



Dual Energy and DSCoVer

Technical Note and Procedure



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Technical Note and Procedure:

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1 Abstract

Measuring how a substance behaves at two different energies can potentially provide information about the material composition beyond that obtained from a single energy. In any given single energy scan with a polychromatic x-ray source, if the materials present are unknown, grey scales may not be enough to help identify similar or different compositional materials. Features with similar gray scales can represent either the same materials type, or different materials with densities that happen to attenuate x-rays in similar amounts. Conversely, features with different gray scales may not necessarily be different materials – they could just be different densities of the same material. The interactions of materials with different x-ray energies can change depending on material composition and density. Enhancement and segmentation of features using 2D histograms that map these interactions at 2 different energies is the principle of Dual Energy.

2 Concepts

2.1 Dual Energy

X-ray contrast from an element depends on three variables: Energy (E), effective atomic number (Z_{eff}) and density (ρ). Therefore, when two scans are acquired using different x-ray spectrums, the contrast differences between the elements now depends only on two variables – Z_{eff} and ρ .

With a change in the energy and comparing two materials, two scenarios can take place:

- Absorption increases or decreases the same in both materials: Materials made up of the same chemical composition will behave in this manner. Both materials have similar attenuation characteristics, therefore they react similarly.
- Absorption increases or decreases differently in the two materials. Objects made up of differing chemical composition will behave in this manner. The two materials have different attenuation characteristics, therefore they react differently.

Materials exposed to x-rays with photon energy ranging from 30KeV to 200KeV exhibit either the Photoelectric Effect (PE) or Compton Scattering (CS), or a combination of the two. The PE dominates in the low energy range and reduces with increased energy. CS is almost constant throughout the energy spectrum and dominates the interactions when primarily higher energy photons are interacting with the sample. This is illustrated in Figure 1.

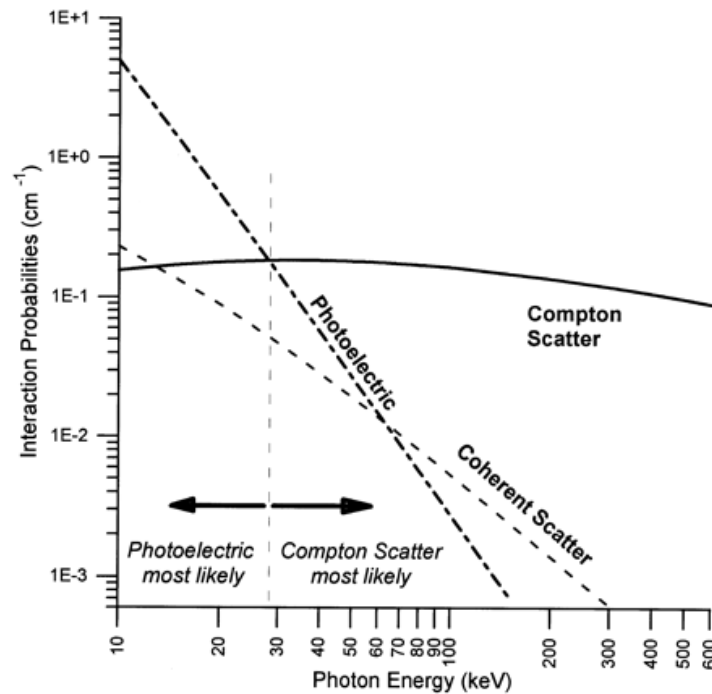


Figure 1: X-ray spectrum interactions with matter

Thus, for most cases considered in computed tomography, the overall absorption (μ) of the x-ray energy (E) can be written in an equation form as:

$$\mu(E) = a * \text{Photoelectric}(E) + b * \text{Compton}(E)$$

All low Z elements have an absorption curve (μ) which changes approximately as $\mu = \rho_e z^{2.8}$ for the low energies due to the PE and a flat section which is relatively constant and proportional to $\mu = \rho_e$ at high energies due to the CS. ρ_e is the electron density of the material. A generalized plot is shown in Figure 2.

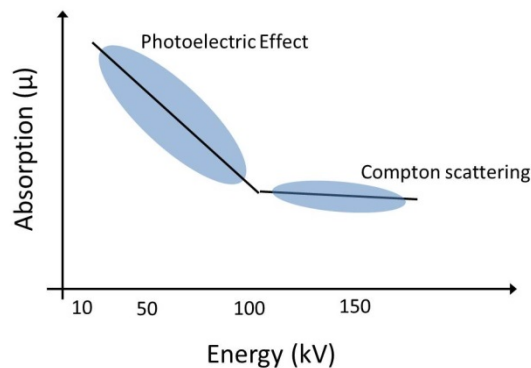


Figure 2: Atomic absorption changes differently with increase in energy due to the energy dependent dominant effects of the two different interactions of x-rays with matter

This allows for a more exact form of the previous equation as:

$$\mu(E) = \rho_e Z_{eff}^{2.8} \alpha(E) + \rho_e \beta(E)$$

To highlight the difference when imaging at different energy levels, a set of two scans is used as inputs to the DSCoVer tool. Scan 1 is used to maximize contrast obtained utilizing the photoelectric effect (low kV) while scan 2 is used to maximize the contrast obtained utilizing Compton scattering (high kV). This is illustrated in Figure 3.

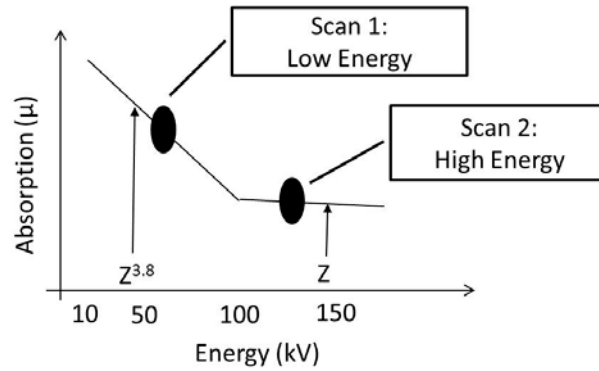


Figure 3: Dual Energy principle

Utilizing these different conditions allows us to distinguish between the 2 unknowns: Z_{eff} and ρ_e .

$$\mu(E_1) = \rho_e Z_{eff}^{2.8} \alpha(E_1) + \rho_e \beta(E_1)$$

$$\mu(E_2) = \rho_e Z_{eff}^{2.8} \alpha(E_2) + \rho_e \beta(E_2)$$

2.2 Dual Scan Contrast Visualizer (DSCoVer)

DSCoVer is an interface which allows the user to register, visualize, make and analyze dual energy scans obtained using the Zeiss Xradia 520 Versa.

Figure 4, below, shows an example of the DSCoVer interface.

