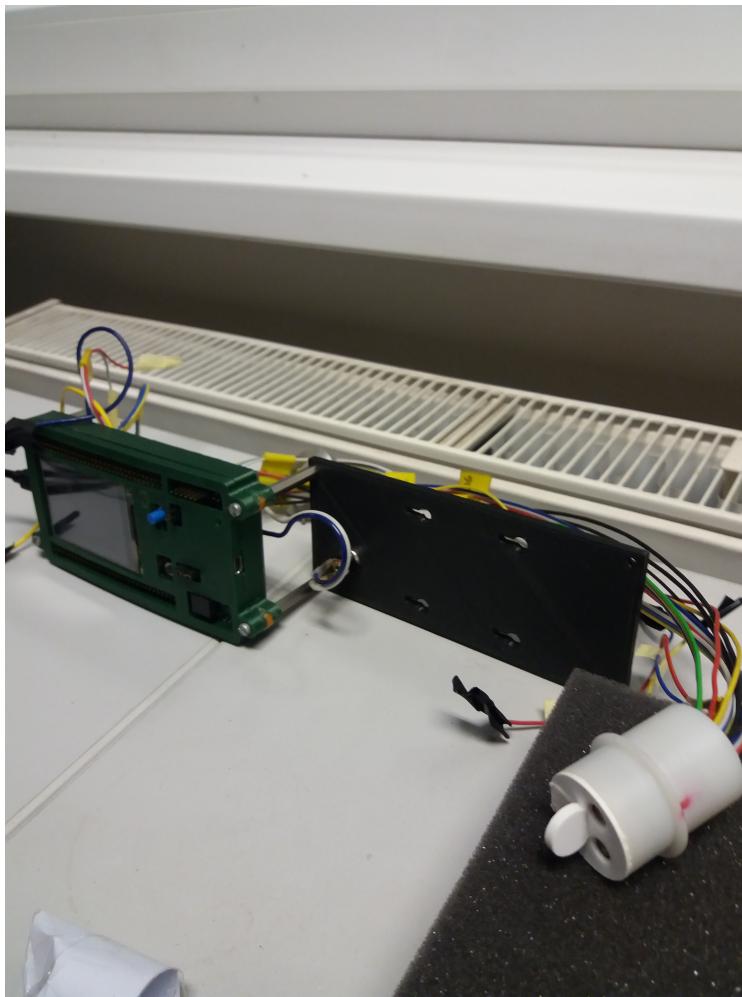


Figure 5.1: UV source constructed according to KIT's template.

Our main task was to test this UV source's longtime stability and develop possible fixes and upgrades.

5.2 Testing and measurement of UV source

For calibration UV source, the longtime stability of optical power and pulse geometry is very important. Because there were no specialized apparatus for this measurement, we had to built and program one by ourselves.

5.2.1 Measuring apparatus

For measuring the optical power we use PM16 power meter (PM) and for determining the pulse geometry we use XP2262 PMT with signal output connected to 2-channel PicoScope 2205A MSO usb oscilloscope. XP2262 PMT is held on $U \approx -680$ V by HV voltage source.

We also use DS18B20 thermometer for PMT temperature monitoring and keysight 34461a multimeter for checking voltages.

The PMT, power meter and the optical head of UV source are mounted in the IS's ports. The IS stops the unwanted external light and distributes the optical power to PMT and power meter.

The entire apparatus is driven by Raspberry Pi (RPi). The RPi takes care of data acquisition and could be used to set the parameters of the UV source. It could be easily accessed over internet for data download or for user to control the experiment.

Oscilloscope was programmed in C language according to its programmer's manual ???. It is capable of 2ns sampling which is enough to capture rising edges of the pulses. The RPi sets basic parameters (DC coupling, range etc.) and then activates oscilloscope's trigger (rising edge). After sampling, RPi receives all samples from oscilloscope's memory.

Main component (IS,PW, PMT with HV source, UV source) are situated in protection box to prevent unwanted manipulations and touching the HV parts. The apparatus could be seen on fig. 5.2 and 5.3.

