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Leveraging Multi-Channel X-Ray Detector Technology to Improve Quality Metrics for Industrial and Security Applications

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ABSTRACT

Sandia National Laboratories has recently developed the capability to acquire multi-channel radiographs for multiple research and development applications in industry and security. This capability allows for the acquisition of x-ray radiographs or sinogram data to be acquired at up to 300 keV with up to 128 channels per pixel. This work will investigate whether multiple quality metrics for computed tomography can actually benefit from binned projection data compared to traditionally acquired grayscale sinogram data. Features and metrics to be evaluated include the ability to distinguish between two different materials with similar absorption properties, artifact reduction, and signal-to-noise for both raw data and reconstructed volumetric data. The impact of this technology to non-destructive evaluation, national security, and industry is wide-ranging and has to potential to improve upon many inspection methods such as dual-energy methods, material identification, object segmentation, and computer vision on radiographs.

1. INTRODUCTION

This work is an expansion of the work presented by Jimenez et. al.,[1] which describes how Sandia National Laboratories is developing a color X-ray Radiography and Computed Tomography (CT) capability for research and development applications in industrial, security, and general non-destructive testing applications. This work is the culmination of exploratory efforts in extracting more information from energy-resolved imaging applications such as that presented by Collins et. al.,[2] and multiple works by Jimenez et. al.[3–5]

It is well known that traditional Computed Tomography acquisition methods using Bremsstrahlung radiation sources have several limitations that create lower-fidelity information; examples include reconstruction artifacts due to beam-hardening, streaking artifacts due to lack of penetration power, and limited ability to execute precise materials classification tasks. Some of these limitations can be somewhat mitigated using additional computational methods[6] or dual-energy approaches,[7,8] but results in extra processing and/or data acquisition.

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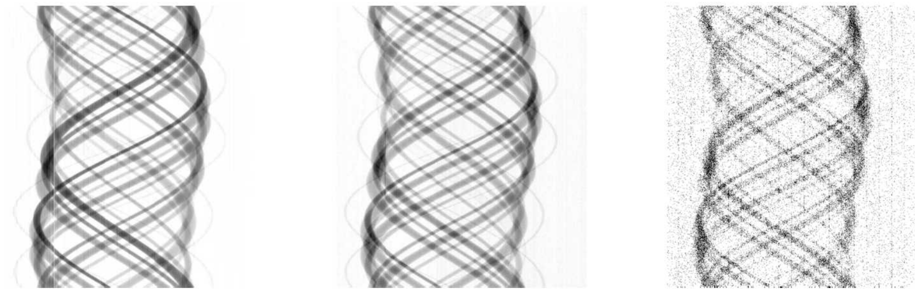

Figure 1: Sample sinogram data across various channels from the modified Multix ME100 linear array.

Energy-resolved x-ray information could potentially lead to new solutions that could create better quality reconstructions or lead to more information being extracted from a given pixel in a radiograph or voxel in a computed tomography reconstruction. Previous work by Jimenez et. al.[1] focused on radiography capabilities showing that potential exists, but the data acquired is noisy, leading to some limitations. In this work, the authors will focus on energy-resolved computed tomography and its application improving image quality and artifact reduction.

2. BACKGROUND

The Color CT system at Sandia National Laboratories consists of five customized Multix ME100 modules calibrated for 300 keV across 128 channels configured into a linear array for a total of 640 pixels across a 0.5m field-of-view, four axis motion control (one rotary, three translation), and a Comet x-ray source capable of up to 450keV/20uA. The system has a source-to-detector distance of approximately 2.06m and variable source-to-object distance. In the near future, a second vertical axis will be added to the detector to allow for an effective scan height of approximately 2.75m; up from its current vertical travel of approximately 1.4m.

The system has been acquiring data since May 2016 with sinogram acquisition capability added May 2017. Figure 1 shows sinogram data for channels 0, 63, and 127 for a given CT scan. Like many x-ray energy-resolved applications, the main limitation will be the noise content of the system as photon-starvation in the individual channels as well as noise from issues such as pulse pile-up, scatter, and spectral drift could become an issue.

