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Beam hardening correction for X-ray computed tomography of heterogeneous natural materials

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ABSTRACT

We present a new method for correcting beam hardening artifacts in polychromatic X-ray CT data. On most industrial CT systems, software beam-hardening correction employs some variety of linearization, which attempts to transform the polychromatic attenuation data into its monochromatic equivalent prior to image reconstruction. However, determining optimal coefficients for the transform equation is not straightforward, especially if the material is not well known or characterized, as is the usual case when imaging geological materials. Our method uses an iterative optimization algorithm to find a generalized spline-interpolated transform that minimizes artifacts as defined by an expert user. This generality accesses a richer set of linearization functions that may better accommodate the effects of multiple materials in heterogeneous samples. When multiple materials are present in the scan field, there is no single optimal correction, and the solution can vary depending on which aspects of the beam-hardening and other image artifacts the user wants to minimize. For example, the correction can be optimized to maximize the fidelity of the object outline for solid model creation rather than simply to minimize variation of CT numbers within the material. We demonstrate our method on a range of specimens of varying difficulty and complexity, with consistently positive results.

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 (Carlson and Denison, 1992; Flannery et al., 1987; Ketcham et al., 2005; Koeberl et al., 2002; Lindquist and Venkatarangan, 1999; Proussevitch and Sahagian, 2001), fracture aperture and roughness (Johns et al., 1993; Ketcham et al., 2010; Van Geet and Swennen, 2001; Voorn et al., 2013), and structural fabrics (Desrues, 2004; Ketcham, 2005). It has been usefully employed in virtually every geoscientific discipline, and more applications are continuously being developed.

The ability to use CT data quantitatively hinges on the degree to which the images retain fidelity to the features being analyzed. A variety of non-idealities in the CT imaging process create artifacts that can complicate or even preclude use of the data for 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 (Herman, 1979; Hsieh, 2003; Ketcham and Carlson, 2001).

In this contribution we present a new method for reducing 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. We furthermore demonstrate that the optimal correction will vary based on the objective of the scan.

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

$$I = I_0 e^{-\mu x}, \quad (1)$$

where I_0 and I are the initial and final intensity of the X-ray beam, respectively, μ 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

$$I = I_0 e^{-\Sigma \mu_i x_i}, \quad (2)$$

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

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being imaged by a polychromatic beam, Eq. (2) becomes

$$I = \int I_0(E)[\sum_i e^{-\mu_i(E)x_i}]dE, \quad (3)$$

The crux of the beam-hardening problem is that standard CT reconstruction algorithms presume that each material in the volume has a single attenuation coefficient, rather than an energy-dependent range of values.

1.2. Beam hardening and other 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 images, particularly for irregularly-shaped objects, is that beam hardening will tend to cause darkening toward the centers of the longest X-ray paths though solid material, and brightening toward the ends; an example is given in Fig. 1. The long-path principle can be used to identify many instances of beam hardening that are otherwise difficult to detect. A notable exception is that sharp corners can be darkened, as will be shown in a subsequent example.

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 somewhat 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 dimensions from CT data, and should be avoided.

Importantly, there are other sources of spurious variation in CT images aside from beam hardening, including streaking from edge effects, ring artifacts, and scattering. Unhelpfully, their respective effects are frequently intermixed, complicating interpretation and correction. For example, streaking associated with straight edges caused at least partially by the exponential edge gradient effect (EEGE; Joseph and Spital, 1981) is significant in some scans in this study; these will be pointed out as they arise, and their ramifications addressed in the discussion.

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 within a material of similar X-ray attenuation. In Fig. 1B the specimen is packed in a garnet powder, and the X-ray signal was calibrated through powder rather than air, what is known as a "wedge" correction (Ketcham and Carlson, 2001). By equalizing beam paths and ensuring that the X-ray spectrum detected during calibration matches to that obtained during scanning, the beam-hardening artifact was virtually eliminated. Unfortunately, this technique increases required scan time to overcome the loss of beam intensity in the surrounding material, and complicates 3D visualization and model creation. Pre-filtering the X-rays by passing them through an attenuator that eliminates low-energy X-rays 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 because higher-energy X-rays are also reduced.

One of the original software beam-hardening correction methods, and still the most common for industrial CT systems, 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. For homogeneous, man-made materials, 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 values

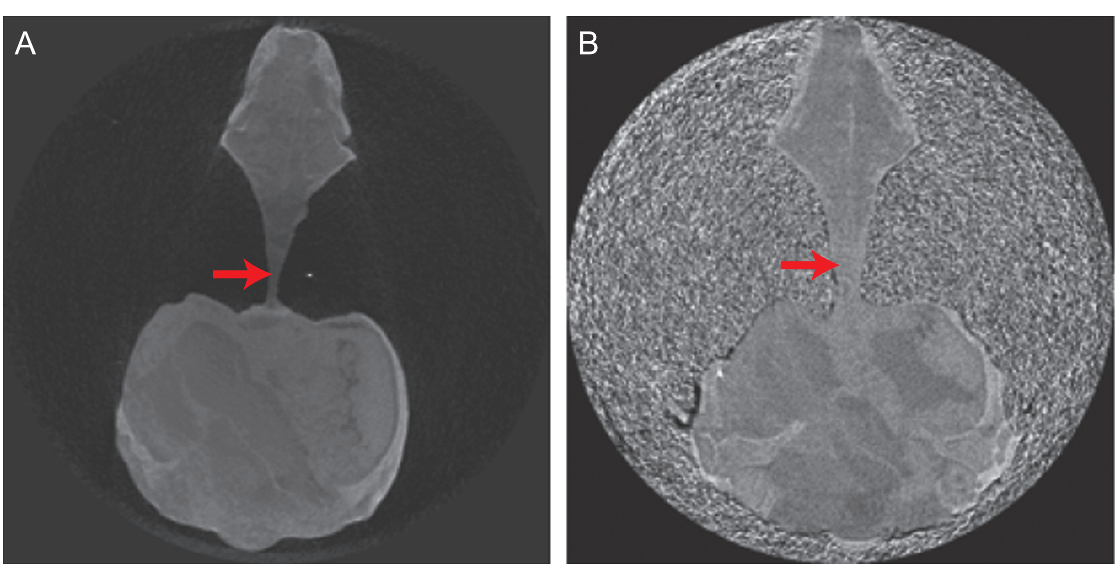

Fig. 1. Two CT scans through the skull of the fossil primate *Rooneyia viejaensis*, field of view 50 mm. The darkening in the thin central part of the fossil indicated by the arrow in (A) is due to beam hardening, as it is also the center of the longest beam paths through solid material. For comparison, (B) shows the same specimen scanned surrounded by garnet powder, making all beam paths roughly equivalent. Beam hardening is avoided in (B) by calibrating the X-ray beam through garnet powder rather than air, an effective but often impractical approach.