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Prototype 9.7m Schwarzschild-Couder telescope for the Cherenkov Telescope Array: Project overview

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A full scale 9.7m Schwarzschild-Couder (SC) Telescope is a prototype for the Medium Size Telescopes (MSTs) of the Cherenkov Telescope Array (CTA) observatory. The SC-MST has been proposed as an instrument capable of achieving the ultimate performance of the imaging atmospheric Cherenkov technique (IACT) in the energy range from 100 GeV to 10 TeV for the CTA installation. Comparing to the present day IACT observatories, the SC-MST employs an aplanatic two-mirror optical system to simultaneously increase the field of view to 8 degrees and significantly improve the imaging resolution via reduction of the camera pixel size to 0.067 deg. The fully populated compact SC-MST camera will have a diameter of 80cm and is assembled from 11,328 SiPM pixels augmented with fast, highly integrated electronics based on custom ASICs and FPGAs. The project has been in development since 2012 and prototype SC-MST construction started at the Fred Lawrence Whipple Observatory in southern Arizona in early 2016. In this contribution we will provide an overview of the project and its status.

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1. Introduction

The Cherenkov Telescope Array (CTA[1], [1]) is being developed as the next-generation very high-energy (VHE) ground-based gamma-ray observatory for astronomy in the energy range from ~ 20 GeV to ~ 300 TeV. The observatory utilizes large arrays of imaging atmospheric Cherenkov telescopes (IACTs) to improve the sensitivity by an order of magnitude over the current generation VHE IACTs. CTA will enable the study of the VHE sky with unparalleled energy, temporal and sky solid angle coverage [1], which will be conducted with unprecedented angular and energy resolution by utilizing the technique of stereoscopic observations. Two CTA installations, one in the South (Paranal grounds in Chile) and one in the North (La Palma, Canary Islands), will consist of arrays of IACTs with three apertures: D$\sim$ 23m, large size telescopes (LSTs), D$\sim$ 12m, medium size telescopes (MSTs) and D$\sim$ 4m, small size telescopes (SSTs), which are tailored to provide cost-effective solutions for the VHE band spanning four orders of magnitude in energy.

Traditionally, IACTs have been constructed as instruments using the prime focus optical system (OS) in which the primary mirror is segmented and realized either with the parabolic or Davies-Cotton (DC) [2] configuration. These optical designs, however, do not fully exploit the benefits afforded by the large arrays of MSTs, such as in CTA installations in the Southern (25 telescopes) or Northern (15 telescopes) hemispheres. The optical system of the novel Schwarzschild-Couder (SC) IACT [3] was developed in the US as an ultimate concept [4] for the Medium Size Telescope array in CTA, in which its performance would be limited only by the physics of atmospheric cascades rather than by the under-performing DC-MST implementation [5]. Although the SC-MST is more challenging to construct and align its dual-mirror segmented OS, it offers a number of advantages compared to the DC-MST.

The aplanatic SC-MST design provides a natural solution for wide field-of-view (8°) imaging combined with a significantly smaller focal surface scale than the conventional DC-MST. This unique capability of the Schwarzschild telescope [6], in which the secondary mirror de-magnifies the image, permits the use of the high angular resolution IACT camera, which has a factor of 6.3 larger number of imaging pixels ($11,328$) than in a DC-MST while keeping the SC-MST camera diameter (0.8 m) a factor of 2.9 smaller than conventional. The small plate scale of the SC-MST camera is compatible with the novel semiconductor photon sensitive devices (PSDs) and with silicon photomultipliers (SiPMs), which are significantly less expensive than the traditional photomultiplier tubes (PMTs) used in DC-MST camera implementations as well as in all present major ground-based Cherenkov observatories: VERITAS, HESS, and MAGIC. In addition, the SC-MST optics are synchronous, unlike DC-MST, which may provide further benefits for the reduction of the cosmic ray background at low energies and improve performance for intensity interferometry applications of CTA telescopes.

