1 of 1

Conf-940449--10

UCRL-JC-116023
PREPRINT

Recent Progress in Single Sided Gamma-Ray Tomography

Robert S. Thoe

This paper was prepared for submittal to the
International Society for Optical Engineering
Orlando, Florida
April 5-8, 1994

April 1994

This is a preprint of a paper intended for publication in a journal or proceedings. Since changes may be made before publication, this preprint is made available with the understanding that it will not be cited or reproduced without the permission of the author.

MASTER

ds
DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED

DISCLAIMER

This document was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor the University of California nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial products, process, or service by trade name, trademark, manufacturer, or otherwise, does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or the University of California. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or the University of California, and shall not be used for advertising or product endorsement purposes.

Recent Progress in Single Sided Gamma-Ray Tomography

R. S. Thoe

Lawrence Livermore National Laboratory
P.O. Box 808, M/S L-43
Livermore, Ca. 94551

ABSTRACT

The use of scattered radiation for radiography has many potential advantages over conventional projection techniques: For high energy photons the scattering process strongly dominates all other processes. The intensity of scattered radiation is due directly to the electron density and highly insensitive to chemical composition. Finally, the use of scattered radiation allows the investigator to position the radiation source on the same side of the object as the detector. In this paper I will present some recent results of a set of measurements made with our uncollimated Compton backscattering tomography apparatus. This technique uses the Compton energy shift of scattered gamma rays to determine the scattering site. By measuring the spectrum of these scattered gamma rays it is then possible to determine the electron density of the object being investigated.

I will give a brief description of the apparatus and present the results of numerous measurements made on a brass phantom with voids placed at various depths. These results imply that for this crude apparatus occlusions as small as one cubic millimeter may be located to an accuracy of about one millimeter at depths of about 15 millimeters in solid brass.

2. INTRODUCTION AND BACKGROUND

Although burdened with many technical difficulties, the use of Compton scattered gamma rays for doing tomography has many highly attractive features. Gamma rays of moderately high energy are the most penetrating photons. Radiographs obtained using scattered radiation show contrast proportional to density variations only and can thus be highly insensitive to opacity effects. In fact the opacity is due almost entirely to scattering and thus independent of stoichiometry over a very wide range of photon energies. Techniques for doing this type of radiography can and have been developed that do not require the source and detector be located on opposite sides of the object to be imaged. Therefore, this type of radiography may be employed on structures which would ordinarily not permit such measurements. For example, using scattered radiation, oil pipelines may be radiographed without the necessity of interrupting the flow of oil or removing any external insulation. Subterranean tanks may be radiographed. Aircraft parts, building foundations, ships hulls, large castings, well casings, solid propellant rocket motors, etc. can all be radiographed in situ without the need of obtaining access to both sides of the structure. In the field of medical diagnoses, radiography using scattered radiation can provide a direct

and quantitative measurement of the density of the object being studied. The diagnoses of osteopathic diseases especially might greatly benefit with this technology.

Almost all previous attempts to image using scattered photons have involved the use of both highly collimated detectors and an equally highly collimated source^{1,2,3,4}. Although such systems were indeed able to obtain reasonably high resolution and contrast, the consequences of using such drastic collimation were twofold: First, it was necessary to raster the entire volume being imaged. This meant that the amount of time required for an image scaled as the size of the image cubed. For medical applications the necessity to raster the entire radiographed volume also meant that the dose received by the patient might be unacceptably large. Second, for this highly penetrating radiation the implication is that collimation on the detector and the source has to be both thick and heavy. Therefore, the apparatus will necessarily be large and unwieldy. What is needed is a method which increases the efficiency of the system by factors of a hundred or more while at the same time decreases the size and weight of the device. There are three obvious means achieve this efficiency. First, the detector(s) need to view more than a single voxel at a time. Viewing a multiplicity of voxels simultaneously not only increases the acquisition rate but also decreases the dose absorbed by the object being imaged. Second, the detector(s) should subtend as large a solid angle as possible. Finally, the efficiency of the source needs to be improved by either using multiple beams or decreasing the source collimation.

All three of these solutions are frustrated by the penetrability of this high energy radiation. It is difficult to imagine a collimation scheme (on either the source or detector) that has simultaneously good collimation and high efficiency.

