X-RAY BACKSCATTER IMAGING: PHOTOGRAPHY THROUGH BARRIERS

Joseph Callerame
American Science & Engineering, Inc.
829 Middlesex Turnpike, Billerica, MA 01821

ABSTRACT

X-ray imaging techniques based on Compton backscatter permit inspection and screening of sea containers, a wide variety of vehicles, luggage, and even people. In contrast to more commonly used transmission images, backscatter imaging involves positioning both source and detection apparatus on only one side of a target object. This presents the user with inspection opportunities in situations that may be extremely difficult, if not impossible, for transmission systems that require access by the detector subsystem to the opposing side of the target. The backscatter image is somewhat akin to a photograph of the contents of a closed container, taken through the container walls. Techniques for producing X-ray images based on Compton scattering will be discussed, along with wide-ranging examples of how systems based on these principles are used to perform inspections for both security applications and for the detection of contraband materials at ports and borders. Potential applications in the area of non-destructive evaluation will also be considered. Differences in the type of information displayed by transmission and backscatter images will be highlighted, and tradeoffs between backscatter image quality and interpretability, scan speed, effective penetration, and X-ray tube voltage will also be discussed. The method used in scanning the target object results in an extremely low radiation dose, a result that significantly broadens the application spectrum for this imaging technique.

INTRODUCTION

X-ray imaging based on Compton backscatter\(^1\) forms the basis for a unique inspection tool that can be used to peer into closed containers without the need for a transmission detector to be deployed on the far side of the object under inspection. This ability to perform scanning with both the X-ray source and detector co-located permits visual images of vehicle contents, for example, to be gathered easily and quickly, without concern over access to the opposite side of the target container. This technology, for example, enables an appropriately equipped vehicle to drive down a street at speeds up to 10 km/hour and inspect parked cars or trucks to determine whether their contents may pose a security threat. Examples of the type of image that can be seen are shown in Figures 1 and 2. Note that organic materials, such as the explosive simulants placed in the automobile, as well as the nearby tree and certain other objects on the table, appear bright in the image, whereas the metallic parts of the car appear relatively dark. This characteristic of Compton backscatter, namely the ability to discern low atomic number
materials by virtue of their brightness, is the key reason why this technology is so useful for detecting explosives, drugs, stowaways in cargo, and other organic contraband. Similarly, the bright objects inside the truck indicate the low atomic number of its cargo, as well as the uniformity of its distribution through the truck’s interior. The effect is somewhat akin to taking a black and white photograph of the contents of the vehicle through its metallic skin.

Figure 1. Example of a backscatter X-ray image of an automobile with various threats placed in the trunk and inside its doors and fenders

Figure 2. Image of the contents of a closed cargo container, illustrating nature of its cargo.
In this paper, the basic principles behind the formation of a Compton backscatter image will be discussed, as well as issues such as optimal X-ray energy, scan speed, and radiological dose to cargo.

IMAGE FORMATION

Compton X-ray backscatter images are formed by scanning a pencil-shaped beam of X-rays along one dimension of an object that is being inspected. At each position of the scanning pencil beam, Compton scattered X-rays are collected by large detectors placed on the same side of the system as is the X-ray source. By tracking the beam’s instantaneous position on the object, and measuring the overall intensity of the scattered x-rays that are incident on the detectors, one can associate a scattered intensity to each beam position on the examined object. This translates to an intensity modulated line of data whose high intensity portions correspond to the atomic number of the contents behind the container wall. The entire two-dimensional image can then be constructed by moving either the object under inspection or the conveyance containing the X-ray source-detector combination in a direction perpendicular to the beam scan direction. Thus, line by line, the object under investigation can be scanned. Typically, the beam scan speed is 10’s of milliseconds per line, far more rapid than the translational speed of the conveyance (1 km/hr corresponds to approximately 30 cm/sec, so that, for example in 30 milliseconds the translational motion is only 9 mm). As a result, image distortion due to the horizontal component of motion is not observable.

Several factors must be considered when designing an imaging system such as this. Among these issues are X-ray energy, X-ray flux on target, image resolution, time required to scan a line of data, desired transverse scan speed of either the target or the conveyance carrying the X-ray source, desired angular subtense of the beam on the target (i.e., vertical field of view), and range of source to target distances expected. Many of these factors are interrelated.

