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Compton Imaging for Standoff Radiation Detection: Report A

Further to the MOU on "Compton Imaging for Standoff Radiation Detection" between DRDC and NRCan and to the "Compton Imager Development for Standoff Radiation Detection" Annex to the Research and Development MOU between DRDC and NRC, 2012 – 2014

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Abstract

With funding from the Department of National Defence's (DND) Centre for Security Science, over the years from 2007 to 2012 a research team composed of scientists from Natural Resources Canada (NRCan), the National Research Council (NRC), and McGill University developed imagers to find radioactive sources and show their location overlaid on a photograph. These imagers were developed primarily for use in security/surveillance, and in consequence management. A follow-on DND-funded project called "Compton Imaging for Standoff Radiation Detection", governed by memoranda of understanding between DND and NRCan [1] and between DND and NRC [2], has been established in order to provide information useful in determining whether the Canadian Forces should procure Compton imagers. This is Report A specified in those agreements. We provide an introduction to Compton imaging, discuss the current technology readiness level of Compton imagers in Canada, and provide a status report of work under the project to date.

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1. Introduction

1.1. Background

Compton imaging is a technique, first described in 1974, which permits the construction of a two-dimensional image of a distribution of gamma-emitters, from measurements taken using layered, position-sensitive gamma detectors [3]. Also known as "electronic collimation", Compton imaging differs from "mechanical collimation" (coded-aperture, or pinhole imaging), in that a heavy mask at the front of the imager is not necesssary in order to reconstruct the direction of the incoming gamma-rays. In Compton imaging, the gamma-sensitive volume constitutes most of the weight of the imager, making it the most efficient method for mobile applications.

A gamma ray of energy greater than about 300 keV encountering absorbing material, will typically Compton scatter one or more times before undergoing a photo-electric absorption event. A "golden event" for a Compton imager is the coincident detection of the positions and energies of an event in which a single Compton scatter occurs followed by the subsequent photo-absorption of the scattered gamma ray. From the scatter and absorption energies, the angle θ_C through which the gamma scattered is determined up to an unknown azimuthal angle. Thus the position of the emitter is constrained to lie on a cone with opening angle θ_C and axis along the line between the scatter and absorption positions. This process is illustrated in Fig. 1. By back-projecting several such "Compton cones", or applying a more sophisticated fitting algorithm, an image of the distribution of the gamma emitters may be built up.

Compton imagers have been used in astrophysics experiments [4–6], to image galactic and extra-galactic sources of gamma radiation. They are being explored for use in medical imaging [7] to image the distribution of radioactive tracers in the body. Compton imagers also have been developed for industrial use [8, 9].

The use of Compton imagers for emergency response, security, and defense, is still very new. A number of the designs which have been put forward involve solid-state components which are highly expensive if the imager is to have a large enough gamma-sensitive volume for fast time-to-image [10–12].

A group lead by Dr. Laurel Sinclair at Natural Resources Canada built laboratory demonstration units of Compton imagers, designed specifically for use by Canadian security forces [13–17]. These imagers rely on solid inorganic scintillator for gamma detection, a material which has high sensitivity for reasonable cost, and proven performance in mobile applications in outdoor environments in Canada. This was a project funded by Canada's Chemical, Biological, Radiological/Nuclear and Explosives, Research and Technology Initiative (CRTI) (now the Canadian Safety and Security Program (CSSP)), project CRTI 07-0193RD.

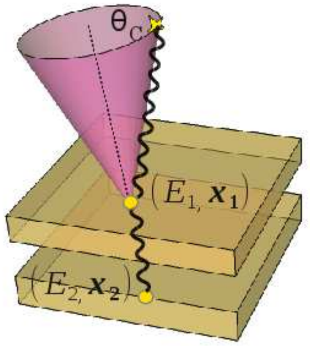

Figure 1: Generic Compton imager showing a Compton scatter with energy E_1 at position $\boldsymbol{x_1}$ in the scatter detector, and the subsequent absorption of the scattered gamma ray leading to energy deposit E_2 at position $\boldsymbol{x_2}$ in the absorber detector. The cone-shaped locus of possible source locations as reconstructed from the energy deposits is also shown.

In 2007, the United States Domestic Nuclear Detection Office awarded over $40M to four institutions to develop vehicle-sized gamma imagers for threat detection [18]. These were rapid-turnaround programs making use of commercial off-the-shelf components. Like the imagers designed under CRTI 07-0193RD, these systems make use of solid scintillator in order to achieve high sensitivity in a mobile application. However, three of these setups employed conventional (and one could say obsolete) shielded imaging techniques (coded-aperture imaging). One of the designs did make use of a hybrid technique involving Compton imaging as well [19]. This is quite a promising approach. A quantitative analysis of the performance characteristics and cost of this instrument does not appear to be publicly available, however it is clear that a device of this scale, confined to a dedicated vehicle, is not optimal for use by Canadian security teams. (Should this scale turn out to be optimal for the Canadian military, we can produce an optimized design and calculate performance characteristics for it, as will be discussed in Section 3.1.)