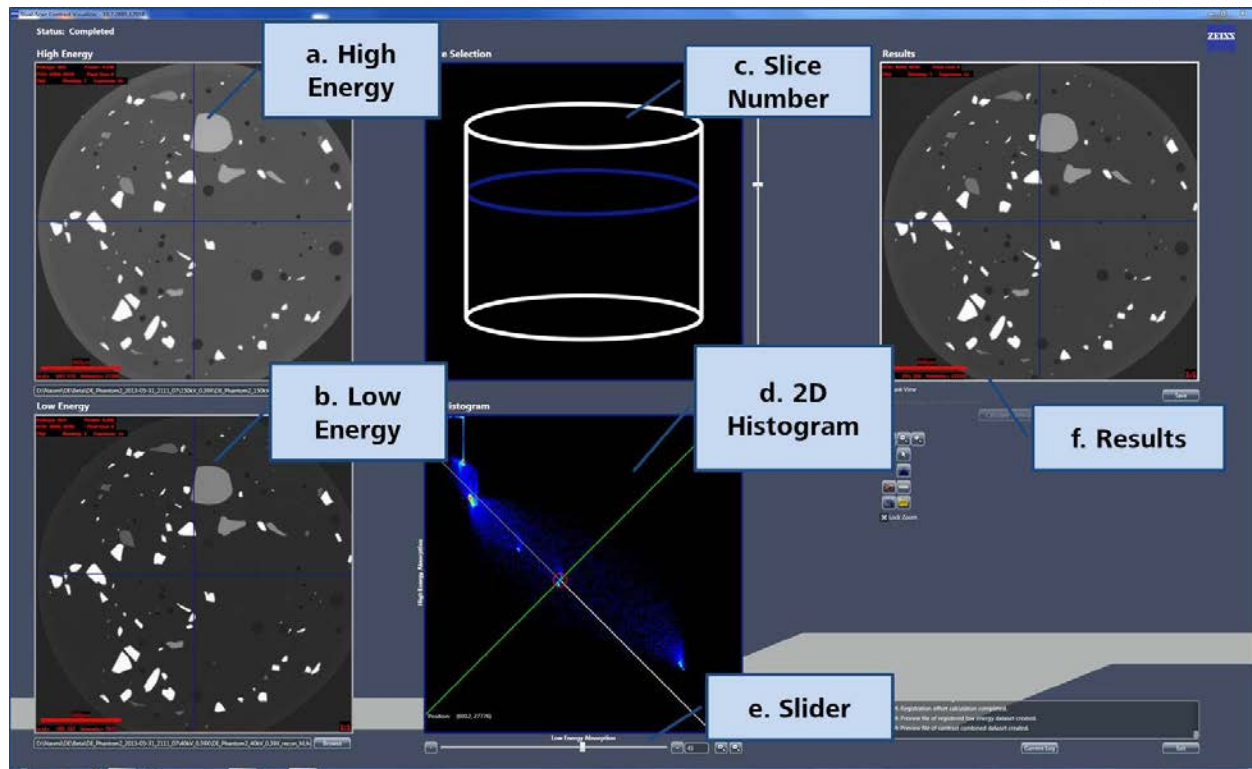


Figure 4: DSCoVer User Interface

- High Energy (HE):** High Energy filtered scan is selected in this window
- Low Energy (LE):** Low energy filtered scan is selected in this window
- Slice number:** the vertical slider is used to move through the registered slices
- Intensity 2D Histogram:** The 2D histogram plot is an intensity plot for the current slice with the LE Absorption on the x-axis and the HE Absorption on the y-axis.
- Slider:** The slider dictates the mixing proportions of the LE and HE scans as shown in the results window and is proportional to $\cos\theta * LE + \sin\theta * HE$
- Results:** The combined scan based on the settings chosen in the 2D Histogram.

2.2.1 Intensity 2D Histogram

The 2D histogram plot is an intensity plot for the current slice with the LE Absorption on the x-axis and the HE Absorption on the y-axis. The origin of the histogram (0,0) is at the top left part of the plot. The pseudo color represents the frequency of occurrence of those intensity combinations as shown in

Error! Reference source not found.. The 2D histogram is a map of every pixel in the images, shown in intensity of that pixel.

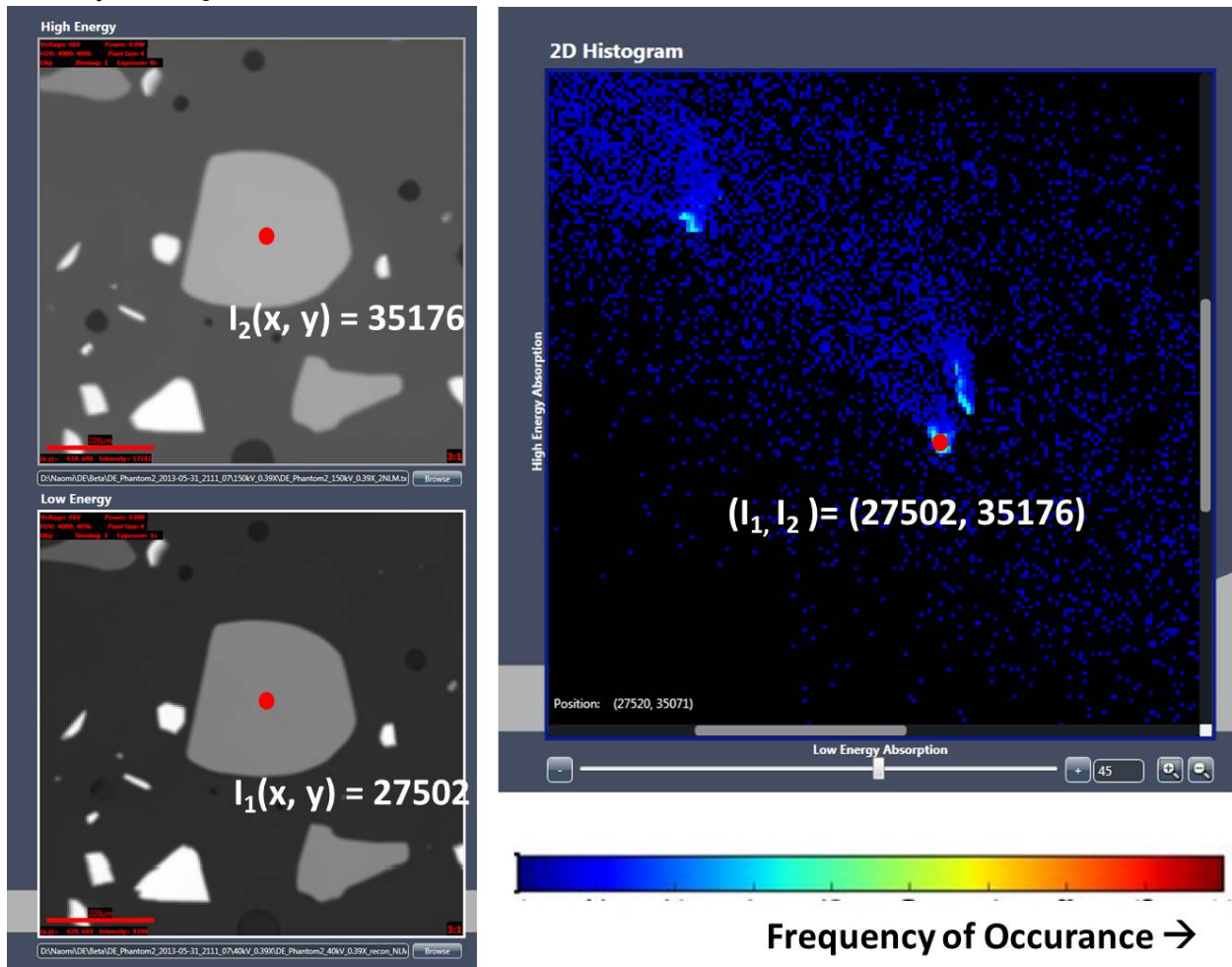


Figure 5: Understanding the 2D histogram: Pixel at location (x, y) on the images has 2 absorption intensities, I_1 for LE scan and I_2 for the HE scan. This point (x,y) is plotted as (I_1, I_2) on the 2D histogram. The color represents the frequency of these intensity combinations with the increase in the frequency shown as color change from blue to red.

