Analysis and simulation of the "Pi of the Sky" detector response

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"Pi of the Sky" experiment

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The "Pi of the Sky" experiment

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- Independent detection of GRB optical counterparts

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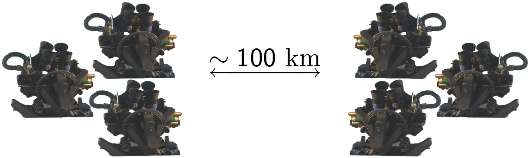

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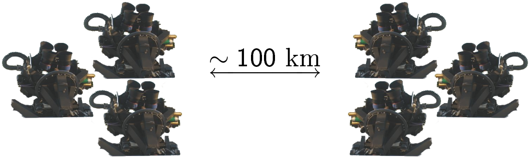

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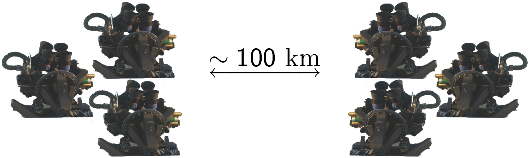
"Pi of the Sky" currently consists of:

- two-camera prototype (Chile): since 2011 in SPdA, in years 2004-2009 in LCO
- first detector of the final system operational from October 2010 at INTA, Spain (Bootes-1 site)



The "Pi of the Sky" experiment (2)

- Constant high-time resolution sky monitoring
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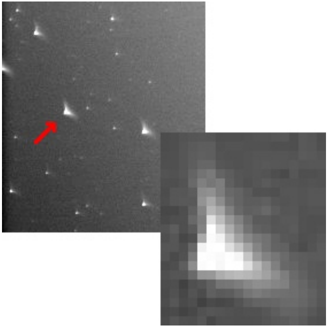

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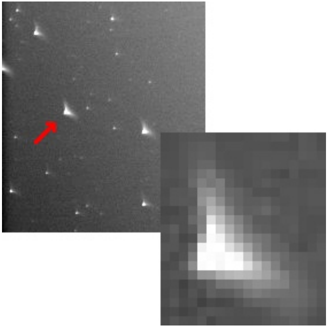
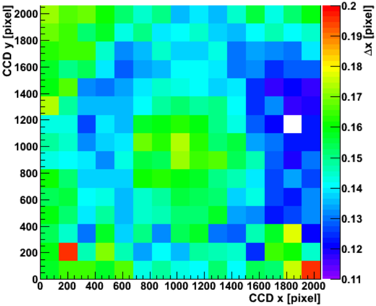


Very large field of view $\Rightarrow$ Very large deformations of image near frame's edges

Results of the image deformation

For stars with deformed images:

- large uncertainty of star position measurement – astrometry



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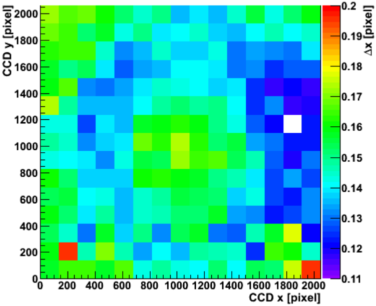

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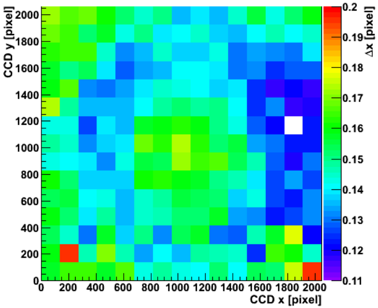
How to improve measurements:

- discard deformed stars (applicable to objects with big statistics only)



Results of the image deformation

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How to improve measurements:

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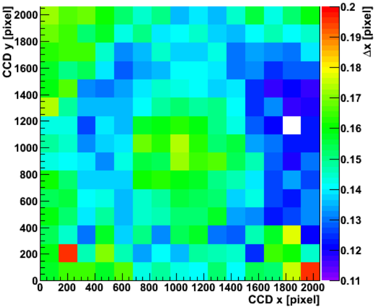
- parametrize deformations

Two approaches to parametrization considered:

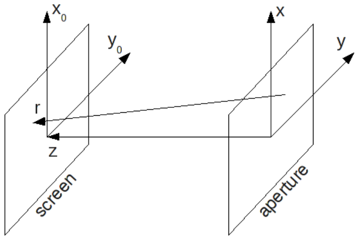
- diffractive approach
  — light propagation through lenses
- effective approach
  — direct image shape parametrization



