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# Dual-energy X-ray radiography for automatic high-$Z$ material detection

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**Abstract**

There is an urgent need for high-$Z$ material detection in cargo. Materials with $Z > 74$ can indicate the presence of fissile materials or radiation shielding. Dual (high) energy X-ray material discrimination is based on the fact that different materials have different energy dependence in X-ray attenuation coefficients. This paper introduces the basic physics and analyzes the factors that affect dual-energy material discrimination performance. A detection algorithm is also discussed.


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*Keywords:* Dual-energy X-ray; Radiography; Nuclear material detection

## 1. Introduction

Dual-energy X-ray radiography and tomography have been widely used for some time in the security industry to detect explosive materials in airline passenger bags. It exploits the rapid change in photo-electric cross section with photon energy and generally involves X-rays of around 160 kV. Recently, there has been interest in adding nuclear material detection capability into cargo X-ray imaging systems [1].

In order to see through large objects, cargo imaging involves X-ray sources of a few MV. The dominant interaction processes in this energy range are Compton scattering and in some cases pair production. The detectors usually work in current mode and measure the overall attenuation of the X-rays. The detector signal at each pixel in the image is:

$$s = \int_0^{E_{\max}} I(E) \times \mathrm{e}^{-\sum_i \mu(E,Z_i)\times t_i} \times D(E) \times \mathrm{d}E, \qquad (1)$$

where $I(E)$ is the source X-ray spectrum, $\mu(E, Z_i)$ is the attenuation coefficient of a material at a given photon energy, $t_i$ is the thickness of a material in the X-ray beam path and $D(E)$ is the detector response. $E_{\max}$ is the cut off photon energy of the X-ray source.

Fig. 1 gives the total attenuation coefficients of different materials. At both lower energies (<1 MV) and higher energies (>3 MV), high-$Z$ materials, such as lead and uranium, are more attenuating than low-$Z$ materials, such as most organic goods. This is due to photo-electric effect and pair-production, respectively. In the Compton dominant region, higher-$Z$ materials have smaller mass attenuation coefficients because they have fewer atomic electrons per unit mass (lower $Z/A$ ratio).

The total attenuation coefficients change with photon energy. Therefore, the detector signal will be attenuated differently by the same object at different source energies. For example, 9 MV X-rays are more penetrating than 6 MV X-rays. For light material, such as plastic, the difference is the most significant. For high-$Z$ material, pair production increases the 9 MV attenuation and the difference between 6 MV attenuation and 9MV attenuation is much smaller. After an object is imaged with X-rays of both energies, we can plot the low energy (6 MV) attenuation versus high energy (9 MV) attenuation, which represents the object thickness. This is called the dual-energy map and different materials show up in different regions in the plot.

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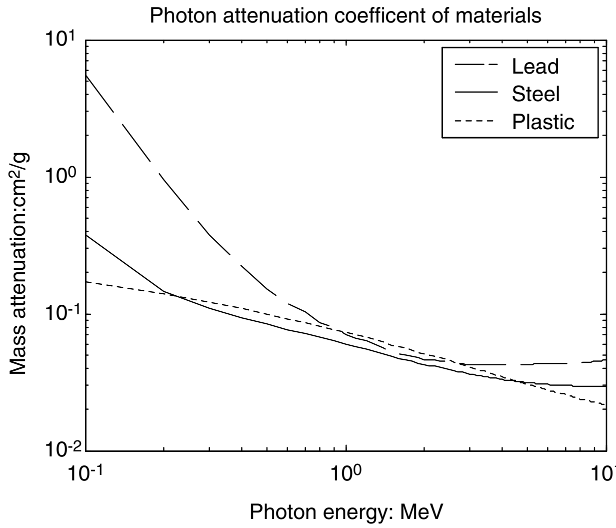


Fig. 1. X-ray attenuation coefficients of materials.

