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TECHNICAL REPORT

The prototype opto-mechanical system for the Fluorescence detector Array of Single-pixel Telescopes

FAST
Fluorescence detector Array of Single-pixel Telescopes

FAST collaboration

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ABSTRACT: The Fluorescence detector Array of Single-pixel Telescopes is a proposed low-cost, large-area, next-generation experiment for the detection of ultrahigh-energy cosmic rays via the atmospheric fluorescence technique. The proposed design involves the deployment of several hundred large field-of-view fluorescence telescopes on a regular grid of several thousand square kilometers in ground area. This paper describes the optical design of the prototype telescope, as well as its mechanical support structure.

KEYWORDS: Large detector systems for particle and astroparticle physics; Particle detectors

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Contents

1 Introduction

Measurement of the properties of ultrahigh-energy cosmic rays (UHECRs) via the faint fluorescence light emitted by the particle cascades they produce in the Earth's atmosphere is a long-standing and well established technique [1]. Following the interaction of a highly energetic cosmic ray with the Earth's atmosphere, a cascade of secondary particles, an extensive air shower (EAS), is produced. The developing EAS in turn results in the emission of a large number of fluorescence and Cherenkov photons in the UV wavelength band ($\sim$ 300–420 nm) [2–4], which can be detected at ground level using large field-of-view telescopes focusing the light onto a matrix of photomultiplier tubes (PMTs).

The origin and nature of the highest energy cosmic rays, having energies exceeding 10^{19} eV, is still largely unknown. Measurements of their mass composition, energy spectrum, and arrival direction are severely limited by their minute flux. Extremely large ground areas must therefore be instrumented in order to collect sufficient statistics to advance the field, and the next generation of detectors will require an aperture which is larger by an order of magnitude relative to current generation experiments. Such a ground coverage could be achieved by observing the atmosphere from space, as in the proposed JEM-EUSO mission [5], or by deploying ground-based detectors in a grid over a very large area. The latter option will naturally require a detector unit which is easily deployable, requires minimal maintenance, and can be produced at low cost.

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2 The Fluorescence detector Array of Single-pixel Telescopes

The Fluorescence detector Array of Single-pixel Telescopes (FAST) [6] is a design concept for a low-cost, ground-based fluorescence detector. A FAST telescope would consist of just four pixels covering a $30^\circ \times 30^\circ$ patch of the sky with a $\sim 1\,\mathrm{m}^2$ collecting area. Its low cost would facilitate deployment over a very large ground area, making it a viable candidate for a next-generation cosmic ray observatory. Such a design comes at the expense of low energy performance, as the signal-to-noise (S/N) ratio measured by a PMT is proportional to $\sqrt{A/\Delta\Omega}$ [7], where A is the light collecting area and $\Delta\Omega$ is the pixel solid angle, which is $\sim 15^\circ$ in the FAST design (compared with, for example, $A \sim 3\,\mathrm{m}^2$ and $\Delta\Omega \sim 1.5^\circ$ for the fluorescence telescopes of the Pierre Auger Observatory [8]). In addition, reconstruction of the geometry of an EAS with adequate resolution using data collected by a single FAST telescope is unlikely, as the coarse granularity of a 2×2 matrix of PMTs does not supply sufficient timing information to remove degeneracy in the determination of the shower axis. However, showers of sufficiently high energy would be observed by multiple FAST telescopes in an array, in which case timing information from the involved telescopes, along with the shape of the detected light pulse, could allow for reconstruction of the shower geometry with reasonable accuracy. An array of FAST telescopes would also be well suited as a complementary fluorescence detector to a sparse array of ground-based particle detectors, which could supply the shower geometry independently.

