The CSPD-2 Gamma-Ray Imaging System

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Abstract

A compact portable γ-ray vision system consisting of a lead multi-hole collimator, CsI(Tl)/photodiode detector array, CCD camera and personal computer, has been constructed and tested. The optical picture obtained with a CCD camera is overlaid with γ-ray intensity distributions at different energies to enable immediate localization of multiple radioactive sources. The γ-ray detector employs a shielded array of sixteen $1\times1\times3$ cm CsI(Tl) scintillation crystals, each of which is viewed by a 1 cm square Hamamatsu PIN silicon photodiode. The device operates in the energy range from 100 keV to 3 MeV with an average energy resolution of about 7% FWHM and angular resolution of about 4° FWHM at 662 keV. The collected γ-ray distribution is processed using a maximum-likelihood algorithm to provide a more precise reconstruction of the γ-emitter distribution. The detector system is mounted on a pan-and-tilt table; the total weight of the imaging system is about 30 kg. The performance of this instrument has been tested in our laboratory and the results show that this system should be a competitive candidate for radiation monitoring in nuclear facilities.

I. INTRODUCTION

Portable γ-ray imaging systems operating in the energy range of $\sim$100 keV to $\sim$3 MeV are of interest in nuclear medicine, astrophysics, and industrial/national laboratory applications. Different γ-ray imaging techniques have been developed over the past three decades. Spatially modulated coded-masks [1, 2] have been employed in γ-ray astronomy due to their high detection efficiency and superior performance for point sources, but are not attractive for distributed sources. Time modulated coded-masks [3] were investigated in medical γ-ray tomography. Compton-scatter γ-ray imagers have been employed in astronomy [4] and explored for radiation monitoring [5], but are also not yet practical for a portable system. Pinhole collimators [6, 7] and diverging multi-hole collimators [8, 9] remain the practical choices for compact systems. However, devices which employ pinhole collimators usually operate in the energy range well below 1 MeV because the pin-holes become ineffective and it is also difficult to obtain good position resolution on the γ-ray detectors at higher γ-ray energies.

During the past two years, the applicability of a γ-ray imaging system employing a diverging multi-hole collimator and a compact CsI(Tl)/photodiode detector array was studied [8] and a prototype was built and tested [9]. The results showed that this type of γ-ray imager should be a competitive device for a number of applications, such as radiation imaging in nuclear power plants, nuclear waste inspection and radiation mapping in contaminated rooms. The CSPD-2 system has now been constructed using an array of 4×4 CsI(Tl)/photodiode γ-ray detectors. An electronic interface was built for 16-channel data acquisition and a CCD camera has been integrated into the system to provide the visual image of the radioactive area. A maximum-likelihood image reconstruction algorithm has been implemented to give a more precise estimation of the source distribution. Laboratory tests have shown that this device can distinguish multiple sources within the same field-of-view (FOV) even with source activities differing by $\sim$50 times of magnitude.

II. SYSTEM CONFIGURATION

A schematic diagram of the CSPD-2 γ-ray imaging system is shown in Fig. 1. The γ-ray detector consists of an array of sixteen $1\times1\times3$ cm CsI(Tl) scintillation crystals, each of which is viewed by a 1×1 cm Hamamatsu PIN silicon photodiode (S3590).

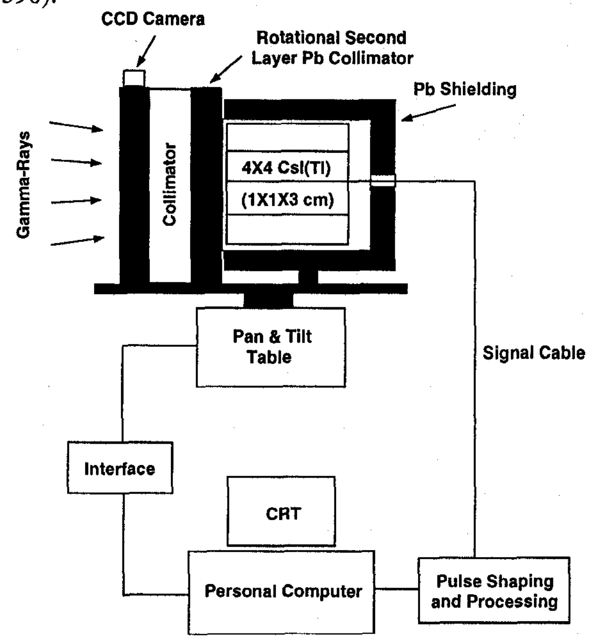

Figure 1 : Schematic diagram of the CSPD-2 γ-ray imaging system.

