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Evaluation and benchmarking of a commercial cadmium zinc telluride (CZT) gamma imaging camera

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ABSTRACT

Illicit transportation and trafficking of nuclear materials and other radioactive sources across the national borders is a constant global threat. Demands for efficient and rapid response security measures and nonproliferation technologies are on the rise. The capability to rapidly localize a kilogram quantity of a gamma ray emitting source in transport and register the threat within the context of the scenario via compelling visualization is a requirement for today's law enforcement organizations. Gamma ray imaging devices with fast response function have become an integral part of transboundary portal monitors at airports and seaports. We have assessed the efficacy and application of a commercially manufactured cadmium zinc telluride (CZT) gamma imaging camera. The imaging system manufactured by H3D Corporation (Ann Arbor, Michigan) is intended for practical field applications by first responders and nuclear power plant surveyors. The H3D imager (Model H420) uses a position-sensitive, pixelated CZT element >19 cm^3 in volume with gamma energy resolution of <1.1% FWHM at a reference gamma energy of ^{137}Cs (662 keV) to develop fast (less than 2 minutes start-up time), lightweight (8.6 lbs.) gamma imaging systems.

The H3D H420 gamma imager's automated mask/anti-mask uses a rank-19 coded-aperture mask for improved signal-to-noise ratio and cleaner images; it also benefits from the Compton imaging technique. Options for better quality CZT crystals with ≤0.8% FWHM resolution at 662 keV are available. The system's integrated range finder can precisely overlay gamma ray and optical images from point-like or extended gamma emitting sources alike, which can show the extent of a radiological spill. The CZT imager enhances the surveillance capability of the first responders in targeted search and radiological emergency response.

The performance and imaging capability of CZT detectors have improved steadily over the past decades. The first CZT Compton camera was developed at the University of Michigan, Ann Arbor, in 2001. The device had only two 1 cm^3 CZT crystals separated by 5 cm, with an intrinsic efficiency of 1.5×10^{-4} at gamma energy of 511 keV. The measured angular resolution was 5.2° at 662 keV. The improved design of the application-specific integrated circuit (ASIC) that occurred within the next three years made it possible to acquire the three-dimensional position information of multiple gamma ray interactions in a single detector by measuring the electron drift time. The measured intrinsic efficiency improved three orders of magnitude to 1.86% for a single CZT crystal gamma imager of dimension 1.5 × 1.5 × 1.0 cm.

Comparative in-depth references will be made to the progress made since the original concept of applying three-dimensional, position-sensitive, pixelated CZT in the area of materials development (crystal growth techniques), detector mounting, electronic readout of the ASICs, event reconstruction algorithm, calibration procedures, and noise reduction techniques to imaging.

Keywords: semiconductors, gamma imaging camera, mask, anti-mask, coded aperture, cadmium zinc telluride (CZT), Compton imaging, radiological emergency response

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1. BACKGROUND

To evaluate and benchmark the performance of a CZT camera, we need to understand the following properties of a camera. The core performance is directly related to a quantitative metric of the sharpness and details of the images. Fluctuations of light yield with energy, in particular the non-proportionality of light output as the gamma energy varies, degrade the spatial resolution of the image. Mathematically, the spatial resolution is expressed as $\Delta R \propto 1/\sqrt{Nph}$ and $\propto 1/\sqrt{E_\gamma}$, where Nph is the number of incident photons, and E_γ is the energy of the incident gamma energy.[1]

Intrinsic detection efficiency of the spectroscopic element of the camera is also an important metric; electron-rich high-Z dense materials are favored for increased detection efficiency. The energy resolution of solid-state detectors ranges from 0.2% to about 2%,[2] which is superior than the energy resolution obtained from even the best scintillators (cerium-doped lanthanum bromide with resolution <3%). Cryogenically cooled high purity germanium (HPGe) detectors can provide the best resolution of 0.2%, but they require ancillary cooling systems, which makes the detection system bulky and less maneuverable, even with an electromechanically run Stirling cooling system. CZT bridges the energy resolution gap between the best semiconductor and best scintillator. The energies required to create charge carriers (electron-hole pair) in CZT and HPGe are 4.6 and 2.98 eV respectively,[3] which means that a 1 MeV photon beam will create 2.17×10^5 electron-hole pairs from CZT and 3.35×10^5 electron-hole pairs from HPGe, whereas the same photon beam will create approximately 3.8×10^4 photons.

Imaging cameras are limited in terms of the gamma flux rate they can handle because of the long processing time. The effect of large dead time is two-fold: it creates full energy gamma peak shape distortion and photon counting losses. The pile-up effect caused by high flux rate starts to affect smaller cameras at and above 10^5 cps gamma rate.

