THE PROBLEM OF NONUNIFORM BACKGROUND RATES IN A CODED APERTURE GAMMA-RAY TELESCOPE

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1. Introduction. The application of the coded aperture imaging technique to γ-ray astronomy offers a means of obtaining high-resolution images of the γ-ray sky. In essence, a coded aperture imaging telescope consists of some suitably coded aperture mask located above, and parallel to, a position sensitive photon detection plane. The purpose of the detection plane is to spatially resolve the modulation of the source flux which results from the presence of the mask. In general, the background counting rate within the detection plane is not uniform. These nonuniformities may arise due to variations in relative shielding within the detection plane, variations in photomultiplier tube gain, or (in the case of discrete detector elements) intrinsic differences among the detectors. The effect of these systematically varying background rates (or "background systematics") on the imaging process is to introduce a noise pattern which remains fixed within the field-of-view. For typical γ-ray experiments, this noise pattern will usually totally obscure any source signal. In this paper, we will review two possible approaches for dealing with this noise problem. One approach involves the use of an antimask. The second approach involves the direct evaluation of the *relative* background rates. Both approaches depend on the assumption that the relative background rates within the detection plane do not vary with time. These procedures have been developed in connection with the UNH Directional Gamma-Ray Telescope (DGT) [1]. This instrument operates over the energy range 160 keV to 9.3 MeV and can image a field-of-view of 22.8° by 15.2° with an angular resolution of 3.8°. The detection plane consists of an array of 35 individual BGO scintillation crystals, each of which is 5.1 cm in diameter by 2 cm thick. A successful balloon flight of this experiment, on 1–2 October 1984, has provided the opportunity to directly assess the effects of a nonuniform background and to evaluate the effectiveness of our correction procedure.

2. Mask – Antimask Procedure. The antimask approach utilizes two separate images. The first image is obtained with the initial mask pattern. A second image is then obtained with the antimask pattern under identical observational conditions (i.e., the same exposure time and pointing aspect). The pattern for the antimask is the complement of that for the mask (i.e., the opaque and transparent elements are interchanged). The noise pattern produced in the antimask image is therefore the same as that produced in the mask image, except that the "polarity" is reversed. Thus, the direct addition of these two images will cancel out the noise pattern within the FOV. The resulting image suffers from statistical noise only.

The effectiveness of the antimask procedure has been previously demonstrated using both computer modeling and laboratory testing [2]. These tests clearly show that the use of an antimask is a viable approach for dealing with the problem of systematically varying background rates.

However, the implementation of such a procedure on a balloon-borne experiment is not without its difficulties. The major problems are mechanical in nature. The principal difficulty is that of changing between mask and antimask. The development of hexagonal URA patterns [3] may represent one solution to this problem. It is also imperative that the detector maintain a fixed pointing aspect throughout the course of an image cycle (defined to be one mask and one antimask image). If this is not the case, then the source response will be smeared in the resulting image. A final concern is that any change in the mass distribution in front of the detection plane (resulting from a change between mask and antimask) will perturb the radiation field surrounding the telescope and may result in a change in the background nonuniformities. Such an effect would reduce the effectiveness of the antimask.

3. Evaluation of the Relative Background Rates. Due in large part to the mechanical limitations of the present UNH gondola, we have developed a second technique for minimizing the effects of background systematics. This approach involves the direct measurement of the *relative* background rates within the detection plane. More specifically, we determine the relative background rates in terms of a *systematics factor*, ϵ, which is defined by,

$$B_i = \epsilon_i < B > \tag{1}$$

where B_i is the counting rate in the i^{th} detector element and $< B >$ is the average counting rate per detector element (i.e., $\Sigma B_i/N$). The systematics factors (ϵ) are determined from background data, which ideally would contain no source counts. However, with a large field-of-view instrument this may not be practical. Fortunately, under some circumstances, it is feasible to determine the systematics even in the presence of source emission. This is possible in the background-dominated environment normally encountered in γ-ray astronomy experiments, since the source intensities are much less than the associated background ($S/B < 2\%$). In this case, a *drift scan* observational procedure is employed. The drift scan method allows the source under observation to drift through several image elements within the FOV. Hence, any source counts which are detected during the accumulation period will be randomly distributed throughout the detection plane. If the accumulation of the *systematics data* is made without regard for detector aspect, then the source photon distribution will constitute an unmodulated component which is negligible for the purpose of evaluating the background systematics.