The detectors and preamplifiers [10] are contained in an aluminum housing which has outside dimensions of only

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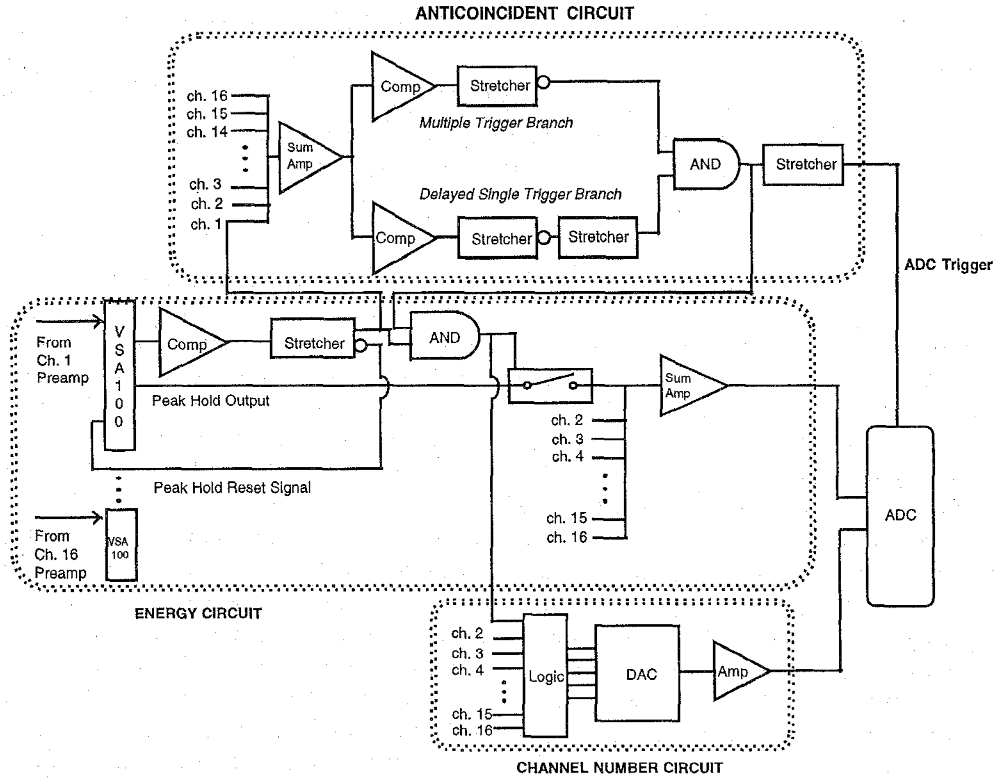


Figure 3 : Schematic diagram of the pulse-processing electronics.

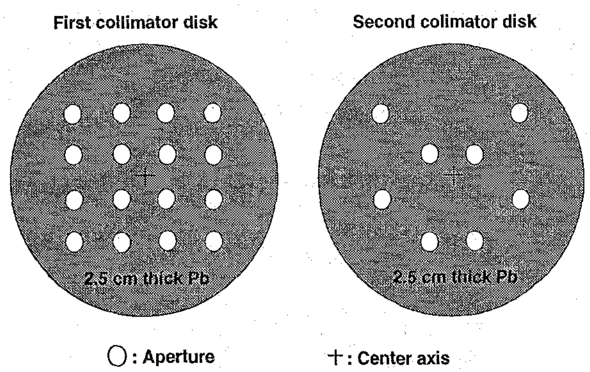


Figure 2 : The front view of the collimator disks.