There are many motivating factors to developing a high-energy color CT capability. Until recently, this technology was largely infeasible for all industrial x-ray imaging and CT applications. Infeasibility was due to various factors such as size, cost, acquisition time, and dataset size. However, many of these limitations are being overcome through the advancement of technology and computing resources. While this technology has not quite evolved to be feasible for each and every application, there are emerging applications that could currently benefit; some examples in which this technology could readily impact industrial and security non-destructive testing include:

2.1 Materials Classification

As mentioned earlier, Jimenez et. al.[3–5] investigated radiography-based methods to identify materials based off of the x-ray transmission signature in numerical studies while Collins et. al.[2] investigated this experimentally. Although some k-edges could be resolved both numerically and experimentally, the data was generally too noisy. Separately, Wurtz et. al.[6] proposed a method to perform some limited materials classification which Jimenez et. al.[1] showed potential in combining this method with energy-resolved information to expand the capability of the Wurtz et. al. approach.

The expectation is that with multi-channel radiography data, the signal has a more direct correlation with the energy dependent attenuation profile compared to traditional imaging detectors; can one leverage this to distinguish between materials of similar composition? Additionally, will multi-perspective data from CT sufficiently suppress noise to reliably perform materials classification/identification tasks?

2.2 Data Quality

There are many motivating factors that lead the industrial non-destructive testing and evaluation community to pursue better quality data than what is currently available. Energy-resolved radiography could be one path to better data through rejection of information-starved channels and weighing of channels that contain high amounts of relevant information. However, as Roessl and Proksa[9] point out, using single or limited bins of information could lead to photon starvation thus effectively degrading signal-to-noise; although this could indeed be an issue in practice, for this work, industrial applications are only considered (as opposed to medical) and thus for almost all possible relevant absorbers, radiation dose is not a concern.

2.3 CT Reconstruction Quality

Building on the possible benefits mentioned above, computed tomography reconstruction would also benefit. Many popular reconstruction algorithms used in the non-destructive testing and evaluation community, such as the FDK algorithm by Feldkamp, Davis, and Kress,[10] assume that a linear operator defines the imaging system; for traditional radiography this cannot be the case when using a Bremsstrahlung source, an absorber, and an integrating detector. For energy-resolved CT, using a single bin of information to generate sinogram data could potentially more closely approximate a linear system thus providing a more accurate reconstruction both numerically and spatially if noise does not dominate the data.

Two works that cause some concern in our investigation are those by Wang et. al.[11] and Ding et. al.[12] which show severe artifacts in reconstruction when using photon-counting data. Wang et. al. claim this is due to random variations in energy response while Ding et. al. claim the corruption comes from spectral distortions caused by the variation in the spectral absorption throughout the scan process. Both works provide reconstruction examples of cylindrical phantoms that indeed show essentially unusable reconstructions due to severe artifacts.

3. APPROACH

This work will evaluate data quality for CT performance with respect to three performance goals by acquiring a single slice Color CT dataset and reconstructing each individual channel separately.

First, the reconstructed data will be used to evaluate the waveforms and their corresponding signal-to-noise with respect to channel from the reconstructed voxels for various materials, in particular materials of similar composition; second, artifact reduction will be evaluated compared to a traditional CT dataset; finally, a comparison of different reconstruction algorithms on the same input energy-resolved input sinogram to evaluate numerical differences.

4. EXPERIMENTAL DESIGN

All sinogram data was acquired using the system and geometry in our laboratory described above in section 2 with a source-to-object distance of approximately 1.68m. All scans consisted of 720 projections at 250keV and 0.5mA with an exposure time of one second per projection. The majority of scans were performed were reconstructed using Recon, a reconstruction algorithm developed by Los Alamos National Laboratories and Sandia National Laboratories;[13, 14] for comparison, one dataset was also reconstructed with a third-party reconstruction algorithm. It should be noted that only a single point gain correction was made to the data and no calibration was done to account for spectral drift/distortion as this work is currently under way and will be reported in future work. Four objects were scanned:

1. **Wide Spectrum Survey:** This scan consists of 17 cylindrical samples in a circular orientation consisting of an empty polyethylene bottle, Nylatron, Delrin, SAE 30 motor oil , acrylic, nylon, two samples of water, teflon, polyethylene, the soft-drink Pepsi, lexan, the diet soft-drink Diet Coke, aluminum, magnesium, salt, and phenolic. All granular materials and liquids are contained in the same type of bottle as the empty bottle listed. The solid materials are cylindrical in shape with a diameter of approximately 12mm and the bottled materials have a 25mm diameter with a 1.1m wall-thickness.
2. **Explosives Simulant:** Two 0.45 kilogram explosive simulants that simulate two different but similar explosives were scanned within the same field-of-view to evaluate whether the reconstructed waveform signatures can be distinguished based on particular type of simulant.
3. **Sugar-based Soft Drinks:** Three different types of sugar-based soft drinks in aluminum cans were scanned within the same field-of-view to evaluate whether the waveform signatures from the reconstructed voxels will allow one to distinguish between similar types of sugar-based soft drinks. This dataset was reconstructed using Recon as well as a popular third-party reconstruction algorithm to evaluate statistical numerical behavior.
4. **Wax and Wax-Aluminum Powder Cylinders:** Two 7.5cm cylinders were scanned in the same field-of-view. The first cylinder consists of wax in a polyethylene bottle and the second consists of a mixutre of the same wax combined with aluminum powder. This scan was done to evaluate beam-hardening artifacts between energy-resolved CT and traditional CT. In order to preserve resolution, a surrogate for the traditional CT dataset was used which consisted of the summation of all channels to produce single sinogram which was then reconstructed using the same reconstruction algorithm.

5. RESULTS

5.1 Wide Spectrum Survey

Figure 2 shows a single bin reconstruction of the wide spectrum scan. It should be noted that the 4 circular regions at approximately the north-east-south-west positions are aluminum rods that

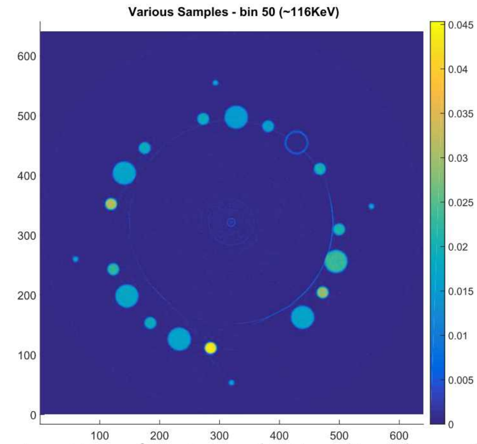

Figure 2: Single bin reconstruction of various plastics, liquids, and metals (bin 50, 116keV).

hold the fixutre together and are not included in the evaluation. Figures 3 and 4 show the average waveform of various liquids along with signal-to-noise ratios respectively; which seems to imply that the main absorber in this set is the sugar contained within the Pepsi as Diet Coke is visually indistinguishable to the two samples of water, the signal-to-noise ratios of these regions do not indicate a degraded signal for any of the materials. It should be noted that all figures reconstructed using Recon contain error bars which indicate that there was very little relative variation in the waveforms for a given material.

Figures 5 and 6 compare the average waveforms of the air contained within the empty bottle and the air in the center of the reconstructed slice; while at first glance the waveforms seem to differ significantly, it should be noted that the signal-to-noise ratio was very low which would seem to indicate that insufficient absorption due to air and/or numerical processing in the reconstruction do not allow for a sufficient measurement.

Figures 7, 8, and 9 display the remaining waveforms which seem to indicate that each of the materials in the field-of-view can be distinguished visually based on the waveform.

5.2 Simulant Explosives

Figures 10 and 11 show a single-bin reconstruction of the explosive simulants along with their average profiles respectively. It should be noticed that the differences in intensity in figure 10 are essentially indistinguishable; however, when observing the full waveform it is clear there is a significant difference between similar types of simulants.

