Embedded System for an airborne payload to determine cosmic ray flux

Sanket Deshpande, Lucky N. Kapoor
Department of Physics
Birla Institute of Technology and Science, Pilani
Goa, India
sanket@ieee.org, luckykapoor03@gmail.com

Dr. Satyanarayana Bheesette, Ravindra R. Shinde
Department of High Energy Physics
Tata Institute of Fundamental Research
Colaba, Mumbai, India
bsn@tifr.res.in, rrs@tifr.res.in

***Abstract* — Radiation due to high energy Cosmic Ray particles is known to cause anomalies in the electronic devices. As the devices get smaller the effects could lead to drastic results. A near space experiment was designed to study the variation of the cosmic rays with altitude. This paper presents the details of the experiment focusing on the embedded system designed specifically for the experiment. The data acquisition system and power supply circuits have been discussed along with various precautions that are needed to ensure precision measurements of the experiment.**

Keywords — High Energy Cosmic Rays; Embedded System; Data Acquisition System; High Voltage Power Supply; Near Space Experiment

I. Introduction

In the past 100 years, since the discovery of cosmic rays, a lot of research has been done to determine their origin and their interaction with the earth's atmosphere. The most basic way to understand these cosmic rays is that they are high energy particles from the space. These particles are of extreme importance to scientific pursuits involving high altitudes and space exploration. The scientific goal of our experiment is to study the variation of the flux of cosmic rays with altitude. The data acquisition (DAQ) system and power supply for such an experimental setup are the focus of this paper.

From extensive study of high energy cosmic rays, it is known that these particles on interaction with the atoms and molecules initiate reactions which might cause harmful effects on the human body[1] and anomalies in electronic devices[2]. Hence precautions are needed to ensure that such interactions are kept to a minimum. However, exposure to cosmic rays varies with altitude. Therefore, shielding from these cosmic rays will have different requirements depending on the altitude. This experiment aims at providing the data which will ensure that shielding is done according to the altitude at which the device will be used. To accomplish this aim, a high altitude balloon (HAB) is used to send the experimental setup to near space.

As the cosmic ray particles travel close to the speed of light, the signals generated by these particles have pulse widths in the range of nanoseconds. Hence the circuits should be able to faithfully and efficiently process such tiny and narrow signals. These circuits should also ensure that the acquired data represents the true experimental conditions. The power supply to such a system should provide the required supply voltages strictly within ratings as well as maintain very low noise - both of low and high frequency types. As the experimental setup has to be sent in a HAB, the power supply circuits have to be designed accordingly. While the cosmic ray detectors onboard require high voltages for their operation, the signal processing electronics needs 5V regulated DC supply. Due to these requirement as well as since the instrument is going to be near space borne, precautions have to be taken for excellent isolation and shielding of the power supplies.

This paper is organized as follows. Section II explains the basics about cosmic rays and the methods of its detection. Section III presents the flight plan for the near space experiment. Section IV presents the design of the cosmic ray detector used for the experiment and the setup of these detectors. Section V provides the details of the data acquisition system custom-designed for the experiment. Section VI discusses the two different circuits required for supplying power to the system. Section VII concludes the paper.

II. Cosmic Rays and Its Detection

Cosmic rays consist mainly of beta particles, hydrogen nuclei, alpha particles and atomic nuclei of heavier elements. A small proportion of positrons and antiprotons have also been detected in the cosmic rays[3]. Even though the origin of high energy cosmic ray particles is an ongoing research, various theories suggest that the majority of them originate from deep space sources such as the supernovae of massive stars. Other potential sources of cosmic rays are quasars[4] and active galactic nuclei[5]. The energy of these particles span a wide range from 10^7 eV to 10^{20} eV. The peak of the cosmic ray energy distribution is in the range 100MeV – 1GeV. While the occurrence of the lower energy particles ($<10^{14}$eV) is fairly common, the detection of ultra-high-energy cosmic rays is rare[6].