PSF – point spread function

Image of the point object on the screen/frame – point spread function (PSF)

- Image formation (in general) – light diffraction theory
- Simplifications for PSF analysis:
  - vector diffraction theory
  - scalar diffraction theory
    $\rightarrow$ Rayleigh-Sommerfeld's formula



$$PSF(x_0, y_0, z) = \left| \frac{1}{i\lambda} \iint_{-\infty}^{\infty} U(x, y, 0) \frac{z e^{ikr}}{r^2} dxdy \right|^2$$

$U(x, y, 0)$ – wave amplitude on the aperture, x, y – coordinates on the aperture, x_0, y_0 – coordinates on the screen, z – aperture-screen distance, r – distance between $(x, y, 0)$ and (x_0, y_0, z), λ – wavelength

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$\pm\infty \rightarrow$ aperture

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$$|z| \gg L_1 + L_2$$

L_1 – aperture size, L_2 – screen size

$$PSF(x_0, y_0, z) = \left| \frac{e^{ikz}}{i\lambda z} \iint_A U(x, y, 0) e^{\frac{i\pi}{\lambda z}((x_0 - x)^2 + (y_0 - y)^2)} dxdy \right|^2$$

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$$z \gg \frac{kL_1^2}{2}$$

L_1 – aperture size

$$PSF(x_0, y_0, z) = \left| \frac{e^{ikz}}{i\lambda z} e^{\frac{ik}{2z}(x_0^2+y_0^2)} \iint_A U(x,y,0) e^{\frac{i2\pi}{\lambda z}(x_0 x + y_0 y)} dxdy \right|^2$$

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$$z \sim L_1, L_2$$

in "Pi of the Sky"

$$PSF(x_0, y_0, z) = \left| \frac{1}{i\lambda} \iint\limits_A U(x, y, 0) \frac{z e^{ikr}}{r^2} dxdy \right|^2$$

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PSF – point spread function (2)

The real optical system – optical aberrations of the wavefront

$$PSF_L(x_0, y_0, z) = \left| \frac{1}{i\lambda} \iint_A U(x, y, 0) \frac{z e^{ikr} e^{W(x,y)}}{r^2} dxdy \right|^2$$

where $W(x, y)$ – aberrations function – is the deviation of the wavefront from sphericity.

Seidel parametrization:

- defocus

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Seidel parametrization:

- defocus
- coma

$$W_C(\rho, \phi) = C\rho^3 \cos(\theta)$$

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where $W(x, y)$ – aberrations function – is the deviation of the wavefront from sphericity.

Seidel parametrization:

- defocus
- coma
- astigmatism

$$W_A(\rho, \phi) = A\rho^2 \cos(2\theta)$$

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where $W(x, y)$ – aberrations function – is the deviation of the wavefront from sphericity.

Seidel parametrization:

- defocus
- coma
- astigmatism
- spherical aberration (higher order defocus)

$$W_S(\rho, \phi) = S\rho^4$$

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Seidel parametrization:

- defocus
- coma
- astigmatism
- spherical aberration (higher order defocus)
- higher order and different aberrations, superposition

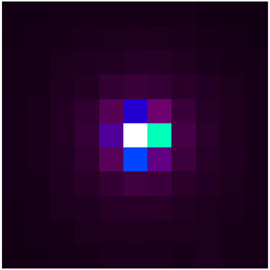
$W = W_C + W_A + W_S + \ldots$

Often parametrized with similar (but orthogonal) Zernike polynomials.

PSF parametrization method

Standard method of the PSF shape determination:

- reconstruction of a high resolution profile
  $\leftarrow$ superposition of multiple star(s) images
- fit of the shape parameters (Gauss, Voigt, Moffat, etc. profiles)



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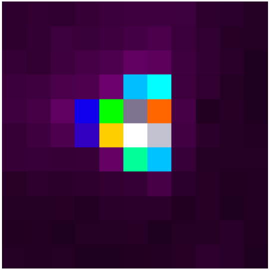

Drawbacks in the "Pi of the Sky" case:

- we search for a shape, not fit parameters of a known shape
- poor stars superposition – difficult centre determination for deformed profiles
- stars colour influence
- image blur – mount vibrations, fluctuations, etc.

