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Pybkgmodel - a background modelling toolbox for the CTA

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Despite the advancement in background rejection techniques, observation of the very-high-energy gamma-ray sky by imaging atmospheric Cherenkov telescopes (IACTs) are subject to an irreducible background from gamma-like hadron- or electron-induced air showers. The determination of this residual background is crucial for accurate spectral and spatial measurements.

The Cherenkov Telescope Array (CTA) will become the next generation of IACTs. To unveil its full potential, the improved reconstruction performance of CTA needs to be coupled with a reliable background estimate across the entire field of view. This may become especially important in the case of the planned surveys of large areas of the sky.

In this contribution we will present pybkgmodel, an open-source python software package developed for CTA. It aims at providing in a consistent way the various background modelling methods, based on the experience from current IACTs such as H.E.S.S, MAGIC, and VERITAS. It is designed as a toolbox allowing a user to easily choose the optimal reconstruction approach for various target regions or a combination of several algorithms. We will introduce the design of the package as well as demonstrate its functionality using data for the CTA Large-Sized Telescope prototype (LST-1).

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1. Introduction

Imaging Air Cherenkov Telescopes (IACTs) observe the high-energy γ-ray universe by detecting the flashes of Cherenkov light resulting from extensive air shower (EAS) induced by the cosmic γ-rays in the atmosphere. Thus, these kinds of telescopes are subject to a high background of EAS induced by cosmic rays (CRs). In recent decades, the advancement in machine learning techniques in combination with the usage of Cherenkov stereo systems has greatly reduced this background, still the non-negligible γ-like CR induced events pass the event selection criteria. Most of these events contain one or several π^0 sub-cascade early on in their development [1–3]. The irreducible background events are distributed throughout the field of view (FoV) and the distribution approximately follows the camera response to an isotropic flux. The camera acceptance for hadronic showers only agrees to a certain extent with the one for gamma-ray showers. The shape and intensity of the distribution depends on the observational conditions (e.g. weather, pointing position of the telescope). Hence, the background level has to be determined either by measuring it or estimating it from Monte-Carlo event simulations. The latter approach is computationally heavy and subject to the larger uncertainties in the hadronic interaction models used for the hadronic EAS compared to electromagnetic showers [4].

Traditionally, data from IACTs are analysed using an "aperture photometry" like approach, where the signal is determined as the difference of event counts from the expected source location and one or several background control regions. The regions for the background determination are usually placed at a similar offset from the pointing position and have a similar extension as the source location, the so-called reflected regions method. This method however is not well suited to analyse extended sources, regions with overlapping emission regions, and sources with uncertain localisation, where an imaged-based analysis approach is preferable. Hence, in addition to the traditional approach, *Gammapy*[1], the science tool for the Cherenkov Telescope Array (CTA), provides routines such as a spatial likelihood fit of a spatial model to the data [5, 6]. This requires an accurate background model for the entire FoV of the instrument. As demonstrated by [7], the optimal method for the background determination will depend on the source and is usually a trade-off between statistical and systematic precision.

The CTA is the next generation of IACTs and currently under construction at La Palma, Spain, and Paranal, Chile. It is expected to observe and resolve a plethora of gamma-ray sources including scans over a large fraction of the sky, particularly the Galactic plane. Hence, a flexible and accurate background modelling will be crucial. CTA is already boosting the development of open-source software for IACTs and other gamma-ray instruments. This contribution will introduce the *pybkgmodel* toolbox aiming to provide several of the available background methods and supposed to fill the remaining gap in the high-level analysis chain.

2. The *pybkgmodel* package

pybkgmodel aims to provide methods for generating background models for gamma-ray instruments, predominantly for IACTs. Its output products are compatible with the data formats for

[1] https://gammapy.org/

Figure 1: Data levels of the CTA software ecosystem including a short description of their content.

gamma-ray astronomy (GADF)[2]. The software is publicly available at the CTA Observatory github repository[3] and published as open-source under the BSD3-Clause license. It is fully implemented in python and builds on the scientific python package in astronomy, mainly *astropy*[4] and *numpy*[5] [8, 9]. It can be easily installed via the python package manager *pip*.