1.2. CRTI 07-0193RD

It is reasonable to expect that the Compton imager designs developed for Canadian security and emergency response teams are a good starting point for designing Compton imagers for use by the Canadian military.

A Compton imager typically consists of two sections; the “scatter detector” at the front initiates the Compton scatter, and the “absorber detector” at the rear collects the energy of the scattered gamma ray. The trick is to find a way to collect information from the scatter detector without introducing dead material in the path of the scattered gamma ray from the scatter detector to the absorber detector. Through the research conducted under CRTI 07-0193RD, two alternate methods for light collection were explored. In the “bar” detector, conventional photo-multiplier tubes (PMTs) were employed, but they were moved out of the path of the gamma-rays by locating them at the ends of long bars of scintillator [14, 15]. This approach provides the added advantage of reducing the number of read-out channels compared to a pixellated detector, with concomitant cost savings. The draw-back of this method is that some light must be lost in order to achieve sufficient position resolution along the bars, and this has a negative impact on the energy resolution of the imager/spectrometer.

In the other detector, called the “pixel” detector, the scatter layer was divided into fine scintillator “pixels”, and the light from each pixel was collected using silicon photo-multiplier arrays (SPMArrays). The SPMArrays were specially designed for CRTI 07-0193RD by SensL[1] to be extremely light and thin so as to introduce a negligible amount of dead material in the path of the scattered gamma ray. This is currently an expensive way to go as each individual pixel is instrumented with an SPMArray and readout electronics. However, rapid price reductions are occuring in both these areas so this is considered to be likely the more promising route for the future.

As of the close of CRTI 07-0193RD, two laboratory prototypes are running at the Ionizing Radiation Standards laboratory of the National Research Council at 1200 Montreal Road in Ottawa. These two prototypes are capable of producing a gamma image overlaid on an optical photograph. In a wide field of view (±45° x ±45°), the imagers are able to localize a point source to within one degree of angular resolution within well under a minute of data-taking for a 10 mCi Cs-137 source situated 40 m away. Fig. 2 shows a reconstructed image for just four seconds of data taking with a ^{137}Cs source at 20°, 10 m from the imager.

1.3. Technology Readiness Level

As of the end of CRTI 07-0193RD, and the beginning of this project, the two Compton imager prototypes are at a Technology Readiness Level (TRL) of 5. Two Compton imager demonstration units have been validated in a laboratory environment. Moreover, the performance of the imagers has been validated under some relevant operational conditions such as production of an image in a timely manner, and presence of multiple sources in the field of view.

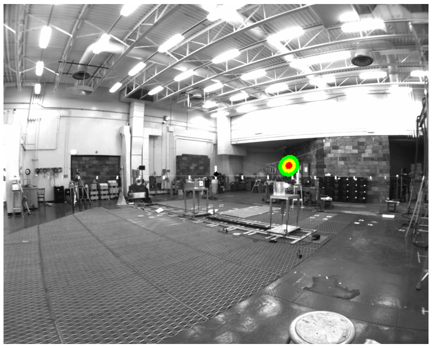

Figure 2: Image reconstructed from 20 seconds of data with ∼0.6 mCi ^{137}Cs source at 20°, 10 m from imager.

To progress to TRL 7, demonstration in an operational environment, the imagers would have to be ruggedized. Each design has particular engineering challenges which would have to be addressed. In the case of the pixel imager, it has been discovered that the active material of the SPMArray has been compromised by absorption of

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[1] SensL Technologies Ltd, Cork, Ireland

contaminants from the optical gel used to mate the SPMArray with the CsI(Tl) crystal, and a replacement model must be found (more on this below). In the case of the bar design, the crystal manufacture turned out to be challenging for the suppliers. A fraction of the bars has failed due to a) loss of the hermetic seal which protects the hygroscopic NaI(Tl) scintillator from humidity in the environment and b) the fragile nature of a long, thin bar. Some development work would have to take place to design a more effective housing for these crystals.