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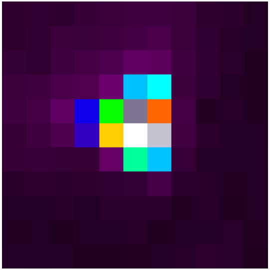

Solution: laboratory measurements

Laboratory setup

Star

as seen from Earth – a point source

A point source

image of the source much smaller than the angular resolution given by a pixel size

Laboratory setup

Star

as seen from Earth – a point source

Light source,
ϕ=0.4 mm

A point source

image of the source much smaller than the angular resolution given by a pixel size

- light source: LED diode (colour or white)
  - covered by a pinhole of 0.4 mm diameter
  - powered by a pulse generator
  - placed on a movable stand

Laboratory setup

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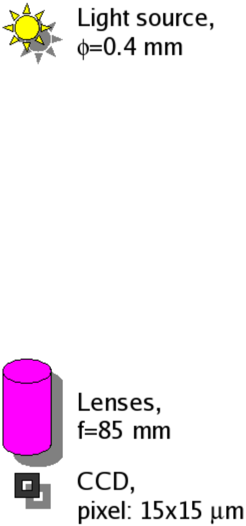

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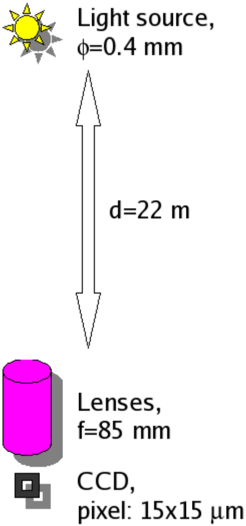
- camera
- distance: 22 m (corridor length)



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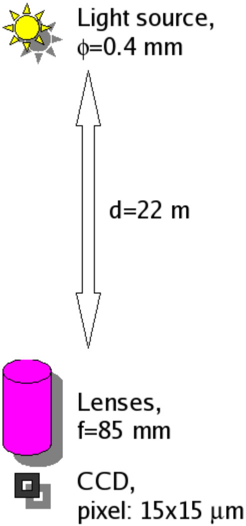
Fulfills the point-source requirements



Spatial pixel response function (PRF)

Source signal measured in a specific pixel vs. a spot position in respect to the pixel edge (measurement with reduced lenses opening – PSF close to pointlike).

An ideal case: constant inside the pixel, equal to zero outside the pixel.

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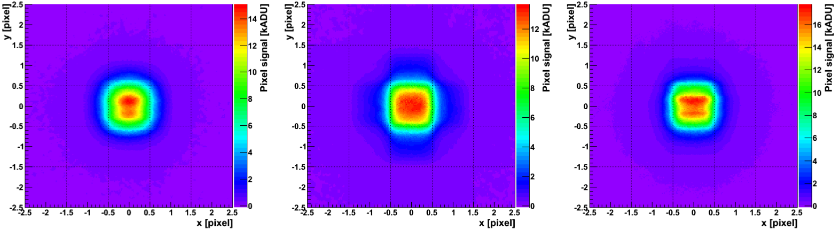


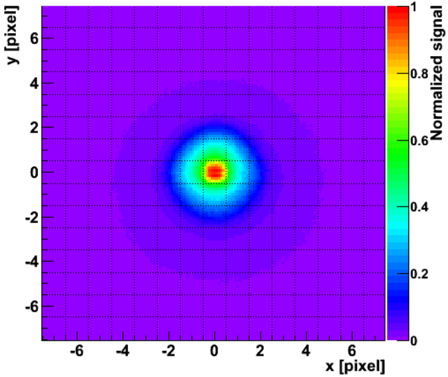
blue white red

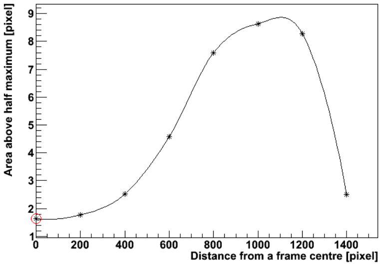
The real case:

- nonuniform inside the pixel – pixel sensitivity depends on it's structure (electrodes, light penetration depths)
- sloping near the pixel edges – spot's finite size
- non-zero outside the pixel – finite PSF size or charge diffusion between pixels

PSF reconstruction

High resolution PSF profile – superposition of the images placed on the net of 20 × 20 positions on the pixel.





