Tracking Mirror For Measurement of Extreme Energy Cosmic Rays from Space

I.H. Park,[1] G.K. Garipov,[2] and B.A. Khrenov[2]
(1) Department of Physics, Ewha Womans University, Seoul, 120-750, Korea
(2) D.V. Skobeltsyn Institute of Nuclear Physics of Moscow State University, Moscow, 119992, Russia

Abstract

We propose a new idea of tracking mirror for a space based detector, observing atmosphere fluorescence, radiated by EAS, initiated by extreme energy cosmic rays. The concept of the tracking mirror is based on recent development on semiconductor MEMS (Micro Electro Mechanical Systems) technology. The tracking mirror consists of a large number of micro mirror arrays each of which is controlled independently by addressing signals from the active silicon matrix. The array system is programmed and configured at a given instance to be a mirror-concentrator with axis direction and focal distance both under control in real time. When an EAS event is detected the mirror is rearranged to track the event by minimizing aberrations.

1. Introduction

Recently several projects of space detectors for study of origin of the Extreme Energy Cosmic Rays (energy greater than 5×10^{19} eV, EECR) were proposed (TUS/KLYPVE [1,2], EUSO [3]). Detectors observe the fluorescent light radiated by charge particle disc of Extensive Air Shower (EAS), generated by the EECR. The flux of EECR particles is extremely low as reported by successful studies of this phenomenon and thus observatin of the large area of atmosphere, comparable to the area of the Earth, is important. A detector with field of view (FOV) Ψ at orbit height R observes the atmosphere area $\Sigma = (R \times tan(\Psi/2))^2$. Large area Σ could be achieved with wide FOV at moderate value of R if aberrations of detector optics are kept small. On the other hand, high resolution of EAS track in space and time is provided by the use of a large number of small size photomultiplier tubes (or tube channels) in a retina of a detector of photo receiver.

In the EUSO project a complicated optics using double Fresnel lens is applied to have FOV 60^o. In the option of simple optics using a mirror- concentrator [1] the FOV is limited due to aberrations of the mirror. We propose a new idea of tracking mirror that removes aberrations in the direction of an EAS

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event. The concept of the tracking mirror is based on MEMS technology [4], the recent technological advance in semiconductors. The tracking mirror consists of thin-film micro mirror arrays. Each array is controlled by addressing signals from an associated VLSI circuit of active silicon matrix. At the first stage of operation (EECR event finding), the mirror collects light from various direction (mode of wide FOV) to search for the position of an EAS disc. When the position is identified, the mirror is subsequently reconfigured for a good focusing in that direction. A candidate of EAS event is selected from a signal arrived in a rather short integration time (much shorter than an expected EAS track signal), and therefore the trigger rate might be high at this stage. The final decision on the event registration and recording is made at the second stage when the measurement with high resolution has started to recognize the movement of EAS.

2. The design of tracking mirror

The tracking mirror consists of micro mirror arrays, each $d \times d$ in size ($d = 50-250m$), piezoelectric actuators and MOS circuits underneath, all fabricated on the same silicon wafer (Fig.1). Each array is controlled in two directions: along x and y axis. The angle $\delta_{x,y}$ in each direction linearly varies with the driving voltage on the piezoelectric actuator. In the baseline arrangement the mirror concentrates light into a given spot size with an efficiency uniform over FOV. The FOV of the detector with a mirror diameter D and focal distance f is limited by shadowing effect of the photo receiver. For 20% shadowing and D=f the FOV is 22^o. Light collection efficiency of $\geq 50\%$ sets a limit in the ratio of focal spot to pixel size of the photo receiver.

We propose to use the experimental resolution in different way. At the stage of EAS event registration the resolution should be high but should not exceed the limit, set by the EAS disc size, 0.5-1 km in atmosphere or 2 mrad in angle for $R = 400km$. At this stage, the tracking mirror will keep the EAS image in a rather small high resolution area of the photo receiver, 2×2^o, for example. At the stage of event finding, the resolution could be much poorer. The position of a EAS candidate is estimated with an accuracy of about 1^o, half size of the high resolution area of the receiver. The number of pixels used in these two stages of operation is much smaller than conventional detectors [1-3]. As an initial configuration for event finding, a symmetrical radial arrangement of arrays can be chosen and determined by the formula $\delta_r = 0.5 \times atan(r/f)$ where r is the distance from an array to the center of the mirror. The pixel size of $0.015f$ gives light collecting efficiency 50% at the edge of FOV 22^o, which leads to the total number of 625 pixels at the first stage of operation. At the second stage the high resolution pixels have to cover the angular field of 2×2^o. The arrangement of arrays for the high resolution observation has to be preprogrammed. The code for this arrangement of arrays is being prepared and will be published separately.

