



Results of analysis of the detector response of the Pi of the Sky experiment

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Abstract. The large coverage of the Pi of the Sky apparatus requires the use of cameras with very-wide angle lenses ($20^\circ \times 20^\circ$ field of view). However, such optics introduce significant deformations of the point spread function (PSF), increasing with the distance from the frame center. Deformed PSF introduces additional uncertainties in results of data analysis. In order to reduce these uncertainties, a model describing the PSF in our experiment has been developed. Laboratory measurements of the Pi of the Sky PSF, its parametrization and results of application to photometric and astrometric algorithms are shown in this paper, as well as a realistic simulator of the Pi of the Sky frame.

Keywords : Gamma-ray Bursts (GRB) – point spread function (PSF) – wide-field camera

1. Introduction

The “Pi of the Sky” experiment (Zaremba et al. 2012) is designed for continuous monitoring of a large fraction of the sky with high (in astronomical terms) time resolution (~ 10 s). A real time analysis of the data stream, based on a multi-level triggering system, allows discoveries of GRB optical counterparts independent from satellite experiments. Additionally, self triggering capabilities allow detections of other rapidly varying sources, such as nova and flare stars or even not yet classified phenomena. This approach resulted in autonomous detection of the “naked-eye” burst GRB 080319B at its very beginning (Racusin et al. 2008).

To meet the requirement for monitoring a large fraction of the sky, “Pi of the Sky” apparatus makes use of cameras with a very wide field of view – about $20^\circ \times 20^\circ$ each. However, for stars positioned far from the optical axis, this causes significant deformations of images, much bigger than in other astronomical experiments (as in the case of GRB 080319B, see Fig.1, left).

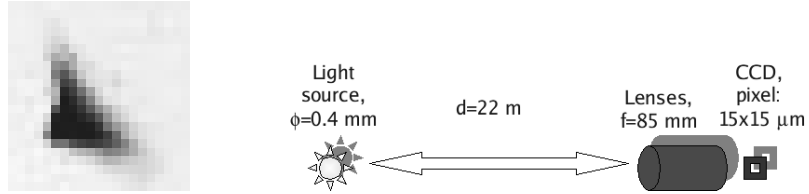


Figure 1. Left: The second exposure of GRB 080319B taken with the “Pi of the Sky” apparatus, when the optical emission was strongest. The GRB was recorded close to the corner of the frame, thus its shape is very deformed; **Right:** The set-up for laboratory measurements.

Therefore both profile and aperture astrometric and photometric algorithms, assuming standard PSFs shape introduce large uncertainties. To improve brightness and coordinate measurements an elaboration of the PSF in the “Pi of the Sky” system is required. This demands obtaining high-precision profiles of the point-sources in different parts of the frame and finding a mathematical model properly describing them.

2. Laboratory measurements and modeling

The derivation of a PSF requires a star profile with sub-pixel resolution, which could be obtained from a superposition of single star images. However, the superposition of real images introduces big uncertainties due to the fact that the exact shape and thus center of the star image is unknown. Additionally, stars are blurred due to mount vibrations when following the sky movement etc. These factors showed that ample data should be obtained in laboratory measurements.

The apparatus for laboratory measurements consisted of a LED diode (color or white) put behind a pinhole of 0.1 to 0.4 mm diameter and placed at a distance of 22 m from a CCD camera. A pixel size of the CCD sensor was $15 \times 15 \mu\text{m}$, and the camera was equipped with CANON lenses with focusing length of 85 mm (Fig.1, right). This set-up gives a geometrical spot size of the diode on the CCD sensor of less than 0.1 pixel – fulfilling the requirement of a point source. Prior to the main measurements, a number of test-measurements and calibrations were performed, to ensure the stability of the laboratory set-up (Piotrowski 2011).

2.1 Intra-pixel measurements

The way the CCD sensor is designed causes a single-pixel sensitivity to light to be not spatially uniform (Toyozumi & Ashley 2005). That is mainly due to electrodes placed across the pixels and channel stops separating the sensor’s columns. The described setup with additional diaphragm of 20-mm radius on the lenses (reducing the PSF

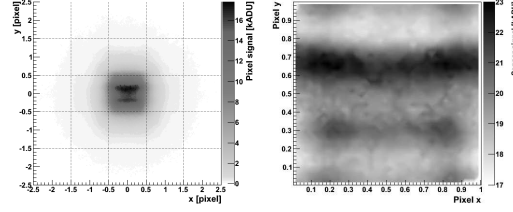


Figure 2. Left: pixel response function; Right: pixel sensitivity function for a red diode.

