A Not-So-Short Guide to Using the X-Ray CT

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Summary

This document provides a summary of the operation of the Bruker SkyScan micro-CT scanner, from setup of the machine to running scans and processing of the data. This information is based on the official training session provided by Micro Photonics. Scan parameters and reconstruction are covered in depth, while analysis is covered more generally. Beware that there is a sprinkling of cringe-worthy humor throughout. *Comments, questions, and errors can be sent to steven.zeltmann@nyu.edu.*

1 Preliminaries

1.1 What is X-ray CT?

X-Ray Computed Tomography (CT) is a powerful technique for determining the internal structure of materials. The contrast mechanism is based on absorbance of X-ray radiation by the specimen, which is essentially a function of the material density. The basis of the technique is that a conical beam of X-ray radiation irradiates the specimen, and the transmitted radiation is captured by a "camera." The *projection images* are captured at discrete rotations of the specimen as it is turned through 180°. The projection images are *reconstructed* into a 3 dimensional density map of the specimen. This density map can be used for visualization as well as for analysis. The map can also be used to create finite element meshes for structural analysis.

1.2 What can I scan?

The short answer is, practically anything that fits. The long answer:

- The specimen should fit in a cylinder[1] of $\varnothing = 50$ mm and $h = 60$ mm.
- If you're using the tension/compression system, the specimen should be less than the diameter of a US quarter (compression) or less than half an inch wide (tension). The load limit of the cell is 440 N.
- The material should be dense enough or thick enough to have decent absorption of X-rays. Polymers are often on the low side of the density spectrum, and heavier metals are on the high end. Keep polymeric specimens larger, and metallic ones smaller. Very dense metals (Pb, Au, etc.) are practically impossible to image.

[1] If the specimen fits in the machine and clears the hole in the bottom plate, *it fits*. The chamber is at its smallest when the door is open.

- The specimen should be *stable*. Any microscopic movement during the scan will make reconstruction difficult, and motions of more than a few μm will make the data unusable. Powdered materials should be thoroughly settled or bonded. Biological materials should be sealed to prevent drying.

- Very flat objects are more difficult (though certainly not impossible) to scan because the transmission through the thickness is very different than the transmission through the breadth.

- Don't scan anything that will leave residue in the chamber or that may fall off the stand. Cleaning under the guard requires a service call from the company.

1.3 What do I need?

All you need is love.
—The Beatles

The above quote is obviously false. What you'll need is:

- Your material (duh).
- The keys to the machine (should be kept in the machine, or may be at the front desk).
- Sample stage and tools (in the drawer).
- Mounting supplies:
  - Styrofoam
  - Parafilm
  - Plastic tubes
  - Clay
  - Planting foam
  - Dental wax
- *(Optional)* Love.

Some of the mounting supplies are going to be available with the machine, but others will have to be sourced to fit the needs of your particular scan. More on this in §2.2.

2 Scanning

This section covers the process of setting up the scan and acquiring the projection images. The basic steps are:

- Mount the specimen and load into scanner.
- Position the specimen in the chamber.
- Set the beam energy and filter to achieve desired contrast.
- Perform the flat-field correction.
- Configure and begin the scan.

2.1 Starting the Scanner

To start the scanner, insert the key in right side panel. Turn to the Start position and release. Depending on how long the machine has been off, the x-ray source will require some conditioning to stabilize its output. The machine calculates this automatically. If the machine has been off for a few hours, this takes 15 minutes. After two weeks of inactivity, the time is 40 minutes. Two months of inactivity requires 2 hours of aging! Check all the cable connections while you're back there. Open the SkyScan software.

2.2 Specimen Mounting

Three specimen stages are found in the accessories kit, in different sizes. The smallest stage that can sturdily hold the specimen should be used so that the specimen can be brought as close to the source as possible. The stages are opaque to X-rays, so the area just above the stage is almost impossible to

image well. When the bottom of the specimen is of interest, use a piece of styrofoam under the specimen (the foam is nearly transparent to X-rays). If the bottom is not important, use the clay to hold the specimen. Clay can be used to affix the styrofoam. Specimens can be attached to the stage by wrapping a few times with a strip of parafilm, which is also nearly transparent.

The stage is mounted in the chamber by inserting the rotary nut in the threaded hole in the base, inserting the stage, and tightening the thumbscrew. Do not overtighten. *Do not drop the rotary nut in the machine, it is practically impossible to get out from under the base plate.*

For very small specimens, or when centering is difficult manually, the micropositioning stage (MPS) is used. See §8 for more details.

2.3 Positioning

Once the specimen is mounted, close the door and energize the beam. Start the light camera to see a video feed from the inside of the chamber. This helps with seeing where the widest spot is.

