THE ULTRA FAST FLASH OBSERVATORY PATHFINDER – UFFO-P GRB IMAGING AND LOCATION WITH ITS CODED MASK X-RAY IMAGER UBAT

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Abstract. The UFFO pathfinder mission will attempt to locate the optical afterglow of a GRB within seconds of its detection and location by a wide field X-ray imager. It will be mounted on the Lomonosov spacecraft for launch in 2013 and consists of a coded mask X-ray imager UBAT to detect a GRB and estimate a direction vector which will be passed to the SMT optical system which will rotate a moveable mirror to lock onto the GRB and direct the optical afterglow to a camera with a $\sim 17'$ wide aperture. We present the design geometry of the UBAT instrument only, with results of simulations for a range of GRB types to show probable photon integration times to be expected to extract a significant FOV image reconstruction and GRB location.

1 Introduction

The Ultra Fast Flash Observatory pathfinder is designed to observe GRB light curves within seconds, or minutes at most first with an X-ray imager to detect a GRB and estimate, within a $\pm 32 \times 32^\circ$ FOV, its local direction vector – which is then passed to a slewing optical camera SMT which will then record the subsequent GRB light curve. Construction and functional details of UBAT, SMT, their electronics and triggering have been described in other papers (Jung *et al.* 2012) from the UFFO collaboration and will not be discussed further – we present here only imaging methods and the theoretical imaging location performance to be expected from an instrument like UBAT.

2 UBAT detector-mask configuration and correlation imaging

UBAT has two principle components – a detector array and a coded mask – whose geometrical configuration is shown in Figure 2 (left). The detector is *logically*

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Fig. 1. The UBAT coded mask X/γ-ray imager (*left*) and SMT optical camera (*right*) on UFO.

Fig. 2. The UBAT detector-mask configuration (*left*) and detector-mask shadow geometry (*right*).

a 48×48 array of 2.88×2.88 mm square YSO cells – but is *physically* a 58×58 array, with 5 pairs of inactive columns and rows.

The coded mask is a 68×68 array of $5.76 \times 5.76 \times 1.0$ mm square Tungsten elements in a random pattern, with a $\sim 50\%$ open fraction. It will cast a variable

illumination pattern (or shadowgram) on the detector array below it, depending on the location of a γ -ray or X-ray point source in the instrument field of view above. The mask pattern, and a subset of it which will illuminate the 58×58 detector array due to an on-axis source is shown in Figure 2 (right).

A source in the UBAT FOV will cast a unique random illumination pattern on the detector array, and its location – as a vector offset from the detector centre – can be found simply by moving the detector pattern over the mask hole pattern to find the best correlation as shown in Figure 3 (left).

Fig. 3. Detector-mask correlation possibilities (*left*) typical correlation image extracted (*right*).

The location of a GRB must be done in real time and using Freely Programmable Gate Arrays (FPGA) imbedded in the onboard DPU – therefore the imaging algorithm used will require a fixed system of mask and image arrays to minimize processing time. Arrays used will have a pixel size of the detector cell dimensions of 2.88 mm to avoid any floating point calculations when correlating one array with another.

The array system used for image reconstruction is shown above in Figure 3 (left) where the 68×68 coded mask pattern pixels are embedded as a 136×136 array of (red-black) pixels – with values of (0,1) – in a 192×192 array of zeroes (green). To find a location where a 58×58 detector pattern (excluding dead columns/rows) has the best correlation with a 58×58 mask pattern subset, the detector-array is simply shifted stepwise on all possible locations within the 192×192 array, and at each step a correlation is made with the aim of finding that with a maximum signal-to-noise-ratio (SNR).

It can be seen that the 58×58 detector pattern has only one array of 135×135 possible correlation positions and this constitutes a *raw correlation image* made up of a quasi- uniform background (or DC-level) with an image peak, or

maximum, projecting out at the location corresponding to that of the GRB in the FOV.

The raw correlation image $C[i,j]$ can be calculated most simply as follows

$$C[i,j] = \sum_{d,e} M[i+d, j+e] * D[d,e]$$

$C[i,j]$ ($i,j = 0,134$) are correlation image pixel values

$M[m,n]$ ($m,n = 0,191$) are mask pattern values of (0,1)

$D[d,e]$ ($d,e = 0,57$) are detector array pixel values.

Another modification of this to subtract out any image background or DC-level is

$$C[i,j] = \sum_{d,e} \{ M[i+d, j+e] - O[i,j] \} * D[d,e]$$

where $O[i,j]$ is the open fraction, of detector pixels which correspond to a mask hole, and usually fluctuates around a value of 0.5. When $D[d,e]$ is uniform $C[i,j]$ is about zero.

