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A lightweight Schmidt space telescope configuration for ultra-high energy cosmic ray detection

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ABSTRACT

One of the most challenging open questions of modern astrophysics and particle physics is the determination of the origins and the production mechanisms of the Ultra-High Energy Cosmic Rays (UHECR), i.e. particles with energy above the Greisen–Zatsepin–Kuzmin (GZK) limit, which is about 5×10^{19} eV.

UHECRs can be studied in two ways: either via direct detection of the secondary particles, i.e. extensive air shower (EAS), produced by UEHRCs interaction with the atmosphere, or by observing during night the track of the UV fluorescence emitted by EAS. The origin direction of the cosmic rays can be therefore determined.

While ground-based observatories are already operative, different optical configurations, based mainly on the Schmidt camera layout or double Fresnel lenses concept, can be envisaged for future space-based ones. Both solutions faced in the past technological issues: transmission and resolution at large field angles for Fresnel lenses and weight of the primary mirror for the Schmidt. However, recent advances in the technology of ultra-lightweight, large and deployable active mirrors made the Schmidt camera approach feasible, becoming the preferred option.

This work describes a lightweight Schmidt space telescope design for UHECRs detection conceived for a mission intended to orbit at 600 km altitude.

The instrument concept is a fast, high-pixelized, large aperture and large Field-of-View (FoV) digital camera, working in the near-UV wavelength range with single photon counting capability. The telescope will record the track of an EAS with a time resolution of 2.5 μs and a spatial resolution of about 0.6 km (corresponding to ~ 4’), thus allowing the determination of energy and direction of the primary particles.

The proposed design has about 50° FoV and a 4.2 m entrance pupil diameter. The mirror is 7.5 m in diameter, it is deployable and segmented to fit the diameter of the considered launcher fairing (i.e. Ariane 6.2). The Schmidt corrector plate is a lightweight annular corona.

This configuration provides a polychromatic angular resolution less than 4' RMS over the whole FoV with a very fast relative aperture, i.e. F/# 0.7. Thanks to its very large pupil and large FoV, the design could be fit for a space-based observatory, thus enhancing the science achievable with respect to the presently operating ground-based counterparts, such as Telescope Array and Auger. A key advantage of this catadioptric design over the classic all refractive adopted in the past is the higher attainable global throughput. This parameter guarantees to reach and fulfil the required instrument photon collection specifications.

Keywords: Schmidt telescope, active telescope, large segmented mirrors

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1. INTRODUCTION

1.1 Ultra-high Energy Cosmic Rays detection

Cosmic rays, constantly hitting Earth's atmosphere, carry information about the Universe. Their origin and the production mechanisms still remain open questions. It is also difficult to locate the sources of cosmic rays, as they are mostly charged particles and thus their incoming direction is affected by the magnetic fields encountered during their journey. Hence it is extremely important to study the most energetic cosmic rays that are the less affected by the magnetic fields.

The Ultra-High Energy Cosmic Rays (UHECR) are particles with energy above the Greisen–Zatsepin–Kuzmin (GZK) limit [1] [2], which is about 5×10^{19} eV. They interact with the cosmic microwave background radiation and this limits their travel distances to about 200÷300 million light years.

When an UHECR enters the Earth's atmosphere, it produces a cascade of secondary particles, i.e. an extensive air shower (EAS); the most abundant particles in EAS are electrons, positrons, and photons. Passing through the atmosphere, the relativistic charged particles emit Cherenkov radiation and produce fluorescence light due to their interaction with air molecules [3]. The methods to measure EAS can be divided in two groups: experiments detecting directly the secondary particles, and observation of the emitted Cherenkov or fluorescence photons. To detect UHECRs and study their production mechanism and origin, a number of ground- and space-based facilities have been conceived.

The Pierre Auger Observatory is a 3000 km^2 international cosmic ray observatory in the Mendoza Province in Argentina, which can detect directly the EAS secondary particles [4]. However, even with such a large collecting area, the number of observed events is presently limited, not allowing to determine with confidence the direction of possible sources [5].

