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Robert S. Thoe

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Single Sided Tomography of Extremely Large Dense Objects

Robert S. Thoe
Lawrence Livermore National Laboratory
NTES, L-Division
P. O. Box 808, L-43
Livermore, California 94551

ABSTRACT

One can envision many circumstances where radiography could be valuable but is frustrated by the geometry of the object to be radiographed. For example, extremely large objects, the separation of rocket propellants from the skin of solid fuel rocket motor, the structural integrity of an underground tank or hull of a ship, the location of buried objects, inspection of large castings etc. In our laboratory I have been investigating ways to do this type of radiography and as a result have developed a technique which can be used to obtain three dimensional radiographs using Compton scattered radiation from a monochromatic source and a high efficiency, high resolution germanium spectrometer. This paper will give specific details of the reconstruction technique and present the results of numerous numerical simulations and compare these simulations to spectra obtained in our laboratory.

In addition I will present the results of calculations made for the development of an alternative single sided radiography technique which will permit inspection of the interior of large objects. As a benchmark I will seek to obtain three dimensional images with a resolution of about one cubic centimeter in a concrete cube 30 centimeters on a side. Such a device must use photons of very high energy. For example 30 cm of concrete represents about 15 mean free paths for photons of 100 keV, whereas at 1 MeV the attenuation is down to about five mean free paths. At these higher energies Compton scattering becomes much more probable. Although this would appear to be advantageous for single sided imaging techniques, such techniques are hampered by two side effects. First, multiple scattering completely dominates the scattered radiation from depths of over a couple mean free paths destroying image fidelity. Second, the energy of the Compton scattered photons is lowered significantly. This decrease in energy causes a large increase in the attenuation of the scattered beam. In this paper I will give the results of numerous Monte Carlo calculations detailing the extent of the multiple scattering and I will explore the feasibility of a variety of imaging schemes.

1. INTRODUCTION

For over a year now I have been studying the problems involved in single sided x-ray tomography. That is, three dimensional imaging of opaque objects by use of an apparatus which has both detector and radiation source located on the same side of the object. Although the present state of the art in this field is extremely immature, the potential uses for such a system, if it could be developed to a practical apparatus would provide an very high payoff. Such systems would find uses on all sorts of objects which had very limited
access. For example, buried pipes or tanks, building foundations, the hulls of ships the list is almost endless. In addition such a technology would prove useful for examining very large objects. Such objects are difficult to image using conventional techniques for several reasons. First, radiation must be of sufficient intensity and energy to penetrate the object. Radiation of high energy is typically scattered rather than absorbed. This contributes to the overall background in the image. More importantly, increasing the energy (penetration) of the radiation must directly decrease the contrast of the projected image.

In thinking about the solution to this problem I am led to the conclusion that there are only about three physical processes that might be useful. They are: scattering, pair production, and nuclear activation. In this paper I will examine two of these processes - scattering and pair production in detail. I shall give examples of several imaging schemes and in some cases the results of detailed calculations. Finally, in the last section I will present the results of numerous Monte Carlo calculations which I used to estimate the intensity due to multiple Compton scattering.

2. PAIR PRODUCTION

At energies greater than about two Mev, electron-positron pair production begins to compete with the Compton effect in most materials. This process appears to be very promising for use in radiography for several reasons. First, photons in the energy range of from two to thirty Mev are very penetrating with mean free paths of many centimeters in most materials. Even at the highest energies where the dominance of pair production decreases the mean free path, effective penetration may be achieved in the form of a cascade shower which produces copious electron-positron pairs. For many materials of interest the cascade unit associated with these showers is several centimeters and energy loss typically takes the form of production of high energy positron electron pairs. These high energy particles produce high energy photons either through annihilation or bremsstrahlung. In either case these high energy photons are directed into the object where they may produce more electron positron pairs. This process will continue until the energy of the bremsstrahlung is less than a few MeV. In the final stages of this shower we might expect large amounts of 511 keV photons to be emitted isotropically from deep within the object. These photons may then be detected with an energy sensitive detector.

