Low Cost, Pervasive Detection of Radiation Threats

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Abstract—**The recent nuclear crisis at Fukushima, Japan is a stark reminder that radiation emergencies can and do happen. In addition to accidents, the potential use of radioactive materials by terrorists has raised serious concerns. While the primary concern has been with preventing these materials from entering the United States, thousands of dangerous radiological sources are already here within our borders, located in vulnerable locations in hospitals, food processing plants, and industrial sites. These sources pose a risk for use in two terrorist threats described by the Department of Health and Human Services (DHHS): the Dirty Bomb and the Silent Source. In a Dirty Bomb attack, radioactive material is dispersed using a conventional explosive. In a Silent Source attack, radioactive material is hidden in locations where people congregate (restaurants, airports, subway stations, shopping malls, etc.). Both scenarios can injure or kill people and cause significant political, social and economic disruption. This paper will describe the GammaPix™ technology, which has the potential to provide low cost, pervasive detection of, and warning against, radiation threats. The GammaPix technology is based on software analysis of the images produced by a surveillance or smartphone camera to measure the local gamma-ray radiation exposure at the device. The technology employs the inherent gamma-ray sensitivity of CCD and CMOS chips used in the digital image sensors of these devices. This paper describes the use of the technology in calibration and testing scenarios using installed video cameras and smartphone cameras.**

Keywords – Radiation; Radiation Detection; Gamma Rays; Gamma-Ray Detection; Nuclear Physics; Dirty Bombs; Silent Sources; Radiological Sources; Radiation Emitting Devices; CCD; CMOS; Surveillance Cameras; Smartphone Cameras; Video-centric Detection

I. INTRODUCTION

The recent nuclear crisis at Fukushima, Japan is a stark reminder that radiation emergencies can and do happen. The potential for other such disasters exists at the nearly 500 other nuclear power plants around the world, some with designs identical to those in Fukushima. Other types of radiation accidents have also occurred, such as the April 2010 radiation exposure in Mayapuri, India, in which several individuals received significant radiation doses, resulting in eight hospitalizations and one fatality.

In addition to accidents, the potential use of nuclear and radioactive materials by terrorists has raised serious concerns [1-3]. Preventing criminal transport of nuclear and radiological material has been a national security priority. Since 2002, the U.S. has spent more than $3 billion on nuclear monitors at Canadian and Mexican land border crossings and U.S. seaports, and another $2 billion on security for nuclear power plants. While the primary concern has been with bringing radiological material into the United States, thousands of dangerous radiological sources are already here within our borders, located in vulnerable locations in hospitals, food processing plants, and industrial sites. These sources pose a risk for use in two terrorist threats described in Department of Health and Human Services (DHHS) reports [4,5]: *Dirty Bombs* and *Silent Sources*. In a Dirty Bomb attack, radioactive material is dispersed using a conventional explosive. This is also known as a Radiological Dispersion Device (RDD). In a Silent Source attack, radioactive material is hidden in locations where people congregate (restaurants, airports, subway stations, shopping malls, theaters, etc.). This is also known as a Radiological Emitting Device (RED). A Silent Source attack using the radioactive material from just one hospital source could invisibly poison tens of thousands of people and cause thousands of fatalities even before the source of the danger was discovered, a terrifying outcome. Computer files captured by the U.S. Government from al Qaeda detail the above scenarios, and many analysts believe that such attacks are likely within the next five years. The 1 May 2010 bombing attempt in Times Square reminds us that the terrorist threat is very real.

The Council on Foreign Relations is in agreement that it is likely that terrorists will try to use radiation as a weapon [6]. In addition, there have been several recent instances of specific radiological threats from terrorist groups along with documented intelligence indicating that these groups remain committed to acts that would produce mass casualties [7]. Are radiation sources well protected? The answer is no! "Since 1998, more than 1,300 incidents have taken place in the United States alone where sealed sources have been lost, stolen, or abandoned" [8]. In India, such a lost source, improperly disposed of by the Chemistry Department at Delhi University, killed one person in April 2010 and poisoned six others [9]. In

Argentina, a radiological source was stolen in February 2009, but fortunately was recovered in a police raid [10].

