Laboratory measurements and modelling of the "Pi of the Sky" detector response for more effective detection of GRB optical counterparts

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Abstract.
The ultimate goal of the "Pi of the Sky" apparatus is observation of optical flashes of astronomical origin and other light sources variable on short timescales, down to tens of seconds. We search mainly for optical emissions of Gamma Ray Bursts, but also variable stars, novae, blazars, etc. This task requires a precise photometry - accurate measurement of the source's brightness (and it's variability). "Pi of the Sky" single cameras' field of view is about $20^\circ \times 20^\circ$. This causes a significant deformation of a point spread function (PSF), reducing quality of brightness and position measurement with standard photometric and astrometric algorithms. Improvement requires a careful study and modelling of the PSF. A dedicated laboratory setup has been created for obtaining isolated, high quality profiles, which in turn were used as the input for mathematical model. Results of it's application to brightness and position measurements as well as search for precursor of the naked–eye burst GRB080319B are shown in this paper.

Keywords: Gamma Ray Bursts (GRB), afterglows, optical flashes, detectors, robotic telescopes, optical observations of large sky areas, prompt optical emission, point spread function, aberrations
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INTRODUCTION

With the launch of the SWIFT satellite number of alerts with accurate Gamma Ray Bursts coordinates available quickly after the satellite trigger increased significantly. Nevertheless a big disproportion between number of GRBs observed in gamma and optical bands remains, and the number of GRBs optical counterparts observed from the very beginning of the explosion is not increasing.

The main reason behind just 3 optical detections of GRBs at their very beginning is the approach to these observations. Satellites perform a gamma-ray monitoring of a large fraction of the sky, aimed at detecting a burst, while on-ground optical facilities are designed as follow-up experiments. "Follow-up" in this case causes a systematic delay in observations due to the time before coordinates are received and the time required for the apparatus repointing.

These issues are addressed by the "Pi of the Sky" experiment which, similarly to the satellite experiments, is designed for constant monitoring of a large fraction of the sky with high (in optical terms) time resolution (about 10 seconds). 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[1]. 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" GRB080319B at it's very beginning[2].

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, this causes significant deformations of images of stars positioned far from the optical axis, much bigger than in other astronomical experiments. As a result, measurements of brightness and position of observed sources, so called photometry and astrometry, become much more difficult.

Years of use and study of astronomical instruments caused the point spread function (PSF) to be well described in most cases and the photometric and astrometric algorithms to provide quite precise results for standard experiments. However, these algorithms do not provide good results in case of the "Pi of the Sky". The significant PSF deformation developed along the distance from the optical axis makes the shape of the star image very different from a gaussian-like encountered in most optical astronomical experiments. The first 3 images of "the naked-eye burst" taken in the corner of the frame resemble rather a winged triangle than a gaussian (fig. 1, left).

In such case, both profile and aperture algorithms utilizing standard PSFs introduce large uncertainties. In the first case they result from fitting a function not describing the data, in the second case – from not distinguishing

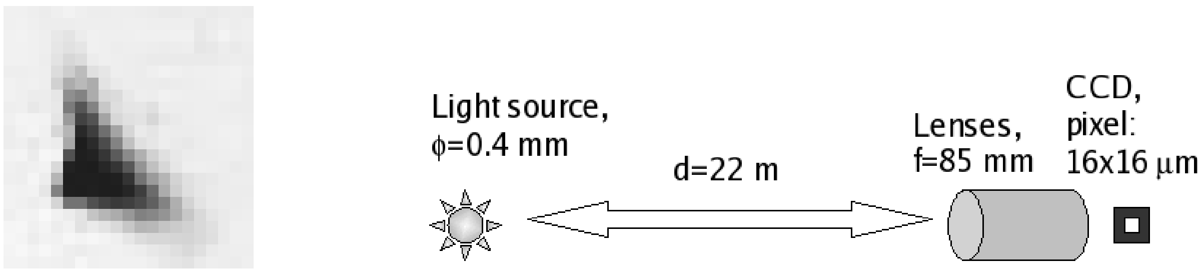

FIGURE 1. **Left:** The second exposure of GRB 080319B taken with the "Pi of the Sky" apparatus, during which the optical emission was strongest. The GRB was recorded close to the corner of the frame, thus it's shape is very deformed; **Right:** The setup for laboratory measurements.

between pixels containing signal and background. Therefore, to improve brightness and coordinates 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.

LABORATORY MEASUREMENTS

Most of single star images consist of less than 30 pixels. While this amount of data is enough for fitting parameters of a well known function, it is far from enough to derive the profile's shape. The derivation requires a profile with sub-pixel resolution, which could be obtained from a superposition of single star images. However, the superposition of real stars introduces big uncertainties due to the fact, that the shape and thus centre of the image is unknown. Additionally, stars are blurred due to mount vibrations when following the sky movement, seeing in the atmosphere, etc. These factors showed that ample data should be obtained in laboratory measurements.

The apparatus for laboratory measurements consisted of a LED diode (red, green, yellow, blue 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 $15 \times 15\mu$m, and the camera was equipped with CANON lenses with focusing length of 85 mm (fig. 1, right). This setup 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.

Intra-pixel measurements

The way the CCD sensor is designed causes a single-pixel sensitivity to light not spatially uniform[3]. 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 size) allowed for measurements of two functions describing the non-uniformity: pixel response function and pixel sensitivity function.