Area above 50% of the maximal signal.

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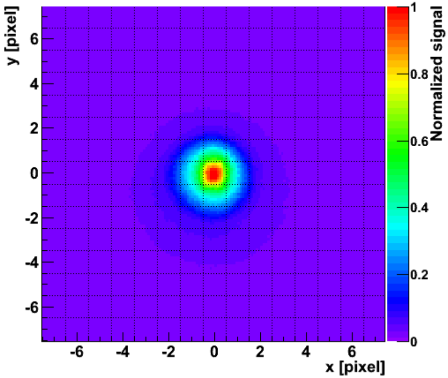

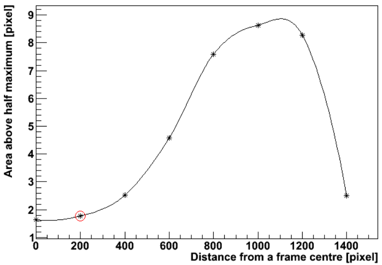

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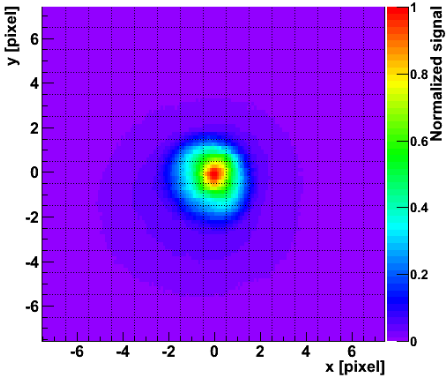

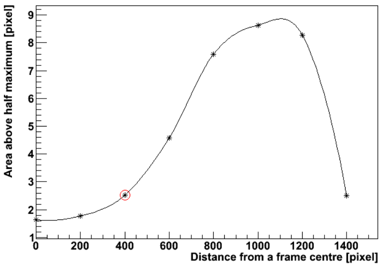

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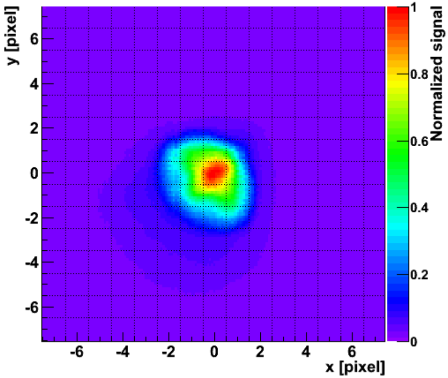

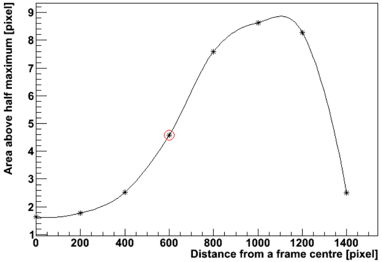

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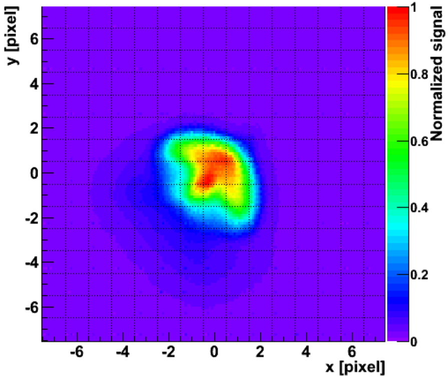

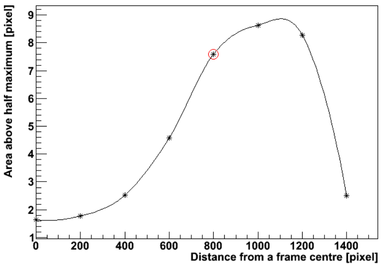

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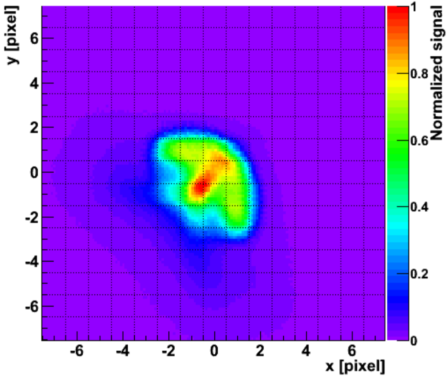

