ANALYTICAL CORRECTIONS FOR BEAM-HARDENING AND OBJECT SCATTER IN VOLUMETRIC COMPUTED TOMOGRAPHY SYSTEMS

F. Hopkins[1], Y. Du[1], B. Lasiuk[2], A. Abraham[1], and S. Basu [1]
[1] General Electric Global Research, Niskayuna, New York, USA; [2] General Electric Water Technologies, Houston, Texas, USA

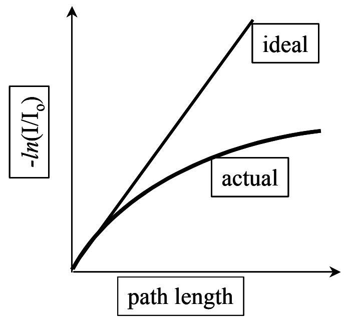
Abstract: The advent of the use of digital area detectors in Volumetric Computed Tomography (VCT) systems has brought with it the challenges of achieving image quality comparable to that provided by earlier planar industrial CT systems equipped with highly collimated and efficient linear detector arrays. Particularly for imaging with higher voltage x-ray sources up to 450kVp, among the most distinct imaging artifacts encountered are those associated with the phenomena of beam hardening and object scattering. Where large (20cm+) flat panel digital detectors with typical scintillator depths and no anti-scatter collimation are used for the highest throughput VCT, these effects can dominate image quality for certain applications.

In the current work, analytical approaches have been developed to correct for both of these effects in VCT imaging. The corrections are based on calculations of the attenuation and scattering processes characteristic of, in the simplest case, an object composed of a single material, as is the situation with castings. The beam-hardening corrections can be applied a priori directly to projection data prior to reconstruction. The scattering corrections are derived in a two-step process, whereby object geometry is extracted from an initial three dimensional data set reconstructed with uncorrected projection data. Subsequently an innovative analytical method is utilized to extract specific scattering profiles for subtraction from the projection data on a view-by-view basis.

These corrections have been applied successfully to empirical VCT data of several test samples and industrial components, composed of materials such as aluminum and steel. The use of the analytical corrections obviates the need for the conventional empirical correction approaches, which entail appreciable difficulty of implementation, limitations, and errors.

Introduction: The advent of the use of area x-ray detectors, particularly digital flat panel detectors, in Volumetric Computed Tomography (VCT) systems highlights the need for improved object scatter reduction and correction techniques. Scatter can be significant for a wide range of x-ray energies, e.g. from 100kVp to 450kVp and, along with the phenomenon of beam-hardening, leads to underestimations of material penetrated and corresponding low-frequency artifacts that can severely compromise VCT image quality. Empirical approaches for correcting for scatter are very difficult to implement: simulation-based analytic corrections offer the promise for a flexible solution to this problem, as well as a more accurate and flexible alternative to empirical measurements for the purpose of correcting for the effects of beam-hardening.

The phenomenon of beam-hardening (BH) arises due to the preferential attenuation of lower energy x-rays in a polychromatic spectrum as it penetrates through a material and the resulting change in spectral profile. In general the change is towards a profile with a higher average energy which penetrates more efficiently than does the initial spectrum, hence the term hardening applies. The average attenuation value as a function of depth of penetration departs from linearity as shown in Figure 1a.



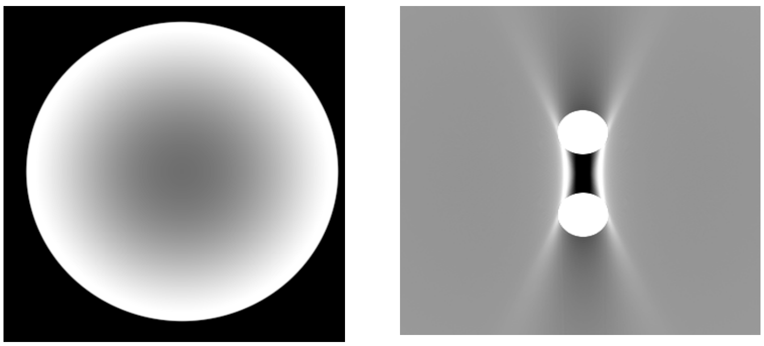


Figure 1a. Non-linearity of attenuation values as a function of depth of penetration due to the BH effect

Figure 1b. Typical artifacts from BH as illustrated in simulated CT images; cylindrical shape with cupping artifact (left), shading induced by adjacent objects (right)

The result of this non-linearity is an underestimation of the attenuation and a lowering of opacity values along the ray paths most suffering from this error. Examples of the typical artifacts in CT images arising from this effect are shown in Figure 1b. The increasing depression of opacity values toward the center of the cylindrical object (left part of Figure) is the well know "cupping" artifact characteristic of regular shapes.

