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IMAGING DESIGN OF THE WIDE FIELD X-RAY MONITOR ONBOARD THE HETE SATELLITE

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Abstract. The High Energy Transient Experiment (HETE), to be launched in 1995, will study Gamma-Ray Bursts in an unprecedented wide wavelength range from Gamma- and X-ray to UV wavelengths. The X-ray range (2 to 25 keV) will be covered by 2 perpendicularly oriented 1-dimensional coded aperture cameras. These instruments cover a wide field of view of 2 sr and thus have a relatively large potential to locate GRBs to a fraction of a degree, which is an order of magnitude better than BATSE. The imaging design of these coded aperture cameras relates to the design of the coded apertures and the decoding algorithm. The aperture pattern is to a large extent determined by the high background in this wide field application and the low number of pattern elements (~ 100) in each direction. The result is a random pattern with an open fraction of 33%. The onboard decoding algorithm is dedicated to the localization of a single point source.

Key words: X-rays Gamma-rays coded aperture imaging

1 HETE, its scientific objective and instruments

In recent years the database on gamma-ray bursts (GRBs) has expanded tremendously thanks to the *Compton Gamma Ray Observatory* (Fishman et al. 1994, Meegan et al. 1994). Although this has advanced the understanding of these phenomena, it is generally accepted that the identification of GRBs with some known class of celestial sources in another wavelength band will provide the ultimate key to their nature. In order to obtain a unique identification between a GRB and a counterpart in another wavelength range, a good GRB location accuracy is crucial.

Instruments dedicated to the study of GRBs have until now mostly emphasized population studies rather than individual studies. As a result, accurate locations (any less than 1 degree) are rare. The best location accuracies, to 1', have so far been reached by the technique of arrival time lags as measured by gamma-ray detectors on interplanetary networks.

Finding GRB counterparts outside the gamma-ray band was the incentive for the design of the *High Energy Transient Experiment* HETE (Ricker et al. 1992). The scientific objective of HETE is to rapidly disseminate error boxes of high energy transients, most notably GRBs, for swift follow-up studies from ground-based observatories, and perform spectral studies on high energy transients simultaneously over a wide range of wavelengths.

HETE consists of three instrument packages, that all point in the same direction and have wide field of views (FOVs) of roughly a few steradians: 1) an ultraviolet transient camera array; 2) a set of four gamma-ray detectors, active between 6 keV and ~ 1 MeV; 3) a wide field X-ray monitor (WXM). Apart from the scientific capabilities of each of the three HETE instruments separately, they will in the following combined way serve the objective of fast and accurate GRB localization. The gamma-ray instrument will provide the alarm signal; the WXM will determine the sky location of the X-ray signal within $18'$; the UV cameras will determine the position of UV emission within at best about $10''$. The best location obtained for the GRB depends on whether a significant detection occurs in the X-ray and UV instruments. Burst information will be disseminated via radio to low-cost secondary ground stations which are located at several tens of radio, IR and optical observatories, where immediate follow-up study may occur.

2 WXM description

The WXM is based on the principle of coded aperture imaging (for a review, see Caroli et al. 1987). It has 4 identical 1-dimensional position-sensitive proportional counters, sensitive between 2 and 25 keV, 1 pair in each direction. Each detector is filled with 1.4 atm xenon and contains 3 carbon fiber anode wires for event location. The position of an absorbed photon along the wires is determined from the measurement of the ratio of the pulse height at both ends of each anode wire, and the photon energy through the summation of pulse heights over both ends. Each wire is read out separately, to furnish a rough spatial resolution perpendicular to the wires.

The geometric area of each detector module is about 9 by 14 cm²; about 70% of this area is active. The nominal position resolution of the detector is 1 mm full-width at half maximum (FWHM) at 6 keV (where the response function peaks), and improves with the square root of photon energy. The FOVs of both X- and Y-instruments are approximately 90×90 square degrees, and the overlap between the X- and Y- FOVs is about 90%. The spectral resolution is better than 20% FWHM at 6 keV.