In 2014 a proof-of-concept detector, comprising a single 200 mm PMT at the focus of the prototype optics of the JEM-EUSO telescope, called EUSO-TA [9] (a series of two $\sim 1\,\mathrm{m}^2$ Fresnel lenses protected by a UV transparent acrylic plate) at the Black Rock Mesa (BRM) site of the Telescope Array experiment (TA) [10] in central Utah, U.S.A., was successful in demonstrating the viability of such a detector. The single-PMT telescope was used to observe laser shots at distances of up to 21 km, as well as 16 highly significant cosmic ray shower candidates in coincidence with the TA fluorescence detector. Using this small sample of coincident events, a single FAST PMT was shown to be capable of measuring the signal produced by a 10^{19} eV shower with a significance of $\geq 5\sigma$ at distances of up to 20 km. In addition to the encouraging results of these field measurements, it has also been shown, using accurate simulations produced with the `CORSIKA` shower simulation package [11], that a detector resembling the FAST reference design, consisting of four PMTs at its focus, could achieve energy and X_{max} resolutions of $\sim 10\%$ and $\sim 35\,\mathrm{g/cm}^2$ respectively when deployed on a triangular grid with a 20 km spacing, if the shower geometry is supplied by a complementary surface detector. These resolutions are comparable to those of current generation cosmic ray observatories, such as TA [10, 12] and the Pierre Auger Observatory [13]. A detailed discussion of these simulations and the results of the proof-of-concept test at the TA site can be found in [6].

Motivated by the positive results of the preliminary FAST test at the TA site, a full-size prototype telescope has been developed. The prototype utilizes a large segmented mirror telescope of $1\,\mathrm{m}^2$ collecting area to focus light onto a camera consisting of four 200 mm diameter PMTs. The prototype has been installed in a dedicated building alongside the fluorescence telescopes at the BRM site of TA, where the design will be tested. Two additional FAST telescopes will eventually be installed at the same location, covering a total of 90° in azimuth, with the first of these already under construction. The deployment of additional FAST telescopes will allow for a three-fold increase in

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the prototype aperture, greatly increasing the number of showers observed in coincidence with the TA fluorescence telescopes.

3 The FAST prototype telescope design

The primary design goal of an individual FAST telescope is to have an optical system with an effective collecting area of $\sim$ 1 m^2 and a $\sim$ 30° × 30° field-of-view which is capable of focusing atmospheric fluorescence light onto a matrix of several 200 mm PMTs. In addition, it is required to be low-cost, straightforward to maintain, and easy to transport and install. The low cost requirement makes it necessary to minimize the number of optical elements in the telescope, and both refractive and reflective options (as well as a combination of both) have been considered.

3.1 The refractive solution

A simple refractive solution might consist of a series of Fresnel lenses, such as the setup used for the FAST proof-of-concept test at the TA site in 2014 [6]. Such a configuration would result in the cheapest and simplest possible design. The largest commercially available low-cost acrylic (PMMA) Fresnel lenses are used predominantly in solar applications, but unfortunately exhibit significant off-axis aberrations, making them a poor choice for wide-angle optical setups such as a FAST telescope. In addition, the typical maximum size of commercially available flat Fresnel lenses is approximately 0.6 m × 0.6 m, offering a total collecting area of only ~0.36 m^2, which is significantly less than the 1 m^2 FAST design requirement. The field-of-view of the optical system formed by a series of Fresnel lenses could be increased by adding a number of meniscus shaped lenses. This design, as an example, is used in the proposed space-based JEM-EUSO fluorescence detector. The diameter of the custom made lenses is approximately 2500 mm, offering a total angular field-of-view of 60°. The optical system of the JEM-EUSO telescope is extremely technologically complex to produce, leading to its high price. For verification of this technology, simplified variants of the JEM-EUSO optics, EUSO-Balloon [14] and EUSO-TA [9], were built. The EUSO-TA telescope is a combination of two planar Fresnel lenses with a 1 m × 1 m size, offering a total angular field-of-view of 15°, which is a consequence of the simplification of the meniscus lens to a planar shape. This collecting area and field-of-view fulfilled the FAST design specifications for a single pixel, and the EUSO-TA telescope was therefore previously used as a test-bed to validate the FAST concept. An increase in the field-of-view of such a configuration (to meet the full-scale prototype design requirement) could be achieved by using additional planar Fresnel lenses. However, this comes at the expense of the transmission of the optical system. Fresnel lenses consist of a "stepped" refracting surface, whereby, in the case of off-axis beam transmission (larger angles to the optical axis), the steps (grooves) serve as a radiation shield and lead to a decrease in the transmission. In addition to this drawback, another considerable disadvantage of a Fresnel lens design is the potential build up of dust in the lens grooves. This is not an issue in the JEM-EUSO design, as the telescope will be operated in a dust-free space environment. It does however pose a significant problem for the FAST concept, as an eventual array of FAST telescopes would consist of several hundred autonomous stations spread over thousands of square kilometers, where frequent cleaning and maintenance will be infeasible.

