OPTIMIZING SPATIAL RESOLUTION WITH THE MECHANICAL DESIGN OF AN X-RAY COMPUTED TOMOGRAPHY SCANNER

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INTRODUCTION

With an understanding of the x-ray physics of a computed tomography (CT) [1-4] scanner with discrete detectors, and with knowledge of the scanner's geometry (the spatial relationship among the x-ray source, the detectors, and the object being scanned), it is possible to predict the achievable spatial resolution in images of objects of a certain size and density. However, if the size of the x-ray focal spot must be changed or if an object larger or smaller than the one for which the scanner is optimized is to be scanned, the spatial resolution may change. To maximize spatial resolution for a range of objects and x-ray sources, a scanner can be designed with a variable geometry, so that the spatial relationship of the scanner components can be changed to best fit each application.

This paper first describes how the scanning geometry is related to spatial resolution, then illustrates how the geometry must differ for optimal scanning of different objects. We then describe the Advanced Computed Tomography Inspection System (ACTIS), a second-generation CT scanner with multiple x-ray sources and a variable geometry, emphasizing the features that allow optimal and convenient scanning of a wide range of objects.

DETERMINING MAXIMUM SPATIAL RESOLUTION

Contrary to a popular misconception, the spatial resolution of a CT scanner is not limited by sampling, provided the scanner is well designed. Since the sample spacing should be set fine enough to avoid aliasing, all available fine detail will be reproduced and the spatial resolution will be limited by other factors [5-7]. The most elemental of these are two factors related to properties of the x-ray beam itself: the profile of the beam between the x-ray focal spot and the detector, and the position of the object being scanned in relation to the focal spot and detector.

The first factor, the beam profile, varies with focal spot size, detector aperture, and position between the source and detector. Figure 1 shows an x-ray focal spot at the top and a detector at the bottom. (The dimensions of the focal spot and detector aperture are exaggerated with respect to the distance between them to illustrate the concept.) Each point of the focal spot emits a fan of radiation; in the figure we see fan beams from both edges of the focal spot. While the beam most likely covers an area wider than the detector, all that is significant is the part that strikes the detector. If we consider the sensitivity of this beam to an object placed within it, we find that the profile of the sensitivity varies with position. For instance, if a lead sheet is passed across the beam immediately in front of the detector (point A in the figure) or the focal spot (point B), the amount of the beam that is blocked will be directly proportional to the amount of the surface area that is covered: the profile will be a

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rectangle. However, if the lead sheet is passed across the beam at the midpoint, point C in the figure, it will block only a small percentage of the x-rays as it passes through the edge of the beam. As it moves across the beam, it blocks increasingly more x-rays until it reaches the center. The profile at this point, therefore, is a triangle. At other points within the beam, such as point D, the profile will be uniformly sensitive near the center of the beam but will fall off at the edges, forming a trapezoid.

To illustrate how this variance in profile relates to spatial resolution, we must consider the beam width along the length of the beam. At point D in Figure 1, the thick line is the beam width measured using the full width at half maximum (FWHM). If the endpoints of the FWHM lines along the entire length of the beam are plotted, the result is the beam shape shown in Figure 2a. The beam width is as wide as the focal spot and the detector aperture at the respective ends of the beam, but it narrows to a thin waist at some point in between. The point at which the beam width is smallest is known as the half power crossover. Figure 2b gives formulas for the beam width at different positions between the focal spot and the detector. Note that the only variables in the formula for the beam width at the half power crossover are the focal spot width and the detector aperture; therefore, the minimum beam width is independent of its position between the focal spot and detector.

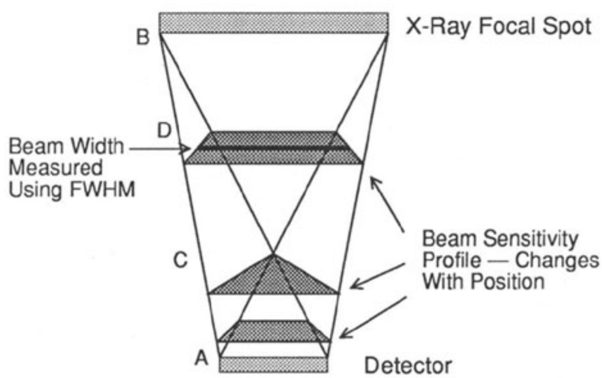

Figure 1. The drawing illustrates the beam sensitivity profile for different positions along the beam path.

