The Owl/Airwatch Experiment: the Focal Plane Detector

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Abstract

We propose to observe Extensive Air Showers (EAS) produced by Extreme Energy Cosmic Rays (EECR) with an opto-electronic instrument mounted on a satellite (Owl/Airwatch concept, OA). EAS will be detected by measuring the fluorescence produced by their interaction with atmospheric N_2.

One key element of the system is the detector. The requirements of large sensitive area and curved surface to match the focal plane design can be satisfied by using a mosaic of detectors. Commercial detectors exist with the required single photon sensitivity, pixel size, gain, fast response time, low intrinsic noise, weight and dimensions. Other characteristics still require a dedicated R&D program with the industry in order to get the final detector.

1 Introduction:

The Earth atmosphere constitutes an ideal target for the extraterrestrial radiation of very low flux like “Extreme Energy Cosmic Rays” with $E>10^{19}$eV. EECR primaries colliding with air nuclei produce a propagating cascade of particles. In the complex hadron-electromagnetic cascade the most numerous particles are electrons, their number at shower maximum is proportional to the energy of the primary. These electrons moving through the atmosphere ionize the air atoms and excite metastable electron levels. With minimum relaxation time, electrons from those levels return to the ground level emitting a characteristic fluorescence light that extends from IR to UV with peaks at wavelengths from 330nm to 450nm. The emitted light is isotropic and proportional to the shower size at any given depth in the atmosphere. A high energy EAS forms a significant streak of scintillation light over about 10km along its passage in the atmosphere depending on the primary energy and angle with the vertical.

Observation of this fluorescence light with a detector at distance from the shower axis is the best way to control the cascade curve. The detector records the shower emitting the fluorescence light, the resulting event seen by the detector looks like a narrow track in which the recorded amount of light is proportional to the shower size at various penetration depths in the atmosphere. The total light recorded is proportional to the primary energy and the shape gives an indication on the nature of the primary.

The OA project has the double role of measuring the intensity and the direction of the EECR. This goal is met by means of a detector at such high speed to allow a complete 3-dim shower reconstruction.

2 Detector Requirements:

The detector parameters depends on the OA optical system. The design criteria, based on the a 500km orbit, is a collection of unusual specifications: a large aperture (3÷4m) and a high transmission efficiency to collect a sufficient quantity of light onto the detector, a wide Field of View (FoV about ±30°) aiming to 2.6×10^5km^2 on Earth, a low F/# (of the order F/1) to keep the detector size within technological and practical limits. These physical conditions require a detector system of new concept:

1. fast response (of the order of few μs with sampling times of tens of ns) to determine the shower direction from one single observation point and be able to follow the space-time development of the shower avoiding the pile-up of photons produced by very high energy showers;

2. high gain, low noise and good signal to noise ratio to detect the faint signal produced by less energetic showers (E~10^{19}eV) and discriminate it from background in order to connect the observed energy spectrum with observations from previous experiments at lower energy;
3. single photon sensitivity in the 330-400nm wavelength range which includes emission bands of the nitrogen fluorescence light and in which the atmosphere is relatively transparent;
4. large collecting aperture and large FoV;
5. adaptability to a curved surface to fit the focal plane (many detector elements in a mosaic design).

The information can be obtained with a system having only a limited spatial resolution (of the order of 1mm corresponding to 1km on Earth). Radiation hardness, low sensitivity to magnetic fields, low power consumption, low weight, small dimensions, high reliability and stability over long periods as well as space qualification are also major requirements. We have investigated different detectors to determine the most suitable for our application. We have limited the analysis either to fully commercial detectors or to detectors in an advanced phase of development. The characteristics of the Multi-Anode PhotoMultiplier Tubes (MAPMT) are close to the above requirements but present devices have a too low sensitive/total area ratio (typically of 0.5). The small number of channels of commercial devices requires a close packing of a very large number of small devices on the focal surface. If the focal surface is curved the packing of the devices has to be optimized to reduce losses in the geometrical acceptance due to dead regions.

3 Multi-Anode PhotoMultiplier Tubes:

Hamamatsu Photonics produces multi-anode photomultiplier tubes (R5900 series) with up to 64 pixels. The 64 channel version has 8×8 square pixels of 2mm side while the 16 channel version has 4×4 square pixels of 4mm side. A four and single channel version are available with comparatively larger pixel size. The availability of different pixel sizes might prove to be very useful to match the pixel size to the focal length and point spread function of the optics. The response time is very fast (few ns).