Although I have only just begun to examine the possibility of such a system, my initial calculations are very encouraging. Figure 1 is a plot of the bremsstrahlung spectrum calculated using the Monte Carlo code EGS4. The calculation took a few hours and explicitly calculated all the electromagnetic interactions of 30,000 29 Mev electrons incident on a 1 cm tungsten target. The several curves indicate the angular bins into which the photons are 'detected'. This figure makes two important statements. First, that the efficiency for producing these photons is incredibly high. Typically two photons are produced for each electron that comes down the accelerator. Second, most of this radiation goes in the forward direction. Therefore, most of the photons made by this process can be directed into the object to be radiographed. On the negative side most of these photons are below 2 Mev and therefore less useful for pair production. It remains to be seen how much optimization can be done in this regard.
I have also run non-relativistic Monte Carlo calculations using the program COG to examine the feasibility of detecting the 511 kev annihilation radiation for massive targets. In one problem I input a beam of 2 Mev photons into a 30 cm cube of aluminum and simply looked at the emerging photons. The incident beam was monochromatic and isotropically launched into a cone of half angle 45 degrees. The results are shown in figure 2. Figure 2a is the spectrum obtained by using a detector with only ten percent energy resolution and an acceptance angle of 45 degrees measured from the normal to the surface. Clearly, no annihilation peak can be seen and indeed the code reports that the average number of collisions a detected photon undergoes is about four or five. Fully 30 percent of the detected photons make three collisions while only three percent undergo two collisions - pair production plus annihilation. Figure 2b shows the same situation only this time the detector is collimated to a 20 degree half angle. In this case the annihilation radiation is still not resolved but note that there is now a five order of magnitude drop in signal for photons of energy greater than 0.55 Mev. In figures 2c and 2d the detectors were both collimated to a 10 degree half angle and in figure 2d the resolution was increased from ten percent to two percent. In these two detectors the annihilation radiation appears from three and a half to over six orders of magnitude brighter than the scattered radiation.

Figure 3 is a cartoon of how I envision such a radiography system would appear. Such a system could be made portable, but of course, would represent significant radiation hazards when in operation. High energy electrons are produced in pulses by the linac. Those electrons passing through the target are dumped in the beam dump. Two of an array of Gamma Ray Imaging Spectrometers (GRIS) are shown. These spectrometers typically use a scintillator NaI(Th) or CsI(Th) coupled to a position sensitive detector to obtain both energy resolution and position resolution. The actual imaging is done by placing a coded aperture in front of the detector. Such instruments while not common are presently in use by astrophysicists in my laboratory and at many other laboratories around the world. These 'telescopes' typically have better than ten percent energy resolution and better than a few tens of arc minutes angular resolution.

Let me summarize the advantages of using pair production-annihilation radiation for radiography.

1. The incident radiation is highly penetrating.
2. The production of this radiation is highly efficient.
   Not only is the bremsstrahlung process which produces the incident beam very efficient, but the incident beam is mostly directed into the target. Each electron-positron pair produces two photons and these photons are emitted isotropically. In the corresponding case of Compton scattering the photons emerge at mostly forward angles.
3. The energy of the annihilation photons is exactly 511 kev.
   Therefore this energy may be used to discriminate against multiple scattering events.
4. The annihilation photons typically have very much more energy than a large angle Compton scattered photon. Therefore penetration back out the object will be much more efficient.

5. The pair production cross section varies like the atomic number squared allowing possible discrimination of atomic species within the target.

Lest the reader be left with the wrong impression about the development of this technology, I close this section with a brief list of questions which at this time remain unanswered.

1. Is it possible to operate a GRIS in the vicinity of an operating linac? Even if it were possible to gate off the detectors during the radiation pulses, the environment close to the accelerator would be very hostile.

2. How accurately is it necessary to know the radiation spectrum and angular distribution emitted by the accelerator?

3. How do these high energy photons interact with matter?
   a) What is the spectrum emerging from the target as a function of energy, angle, and target density?
   b) What is the ratio of single quanta to two quanta annihilation radiation for moderately high Z targets?
   c) What is the ratio of 511 kev annihilation photons to other energy annihilation photons?
   d) What is the ratio of the 511 annihilation photons to the 511 kev compton scattered photons?

4. What kind of spatial resolution can we expect from a GRIS which has been optimized for microscopy rather than telescopy?