There is increasing awareness of the need for better radiological threat detection (RTD). The New York Times [11] and other publications have discussed the efforts of New York City law enforcement officials to expand the RTD network out from lower Manhattan to include the entire city. In November, 2009, the U.S. completed its border system to monitor incoming radiation. According to an article in the Ottawa Citizen [12], "every car, truck and passenger entering the United States by land from Canada is now searched for nuclear weapons.... Preventing terrorists from detonating a nuclear weapon in a major U.S. city is therefore a key national security priority, with more than $3 billion U.S. spent since 2002 on nuclear monitors alone at Canadian and Mexican land border crossings and U.S. seaports." However, with tens of thousands of radiological sources located in ill-defended locations already inside the U.S., the need for affordable and pervasive RTD remains. The capability is needed to: 1) help to secure radiological materials against accident, theft and unauthorized transport; 2) provide an alarm to warn of the presence of radiological material released by accident or terrorism; 3) provide the military and first responders with additional tools to manage radiological emergencies; and 4) provide the public with a tool with which to assure that the environment is safe from excessive radioactive exposure.

The GammaPix[TM] technology, developed at Advanced Fuel Research, Inc. (AFR) and recently acquired by Image Insight, Inc., has the potential to provide low cost, pervasive detection of radiation threats. This technology is a unique, software-based approach that is intended to provide gamma-ray radiation detection capability using the installed base of hundreds of millions of existing digital surveillance cameras, web cams, and smartphones. Once installed and calibrated, the patented, proprietary technology has the potential to: help prevent the theft and illegal transport of radioactive sources; help protect people from radiation accidents, Dirty Bomb or Silent Source attacks; and assist first responders in case of radiation emergencies. The GammaPix technology uses software to measure the local gamma-ray dose rate by analyzing the images produced by the CCD or CMOS chips of surveillance cameras or smartphones. Because the technology requires only software and already available hardware, it could be rapidly and inexpensively deployed by internet downloads to hundreds of millions of devices. In particular, the dramatic increase in the use of camera-equipped smartphones presents a unique opportunity to combine radiation threat data over a wide geographic area from both public and private sources.

II. TECHNOLOGY OVERVIEW

The GammaPix technology was conceived by Dr. Eric Rubenstein in 2002 and reduced to practice at AFR in 2004. The technology received its first U.S. Patent (US. 7,391,028) in 2008 [13]. A second US patent (US 7,737,410) has since been received together with foreign patents [14]. The application of the technology to video surveillance cameras was supported from 2004 to 2010 by the National Academy of Sciences [15] and the Department of Homeland Security [16]. Successful tests and calibrations of surveillance camera prototypes have been conducted at Oak Ridge National Laboratory (ORNL), Hartford Hospital, and the Washington, D.C., Metro [16-19]. Under the sponsorship of the Defense Advanced Research Projects Agency (DARPA), we have successfully demonstrated the use of the technology for camera-equipped smartphones [20]. As part of this project, calibrations and testing of several phone models were done by National Institute of Standards and Technology (NIST).

The GammaPix technology is based on software analysis that operates on the digital images produced by a surveillance or smartphone camera to measure the local gamma-ray radiation exposure at the device. The GammaPix technology employs the inherent gamma-ray sensitivity of CCD and CMOS chips used in the digital image sensors of surveillance cameras and smartphones. The gamma-ray detection works by counting the number of gamma rays whose impact on the device's image sensor produces bright pixels, as shown in Fig. 1 for an image collected at ORNL in an 800 R/hr radiation field caused by a 600 Ci ^{137}Cs source. The image is only illustrative for demonstration purposes, as the technology is sensitive to dose-rates more than a million times smaller. It is sensitive
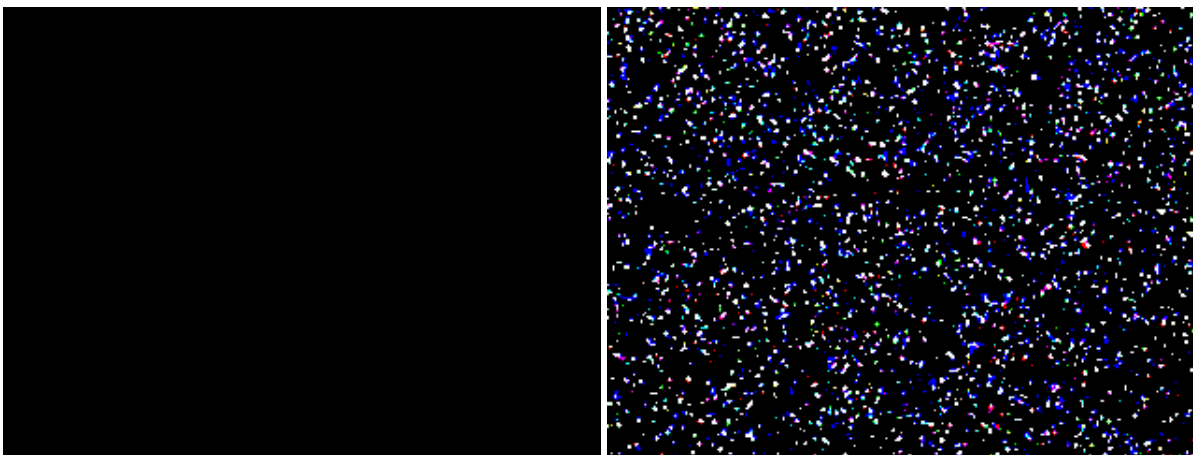