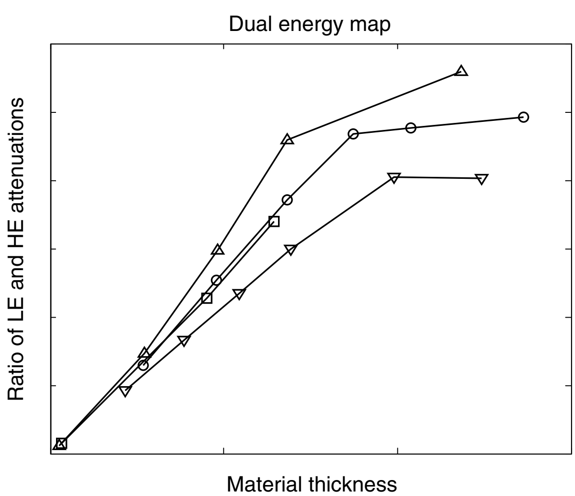


Fig. 2. Illustration of a dual-energy map. When attenuation ratio is plotted against object thickness, different materials show up on different curves. This is the basis of material discrimination with dual-energy X-ray radiography. Please note that this figure is for illustration only and does not represent actual calculated or experimental data.

Fig. 2 demonstrates this concept. Automatic detection algorithm relies primarily on such material signatures and nuclear material is recognized by the fact that they have very high $Z$.

## 2. System design issues

Many factors can influence the material discrimination performance of a practical dual-energy cargo imaging system. This section analyzes the impact of statistical noise, X-ray energy and dose rate drop off, source energy selection, source energy fluctuation and scattered radiation. It is found that statistical noise and source energy fluctuation are the most important factors.

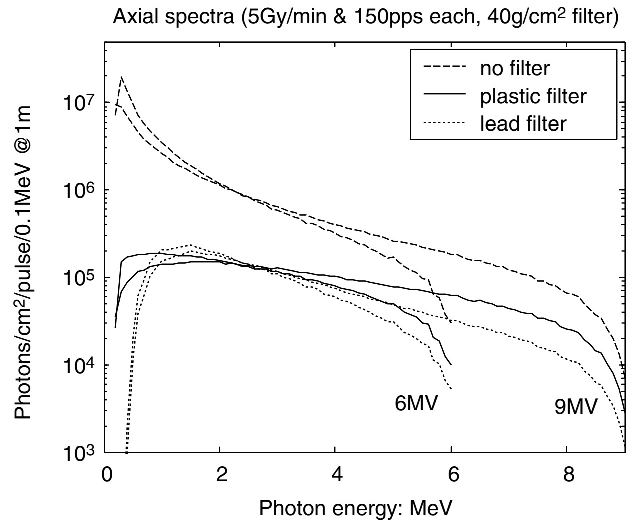


Fig. 3. 6 MV and 9 MV X-ray spectra.

In order to be quantitative, the analysis is based on a hypothetical imaging system, with 6 MV as low energy and 9 MV as high energy X-ray sources and cadmium tungstate detectors. Fig. 3 shows the axial X-ray spectra with and without beam filters.

### 2.1. Statistical noise

The thicker the object, the greater will be aggregated difference between the two images. However, this does not mean better material discrimination because pixel noise gets larger with increasing object thickness and decreasing photon number. In general, stronger X-ray source and larger detectors will lead to more initial photons per pixel and therefore larger object thickness at which material discrimination is still possible.

The amount of X-rays in each pixel is also affected by factors such as throughput, penetration, contrast sensitivity, imaging resolution and radiation safety consideration [2]. In Ogorodnikov's paper, the maximum material thickness is 140 g/cm$^2$.

### 2.2. X-ray energy and dose rate drop off

Electron Linear Accelerator (Linac) based X-ray sources have angular drop off. That is, both dose rate and photon energy gets lower at off axis beam angles. As a result, different locations will have slightly different dual-energy maps and should be calibrated individually. In theory, it is possible to monitor the X-ray energy on a pulse to pulse basis and make an appropriate compensation in the dual-energy calculation.

### 2.3. Source energy selection

The selection of source energy is a balance between sensitivity (separation) and dynamic range, or the object thickness behind which the method still works. Lower low-energy (such as 5 MV) leads to better sensitivity at thin-background object condition, while higher low-energy (such as 7 MV) leads to larger dynamic range. The high energy is generally limited by safety concerns associated with activation and neutron production. We have found that 6 MV as low energy and 9 MV as high energy are appropriate.

### 2.4. Source energy fluctuation

The biggest factor that affects the dual-energy material discrimination performance is the source energy fluctuation. Material discrimination is based on ratio of X-ray attenuation at two different energies. The instability in the source energy will cause variation in this ratio. For example, a 6 MV/9 MV source combination will have different attenuation ratio from a 6.3 MV/8.7 MV combination.