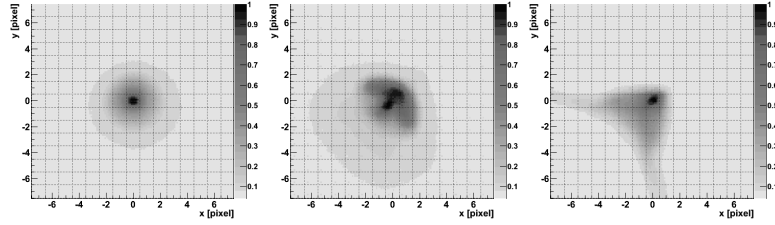


Figure 3. Measured PSFs 0, 800 and 1400 pixels from the frame center, along the diagonal.

size) allowed for measurements of two functions describing the non-uniformity: pixel response function (PRF) and pixel sensitivity function.

PRF describes a single pixel signal value vs. position of the spot relative to the pixel edge. The spot only partially contained in the pixel causes a sudden drop of PRF close to the pixel border (Fig.2, left). However, the function is non-zero for spot fully outside the pixel. That may be caused by PSF size, diffraction of the spot, or a charge diffusion between pixels. In the last case, the PRF contributes to the whole PSF shape¹.

Pixel sensitivity function is defined similar to the PRF, however an overall CCD signal value is taken instead of the single pixel signal. Changes in pixel sensitivity are the main factor responsible for signal changes caused by the image movement across the CCD. With the knowledge of the function and the position of the source's center on the pixel one can compensate for this effect, performing more precise measurements of the brightness.

¹The presented PRF is convoluted with a finite PSF of the diode of geometrical size 0.1 pixel. To obtain the most precise measurements of the PRF a proper deconvolution should be performed. We assume, however, that the uncertainty introduced in PSF modeling due to PRF convolution is negligible compared to other factors

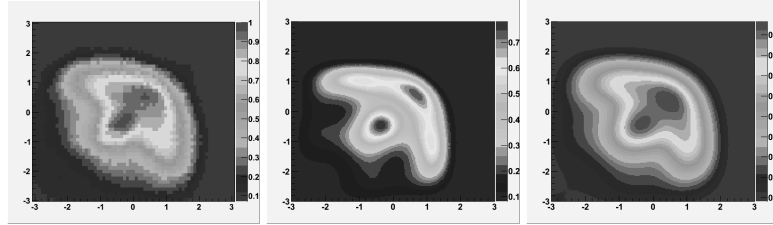


Figure 4. PSFs for 800 pixels from the frame center. **Left:** measured; **Center:** polynomial model; **Right:** polynomial model convolved with Pixel Response Function.

2.2 PSF measurements and modeling

A high resolution profile for selected coordinates on the frame was obtained using multiple images of a diode. Each exposure was taken for a specific position of the diode's center, the full set of images was covering 10×10 points inside a single pixel. All the images were superimposed, taking into account coordinates of each image. Sample profiles obtained for 0, 800 and 1400 pixels from the frame center along the diagonal are visible on the Fig.3.

The spread of the image of the point source, PSF, is caused by deformations of the wavefront of the light passing through the optical system. In the “Pi of the Sky” case the PSF should be described by a Rayleigh-Sommerfeld diffraction formula with aberrations, within a Kirchhoff approximation. It is not possible in the case of wide-field lenses used in our project to use any of the paraxial approximations, which lead to a FFT, thus the formula has to be calculated directly. Therefore, even though this approach should finally lead to satisfactory results, a faster model had to be developed. We use a set of modified Zernike polynomials to describe the image directly (Piotrowski 2011). For each measured profile PSF modeling is obtained by fitting polynomial coefficients to the data (Fig.4). The general model is obtained by interpolating coefficients determined for selected coordinates on the frame.