The advantages of the SC-MST design come at the cost of highly aspheric optical system and demanding alignment and optical figure tolerances. In fact, a telescope with SC optics operating in the diffraction limit has never been constructed despite being theoretically discovered more than 110 years ago [6]. Although SC-MST operates in the regime $\sim 10^3$ times above the diffraction limit, its aspheric OS represents the major challenge and the highest risk for practical, economic implementation of the SC-MST design in the context of CTA. Hence, a consortium of US insti-

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tutions was organized in 2012 to construct the prototype Schwarzschild-Couder telescope (pSCT) with a 9.7m aperture to demonstrate the capabilities of recently developed and relatively inexpensive replication technologies for the production of aspheric mirrors, to confirm the possibility of the use of SiPM technology in the IACT applications, to prove that the highly integrated electronics based on custom ASICs and FPGAs can become a cost effective solution for the pSCT camera, and, ultimately, to test the feasibility of an innovative SC-MST design for the CTA observatory.

The pSCT project[2] has been made possible through the major research instrumentation (MRI) program of the US National Science Foundation (NSF) and it was joined by the international partners, participating in the CTA consortium, from DESY, MPIK & FAU.EU (Germany), INAF & INFN (Italy), STEL (Japan) and UNAM (Mexico)[3]. At present, the SC optics design is well recognized as a viable option for the implementation of IACTs in the CTA observatory and it is also being pursued by the ASTRI and GCT projects with the goal of constructing SC-SSTs with $\sim$4m aperture for CTA. A description of these projects and reports of their important successes, demonstrating the fruitfulness of the SC optics for IACTs, can be found elsewhere in these proceedings. This contribution describes the status of the complex and demanding project of demonstrating the full scale 9.7m prototype for the SC-MST, which is currently under construction at the Fred Lawrence Whipple Observatory (FLWO; location of the VERITAS gamma-ray observatory) in southern Arizona near Tucson.

2. pSCT Mechanical System

The design of the mechanical structure for the pSCT has been mainly driven by the motivation to adapt, as much as possible, the telescope tower and telescope positioning system from the DC-MST design [7] developed for the CTA project at DESY, Germany. Only minimal changes were made to accommodate the existing constraints at the site of the pSCT construction, and the specifications of the pSCT dual-mirror OS. The main physical parameters, which drive the mechanical designs of DC-MST and SC-MST, such as optical support structure (OSS) weight and its moment of inertia, are nearly identical by the design choices of the pSCT.

One of the changes implemented was a necessity to shorten the DC-MST telescope tower, designed for 12m aperture telescope, to be able to use existing concrete foundation previously constructed for the VERITAS prototype telescope at FLWO. Even with this customization, this foundation required additional reinforcement and relevant civil engineering work was completed at FLWO in January of 2016. Comparing to the prototype DC-MST constructed near Berlin, several other upgrade changes were included, such as casted head and yokes, higher strength and higher resolution Azimuth bearings. The height of the tower and all upgraded elements are envisioned to be identical for the future installations of either DC-MST or SC-MST in CTA.

The single essential change in the pSCT motion control system is the realization of three parking positions required by the dual-mirror nature of the pSCT OS. The pSCT parking concept is illustrated in Figure 1. The avoidance of the sunlight during day parking of the telescope is achieved by the combination of baffles around the primary (M1) and secondary (M2) mirrors and cyclic change of parking elevation positions throughout the calendar year. The solution tailored

[2]http://cta-psct.physics.ucla.edu/

[3]The full list of US and International Institutions participating in the pSCT project is provided at http://cta-psct.physics.ucla.edu/institutions.html

for pSCT uses three parking positions and the heights of M1 and M2 baffles of 1.5m and 1.0m respectively. The system of baffles is designed for three purposes: to protect OS from sunlight during daytime, to provide stray-light control during observing time at night, and to ensure human and environmental safety during pSCT operation and maintenance.

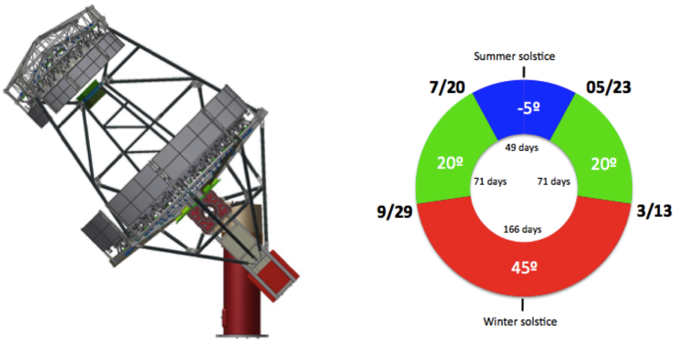

Figure 1: pSCT Parking concept. Three parking positions at elevations -5°, 20°and 45°will be used during the year.