The EAS particles ionize or excite air molecules, mainly nitrogen ones. The excited molecules then relax to their ground state partially by emitting fluorescence photons, and most of the this light is emitted in the 300-400 nm UV range. The fluorescence light is emitted isotropically, thus it can be viewed from any direction and observed by telescopes with large field of views looking at an extended volume of the atmosphere to increase the observation likelihood. Having this in mind, a space-based observatory looking downwards during night to detect the emitted EAS fluorescence UV light can be proposed.

The first idea to implement this method was the OWL (Orbiting Wide-angle Light-collectors) concept, consisting of a pair of telescopes in low inclination (10°), medium Earth orbit (altitude 1000 km) [6]. The stereo vision produced by the two telescopes would allow the determination of the particle arrival direction.

A slightly different approach is the concept of MASS (Maximum-energy Auger (air)-Shower Satellite): the use of a single fast detector (an array of multi-anode photomultipliers) allows the track direction reconstruction [7]. At the beginning of 2000s, this configuration was proposed as the Airwatch Observatory [8] on board of the International Space Station (ISS) and submitted to the European Space Agency (ESA) with the name EUSO (Extreme Universe Space Observatory)[9] by an international consortium including several European countries, Japan and USA. Few years later the EUSO programme stopped, but soon after a re-organization of the team, the project re-started with the name of JEM-EUSO, being led by a similar consortium but with Japanese leadership (the addition JEM because it was planned to be attached to the ISS Japanese's JEM module) [10].

1.2 The JEM-EUSO collaboration present status

At present the JEM-EUSO consortium is promoting an updated design of the observatory, either to be attached at the ISS or orbiting as a free flyer. Maintaining the same science requests, and therefore also the first order optical requirements, the proposed instrument still consists of a telescope working in the near-UV range (330-400 nm, for UHERC detection) with single photon counting capabilities.

To implement the technology and to assess the science case, in the recent years some precursors are being realized or envisaged:

- EUSO-TA: an on-ground observatory, made with Fresnel lenses and operative since 2013 at the Telescope Array in Utah [11];
- EUSO-Balloon and EUSO-SPB: two payloads on board stratospheric balloons [12];
- Mini-EUSO: an instrument operating inside the ISS made with two small Fresnel lenses, looking downwards from the Russian UV transparent window [13];
- K-EUSO, to be placed outside the ISS [14];

- POEMMA (Probe Of Extreme Multi-Messenger Astrophysics): a mission dedicated to observe ultra-high energy cosmic rays and cosmogenic tau neutrinos [15].

The optical designs adopted for the UHECRs observatories were mainly based on the Schmidt camera layout (e.g. OWL), or double Fresnel lenses concept (e.g. MASS, EUSO, JEM-EUSO). Both solutions faced in the past technological issues: transmission and resolution at large field angles for Fresnel lenses and weight of the primary mirror for the Schmidt. However, recent advances in the technology of ultra-lightweight, large and deployable active mirrors made the Schmidt camera approach feasible, becoming the preferred option.

After an introduction on the Schmidt telescopes optical configuration, this paper describes the main requirements and the conceived telescope optical design for the Free Flyer (FF) version of the JEM-EUSO mission, i.e. EUSO-FF, which was originally considered to be proposed as an M5 mission for the 2016 ESA call. Optical performance and some technological aspects of the proposed configuration are presented and discussed.

2. SCHMIDT TELESCOPE CONFIGURATION

Most of the wide field telescopes for ground- and space-based observatories are presently based on the idea proposed by Bernhard Schmidt in 1931, or variants, such as the Maksutov and the Baker-Nunn [16][17].

The standard layout of the Schmidt telescope consists in a spherical mirror, a corrector plate and a focal surface. The underlying idea is that the aperture stop, placed at the center of curvature of the spherical mirror, allows to obtain a system behaving in the same way for whatever orientation of the incoming parallel beams. Therefore exactly the same optical performance is attainable over a wide spherical focal surface concentric with the mirror. The corrector plate, i.e. a thin, nearly plane-parallel plate, placed at the center of curvature, compensates the spherical aberration originated by the mirror.

