R4-C.3: Advanced Cargo Screening

I. PARTICIPANTS

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II. PROJECT DESCRIPTION

Core funding for this project ends in Year 3 per the outcome of the Biennial Review process.

A. Project Overview

A national security goal is the uniform screening of all cargo and checked baggage. Meeting this goal is challenging because of the volume of goods to be screened and the nature of screening required. This project aims to develop accurate physics-based models of cargo and checked baggage sensing, and to use these models to create methods for physics-based reconstruction and explosives recognition using novel multispectral modalities for cargo imaging. These methods will incorporate tools from compressed sensing and computational imaging to yield superior image quality from reduced measurement geometries and limited photon budgets that are typical for cargo applications. The methods developed will lead to more accurate and efficient screening of cargo, improving throughput, increasing detection, and reducing false alarm rates.

B. Biennial Review Results and Related Actions to Address

The project had high technical merit for developing methods to improve the image reconstruction and the automated detection capability for nuclear resonance fluorescence (NRF) as developed by Passport Systems. The team has a limited set of data provided by Passport, which is a critical aspect of moving the project along so that they have something tangible to work with.

The project targeted a very specific and rare product, and therefore does not address a significant knowledge gap for security that affects a well-established market or need. The recommendation was to discontinue the project. In response to this, the project will not proceed beyond June 2016.

C. State of the Art and Technical Approach

Conventional methods for baggage and cargo screening consist of fully helical CT for smaller objects (checked baggage), planar radiography, or trace detection for larger cargo. Such methods usually involve imaging the absorption properties of cargo of interest, and in cases where dual energy systems are used, imaging additional properties such as the effective atomic number. Helical CT is complex and expensive because of the need to encircle the cargo containers, requiring large instruments, and thus is not practical for larger cargo. On the other hand, planar radiography yields only limited information that makes threat identification and localization difficult.

In this project we aim to develop the tools necessary to create fully 3-dimensional property maps (i.e. reconstructions) from limited view, potentially high-energy sensing modalities. One aspect of this work has focused on developing models and methods for non-rotational, limited angle tomography. A new aspect of this project that we have begun is focused on developing non-rotational methods for tomographic imaging of modalities that can capture additional spectral properties of the materials contained in the field of view, such as nuclear resonance fluorescence (NRF) [1-6]. NRF is the process of resonance excitation of specific nuclear levels by absorption of photons and subsequent decay of these levels by re-emission of equivalent radiation. Since the energy level structure is unique for each isotope, the observed energy spectrum of the resonantly scattered photons can be used to identify the presence of specific isotopes.

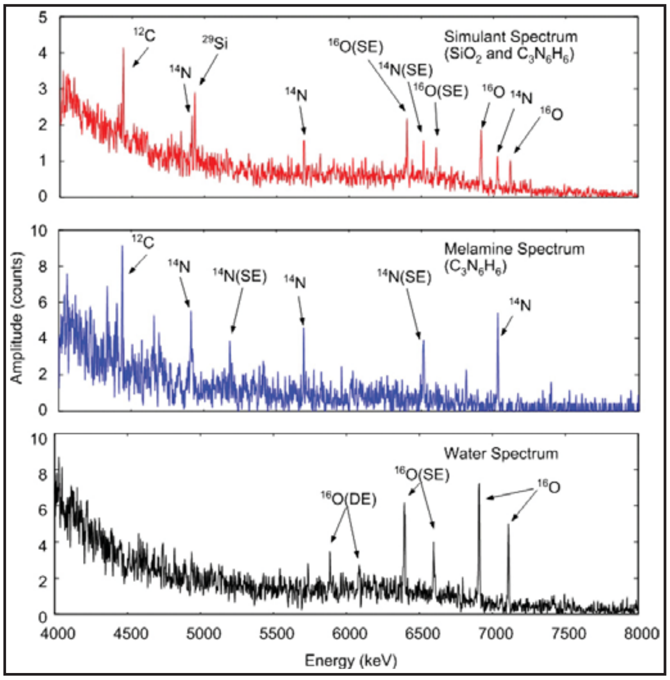


Figure 1: NRF Spectra for water, melamine, and a simulant explosive done by Passport System, Inc.

