Contrast with a 3D X-ray Microscope
For Difficult-to-Image Materials
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X-ray imaging contrast typically results from the absorption of X-rays in a given sample. As a consequence, X-ray systems have traditionally been used to image dense and high-Z materials that provide sufficient imaging contrast, such as large metal parts and bones. ZEISS 3D X-ray microscopes (XRM) feature unique contrast enhancing architecture and software tools that provide unprecedented resolution and contrast of materials that have thus far been “difficult-to-image” by the X-ray community.

Examples of these challenging materials include:

- Low atomic number (low Z) materials, such as soft tissue and polymers
- Materials of similar Z indices, such as ceramic compounds sintered from multiple elements of similar atomic number, or insects and fossils trapped in amber

Due to its unique system architecture, the Xradia Versa family of 3D X-ray microscopes (XRM) provides high contrast for traditionally “difficult-to-image” materials to reveal details that enable visualization and quantification of features.

The Xradia Versa family of 3D X-ray microscopes (XRM) was designed to increase material imaging flexibility by employing several contrast enhancing features:

1. Enhanced Absorption Contrast Detectors: ZEISS’s detector system consists of multiple highly specialized proprietary detectors that are each optimized to maximize collection of contrast-forming low energy X-ray photons.

2. Advanced Compositional Contrast Tool: Dual Scan Contrast Visualizer (DSCoVer), exclusive to Xradia 520 Versa, extends the detail captured in a single energy absorption image by combining information from tomographies taken at two different X-ray energies and can highlight material differences that would otherwise be indistinguishable.

3. Tunable Propagation Phase Contrast: The unique phase contrast technique measures the refraction of X-rays and is different than standard absorption contrast, which measures the absorption of X-rays. Phase contrast enables visualization of materials with poor absorption contrast.

These unique system features enable ZEISS X-ray microscopes to provide superior contrast for a range of “difficult-to-image” materials.

Soft Materials
Unstained Soft Tissue
Plants

Phase and absorption contrast were used to obtain a high resolution image for quantification of pore size and wall-thickness measurements, and degree of interconnectivity of this porous xerogel.

Phase contrast was employed to image unstained cartilage in a mouse knee.

Pear imaged with absorption contrast – no visibility of cell walls (left), and pear imaged with phase contrast, showing details of cell walls in normal cells and stone cells (right).
Xradia Versa: Advanced Absorption Contrast
Absorption contrast, the common imaging modality used by most X-ray imaging equipment, measures the attenuation of an X-ray beam through the sample. For absorbing materials, this type of contrast is familiar, relatively fast, and easy to segment for quantitative analysis.

Xradia Versa employ a unique detector system comprising a rotating detector turret with selectable magnification and field-of-view pairings, analogous to an optical light microscope. In addition to providing different resolutions, each detector objective also features a matched scintillator that optimizes contrast for that objective. Each optimized detector preferentially images within its contrast-forming useful energy band, while minimizing detection of higher energy X-rays above this energy band that tend to be unattenuated and wash out the contrast in an image.

In comparison, conventional micro-computed tomography (micro-CT) systems commonly use a single large area detector such as a flat panel that must cover the entire range of X-ray imaging operating conditions. These detectors are often designed to optimize efficient capture of the system’s higher X-ray energies, which causes inefficiencies in capturing lower energy X-rays. This results in a trade-off in contrast for a large variety of low Z materials such as soft tissue, fluids and gels, carbon and glass fibers, polymers, and silicon.

Dual Scan Contrast Visualizer (DSCoVer):
Compositional contrast feature
The Xradia 520 Versa expands the absorption contrast capabilities of the Xradia Versa family with the DSCoVer tool, which combines two absorption contrast images taken at different X-ray energies in order to maximize compositional contrast. This capability can provide distinction between similarly absorbing materials, including silicon and aluminum, which are well-known to have extremely similar X-ray attenuation characteristics.

How it works
In standard single absorption tomography, the resulting grayscale signal depends upon the material’s effective atomic number (Zeff) and electron density (ρ). The contrast weighting of these material properties depends upon the X-ray energy used to image the sample:

- At lower X-ray energies, the photoelectric effect dominates (related to a material’s effective atomic number, Zeff)
- At higher X-ray energies, Compton scattering dominates (related to a material’s electron density, ρ)

![Figure 1a: Photoelectric effect and Compton scattering as a function of photon energy for a particular material.](image)

![Figure 1b: X-ray attenuation coefficient as a function of X-ray energy for four common rock materials.](image)

These two phenomena describe how an X-ray interacts with electrons. In the photoelectric effect, the X-ray is absorbed by an inner shell electron, which is ejected. In Compton (inelastic) scattering, the photon collides with an outer shell electron that is recoiled and loses some of its energy to the electron. In both cases, incoming X-ray energy is decreased by material absorption, but through different mechanisms and providing varying levels of contrast.