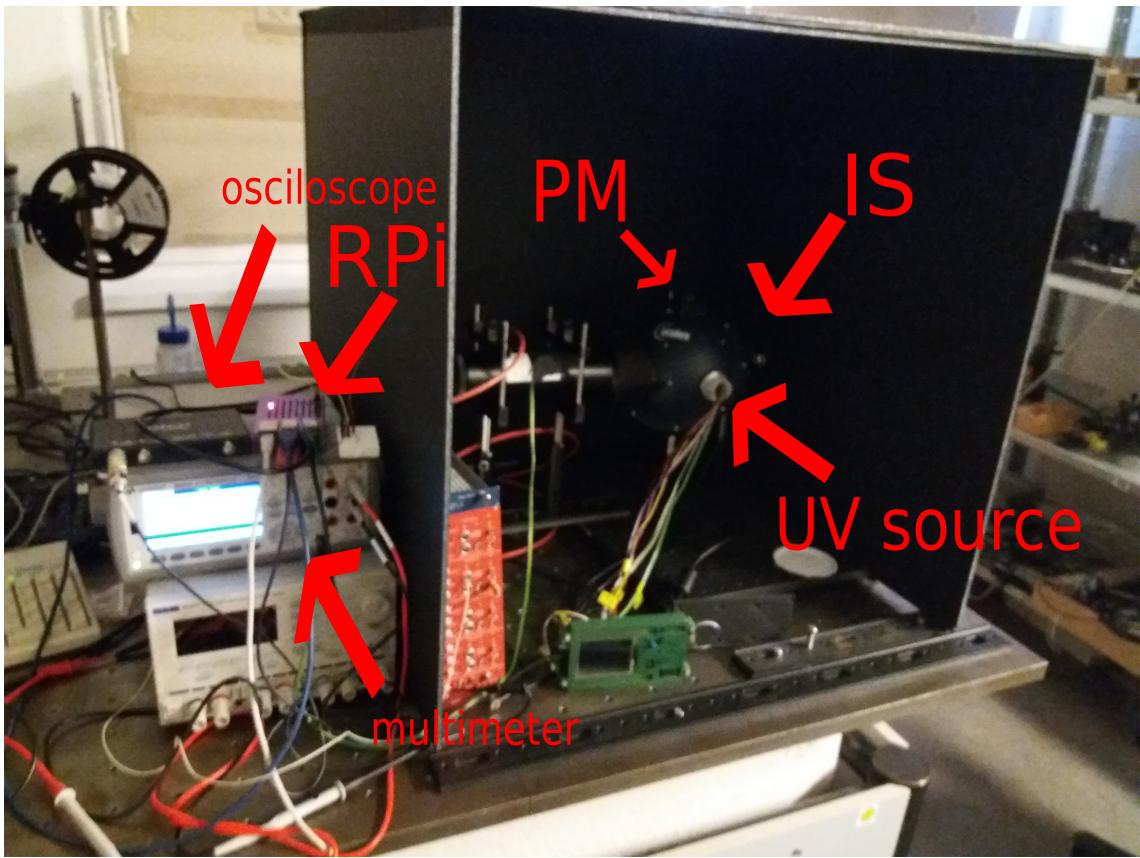


Figure 5.2: Measuring apparatus.