8×7×7 cm. The CsI(Tl)/photodiode detectors were chosen for their compactness, ruggedness, good stopping power and competitive energy resolution at the γ-ray energies of interest (up to a few MeV) [11]. All sides of the detector housing are shielded by 2.5 cm thick lead which attenuates about 95% and 73% of normally incident γ-rays at 662 keV and 2 MeV respectively. The imaging ability of the system is derived from a lead diverging multi-hole collimator. The collimator is composed of two 2.5 cm thick lead disks. The thickness of the detector shielding and the collimator was chosen by considering the energy response of the system, the cost, and availability of the material. The front view of the two collimator disks is shown in Fig. 2. The first-layer disk of the collimator (furthest from detector) has an array of 4×4 open apertures, each having a diameter of 6 mm. The second layer disk has only 8 open apertures with the same diameter. These 8 open apertures form a 180° anti-symmetric pattern relative to the center of the disk. Therefore, source and background observations can be made simply by rotating the second layer collimator 180° around the center axis. This collimator configuration can minimize most of the systematic errors in estimating the source flux, such as those caused by septal and shield penetration. The separation between the two lead disks is 3.5 cm so that each open aperture has a FOV with a FWHM of 4°. The angular separation between adjacent apertures in the same row or column is also 4°. Thus the diverging multi-hole collimator has a FOV of about 16°×16° and an angular resolution of ~ 4° FWHM. The detector system weighs about 30 kg and is mounted on a pan-and-tilt table so that a wider FOV can be observed by pointing the central axis of the system. In some applications, the detector could be transported by a mobile platform to survey contaminated rooms.

The signals from the γ-ray detector are passed through a 6 meter long cable to an electronic interface circuitry [12]. The long cable enables the operator to be at safe distance from radiation sources.

A small CCD camera with outside dimensions of 4×4×6.5 cm is mounted on top of the first disk of the lead collimator. The center of the FOV of the CCD camera is approximately parallel to the pointing direction of the γ-ray detector. Since there is a parallax between the axis of CCD camera and the γ-ray detector, calibrations were performed so that the optical image of the FOV can be overlaid correctly onto the γ-ray distribution when the approximate source distance is known.

III. Pulse Processing Electronics

The outputs of 16 preamplifiers are sent in parallel to the pulse processing electronic circuitry and are condensed into 2 channels of analog outputs corresponding to the channel number and the pulse amplitude of the γ-ray interaction [12]. This requirement of analog output signals adds complexity in the channel number conversion, but allows our current ADC board to act as the sole processing unit. This interface has been fabricated on a printed circuit board consisting of 16 shaping and peak-hold hybrid chips graciously provided by Southampton University (U.K.) [13], and a pulse processing circuit designed by the authors. The schematic diagram of this electronic circuitry is shown in Fig. 3 and the pulse processing timing sequence is shown in Fig. 4.

The circuitry is composed of 3 major components as shown in Fig. 3:

- The energy circuit performs the pulse shaping and amplification, and passes the pulse amplitude to the ADC.
- The channel number circuit produces an analog output for the ADC to identify the detector element which was activated.
- The anticoincident circuit ensures the interactions occurred in only one detector element [12].

The logic control circuit triggers the ADC board (mounted in a personal computer) only when a single detector element detects a signal. This design makes each detector element act as an active veto to all other detector elements so that Compton scatterings which deposit energy in more than one detector element are not recorded. This guarantees the unique correspondence between detector element and aperture so that the incident direction of the γ-ray can be backprojected without error. Our test results show that the anticoincident mode rejects about 13% of all counts at 662 keV when the count rate is about 1 kHz. This has demonstrated the importance of the coincidence veto since otherwise, these events would have given incorrect directional information. The pulse processing time for each event is about 20 μs.

