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ROBAST 3

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The ROOT-based simulator for ray tracing (ROBAST) is an open-source C++ library to simulate various types of cosmic-ray (CR) and gamma-ray telescopes. It is used in multiple purposes in all the different telescope designs of the Cherenkov Telescope Array and is a promising tool for use in other future projects in optics simulations. We have released ROBAST 3 that supports interference calculations in multilayer coating in addition to geometrical optics. Here, we present its new functionality and several recent applications in future CR telescopes.

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1. Introduction

The ROOT-based simulator for ray tracing (ROBAST)[1][2] is an open-source C++ library [1], used for non-sequential ray-tracing simulations in several cosmic-ray (CR) telescope projects. Its initial development started in 2007 when it was used to simulate a modified Baker–Nunn optical system [2] that was composed of segmented spherical mirrors, three aspherical lenses, telescope frame, and many camera components intricately obscuring incident photons. Calculating the effective area of this complex optical system or embedding it in a Monte Carlo (MC) simulation was difficult, more so, no open-source software suitable for similar CR telescopes existed. ROBAST development aims to provide a ray-tracing simulation library for the CR physics community, which is freely available, equipped with necessary functions for CR telescopes, easily used in a common programming language (C++), and well debugged in multiple CR telescope projects.

Utilizing the ROOT geometry library and its particle tracking engine [3], complex CR telescopes are easily built in ROBAST, allowing users to simulate mixed reflections, refraction, and scattering of individual photons. Added to the pre-defined ROOT primitive geometry classes, ROBAST has its own geometry classes (shapes) for simulating aspherical surfaces and light concentrators [4], for modeling most CR telescopes without requiring users to implement a new geometry class.

The earliest applications of ROBAST after the Baker–Nunn optics simulation are the segmented parabolic telescope, Schwarzschild–Couder telescopes, and hexagonal light concentrators in the Cherenkov Telescope Array (CTA) [5, 6]. ROBAST not only simulates the point spread functions (PSFs) and effective areas of CTA telescopes, it is also used for mirror alignment tolerance analyses, sunlight avoidance calculations, and optimization of light-concentrator designs in CTA [1, 4]. As of 2021, ROBAST is used for all the telescope subprojects in CTA; the Large-sized Telescopes (LSTs, a segmented 23 m parabolic system), two Medium-sized Telescopes (MSTs, 12 m Davies–Cotton and 10 m Schwarzschild–Couder systems), and the Small-sized Telescopes (SSTs, a 4 m Schwarzschild–Couder system), for various purposes.

Optical simulations in gamma-ray and CR telescopes usually employ geometrical optics (ray tracing) because the mirror roughness in a macro scale is much larger than the Cherenkov and fluorescence wavelengths and their PSF sizes are wider than the diffraction limit by several orders of magnitude. However, multilayer coating, requiring interference calculation, is frequently applied on mirror surfaces to protect the specular aluminum layer and enhance the reflectance in 300–500 nm. In multilayer coating, the angular and wavelength dependence of mirror reflectance are not negligible when the number of layers is large, thus they are often pre-calculated and the lookup tables are inputted into a geometrical ray-tracing simulation in CR telescopes. For example, this approach is employed in *sim_telarray*, the standard array simulation MC software in H.E.S.S. and CTA [7]. However, using separate simulation tools for multilayer and ray-tracing simulations is not suitable for some simulation studies, such as the simultaneous optimization of a specular light-concentrator shape and its surface coating design. Additionally, silicon photomultipliers (SiPMs) show strong wavelength dependence in photon detection efficiency (PDE) curves due to SiO_2 and SiN layers when the surface resin coating is removed to suppress their optical crosstalk [8, 9]. To

[1] https://robast.github.io
[2] https://github.com/ROBAST

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simulate these quantum effects within a single simulation library, we implemented new ROBAST functionality to simulate multilayer coating in its latest major release (ROBAST 3[3]).

This study reports the new functionality for multilayer simulations in ROBAST 3 and presents recent applications of ROBAST in different types of CR telescopes.