As shown in Figure 6a, the 2D histogram has two lines: a green line and a white-grey line perpendicular to one another. The green line divides the 2D plot area into two regions and dictates the segmentation of the images with the help of the grey-white pointer. The center location is chosen by clicking on the 2D histogram while the orientation of the lines are adjusted by the slider bar based on the relation: $\cos\theta * LE + \sin\theta * HE$. Thus, there is 100% LE scan at $\theta = 0^\circ$ and 100% HE scan at $\theta = 90^\circ$. The combined result is shown in the “Results” window, shown in Figure 6b. Mixing the two scans can provide additional contrast or reduction in artifact.

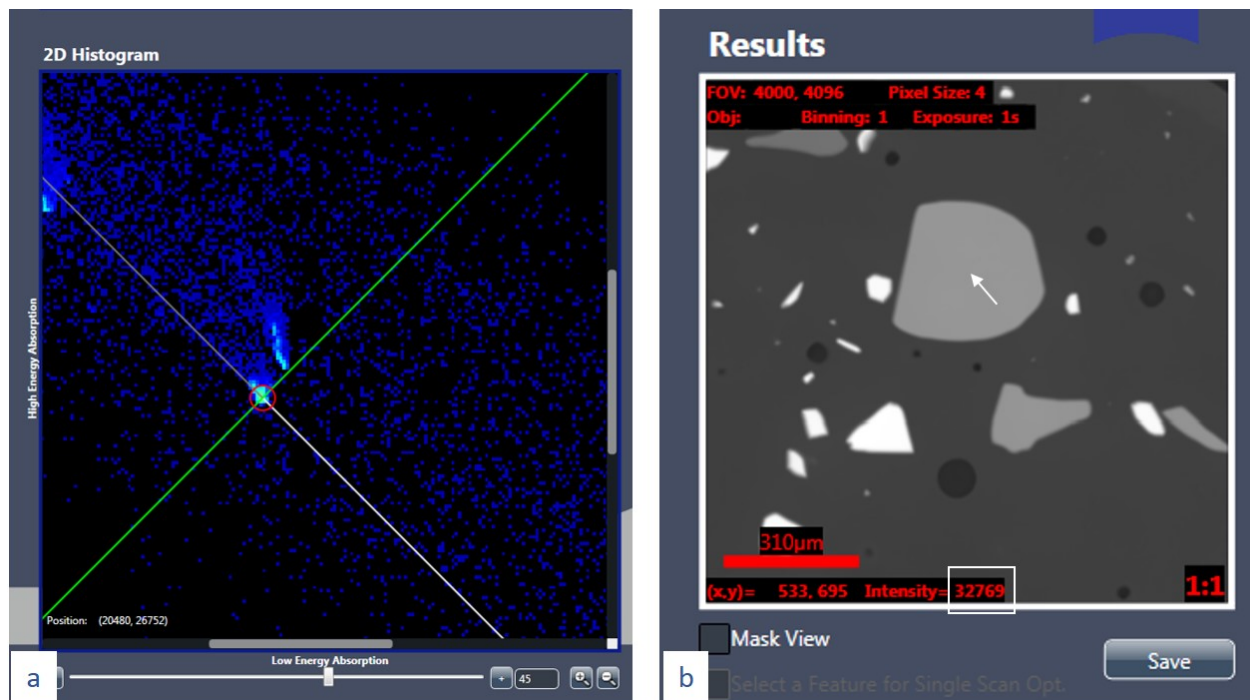


Figure 6: (a) Understanding the function of the lines in the 2D histogram plot. (b) All pixels in the 2D histogram on the gray side of the green line will appear darker, and all pixels on the white side will show in whiter in the gray-scale results image, centered around 32767.

For the image shown in the results window (Figure 6b), the grey scale intensities are all scaled from 0 to 65536 (2^{16}):

- o The intensities of pixels lying in the region pointing in the direction of the “white” part of the line are scaled from $\frac{2^{16}}{2}$ to 2^{16}
- o The intensities of pixels lying in the region pointed by the “grey” part of the line are scaled from 0 to $\frac{2^{16}}{2}$.
- o When the ‘mask’ feature in the Results is selected (explained under the Results section) the images are not changed from the above scale, but just the histogram is set to min=max=32767. Thus all pixels above 32767 appear white, and all pixels below appear black.

The combination image that results by mixing images between 0 to 90 degrees might be possible using just a single scan, but for all other angles outside this range there are no single scan equivalents, thereby providing opportunities to examine the data in new ways.

The combined scan can then be output as a .txm and be used for further analysis.

Reading the 2D Histogram

Figure 7 is an example of 2D histogram obtained after performing Dual Energy scans on a phantom consisting of the materials listed in the image.

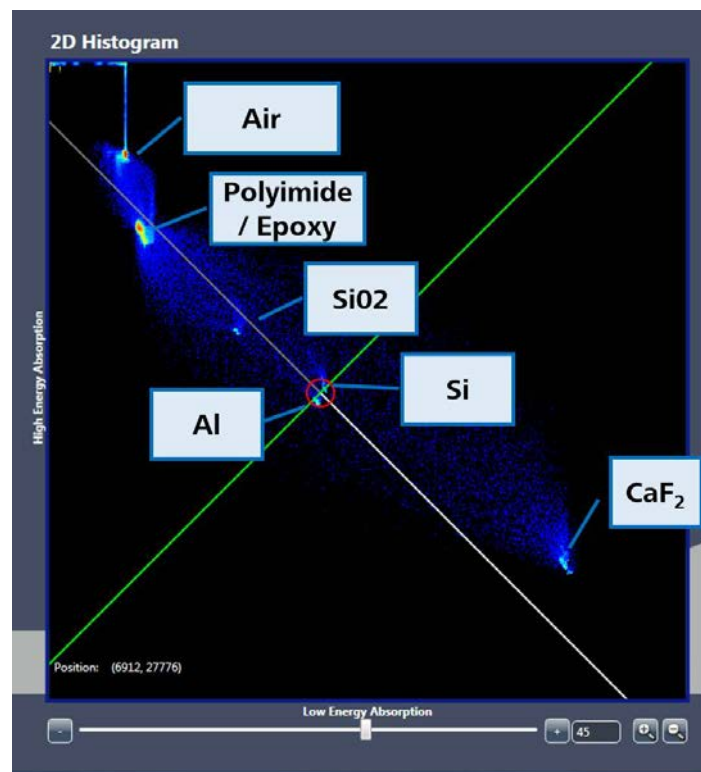


Figure 7: Example of 2D histogram. The larger clusters represent same materials.

We see the clusters of intensity pairings, each representing a particular material present in that slice. We should concentrate on the bigger clusters and disregard the single pixel combinations.

Figure 8 can help read the 2D histograms. Taking air as a reference, diagonal lines can be drawn. If the center of the cluster lies on a same line, it represents same material (Z_{eff}) but with different densities (ρ). Similarly, clusters which lie on the different lines, represent difference in material composition.