X-RAY BEAM FORMATION

Because a continuous stream of data is desired with no significant parts of the target image missing, the X-ray source must produce either a continuous or high duty cycle fan beam output. In order to cover a reasonable field of view, the fan beam opening angle should be large also. Then, to enable a pixel-by-pixel beam scan on the target, it is necessary to position a moving collimator in front of this fan beam with an opening designed to allow the desired size pencil beam through. As the collimator moves, different parts of the X-ray fan beam are selected by the collimator, with the effect of scanning the pencil beam in one dimension (i.e., a line scan) across the target. Most commonly, this function is performed using a rotating collimator (a “chopper wheel”) rather than a reciprocating motion. Wheel rotation can vary from 100 rpm to thousands of rpm, depending upon the image qualities desired. An illustration of one type of chopper wheel collimator is shown in Figure 3 below. In this case, the X-ray source is located at the center of the wheel, but many other geometries are possible. Ultimately, the resolution of the system is determined by a combination of the chopper wheel aperture,
X-ray tube focal spot size, the size of the chopper wheel, and the distance to the object being interrogated. The backscatter detectors are designed to be large enough to collect the needed backscatter flux, and play no role in the image resolution. Depending upon the application, a transmission detector, also shown below, may be added, if access to the opposite side of the object under inspection is available. In this case, two images can be displayed: the transmission image and the Compton backscatter image.

![Illustration of X-ray beam formation used for creating Compton backscatter images.](image)

**Figure 3.** Illustration of X-ray beam formation used for creating Compton backscatter images. The X-ray pencil beam is created by the rotating collimator on the right, and is scanned vertically while the object being inspected moves horizontally (in this case on a conveyor belt). The X-ray beam itself passes between two large Compton detectors, and scattered X-rays are collected and registered at each beam position. An optional transmission image can also be formed if access to the far side of the object is available.

**ENERGY CONSIDERATIONS**

The choice of an appropriate X-ray tube depends to a large extent on the types of objects being investigated. For example, these objects can be briefcases, cars, trucks, large sea containers, or even people. Generally speaking, most X-ray sources for these applications produce Bremsstrahlung X-rays with a peak energy that lies in the range of 50kV to 450kV. Penetration falls off rapidly below 50 kV, and tubes above 450 kV peak are not easily available in the commercial marketplace. Flux on target is also an important issue, so the tubes used for this application tend to range from a few hundred watts of beam power to several kW. In addition, focal spot size must be relatively small since this, together with the chopper wheel collimator aperture, and the distance to the target object, determine beam size on target, and thus resolution. Worthy of note is the fact that, for Compton scattered X-rays, the energy of the scattered photons is always less than the incident photon energy. In fact, for scattering in the fully backward direction, energy and momentum conservation mandate that the energy of the backscattered photon cannot exceed 255 keV, no matter what the incident X-ray energy. As a result, developing X-ray
sources with higher peak photon energy does not improve penetration into the cargo as much as might be expected from a simple tube output analysis. Although there is typically a flux increase with peak X-ray tube voltage, other factors come into play in the design of a commercially viable system that work in the direction of lower energy. Among these, for example, are the size and weight of the beam-forming chopper wheel. Both of these factors have an effect on the cost and size of the conveyance that carries the system, as well as on the speed at which a scan can be performed, due to practical limits on the rotational velocity of the chopper wheel if it becomes too large. For these reasons, most systems, especially mobile systems, require X-ray sources with a maximum voltage no higher than a few hundred kV.

FIELD OF VIEW CONSIDERATIONS

The field of view, as well as the range capability of Compton backscatter systems, are also important system design considerations. As one example, we have designed one of our systems, the Z Backscatter Van, or ZBV, to cover a vertical field of view 390 cm (13 feet) high at a ZBV to target object distance of 150 cm (5 feet). The primary consideration here was to have the capability to inspect trailer trucks and containers, as well as automobiles, in a drive-by mode. An artist’s conception of how Compton backscatter can be used to examine the contents of a container is shown in Figure 4. Figure 5 shows an actual image of the contents of a truck.