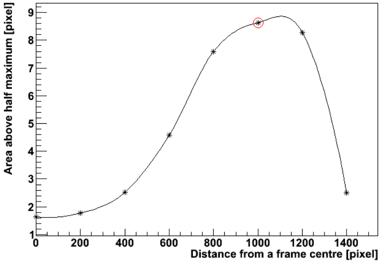

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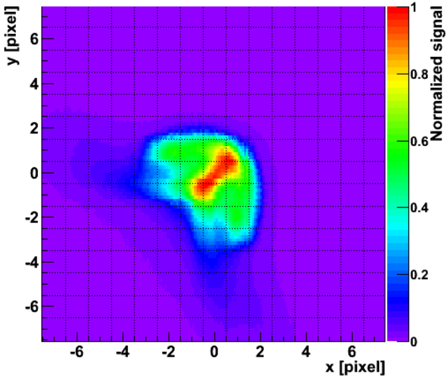

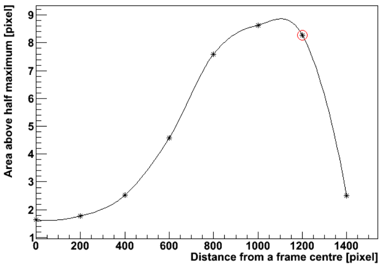

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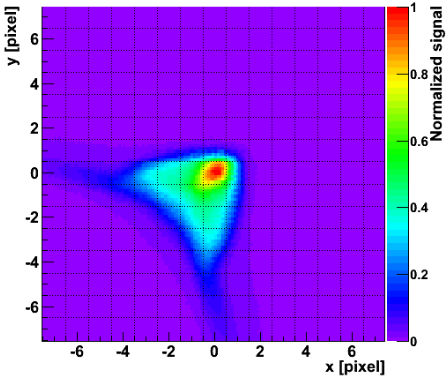

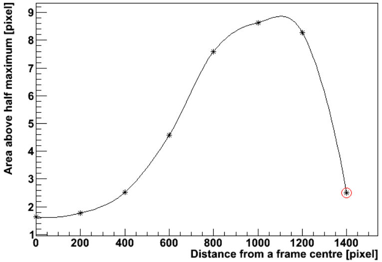

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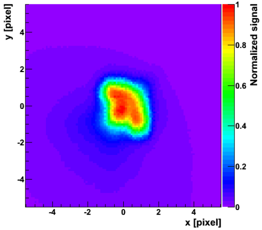
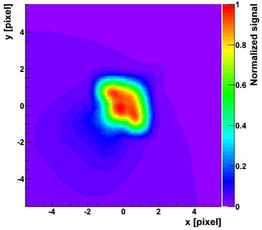
Diffraction model

Fit of the parameters to the Rayleigh-Sommerfeld's formula with aberrations.

The fit has been performed with 11 free parameters:

- **aberrations:** coma, coma', astigmatism, spher. ab., spher ab.', trefoil
- **image coordinates:** (x_0, y_0, z)
- background and a scaling coefficient





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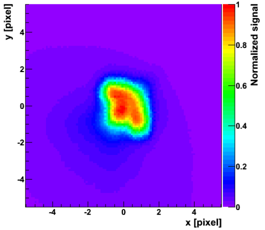
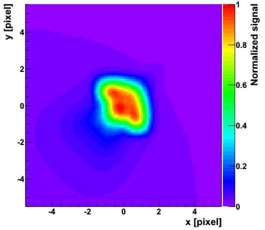


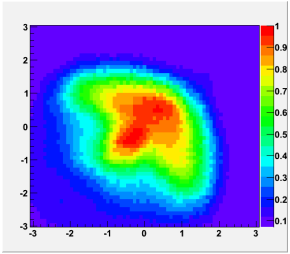
Drawbacks:

- very time-consuming computation
- simplification of the real case
- not successful at multi-wavelength fits
- not successful for other distances from the frame centre



Polynomial model – formulation

Effective model focusing on the PSF shape on the frame, not on the "physics" of the shape's creation.



