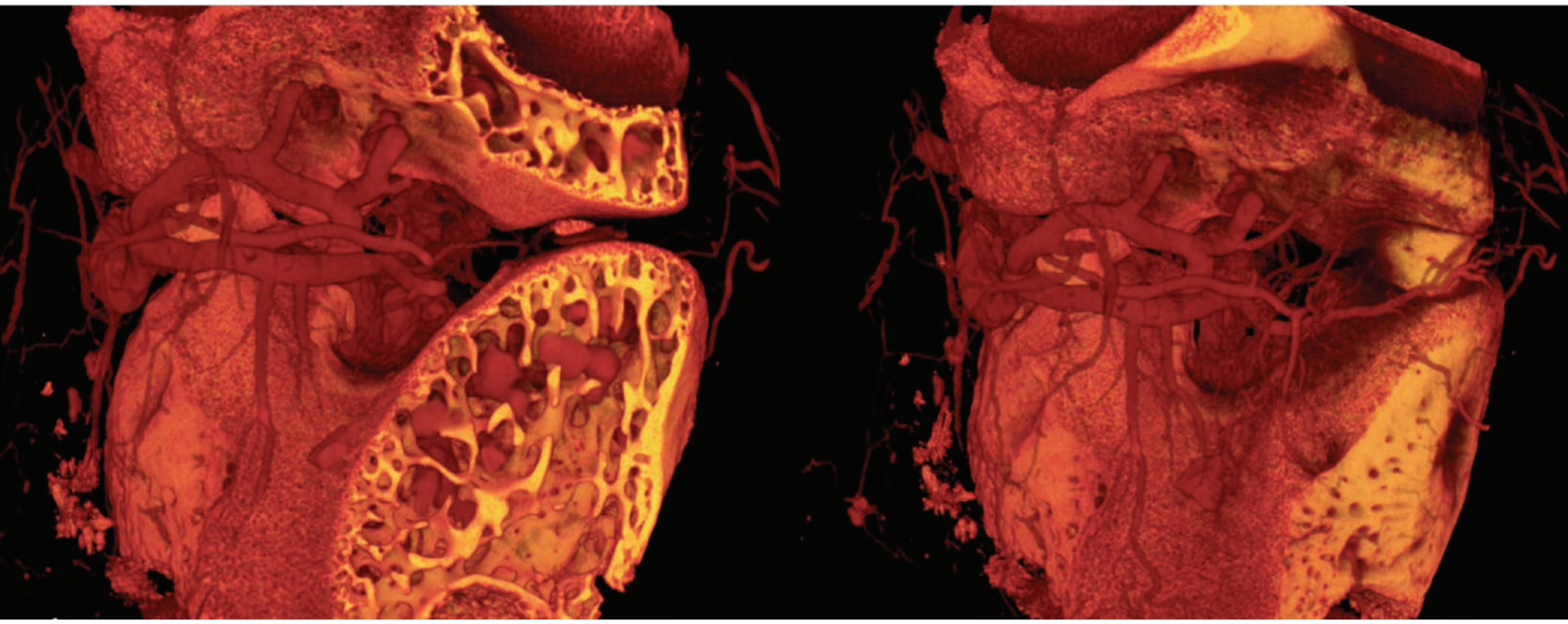
Technical Note



Resolution of a 3D X-ray Microscope

Defining Meaningful Resolution Parameters for XRM

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Resolution of a 3D X-ray Microscope

Defining Meaningful Resolution Parameters for XRM

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Date: July 2013

Although the definition of resolution may seem straightforward, several non-equivalent terms are used to represent the resolution capabilities of 3D tomographic instruments. ZEISS specifies on spatial resolution, the most meaningful measurement of an microscope's performance. This Tech Note explains how to objectively evaluate the resolution performance of 3D X-ray microscopes and other computed tomography (CT) instruments relevant to the user's research and production goals.

Micro-CT and nano-CT technology have made considerable strides in resolution during the past decade. The recent introduction of 3D X-ray microscopy (XRM) brings yet another advancement at even higher resolution.

