Swift Catching gamma ray bursts on the fly . . .

Swift XRT On Orbit Calibration Plan

XRT-OAB-PR-003

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1. Mission Calibration Overview and Priorities

The Swift Mission's primary goal is to understand gamma-ray bursts (GRBs). Where are the GRBs? What is the environment of a GRB like? What are the classes of GRBs? How do the blast waves of GRBs evolve and interact with its environment? What can GRBs tells us about the early/distant universe? Furthermore, Swift is to provide information about any detected bursts to the community quickly enough so that other observatories can provide additional information. Secondarily, Swift will provide a unique hard X-ray map of the sky to a sensitivity more than an order of magnitude deeper than previously possible.

To achieve these mission goals, Swift will make a suite of measurements, all of which need to be calibrated. These measurements are listed below in approximate descending order of priority.

- Position of GRB
- Multi-wavelength Light Curve of GRB
- Spectrum of GRB

To calibrate the instruments that will make these measurements, Swift has approximately 2352 ks at the beginning of the mission to establish a baseline calibration. Additionally, another ~200 ks of mission time will be used every year to monitor trends in the instruments that may happen due to radiation damage, contamination and other aging effects.

This calibration time will be spent observing particular astrophysical targets with known properties. Each observation will be compared to a model, which folds the known properties of the target with the instrument response. Deviations will result in a modification of the instrument response. In many cases, several different observations of the same target will be done for different instrument modes or offset pointing angles. Some targets will be revisited routinely to monitor instrument degradation. The final result is to produce an instrument response model that will allow scientists to produce GRB measurements in units that are universally recognized.

The instruments on board Swift have to be calibrated within the first few months after launch so that useful data may be released to the public as soon as possible. The data will start to be put into a public archive by day L+135. Analysis pipeline software, written by the ISAC-ASI, will also be available for the public to use. The pipeline is put together and run by the SDC and which outputs go to the archives. It is therefore imperative that appropriate observations are made and appropriate, tested and documented calibration data products are available before this deadline.

2. Scope of this document

This document covers the following topics:

i) The observations required for obtaining the calibration data and the responsibilities of the observation responsible;

ii) A list of calibration observations with priorities;

iii) Team members and their responsibilities;

iv) Assignments of members of the team to particular products for which they will take responsibility;

v) A list of the calibration products with descriptions and priorities;

vi) Recipes for analysis of the data, including discussion of targets and descriptions of any software tools required;

vii) Outline schedule of analysis, verification, production of final calibration files and documentation.

3. XRT calibration requirements

The XRT instrument has several scientific requirements. Here we list the main ones that have to be verified by an efficient calibration plan.

- GRB positioning better than 5”
- Angular resolution (Half Energy Width, HEW) better than 20” at 1.5 keV and better than 30” at 8.1 keV
- Spectral resolution FWHM < 150 eV at 6 keV at start of the mission and FWHM < 400 eV at end of the mission (2 years nominally)
- Total effective area > 100 cm^2 at 1.5 keV and > 15 cm^2 at 8.1 keV
- Flux limit in the 0.2-10 keV energy band of 2×10^{-14} erg cm^{-2} s^{-1} in 10 ks exposure time
- 10% absolute flux accuracy
- 10 ms timing accuracy in Photodiode mode
- Observe sources up to a flux of 15 Crab

4. XRT readout modes

A few insight in the operation of XRT are needed to understand the calibration plan. XRT has four operating modes needed to handle the highly variable flux from a GRB:

- **Imaging mode (IMG)**: the CCD is operated like an optical CCD, collecting the accumulated charge from the target and reading it out *without* any X-ray event recognition. For a typical GRB, this image will be highly piled-up and will therefore produce no spectroscopic data, but it will produce an accurate position and a rough flux estimate. Image mode is operated with low gain to allow observations up to the full well capacity of the CCD (in normal gain, we are limited by the ADC range rather than the full-well). It uses either 0.1 or 2.5 second exposures, depending on the source flux. Imaging mode can be used to determine on-board centroids for source fluxes between 25 mCrab and 37 Crab. The following data products are produced: the GRB centroid position and X-ray flux estimate (telemetered through

TDRSS and distributed immediately to the community through the Gamma-ray burst Coordinate Network (GCN); a postage-stamp image (2'×2'), also telemetered via TDRSS and distributed through the GCN; and a compressed image (pixels above a threshold) in our normal science telemetry stream. The X-ray flux estimate assumes a Crab-like spectrum.

- **Photodiode mode (PD)**: a fast timing mode designed to produce accurate timing information for extremely bright sources. This mode alternately clocks the parallel and serial clocks by one pixel each. Charge is accumulated in the serial register during each parallel transfer, with the result that each digitized pixel contains charge integrated from the entire field of view (although not simultaneously). For the GRB case, where we expect the image to be dominated by a single bright source, photodiode mode produces a high-speed light curve with time resolution of about 0.14 ms. This mode is useful for incident fluxes below 15 Crab, and has manageable pileup for fluxes below 0.5-1 Crab (at 5%, based on ground calibrations). Thus, two different flavors of photodiode mode are possible: Piled-up photodiode (PUPD) and Low Rate Photodiode (LRPD). Only LRPD data can be used for scientific analysis, PUPD suffers from severe pile-up. Both obviously have to be tested since they involve a different way of telemeter the data. Data products in photodiode mode are FITS binary table files with the time, energy, and grade (or pattern) of each recorded event (unless the data are too piled-up to identify individual photon events).
- **Windowed Timing mode (WT)**: restricted to a 200 column window covering the central 8 arcminutes of the field of view. Imaging information is preserved in one dimension (in Right Ascension for zero degrees spacecraft roll). Pixels are binned by 10x along columns. This mode has 1.8 ms time resolution for a 200 pixel window. It is useful for fluxes below 250 mCrab. Data products are FITS binary table files with the 1-D position, arrival time, energy, and pattern of each event.
- **Photon-counting mode (PC)**: retains full imaging and spectroscopic resolution, but time resolution is only 2.5 seconds. It is useful below 0.5 mCrab. Data products are FITS binary table files with the 2-D position, arrival time, energy, 3×3 pixel "neighborhood" centered on the event, and the grade (or pattern) of each event. Grades are recorded using a scheme similar to the XMM-Newton MOS library pattern.

Only the last three modes (PD, WT and PC) provide spectral information on the source.

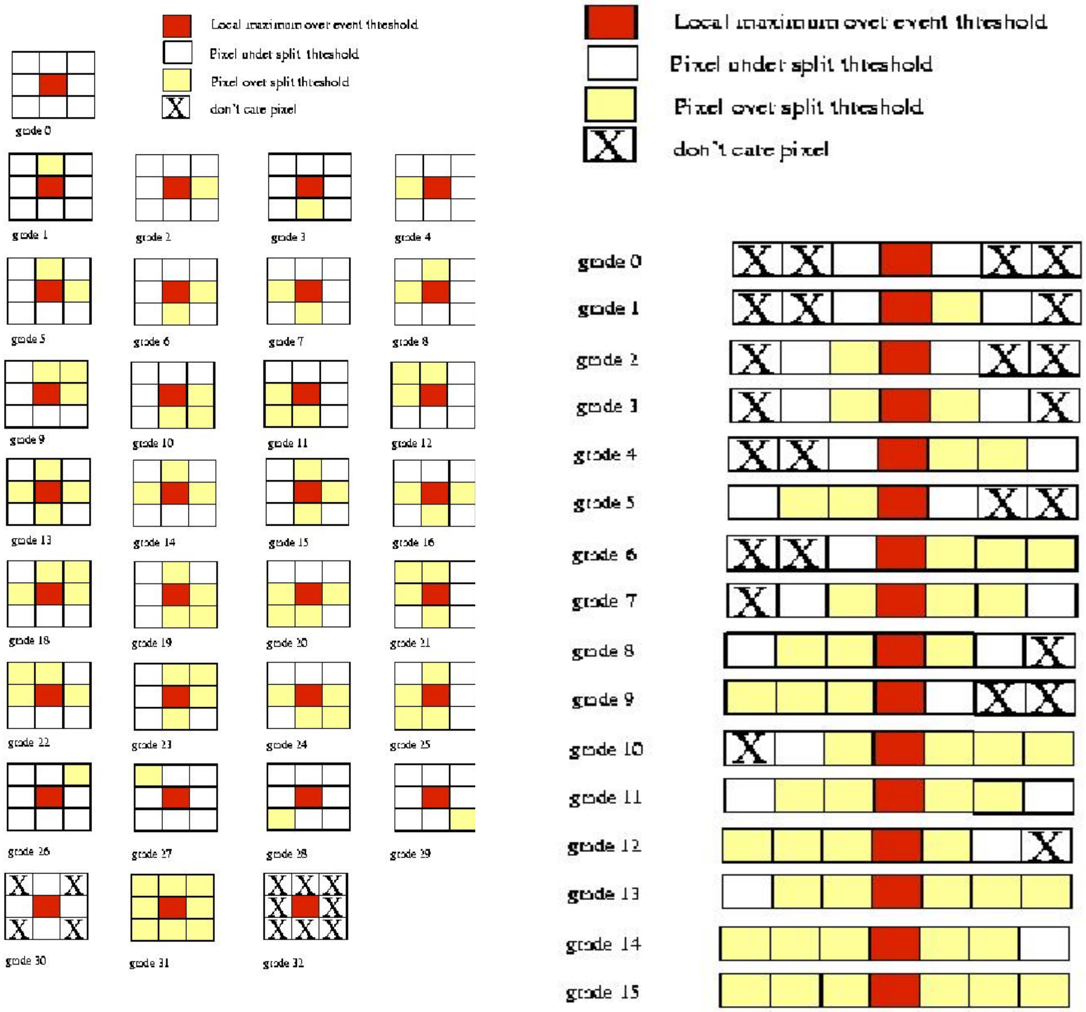


Figure 1: event grades in PC (left) and WT and PD (right) modes.

5. Status of the end-to-end ground calibrations

Ground calibrations have been carried out at the Panter X-ray facility (Neurid, Germany) of the Max Plank Institute. Calibrations were performed over one week, 24 hr a day. The ground calibrations were successful. We obtained a good description of the angular response of the instrument, with an analytic description of the Point Spread Function (PSF) of the instrument at five energies, as well as a vignetting map. The counts collected were not sufficient for a thorough analysis of the spectral capabilities, which relied mainly on previous tests on CCD carried out at LU. The main worry coming from these calibrations is the lack of a comprehensive understanding of the effective area of the instrument in the different operating modes. Effective areas are particularly under the expectations at high energies. To this aim a dedicated set of observations will be carried out during the in-orbit calibration phase, in order to collect a large number of counts.

6. Initial Verification and Calibration Targets

Table 1 lists targets suggested by the instrument teams for the initial calibration period beginning 6 weeks after launch and gradually completed by L+14 weeks (as shown in Figure 2). The integrated calibration time during this initial period is approximately 2352 ks.

7. Target List

Here, we list the calibration targets that we will use. First, we will list the initial verification and calibration targets, followed by those targets which we will visit throughout the mission for routine monitoring, and finally targets that will be used for cross calibration with other missions. In the following Sections, we will give the rationale for each target.

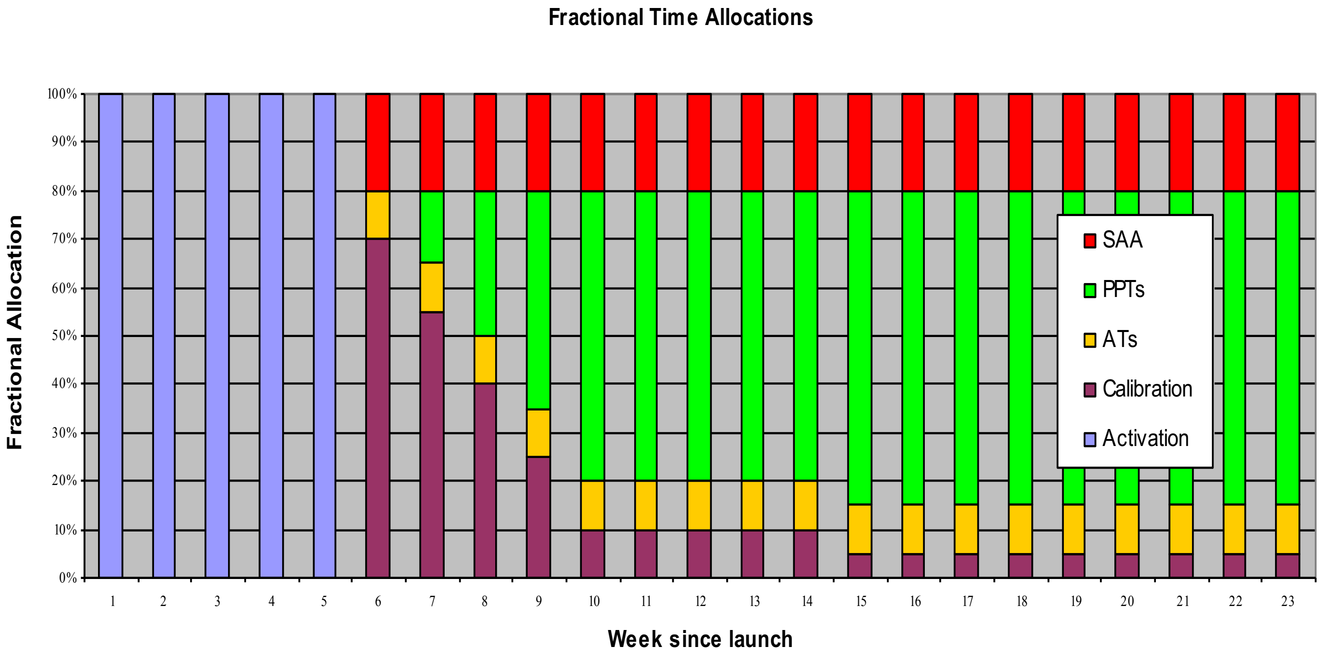


Figure 2: allocation of time for activation, calibration, and science operations after launch.

Table 1 lists the calibration targets. "Ra" and "Dec" columns are at J2000. The "Observing Mode" column indicates which XRT mode is required for that target, while "Purpose" indicates the particular calibration goal. The "Exposure Time" column indicates the required time to achieve the goal. For many of the targets, multiple observations will be carried out. The "Visibility" column indicates when the target's location does not violate the Swift Sun-Angle avoidance requirement. However, it does not involve Moon and Earth avoidance requirement which will modulate this visibility window on the 90-

minute and 1-month timescales. Finally, the last column gives the priority of the observation from 99 (most important) to 0.

Target Name	Count rate	Obs. Mode	Opt. Mag	Approx Total Exposure [ks]	Multiple Pointing	Purpose	Visibility	Priority
Mkn 421	20-40	IM	V=13.6	21	Yes (16)	XRT telescope axis	Sep 30-Jul 18	99
4U 0142+63	3.65	IM	No	9	Yes (9)	Centroiding accuracy	Always	75
GX 1+4	4.99	IM	V=19.0	9	Yes (9)	Centroiding accuracy	Always	75
Cir X-1	480	IM	V=21.4	9	Yes (9)	Centroiding accuracy	Dec23-Oct30	75
Cyg X-1	60	IM	V=9.0	9	Yes (9)	Centroiding accuracy	Always	75
Sco X-1	1200	IM	V=12.2	9	Yes (9)	Centroiding accuracy	Always	75
Her X-1	8	IM	V=13.0	9	Yes (9)	Centroiding accuracy	Always	75
WGA J1958.2+3232	0.15	PC	V=16.0	20	No	First boresight and first spectrum in PC	Always	80
NGC 2516	0.002-0.01	PC	V>5.8	50	No	Accurate boresight	Always	95
EXO 0748-676	0-20	All	V=16.9	55	No	XRT automatic mode changing	Always	85
RX J0720.4-3125	0.16	PC	No	105	Yes (3)	PSF core (soft spectrum)	Always	80

RX J0720.4-3125	0.16	PC	No	45	No	PSF core 10’ off-axis	Always	60
RXS J1708-4009	7.2	PC	No	70	Yes (3)	PSF wings (soft sources)	Jan28-Oct31	75
Mrk 876	0.38	PC	V=15.5	120	Yes (3)	PSF core (hard spectrum)	Always	80
Mrk 876	0.38	PC	V=15.5	60	No	PSF core 10’ off-axis	Always	60
GX 1+4	4.99	PC	V=19.0	70	Yes (3)	PSF wings (hard sources)	Always	75
2E 0102-7217	3.8	PC		155	Yes	Effective area, gain, vignetting	Always	80
2E 0102-7217	3.8	WT		155	Yes	Effective area, gain, vignetting	Always	80
2E 0102-7217	3.8	LRPD		15	No	Effective area, gain, vignetting	Always	60
Cas A	21.2	PC		150	Yes	Effective area, gain, vignetting	Always	80
Cas A	21.2	WT		150	Yes	Effective area, gain, vignetting	Always	80
Cas A	21.2	LRPD		10	No	Effective area, gain, vignetting	Always	60
Crab	787	LRPD	V=8.4	10	Yes	Effective area, gain, vignetting	Aug01-Apr29	80

