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On-flight calibration of the Swift-XRT telescope

Giancarlo Cusumano[1], Valentina La Parola[1], Vanessa Mangano[1], Teresa Mineo[1], Sergio Campana[2], Milvia Capalbi[3], Guido Chincarini[2,4], Paolo Giommi[3], Alberto Moretti[2], Matteo Perri[3], Patrizia Romano[2], Gianpiero Tagliaferri[2],

[1] INAF- Istituto di Astrofisica Spaziale e Fisica Cosmica Sezione di Palermo, Via Ugo La Malfa 153, 90146 Palermo, Italy; e-mail: cusumano@pa.iasf.cnr.it
[2] INAF – Osservatorio Astronomico di Brera, Via Bianchi 46, 23807 Merate, Italy
[3] ASI Science Data Center, via Galileo Galilei, 00044 Frascati, Italy
[4] Università degli studi di Milano-Bicocca, Dipartimento di Fisica, Piazza delle Scienze 3, I-20126 Milan, Italy

Abstract. The Swift Gamma-Ray Burst (GRB) Explorer was launched into orbit on November 20, 2004. The X-ray Telescope (XRT) is designed to perform prompt, automated observations of GRBs beginning about a minute after localization of bursts by the Burst Alert Telescope (BAT). The XRT is performing well in its initial months on orbit. In this paper I show the status of the on-flight calibration of the XRT effective area.

Key words. X-rays: general – space vehicles: instruments – instrumentation: detectors

Swift XRT is designed to detect and localize GRB and provide autonomous rapid-response observation and long-term monitoring of their afterglow emission in the X-ray and UV/optical band. The observatory incorporates three primary instruments: the Burst Alert Telescope (BAT: Barthelmy et al. 2005), the X-ray telescope (XRT: Burrows et al. 2005) and the

Ultra-Violet/Optical Telescope (UVOT: Roming et al. 2005). The XRT is a focusing X-ray telescope operating in the 0.2-10 keV energy band. Is is provided of grazing incidence Wolter I mirrors (originally built for JET-X telescope) that focus X-ray onto a single E2V CCD-22 detector at the focal plane, similar to the EPIC MOS detector flown on XMM-Newton. The focal plane detector covers a field of view of 23 arcminutes diameter and it is equipped with four calibration sources located at each corner of the detector. The telescope provides a position accuracy of celestial sources of 3 arcsec and a Point Spread Function of 18 arcsec and 22 arcsec (HEW) at 1.5 keV and 8.1 keV, respectively. The XRT effective area is 135 cm^2 at 1.5 keV and 20 cm^2 at 8.1 keV.

XRT supports four different read-out modes, each dependent on the brightness of the observed source, to cover the dynamic range and rapid variability expected from GRB afterglows. The transition between two modes is automatically performed on-board (see Hill et al. 2004 for an exhaustive description on XRT observing modes).