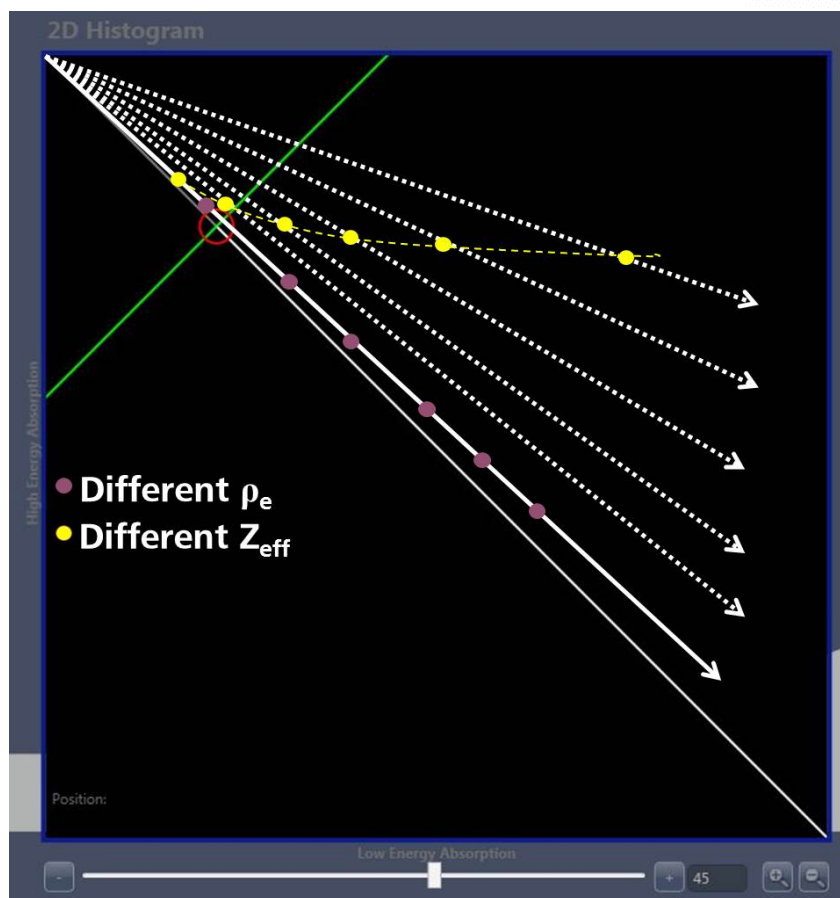


Figure 8: Guide to read the 2D Histogram. Two "clusters" lying on the same line drawn from air, represent materials with the same Z_{eff} but different densities. Similarly, two "clusters" lying next to each other represent two different Z_{eff} .

2.2.2 Results

- The LE and HE images are combined using the slider. The combined result is shown in this window, shown in **Error! Reference source not found.d**.

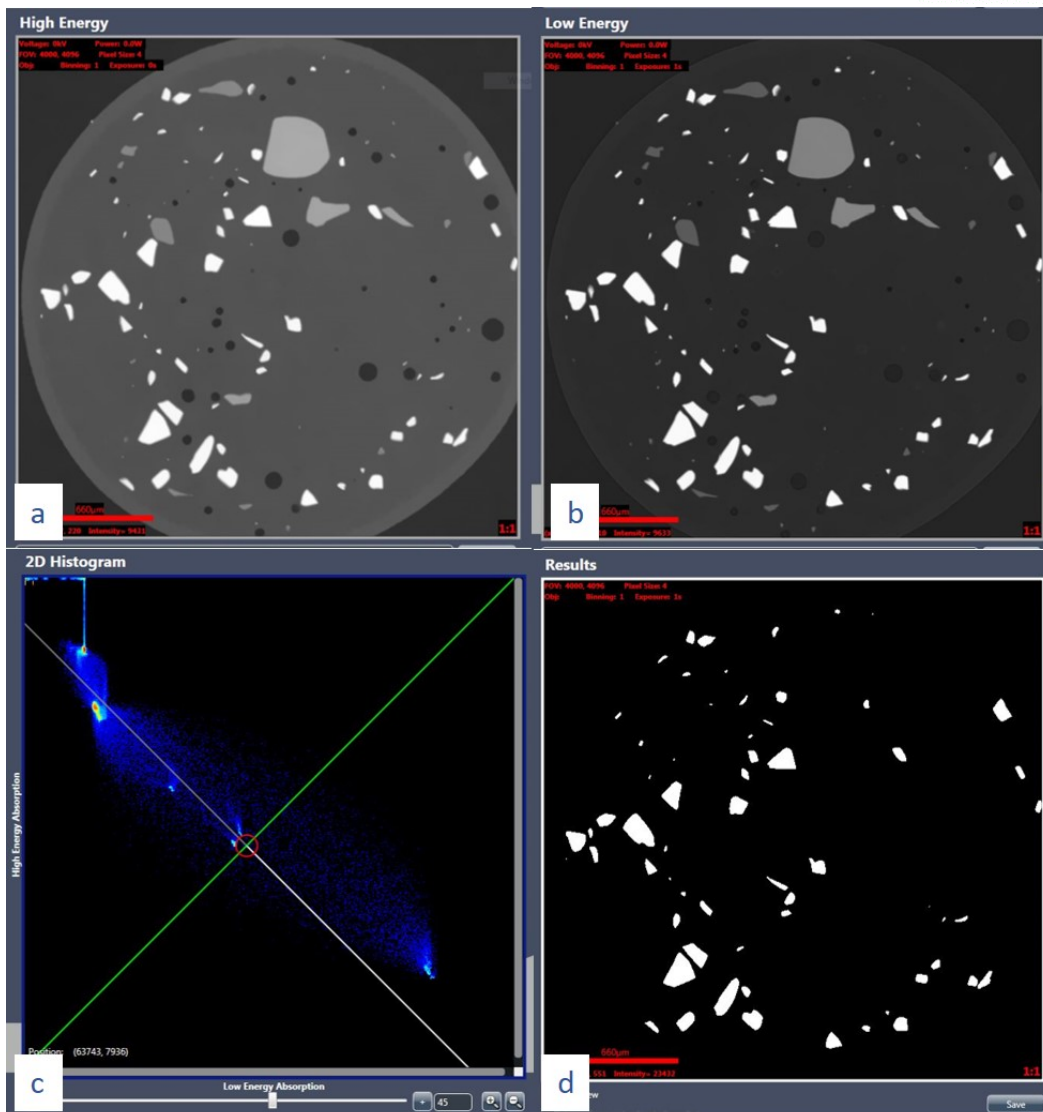


Figure 9: The green line divides the 2D histogram (c) in two parts. When the mask function is selected, the combined image is binarized. Here, the brighter objects (which lie in the region pointed to by the white line) in (a) and (b) are the only ones shown in (d) and given the value of 1.

- The masking option placed below the “results” window is used to segment the result (shown in Figure 9d). Elements in the area pointed by the “white” part of the grey-white line are kept in the masked image, while the elements in the region pointed by the “grey” part of the line are segmented out (Figure 9c and d).
- Carefully selecting the “clusters” on the 2D histogram, allow us to segment out various elements. This segmented dataset can be then output as a .txm.



2.2.3 Outputs

- 0 Datasets can be exported in the .txm format using the “Save” button below the results window.

The different dataset output options are as shown in Figure 10 and examples of these datasets are shown in Figure 11.