Approaches for correcting for this effect are either empirical or theoretical. Most often, empirical measurements are utilized, which are based on producing a set of calibration data by scanning of regular shapes of the material of interest, e.g. step-wedges or triangular wedges. This approach is time-consuming and vulnerable to errors in phantom dimensional or composition non-uniformity and alignment errors during the scanning process. Further, the use of a new material, source setting (kVp), and/or source filtration requires a new calibration series. Lastly, in a Volumetric CT (VCT) geometry, there is substantial error in these measurements due to the significant contributions to detector signal from object scattering.

The approach reported here consists of an analytic, simulation-based correction, based on modeling of simulated x-ray spectral profiles and the Geant4 attenuation database. The generation of the corrections are fast and flexible, easily calculated within a few minutes for an arbitrary combination of source energy/voltage, filter, and object material. The errors limiting accuracy of the measurement process are eliminated.

In addition to beam-hardening, the other major phenomenon that can significantly compromise the accuracy of the VCT projection data and lead to artifacts in the images is object scatter. The attenuation processes in the object of interest in the energy regime discussed here include photo-absorption and scattering. Both Compton and Rayleigh scattering may contribute to the scatter component. The detection of scattered x rays in a particular detector channel introduces an error in the total signal due to the additional signal beyond what is recorded for the directly transmitted beam. This lead to an underestimation of opacity in the projection data and a depression of opacities along that particular ray path, as shown in Figure 2.

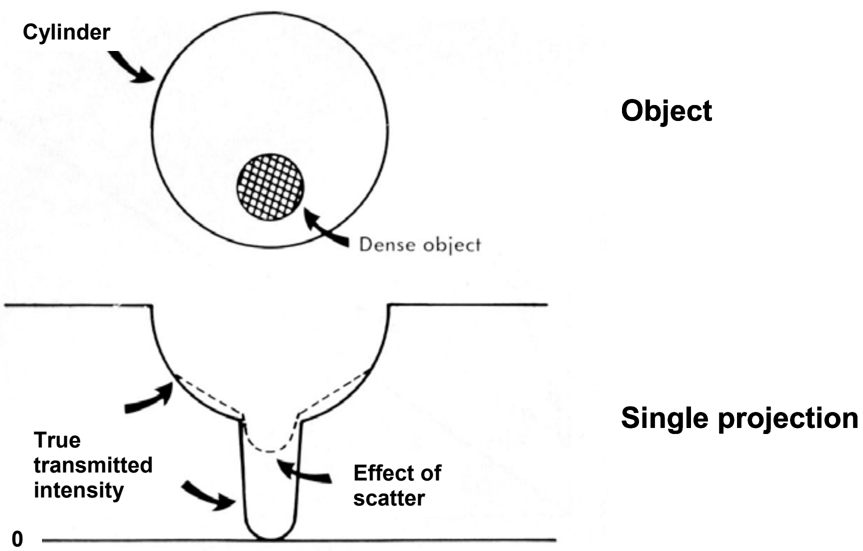


Figure 2. The erroneous increase in signal in the mid-line of a VCT projection due
to additional signal arising from the detection of object-scattered x rays.

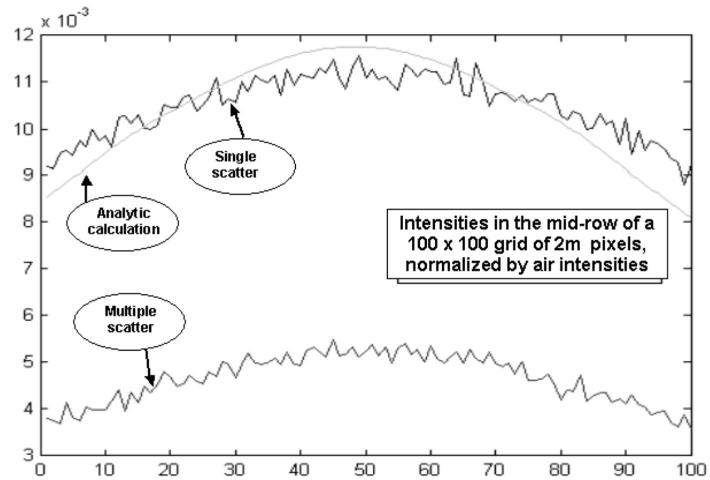
Among the different techniques available for correcting for scatter are the ones listed in Table 1. The approach presented in this paper is the analytic correction, which combines essentially the accuracy afforded by the very time-consuming Monte Carlo simulation with a more flexible and easily accomplished two-step procedure.