An NRF system for imaging of shipping containers has been built [1, 2] and is undergoing evaluation for detection of different materials. This system uses the conventional method of localization based on the combined use of source and sensor collimation, and thus collects only a small fraction of the fluorescence emissions. Tomographic methods offer the potential for collecting an increased fraction of the fluorescence emissions, but pose a difficult reconstruction problem to isolate and localize the different emission sources. Our goal is to develop algorithms for tomographic reconstruction of NRF emissions with non-rotating, limited views, and evaluate whether the reconstructed imagery provides appropriate quality for material discrimination.

Nuclear resonance fluorescence achieves its effect by exciting nuclei through photon absorption. These excited states subsequently decay by the emission of (gamma-ray) photons in all directions [1]. Further, the energy distribution or spectrum of such emissions provides a signature of a material related to its chemical composition. Figure 1 shows such spectra obtained for three different materials [1]. The three materials can be identified by their unique spectra.

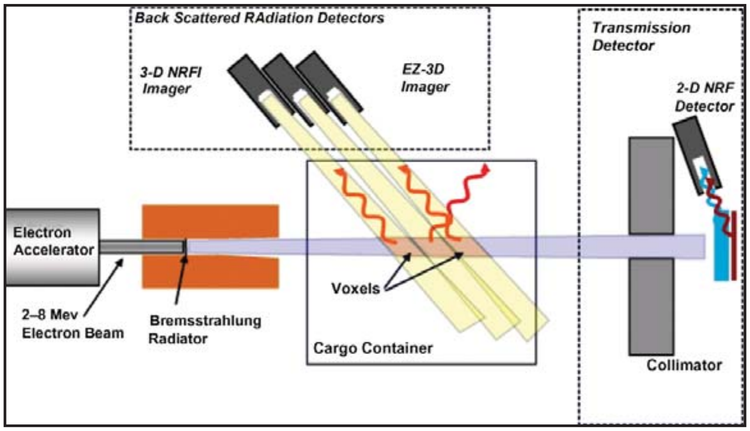


Figure 2: Diagram of a NRF system setup from Passport Systems, Inc.

This material specific signature produced by NRF provides the potential to non-intrusively interrogate the composition of cargo. The interrogating photons are of high energy, in the range of 2-8 MeV, and thus can penetrate thick and dense materials typically found in shipping container applications. A cargo inspection system utilizing this idea is being developed by Passport Systems [2]. In this system, an electron beam of broad energy distribution and narrow focus illuminates a confined line of an object, as illustrated in Figure 2. Only the locations in the illuminated beam are excited, which then fluoresce in all directions. To achieve spatial localization along the illuminated line, a set of collimated energy sensitive detectors are used. The intersection of the illumination line and the collimation opening localizes the measured response to a single spatial location. The energy sensitive detectors allow measurement of the material spectrum, which can be used to identify the material.

Collimation based localization eliminates the need for image reconstruction, since the geometry of the problem localizes the spatial response. However, the cost of this simple sensing scheme is that a majority of the emitted resonance photons are never measured. The relative photon efficiency of the collimation approach can be seen to be limited to a fraction of the circle observed by the collimated solid aperture angle. The consequence is a significantly reduced signal to noise ratio (SNR) and the need for long integration times. This is coupled to the need to scan the illuminating beam through the entire volume, thus slowing the scanning operation. To overcome this, the Passport Systems approach is to perform a limited angle CT tomographic reconstruction to identify areas of interest, before focusing the multispectral collection on the areas of interest to dwell and collect enough photons to achieve accurate estimation of material composition. We propose to study alternative architectures and algorithms that have the potential to collect enough photons to make a broader multispectral tomographic reconstruction. In addition, we are also interested in determining the classification performance that can be achieved by automated classification algorithms that exploit this information to identify potential explosives/contraband.

One aspect of this work is focused on replacing the current collimation-based localization approach with a coded aperture approach [11]. To this end, the collimators are replaced with a coded mask, as illustrated in Figure 3. In this architecture, emissions from the illuminated voxels can scatter to multiple radiation detectors, increasing the effective number of photons measured. This poses the subsequent challenge for processing the detected emissions to reconstruct the emissions generated by each voxel.