The design of the pSCT OSS, previously reported in [8], includes M1 and M2 mirror support structures, a camera installation tower combined with M2 OSS support arms, and a counterweight structure combined with the M1 OSS reinforcement space frame. The counterweights and the central plate for the M1 OSS are interfacing the yokes of the pSCT positioning system. The telescope tower and the pSCT motion system, fabricated in Germany, were successfully delivered to FLWO and installed in early spring of 2016. The pSCT OSS structural elements were fabricated in the US. The assembly of OSS was done by the technical personnel at FLWO and the OSS integration with the pSCT positioning system was completed in August of 2016.

Figure 2 shows the assembled pSCT mechanical structure at FLWO as of June 2017. After completing the assembly of the positioning system and OSS, initial metrology of the M1 and M2 mirror support structures was conducted to verify compliance with the specifications. The counterweights of the telescope were balanced in the current assembly state and the motion drive system was fully tested in April of 2017.

Figure 2: The current state of the pSCT construction at FLWO.

During this commissioning process it was verified that the pSCT is able to slew with maximal speeds of up to 6°per sec in Azimuth and 3°per sec in Elevation. Small oscillations in the pSCT structure during slewing were detected with amplitudes well below specifications. No fine tuning of the feedback loops of motion controllers were done during these tests but will be done after the full pSCT structure, optics and camera are installed. Anti-backlash controllers and position offset reduction controllers on both axes operated as expected. No abnormalities in the operation of motors were observed; friction of the azimuth and elevation bearing was found to be proportional to the axis velocity. The accuracy of pSCT tracking was verified and found to be better than 4 arcseconds for the elevation axis and 3 arcseconds for the azimuth axis. This result exceeds specification for the tracking error prior to calibration by nearly a factor of ten.

The commissioning phase of the pSCT mechanical structure also included on site tests of the telescope slewing control emergency cabinet, which was developed at DESY and delivered to FLWO in early spring of 2017. This second level emergency redundant sub-system is powered by an independent generator to bypass the main motion control cabinet of the pSCT and to drive the telescope to the parking position should both power and pSCT motion control equipment fail.

3. pSCT Auxiliary Equipment

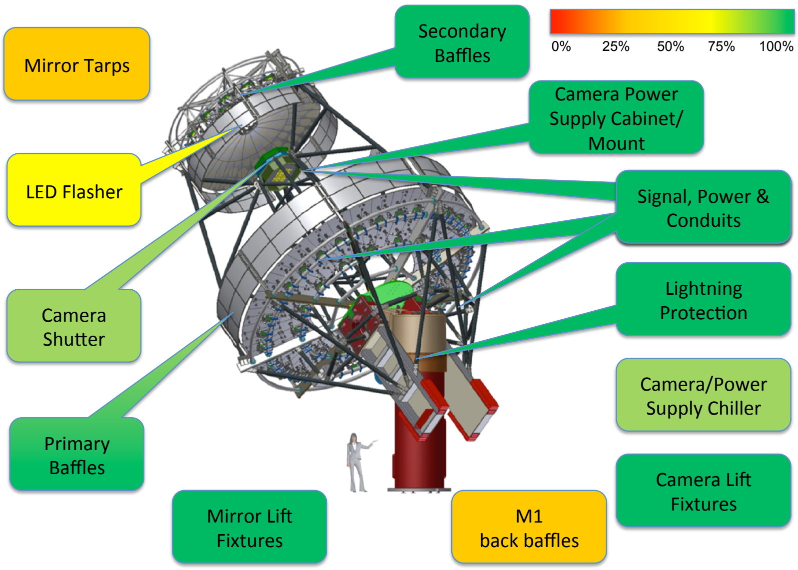

Figure 3: Completion Status of pSCT Auxiliary Equipment.