Our technique Uncollimated Compton Backscattering Tomography (UCBT)⁵ overcomes these difficulties by doing away with the detector and its collimation and replacing it with a high efficiency gamma ray spectrometer and its associated baffling. The kinematic energy shift of the scattered radiation is accurately measured and used to calculate the location of the scattering site. Since the detector subtends a large solid angle, each scattering site gives rise to a spectrum of energies corresponding to the angular limits of the detector as viewed from that scattering site. The purpose of the baffling is to vignette the detector and therefore distort the spectrum depending on where the scattering takes place. The net result is that each scattering position gives rise to a unique spectrum called a basis. In order to reconstruct the objects' density, all that is necessary is to decompose the acquired spectrum into its basis set.

In the sections below I give a brief review of the prior techniques developed for imaging with scattered X or gamma rays. and then describe UCBT. In the main body of this paper I will present the results of some preliminary experiments which use this technology to examine a set of small voids embedded in both steel and brass phantoms.

3. PRIOR ART

In this section I briefly describe the 'standard' technique used for one-sided x-ray tomography. Other systems differ in certain details but very little in physical concept. Figure 1 (ref 1) is a drawing illustrating the basic components of the apparatus.

This technique typically uses an intense (>10 ci) x-ray or gamma-ray source. Both source and detector are highly collimated into a pencil of very small angular size. The collimation must be highly opaque to both the incident and scattered radiation since it is the collimation which determines the resolution of the system. These collimators define a scattering volume. If the specific intensity of the source is known and the detector efficiency is known and the geometry is understood, then it is possible to use the measured x-ray flux to determine the electron density of the object. In order to do this, however the entire volume must be scanned and it must be scanned a voxel at a time. It is the small magnitude of the scattered signal together with the necessity of scanning the entire volume which makes this technology unattractive. The collimators are problematic in two specific ways: First, they radically reduce the efficiency of the system. Second, in order for them to be effective they must necessarily be both heavy and bulky.

Figure 1. Conventional method of using Compton scattered radiation for radiography

The overall efficiency drops extremely rapidly with increased resolution --mostly due to the source collimation. For example, to increase the resolution by a factor of two the source collimators must be decreased by this same factor. This in turn decreases the incident photon flux decreases by a factor of four due to the decrease in solid angle, and another factor of four due to the decrease in source size. The scattering volume decreases by a factor of eight. The detector may stay the same size but its collimation must decrease by a factor of

four and this may be difficult to fabricate. Finally, the scan must include eight times as many voxels per unit volume. Therefore the efficiency decreases by a factor of 128. The time required per unit volume will increase by a factor of 1024!

The key to radically improving the performance of one sided radiography is the removal of the constraints imposed by the drastic collimation and the necessity of rastering the detector and incident beam.

Figure 2 is a sketch which serves to illustrate how it is possible to obtain a radiograph using scattered photons without the necessity of rastering in three dimensions or collimating the detector. This is the method employed by Farmer and Collins⁶ and utilizes the energy resolution of the detector along with the Compton shift of the scattered photon to localize the collision site. Although considerable gain was realized by the elimination rastering over the X direction this advantage is offset by the necessity of collimating the incident beam and the necessity of using small detector apertures. As can be seen by inspecting figure 2, the spatial resolution of this technique is limited not only by the energy resolution of the detector but also by the detectors' entrance pupil.

For a 'point' detector the spatial resolution of this system is given simply by the variation with angle (dispersion) of the Compton energy times the detector resolution times the detector-beam distance. For photons in the hundreds of keV energy region the energy shift with angle is quite large and easily measurable with modern gamma ray spectrometers. Figure 3 is graph of these energy shifts along with their variation with scattering angle.

Although the peak in the dispersion is typically located at forward angles, the dispersion is still quite large ≈ 50 keV/rad even at scattering angles greater than 120 degrees for 0.5 MeV incident photons. This implies that for a detector of 1 keV resolution, the corresponding spatial resolution of $R/50$, where R is the distance from detector to voxel. This is comparable to the spatial resolutions obtainable with hard collimation techniques.