The coded mask, denoted by h, filters the spatially distributed emission data x, through a linear convolutional process to create the measured signal y:

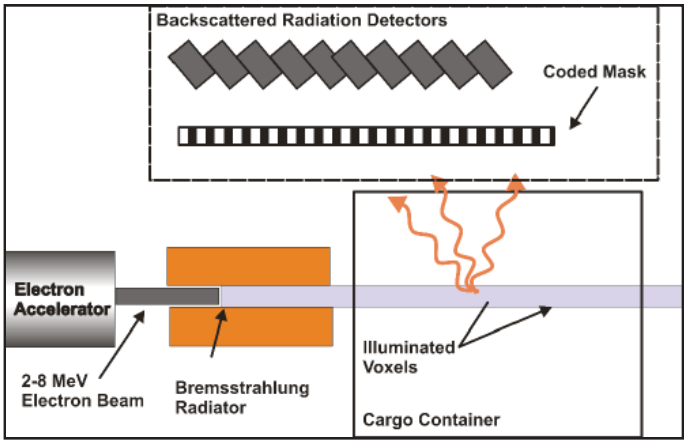


Figure 3: Diagram of proposed NRF system with coded mask localization.

$$y = h * x \tag{1}$$

Since the process is governed by counting statistics, the Poisson distribution applies. The overall SNR is then determined by the mean of the resulting measurements. In the coded mask case, this mean can be higher, since more overall counts are obtained at each detector at each of the energy bins measured. The penalty that is paid is that the spatial material distribution is now coded in the measurements and cannot be simply observed at the detector output. Instead, the equation (1) must now be inverted. This process is shown schematically in Figure 4 (on the next page). A simple model assumes that the emissions at each energy bin add linearly from the different fluorescing sources, therefore the reconstruction problem decouples into independent problems at each energy bin. In practice, we solve a regularized version of the implied inverse problem, with a regularization parameter chosen to suppress noise [10]. In the analysis that follows we focus on a reconstruction for a single energy bin.

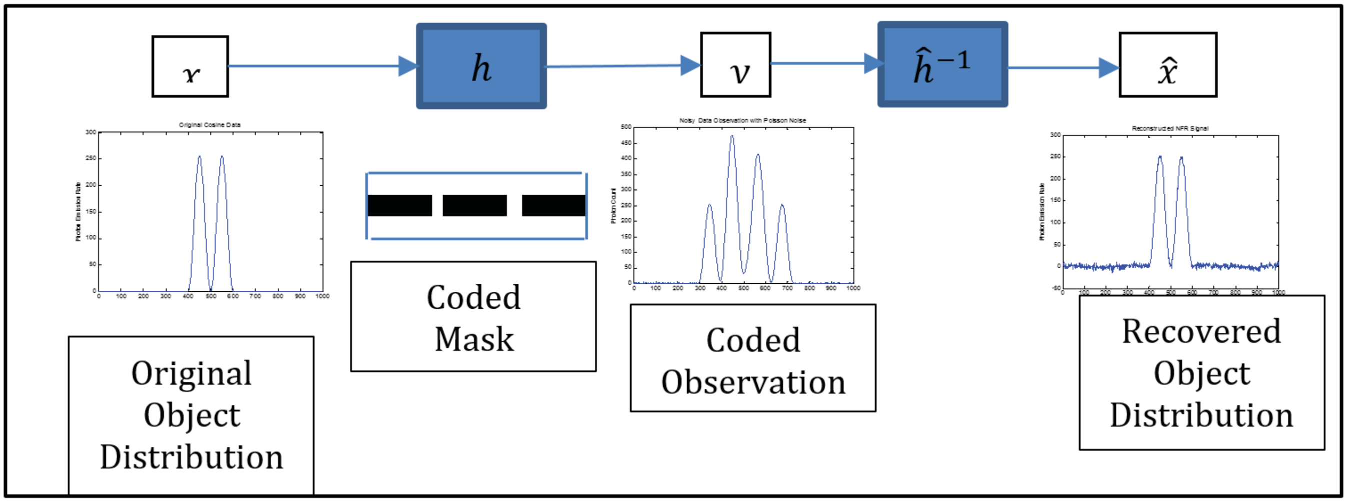


Figure 4: Schematic Illustration of Coded-mask Observation and Processing.