In addition, there is considerable engineering and development work which is common to the two designs:

- Implement gain stabilization
- Devise shock mounting to prevent breakage of crystals and components
- Develop custom electronics for
  - voltage supply
  - pulse amplification
  - pulse digization
- Develop exterior housing for
  - water resistance
  - temperature stability
- Make interface and packaging user friendly, including
  - simplified calibration
  - integration with Global Positioning System (GPS) measurements

(Please note that the discussion on technology readiness level included here has largely been copied from the CSSP project closeout report for CRTI 07-0193RD.)

2. Progress in 2012 – 2013

Work done under the Compton Imaging for Standoff Radiation Detection agreements was dominated by studies into the nature of the observed degradation of the SenSL SPMarray light output. Originally a mystery, after several discussions with the manufacturer on possible causes and many experiments at NRC comparing used and unused SPMarrays, it was finally concluded that the optical grease used to couple the CsI(Tl) crystals to the SPMarrays was contaminating the silicon, owing to a defect in the manufacturing process. Specifically, the company admitted that the edges of the SPMarrays had been left unsealed, so that slow, mobile charge carriers (such as sodium or calcium ions from the optical gel) could be introduced into the silicon on contact. A detailed comparison of the forward-biased and reversed-biased I-V curves for used and unused SPMarrays produced the evidence for this explanation. Fortunately, SenSL's SPMarray products are normally completely sealed, so this was a one-time defect peculiar to the specific design custom-developed for our CRTI project. Consequently, it is not expected to be an issue for future SPMarray units employed in an imager.

In going forward, it is necessary to come up with an alternative low-mass version of the SPMarray. From discussions with the supplier, it turns out there is at least one suitable off-the-shelf model that has an amount of dead material commensurate with our existing units. Given how quickly the field is advancing and that these are recent products, the units offer substantial improvements over our existing SPMarrays in terms of light collection efficiency and spectral range, and should lead to superior imaging performance. With the funds provided by DRDC we were able to obtain several units for testing.

Other procurements in the 2012 – 2013 fiscal year include: a large CsI(Tl) crystal to investigate the feasibility of migrating to an all-CsI(Tl) design, entirely read out by SPMarrays; an eight-channel thermocouple unit for monitoring CsI(Tl) temperatures; assorted RG-174 lemo cables and RG-58 BNC cables for the readout; a light-weight, compact high voltage crate to power the PMTs and SPMarrays, thus improving portability of the imager for field testing; a VME crate with digitizer and trigger cards for test-stand developments at NRCan and as back-up in case of failures; a digital colour camera with wide-angle lens for the optical image overlay; a small, USB-controlled, 360-degree rotation platform to automate the determination of the camera image mapping to true direction in space; digital pulse processing software for spectroscopic studies; firmware for a four-channel desktop digitizer for spectroscopy and coincidence studies; and a Cr-51 source for testing imaging efficiency at 320 keV.

3. Adaptation for Military Use

In order to design the optimal imager for military use, the project team members require information from the military on how they operate, and how their operations might be improved if they had an imager. We feel that it would be necessary for us to meet with experts on military operations in order to answer these questions before we could finalize designs for an imager for military use. We propose that a full development of two differing scenarios would provide us with the information that we need. That is, for two different prospective occurances, develop detailed scenarios including answers to the following questions.

- Who is the perpetrator? What are their resources? How many simultaneous threats/offensives are to be prepared for? Across what geographic extent?
- Incident has occurred, or is suspected?
- What are anticipated operating conditions? Outdoor, anywhere, anytime? Temperature, moisture, dust are all to be considered.
- What is the threat material? Dispersed or contained? Fissionable versus radioactive?
- How does the military respond? How many people? What equipment do they have? What vehicles?
- Is the military operation anticipated to be covert or overt?
- Does the military anticipate devoting a particular vehicle or other platform to the imager, or should the imager be transportable among platforms?
- A larger device is more costly but produces a faster time-to-image. Is this preferable? Or are several less-expensive imagers which take longer to image, preferred? Frank discussion of potentially available funding will be necessary.

We think that these answers can only be arrived at through a joint discussion among the scientists and military experts of what can happen and what response would be possible. Therefore we propose to hold a "utilization meeting" sometime in the fall of 2013, among the project scientists and military experts.

3.1. Way Forward

Based on the results of the utilization meeting, the suitability of the two current Compton imager models for use by the military will be assessed. The ruggedization of these designs so that they can at least be used for the security application for which they were designed should go forward. It is likely that the market conditions for the security application alone are insufficient to justify the risk and cost of this work being borne by a private-sector company alone. We will therefore seek funding opportunities to support this work.

Should it be decided that a completely different form factor for the imagers is necessary for military use, for example a much larger or much smaller device, a new design will be developed in software. The performance of this design will be determined through detailed simulation where the simulations have been validated against experimental results from the two working laboratory prototypes.

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