In–flight calibration of the Swift XRT Point Spread Function

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Abstract. The *Swift* X–ray Telescope (XRT) is designed to make astrometric, spectroscopic and photometric observations of the X–ray emission from Gamma–ray bursts and their afterglows, in the energy band 0.2–10 keV. Here we report the results of the analysis of *Swift* XRT Point Spread Function (PSF) as measured in the first four months of the mission during the instrument calibration phase. The analysis includes the study of the PSF of different point–like sources both on–axis and off–axis with different spectral properties. We compare the in–flight data with the expectations from the on–ground calibration. On the basis of the calibration data we built an analytical model to reproduce the PSF as a function of the energy and the source position within the detector which can be applied in the PSF correction calculation for any extraction region geometry. All the results of this study are implemented in the standard public software.

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The *Swift* satellite was successfully launched on 2004 Nov 20. The XRT first light was on December 12th and the verification and calibration phase ended on April 5th 2005. The XRT is a sensitive, autonomous X-ray CCD imaging spectrometer designed to measure the flux, spectrum, and light curve of GRBs and their afterglows over a wide flux range covering more than seven orders of magnitude in flux in the energy band 0.2–10 keV. XRT utilizes the third flight mirror module (FM3) originally developed for the JET–X program: it consists of 12 nested, confocal and coaxial mirror shells having a Wolter I configuration. The mirror diameters range from 191 mm to 300 mm, the nominal focal length is 3500 mm, the total field of view is about 40 arcminutes (at 50% vignetting level) and the effective area at 1.5 keV is $\sim$ 135 cm^2. The XRT imaging array is a e2v technologies CCD22 consisting of 600 x 600 pixels, each 40μm $\times$40μm, with a nominal plate scale of 2.36 arcseconds per pixel, which makes the effective field of view of the system $\sim$ 24 arcmin (see [1] for a detailed description of the instrument).

Here we present the recent results of the in–flight instrument calibration phase which lasted for the first 4 months of the mission (see [2] for a detailed description of the observations and the analysis). In this period some ad–hoc observations of faint point–like sources with different spectral properties were performed in different positions of the detector in order to observe the surface brightness (SB) profile as function of the energy (E) and the distance from the optical axis of the telescope, usually called off–

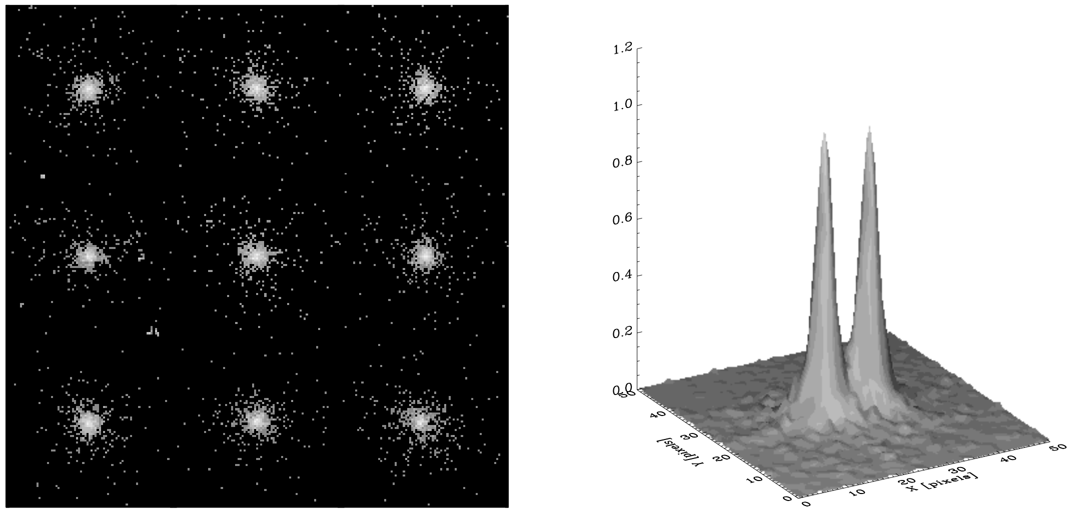

FIGURE 1. Some examples of the images we used in this work. Left panel. Each row corresponds to a different energy bin, 0–1(bottom), 1–2 (middle), 2–10 (top). The columns correspond to different off–axis angles in the range $1'$-$9'$ (increasing from left to right). Right Panel. We show twice the same on–axis observation of RXJ0720.4–3125, where one image has been artificially displaced by $20''$, equivalent to 8.5 pixels (1 pixel=$2.36''$).

axis angle (θ). The in–flight PSF calibration aimed to confirm that the launch and the pre-launch operations did not introduce any distortions of the optics and to measure the PSF shape with a point–like source positioned at infinite distance [3]. The final product of this calibration is an analytical model that reproduces the SB profile of a generic point–like source and can be used for the calculation of the PSF corrections.