Figure 3 summarizes the status of completion of pSCT auxiliary equipment. Its major components such as the lightning protection system, stray and sun light control system (baffles), camera cooling, camera power supply, and conduits system for signal, power and Ethernet cable distribution on the OSS are either completed or near completion. All auxiliary equipment critical for installation of the pSCT optical system is mounted and connected.

4. pSCT Optical System

The dual mirror pSCT Optical System (OS) is derived from the exact Schwarzschild solution with aplanatic constants $q = 2/3$ and $\alpha = 2/3$, as this OS design was shown to be nearly optimal for the IACT application through extensive simulations [9]. The effective focal length of the OS is 5.586m with an on-axis light collecting area of 50m^2 (47.7m^2 at the edge of FoV). It is a fast OS ($f/0.5781$) optimized for 8°FoV with a focal surface plate scale of 1.625mm per minute of arc. The de-magnifying Secondary mirror has a diameter of

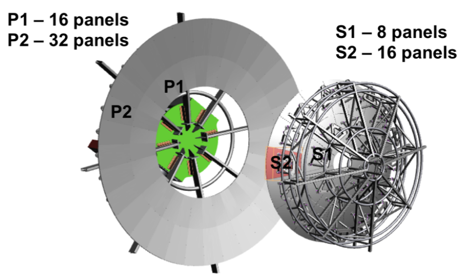

Figure 4: pSCT OS segmentation; M1 *(Left)*, M2 *(Right)*

5.4m and is highly aspheric. Both M1 and M2 mirrors are segmented with two types of segments in each as shown in Figure 4. The focal surface is slightly parabolic to minimize astigmatic aberrations at the edge of the FoV (maximal sag is -22mm at the camera edge radius of 39cm). Further details of the pSCT OS are given in the previous reports [10–12].

The detailed status of the pSCT optical system is reported elsewhere in these proceedings [13] to which we refer the reader. Here we summarize that all M1 mirror panels are fabricated. Technological risk of manufacturing of M2 mirror panels is retired and manufacturing of all panels is near completion. All elements of the alignment system are fabricated and undergoing integration.

5. pSCT Camera

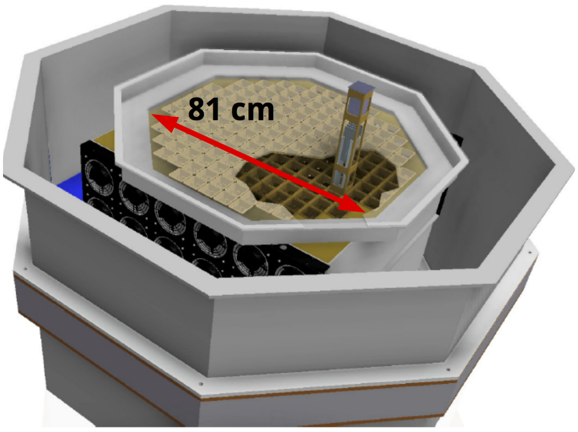

Figure 5: pSCT camera hierarchical concept. One of 177 FEE modules is pulled up and shown.

The overall design of the SCT camera with 11,328 SiPM pixels has been previously described in [14]. The hierarchical assembly of the camera, shown in Figure 5, is divided into 177 Front-End-Electronic (FEE) modules, which are distributed over 9 trigger sectors. For the pSCT camera, only the inner most sector of 5×5 FEEs will be populated (see Figure 6), which is equivalent to a FoV of about $2.5° \times 2.5°$. Although this limitation of FoV is made due to cost considerations of the project, the pSCT FoV is sufficient to validate the performance of the camera electronics as it forms a complete trigger sector controlled by a single backplane board. The FoV can be later upgraded to a full 8.0°diameter envisioned for the SCT. A FEE module has $8 \times 8 = 64$ pixels with a size of 6.5×6.5 mm^2 each (0.067°on sky). The SiPM, Hamamatsu type S12642, is selected as the photon detector for 16 FEE modules of the pSCT camera.

