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DETECTION AND ANALYSIS OF UNCHARGED PARTICLES UTILIZING CONSUMER-GRADE CCDS

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Abstract

In the current climate of increased global terrorism, the threat of a radiological incident is becoming more realistic than ever, and as such, the necessity of early-warning detection is paramount to national security. To assist with this need, we have investigated the detection of uncharged particle emissions from radiological sources using Charged-Coupled Devices (CCDs), which are contained within a variety of products, including consumer cellphones and traffic cameras. Because the CCD is intrinsically sensitive to charge accumulation as a result of linear energy transfer by the incident particles, each event can be counted and quantified using video-image processing, and an estimated energy band assessed by the properties of the pixels. In an effort to make this process applicable to the widest possible range of CCDs available, this experiment was conducted using low-quality CCDs contained within consumer-grade, budget web cameras. Within a ^{239}Pu -Be neutron howitzer, particles were detected using several camera models: Gigaware X76, Z76 and Logitech C170, C270. Particle detection events were counted by post-processing with Matlab and an efficiency for each CCD was determined relative to both a theoretical flux model and a calibrated ^3He tube detector. The relative detection efficiencies for the cameras tested fell within the range 14–18% and showed a linear correlation between incident energy and pixel response.

INTRODUCTION

Considering the current rates of terrorism and the existence of concentrated radioactive materials, the threats of accidental and deliberate radiological release are becoming increasingly realistic (Pennington 2010, NCSTRT 2018). According to the Nuclear Threat Initiative report on the state of radiological security (NTI 2016), there are thousands of sites in more than 100 countries which contain many of the radiological materials necessary to construct a Radiological Dispersal Device (RDD). While there exists a global system for tracking such radioactive materials, up to 25% of the countries mentioned have gaps in inventory records, and lack sufficient security to prevent theft of radioisotopes such as Cs-137 or Co-60 (NTI 2016). These are two predominant choices in building RDDs.

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Despite the elevated risk factors for a radiological attack, counterterrorism experts propose expanding the radiological monitoring framework within the United States as an effective countermeasure (NNSA 2015). Outside of nuclear facilities, the majority of radiological monitoring is currently confined to entry points such as airports, naval docking locations, border crossings, and ambient air surveying via the RadNet program (IAEA 2005). Though in some ways expansive, the existing framework has insufficient capability for comprehensive tracking of radiological weapons once inside the United States. To address this, the National Nuclear Security Administration has proposed using an on-demand Air Monitoring System mounted on drones or helicopters and deploying more detectors at critical junctions within large cities (NNSA 2015).

This research aims to further investigate the potential for using charge couple devices (CCDs) as a cost-effective approach for detecting uncharged particles by testing various low-cost, consumer-grade models. If efficient enough, these would serve as not only a baseline that many other CCDs should outperform, but also would provide a low-cost method of detecting radiation. Because CCD imaging is digital (Inoué and Spring 1997), both real-time and post-event analysis can be viewed off-site from the detectors as long as the remote computer has access to the monitoring network (Richards 2013). This enables the potential to create a ‘detection grid’ in any location where compatible CCDs are in place, and where the data could be transmitted to a central hub for observing the radiological levels. This scheme is similar to the mechanism by which RadNet monitors ambient, environmental radiation around the United States.

METHODS

Calibration and Comparison Models

Before making experimental measurements with the CCD-based instruments, the LND 25185 Helium-3 tube, which will be required for comparison purposes, was calibrated for work within the neutron howitzer. To do this calibration, radiation-sensitive film badges (Landauer Neutrack CR 39 made from plastic with polyethylene moderator for fast neutrons) were placed at various distance intervals within the howitzer bombardment chamber and dosed with neutron flux for interval time periods (Cummings 2017). Calibration resulted in a measurement of dose equivalent as a function of distance, as determined by Landauer, which we then converted into counts as a function of distance using the theoretical model (see below). Counts were acquired for the same interval but at different distances using a Ludlum LND25185 Helium 3 detector. Count values obtained from the Landauer film badge results were correlated with those measured with the LND 25185 with applicable Ludlum Rate Meter (Nugent 2015) to obtain a calibration for the LND 25185.