Crab	787	LRPD	V=8.4	8	Yes	Effective area, gain, vignetting	Aug01-Apr29	80
Crab	787	WT	V=8.4	5	Yes	Pileup study	Aug01-Apr29	80
Crab	787	PC	V=8.4	5	Yes	Pileup study	Aug01-Apr29	80
RXS J1708-4009	7.2	WT	No	10	No	Timing accuracy	Always	40
PKS 0745-19	1.1	PC	V=19.6	30	No	Low energy shelf	Jan28-Oct31	60
Cen X-3	10	WT	V=13.3	5	No	Low energy shelf	Always	60
GX 17+2	276	LRPD	No	5	No	Low energy shelf	Feb 06-Nov 12	60
RXJ 1856.5-3754	0.64	PC	No	20	No	Low energy response	Feb 13-Nov 20	60
AB Dor	3.91	PC (wings)	V=6.9	40	No	Spectral resolution	Always	75
AB Dor	3.91	WT	V=6.9	20	No	Spectral resolution	Always	75
AB Dor	3.91	LRPD	V=6.9	20	No	Spectral resolution	Always	75
HR 1099	2	WT	V=5.9	30	No	Line shoulder	Jun25-Mar31	70
PKS 0537-441	0.45	PC	V=15.5	100	No	Point source featureless	Always	80
Mkn 421	20-40	WT	V=13.5	8	No	Point source featureless	Sep30-Jul18	80
3C273	11	WT	V=12.9	13	No	Cross spectrum	Nov12-Aug13	70

Cen A	**TBD**	WT	V=7.0	20	No	Cross spectrum	Dec03-Sep26	70
1ES 0927+500	0.3	PC	V=17.2	20	No	Debris	Sep02-Jun27	60
HD216108	Few	PC	V=8.0	10	No	UV leak	Always	50
HD206749	Few	PC	V=6.0	10	No	Red leak	Always	50
HD 5382	Few	PC	V=6.1	10	No	UV leak	May 26-Mar 03	51
HD 216228	Few	PC	V=3.5	10	No	Red leak	Always	51
Sco X-1	12000	PUPD	V=12.2	5	No	PUPD	Jan10-Oct24	80
Her X-1	8	All	V=13.0	15	No	Pile up study (5+5+5)	Always	60
Cyg X-1	31	All	V=9.0	15	No	Pile up study (5+5+5)	Always	60
Crab	few	PC	V=8.4	40	Maybe	X-ray stray light	Aug01-Apr29	20
H1426+428	1.9	WT	V=16.5	20	No	Intercalibration	Always	80
Mkn 421	20-40	IM	V=13.5	16	No	TAM calibration	Sep30-Jul18	50
4U 1626-676	2.65	WT		30	No	Timing intercalibration	Dec16-Dec4	70

TABLE 1

8. Targets for Routine Monitoring

In addition to the baseline calibration at the beginning of the mission, Swift will require routine calibration to track changes in the instruments due to several effects such as radiation damage and contamination buildup. Observations on the two effective area calibrators (E0102, 10 ks, and Cas A, 10 ks) are required as well as a low energy response source to put in evidence eventual degradation of the low energy response (RXJ1856, 30 ks). Finally, together with the on-board calibrations sources, observations of sources with lines are required to monitor spectral resolution and gain variations (AB Dor, 50 ks). Observations of a subset of these targets every 6 months will be necessary. Details of these observations will be given in the following sections. Approximately 100 ks of observatory time can be used every 6 months to perform this calibration maintenance.

9. CALDB Products

HEASARC will maintain a calibration database for Swift as part of the CALDB system. This CALDB data can be accessed by users and software alike to determine which calibration datasets are available and which should be used for data reduction and analysis. Since calibration data can change with time, the CALDB will maintain time dependent calibration data for all three Swift instruments.

The calibration database will include pre-launch and post-launch calibration data. The post-launch calibration data will be updated as new data are obtained. Some calibration products, such as flat-field data for the UVOT, will not be available until after launch.

Each instrument will have a set of calibration products. Each product is stored as a FITS file with one or more extensions. The format for each of the calibration products has been defined and the format description given in the "Description of thr XRT calibration files"(http://heasarc.gsfc.nasa.gov/docs/docs/heasarc/caldb/swift/docs/xrt/xrt_caldb_v1.pdf). This includes also the specific settings for the CALDB required keywords as CAL/GEN/92-011 Mandatory keywords for Calibration Index Files

(http://heasarc.gsfc.nasa.gov/docs/heasarc/caldb/docs/memos/cal_gen_92_011/cal_gen_92_011.html).

The calibration products are described briefly below.

TABLE 3

Datatype	*Description*
Basic Calibration files (BCF)	
Telescope file definition	Contain definitions for telescope coordinates system detector alignment
Detector Gain	Contain coefficients of the relation that describes the conversion from PHA to Pulse Invariant. There is one file for each of the operating XRT data mode (Photon counting, Windowed Timing, Photodiode) and the information is time dependent
Bad pixel	Position of the CCD bad pixels and columns. CALDB stored the on-board as well as the ground bad pixel table. The information is time dependent
Housekeeping conversion factor	Contain the conversion factors for the HK telemetry values into physical units

Housekeeping range	Contain the HK nominal range values.
Quantum efficiency	Contain the Quantum Efficiency of the CCD. It is provided for different grades as function of energy. There is one file for each of the operating mode (Photon Counting, Windowed Timing and Photodiode).
Mirror Effective area	This is the on-axis Mirror Effective Area as function of energy (0.1-12 keV)
Filter transmission	This is filter transmission (blocking for optical light) as function of energy (0.1-12 keV)
Tam Definition parameters	Contains the reference position of the LEDs on the primary and secondary image of the Telescope Alignment Monitor.
Bias value	Record the bias values for the Imaging and Photodiode mode. For these modes the bias is not applied on board and will be applied on ground software
CCD temperature	Record the CCD operative temperature. Time dependent file
Wave form	Record the waveform, amplifier and gain for different readout modes
Background	Background events file for the different operating modes to be use to extract background spectra (NOT yet available)
Grade definition	Store the Grade definition for Photon Counting and Timing modes. These definition is applied when defining events.
Position error	Contain the parameters to calculate the error box on source position
Calibration source position	Contain the calibration source position in the detector
Flux Conversion	Contain the conversion factor to translate the DN into flux obtained using different Nh and a Crab spectrum
Selection criteria	The standard selection criteria for events as well as column and selection for the make filter file are stored into calibration files.
Calibration product File (CPF)	
Point Spread Function	Contain the coefficients of the relation that describes the PSF as function of the off-axis angle and energy.
Encircle Energy Function	Contains EEF for a grid of 5 energy in 5 position on the detector (TBD)
Vignetting	Contain the coefficients of the relation that describes the vignetting as function of the off-axis angle and energy
Response matrices (PI, PHA)	The response matrices are provided for each of the data mode, Photon Counting, Windowed Timing and Photodiode for a selection of grade ranges. The matrices are in PI. Updates will be delivered during the missions. Response matrices in PHA are provided to analyze the spectra sent via TDRSS.
Ancillary Response	The ARF is provided for each of the operating mode (Photon Counting, Windowed Timing and Photodiode) for the on axis position. Software tool generates specific arf

10. XRT Calibration Plan

The XRT calibration plan aims to address the science requirements of XRT necessary for Swift to achieve its mission goals. First we list the requirements in general terms, then go through the various specific calibration observations. Note that there are four readout modes for XRT. A typical GRB will have XRT data in all of these modes, thus a significant duplication in the calibration program is necessary to cover mode dependences.

The calibration program is split into several Work-Packages (WP) reflecting institute's previous work:

a) Gain in-orbit variations (pre-calibrations phase)	: PSU	Hill
b) Angular response (PSF, vignetting, alignment)	: Brera	Moretti
c) TAM alignment	: LU	Abbey
d) Centroiding algorithm	: PSU	Hill
e) UV & red leak & Debris	: LU	Abbey
f) Spectral response (spectral resolution, gain, rmf)	: LU	Beardmore
g) Timing accuracy (all modes)	: Palermo	Cusumano
h) Global response matrix (rmf + arf)	: Brera+LU	Campana
j) Intercalibration within Swift & with other X tel.	: Brera+LU	Campana
k) Software interface	: ASDC	Tamburelli

The overall responsibility for the calibration is with S. Campana (Brera). He is responsible for the overall accomplishment of the on-orbit calibration program. He is responsible for the determination and resolution of any out-of-limits conditions. He is also responsible for achieving the objectives of the program. Any major changes to the calibration observation procedures must have his concurrence.

The WP responsibles are responsible for implementing and accomplishing all the activities of the calibration observation procedure. They have to ensure that: a) the targets to be observed are appropriate for their purpose, b) the observations are long enough to give sufficient signal to noise, c) the target are observable. They are also responsible for the analysis of the calibration data and the production of the calibration products. The CALDB file monitor will populate the CALDB with the products when they are ready.

During LEO calibrations, the science planners will forward a list of planned observations to the Science Operation Team (SOT) Lead, who will notify the assigned WP responsible for each calibration observation that the observation is scheduled. The WP responsible will then be responsible for tracking data acquisition for that observation. A message should also be sent by the WP responsible to the Calibration responsible at the end of any observation (via e-mail at campana@merate.mi.astro.it). A Web log book will be set up and maintained by the Calibration responsible at Brera (password protected). WP responsible have to send within a week from the data arrival a quick look report for each observation (to be detailed later, containing, e.g. exposure on-time, source count rate, source position, etc.) and if the data collected are good enough for the purposes they have been taken (see also Figure 3).

Local managers for the calibrations to whom WP responsible should address internal questions are S. Campana (Brera), J. Osborne (LU), P. Giommi (ASDC) and D. Burrows (PSU).

After a calibration product is created the file is sent to ISAC-ASI (xrt_sw_soft@asdc.asi.it) first where the files are checked for sanity (e.g. fits are written correctly, keywords are there, etc.). ISAC delivers the CALDB files to the SSC which delivers this to the HEASARC (see also the document "Description of the XRT calibration files").

Calibration delivery will take place into three steps. Product ready for February 14 2005 will be sent to ISAC for inclusion in the Mar 3 2005 release. Other products ready within Mar 1 2005 can be included if tested by WP responsibles. Other calibration products should be released by Mar 14 2005.

In the following we provide a brief description of the WP tasks and methodology.

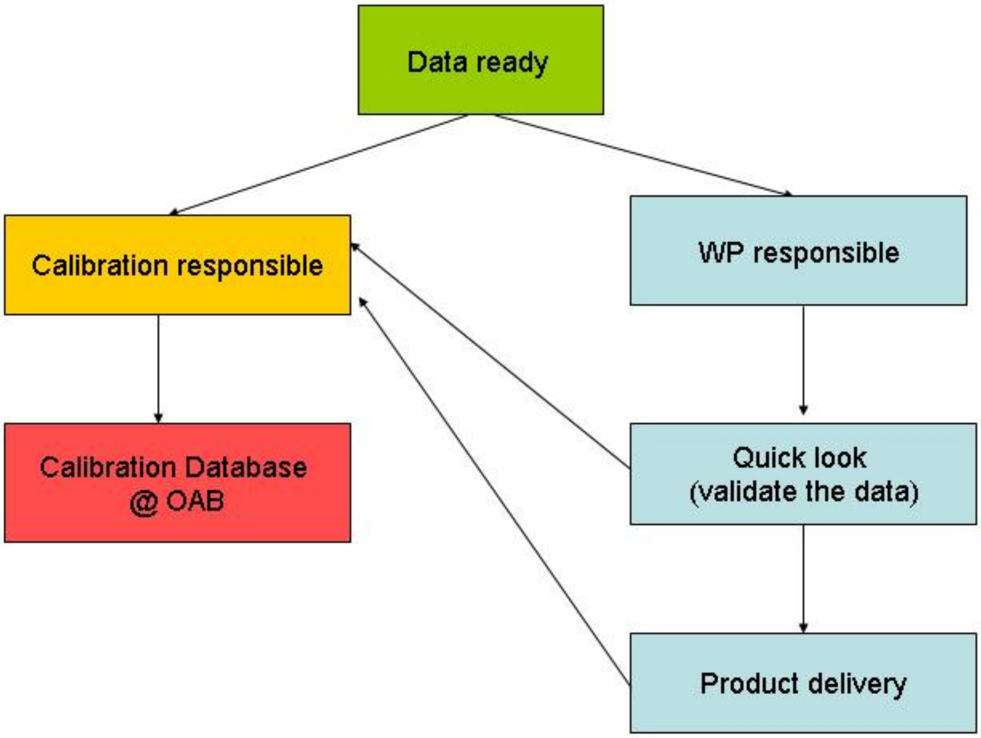


Figure 3: diagram of calibration data flow after the data production. Arrows indicate e-mail messages.

10.1 Gain in-orbit variations

After achieving operating temperature, the CCD gain will be monitored in all modes throughout at least one orbit. These measurements will be used to examine the data for any orbital variations in the gain. In-flight gain values will be established on the basis of the Fe-55 door source prior to opening the FPCA door, and will be updated as needed on the basis of observations of celestial sources with bright X-ray lines.

10.2 Angular response

10.2.1 Point spread function

The primary goal of the PSF calibration is to measure both the differential profile (PSF) and the integral profile (EEF) of the point-like source observed by XRT. They depend on the distance from the focal point of the telescope and on the energy of the spectrum. The final aim is to produce an analytical model of the PSF which will be used in the calculation of the PSF correction. As showed in the analysis of Panter end-to-end calibration data the PSF slightly depend on the XRT operational mode, because different modes have different event reconstruction algorithms. The PSF calibration observations are planned in Photon Counting which is the only mode which can provide image and spectral information at the same time and can provide a very good approximation for the other modes. We have planned to observe two faint sources (~0.2 c/s) with different spectral characteristics to model the core of the PSF in 4 different positions of the FOV.

They will provide us with a good statistic in the inner 60" of the PSF without any pile-up effect. Moreover, two observations of bright sources (~5 c/s) are planned; in this case while the PSF core will be distorted by the pile-up effect, we will be able to model the PSF wings in the annulus between 60" and 150" (typically 10% of the flux). The PSF is expected to be azimuthally symmetric and it will be modeled by means of a Gaussian function that takes into account the very central part of the profile and a King function which describes the external faint wings. The data reduction will be performed by means of the HEADAS standard software, and the PSF profile reconstruction and fitting procedure uses IDL and DAOPHOT routine which have already been successfully used in the ground calibration data analysis.

The final product of this work will be:

1) a CALDB file which contains the numerical value of the analytical model. This file is used by the HEADAS task which make use of the PSF correction (e.g. xrtmkarf).

2) A CALDB file which will contain the EEF profiles for a grid of input energy spectrum and of off-axis angle.

10.2.2 Vignetting

The main aim of the vignetting calibration is the measurement of the off-axis reflection efficiency and the off-axis geometric collecting area of the telescope. We do not plan to have specific observations to this aim. Instead we plan to use the observations performed for the PSF core characterization (which are stable sources). From the comparison from the (PSF corrected) flux measurement on- and off-axis we will be able to calculate the vignetting factor at different energies. In order to be able to calculate the vignetting correction for a generic spectrum in any position of the detector we will build an analytical model as a function of the off-axis angle and energy. The data reduction will be performed by means of the HEADAS standard software, and the analysis will be performed by simple IDL routines which have already been successfully used in the ground calibration data analysis.

The final product of this work will be a CALDB file which contains the numerical value of the analytical model parameters. This file is used by the HEADAS task which make use of the vignetting correction (e.g. xrtmkarf).

10.2.3 Boresight

The primary goal of the Boresight calibration is to measure the systematic errors in the sky reconstruction of the XRT field of view. To this aim a deep observation of NGC2516 is planned. NGC2516 is an open cluster already used for the same calibration by Chandra and XMM-Newton. With a 50 ks observation we aim to get at least 10 sources with more than 100 counts in order to provide absolute position uncertainties of the order of 1 arcsec all over the XRT filed of view. First we will perform a simple detection of the brightest sources within the FOV; the centroid position will be accurately re-measured by means of the DAOPHOT centroid algorithm. The measured positions will be compared to the Chandra catalog (more details in the NGC 2516 observation section).

In addition a first set of observations in imaging mode on a bright target will be carried out in a way similar to what performed at Panter to locate the telescope optical axis with a precision of 0.25".

10.3 TAM alignment

The Telescope Alignment Monitor (TAM) is used to correct the on-board XRT position centroids by measuring positions of two infra-red reference beams which monitor the XRT mirrors and star tracker position w.r.t. the XRT focal plane. Pre-launch measurements have been made at Panter, in the GSFC clean room, and during thermal vacuum testing of Swift of the sensitivity of these positions to differential heating of the XRT telescope tube and star tracker mounting plate temperature, but the final confirmation of the accuracy of the system can only come from in-orbit testing. It is proposed that a reasonably strong point source of X-rays (10 - 100 c/s) should be monitored in imaging mode for several orbits under different conditions of earth and solar irradiation (and possibly changes to commanded heater set-points), and the TAM centroid positions telemetered at 5 minute (or 1 minute) intervals. The on-board reporting of the position of the X-ray source needs to be reported via the equivalent of TDRSS, since these positions are corrected by the TAM algorithm before transmission. By monitoring the star tracker position information, the XRT centroids, the TAM centroids and the corrected XRT positons we will be able to determine if the TAM correction factors are performing the correct function of removing any structural deformation affects on the star tracker and XRT telescope, and calculate new ones if necessary. Monitoring of the XRT and spacecraft housekeeping reports of structure temperatures will also enable us to calibrate the system sensitivity to solar and earth thermal radiation.

In addition to the specialist image mode pointings specified above, it will be possible to get lower update frequency position centroids from ground processing from any PC mode point source observation. Specific calibration observations for this purpose are not required given the PC mode point source observations already planned. The rates used for PC mode to avoid pile-up (typically <1 c/s) will only produce accurate position centroids every few minutes.

