

# A DIRECTIONAL GAMMA-RAY TELESCOPE USING CODED APERTURE TECHNIQUES

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## ABSTRACT

A directional detector for  $\gamma$ -ray astronomy has been developed to image sources in the energy range 0.1 to 5 MeV. An array of 35 gain stabilized bismuth germanate detectors, together with a coded aperture mask based on a Uniformly Redundant Array (URA), allows imaging in  $4^\circ$  square sky bins over a  $16^\circ \times 24^\circ$  field-of-view. The position of a strong point source, such as the Crab Nebula, can be determined to within  $\approx 1^\circ$ . A complementary "anti-mask" greatly reduces systematic effects arising from non-uniform background rates amongst the detectors. The telescope has an effective area of  $190 \text{ cm}^2$  and an energy resolution of 19.5% FWHM at 662 keV. Results of laboratory tests of the imaging system, including the ability to image multiple sources, uniformity of response over the field-of-view, and the effect of the "anti-mask", are in good agreement with computer simulations. Features of the flight detector system are described and results of laboratory tests and computer simulations are reviewed. A balloon flight of the telescope is planned for the fall of 1982.

## INTRODUCTION

Recent trends in the field of  $\gamma$ -ray astronomy have been motivated by a need for improving the angular resolution of existing instruments. This motivation is especially strong in the low energy regime (30 keV up to 10 MeV), where angular resolution has generally been determined by instrumental collimation. These collimated devices have achieved angular resolutions of a few degrees, but they suffer from a limited field-of-view.

Several groups have recently begun to investigate the use of coded aperture devices, which employ a coded mask to modulate the flux falling on some position-sensitive device [1]. This concept can result in an increased angular resolution while retaining a large field-of-view. A further advantage is that during a source observation background can also be measured, which is not the case for a collimated detector.

This paper presents the design and latest progress in the development of one such instrument - the UNH Directional Gamma Ray Telescope (DGT). This design incorporates an array of 35 bismuth germanate (BGO) detectors operating in the energy range 100 keV to 5 MeV. A coded mask based on a  $5 \times 7$  Uniformly Redundant Array (URA) is used to achieve an angular resolution of  $4^\circ$  over an effective field of view of  $16^\circ \times 24^\circ$ . In addition an anti-mask technique has been developed to eliminate image problems which may arise from any background rate non-uniformities within the BGO array. A series of laboratory tests have already confirmed the imaging capabilities of the system. Plans are now proceeding toward a fall, 1982 balloon flight of this system from Palestine, Texas.

## INSTRUMENT DESCRIPTION

The position sensitive sensor of the DGT consists of 35 discrete detector elements arranged in a  $5 \times 7$  pattern. Each element is an integral unit composed of a 5.1 cm diameter by 2 cm thick BGO scintillation crystal mounted on a 5.1 cm diameter photomultiplier tube (PMT). High voltage converters are mounted directly below the PMT complete each assembly. BGO has been chosen over NaI in order to achieve a high sensitivity-to-volume ratio, despite the sacrifice in energy resolution (about a factor of 2 at 662 keV).

Each detector unit has 1024 pulse height channels covering the energy range from 100 keV to 5 MeV ( $\approx 5$  keV per channel). Preliminary analysis of recent calibration data reveals that the linearity of the BGO is at least as good as NaI. The energy resolution of each individual detector ranges from 14% to 18% at 662 keV; this variation seems to arise primarily from the variations in PMT resolution.

Overall gain stability of the array is achieved via the use of a system which employs tagged  $^{60}\text{Co}$  calibration events. (This technique is analogous to the one used on the SMM Gamma Ray Spectrometer Experiment [2, 3].) Plastic scintillator buttons doped with  $^{60}\text{Co}$  are mounted on 1/2" PMT's. Event tagging is then achieved by the detection of the  $\beta^-$  particle associated with each decay event. A tagging efficiency of  $\sim 95\%$  can be achieved. Four such  $^{60}\text{Co}$  units are placed around the outside of the detector array. A given detector receives from 3 to 6 tagged events per second. The relative counting rates in two broad digital windows in the calibration pulse height spectrum (each covering about 30% of the total source spectrum) are used to determine whether the high voltage should be increased or decreased. The  $^{60}\text{Co}$  spectra from each detector are monitored to verify uniformity and stability of the gain.

Preliminary measurements of the energy resolution of the entire gain stabilized array are shown in figure 1. Note that at 662 keV, the resolution is 19.5% FWHM. Further improvements are anticipated as adjustments on the gain stabilization system are made.

Figure 2 presents preliminary data on the detection efficiency of the BGO array. These results are for the full, unmasked detector array. Inclusion of the mask transparency reduces the effective area by a factor of  $\sim 1/2$ , so that at 662 keV, the total instantaneous effective area is actually  $\sim 190\text{ cm}^2$ .

