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Pi of the Sky: modelling of the detector response for more effective search for optical GRB counterparts.

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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 measurement with standard photometric algorithms. To improve photometry, an attempt to investigate PSF based on real star images was made. However, results turned out to be inconclusive due to miscellaneous sky-observing effects. Therefore we decided to perform laboratory measurements, using a CCD camera and an artificial light source as a star simulator. This work shows preliminary results of this study - a set of high resolution PSF shapes, pixel response and pixel sensitivity functions. Finally, an idea how to simulate a real star image in the “Pi of the Sky” system is presented.

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1. Introduction

Gamma Ray Bursts (GRB) are the most powerful explosions known by man, taking place on cosmological distances. The largest fraction of their energy is radiated in gamma-rays, but there is often an associated emission in X-ray, optical and radio frequencies[1]. Up to now there were a few thousands of GRBs detected by dedicated gamma-ray satellite experiments. But only a fraction of those bursts were also observed in other wavelengths, and there were only 3 simultaneous observations of optical and gamma-ray emissions.

Optical observations of GRBs from their very beginning are crucial for understanding this phenomena. “Pi of the Sky” is the experiment designed for constant monitoring of a large fraction of the sky with high (in optical terms) time resolution of about 10 seconds. A real time analysis of the data stream, based 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 flaring stars or even not yet classified phenomena[2].

To meet the requirement for monitoring a large fraction of the sky, “Pi of the Sky” apparatus consists of cameras with a very wide field of view (FoV) - about $20^\circ \times 20^\circ$ each. However, this causes significant deformations of images for stars positioned far from the optical axis. In the corner of the frame they become triangle-like and results of standard brightness measurement algorithms assuming symmetric profiles are a subject to large uncertainties. The famous GRB 080319B[3], observed by “Pi of the Sky” experiment from the very beginning, was visible very close to the corner of the frame on the first 3 exposures (fig. 1). To improve photometry for such peripheral objects precise parametrization of the star image on CCD (so called point spread function: PSF) for every position on the frame is needed.

Detailed PSF parametrization can be obtained only from a high resolution PSF profiles. One method to obtain required data is to create an averaged profile from many star images. The task is difficult for peripheral positions, where the centre of the profile cannot be precisely defined, due to the lack of knowledge of the profile’s shape and the images cannot be properly superimposed. Those issues can be eliminated or at least vastly reduced, when the data for PSF parametrization is obtained from laboratory measurements.

2. Laboratory measurements

The apparatus for laboratory measurements included a LED diode (red, green, yellow, blue or white) placed behind a pinhole of 0.1 to 0.4 *mm* diameter and placed at a distance of 22 *m* from a CCD camera. This setup gives a geometrical spot size of the diode on the CCD sensor of less than 0.1 pixel and thus we can consider it a point-like source. The diode was placed in a mechanic mount, driven by two stepmotors, that allowed a precise movement in vertical and horizontal axis.

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. Similar measurements were performed for 5 angles and 6 distances from the frame centre, covering 1/4 of the CCD.

A significant deformation develops with the distance from the frame centre, causing not only the shape of the profile to change, but also the area containing the signal to grow. The area covered by PSF profile at half-maximum, as visible on fig. 2, increases from slightly more than 1.5 pixel for the central profile to nearly 9 pixels for the profile 1000 pixels from the frame centre.

3. PSF parametrisation

Obtained data is sufficient for PSF parametrization (fig. 3). However, we have to deal with a multicomponent PSF, which is clearly a superposition of more than one simple function. Additionally, each of the components deforms differently, making a popular approach - simple kernel based transformations - impossible.

An attempt to parametrise a profile for each position was made. The idea was to find a set of functions superposition of which properly describe a slice of the profile taken along the profile radius. Then, the rotation was applied with a set of harmonic functions, giving the profile $P(r,\phi) = \sum_{i,j} f_i(r) g_j(\phi)$. However, such a parametrisation gave only very approximate parametrization of PSF, for there was no clue were to place the rotation axis of a profile, and the profile is clearly not factorized in polar coordinates. It seems, that neither polar nor carthesian coordinates are natural for proper parametrisation. Thus we decided to use a more fundamental approach - simulate an image generated by a light wavefront passing non-perfect lenses.

