SST Programme: Performance Analysis Report

SST-PRO-ANR-010

Version 1a

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1 Introduction

The construction of any new-generation telescope requires a precise evaluation of its expected performances at the simulation level, prior to the deployment of the instrument at the observing site.

The SST Consortium is a project aimed at developing, testing and validating the expected performances of the 4-m diameter Schwarzschild-Couder telescopes to be deployed at the Southern CTA site as a part of CTA South. The analysis report presented here aim to outline the SST single-telescope performances in sufficient detail, considering the required precision and computing constraints.

1.1 Scope & Purpose

This is the user-requirement document of the performance analysis for the SST model. Its purpose is to collect and describe the results of the simulation-level analysis on the single telescope for evaluating its instrumental performances.

1.2 Applicability

The content reported here is the output obtained by validating the SST hardware through the analysis of dedicated MC simulations, either produced by official pipelines [RD1, RD2] or by external software (e.g., ROBAST; [RD3]).

1.3 Document Roadmap

This is a live document that is expected to be constantly updated with the outcome of the simulations dedicated to the study of the expected SST single-telescope performances. The current version of this document only contains a preliminary description of the performances of the separate telescope components determined with external tools or dedicated analyses. The SST WT8 will soon assess the feasibility of running MC simulations devoted to estimating the expected single-telescope performances of the SSTs prior to the release of major simulative productions that aim at providing the response of the entire SST array (e.g., the CTA Prod6).

1.4 Linked Documents

1.5 Applicable Documents

[AD1]	SST Optical Design	SST-OPT-DES-001
[AD2]	SST Camera Input to Prod6 MC Parameters	SST-CAM-TEC-017

[AD3]	Input to Monte Carlo Model (MCM)	SST-PRO-MAT-005
[AD4]	Telescope Technical Requirements Specification	SST-PRO-SPE-001

1.6 Reference Documents

[RD1] https://www.iap.kit.edu/corsika/
[RD2] Bernlöhr, K. (2008), Astropart. Phys. 30, 149
[RD3] Okumura, A. et al. (2016), Astropart. Phys. 76, 38
[RD4] https://www.zemax.com/
[RD5] Vassiliev, V. et al. (2007), Astropart. Phys., 28, 10

1.7 Definition of Terms and Abbreviations

1.7.1 Abbreviations and Acronyms

ACADA	Array Control and Data Acquisition System
AIT	Assembly Integration and Testing
AIV	Assembly Integration and Verification
ASTRI	Astrophysics with Italian Replicating Technology Mirrors
BKO	Bridging phase Kick-Off
CDR	Critical Design Review
CTA	Cherenkov Telescope Array
CTAO	Cherenkov Telescope Array Observatory
FAR	Final Acceptance Review
FRC	France Contribution
DR	Delivery Review
DVER	Design Verification Engineering Review
ERIC	European Research Infrastructure Consortium
ESC	Executive Steering Committee
IKC	In Kind Contribution
INAF	Istituto Nazionale di Astrofisica
INSU	Institut National des Science de l'Univers
KO	Kick-Off
MPIK	Max-Planck-Institut für Kernphysik
OP	Observatoire de Paris – PSL, CNRS
PA	Product Assurance
PBS	Product Breakdown Structure
PM	Project Manage
PR	Product Review
PMP	Programme Management Plan
PO	Project Office
PQR	Production Qualification Review
PR	Product Review
PRM	Programme Manager

PRR	Production Readiness Review
PSE	Programme System Engineer
QA	Quality Assurance
QM	Quality Manager
RAMS	Reliability, Availability, Maintainability & Safety
SE	System Engineer
SST	Small Size Telescope
TRR	Test Readiness Review
WBS	Work Breakdown Structure
WP	Work Package
WPD	Work Package Description

