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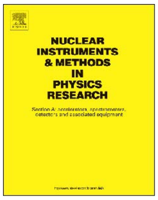

Principles and applications of gamma-ray imaging for arms control

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ABSTRACT

The ability of gamma-rays to penetrate matter makes them an excellent signature for the detection of nuclear materials—except that this very ability makes their detection difficult. This is particularly true if one wishes to make images, since general-purpose focusing optics do not exist. Various indirect imaging techniques have been successfully applied to obtain gamma-ray images, including Compton and coded-aperture imaging. This paper reviews the different approaches, and discusses their advantages and disadvantages as illustrated with results obtained from different instruments designed for use in nuclear security applications.

1. Introduction

Gamma radiation emitted by special nuclear materials (SNM) has long been used as a key observable to both detect and characterize assemblies of such materials. They are useful both because they can reach a remote detector through overlying materials and because different isotopes emit different characteristic spectra. For passive work, gamma-ray energies from a few 10's of keV out to several MeV are important. Much of the work has been concerned with the spectra emitted by an assembly since line emissions can be used to uniquely identify which isotopes may be present. If multiple lines at different energies are available, then information on material thicknesses and the properties of overlying materials can be determined through differential attenuation. Additional information is also available from the continuum radiation that scatters in an object and overlying materials before the radiation reaches the detector. However, results are frequently limited because the amount of radiation that reaches a detector is proportional to the emission surface area (since gamma-rays have a limited range in dense, high-Z materials) and because a detailed analysis requires knowledge of both source and background spectra.

To obtain additional information on the distribution of SNM one can take advantage of the spatial distribution of the radiation field. Gamma rays are after all high-energy light, so that an image made based on unscattered radiation provides a measure of the distribution of the material. Even radiation that is scattered on the way to the detector can carry useful information because an image made with this radiation shows where scatters occur. In addition, if one knows where radiation originates, then one has a means of separating the background from the foreground. Over the preceding ~25 years, significant progress has been made in the ability to create images using the passive gamma-ray emissions from SNM and other radio-nuclides. Because of the highly penetrating nature of gamma-radiation, special techniques must be used to create the images, since general purpose lenses and mirrors do not exist to project the images from a source region onto a detector.

To evaluate the performance of different types of imagers to arms-control applications, it is important to differentiate the resolution of an imager from its ability to localize an object. An imager's resolution [or point spread function (PSF)] is determined by its ability to resolve two point sources that are closely spaced in the imager's field of view (Fig. 1). This can be defined either as an angular resolution or as a spatial resolution (which is nothing more than the angular resolution applied at a fixed source distance).

Occasionally system developers will misreport an imager's source localization ability as the imager's resolution. It is not. The resolution is similar to the Rayleigh criterion for optical systems and represents the minimum size scale for which information on source distributions can be determined. However, the source localization ability can also be an important imager specification; it represents the ability of the imager to determine where a given source is. This property is often obtained by fitting a geometric shape to locate the center of an object, and the performance improves as more data are acquired. Ultimately, source localization will be limited by systematic information about where the imager is pointed and how carefully any accompanying visible-light image is aligned with the radiation image.

The different techniques used to generate gamma-ray images are discussed in the following sections.

2. Direct imagers

For the purposes of this paper, direct imagers are defined as systems that have a one-to-one correspondence between the signal in

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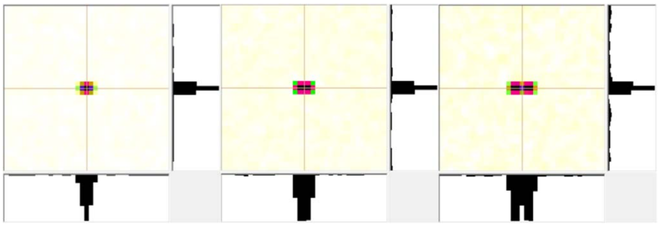

Fig. 1. Simulated coded aperture images of two point sources with progressively greater separation (left to right.) In the rightmost image the sources are just separated by the spatial resolution of the imager. The histograms below and to the right of each image are the counts under the cursor lines in the images.

a given region of a detector and a region of the image. Consider how a lens projects a visible-light image onto the sensor in a camera; each pixel of the detector records the signal from a given region of the image so that the noise and other performance metrics are spatially localized on the detector. Another way to view this is that the camera determines the direction of incidence of each photon. This type of system is preferred because analysis is straight forward, artifacts are few, and signal-to-noise (SNR) is straightforward. There are two broad classes of such systems discussed below.

2.1. Bragg diffraction

One can make a direct imager by taking advantage of the wave nature of gamma-rays using Bragg refraction. A finely spaced periodic structure with spacing, d¸ can be used to deflect radiation of wavelength, λ, through an angle, θ, given by the well-known Bragg equation:

$$2d\,\sin\theta = n\lambda, \tag{1}$$

where, n, is the order of the maximum. This basic physics can been used in two forms: as a “reflector,” where finely spaced multilayer materials are deposited on surfaces of revolution (Fig. 2) [1–4], or in transmission, as Laue diffraction through different crystal arrays (Fig. 3) [5,6]. Both techniques are viable over energies of interest; with mirrors having been demonstrated out to over 600 keV [7] and gamma-ray astronomy missions proposed by the astrophysical community to over 1 MeV [6].