2. Multilayer Support in ROBAST 3

2.1 Implementation

Multilayer simulation needs in CR telescopes are often found in mirror development because it needs high (> 90 %) reflectance in the UV–blue region for Cherenkov and fluorescence photons and low reflectance (high absorptance) in the red region to reduce the night-sky background. Most coating companies use commercial and proprietary software in the material selection and thickness optimization phase of layer design in multilayer coatings. However, the interference of multilayer coatings can be calculated using basic knowledge of plane waves. Also, several open-source libraries for multilayer simulations are available.

We did not reinvent a wheel in developing ROBAST 3, rather we re-implemented an existing Python package, *tmm*[4], in C++. The *tmm* package and its calculation methods are used in several studies, and the details are described in [10].

2.2 Bandpass Multilayer Coating

Fig 1 shows an example of a combined multilayer and geometrical ray-tracing simulation of hexagonal light concentrator (Winston cone) using ROBAST 3. In this example, we assumed that nine thin layers composed of SiO_2, Ta_2O_5, Al, and Al_2O_3 were applied on a hexagonal plastic cone to suppress reflectance in long wavelengths [11]. The collection efficiencies of the cone for six wavelengths are shown as functions of angles of incidence, with ∼50 % reflectance suppression in 600–800 nm observed. The peaks and valleys found in the curves are due to angular-dependent reflectance caused by interference in the coating.

2.3 Silicon Photomultipliers

The use of SiPMs instead of conventional photomultiplier tubes (PMTs) was technically validated by the FACT collaboration [12] and is currently planned by other telescope projects. The focal-plane cameras of the CTA SSTs and MSTs use spherically aligned SiPM arrays, and their prototypes succeeded in Cherenkov observations and Crab detection [13, 14]. Trinity, a wide field-of-view earth-skimming air-shower telescope project, also plans to use SiPMs as photosensors [15–17].

The angular dependence of SiPM PDE can be roughly characterized using Fresnel reflection at the media boundary between air and silicon. However, thin SiO_2 and SiN layers on the surface of silicon substrate causes interference when the SiPM surface is unprotected by thicker (100–300 μm) resin coating, resulting in complex angular dependence, as shown in Fig. 2. Also, ROBAST 3 can simulate the interference effect and is promising tool for camera calibration in CR and gamma-ray telescopes.

[3] Version 3.2.0 is the latest as of Jul 2021. See https://github.com/ROBAST/ROBAST/tags.
[4] https://pypi.org/project/tmm/

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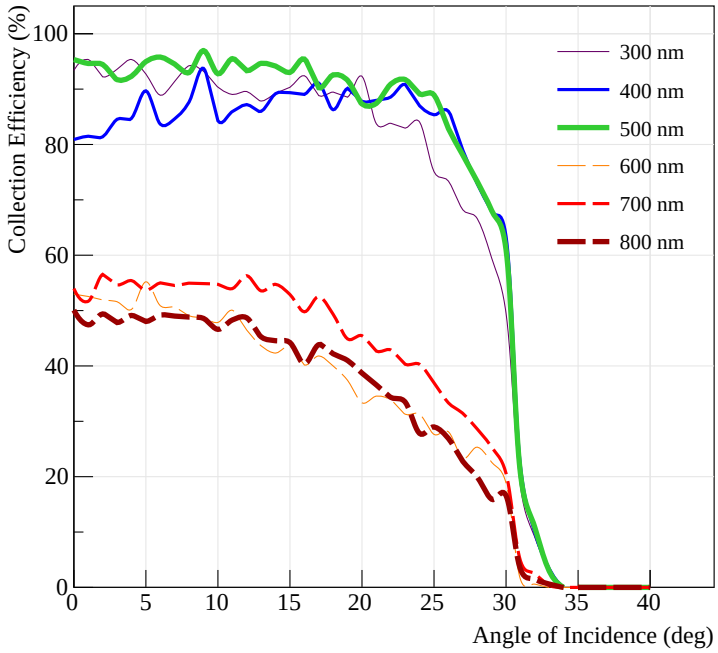

Figure 1: A ROBAST simulation of a hexagonal light concentrator with multilayer coating on the specular surfaces. The solid and dashed curves show the collection efficiency as functions of angles of incidence in UV-to-green and red wavelengths, respectively. The figure was taken from [11] and colorized for this paper.