IV. γ-Ray Spectroscopy

The spectroscopic performance of the CsI(Tl)/photodiode detector array was tested using both ^{58}Co and ^{137}Cs γ-ray sources. The sources were located about 10 cm in front of the bare detector array (without the collimator). The energy spectra from one detector element are shown in Fig. 5. One can see that the low energy threshold is below 100 keV which is sufficient for the energy range of intended use. The energy resolutions of the 16 detector elements range from 6.5% to 7.5% FWHM at 662 keV, with one exception of 8.5% FWHM.

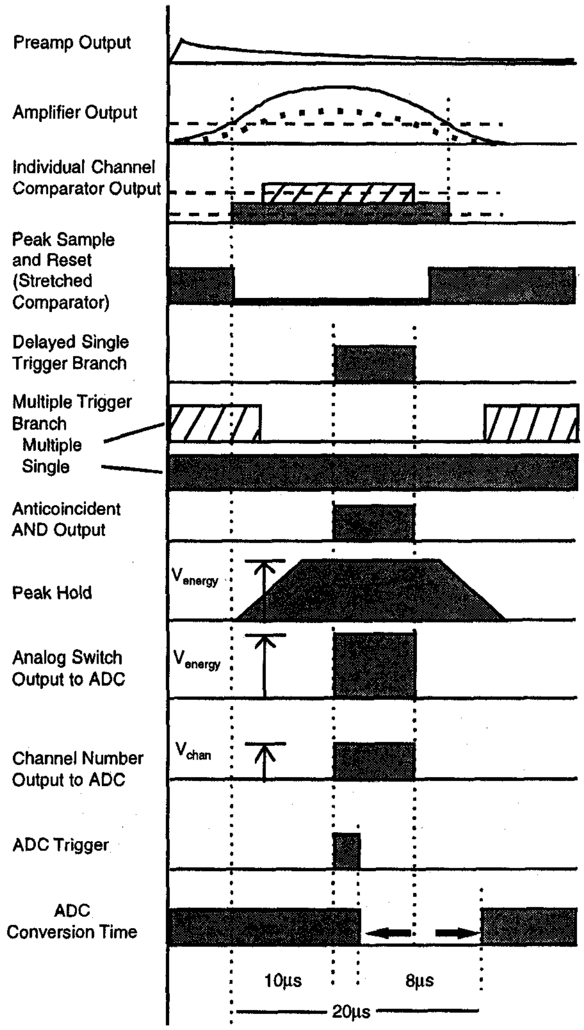


Figure 4 : Timing sequence for anticoincident pulse-processing electronics. Hatched areas correspond to output for coincident pulses and are shown for example only. The rest of the diagram assumes no coincident interactions occurred.

The entire CsI(Tl)/photodiode detector array was manufactured by eV Products [10].

V. Spatial Resolution

The angular resolution of the device is primarily determined by the FOV of the apertures which have a geometric FWHM of 4°. The effective angular resolution is poorer at higher γ-ray energies due to the penetration of γ-rays. The angular response of a single aperture viewing a ^{137}Cs γ-ray point source located one meter from the detector is shown in Fig. 6. One can see how the detection efficiency changes as a function of incident direction of γ-rays relative to the aperture axis. The net signal in Fig. 6 is the result of background subtraction and shows the angular resolution to be about 4° FWHM at a 662 keV γ-ray energy.

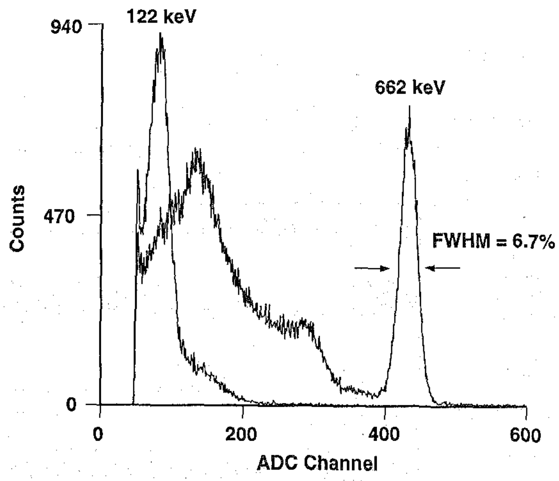


Figure 5 : Energy spectra of ^{57}Co and ^{137}Cs obtained from one of the detector elements .

