

PALACKÝ UNIVERSITY OLMOUC
FACULTY OF SCIENCE
JOINT LABORATORY OF OPTICS

BACHELOR THESIS

Calibration and monitoring of astroparticle
telescopes



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| Study program: | B0533A110007 Applied Physics |
| Field of study: | 1702R001 Applied Physics (AFYZ) |
| Form of study: | Full-time |
| Supervisor: | Ing. Ladislav Chytka, Ph.D. |
| Deadline: | April 2022 |

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 September 1, 2021

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| The year of presentation | 2022 |
| Abstract | Lorem ipsum dolor sit amet, consectetur adipiscing elit. Curabitur et lectus sit amet lectus vestibulum dignissim. Cras sit amet enim vitae mi elementum blandit eget nec tortor. Curabitur eget eros vitae arcu luctus varius commodo vel mauris. Nam elementum convallis pretium. Nunc dignissim pulvinar urna, nec blandit ante fringilla at. Ut et magna purus, vel pellentesque massa. In tortor nisi, faucibus condimentum cursus ut, sollicitudin quis leo. Ut at purus nec arcu accumsan tincidunt id id massa. Nam id vehicula mi. |
| Keywords | keyword 1, keyword 2, ... |
| Number of pages | xx |
| Number of appendices | x |
| Language | english |

Bibliografická identifikace

| | |
|-------------------------|---|
| Jméno a příjmení autora | Daniel Staník |
| Název práce | Kalibrace a monitorování astročásticových teleskopů |
| Typ práce | Bakalářská |
| Pracoviště | Společná Laboratoř Optiky |
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| Rok obhajoby práce | 2022 |
| Abstrakt | Lorem ipsum dolor sit amet, consectetur adipiscing elit. Curabitur et lectus sit amet lectus vestibulum dignissim. Cras sit amet enim vitae mi elementum blandit eget nec tortor. Curabitur eget eros vitae arcu luctus varius commodo vel mauris. Nam elementum convallis pretium. Nunc dignissim pulvinar urna, nec blandit ante fringilla at. Ut et magna purus, vel pellentesque massa. In tortor nisi, faucibus condimentum cursus ut, sollicitudin quis leo. Ut at purus nec arcu accumsan tincidunt id id massa. Nam id vehicula mi. |
| Klíčová slova | klíčové slovo 1, klíčové slovo 2, ... |
| Počet stran | xx |
| Počet příloh | x |
| Jazyk | anglický |

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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

1.2 Ultra-high energy cosmic rays (UHECRs)

1.3 Detection principles

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.

2.1 Principle of operation

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

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 necessary to monitor and protect PMTs from unwanted light sources. Even a low-intensity sources could decrease PMT's service life.

2.2 Remote control and monitoring

2.3

Chapter 3

Instrumentalization and measurement preparation

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

3.1 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. 3.1).



Figure 3.1: 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 [1].

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.

3.2 Photomultiplier tube

Photomultiplier tube (PMT) is considered to be a high voltage optoelectronic 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 PMT.

3.2.1 Operating principle

PMT consists of 6 main elements, which can be seen on scheme 3.2.



Figure 3.2: Photomultiplier tube scheme.

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:

$$G = \frac{I_a}{I_p}, \quad (3.1)$$

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:

$$\frac{G_2}{G_1} = \left(\frac{V_2}{V_1}\right)^{\alpha N}, \quad (3.2)$$

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 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.

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. 3.2 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 necessary 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. For

3.2.2 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.

3.2.3 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 pulse width time t_w .

Another time delay is caused by

3.2.4 Operating life and degradation

The operating life of PMT is defined as the time required for anode sensitivity to be halved.

3.2.5 FAST's PMTs

3.2.6 Calibration

3.3 Silicon PM

3.4 Hardware for experiment control

3.4.1 Raspberry Pi

3.4.2 STM32 based microcontrollers

3.4.3 USB oscilloscope

3.4.4 Power meter

3.5 Sensors and other electronics components

3.5.1 MPU6050

3.5.2 servo motors

3.5.3 Dallas DS18B20 thermometer

Chapter 4

Calibration UV optical source

Blah blah we need it.

4.1 Karlsruhe UV source

4.2 Testing and measurement of UV source

4.3 Adding optical feedback

4.4 Modified UV source for drone mounting

Chapter 5

FAST Calibration data analysis

5.1 Photomultiplier relative calibration

5.2

5.3

Conclusion

We are completely f****d.

Bibliography

- [1] Martin Vacula, Pavel Horvath, Ladislav Chytka, Kai Daumiller, Ralph Engel, Miroslav Hrabovsky, Dusan Mandat, Hermann-Josef Mathes, Stanislav Michal, Miroslav Palatka, Miroslav Pech, Christoph M. Schäfer, and Petr Schovanek. Use of a general purpose integrating sphere as a low intensity near-uv extended uniform light source. *Optik*, 242:167169, 2021.
- [2] M. Malacari, J. Farmer, T. Fujii, J. Albury, J.A. Bellido, L. Chytka, P. Hamal, P. Horvath, M. Hrabovský, D. Mandat, J.N. Matthews, L. Nozka, M. Palatka, M. Pech, P. Privitera, P. Schovánek, R. Šmída, S.B. Thomas, and P. Travnicek. The first full-scale prototypes of the fluorescence detector array of single-pixel telescopes. *Astroparticle Physics*, 119:102430, 2020.
- [3] Lenka Tománková. *Optical Properties and Calibration of the Pierre Auger Fluorescence Detector*. PhD thesis, Karlsruher Institut für Technologie (KIT), 2016.
- [4] Photonis: Photomultiplier tube basics.

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