Readout Modes and Automated Operation of the Swift X-Ray Telescope

J.E. Hill[a], R. Klar[b], C. Cheruvu[a], R.M. Ambrosi[c], D.N. Burrows[a]

[a]Department of Astronomy & Astrophysics, Penn State University, US., [b]SouthWest Research Institute, US., [c]Physics & Astronomy Department, University of Leicester, UK.

The Swift X-ray Telescope (XRT) is designed to make astrometric, spectroscopic, and photometric observations of X-ray emission from Gamma-ray Bursts and their afterglows in the energy band 0.2-10 keV. In order to provide rapid-response, automated observations of these randomly occurring objects without ground intervention, the XRT must be able to observe objects covering some 7 orders of magnitude in flux, extracting the maximum possible science from each one. This requires a variety of readout modes designed to optimize the information collected in response to shifting scientific priorities as the flux from the burst diminishes.

The XRT will support three major readout modes: imaging, timing, and photon-counting, with several sub-modes. We describe in detail the readout modes of the XRT. We describe the flux ranges over which each mode will operate, and the automated mode switching that will occur in the XRT. We also discuss the methods used for collection of bias information for this instrument.

IMAGE MODE

Swift must transmit Gamma-Ray Burst (GRB) positions to the ground within 100 s of the burst. The XRT must determine the position of the GRB in less than 5 secs and to an accuracy of better than 5 arcsec.

To acquire position at the highest fluxes, the photons are allowed to pile-up (i.e. more than one X-ray per pixel), using a low gain imaging mode with one of two integration times. The CCD waveform integrates the 1st frame for 0.1 sec and then while clocking the data out a 2.5 second integration image is obtained. Initial processing occurs on the 0.1 second frame; if the software determines there are too few photons to calculate a centroid the processing continues on the 2.5 sec frame. If the software determines either image has a centroid sigma too large or the convergence term for two consecutive centroids is not met the SW retakes an image of the same length integration, flushing the image and store section before the next integration.

Centroids are calculated for GRBs over a flux range from 23 mCrabs in Long Image to 37 Crabs in Short Image, where the full well of the CCD is reached

The Algorithm:

In order to meet the timing and accuracy requirements a rapid and accurate centroiding algorithm is needed, that is robust in the presence of cosmic ray events and detector defects.

The algorithm for computing the centroid is divided into two phases, shown in the images above:

PHASE1 – Phase 1 locates the wings of the GRB amidst the cosmic rays and noise. This is done by locating the window with the maximum density of 'isolated single pixel events' or ISPEs. An ISPE is defined as an isolated pixel above the LLD. It can be seen that towards the edge of the PSF there is a high density of isolated single pixel events in the image. Cosmic-rays almost always appear in the image as completely connected blobs without any ISPE around them. So Phase 1 effectively filters out cosmic rays while at the same time identifying the wings of the GRB.

PHASE2 - The second phase starts with the window with maximum number of ISPEs derived from phase 1, and computes the centroid position using a center of gravity formula, starting with the initial image. The window is then centered on this newly computed centroid and the centroid of this new window is again computed. This process of repositioning the window on the newly computed centroid is iterated until two successively computed centroid values coincide. The effect of Phase 2 is that a window is placed on the wings of the GRB sliding towards the center until the center of the window coincides with the actual centroid of the GRB due to the increasing density of X-rays from the edge towards the core..

Algorithm Parameters

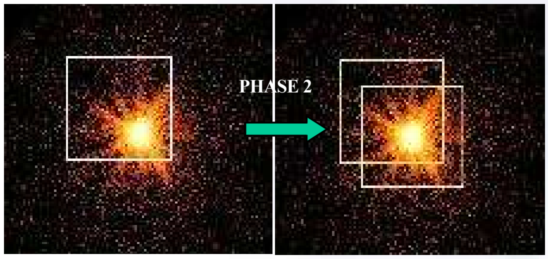
The algorithm requires four parameters;

i) The 'Event Threshold' - which is the intensity threshold for the X-ray events.

ii) The 'convergence parameter' - this determines how close the successive values of the centroid should be before the algorithm stops iterating in phase 2.

iii) The 'window size' - the size of the window used for locating the maximum ISPE density region in phase 1, and performing the iterative centroiding calculation in phase 2.

iv) 'Sigma' – this determines if there is more than one source in the FoV.



Phase 1 of the algorithm – Identification of the wings of the PSF.

Phase 2 – The iterative procedure moves the window from the wings of the PSF to the centroid of the Point Source using an iterative procedure.

PHOTODIODE MODE; Low Rate and High Rate

Photodiode (PD) mode operation is used to achieve the high accuracy timing required for the rapidly changing flux of a GRB. In this mode the charge from the entire CCD is effectively clocked into a single pixel by clocking a row into the serial register and then clocking a pixel onto the output, followed by another row and another pixel and so on.

The timing resolution from this mode is 0.14 ms for fluxes up to 62 Crab. For sources brighter than 3 Crab pile-up is significant so change in flux is measured and spectroscopy is not possible.