When evaluating these high resolution systems it is helpful to understand the numerous terms used in the industry to describe resolution that, if not clearly understood, can confuse comparisons between systems. These terms include:

- Spatial resolution
- Voxel size
- Nominal resolution
- Spot size
- Detail detectability

Each of these terms conveys vastly different representations of a system's performance. While spatial resolution provides a direct measurement of the system's complete imaging capability, metrics such as voxel, nominal resolution, and spot size are isolated contributors to resolution that, by themselves, do not describe the performance of the system as a whole.

Meaningful resolution measurements should reflect total system performance, be based on standards that enable unbiased comparisons, and be considered at multiple working distances that reflect the range of intended applications and sample sizes. In order to make an objective comparison of systems, a clear understanding of each term is required.

Spatial Resolution: The Most Meaningful Measurement

Spatial resolution refers to the minimum separation at which a feature pair can be resolved by an imaging system. It is typically measured by imaging a standardized resolution target (Figure 1a) with progressively smaller line-space pairs. As the feature pairs become spaced closer than a system's resolution capability, they cannot be distinguished (resolved) from one another and increasingly appear as one single feature (Figure 1b).

Historically, spatial resolution came from attempts to describe a telescope's resolution by the minimum separation of stars

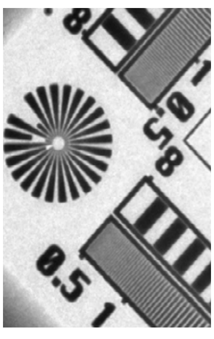


Figure 1a – A standard spatial resolution target.

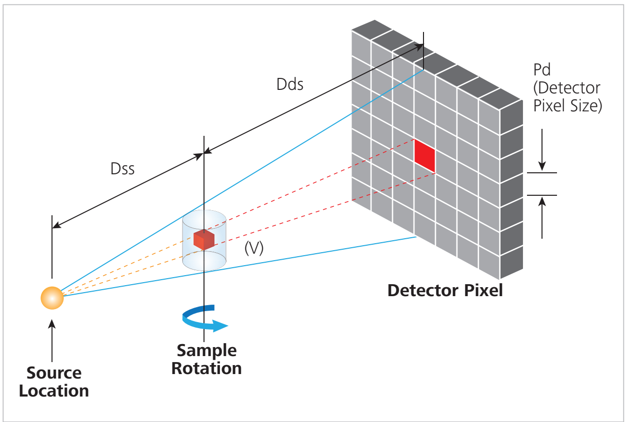
Figure 1b – Spatial Resolution as a Function of Feature Separation. As the same pair of features becomes separated by spacing smaller than the resolution of a system, it becomes indistinguishable as a pair by the imaging system.

that could be resolved. It still serves as the standard scientific measurement of resolution for most imaging systems, used for everything from medical CTs to common optical microscopes.

Spatial resolution is the most meaningful and comprehensive metric because it is measures the output of the system (an image) and accounts for all imaging system characteristics, including X-ray source spot size; detector resolution; vibrational, electrical and thermal stability; magnification geometry; and imaging conditions. This is the metric that ZEISS uses to specify resolution of the Xradia Versa and Xradia Ultra instruments.

Voxel: A Calculation of Pixelation

Voxel (3D) or pixel (2D) size is a geometric calculation referring to a cross-sectional area in the sample that is imaged onto a single detector pixel. This calculation accounts for only the detector pixel size and system geometry and does not account for source blur, source and system stability, imaging artifacts, and other key aspects of a system's actual output that contribute to or detract from image quality.



The fallacy of relying on a geometric term such as this can be seen in Figure 3 in side-by-side images of a carbon fiber composite at a voxel size of 1.0 µm. Although both images were taken at the same voxel on different systems, only the right-hand image can resolve the carbon fibers.