We have selected Mkn 421 for this purpose. It has a count rate of ~30 c/s and is a well isolated X-ray source. There are 2 stars nearby (magnitude 6.2 and 7.9), but these are not expected to be significantly visible through the XRT filter. As near continuous observation as possible for 3 orbits (i.e. < 16 ks) making continuous GRB-type IM mode sequences (ie 1x0.1sec then 10x2.5 sec exposures) would be suitable, the normal TDRSS downlink associated with this type of observation is not required.

10.4 Centroiding algorithm

The on-board centroiding algorithm will be tested being position determined (Image Mode) observations of a number of bright X-ray sources. The on-board centroids will be compared with ground calibration using the IM mode frame and postage stamp images.

10.5 UV & red leak & Debris

TBD

10.5.3 Debris

Need to investigate the absorption characteristics of the pieces of debris on the CCD. The debris can be located with the LED and then an unabsorbed BL Lac can be positioned over the spot. 1ES 0927+500 (PC mode as required) would be suitable, with a 20 ks observation. If the debris is polypropylene ($C3H6$), the main signature will be a strong Carbon absorption edge at 300 eV; if mylar ($C10H8O4$), there will be an additional, weaker Oxygen edge as well. Above ~1keV, the transmission is 100%, so no additional features will be seen. (Thickness of 1 micron was assumed; from previous work, it assumed to be a "flake" and, so, very thin). For an unabsorbed source count rate of 0.34 c/s, polypropylene decreases this to 0.25 c/s and mylar to 0.21 c/s.

10.6 Spectral response

After the spectra have been obtained, they will be checked for any unexpected pile-up problems, by looking at the core of the PSF. Suitable models will then be fitted, depending on the target of interest: black body for the isolated neutron stars, (broken) power-laws for the BL Lacs/AGN and more complicated line emission modes for the gain targets and those for which the line shoulder is being investigated. For the low-energy shelf, the flattening of the spectra below 0.5 keV must be analysed. For the low-energy response, the temperature and normalisation of the black body is required. For the line shoulder, how well the model fits the low-energy side of the line (at ~10% level) will be looked at, while, for the gain targets, the line energies should be compared to previously known values. To investigate the debris, assuming it is still visible, any absorption edges etc on the featureless spectrum must be identified; likewise, when looking at the featureless point sources, if there are any spurious detector lines, these must be understood. Finally, the RMFs will be produced using the LU CCD22 Monte Carlo simulation code, which will be refined to match the calibration data.

10.6.1 Low-Energy Shelf

Below ~0.5 keV, a shelf is seen in the Panter data. Strong absorbers required, in all 3 modes, to investigate this:

PC mode - PKS 0745-19
WT mode - 1E 2259+586
PD mode - GX 3+1

10.6.2 Low-energy Response

The XMM MOS response has been found to evolve below the Oxygen edge, so routine soft monitoring needs to be performed throughout the mission to check on any changes in the low-energy redistribution.RXJ 1856-3754 is better than RXJ 0720 for long-term monitoring, because its BB temperature remains close to constant (WT mode observation). However, RXJ 0720.4-3125 is being scheduled for an XMM observation, so a close-to-simultaneous Swift look would also help to constrain the low energy response. 5 ks observations will produce acceptable spectra for these neutron stars.

10.6.3 Line Shoulder

In multiple-pixel events, there is a "shoulder" in the line profiles (on the lower-energy side), strongest in the low-energy lines. Only visible at the 10% level, but should be investigated. 2E 0102-7217 has suitable strong low-energy lines and lines up to about 1 keV can be measured down to 10% in about 20 ks. Since 2E 0102 is scheduled for multiple observations up to 252 ks, this will be easily done. As an additional check on the shoulder, HR 1099 (an RS CVn type variable star, V mag ~ 5.9) could be observed. Stars are better, to some extent, because they are not extended and the lines are more likely to be very narrow. HR 1099 has a strong, distinct Oxygen line, which a 30 ks should reveal. This can be observed in WT mode.

10.6.4 Gain

In the calibration review last month, the panel were concerned about the varibility of AB Dor. However, although it does vary, we still believe it would be an acceptable target for gain measurements in WT and PD mode (20 ks in each). The lines are weaker during quiescence, but they are still sufficiently strong. PKS 0745-19 (being used for low-energy shelf) has He- and H-like Fe lines (~6.7 and 6.9 keV) which can be used for high-energy gain measurements in PC mode. Compact SNR can be used for gain measurements; 2E 0102 is used by XMM-Newton, for example. 2E 0102 is in the cal plan for other reasons (e.g. investigating the line shoulder at low energies), so can be used for gain measurements as well.

So, for gain, we can use AB Dor (20 ks in each of WT and PD; 40 ks for PC, since the core will contain most of the counts), PKS 0745 (30 ks; already in plan for low energy shelf) and the compact SNR 2E 0102 (currently down for 252 ks in total, but 20-30 ks will be fine).

10.7 Timing accuracy

The observations dedicated to the Crab will verified the absolute timing capabilities of the XRT. Calibration observation of the Crab, contemporaneous with the Rossi X-ray Timing Explorer will be used to measure the absolute phase of the main pulse of the Crab pulse profile using the same Jodrell bank radio ephemeries. The timing resolution of XRT will be measured by studying the Crab pulse profile (main peak width, peaks phase distance). Additional observations of the anomalous X-ray pulsar (AXP) RXS J1708-4009 for WT and RX J0720-3125 in PC will establish timing capabilities in the other modes. During observations with other satellites we can break the degeneracy on multiples of the spin period of these sources.

10.8 Global response matrix

Response matrices are clearly the most delicate issue in the calibration. Concerning the spectral part of the response matrices, this has been described above. The overall shape of the effective area of XRT, needs to be well characterized. This is more importantly after the ground end-to-end calibrations. These calibrations indicated there is deficit in the effective area at different energies with respect to the nominal one, with a progressive increase in the area loss at high energies. To calibrate properly this effective area roll over we need a large amount of counts. This can be achieved easily in PD and WT modes but in PC we are limited by pile-up. The only way to circumvent this problem in PC is to observe bright extended objects. We identified two bright supernova remnants (SNR) one with a soft spectrum (2E0102) and the other with a hard spectrum (Cas A). These are well known calibration sources. Emission lines are present and should provide further insight in the calibration of the redistribution matrix. Sources will be observed on-axis and at different position to monitor also the vignetting.

The final product of this work will be a CALDB file which contains the on-axis effective area (mirror+filter) in flight conditions. This will be used to generate the arf file by the xrtmkarf program within FTOOLS. The CCD quantum efficiency is instead contained in the rmf files.

To further check the final response matrix featureless and straight spectra of AGN are in the calibration plan. These sources provide a verification for the lack of emission7absorption line feature and no upward/downward warping of the source spectrum. We should observe one source in each mode:

PC mode - PKS 0537-441
WT mode - Mrk 421
PD mode - Crab

10.9 Intercalibration within Swift and with other X-ray telescopes

We need first an intercalibration within XRT for the different observing modes. This is mainly spectroscopic but also timing has to be investigated. We plan to observe on-axis the two SNRs E0102 and Cas A in PC and WT for effective calibration purposes and in PD to have the same (stable) target observed in all modes without pile-up. Timing accuracy can be obtained by looking at the Crab in all the three modes and by taking only the non-piled-up part of the 1D/2D images for timing analysis.

Intercalibrations with other Swift instruments has also to be obtained. Intercalibration between XRT and BAT can be obtained observing some of the bright targets observed by BAT (Crab, Sco X-1, Cyg X-1) for the spectra whereas Crab observations will cope the timing part. Intercalibration between XRT and UVOT can be obtained on non-absorbed targets with relatively bright optical counterparts (see list below).

A further aspect is the Intercalibration of XRT with other X-ray facilities in terms of spectral and timing properties. We are arranging (quasi-)simultaneous observations of targets with XMM-Newton (PKS0537-286 and H1426+428). A contemporaneous observation with XMM-Newton on EXO 0748-676 can take place late in Winter (due to problems in visibility) to check the mode changing with an external reference. Timing capabilities (and effective area) will be checked with coordinated observations with RXTE (Crab, RXS 1708-4009 and Cen A).

10.10 Software interface

During the in-flight Calibration activities software changes may be needed due to different reasons (the implementation of a different calibration algorithm; the handling of a new calibration file or general fixes of the software discovered during the calibration activities). The changes of the XRT software have an impact in the outputs of the SDC pipeline which produces the Level 1 and up of the science data file. To request a software change during the calibration phase, the XRT Team Responsible for a specific WP of the XRT calibration should send an e-mail to the ASDC at the xrt_sw_soft@asdc.asi.it (and in cc to campana@merate.mi.astro.it) mailing list including either a Software Problem Report (SPR) or a Software Modification Request (SMR). The SPR should include a complete description of the software problem found, the log of the screen outputs, the input and/or output files and the operating system where the software was run. The SMR instead should clearly explain the software modification requested for a specific task. Both of them should also specify the severity level of the changes by specifying Normal or Urgent. Requests may be called Urgent when the software fails because of a bug or requires changes in some calibration definition (for example new grade definition) or algorithm (different gain) and in both cases if there are not other solutions. Requests may be called Normal if a work around is possible while waiting for the software changes. The severity level is needed by the ASDC staff to plan and implement the changes.

After a preliminary analysis, a confirmation e-mail including either an estimated time for the implementation or a request for additional information will be sent back within 2 working days. The time necessary to implement an SPR or SMR depends on the type of changes requested. These can affect tasks only related to the XRT and/or XRT CALDB files but it is possible that they affect general Swift tasks (such as for example swiftxform) and/or generic FTOOLS (as for example makefilter). For any request involving generic Swift or FTOOLS tasks the ASDC will contact the responsible of that task and will verify the applicability of changes and the time needed to correct the task.

For SPR or SMR strictly related to the XRT tasks and the XRT CALDB files, the goal time to implement a typical (non major) request are:

Urgent SPR: - 3 working days (software change in an XRTDAS task)
- 4 working days (software change in an XRTDAS task + CALDB file changes)
Normal SPR: - 5 working days (software change in an XRTDAS task)
- 6 working days (software change in an XRTDAS task + CALDB file changes)
Urgent SMR: - 5 working days (software change in an XRTDAS task)
- 6 working days (software change in an XRTDAS task + CALDB file changes)
Normal SMR: - 7 working days (software change in an XRTDAS task)
- 8 working days (software change in an XRTDAS task + CALDB file changes)

These times start from the confirmation E-mail or from the availability of the additional information requested by the ASDC and assume a clear understanding of the problem to correct or implement existing tasks.

The ASDC delivers the new XRT software changes to the main Swift CVS repository at GSFC which are made available following the standard software distribution procedure. After launch, it is foreseen to deliver software distributions on a 10-14 days timescale base. During the calibration activities, the ASDC can provide a preliminary patch to the instrument calibration team for Urgent requests if the next normal distribution is more then a week away from the closure of the SPR or SMR.

11. People involved in the calibrations

The task force for the XRT calibration involves directly several people in the different institutions

Brera : S. Campana, A. Moretti, P. Romano, G. Tagliaferri (50%)
Palermo : G. Cusumano, V. Mangano, V. La Parola
LU : A. Beardmore, T. Abbey, O. Godet
PSU : J. Kennea, J. Hill (50%), D. Morris, C. Pagani
ASDC : M. Capalbi, M. Perri, F. Tamburelli

12. Connections

One telecon will be held every week (at least). Every Tuesday 11a.m. US time, 4p.m. UK, 5p.m. Italy. This will serve as a routine channel of communication. More frequent telecons can be planned as needed. At the telecon each WP responsible should report on the status of the calibrations. In case of problems vis-à-vis encounters can be set up. A 'calibration' mailing list is already available: xrtcal@merate.mi.astro.it .

13. XRT Calibration Targets

In the following we will describe in some details the calibration observations to be carried out and listed in Table 1. We refer to Table 1 for the general information (e.g. visibility, priority, etc.). For each target we describe the purpose of the observation, a few details of the selected target (together with an ASM/RXTE light curve). We point out once more that each observation has been listed for one main task but it is useful also for other aspects, e.g. an observation of a source for studying the soft core of the PSF can (and have to) be used to calibrate also the effective area at low energies and the low energy response.

All the observations in the calibration plan have been simulated with the latest response matrices (Build 10) and/or with the ASDC Swift XRT simulator developed by ASDC at http://www.asdc.asi.it .

13.1 Absolute telescope optical axis search

A bright source will be observed at several positions across the focal plane in IMG mode to assess precisely where the optical axis of the telescope is located. A cross along the RA and Dec. of the selected target at 0’, ±1’, ±3’, ±5’, ±7’ and ±10’ off-axis will provide an assessment of the source optical axis. A source providing 5000 counts will make possible the location of the axis with a precision of 0.25” in each axis (90% c.l.).

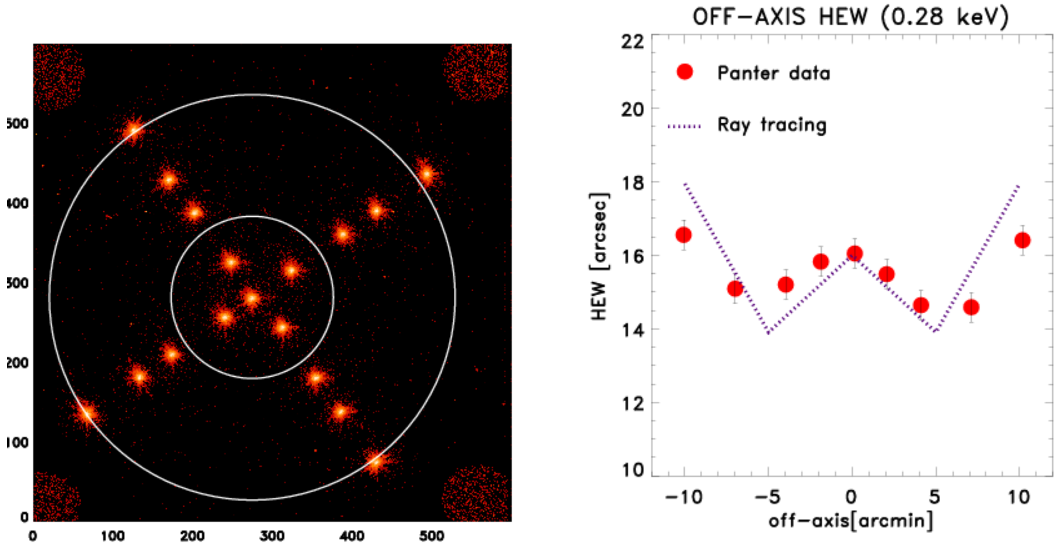


Figure 4: calibration source cross (left) and variation of the HEW with the off-axis

The selected source is Mkn 421, a Bl Lac object. It is a bright variable blazar proving between 20-40 c/s (Figures 4 and 5). Exposures in IM mode lasting 1 ks each are required. A total of 21 ks of net exposure time is requested.

Data will be analyzed using standard packages (XIMAGE, IDL, Q software) to derive positions and HEW values. Fitting of the HEW values along with the off-axis angle will be made through standard software (IDL and QPD).

Data analysis responsible: S. Campana (OAB).

Final product: optical axis location.

CALDB file: telescope file definition & vignetting map

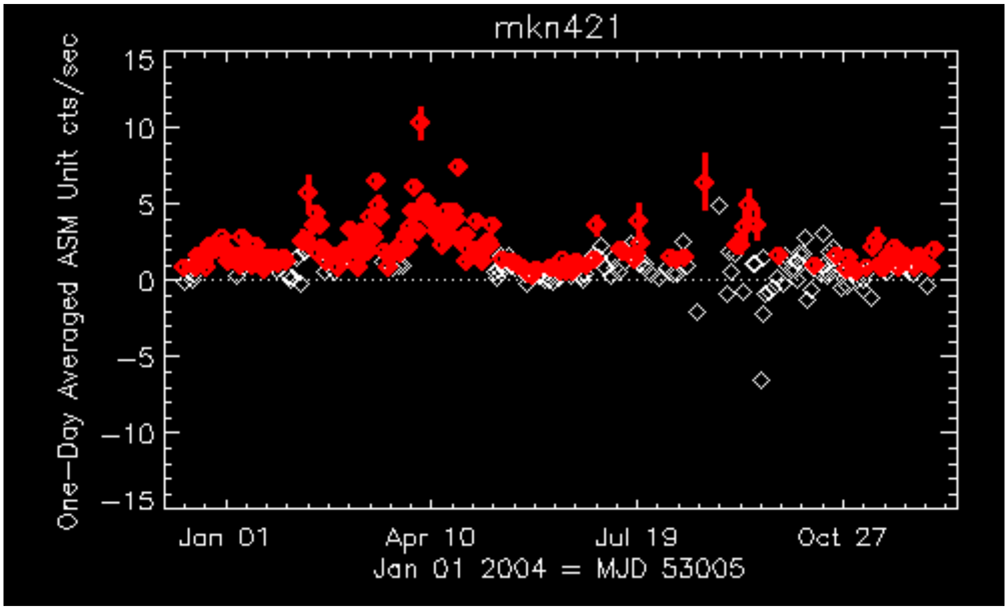


Figure 5: Long term behaviour of Mkn 421 as observed with the RXTE/ASM.

13.2 First Alignment

A first alignment and observation in PC mode will provide an assessment if XRT is performing nominally and will give a 3 sigma alignment accuracy of about 1” between the XRT, UVOT, and the TAM (Telescope Alignment Monitor).

The 1st light target for the XRT will be the cataclysmic variable 1WGA J1958.2-3232 (V2306 Cyg). Based on a BeppoSAX spectrum it will have a count rate of 0.15 c/s (PC) which will yield 3000 XRT counts in a 20 ks observation. The target is a V=16 star in a crowded field with the brightest star at V = 10. The nearest star to V2306 Cyg is at 10”. The source is also pulsating at 1467 s.