Send offprint requests to: G. Cusumano

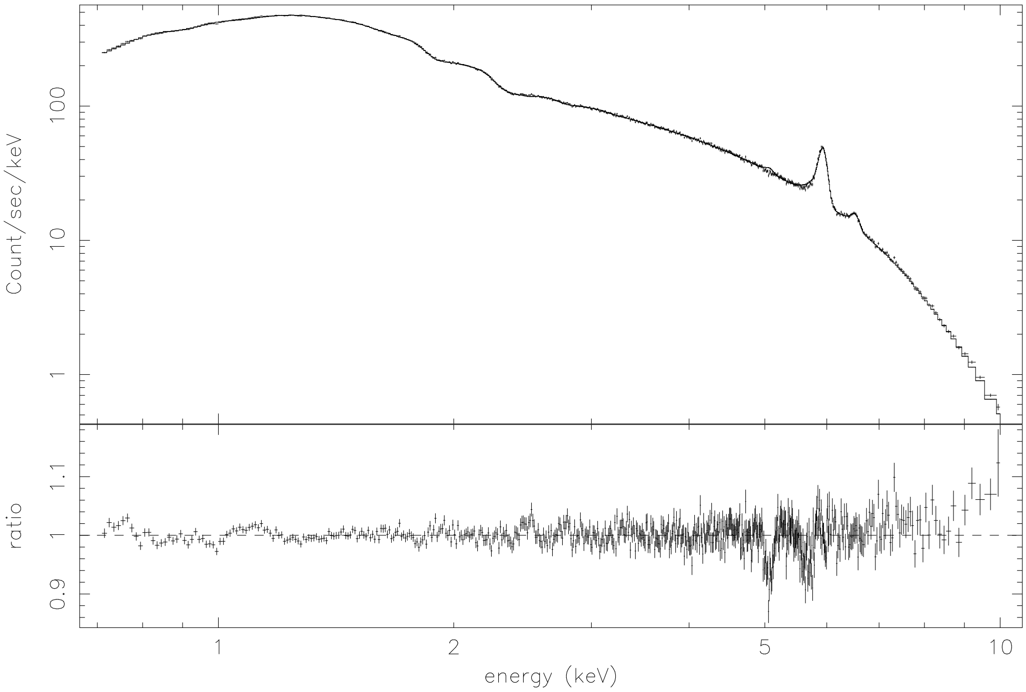

Fig. 1. Data, best fit model and residuals of the Crab spectrum obtained with the on-flight LRPD ARF files.

The Imaging mode (IM) works at the very beginning of the GRB aftertglow and it gives the prompt image of the field of view to provide a rapid evaluation of the source coordinates of the X-ray GRB counterpart. The CCD operates collecting the accumulated charge on the detector without any X-ray event recognition. The image is highly piled-up and produces no spectroscopy data. The Photodiode mode (PD) is designed for very bright sources and for high timing resolution. Depending on the source rate, data are telemetred on ground into two different modes: at high fluxes (< 60 Crab) data are telemetred in Piled-up PD (PUPD) mode in which data are grouped and spectral information is degraded; at lower fluxes (< 3 Crab) data are telemetred in Low Rate PD (LRPD) and full spectral information is available. High resolution light curves with a time resolution of 0.14 ms ara generated. The Windowed Timing (WT) mode is obtained by binning and compressing 10 rows into a single row, and then reading out only the central 200 column of the CCD. Therefore, it covers the central 8 arcminutes of the field of view and provide one dimensional imaging and full spectral capability with a time resolution is 1.7 ms. This mode is used for fluxes between 1-600 mCrab. Finally, the Photon Counting mode (PC) allows full spatial and spectral resolution for source fluxes below 1 mCrab with a timing resolution of 2.5 seconds.

Crab-like supernova remnants are sources characterized by well known and stable power law spectral distributions. Thanks to these characteristics these objects are the best candidates for in-flight calibration of the global effective area of X-ray telescopes. The XRT effective area for the three XRT observing modes (LRPD, WT and PC) has been calibrated using the Crab nebula for LRPD and WT mode and PSR B0540-69 for PC mode. XRT data are first processed by the Swift Data Center at NASA/GSFC to calibrate and quality flag the event lists (level 1 data products). They are then filtered and screened using the XRTDAS (v.1.2) software package to produce cleaned photon list files. Only observing time inter-