These systems are direct imagers in the best sense because the spatial distribution of the radiation at the detector directly represents that of the emission region, and because one can develop focusing optics that concentrate the radiation so that a small detector area records the radiation intercepted by a larger optic. This both improves the signal-to-noise ratio (SNR) because the noise (background radiation) typically increases with the detector area, and means that expensive large-area position-sensitive detectors are not required. Of course the latter is really only a benefit if the cost per unit area of the focusing optic is not more expensive than an equivalent area of detector material.

Unfortunately, the deflection angles, θ, that one can achieve are very small, which means that such instruments have very small fields of view (measured in arcminutes) and require very long focal lengths (measured in meters). Hence, aside from a few specialized applications [9], the technology is of little value for day-to-day arms-control applications.

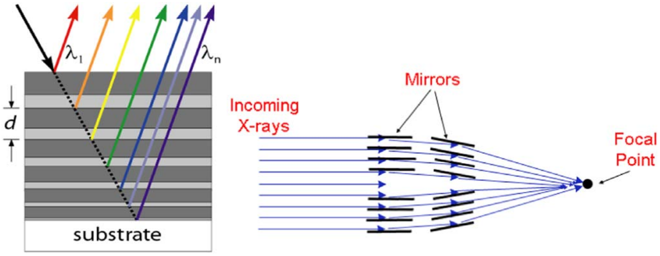

Fig. 2. (Left) schematic diagram of a multilayer surface that has a graded spacing to increase the energy/angle response. Note that the angles are exaggerated. (Right) schematic diagram of a Wolter telescope [8] that focuses parallel radiation to a point. The mirrors are conic approximations to hyperbolas and parabolas.

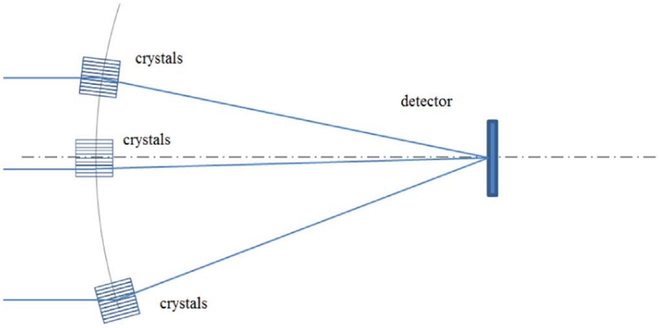

Fig. 3. Schematic diagram of a gamma-ray telescope based on Laue refraction. Different crystals are used in different parts of the aperture to maintain the angular relationship needed to focus to a point from a given radius. In the diagram only some crystal sets are included for clarity.

2.2. Pinhole cameras

One can also make a direct imager using the pinhole technique [10]. In this type of camera (Fig. 4), the detector is surrounded by shielding to limit the radiation that reaches it to a single opening (pinhole) in the shielding at the front of the camera (Fig. 4). The pinhole projects an image of the scene onto the position-sensitive detector with an angular resolution, $\delta\theta$, given by

$$\delta\theta = \frac{a}{f}, \tag{2}$$

where a is the pinhole size and f, the focal length, is the spacing between the plane of the pinhole and the detector. Physically, this is the angular displacement of the source needed to shift the pinhole by one diameter at the detector. To obtain the spatial resolution at the target,

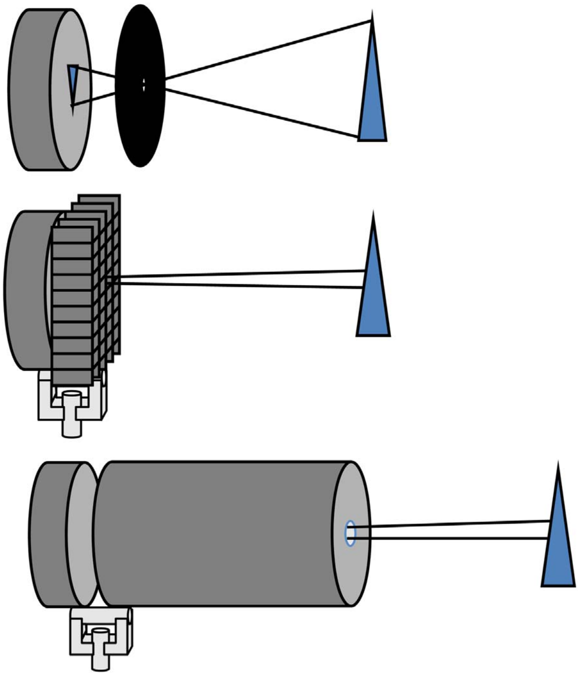

Fig. 4. Different versions of pinhole cameras. The bottom two systems are collimated to see just one pixel of the scene with the whole detector and must be scanned to generate an image. In practice, for the near field, the collimation of the middle system would have converging collimation (not shown).