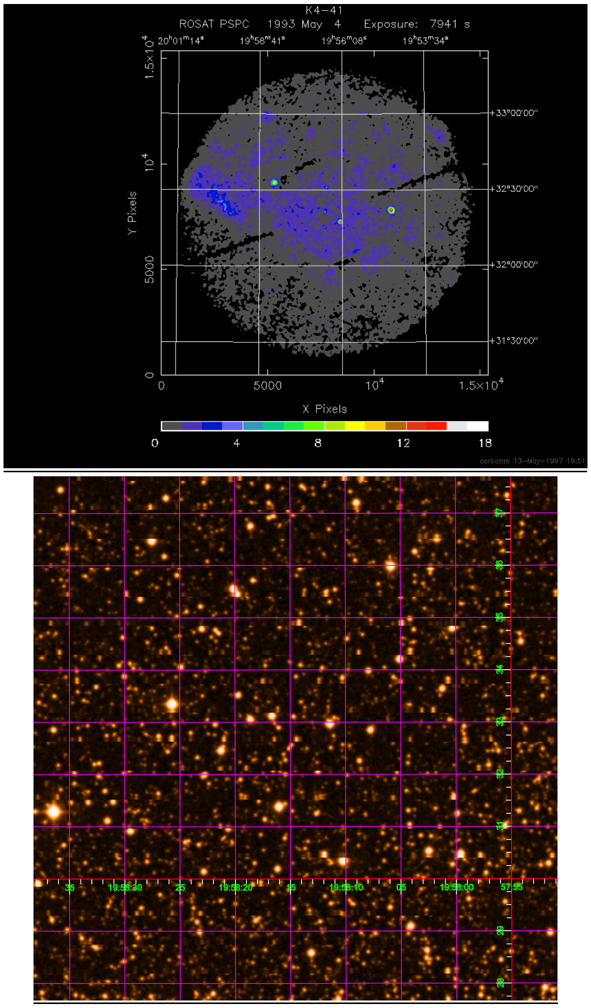


Figure 6: ROSAT PSPC image of 1WGA J1958.2-3232 field. The source is on the left-top part of the image. Below is the DSS image of the field with the source at the center.

Data analysis responsible: A. Moretti (OAB) for XRT.
Final product: first boresight with UVOT and TAM.
CALDB files: telescope file definition.

13.3 Accurate Boresight

A more accurate alignment between XRT and UVOT that will provided coordinate reference, plate scale verification, rotation, and distortion information must involve a field with multiple targets (greater than 10) each providing a good number of counts while it is in PC observation mode. For this more accurate alignment, XRT plans on using the open cluster NGC2516. This source has been used for Chandra (see Figure 7) and XMM-Newton calibrations too. The brightest sources in the field provide ~0.01 c/s. The brightest optical target in this field has a magnitude V=14.0. From the Chandra observation, the necessary XRT exposure on this field for alignment calibration is 50 ks.

Input data were taken from Chandra source catalog (Markevitch personal communication) and an optical (proper motion updated) catalog. In a 50 ks XRT image, 26 sources with more than 20 counts can be detected. Of these 15 are sufficiently isolated to allow a unique optical counterpart search (taking 100 ks we got 51 sources and 25 isolated). Matching the position of these 15 sources we obtain a boresight solution (assuming no distortions) of <1".

Data analysis responsible: A. Moretti (OAB).

Final product: final absolute boresight and with UVOT.

CALDB files: telescope file definition.

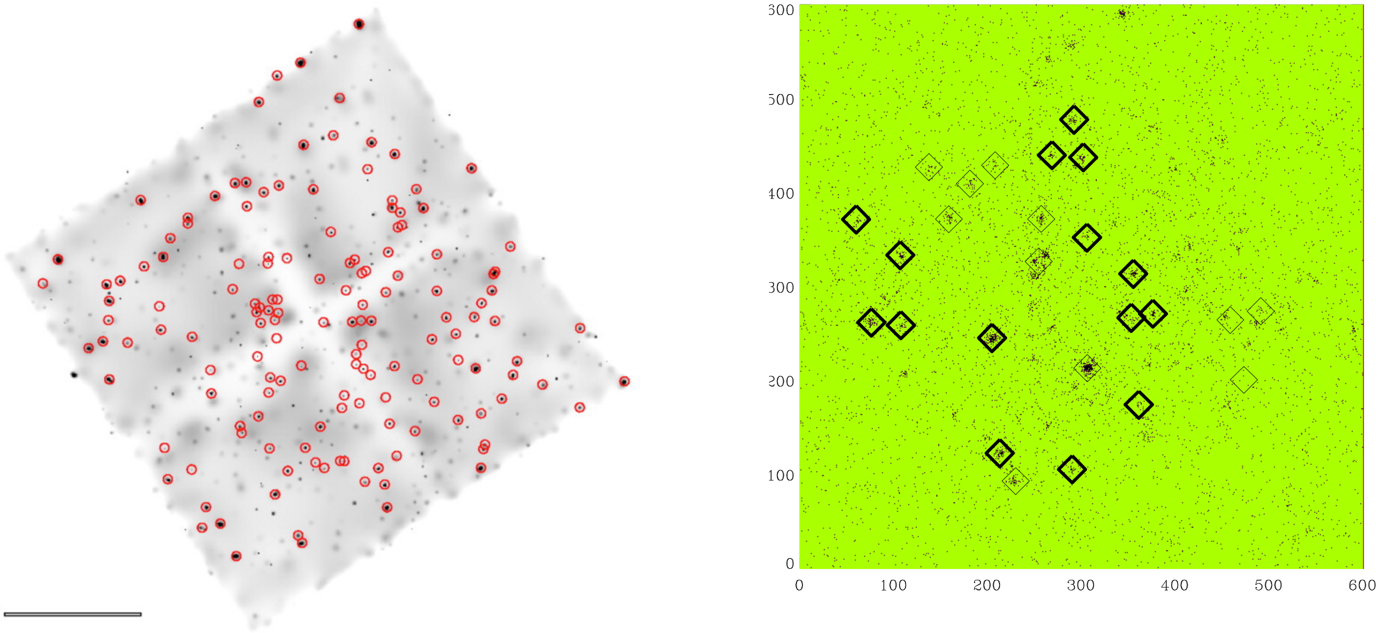


Figure 7: Chandra (left) and simulated Swift (right) images of NGC2516 (bold diamonds are sources used for the boresight, light diamonds source detected).

13.4 Mode Changing

For Gamma-Ray Bursts, XRT will be undergoing mode changes as the source intensity changes. This is done so that XRT can provides its highest quality data on the rapidly dimming X-ray component to the GRB. It is essential that the automatic transition between these modes be tested. For this purpose, XRT requires a target which will vary in flux by more than an order of magnitude over short periods of time.

XRT will use the LMXRB EXO 0748-676 target for this purpose. The target has known dips and eclipses every 3.82 hours (see Figure 8). In addition, it has bright Type

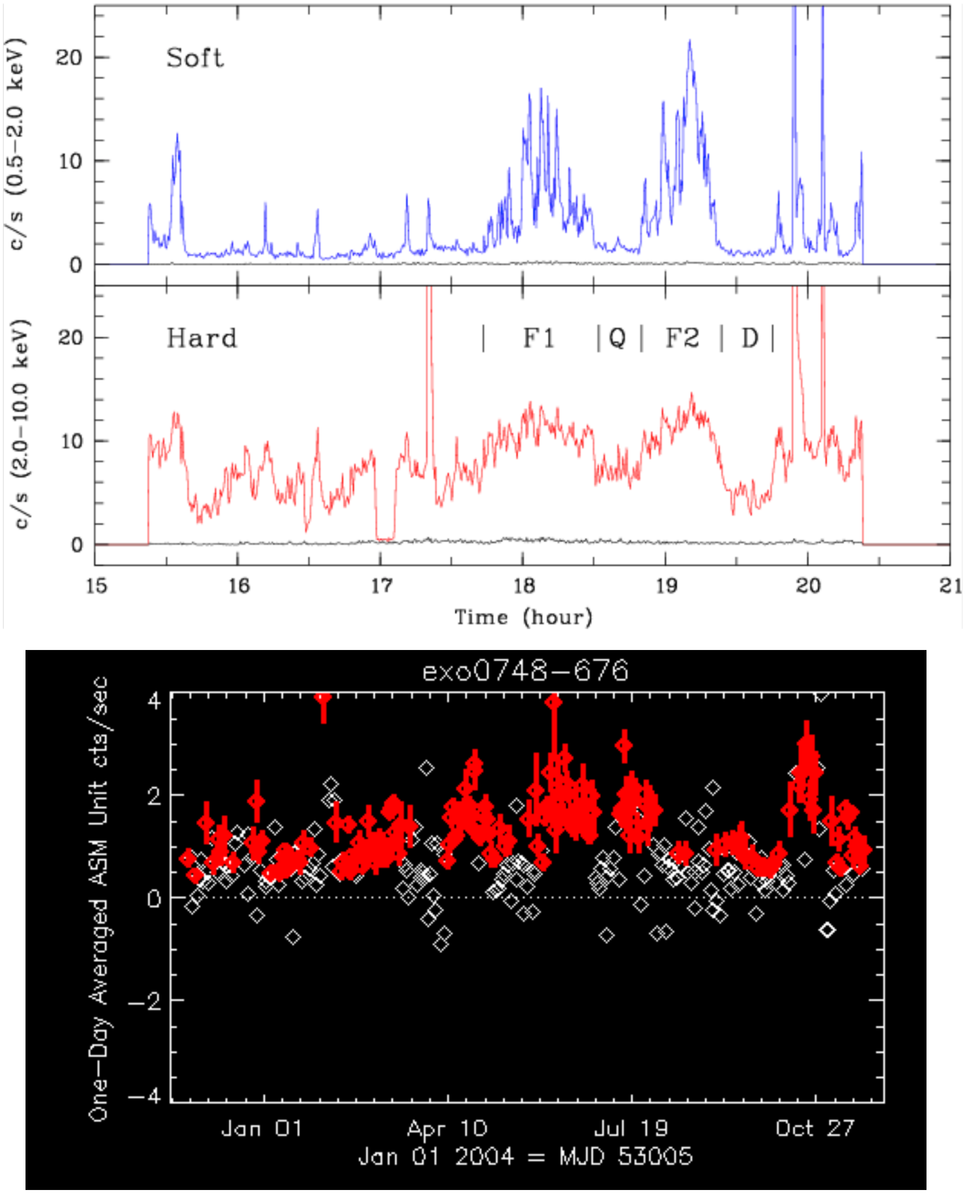


Figure 8: Upper panel shows the XMM-Newton light curve of EXO 0748-676. A scaling to XRT is by about a factor of 10 in the count rate. Lower panel represents the RXTE/ASM light curve.

I X-ray bursts. An observation of 55 ks guarantees a number of large flux transitions (0-20 c/s estimated) to test this mode. Simultaneous observation with RXTE, Chandra, or XMM-Newton are mandatory if one wants to assess the exact timing of the mode changing (i.e. if mode changing occurs the exact frame after the variation or a few frames later).

We are trying to coordinate an observation with XMM-Newton to assess the extact timing of the mode changing over a limited common observing period (55 ks XMM-Newton observation for about 13 ks, i.e. one orbital period, common coverage).

Data analysis responsible: J. Hill (PSU).
Final product: check on mode changes, no product deliverable.
CALDB files: none.

13.5 Point Spread Function

The goal of the PSF calibration is to study the surface brightness profile (SBP) of the point-like sources as function of their spectrum and their position within the instrument FOV. The final product of this calibration will be an analytical model that will be reproduce the SBP of a generic source. This model will be used for the PSF correction in the flux calculations. To this aim we are planning to observe 2 different point-like sources with different spectra (one soft and one hard) at 3 different distances from the telescope optical axis. As already shown during the ground end-to-end calibration the event reconstruction procedure slightly influences the PSF shape. To quantify this effect we recall that, at 1.5 keV we measured an HEW of 17 arcsec in imaging mode (no event reconstruction) and 18 arcsec in photon counting with the standard grade selection; the HEW is even worse when we select only single pixel events. Due to the large number of counts required by the PSF characterization we divided the procedure into two parts: characterization of the inner PSF core as well as that of the outer PSF wings. For the PSF core calibration, relatively low counting rate targets are required to reduce the distortion due to “piled up” events. However, for the wings, a more efficient route is to use a very bright target. Given this, a number of different observations are planned to evaluate the XRT PSF.

13.5.1 PSF Core for Hard X-ray Sources

XRT will use the absorbed Bl Lac Mkn 876 to calibrate the core of the PSF for hard sources. This source has an expected count rate of 0.38 c/s. An on-axis observation of 30 ks will provide 11400 counts of which 40% are above 2 keV (see Figures 9, 10 and 11). Other off-axis observations will be carried out at 3’, 7’ and 10’ for 35, 40 and 45 ks each. Multiple snapshots of this target will be required. The success of the calibration relies on the registration of these snapshots- which depends on the careful alignment calibrations

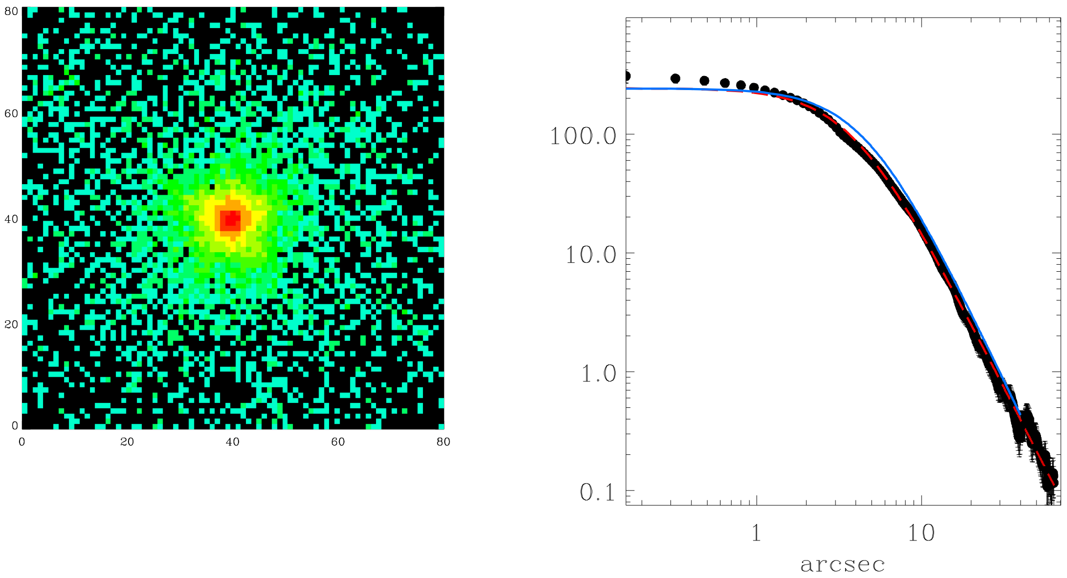


Figure 9: simulated 30 ks image of Mkn 876 image on-axis (left). Point spread function of the simulated image in the full energy range (0.3-10 keV) with the ground XRT model over-plotted (red) and the XMM-Newton PSF model (blue). A method of sub-pixelization similar to XMM-Newton has been adopted (right panel).

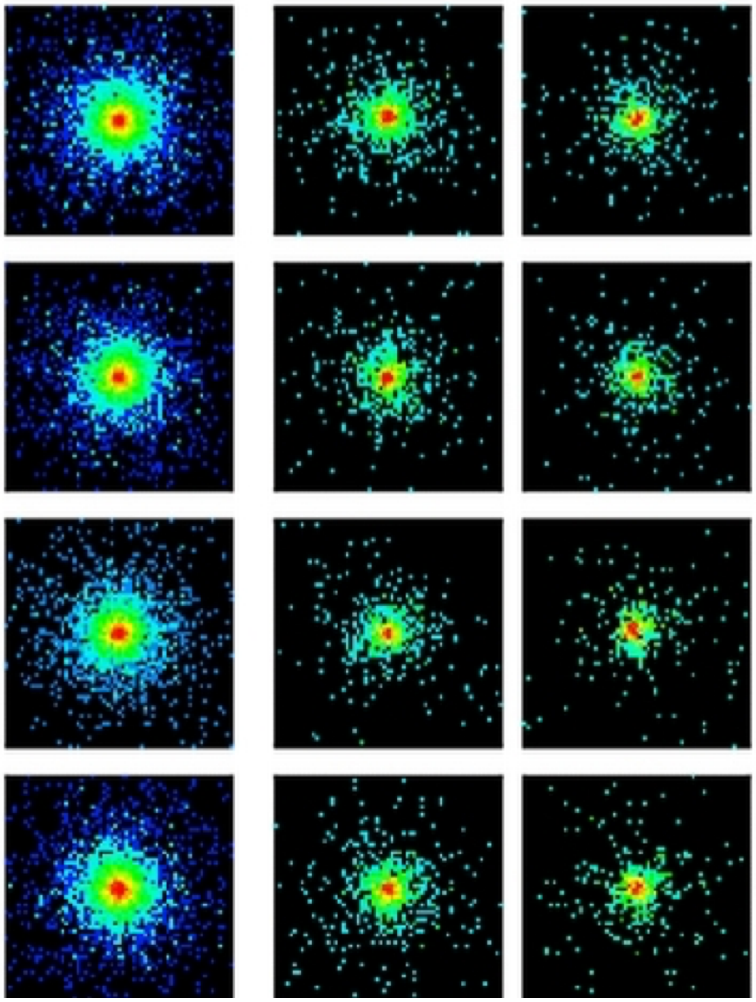


Figure 10: XRT simulated image of Mkn 876 with 30 ks each at different off-axis angles (vertical direction: 0’, 3’, 7’ and 10’) and in different energies band 0.5-2 keV, 2-4 keV and 4-10 keV (horizontal direction).