1. Aligned Low Energy (ALE): The low energy scan after undergoing registration and alignment with the high energy scan. (**Error! Reference source not found.a**)
2. Aligned High Energy (AHE): The high energy scan after undergoing registration and alignment with the low energy scan. (**Error! Reference source not found.b**)
3. Contrast Combined (CC): The result combining the LE and HE scans using the slider, and shown in the results window. (**Error! Reference source not found.c**)
4. Contrast Mask (CM): The segmented and binarized result of the combined images of the LE and HE scans, as shown in the results window, with the “mask” option selected. (**Error! Reference source not found.d**)
5. Aligned Low Energy with Mask (ALEM): This is a masked LE grey scale dataset which shows only the features that were segmented. (**Error! Reference source not found.e**)
6. Aligned High Energy with Mask (AHM): This is a masked HE grey scale dataset which shows only the features that were segmented. (**Error! Reference source not found.f**)
7. 2D Histogram (HIS2D) : This dataset contains the 2D histogram of each slice (**Error! Reference source not found.g**)

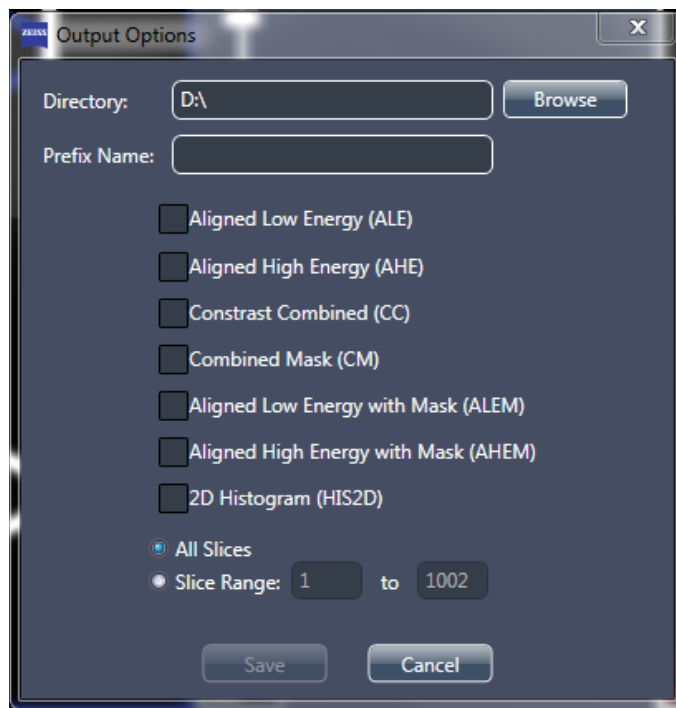


Figure 10: Different outputs can be created as .txms using the save button

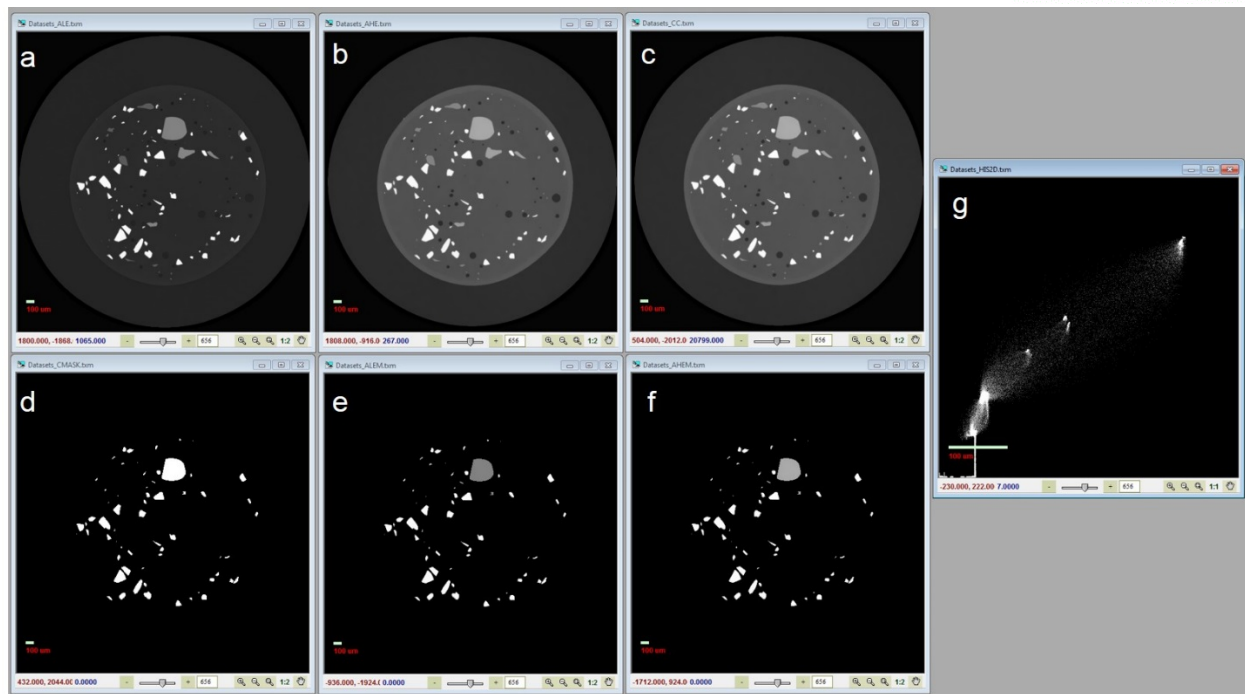


Figure 11: Examples of the output datasets types

3 Procedure

3.1 Scan Setup

3.1.1 Setup the two scans using the general procedure in the Xradia Versa User Manual. A good starting point is the following two kV and filter combinations. As covered in section 2 earlier, the two energies used should be such that the LE enhances the Photoelectric Effect while the HE enhances the Compton Scattering effect.

3.1.1.1 Low Energy (LE) scan: 40kV/3W and no filter is a good starting point for the LE scan. As seen in Figure 12(a) the average spectral energy is approximately 12.5kV. If the transmission values are very low (<12-15%) then try a combination of 70kV/6W and HE1 which gives an average spectral energy 38.2kV (Figure 12b). If this is still too low try 90kV/8W and HE1. If you are working with very high density or high atomic number materials, you may have to reconsider using DE due to the limitations of the available spectrum.

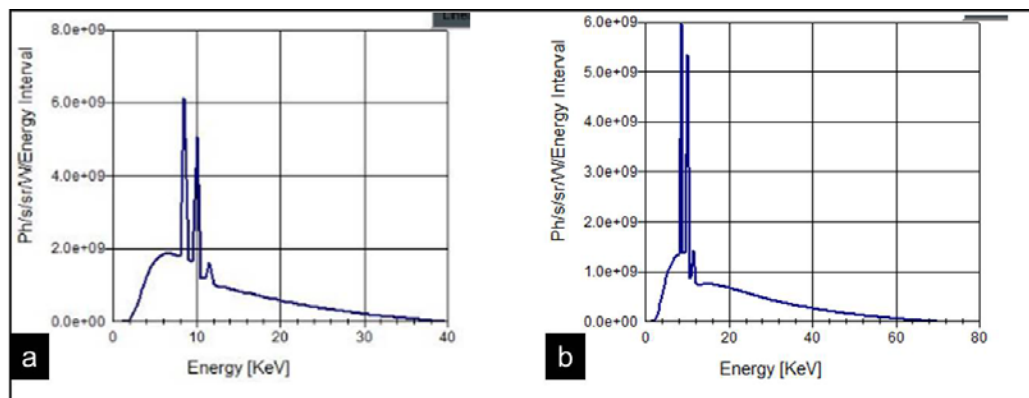


Figure 12: The spectrums for (a) 40kV and no filter and (b) 70kV and HE1 are shown. These are good starting points for the LE scan.

- 3.1.1.2 High Energy (HE) scan: 150kV with an HE6 filter allows us to obtain the highest average spectrum energy possible with the Xradia 520 Versa using the standard filters. As seen in Figure 13 the use of HE6 increases the average spectral energy from 43kV (Figure 13a) to about 71kV (Figure 13b). To get to the CS range, you may also have to consider special filters made up of heavier materials such as brass.

