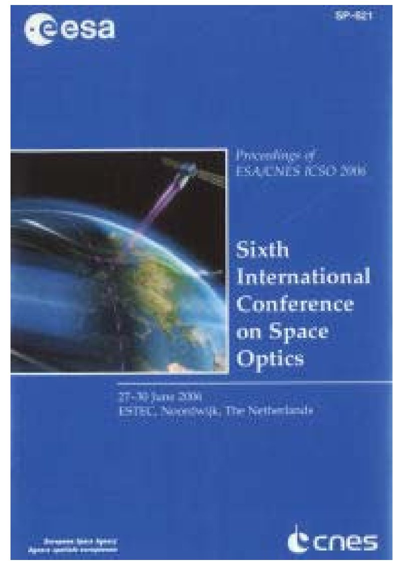
International Conference on Space Optics—ICSO 2006

Noordwijk, Netherlands

27–30 June 2006

Edited by Errico Armandillo, Josiane Costeraste, and Nikos Karafolas



Advanced optical systems for ultra high energy cosmic rays detection

L. Gambicorti, E. Pace, P. Mazzinghi

International Conference on Space Optics — ICSO 2006, edited by Errico Armandillo, Josiane Costeraste,
Nikos Karafolas, Proc. of SPIE Vol. 10567, 105673Q · © 2006 ESA and CNES
CCC code: 0277-786X/17/$18 · doi: 10.1117/12.2308137

ADVANCED OPTICAL SYSTEMS FOR ULTRA HIGH ENERGY COSMIC RAYS DETECTION

L. Gambicorti[(1,2)], E. Pace [(1)], P. Mazzinghi [(2)]

[(1)] *Dep. of Astronomy and Space Science, Florence University, Largo E. Fermi, 2 – 50125 Firenze, Italy*
[(2)] *CNR-INOA National Institute of Applied Optics,(Italy), Largo E. Fermi, 6 – 50125 Firenze, Italy*
Emails: lisag@arcetri.astro.it; pace@arcetri.astro.it; piero.mazzinghi@inoa.it

ABSTRACT

A new advanced optical system is proposed and analysed in this work with the purpose to improve the photons collection efficiency of Multi-Anode-PhotoMultipliers (MAPMT) detectors, which will be used to cover large focal surface of instruments dedicated to the Ultra High Energy Cosmic Rays (UHECRs, above 10^{19}eV) and Ultra High Energy Neutrino (UHEN) detection. The employment of the advanced optical system allows to focus all photons inside the sensitive area of detectors and to improve the signal-to-noise ratios in the wavelength range of interest (300-400nm), thus coupling imaging and filtering capability. Filter is realised with a multilayer coating to reach high transparency in UV range and with a sharp cut-off outside. In this work the applications on different series of PMTs have been studied and results of simulations are shown. First prototypes have been realised.
Finally, this paper proposes another class of adapters to be optically coupled on each pixel of MAPMT detector selected, consisting of non-imaging concentrators as Winston cones.

Key words*:* Photo-detector; Photo-multiplier; Light collector; Lens; Optical adapter; Filter

1. INTRODUCTION

In the last 40 years, UHECRs and particles detection led to several new questions concerning Astrophysics, Nuclear and Neutrino Physics. In particular, the unsolved questions are about their origins, propagation in space and spectrum of energy, which seems to have no extension limit according to actual data, [1].
A lot of experiments, [2][3], have been planned to observe from space the Extensive Air Shower (EAS) produced by UHECRs striking the Earth's atmosphere. Their low events flux (1 event/km^2/sr/century) requires to maximise the efficiency of telescopes used.
All these instruments will have a wide Field of View (FoV), to observe a large volume of atmosphere working as a scintillator by means of the interaction of such high energy particles, and large collection area to maximise the number of photons collected. The small f/# obtained for these instruments permits large focal surfaces [4], which allow recovering the photon signal generated with segmented and pixelated structure to reconstruct the trajectories of the particles, thus collecting the largest amount of photons while minimising the losses [5][6].
Advanced typologies of Multi-Anode-PhotoMultipliers (MAPMTs) detectors, developed by Hamamatsu corp., [7], will be used to cover large focal surfaces mixing the versatility of a segmented surface with a modular structure. Main interesting properties of these PMT are: a high sensitivity in UV and Visible wavelength range, single photon detection, a fast time of response, with a compact read out electronic and the photon position determination with the order of the pixel size, but the ratio sensitive/total area of considered PMT limits their efficiency (it is 45% for R7600 series, 74% for R8900 and 89% for the R7400).
In this paper an ancillary optical system is proposed and analysed to collect the photons only on the sensitive area of PMT selected, therefore minimising the share of dead area. Since the sensitivity of all the MAPMT series considered is between 300nm and 650nm, peaked at 420nm, a filter solution must be taken in consideration to avoid the detection of the 400nm to 650nm unwanted signal. As the employment of these detectors in previously mentioned experiments is limited, filtering capabilities have been included in such adapter through the implementation of a multilayer filter, to limit the detected radiation only to the wavelength range 300÷400nm, thus improving the detector signal-to-noise ration and reducing the MAPMT wavelengths pass band to the UV range.
In next sections of this paper the main characteristics of the advanced collection system will be described, as well as the optimisation procedures and performances evaluation of optical system designed to improve the MAPMT performances.
Finally, the results of ray-tracing simulations will be shown, together with the conclusions.