The background in this image fluctuates - image noise - with some standard deviation and with this a second **SNR correlation image** can be created - this image is then scanned to find the pixel location of the peak with the largest SNR.

From this pixel location an offset vector from the centre of the image is calculated and with the addition of the height of the mask above the “detector interaction plane” a 3D direction vector for the GRB can finally be extracted. When this calculation is applied to each pixel in the raw SNR image a FOV zenith image shown in Figure 3 (right) can be created, showing clearly the angular location of the GRB.

It is to be noted the FOV-axis of UBAT will not be constant during the 10–100 seconds expected duration of GRB pulses – because the Lomonosov carrier spacecraft will be constrained to point its Z-axis along an earth radial, causing the FOV-axis of UBAT to rotate continuously at ~ 3.75 arcmin/sec. Therefore correlation imaging will be made in steps of 0.5 second intervals and each new correlation image will be given a spatial rotation to compensate for the FOV movement and accumulated in a **raw correlation image** which will be in a reference system of the time the GRB was triggered.

3 Evolution of image peak signal-to-noise-ratio with time

Correlation imaging takes place in intervals of 0.5 seconds to compensate for any FOV movement but also to examine the accumulated raw correlation image to decide if the SNR peak is significant enough to decide if the GRB has been located. Further imaging is then stopped, a more accurate centroid location of the correlation image SNR peak can be calculated and a final GRB direction can be passed to the SMT for slewing operations to record the GRB optical lightcurve.

It is therefore of interest to know how the SNR of the image peak in the accumulated raw correlation image evolves to decide on the correct criteria to

stop imaging and calculate a final GRB direction vector in the minimum possible time.

In Figure 4 below are plotted the results of four separate simulations of correlation imaging for UBAT observations of a GRB pulse of width 30 seconds (a mean value observed) and mean pulse flux values of 2,4,8,16 ph/cm²/sec to show how the SNR of the image peak varies with time. Each of the four colours plotted shows the repetition of 10 Monte Carlo simulations to show the statistical variance in any SNR curve.

Fig. 4. Time evolution of the SNR of the correlation image peak for GRBs of different strength.

Each curve shows that the SNR increases to a maximum with a variable fall off to zero as no further GRB flux is accumulated in the correlation image – only background noise.

More important is that the maximum SNR asymptotes to a value of ~ 36 which is due to the fact UBAT uses a random coded mask pattern. In this case any 58×58 subset of the mask pattern will give a maximum correlation at one location on the mask and a lesser ($\sim 50\%$) flat but fluctuating value at all other mask locations. This means the ratio of the maximum correlation value to the standard deviation of the flat pixel fluctuations will be finite, ~ 37 in the case of the UBAT mask pattern – a systematic error so that the correlation image peak SNR will never increase uniformly with GRB flux strength.

4 GRB imaging location time as a function of pulse width

Examination of the image peak SNR evolution curves in Figure 4 above shows, for a 30 second pulse width an peak SNR of ~ 10 can be attained within 2–10 seconds of trigger time depending on the GRB flux strength.

Further simulations were made for a range of GRB pulse width values covering 2–120 seconds. In Figure 5 below is a plot showing the distribution of GRB “imaging location times” for each pulse width – for an image peak SNR threshold value of 10 – and repeated 10 times to show the statistical variation.

Fig. 5. The distribution of GRB imaging location time for weak and strong GRB flux values.

5 Conclusion

From repeated Monte Carlo simulations of the UBAT coded mask imager using the 0.5 second stepwise correlation imaging procedure described above we can derive its correlation image peak SNR evolution curves, as a function of GRB mean flux strength.

We can also estimate probable GRB “imaging location times”, depending on the GRB flux strength and pulse width. An example of the performance of UBAT for an expected weak GRB mean flux of ~ 2 ph/cm²/sec shows a GRB location

time with an order of magnitude of $\sim 5 \pm 2$ secs for a pulse width of ~ 30 secs, and $\sim 16 \pm 9$ secs for longer pulse widths of ~ 120 secs.

This is still a work in progress and will be repeated in greater detail when the final UBAT detector response matrix at launch for UBAT becomes available.

References

- Jung, A., Ahamad, A.S., Barrillon, P., *et al.*, 2012, Design and implementation of electronics and data acquisition system for Ultra-Fast Flash Observatory, Proceedings GRB 2012 Symposium (Marbella, Spain, Oct. 2012)