A side-view schematic of the DGT is displayed in figure 3. The BGO array is surrounded on all sides and back by active NaI shielding. The back plug is a solid piece of NaI, 11 1/2" in diameter by 4" thick. All other elements (10 in number) are composed of pieces of NaI immersed in silicone oil ( $\sim 70\%$  packing fraction, 4" thick) in aluminum containers. This anticoincidence system is the same as that used on a previous University of New Hampshire balloon experiment [4], except for the inclusion of four additional shield elements.

Each of the two mask units (mask and anti-mask) are mounted on aluminum support arms and positioned 80 cm from the front surface of the BGO array. The lead mask elements are each 5.3 cm square by 2 cm thick; this allows for an attenuation of 90% of the incident flux at 662 keV. These lead elements are sandwiched between .020" thick aluminum sheets; each assembly weighs 40 kg. Both mask and detector assembly can be moved in elevation to track a source anywhere in the range of zenith angles from  $10^\circ$  to  $90^\circ$ . The mask and anti-mask are located on opposite sides of the main gondola support arch; the detector assembly can be rotated about the horizontal axis to move from one mask to the other. (A change in gondola azimuth angle of  $180^\circ$  is then required to return the detector to the original pointing direction.) The entire gondola frame is  $\sim 3\text{ m}$  tall and weighs some 590 kg.

#### IMAGING PROPERTIES

The imaging capabilities have been evaluated with both computer simulations and confirmed with actual laboratory imaging tests. A complete discussion of the imaging design and associated tests has been given elsewhere [5]. Only a brief review will be presented here.

The DGT system has the advantages of: a uniform response throughout the effective field-of-view ( $16^\circ \times 24^\circ$ ), freedom from spurious images (ghosting effects) in the imaging of bright point sources, ability to resolve a limited number of multiple sources, and reduction of image noise (resulting from a non-uniform detector array background rate) via a two-mask technique (mask and anti-mask). It should also be noted that changes in resolution and field-of-view could be achieved (for future flights) by a simple change in detector-mask separation.

The anti-mask technique mentioned above can be described briefly as follows. Two equal exposure images of the source are obtained -- one with the mask and one with the anti-mask. (The anti-mask is an aperture whose pattern is identical to that of the mask, but with opaque and transparent elements interchanged.) Any spurious peaks in the images which result from non-uniform background rates amongst the BGO detectors will be of equal magnitude in the two images, but will have opposite signs. Hence, a simple summation of the mask and anti-mask images will produce a net result which cancels out these undesirable effects. (Real source images will, on the other hand, be equal in magnitude and sign and hence will add.)

#### FLIGHT PLANS

Progress is now proceeding smoothly toward a fall, 1982 flight of the DGT from Palestine, Texas. Outdoor cold-testing of the instrument (at temperatures as low as  $-20^\circ\text{C}$ ) has been performed to check out the thermal and mechanical properties of the instrument at low temperatures. Further outdoor testing of the fully integrated flight system prior to the flight is planned to verify among other things, the pointing accuracy of the gondola. A pointing accuracy of  $\sim 1/2^\circ$  is expected.

Primary goals of this first flight will be to ascertain the effectiveness of the DGT design

by imaging both the Crab Nebula and the energetic sources in the Cygnus region (Cyg X-1, Cyg X-3). The expected response of the Crab is displayed in figure 4a. (The array of 35 numbers represents the response of each  $4^\circ \times 4^\circ$  sky bin in terms of the number of standard deviations above the average background level.) This result represents 2 hours of exposure to the Crab in the energy range 100-400 keV. Background levels are estimated from balloon data obtained on a  $3'' \times 1''$  BGO crystal flown over Texas in the fall of 1980. Note that the Crab Nebula itself shows up as a  $33\sigma$  response at the center of the field-of-view; this response should allow the position of the radiation source to be determined with an accuracy of  $1^\circ$  or better. Figure 4b represents a 1 hour exposure to the Cygnus region, again in the 100-400 keV energy range. Source responses are  $28.7\sigma$  and  $5.9\sigma$  for Cyg X-1 and Cyg X-3, respectively.

#### SUMMARY

We have presented here the design and preliminary test results of the University of New Hampshire Directional Gamma Ray Telescope (DGT), which combines high sensitivity with all of the advantages of coded aperture devices (including simultaneous source/background measurements). A balloon flight of the instrument from Palestine, Texas in the fall of 1982 is planned. At that time, a full evaluation of the capabilities DGT design will be made under actual flight conditions.

#### ACKNOWLEDGEMENTS

The authors would like to thank Bob David, Indulis Gleske, Jon Googins and Mogens Lauritzen for their assistance with this project, and Mary Chupp for editing and Karen Avery for typing the manuscript. This work was supported by NASA grant NGL 30-002-021.