2. IMAGING OPTICAL ADAPTER

The ancillary optical system designed consists in a hemispherical lens as adapter. This shape allows

Proc. '6th Internat. Conf. on Space Optics', ESTEC, Noordwijk, The Netherlands, 27-30 June 2006 (ESA SP-621, June 2006)

maintaining the imaging capability, that in several experiments is a requirement necessary to obtain a well defined image on detector. High transmittance and low density of hemispherical lens bulk are main constraints for optical and space application respectively. For such purpose Fused Silica and UV grade PMMA (*Poly-Methyl-Meta-Acrylate*) have been selected, considering the transmissivity measured. In the whole spectral range (300nm 400nm) the PMMA transmittance, including reflection losses, is over 90% [8].
The solution that has been proposed in this paper is to design the optical adapter coupling the filter with the lens, obtaining a system with imaging an filtering capability.

2.1 Filter

A BG3 filter, consisting in coloured glass from Schott Glass [9], has been selected to be covered with a multi-layer, studied and optimised to limit the pass-band filter, maximising the transmittance in UV range.
The optimised multi-layer coating allows obtaining filtering properties to avoid background photons from nearby spectral regions and to minimise the wavelength shifting with respect to the increasing of the incident angle. The spectrum of transmissivity has been realised with high transparency in wavelength range of interest and with a sharp cut-off outside.

Fig. 1 shows the measured transmittance of 1mm of BG3 filter (blue line) in comparison with the transmittance of the 1mm BG3 filter covered with the realised multi-layer (red line). These measurements have been carried out in normal incidence.

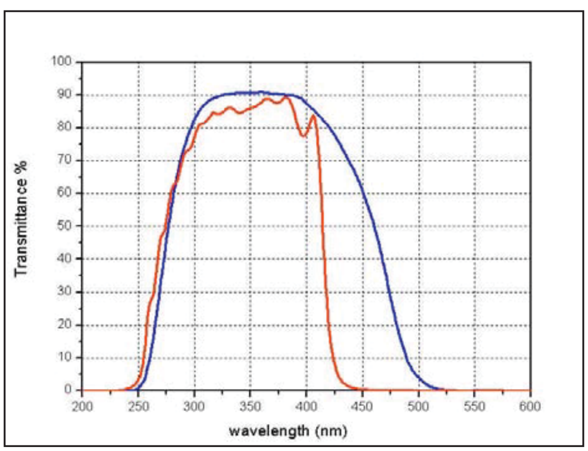


Fig. 1. Transmittance of 1mm of BG3 filter (blue line) in comparison with the transmittance of the BG3 filter covered with the realised multi-layer (red line).

2.2 Optical design

Ray-tracing programs have been used in order to optimise the design and the optical parameters of lenses as, for example, curvature radius and thickness for each MAPMT detectors series considered [10]. The lens is designed with squared section to fit total area of PMT and to focalise photons on sensitive area of detectors, minimising the photons losses in dead areas. A reflecting empty and truncated pyramid structure of four mirrors is placed on the flat back of the hemispherical lens in order to fit the lens size with the sensitive area of the detector side and collecting on it the amount of photons that still fall in dead area.
Fig. 2 shows the lens adapter section optimised for R8900-MAPMT detector series.