It complements *pyirf*[6] [10], providing the instrument response functions (IRFs) and *Gammapy*, providing the high level analysis based on the data, IRFs, and background. A detailed example of the construction and validation of such a background model for *Gammapy* based on one method, the construction from source-free sky regions, is provided in [11] using the large dataset of the H.E.S.S. Galactic Plane survey.

pybkgmodel has a modular structure, which allows the user to change between different input formats and background reconstruction techniques. For the input format, *pybkgmodel* can process data after the event selection at, corresponding the data level 3 (DL3, see Figure 1), as well as before at DL2, since some background modelling techniques such as the template background depend on the event classification parameter [12]. The output can be either generated for each observation run separately (run-wise) or stacked across all runs. Following the concept of the GADF, the background is reconstructed and the output provided in the camera coordinate system. The package can be used as a ready-made program with the settings provided in a configuration file or the sub-modules can be integrated into a larger framework. The package consists of the following sub-modules:

`pybkgmodel.processing`: this sub-module provides the processing units, which store the input data, perform the steps to reconstruct the run-wise or stacked camera images.

`pybkgmodel.data`: this module provided the data readers and functionalities to identify the runs used for the background reconstruction. As of now it can process DL2 in *hdf5*, DL3 files in *fits* format, and for legacy purposes *ROOT* files, though additional file readers can easily be added.

`pybkgmodel.model`: contains the algorithms for generating the background models for each run. Currently it provides two reconstruction methods adopted from the SkyPrism package for the MAGIC telescopes, the wobble and the exclusion map [13]. The advantage of these methods is that they can construct a background model based on the source data alone given they were taken in the so-called wobble mode [14].

[2] https://gamma-astro-data-formats.readthedocs.io/
[3] https://github.com/cta-observatory/pybkgmodel
[4] http://www.astropy.org
[5] https://numpy.org/
[6] https://github.com/cta-observatory/pyirf

`pybkgmodel.camera` contains the camera geometry. At the moment only 3D Cartesian geometry of the GADF (x,y,energy) is supported. Since the GADF requires the background to be saved as a rate, the camera model stores the data in counts and observation time separately, so they can easily be stacked for the stacked output option.

3. Demonstration

This section shall demonstrate the functionality and output of *pybkgmodel*. For this demonstration, we use data taken by the Large-Sized Telescope prototype (LST-1)[7] on the Crab Nebula at large Zenith angles. Since 2019, LST has already accumulated over 40 h of high quality data on the Crab Nebula, using the wobble pointing scheme, which has been used to study the performance of LST-1 as reported in [15]. This allows for the testing and refining of CTA software packages including pybkgmodel.

In the following we use a Crab Nebula data sample of 11.1 h effective observation time taken by the LST-1 at $Zd > 56°$. The event selection cuts in the following examples are rather arbitrary as they are rather for illustrative purposes, but we used an cut on the Cherenkov light yield of each event of $Intensity > 200$ ph.e. and a gammaness survival efficiency for the gamma-hadron separation of above 80 %. Once the data are processed to DL2 or DL3, the user can run *pybkgmodel* using a configuration file in yaml format. In the file the user can define the directories for the input and output files, whether the output should be run-wise or stacked, and which background reconstruction algorithm should be used. Furthermore, it contains the selection parameter to identify the runs used to generate the background model for a target run as well as the spatial and energy binning for the camera maps, which will be filled with the background events.