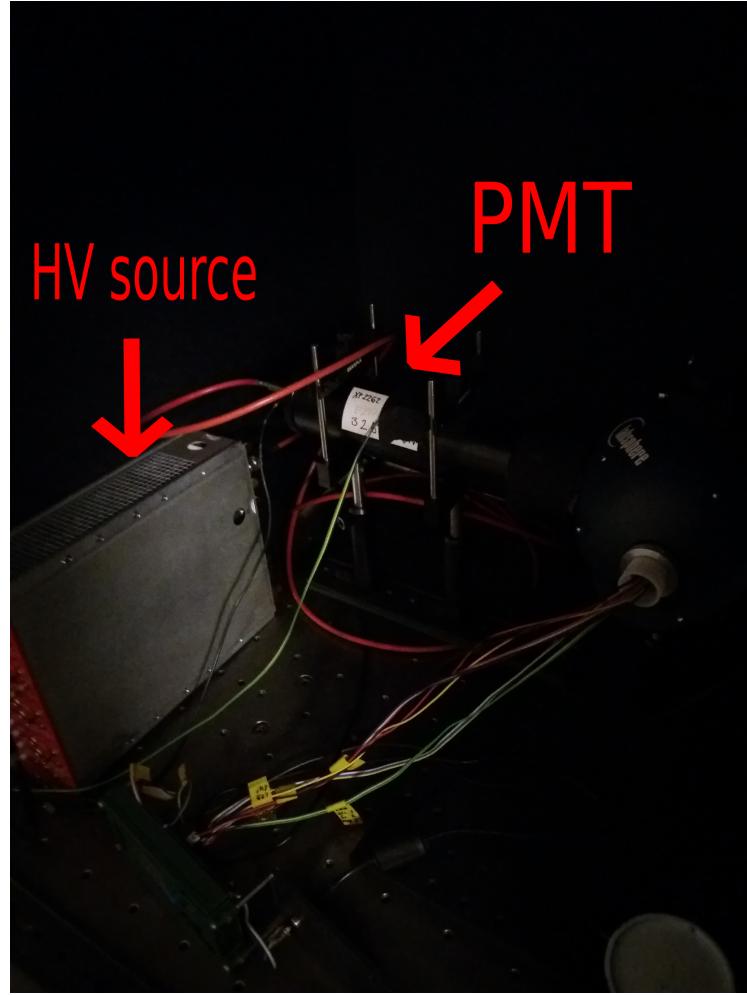


Figure 5.3: PMT mounting and HV source.

5.2.2 Data acquisition and analysis

All the data are taken in specified interval (15 or 30 minutes). Two files are produced - oscilloscope waveform file and a file with 30 samples of power meter, multimeter and a thermometer readings.

The data from oscilloscope contains the square pulses with noise (fig. 5.4). From them we need to extract the information of pulses height, slope and time of the rising edge.

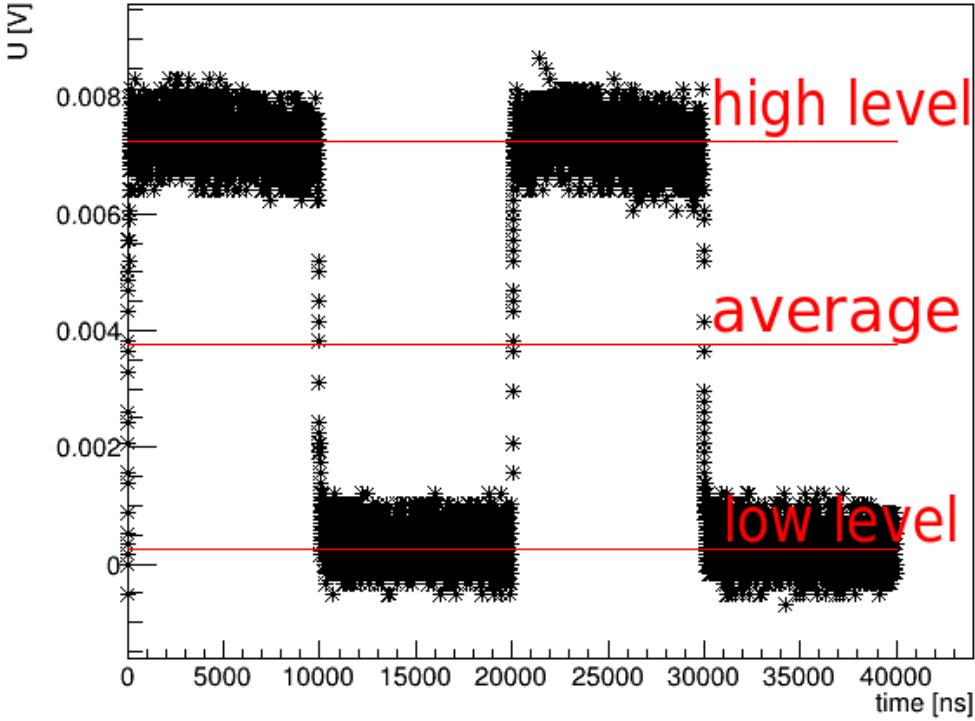


Figure 5.4: Determining the basic pulse properties - average, low and high levels of signal.