1.7.2 Glossary

TERM	DEFINITION
"As Built" Configuration	The as-built configuration or applied configuration is defining the as-built status per each serial number of Configuration Item (CI) subject to formal acceptance.
"As Designed" Configuration	The as-designed configuration or Applicable configuration is defining the current design status of a Configuration Item (CI)
AIV	AIV is the Assembly Integration and Verification, which is referred to the integration activities related with the verification of the system or sub-system. In the framework of SST for briefness this term includes also the Assembly Integration and Testing which is related with the integration activities and testing to be performed during the integration at system and subsystem levels
Baseline	Set of information which describes exhaustively a situation at a given instant of time or over a given time interval.
Change	Vehicle for proposing modifications to an approved baselined data or the business agreement.
Configuration	Functional or physical Characteristics of a product defined in configuration definition documents subject to configuration baseline.
Configuration Item	Aggregation of hardware, software, processed materials, services or any of its discrete portions, that is designated for configuration management and treated as a single entity in the configuration management process. **NOTE:** A configuration item can contain other lower level configuration item(s).
Deviation	Written authorization to depart from the originally specified requirements for a product prior to its production.
Firmware	Firmware is software programmed onto an electronic device which is treated like a pure hardware.
Executive Steering Committee	The SST Executive Steering Committee (ESC) is the high-level decision-making body which will manage the strategic direction of the Programme and will be in charge of overseeing progress and facilitating global collaboration among the participating groups.
Institutes	Research Institutes involved in the SST Programme.
Contractor	Industry involved in the SST Programme which has a contract whith an institute
SST-PRO	It is the team composed by Institutes and Contractors responsible , involved in the production of SST telescopes elements, which coordinate the project level activities.
Hardware	Hardware is a single or an assembly of physical electronic devices which cannot be changed in its user environment.
Item	Any part, component device, sub-unit, unit, equipment or device that can be individually considered.
Model	Physical or abstract representation of relevant aspects of an item or process that is put forward as a basis for calculations, predictions or further assessment useful for the preparation of SST production
Partners	are those entities taking responsibility for IKC delivery by signing IKC agreements with CTAO, plus any organisation identified by these signing entities as playing an essential role in SST delivery. The institutes are the partners of the CTA-SST consortium.
Product	A product (hardware, software, service) required in the frame of the program and included as element of the product tree having a unique identifier. A product may be deliverable or not.
Product Breakdown Structure	Hierarchical structure depicting the product orientated breakdown of the project into successive levels of detail down to the configuration items necessary to deliver the required functions. The Product Breakdown Structure

TERM	DEFINITION
	(PBS) in general is influenced by Institutes/partners decisions to group certain products or by program history. It identifies products and their interfaces, it serves as the basis for the WBS
Service	Service is the result of at least one activity necessarily performed at the interface between the SST consortium and CTA and is generally intangible.
Software	Set of computer programs, procedures, documentation and their associated data.
SST-E2E	The SST end-to-end telescope, or simply SST, will consist of the SST Structure and the SST Camera (including all mechanics, mirrors, auxiliary devices and required software), integrated and commissioned on-site including all required documents. It ends at (and integrates into CTA via) the system interfaces specified by the CTA PBS.
SST Consortium	The SST Consortium then consists of the Partners and their associated Teams, where a Team is a set of individuals within a single organisation at a single location (such as a University group).
System	An entity of products assembled or working together for a well defined specified purpose. In SST the term system can be utilised in alternative to Telescope End-to-End.
Sub-System	Like a system but a lower level. In SST the SST system is composed by the subsystem SST-MECH, SST-OPT, SST-TCS and SST-CAM.
Waiver	Written authorization to use or release a product which does not conform to the specified requirements
Work Breakdown Structure	Hierarchical representation of the activities necessary to complete a project.

2 Analysis of the SST Performances

The derivation of the SST single-telescope performances requires the production of several MC simulations that are each devoted to the estimation of a specific subset of quantities (Cherenkov detection efficiency, total system throughput, system calibrations). In detail, the following products are needed:

- Scientific simulations of different types of Cherenkov data (point-like and diffuse photons, protons), with less events (1% to 10%) than a full MC production.
- Simulations of pedestal (events acquired with open camera lids and random trigger) and LED events (events acquired by SST-Cam flashed with a pulsed light source) for camera calibration.
- Simulations of illuminator events to evaluate the system throughput.

All of these MC simulations will be carried out taking advantage of the MCM inputs provided to CTAO for their MC Prod6 [AD3] and are intended to be valid until further modifications of the input parameters still under discussion/validation will take place.

2.1 Telescope Optics

The SSTs are dual-mirror telescopes built in Schwarzschild-Couder (SC) configuration consisting of three optical surfaces: the primary mirror (M1), the secondary mirror (M2), and the curved focal surface (FS) populated with SiPM sensors. M1 has a diameter of 4.3 m and is segmented into 85-cm wide hexagonal sections; M2 is instead monolithic, with a diameter of 1.8 m (Figure 2-1). Both mirrors are coated with the same reflective layer made of Al+ZrO_2: such a coating grants a reflectivity of up to 95% in the wavelength interval of maximum Cherenkov emission (300 ÷ 550 nm).