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3.2 The reflective solution

A reflecting telescope design offers fewer drawbacks. A large $30^\circ \times 30^\circ$ field-of-view can be covered easily using a single or segmented mirror, and the mirror itself can be protected from the external environment by a shroud. The simplest reflective solution could be realized using a single spherical mirror. If the mirror is used in conjunction with an aperture at its radius of curvature the design is known as a Schmidt camera [15]. An aspherical corrector plate is typically used to eliminate on-axis optical aberrations. However, such a design is suitable only for small field-of-view applications, as the size of the optical spot increases with angle to the optical axis. In the absence of a corrector plate, a so-called lensless Schmidt camera [16] can be used to cover a large field-of-view. In this case the optical spot size is increased, but it is not a function of the arrival angle of the incident light.

4 The optimal FAST telescope design

A Schmidt type optical design was adopted for the full-size FAST prototype. In a typical Schmidt telescope a corrector plate is placed at the entrance aperture (located at the mirror's radius of curvature, a distance of $2f$, where f is the focal length) to facilitate the control of off-axis aberrations: coma and astigmatism. Field curvature and spherical aberration are still present, although the former can be eliminated by placing a suitably curved detector in the image plane. The size of the optical point spread function (PSF), which describes the spatial distribution of light on the focal surface, is a function of the spherical aberration of the system, and is typically circular in shape for both on- and off-axis beams.

The coarse granularity of the FAST camera, having only four PMTs each covering an angular field-of-view of $\sim 15^\circ$, allows the requirements on the size and shape of the telescope's PSF to be relaxed. The FAST prototype telescope therefore takes the form of a lensless Schmidt camera, as residual coma and astigmatism present due to the lack of a corrector plate does not affect the functionality of the telescope. The telescope mirror is reduced in size, and the distance between the mirror and the focal surface shortened relative to a regular Schmidt telescope, with the entrance aperture located closer to the focal surface.

The dimensions of the FAST prototype telescope are shown in figure 1. An octagonal aperture of height 1.24 m is located at a distance of 1 m from a 1.6 m diameter spherical mirror. The design fulfills the basic FAST prototype requirements, with an effective collecting area of 1 m^2 after accounting for the camera shadow, and a field-of-view of $30^\circ \times 30^\circ$.

Figure 2 shows the results of a ray-tracing simulation of on-axis (blue) and off-axis (green) optical beams performed with the Zemax software package [17]. The size and the shape of the spot is of particular importance, and is shown in figure 3 (note that this figure depicts the geometrical spot shape along with the intensity of the spot relative to the maximum). The top (bottom) row shows the spot shape for an on-axis (off-axis) optical beam as a function of the distance from the focal plane. The 300 mm scale represents the maximum size of the spot. This should be compared with the 200 mm diameter of the PMTs which will be installed in the camera located in a custom-built box at the focus of the optical system. The characteristic "star" shape of the optical spot is a result of the octagonal shape of the entrance aperture. The spot shape becomes circular in nature for positive defocusing of the telescope (the image plane moved closer to the mirror), with a central hole corresponding to the shadow of the camera box. In order to minimize the effect of