3. SCATTERING

Coherent scattering has less to offer in that it is the dominant form of scattering in the same energy region where photoelectric absorption is dominant and the photoelectric effect is generally many orders of magnitude stronger. On the plus side coherent scattering is proportional to the atomic number Z squared and contains resonance features which can be exploited for quantitative analysis. For instance Harding and Kosanezky have used coherent scattering of 60 kev photons off various plastics to not only determined the structure of these objects, but to also identify their stoichiometry. For large dense objects it is difficult to imagine how coherently scattered radiation could be used effectively.

At energies over about 200 keV Compton scattering is often the dominant interaction of radiation and matter. This dominance occurs at precisely the energies where the matter is the most transparent. Also the contrast available from most imaging schemes using scattered photons is independent of the opacity.
Therefore Compton scattering has been used by numerous authors for obtaining three dimensional radiographs. Probably the most common method uses a highly collimated beam of high energy X or gamma rays incident on the object in conjunction with an equally highly collimated detector. The intersection of the incident beam with the viewing cone of the detector uniquely defines the scattering region. It is therefore possible to reconstruct the electron density uniquely if the entire volume is scanned from the outside inward. The reconstruction is therefore quite straightforward. The high degree of collimation coupled with the need to scan the entire object in three dimensions places severe limitations on the usefulness of this method.

Farmer and Collins, and Prettyman have sought to overcome these limitations through the use of high resolution solid state spectrometers for their detectors. By measuring the energy shift of the detected photons it is possible to reconstruct their trajectory without the high degree of collimation from either source or detector. This has the effect of increasing the efficiency of the system and at the same time allows a large number of voxels to be measured simultaneously. The primary drawback of this technique is that multiple scattering contributes much more to the signal than in the above technique.

In the remaining section of this paper I will discuss my own designs for using the energy spectroscopy method for obtaining single sided tomography of large objects.

Our apparatus is shown schematically in figure 4. A 300 mci Cs-137 source, 3 mm in diameter is located as shown in the center of a 10 cm radius lead pig. Running diagonally through this pig is a 12.5 mm diameter tube into which a cylindrical tantalum collimator may be placed. The object to be radiographed is placed on an X-Y-Z positioning table as shown. A 65% relative efficiency intrinsic germanium spectrometer is mounted behind the set of tantalum slits. The slits serve a dual purpose. First, they confine the viewing region of the detector to the plane defined by the incident beam and the slits. As I will demonstrate this has the effect of greatly reducing the multiple scatter into the detector without sacrificing any signal. Second, they serve to vignette the beam-collision area. This greatly improves the contrast. A photograph of the actual apparatus and the slit assembly is published in the accompanying article (1942-22).

A great deal of effort went into the slit design. Since its geometry directly effected the imaging capability of the system, it could be designed only after the reconstruction algorithm was written. On the other hand it proved to be very difficult to write a reconstruction program without at least some idea of the final geometry. The above design was arrived at by calculating the spectra with COG from scores of different designs. These calculations often took up to an hour on the LLNL Cray YMP supercomputer. In these problems the efficiencies were generally so low that only 'point' detectors which used a point flux estimator technique could be used to obtain meaningful output. Therefore, since most of my design schemes depended explicitly on large area detectors for reconstruction, a new program SUPERMAN was written. SUPERMAN simply ignores multiple scattering and calculates directly the attenuation and scattering of the beam into the detector. This was done to help estimate the efficiency of the design as well as maximize the contrast. COG was then used to check on the effects of multiple scatter. As a further check the multiple scattering in COG could be turned
off and the spectrum could be directly compared to that obtained from SUPERMAN which could be run with an infinitesimal detector.

3.1 COG simulations

Initially, I was using COG to seek guidance in obtaining a design that had both good contrast and a minimum of multiple scattering contamination. Although COG has an excellent geometry package that allows precise modeling of almost any geometry, the first problems I ran were quite simple. I input the geometry implicitly with the detector and source definitions. That is, instead of defining physical collimation, I simply restricted the angles of emission of the source and the angles of acceptance for the detectors. This both simplified the code and increased its efficiency. After the design matured, I then carefully modeled all the collimation.