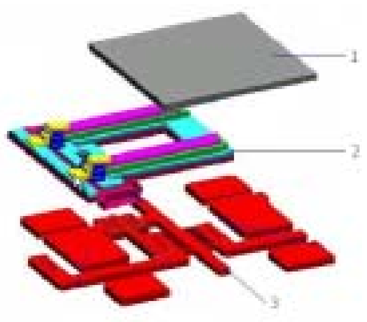

Fig. 1. A micro mirror array. 1- mirror, 2- actuator, 3- MOS circuit

3. The operation of tracking detector

Operation of the detector using a tracking mirror is presented below for a variant of the detector at the orbit of International Space Station (ISS), $R = 400km$. The parameters of the baseline detector are: mirror area $S = 1.5m^2$, focal distance $f = 1.5m$, pixel size of photo receiver for event finding $20mm$. The retina of 625 pixels covers the FOV=22^o, while the high resolution ($0.015rad$) area contains 196 pixels of 4 mm size. The EAS event is selected from the signal in one of the event finding pixels for the integration time of $6\mu s$ (signal duration in an EAS path of 2 km) with a threshold q_{thr}. The threshold value has to be high to keep the rate of background events low. Assuming the background rate of 1 Hz, 1/625 Hz per pixel, the threshold value q_{thr} has to be of about $3sigma$ of pixel noise. At moonless night the noise in pixel is expected to be $\sigma = 10p.e.$ and $q_{thr} = 30p.e.$, which corresponds to the energy threshold of EAS $E_{thr} = 3 \times 10^{19}eV$ and to the EAS event rate of 0.5 per hour for the detector geometrical factor in atmosphere of $6 \times 10^4 km^2 sr$. On event triggering the detector is moved into event tracking mode where the mirror is rearranged to trace the event by focusing to the high resolution area of the photo receiver. Most of the events are background which should be rejected at this stage and the mirror comes back to the initial arrangement. The size of signal of an EAS event registered in the high resolution pixels is much larger than noise (S/N = 12 at the threshold energy) which allows to make a measurement of EAS in precision. Due to the time required for the event finding ($6\mu s$) and for rearrangement of the mirror (determined by the tilting speed, 1^o per μs at present), high resolution measurements at energy E_{thr} will be available about 10 μs later, slightly after the cascade maximum. For higher energy, above $> 2 \times E_{thr}$, the track can be registered with a high resolution even before the maximum. With a high tilting speed in comparison to the moving speed of the EAS disc image (0.1^o per μs at the ISS orbit) it is possible to keep track of the EAS disc position and image in the high resolution area of the detector. In the example presented here the tracking mirror telescope will observe the EECR particles ($E > 5 \times 10^{19} eV$) at the rate of 350 events per year.

A wider FOV observation could be organized by division of the mirror in n sections. Each mirror section focuses light from different directions to one photo receiver. The section covers area Σ, corresponding to FOV$\cong 22^o$, then the total area of atmosphere at the stage of event finding is $n \times \Sigma$. The energy threshold in the section mode is n times higher than in the baseline mode. On event finding in the section mode all sections of the mirror is rearranged into one mirror focusing the EAS disc to high resolution area of the receiver as same as the baseline mode. Therefore, the rate of highest energy events ($E \geq n \times E_{thr}$) will be n times higher than in the baseline mode. Rearrangement of the mirror at angle larger than $> 11^o$ requires fast tilting speed, $> 5^o$ per μs, and a possibility of applying the tracking mirror for such a fast operation will depend on the progress in MEMS technology.

The tracking mirror could be used as a second mirror in the Cassegrain optics of the detector. The main mirror could be a Fresnel mirror with a large diameter D_1, particularly important for experiments at high orbits, while the second mirror of diameter D_2 might be small: $D_2 = 0.1 \times D_1$. The second mirror will allow us to correct aberrations of the main mirror and to track the EAS image.

4. Conclusion

We propose a new idea of tracking mirror for measurements of extreme energy cosmic rays in space. Advanced MEMS technology allows us to design and build a new type of controlled mirror-concentrator for EECR detectors, which promises to make excellent measurements of EECR events at the large area of the atmosphere.

5. References

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