Pulse to pulse energy fluctuation of a Linac based X-ray source can usually be traced to the RF (Radio Frequency) source (a magnetron or a klystron) and change in tuning in the RF power chain.

### 2.5. Scattered radiation

In a typical cargo X-ray imaging system, the scattered radiation can be as much as one percent of the primary beam at the detector location. If the scattered radiation is not properly controlled, the dual-energy material discrimination method will only be effective when the object is less than 150 mm steel equivalent, as the curves in the dual-energy map flatten out for objects thicker than this. Beam filtering and collimation in both directions can greatly reduce the scattered radiation and extend the dynamic range.

## 3. Automatic detection

Automatic detection is the process of combining information from the images at both energies and deciding whether there are threat objects in the images.

We can draw lines on the dual-energy map, to produce regions representing a range of $Z$ values. Each pixel in an image can then be assigned a material (or $Z$) class. The information is processed in the coordinate system of attenuation ration and object thickness (high energy attenuation). In practice, it is usually easier and more quantitative to work on decoupled linear coordinates. Through some transformation and only for the purpose of attenuation power, each pixel can be expressed as having some thickness of a very low-$Z$ material and some thickness of very high-$Z$ material. For example, in baggage screening, the two representing material can be boron and iron. Materials having $Z$-value in between can be expressed as having some amount of boron and some amount of iron.

As with any imaging analysis algorithm, the basic way of finding objects of interest in an image is to take the gradient image, process edges, produce a segmentation image and identify objects of interest, if any. Threat detection needs to combine information such as material, shape, size, density and/or total weight. Not all of this information can be obtained from the X-ray radiography images; therefore it is important that the algorithm has self-learning capability.

The pixel value in an X-ray radiography image is a measure of overall attenuation along the X-ray path. That is, if objects overlap in an image, the attenuation value of a pixel will be sum of the attenuations by each object. It can be very helpful to strip the background objects off a region of interest to derive the material information for a specific object. While not all situations can be resolved, this approach can greatly improve detection performance.

Fig. 4 shows how a typical detection algorithm works. The image was taken at 6 MV and 9 MV at an existing L-3 Communications installation. The high-$Z$ material signature was generated through dual-energy information processing, machine vision and topology analysis, and background object striping. The treat objects were then marked based on this information (lead in this example).

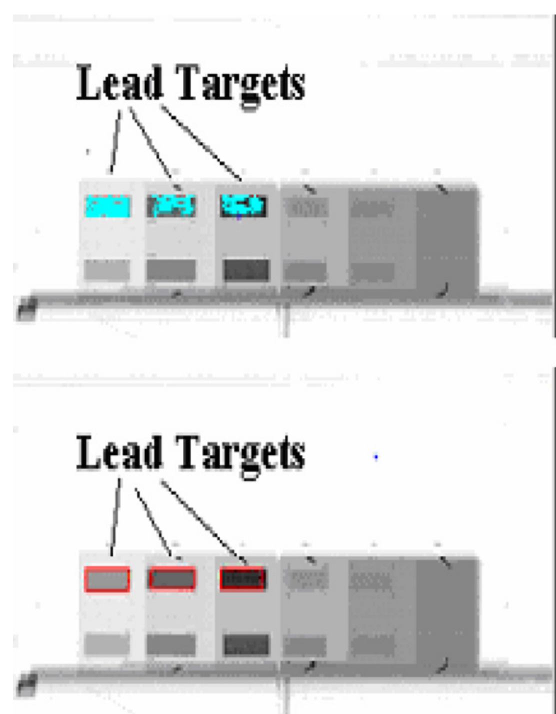


Fig. 4. Automatic detection of lead targets in test images. The images were taken at 6 MV/9 MV at an existing L-3 Communications installation. The background object is a high density board step wedge of 250 mm, 500 mm, 750 mm, 1000 mm, 1250 mm and 1500 mm thickness. The target objects are lead, steel sugar and salt of various thicknesses. The automatic detection algorithm generates high-$Z$ material signature (top) and identifies the three lead targets (bottom).

## 4. Summary

Automatic nuclear material detection can be achieved with dual-energy X-ray radiography by utilizing the high-$Z$ signature of these materials. Detection algorithm with self-learning capability combines all available information and makes threat detection decisions.

## References

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