The aperture patterns for X and Y are identical (except for small regions along the edges) and completely 1-dimensional. Since only one burst at a time will occur, a 2-dimensional aperture is not needed.

The detector data is processed in a digital signal processor. The processing can occur in 2 modes: monitor and burst mode. In the monitor mode the detector data is collected in histograms. The definition of the binning can be commanded from the ground. In the burst mode, photon-tagged data is produced and an onboard location algorithm activated.

3 The coded aperture

The aperture is about 50% larger than the detector, to ensure a large FOV within the spatial resources. A one dimensional coded aperture is defined by four geometrical parameters: the element size, the number of elements, the

fraction of open elements and the pattern of open and closed elements. We consider the optimum configuration of these four parameters for detecting GRBs with the WXM.

Mask element size. In combination with the spatial detector resolution and detector photon penetration depth, the mask element size (MES) determines the point-spread function (PSF) and thus the sensitivity, sky source location accuracy and angular resolution of the instrument. When the optimum MES with respect to these three parameters is searched, it is important to recognize that the detector resolution and the detector photon penetration are strong functions of photon energy and the photon penetration also of off-axis angle. Thus, the point-spread function (PSF) depends on the spectrum and FOV-position of the point source. To accommodate this, we used the average characteristics of GRBs that were detected by the Ginga gamma-ray detector down to a few keV (Strohmayer et al. 1994).

The angular resolution is given by the ratio of the FWHM of the PSF in the decoded image and the mask-detector distance (186 mm). For the average GRB in 1 to 20 keV, the FWHM increases monotonically with MES; at MES=2.0 mm it is 3.5 mm. The best signal-to-noise ratio S/N of a point source is achieved if it is imaged in a single pixel. When 'smearing' causes intensity to leak to neighboring pixels, the S/N will decrease (it is typical for a decoded image that the variance varies only very slowly over the image). Obviously, the S/N increases with the MES. From MES=1 to 2 mm the relative increase is 35%. The 1-sigma source location accuracy scales to the angular resolution and to the inverse of the signal-to-noise ratio S/N. Averaged over all off-axis angles and GRB characteristics, the optimum accuracy is found at MESs of roughly 1 to 2 mm.

In the burst mode, an optimum burst source location accuracy has the highest priority. Sensitivity and angular resolution are of secondary priority. Given these motives, a good compromise for the MES seems to be 2 mm; thus, the aperture patterns will measure about $N=100$ pattern elements. The accompanying angular resolution is $40'$ on-axis to $70'$ half way to the edge of the FOV, between 1-20 keV. The error box size for a burst like GB880205 is expected to be a few arc minutes when analyzed on the ground.

Fraction of open mask elements. The open fraction of the pattern (f , the ratio of the number of open pattern elements to the total number of pattern elements, *not* the ratio of open to total area) which is optimum for the detection of point sources in a reconstructed image (we exclude the sensitivity in the count rate time profile) usually is *not* 50%. 50% only applies if the particle background dominates over all other sources of events.

If the reconstruction of a GRB position and intensity is performed with a PSF fit and the particle background is not important (such as in the WXM), then exercising the formulation by In 't Zand et al. (1994) results in an optimum open fraction of about 20% for a faint GRB and 39% for a bright on-axis GRB. Thus, a compromise would be about 30%.

The pattern. The pattern is chosen to be non-repeated. Thus, there is no

fully coded FOV (FCFOV) present. This choice is motivated by the desire to only need a simple onboard burst location algorithm.