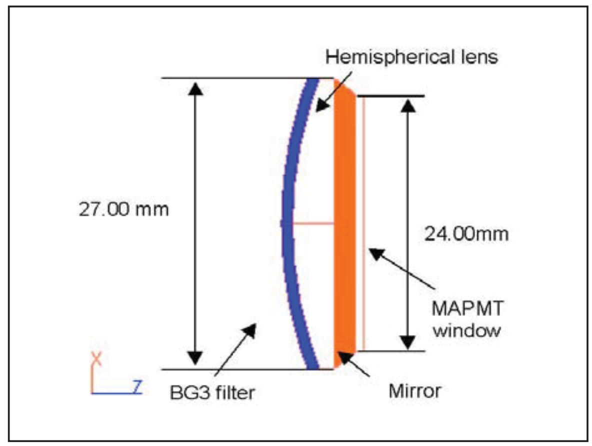


Fig. 2. View and section of PMMA filter lens optimised for R8900 MAPMT series. In blue the curved filter glued on hemispherical dome is showed and in red colours the mirrors structure on back of lens.

2.3 Ray-tracing simulation and results

The filter lens adapter performances have been evaluated with ray-tracing analysis using ZEMAX software. An extended uniform source emitting at atmospheric fluorescence wavelengths has been simulated representing photons generated from EAS and collected on focal surface.
Fig. 3 shows an example of the Encircled energy collected in each pixel of 2x2mm^2 for the R7600-M16 detector, using the filter lens designed.

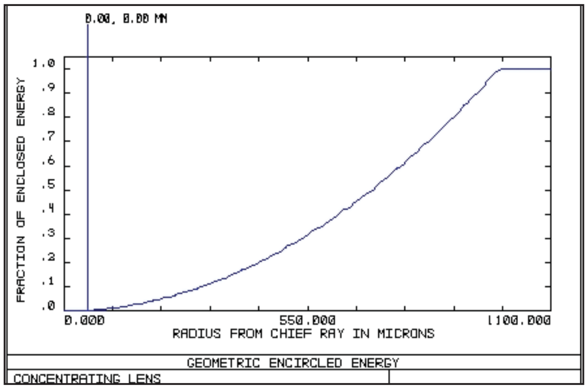


Fig. 3. Encircled energy collected in each pixel for the R7900-M16 detector, using the filter lens designed.

The geometric and the radiometric efficiency[i] are the parameters that determine the collection system efficiency of detector coupled with optical adapters.
For example Fig. 4 shows the layout of total area of R7600-M16 PMT after the ray-tracing simulation using hemispherical filter lens adapter coupled on MAPMT R7600-M16.

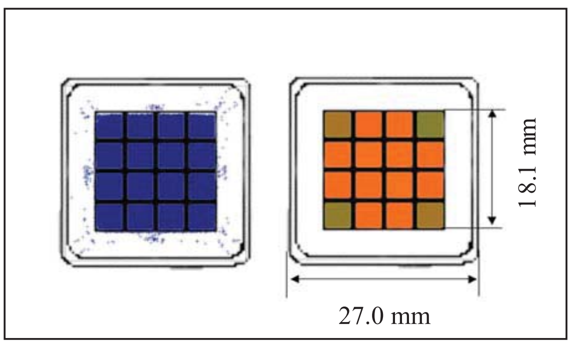


Fig. 4. R7600-M16 layout of total area illuminated with 10^6 rays at 357nm.

Geometric efficiency is represented in left side and the radiometric efficiency in right side of Fig. 4. The photons are concentrated in central region of sensitive area of detector where pixels are mostly illuminated. The ray-tracing results of geometric and radiometric collection efficiency for each filter lens series designed are obtained with simulations at wavelengths of nitrogen fluorescence peaks, Fig. 5.

The radiometric efficiency of the R7600 PMT and for R8900 PMT series results improved from 45% to 74% and from 74% to 95% respectively using these optical adapters. Therefore the advanced UV optical materials allows maintaining the low weight (including filters and mirrors) to be employed in space applications.