Parametrization in the image plane (not aperture):

- Simplified formulation
- Much shorter computing time

Model basis – modified Zernike polynomials:

- finite aperture diameter $\rightarrow$ infinite image size

$$Z(r,\phi) \rightarrow Z(u,\phi),\ \ u = 1 - e^{\frac{r}{\lambda}}$$

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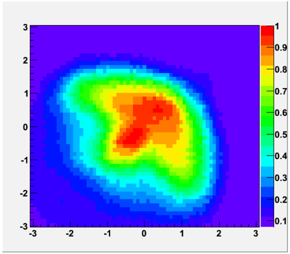

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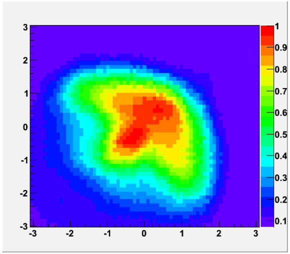

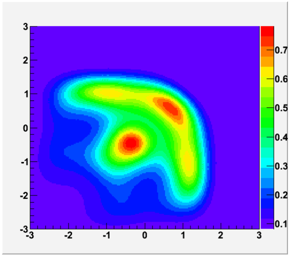

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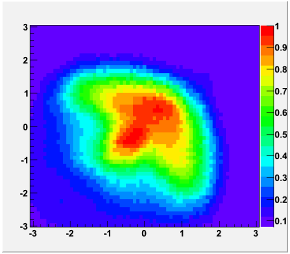
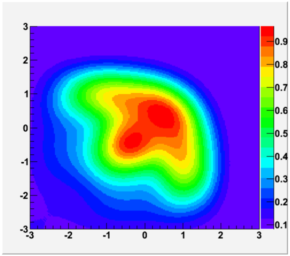
+ convolution with the pixel response function

$$PSF(r,\phi) = \iint_{CCD} PRF(r',\phi') \cdot PSF_L(r',\phi') dr' d\phi'$$

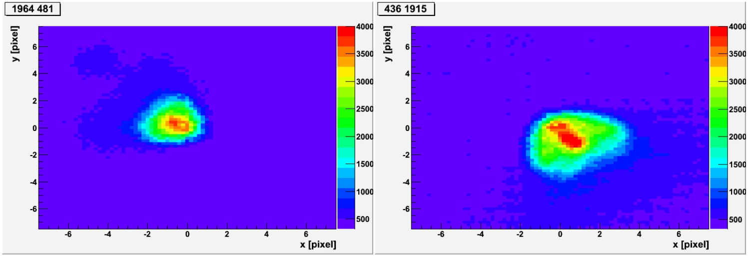




Polynomial model – the real stars case

Profiles of the real stars:

- slightly different than diode's profiles (different focusing, etc.)
- depend on the azimuthal coordinate on the frame (imperfect camera assembly – optical axis $\nparallel$ CCD axis)



Model recalculation procedure:

1. reconstruction with the diode PSF

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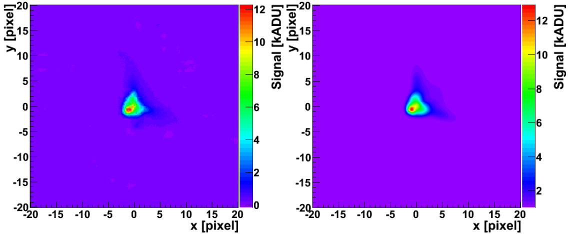


Model recalculation procedure:

1. reconstruction with the diode PSF
2. refit of the polynomial coefficients

Possible model applications

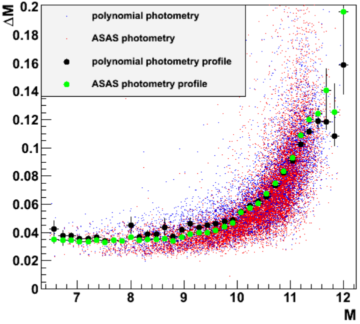
The obtained polynomial model can be applied, among others, to:

- profile photometry and astrometry
- search for sources on the border of the detectors range
- more precise limits determination
- simulation of the "Pi of the Sky" frame

Profile photometry with the polynomial model

Comparison with the ASAS (aperture) photometry:

- similar results and behaviour
- bigger instability (expected)
- slightly better results for dark stars



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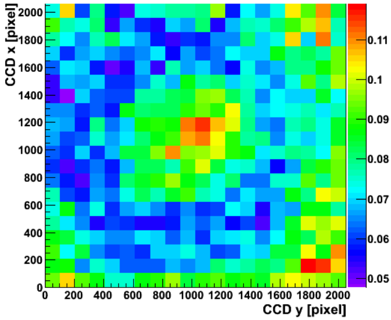