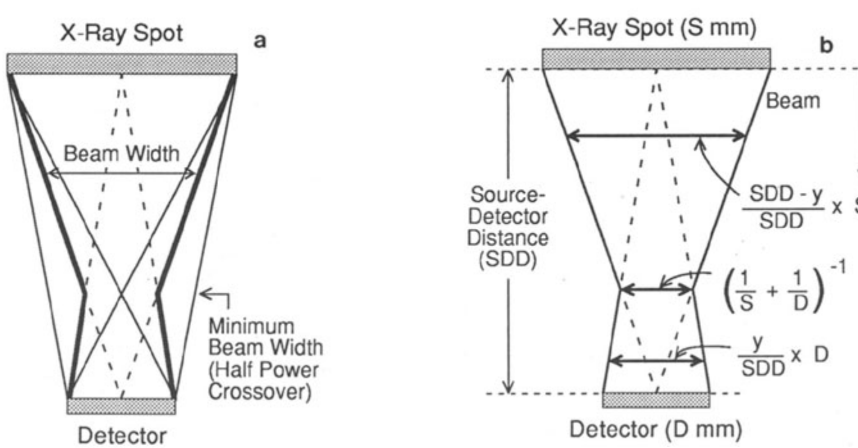

Figure 2. Drawing a shows the beam width obtained by plotting the FWHM lines; drawing b gives formulas for the beam width in different regions of the beam path.

Of course, changing the dimensions of the focal spot or detector will change the width of the beam. Figure 3 is a graph plotting the beam width for two focal spots, 2 mm and 1 mm, with a detector aperture of 1 mm. The beam width is smaller with the 1 mm source and, since the focal spot width and detector width are the same, the half power crossover is halfway between the source and detector. The graph not only illustrates that a smaller beam width is achieved with a smaller focal spot (or a smaller detector), but shows that making such a change also changes the location of the half power crossover. This becomes important when a scanner uses more than one x-ray source, or an x-ray source with more than one spot size, in order to provide the best density resolution for objects with different attenuation.

The position of the half power crossover is an important consideration in scanner design because spatial resolution is limited by the beam width as the beam passes through the object being examined. The resolution, in fact, is essentially equal to the width of the beam in the part of the object that is closest to the detector. This leads to the second factor in determining spatial resolution, the position of the object in relation to the focal spot and detector. Since the spatial resolution is greatest when the beam passing through the object is narrowest, the object should be positioned at the half power crossover for optimal resolution.

Theoretically, one could also increase the resolution by decreasing the focal spot size or detector aperture. It is important to note, however, that the laws of physics preclude decreasing the focal spot size and detector aperture arbitrarily. The energy of the x-ray emission must be spread out over a certain area to avoid melting the anode, and the detector must have a large enough area to receive a significant number of x-ray photons.

OPTIMIZING A CT SYSTEM FOR AN APPLICATION

With the knowledge from the above section, we can design a scanner that will have the mounting device for the object positioned so that a certain object will be at the half power crossover. For instance, if we have a scanner with a focal spot size of 1 mm, a detector aperture of 1 mm, and a source-to-detector distance of 1.5 m, and we want to optimize it for turbine blades (maximum diameter of 5 cm), we can place the turbine blade halfway between the source and detector as shown in Figure 4 and scan it with a spatial resolution of 0.5 mm. This equals a cutoff frequency of 2 line pairs/mm, as defined by equation 1.

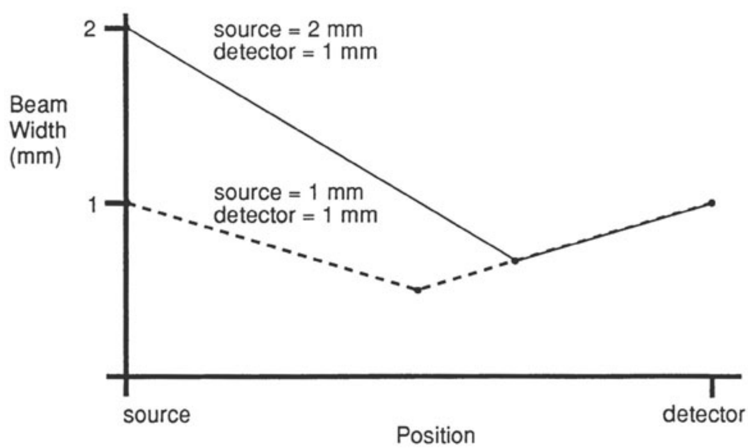

Figure 3. The graph shows beam width as a function of position between the source and detector for two focal spot sizes.