#### REFERENCES

1. A. J. Dean, this volume.
2. D. J. Forrest, P. R. Higbie, L. E. Orwig and E. L. Chupp, Nucl. Instrum. Methods **101**, 567 (1972)
3. I. U. Gleske and D. J. Forrest, IEEE Trans. Nucl. Sci. **NS-27**, No. 1, 313 (1980)
4. P. P. Dunphy, D. J. Forrest, E. L. Chupp, M. L. Cherry and J. M. Ryan, Ap. J. **244** 1081 (1981)
5. M. L. McConnell, D. J. Forrest, E. L. Chupp and P. P. Dunphy, IEEE Trans. Nucl. Sci. **NS-29**, No. 1, 155 (1982)
6. F. P. Penningsfeld, U. Graser and V. Schonfelder, in Proceedings of the 16th International Cosmic Ray Conference, 1979, Paper OG 4-1.
7. C. A. Meegan, G. J. Fishman and R. C. Haymes, Ap. J. (Letters) **233**, L123 (1979)

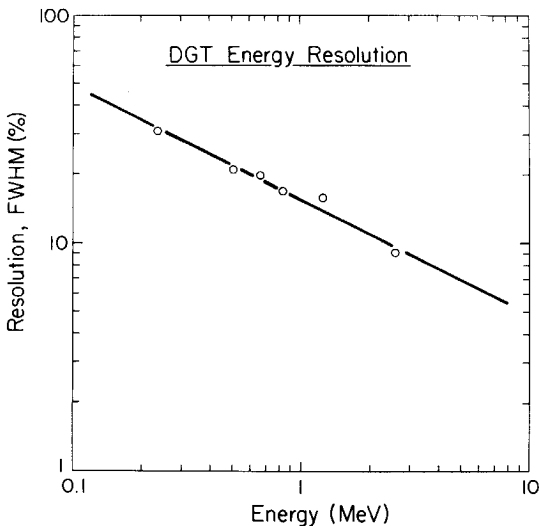


Fig.1 Energy resolution (preliminary data) of the 25 element gain-stabilized BGO array.

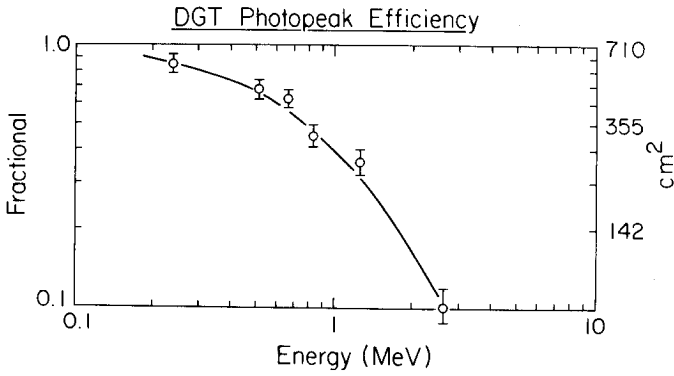
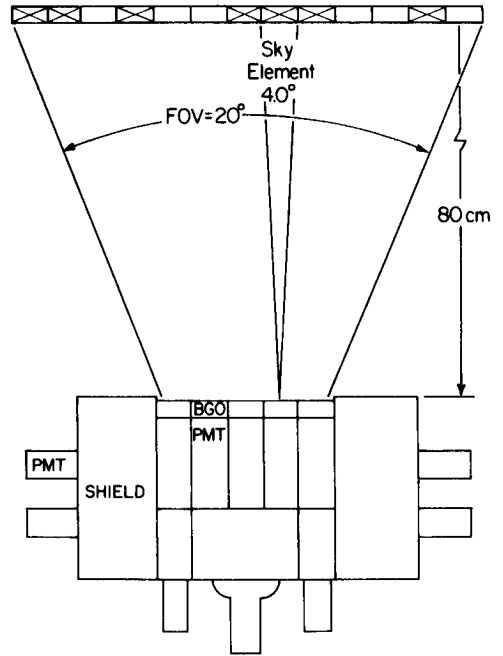


Fig.2 Detection efficiency (preliminary data) of the unmasked BGO array.

Fig.3 Side view schematic of DGT showing relationship between the BGO array, the active NaI shield elements and the coded mask.



a.	1.5	0.8	0.3	- 4.4	-4.4	0.9	4.1
	-0.4	-1.5	-2.8	2.9	-3.2	-2.7	-1.1
	0.7	0.3	-0.5	<b>33.2</b>	0.1	-0.5	-3.9
	-0.1	-2.9	0.4	- 2.4	-1.4	-2.9	-1.0
	-1.1	-1.2	1.7	1.1	-0.6	1.4	0.8
b.	1.9	1.5	- 2.1	-3.0	0.4	-5.4	-1.3
	0.0	-0.6	0.3	-2.1	-2.2	-2.7	-0.6
	2.5	-3.8	<b>28.7</b>	-2.3	<b>5.9</b>	-3.2	1.7
	-2.1	-2.6	- 3.9	-1.5	-3.3	1.5	-2.4
	2.6	-0.1	- 0.2	0.6	-1.7	-2.4	2.0

Fig.4 The values in each array represent the response of the 4° X 4° sky bins in terms of the number of standard deviations above or below the average background.

a. DGT response to Crab Nebula flux [6]. 2 hour exposure in the energy range 100-400 keV ( $1\sigma = 1490$ ).

b. DGT response to Cygnus region flux [7]. 1 hour exposure in the energy range 100-400 keV ( $1\sigma = 1060$ ).