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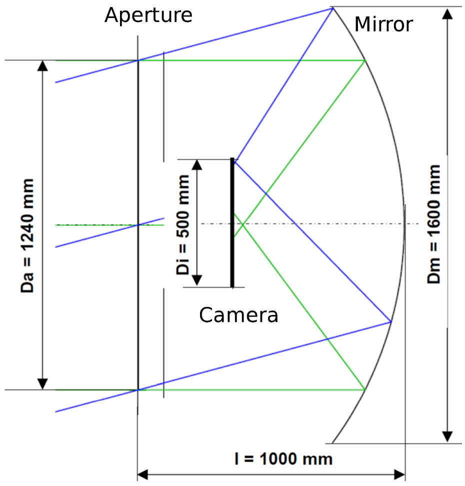

Figure 1. The dimensions of the FAST prototype telescope's optical system. D_a is the face-to-face size of the octagonal telescope aperture, D_i is the side length of the square camera box, D_m is the diameter of the primary mirror, and l is the mirror-aperture distance.

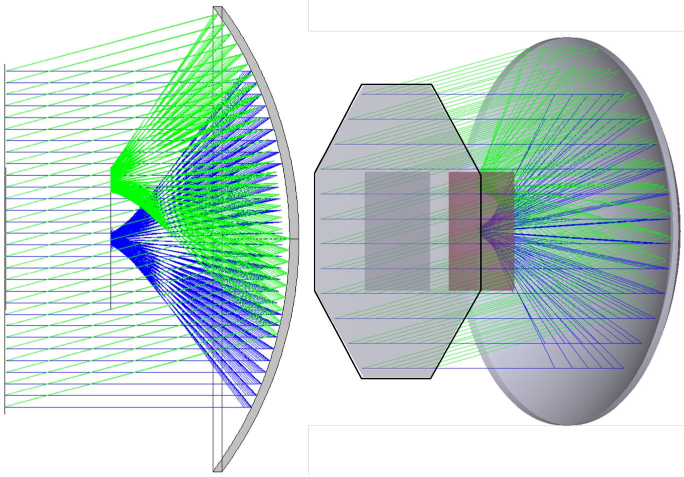

Figure 2. Ray-tracing simulations (2D and 3D) of the prototype telescope optics. The configuration of the aperture, mirror and camera is identical to that shown in figure 1. The parallel lines indicate ray-tracing simulations of on-axis (blue) and off-axis (green) beams.

the dead space between PMTs, a 25 mm negative defocusing was utilized in the prototype design. This serves to eliminate a complete loss of signal for on-axis optical beams where light is focused in the central point between all four PMTs. These simulations were performed assuming a single compact primary mirror, while the constructed FAST prototype uses a segmented primary mirror, complicating the shape of the optical spot. Nevertheless, these simple simulations accurately predict its size. A more detailed description of the prototype optical system is in preparation, including ray-tracing simulations taking into account the segmented nature of the primary mirror, the complex shape of the camera plane (with four large curved PMT surfaces), and the light collectors which are attached to the periphery of the camera box to increase the collection efficiency for off-axis beams.