Many authors dealt with the design of wide FoV imaging Schmidt systems, focussing on the profile analysis of the corrector plate [18]. The complete correction of the spherical aberration can be achieved only for monochromatic light and for one field in the FoV. The corrector plate introduces chromatic aberrations, mainly spherochromatism, which are difficult to be corrected. However, this is generally not an issue given the usual narrow operating spectral bandwidth of this system. For designs with large FoVs, it is necessary to find a balance of the aberrations all over the FoV, possibly at the expenses of the image quality on-axis.

A remarkable benefit of the Schmidt layout consists in having the image surface not facing the object plane, avoiding the radiation from potential out-of-field sources (e.g. scattered out-of-field Earthshine) directly impinging on the image surface. This aspect, combined with the small number of optical elements, makes the stray light suppression both in-field and out-of-field particularly efficient. As a disadvantage, though, the focal surface is not easily accessible, and the detector electronics has to face the object space.

Presently, there are a number of operative Schmidt cameras: the ground-based imaging air Cherenkov telescope for gamma ray astronomy is a Schmidt camera covering 15° FoV with 1 arcmin angular resolution, while the fluorescence detector [19] of the Pierre Auger Observatory is based on an array of Schmidt telescopes, each one covering a field of view of 40° [20].

3. OPTICAL DESIGN AND PERFORMANCE

The optical design presented in this paper has been originally tailored to EUSO-FF, but it can be anyway used as a basis for other space missions.

3.1 EUSO-FF

EUSO-FF has been conceived as a Free-Flyer orbiting fluorescence detector dedicated to the detection of UHECRs, but also a precursor of an observatory of ultra-high energy neutrinos.

EUSO-FF was planned to be launched in 2029 with an Ariane 5, or 62, and the expected mission duration was about 5 years.

The instrument consists of a UV wide-field telescope, operating at an orbit altitude of approximately 600 km. The detector is made by a grid of about 5000 multi-anode photomultipliers (MAPMT), each one having 64 square pixels with 3-mm pitch [21] powered from the platform.

3.2 Telescope design requirements

The design requirements for the telescope, flown down from the scientific requirements for the mission, are summarized in Table 1 [22] [23].

To collect enough signal, the minimum acceptable entrance pupil diameter (EPD) is set to be at least 4 m and the on-axis useful fraction of the entrance pupil area, referred from now on as Geometrical Vignetting Factor (GVF), has to be greater than 60%. These two requirements considered together correspond to an equivalent useful collecting area of 7 m^2, i.e. 3 m diameter.

Table 1. Optical requirements of the Schmidt camera for EUSO-FF.

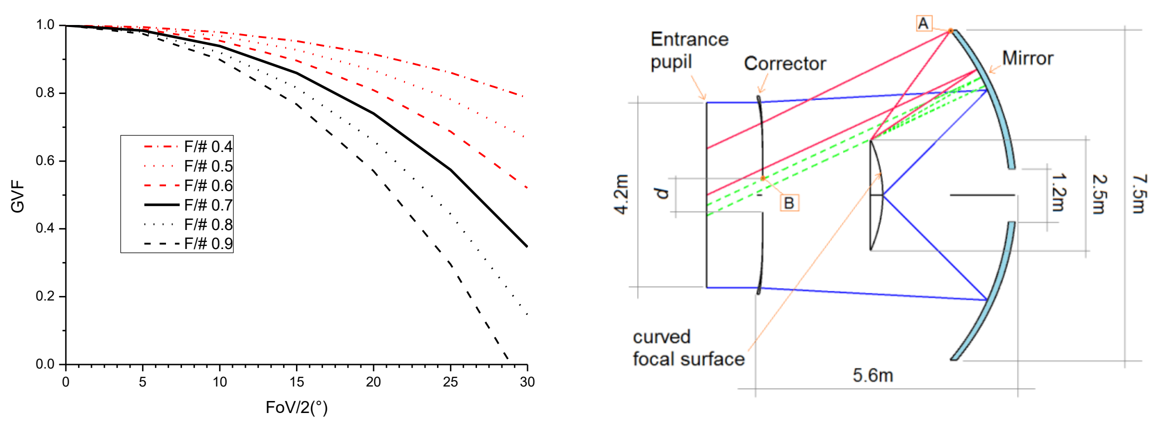
Parameter	**Value**
Entrance Pupil Diameter	> 4 m
Geometrical Vignetting Factor	> 60%
FoV	> 50°
Angular Resolution	2.9' < iFoV < 5.7'
Spectral Range	337-391 nm
Polychromatic RMS Size	3 mm

The EPD considered for this study is 4.2 m, leading to a 4.48 m diameter corrector, compatible with the inner diameter of the fairing of the Ariane 5 and 6.