2. PHYSICS PRINCIPLES

2.1 Compton imaging

In the gamma energy range above 250 keV, Compton scattering is the dominant gamma ray interaction with CZT at intermediate energies (from a few hundreds of keV to several MeV). CZT systems are suitable Compton cameras. Compton imaging requires that each photon interact at least twice within a detector, beginning with a Compton scatter and ending with a photoelectric absorption. For each interaction, the deposited energy and the *x*-, *y*-, and *z*-coordinates are known. The scattering angle θ is a function of the incident photon energy E_γ and the scattered photon energy E'_γ, where $E'_\gamma = E_\gamma - E_{e^-}$, as shown in (1).

$$E_{e^-} = E_\gamma \left[\frac{\frac{E_\gamma}{m_e}(1-\cos\theta)}{1+\left(\frac{E_\gamma}{m_e}\right)(1-\cos\theta)} \right], \tag{1}$$

where E_{e^-} is the recoil electron energy, and m_e is the rest mass of electron 0.511 MeV.

Pixelated CZT detectors can provide three-dimensional position reconstruction with proper charge-sharing electronics. This enables 4π Compton imaging of gamma rays with a single detector. For pixelated detectors, two dimensions of position sensitivity are determined according to which pixel collects charge (*x*- and *y*-coordinates on a Cartesian system). The third dimension comes from the signal ratio of the planar cathode to the pixelated anode, or from the electron drift time for each pixel that collects charge.[4]

2.2 Coded aperture imaging

Coded apertures or coded-aperture masks are grids, gratings, or other patterns of materials opaque to various wavelengths of electromagnetic radiation. The wavelengths are usually high-energy radiation such as x-rays and gamma rays. By blocking radiation in a known pattern, the coded aperture casts a coded “shadow” upon a plane. The properties of the original radiation sources can then be mathematically reconstructed from this shadow. The H3D H420 camera uses an automated rotating patterned attenuating mask to perform mask and anti-mask measurements alternately. The coded-aperture system provides improved signal-to-noise ratio and adjustable field of view advantages. We can exploit these advantages to reduce exposure times and improve spatial resolution of the images. The H420 imager uses the modified uniform redundant array (MURA) rank-19 coded aperture.

3. METHODOLOGY

We covered a large measurement parameter space including (a) communication modes: Bluetooth, Wi-Fi, Ethernet; (b) distance: near field (2–3 m), medium field (3–10 m), far field (>10 m); (c) source energy: low (60–250 keV), medium (250–700 keV), high (>700 keV); (d) source strength: low (0.001–0.1 mCi), medium (0.1–1 mCi), strong (1–50 mCi); (e) field of view: vertical, horizontal (consider 360° including beyond the camera); (f) shielding condition: cardboard, plexiglass, steel doors, corrugated CONEX storage room wall, trunk of a car, etc.; and (g) image type: Compton and/or mask/anti-mask coded aperture.

A common metric used in determining the quality of a radiation image was the number of intersected Compton rings within a fixed amount of time for a given source and imager configuration. All the measurements have been made in static search mode looking at the gamma energy spectrum collected versus the image being formed.

4. DEVICE DESCRIPTION

Figure 1 shows an image of the Model H420 gamma camera manufactured by H3D. It shows the different operational buttons and USB ports available on the body of this easily portable instrument. There are two USB ports to collect images and spectra and facilitate Bluetooth connection. The red button is to turn the device power on and off, while the black push button is to control the data acquisition. The front end has a laser ranger aperture through which the system can determine an accurate distance to an object by measuring light reflected from the surface. The tablet can be operated with Wi-Fi and carried in a slot provided at the back of the camera. Underneath the circular cover is the 3D-printed plastic mask holder with MURA rank-19 pattern. The system uses thin tungsten pieces as masts and to provide mask and anti-mask measurements. The circular masking panel rotates with a certain periodicity. The camera uses lithium-ion batteries, which can be charged from completely depleted state to 90% charged state in 4 hours. From top to bottom, on the back right side of the instruments are the LED display light to indicate the status of the device, measurement push button, power button, two USB sockets, and the fuse. The Ethernet connection and the power input socket are on the thin right edge. Table 1 provides the nominal technical specification of the H420 CZT camera.[5]

Figure 1. Front and back of Model H420 CZT-based gamma imaging camera manufactured by H3D Inc.

Table 1. Nominal technical specification of Model H420 CZT camera.