However, this technique still suffers from the effects of small detector size, small source efficiency, and the necessity of rastering in two dimensions. Clearly it would be desirable to develop technologies that would enable the use of the large, efficient spectrometers currently available and do away with the necessity of rastering the incident beam.

3.1 UCBT

Figure 4 is a sketch depicting the major design features of the UCBT apparatus which I call superman. The source is collimated to an approximate pencil by a long tantalum cylinder. The detector is uncollimated but views the intersection of the beam with the object through a set of tantalum baffles.

Figure 2. Diagram of the Farmer Collins apparatus

Figure 3(a) The variation of photon energy vs. scattering angle for photons with incident energy 0.5, 1.0, 2.0, and 5.0 MeV(b) The dispersion $dE/d\theta$ vs. scattering angle for the same incident energies of (a)

The design of these baffles is critical and probably not yet optimized. They serve two purposes: First, they are coplanar to incident beam and confine the detectors field of view to this plane. This reduces the backgrounds due to multiply scattered radiation by many orders of magnitude. Second, the field of view is strongly vignettted by these slits. This vignetting is important because it allows different depths to be identified by a unique spectrum. If the spectra from these various depths are known, then by adding these spectra together one can synthesize the spectrum of the entire object. Of course obtaining these spectra as a function of depth is not straightforward because all spectra that originate below the surface will be highly distorted by attenuation both of the incoming beam and the scattered beam. Although this attenuation is originally unknown, if the scan (reconstruction) proceeds in the proper direction as shown by the arrow in figure 4, the attenuation of the scattered beam becomes better known as the calculation proceeds since the scattered beam is traveling through matter whose density distribution has already been at least approximately determined. This is important since the scattered beam is much lower in energy than the incident beam and therefore undergoes much stronger attenuation affects.

SUPERMAN APPARATUS

Figure 4. UCBT prototype apparatus.

The results of Monte Carlo simulations of this system indicate that the best efficiency that might be expected is about 10^{-8} . Although this efficiency would provide reasonable

count rates for sources of moderate activity, several minutes would be required to obtain a spectrum with adequate statistics and this spectrum would only reconstruct a volume equal to the cross section of the beam multiplied by the length of the beam - about 0.2 cm^3 . To obtain information about large volumes would be not only time consuming but very difficult. Increasing the efficiency by simply using multiple beams incident on arrays of detectors is very difficult because of the large physical size of collimators and detectors. Designs along these lines have been tried by investigators using collimated detectors with only limited success. A more promising approach is to use a technique which I call virtual collimation. It is shown schematically in figure 5.

Figure 5. Advanced UCBT apparatus with virtual collimation

The technique of virtual collimation does away with the physical collimation of the source almost entirely and instead uses the coincidence technique to determine the path of the incident radiation. The radioactive source must be a positron emitter such as ^{22}Na . Positrons emitted by source nuclei are quickly brought to rest inside the source where they decay by annihilation with their antiparticle the electron. In order to conserve both momentum and energy, this decay results in the release of two photons traveling in opposite directions-- each with an energy of 511 keV. Therefore detection of a photon by one of the virtual collimator array detectors guarantees that the other photon was launched in the opposite direction. If a photon were detected in the spectrometer in time coincidence with a photon detected by the virtual collimator array it would be the same as if that photon had traveled through a collimator. These collimator detectors could consist of one

dimensional arrays and perhaps could be arranged in rows as shown in the figure. It is not difficult to imagine several square centimeters worth of these detectors giving an increase in sensitivity of perhaps several hundred. But this is not all. In going to the virtual collimation technique, the source can be transported to within a centimeter or two of the object giving another factor of ten increase in efficiency. Furthermore by simply increasing the distance to the collimator detectors, the spatial resolution for this system could be greatly enhanced without loss of efficiency.

For a numerical example, consider a virtually collimated source placed five centimeters from the object. and an array of collimators arranged so that the incident beam has a cross section of three millimeters by one centimeter. This is an increase over the superman geometry of 9 (solid angle of source) times 30 (beam area) or almost 300! For a 100 mci source the count rate in the virtual collimator array would be about three million per second. For an array consisting of 100 detectors of 50 percent efficiency this would be about fifteen thousand per second per detector which is about ten to one hundred times slower than the throughput of commonly used commercially available coincidence electronics. It should be remembered that this detector array does not need good energy resolution.