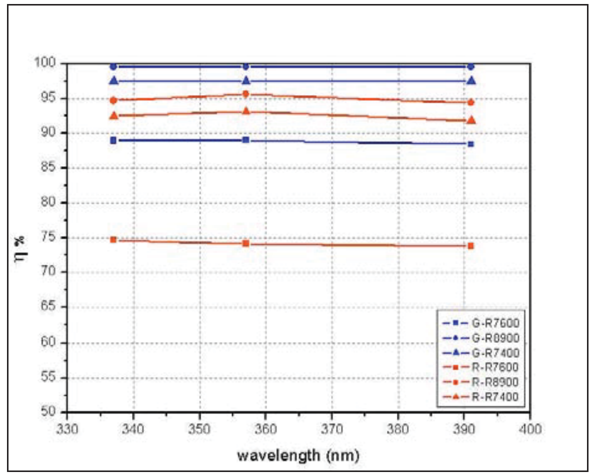


Fig. 5. Geometric, G, and radiometric, R, collection efficiency for each filter lens series designed at wavelengths of nitrogen fluorescence peaks, 337nm, 357nm and 391nm.

These results show the improved collection efficiency of detectors using the optical adapter designed in comparison with the ratio sensitive-total area of detectors. A similar study has been realised also for Flat Panel R7400-PMT and results are reported in Fig.5. Its efficiency increases up to 93% using filter lens adapter. In order to evaluate the imaging performance of the filter lens adapter, the simulation of a track has been performed for each PMT series [9].
A specific light source, diagonally crossing the MAPMT, has been simulated and the track results well defined on sensitive area of each PMT series. Fig. 6 shows an example of track obtained on R8900-M25.

Simpler version of hemispherical lens filter adapter has been realised for MAPMT 8900-M25/M36 detector. In this version the filter is the truncated pyramid and it is glued on flat back of Fused Silica hemispherical dome[ii]. The prototype of simpler hemispherical filter lens adapter has been realised, Fig. 7.

[i] Geometric efficiency: Ratio between rays collected on sensitive area with respect to the number of rays started from source.. Radiometric efficiency: Ratio of photons on sensitive area with respect to photons started from source, considering the absorption coefficient of adapter materials.

[ii] **CNR-INOA**, National Institute of Applied Optics, in collaboration with **INFN** section of Florence, realized the prototype of simpler hemispherical filter lens adapter, actually under test in laboratory.

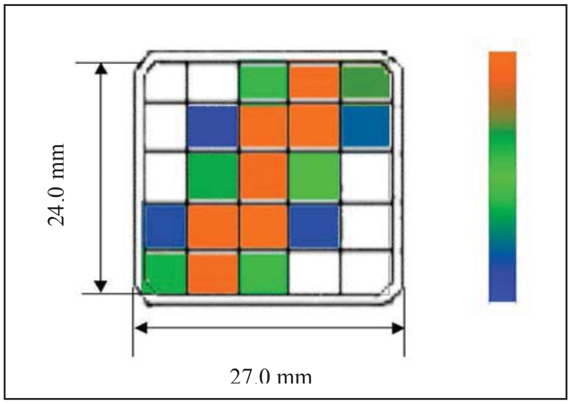


Fig. 6. Track simulated on optical adapter coupled with R8900-M25. Picture shows that it is well defined on sensitive area of PMT.

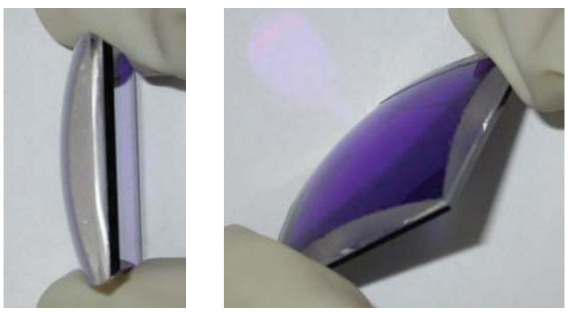


Fig. 7. Sections of Fused Silica filter lens realised.

3 NON-IMAGING OPTICAL ADAPTER

New type of concentrator is proposed, studied and simulated to be coupled on UV window of detector considered in this paper, allowing collect the photons on each pixel of detector.