We have created a single energy reconstruction framework based on a penalized likelihood reconstruction framework with on a Poisson likelihood function:

$$\hat{X} = \arg\min_{x} HX - Y\log(HX) + \alpha\left\|Dx\right\|^2 \tag{2}$$

where X is sought after a set of estimated spectral profiles, Y is the coded set of observations, and H captures the image coding operator. We have implemented this approach on simulated data for a 256x256 phantom using XCOM photon cross sections.

In the Figure 5 (on the next page), we show the imaging geometry, as well as results at a single energy slice:

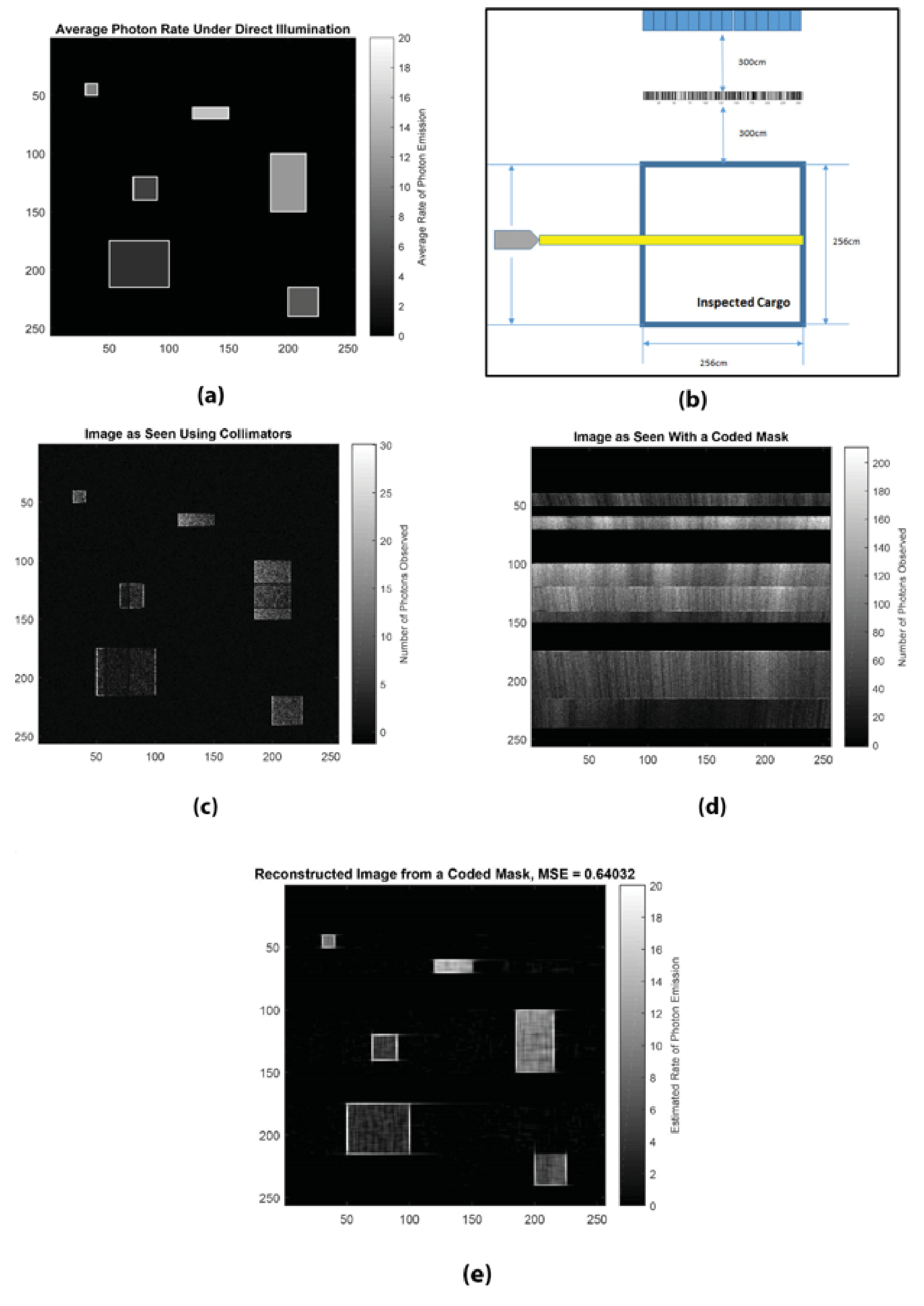


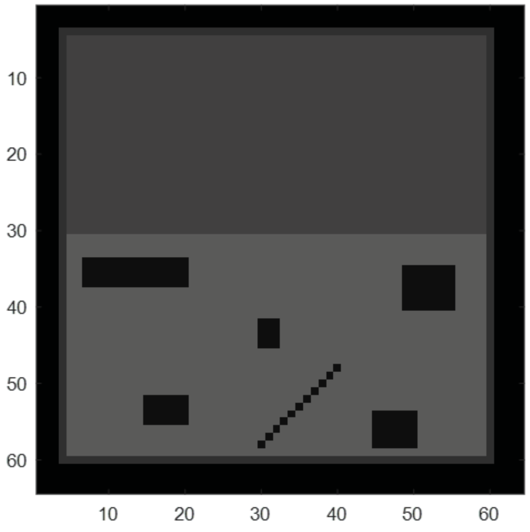
Figure 5: (a) Truth; (b) Imaging geometry; (c) Image as seen with collimated detectors; (d) Image as seen with a coded mask; and (e) Reconstructed image from a coded mask.

More recently, we have extended this framework to a fully 3-D (2-D space plus spectra) method directly incorporating estimation of material label:

$$(\hat{X},\hat{Z}) = \underset{X\in R^n, Z\in L^n}{\arg\min} \left\|Y - HX\right\|^2 + \alpha\left\|Dz\right\|_1 + \beta\left\|X - z\right\|^2 \tag{3}$$

where now z is constrained to be one of a finite set of spectral signatures associated to a set of materials of interest, and X is the continuum underlying spectrum. We solve this formulation by a coordinate descent alternating between the continuum X and discrete z using graph-cut methods for efficient solution of the discrete problem.

We have applied this method to fully spectral 3-D data (2-D space plus spectral) material recovery. The system geometry is the same as the above simulation. The materials and truth scene is provided in Figure 6.



(a)

Index	Material	Index	Material
1	Carbon	11	Bentonite
2	Lead	12	Fertilizer
3	Steel	13	Tobacco
4	Aluminum	14	Wood
5	Water	15	Vodka
6	Melamine	16	Gasoline
7	Sodium Chloride	17	Hydrogen Cyanide
8	Calcium Chloride	18	ANFO
9	HDPE	19	Blackpowder
10	Cocaine	20	Reddot

(b)

Figure 6: (a) Truth labels; and (b) materials list for fully spectral 3-D data material recovery.

We compare our coded-aperture integrated graph-cut approach to simple nearest-neighbor labeling in Figure 7 (on the next page). As can be seen, our integrated formulation provides superior results.