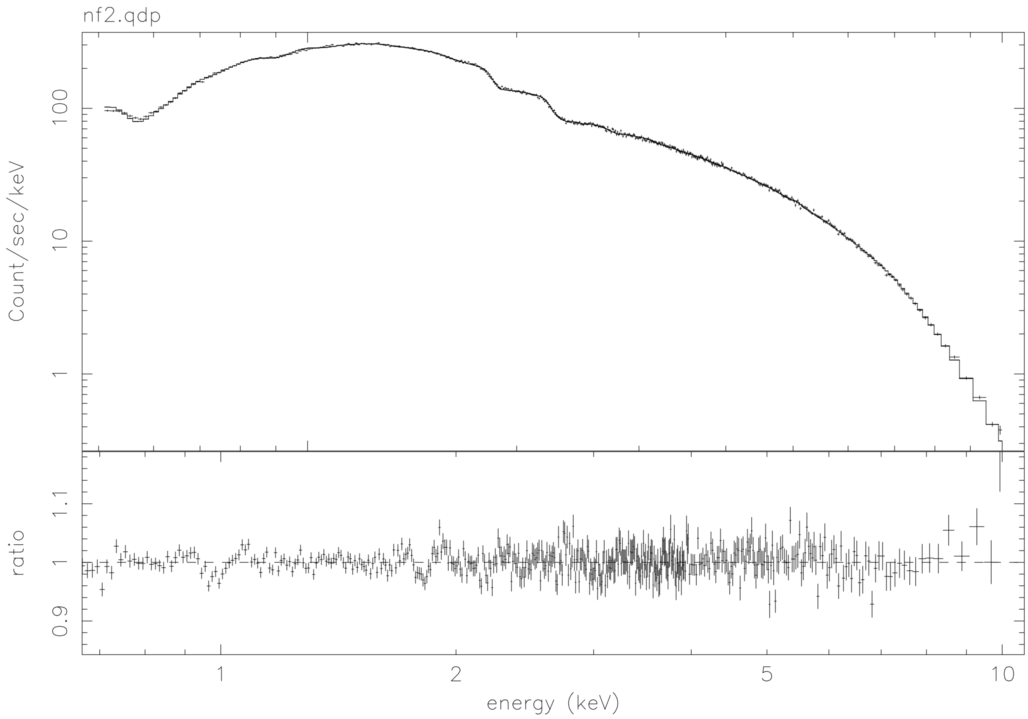

Fig. 2. Data, best fit model and residuals of the Crab spectrum obtained with the on-flight WT ARF files

vals with a CCD temperature below -47 degrees Celsius are used. Further non-standard selections are performed to remove time intervals with high background rate caused by either dark current or by the bright Earth limb. Hot and flickering pixels are also removed.

There are two different ways of improving the instrument ancillary files. A first method relies on the knowledge of the physical processes related to the X-ray photon detection and aims to change physical parameters (e.g. gold density, inclusion of a carbon layer, CCD depletion depth, etc.). These improved ARF files are then compared with well-known astrophysical sources in order to optimize the physical parameters. A second method does not involve the knowledge of the micro-physics but simply relies on the spectra of well-known and stable astrophysical sources. The idea behind this approach is that the XRT spectrum is compared and optimized (modelling in depth the residuals) to be consistent with the observed one. Within XRT we perform an hybrid method. With regard to the CCD quantum efficiency, we improve our description of the photon detection with a micro-physic method (especially for the spectral line resolution) and then apply the second method to reduce the amplitude of the remaining residuals. To calibrate the LRPD ancillary files we consider an on-axis 6742 s exposure of the Crab, resulting in 5.5×10^6 counts in the energy range 0.5-10.0 keV. The high absorption at low energies does not allow to calibrate the spectrum below 0.5 keV. A procedure of ARF optimization was applyed to the LRPD ancillary files generated from on-ground calibrations in order to have a good description of the Crab data with the very well known spectral model parameters reported in the literature. This procedure allows us to produce a final LRPD ARF file that, when applied to Crab data, reproduces its spectral energy distribution with best fit parameters consistent with those reported in previous works based on data from other satellites (BeppoSAX: Massaro et al. 2000;