Figure 1. Images taken a half-second apart with a CMOS video camera at Oak Ridge National Laboratory. The left image is with the source hidden, while the right is after a large ^{137}Cs source had been exposed nearby.

enough to detect within seconds highly dangerous levels of radiation that could cause serious radiation poisoning with an hour or less of exposure at close range. Such a dangerous source can safely be detected on certain GammaPix equipped smartphones, in some cases at up to 100 meters away from the source. Collecting data over minutes can detect radiation exposure levels that pose health hazards for exposures of days, weeks or years. Using even longer times, low natural levels of radiation from cosmic rays and terrestrial gamma rays can be detected on such platforms.

The GammaPix technology has been tested with many different cameras, and functions well for video cameras, webcams, and other digital cameras. The sensitivity of the system depends on the physical size of the CCD or CMOS chip present in the camera. Our experiments have demonstrated that, for similar environmental factors, once a particular model camera has been calibrated, such cameras have a well-characterized response to a particular exposure rate.

III. VALIDATION

The GammaPix technology was first subjected to detailed validation tests at the Oak Ridge National Lab (ORNL) in July 2007 [17]. These tests were repeated and extended in April 2010 [18,19]. In the more recent work, a three-camera system was brought to ORNL for test and evaluation of its response to varying levels of gamma radiation and ambient lighting conditions. Four tests were conducted to evaluate the system's functionality, sensitivity, and resistance to false positives. Success was determined by reference to the statistical framework for metrics based on the ANSI N42.38 standard, although no existing ANSI N42.xx consensus standard applies to this novel technology. The GammaPix technology successfully passed all four tests demonstrating:

- No false alarms during more than 24 hours of continuous operation in both lit and dark environments, including a stairwell that people routinely used. The ANSI N42.38 standard permits up to 3 false alarms per day.

- Rapid alert notification of a simulated Radiation Emitting Device (RED) under various lighting conditions, as shown in Fig. 2. The test replicated the radiation field arising from a 30 Ci ^{137}Cs source at a distance of 10 m, 92 mR/hr, and was performed at three different light levels from dark to the illumination typical of a hospital Emergency Department (200 lux). Detection was, on average, within 12 s at normal room lighting, and faster at dimmer light levels.

- Radiation alerts were generated at radiation dose rates down to 4 mR/hr in the dark, and 40 mR/hr under moderate lighting at the selected system sensitivity settings, as shown in Fig. 3. The system reported elevated radiation levels down to 20 mR/hr under moderate lighting and 40 mR/hr under brighter lighting, although the significance was not sufficient to trigger an alert with the selected system sensitivity settings.

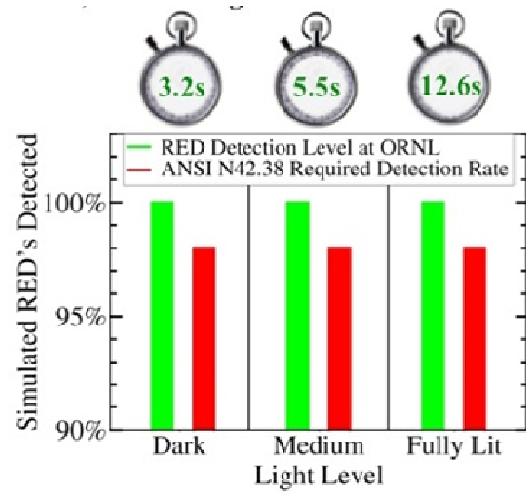- Prompt detection of very high radiation levels of 800 R/hr, as seen in Fig. 1.