A great deal of effort went into slit design since slit geometry directly effects the imaging capability of the technique. On the other hand it was very difficult to design a reconstruction technique until at least some of the basic fundamentals of the mechanical design was known. For this reason I utilized a Monte Carlo code -- Cog, developed here at LLNL to calculate the signal from a wide variety of system designs⁷. Cog has many features which make it ideal for this type of calculation. It has virtually all the physical processes which are important in these problems including photoelectric absorption, both coherent and incoherent scattering, pair production, even nuclear processes are accounted for. It has an excellent geometry routine which easily allows the user to generate and inspect any geometry using any materials he may desire. Since it is a Monte Carlo calculation it handles not only single scatter events but multiply scattered events.

After performing many calculations it became clear that the use of Compton scattered radiation for imaging would require the following: The source must necessarily be small in size. Therefore, a bright signal would require a source of high specific activity. The angular divergence of the incident beam(s) must be minimized as much as possible. These first two items together implied that for a single beam prototype apparatus, the source size needed would be about a square millimeter. The maximum efficiency of a single beam device would be about 10^{-8} . The vignetting slits needed to be a few centimeters long and could be up to about five millimeters wide.

The low efficiency of this process required that a great many photons be launched for each detected photon. In order to accomplish such a calculation 'point detectors' which use a point flux estimator technique were used. These detectors derive the maximum information from each photon launched by calculating the probability that photon would be detected at each collision. Unfortunately since these detectors are by definition dimensionless, they do not lend themselves easily to the synthesis of a vignetted spectrum. To solve this problem a direct calculation was performed by ignoring all multiple scattering

events and calculating the direct scattering signal through the vignetting slits. In this way different slit geometries could be tried and the contrast could be maximized rather quickly by trial and error. This geometry was then input into a Cog calculation to check on multiple scattering. The calculation used enough point detectors to completely cover the entrance apertures. These Cog calculations were all performed on the LLNL Cray YMP supercomputer. Typical execution times ranged from about 20 minutes to almost 400 minutes depending on the desired accuracy, the complexity of the geometry, and the number of detectors used. Some of the results of these simulations may be seen in references 5 and 8. Table one is a summary of series of calculations showing the effects of multiple scattering vs. slit width on the contrast observed from a 2mm³ void placed 25 mm inside a 50 mm slab of normal density steel. In this table the fraction of single, double, and triple collisions are shown for slit widths ranging of from 1 to 8 mm. The contrast was obtained by measuring the signal at the energy corresponding to the void divided into the signal at the low energy side of the void--see figure 8 reference 7.

TABLE 1
NUMBER OF COLLISIONS

SLIT WIDTH mm	SINGLE	DOUBLE	TRIPLE	CONTRAST
1	.70	.20	.05	6.5
2	.56	.26	.11	6
3	.43	.28	.1	5.9
4	.39	.33	.19	3.7
6	.36	.37	.14	5.5
8	.36	.31.	.18	3.7

The details of the reconstruction method has already been given, therefore only a brief outline of the technique is given here; for a more complete description the reader is referred to reference 5. It can be shown that for voxels whose dimension are small compared to the mean free path of the scattered gamma rays, the lowest order contribution of that voxel to the spectrum is due to scattering. Furthermore, it can be assumed that to first order all the attenuation is due to scattering. Therefore, the attenuation is a function of density alone and independent of stociometry. To reconstruct the density matrix corresponding to a given set of spectra, one initially assumes that the density is homogeneous. In what follows I will seek to find not the density matrix, but the matrix of density coefficients. One starts by initializing this matrix to all ones. Next a set of functions is generated to be used in a least squares fitting routine. These functions are the spectra as would be measured from each row in the density matrix. That is, each function is the spectrum that would result from the scattering from a given row in the density matrix after accounting for the attenuation of the incident beam and the attenuation of the scattered beam by a homogenous slab of thickness equal to the depth of that row. Next a least squares fitting routine is used to fit the observed spectra using these function as a basis. The fitting parameters are then the density multipliers. With this done the next spectrum is fit, except