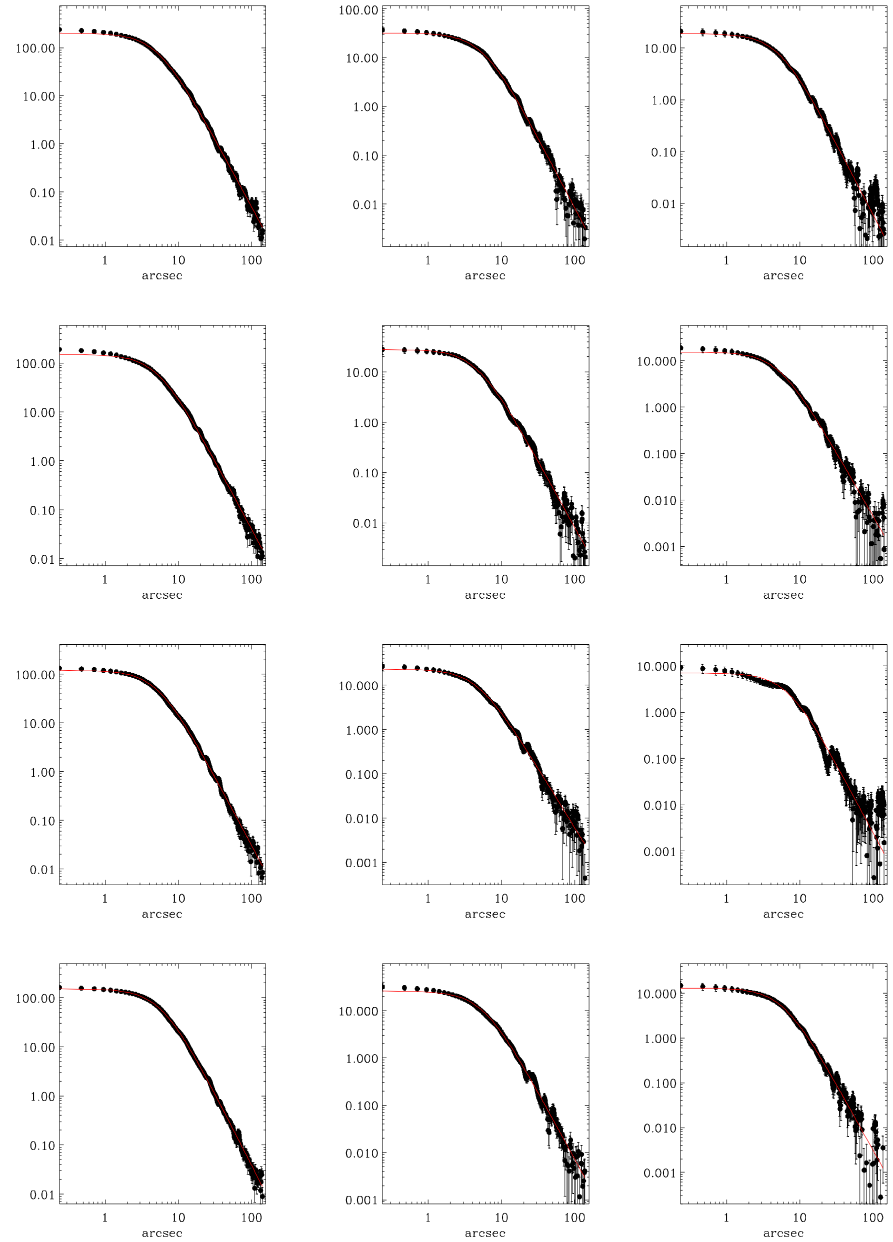


Figure 11: XRT modeled PSF, arranged as Figure 10, with fitted PSF profiles overlaid in red.

13.5.2 PSF Wings for Hard Sources

PSF wing characterization is important since for particularly bright x-ray emission from GRBs, the wings of the PSF may be the only good indicator of the GRB position. Again, this is dependent on the X-ray spectrum. To calibrate the hard wings of the XRT PSF, we will use the galactic binary source GX 1+4 at 3 positions (on axis, 3’ and 7’ off axis). The source is bright enough (5 c/s) so that we can get ~30,000 counts for the wings in a total exposure of 20 ks (for 3 observations).

A complication of this target is that we need to force XRT to stay in “PC” mode. This requires a deactivation of the automatic mode changing used in normal XRT observations.

In addition, the source has a spin period 138.7 seconds (see Figure 12) that could be used for timing calibration. This pulsation is present at a low level also in the optical when the source is brighter than R<15.5 with an amplitude of 4%.

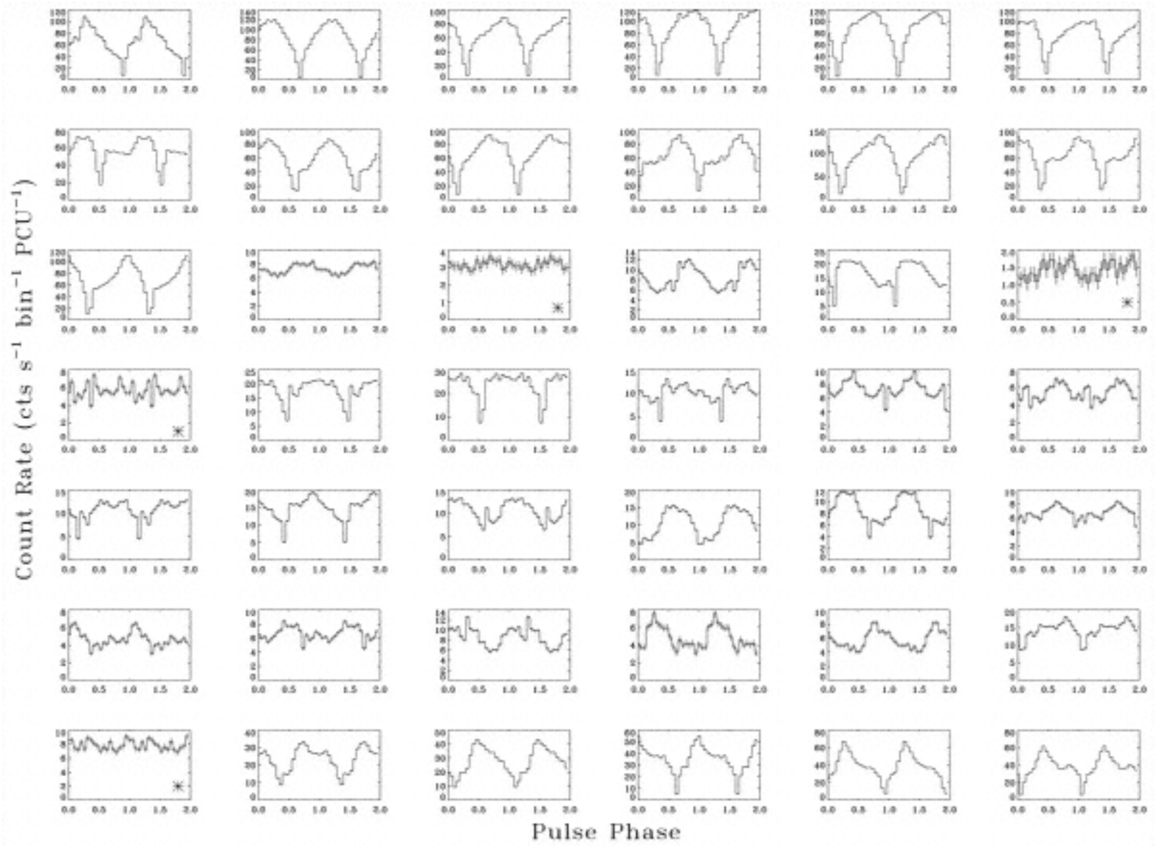


Figure 12: RXTE pulse profiles as a function of the count rate in GX 1+4.

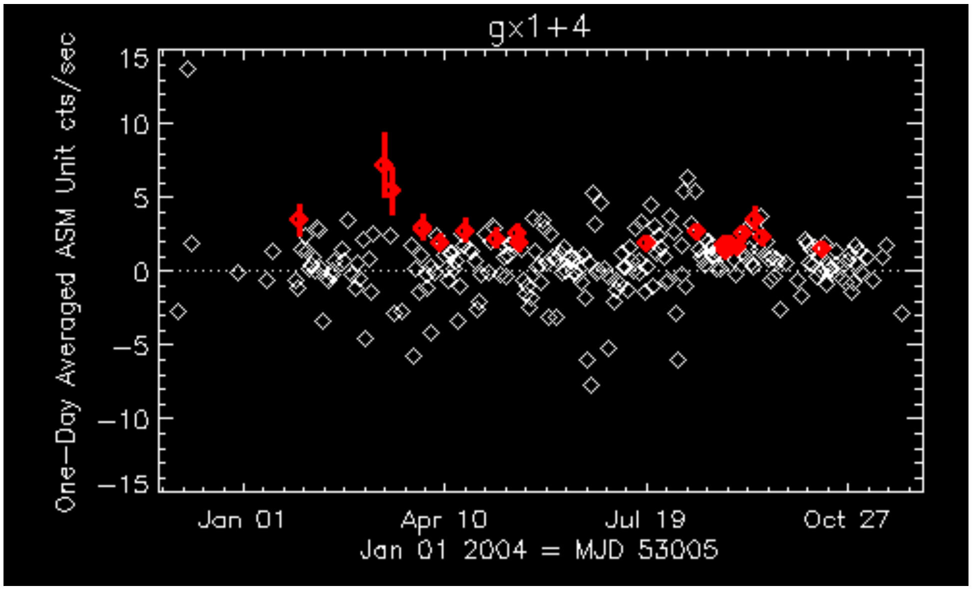


Figure 13: long term light curve of GX 1+4 as observed with RXTE/ASM.

13.5.3 PSF Core for Soft Sources

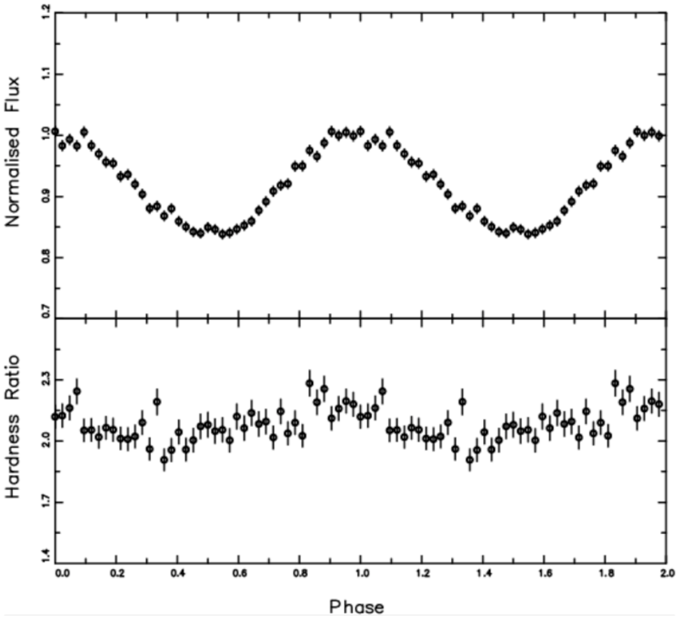
The PSF core for soft X-ray sources will be calibrated by looking at the isolated Neutron Star RXJ0720.4-3125. This target has an estimated XRT count rate of 0.16 c/s and is bright enough that it could be used for on-axis PSF calibration as well as calibration at 3 offset positions (3', 7' and 10' off-axis). The last one has a lower priority. A total 30, 40, 45 and 45 ks is requested for the four observations, providing ~5000 counts each. RXJ0720.4-3125 has been recognized to have an (unexplained) slowly variable spectrum. This is likely not a problem since spectral variations were recognized over a several-years interval. Moreover, to compare the XRT spectrum we can rely on an XMM-Newton observation of this target in July 2004. Eventually, if we will encounter problems we will ask for a coordinated Swift/XMM-Newton observation, being the source periodically monitored by XMM-Newton.

In addition, RXJ0720.4-3125 is coherently varying its flux with a period of ~8.37 second (see Figure 14). This can be used to test the XRT timing capability in PC mode.

<u>Data analysis responsible</u>: A. Moretti (Brera).

<u>Final product</u>: obtain (and confirm) analytical model for PSF and EFF at different energies.

<u>CALDB files</u>: PSF and EEF files, vignetting map.



13.5.4 PSF Wings for Soft Sources

To calibrate the PSF wings for soft sources, XRT will use the anomalous pulsar RXSJ1708-4009. It has an expected count rate of 7.2 c/s. Multiple pointings with a total integration time of 20 ks will provide the necessary number of counts to characterize the soft wings. As with the hard wing source, a complication of this target is that we need to force XRT to stay in PC mode. This requires a deactivation of the automatic mode changing used in normal XRT observations. In addition, the source has some variable period 11.0 seconds (see Figure 15) that could be used for timing calibration.

Figure 14: XMM-Newton light curve of RXJ0720.4-3125 as a function of the spin period.

Final product: analytical model for the PSF and the EEF as well as the vignetting function.

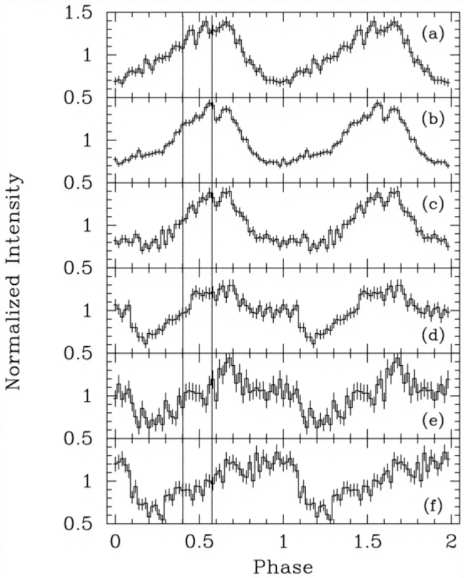


Figure 15: light curves for RXS1708-4009 in the following bands: a) 0.1-2 keV, b) 2-3 keV, c) 3-4 keV, d) 4-5 keV, e) 5-6 keV, f) 6-10 keV as a function of the spin period phase.

13.6 Centroiding

The centroiding of a GRB position is the first and most important thing XRT will do after Swift swings to a new GRB. This is done in an imaging mode and the quality of the reported position will depend on the source brightness, spectrum, as well as how accurately the BAT position is translated into a position within the XRT FOV.

To fully characterize the XRT centroiding capability, XRT will require multiple sources with a wide range of fluxes. Also, a wide range of offset positions must be evaluated both horizontally and vertically from on axis to ±3’ and ±7’ off axis in RA and Dec. directions. Each individual observation will consist of 100 exposure of 2.5 s each.

For this calibration, XRT will use the following targets:

Source	**Exposure time (multiple pointings) [ksec]**	**On-axis Count rate (c/s)**
4U 0142+63	9	3.7
GX 1+4	9	7.4
Cir X-1	9	480
Cyg X-1	9	31
Sco X-1	9	12000
Her X-1	9	8

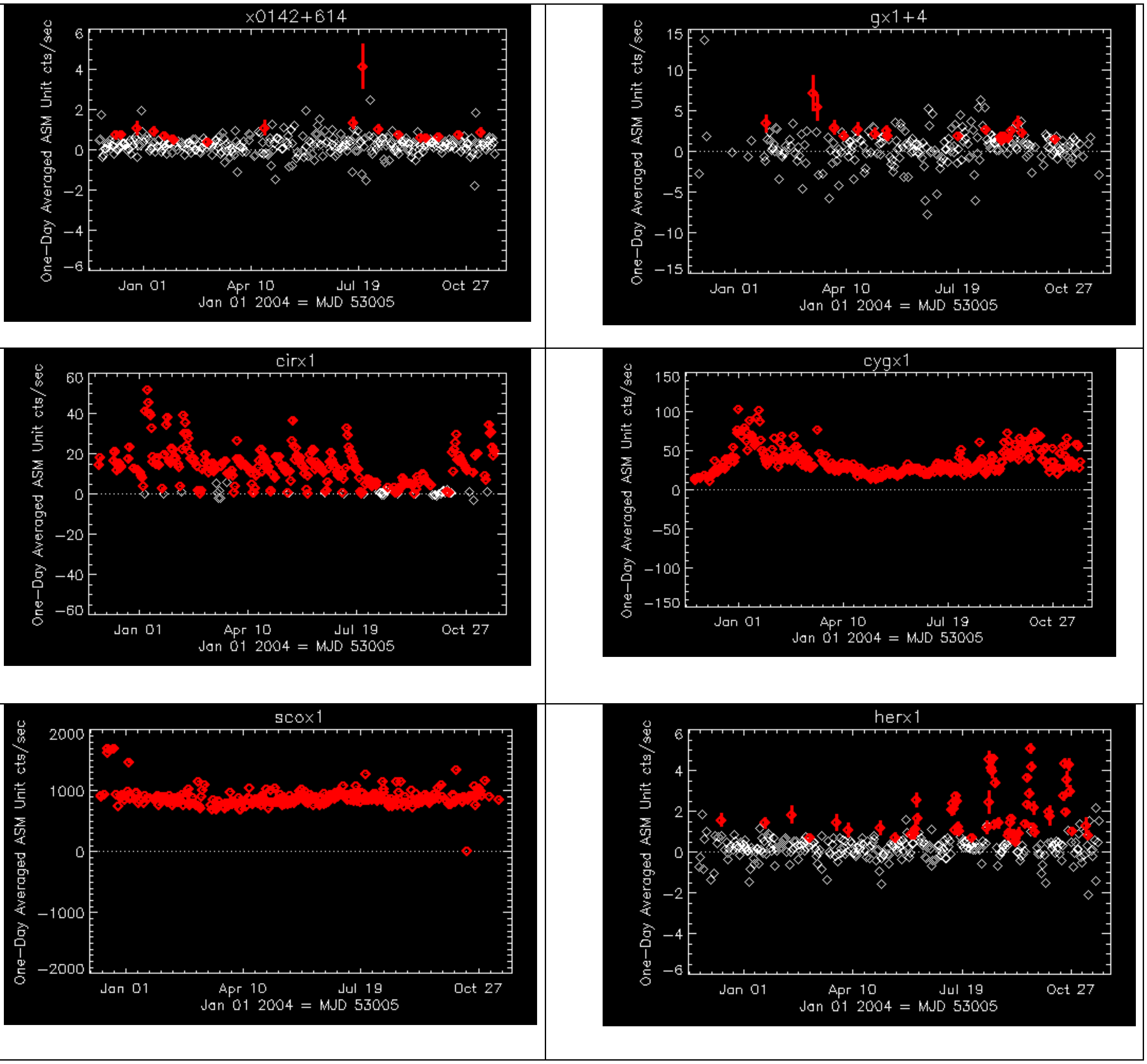


Figure 16: RXTE/ASM long term light curves of centroiding sources.