Two telemetry formats are used to deal efficiently with pileup. At the highest fluxes where the data are substantially piled up, all pixels are telemetered to the ground. At lower fluxes, only pixels above the threshold are telemetered to the ground. No event recognition is done onboard and the bias, determined from a frame telemetered in Piled-up Photodiode format during the slew, is subtracted on the ground.

WINDOWED TIMING MODE and Bias Row

Windowed Timing (WT) mode operation is used to achieve high resolution timing (1.1 ms) with 1-D position information, for a flux less than 120 mCrab. The CCD waveform bins 10 rows into the readout register. The first 255 pixels are dumped on the output with no conversion by the ADC, and the next 100 pixels are clocked and converted at the standard XRT rate of 6.6 μsecs/pixel. The next 10 rows are then binned in the serial register, overlapping the remaining 255 dump pixels with the first 255 dump pixels from the next row.

A bias row is calculated from 5 WT rows taken during each slew. A Lower Level Discriminator (LLD) is applied to the data. In the first WT row, any pixel below the LLD is added into the bias row. The second row is then averaged into the bias row with a running mean length applied unless a zero exists in the bias row. This continues for all 5 rows. It is assumed that the X-ray flux is low enough during slew that for at least one of the 5 rows, no X-rays are detected.

For every subsequent row of window timing data the bias row is subtracted. No event recognition is applied to the data; every pixel above the WT LLD is sent to the ground. Post-processing event reconstruction will be performed by the XRT Level 2 ground SW.

PHOTON COUNTING MODE and Bias Map

Photon Counting (PC) mode is the more traditional operation of an X-ray CCD camera. This is high gain, 2.5 second integration, yielding 2-D position and spectroscopy but limited timing information. This instrument is operated in this mode at very low fluxes.

The bias map is calculated from 5 PC frames taken during slew. A LLD is applied to the data. Any given pixel below the LLD is added into the initial map, a zero is in the map for all pixels > LLD. The second frame is then averaged into the map with a running mean length applied unless a zero exists in the map. This continues for all 5 frames. It is assumed that the X-ray flux is low enough that for at least one of the 5 frames no X-rays are detected

PC frames have 20 overclocks at the end of each row. The average of the overclocked pixels is subtracted off each pixel in the row. The bias map, which is also baseline subtracted, is then subtracted from the data.

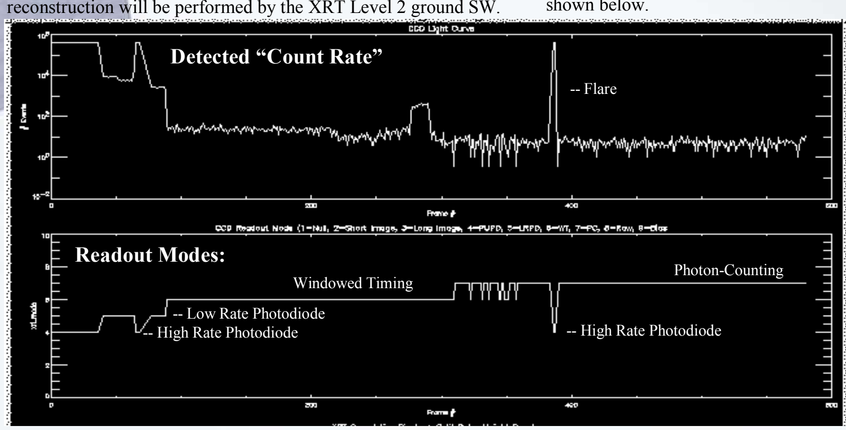
For each pixel above the LLD and below the ULD the SW checks to ensure the pixel is the local maximum in a the surrounding 3 x 3 and that no pixels in the surrounding 5x5 are above the outer ring threshold. The 3x3 event is then telemetered to the ground.

AUTOMATED MODE SWITCHING

This is the main operational mode of XRT. As the S/C slews to a GRB target, 5 WT rows are taken to calculate a bias row and 5 PC mode frames are taken to calculate a bias map. If the raw frame flag is set, a raw frame in PC mode is taken for diagnostic purposes. For the remainder of the slew the instrument switches into PD mode until the S/C becomes settled on the target. Because the waveform for PD effectively bins up the image into a single pixel the lightcurve of the GRB is measured as soon as it enters the instrument field of view.

When the S/C settles a 0.1 second Image Mode frame is taken and a centroid determined; if the flux is too low for an accurate centroid the 2.5 second frame is processed and a centroid calculation performed. If the centroid is successful, it is sent to the ground via TDRSS and distributed through the GCN. If a centroid still cannot be determined, short and long images continue to be taken for up to 30 seconds. A centroid error message is sent out if a centroid cannot be determined.

The instrument then switches into the light curve mode of operation, where it switches between PuPD, LrPD, WT and PC modes depending on count-rate or flux, as shown below.



Top Panel: on-board estimate of count rate vs time, log scale, from data run at Panter calibration facility, using simulated GRB light-curve.

Bottom Panel: Readout Mode flag, showing automated mode switching as flux changes.