Figure 2. Detection of simulated REDs for various lighting conditions compared to the ANSI N42.38 required detection rate. The times above each panel give the mean time to detection at each light level.
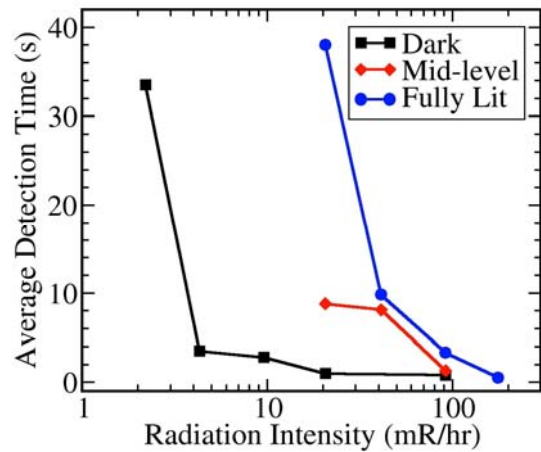

Figure 3. Average detection times versus radiation intensity for various lighting conditions. The sharp uptick in the detection time indicates the approximate location of the limiting radiation dose rate at each light level.

IV. INSTALLATION, TESTING, AND CALIBRATION

A. Hartford Hospital

Since hospitals are major potential sources of radiological materials, extensive testing was performed in hospital environments [15]. Results from tests of the technology at Hartford Hospital using a video camera are shown in Fig. 4. The average, frame-by-frame, radiation intensity level is plotted as a function of time. In the left panel of Fig. 4, the plot tracks gamma-ray hits during a two minute period in the Radiation Therapy Treatment Room. The immediate increase and decrease in radiation intensity occurs as the source was exposed and then shielded. The radiation level when the source
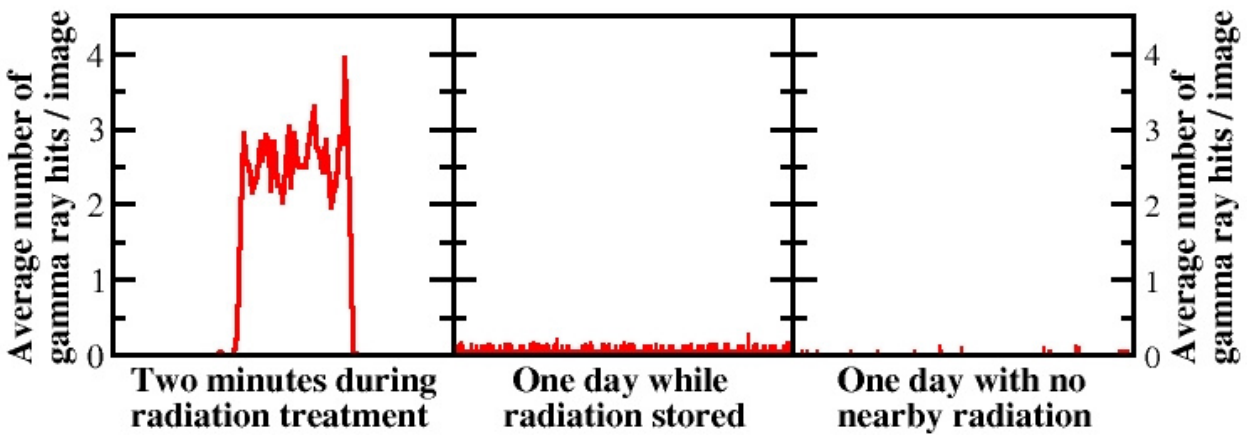
Figure 4. Gamma-ray levels for a radiation source at Hartford Hospital. Left: Source in use during a two-minute interval; Center: Source stored in a lead storage cabinet; Right: natural background

was exposed is well above the ambient level shown in the center panel. These data were taken over a period of one day, where the source was enclosed in its lead cabinet, but was still nearby. The low level of gamma-ray hits shows that the source is still detectable since the radiation level in the center panel is above the level shown in the right panel, where no source is in the vicinity of the detector. Since GammaPix detects the source, even when it is shielded, an extra layer of source security can easily be put into place. Sensitivity testing was also performed at Yale-New Haven Hospital, CANBERRA Albuqureque, Inc., and Landauer, Inc. [15].