This data was also plotted together with predictions from an analytical model for the neutron howitzer chamber (Nugent 2015), based on a steady-state reactor model with a set of PuBe core sources producing neutrons and a cylindrical paraffin blanket surrounding it (Foster and Wright 1983). The blanket scatters (reflects) the neutrons in multiple directions generating a distribution of neutron energies. Scattering through the blanket into the sample chamber was described by a cylindrical geometry of 5 point sources of PuBe, which was modeled to

closely describe the same distance dependence as was observed in measurements using Landauer film badges placed in the sample chamber as a function of distance from the core. The model predicts counts versus distance as would be measured by the LND25185 Helium 3 detector, and was also used to fit the dose vs. distance for the film badges. Distances are measured from the center core radially outward, and included positions as far away as the opening of the ports on the side of the howitzer. The paraffin blanket moderator was approximated to be primarily diffusive in nature (Nugent 2015). While functionally similar, but deviating in magnitude, both the measurements and theoretical model were used to compare against when determining the neutron detection efficiency of the CCD-detectors within the neutron howitzer.

CCD Experimental Procedure

Because the $^{239}\text{PuBe}$ isotopic source produces a flux which contains both gammas and neutrons, proper shielding is required in order to analyze either of these particle types independently (Curtiss 1959). Borated polyethylene disks were utilized to block the neutrons, and lead shielding of varied thicknesses were utilized to shield the gammas. An absorption shielding formula is used to calculate the thickness of lead required to reduce transmission intensity of gamma flux (Morgan and Turner 1967):

$$\begin{aligned} I_1(r) &= I_0 \frac{r_0^2}{r^2} \\ I_2 &= I_1 e^{-ux} \end{aligned} \quad (1)$$

where $I_1(r)$ is the intensity of the gamma particles after distance-decay, I_0 is the intensity emitted by the source at distance r_0 , where I_2 is the intensity of the gamma particles continuing beyond the shielding, x is the thickness of the shield, and u is the linear attenuation coefficient (LAC) (Heslep 1968). Rearranging to solve for shielding thickness, we find:

$$x = -\frac{1}{u} \ln\left(\frac{I_2}{I_1}\right) \quad (2)$$

This expression can be solved for any percentile decrease of intensity for a given incident particle energy by increasing the thickness (x) and using the correct energy-dependent attenuation coefficient u (Hubbell 1982, Hubbell and Seltzer 2004). The $^{239}\text{PuBe}$ source produces a range of gamma particle energies (Cember and Johnson 2009); based on the energy spectrum shown in (Vega-Carrillo et al. 2002) we estimate that the highest energy gammas will be approximately 7–8 MeV. While this equation strictly holds only for the highest photon energies, because the uncollided flux is highly attenuated, this approximation is expected to suffice. Thus, we used published densities and mass attenuation coefficients to estimate thickness of Pb needed to stop 99% of gamma particles at various relevant energies, according to the following expression:

$$x = -\frac{1}{u} \ln \left[\frac{I_0}{I_0 \left(\frac{1}{100} \right)} \right] \quad (3)$$

where $u = \rho\sigma$, using the mass density ($\rho=11.35 \text{ g/cm}^3$ for Pb)(Hubbell and Seltzer 2004) and the mass attenuation coefficient (σ) at a given energy. We estimate that thicknesses of Pb of 8.68 cm at 8 MeV, 9.24 cm at 6 MeV, and 9.58 cm at 3 MeV, respectively, are required to stop 99% of gamma particles. Therefore, the 8 cm of Pb used will effectively stop the majority of gammas from reaching the CCD.

With an approximately 8cm thickness of lead shield in place, the next step was to prepare the CCDs for the neutron measurements. To do so, each model of web camera (Gigaware X76, Z76 and Logitech C170, C270) was taken apart to remove the pertinent electronics from the chassis. This was done to prevent obstruction of the CCD interface and to maximize the number of detected events. Additionally, the CCD interface was covered with black electrical tape to prevent visible light photons from causing false positives when measuring for gammas and neutrons (McLean 2008). Once inside the howitzer chamber, each of the CCD-detectors was bombarded independently at various radial distances for 30-second time intervals while video capture software recorded the results. Longer bombardment times were also tested, but in each case similar results were obtained (within counting error) compared to the 30-second interval, so the acquisition time of 30s was then used in general. Each of the trials was repeated 3 times at each distance interval and their results averaged.

