On the Application of Beam Hardening Correction Using the Alvarez-Macovski Model

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Summary: An X-ray beam-hardening correction algorithm is proposed that is based on the Alvarez-Macovski (AM) model for X-ray attenuation as a function of X-ray energy. We outline the heuristics used to identify the parameters required to reconstruct several real world large scale datasets with this algorithm.

1. INTRODUCTION

The effects of beam hardening form one particular vexing class of artefacts in X-ray Computed Tomography (XCT). They result from the inconsistency between the assumed model, where X-ray attenuation at different energies are reversibly combined in projected attenuation space, and reality, where they are irreversibly combined in intensity space. Assuming X-rays to be monochromatic when they are not causes distortions such as cupping (overestimation of attenuation near the edge of objects) and streaking ("bleeding" of the attenuation next to high attenuation objects into the surrounding regions) that make material identification far more difficult (see Fig. 1a). Dealing with it in practice involve pre- or post-processing corrections which are fast but inaccurate. Iterative methods can significantly improve accuracy but remain largely proofs-of-concept, being slow and complex. We propose a compromise: a general purpose reconstruction algorithm of lab-based polychromatic XCT that is not only reasonably fast and accurate but also simple to understand and implement. This is desirable because even moderately artefact-free reconstructions can markedly improve our ability to discriminate between the materials and make them more useful analytically.

The algorithm, presented at ICTMS 2017 [1], utilises the AM model to incorporate the polychromatic variation of X-ray attenuation[2] into existing iterative reconstruction techniques. Unlike the typical *post hoc* corrections, our method, using knowledge of the input spectrum, has the potential to provide truly accurate reconstructions without needing to massage the result into what one believes the object should resemble.

However the algorithm lacks flexibility because several parameters relating to the object need to be specified manually. The AM model takes two free parameters, which are the coefficients of Photoelectric absorption (PE) and Compton scatter (CS) components respectively (K_1 and K_2). The two independent variables, atomic number (Z) and density (ρ), depend on the material properties. Equation (1) cannot be solved directly without simplification since the measured data only provides one value while there are two unknowns. The problem then lies in determining what simplification achieves the most accurate reconstruction.

$$\mu(E) = K_1 \rho Z^{n-1} \cdot \frac{1}{E^m} + K_2 \rho \cdot f_{KN}(E) \tag{1}$$

No single simplification method can be valid for all possible scenarios, thus there is no universal correction algorithm based on a single assumption that can serve as a *silver bullet* to the problem of beam hardening. However we have devised several simplifications using different assumptions that, when taken as a whole, are applicable to a broad range of scenarios. These assumptions include: attenuation by PE only ($K_2 = 0$), constant ρ, constant Z, and $Z \propto \rho$. We therefore have some degree of freedom to select the assumptions and tune the corresponding parameters to achieve quantitative attenuation values that can be compared directly across different reconstructions; a significant advance from the current state of affairs.

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2. EXPERIMENTAL METHOD

The heuristics used to automatically find the appropriate simplification and best values for the corresponding model parameters is given below.

1. *Preparation stage:* The coefficients of the AM model are given by spectrum-weighted optimisation functions which minimise the L^2 difference between the model attenuation values and actual attenuation values (from NIST) of several reference materials.
2. *Trial stage:* Measured data is downsampled to allow for quick "trial" reconstructions with different assumptions and parameter values. Parameter values are chosen to minimise the residual, or the L^2 difference between the projection of the reconstructed volume and the measure data in intensity space. Additional information about the composition of the object can be used to refine the search space.
3. *Reconstruction stage:* Reconstruction of the full-scale data is performed using the optimised assumptions/parameters determined from the downsampled data. Further optimisation such as selecting the simplified AM model can be used here, particularly if the simplification reduces the number or projections and speed up the reconstruction process.

The full scale reconstruction carried out in this way should be largely free from beam-hardening artefacts that often considerably hinder material identification. These steps are fully automated with the algorithm only requiring an input X-ray spectrum and the measured data. Additional information (as mentioned in step 2 above) which may be beneficial can be fully specified in advance, such as the starting value and ranges for the parameters, the order of the correction, and the particular simplification of the AM model. We will discuss the scenarios where such fine tuning may be desirable at the conference.

3. RESULTS

An example of two of the simplifications of the AM model are given below for small printed Ti part. Figure 1a shows the result of the reconstruction without any correction. Cupping can be seen at the edges and substantial streaking can be seen at protrusions at the edge. The air gap in the middle of the object is also significantly obscured by streaking from the body of the object. Figure 1b shows the result assuming attenuation is comprised of solely the photoelectric component ($K_2 = 0$ in Eq (1)). The cupping is significantly reduced and the attenuation has been equalised across the body. The value of air at the centre of the object is brought much closer to the value of air outside the object. Figure 1c shows the result assuming the atomic number is constant in the object (Z =const in Eq (1)). The effect of the correction on the beam hardening artefacts is similar to that in Fig. 1b.

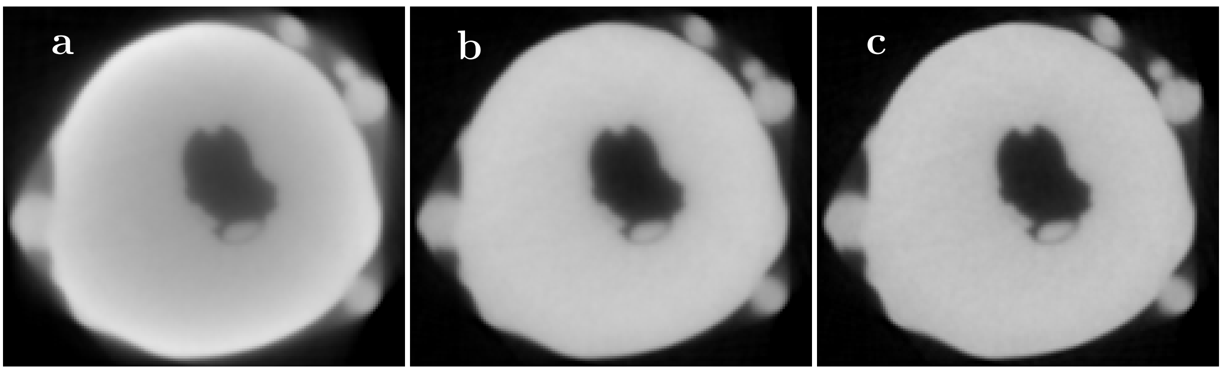

Figure 1: Horizontal slices through a reconstructed volume: a) without any correction, b) modelling attenuation as photoelectric ($K_2 = 0$ in Eq (1)), c) assuming a constant atomic number of material (Z = const).

References

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