The XRT supports different readout modes to enable it to cover the large dynamic range and rapid variability of the GRB afterglows (see [4]). The only readout mode useful for the PSF calibration purposes is the photon counting (PC) mode, which allows full spectral and spatial information for source fluxes below 1 count per second.

For the PSF calibration, low count rate targets are required to completely avoid any PSF distortion due to the pile–up effect. In PC data this effect is significant for count rates > 0.7 counts per second. We used the Isolated Neutron Star RXJ0720.4–3125, which has a count rate of 0.3 counts per second in the 0.2–10 keV band, and a very soft spectrum to study the PSF at low energies (< 2 keV). In order to observe the hard energy PSF we used the observation of the active galactic nucleus Mkn 876 which has a typical count rate of 0.2 counts per seconds in the band 0.2–10keV

We have 12 useful observations, 7 of Mkn876 and 5 of RXJ0720.4–3125, taken in different positions within the field of view, in the $0.1'$ to $9.9'$ range. To study the energy dependence of the PSF, we split the events of all the observations in 3 different energy bins, 0.2–1, 1–2, 2–10 keV (see Fig.1). This binning is a trade–off between having a good energy resolution and a significant number of photons for each bin. Note that the RXJ0720.4-3125 observations have the third energy bin completely empty. This resulted in a list of 31 images ($5\times2+7\times3$). The PSF profile analysis was performed by means of some home–made IDL routines and some DAOPHOT routines within the IDL Astronomy Library(*http://idlastro.gsfc.nasa.gov*).

The Half Energy Width (HEW), defined as the diameter that contains 50% of the total flux, is a very useful parameter to test the performance of our optical system and to study the dependence of the PSF on the different energies and positions in the focal plane. The HEW on–axis ($18.0\,'' \pm 0.7$ at 1.5 keV) is a local maximum and the HEW decreases for off–axis angles up to $6'$ ($17.2\,'' \pm 0.8$ at 1.5 keV). The same feature is expected and was also observed from the ground calibration data. This is due to the fact that the CCD is intentionally slightly offset along the optical axis from the best on–axis focus in order to have a uniform PSF over a large fraction of the field of view. The comparison of the data with the HEWs expected from ray tracing indicated that the offset is about –2 mm [3]. The result is that the optical response of the system is highly uniform over the central $\sim 8'$ radius region of the field of view. Because of the particular operational procedures of the satellite, many XRT observations are performed with the source not perfectly on–axis: the detector position along the optical axis represents a good trade–off between having a good spatial resolution and a larger field of view. We also note that beyond $\sim 8'$ the HEW increases considerably.

The crucial point in our PSF analysis is the construction of an analytical model which describes the PSF as function of (E,θ). The main goal of building this model is the calculation of the PSF correction, which gives for a generic observed source the fraction of the flux contained in the extraction region with a generic shape (square, circle or annulus for example). This is a fundamental ingredient in the photometric measurements and also in the construction of the Ancillary Response File necessary for spectroscopic analysis.

We selected all the observations of the 2 calibration sources up to $9'$ of off–axis angle and for each observation we split the events in three energy bins (0.2-1,1-2,2-10 keV). For each choice of energy bin and off–axis position, the PSF profile can be well fitted by a King function:

$$PSF(r) = (1 + (\frac{r}{r_c})^2)^{-\beta}). \qquad (1)$$

One of the main advantages of this function is that it is analytically integrable in rdr and therefore the integral profile (or Encircled Energy Fraction, EEF) and correspondingly the total flux of a source are also analytically characterized.

$$EEF(r) \equiv \int_0^r PSF(r')2\pi r'dr' = \frac{\pi r_c^2(1-W)}{1-\beta}((1+(\frac{r}{r_c})^2)^{1-\beta} - 1) \qquad (2)$$

$$EEF(\infty) = \pi r_c^2/(\beta - 1) \qquad (3)$$

The model has 2 free parameters (plus the normalization), the core radius (r_c) and the slope (β) which are functions of the energy E and position, $r_c = r_c$(E,θ), $\beta = \beta$(E,θ). To make the model useful for our purposes, i.e. the PSF correction for a generic source, we need to make it predictive and we used the following procedure.

