Palacký University Olomouc
Faculty of Science
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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 October 23, 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 encontered cosmic radiation. Since those times the techniques and methods of detection have been strongly improved. We have moved up from elevating electroscopes by ballons 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 a 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 athmosphere. Secondary cosmic rays (also refered as showers) are particles, which have origin in particle interaction between primary cosmic rays and the athmosphere.

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 athmosphere. The Earth's magnetic field affects their trajectories and prevents the low-energetic (less than 100 MeV) particles from arriving to the athmosphere [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 athmosphere have the function of calorimeter. When the UHECR interacts with athmospheric nuclei, the cascade of particles is induced. This cascade concists of three main components: electromagnetic, hadronic and muonic.

1.3 UHECRs detection techniques

Commonly used techniques for detecting Cosmic rays proved un Nowadays there are three main proven techniques to detect UHERCs - air fluorescence, surface particle detection and Cherenkov light detection.

1.3.1 air fluorescence

1.3.2 surface particle detection

1.3.3 Cherenkov light 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 UHERCs.

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 UHERCs induced UV shover 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 theirs reflectivity. It is also neccessary 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 refered 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 phenomenas. To do that, operator could access webcam (2.1), meteostation with thermometers, humidity, wind and light sensors and the Allsky camera (2.2).

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 theoreretical 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 astroparicle 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 Polytetrafluoroethylene). 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 radialy distributed. In output port this produces a homogenous light source. The homogenity 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 pusrposes, 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 intesity 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 scintilator 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 electrostatitc 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:

$$G = \frac{I_\mathrm{a}}{I_\mathrm{p}}, \tag{4.1}$$

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 variing the supply voltage. By variing supply voltage we can adjust gain according to an euqation:

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

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 neccesary 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, unstability 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 efficenty. It is refered 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 sufficent quantum efficenty. Prefered materials are usually alkali antimodes.

Electron multiplier

The electron multiplier consists of dynodes and one anode. Dynodes are electrodes, which produce more electrons through secondary emission. To maintain elecrostatic 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 aplications, 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 oscillacions 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 sufficent gain, high voltage (thosands 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

Insufficent 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 refered as cold emission.

Radioactivity

The radioactivity of PMT's components depends only on the material composition. In some aplications, such as astroparticle detection, it is neccessary 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 distorsion 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 efficency.
2. **Fast tubes** - compromise between timing performance and collection efficency
3. **General-purpose tubes** - simple optoelectronics, good collection efficency, 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 μA. Aging is accompanied by increasing or decreasing gain at stable voltage. Operating life of PMT is measured in thousands of operating hours.

By exposuring PMT to bad conditions, such as humidity, mechanical stress, high temperatures or the high-intensity light, the PMT's operating life could be shorten 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 microcontrolers

4.4.3 USB osciloscope

4.4.4 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

5.2 Testing and measurement of UV source

5.3 Adding optical feedback

5.4 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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