Description	Advantages	Disadvantages
Subtraction of constant background	Simple, fast, easy to implement	Limited accuracy, particularly for complex shapes
Conovolution of primary projections with exponential kernal	Moderate accuracy	Difficulty in tuning of kernal based on system parameters
Monte Carlo simulations	Best accuracy	Prohibitive simulation time for realistic (complex) objects
Analytic	Accuracy approaching Monte Carlo, automated process of determination of correction and fast application of corrections	Calibration required (post processing)

Table 1. Summary of the advantages and disadvantages for different techniques for
correcting for object scatter in VCT projection data

The first step in the current work was to validate the accuracy of the analytical model used for single scattering. Several different situations were simulated with a three dimensional Monte Carlo (MC) program based on Geant4 and the corresponding single scatter profiles calculated for comparison. An example of the results for 120kVp VCT imaging of a 3cm by 10 cm Al block and with the 10cm side perpendicular to the system centerline, is shown in Figure 3. The analytic profile agrees with the MC results within less than 10%, for the single scatter profile. The MC multiple scatter profile is also shown, which exhibits a shape very nearly the same as that of the single scatter profile. In general these conclusions applied to the different cases (sizes and shapes of objects) tested, i.e., the single scatter profiles were very similar and the multiple scatter profiles (and hence the total scatter profiles) were approximately the same as obtained by a scaling of the single scatter profile. This agreement furnished the basis for extracting analytically the total scatter profile by applying a multiplier greater than one to the single scatter calculation.

Figure 3. A comparison of the single scatter profiles produced by a Monte Carlo simulation and an analytical calculation for 120kVp imaging of an Al block.

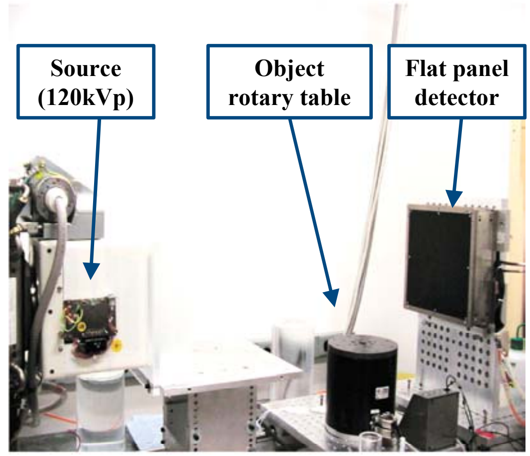


The basics steps for this scatter correction procedure are the following:

(1) Calculate the single scatter profile by using the cross section and angular distribution for the Compton and Rayleigh scatter.

(2) Multiply the calculated single scatter profile by an adjustable factor to include the multiple scatter contribution and subtract from projection data on view by view basis (optimum factor chosen to minimize low-frequency artifacts, i.e. basically optimize the uniformity of the opacity of regions expected to be homogeneous).

Results/Discussion: The simulations produced here were validated by correcting data produced with the laboratory VCT system pictured in Figure 4. The system utilizes a GE Maxiray 150 pulses x-ray source with beam spot size of 0.6mm in plane and 0.9mm vertical, equipped with a variable source collimator. It employs a GE RevolutionTM Detector , an amorphous silicon flat panel with 20cm field-of-view, 200micron pixel pitch, and a quantum detection efficiency of ~50% for the 120kVp beam used in this imaging. The system geometry included a source-to-detector distance of 110cm and a magnification of 1.16. Scanning parameters included 900 views at 30 seconds total exposure time (~30millisec. per view) and reconstruction was accomplished with a 300micron pixel.



An example of analytical corrections for beam-hardening is shown in Figure 5. The scanning was of an aluminum annulus (pipe) was accomplished with a restrictive source collimator, limiting the beam to approximately 1cm in height at the detector. The intent was to reduce object scattering to a minimum to test the effectiveness of the BH correction independent of scattering and compare it to empirical corrections based on a step-wedge measurement. The leftmost image and trace reveal the lowering of the apparent opacity towards the inside of the wall, a characteristic effect for this shape. As can be seen in the CT images and the on-diameter opacity traces below, the analytic correction most effectively reduces the artifacts (resulting in symmetric wall profiles and minimal skewing of the profile edges at the bases of the walls into the adjacent air region).