URA patterns perform superior to any other type of pattern, provided that every sky position is coded with the full basic pattern (Fenimore & Cannon 1978). If the coding is not complete, due to the lack of a FCFOV, this superiority is not as strong or may even be absent. The latter may occur when for a substantial part of the FOV the coding is performed by only a few open elements, typically less than about 50, as in the WXM. For so few elements the probability is high that sizeable non-uniformities occur in the local open fraction. The reason for this is that a URA should sample all spatial scales evenly, with just a few mask elements this means heavy clustering or non-uniformity of the open fraction. With a severe non-uniformity in open fraction, a relatively large error will be made in the cross correlation for non-source positions because the cross correlation subtracts the source counts as if they were uniformly distributed. If the open fraction is strongly non-uniform, the point source counts are far from evenly distributed over the detector. Thus, the coding noise will be relatively high. The only way to minimize this effect while retaining the low number of open elements is to distribute them as uniform as possible. Since URAs do not allow this freedom while random arrays do, there may exist particular random arrays that perform better than URAs when incomplete coding is important.

To find an optimum HETE pattern, we tested patterns with $N = 103$ and $t = 0.33$. Apart from the one triadic pattern (this is a near-URA pattern, see In 't Zand et al. 1994), we tested 10^5 random patterns. The first test involved putting a point source at 3 positions (on-axis and two half way off-axis), calculating the sky images in units of standard deviations through cross correlation, determining the maximum non-source value for each of the three point source positions and adding these three values. This number is an indicator for the amount of pattern-dependent coding noise. Of the 10^5 patterns, the best 20 were selected (i.e., with the smallest coding noise indicator numbers) and tested further by extending the number of point source positions from three to the total number of binned FOV positions. Again a coding noise indicator number was evaluated which guided our final choice for the pattern (black is closed and white open):

4 Fast onboard burst location algorithm

In the burst mode, the location of the burst needs to be determined onboard fast (within ~ 1 s), so that the UV cameras (bin time 4 s) can reduce the amount of telemetry data. Therefore, the reconstruction of the coded detector data towards sky data needs to be as simple as possible. Fortunately, this is possible for a burst like phenomenon.

In a coded aperture camera without a fully coded FOV or with a random pattern, such as the WXM, coding noise is common throughout the FOV.

Coding noise introduces extra crosstalk between two or more point sources, on top of the Poisson noise. However, if there is only one source in the FOV, the single source will not be influenced by coding noise, and the coding noise peaks that this source produces elsewhere in the FOV are always smaller than the source peak itself, apart from Poisson noise, if this peak is expressed in number of Poisson standard deviations. We plan an onboard burst-locating algorithm consisting of the following points: 1) As soon as a trigger is available, a pre- and in-burst time interval is defined; 2) The pre-burst data is subtracted from the in-burst data, after renormalization with the exposure times; 3) The cross correlation algorithm is performed on this subtracted data, resulting in 4 arrays: 2 intensity arrays (in $\text{cts s}^{-1} \text{cm}^{-2}$), one for each X- and Y-instrument, and 2 Poisson standard deviation arrays; 4) Each intensity array is divided by the appropriate standard deviation array, resulting in intensity arrays with unit standard deviations; 5) The subtraction in step 2 ensures that the coding by all persistent sources is eliminated, provided they do not show variability on time scales equal to the time intervals used in this procedure. Therefore, only the coding of the burst source is preserved; the strongest peak in the intensity array will be the most probable location of the burst. Both X- and Y- locations are provided to the UV cameras in off-axis angle format.

5 Expected performance

With the above pattern and the definition of the reconstruction, the WXM is optimized for the detection and localization of GRBs. Given the FOV and the expected duty cycle, we expect that the WXM will detect about 24 GRBs per year for which the location can be determined to $18'$ onboard and better than $10'$ on the ground. With respect to persistent X-ray sources, the performance is limited by source confusion. In particular, the limit is introduced by the fact that observations, in essence, reveal separate lists of X and Y off-axis angles. The difficulty lies in combining the correct Y to each X coordinate. We expect the WXM to be able to deal with this easily as long as no more than 5 significant sources populate the FOV.

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