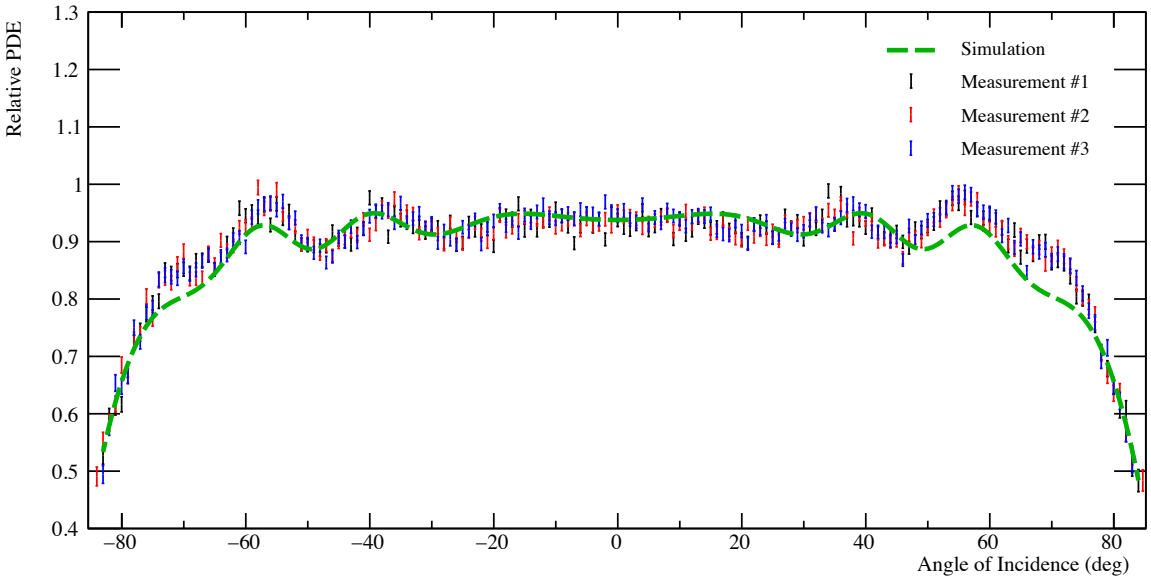

Figure 2: Comparison of measured SiPM PDE at 820 nm and ROBAST simulation.

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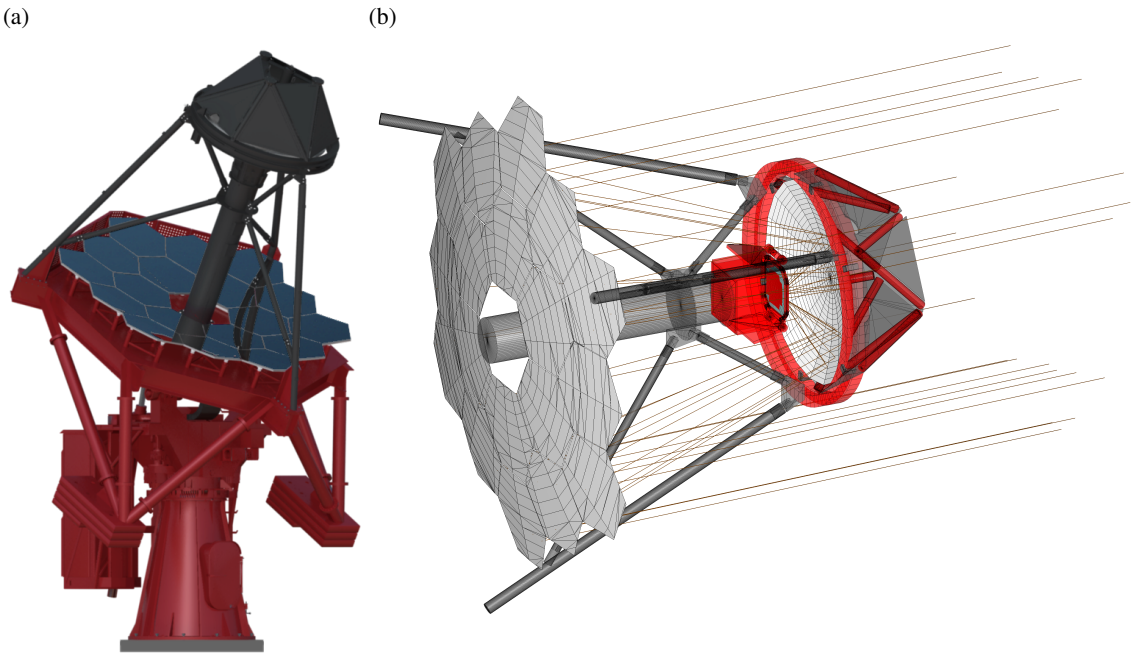