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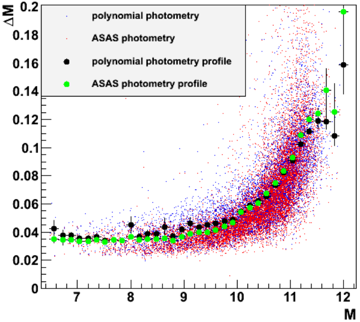

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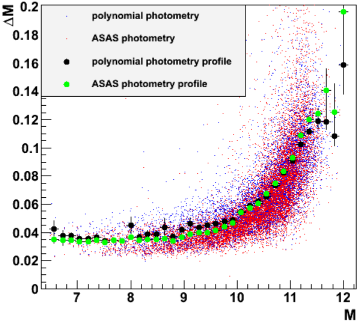
The lack of general improvement may be due to:

- different stars influencing fit
- real brightness fluctuations domination (not PSF shape)
- versatility of a circular aperture (highly improbable)



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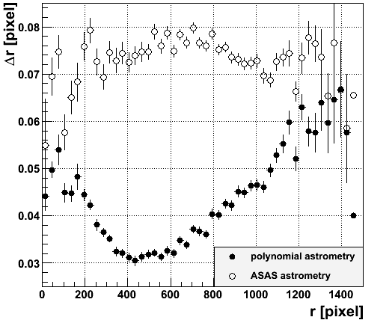

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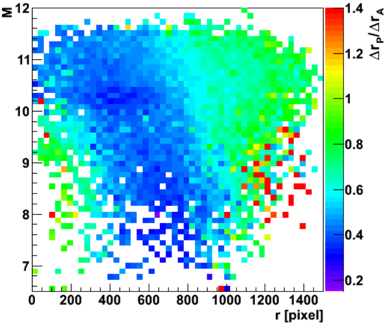

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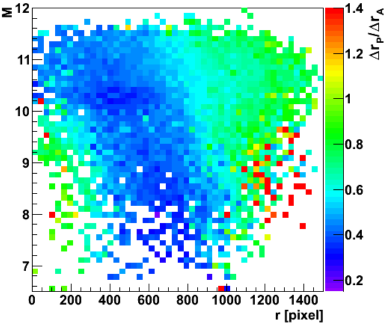

The polynomial astrometry is a preferred choice for objects of special interest – which allow for a longer computing time

"The naked-eye burst" precursor search

The brightest (optically) burst so far – GRB080319B – could be preceded with a bright optical precursor.

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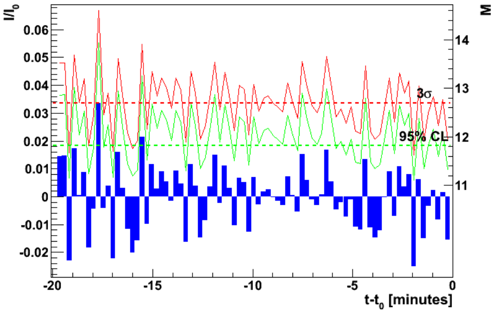
...in the corner of the frame.

The polynomial model has been used to:

- GRB precursor search – no signal exceeding 3σ has been found
- more precise limit determination



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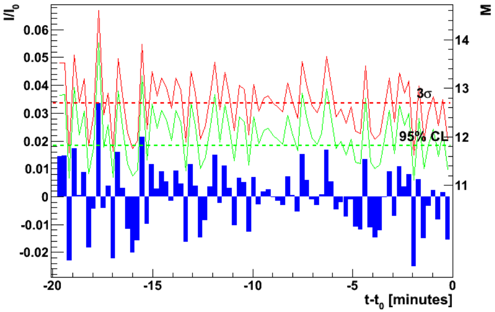
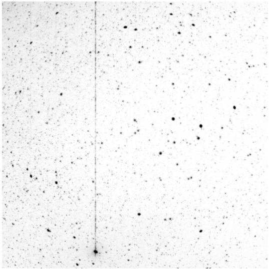


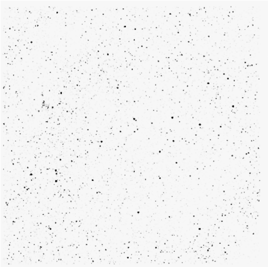
New limit: 12.25^{m} compared to previous 11.5^{m}. 0.75^{m} limit improvement.