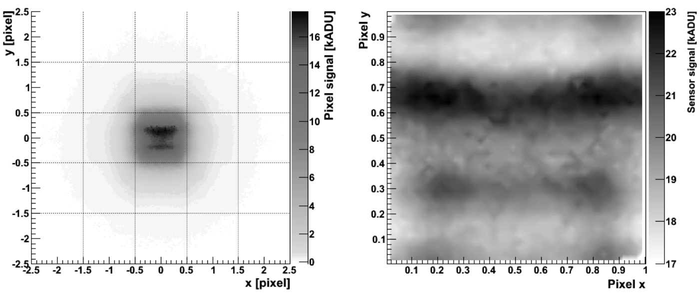

FIGURE 2. Intra-pixel measurements for the red diode. **Left:** Pixel response function; **Right:** Pixel sensitivity function.

Pixel response 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 – illuminating a single pixel causes some charge to be accumulated in a neighbouring pixel. In the last case, the PRF contributes to the whole PSF shape.

Pixel sensitivity function is defined similar to the pixel response function, 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 pixel sensitivity function and the position of the source's centre on the pixel one can compensate for this effect, performing more precise measurement of brightness.

PSF measurements

A high resolution profile for selected coordinates on the frame was obtained using multiply images of a diode. Each exposure was taken for a specific position of the diode's centre, 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 centre along the diagonal are visible on the fig. 3.

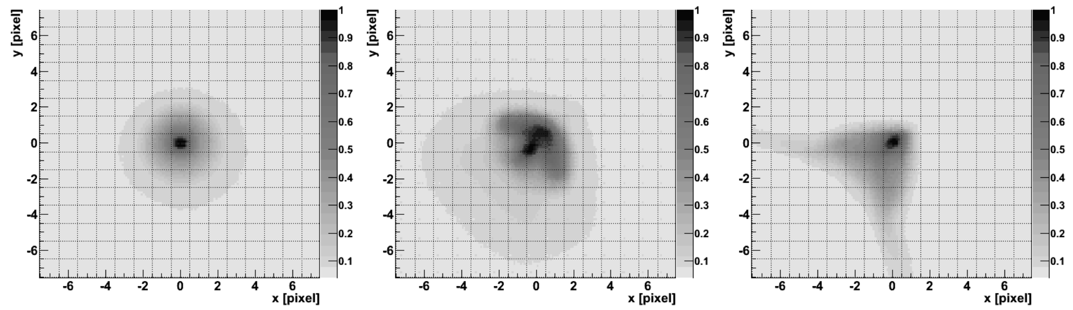

FIGURE 3. Measured PSFs along the diagonal of the frame, 0, 800 and 1400 pixels from the frame centre.

PSF MODELLING

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. This introduces integrating the wavefront over the lenses aperture. 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. For each measured profile PSF modelling is obtained by fitting polynomial coefficients to data (fig. 4). The general model is obtained by interpolating coefficients with coordinates on the frame.

MODEL APPLICATIONS

Described polynomial model can be used for multiply purposes. The most straightforward 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 star signal, caused by miscellaneous factors in the experiment, dominating the measurement. However, determining the position of the stars on the frame is up to factor of 2 more precise in the polynomial model (fig. 5, left).

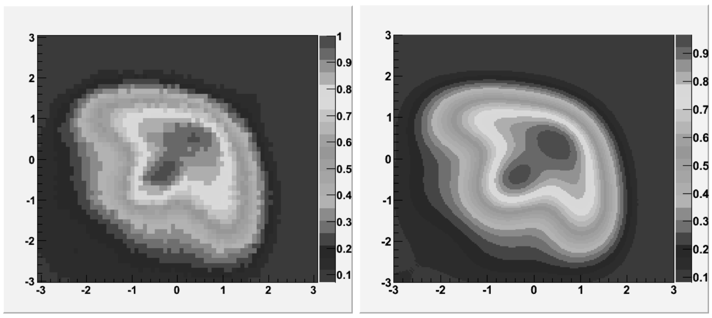

FIGURE 4. PSFs for 800 pixels from the frame centre along the diagonal. **Left:** measured; **Right:** polynomial model.

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” GRB080319B[4]. “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. Unfortunately, no signal exceeding 3σ, coinciding on two cameras, was found by fitting modelled PSF to the frames preceding the burst (fig. 5, right).

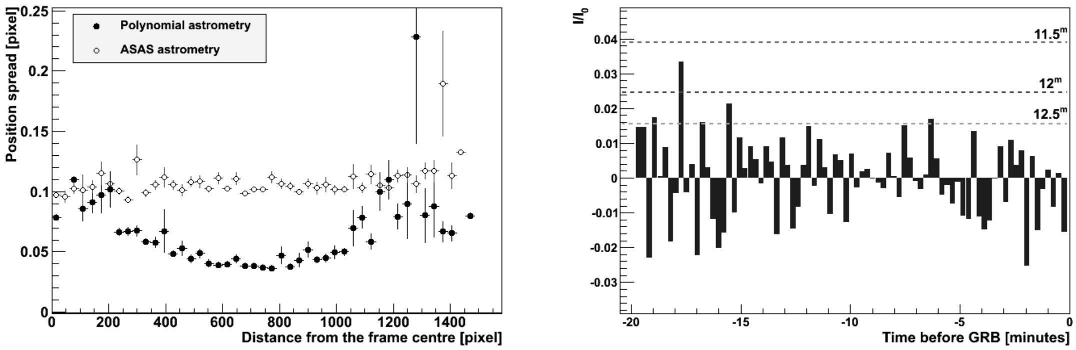

FIGURE 5. **Left:** Comparison of polynomial model profile astrometry and ASAS aperture astrometry for stars brighter than 9^m; **Right:** Signal resulting from the PSF model fit to “the naked-eye” burst coordinates prior to the explosion (data from one camera).

SUMMARY

Due to the very large field of view, PSF in the “Pi of the Sky” detector is 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 perhaps other, future very 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 good results.

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