Characteristics	Specifications
Instrument dimensions	9.6″ × 3.75″ × 7″ (24 × 9.5 × 18 cm)
Weight	7.8 lb (3.5 kg)
Power supply	100–240 V, 47–63 Hz
Energy resolution	≤1.1% FWHM at 662 keV (coincident interactions combined); 0.8% resolution is optional
Energy range	50 to 3000 keV (spectroscopy)
Cooling method	Proprietary external heat sink and removable fan
Optical field of view	>162° horizontal, >122° vertical; full color
Crystal volume	>19 cm^3
Count rate limit	5 mSv/hr bare ^{137}Cs equivalent
Angular resolution	~30° FWHM for all 4π (real time) ~20° FWHM for all 4π (post-processing)
Sensitivity	Detect ^{137}Cs producing ~3 μR/hr in <16 s (spectroscopy) Localize point source of ^{137}Cs producing ~3 μR/hr in <90 s
Angular precision	±1° source localization for all 4π (real time)
Display	7″ 1280 × 800 HD tablet (mountable to back cover)
Communication	Ethernet RJ45 port; TCP/IP

5. OTHER COMMERCIAL CZT GAMMA CAMERA

5.1 iPIX gamma imager

iPIX is a gamma imager manufactured by Mirion Technologies, Inc. Using 1 cm^3 CZT crystal containing 256 pixels, iPIX locates and identifies low-level radioactive sources from a distance while estimating the dose rate at the measurement point in real time.[6] The iPIX gamma imager is an appropriate instrument to detect any suspicious radioactivity in security and safeguard applications, as well as for emergency situations such as Fukushima. The camera takes less than 30 seconds to detect ^{241}Am generating 25 nSv/hr incremental dose rate above background at the camera position and less than 30 seconds to detect ^{137}Cs generating 2 µSv/hr incremental dose rate above background at the camera position. The iPIX gamma imager is a real-time ultra-portable gamma-ray imaging system mostly designed for in situ gamma measurements to locate radioactivity at nuclear sites. When planning for maintenance or decommissioning operations, you can use it to provide radiation intensity maps of the area. Figure 2 shows the back side of this gamma imaging system.

The best angular resolutions quoted are as follows: 2.5° with rank 13/2 mm thickness blue mask; 6.0° with rank 7/4 mm thickness yellow mask; and 5.0° with rank 7/8 mm thickness red mask.

Figure 2. iPIX gamma imager is a lightweight camera that uses pixelated CZT crystal with MURA rank 7 and rank 13 coded apertures.

5.2 NuVISION

NuVISION is a compact portable spectrometric gamma camera based on pixelated CZT semiconducting detectors utilizing coded aperture and Compton imaging techniques.[7] It is manufactured by NUVIATech Instruments Corporation in France in cooperation with CEA-LETI (Laboratoire d'électronique des technologies de l'information), Grenoble. The portable system weighing only 3 kg provides users a sensitive system (with sensitivities of 1800, 280, 160 cps/µSv/hr at ^{241}Am [59.54 keV], ^{137}Cs [661.6 keV], and ^{60}Co [1332.3 keV] gamma energies respectively). The CZT detector (9.6 cm^3 in volume) can detect, localize, identify, and image gamma emitting radioactive sources between the energy of 20 and 1400 keV. The gamma imaging system has fast enough processing speed to produce real-time gamma source imaging from static or moving sources. It also measures ambient dose rate in H*(10) and is capable of providing dose rate measurements in the range between 1 nSv/hr and 100 mSv/hr. CZT provides gamma energy resolution (FWHM) of 2.5% at 122 keV and 1.5 % at 662 keV. Each gamma event is localized on a 128 × 128 pixel array. The entire package measures only 24 × 10 ×10 cm. The system is sensitive enough to localize a 50 nSv/hr ^{57}Co source in natural background in less than 1 second and a 50 nSv/hr ^{137}Cs point source in less than 1 minute. Figure 3 shows NuVISION gamma imaging camera on a tripod stand ready to collect data and transfer the image to a tablet wirelessly.

The angular resolution is 3.5° with coded aperture and 15° with Compton imaging. The field of view is 45° with coded aperture and 360° with Compton imaging.

Figure 3. NuVISION portable CZT-based gamma imaging camera transmitting data to a tablet wirelessly.

6. MEASUREMENTS AND RESULTS

6.1 Small-source short-distance parameter space

We placed two pairs of radioactive button sources of different isotopes, namely ^{207}Bi and ^{241}Am, at a separation of 0.58 m and used them to measure the angular resolution of the camera in short distance measurements. The pair of ^{207}Bi button sources created a radiation field of 4.6 μR/hr and the pair of ^{241}Am button sources created a field of 2.3 μR/hr as measured by the camera at a perpendicular distance of 2.4 m away from the sources. Sharp, separate, and distinct images were obtained as shown in Figure 4, providing an angular resolution better than 14^0. The metric of equal number of intersecting Compton rings to form a quality image could have been used, but a subjective decision was made to call an image of "good" quality when they appeared clear to the naked eye.