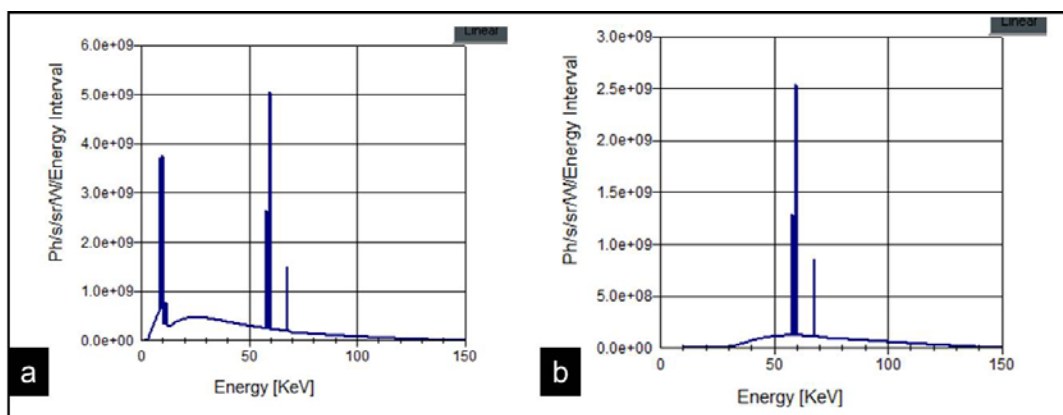


Figure 13: 150kV spectra (a) without any source filter and (b) with HE6, the thickest standard filter, are shown.

The parameters below should be considered as guidelines for deciding the scanning parameters:

- 3.1.1.3 Optimal Contrast: The 0.4X objective is the most preferred objective due to the high sensitivity of its optics for the higher kV scans. 20X and 40X objectives are not suitable for the same reasons.
- 3.1.1.4 File size: Binning 2 datasets are recommended due to file size and time considerations.
- 3.1.1.5 Voxel Resolutions: The current use of Dual Energy is optimized to about 3-5 μ m voxel size (maximum geometrical magnification using the 0.4X).
- 3.1.1.6 Feature Sizes: Features need to be large enough to provide correct signal information. Features which are at least 8-10 voxels are optimal.
- 3.1.1.7 Field of View: Although interior tomography scans can be run, it is always easier to start with Full Field of View (FFOV) scans. This is to get air around the sample which is considered as a reference point.
- 3.1.1.8 Signal to Noise Ratio: High SNR is required to plot the 2D histograms efficiently. To do so, acquire longer scans than normal.
- 3.1.1.8.1 For the LE scans, setup a regular scan: target at least 6000-7000 counts and about 2001 - 2501 projections at least for FFOV scan setups. If the samples are very dense, you may choose longer acquisition times or take more projections.
- 3.1.1.8.2 For the HE scans, acquire at least 4 - 5 times the total dose of the LE scan. Due to the high kV, you will achieve high counts in short exposure times. But, it is



imperative to remember that these counts are due to Compton *Scattering* and involve higher noise. Choose an acquisition time which maximizes counts (~30,000) without causing camera saturation (>60,000 counts). You can calculate the required number of projections to get at least 4X the dose of the LE scan in the following way:

$$4 \times \text{Counts in LE} \times \text{No. of Projections in LE} \\ = \text{Counts in HE} \times \text{No. of Projections in HE}$$

- 3.1.1.8.3 For best results, please take a 1 hour warm-up scan each, with parameters identical to the dual energy scans. You may reduce the number of projections and/or single image acquisition time of the DE scans to achieve this.

Run the recipe. After the acquisition you may delete the warm-up scans.

3.2 Reconstruction

3.2.1 Refer to Xradia Versa User Manual for reconstructing the datasets.

3.2.2 Adjust beam hardening as needed to minimize artifacts if present.

3.3 Post Reconstruction Filtering

To further improve SNR, it is necessary to filter both the datasets after reconstruction. An excellent option is to use a Non Local Means De-noising (NLM) Filter if available. If not, use the 3D median filter in the XMController (under Process> 3DFilters>Median. Use Kernel Size 7). Both these steps are memory intensive and may take several hrs. per dataset depending on your computing capability. Please filter the HE scan twice.

3.4 Segmentation using DSCoVer

An example of using DSCoVer for dual energy analysis is described in this section. A phantom consisting of the following materials, Air, SiO₂, Al, Si and CaF₂, was scanned. The particles are in an epoxy matrix, placed inside a polyimide tube as seen in Figure 14a. The materials were chosen because Al and Si are normally difficult to separate effectively using a single tomography. To help in clear identification of the materials, we have purposefully used different shaped particles for Al and Si. The easily identified cylindrical features in the raw 2D image are ~99% pure Al. (Figure 14b)

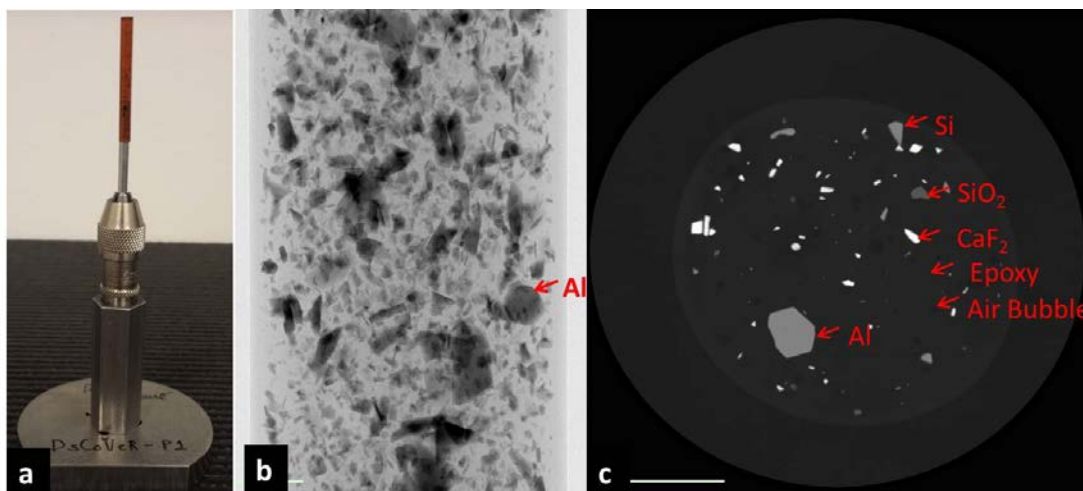


Figure 14: a) phantom as mounted for scanning; b) 2D projection of the phantom; c) reconstructed slice of the phantom. The silicon pieces are identifiable by their sharp edges while the aluminum pieces are more rounded.

Figure 14c shows that Al and Si, having very similar Z values, have virtually no contrast difference between them. SiO_2 and CaF_2 are easily identifiable due to their clearly different grey scale values.

In this example we would like to segment the dataset using the 2D histogram to obtain datasets showing only the Aluminum particles.

- 3.4.1 In order to separate the Al, the green line is positioned between the clusters representing Al and Si. The lines are then rotated using the slider to have the white part pointing towards the region containing Al cluster (Figure 15b insert) to include it in the masked image (enable by checking the “mask” button at the bottom of the results window) (Figure 15c).. However, using the current capabilities, separating Al, will also include the High Z particles (CaF_2) in the segmentation; due to the orientation of the green line (Figure 15b).