B. Washington, DC, Metro Station

The purpose of our project under the National Academy of Sciences Transit IDEA program was to test and evaluate a prototype system to detect dangerous levels of radioactivity in rail transit stations [15]. A prototype, three-camera system was installed at the Medical Center station of the Washington Metropolitan Area Transit Authority (WMATA) on 13 January 2009 and has been running almost continuously since its installation. One of the cameras is shown in Fig. 5. The data collection allowed determination of the sensitivity under ambient lighting conditions. Use of preexisting security cameras and network infrastructure will greatly reduce cost and facilitate broad coverage. Transit stations are potential targets

Figure 5. One of three cameras (circled) deployed in a test installation of the GammaPix technology at the Medical Center Station of the Washington, D.C., Metro system.

for terrorist attacks because they serve large numbers of people daily. To protect against that threat, pervasive radiation detection is needed at all times. Transit systems pose special detection problems due to limited line-of-sight regions in transit stations arising from radiation blocking obstructions, e.g., concrete, steel, and earthen walls and supports.

While exploratory work under a contract from the Domestic Nuclear Detection Office (DNDO) of the Department of Homeland Security (DHS) suggests that the method can also be applied to analog camera networks [16], in practice the current algorithms are optimized for use with digital cameras.

We tested the efficiency of the system with an after-hours test where we brought a small radiation source into the station. The work was performed in collaboration with representatives from the Communications Division of WMATA and the Metropolitan Transit Police of WMATA. The conditions of the test were controlled so that it was possible to estimate the effective sensitivity of the detection system. An alarm was produced when the camera was exposed to a radiation field of about 17 mR/hr, a field approximately equal to what would be expected about two feet from a patient treated with nuclear medicine. As another comparison point, the Nuclear Regulatory Commission (NRC) and DHS have agreed that a "Threat-level" source of the radioactive isotope ^{137}Cs is 27 Ci, which the system can detect up to ~25 meters now, and eventually up to 50 meters or more. Such a powerful source is smaller than a pea and could very easily be mixed with putty or gum and stuck on the underside of a train seat. The GammaPix system would easily detect such a weapon within seconds of a train pulling into a station.

C. Smartphone Cameras

In October 2010, we started development, under a DARPA contract, of a smartphone implementation of the GammaPix technology. The initial version was developed for the Android™ platform. In response to the Fukushima accident, we rapidly sped up development of the app. Within a week of the nuclear accident at the Fukushima Daichi nuclear plant, NIST had carried out calibration experiments for two phone models. The next week, the sensitivity of the calibrated, prototype app

was also tested at NIST. At the date of this writing (June 2011), NIST has conducted two further rounds of testing. One, in April 2011, improved the ^{137}Cs calibration and extended it other phone models. The second, in May 2011, extended the calibration to lower energy gamma rays using an X-ray reference. Screen shots of the current beta version of the Android app are shown in Fig. 6.

Fig. 7 shows the results of March and April calibration tests conducted by NIST on eight smartphones. Five examples of the HTC Desire were tested, representing three different sub-models. In addition, two Dell Streak 5 phones and a single Nexus One (also built by HTC) were tested. A ^{137}Cs source was used for these tests and the phones were exposed in pairs. The strength of the radiation field was adjusted by the use of lead attenuators. The response curve is linear over a wide range of radiation dose rates. Phone-to-phone variations within a model are small, but clearly the three submodels of the HTC Desire do show some differences. Nonetheless, a single calibration can be used for all five phones at all dose rates tested with better than 10% precision. The calibrations of the two Dell phones are similarly consistent. For the Nexus One, the calibration is good to 3% below 500 mR/hr. Above that dose rate, there are small dead-area effects that bend the response curve downwards slightly, but further software improvements will reduce or eliminate this purely numerical effect. Variations between phone models are much larger. The Nexus One is slightly less sensitive than the HTC Desire phones, but the Dell Streak 5 is

nearly 20 times less sensitive than the HTC Desire. In the absence of information on the true exposure time in the current Android API, it is difficult to determine if these differences arise in the hardware or software of the varying camera modules.

NIST also tested an early prototype of the calibrated app on the HTC Desire against known radiation fields of various strengths. These tests demonstrated successful detection of gamma-ray exposures at a level of 0.4 mR/hr within 7 minutes for two smartphone models. This is over 6 times less than the occupational limit of 2.5 mR/hr for radiation workers while on the job. The natural gamma-ray exposure level was detected using a smartphone in 8 hours. Further developments of the app have reduced these detection times by a factor of two.