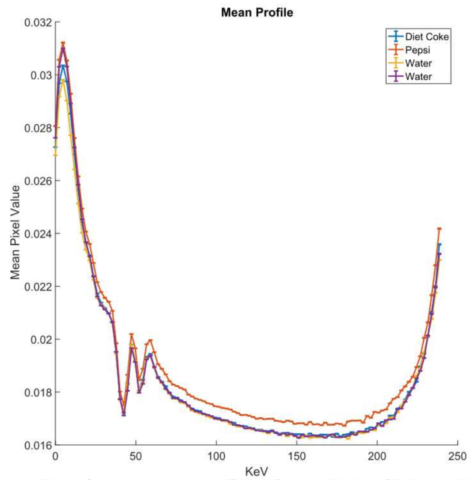

Figure 3: Average profile for Diet Coke, Pepsi, and Water from figure 2.

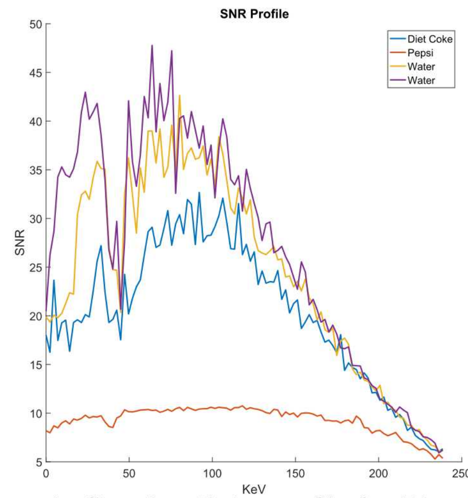

Figure 4: Signal-to-Noise profile for Diet Coke, Pepsi, and Water from figure 2.

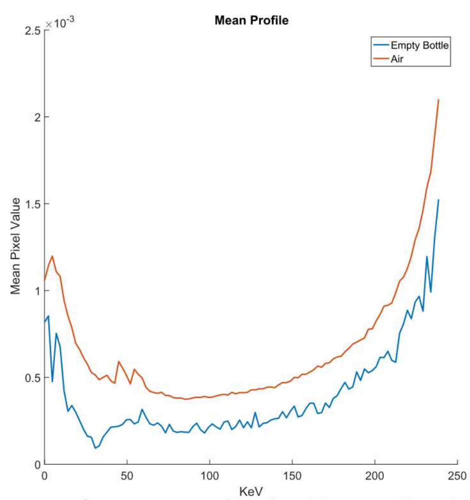

Figure 5: Average profile for Empty Bottle and Air from figure 2.

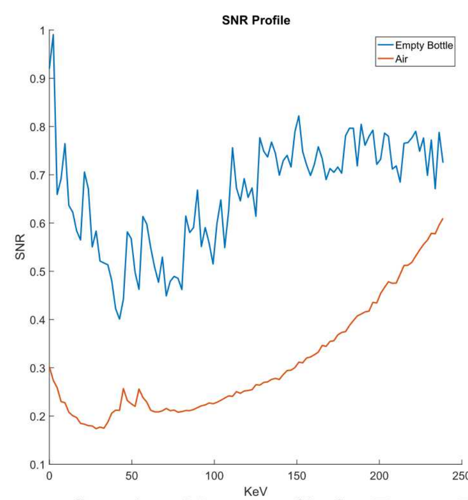

Figure 6: Signal-to-Noise profile for Empty Bottle and Air from figure 2.

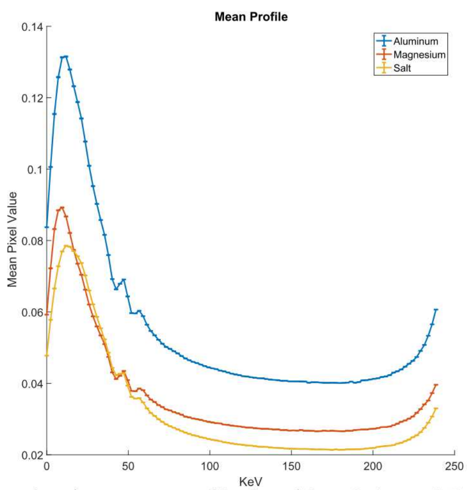

Figure 7: Average profile for Aluminium, Magnesium, and Salt from figure 2.