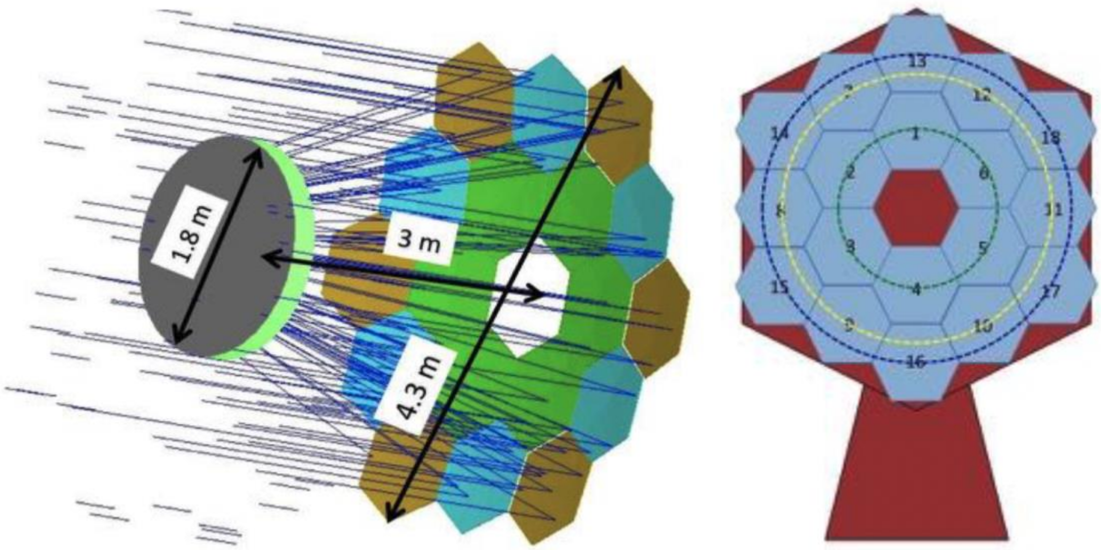


Figure 2-1: The Schwarzschild-Couder optical design adopted for the SSTs (left) and a sketch of the disposition of the primary mirror segments (right).

The optical system (OS) design of the SSTs was developed in compliance with the requirements of having a PSF (described by the diametric dimension D_{80} containing 80% of the energy) smaller than

0°.25 and a geometrical area larger than 5 m^2 across a FoV of at least 8° [AD1]. The design has been performed using the commercial software for optical system design ZEMAX [RD4].

The effective focal length of the obtained OS is F = 2154 mm. The distance between M1 and M2 is F/q = 3108.4 mm, where q = 0.6888 is the first Schwarzschild aplanatic parameter. The distance between M2 and FS is $(1 - \alpha)F$ = 519.6 mm, where α = 0.7573 is the second parameter, which together with q defines the Schwarzschild aplanatic solution. It has been shown [RD5] that the optical systems in the vicinity of q = 2/3 and α = 2/3 are nearly optimal for applications in ground-based gamma-ray astronomy. The SST aperture is D = 4306 mm, which makes its OS very fast with F/D = 0.50. The other OS parameters are summarized in Table 2-1.

Table 2-1: OS main dimensions.

Element Name	Diameter (mm)	Radius of Curvature (mm)	Shape	Distance to: (mm)
M1	4306	-8223	Even asphere	M2: 3108.4
M2	1800	2180	Even asphere	Det: 519.6
FS	360 (side)	1060	Spherical	---

The OS of the SSTs was designed to provide correction of aberrations within the full camera field of view by polynomial optimization of the SC configuration. Hence, the sagitta z of each of the three optical surfaces of the OS was parameterized by a spherical term and conical constant (describing the SC system) with the addition of polynomials representing aspheric corrections. The OS radial profiles are expressed as:

$$z = \frac{cr^2}{1 + \sqrt{1 - (1+k)c^2r^2}} + \sum_{i=1}^{n} \alpha_i r^{2i}$$

where:

- r is the surface profile (<2154.5 mm);
- c is the curvature (i.e. the reciprocal of the curvature radius of -8223 mm);
- k is the conical constant (k = 0 for the SST mirrors);
- α_i are the aspherical coefficients.