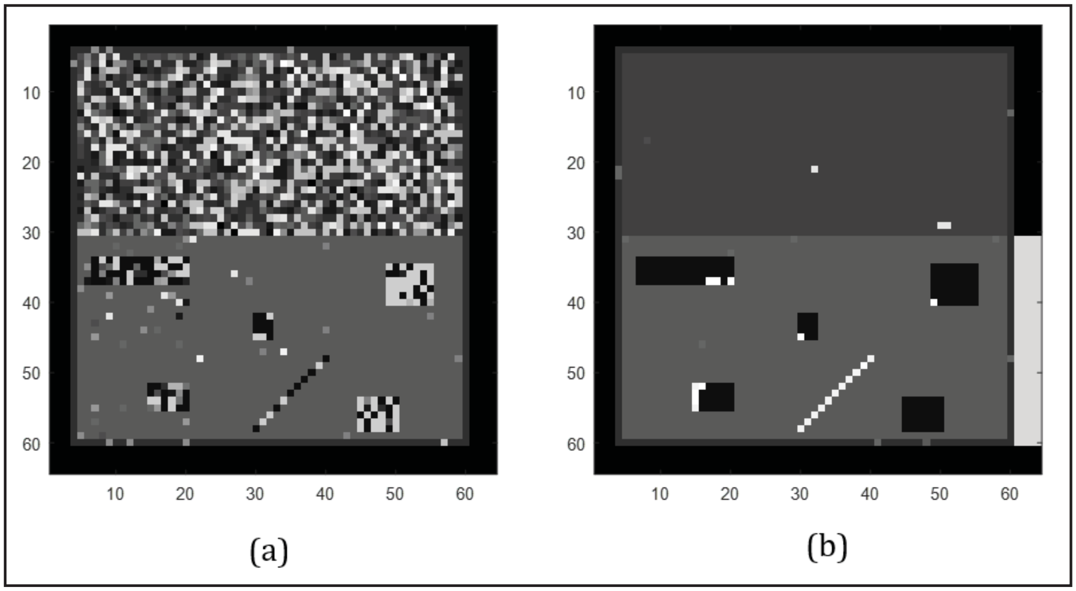


Figure 7: (a) Newest neighbor labeling approach compared to (b) new integrated graph-cut based approach.

D. *Major Contributions*

We performed a literature survey to identify areas of opportunity for enhanced algorithms for cargo inspection. We developed physical models for NRF sensing to develop approaches for new tomographic reconstruction techniques and for automatic material recognition algorithms. We have developed simulation models for generating test data to support algorithm development, and incorporated and modeled a coded aperture into the Passport system. We then developed reconstruction algorithms that incorporate both physical models, coded apertures, and noisy data, as well as prior models of field behavior. These include a novel integrated direct labeling and classification based approach using graph-cut algorithms for efficiency. We have also collaborated with Passport Systems, the developer of a commercial NRF imager for container screening, and obtained experimental data to support our model and algorithm development. We have developed a set of approaches for material recognition, and characterized the expected accuracy for estimating the mass fraction associated with different elements.

E. *Milestones*

- Development of initial high-energy X-ray sensing model of nuclear resonance fluorescence.
- Design of efficient coded aperture masks.
- Development of enhanced coded aperture inversion algorithms.
- Evaluation of signal-to-noise enhancement for coded aperture NRF tomographic reconstruction.
- Characterization of performance for element detection algorithms.
- Development of robust compound detection algorithms.
- Evaluation of robust compound detection algorithms.

F. *Future Plans*

This project was terminated as of June 30, 2016.

III. RELEVANCE AND TRANSITION

A. Relevance of Research to the DHS Enterprise

The development of new methods of fully three-dimensional non-helical screening and direct material identification of checked baggage and cargo would provide increased security. Currently, inspection of cargo materials is required, but is often done only with exterior sampling rather than with imaging of the cargo contents. However, there is a desire to have more accurate inspection of cargo and shipping containers that can detect hidden explosives. If our technology proves feasible, it could reduce the scanning time for shipping containers and provide a modality that can provide atomic composition of materials in areas of interest, as well as automatic threat detection and identification algorithms. Such approaches could have direct relevance at the checkpoint.

B. Potential for Transition

This project is directly relevant to the shipping container screening system developed by Passport Systems, Inc. Passport Systems has provided data for our use and a joint project on the classification aspect of the problem was done with them. Furthermore, the concepts can be scaled down for smaller cargo inspection systems, provided acquisition time is reduced. The technology for limited angle tomographic reconstruction can also be applied to 3-D X-ray systems with constrained source-detector geometries.

C. Transition Pathway

- We plan to disseminate our work to different vendors through workshops and conference presentations.
- We have provided our results and conclusions to Passport Systems for their system design.
- We completed a separate project with Passport Systems funded via the John Adams Innovation Institute collaboration with ALERT.

D. Customer Connections

Cody Wilson, of Passport Systems, Inc. is in contact with us.

IV. PROJECT ACCOMPLISHMENTS AND DOCUMENTATION

A. Peer Reviewed Conference Proceedings

1. Z. Sun, W. C. Karl, and D. Castanon. “Enhancing Nuclear Resonance Fluorescence with Coded Aperture for Security Based Imaging,’’ in Computational Imaging, C. A. Bouman, K. Sauer, editors, Proc. of Electronic Imaging, San Francisco, CA, February 14-18, 2016.

B. Student Theses or Dissertations Produced from This Project

1. Z. Sun. “Explosives Detection with Limited Data.” Ph.D., Boston University, Department of Electrical and Computer Engineering, August, 2016.

C. New and Existing Courses Developed and Student Enrollment

New or Existing	Course/Module/ Degree/Cert.	Title	Description	Student Enrollment
Existing	**Course**	**Image reconstruction and restoration.**	**Graduate course on image formation**	**15**

V. REFERENCES

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