$$\text{Cutoff (lp/mm)} = \frac{1}{\text{Beam Width(mm)}} \tag{1}$$

But what if we want to scan a larger object—for example, a rocket exit cone 0.5 meter in diameter—with this scanner? If the cone is placed on the mounting device in the center of the scanner, its wall will be intersected by the beam as shown in Figure 4. The width of the beam as it passes through the wall will be 0.667 mm, giving a cutoff frequency of 1.5 lp/mm. Thus, the same scanner will scan two different objects with different resolutions. To optimize the scanner for the exit cone, it will have to be constructed with the mounting device placed so that the wall of the exit cone closer to the detector is at the half power crossover, as shown in Figure 5. Though there are now two beam widths passing through the cone (0.833 mm and 0.5 mm), experience has shown that the minimum beam width dominates on a 360° scan. Note also that when the turbine blade is mounted on this scanner, it is intersected by a beam with a width of 0.667 mm (1.5 lp/mm).

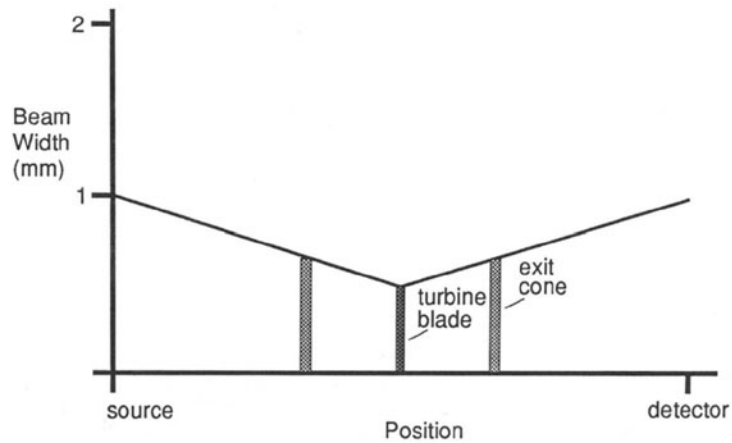

Figure 4. The graph shows the beam width as the beam passes through a turbine blade and an exit cone when the geometry is optimized for the turbine blade.

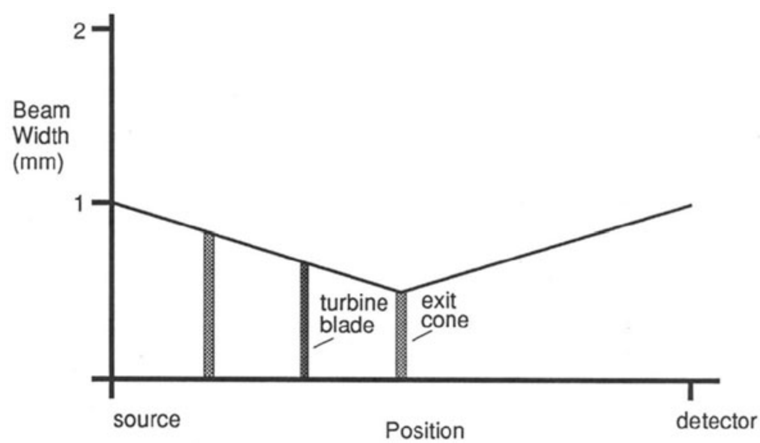

Figure 5. The graph shows the beam width as the beam passes through a turbine blade and an exit cone when the geometry is optimized for the exit cone.