The diameter of the circle corresponding to an enclosed energy (EE) of 80%, i.e. the D_{80} parameter, was used as a figure of merit for the optimization of the α_i parameters. It has been required in the optimization process that the EE should be larger than 80% across the full FoV. The effects of mirror fabrication and misalignment errors on the PSF, D_{80}, and EE were not considered during the optimization of such coefficients, assuming an ideal OS implementation. The polynomial optimization approach follows a method that is like that of the Ritchey-Chrétien design, since on-axis aberrations are admitted in order to contain off-axis ones in order to obtain an angular resolution almost flat across the entire FoV. This can be considered a customization of the SC design for Cherenkov telescopes purposes. The optimization has also been performed using the ZEMAX software; the coefficients to be set in the optical design formula to describe the three OSs are listed in Table 2-2.

Table 2-2: Coefficients to be set in the optical design formula to describe the radial profile of the three OSs (note that the FS coefficients are all identically null).

Coefficient	M1	M2
a_1	0	0
a_2	9.61060e-13	1.62076e-11
a_3	-5.65501e-20	-2.89584e-17
a_4	6.77984e-27	8.63372e-24
a_5	3.89558e-33	3.34856e-30
a_6	5.28038e-40	-1.03361e-36
a_7	-2.99107e-47	-6.73524e-43
a_8	-4.39153e-53	-3.06547e-49
a_9	-6.17433e-60	3.17161e-55
a_{10}	2.73586e-66	-3.71183e-62

All the characteristics of the SST OS were obtained by geometrical ray-tracing simulations performed with an IDL tool. The simulation code inputs set to obtain the optical performance were:

- the photon surface density hitting M1 (in cm^{-2});
- a point-like source located at a distance of 10 km;
- an off-axis angular range between 0° and 5° to be scanned in steps of 10’;
- two off-axis source directions of 0° and 30°, respectively (corresponding to shorter and longer radial coverage of M1).

The EE curves corresponding to this set-up have been evaluated from the dimensions of the resulting focal spots at known off-axis angles. In all cases, 80% of the photons is always contained in a radial dimension less then 3.5 mm (i.e. the pixel radial dimension); as a result, D_{80} is always fully contained in a Cherenkov pixel of 7 mm and thus well below the 0°.25 requirement across the full FoV.

