Expert-guided CT beam hardening correction for heterogeneous natural materials

Richard KETCHAM\textsuperscript{1}, Romy HANNA\textsuperscript{1}
\textsuperscript{1}Jackson School of Geosciences, University of Texas at Austin, USA,
ketcham@jsg.utexas.edu

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Abstract

We present a new method for correcting beam hardening artifacts in CT data. Software correction typically consists of a polynomial transform of the raw data, but determining optimal coefficients is not straightforward, especially if the material is not well known or characterized, as is the usual case when imaging geological materials. Our method lets an expert user guide an iterative optimization algorithm in finding a generalized spline-interpolated beam-hardening transform, which in turn can define a polynomial of arbitrarily high degree. This generality accesses a richer set of transforms that may better accommodate the effects of multiple materials in heterogeneous samples.
1 Introduction

X-ray computed tomography (CT) is a nondestructive method for imaging the interiors of solid objects, based on their respective ability to absorb or scatter X-rays. CT allows three-dimensional characterization of many features, including size and spatial distributions of crystals, clasts, vesicles and pores (Ketcham et al., 2005; Koeberl et al., 2002; Lindquist and Venkataraman, 1999; Proussevitch and Sahagian, 2001), fracture aperture and roughness (Johns et al., 1993; Van Geet and Swennen, 2001), and structural fabrics (Ketcham, 2005). It has been usefully employed in virtually every geoscientific discipline, and more applications are continuously being developed.

The ability to use CT quantitatively hinges on the degree to which the imagery retains fidelity to the features being analyzed. A variety of non-idealities in the CT imaging process create artifacts that can complicate or even preclude utilization of the data for making reliable measurements. Chief among these is beam hardening, which can cause the CT number for a material to vary due to its position within a solid.

In this contribution we present a new method for ameliorating or eliminating beam-hardening artifacts that can be effectively applied on any geological specimen without need for prior calibration or characterization of the material being imaged.

1.1 X-ray CT imaging

X-ray computed tomography is based on the attenuation of X-rays as described by Beer’s Law, which for a monoenergetic beam passing through a single material is:

\[ I = I_0 e^{-\mu x}, \]  

where \( I_0 \) and \( I \) are the initial and final intensity of the X-ray beam, \( \mu \) is the linear attenuation coefficient of the material being traversed, and \( x \) is the distance traversed through the material. If multiple materials are intersected by the ray path, the equation becomes:

\[ I = I_0 e^{-\sum \mu_i x_i}, \]  

where the \( i \) subscripts denote different materials, each with their own thickness. The attenuation coefficient is a function of both the material and the X-ray energy. Thus, if multiple materials are being imaged by a polychromatic beam, Equation (2) becomes

\[ I = \int I_0(E) \left[ \sum e^{-\mu_i(E) x_i} \right] dE, \]  

The crux of the beam-hardening problem is that standard CT reconstruction algorithms presume a single attenuation coefficient at all points, rather than an energy-dependent range of values.

1.2 Beam hardening artifacts

As polychromatic X-rays pass through an attenuating material, the lower-energy X-rays are preferentially absorbed or scattered, raising the mean energy of the X-ray beam even as overall intensity falls. As a result, regions interior to an object are traversed with higher-energy X-rays than regions toward the edge, making the edges effectively more attenuating than interiors. When this occurs to an appreciable degree during tomographic imaging it leads to reconstructed objects appearing to have brighter rims and darker centers.

A more general way of viewing and recognizing this phenomenon in CT imagery, particularly for irregularly-shaped objects, is that beam hardening will tend to cause darkening at the centers of the longest X-ray paths though solid material, and brightening at the ends; an example is given in Figure 1.
Beam-hardening artifacts are also frequently manifested in the air that surrounds an attenuating object, as dark or occasionally light regions or streaks. These artifacts can be distracting, and a common practice is to scale CT reconstructions so that air is truncated (i.e., given an effective CT number of far less than zero, causing it to appear as flat black in digital images where zero is the minimum value). Although this technique often results in more visually appealing images, it represents a loss of information that interferes with obtaining accurate dimension from CT imagery.

1.3 Beam-hardening correction

Beam hardening can sometimes be addressed during calibration and/or scanning, by pre-filtering the X-ray beam or packing the specimen a material of similar X-ray attenuation properties. In the right-hand image in Figure 1 the specimen is packed in a garnet powder; by calibrating the X-ray signal through powder the beam-hardening artifact was avoided. Unfortunately, this technique increases required scan time to overcome the loss of beam intensity in the surrounding material, and complicates 3D visualization. Pre-filtering the X-rays by passing them through an attenuator is often helpful, but tends to diminish the artifact rather than eliminate it, and also increases scan time to achieve a comparable signal-to-noise ratio.