Figure 3: (a) A computer rendering of the CTA SST optical system. Image Credit: G. Pérez, IAC, SMM, via Flickr.com (the Creative Commons Attribution-NonCommercial-NoDerivs 2.0 Generic; CC BY-NC-ND 2.0) (b) An equivalent 3D model of the SST optical system built in the ROBAST framework, where only telescope components that affect the optics performance are simulated. The original 3D CAD file was provided to the author from the CTA SST optics team.

3. Recent Applications

ROBAST is the most heavily used in CTA for their optics simulations. Figs. 3(a) and 3(b) compare a 3D model of the CTA SST optical system [18] and its equivalent ROBAST model, manually converted. The complex telescope beams and the secondary mirror system that partly obscure incident photons are modeled using ROBAST, enabling us to calculate the effective area and vignetting accurately.

After the successful use of ROBAST in CTA, various future telescope projects use it for optics simulations [19–21]. Figs. 4(a) and 4(b) shows examples of ROBAST being applied to the Trinity and CRAFFT telescopes [22, 23]. Trinity uses a MACHETE-like optical system [24] combined with SiPMs and light concentrators, and CRAFFT uses a Fresnel lens system to realize a less expensive wide field-of-view telescope without mirrors. Both optical systems can be modeled and simulated using ROBAST without adding any new classes dedicated to individual telescopes.

4. Conclusion

ROBAST 3, a new major version of non-sequential ray-tracing software for CR telescopes with interference calculations of multilayer coating, has been released. Currently, ROBAST is used in various optical systems and projects using its functionality to simulate aspherical mirrors and

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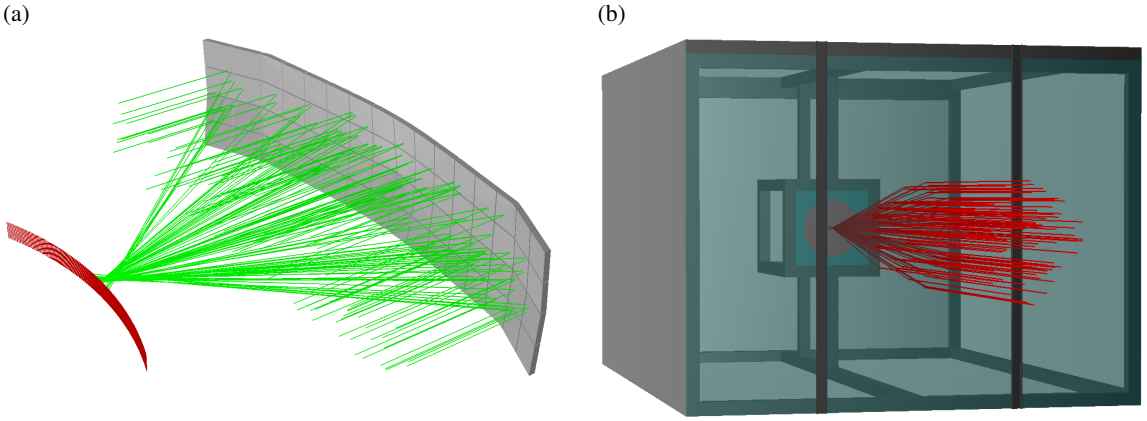

Figure 4: (a) A ROBAST model of a MACHETE-like optical system planned in Trinity. Image credit: The Trinity Collaboration (b) A ROBAST model of the Fresnel lens system and the telescope hut of CRAFFT. Image credit: Yuichiro Tameda

light concentrators. In addition to geometrical optics simulations that were already supported in ROBAST 2, further ROBAST applications with SiPMs and multilayer coating are expected.

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