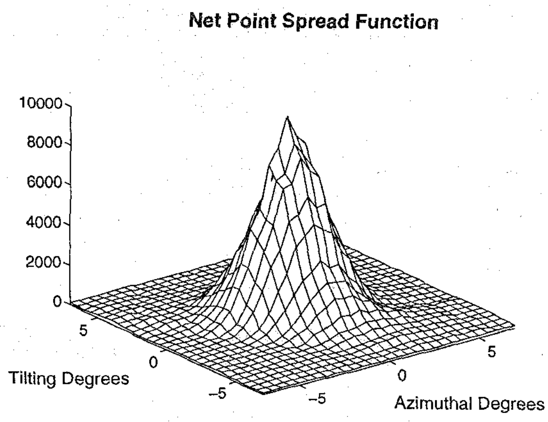
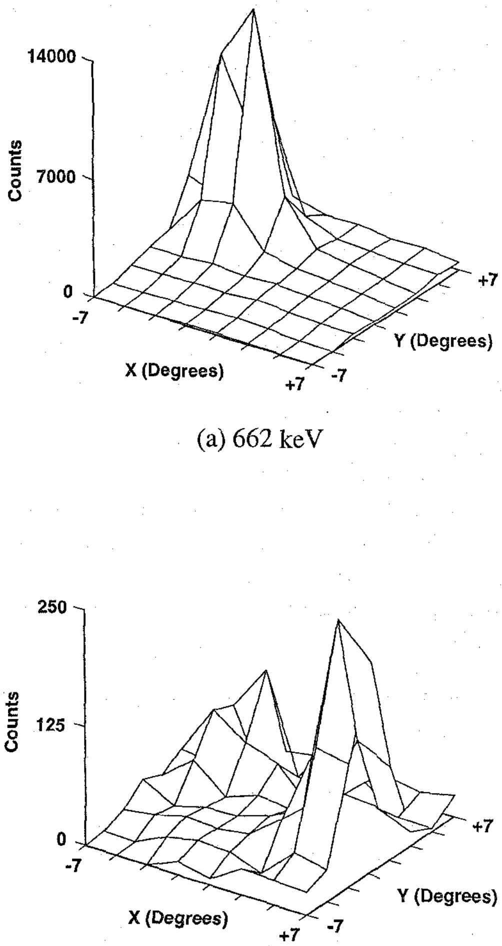


Figure 6 : Measured angular response of one aperture at 662 keV.



(a) 662 keV

(b) 811 keV

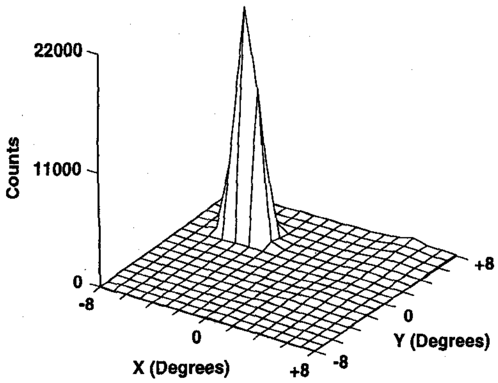
Figure 7 : Raw data observed from a ^{137}Cs and a ^{58}Co sources located 2.1 meters from the device.

VI. Imaging Performance

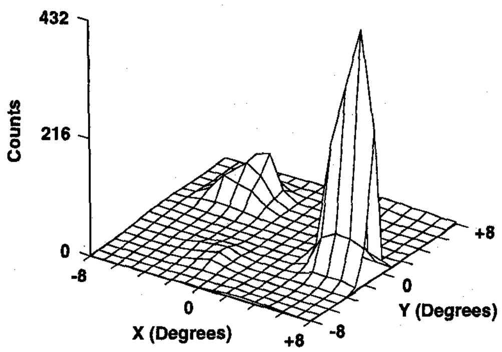
The imaging performance of the CSPD-2 system was tested using two radioactive point sources: a 10 mCi ^{137}Cs source and an irradiated Ni source (^{58}Co emitting 811 keV γ-rays) with activity $\sim$ 200 μCi. Both sources were located about 2.1 meters from the detector and were separated by about 10 degrees in angle as viewed from the device. A FOV of $14^\circ \times 14^\circ$ covering both sources was observed with $2^\circ \times 2^\circ$ image pixels obtained by scanning the pointing direction of the detector array at 2 degree steps for 2×2 directions. The observation time at each direction was about 40 minutes for both signal and background observations. The number of net γ-rays recorded versus the pointing direction of apertures is shown in Fig. 7.