<u>Data analysis responsible</u>: J. Hill (PSU).

<u>Final product</u>: table with mean positional error (1σ) in the source position at different off-axis angles and for different input spectra as a function of the source count rate.

<u>CALDB files</u>: none.

13.7 Effective Area

Effective area knowledge is critical to assessing the presence of emission/absorption lines or slope changes in the power law emission of the afterglow as well as to converting an XRT count rate to physical units. Ideally, it requires building a matrix for every observing mode and for every grade selection chosen. This will require a huge number of photons. At variance with other items (e.g. PSF), effective area is poorly known from ground calibrations. At the Panter facility we checked the total effective area at 5 energies in all three modes (in imaging mode we do not have a affective area). Carbon emission line (0.3 keV) data were too poor to derive firm conclusions due to CCD noise. Data at 6.4 and 8.1 keV gave problems in terms of pile-up, loosing part of the counts without having knowledge (since the first pile-up peak is just outside the energy range). In any case, the derived values (with large errors in some cases) are all below the theoretical effective area (based on a combination of the mirror reflectivity, filter transmission and CCD quantum efficiency for photons of a given grade) and with a variable loss increasing with photon energy. This effective area roll over is particularly important and have to be carefully calibrated if we want to derive accurate spectral slopes. To address these concerns, XRT will observe three celestial sources.

13.7.1 E0102-7217

E0102-7217 is a supernova remnant (SNR) in the LMC with approximately 1' diameter. It is a stable source with low energy lines (< 1 keV) with a total flux of about 3.8 c/s on axis for XRT. This object will be observed in PC mode and WT mode on a 3x3 grid across the XRT FOV (0', 3', 6') for a total of 155 ks. Its higher energy emission lines (~1 keV) should be immune to changes in the gate structure thickness and variations in ice buildup. Comparing this flux for the various positions will yield the vignetting map. The ratio of line emission at 0.5 keV to the higher energy lines is a well known quantity from other missions (e.g. Chandra, XMM-Newton) and can be used to verify the XRT CCD detector model and check to see if ice has accumulated on its cold surfaces. In fact, there will be regular observations of this target to look for changes in this ratio to detect ice buildup or sublimation.

The same observations (155 ks) will be carried out in WT mode. Finally one single observation 15 ks long will be carried out in LRPD mode to compare the spectra of the same source into the three different observing modes.

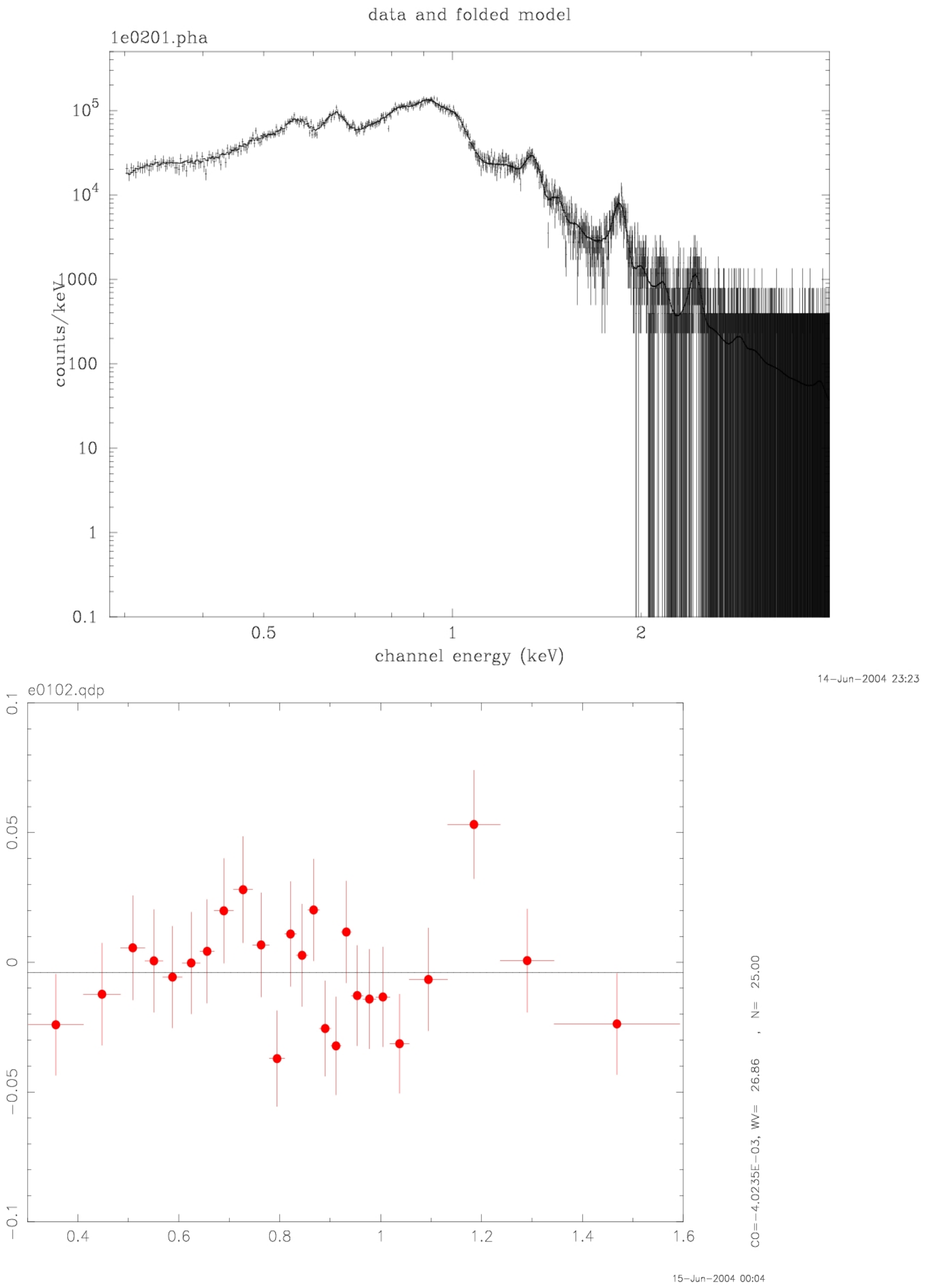


Figure 17: Simulated spectrum of E0102 on-axis for 10 ks. The spectrum can be tracked up to 2 keV. In the panel below we show that an accuracy of 3% can be achieved.

13.7.2 Crab

The Crab is a standard X-ray calibration source with a well known flux and spectral shape. It is also a bright object (787 c/s on axis) that will require LRPD mode for measurements. Approximately 11 ks of observations over a 3x1 grid will give us additional information on the vignetting map as well as the efficiency of photodiode mode. These observations are the primary calibrator for the LRPD mode. These will provide first the effective area as well as the photon reconstructed light curve, given as input the source position. Testing this reconstruction will be possible searching for the pulsed signal at ~33 ms. Since in the Crab spectrum there are no lines, we expect to experiment the goodness of the background subtraction and in particular of the calibration sources which are present in the data. Observing at 3’ and 7’ off-axis we will probe our vignetting and arf generator.

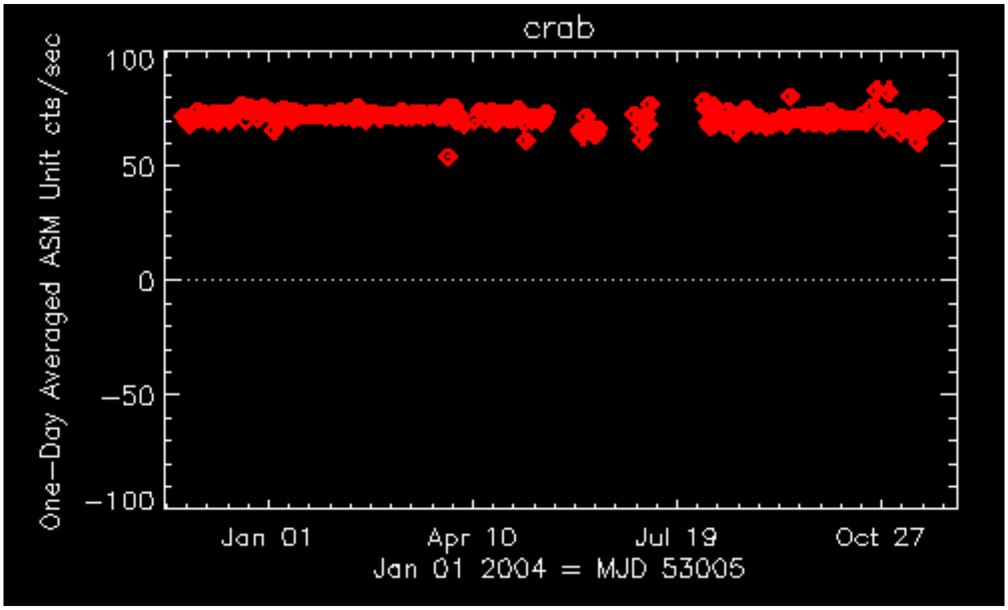


Figure 18: RXTE/ASM long term light curve of the Crab.

13.7.3 Cas-A

Cas-A is another SNR. It is about 7’ wide (diameter). Since it is also ‘nice’, it has been selected for the first (press-release) light image. It is highly absorbed and has several high energy lines (see figure below). It is a bright (21 c/s) but diffuse object. XRT will make a 3x3 raster scan of this object for a total of 150 ks in both PC and WT mode (each). It will provide efficiency information at the higher energies.

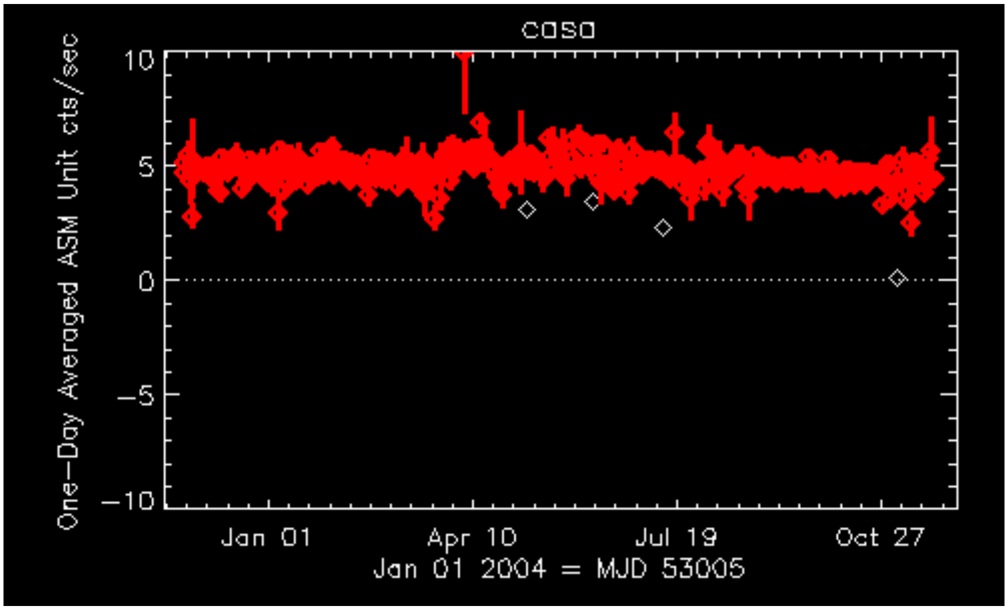


Figure 19: RXTE/ASM long term light curve of Cas A SNR.

13.7.4 Featureless power law spectra

SNR will provide very good spectra with a large number of counts, which are inaccessible to any point-like source. Despite this, point-like sources with smooth (possibly simple power law and with low absorption) are extremely useful in providing the final check for response matrices. To this aim we will observe three AGN/Bl Lac known to have featureless spectra (even if they are variable). In PC we will observe PKS 0537-441. This source will provide a 0.45 c/s and will be observed for 100 ks (this is a multi-purpose source, see below). In WT we will observe Mkn 421, yielding a count rate in the 20-40 c/s range (depending on its state) for 8 ks, and 3C 273 with 13 c/s for 13 ks. Finally, for LRPD the Crab will suffice.

Data analysis responsible: S. Campana (OAB).

Final product: effective area for all the modes and at least standard grades. Input for the xrtgenarf program.

CALDB files: response matrix, ancillary response

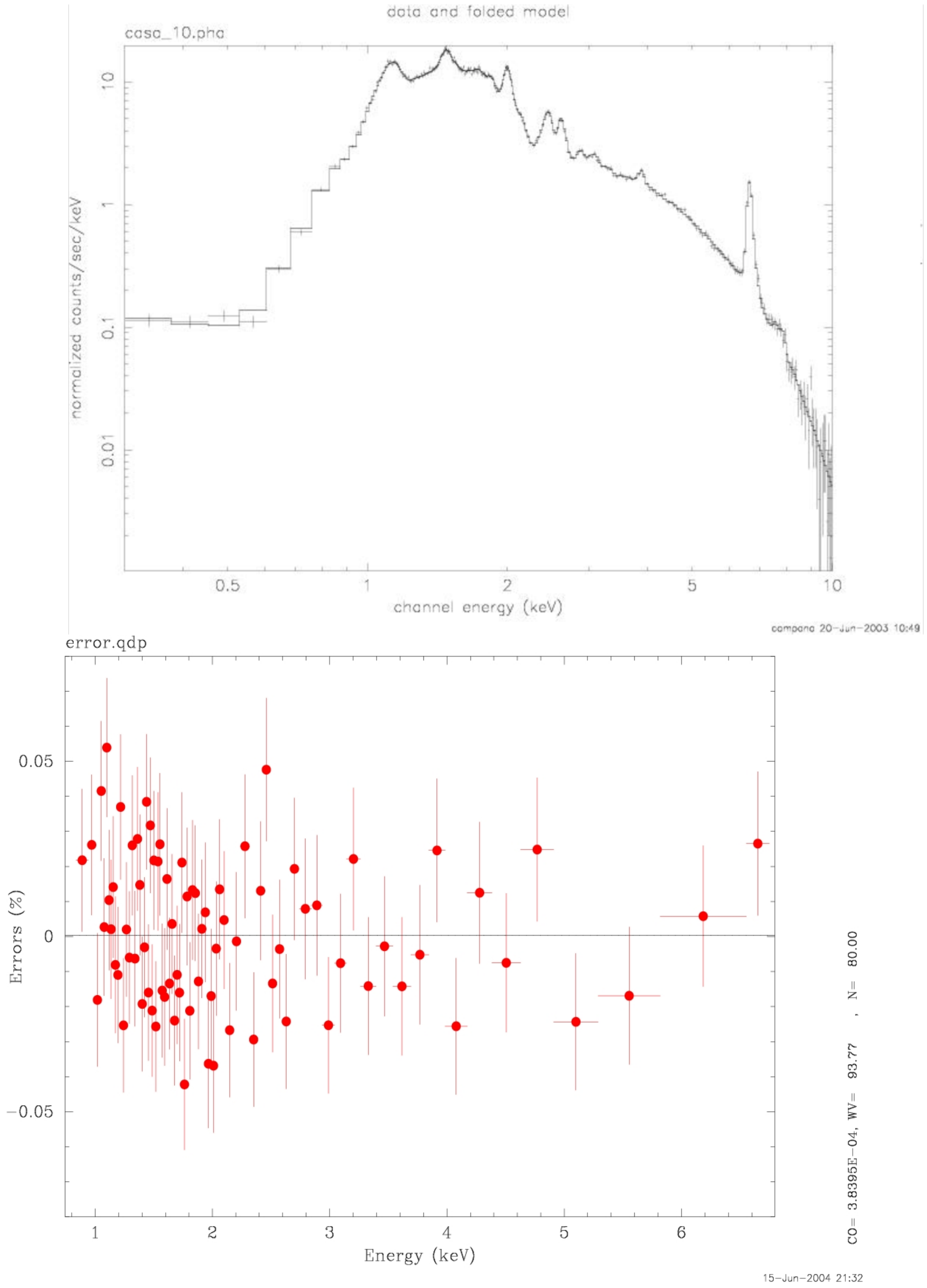


Figure 20: Swift observation of Cas-A. The spectrum can be tracked with a 3% precision at to about 7 keV.