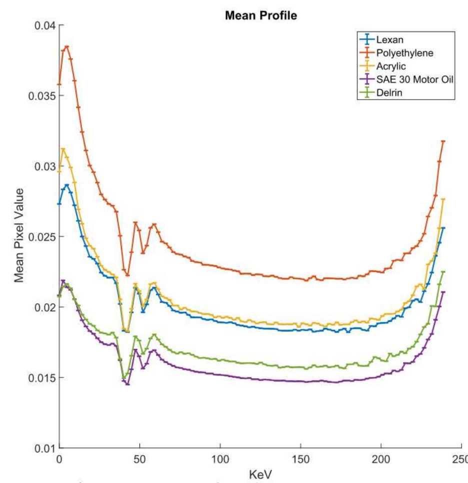

Figure 8: Average profile for Lexan, Polyethylene, Acrylic, SAE 30 Motor Oil, and Delrin from figure 2.

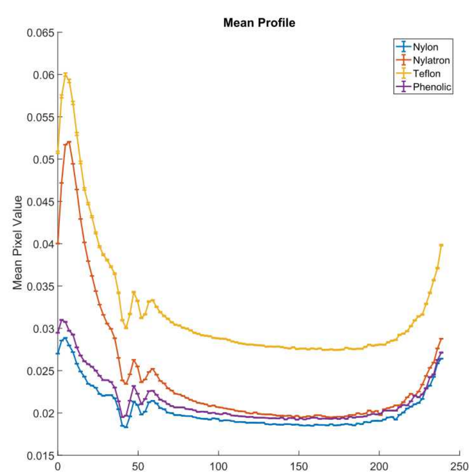

Figure 9: Average profile for Nylon, Nylatron, Teflon, and Phenolic from figure 2.

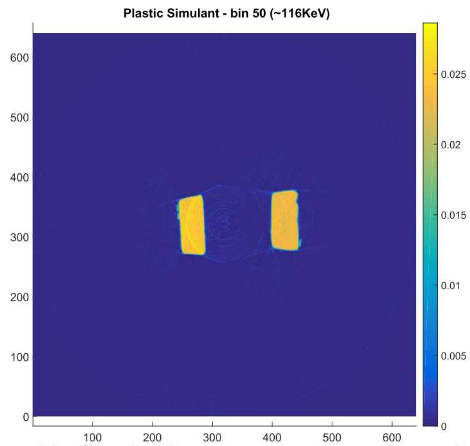

Figure 10: Single bin reconstruction of two similar explosive simulants (bin 50, 116keV).

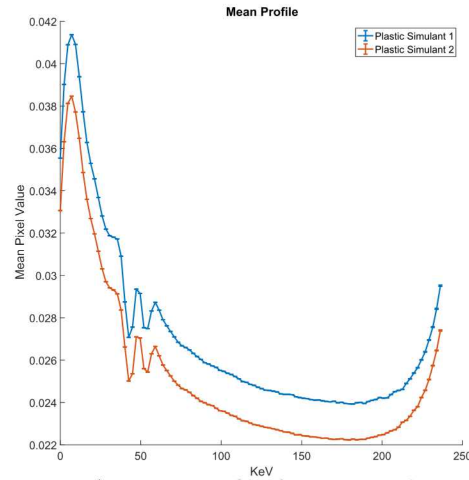

Figure 11: Average profile for two explosive sim-
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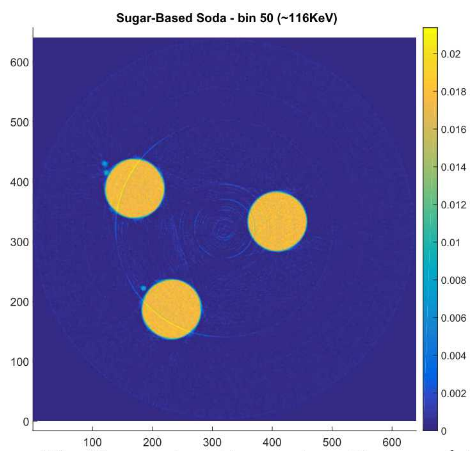

Figure 12: Reconstruction using Recon of three sugar-based soft drinks.