Figure 4. Optical and radiation images of two button sources (each of ^{207}Bi isotope) placed 0.58 m apart. The sources were imaged with enough clarity to be distinguished from a perpendicular distance of 2.4 m. The time taken to image was 12 minutes 21 seconds. Compton rings of colored bands started to show long before a good quality image was obtained.

6.2 Angular response of the Model H420 CZT camera

To determine the relative angular response of the camera system, we placed a depleted uranium plate weighing 411 g and containing 140 µCi of the isotope in the form of a thin square on an arc radius of 2.4 m at angles of 0^0 through 90^0 inn steps of 15^0 on one quadrant of the area in front of the camera. Time to image the source in seconds were recorded and tabulated in Table 2.

Table 2. Time to image a source positioned at a different angle with respect to the center of the camera.

Angle (°)	**Dose Rate (µR/hr)**	**Time to Image (τ) (s)**	**Response Metric $1000 \times \tau^{-1}$**
0	24.6	7	142.8
15	24.2	7.2	138.9
30	23.8	8	124.3
45	23.2	8.7	114.2
60	22.9	10.4	96.3
75	19.1	13.3	75.1
90	15.6	38	26.3

6.3 Shielded ^{137}Cs source imaging at a distance of 6.15 m

We used a heavily shielded ^{137}Cs source (~ 34 mCi) inside a 2 cm lead pig carried in a 2 mm thick steel to cover the medium to long distance measurement parameter space. The source created a radiation field of 7.04 µR/hr at a distance of 6.15 m as measured by the CZT camera. An image of the source is shown in Figure 5.

Figure 5. The physical location of the shielded source inside a steel canister (*left*) and the gamma energy spectrum from ^{137}Cs and the overlay of optical image on the radiation image taken within 6 minutes 35 seconds (*right*).

6.4 Distance versus imaging time measurement using heavily shielded ^{137}Cs source

We used a ^{137}Cs source (of strength 34 mCi) that was heavily shielded with lead pig and carried in a steel cannister to carefully measure the distance between the source to the imager and the time to image the source. The data are shown in Table 3.

Table 3. Distance versus time to image a source.

Source	34 mCi of ^{137}Cs in 2 cm lead pig and 2 mm thick steel can			
Distance (cm)	**Dose rate (μR/hr)**	**Time to Compton ring formation (mm:ss)**	**Time to full image (mm:ss)**	**Comments**
55	493	00:05	00:16	Sharp image
175	47.4	00:22	01:02	Sharp image
275	4.94	00:34	01:48	Sharp image
345	15.8	00:52	02:50	Sharp image
615	7.04	02:27	06:35	Sharp image (shown in Figure 5)

6.5 Shielded source on second floor from parking lot

The shielded ^{137}Cs source was placed at the window of second floor office room facing the parking lot, and the gamma imager was inside the car with an unobstructed view of the source (requiring a large field of view to image the source). The vertical angle of the source would be about 60° with respect to the imager. The large footprint of the Compton image obtained in 22 minutes 10 seconds is shown in Figure 6.

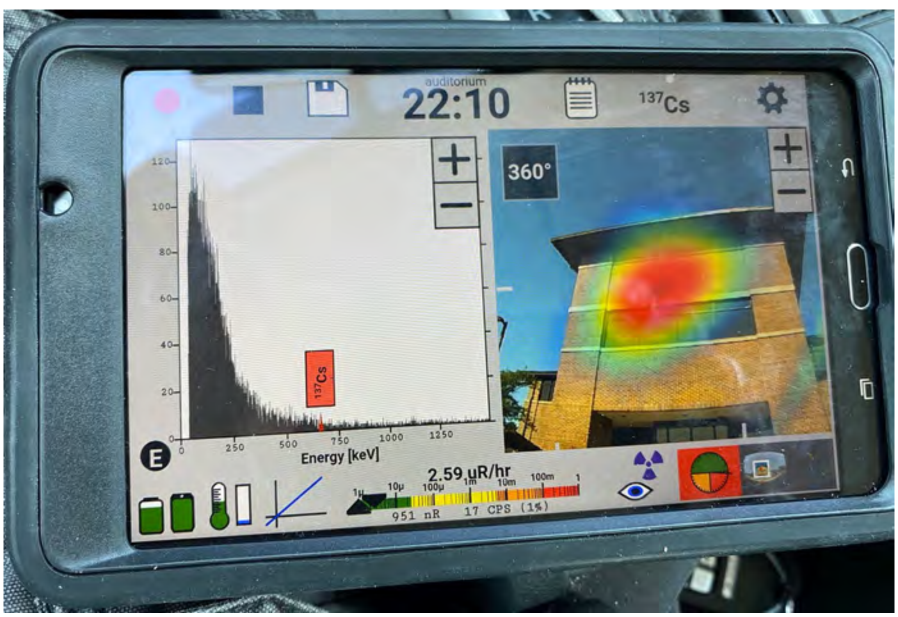

Figure 6. A shielded source placed on the second-floor office window is imaged by a CZT camera from inside of a car in the parking lot.