Processing Captured Video

To make use of CCDs as detectors of uncharged particles, all incident events over an arbitrary time interval needed to be processed by means of a post-event analysis. To do this, the Matlab built-in video input library was utilized to read the .wmv (Windows Media Video) file and then it was broken down frame-by-frame within a 'for loop' to scan for pixels above a numerical threshold. The threshold is designed to filter out the background within the video, and allow detection of the elevated pixel values produced as a result of the incident particle flux onto the CCD. The threshold for the pixel intensity associated with these randomized, nuclear events is defined below:

$$T = \bar{x} + n\sigma \quad (4)$$

Where $\bar{x}$ is the arithmetic mean pixel value (i.e. mean pixel intensity) for the entire image (which is a measure of the background level) and $n\sigma$ is a multiple of the standard deviation for a well-defined counting region. By increasing the threshold, the effect of noise is reduced until a desired filtering occurs and only substantive pixels remain to be counted. These are reported in a histogram of pixel areas and intensities for all events above threshold using $n=9$ (Figure 3), analogous to a pulse height spectrum (Figure 3E–F).

The threshold used in image A was calculated using Eq. 4 with $n=3.21$. For this particular method of processing, values of $n < 3$ and $n > 10$ resulted in over-detection (false positives)

or under-detection (false negatives), respectively, for events within the frames. For this experiment, $n=3.21$ was chosen for the Logitech cameras and $n=7.5$ for the Gigaware, which produced acceptable identification of events within the frames, as well as the smallest variance in the data. Once chosen, these values were unchanged for the entirety of the experiment. When examining the video data, the more energetic incident particles result in higher pixel intensities observed on the recorded video. Additionally, in runs where gamma particles were present, we observed “streaking” events, as can be seen in the above figure by the faint lines of connected pixels with elevated intensity (Figure 3B–C).

The streaking events seemed to arise from a fraction of detected gamma particle which presumably interacted with the CCD interface at an oblique angle and resulted in internal scattering (Meyerhof and Meyerhof 1967). This is evident by the declining brightness of the individual pixels in the chain, correlating to the energy loss of the gamma particle with subsequent interactions in the active layer of the CCD (Hardage and Pickel 2003).

To quantify events within the CCD resulting from interaction with particles, the event detection algorithm was configured to identify contiguous pixel areas above the threshold T . Specifically, a Boolean mask was generated from all pixels within a given camera frame, and those above pixel value T were assigned the value 1, while those below threshold were assigned a 0. Following published procedures used in localization-based super-resolution microscopy (Hess et al. 2006, Gould et al. 2009, Gudheti et al. 2013, Curthoys et al. 2019), the Boolean mask was used as an input for the Matlab regionprops function, which quantifies properties of contiguous high pixel areas (“clusters”) within an image. For each cluster, regionprops was configured to output a list of pixel indices, an area, perimeter, and eccentricity value ϵ , which is determined for the ellipse with the same second moments as the cluster being analyzed, and is defined as the ratio of the distance between the foci and the major axis length. For a circular region (or a 1×1 pixel cluster), $\epsilon=0$; for a two-by-one rectangle, $\epsilon=0.866$; for even longer rectangles, ϵ will approach 1. Thus, the selection of $\epsilon>0.6$ rejects single (1×1) pixel clusters, keeping all other geometries.

Using the pixel indices, the sum of pixel values (S) in the original image was obtained for each cluster. It was noted that for $\epsilon>0.6$, the number of clusters per frame (n_{CPF}) detected in the absence of a known radioactive source (i.e. the background count rate) was significantly lower, while significant n_{CPF} values were observed in the presence of various sources (Figure 8). Thus using eccentricity value ϵ as a further threshold for areas of multiple connected pixels yielded lower background count rates (n_{CPF} in the absence of a source) while maintaining significant signal from radioactive sources. Histograms of cluster S values for various sources and background are shown in Figure 8A.