While the earth's atmosphere shields us from the harmful effects of the cosmic rays, it also makes direct observation of cosmic rays inside the earth's atmosphere extremely difficult. Detecting the cosmic rays directly would require an experimental setup above the earth's atmosphere. Various methods have been developed to detect cosmic rays indirectly where the interaction of the cosmic rays with the earth's atmosphere is studied, hence making the earth's atmosphere itself a giant cosmic ray detector. One of the most common methods using a plastic scintillator has been used in our experiment.

When a scintillator is struck by a charged particle, it absorbs the energy of the particle and emits light proportional to the energy of the particle. Scintillators are used for various applications where the aim is to track and measure energy of particles. Apart from high energy particle physics experiments, they could also be used to detect x-rays and radioactive contamination[7]. In this experiment, the scintillator has been coupled with a photomultiplier tube (PMT). PMT is an extremely sensitive detector of light. It multiplies the current produced by the incident light by several hundreds of times and therefore is suitable for detecting the fluorescence produced by the scintillator. Therefore, a scintillator coupled with an appropriate PMT forms a perfect setup for a high energy cosmic ray (HECR) detector.

III. Flight Plan

To accomplish the aim of our experiment, a high-altitude balloon (HAB) would be used to send the payload to an altitude of approximately 25 kms. A high-altitude balloon can sustain high pressure differences and hence can cover high altitudes before bursting. The experimental setup along with all the electronic components would be integrated inside a polyurethane box and tied securely to the HAB. A small parachute would also be attached to the payload to ensure smooth return of the payload to the ground once the balloon bursts. The material of the box has been chosen to ensure that the temperature inside the box is not affected drastically by the temperature outside which is expected to vary from 30º C to -60º C. The payload will also have a transmitter to send data to the ground station. This would include the experimental data as well as the current location of the payload. Relaying continuous and accurate data to the ground station is important as the trajectory of the HAB flight cannot be controlled and hence might lead to the payload ending up in a hostile location at the end of the flight. It will ensure that even if the payload is lost, there would be a copy of the data collected at the ground station.

IV. Detector Design and Experimental Setup

The scintillator chosen for this experiment is a plastic scintillator, Eljen Technologies EJ 208. It is coupled with a photomultiplier tube, Hamamatsu R6233. This combination is chosen because the light output of the scintillator peaks at 430 nm wavelength while the sensitivity of the photomultiplier tube peaks at 420 nm which makes them highly compatible with each other. The photomultiplier tube is coupled with the scintillator crystal with the help of an optical glue as shown in Figure 1.

The photomultiplier tube generates analog signals. The amplitude of these pulses corresponds to the intensity of light detected by the photomultiplier tube. The intensity of light depends on the energy lost by the charged particle striking the scintillator block. Hence, this setup also enables us to measure the energy of the incident charged cosmic ray particles (though this is not the aim of the experiment).

The detectors have been designed to detect charged particles (excited to an energy above a certain threshold) incident on them. Apart from cosmic ray particles, there are several other charged particles present in the ambience which are capable of generating a signal in the detector. These background signals might be generated due to in-situ radiation or similar sources. Therefore, all the pulses generated by a detector do not necessarily indicate incidence of a high energy cosmic ray particle.

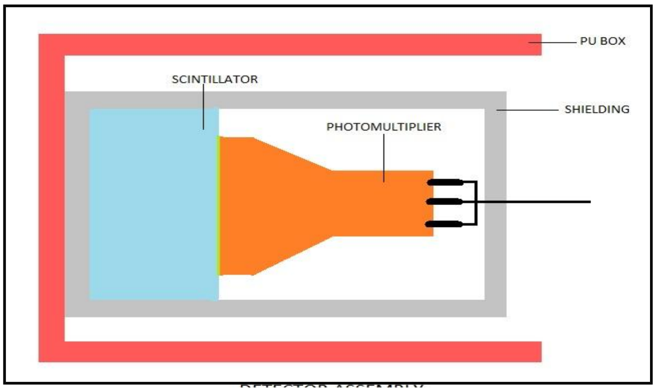

Figure 1: A sketch of detector assembly

Since cosmic rays are incident on the surface of earth from the outer space, their incidence path is considered to be in a straight line perpendicular to the earth's surface. The ambient charged particles produced on earth move in arbitrary directions and hence do not follow the phenomenon of vertical incidence. Therefore, if we mount a detector vertically above another, simultaneously generated pulses in both the detectors shall indicate the incidence of cosmic ray particles while the uncorrelated pulses are considered as background and therefore discarded.