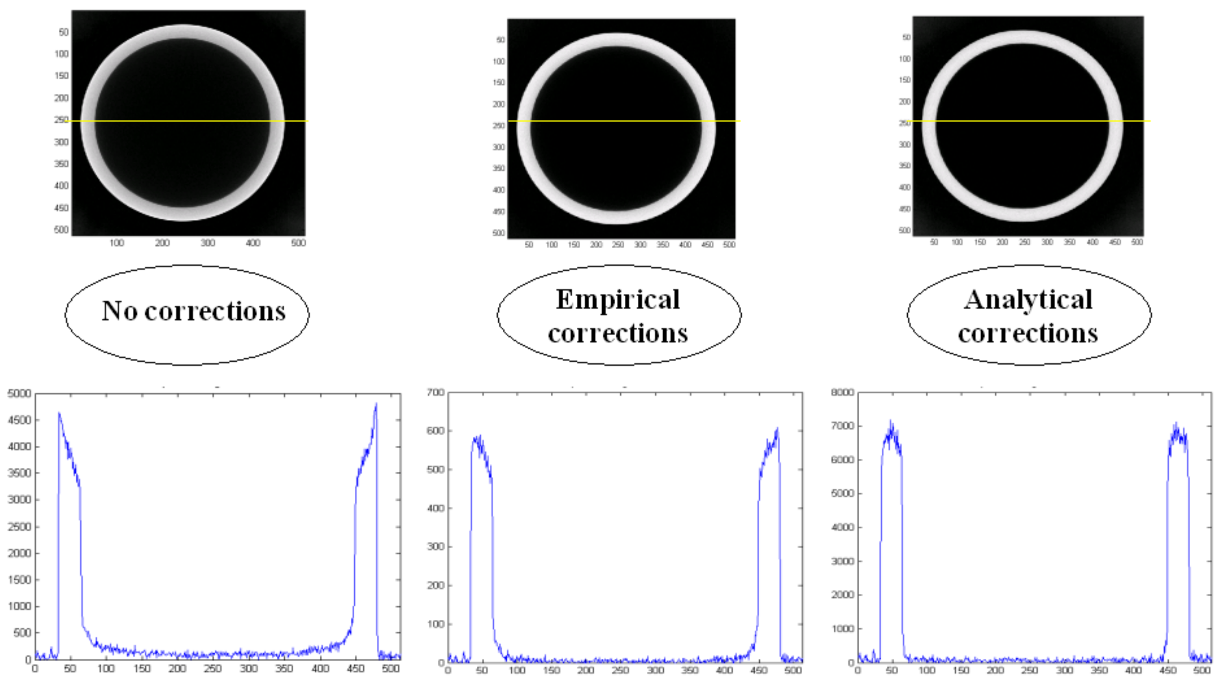
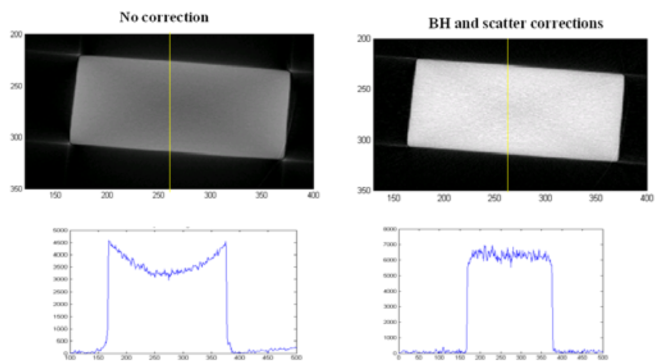


Figure 5. Test Case #1: Mid-plane CT images and corresponding opacity profiles, from VCT data set, for 120kVp imaging of 150mm diameter, 9mm wall Al annulus; comparison of cases for no corrections, empirical corrections, and analytic corrections

In Test Case #2, an aluminum block was scanned with no source collimation, allowing for maximum object scatter, and analytic corrections were applied. The image to the left in Figure 6 has another characteristic X artifact pattern (corner to corner) typical for rectangular cross sections degraded by BH and scatter. The corrected image to the right is almost artifact free, with just a slight residual X-shaped pattern.



Test Case #3 involved the Al annulus, where the VCT scanning was repeated with no source collimation. The image improvement first with the BH correction alone (middle image and profile) and then with both BH and scatter (right image and profile) are shown in Figure 7. The quality of the final result is encouraging.