![Figure 4. Artist’s conception of the effect of scanning a truck-borne container in Drive-By mode. Drive-by speeds can be up to 10 km/hr. The image is displayed in real time inside the van, and is accessible to both the driver and a passenger.](Property of American Science & Engineering)
Field-of-view of a Compton backscatter imaging system depends primarily on the angular output of the X-ray beam produced by the tube, and of course by the design of the chopper wheel aperture.

Luggage scanners making use of Compton backscatter imagery are also available. Typically, these systems operate at significantly lower tube voltages than do mobile scanners. Personnel scanners operate at even lower voltages, since the primary goal is only to search for hidden threats under clothing.

**SCAN SPEED**

The speed at which the object under inspection is scanned depends upon several factors. Basically, this is determined by the time it takes to gather a single line of backscatter data. In order to reduce image distortion, it is desirable to ensure that the target’s horizontal motion relative to the beam during this single line scan time is small, ideally less than a pixel or so from the top to the bottom of the field of view. However, the line scan rate cannot be increased at will, inasmuch as X-ray flux per pixel on target must be adequate to produce the desired image quality. This X-ray flux per pixel is in turn dependent on tube power, on pixel size, field-of-view, and on the beam dwell time per pixel. Depending upon the specific requirements of the system, systems have been produced with scan speeds up to 10 km/hr, and more.

**COMPARISON WITH TRANSMISSION IMAGERY**

Backscatter and transmission images often offer complementary information regarding the presence of contraband in inspected objects. A transmission image produces a familiar shadow-gram of all objects in the beam path, with dark regions indicating low penetration and lighter regions higher transparency. Backscatter provides a very different view of the inspected object, highlighting shapes and textures of materials in the closed container, especially on the X-ray source side of the object, with lower atomic number materials appearing bright, and higher atomic number materials appearing dark. A comparison of the difference in images is shown in Figure 6. Multiple backscatter views are also possible, and in fact systems with simultaneous backscatter views of three sides
(left, right, and from the top) of a cargo container have been deployed, in order to sample the cargo contents from different perspectives. A transmission image can also be added to any system containing backscatter, if desired. However, one of the most useful aspects of backscatter imagery is that access to the far side of the object under inspection is not required. In situations where it may be difficult (due to an obstacle, for example) or even dangerous (an unattended suspicious briefcase leaning against a wall) to insert a transmission detector behind an object, backscatter may be the only option. Moreover, Compton backscatter, because of its sensitivity to low atomic number materials, is especially good at imaging explosives and drugs.

![Comparison of X-ray transmission and backscatter images in a cargo container. Contraband materials hidden in the cargo are highlighted](image)

**Transmission**  
**Backscatter**

**Figure 6.** Comparison of X-ray transmission and backscatter images in a cargo container. Contraband materials hidden in the cargo are highlighted

**RADIATION DOSE**

The beam scanning requirements for generating a Compton backscatter image mandate a pencil-shaped beam that quickly scans, pixel by pixel, over a target object, with each pixel having a very short dwell time on a given region of the object. In addition, backscatter detectors are highly efficient. Moreover, all of the radiation incident on the target object contributes to the backscatter signal to the extent of the solid angle covered by the detectors, and the illumination intensity required to produce a visually pleasing and useful backscatter image is surprisingly low. These factors result in extremely low doses to the object being interrogated, typically less than 10 microrem per scan. For comparison, this is roughly equivalent to the increased radiation dose due to cosmic rays as a result of flying for 2 minutes, at altitude, in a commercial jet.
SUMMARY

Compton X-ray backscatter imaging has been widely deployed in systems around the world to detect potential threats and other contraband in large containers, vehicles, and smaller baggage. The imaging effect is akin to taking a photograph of the container contents through the optically opaque wall of the container with image brightness highly correlated with the average atomic number of the components of the image, as shown in Figure 7 below. Moreover, these images can be taken at relative system vs. target object speeds of 10 km/hour and more. Such systems can be designed with a wide range of tradeoffs between resolution, scan speed, and field-of-view and offer unique one-sided imaging capabilities that are not possible with simple transmission X-ray systems.

However, if desired, transmission imaging capability can be added onto any backscatter system. Multiple views are also possible with proper system design, so that cargoes may be imaged from several different directions.

Figure 7. Compton backscatter image of stowaways in a truck filled with produce

REFERENCES