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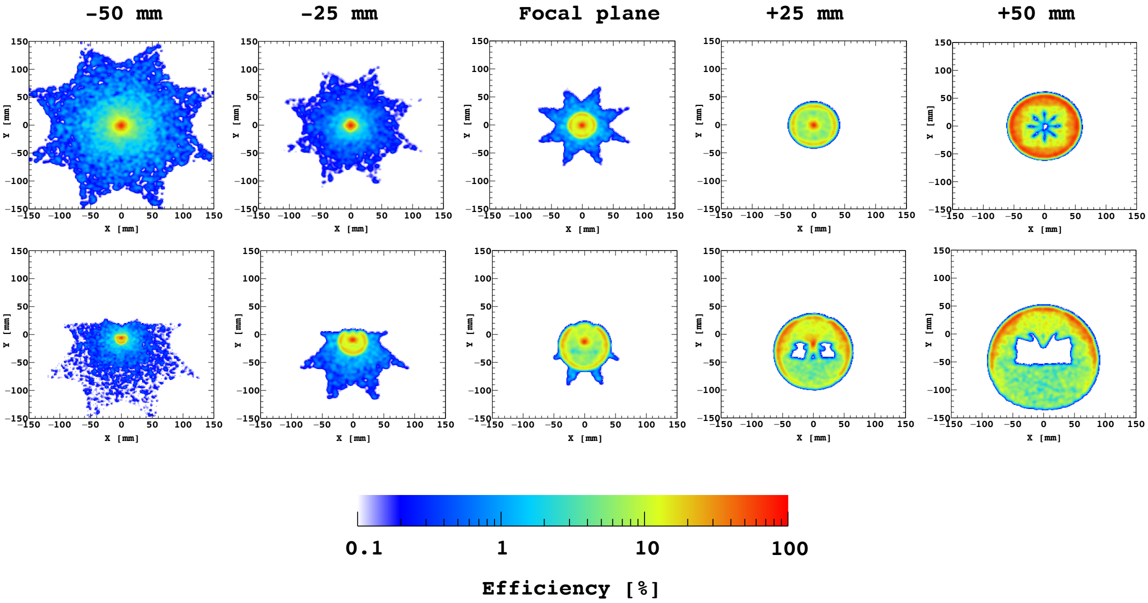

Figure 3. Geometrical spot diagrams from ray-tracing simulations of the FAST prototype optics. The spot diameters are shown for both on-axis (top) and off-axis (bottom) beams as a function of the distance from the focal plane (defocusing). Negative defocusing corresponds to moving the focal plane further from the mirror, and vice versa for positive defocusing. The color scale represents the relative intensity profile of the spots.

5 Mirrors and filters

The simplest and least expensive realization of a 1.6 m diameter spherical mirror is a segmented design. While a single mirror solution would be optimal, it is technologically very difficult to produce, as well as being extremely expensive. The sagitta of a single mirror would be ~ 250 mm.

Our FAST telescope design consists of a central circular mirror and 8 side mirrors, or "petals". The diameter of the individual mirror segments was limited by the technology available in our laboratory. The arrangement of the mirror segments was optimized to achieve a resultant effective area that was within the FAST design specifications. This could be achieved by using 6 circular side mirrors and one central circular mirror, all with the same diameter, resulting in the lowest cost. The mirrors could be overlapped (to minimize the dead area between segments) — see figure 4(a), although in this configuration a different radius of curvature is required for the side mirrors, resulting in a complex optical spot shape. An alternative solution is to cut the overlapping areas of the side mirrors as shown in figure 4(b). The dead area between the mirrors is, however, still significant in this configuration, decreasing the final mirror area. This dead space could be reduced by cutting the side mirrors and utilizing a hexagonal central mirror as depicted in figure 4(c). As the dimensions of the custom-made mirror substrate are already set, this solution results in a decrease in the area of the reflective surface. The optimal configuration is a circular central mirror surrounded by 8 "petal" shaped mirrors, which offers a nearly 10% increase in the surface area relative to the design depicted in figure 4(b). The resultant reflective area of the segmented mirror is 2.39 m^2.