3. Model applications

3.1 Photometry, astrometry and search for weak sources

Obtained polynomial model can be used for multiple purposes. The most straightforward use is the photometry and astrometry of stars, GRBs and other objects of interest. As for the photometry, when testing on a selected data samples, the model did not prove better in determining brightness of stars than ASAS aperture photometry used in our experiment. This is probably due to the real fluctuations of a star signal, caused by miscellaneous factors in the experiment, dominating the measure-

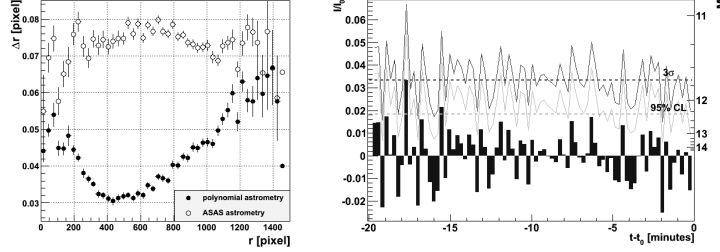


Figure 5. Left: Comparison of position determination accuracy from polynomial model profile astrometry and ASAS (Pojmański 2002) aperture astrometry, for stars brighter than 9^m ; **Right:** Signal resulting from the PSF model fit at the “naked-eye” burst position prior to the explosion (bars) and extracted precursor limits (lines) (data from one camera).

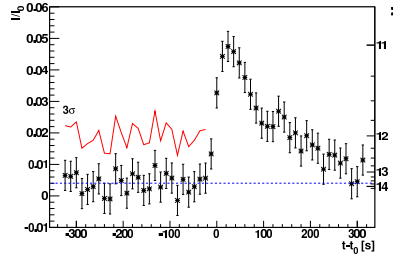


Figure 6. EG UMa outburst measured by the “Pi of the Sky” cameras. The solid line shows the 3σ limiting brightness in a presence of a signal, prior to the burst, and the dashed line corresponds to sky background.

ment. However, determining the position of the stars on the frame is up to factor of 2.5 times more precise in the polynomial PSF model (Fig.5, left).

Another application of the model is a dedicated search for signal in specific coordinates, such as a search for optical precursor to the “naked-eye” GRB 080319B (Paczynski 2001). “Pi of the Sky” started observing the position of the burst more than 19 minutes before the trigger, thus providing data well suited for this task. No signal exceeding 3σ , coinciding on two cameras, was found when fitting modeled PSF to the frames preceding the burst. However, the limiting magnitude has been improved from 11.5^m (resulting from standard photometry) to 12.25^m (Fig.5, right).

As for now, we have preliminarily recalculated the PSF model parameters for the new set of cameras operating in INTA ², Spain. The result has been successfully

²<http://www.inta.es>

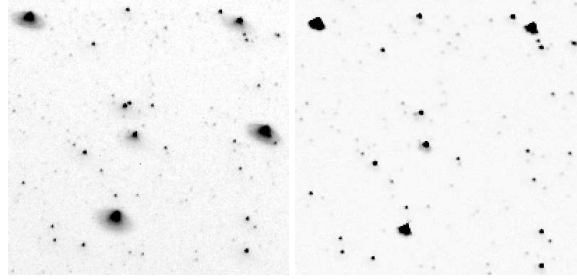


Figure 7. The real (left) and simulated (right) parts of a “Pi of the Sky” frame, close to the frame’s corner (large PSF deformation). The shapes of the stars are very similar, except for the halo (a second order effect containing roughly 5 – 10% of the signal) visible for the brightest objects and not included in the developed PSF model.

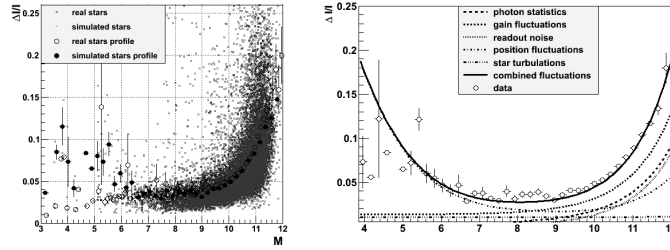


Figure 8. Left: Polynomial photometry results for simulated and real sky images. “Profile” stands for a histogram with averaged stars $\frac{\Delta M}{7}$; **Right:** Relative error of the photometry performed on the simulated data, as a function of the star brightness (points) and the estimated contribution from different sources of variability (lines). The bright stars large variations are due to saturation and CCD-nonlinearity for large signals.

applied to the lightcurve of EG UMa star outburst detected by the “Pi of the Sky” system (Fig. 6) and significantly improved quality of the lightcurve and its statistical significance compared to the previous results.