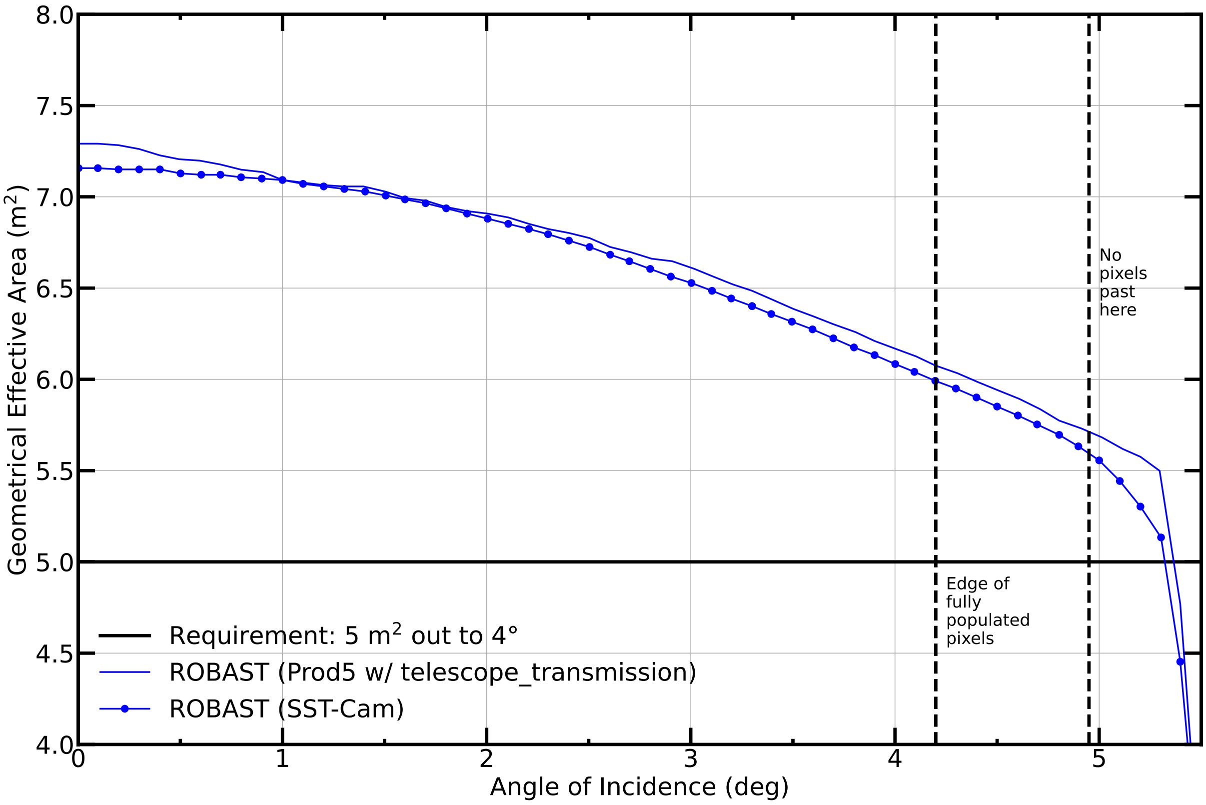


Figure 2-2: geometrical effective area produced by the SST optical configuration as a function of the incidence angle.

The OS plate scale was obtained through a linear fit of the radial positions of the PSF barycentre obtained for sources at different off-axis angles across the FoV. The obtained plate scale is ~37 mm/deg, with local fluctuation within 10”. Considering the obtained plate scale, a FoV of 8° is covered placing at the focal plane a Cherenkov camera with an active area diameter larger than 301 mm.

The time dispersion of the optical system was obtained considering the PV values of the optical path length across the FoV divided by speed of light. The obtained isochronicity falls in the range 0.65 ÷ 1 ns.

The geometrical effective area of the SST optical configuration as seen by SST-Cam – considering the shadowing produced by the telescope structure and the size of the camera itself – was evaluated as the fraction of photons reaching the focal plane with respect to the photons launched on M1 surface normalized to M1 physical area. Due to the shadowing-induced area losses, it is dependent on the off-axis angle. The result is fully compliant with the CTA requirement of 5 m^2 out to 4° off-axis (Figure 2-2).

2.2 Cherenkov Camera

The Cherenkov camera SST-Cam is located at the SST secondary focus. It is composed by SiPM photodetection modules (PDMs), each containing 64 6-mm wide pixels arranged on tiles (Figure 2-3).