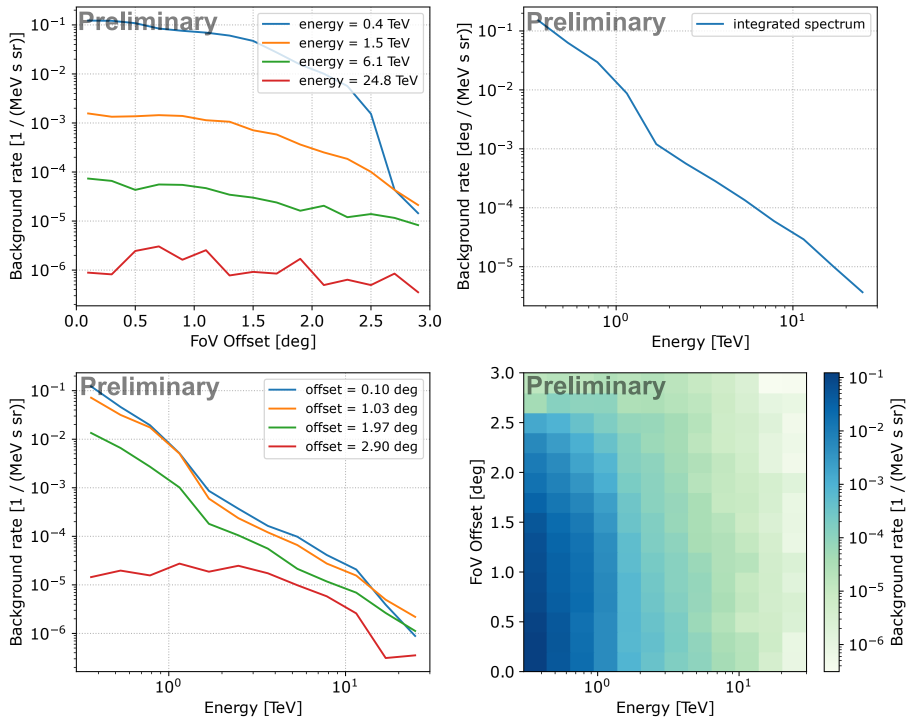
When the background model files are generated they can either be included as a HDU layer to the data file, or added to the runs within *Gammapy*. An example of a background model generated from several runs is displayed in Figure 2. For simplicity, the output is stacked in this example. The model is generated using the exclusion map method, so the entire camera is used for the background excluding a circle of 0.35° around the Crab Nebula. As required by the GADF and *Gammapy*, the background is provided as a rate per energy and solid-angle.

The following examples will use the same files and background method, but uses the run-wise maps added to the corresponding runs within *Gammapy*. Figure 3 shows the count map and the background fit to the data using the FoV background excluding the 0.35° region around Crab. The maps are binned into pixels of 0.02° and the maps are smoothed with a kernel of 0.04° for a better visual comparison between the maps. The maps indicate that the background indeed can be correctly reproduced in terms of shape across the FoV.

From the excess map and the background map, *Gammapy* can estimate an excess and significance map allowing for a more detailed assessment of the agreement between the background model and the diffuse background in the count map. Figure 4 displays the excess and significance map using a correlation radius estimating the counts of 0.06°, which is roughly the size of the points spread function of the LST. One can see that the background map does not produce any significant artefacts in FoV. It is confirmed by the significance distribution of pixels. If the background is well

[7] https://www.lst1.iac.es

Figure 2: Example of a background file obtained from several runs using a stacked exclusion map method and loaded into *Gammapy*.



described by the model, the distribution of the background pixels outside the source region (shown in purple in Fig. 4) is centred around zero with a width of $\sigma = 1$, which is almost the case here. Slight deviations are to be expected and can be caused by choice of event selection parameters and possible systematic uncertainties.

4. Summary and future extensions

While *pybkgmodel* is still in the early phase of its development, it is already fully functional for basic background model reconstruction and contains all the necessary base classes for further expansion. We consider adding additional background reconstruction methods such as the template background [12]. For cases of low statistics interpolation methods might be crucial, though they depend on approximate knowledge of the background shape. Moreover, an automatic benchmarking tool is being developed for the testing the different methods on different scenarios. [11] includes a description of a systematic validation approach.