The mirrors are produced on site, in the Joint Laboratory of Optics of the Palacky University, and the Institute of Physics of the Academy of Sciences of the Czech Republic, from a custom-made

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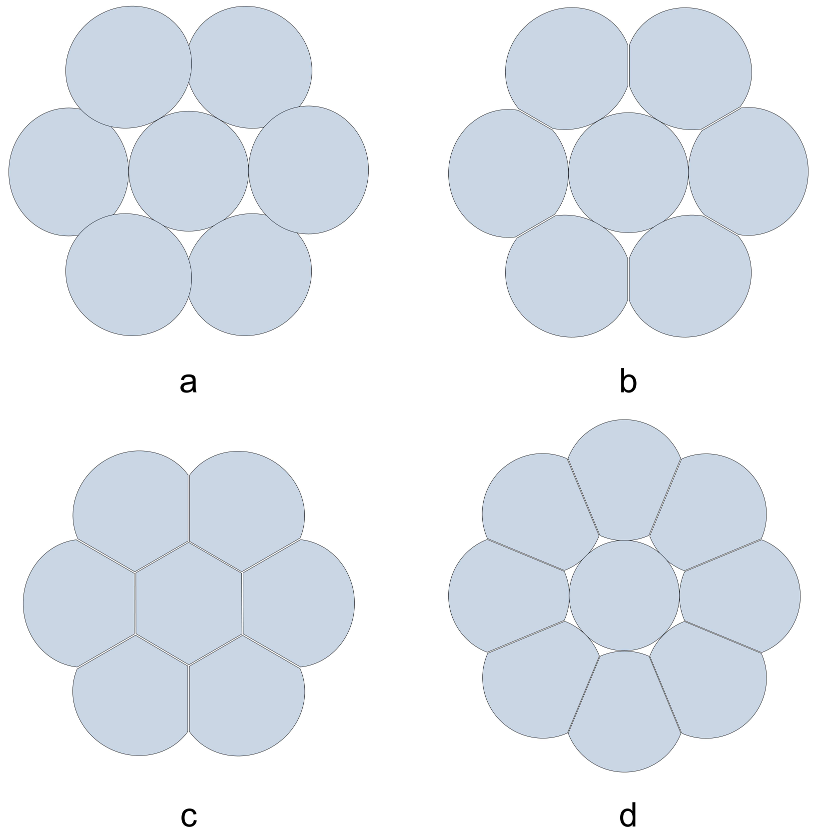

Figure 4. The segmentation of the FAST primary mirror. In a) the use of identical overlapping circular mirrors, b) identical circular mirrors cut to remove overlap between adjacent segments, c) identical circular mirrors cut to reduce dead-space between segments, and d) the optimal solution — one central circular mirror surrounded by 8 "petals".

substrate. The substrate is a borosilicate glass with good optical and mechanical quality. The reflective surface consists of vacuum coated Al and SiO_2 layers. The typical spectral reflectance, filter transmission and total optical efficiency between 260 nm and 420 nm is shown in figure 5. The reflectivity is relatively constant over this wavelength range, with a maximum of ~ 90% at 420 nm, and a minimum of ~ 75% at 260 nm.

A UV band-pass filter is installed at the aperture of the telescope to reduce the exposure to night-sky background light. The maximum angle of incidence of the light passing through the filter is ~ 20°, with Fresnel losses being negligible compared to the losses which would be present if the filter were installed on the telescope camera (the maximum incidence angle of light on the filter is ~ 60° in this configuration). In this case, an additional glass window would need to be installed at the aperture to protect the telescope against the environment, resulting in further transmission losses. In addition to reducing the camera's exposure to night-sky background light, the UV filter serves as a protective window against dust and aerosols. We use a ZWB3 filter manufactured by Shijiazhuang Zeyuan Optics. Its spectral transmission is shown in figure 5. Traditionally the Schott Desag M-UG6 filter has been used in atmospheric fluorescence experiments, but unfortunately the production of large format filter glass has been discontinued. We therefore opted for the same glass