13.8 Spectral Resolution and Gain

The energy gain of the XRT instrument plays a critical role in the overall Swift Mission. The correct gain calibration will lead to a proper redshift determination if X-ray spectral features are found in GRB afterglows. In addition, the spectral resolution of XRT plays a key role in determining if spectral features in GRBs are broadened, providing relevant information about the environment of GRBs. While the onboard Fe55 source will provide gain and spectral resolution data around 6 keV at the edge of the FOV, XRT will require gain measurement near the center of the FOV where most GRBs will be automatically positioned (even if ground experiment showed that gain does not depend very much on position). Also, it will be important to verify the gain linearity - so multiple energies need to be checked. In addition, the gain and spectral resolution will depend on instrument mode and perhaps count rate - so a number of different sources that force different XRT operation modes will be required. Gain and spectral resolution will probably be the first attributes to degrade as a result of radiation damage - so repeated observations - not only within the calibration phase of the Swift mission, but also through out the mission life, will be needed.

13.8.1 Gain

Gain will be calibrated primarily with Fe55 lines. Observations of several targets can help the gain calibration, in primis long observations of the line rich SNR E0102 and Cas A. In any case we foresee to observe one point-like line rich object to study different line energies and monitor the gain evolution across the mission. We selected the same target in all the three modes. AB Dor is a bright emitting star with a number of emission lines (as testified by grating observations). At least 6 emission line can clearly be detected also in the quiescent emission and the source is detectable up to 10 keV. Simulations show that we can locate these 6 emission lines (0.65-3.13 keV) with a precision better than 2% (90% c.l.). AB Dor has an average count rate of 3.9 c/s in XRT. In PC this source will be severely piled-up, but we plan to carry out the analysis in a circular corona around the piled-up core. In PC we plan to observe AB Dor for 40 ks (since we discard a sizable number of photons), in WT and LRPD for 20 ks. In addition, AB Dor often flares, which can allow us to test again the automatic mode changing in XRT.

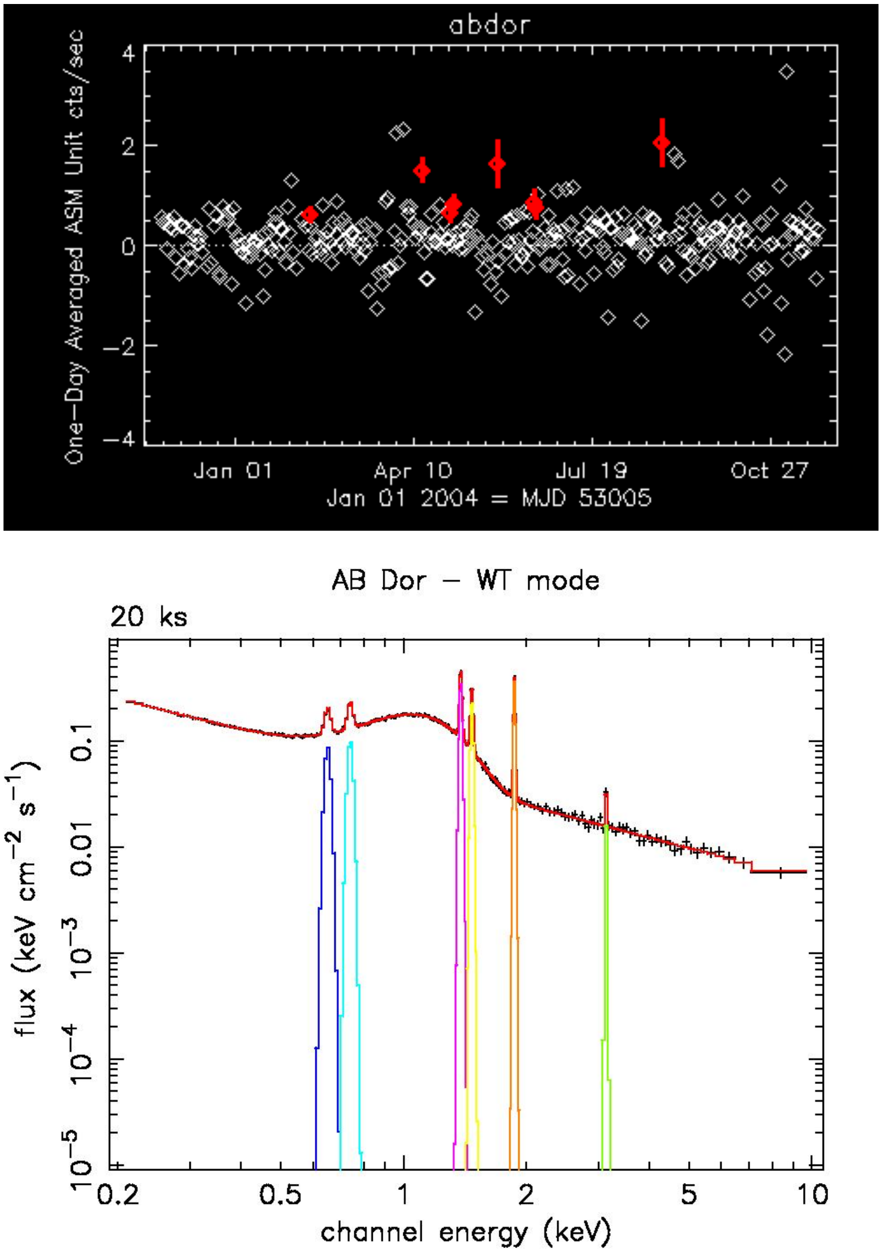


Figure 21: Long term behavior of AB Dor as observed with the RXTE/ASM (upper panel). Swift simulated spectrum of AB Dor.(lower panel).

The gain can also be calibrated with a 30 ks PC observation of the (slightly extended) AGN PKS 0745-19. This source shows two iron emission lines at 6.70 and 6.93 keV and which can be located to a precision better than 1% (90% c.l.).

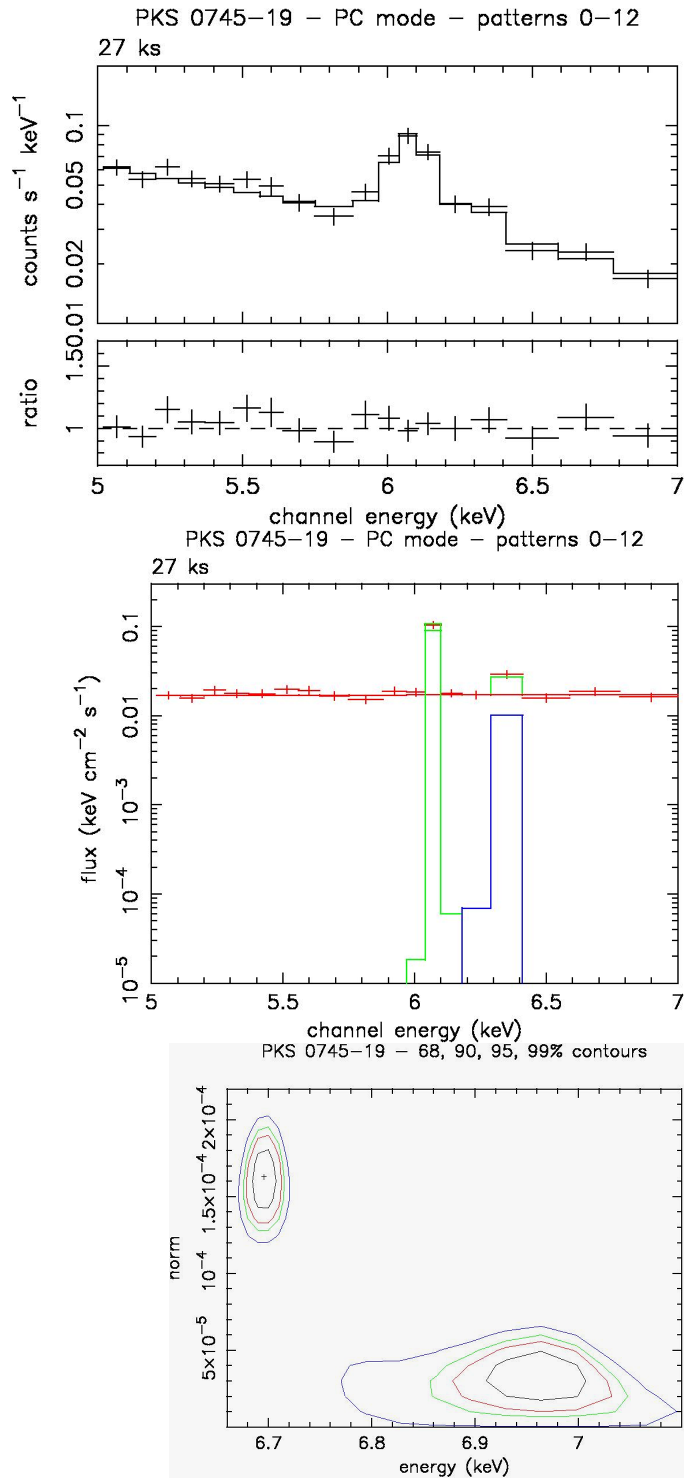


Figure 22: Upper: simulated Swift spectrum of PKS 0745-19 around the iron line complex. Medium: unfolded spectrum in the iron region. Lower: contour plot ot the normalization and line energy for the two mission lines.

<u>Data analysis responsible</u>: A. Beardmore (LU).

Final product: gain coefficients of the relation that describes the conversion from PHA to Pulse Invariant. There is one file for each of the operating XRT data mode (Photon counting, Windowed Timing, Photodiode) and the information is time dependent. Generate a map if needed.

13.8.2 Low-Energy Shelf

Ground calibration at Panter facility showed problems in the low energy spectral response. Below there is a plot of the response to the 1.5 keV Al line in PD mode, showing a shelf below 0.5 keV, which is unmodelled by the response matrix. This is not a serious problem since the shelf is at 0.1% of the line peak. In any case we want to test the low energy shelf in all the observing modes. We will use the 30 ks observation on AGN PKS 0745-19 (taking advantage of the gain observation). The source is absorbed at 5x10^{21} cm^{-2}.

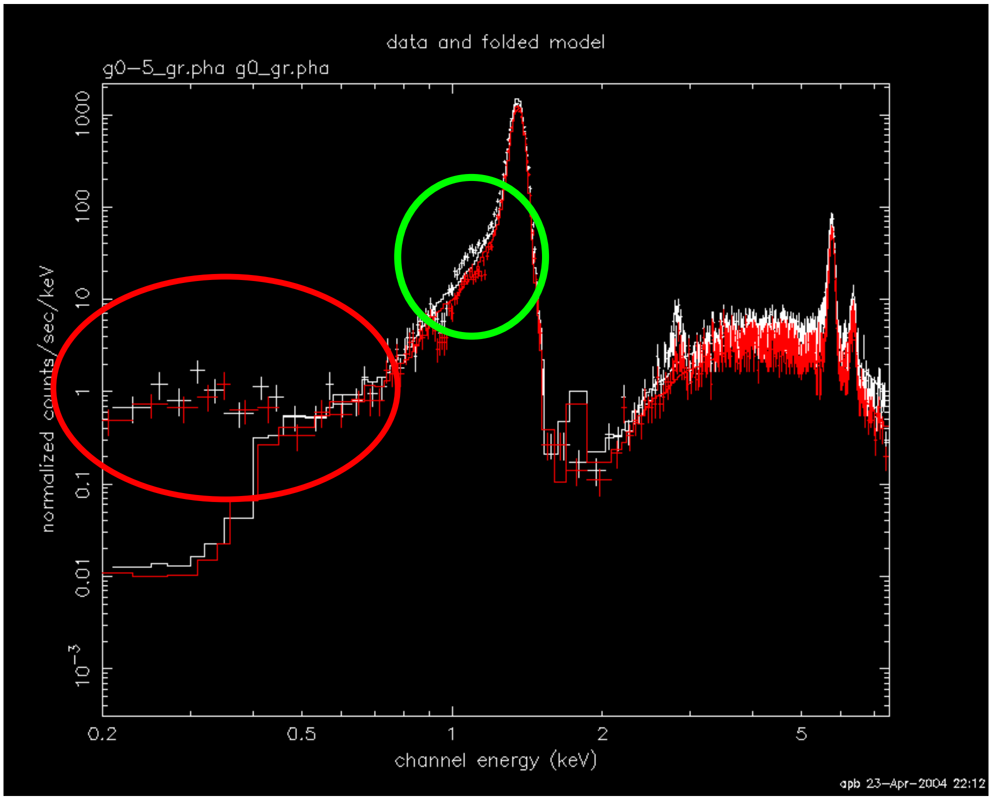


Figure 23: Aluminum K-alpha line (1.49 keV) as observed in LRPD mode at the Panter facility. The response circled in red is higly deviating from the model.

As observations in WT and LRPD modes we selected Cyg X-3 (N_H=8x10^{22} cm^{-2}) and GX 17+2 (N_H=2.2x10^{22} cm^{-2}). These are two highly absorbed and variable X-ray binaries. The expected count rate are 10 c/s and 276 c/s, respectively. We require for each of these targets a 5 ks exposure.

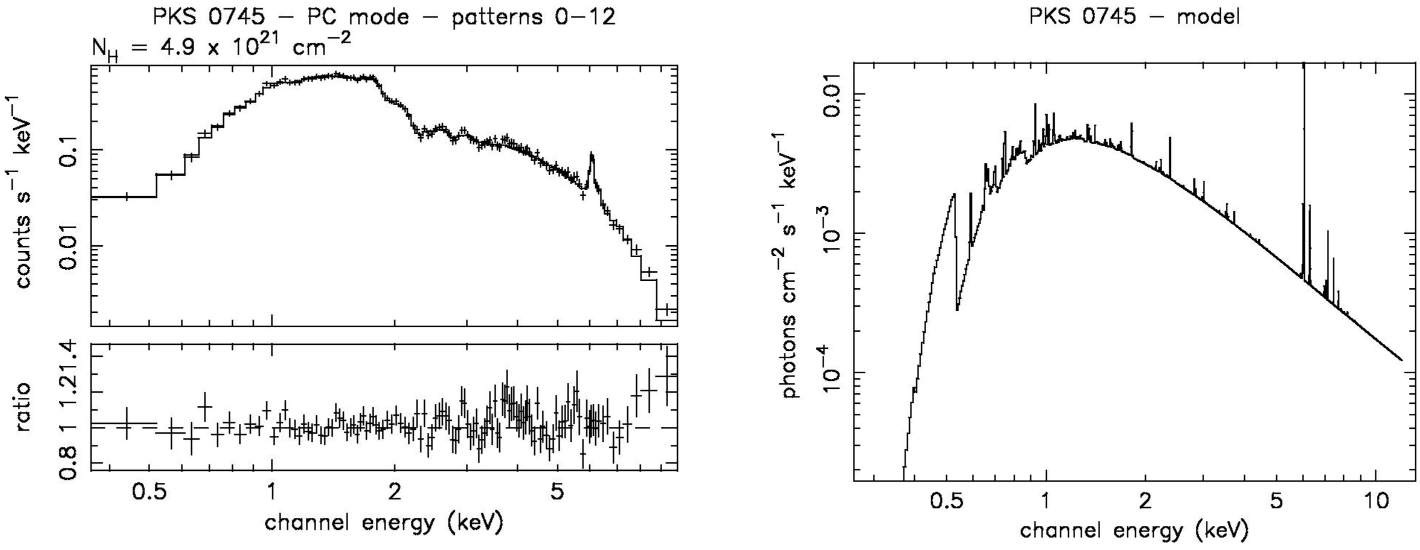


Figure 24: simulated spectrum of PKS0745 showing the low energy response.

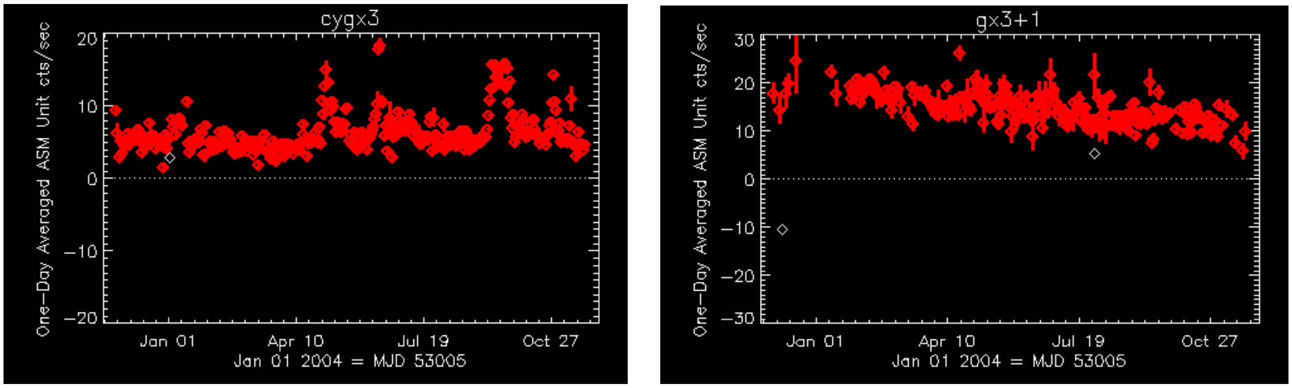


Figure 25: RXTE/ASM light curve of Cyg X-3 and GX 3+1

Data analysis responsible: A. Beardmore (LU).
Final product: This is part of the RMF matrix (other parts will follow).
CALDB files: response matrices, detector gain

13.8.3 Low-energy Response

XMM-Newton MOS have shown a variable response at low energies, especially below the Oxygen edge. It is well known in fact that the energy response below this energy changes with time. We monitor these changes which are important for the study of the low energy emission/absorption of GRBs, we have to monitor the response with a stable source. Isolated neutron stars are by far the best targets. RX J0720 is one of them, however XMM-Newton has shown a slowly variable spectrum. We will keep observing this source (together with XMM-Newton), in fact it is used to verify the soft PSF core in PC. In addition, we require an observation of a brighter isolated neutron star RX J1856.5-3754. This has a 63 eV black body spectrum and gives 0.64 c/s. We require a 5 ks exposure and we will be observed throughout the mission to check on any change in the low energy redistribution.