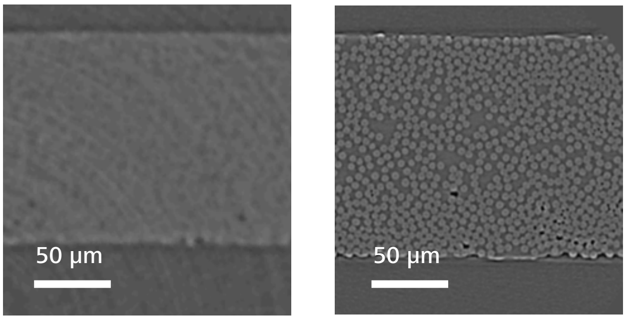


Figure 3 – Voxel Size versus Spatial Resolution. Although the same carbon fiber composite sample was imaged at the same voxel size of 1.0 µm, the resulting image quality differs greatly. [Left: non-ZEISS commercially available CT system at 1.0 µm. Right: Xradia Versa at 1.0 µm

Minimum Voxel: Theoretical versus Practical Calculation

Minimum voxel size is calculated assuming an extremely small sample placed as close to the source and as far from the detector as possible to deliver maximum geometric magnification. However, operating at high geometric magnification causes problems that can limit true resolution, such as source blur and motion blur that can occur due to heating if the sample is placed too close to the source.

Thus the minimum voxel size is often meaningless in depicting the system's actual resolution performance. In fact, a minimum voxel may produce lower quality and worse resolution than images taken at a larger voxel size.

It should be noted that while minimum voxel can be misleading, the effective voxel can be relevant. When voxel size becomes approxi-mately equivalent to all other resolution limiters, it is referred to as the effective voxel. This is discussed further in the spot size section.

Nominal Resolution: "In Name Only"

Nominal means ideal or theoretical and is used to emphasize the difference between theory (system design) and reality (system performance). Nominal resolution is a theoretical specification, and does not provide evidence of a system's true performance. In the practice of microCT the term is often used to refer to the minimum voxel size. A common oversight is to assume nominal resolution is equivalent to the spatial resolution of a system; rather is a purely geometric term that becomes meaningless when other system resolution factors, such as stability or source blur, are dominant.

Spot Size: Only Relevant for Geometric Magnification-Based Systems

Spot size is the measured diameter (full width at half maximum, FWHM) of the X-ray beam at the source. It is one of many factors that define a system's ultimate spatial resolution, but its impact is highly dependent on a system's optical and imaging design.

The source spot size relates to resolution due to spot-size-induced image blur, referred to as "spot blur" or "penumbral blur," which is proportional to both the source spot size and geometric magnification. This spot blur can significantly limit resolution (as seen in Figure 4) for geometric magnification-based systems. As a result, conventional micro-CT and nano-CT manufacturers have focused on developing the smallest system spot size.

However, not all system architectures are equally dependent upon spot size. Two-stage magnification (geometric + optical) designs employed by ZEISS X-ray microscopes reduce dependence upon geometric magnification and minimize spot blur, which removes the conventional limitations of spot size on resolution.

Thus, while spot size can limit resolution for geometric magnification-based systems including conventional microCT/nanoCT, it should not be used as a comparative metric when the comparison includes systems such as X-ray microscopes that use two stages of magnification and are not solely dependent on geometric magnification.

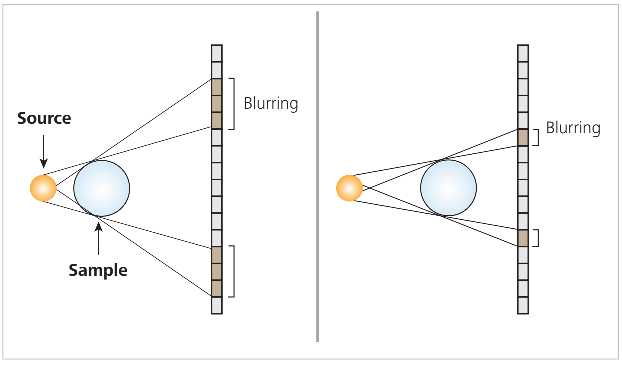


Figure 4 – Spot Blur at Varying Geometric Magnifications. Spot blur can be significant at high geometric magnifications (left), but can be significantly reduced when operating at lower geometric magnifications (right).