Those adapters are Non-imaging Compound Parabolic Concentrator (CPC), designed with marginal ray method [11]. The longitudinal profile is a parabolic section and the concentrator is obtained through a revolution around the axis, resulting with cylindrical symmetry. In particular, we have carried out the design and simulations using ray-tracing programs to improve the collection efficiency of R7600-M16/M64.
The non-imaging concentrators performances have been simulated showing the efficiency of the solid CPC that arrive until 99%, but being the CPC with circular section respect to squared pixel, they cover the 78.5% of sensitive area.
An other non-imaging concentrator designed is the Flow Line Concentrator (FLC) [12], with hyperbolic profile, Fig. 8.

The FLC concentrators are in development and preliminary results of simulations show their high efficiency.

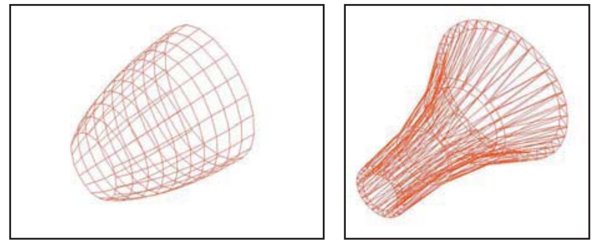


Fig. 8. Layout for the 3D-CPC and 3D-FLC simulated by Zemax in non-sequential mode.

4 CONCLUSION

In conclusion a new optical adapter system has been designed for space applications.
This system is capable to improve the collection efficiency of the R7600/R8900/R7400PMTs detectors, maintaining the imaging capability. A filter solution, to match the detectors wavelength pass band to the UHECRs detection, has been proposed and realised. Simulations demonstrate that, using these optical adapters, the collection efficiency results improved from 45% to 75% for R7600 MAPMT, from 79% over to 95% for R8900 MAPMT and from 89% to 93% for R7400 Flat Panel PMT, maintaining imaging and filtering capability.
Due to its general characteristics, this work can be modified to match all detectors that require collection improvements. Different filter solutions can also be studied to choose the sensitivity spectral range.
In last part of this paper design and simulations of non-imaging adapters are described to improve the collection efficiency of selected detectors.
The example of R7600-PMT shows that the CPC concentrators allow to improve the efficiency from 45% to 78%, collecting the photons on each pixel of detector. Other non-imaging adapters considered are the FLC concentrators. This new type of adapters is in development and preliminary results of simulations show their high efficiency.

5 REFERENCES

1. Stecker F.W., The curious adventure of the ultrahigh energy cosmic rays, arXiv:astro-ph/0101072 v2 11 Jan 2001.
2. EUSO- Extreme Universe Space Observatory, Original Proposal for the ESA F2/F3 Missions, January 2000.

3. OWL -Orbiting Wide-angle Light-collectors, http://owl.gsfc.nasa.gov/
4. Mazzinghi P. et al., Large aperture and wide field of view space telescope for the detection of Ultra High Energy Cosmic Rays and Neutrinos, *Proceeding of this Conference*.
5. Bratina V. et al., Overview of possible optical adapter for EUSO, Proc. Spie Vol. 5164, UV/EUV and Visible Space Instrumentation for Astronomy II; Oswald H. Siegmund; Ed. (2003) 100-112.
6. Petrolini A., A comparative study of light collector systems for use with multi-anode photo-multipliers, *Nucl. Instr. and Meth. A* 497 (2003) 314-330.
7. Multi-anode Photo-Multiplier tube R7600-M16/M64 series, R8900-M25/M36 series, R7400-M256 series, Hamamatsu Photonics K. K., Electron Tube Center, 314-5, Shimokanzo, Toyooka-village, Iwata-gun, Shizuokaken,438-0193,Japan, http://www.hamamatsu.com.
8. Gambicorti L. et al., Optical adapters to improve the collection efficiency of the Multi-Anode Photo Multipliers detectors, *Nucl. Inst. and Meth* A, 4th International Conference New Developments in Photodetection, Beaune, Fr. June, 2005.
9. FusedSilica, SchottGlass,datasheet, www.schott.com
10. Gambicorti L. et al., EUSO Optical adapters: Comparison between UV filtering optical adapters optimized for EUSO focal surface, EUSO- FS Tech. Rep. 012, 20 July 2004.
11. Winston R., Welford W.T., *High Collection Non-imaging Optics*, Academic, New York, 1989.
12. Winston R., Welford W.T., *J.Opt. Soc. Am*., Vol. 69, No. 4, April 1979.