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Automatic analysis of Swift-XRT data

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Abstract. The *Swift* spacecraft detects and autonomously observes ∼100 Gamma Ray Bursts (GRBs) per year, ∼96% of which are detected by the X-ray telescope (XRT). GRBs are accompanied by optical transients and the field of ground-based follow-up of GRBs has expanded significantly over the last few years, with rapid response instruments capable of responding to *Swift* triggers on timescales of minutes. To make the most efficient use of limited telescope time, follow-up astronomers need accurate positions of GRBs as soon as possible after the trigger. Additionally, information such as the X-ray light curve, is of interest when considering observing strategy. The *Swift* team at Leicester University have developed techniques to improve the accuracy of the GRB positions available from the XRT, and to produce science-grade X-ray light curves of GRBs. These techniques are fully automated, and are executed as soon as data are available.

1. Introduction

The *Swift* satellite triggers on ∼100 Gamma Ray Bursts (GRBs) per year, and the X-ray telescope (XRT, Burrows et al. 2005) provides localisations accurate to ∼5 arcsec for $> 90\%$ of these. However, GRBs, and their optical counterparts, fade rapidly and ground-based observers have limited telescope time available to use for observations. It is thus desirable to produce precise, accurate positions rapidly. Furthermore, a key indication of the scientific interest of a GRB comes from the *Swift*-XRT light curve. These are non-trivial to produce correctly, but it is desirable to generate them accurately and rapidly.

We describe how these two challenges are being met by the *Swift* team at Leicester, providing automatic data analysis which gives results of publication-grade quality. While our work is specific to *Swift*, rapid response time-domain astrophysics is a fast-growing field, and this type of software will be increasingly useful to astronomers.

2. Positions

To locate sources on the XRT detector we first perform a cell-detect search. We then centroid accurately on these sources using the point spread function (PSF)-fitting technique described by Cash (1978). Since the XRT's PSF is known, our fit has just two interesting free parameters, the x and y position of the object. Further, the presence of hot pixels has a very minor effect on the fit and will be correctly accounted for in the uncertainty. Following a micrometroid impact

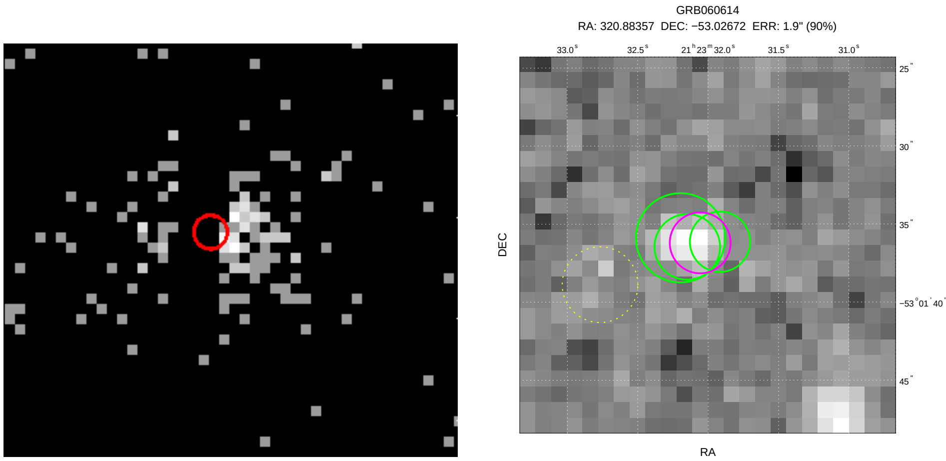

Figure 1. *Left*: An image of GRB 070429A, generated from SPER data. The red circle shows the automatically determined GRB position. Despite the bad columns, the centroid is accurate.
Right: The UVOT-enhanced XRT position of GRB 060614. The image is the UVOT V-band image. The magenta circle shows the final position. The green circles are the individual positions which contributed to this, and the yellow circle was rejected as an outlier.

in mid-2005, there area several bad columns on the XRT detector, which are permanently masked out. The location of these is known, and the fitted PSF is adjusted to account for this, giving accurate positions even when the object lies right over the bad columns (Fig. 1).

2.1. Rapidly available positions

When *Swift* detects a GRB, the XRT takes up to three short (< 3 s) images and attempts to find a source; if successful it performs a barycentric centroid and dispatches a GCN Notice announcing the position to the community. For the first spacecraft orbit after a GRB is detected, limited data products are immediately telemetered to the ground, some of which ('SPER' – Single Pixel Event Report – data) can be used to improve this position, or determine a position if none was found in the short images. As soon as SPER data are received, usually within 10–20 minutes of a GRB detection, an automatic process triggers the search and centroid routine described above. Within seconds the source position is found and relayed to the international community via the GCN Notices system. Results are also published online at http://www.swift.ac.uk/spertable.php.

2.2. Enhanced positions

The above positions are subject to the uncertainty in the spacecraft boresight, derived from the on-board star tracker, which is approximately 3.5". We have developed a technique to remove much of this uncertainty.