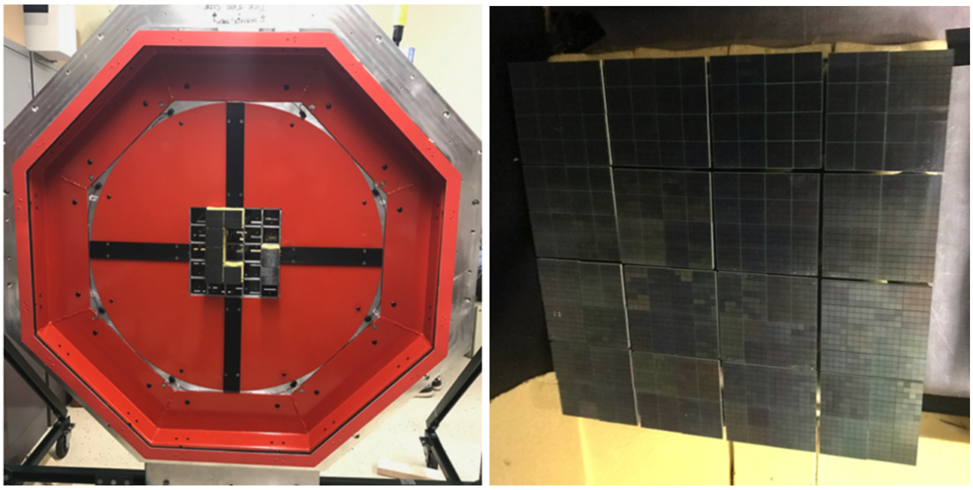

Figure 6: Assembled mechanical structure of the camera *(Left)*. Eight FEE modules installed into pSCT camera *(Right)*.

The design of the focal surface of the SC-MST, mechanical integration, environmental control and the preamplifier are described in [15]. The focal surface of photon sensors is temperature controlled to better than 0.1°C. The readout electronics and the pre-amplifiers for a single FEE module are integrated on two boards directly behind the photon sensors. The signal digitization and first level trigger decision is implemented with a dedicated ASIC, TARGET 7 [16], which uses a switched capacitor array that is sampled with 1 GS per second. TARGET 7 has 16 channels and provides 16 microseconds buffer depth at this sampling rate. Upon receiving a readout command, the sampling is stopped and the stored analog signals are digitized with an effective resolution of 10 bit. The FEE modules connect to a backplane, which facilitates communication with and data transfer from them. Integrated into the backplane is also the combinatorial trigger, which is a programmable n-fold coincidence trigger of neighboring pixels.

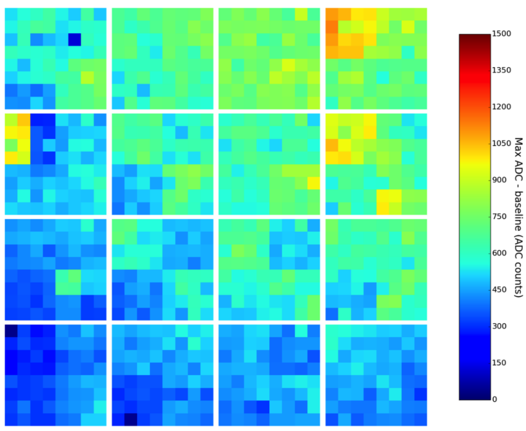

Figure 7: Uncalibrated image of a light flash recorded with the prototype camera in the laboratory

At present, the pSCT camera mechanical system, 16 FEE modules and backplane trigger board of the camera electronics are fabricated integrated and undergo extensive calibration and testing in the laboratory setting. Figure 7 shows an uncalibrated image of an LED flash recorded by those 16 modules. The gradient across the image can be attributed to an intensity gradient in the LED flash. The 16 modules of the inner sector of pSCT camera will be augmented by 9 FEE modules equipped with a different SiPMs sensor manufactured by FBK. The recent progress in the production and calibration of these FEE modules is reported in [17]. The Data Acquisition System of the pSCT camera, initially described in [18], is currently being tested on the integrated camera hardware.

6. Summary and Outlook

We have presented the current status of the pSCT project, the goal of which is to demonstrate the feasibility of a novel, advantageous SC-MST design for the CTA observatory. The project enters into the final stage of the construction phase, with installation of the optical and alignment systems scheduled to begin in July 2017, followed by the installation of the camera in the fall of 2017. Commissioning of these major pSCT subsystems is expected to start immediately after the installation.

7. Acknowledgments

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