The most common software method for addressing beam-hardening artifacts is to use a function that attempts to transform the polychromatic attenuation data into equivalent monochromatic data, an operation referred to as linearization (Herman, 1979). This function is typically an exponential or polynomial of undetermined degree or coefficient values. When homogeneous, man-made materials are imaged, polynomial coefficients can be derived by imaging phantoms of various thicknesses. However, when materials are heterogeneous or not well characterized, as is usually the case with geological research, such methods are not available. Although many CT reconstruction packages allow entry of beam-hardening correction coefficients, there is often no useful means of determining what these coefficients should be other than trial and error. This approach is often time-consuming, and the set of functions available tends to be simplified, and may not encompass the optimal corrections, which may be of high degree. Herman (1979) found
that a 2nd degree or 3rd degree polynomial is sufficient for low-resolution medical CT data, but for industrial materials such as aluminum and steel Hammersberg and Mångård (1998) suggest that the polynomial has to be of at least 8th degree. Beam hardening can also be addressed by dual-energy scanning (Van Geet et al., 2000), which depends on scanning a specimen twice at different energy settings in an attempt to segregate the attenuation contributions of photoelectric absorption, which is most strongly dependent on composition, and Compton scattering, which is a linear function of density (Markowicz, 1993).

Another set of correction methods consists of attempting to characterize the X-ray spectrum as a dual-energy system, in which attenuation in one is dominated by photoelectric absorption and the other by Compton scatter (Van de Casteele et al., 2002, 2004). Although somewhat more closely tied to the underlying physical processes, it remains a substantial simplification requiring empirical calibration.

A problem common to all of these techniques is this necessity for calibration, which generally consists of scanning sets of phantoms of known composition, density, and dimension. These calibrations will be unique to the scanning configuration used, in particular the X-ray source and its energy settings and filtration, and the detector. Furthermore, a given correction only tends to describe a single material, though similar materials may be corrected by similar functions.

The challenges posed by natural geological materials confound these previous approaches. Complications include variable modal mineralogy; solid solution and compositional variation of minerals; microporosity and fractures; inclusions; weathering and alteration; and small grain sizes. In many cases, the composition of the object being scanned is not known in detail, particularly in the case of fossil specimens. Most geological specimens are unique, making it difficult to define a priori what a successful correction consists of.

2 Method

We have attempted to address the shortcomings of current beam-hardening methods by creating a set of procedures that let an expert user guide an iterative optimization algorithm in finding a generalized beam-hardening transform function. The procedure relies on an expert user that can identify the regions of a reconstructed image that most clearly manifest beam hardening artifacts. These regions are flexibly used to construct a merit function that quantifies the severity of the artifact. An iterative optimizing procedure is then used to test possible transforms until the beam-hardening artifact is minimized. The expert can then evaluate the correction, and adjust the definition of the merit function and re-run the iteration to improve the result until an acceptable correction is found.

2.1 Merit function

The merit function consists of statistics characterizing the CT numbers in a series of regions of interest (ROIs) defined by the user in a reconstructed CT image, as shown by examples below (Fig. 3, 4). ROIs are either rectangular or elliptical in shape, and ideally should encompass only a single material, or void space. The merit function consists of the relative variation of CT numbers in these ROIs (i.e. the standard deviation divided by the mean), either individually or in various combinations.

A number of strategies are available for defining optimal ROI locations. Individual ROIs can encompass areas both affected and unaffected by beam-hardening artifacts, or through which diagnostic features such as streaks pass, in which case minimizing the artifact can be defined as minimizing the relative CT number variation in the individual ROI. Alternatively, multiple ROIs can be specified in different regions of the image that contain the same material, but have differ-
ent degrees of beam hardening, in which case the merit function can consist of minimizing the relative variation across all of the ROIs. This strategy can be extended into two materials, minimizing variation across the ROIs in each.

2.2 Transform function

The beam hardening correction ultimately consists of a conversion of the raw sinogram data. Each detector reading $I/I_0$ can be considered as a polyenergetic ray sum $p$. We seek a transform $f$ that transforms each $p$ into the value it would have had if the X-ray beam were monoenergetic, $m$:

$$m = f(p).$$

Using a polynomial or exponential form and varying the coefficients iteratively tends to result in wild and absurd variations that substantially complicate any attempt at algorithmic optimization. Instead, we use a set of evenly-spaced points over the data range of the raw values, and interpolate between them with a cubic spline to ensure a continuous solution. We have further found that the endpoints of the function can be fixed to the data values (so the lowest and highest data values are unchanged), which further confines the space to be searched for an optimal solution; we have run a series of tests that indicate that this simplification does not adversely affect the ability to find an optimal solution.