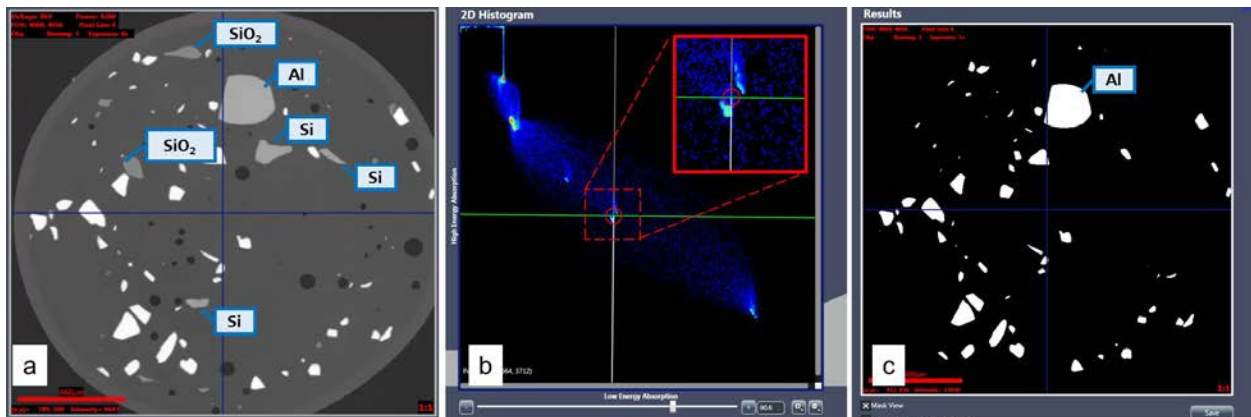


Figure 15: Segmentation of Al particles also includes the CaF_2 particles.

- 3.4.2 Some more slices could be checked to make sure the segmentation is done well. To output the dataset containing only the Al and the CaF_2 particles, the Save button is clicked and the “Combined Mask” option (Figure 16) is selected. A binarized 16-bit dataset will be saved in the specified directory.

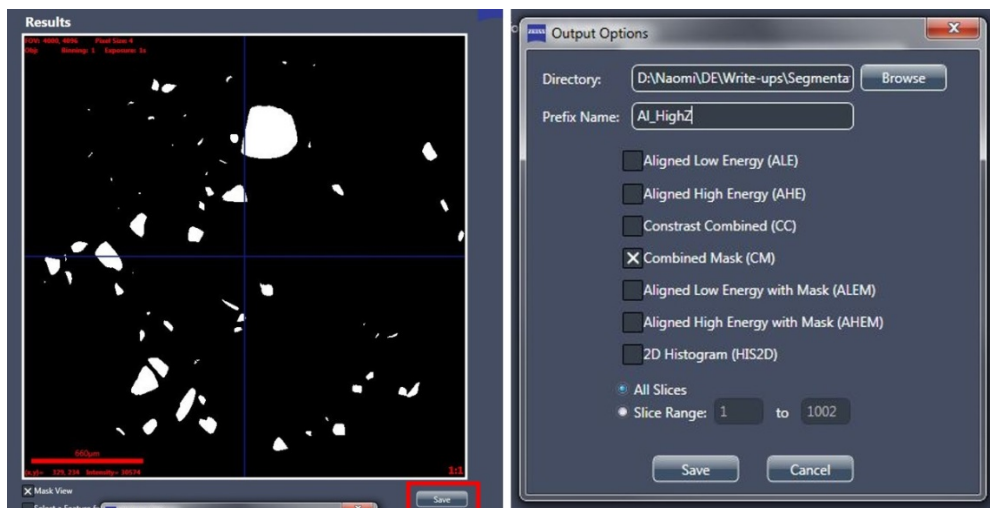


Figure 16: Saving the binarized segmented dataset

- 3.4.3 In order to obtain just the Al particles, a dataset containing only CaF_2 particles is required to subtract it from the dataset containing both Al and CaF_2 particles. Using a similar procedure as above, the dataset with only with the CaF_2 particles (Figure 17b insert) is segmented and the output is saved (Figure 17c).

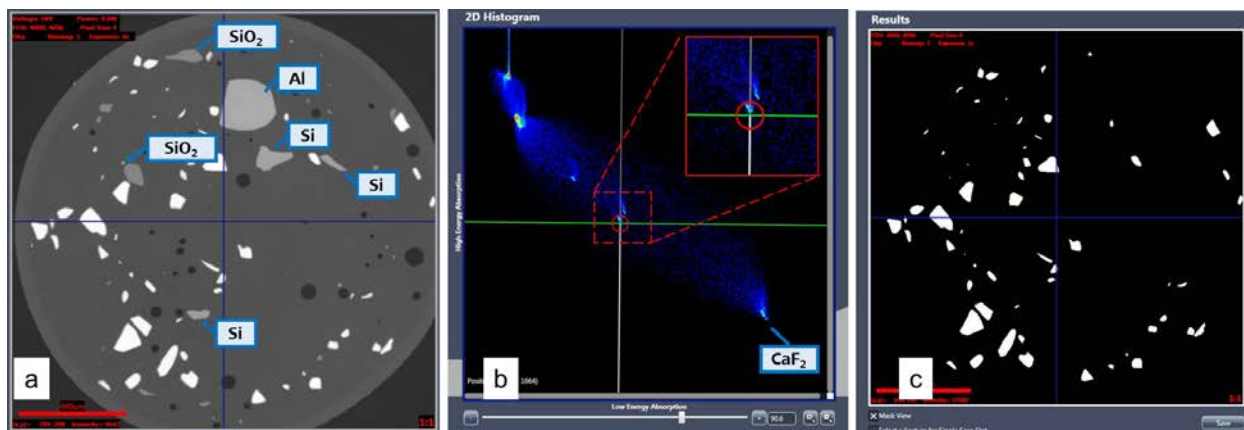


Figure 17: The dataset with only the CaF_2 particles is exported which will be then subtracted from the Al+ CaF_2 segmented dataset

- 3.4.4 The dataset with the CaF_2 particles needs to be subtracted from the $\text{Al}+\text{CaF}_2$ dataset to obtain just the Al particles. To do so, both the datasets are opened using the XMController.
- 3.4.5 Subtraction is performed on the datasets by using the Image calculator tool (Go to Process> Image Calculator). Subtraction is selected under “Operation” tab and the inputs are selected as shown in Figure 18. Clicking on the Calculate button opens a dialogue box to select the output mode. To limit the dataset size, “Unsigned Char” is selected and a new dataset is saved.

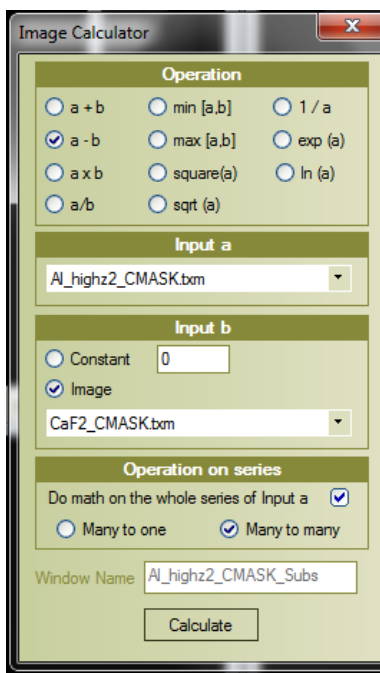


Figure 18: Subtracting the 2 segmented datasets in the XMController.