In order to improve interpretation of the imaging events observed, the measured field of view of the Gigaware X76 CCD ($42.4 \pm 0.6^\circ$), the known focal length of the imaging lens ($f=4.3$ mm), and the sensor size (1280×1024 pixels) were used to calculate w_p , the width of individual pixels within this particular sensor ($w_p = 3.07 \pm 0.04 \mu\text{m}$). The pixels within videos (acquired with 2×2 binning) are therefore $6.14 \pm 0.08 \mu\text{m}$ in width.

Measurement of Energy Sensitivity of Webcam CCD

Experiments were carried out to determine energy sensitivity of the CCD within the Gigaware 1.3 MP camera. The camera was kept intact (not disassembled), and the lens was covered with several layers of black electrical tape to block all visible light. All video data collected was at 640×480 resolution at 30 frames per second. The following sources were used: ^{137}Cs (8.5 μCi) and ^{60}Co (1–5 μCi) button sources, a ^{109}Cd (20 μCi) XRF exciter source, and the neutron howitzer. The button sources were placed directly on the camera. The camera was placed directly on the ^{109}Cd source, and for all runs in the neutron howitzer, the camera was placed at a fixed distance 4 cm from the interior end of a sample tray. Videos of both 5 and 15 minute duration were taken. Video data for the neutron howitzer was taken with (a) no shielding material, (b) 4 cm of lead in front of the camera, or (c) 4 cm of boron-infused plastic in front of the camera. Videos were also taken with the camera far from all sources to represent the background from the laboratory and electronics.

The video files were then analyzed using the Matlab script described above. Histograms of the pixel intensity of all fitted clusters for each file were generated. After setting a threshold to remove all clusters with summed count values $S < 1000$, which helped to remove noise from camera electronics and other sources of background, cumulative histograms of S were obtained for each standard histogram of S . The S_{95} , defined as the S value below which 95% of the clusters were observed in the cumulative histogram was determined for each data file. The S_{95} was chosen as a good estimate of the upper limit of the Compton-like continuum of each histogram, which should correspond to the energy of gamma rays emitted by each source. A plot of gamma ray energy versus S_{95} was generated for the lab background, ^{109}Cd , ^{137}Cs , and ^{60}Co sources. The highest energy photon emitted by the source was used in the case of sources which emit multiple photons, such as ^{60}Co and the silver K-shell x-rays from the ^{109}Cd . Results for the neutron howitzer were obtained, but are not shown because the Pu-Be reaction does not produce gamma rays of a single energy.

RESULTS AND DISCUSSION

When placed in the vicinity of a neutron howitzer, we observed that several consumer-grade cameras showed a substantial increase in the number of bright pixels. In most cases, several bright pixels were observed adjacent to one another (Figure 3B,C), typically yielding a shape which was somewhat elongated. This observation led to a quantitative investigation of the use of low-cost CCD detectors as uncharged particle detectors.

First, the relative efficiency of the CCD-detectors was determined by comparing the number of events observed by each CCD to that measured by a calibrated Helium-3 proportional counter. As theoretically expected, the CCD units containing Boron (Gigaware Z76, Logitech C270) are marginally better neutron absorbers (Krane 1987) compared to those without, as observed in the reported count rates. The count rates for the CCDs are as shown in Figure 4. Figure 5 shows measured count rates for various CCDs plotted together with the theoretical diffusion model and data from the LND25185 He-3 proportional counter.

Though there is a disparity in magnitude of the detected count rate comparing the CCD-detectors with both the theoretical model and LND25185, the functional behavior of the data

is similar. Because of this similarity, once the efficiency for each of the CCDs is determined, the experimental data could be reliably scaled in magnitude to better reflect the neutron count rate inside the chamber. The relative efficiencies for each detector are shown in Figure 6. Note that the CCD efficiency is expressed as relative to that of the He-3 detector.

Next, a correlation between incident gamma particle energies and the intensity of pixel levels in recorded video from the CCD detectors was determined. This was accomplished through use of varied thicknesses of lead shielding and multiple runs at the same radial distances to compile data. Due to the limitations in the availability of shielding thicknesses and the limited intensity of some energy ranges of emitted gammas by the ^{239}Pu -Be source (Vega-Carrillo et al. 2002) larger MeV intervals were chosen as opposed to smaller (narrower), keV intervals. These ranges are; 0–6MeV (total high-probability emission for ^{239}Pu -Be source), 0–1MeV, 1–2MeV, 2–3MeV, 3–4MeV, and 4–6MeV (effectively the tail end of the emission; while there is a small percentage of gammas which can have energies as high as 7MeV, they are low probability events).