![Figure 2: Solution space for general beam-hardening transform.](image)

Figure 2 shows the general region of the solution space through which the optimal function must pass. Its upper bound is the 1:1 line $m=p$, and the lower bound is the range of monotonically increasing functions that connect the end-points. The effect of beam-hardening correction can thus be considered as adding back in the attenuation that would have occurred among low-energy X-rays had they not been preferentially lost.

2.3 Optimization

The set of points defining the spline are varied iteratively using a simplex method (Press et al., 1988) that is constrained to vary only within confined bounds. The points are evenly distributed along the $p$ axis, and can either vary randomly within the vertical range defined by Figure 2, or they can be varied such that the first or second derivative is positive at all points. The former condition is enforced by varying a series of factors $c_j$ that define fractional increments of rise in $m$ at each spline point:

$$m_j = m_{j-1} + c_j(m_n - m_{j-1}).$$

(5)
which defines \( m_2 \) through \( m_{n-1} \), with \( m_1 = p_1 \) and \( m_n = p_n \) and \( n \) being the number of spline points. Enforcing a positive second derivative consists of ensuring that the rise slope rises at each point using a conditioning routine applied to each new set of coefficients generated by the simplex algorithm.

For every set of coefficients tested, a reconstruction is performed using the transformed data \( m \) using a standard filtered backprojection, and the merit function is evaluated. By far the slowest operation is the reconstruction, and this step can be accelerated by performing an initial optimization through reducing resolution by a factor of 2, 4, or 8, and then re-optimizing at full resolution.

Once a transform is defined for a slice image, it can be applied to reconstruct an entire data set. Because the spline is only well defined between its endpoints, it is important that that image being used for optimization has close to the maximum range of raw data values.

3 Implementation

We implemented our method in IDL, with external function calls to a C program that performed the reconstructions (i.e. backprojections). The reconstruction program is specific to the BIR/Varian ACTIS series of industrial CT scanners. Although our method is fully general and can be employed for data from any scanner, most scanners use proprietary file formats and reconstruction software, and may not make their reconstruction routines available via a command-line interface as required to communicate with our program.

4 Results

We demonstrate our method using illustrative examples.

4.1 Leopard Seal Skull

In the scan of a leopard seal skull and mandible shown in Figure 3, the beam-hardening artifact is most obvious as a dark streak in the air and light foam between adjacent teeth. By specifying an ROI around this artifact so that the merit function consisted of the relative variation of CT numbers in this zone, a transform function was determined that was superior to the beam-hardening correction applied by a human operator during earlier processing of this data set. In the uncorrected image, the lower margin of the mandible (upper part of the image) appears somewhat denser than other thick bone. However, in the corrected image the bone is uniform, as would be expected. Thus, correcting the artifact in the air resulted in correcting other parts of the image as well.
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4.2 Fossil mosasaur brain case

Beam hardening greatly complicates the interpretation of the fossil mosasaur skull shown in Figure 4, in which the contrast between bone and matrix is subtle and variable. Again, by minimizing the beam hardening artefact in the air, solid is corrected as well. Worthy of particular note are the brighter regions in the corrected image, showing late-stage pore-filling mineralization, which is not discernable at all in the uncorrected image due to beam hardening.

Figure 3: Uncorrected (left) and corrected (right) CT images of leopard seal skull and mandible, shown in the correction software interface. The correction consisted of finding the transform that minimized the variation in the ROI (green), drawn to encompass the streak artifact between adjacent teeth. Field of view is 220 mm. Specimen courtesy of Blaire Van Valkenburgh, UCLA.

Figure 4: Uncorrected (left) and corrected (right) CT images of fossil mosasaur *Tethysaurus*. The correction consisted of finding the transform that minimized the variation across multiple ROIs (green), drawn to encompass various artifacts in the air surrounding the specimen. Field of view is 80 mm. Specimen courtesy of Mike Polcyn.
5 Discussion

The empirical correction method demonstrated here is not without its dangers, as it is very possible to introduce over-corrections or other artifacts. Furthermore, newly introduced artifacts may be hard to discern, as they do not naturally flow from the usual principles of polychromatic CT imaging, and thus may not be recognized by an expert familiar with CT imaging. It is thus prudent to remain conservative in applying the method, using well-constrained touch-points (such as the fact that air should have uniform density) to construct a correction.

Even with this caution, the potential utility of this method is considerable. In practice beam-hardening corrections are often selected by eye, on an ad hoc basis, and ultimately determined by the expertise of the instrument operator in any event. Basing the selection on quantitative criteria is very desirable a step forward.

Furthermore, the set of beam-hardening corrections offered by reconstruction software is typically limited to a simplified subset of the possible functions. Even if they offer the capability to input several polynomial terms, they cannot offer guidance on what the coefficients should be, and so the user is forced to experiment with possible values, which necessarily limits the degree of polynomial that can be used. We have run a series of tests on data sets corrected by second and third-degree polynomials entered by trial and error, and have consistently found our new method to give a superior result.
References