To maximize the covered atmospheric volume, the telescope FoV has to be as large as possible, i.e. of the order of 50°-60°. To be able to reconstruct the path of the cosmic ray, the Ground Sampling Distance (GSD) must be between 0.5 and 1 km, which, coupled to the required angular resolution (2.9' < iFoV < 5.7'), determines an orbital height of 600/700 km.

The pixels of the multi anode photo multipliers detector are about 3 mm in size and they must cover an atmosphere portion corresponding to that GSD. Having fixed the maximum EPD, the GSD requirement is equivalent to set the system F/# in the range 0.4 to 0.8, or equivalently the focal length between 1.8 m and 3.6 m.

As for the required optical performance, the polychromatic RMS spot size must be of the order of the pixel size.



(a) (b)

Figure 1. (a) GVF as a function of the system FoV and for different relative apertures (F/#). (b) Selected Schmidt telescope configuration.

It is well known that in the Schmidt design the focal surface (FS) blocks some of the incoming rays; dependent on the focal length and the FoV, this central obstruction is thus a limiting element for the attainable global throughput of the system.

The on-axis useful fraction of the entrance pupil area (GVF) can be calculated as:

$$GVF = 1 - \frac{A_{FS}}{A_{EnP}} = 1 - 4 \cdot (F/\#)^2 \cdot tan^2\left(\frac{FoV}{2}\right) \quad (1)$$

where A_{FS} is the area of the obstruction and A_{EnP} is the area of the entrance pupil. Therefore, the smaller the F/# the smaller is the on-axis obstruction for a given telescope FoV.

Figure 1a shows the GVF versus the system FoV calculated for different values of the F/#. It is worth noting that if the F/# is greater than 0.9, a telescope with a FoV more than ±30° is not acceptable since the on-axis beam is completely stopped and the real collecting area becomes 0.

The system throughput is proportional to the GVF and so it is a function of the FoV and the F/#. Thus the values of FoV and F/# have to be determined as a compromise between the obscuration, due to the FS, and the achievable optical performance, meaning that the residual aberrations have to be compatible with the required spot size.

As a conclusion of this trade-off, the selected F/# for the telescope is 0.7. From Figure 1a it can be seen that for such an F/# the GVF is greater than 60% for a system with a FoV up to ±25°. Assuming an EPD of 4.2 m, the equivalent on-axis useful entrance aperture is greater than 3 m as required to meet the necessary photon collection capability. The corresponding focal length therefore is 2.94 m, the GSD at nadir 610 m and the angular resolution 3.5'.

3.3 Telescope optical design

Starting from the requirements, the telescope layout has been optimized on the basis of geometric optics and raytraced with Zemax OpticStudio [24]. A classic Schmidt layout has been considered as the initial configuration. A default sequential RMS spot radius merit function with a constraint on the effective focal length and various variables has been defined. The corrector was configured with both surfaces as even aspheres, the mirror was given a 2nd order aspheric coefficient. The aperture stop was left free to move along the optical axis, in front and behind the corrector plate, its position being driven by the overall polychromatic performance for such a wide FoV.

Figure 1b shows the layout of the optimized solution for the Schmidt telescope and the optical characteristics of the selected Schmidt design are summarized in Table 2.

Table 2. Optical characteristics of the Schmidt design for EUSO-FF.