Figure 5 – Detail detectability measures the presence of something without the requirement to resolve that object. When is the feature, the letter R, detected versus resolved in these images? Detection occurs in the second or third image from the left, well below where the feature is resolved.

Detail Detectability: Non-Standard Term

Also known as "feature recognition," the term "detail detectability" is used in various ways among the imaging community. Detail detectability, depending on how it is defined, can be used to characterize system performance. However, due to dissimilar definitions within the CT community and the lack of a standardized reference target, it generally cannot provide the complete basis for evaluation.

This term has been used confusingly in different contexts to refer to minimum voxel, to half the source spot size, or to the smallest high-Z feature that an observer would interpret as detected. Defining detail detectability as the smallest high-Z feature that can be detected is the most conventional definition, but there is not a common method of determination.

Such quantification of detail detectability is problematic because it is influenced by:

- Observer bias: an observer may visualize a slight gray scale shift and subjectively claim the particle is "detected" but interpretation may vary by observer.
- Feature construction: there is no standardardized reference target for micro-CT, which can lead to dissimilar detail detectability numbers that are reliant on variable measure ment techniques. Such techniques may include creating a feature from highly X-ray absorbing materials with high aspect ratios (small only in one of the three XYZ dimensions), which then enables detail detectability claims equal to the smallest feature dimension. In other words, because no standard measurement technique exists, relying on detail detectability as a measurement of resolution in an evaluation may lead to erroneous conclusions.

Even if a standardized test method is constructed in the future, detail detectability is still a limited measurement because of its subjective nature.

The Distance Factor

When evaluating the performance of an X-ray imaging instrument or comparing capabilities of several different instruments, measurements of spatial resolution should not just be assessed under best case scenarios for a system. Resolution can degrade as working distance increases so it should be evaluated across realistic imaging conditions that include larger working distances for a wide range of samples sizes relevant to the user's intended applications.

For example, if one wishes to image a range sample sizes 10 to 100 mm diameters or conduct in situ experiments to observe samples under specific conditions such as temperature changes or compression and tension, then spatial resolution at working distances appropriate to those dimensions will be most relevant. By obtaining spatial resolution measurements at multiple working distances, a proper evaluation can be made for the resolution achievable across the range of samples the user cares about most.

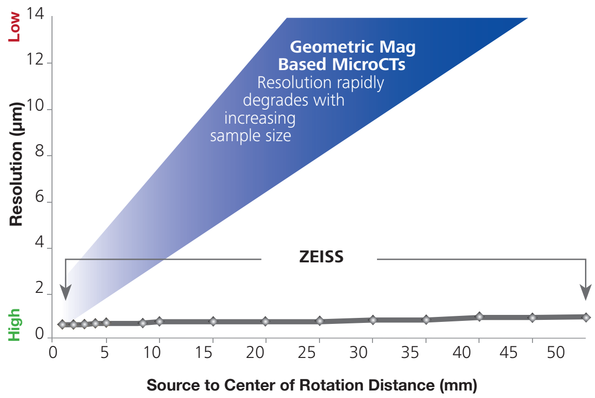


Figure 6 – Xradia Versa deliver resolution at a distance, or RaaD™, to maintain the highest resolution at a wide range of working distances. Using RaaD, the resolution achieved by Xradia Versa, which are maintained at around ~1 µm, remains high while the resolution of micro-CT and nano-CT rapidly fall off to coarse representations. ZEISS delivers the highest resolution for in situ studies with flexibility for a wide range of sample sizes, conditions, and distances.

Summary: Comparing and Selecting a 3D X-ray Imaging Instrument

- Spatial resolution provides the most meaningful method of evaluating an instrument's performance, and thus should be used to compare systems objectively.
- While minimum voxel, nominal resolution, spot size, and detail detectability each can provide some information about the system's ability to resolve an image, each is incomplete on its own and can misrepresent the true imaging performance of the system.
- Spatial resolution should be assessed at working distances relevant to the user's intended applications.
- To choose the correct system, users must apply consistent definitions while evaluating imaging solutions.
- ZEISS XRM deliver delivers the highest spatial resolution across the widest range of working distances.

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