NIST conducted further testing in May 2011 to investigate the consistency of the calibration with energy. To complement the 662 keV ^{137}Cs data, an X-ray machine was used to produce lower-energy radiation fields. The NIST Standard H100, H200, H250, and H300 spectra were used. The numerical part of the name indicates the X-ray machine potential in kV, with the effective gamma-ray energy being about 20% less. The results of this testing are shown in Fig. 8, which shows that the effective efficiency response is consistent to within about 30% for radiation with energies from 166 keV up to 662 keV. Since the efficiency is higher at 80 keV, the reported dose rate for gamma-rays of this energy will be overestimated.
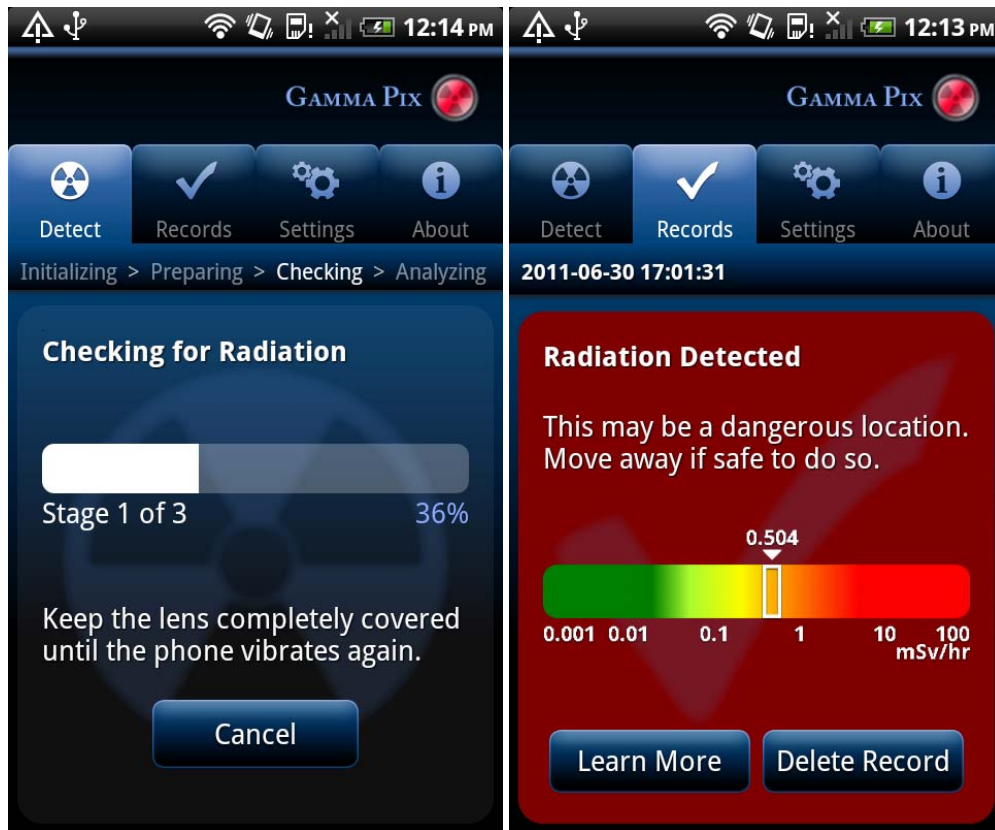

Figure 6. Screen shots of the GammaPix™ smartphone app running on an HTC Desire phone under the Android 2.2 (Froyo) operating system. Left: The app collecting its data. It is a requirement that the lens be covered. Right: The results screen for a positive detection of radiation. Units are in mSv/hr as per DARPA requirements. This ~60 mR/hr source was easily detected with less than 15s of data collection.
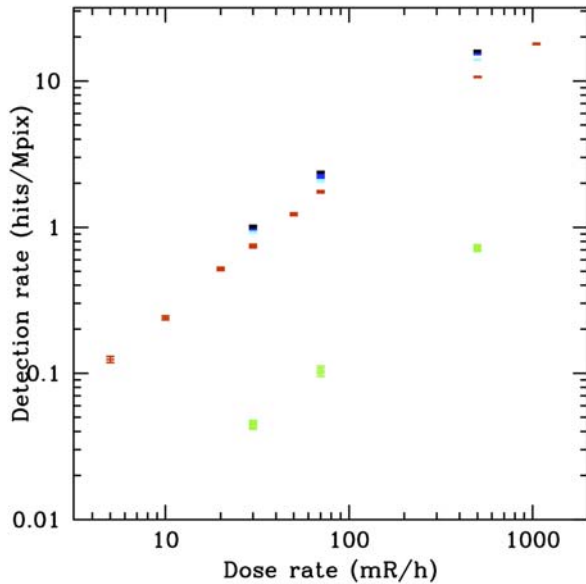
Figure 7. Dose rate response for eight phones based on March and April 2011 NIST testing. Green: Dell Streak 5 (2), Red: Nexus One (1), Cyan: HTC Desire 5VDC (1), Blue: HTC Desire LCD (2), Black: HTC Desire A8181 (2). (Number in parenthesis indicates the number of phones tested.)