The use of the 64 channel device will be assumed in the following. The tube is equipped with a bialkali photocathode and a UV-transmitting window which would ensure good quantum efficiency for wavelengths well below 300nm with a peak of 20% at 420nm. Results of preliminary tests carried out recently at Genova and CERN show a good agreement with the manufacturer specifications. With an applied voltage of 0.8kV corresponding to a PMT gain of 3×10^{5}, the background is expected to produce an average anode current of about 3μA and a low cross-talk of 2%. Using a resistive voltage divider the power consumption required to keep the output linearity to the per cent level (using appropriate decoupling capacitors) would be about 0.2W/device. If one accepts an output linearity to the 10% level a considerable factor can be saved in power. Alternative setups are being considered to save power.

3.1 Geometrical acceptance: An R&D program is under way to find possible solutions to the problem of the small geometrical acceptance. The acceptance could be improved by means of a suitable light collector system to be placed in front of each device performing the required demagnification. This might be a lens system, a system made of a bundle of tapered light pipes or a tapered fiber optics array.

3.1.1 Tapered light pipes: A system made of tapered light pipes has been fully simulated (Gracco, Petrolini, 1998). It consists of 8×8 square-section tapered slanted light pipes, one for each pixel, in such a way that the exit face has the dimensions of the MAPMT pixel and the entrance face dimensions of 1/8×1/8 of the $25.7\times25.7\text{mm}^2$ corresponding to the physical dimensions of the tube. The packing could be optimized to fit the required pixel size on the focal surface and the focal plane curvature. Each pipe would have the shape of a truncated skew pyramid with square bases. Photons would be driven to the photocathode by total internal reflection. The length of the pipe has to be a compromise between the need to avoid violation of the total internal reflection condition and the need to minimize the absorption losses inside the pipe. The optical performance of the light collector system has been studied by full ray tracing. Simulations with uniform angular and spatial distribution show that for a 50mm pipe length, any angular distribution with rays having up to 40° maximum angle of incidence has losses below 3%. Anyway if one accepts to lose about 10% of rays the length can be decreased to 20mm, which would improve considerably the effect of possible absorption losses inside the material. The performance is clearly strongly dependent on the maximum incidence angle of the rays which only depends, to a first approximation, on the F/# of the optics. If the maximum angle of incidence is kept below 30°, as is the F/1 case, a loss of ≈2% can be obtained with a 20mm length light pipe. The system performance has to be more precisely assessed by using the exact photon angular distribution provided by the optics. Possible methods to build the system are under study.

3.1.2 Lens system: Different lens systems have been studied to recover the geometrical acceptance of the MAPMT (Forty, 1998). One appealing possibility is to exploit the well known properties of hemispherical lenses in a system consisting of a plano-convex lens located in front of the MAPMT. The plane face is in optical contact with the MAPMT square input window. In the paraxial approximation a single spherical refracting surface will re-focus incident rays on a demagnified image. The lens radius of curvature is a free parameter to be optimized in order to limit aberrations (significant for a small curvature radius) and reduce absorption losses inside the lens (significant for large curvature radius). Aberrations, geometrical as well as chromatic, are important but not critical because of the low spatial resolution required. The system is very attractive because it is simple and cheap. Results of full ray-tracing simulation of the system are encouraging but are strongly dependent on the angular distribution of incident rays. The exact performance can be defined only after the optics has been designed.

3.1.3 Materials: The performance of the light collection system is strongly dependent on the availability of a suitable UV-transmitting material since a successful event reconstruction requires that light losses are kept to the minimum. The same plastics material used for the optics might be used for the light collection system. Quartz would not give any problem for the transmission but would increase significantly the weight. The sol-gel silica technology (Laser Focus World, 1995), allowing to produce high purity silica optics by means of a molding process, might prove to be a very appealing option.

