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Data Acquisition and Performance Studies in Cosmic Ray Experiments

Pedro Jorge dos Santos de Assis

(Mestre)

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Resumo

Esta tese insere-se no âmbito do estudo de detectores de Raios Cósmicos e seus sistemas de aquisição de dados.

Os sistemas de aquisição de dados baseados na técnica Single Photon Counting mereceram especial atenção. Os algoritmos de trigger da missão EUSO foram estudados e implementados na simulação geral. O desenvolvimento e teste de grande parte do firmware de GAW é da responsabilidade do LIP. Os trabalhos efectuados neste domínio estão aqui reportados.

O desenvolvimento de firmware neste quadro requereu a instalação do LIP-eCRLab, equipado com equipamento de teste e medida de grande desempenho. Neste laboratório existirá também uma vertente ensino, nomeadamente em electrónica digital avançada. Foram também desenvolvidos sitemas autónomos de aquisição de dados baseados na LIP-PAD e projectada a sua sucedânea - a LPV3.

No âmbito do Observatório Pierre Auger foi estudado o desempenho dos seus telescópios de fluorescência utilizando a simulação desenvolvida no LIP. Neste estudo estimaram-se os parâmetros ópticos do telescópio bem como a sua eficiência. O estudo da eficiência relativa ao longo da câmara abre a perspectiva para estudos aprofundados utilizando dados reais.

Palavras-chave: Raios Cósmicos, Aquisição de Dados, GAW, ULTRA, EUSO, Auger

Abstract

This thesis reflects the work developed in Data Acquisition systems for Cosmic Rays detectors and performance studies of such detectors.

Electronics firmware was mainly developed in the context of Single Photon Counting detectors. The EUSO mission triggering system algorithms and implementation in simulation, complying with the electronics constraints of the mission are reported. The EUSO detector concept is being applied in GAW, a gamma-ray experiment. The firmware of great part of GAW electronics is being developed at LIP and already some interface boards were produced and tests performed.

The requirements of such developments led to the creation of the e-CRLab, a digital electronics laboratory equipped with state of the art test and measurement equipment. Teaching activities in digital electronics and FPGAs are also planned for the e-CRLab. A new generation of LIP-PAD, successfully used in ULTRA and TRC, is being designed.

In the Pierre Auger Observatory the fluorescence telescopes performance was studied using a new simulation developed at LIP and integrated in the Auger simulation framework. This study led to the estimation of optical parameters of the telescope and its efficiency. Studies on relative efficiencies throughout the whole focal surface open a window to explore data.

Key-words: Cosmic Rays, Data Acquisition, GAW, ULTRA, EUSO, Auger

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Chapter 1

Introduction

The history of cosmic ray physics is almost one century long. It started in 1912 when a flux of charged particles coming from above was detected using electroscopes. In the 1930s cloud chambers with magnetic fields were used to study cosmic rays. The observation of tracks similar to those of electrons but bending in the opposite direction led to the discovery of the positron - experimental particle physics was born. In its early years experimental particle physics developed through cosmic ray studies, with the discovery of several elementary particles. In the 1950s, with the first particle accelerators, a controlled, high-luminosity, beam of particles became available and the two fields of research took different paths. However, in the last twenty years, perhaps the most important result in particle physics came from a non-accelerator experiment - Super Kamiokande - with the discovery of neutrino oscillations. In fact, in the last decades, the communities of particle physics, cosmic rays and astrophysics have become increasingly aware of their similarities in terms of methods, tools, language and goals, and of the complementary nature of their probes to the frontiers of our knowledge of the Universe. This opened the field known as astroparticle physics, and has led to a new generation of cosmic ray experiments, which nowadays incorporate the complexity of interaction models, simulation tools, large collaborations and detectors typical of accelerator environments.

Historically, the great steps forward in cosmic ray physics were always linked to the evolution of detectors, progressively becoming more sensitive, precise and autonomous. This was the case in the discovery of Extensive Air Showers (EAS), made possible by fast timing coincidence units with a resolution better than five microseconds. The discovery of air showers was in fact crucial in terms of making sense of the observations: particles often came in bunches originating from a single particle hitting the top of the atmosphere, and what reached ground, actually secondaries, depended on the original energy. We were no longer simply counting particles actually created in the atmosphere, but now had the concept of a primary particle coming from somewhere in the cosmos, and more and more rare as it became more energetic. The ground observations of EAS became the way of indirectly extracting information about these primary particles, in an attempt to understand their properties and origin.

Large aperture EAS detectors on the ground were for decades the only way to detect high energy cosmic rays hitting the top of the atmosphere. These detectors, composed by particle detectors disposed in arrays, became steadily larger and more sophisticated. The increase in the aperture compensated the power law reduction of the cosmic ray energy spectrum, allowing the study of ever higher energy cosmic rays. New techniques exploiting the light component of the showers appeared more recently: fluorescence telescopes, detecting the light produced by the de-excitation of the nitrogen molecules in the air excited by the shower particles, and Cherenkov telescopes, detecting the Cherenkov light produced by energetic shower particles travelling faster than the speed of light in air. In both cases, the detectors are actually UV telescopes, with optical systems consisting typically of large mirrors and segmented cameras.