Figure 5a shows the results of a simulation in which I varied the acceptance angle of the detector from one degree to seven degrees half angle. In this simulation both the source and the detector are seven cm above the sample and view the sample at an angle of 45 degrees. The source is collimated to a cone of one degree half angle. The singly scattered radiation is clearly visible as a broad peak almost an order of magnitude more intense than the multiply scattered radiation. These curves are remarkable in that they imply that the multiply scattered radiation is almost completely featureless and would therefore appear to be easily subtracted from these spectra. Figure 5b shows the results of the exact same problem but this time the multiple scattering has been turned off. Figure 6 shows the results of a simulation very similar to 5a superimposed on the results of 5a. In this calculation the detector and source are moved to within 1 mm of the slabs surface. Notice that the multiply scattered radiation has remained completely unchanged even though the volumes viewed by the two detectors vary by over a factor of 50. These results are for a detector collimation of six degrees. The reason for radically different shapes in the singly scattered peaks is simply that the detectors of figure 5 views a much wider range of depths (both detector and source are further away) than that of the latter detectors.

Figure 7 displays the results of a simulation somewhat similar to that of figure 6 except that in this simulation the width of the angular collimation remained fixed at two degrees but the axis of this collimation varied from 30 deg to 60 deg. Once again the multiply scattered radiation appears flat and featureless. Finally, figure 8 shows the results of a calculation with the full geometry of figure 3 physically put into the calculation. The dip at about 250 kev is from a void which was included as a check on the resolution of the system. The void is in the form of a cube 2 mm on a side and buried to a depth of one cm.

As a further check on the behavior of the multiply scattered background, the same simulation as in figure 7 was run for slits which varied in width of from one mm wide to eight mm wide. Some representative results are shown in figure 8. Although the backgrounds do increase with increasing slit width, the singles remain highly visible for all the these cases. If the signal to noise ratio is defined as the quotient of the intensity at 245 kev (the edge of the dip)to the intensity at 250 kev (the center of the dip), then the signal to noise varies from about 6 for a 1mm wide slit to about 4 for an eight mm wide slit. This means that
most of the multiple scattered radiation may be suppressed without sacrificing to much signal. Direct comparisons with laboratory measurements are frustrated by the small magnitude of the signal for 'point' detectors and the relatively large natural backgrounds. Specific measurements are presented and discussed in the accompanying paper (1942-22) wide slit. curve b - 8 mm wide slit. The absolute intensities for these two cases should not be compared since different normalizations were used.

4. CONCLUSIONS

In this paper I have tried to describe two differing techniques for doing single sided imaging of large dense objects. I have presented results from some of the numerous Monte Carlo calculations which I have performed in an effort to understand and minimize the backgrounds. The use of annihilation radiation, while it holds much promise for gamma ray tomography requires so much development that for the present it can only be discussed in the most general of terms. Compton scattering, on the other hand is a technique which has already been applied by several laboratories both for nondestructive testing and medical diagnostics. It principle drawback is in its low efficiency and long exposure times. The replacement of collimating apertures by slits and detectors by high resolution spectrometers offers an increase in efficiency of about a factor of twenty due to the increase in volume being measured simultaneously and another factor of ten to twenty due to the increase in detector solid angle viewed by each voxel. In the accompanying paper (1942-22) I show how the efficiency can perhaps be increased by another factor of 1000-10,000 by the use of 'virtual collimation'. These advances together with the steady advances being made in gamma ray spectrometers imply that this method of tomography will perhaps yield practical devices in the next few years.

5. ACKNOWLEDGMENTS

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6. REFERENCES


Fig 1. Bremsstrahlung radiation produced from 29 Mev electrons incident on a 1 cm tungsten target.
Fig 2. Radiation spectrum from 2 Mev photon beam incident on a 30 cm cube of aluminum. (a) detector collimated to a cone of half-angle 45 deg. (b-d) detector collimation 10 deg. (a,b,d) collimation axis normal to surface. (c) axis 10 degrees away from source.
Fig 3. Annihilation radiation tomography facility

- SUPERMAN -
Source/Detector Assembly

Fig 4. Single sided tomography apparatus
Fig 5. Spectrum of scattered photons for various detector angular collimations

Fig 6. Effect of moving the detector of fig 5 closer to the target
Fig 7. Effect of changing the detector axis of collimation.

Fig 8. Spectral dependence of slit width. Curve a - 1mm.