WHAT'S IN A CT NUMBER? MEASURING THE SIZE AND SHAPE OF SMALL OBJECTS IN POLYCHROMATIC CT DATA

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Keywords: x-ray tomography, volume analysis, shape, x-ray attenuation

Summary: This contribution will present an objective and accurate approach to measuring the size, shape and orientation of discrete features within a CT volume that are small with respect to the data resolution, as defined by its point-spread function. The method requires knowledge of the end-member CT number of the phase(s) measured, and challenges of the first-principles calculation will be explored.

1. INTRODUCTION

It is becoming progressively more routine to extract a range of 3D measurements from CT data volumes, as the variety and sophistication of software tools for doing so proliferates. At the same time, there remain few standards for how such measurements should be done properly. A good operating principle, seldom invoked, is that measurements of the same features should be consistent across different instruments and data resolutions.

Small features in geologic specimens, such as small particles, pores, or cracks, are particularly challenging to measure accurately. The blurring endemic to all CT data, characterized as a scan-specific point-spread function (PSF), distributes some of the signal from a voxel among neighboring ones, with the size of the PSF describing the extent of the neighborhood. Any feature of interest that has one or more geometric dimensions that are of the order of the PSF will have its appearance and measurement impacted by this effect.

2. ANALYSIS METHOD AND RESULTS

A recent study [1] describes the PVB (partial volume and blurring) method for accurately measuring discrete small features using the missing attenuation principle, building upon ideas presented at previous ICTMS and GEOX meetings. By calibrating the CT number of the phase of interest (in this case, gold) we were able to accurately measure particles down to <6 voxels in volume in data acquired on two very different instruments, 14 years apart, despite severe beam hardening and photon starvation artifacts. Scan resolutions ranged from 10 to 50 µm/voxel, and the 4-sigma Gaussian PSF radius was ~5.5 voxels in scans acquired in 2003, and ~3.5 voxels in scans acquired in 2017. Figure 1a shows that segmenting these grains accurately via thresholding would require a different threshold value for each one, with a predictable relationship based on PSF size and grain size and shape.

Shape and orientation information are recovered by using the corrected volume data to better delineate the subset of voxels that correspond to each measured feature. Reproducibility depends on specific particle shape and the relation of its major axes with each other and the PSF. Shape measurements based on caliper methods are much more resistant to resolution effects than metrics based on perimeter and/or surface area measurements, as the latter are disproportionately affected by blurring. Caliper measurements are most affected by the presence of sharp edges that become rounded as resolution diminishes. Orientation of a major, minor, or intermediate axis in a near-PSF-size feature can be considered robust if its magnitude differs by a factor of at least two from the others (Fig 1b).

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3. DISCUSSION AND NEXT STEPS

Altogether, the PVB method is accurate, reproducible, resolution-invariant, and objective, all large improvements over any method based on a global threshold. The method is also notable for its favorable error structure, which is nearly independent of particle size, in stark contrast to threshold-based segmentation, which can result in large swings in volume for small features with small changes in threshold.

There are questions concerning its robustness, however, stemming from the use of polychromatic X-rays. The principle difficulty in applying the PVB method is the necessity for determining the CT number of the phase(s) of interest. An attempt to calculate this value based on first principles, combining the X-ray energy spectrum detector efficiency with the known energy-dependent attenuation coefficients, was only partially successful in predicting the relative attenuation of gold and quartz, and how it was impacted by overall sample size and composition. A substantial complicating factor was the beam-hardening correction applied to the data, which even though apparently modest substantially increased the apparent effective attenuation coefficient of gold compared to quartz.

In most cases, the observed effective attenuation of the gold particles relative to quartz was substantially below the theoretically determined value. Interestingly, this discrepancy increased with decreasing resolution, even in otherwise identical scan setups (i.e. sample placed further back in the cone beam). This may be a manifestation of a partial-volume effect, in which an X-ray source-detector path is attenuated less along a parallel rather than perpendicular interface between two materials. A numerical experiment will test this mechanism.

References

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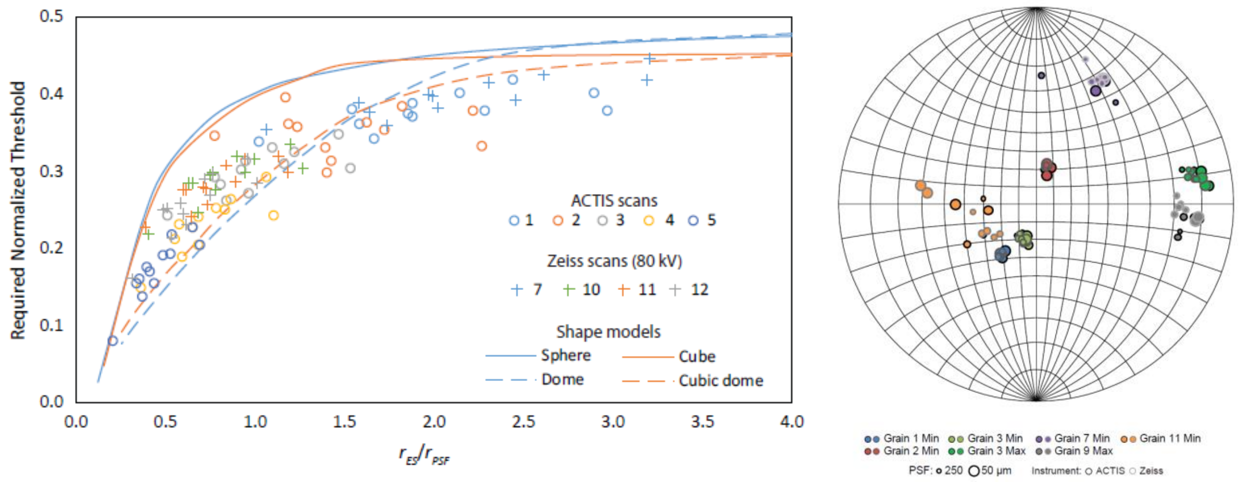

(a) (b)

Figure 1: (a) The threshold required for each gold grain to reproduce its volume, normalized by the difference between the CT numbers for gold and matrix, versus the size of the grain with respect to the PSF for its scan. As the grains gets smaller with respect to the PSF, a lower threshold is necessary. Curves show modeled relations calculated manually by convolving ideal shapes with a 3D PSF; domes are hollow half-shapes with a thickness to diameter ratio of 1/10. The main factors altering the relationship are the surface to volume ratio and the presence of sharp corners and edges. (b) Stereonet showing robustness of various axis orientations of gold particles as a function of PSF.