In 1981 Fly's Eye became the first cosmic ray experiment employing the fluorescence technique. As the faint and isotropic fluorescence light is only intense enough for very energetic showers, and because it allows the observation of a large volume of atmosphere, this technique is particularly well suited for the low flux, high energy, end of the spectrum, where it has the advantage of providing a picture of the longitudinal development of the shower and a relatively more direct measurement of the energy with respect to ground detectors. While new sources of systematic errors arise in this method, the complementarity between the two techniques is in fact one of the keys to precise, well control and reliable results. It is also one of the great strengths of the Pierre Auger Observatory, a giant hybrid observatory combining the two techniques. The southern site of the Auger Observatory has recently been completed. The striking first results have already been made public, firmly establishing the existence of the GZK cutoff and the anisotropy of the highest energy cosmic rays, as well as raising very interesting puzzles concerning their nature and their interactions in the atmosphere.

Imaging Atmospheric Cherenkov Telescopes (IACT), on the other hand, detecting the rather collimated light cone along the shower axis, are well suited for an intermediate energy range, with larger fluxes, and in particular for the detection of the purely electromagnetic showers produced by TeV photons. Cherenkov telescopes are today living a golden age, with the discovery of a large number of new point sources in only a few years and interesting results concerning the diffuse component. R&D in this domain is of the uttermost importance to allow for a future generation of detectors that is not only bigger but also better. One of the limitations of the present Cherenkov telescopes is the very small field of view, and the GAW - Gamma Air Watch - project addresses this issue by testing an innovative optical and light detection system.

While dealing with different primary particles and energies ranges, extreme energy cosmic ray detectors and Cherenkov telescopes have in common the goal of understanding the origin of very high energy particles in the Universe. Also, as light detectors, they share a number of detection techniques and characteristics. Finally, with the great success of the Auger observatory and the very interesting data expected in the years to come, and with the outstanding gamma results and the preparation of the next generation, both fields are today in a very exciting period.

The boom in astroparticle physics, and in particular the interest in extreme energy cosmic rays and gamma rays, grew in Portugal only in the late 1990s. The birth of this thesis is intimately related to this event. In 2000 LIP became involved in the EUSO space mission, an ESA mission to be installed in the International Space Station with the goal of detecting extreme energy air showers from above, with an extremely large field of view. This was the staring point for establishing a framework for high energy cosmic ray research in Portugal. A few years later, the participation in the EUSO trigger system design, as well as in supporting experiments for EUSO, was the starting point of this thesis. EUSO successfully completed, from both the technical and the scientific point of view, the Phase A study. The mission was nevertheless put on hold due to financial and programmatic issues related to the Columbia Space Shuttle accident. LIP joined the Pierre Auger Observatory in 2006. As a natural follow up of its experience in EUSO, the LIP group concentrated efforts in the fluorescence detectors. In this context detailed studies of the Auger fluorescence telescopes were performed, namely through precise Geant4-based simulation tools developed in Lisbon. LIP also became involved in GAW, an R&D project in which some of the solutions studied for EUSO, namely the Fresnel lens optical system, the highly-segmented focal surface and the use of the single photon counting technique are being studied for the next generation of Cherenkov telescopes, in order to build a highly sensitive, large field of view detector. LIP has considerable responsibilities in the development of firmware for the GAW trigger and data acquisition systems. This path from EUSO to Auger and GAW was, in addition, crossed by smaller R&D projects mainly for education and public outreach, but also support activities for the main experiments. These activities relate basically to the development of data acquisition systems for cosmic ray detectors and were an important part of this work.

While the path in this thesis is not a straight one, its key subjects remain clear, and are twofold: the development and detection of air showers, in particular of their light component; and the development of detectors, in particular of trigger and data acquisition firmware. The key projects are, chronologically, EUSO, the Auger Observatory and GAW, together with supporting activities both to the main projects and to education and outreach activities developed at LIP. This thesis is organised as follows: a brief introduction to cosmic ray physics, with emphasis on air shower development and including simulation studies of EAS properties, is presented in chapter 2. An overview of the several relevant projects, EUSO, the Pierre Auger Observatory and GAW, is given in chapter 3. Chapters 4 and 5 relate to the LIP cosmic ray electronics laboratory. While chapter 4 describes the installation and the activities of the laboratory, chapter 5 describes in more detail the design of the data acquisition board LIP-PAD, used both in the ULTRA supporting experiment for EUSO and in the TRC educational project and, in general, well suited for small cosmic ray projects. Chapter 6 and chapter 7 concentrate on the work developed specifically for the main projects. The work developed on trigger design for systems using the single photon counting technique, in the context of EUSO and particularly GAW, is reported in chapter 6. The studies on the performance of the Auger fluorescence telescopes are presented in chapter 7. In chapter 8 some conclusions are drawn.