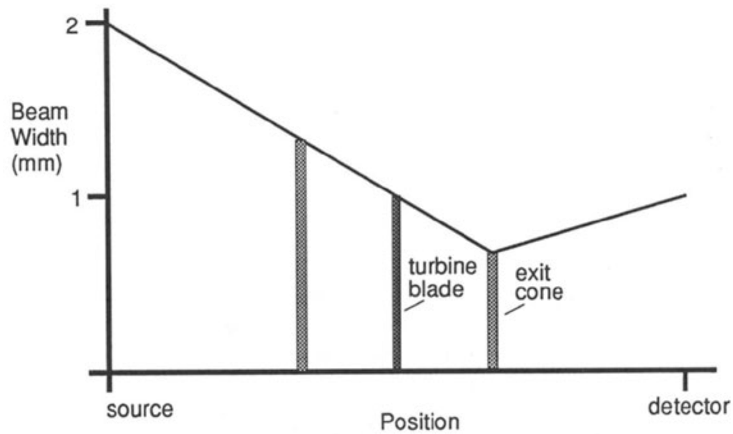

Figure 6. The graph shows the beam width as the beam passes through a turbine blade and an exit cone when an x-ray source with a 2 mm focal spot is used.

As a further complication, suppose that more x-ray penetration is needed and an x-ray source with a 2 mm focal spot size is installed. Figure 6 is a modification of Figure 4 with the focal spot size increased to 2 mm. This geometry will now no longer be optimized for the turbine blade, as the blade will be intersected by a beam 1 mm wide, giving a cutoff frequency of 1.0 lp/mm. Rather, the exit cone will be scanned with better resolution, as the beam width is 0.667 (1.5 lp/mm) as it passes through the cone wall closest to the detector.

Clearly, scanner geometry is application-specific. If one has a need for a large range of x-ray power (which will require multiple sources with different focal spot sizes) and a range of object sizes, significant compromises in spatial resolution will have to be accepted for some objects, or else a method of changing the geometry will have to be implemented.

THE VARIABLE GEOMETRY DESIGN OF ACTIS

ACTIS was conceived as a scanner that would scan both large (up to 1828 mm in diameter) and small (a few centimeters) objects with the best possible density and spatial resolution for each object. As described in the previous sections, there are two general requirements for imaging such a wide range of objects: multiple x-ray sources to penetrate objects of all sizes and densities with optimum density resolution, and a variable geometry to allow source and detector positioning for optimum spatial resolution.

ACTIS operates in several scan modes, each of which is designed to optimally image a certain type of object. These modes are programmed before delivery and are based on the customer's expected applications. The system software allows the user to program additional modes. Data collection parameters (number of views, samples per view, integration time, etc.) for each mode are set so that the ultimate spatial resolution is limited by beam width considerations. The mechanical positioning precision and accuracy are in excess of the limit required to support the highest spatial resolution.

Figure 7 is a concept drawing of the ACTIS gantry which illustrates the variable geometry and multiple sources. Up to three sources can be mounted on the source tower to the left. The detector box, containing a linear array of discrete solid-state detectors, is shifted along the x axis in the drawing to align the detectors with the source being used. The standard source is a 320 kV x-ray tube with small (0.8 mm) and large (1.8 mm) focal spots. With the two spot sizes, this tube's output allows scanning over the range of resolution and aperture designed into ACTIS. Optional sources include 150 kV or 420 kV conventional x-ray tubes, a 150 kV microfocus x-ray tube, a cobalt 60 isotope source, or a linear accelerator with energy ranges up to 16 MeV. The smaller sources will produce better images on certain objects, such as nozzles with thinner walls. The larger sources provide more x-ray penetration for large or dense objects. Since the linear accelerators are pulsed rather than continuous output sources, their pulses are synchronized with the integrator circuit trigger in the detector system.

The source tower, on the left in Figure 7, and the detector tower, on the right, both move along the y axis to provide the variable geometry capability. The object is mounted in the center of the turntable, which rotates and moves along the x axis. Each of the preprogrammed modes has a system geometry that automatically positions the source and detectors at the correct distance from the object in addition to adjusting the data collection and reconstruction parameters. These positions can be manually changed (through software) as well to optimize the geometry for each particular object.

The visible spatial resolution of the system ranges from 5.1 to 19.2 line pairs/cm as defined by a Rayleigh criterion (17% dip between maxima) for standard line pair gauges made up of alternating strips of dense and very light materials using a 10 mm slice width. The following tables present an example of how ACTIS can be equipped and programmed, using the standard 320 kV dual focal spot source, a 420 kV dual focal spot x-ray tube, and a 2 MeV Linatron linear accelerator. This range of sources provides a maximum density resolution of 0.5% for a 1 cm^2 region when a 360° scan is performed.