3.2 Frame simulator

Good description of real sky data opens the possibility to extend the study and to test frame processing as well as dedicated analysis algorithms in controllable circumstances using simulated data samples. This approach, often referred as Monte Carlo method, is widely used in high energy physics, to test and develop new detectors, predict future results and analyze those already obtained. Inspired by methods from experimental particle physics, dedicated simulator code has been created.

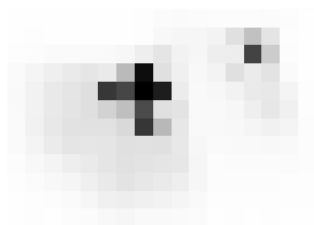


Figure 9. Example image from the simulation of a dense field – three overlapping stars of 5^m , 7^m and 9^m . The dimmest star is roughly visible as an extension to the bottom of the 7^m star in the upper right corner of the figure.

A simulated frame consisting of cataloged stars looks very similar to the real frame (Fig.7), except for the brightest objects, which are surrounded by a dim (compared to the star's core signal) but wide halo. The halo is a second order effect, affecting only the appearance of the frame, thus it has not been included in the model. Photometry results for real and simulated data are in a very good agreement (Fig.8, left). This can be taken as a proof of a good simulation quality. Differences for stars brighter than 6^m are due to the saturation of the CCD, while for the dimmest stars this is mainly the matter of fine-tuning the simulation parameters.

The main simulation parameters, describing photon statistics, gain fluctuations, readout noise, position fluctuations and star turbulence, had to be taken into account to obtain photometric uncertainties similar to the real ones. To estimate the influence of each fluctuation on the photometry quality, the photometry has been repeated for each factor separately. Results show that the photometry quality for stars darker than 8.5^{mag} is most probably limited by gain fluctuations and not by the readout noise as anticipated before (Fig.8, right). This result should be carefully examined when designing future low-noise cameras for sky observations.

There are multiple other studies which can be performed using the simulator. One of them is the possibility of using parallax phenomenon in the “Pi of the Sky” project. In this case simulated data can help determining the maximal distance of the object from Earth for which it could be stated, that it appears in two cameras at different coordinates. Assuming that the smallest measurable position difference of 0.1 pixel ($3.6'$) allows identifying near-Earth objects maximally ~ 1432000 km from Earth surface for sites distant by 100 km and ~ 430000 km for sites distant by 30 km (for cameras from different sites looking at the same coordinates on the sky), in both cases behind the Moon orbit. However, the real separation distance changes (mainly due to the PSF changes and thus astrometry precision for single camera) with coordinates on the frame and can be calculated using the simulated data.

A similar task is studying efficiency of analysis of crowded fields. Simulated images of overlapping stars (Fig.9) of different magnitudes can be used for determining

when the stars become indistinguishable, how their position/brightness measurements depend on their distance, magnitude, position on the frame, etc. Additionally, the simulator allows specifying a function describing a star movement through the frame during specified time. This capacity mimics mount tracking errors and can help in compensating stars variability caused by it.

The design of the simulator allows easy creation of extensions, such as introducing new catalogues of objects like planets or stars, which would help replicating the real sky view in more detail. Simulating near-earth objects could help to develop algorithms for orbits determination. Additionally, more features related to the electronics performance can be added, such as blooming (signal saturation) effect, hot pixels, non-Gaussian distribution of noise, etc., which in some conditions affect the data analysis.

4. Summary

Due to the very large field of view, PSF in the “Pi of the Sky” detector can be highly deformed and not described by general models. Based on the dedicated laboratory measurements we have created an effective model describing PSF dependence on the star position on the frame. These results may help in further understanding and development of the “Pi of the Sky” detector and other future wide field experiments. So far we have successfully introduced the model into photometric algorithm, dedicated signal search and astrometric algorithms, the last one giving very promising results. Additionally, a detailed simulator of the “Pi of the Sky” frame has been created.

Acknowledgments

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