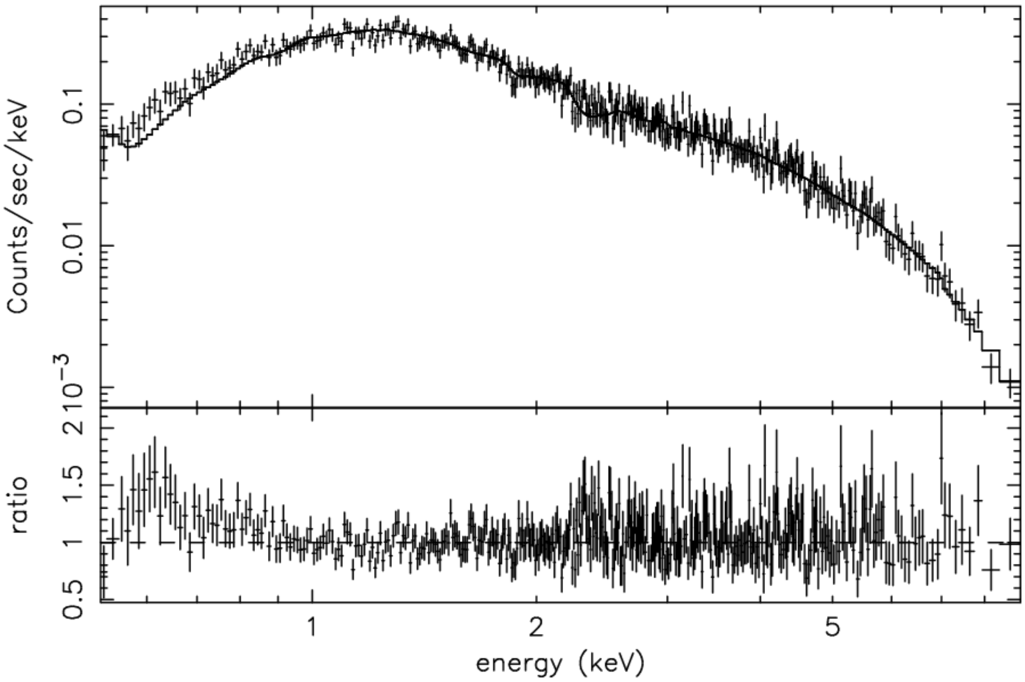

Fig. 3. Data, best fit model and residuals of the calibration source PSR B0540-69 obtained with the on-flight PC ARF files.

RXTE: Pravdo et al. 1997). In Figure 1 we show the residuals obtained fitting the LRPD Crab data with an absorbed power law, after correcting the ARF file. The reduced $\chi 2$ is 1.5 (919 degrees of freedom, dof). We estimate a systematic uncertainty at the level of 5% for all (i.e. different grade selections) LRPD ARF matrices in the 0.5-10 keV energy range. The strongest features are an absorption feature around 5 keV and an excess above 8 keV. In the case of the WT mode we used the Crab nebula as calibrator but in this case we have to deal with a moderate pile-up. To deal with this, we extracted the off-pulse Crab spectrum by applying a phase resolved analysis and verified that during this phase interval the lower average intensity of the nebula reduces the pile-up to a negligeable level. We observed the Crab on-axis in WT mode for 4373 s. We accumulated 2.2×10^6 counts in the energy range 0.5-10.0 keV. Again we tuned the WT ancillary files to reproduce the nebular spectral model parameters reported in the literature with low residuals. Figure 2 shows the residuals obtained by fitting the phase resolved Crab nebula spectrum with an absorbed power law. The fit is relatively good with $\chi 2$ is 1.4 (943 dof). We estimate a systematic uncertainty at a level of 5% for all grades and in the 0.5-10 keV energy range. The most prominent features are an emission line around 0.6 keV and an absorption feature around 1 keV. PC mode ancillary files have been calibrated with the Crab-like plerion PSR B0540-69 (as in this read-out mode the Crab spectrum is too piled-up). The source has a count rate of about 0.7 counts s^{-1} but thanks to its moderate nebular extension (about 10-15 arcseconds) the source deos not suffer significantly from pile-up. Calibration was performed on a XRT data set of 32 ks exposure with a statistics of 22400 counts in the 0.2-10 keV energy band. The PSR B0540-69 best fit parameters based on previous X-ray missions (ROSAT PSPC, BeppoSAX MECS and XMM-Newton) are reported in the literature. Figure 3 shows data, best fit model and the fit residuals obtained with the on-flight PC

ARF files. The $\chi 2$ is 1.3 (130 dof). The statistical uncertainty on the final ARF matrices in PC mode is higher than for the other modes and at the moment it is estimated at 10% level in the 0.5-10 keV energy range. A strong and broad emission feature is present around 0.6 keV.

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