Parameter	Value
Entrance pupil diameter	4.2 m
Focal length	2.94 m
F/#	0.7
Nadir angular resolution	3.5'
Nadir GSD	0.61 m
Corrector plate outer diameter	4.48 m
Corrector central hole d	0.65 m
Mirror diameter	7.5 m
Focal surface diameter	2.5 m

Since the central part of the corrector plays a minimal role in the aberration correction for a limited number of field angles, a design featuring a corrector plate with a central hole was adopted. This choice has essentially no impact on the optical performance of the system, as shown in paragraph 3.4.

Figure 1b shows the rays refracted by the corrector plate (solid rays) and those passing through the central hole (dashed rays) for a field angle of 25°. Rays refracted by the corrector are partly vignetted by the outer edges of the mirror (identified with letter A), while rays passing through the hole of the corrector are limited by the aperture of the hole (identified with letter B). The other rays passing through the entrance aperture are blocked by the focal surface.

As known, vignetting plays a crucial role to define the performance. Mechanical vignetting depends on the available maximum aperture of the mirror and the dimension of the central hole (which is related to the system's F/#). As the aperture stop is free to move along the optical axis, the amount of vignetting is derived by the best trade-off between interdistances, apertures, and the optical performance at the various fields, in particular the photon collecting capability (i.e. projected EPD and amount of transverse aberrations) of the design at large angles.

By “aperture stop” here a combination of stops is considered. The “outer” aperture stop is the external mechanical ring of the corrector plate for the rays refracted by the corrector itself (identified by an arrow in the solid rendering, see b), while for the rays passing through the central hole the “inner” aperture stop is the corrector’s central hole itself.

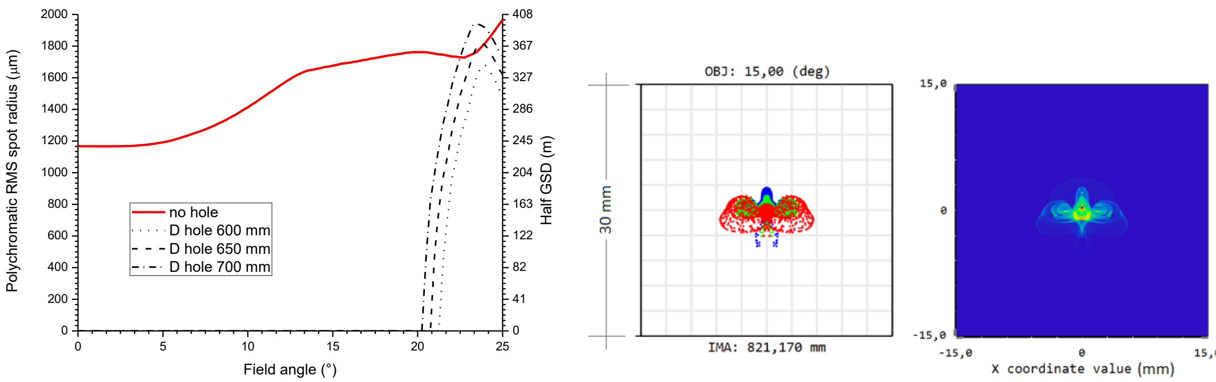
The selection of the working spectral range can be achieved with some possible solutions still to be traded-off:

- a dichroic filter deposited on the mirror; this choice can be implemented if the mirror substrate is glass;
- a dichroic filter deposited on a dedicated substrate;
- a glass filter with an additional band pass coating to limit the spectral content;
- a combination of glass filter, lens and concentrator (e.g. a square frustum), which allows to improve the photons collection efficiency of multi-anode photomultipliers.

3.4 Optical performance

The diameter d of the hole of the corrector plate has to be selected in order to minimize the impact on the system performance.

For the optical layout with a full corrector plate, the polychromatic RMS spot radius versus field angles is depicted, as a solid line, in Figure 2a. The right vertical axis gives the corresponding half GSD. The 3-mm spot diameter requirement is met, for this design, only up to about ±12°, while it increases to up to 4 mm at maximum field. This result has been judged acceptable taking into account that the performance at the edges of the FoV depends also on the diameter of the hole. If needed, the design can be further optimized to better improve the performance at the edges at the expense of the RMS spot radius at the center of the telescope FoV.