Using DSCoVer

By combining two tomographies, with one captured using energy in the photoelectric regime and one in the Compton scattering regime, compositional contrast can be achieved in a very flexible manner. Identifying and understanding the cross-over between the two regimes helps determine which energies to use for the two tomographies. For example, the cross-over energy for most rock types is around 100 kV, therefore requiring a scan below 100 kV (e.g. 70 kV) and another above 100 kV (e.g. 150 kV).

DSCoVer can enhance mass density and atomic density distinction for a wide range of heterogeneous sample types for materials science, rock characterization, and mineral sample analysis.

ZEISS’s Flexible Architecture enables DSCoVer

Tuning contrast with DSCoVer requires collection of tomographies at high absorption contrast at lower kV (photoelectric regime) as well as high kV (Compton scattering regime). Xradia Versa are uniquely suited for DSCoVer, due to its:

1. Superior low kV imaging: Xradia Versa detectors provide optimized collection at low kV in comparison to flat panel detectors, which typically are relatively insensitive to low energy X-rays. Flat panel design is typically optimized for higher energy X-ray collection and commonly uses an absorbent shielding to protect its electronics that can reduce the flat panel’s sensitivity to contrast-forming lower energy X-rays.

2. Flexibility for high kV imaging: Xradia 520 Versa can access X-ray energies up to 160 kV, important to DSCoVer applications such as silicates and mid-Z material characterization. In comparison, non-flat panel micro-CTs that can provide some level of contrast for low energy kVs are designed only to access up to 50 or 100 kV.

Figure 2: A single energy scan shows that aluminum and silicon are virtually identical (left), with very similar grayscale contrast. Using the DSCoVer interface to “tune” and highlight aluminum (middle) enables separation of the particles. 3D rendering shows Aluminum/green; Silicates/red (right).
ZEISS Phase Contrast Advantage

The Xradia Versa family uniquely enables phase contrast imaging through a combination of small effective detector pixel sizes and by providing a flexible range of source and detector travel distances. The size of the phase contrast fringe in laboratory systems is a function of the energy spectrum of the X-rays and the convolution of the source-to-sample distance (R1) and the sample-to-detector distance (R2) (Figure 4). Flat panel detectors of conventional microCT systems, which typically have detector pixel sizes on the order of 50-100 μm, are unable to capture the majority of phase contrast information because the phase fringe-widths tend to be much smaller than the detector pixel size. In contrast, ZEISS X-ray microscope detectors achieve pixel sizes down to a third of a micron (0.34 μm) and are thus small enough to capture detailed phase information.

Phase contrast as a function of X-ray source-sample (R1) and sample-detector (R2) distances is illustrated in Figure 5. The contrast transfer function (CTF) shows where image phase contrast is maximized as a function of R1 and R2. The red line in the upper left represents the operational realm of a typical high-end flat panel-based micro-CT, while the black lines represent the optimum operating range of the medium magnification 4X detector and the high magnification 20X detector on Xradia Versa. The grey box indicates the overall operating range of the instrument.

The flat panel system’s phase contrast capabilities are severely limited due to their large pixel size and requirement for high geometric magnification (R2>>R1), whereas the ZEISS detectors provide the ability to tune the phase contrast in a practical manner to highlight features of interest like material interfaces.
**Optimized Architecture = Superior Imaging**

The Xradia Versa family provides superior imaging in both X-ray absorption imaging mode and propagation-based phase contrast imaging mode. The selectable turret of imaging objectives in ZEISS’s unique X-ray microscope contain scintillators that are optimized by objective to provide the highest absorption contrast. The small detector pixel sizes of the XRM architecture coupled with flexible source and detector travel enables the user to optimize the propagation phase contrast effect. This approach enables imaging of features in materials that are traditionally considered “difficult-to-image,” such as soft biological tissues and polymers, or in samples composed of constituents that are of similar absorption contrasts.

**Suggested Reading:**