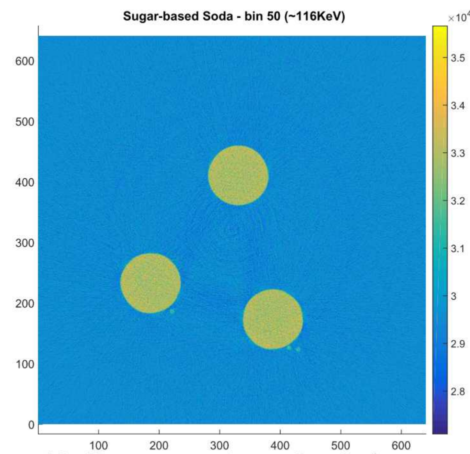

Figure 13: Reconstruction using 3rd-party reconstruction algorithm of 3 sugar-based soft drinks.

5.3 Sugar-based Soft Drinks- Reconstruction Comparison

It is clear from figures 12 and 13 that there is a significant scaling and visual difference between the two reconstruction algorithms and both do not allow for visual differences between different sugar-based soft drinks. It should be noted however that figure **??** seems to show large relative variability in voxel values within the same material; the source of this is not known as it is not clear what type of filters, scaling, or other processing is done by the third-party algorithm.

5.4 Artifact Reduction

Figures 17 and 18 show the reconstructed image of a single bin and of all bins summed respectively; it is clear that there are significant beam-hardening artifacts in the region between the two cylinders in

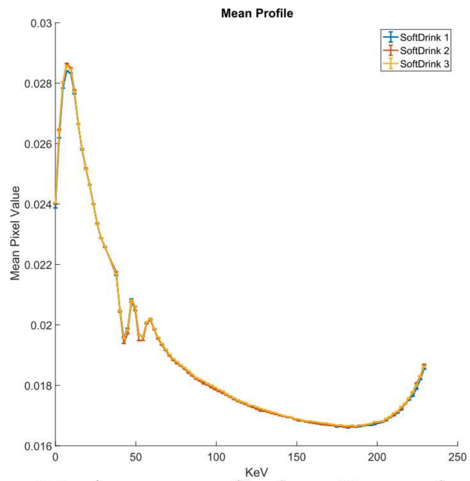

Figure 14: Average profile from Recon of sugar-based soft drinks.

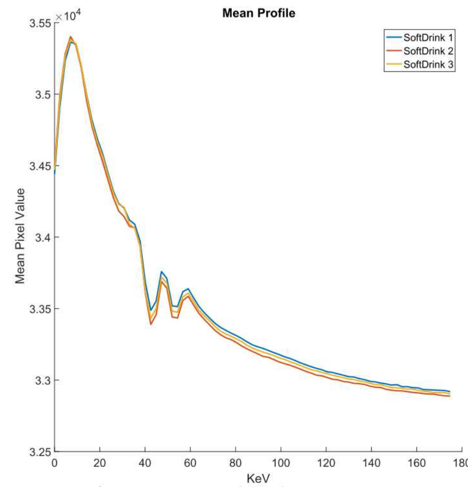

Figure 15: Average profile from 3rd-party reconstruction algorithm of 3 sugar-based soft drinks.