In this experimental setup, three detectors have been arranged vertically one above the other. The simultaneous production of signals in the three detectors is therefore considered to be due to incidence of cosmic ray particle. This method of identifying simultaneous signals from each of the detectors is called as 'coincidence'.

V. Data acquisition System

The photomultiplier tubes generate output in the form of analog signals. The amplitude of these pulses are also indicative of the energy of the incident cosmic ray particles. In this experiment only the flux of the cosmic ray particles is being measured, therefore the energy of incident particles is not significant.

The basic functionality of the data acquisition system is to count the number of cosmic ray particles being detected in a particular time period and store it on-board the payload. Simultaneously, temperature (inside the payload), pressure and GPS coordinates are also recorded. The data is converted to a suitable format and transmitted back to the ground station.

Inputs to the data acquisition boards are fed from the photomultiplier tubes in the form of analog signals. The signals are transmitted using coaxial cables of 50Ω characteristic impedance with a BNC type connector at the end. Termination protection is given so that a spike in the input signal does not damage the remaining circuitry. A blueprint of the DAQ system is shown in Figure 2.

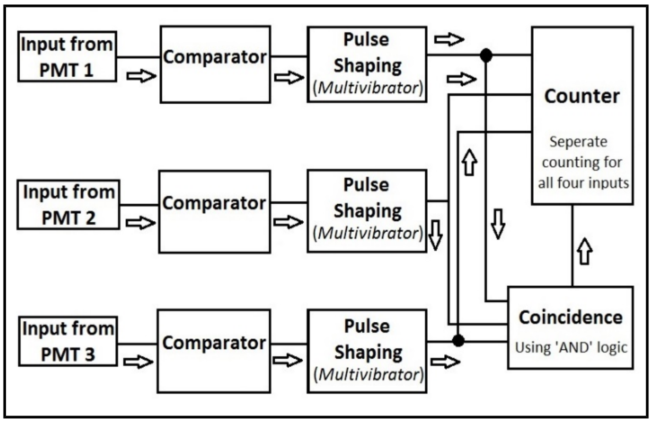

Figure 2: Blueprint of the DAQ System

A. Discrimination: Analog to logic conversion

The first step towards handling the incoming signal is to convert it to a logic signal. The analog input from the photomultiplier tubes is in the form of pulses of negative amplitude. Apart from the signals generated by genuine cosmic ray particles incidence on the scintillator, the PMTs also produce other pulses of lesser amplitude due to noise and background radiation. Eliminating this noise or background signal and converting analog signals into logic signals is the function of discriminator circuits.

Along with the discrimination function, the output logic pulses should be complementary with respect to input, that is, should have positive amplitude. A high frequency differential comparator with complementary TTL outputs, LM360, is chosen for this purpose. Hence, each cosmic ray particle incidence will be represented by a pulse of +5V amplitude with the same time duration as that of the input analog pulse. In the absence of incidence, the output would be 0V. The output is taken from the complementary output pin which is a logic pulse of +5V generated when the analog input pulse crosses a certain threshold value. This eliminates noise which is generally of lesser amplitude than the pulse. The comparator IC requires both, Vcc (+5V DC) and Vee (-5V DC) supplies.

B. Discrimination: Pulse duration

The TTL logic signal generated for each incidence of cosmic ray particle is of a different time duration. Therefore, it is necessary to change the time duration of each TTL pulse to a fixed duration for all signals. For this purpose, a multivibrator IC SN54LS122J is chosen. The time duration is set so that it is greater than the maximum recorded time duration in a calibration experiment but has to be less than the time difference between two consecutive incidences. The time duration of a pulse is adjusted by choosing a suitable resistor-capacitor combination. Same procedure is followed for signals from all three photomultiplier tubes.