The "Pi of the Sky" frame simulator

The "Pi of the Sky" frame simulator, based on the polynomial model:

- generates frame with catalogue stars position and brightness





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The "Pi of the Sky" frame simulator, based on the polynomial model:

- generates frame with catalogue stars position and brightness
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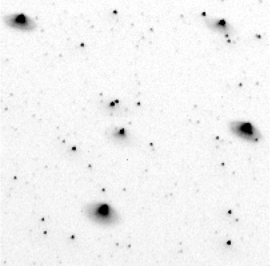
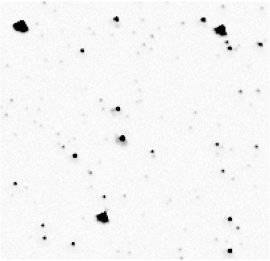
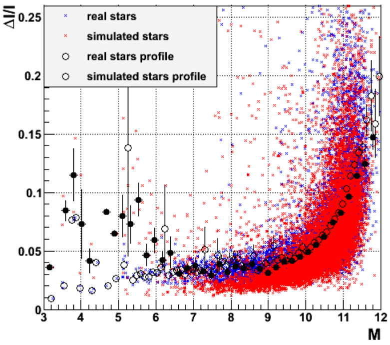




The “Pi of the Sky” frame simulator

The “Pi of the Sky” frame simulator, based on the polynomial model:

- generates frame with catalogue stars position and brightness
- takes into account stars PSF
- simulates miscellaneous fluctuations (Poisson, gain, readout noise, etc.)
    - properly reproduces $\frac{\Delta I}{I}(M)$



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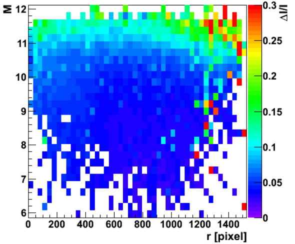

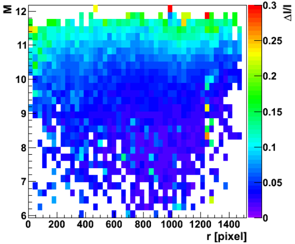

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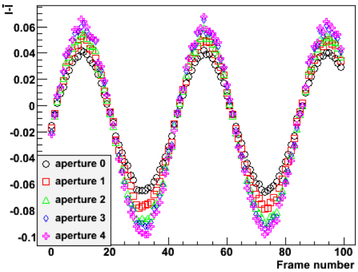

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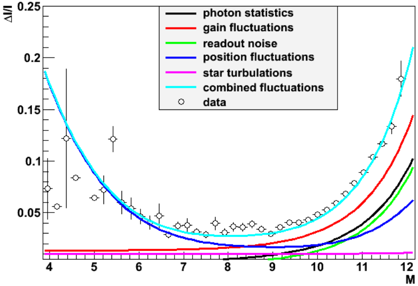
The simulator can be used to:

- analyse photometric uncertainties



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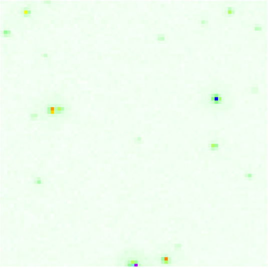

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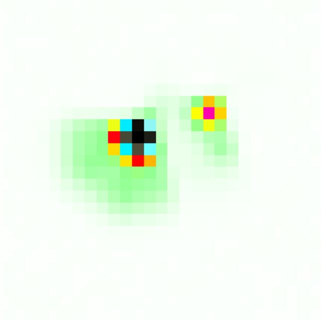
The simulator can be used to:

- analyse photometric uncertainties
- test parallax determination
- test algorithms on crowded fields
- etc.



Summary

- A well working polynomial model of PSF has been created
- Basic model-based photometry and astrometry has been tested
  - photometry may improve on new hardware
  - astrometry already performs much better
- Additionally models can be used for:
  - search for weak signals
  - precise limits determination
- A realistic simulator of a frame has been created, useful for testing algorithms and hardware of the "Pi of the Sky"
- Developed model could be used in future experiments with very large FoV

More details on the covered topics are available in my PhD thesis:
`http://www.fuw.edu.pl/~lewhoo/phd_thesis.pdf`.