3.1.4 Other options: Another possible implementation of the light collection system is by means of a fiber optic taper. The main limits of commercial fiber optic tapers are that they are normally made for use in the visible. The filling factor of the entrance face (sensitive to total area ratio) has also to be optimized. The same geometry used for the tapered light pipe system might be used for a system exploiting reflection on the walls of a set of empty pipes which would have the advantage of no absorption and no limits due to total internal reflection requirement. The large number of reflections requested and the large range of angles of incidence of photons on the wall would require a very high reflectivity in the wavelength range of interest and for a large range of angles up to grazing incidence.

3.2 Other types of detector: We have considered Hybrid Photon Detectors (HPDs) (Gys et al., 1995) as possible candidates fulfilling most of the requirements but the use of HPDs in OA would certainly require a long R&D and they probably cannot be considered a viable solution at least in a short time. Recently Hamamatsu Photonics has announced the release during year 2000 of a Flat Panel PMT promising multi-element connection and large sensitive area, ability of position detection, high speed response, high amplification, low cross-talk and low cost. We are looking forward this kind of detector which might be a viable alternative to the MAPMT providing a better sensitive to total area ratio.

4 Demonstration Model:

The problematic inherent to OA are at the base of the Demonstration Model, it includes in a scaled version most of the parts constituting the instrument planned for the mission. The DM serves to prove either the technological capability of constructing a working hardware unit and demonstrate the proposed technique can resolve the difficulties in detecting and handling EECR signals:

1. collect and focalize as much UV photons it can (optics);
2. detect focalized photons transforming them in electric signals (focal plane detector);

3. record the information (trigger and signals) in a format suitable for telemetry transmission.

The DM is made of three parts: an Event Simulator Display (ESD), a Focal Plane Detector (FPD) and the Fluorescence Imaging Read-out Electronics & trigger (FIRE). A Personal Computer interfaces the ESD and FIRE to get maximum flexibility. Light pulses generated by a changing pattern of a matrix of green LEDs are detected by the FPD and read-out by the FIRE modules. Each LED in the matrix can be single-addressed and a time-sequence of switched-on LEDs simulates an event. The event kinematics is reproduced by tuning the time sequence. Background sparse spots are simulated switching on randomly selected LEDs at a rate corresponding to the expected background. The signal intensity is obtained pulsing the LEDs at a tuned frequency corresponding to one kilometer of spatial resolution. This approach makes possible to simulate the shower profile event by event. For a visual inspection LEDs can be pulsed at a frequency suitable for eyes detection. During this phase the optical system is left intentionally out, lenses will be attached to the instrument after exhaustive tests will have been performed on the detector, trigger and read-out electronic.

5 Front End Electronics:

The large number of elements (of the order of hundreds of thousands channels) requires a sophisticated read-out electronics capable to handle such a large number of channels. The Front-End Electronics (FEE) performs the readout of the signals produced by the detector. High readout speed, low power consumption, low noise and small dimensions are fundamental requirements. The FEE must be able to sample every channel at the desired speed (of the order of tens of ns), buffer the data during the latency time of the trigger and minimize the dead-time during event readout. A simple binary readout would exploit the fast readout speed providing a low pixel occupancy for the signal but can give signal pile-up in the case of the highest energy air showers. A digital readout with an ADC is more suitable and allows to relax the required readout speed and provide more information. FEE interfaces is located close to the detector to minimize disturbances and reduce the number of connections. It performs the following main tasks: amplification, shaping and discrimination of the detector signal. The main characteristic of this front end is to reduce the pixel background rate by enhancing the signal to noise ratio and reduce the processing capability of the on-board computer in charge of the data analysis within acceptable limits. To reach the large scale integration necessary to interface and process a large number of pixel, the FEE is realized with ASIC (Application Specific Integrated Circuits) full custom technology. This implementation allows to get very high speed performances (about 10ns), very low power consumption (about 100μW/ pixel) and minimize the space occupation with respect to the detector sensitive area. To commission a full UV photon detector system a full VME-based data acquisition system, efficient and flexible, has to be installed for the detector read-out. This implies to determine the response speed, the uniformity of the response of different pixels and cross-talk, the detection efficiency and intrinsic noise. The reliability and long period stability will also be tested.

6 Conclusions:

No existing detector is able to fully satisfy all the Owl/Airwatch requirements but MAPMTs seem to represent a first viable solution. The final detector has to be the result of a dedicated R&D program, the available technology should be pushed by means of a collaboration with industry to satisfy the required characteristics and to define possible solutions for interfacing the detector with read-out electronics.

References

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