For each of the different sampling points in the energy–position (E,θ) plane, we fitted the best fit PSF parameter values r_c(E,θ) and β(E,θ) with a plane function:

$$r_c(E,\theta) = a_1 + b_1 \times \theta + c_1 \times E + d_1 \times E \times \theta$$

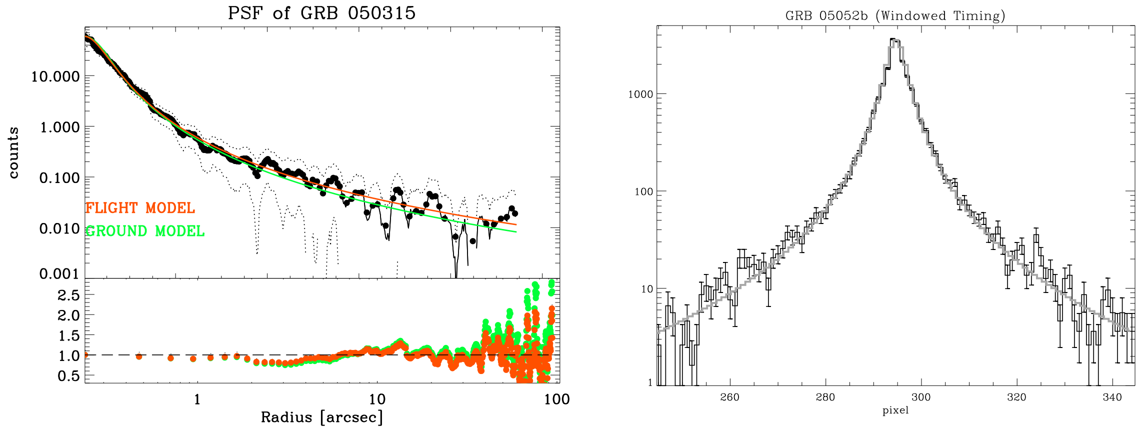

FIGURE 2. **Left Panel.** As an example we compare the data from the second part of the observation of GRB050315 (without any pile–up) with the analytical model. In the lower panel we plot the ratio between the data and the model. We show also the comparison between the model built from the ground calibration and the updated model built by means of the in–flight calibration. We find good agreement between the model and the data, which demonstrates that our goal is reached with a typical accuracy of 5%. **Right Panel.** The analytical model can also be used for the WT data, where only one spatial dimension is registered by the XRT detector. The observation of GRB05052b is shown. Tthe data (black) are compared to the model (grey). The pixel size is 2.36 arcseconds.

$$\beta(E,\theta) = a_2 + b_2 \times \theta + c_2 \times E + d_2 \times E \times \theta$$

The values of the plane function coefficients are stored in the PSF file within the *Swift* XRT CALDB distribution (http://swift.gsfc.nasa.gov/docs/swift/analysis). In this way, given the position within the field of view and the energy for an hypothetical monochromatic source we can calculate the corresponding values of r_c and β and reproduce the PSF by means of this parametrization. To give an accurate description of the PSF profile of a source with a generic spectrum we have to sum the single monochromatic contributions (Fig. 2). The PSF correction is applied by the task *xrtmkarf*, distributed within the HEADAS software (http://swift.gsfc.nasa.gov/docs/swift/analysis).

REFERENCES

1. D.N. Burrows, et al. 2005, Sp.Sc.Rev , 120 , 165
2. A. Moretti, S. Campana, T. Mineo, et al. 2005, proceedings of SPIE, 5898, 360
3. A. Moretti, S. Campana, G. Tagliaferri, et al. 2004, proceedings of SPIE, 5165, 232
4. J.E. Hill, L. Angelini, D.C. Morris, et al. 2005, proceedings of SPIE, 5898, 313