a new basis set is generated using the appropriate density multipliers obtained from previous fits. For example, in figure 4 the diagonal labeled position 1 would be the first spectrum to be fit using the above procedure. When position 2 is analyzed the results of position 1 would determine the approximate values of the densities of the diagonal elements of position 1. By the time position n is analyzed, n diagonal elements of the density matrix are approximately known. When the end of the scan is reached, the fitting procedure starts over again at position 1, but this time all the density elements are approximately known (in the parallelogram specified by the top, bottom and end diagonals), therefore each iteration should increase the accuracy of the density matrix. The procedure is iterated until convergence—no significant change in density is recovered by additional iterations. In simulations, this usually took about 3 iterations.⁵

The basis were obtained by directly measuring the spectra from a thin steel plate located at the appropriate depth from the vignetting slits assembly and then correcting these spectra for attenuation. Since the voxels were all optically thin, it was not necessary to match either the density of the plate or the thickness of the plate to the corresponding voxels density or thickness. Figure 6 shows a basis set which was obtained using a 3 mm thick plate of 300 series stainless steel.

Figure 6. Superman basis set.

This method of obtaining the basis set is probably the single most important detail of this technology. The basis spectra are determined not only by the density matrix but also by the slit geometry, detector efficiency and detector resolution. By directly measuring the basis, all these effects are measured and all that must be accounted for is attenuation. For example, the basis shown in figure 6 all seem to have a broad dip at about 230 keV. It was discovered that this dip could be moved by changing the position of the detector. I suspected

that it was due to a decrease in sensitivity near the center of the detector. In order to prove my suspicion, I made a series of measurements of the absolute photopeak efficiency of the detector as a function of position on its front face. The measurement consisted of acquiring spectra from a series of sources of known intensity. These sources were highly collimated with a heavy tantalum collimator one millimeter diameter aperture placed directly in front of the detector. The position of both the source and collimator were varied after each spectrum was accumulated. The results of this measurement is shown in figure 7.

Figure 7. Absolute photopeak efficiency of the gamma ray spectrometer used in these measurements. Note the dip at the center of the crystal.

Referring to figure 6 each row of these basis was 1.25 mm deep. Therefore, the entire set covers a depth of 25 mm. The reader may note that these spectra are quite well resolved one from another all the way to a depth of 25 mm. One might be optimistic therefore in expecting this system to be useful down to these depths. Such is not the case for this geometry however. The problem is that the basis shown in this figure have yet to be corrected for attenuation. When this is done it is discovered that the basis below about row 15 are very highly attenuated and have very little affect on the quality of the fit.

3.2 Uniqueness of Basis

In order for this technique to work the basis set must be unique; that is they must be a set of linearly independent functions (this set must also necessarily be complete!). The problem is that the basis set itself is a strong function of the density distribution. Therefore, there exists an infinite number of basis sets available for the reconstruction. What must be demonstrated is that there exists a single unique basis set which provides a fit which is within the limits set by the experimental accuracy.

In principle, at least, such must be the case. That is, the spectrum is fit uniquely by a single basis set (mass distribution). This can be seen by inspection of the basis set shown in figure 10. Although the basis functions shown are specific to a given density distribution the energy limits of each basis are determined solely by the geometry of the apparatus. Since each basis has unique limits, it is impossible to construct one of the basis functions from a linear combination of the others —ergo they are linearly independent. Furthermore, if any one of these functions were to increase or decrease (that is the voxel associated with this basis were to increase or decrease), this would necessarily cause a modification to only those basis which originate from voxels located below this function. Is it then possible to obtain the same combined spectra by adjusting the intensities (remember the densities are the fitting parameters) of the rest of the basis functions? The answer is no. This can be seen by examining figure 8 which is sketch of five basis spectra. In figure 8b the density corresponding to basis 3 was arbitrarily increased. Note that this also modifies (in this case decreases) the basis functions 4 and 5 since they originate from rows below row 3. The result of this modification is clear. The observed spectrum is increased at the high energy end but must decrease at the low energy end. Now the part of the observed spectrum lying in region a is completely specified by fitting only the basis 1, 2, and 3. Since basis 1 and 2 are unaffected by the change, the observed spectrum will be fit by adjusting basis 3 only. Once basis 1, 2, and 3 are determined the observed spectrum in region b completely determines basis 4. With the first four basis all determined, basis 5 must be equal to the observed spectrum minus the sum of the first four basis.