For each energy range, and the radial distances of 2.54 and 5.08cm, the results of this were determined for both the mean pixel saturation of the overall video as well as the pixel intensity per unit frame. This was accomplished through another computational algorithm constructed in Matlab which read the same input video files, but instead of counting the number of stimulated pixels, it measured both the average RGB (red, green, blue) and gray levels in the video. This, coupled with a black and white binarization and an adaptive filtering, enables for analysis of not only the pixel saturation per unit frame, but also a mean value for the entire video. Because of LET, the amount of charge accumulated within the MOS capacitors should be linearly related to the energy of the incident particles (Schott 1993). Runs were conducted where the neutrons were blocked using a pair of Grade 1 borated polyethylene absorbing disks, and then different thickness of lead shielding as to restrict energy gaps. Energy ranges used/blocked were based on the published gamma energy spectrum of a ^{239}Pu -Be source (Hubbell 1982).

While the mean grayscale pixel values (intensities) are numerically different for each of the CCD detectors (Figure 7), this is expected since the gray scales in the frames will be influenced by physical and electronic aspects of each device, such as gain, for example. However, the critical observation from this data is that each CCD detector showed the same trend of increasing pixel intensity as the incident energy range was increased (Figure 7), while also showing the expected decrease in count rate as distance from the source increased (Figure 5). In the non-energy-restricted run, the total average pixel intensity is reportedly lower than for the highest energy range, which is expected because the gamma emission events from the ^{239}Pu -Be are more abundant for energies less than 4MeV than for energies greater than 4MeV (Vega-Carrillo et al. 2002). In other words, the lower energy events are more frequent and cause a significant reduction in the average.

Though there is a clear correlation between energy and the pixel intensity within the camera frames, there are two additional factors that could be impact the accuracy of these values that are worth addressing. First, because this is a mean grayscale calculation, it is possible that ‘spill over’ events could have occurred where high-energy incident gammas cause

charge accumulation in multiple adjacent capacitors (i.e. pixels; Figure 3B, C) (Inoué and Spring 1997), and thus introduce additional (potentially lower intensity) pixel values into a group of above-background pixels. This could cause the mean pixel value to be artificially decreased by some magnitude though the particle energy (and energy deposited within the CCD) remains high. Secondly, because it is unknown exactly how much charge the capacitors can hold in each of the CCD detectors, the probability of spillover events cannot be determined. Nevertheless, it is important to note that each of these factors would not prevent meaningful interpretation of the data but could increase the uncertainty in the interpretation of any given CCD high-pixel event. Third, the interaction between the incident particle and the CCD can occur over a finite distance: 3–30 μm for alpha particles or protons ranging from 1 MeV – 10 MeV incident on Si (Williamson et al. 1962). Neutrons from our howitzer are expected to have energies up to 10 MeV (Vega-Carrillo et al. 2002), and those interacting with Boron in the CCD are expected to produce alpha particles (Cox and Pontet 1967, Akgun et al. 2010), gammas (Firestone and Revay 2016) and protons (Mitra and Ghose 1966) with energies <10 MeV. Considering an emitted alpha particle with energy of a few MeV, the expected interaction length is ~3–40 μm (Williamson et al. 1962, Akgun et al. 2010) will span multiple pixels (each ~6 μm square in our case), and images of such interactions may be elongated in shape. We observe this elongation in shape for many of the CCD events in the presence of our neutron source (Figure 3B). Events observed in the absence of the neutron source (presumably background noise within the sensor or other sources of background counts) did not show systematic elongation (data not shown).

Figure 8 shows histograms of S (the total counts in each CCD event) as a function of various radioactive sources in proximity to the CCD. Figure 8B shows a plot of S_{95} vs highest energy of the incident radiation photons. Error bars for the pixel intensity are estimated using the square root of the total number of clusters for each file. Figure 8B shows a monotonic increase of S_{95} as a function of incident gamma photon energy, suggesting that the CCD used is capable of detecting differences in energy.