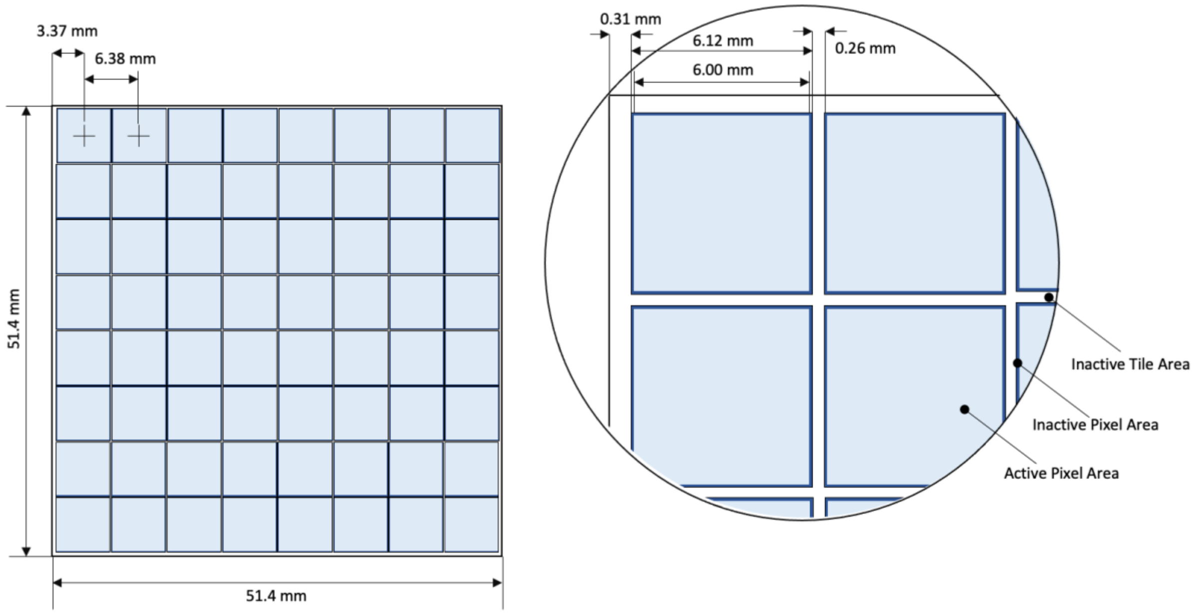


Figure 2-3: SST-Cam SiPM tile and pixel geometry.

The SST-Cam side containing the light-sensitive surface is protected by a transparent window that also filters the red and infrared light out. The transmission of this filter has been measured on a full-sized window and weighted with the distribution of incident angles onto the window expected from the telescope optics. The curve is very close to the result measured at 45^{o} incidence angle (Figure 2-4). The effect of the window coating on the SST requirements C-SST-TEL-1170 PDE and C-SST-TEL-0090 SNR are defined as [AD4]:

C-SST-TEL-1170 Photon Detection Efficiency (PDE): The average efficiency of the focal plane detectors (i.e., conversion