To determine the pulse height, we need to calculate the average value from all the samples at first. Then, we split the samples into two subgroups according to fact, whether they are higher or lower than the average. These subgroups are converted to histograms with fixed binning (around 5000 bins). These histograms are then fitted by gaussian. The means of these two fits determine two levels of the pulse - high (U_h) and low (U_l). The fig. 5.4 shows the real pulse with levels determined by this method. The height of pulse is then simply calculated by subtracting two levels: $U_H = U_h - U_l$.

The properties the rising edge could be specified by two parameters, which we are able to extract from our data - time and the slope of the rising edge. We are able to calculate both of them if we identify the samples, which are taken at the time of the rising. These samples' values should be between 10 % and 90 % of the U_H . First, we need to detect the rising edge in waveform data sequence. However, the signal is very noisy and this could not be simply done by detecting the exceeding of the 10 % of the U_H . To achieve that, we cycle through the waveform until we meet two conditions - the value is higher than average and the derivative is positive. Due to the noise, the derivative could not be calculated from two or three points, thus we use Savitzky–Golay polynom's derivative at chosen point: $y' = \frac{1}{12h}(y_{i-2} - 8y_{i-1} + 8y_{i+1} - y_{i+2})$. However we care only of positive/negative sign, so $\frac{1}{12h}$, where h is the small step, is no use for us. When these two conditions are met at some point, the program cycles back from the point through the waveform until reaches 10% level, and then beginning at the same point, which met the conditions, cycles up to reaching 90% level. All the samples traversed by this way are considered as samples of the rising edge. The rising time is

calculated simply by multiplying the number of these samples by oscilloscope's sample time (2 ns). The slope is calculated from linear fit of these samples (fig. 5.5).

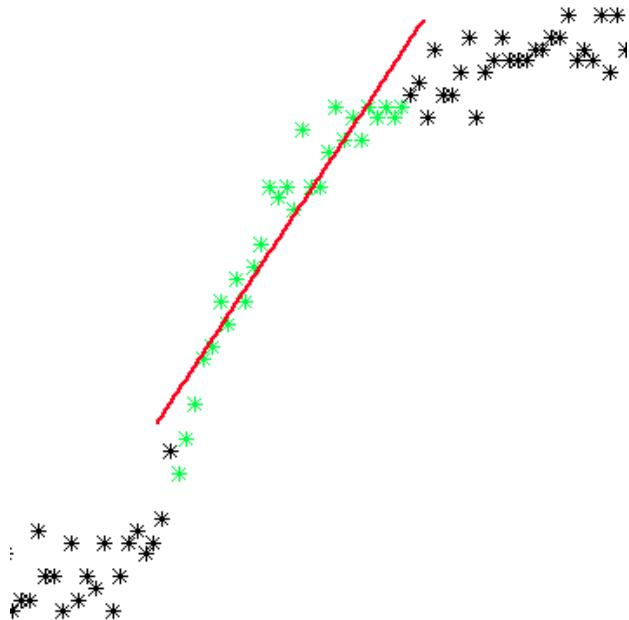


Figure 5.5: Linear fit of rising edge points (marked as green).

5.2.3 Results

5.3 UV LED diode aging

5.4 Optical feedback - potential fix

One way to handle the aging process of UV LED diodes is to monitor the power and according to the changes set the diode current.

5.5 Modified UV source for drone mounting

Chapter 6

FAST Calibration data analysis

6.1 Photomultiplier relative calibration

6.2

6.3

Conclusion

We are completely f***d.

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