The input pulse from the PMT sometimes has an undershoot of magnitude greater than the threshold set for the comparator, as seen in Figure 3.

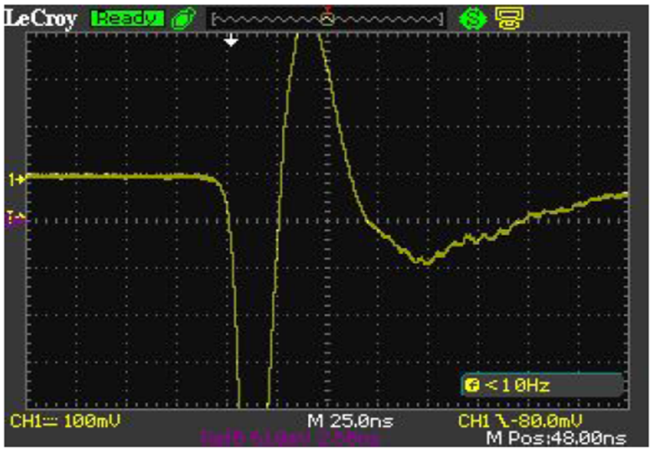

Figure 3: Example of an undershoot pulse from PMT

This leads to generation of two different logic pulses, one for the actual incidence and another due to the undershoot. This is undesirable. With the use of this IC, the input pulse can be extended for a desirable duration of time. The duration of the pulse should be selected so that it extends over the undershoot duration and therefore, only a single TTL pulse is generated corresponding to each particle of incidence. The duration should be less than the time period between two consecutive incidences. These two parameters (time duration of undershoot and time between two consecutive incidences) are determined in a calibration experiment. The time duration of the output pulse is selected with the help of a suitable R-C combination. In this IC, the resistor is inbuilt, therefore only capacitor is connected between the Rext/Cext and Cext pins of the IC.

C. Coincidence

Coincidence is the process of finding the simultaneous pulses in all three detectors. This is achieved by a simple AND operation which ensures that the logic is high only when it is high for all three detectors and low otherwise.

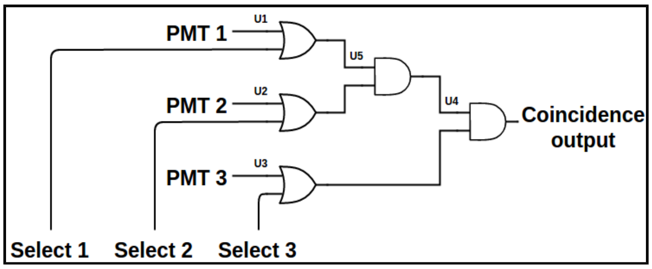

Figure 4: Schematic of coincidence Logic

A special type of arrangement has been made which provides control over the coincidence detectors. The user can choose any two or all three detectors over which coincidence is desired. As seen in Figure 4, there are three OR gates which are further connected to AND gates. Input lines from PMTs via the comparator and multivibrator ICs are given as one of the inputs for each of the OR gates. The other input to each of the OR gates are select lines from the microprocessor. If inputs from PMT 1 and PMT 3 are desired for coincidence, select lines 1 and 3 are set to low logic (0V) while select line 2 is set to high logic (5V). This ensures that only signals from PMT 1 and PMT 3 are passed to the AND gate for coincidence. If all three inputs are desired for coincidence, then all three select lines are set to low logic level (0V) which allows signals from all PMTs to pass through the AND gates for coincidence. The coincidence output signal is again passed through the monostable multivibrator in order to ensure that the pulse duration is restored to the desired value.

D. Counting

There are four signals obtained after the discriminator and coincidence circuits. Counting the number of pulses in each of these signals is required to measure the cosmic ray flux. The time duration over which these four readings are taken is decided by refresh rate set in the microprocessor.