During the actual source observation, the correction factors are used to correct the integrated response of the detector array prior to the image decoding process. If P_i represents the accumulated response of the i^{th} detector, then the modified response (P_i') is given by,

$$P_i' = P_i/\epsilon_i \tag{2}$$

The images produced using the modified detector response (i.e., the P_i') are dominated by statistical, rather than systematics, noise. It should be noted that this process modifies both the background and source contributions of a given detector. The modified background contributions of all detectors are statistically equivalent, thus eliminating the systematics image noise. Although the source contribution of any given detector is changed by this process, the important point to note with regard to the imaging is that the *sum* of the source contributions remains unchanged. (The average value of the ϵ_i is one.)

Although the above procedure succeeds in eliminating the image noise resulting from nonuniform background rates, the act of correcting the individual detector count sums results in a loss of statistical information relative to the ideal case of no background systematics. If the systematics data is accumulated for a time T_{sys} and the source data is collected for a time T_{obs}, then it can be shown [1] that the resulting variance of the elements in the reproduced image is given by,

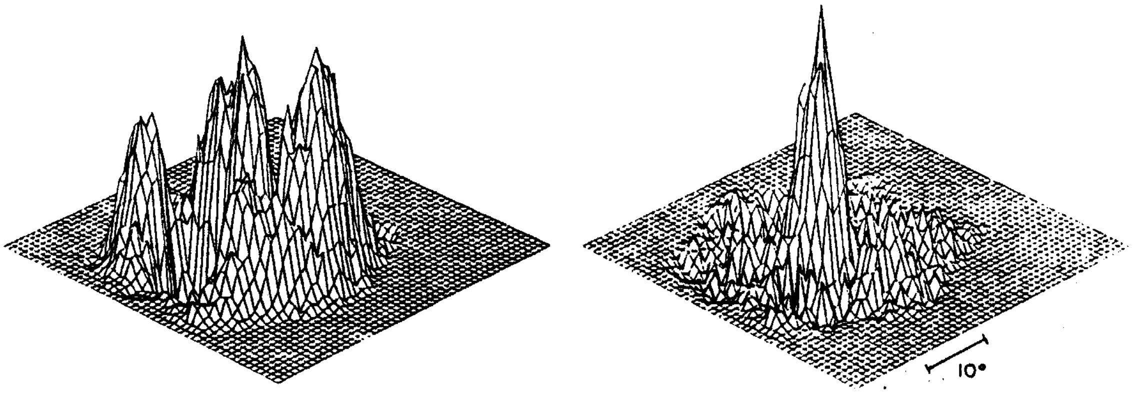
$$\sigma^2 = P_{TOT}\{1 + (1 + 1/N)\ T_{obs}/T_{sys}\} \tag{3}$$

where N is the number of detection plane elements and P_{TOT} is the total number of events (source plus background) measured by the detection plane. This result can be directly compared to the ideal imaging case (i.e., no background systematics),

$$\sigma^2 = P_{TOT} \tag{4}$$

It can be seen from these expressions that the loss of statistical information can be minimized by requiring that $T_{sys} >> T_{obs}$.

As mentioned earlier, the effectiveness of this procedure relies on the assumption that the background systematics, in terms of the ϵ_i, are independent of time. A detailed analysis using the complete flight database indicates that the systematics are indeed constant over a time period of several hours to a statistical level of approximately 0.1% of the background for any given energy range.



a) Uncorrected

b) Corrected

Crab Region 200-600 keV

Figure 1.

4. Observational Results. The analysis of imaging data from the UNH DGT experiment involved the direct evaluation of the background systematics as described above. During the balloon flight, the region of the Crab Nebula/pulsar was observed for a total accumulated livetime of 12842 seconds [4]. In order to correct for the effects of the nonuniform background, the systematics factors were determined from a set of data which was accumulated for 18250 seconds. Imaging data integrated over the energy range 200-600 keV is presented in Figure 1, which shows both the uncorrected (Figure 1a) and corrected (Figure 1b) images. (The response to the Crab has a FWHM of 4.8°.) The uncorrected image demonstrates the extent of the systematics noise. In this case, the Crab signal is completely lost in the noise. In the corrected image, however, the Crab signal is reproduced at the 10.6 σ level. This figure demonstrates not only the need for some type of correction process, but also the efficacy of the systematics evaluation approach.

We have shown that the problem of nonuniform background rates is one that can be effectively dealt with. Of the two approaches discussed here, it is not yet clear which will be most effective in practice. This determination awaits results from experiments which incorporate the antimask scheme (e.g., refs. [5] and [6]). It may be that one approach would be favored over another under certain circumstances. We may also find that some combination of these techniques may prove useful for general use.

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