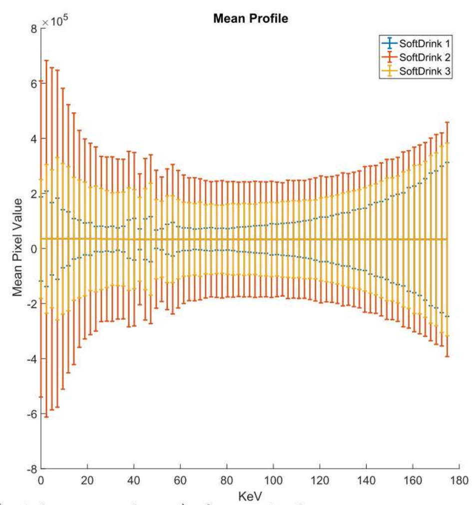

Figure 16: Average profile (with error bars) from 3rd-party reconstruction algorithm of 3 sugar-based soft drinks.

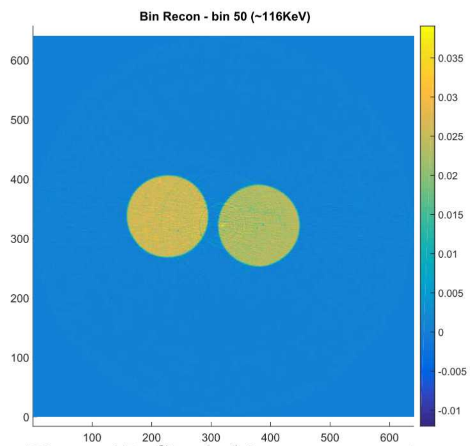

Figure 17: Single bin reconstruction.

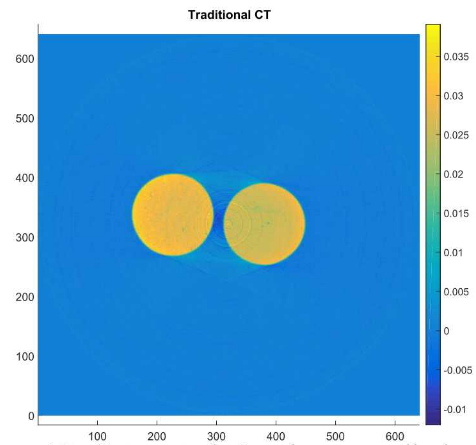

Figure 18: Integrated signal across all channels reconstructed

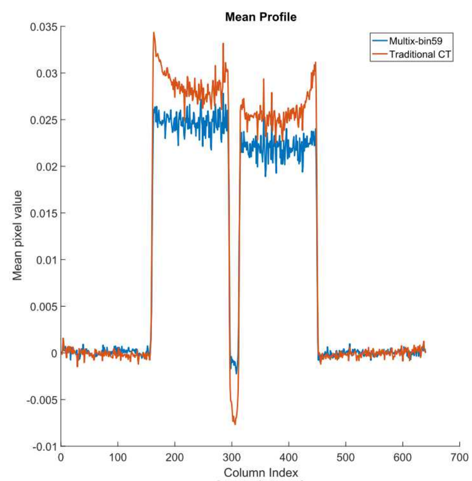

Figure 19: Line profile for figures 17 and 18.

the integrated signal reconstruction. Moreover, further significant beam-hardening artifacts are seen within each cylinder for the integrated reconstruction compared to the single-bin reconstruction. As the circular regions have some noise to them, it is difficult to assess whether subtle beam-hardening artifacts are present in the single-bin reconstruction.

6. CONCLUSIONS

This work has demonstrated the emerging high-energy Color CT capability developed at Sandia National Laboratories. Initial results seem to hold much potential in the ability to non-destructively distinguish between similar materials and to achieve superior reconstruction by reducing reconstruction artifacts due to beam-hardening. The quality is only expected to improve once a spectral correction process to applied to the data prior to reconstruction. Curiously, none of the degradation observed by Ding et. al. and Wang et. al. was observed, but will continue cautiously. Future work consists of not only developing a spectral correction process but also evaluating more complex objects and evaluating reconstruction data quality for suitability in segmentation and recognition applications. This technology has the potential to disrupt the Non-destructive testing and evaluation capability in numerous ways including counterfeit detection, quality assessment, materials identification, as well as verification and validation applications all of which are of significance to various areas within industry and security.

7. ACKNOWLEDGEMENTS

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