(a) (b)

Figure 2. In (a) polychromatic RMS spot radius as a function of the field angle for a full corrector (solid line) and for the rays passing only through the central hole of the corrector, for three different dimensions. In (b) polychromatic spot diagrams for a 15° field angle traced with the sequential/non-sequential (left/right) modalities of Zemax OpticStudio depicted in linear scale. Both spot diagrams are display over 30 mm x 30 mm box.

The spreading of the polychromatic RMS spot due to the “uncorrected” rays (dashed in Figure 2a), namely those passing through the hole, has to be kept negligible. The polychromatic RMS spot radius of these rays has been calculated for three different hole diameters: 0.6 m, 0.65 m and 0.7 m respectively. Because of the obstruction produced by the FS, for field angles smaller than about 20° all these rays passing through the hole are vignetted. This conceptual analysis shows that a corrector plate with a 0.65 m central hole does not worsen the overall spot sizes at large field angles. The on-axis polychromatic RMS is 2.7' (corresponding to an RMS spot radius of 1.2 mm, see) which is well below the dimensions of the pixel.

The polychromatic spot diagrams have been calculated both with the sequential and non-sequential modalities of Zemax OpticStudio. The three wavelengths considered are the central and the extremes of the required wavelength range (Table 1).

As reported in Figure 2b, the sequential and non-sequential spot diagrams for a field angle of 15° are in agreement in shape and dimensions. The non-sequential model includes also the contribution of the surface micro-roughness of the optical items and of the mechanical structure [25].

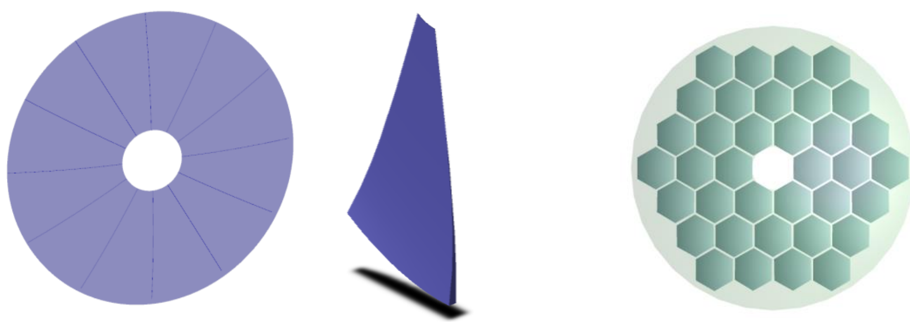
A preliminary telescope tolerance analysis has been done. The worst offenders are the decentering and tilts of the primary mirror. Also a preliminary straylight analysis has been conducted, assessing the stray light level is low enough to allow suitable observation of cosmic rays events [25].

3.5 Corrector plate design and technology

It is well known that while compensating the mirror spherical aberration, the corrector plate introduces chromatic aberrations, mainly spherochromatism. Therefore, the optimal profile of the plate is determined by the best balance for the spherochromatism. The performance of the system is then checked with the analysis of the polychromatic spot diagrams and the aberrations plots.

An even asphere surface type, with high order terms from 2nd to 16th, was used. Mass and corrector plate shape were set to limit the natural bending at the edges arising from the need to correct the in-field aberrations. Furthermore, to minimize the manufacturing and integration risks, the corrector shape was forced to have the outer edges thicker than the centre: this allows to have a mechanical robust edge that simplifies the assembling of the corrector plate in the telescope structure by means of a suitable mechanical holder capable to resist at launch loads.

The final profile of the corrector does not suffer strong bending at the edges thanks to a well-balanced-cooperative role between the slight aspheric mirror and the corrector in the minimization of the geometric aberrations.



(a) (b) (c)

Figure 3 In (a) corrector plate (outer diameter 4.48 m, inner diameter 0.65 m) conceived as an annular corona made of N (e.g. 12) identical radial slices (b). (c) Front view of segmented mirror.