3.4.5.1 The results are seen as below with the Al particles successfully segmented out.

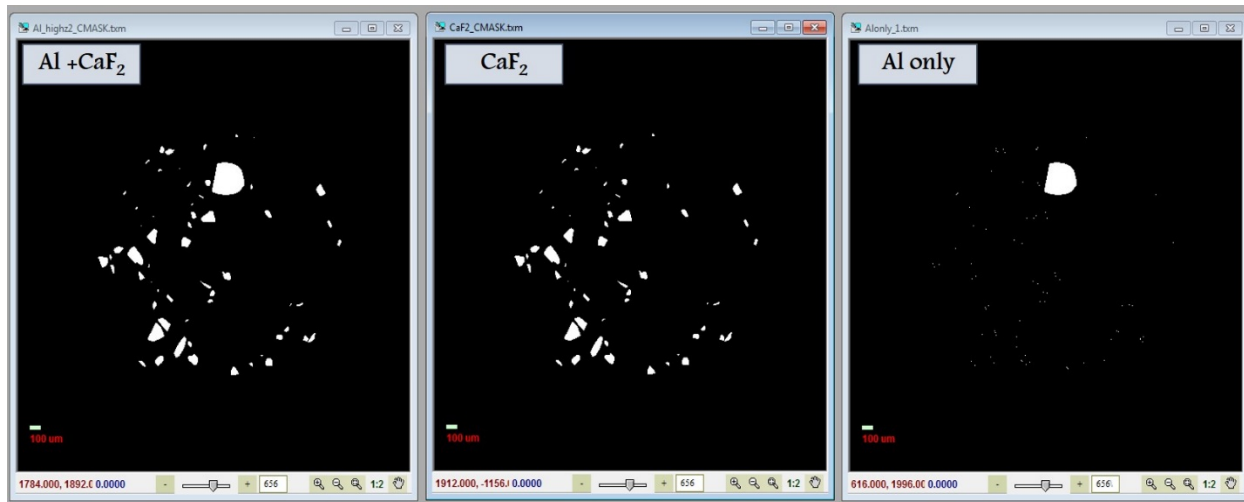


Figure 19: Subtraction of the datasets yields the Al only dataset with some misalignments at the edges.

3.4.6 There may be slight misalignments after the subtraction process. To clean these up, the Despeckle filter can be used (Process>Filters>Despeckle) as shown in Figure 20. This process can be done up to 3 times to clean up the single pixel misalignments.

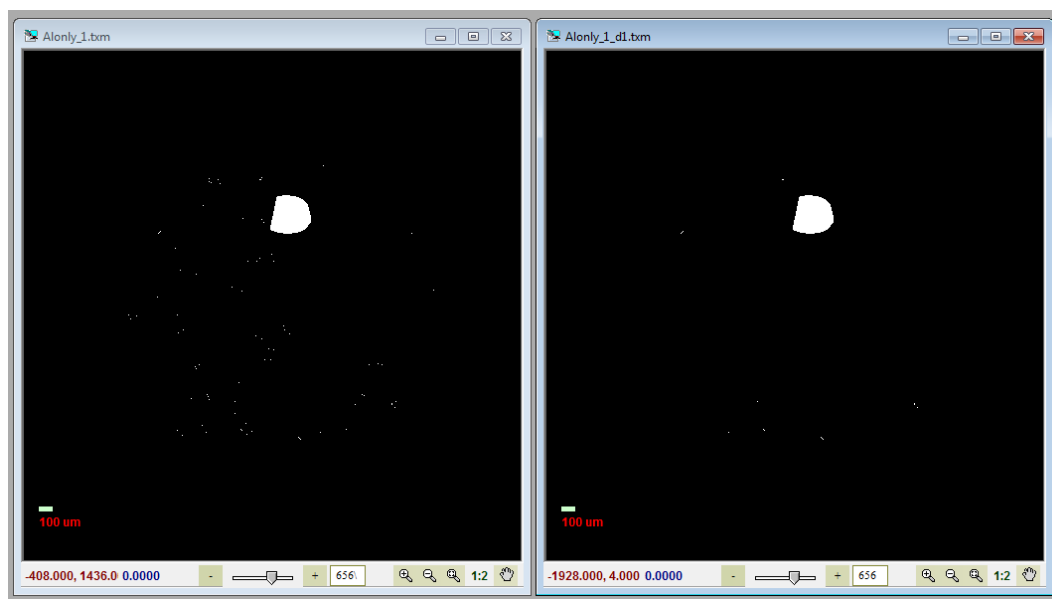


Figure 20: Despeckling enables removal of the slight misalignments

3.4.7 This dataset is then opened using the TXM3DViewer to enable visualization of the segmented dataset in 3D. Optionally open in ORS Visual SI if quantitative information is desired.

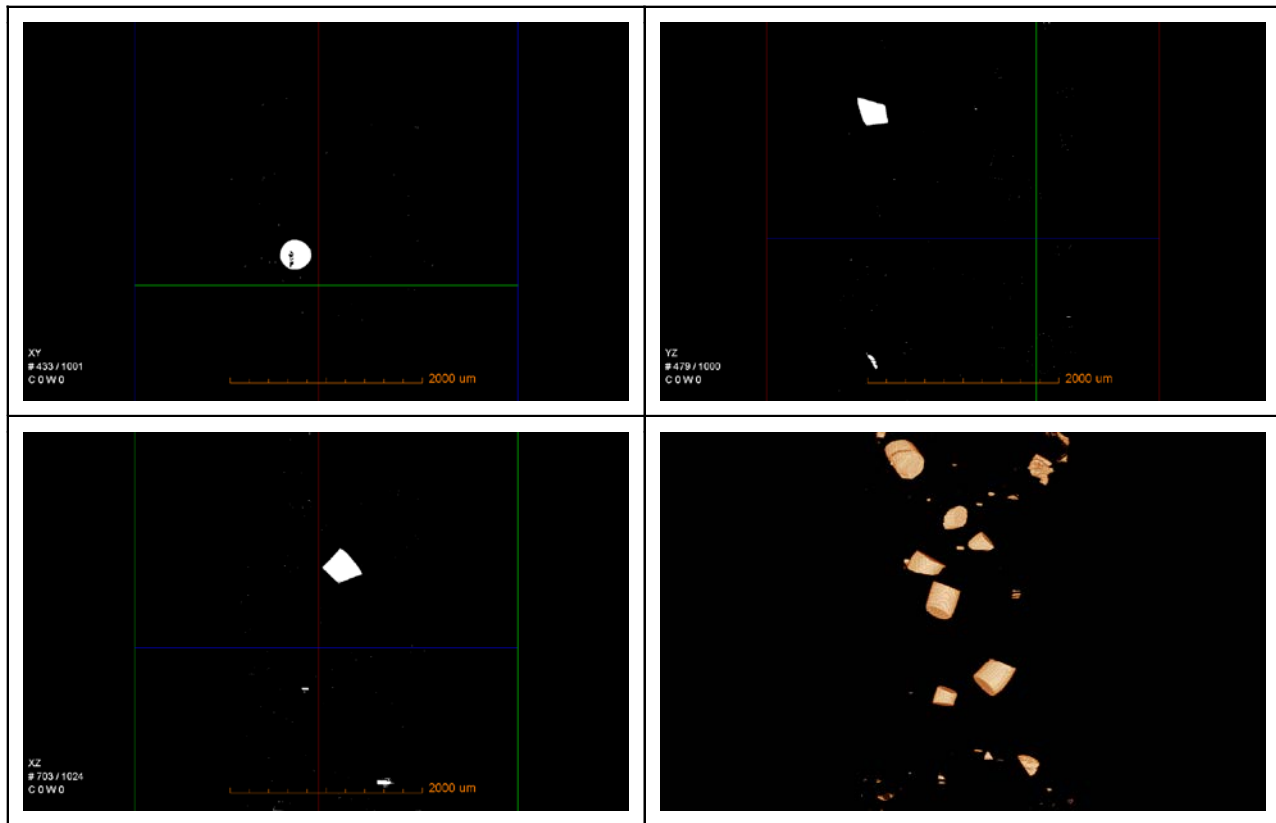


Figure 21: Visualization of the segmented Al dataset in the TXM3DViewer

4 Summary

The basic principles for Dual Energy and the features for the DSCoVer interface are discussed here. Separation of Al- Si, particles which cannot be separated using single energies, is demonstrated using the 2D histogram functionality. An example explaining the method for segmentation of the Al particles from the dataset is also shown.