efficiency from photons to photoelectrons), weighted by the reference Cherenkov spectrum in the wavelength range 300 ÷ 550 nm, including dead-space and the efficiency of any focal plane optics/windows, must be >20%.

C-SST-TEL-0090 Signal-to-Noise Ratio (SNR): The overall optical efficiency of the full Cherenkov telescope to the background light ε_{bkg} (including night sky background and albedo following the Background Light Reference Spectrum and integrated over the full response of the telescope) must be such that $\varepsilon_{sig}/\sqrt{\varepsilon_{bkg}} > 0.35$, where ε_{sig} is the integral over the Cherenkov Reference Spectrum.

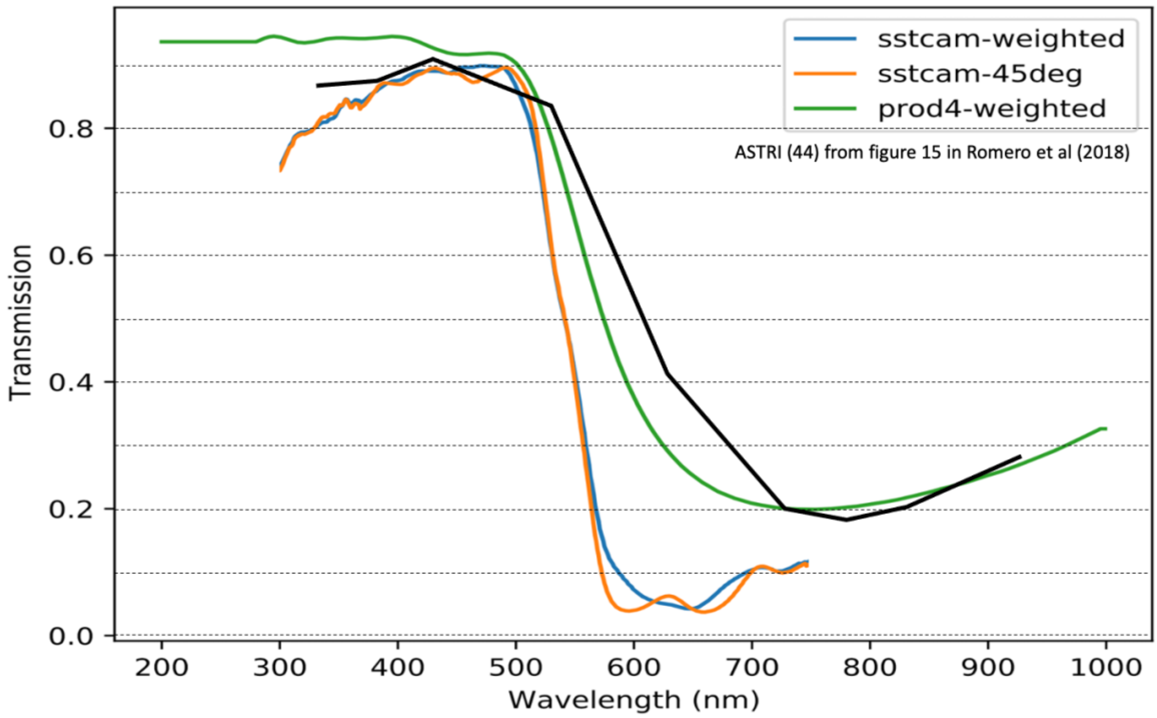
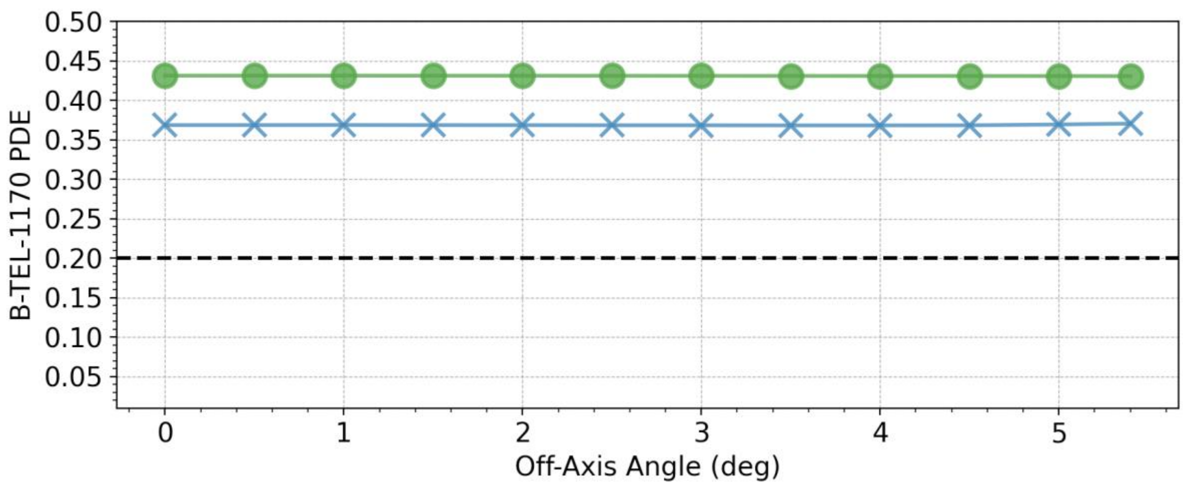