Figure 8

- Sketch of 5 basis functions and their sum
- Similar to a except the density associated with basis 3 was arbitrarily increased. This has the affect of increasing basis 3 and decreasing basis 4 and basis 5.

4. DATA

Due to the weakness of the source, backgrounds were large and considerable effort went into accurately measuring and parameterizing them. This procedure amounted to obtaining a high statistics background spectrum. This was usually done over the weekend or at least overnight. This spectrum was then divided into several overlapping regions. A peak search was done for each region and each peak was individually fit to a gaussian. These gaussians were then subtracted from the background curve and what was left was fitted to a fifth order polynomial. Figure 9 is a sample background spectrum along with its corresponding fit. New background spectra were taken periodically as a check on the spectrometer and electronics or any time the shielding was changed.

Figure 9. A sample background with associated fit.

After background subtraction the spectra obtained from the brass phantom had a much improved contrast. Figures 10 are some representative spectra for voids placed at various depths. Several least squares fitting routines were used, but none gave satisfactory results. The problem seems to be constraining the fit parameters to physically reasonable values, i.e. values greater than zero but less than three or four.

Figure 10. Spectra obtained from brass phantom with 0.1 inch voids located at various depths beneath the surface.

Figure 11. Some of the data of figure 10 is plotted (open circles) The solid line labeled 'fit' in each case is the sum of the basis spectra which has been corrected for attenuation effects. Each row corresponds to a depth of 0.1 inch (2.5 mm)

Figure 11 displays the data of figures 10 but with the corresponding synthesized spectra -labeled 'fit' obtained by accounting for the attenuation of the incident and scattered beam. In these spectra no fitting was attempted. Figure 12 is a demonstration of how sensitive the system is.. In this figure the spectrum obtained with a 0.1 in void 0.3 in below the surface is plotted as the open circles. The synthesized spectra obtained with the void located at depths 0.25, 0.3, and 0.35 inches are also shown. Although none of spectra are perfect fits, the one for the 0.3 in depth is clearly better than the other two.

Figure 12. This is the data of row 3 figure 17 plotted with the corrected basis with voids at depths of 2.5, 3.0, and 3.5 inches labeled basis 4&5, 5&6, and 6&7 respectively.

Finally figure 13 is a graph showing the difference in spectra between solid steel and solid brass. As in the previous figures the curve labeled 'fit' is simply the sum of the basis after correcting for attenuation and the increase in scattering due to the difference in density between brass and steel. It is a significant result that the same basis may be used for steel or brass since this implies that a single basis set can be used for a any material.

Figure 13.

- Spectrum obtained from a solid slab of brass --open circles along with the corresponding synthetic spectrum obtained by summing the corrected basis of figure 6.
- Spectrum similar to part a but from a solid slab of steel. The curve labeled fit in this case was obtained from the same basis as that of part a but with scattering and attenuation corrections appropriate for steel instead of brass.

5. CONCLUSION

Although the data presented in the last section of this paper demonstrate conclusively a proof of principle, I have left unanswered many questions: What is the ultimate resolution? What is the ultimate throughput?

The spatial resolution of this technique depends upon the energy resolution of the detector and the depth of the occlusion. A resolution of about one millimeter at depths of 12 millimeters is probably within reach of the apparatus as it now exists--see figure 12. This resolution is most likely determined by the beam diameter which is about one millimeter. With optimizations of the slit assembly it might be possible to obtain this same resolution at depths approaching 25 millimeters. By going to virtual collimation, the incident beam diameter may probably be reduced to about 250 microns. This does not imply that the spatial resolution will also be 250 microns, although it is clear that it would be difficult to obtain a spatial resolution smaller than the incident beam size. The ultimate resolution is not determined solely by the beam size; the detector resolution and viewing angle affect the resolution as well as the opacity of the slits to the scattered radiation.