The counter IC is a dual 16 bit counter, hence, two ICs are required for four input signals. The chip select lines of the decoders, (G2A)' and (G2B)' are active low and hence kept at lower logic level while G1 is kept at high logic level. The IC has only 8 output lines. Therefore, the output is taken in form of two parts of 8 bits for each counter. The address bus lines A, B and C are inputs taken from the microprocessor for selecting the output display.

E. Microprocessor Control Unit

The microprocessor is an important component of the entire system. It is responsible for controlling the coincidence logic and the counters, obtaining and storing data and sending it to the transceiver. The processing speed of the microprocessor should be able to match the fast incidence rate of the cosmic ray particles. In a testing experiment, the frequency of incident cosmic ray particles was detected to be around 4 Hz on a single detector. This implies that on an average, four particles are detected in one second time interval.

In order to ensure robust processing and lossless data handling, the BeagleBone Black Rev C development board was chosen. It features Sitara ARM Cortex A8 processor (AM3358) from TI. It features a clock speed of 1 GHz and 2000 MIPS. In an approximate comparison, the rate of 2000 MIPS is more than satisfactory for the required rate of detection of 4 particles in one second. Hence, the microprocessor suits the needs of the project.

This development board also features 512 MB DDR3 RAM along with 4GB on flash storage on board the device. It is possible to interface a storage device over USB or a micro SD card with this development board. This provides enough storage capability for recording data of the entire experiment.

BeagleBone Black also provides connectivity with 92 pin headers which includes 69 GPIOs as well as I2C and SPI ports. This makes this development board suitable for interfacing with the data acquisition system and the transceiver (over serial interface).

F. Other considerations for reliable data acquisition

The entire data acquisition system is very sensitive and therefore is prone to errors due to noise in the input signal, bad quality power supplies or due to external disturbances. Hence, following measures are taken to prevent these problems:

- The input signal from the photomultiplier tubes is passed through a spike protection arrangement. This prevents any spikes with relatively high voltage in the input signal from propagating further.
- The power supply for the data acquisition system is a regulated 5V DC. Despite regulation at the source, the VCC terminals of all ICs are provided with decoupling capacitors. This provides ripple protection and prevents variation in output signal due to variation in input power.
- The entire PCB is provided with shielding from electromagnetic radiations (which are prominent at high altitudes) by enclosing it in an aluminum enclosure.

Along with the cosmic ray flux measurements, the experiment also measures temperature and pressure readings simultaneously. The pressure readings can be calibrated to calculate the relative altitude of the payload. Therefore, a cosmic ray flux versus altitude profile can be developed with simultaneous temperature readings.

The data collected and stored by the microprocessor forms the crux of the experiment. Hence, in order to retrieve this data, it becomes essential to retrieve the entire payload after its flight. Although the probability of the payload being damaged or lost after the flight is low, in such a scenario, the experiment wouldn’t bear any fruit. Hence, it is necessary to transmit and record the data in real-time. This is achieved by installing a radio transceiver on-board the payload which is connected with the ground station transceiver on a permitted frequency band. The data is transmitted from the payload to the ground station and securely saved while the payload is in flight.

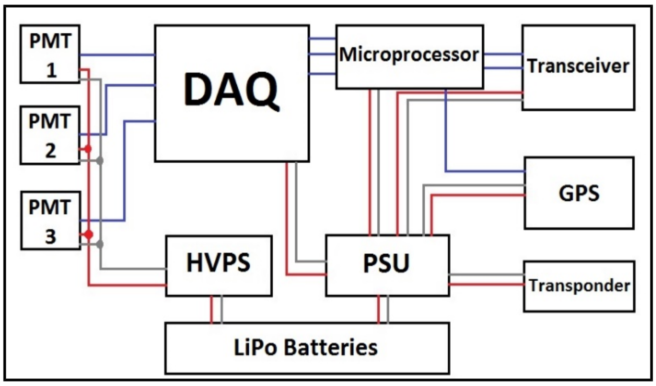

Figure 5: Overall integration of the experiment

VI. Power Supply

A. High Voltage Power Supply (HVPS)

As mentioned above, the detectors consist of a scintillator blocks coupled with PMTs. A photomultiplier tube typically operates at a high voltage power supply.