Chapter 2

Conclusions

The work in this thesis was developed in the framework of astroparticle experiments, namely in the context of EUSO, the Pierre Auger Observatory and GAW. The main focus is in the development of hardware and firmware for data acquisition and trigger systems and detailed studies of the detectors.

In this thesis was presented the first general purpose data acquisition board for cosmic rays developed at LIP - The LIP-PAD. This board was the building block of the DAQ system of ULTRA - a support activity for the EUSO mission, and was able to cope with all the experiment requirements. This board was also applied in the TRC - a public education and outreach project installing cosmic ray detectors in high schools. In the course of the project it was observed that a greater degree of autonomization of the DAQ system was important. This fact triggered the development of a new generation of the board, giving birth to the LPV3, incorporating performance upgrades (200 MHz sampling with 12 bits in resolution) and stand-alone operation (ethernet communication and processing capability). The board is currently in the prototyping phase. The final version will allow a completely autonomous DAQ system in the TRC project and will also provide a simple, yet high performance, data acquisition system for small experiments.

An important achievement was the installation, at Lisbon, of the LIP e-CRLab, an electronics laboratory dedicated to cosmic ray physics. This laboratory has state of the art equipment that will allow LIP to participate in the development of sophisticated instrumentation for cosmic ray detectors. The laboratory is centred on the development and test of firmware for FPGA based DAQ systems. Nevertheless, the laboratory has also the tools to produce electronics boards and prototypes to interface DAQ system and to test the adopted solutions. Some prototype boards have already been produced completely in the laboratory and final versions have been designed and assembled in the laboratory. One other benefit of the laboratory is related with education. From September 2008 onwards, periods of training for first cycle students were organised. The first course in digital electronics, for second cycle students, will begin in the spring semester of 2008-2009. This will give students the opportunity to became familiar with the state of the art techniques and instruments used in digital electronics.

The design and implementation of trigger systems in the context of the single photon counting technique was also pursued. The firmware development and implementation became possible with the installation of the e-CRLab. First, the algorithms are implemented in firmware. Afterwards hardware tests are performed. LIP has taken the responsibility not only for the trigger system but of a major part of GAW DAQ firmware development. The different firmware components needed to be tested separately which implied the production of interface boards. Functional tests of the ProDacq were performed using a prototype interface board designed and produced in e-CRLab. Performance tests will require the board to be operated at maximum frequency (hundreds of MHz). Thus, the interface boards were redesigned for such frequencies and its production outsourced. The first tests have already started. The assessment of the trigger performance passed through end-to-end simulations for the study of the trigger efficiency and rejection parameters.

A detailed performance study of the fluorescence telescopes of the Pierre Auger Observatory was also one of the main subjects addressed in this thesis.

The complete geometry of the telescope was implemented in the Auger $\overline{\rm Off}$\underline{line} simulation framework, using the Geant4 toolkit. The comparison with the existing simulation code showed an overall agreement. However the new code can produce more detailed simulations including some specific features of the telescope optics. Differences on the optical efficiency of the telescope at the level of 1 to 2% were found. The simulation developed constitutes now a tool for detailed simulations of the detector available to the Collaboration. This tool is already being used by the Genoa group to simulate the expected signals induced by muons crossing the detector. The Geant4 simulation is a very versatile tool and allows easy implementation of different geometries of the detector which may be quite important for the design and optimisation of the fluorescence telescopes for the northern site of the Pierre Auger Observatory.

In this thesis detailed performance studies on the light collection efficiency of the FD camera were performed. The light collection efficiency and uniformity are crucial properties of the FD camera. The light collection efficiency of the FD camera pixels has been studied and mapped using simulated data and laser events. For each case, pixel maps of relative efficiency as a function of the position within the pixel have been produced. Using laser events, the sensitivity of the efficiency modulation within a pixel to the physical spot size was exploited.

In recent years cosmic ray experiments have increased their sensitivity and exposure dramatically. Furthermore these new-generation experiments are taking extreme care with the systematic uncertainties and have gone to a higher level of detail in the comprehension of both the detector itself and of the physics processes involved. This path will be followed by forthcoming experiments that will pose stringent requirements in the design of new detectors and will incorporate new technologies. The improvement in the detectors performance will for sure allow to further enhance knowledge in cosmic ray physics

Bibliography

Abbreviations

CAMAC Computer Automated Measurement And Control

CLF Central Laser Facility

FD Fluorescence Detector

I2C Inter-Integrated Circuit (Serial communications protocol)

NIM Nuclear Instrumentation Module

RS232 Recommended Standard RS-232; A standard for serial binary data signals

SD Surface Detector