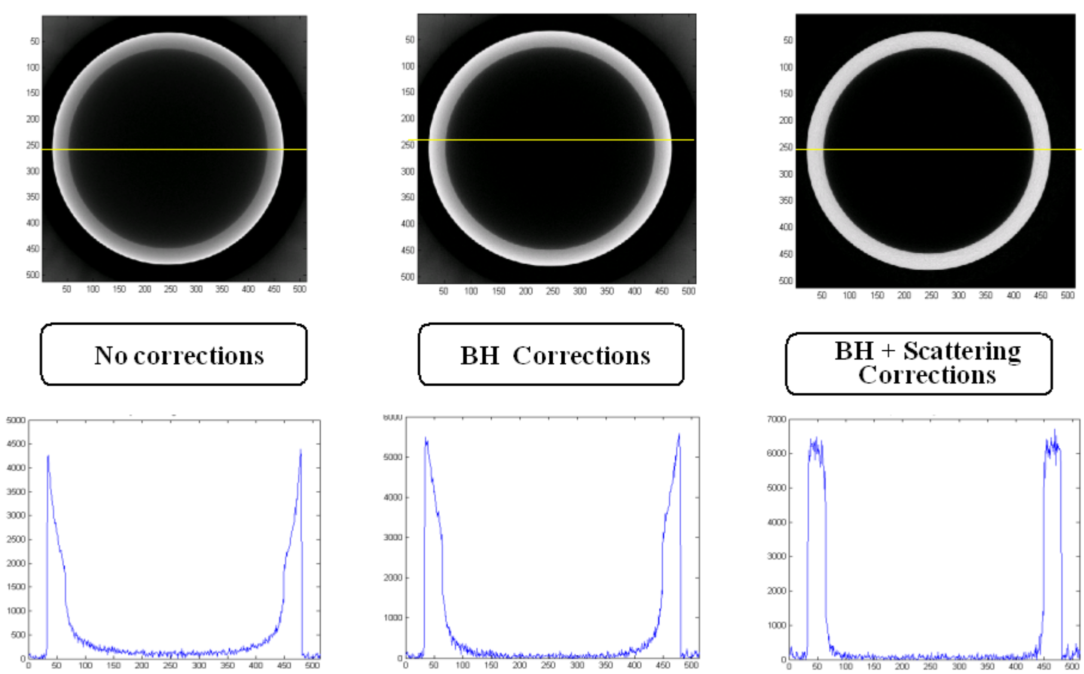
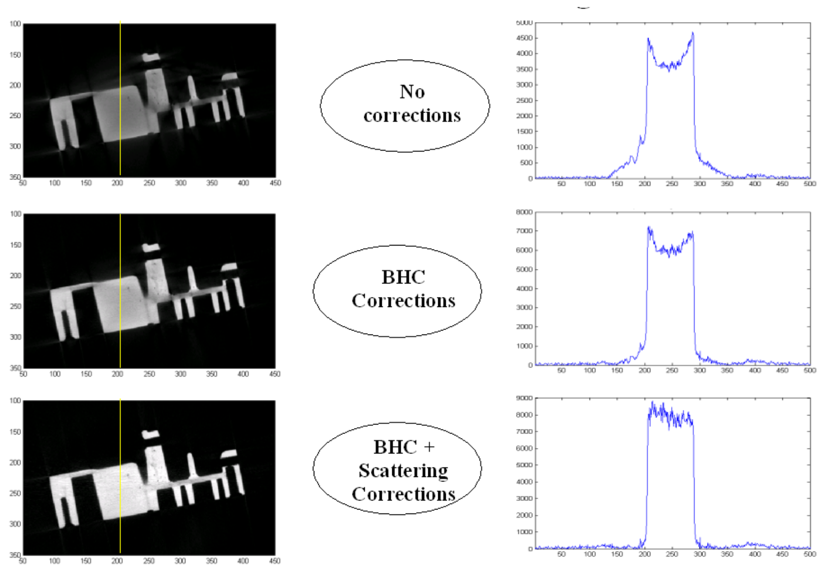


Figure 7. Images and profiles of Al annulus with and without corrections

The final example of the effectiveness of the corrections is presented for a complex cross section of an aluminum end plate for a pump in Figure 8. As with the more regular shapes, the corrections largely eliminate the low-frequency artifacts due to BH and scatter



Conclusions: The conclusions resulting from this work are as follows:

(1) Simulation-based beam-hardening corrections provide an effective and more flexible alternative to empirical techniques for reducing or eliminating beam-hardening artifacts in VCT images

(2) Scatter corrections based on analytical calculation of the scatter profile in a VCT geometry appreciably reduce the related low-frequency artifacts which often compromise VCT image quality.

(3) The speed of application of these corrections is sufficient to negligibly impact VCT reconstruction times