Post data processing using a maximum-likelihood algorithm was proposed and investigated in our previous work and has been integrated into our CSPD-2 imaging system [9]. This image reconstruction includes the knowledge of the angular and energy response of the system and takes into account the stochastic fluctuation of both signal and background. The raw image shown in Fig. 7 was processed after observation and the reconstructed image with 1×1 degree image pixels is shown in Fig. 8. Our results show that this image processing can significantly improve the signal-to-noise ratio of the observed source distribution and the FWHM of the source distribution was reduced to about 2°. From Figs. 7(b) and 8(b), residue of ^{137}Cs source can be seen for both the raw data and reconstructed γ-ray distribution at 811 keV. This was caused by the wide energy window used (3 σ on both sides of the photopeaks for the worst-case detector resolution) and the high intensity of the ^{137}Cs source relative to the ^{58}Co source. The optimized width of energy windows will have to be considered for future measurements to prevent this contamination. The good signal-to-noise ratio of the ^{58}Co source shown in Fig. 8(b) indicate that the source can be identified within a shorter observation time than was used in this case.

The γ-ray image shown in Fig. 8 was then overlaid onto the CCD image and the combined image is shown in Fig. 9. Since the ^{137}Cs source is about 50 times stronger than the ^{58}Co source, the peak amplitudes of the two sources are normalized for display. Both sources were identified at correct locations, although the ^{58}Co source was identified at about 2° right of the true position. More careful calibration between the CCD and the γ-ray distribution is needed for later field tests.



(a) 662 keV



(b) 811 keV

Figure 8 : Reconstructed γ-ray intensity distribution using a maximum-likelihood algorithm.

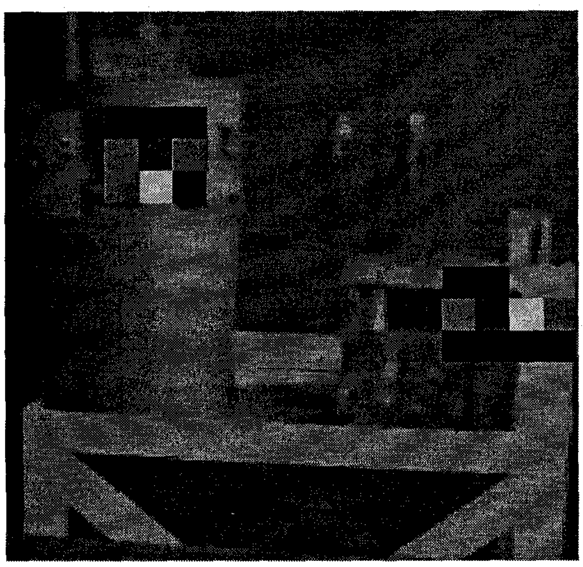


Figure 9 : Reconstructed γ-ray image overlaid with the CCD image.

VII. Conclusion

Following our previous investigations, the CSPD-2 γ-ray imaging system has been constructed and tested. The 4×4 CsI(Tl)/photodiode detector array can significantly reduce the observation time compared with our prototype CSPD-1 system [9]. A 16 channel printed circuit board electronic interface was designed and fabricated for pulse processing. The measured sensitivity of the device is consistent with that estimated in our earlier study [8]. Future tests are planed to verify system performance in realistic radiation environments. This compact system has moderate energy resolution, angular resolution and sensitivity; a combination which should be of interest in a broad range of applications.

VIII. Acknowledgments

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IX. References

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