Figure 8. Gamma-ray energy response for three submodels of the HTC Desire. Colors are as in Figure 7 except that only one A8181 device was tested and the green points are a second LCD. Duplicate points of a single color at a single energy represent two tests with different incident dose rates. The efficiency measure is the ratio between the detection rate in hits/Mpix and the incident dose rate in mR/hr.

V. CONCLUSIONS

Nearly 80 years after nuclear power was first unleashed at the University of Chicago's Stagg Field, public awareness of nuclear hazards is only increasing. In the aftermath of nuclear accidents, such as the meltdowns at the Fukushima Daichi nuclear plant resulting from the Tohoku earthquake and tsunami of March 2011, concern about radiation from industrial events and from possible terrorist activities, requires a proactive response. In the absence of absolute radiation security, there is a need for a low-cost, pervasive mode of radiation detection to both guard against, and prevent injury from, radiation events. For the same reasons, the general public has become interested in knowing more about their radiation exposure, and if possible, in personally monitoring their environment.

As it happens, radiation detectors are now ubiquitous; just unrecognized. The solid state imagers (CCD and CMOS) available on nearly every cell phone and portable computer, and increasingly prevalent in video security systems, can all detect gamma-rays. Our GammaPix technology is a software solution that enables the users to take advantage of this radiation-detection capability. The sensitivity of digital imagers, when combined with GammaPix software, is high enough to quickly detect dangerous radiation levels. Our methods guard against false positives, however, and can be selected to prevent innocent positives from the low-level radiation emitted by some radio-therapy recipients. Higher elevations, such as in airplanes, have increased background radiation and significantly reduced measurement times.

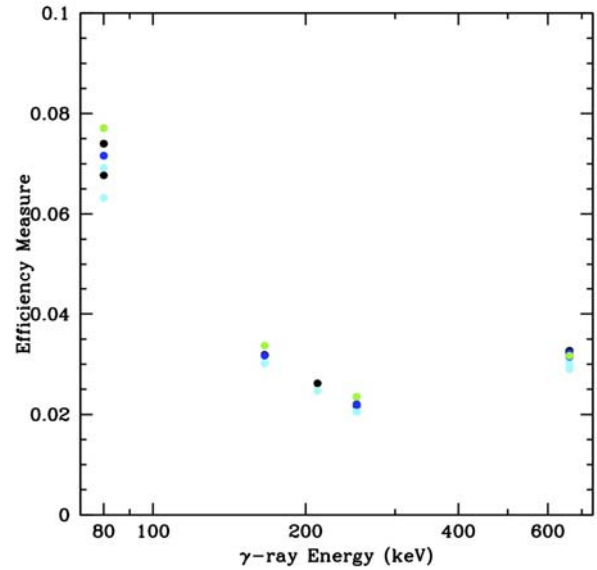The GammaPix system has been successfully tested at ORNL and NIST. Additional testing and a long-term technology demonstration was performed in the Washington, DC, Metro system in collaboration with WMATA. Successful tests were also carried out in hospital environments (Hartford Hospital and Yale-New Haven Hospital), and smartphone implementation of the GammaPix technology is at advanced stages of testing and deployment under a contract from DARPA.

In addition to the app being supplied to the military, we intend to bring commercial versions to market. The apps will contain a social networking capability to allow users to pool their readings and calibrations, compare their results with other users at the same location and retrieve prior readings for locations of interest. For obvious reasons, the commercial version is likely to be first deployed to the Japanese market, with others following. Active development of the technology is ongoing, and we hope to be able to soon supply the need for low-cost, pervasive, radiation detection.

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