In addition to the XRT, *Swift* contains an ultra-violet and optical telescope (UVOT, Roming et al. 2005) which takes data simultaneously with the XRT. We have deduced the transformation from a position on the XRT detector to its equivalent on the UVOT (when the V filter is in use), thus for any source detected in XRT we can determine where it would appear on the UVOT. We then use the standard *Swift* software to translate this into an initial sky position, match serendipitous sources in the UVOT field of view with the USNO-B1 catalogue to determine an aspect correction, and apply this correction to find the true sky position. This removes the spacecraft boresight from the loop entirely, the position accuracy being limited by the accuracy of the XRT to UVOT transformation and the accuracy of the aspect solution. *Swift* usually takes multiple observations of GRB, so we have have multiple datasets on which the above technique can be applied. We can then take the weighted mean of the positions thus produced which reduces the uncertainty arising from the aspect solution. Any outliers are detected and removed, and the weighted mean is recalculated. Fig. 1 shows an example GRB with the weighted mean position, the individual positions which contributed to this, and an outlier. The 90% error radii of these final 'UVOT-enhanced XRT positions' are < 1.9" 50% the time, a factor of 2 reduction compared to the normal, unenhanced positions.

This process is fully automated, and runs as soon as *Swift* data of a GRB are received by the UK Swift Science Data Centre (UKSSDC). Once a position is determined a GCN Circular is automatically dispatched, advising the community of the position, which is also posted online at http://www.swift.ac.uk/xrt_positions. As more data are received, this position is continually revised. Further GCN circulars are not produced, however the website is updated with each run of the software. Full details of this procedure are described in Goad et al. (2007).

3. Light curves

The standard approaches to light curve creation assume essentially uniform event data and produce uniform bin sizes, however for GRBs, whose essential behaviour is to fade, this is not appropriate. Further, *Swift*-XRT data are complicated by the dead columns on the CCD, the XRT's innovative mode-switching technology which allows the XRT to determine its operating mode based on source brightness (which changes), and pile-up – where multiple photons arrive on the same XRT pixel during one readout cycle, and are thus recorded as only a single photon. It is vital that these effects are properly accounted for: optical astronomers, who must decide whether to invest their limited telescope time on a given GRB, must have confidence in light curve features such as gradient changes ('breaks') or flares, which may guide their decision on whether to observe a given burst.

To this end, we have developed a fully automated script which runs every time new *Swift* data of GRBs arrive at the UKSSDC, approximately every ninety minutes. This software dynamically varies the source extraction region and the data-bin size based on the source count-rate (corrected for losses due to pile-up) It builds separate light curves for the different operating modes, and then combines them. Where data from multiple modes overlap, it decides whether both data points are valid, or one is spurious (Fig. 2). If the instrument is toggling rapidly between modes, the data from both modes should be correct. However, if the instrument spends a considerable amount of time in one mode, but a datapoint from another mode spans this interval, the latter point will

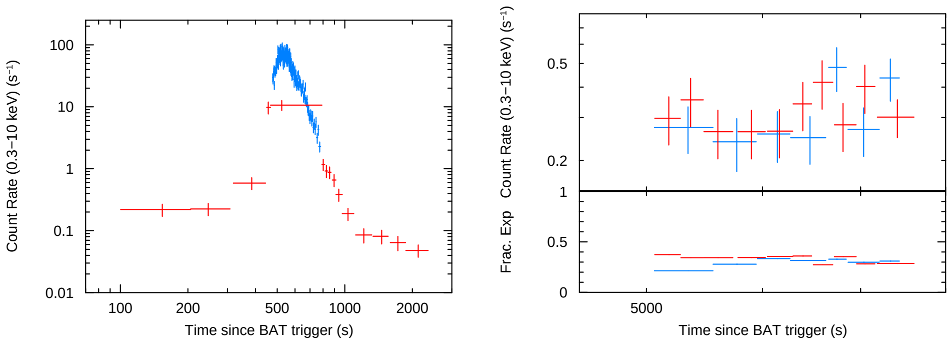

Figure 2. Examples of readout-mode switching/ *Left*: GRB 060929, showing a giant flare. Where data from the two modes overlap the red data-point aroiund 500 s is spurious, and will be rejected by our code (it is left in here for illustrative purposes). *Right*: GRB 050315. Here, the readout mode toggled rapidly, and our software correctly decided that both datasets are both valid, will keep them.

be an average of the count-rate before and after the mode-switch, rather than during it, so should be rejected. Our code also models the PSF of the data to determine whether pile-up was a factor, and if so excludes the bright core of the source from the data extraction, and then corrects the count-rates for data thus lost. For any times where source counts were lost due to the bad columns, the number of lost counts is determined, and the count-rate amended accordingly.

The veracity of these light curves have been extensively tested against those manually built by experienced members of the XRT team, and they are confirmed to be reliable and accurate, suitable both for guiding observing strategy and for use in refereed publications. Once created, light curves are published online at http://www.swift.ac.uk/xrt_curves in both graphical (ps, gif) form, and as ASCII data files. These are updated whenever new data are received.

Full details of this procedure are described in Evans et al. (2007).

4. Closing Remarks

The automated science-grade analysis of data is both achievable, and essential in some fields. With the increasing popularity of time-domain astrophysics, and the advent of rapid response hardware, the demand for such software will only increase.

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