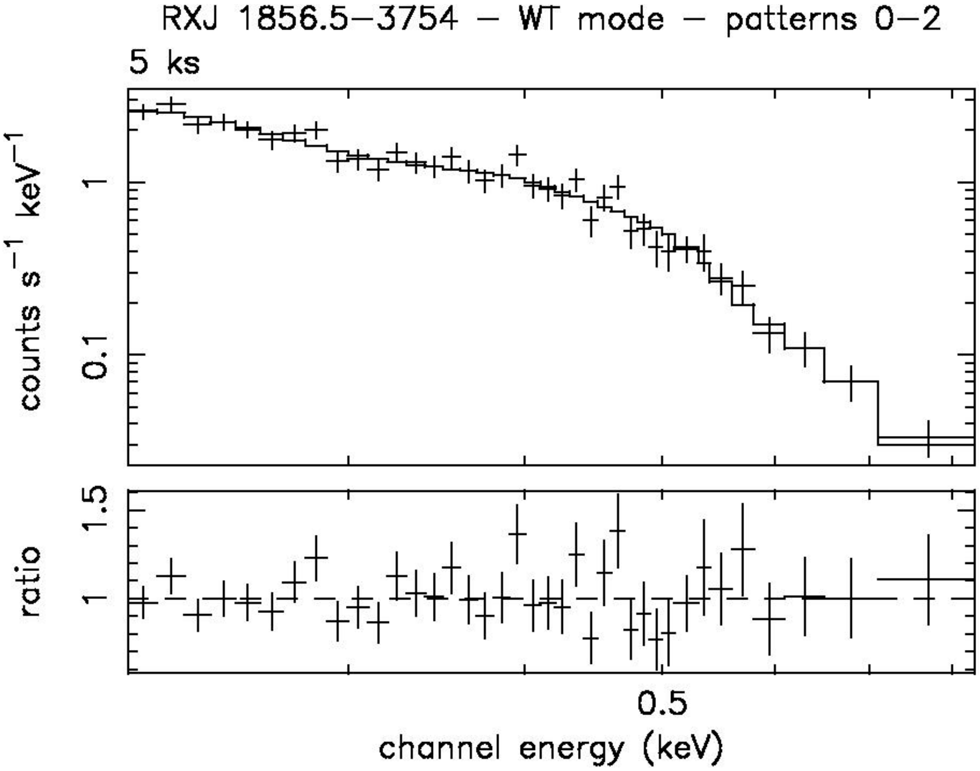


Figure 26: simulated XRT spectrum of RXJ 1856.5-3754.

At extremely low energies (E < 0.5 keV), the RMF depends also from the source position. The plot (Figure 27) below shows how the measured C K line energy varies with position. GRBs will fall where the RMF is constant (centre of field of view), so calibrating off-axis RMF is not a high priority. A hot white dwarf can be used to calibrate this variation.

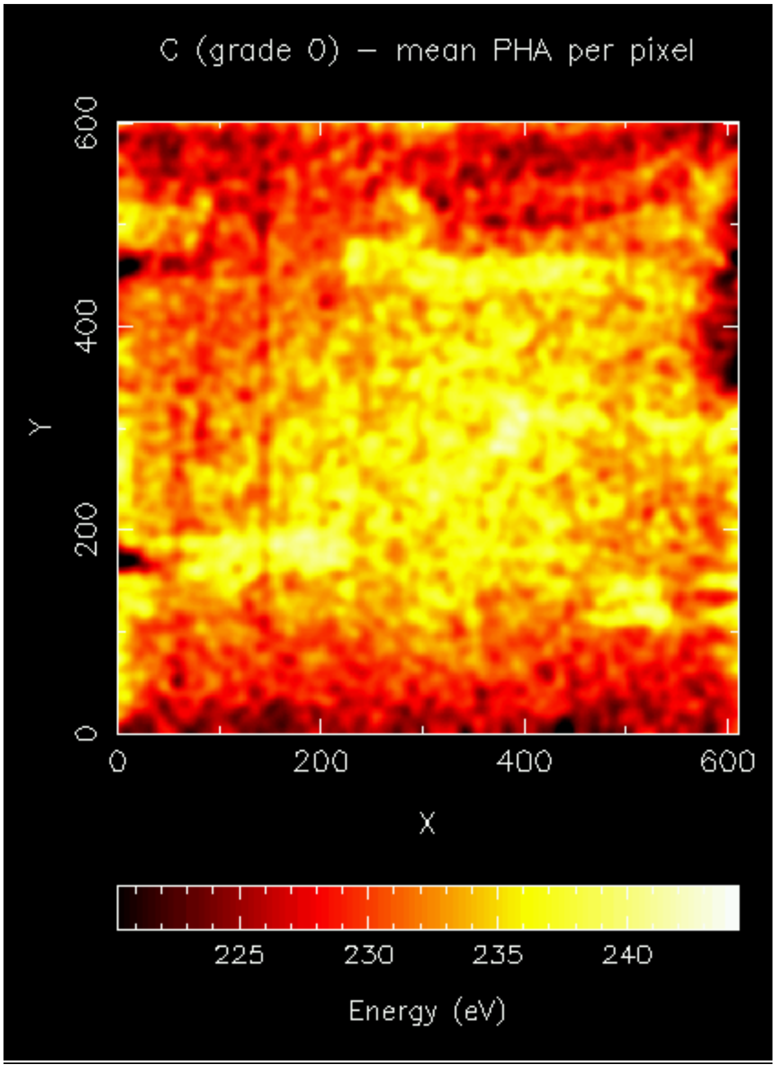


Figure 27: CCD response to single pixel events at C K line. Line energy varies by about ±5% across the field of view.

We do not foresee to calibrate for this effect at this stage.

Data analysis responsible: A. Beardmore (LU).
Final product: This is part of the RMF matrix (other parts will follow).
CALDB files: response matrices

13.8.4 Line Shoulder

Line shoulders usually appears on the low energy wing of emission lines due to charge splitting within the CCD. Modelling line shoulders is important since these are usually strong and have a direct impact of the line residuals. This can be easily visible in Figure 23 above (green circle) where differences between the line model and the observed line at Panter in the region around 1 keV are clearly apparent. To study in details line shoulders one should achieve a 10% accuracy in the line shape of an emission line. This is usually difficult. A co-added observation of the iron Kalpha line in Cas A for a total exposure time of 150 ks will reach the required sensitivity both in PC and WT modes.

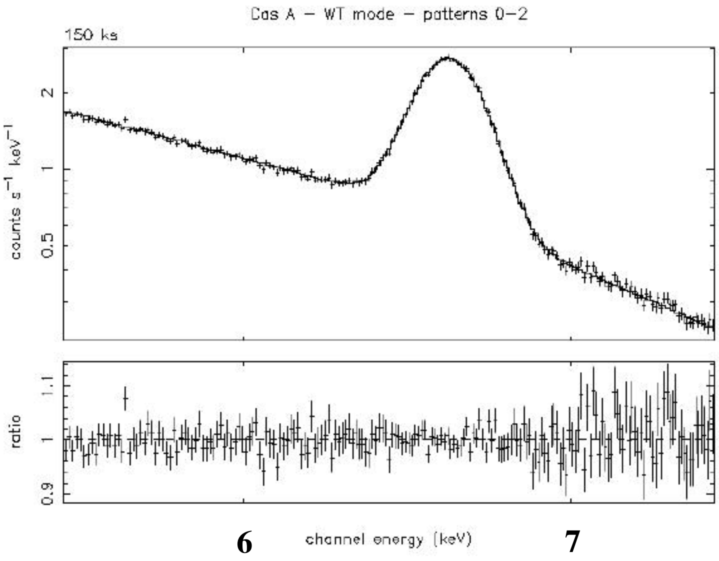


Figure 28: Cas A line modelling for a 150 ks exposure.

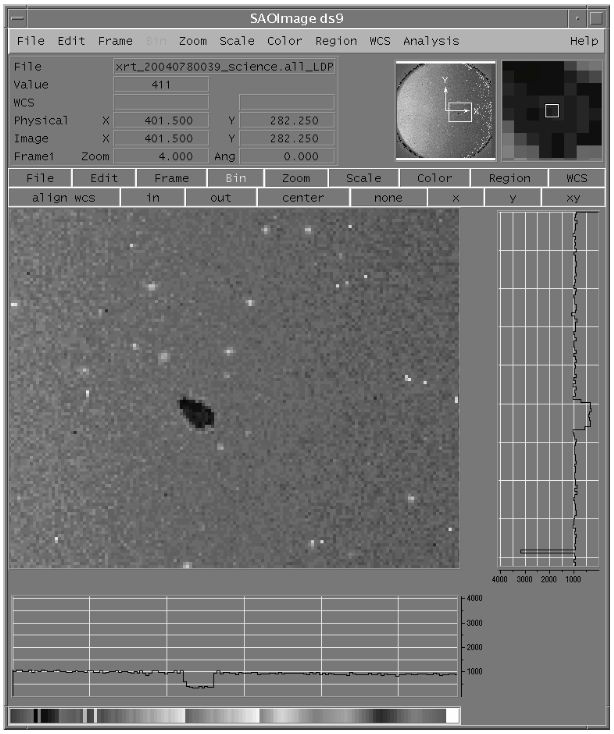
A further 30 ks observation on the active star HR1099 in WT mode will provide about 60,000 counts (2 c/s) to investigate low energy lines.

Data analysis responsible: A. Beardmore (LU).
Final product: This is part of the RMF matrix (other parts will follow).
CALDB files: response matrices

13.8.5 Debris

Two small pieces of debris far off-axis have been individuated during the ground testing phase. Their sizes are 87 and 8 square pixels corresponding to ~485 and 45 arcsec^2. Clearly debris 2 is much smaller and should not create problems. In the first stages of the mission we can individuate their position on the CCD thanks to optical light and verify if they moved. Despite of this, debris 1 is quite large and should be characterized. To investigate absorption characteristics of the debris, an unabsorbed source is required. The

XRT must be in PC mode. A 20 ks observation of the unabsorbed BL Lac 1ES 0927+500 will be performed centered on the debris position.



File xrt_20040780039_science.all_LDP
Value 411
WCS
Physical X 401.500 Y 282.250
Image X 401.500 Y 282.250
Frame1 Zoom 4.000 Ang 0.000

Figure 29: An image of the largest debris with the CCD illuminated in optical light.

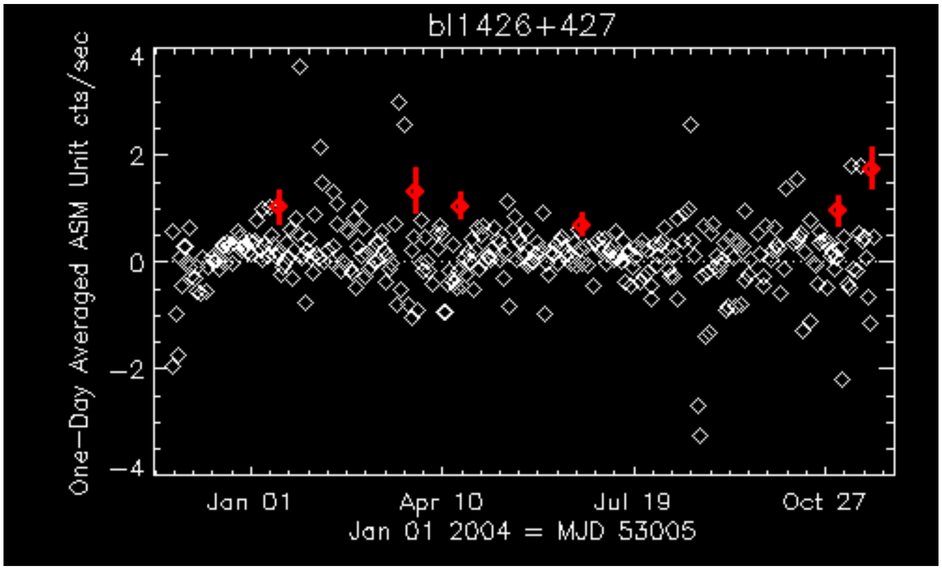


Figure 30: Long-term RXTE/ASM light curve.

Data analysis responsible: T. Abbey (LU).
Final product: Location of the debris and its X-ray absorption spectrum.
CALDB files: none.

13.8.6 Light Leak

The XRT CCD is also sensible to optical light (as any other CCD for X-ray astronomy). To mitigate this a filter (in between the thin and medium filter onboard XMM-Newton) has been mounted. The blocking factor of this filter is of the order of 10^{-4}. The capability of the filter in stopping optical light has been verified on ground and has to be checked in orbit. Two relatively bright stars have been selected. Care must be taken in that the selected stars must have been already observed with an imaging X-ray facility without showing X-ray emission. Stars must also not show any indication of binariety. We selected HD 5382 (67 Psc) which is an A5V star with V=6.08. Since A0 star do not show X-ray emission this is an ideal candidate to test the UV leakage of the filter. This star was previously observed with an upper limit of $8\text{x}10^{-15}$ erg s^{-1} cm^{-2}. A short 10 ks observation is planned. The filter has also a leakage window in the red part of the optical spectrum. HD 216228 is a giant K0 star with V=3.51. Red giant stars are not expected to emit any X-rays too with an upper limit of $5\text{x}10^{-14}$ erg s^{-1} cm^{-2}. Also for this target a 10 ks exposure is foreseen. We also manage to observe less bright sources (which however were not verified to not to emit X-rays): the V~8 A0 star HD216108 and the M2 red giant HD206749, with 10 ks exposure each.

Data analysis responsible: T. Abbey (LU).
Final product: quantify the UV and red leak.
CALDB files: response matrices.

13.9 Intercalibration within different modes of XRT

Intercalibration within different XRT observing modes will be guaranteed by the observations of the two SNR for the effective area (E0102 and Cas A) in the three observing modes. These observations will provide a good number of non piled-up counts in all the three modes.

Additional observations of bright targets (Cyg X-1, Her X-1 and Crab) of 5 ks in rapid succession will help us managing piled-up sources in WT and PC modes.

Data analysis responsible: S. Campana (OAB).

Final product: Intercalibration constant between PC, WT and LRPD.

13.10 Intercalibration within Swift: BAT & UVOT

A few sources have been selected to cross-correlate the response (spectral and timing) within Swift instruments, BAT and UVOT. For what concerns BAT we have selected bright sources to be observed together. We will also take advantage of BAT observations on Her X-1 (169 c/s in BAT) and Cyg X-1 (1793 c/s in BAT). Sco X-1 is too bright for XRT.

Besides these sources, serendipitous sources are also present in the plan which can be used for the same aim. These are:

- GX 1+4: hard PSF wings, even if XRT will observe in it PC with a high pile-up complicating the analysis; it has 7.4 c/s with BAT);
- Cas A: this is point-like for BAT with 87 c/s;
- Crab: this is the main calibrator. It shows up with 928 c/s in BAT;
- Mkn 421: a featureless XRT spectrum source is also visible with BAT with **???** c/s
- 3C 273: a featureless XRT spectrum source is also visible with BAT with **???** c/s

These observations will provide a good cross-correlation from the spectral point of view.

From the timing point of view we will mainly rely on the Crab. Additional information may come from the X-ray binary 4U 1626-676 (see below).

For UVOT we will have serendipitous sources like:

- first scientific light of XRT on WGA J1958+3232.
- boresight observation on NGC 2516;
- very bright X-ray sources as Cyg X-1 (V=9.0) and Her X-1 (V=13.0) can be observed also by UVOT (possibly with the gratings) in order to assure a broad-band coverage of the entire Swift bandpass.

Timing calibration will be achieved with a 30 ks exposure on the X-ray binary 4U 1626-676. This is a pulsating source at 7.67 s with a V=18.5 optical companion. Optical pulsations are at a level of a few % rms but can be detected by UVOT.

Data analysis responsible: S. Campana (OAB).

Final product: Intercalibration constant between BAT, UVOT (grating) and XRT (LRPD and WT).

13.11 Cross-calibration with other X-ray facilities

It is mandatory to cross-calibrate our instruments also with other X-ray facilities already in orbit. This is not trivial since other instruments have different orbits and the effective time in which a source can be observed is limited (this is also due to the fact that Swift can observe any source at maximum for about 20 min over its orbit).

We are planning to observe PKS 0537-286 (30 ks) with XMM-Newton to assess the spectral shape of this AGN, which is variable but featureless. A coordinated observation on the AGN H1426+428 together with FUSE, too, is also planned (10 ks).

With RXTE we are planning to observe the Crab (5 ks, RXTE is observing periodically the Crab so during one of these observations), the AXP RXS J1708-4009 (10 ks) and 4U 1626-676 (30 ks) for timing purposes. RXTE will also observe Cen A to compare XRT and BAT spectra with PCA and HEXTE.

Data analysis responsible: S. Campana (OAB).

Final product: Intercalibration between XMM-Newton and RXTE, not really a final product.