The following are the input power supply characteristics of Hamamatsu R6233 photomultiplier tube:

Type of current: DC
Anode to Cathode Supply Voltage: 1000V
Anode to Cathode Voltage: 1500V (max)
Average Anode Current: 0.1mA (max)
Power source on-board: 12V 5200mAH batteries

Therefore, the high voltage power supply circuit takes power input of 12V from the battery and converts it into a 1000V regulated DC supply. This supply should also be devoid of any ripples or other sort of fluctuations since the photomultiplier tube is highly sensitive device and slight changes in the power supply can lead to large distortions in its output signal.

The voltage conversion is implemented by using a voltage multiplier device. The details of the device chosen:

Manufacturer: PICO electronics
Model: 12AVR1000
Input voltage range: 10.5-13.5V
Load current: 1A (max)
Output voltage: 1000V
Regulation (0-100% load): 0.25% V_{out}
Output Ripple: 0.25% V_{out}, peak-peak
Switching Frequency: 25-33kHz

The output ripple of the chosen device is 0.25% of the output supply voltage (1000V). This is a satisfactorily regulated supply. In order to further reduce the ripple, filter capacitors along with a ferrite bead are added to the output of the voltage multiplier. Two capacitors - a high capacitance electrolytic type and lower value capacitance ceramic type, ensure ripples of both low and high frequencies are eliminated respectively.

Switching frequency is the frequency of operation of the voltage multiplier. Higher frequency ensures a smoother output DC waveform. The chosen model of the voltage multiplier has a switching frequency range of 25-33 kHz which is found to be suitable for our application. The irregularities in the output waveform of the voltage multiplier can be caused by an irregular input supply. Hence, the input supply to the voltage multiplier should be regulated as well. The input voltage for the voltage multiplier is 12V DC. This is obtained from a lithium polymer battery on-board the payload. In order to regulate this supply, a voltage regulator IC LM317 is used. Filter capacitors are used both at the input and output terminals of the regulator.

The final output voltage is then supplied to three photomultiplier tubes in parallel connection. Hence, this circuit ensures a smooth 1000V DC power supply to the photomultiplier tubes.

B. Regulated DC Power Supply Unit (PSU)

Lithium Polymer batteries with output rating, 10.5-12V are used as the power source for the payload. The electronic equipment on-board the payload (except the photomultiplier tubes) have been chosen to work on 5V DC supply. The comparator IC (LM360) which is a part of the data acquisition system requires negative voltage, -5V DC as a reference voltage. Hence a DC-DC converter is required to convert 12V DC power supply to negative voltage, -5V DC output. LMZ34002 is a negative output power module that has been chosen for this purpose. This has been supplemented with LM337 voltage regulator to provide a regulated output power supply.

The remaining circuits require 5V DC regulated power supply. This is obtained by using LM317 regulator IC which converts the 12V DC power supply to 5V regulated power supply. This is further supplemented by using filter capacitors and ferrite bead in order to improve the quality of power supplies. This is essential for sensitive data acquisition systems, since small surges in the power supply may affect the quality of data collected and hence the physics conclusions.

VII. Conclusion

This paper has illustrated the design of embedded system for an airborne payload to detect cosmic ray flux. It considers all design requirements and takes into account the data processing rate required for this purpose. The power supply systems have also been discussed in detail. It also sheds light on the probable causes of errors in data recording and incorporates methods to minimize such errors. Even though the DAQ circuit has been designed for this specific experiment, it could be easily applied for tasks which involve discrimination and coincidence circuits while the HVPS could be used for cases which require low ripple high voltage DC. Many different experiments can also be performed with the minor changes to the experimental setup.

The next step is to test this design in an experimental setup in simulated conditions before conducting the actual experiment in near-space. This will ensure the durability of the setup under harsh conditions. This will be followed by the actual experiment by sending the payload to near space in a balloon flight. Analysis of the recorded data will provide the necessary details to determine the variation of cosmic ray flux with altitude.

VIII. References

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