The presence of the central hole in the corrector plate has some advantages:

1) it simplifies its manufacturing: the plate can be conceived as composed by N identical radial slices (e.g. 12), each one molded on a cast, and then assembled together with a mechanical holder or cemented on the lateral sides as schematically described in Figure 3 a and b;

2) the central hole gives room for other instruments, e.g. a Lidar or internal metrology.

The material baselined for the corrector plate is PMMA-000, a special grade UV-transmitting poly methyl methacrylate (by Mitsubishi Rayon Co. LTD, Japan), with an internal transmission higher than 90% for a thickness of 15 mm and a refractive index of approximately 1.5 in the considered spectral range. Plots of the refractive index and the internal transmission as a function of the wavelength are available in [26]. In its final configuration, the corrector has an outer diameter of 4.48 m, an edge thickness of about 57 mm and a weight of approximately 295 kg.

3.6 Mirror technology

It was already highlighted that the launcher fairing diameter drives the choice on elements' diameters. In the proposed design the aperture and the corrector plate can be built as monolithic, but the mirror has to be conceived as a lightweight, segmented and therefore deployable structure [27].

Considering the mirror design and in particular the vignetting introduced versus performances, a trade-off was executed, which proposed a diameter of 7.5 m. The envisaged segmentation is optimized to simplify the manufacturing and the integration phases. The mirror segments (see Figure 3c) cover only the mirror active area, and not the central hole, so the telescope assumes the aspect of a double donut, hence this optical configuration has been named Double Donut Schmidt Camera (DDSC).

Any large aperture primary mirror must be necessarily lightweight. This in turn triggers the maintenance of the operational optical performance, which can be achieved only if the mirror is actively controlled.

Two recent ESA R&D projects explored the possibility to develop large lightweight and deployable space mirrors. The first, named ALC (Advanced Lidar Concept), studied the general concept of a deployable, lightweight, 4-m aperture space born telescope for Lidar applications [28]. The second, named LATT (Large Aperture Telescope Technology), extended the previous study: an active mirror breadboard 1 mm thick with 400 mm diameter and 5 m curvature radius, made in Schott Zerodur and coupled to a CFRP backplane with 19 actuators controlling the optical surface, was built and successfully tested [29].

The combined results of these two projects proved that a large active primary mirror can be constructed, launched and deployed into space. The areal density can be 17 kg/m^2 and lower, and the power required for the active control is about 4 W/m^2. The stroke of the actuators, approximately 1 mm, guarantees that the optical performances are maintained on-orbit for the cases under scrutiny, compensating for the mechanical deployment errors and for thermo-elastic deformation introduced by the operative environment [30]. This technology makes possible the construction of virtually unlimited mirrors, using the same mechanisms presently used for the deployment of large microwaves antennas.

Furthermore, the LATT technology allows not only the recovering of possible errors (identified in the tolerance analysis) but also the achievement and the preservation of the nominal slight aspheric profile of the mirror through an induced deformation of a spherical profile (whose required stroke is < 1 mm).

4. CONCLUSIONS

A lightweight Schmidt space telescope layout suitable for UHECRs detection has been presented. The design provides a polychromatic angular resolution less than 4' RMS over a FoV of 50° with a very fast relative aperture, namely F/# 0.7. The solution adopted has been conceived for a mission intended to orbit at 600 km altitude but, thanks to its very large pupil and FoV, it could be used for other UHECRs space-based observatory, thus improving the science achievable with respect to the presently operating ground-based counterparts, such as telescope array and Auger.

Schmidt design applied to a space-based telescope for the detection of UHECRs, such as K-EUSO, can be nowadays considered thanks to the remarkable progresses reached in the construction of large-aperture, lightweight, actively controlled segmented mirrors. A breadboard of such a mirror was produced, within ESA R&D. Still, some work is to be conducted to consolidate this technology, but the expectations are high. This achievement boosted the development of the Schmidt design tailored to this particular astrophysical mission, introducing key factors such as the asphericity of the mirror and the particular corrector’s shape, thus resulting into this peculiar design, the Double Donut Schmidt Camera.

A key advantage of this catadioptric design over the classic all refractive adopted in the past is the higher attainable global throughput. This parameter guarantees to reach and fulfil the required instrument photon collection capabilities.

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