The energy resolution of the detector used in this experiment is about 2 keV. For ninety degree scattered radiation the dispersion is about 50 keV/radian. Therefore, the detector resolution is the equivalent of $2 \text{ keV} / 50 \text{ keV/rad} = 1/25 \text{ radian}$. At a depth of 25 mm this is 1 mm.

The mean free path of 200 keV photons in tungsten is only about 1/2 mm. Therefore, one might expect that the ultimate resolution of this device is dependent upon the detector resolution and should be about a millimeter at a depth of 25 millimeters; but at depths of 12 millimeters or less the transparency of the slits should dominate and limit the resolution to about 500 microns.

The efficiency of this system can be improved dramatically. As this apparatus now exists, the source is 300 mci and measures 3 millimeters in diameter. In order to decrease the angular spread in the beam and decrease the source size it was necessary to collimate the beam to one millimeter diameter and move the source 30 centimeters from the sample. The acquisition time for a single spectrum was typically 300 minutes. By simply going to a 300 mci source one millimeter in diameter the intensity would increase by a factor equal to the ratio of these areas--almost an order of magnitude. Since the source is smaller, it could be moved much closer to the sample giving another factor of four. Finally, the use of virtual collimation would increase the entire throughput of the device by another factor of up to 10,000. The ultimate limit on the acquisition rate would be most certainly determined by the counting speed of the detector. By using an array of smaller detectors a count rate of 10,000 cps should be relatively easy to achieve. The spectra shown each took 300 minutes to acquire. They had an average count rate of 5 counts/min/keV and were about 150 keV wide. This is a signal of about 30 counts/min or 0.5 counts/sec. The detectors are capable of an increase in count rate of 20,000 and the virtual collimation scheme is capable of giving this increase. Therefore, the acquisition rate can be increased by 10,000. If the virtual collimation is divided into 100 spectra, each spectrum would take $(100/20,000) \times 300$ or 1.5

minutes. Reconstruction would be much slower unless parallel processors could be implemented.

In this report I have presented data that clearly demonstrate proof of principle for the uncollimated Compton backscattering tomography. This technology clearly has the potential to do single sided tomography on objects as dense as solid steel and locate voids as small as one cubic millimeter at depths of up to 25 millimeters. Using the method of virtual collimation the acquisition times will most certainly be limited by the reconstruction software.

Work performed under the auspices of the U. S. Department of Energy by the Lawrence Livermore National Laboratory under Contract #W-7405-Eng-48.

7. ACKNOWLEDGMENT

I would like to thank Dean Rippee and Ken Visbeck for their technical expertise in both the design and fabrication of this apparatus. I also wish to express my thanks to Bob Steinhaus for his assistance in assembling the electronics package.

8. REFERENCES

1. Stokes, J.A., et al (1982), "Some New Applications of Collimated Photon Scattering for Nondestructive Examination", Nucl. Instru. and Meth., Vol. 193, pp. 261-267.
2. Harding, G., and J. Kosanetzky (1989), "Scattered X-ray Beam Nondestructive Testing", Nucl. Instr. and Meth. in Phys. Res., Vol. A280, pp. 517-528.
3. Battista, J.J., L.W. Santon, and M.J. Bronskill (1977), "Compton Scatter Imaging of Tranverse Sections: Corrections for Multiple Scatter and Attenuations", Phys. Med. Biol., Vol. 22, No. 2, pp 229-244.
4. Holt, R.S., and M.J. Cooper (1984), "Gamma-ray Scattering Techniques for Non-destructive Testing and Imaging", Nucl. Instr. and Meth. in Phys Res., Vol A221, pp.98-104.
5. R. S. Thoe (1993), 'High Resolution Tomography of Objects with Access to a Single Side', SPIE, vol. 1942, pp 218-235
6. Farmer, F.T., and M.P. Collins (1971), "A New Approach to the Determination of Anatomical Cross-Sections of the Body by Compton Scattering of Gamma-Rays", Phys. Med. Biol., Vol. 16, No. 4 pp.577-586.
7. Thomas Wilcox and Edward M. Lent, COG User Manual, Vol. 1, LLNL, M-221-1, 1989
8. R. S. Thoe (1993), "Single Sided Tomography of Extremely Large Dense Objects". SPIE, vol. 1942, pp 289-300

DATE

FILMED

7/18/94

END