The number of clusters of bright pixels in each file was also determined, and together with the number of frames within the acquisition, was converted to a rate of clusters per frame (n_{CPF}) for each video file. The n_{CPF} was plotted against the activity of each source counted, to show efficiency of the CCD camera and analysis software (Figure 8C).

CONCLUSION

This study has found that low-cost, consumer-grade CCDs are effective detectors of uncharged particles, with neutron detection efficiencies ranging approximately 14% to 18% relative to a He3 detector (or ~2% overall efficiency), presumably depending on the presence of boron in the CCD or glass components near the CCD. Gamma particle detection was also successful; we observed both single-event-interactions and internal gamma particle scattering within the sensor. Additionally, by restricting incident gamma energy ranges to bands: 0–1, 1–2, 2–3, 3–4, 4–6 MeV, a (nearly) linear relationship was observed between incident energy and pixel intensity.

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Figure 1. Count Rate vs. Distance from Center of Neutron Howitzer used for calibration of LND 25185 ^3He detector. Points indicate count rate measured by LND 25185 detector (blue) and by Landauer film badge data (orange).

Figure 2. Neutron Count Rate vs. Distance from Source.

Theoretical neutron flux model compared against neutrons observed with LND25185 Helium-3 proportional counter.

Figure 3. Analysis of CCD images for particle detection.

(A) Single image frame taken from an unshielded, Gigaware 1.3MP webcam acquiring at 2.54cm from the source. (B,C) Zooms of region 1 and 2, respectively, shown in dashed boxes in A. (D) Intensity thresholded image used for subsequent event analysis. (E) Histogram of areas (measured in pixels) of events above threshold for entire acquisition. (F) Histogram of pixel intensities (total counts in spot) for all images in the same acquisition.

Figure 4.
Observed count rates for lead-shielded CCD detectors.

Figure 5.

Comparison of count rates measured for lead-shielded CCD-detectors, LND 25185 Helium-3 tube, and predicted by the theoretical diffusion model.

CCD-Detector Efficiency Comparison

Figure 6.
CCD-detector efficiencies determined with LND 25185 experimental data.

Figure 7.
Mean gray levels of pixels recoded during 2.54cm runs vs gamma energy for each CCD.

Figure 8.

(A) Histograms of S generated from multiple video files, showing the frequency distribution of S , the integrated pixel values for each cluster, for various sources in proximity to the CCD (or no source, labeled background). Clusters were identified from images as areas with grayscale values above 150 (arbitrary units). Identified clusters were then thresholded for eccentricity values $e > 0.6$ and S values > 1000 . Neutrons emitted by the howitzer were largely attenuated by 4 cm of boron enriched polyethylene. (B) number of clusters fitted per frame (nCPF) plotted vs Source activity in μCi for different sources. Source activities were corrected for known branching ratios. (C) Plot of S_{95} vs. highest energy of gamma rays emitted for S histograms measured using a CCD in proximity to a ^{109}Cd , ^{137}Cs , or ^{60}Co source. The laboratory background is included as a source of zero gamma ray energy.

Table 1.

Average pixel intensity (mean gray level) for incident gamma ray energy ranges.

Detector	Distance (cm)	Average Intensity (all energies)	Average Intensity (0–1 MeV)	Average Intensity (1–2 MeV)	Average Intensity (2–3 MeV)	Average Intensity (3–4 MeV)	Average Intensity (4–6 MeV)
Gigaware X76	2.54	12.48	10.72	11.22	11.77	12.25	14.73
	5.08	12.39	10.72	11.32	11.87	12.23	14.75
Gigaware Z76	2.54	16.06	15.03	15.40	15.72	15.91	16.91
	5.08	16.03	15.03	15.38	15.72	15.90	16.93
Logitech C170	2.54	1.044	0.790	0.831	0.913	0.987	1.218
	5.08	1.047	0.791	0.831	0.914	0.986	1.218
Logitech C270	2.54	1.198	0.886	0.930	0.998	1.154	1.438
	5.08	1.198	0.887	0.930	0.999	1.155	1.438