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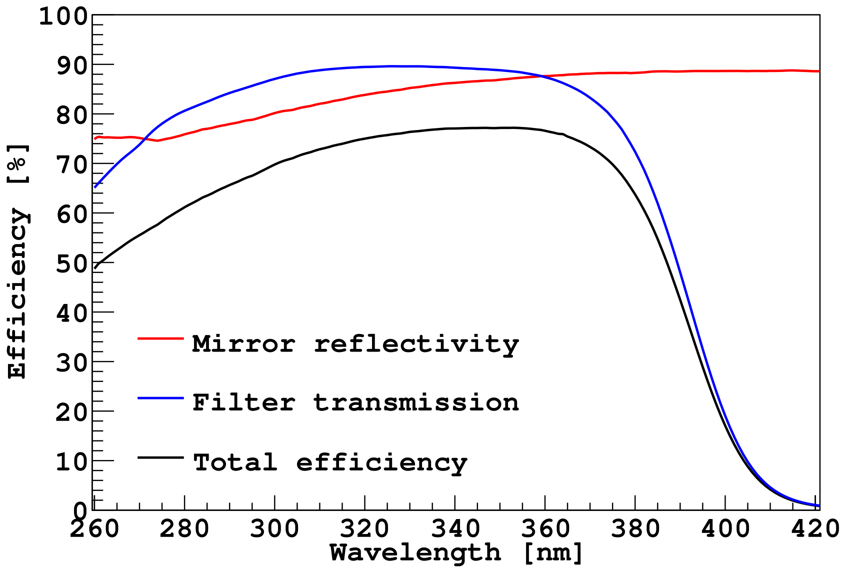

Figure 5. The typical spectral reflectance of the FAST mirror between 260 nm and 420 nm, along with the spectral transmission of the UV band-pass filter. The resultant total optical efficiency is shown in black.

filter used on the Cherenkov telescope of the MAGIC [18] observatory. The filter is constructed from a number of small segments in order to fit the FAST prototype's octagonal aperture. The individual segments are fit together using brass "U" and "H" profiles, resulting in an aperture of 1 m^2 in area.

6 Telescope support structure

The telescope's mechanical support structure was built from commercially available aluminum profiles. This allows for straightforward assembly/disassembly, and easy packing and transport due to their light weight, while also providing an extremely stable and rigid platform for the FAST optical system to be mounted on. The mechanics consists of a primary mirror stand mounted with a single degree of freedom to facilitate adjustment of the telescope's elevation (the elevation can be set to discrete values of 0°, 15°, 30° and 45° above the horizon). The square camera box (side length 500 mm), which holds four 200 mm PMTs, is mounted on a support structure connected to the perimeter of the mirror dish which also holds the octagonal filter aperture. The mirror stand contains 9 mirror mounts, each with 2 degrees of freedom to allow for mirror segment alignment. The whole mechanical construction, shown in figure 6, is covered with a shroud to protect the optical system from the surrounding environment.

7 Conclusion

Following the successful proof-of-concept test of a compact, low-cost air fluorescence telescope using the EUSO-TA optics at the Telescope Array site, we present the design of the first full-size prototype telescope having a $30° \times 30°$ field-of-view and a 1 m^2 aperture, along with its mechanical support structure.

A reflective lensless Schmidt telescope was shown to be preferable to a refractive design, due to its lower cost and superior performance in large field-of-view applications. The chosen design

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Figure 6. The complete mechanical structure. The mirror and the camera are protected from dust and aerosols by a shroud, which also acts as a shield for ambient light.

utilizes 8 “petal”-shaped spherical mirror segments surrounding a central mirror. The optical performance of the prototype system has been investigated using ray-tracing simulations assuming a single spherical mirror. While this simplified treatment ignores complex effects introduced by the advent of a segmented primary mirror, it allows the expected size of the optical point spread function to be estimated. The size of the spot was shown to be between 80–100 mm in diameter for both on-axis and off-axis beams, and ideal for a focal plane comprising large 200 mm diameter PMTs.

The first prototype was installed at the Telescope Array site in September 2016, and two additional telescopes are currently under construction.

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