7. DISCUSSION OF DATA

Perhaps the most insight about the imager came from the following observation. The shielded ^{137}Cs source was placed on the ground in the parking lot in clear line of sight from the CZT camera at a distance >20 m. The source is clearly seen with the naked eye (see the left side of Figure 7). There was a car parked on the left side of the camera field of view. The image formed by Compton scattering appears to be coming from the car, but the vehicle did not have any source in the trunk. The imager can often be fooled to think that the largest scattering object (creator of all the Compton rings) is actually the source.

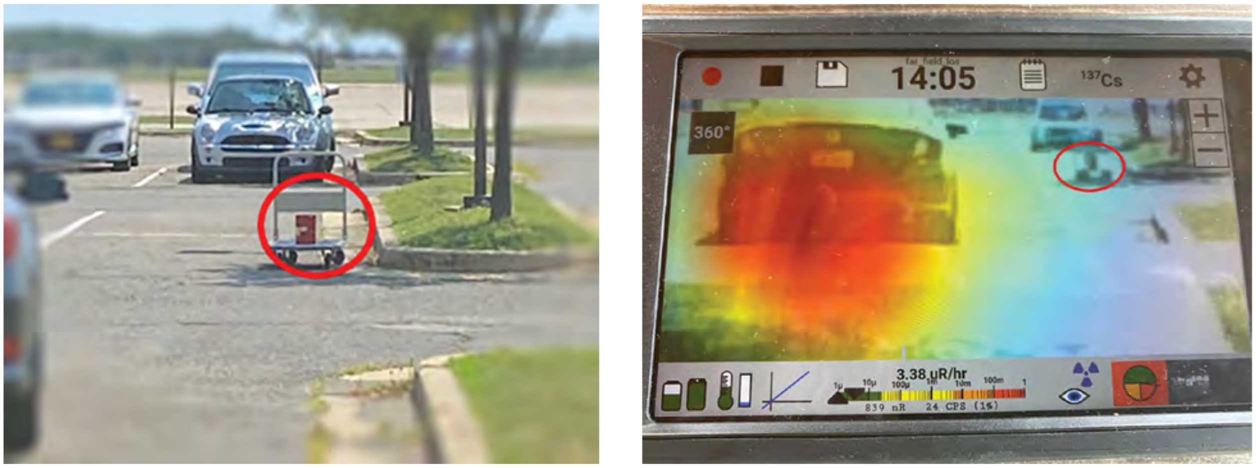

Figure 7. The clear line-of-sight visual camera image of the gamma source on the ground (*left*). The Compton image appears to come from the trunk of the car (*right*) even though there was no actual source in the trunk of the car. This could easily mislead localization of a gamma emitting source. The image needs analysis and most likely parallax correction.

8. CONCLUSIONS

We defined the envelope of measurement parameter metrics for the CZT camera (Model H420 manufactured by H3D, Inc.) through our experiments.

The CZT camera is an excellent lightweight instrument for static surveillance and search in the following mission areas: (a) maritime search operations (localizing sources inside container boxes through shielding of various density and inhomogeneous distribution or packaging), and (b) targeted search operations (ideal for short to medium range (≤10 m) surveillance from concealment). The camera enhances the search capability by providing visual clue of the spatial location of the gamma emitting source along with isotope identification.

We have found that the system works fast (within tens of seconds) for distances of the order of 15 m. The system works well with a small source (<10 µCi) at a short range (<5 m). The CZT camera works on the energy range between tens of keV to 2.6 MeV (not tested beyond 2.6 MeV energy gamma sources because of poor efficiency). The imaging system performs best in the horizontal range of 0° to 60° opening angle horizontally. It can form an image of moderately strong gamma emitting sources shielded inside the trunk of a car. The stand-alone system battery life is >4 hours in the shade, but in the sun, performance worsens rapidly. The LCD is not the best under direct sun. For device communication, Wi-Fi is the best; we had an intermittent problem with Bluetooth while testing.

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