Table 1 gives the physical dimensions of each of three typical preprogrammed geometries. (ACTIS can be programmed for up to seven geometries.) The fan angle is the angle of the x-ray beam that is subtended by the detector array. Table 2 presents the spatial resolution and scan time performance for 15 different scanning configurations. The spatial resolutions listed in Table 2 are cutoff values. Actual visible resolution by the Rayleigh

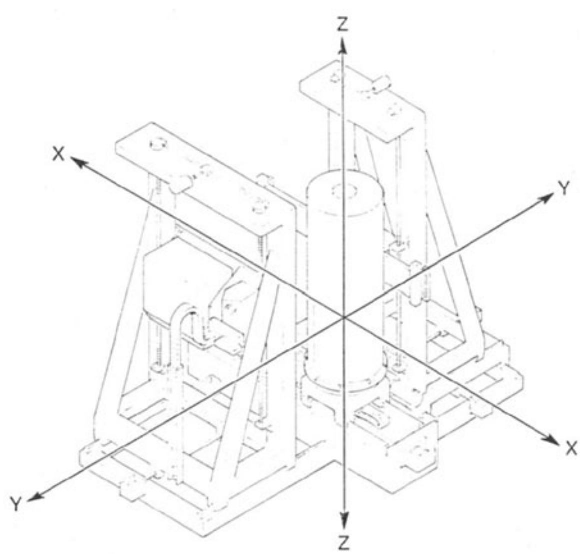

Figure 7. The drawing shows the mechanical configuration of ACTIS. The source tower on the left, which holds up to three x-ray sources, and the detector tower on the right both move along the y axis to vary the scanner geometry.

Table 1. ACTIS System Geometry

Geometry	Fan Angle (degrees)	Source-detector distance (mm)	Source-object distance (mm)	Scan field diameter (mm)
1	36.0	1330	760	380
2	25.7	1881	992	635
3	20.0	2464	1385	1270

Table 2. Performance for ACTIS Scan Modes

Scan Mode	Source	Spot size	Geometry	Spatial res. (lp/cm)	Scan time (minutes)
1	320 kV small	0.8 mm	1	24.1	8.4
2	320 kV small	0.8 mm	2	24.2	10.2
3	320 kV small	0.8 mm	3	19.8	34.8
4	320 kV large	1.8 mm	1	14.9	8.9
5	320 kV large	1.8 mm	2	14.2	15.2
6	320 kV large	1.8 mm	3	13.9	25.7
7/8	420 kV small/2 MeV	2 mm	1	14.0	3.5
9/10	420 kV small/2 MeV	2 mm	2	12.9	6.5
11/12	420 kV small/2 MeV	2 mm	3	13.1	11.1
13	420 kV large	4 mm	1	7.0	2.0
14	420 kV large	4 mm	2	6.4	3.1
15	420 kV large	4 mm	3	8.4	7.5

criterion is approximately 80% of the cutoff value. Each spatial resolution figure quoted is the average over the entire scan field for that mode; the figure is less than the maximum resolution attainable at the half power crossover. All scan times are representative of average sample integration periods. The noise characteristics of resulting images can be controlled by varying the sample time, which ultimately determines the scan time.

As mentioned previously, these or other scan modes can be preprogrammed to achieve optimal performance for an expected mix of applications. The user can select any preprogrammed mode by pressing two console buttons. It is also possible to define new scan modes as the need arises. The selection of source-detector and source-object distances is limited only by the physical constraints of gantry dimensions.

CONCLUSION

We have described the most important factor limiting spatial resolution in a well-designed CT scanner—the x-ray beam width as it passes through the object being examined. Since this factor is dependent on a number of properties, including object size and density, distance from the radiation source to the object, and distance from the source to the detectors, a scanner that is to effectively image a number of different objects must have some way of varying the spatial relationship among the source, object, and detectors (known as the system geometry). We have described ACTIS, a second-generation CT scanner that has a variable geometry to allow a wide variety of objects to be scanned at peak spatial resolution, even with different radiation sources. The design of this system gives the user great flexibility in many x-ray imaging applications.

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