Figure 2-4: SST-Cam filter transmission as a function of the wavelength of the incident Cherenkov photons (blue and orange curves) compared with the curve used for the CTA Prod4 simulations (green curve) and the measurements performed on a sample of the ASTRI-Horn window (black curve).

Whilst the total integrated Cherenkov PDE for is higher for the Prod4 window than for the proposed Prod6 window, the background rejection and hence the overall SNR of the Prod6 window is better (Figure 2-5). The improved background rejection power of the window is expected to reduce the nominal NSB level from ~40 MHz to ~30 MHz. The lack of a strong dependence on off-axis angle is due to the similaritiy in the distributiution of incidence angles across the focal plane (i.e., the SST optics are optimised for a flat PSF across the field of view).



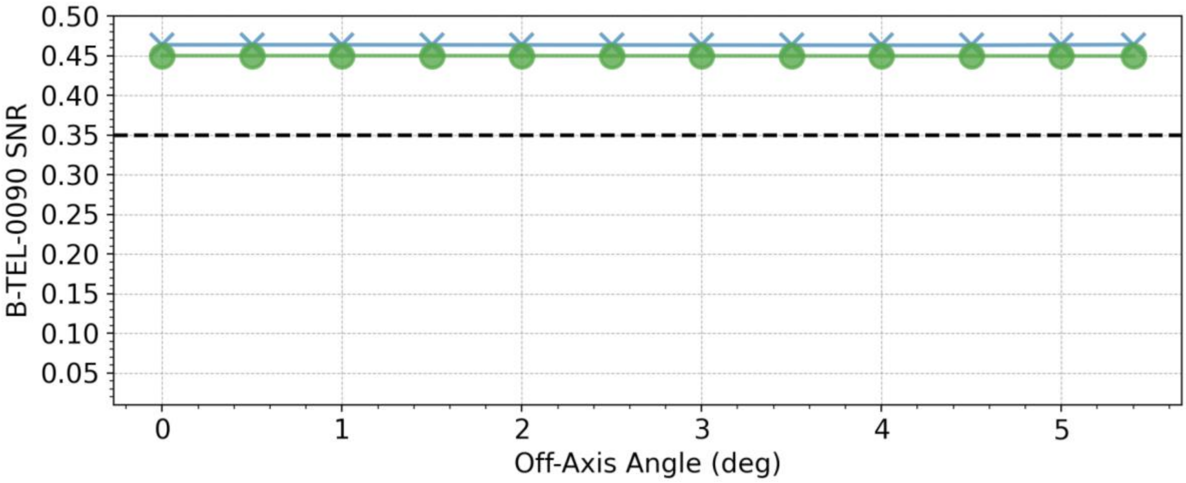


*Figure 2-5: C*alculated PDE and SNR following B-TEL-1170 and B-TEL-0090 as a function of off-axis angle. Prod4 window shown in green, proposed Prod6 window shown in blue.

The minimum image amplitude (i.e., the amplitude of a Cherenkov image that triggers the camera on average 50% of the time) was also compared for the Prod4 and Prod6 windows and found to be within 1% of each other for both protons and gammas. Finally, a preliminary comparison between the trigger efficiency of the SST system equipped with the Prod4 protecting window versus the same instrument equipped with the Prod6 window has shown that the expected performances are equivalent for energies >0.4 TeV (Figure 2-6).

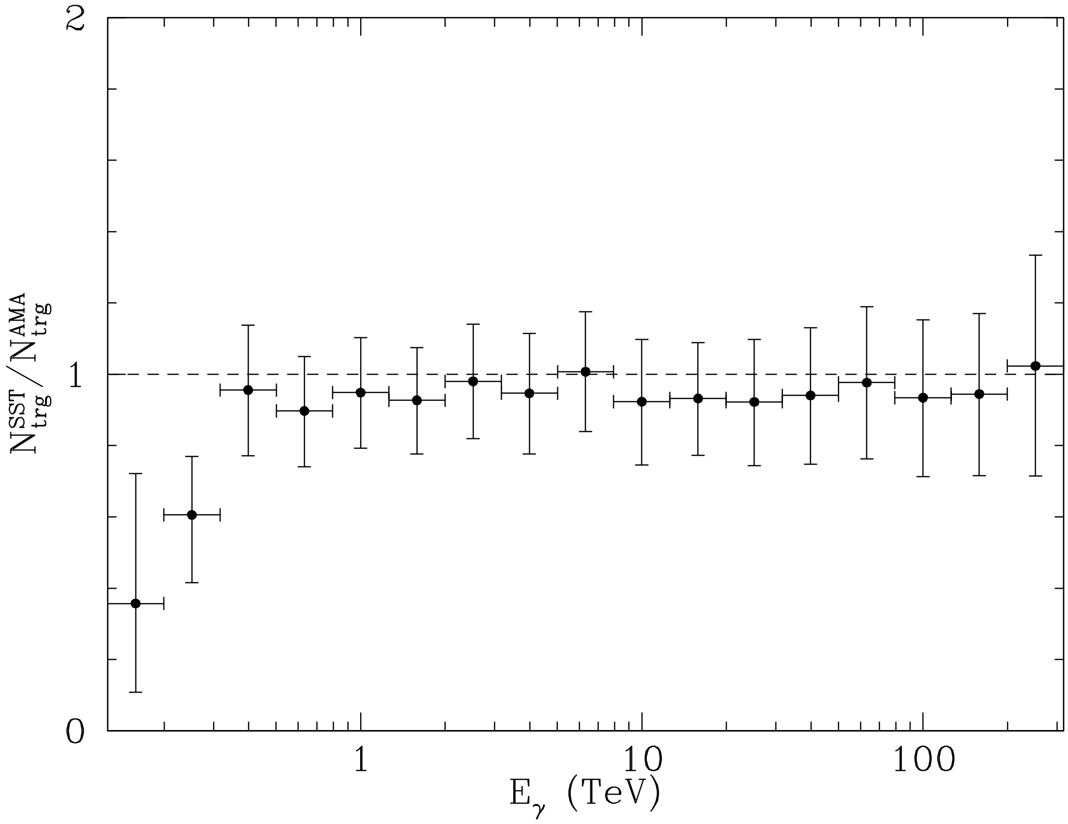


Figure 2-6: Estimated variation of trigger efficiency between Prod6 and Prod4 protective windows as a function of the event energy.

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