As this code is mainly developed within the CTA community, the package is evolving with a focus on IACTs. However, the program might be useful for any instrument following the GADF principles. It complements the existing packages of *pyirf* and *Gammapy* and we aim to further develop it in this direction. We hope it becomes an established, community-driven package in the field helping users and the CTA observatory alike to overcome the challenge of constructing accurate background models.

Figure 3: Count map and corresponding background map generated with pybkgmodel and processed with *Gammapy*. The maps show the event and background maps stacked for all runs. For a better comparison, the central region in the count map containing the Crab Nebula is excluded. Both maps use a binning of 0.02° and are smoothed with a Gaussian kernel of 0.04° width. The smoothing is for visual reasons only and chosen to just reduce the noisiness in the count image, so that visual comparison is possible without affecting the structures in both images too much.

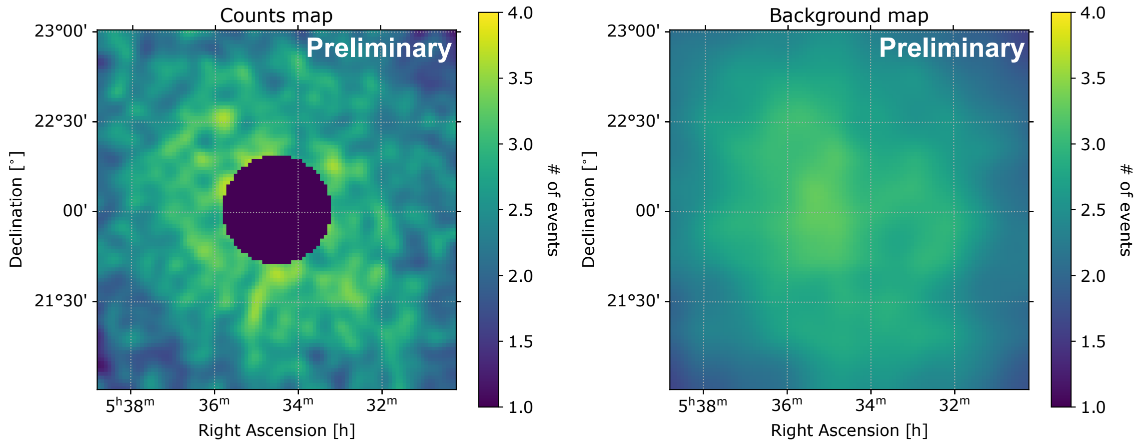
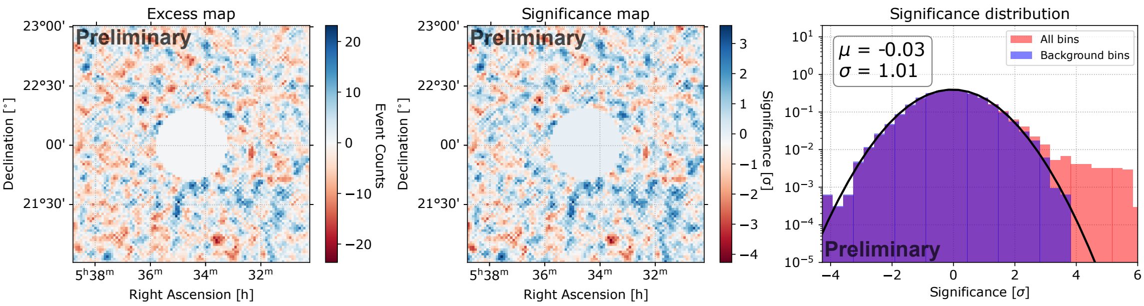


Figure 4: Excess event map, significance map in terms of sigma of a Gaussian, and significance distribution of the pixel values in the significance map. The Gaussian fit in the significance distribution is applied to the purple background bins only. The maps were generated with *Gammapy* based on the fitted background model.



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