3.1 Wavefront aberrations

The standard way for this approach is to obtain a simulated PSF with a Fourier transform of an aberrated wavefront, specific aberrations described by so called Zernike polynomials. However, this is possible only with paraxial approximation, which cannot be used for our large FOV optics. Thus we simulate PSF using Fresnel diffraction of an aberrated light wavefront:

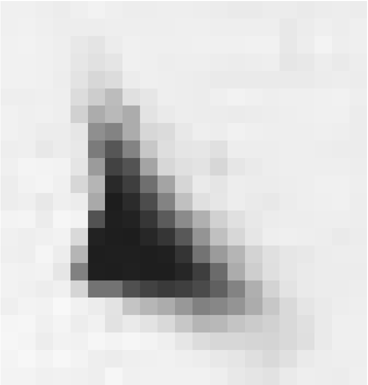

Figure 1: GRB 080319B as seen by the “Pi of the Sky” apparatus at brightness maximum. Image deformation is due to a large distance from the frame centre.

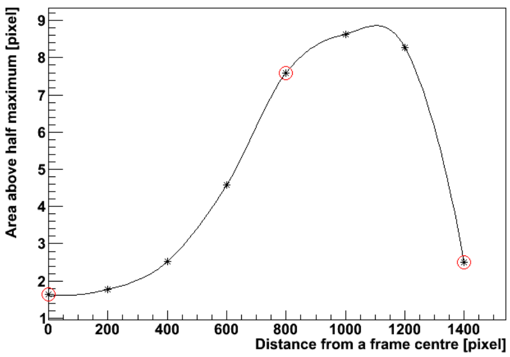

Figure 2: Area covered by the PSF’s full width half-maximum, for different distances from the frame centre. Circles are for PSFs visible on fig. 3.

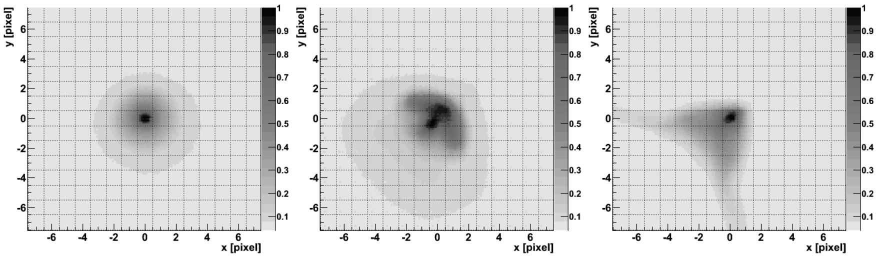

Figure 3: Measured Point Spread Function for (from the left) 0, 800 and 1400 pixels from the frame centre.

$$PSF(x_i,y_i) \sim \left| \int\limits_{aperture} dxdy\, T(x,y)\, \frac{1}{r^2} e^{-ik(W(x,y,\theta)+L(x,y))} \right|^2 \qquad (3.1)$$

where (x_i,y_i) are image coordinates, (x,y) are aperture coordinates, r is a distance between specific point on aperture and image pixel and θ is the wavefront angle in respect to the image plane. $W(x,y,\theta)$ is a wavefront illuminating the aperture, $L(x,y)$ is lenses aberration function and $T(x,y)$ is lenses transmission.

The lenses aberration function is a superposition of standard optical aberrations, mainly defocus, astigmatism, coma and spherical aberration. With knowledge of lenses transmission equation 3.1 could be fitted to a PSF measured for specific coordinates. However, one has to keep in mind, that the real measured PSF is a convolution of the PSF from equation 3.1 and a CCD pixel response function (PRF):

When assuming ideal (step like) PRF, obtained profiles resamblequite well the general shape and very central part of measured PSF profiles. However, still much work has to be done, to obtain results that could be used to improve “Pi of the Sky” photometry.

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