The specimen can be moved up and down, rotated about its center, and moved towards and away from the source. The MPS allows for transverse motion as well, to improve centering. The basic procedure for positioning is:

- Switch to 1K mode, so the live view refreshes more quickly.
- Move the specimen far enough from the source that it is fully visible in the live view.
- Move the specimen up/down to center in the field of view.
- Rotate the specimen (through at least 180°) to check the centering. Off-centered specimens lead to lower resolution by forcing the piece to be farther from the source to fit in the field of view (FOV). If the piece isn't centered, remove from the machine and attempt to manually re-center on the stage. If this is still not satisfactory, use the MPS (§8).
- Rotate the specimen so its projection width is maximal (look at the widest section).
- Move the specimen towards the source so that it fills *most* of the frame. It is best to leave an air gap on both sides to improve the reconstruction speed and accuracy.
- *If the specimen is taller than the FOV,* a multi-part scan can be used and stitched to form one image set. See §7.2. *If the specimen is wider than the FOV at the desired pixel size,* a wide-area scan can be used. See §7.1. If you don't mind scans that take a week, you can do a wide area scan with multiple segments.
- Once the position is set, change the camera resolution to the desired setting for the scan.

2.4 Beam Energy & Filters

Once the specimen position is chosen, the beam energy and filter settings are used to adjust the contrast of the image. This is generally a subjective process. To give a flavor of exactness, we will first muse about some theory:

The fraction of transmitted X-rays through the material is a function of the material properties, specimen geometry (mathematically, the integral of the material ab-

sorbance along the path of the beam), and the energy of the beam. With an ideal (expensive) X-ray source, all of the photons would have the same energy (monochromatic). However, this unit uses a polychromatic source, so there is a distribution of energies ranging from zero up to the nominal value displayed by the software. Because of the presence of a large quantity of lower energy photons from the source, the system is subject to *beam hardening*. Put simply, the low energy photons have a much harder time making it through thick portions of the specimen, which causes artifacts in the reconstructed slices because it is interpreted as a change in density of the material. Denser materials exacerbate this effect. This effect can be controlled by using a *filter*, a piece of material placed in front of the camera that removes all of the low energy photons from everywhere in the image. When imaging thick or dense materials, the filter minimizes the effect of beam hardening and improves the contrast, but diminishes the overall brightness of the image.

Two filters are built into the machine. Custom filters can be made if these prove insufficient (§7.4). Proceed by adjusting the beam energy and selecting different filters until a nicely contrasted image is obtained. The specimen should have no areas of total black or white, and good resolution of the internal structure should be visible in the live image.

2.5 Concerning Power

> *"Everything in the world is about sex except sex. Sex is about power."*
>
> —Oscar Wilde

The gun can be set at energies from about 5 kV up to 100 kV. The maximum current is 250 μA, but the power will never exceed 10 W. At energies lower than 40 kV, the maximum current is not sufficient to supply the full 10 W maximum energy. Because of this, energies lower than 40 kV should not be used. The energy setting window will show the current operating power of the gun. Using lower energies will cause very low transmission through the specimen. The gun is also rather inefficient at low energies.

2.6 Flat Field Correction

Once the scan is set up, the flat field correction (FFC) is used to calibrate the camera and ensure a uniform background brightness. This calibration should be performed whenever the scan settings have changed, or every day if the same settings are used repeatedly. **Follow the instructions carefully, or you will waste a lot of time and feel very bad about yourself.**

- Set the camera resolution[2] you desire (based on desired voxel size, data set size, etc.)
- Note the position of the specimen (height and pixel size) and beam settings. Write them down.
- Now we have to clear the FOV. First, try lowering the specimen to the minimum height (you did write down the height setting, didn't you?). If this empties the FOV, congratulate yourself on what a lucky day you are having. If not, open the chamber, remove the specimen, and curse the universe.
- Go to `Options>Preferences` and turn FFC off.

[2]Options are 1K, 2K, and 4K, which correspond to 2.25, 5, and 11 megapixels. The number displayed next to the focal distance control is the pixel size *at the current resolution setting.*

- Right click the center of the image (in live mode or update the current snapshot). A waveform will appear, along with the average and max brightness. **Check that the average is $\in (0.4, 0.6)$, ideally 0.5.** If the value is not in the correct range:
  - Go to `Options>Acquisition Modes`. If the the menu is not available, press `Ctrl`+`Alt`+`Shift`+`S` to unlock it.
  - An arrow indicates which of the many settings is currently active.
  - **Make sure the beam energy in the box under the active column matches the energy selected. Change if necessary.**
  - Experiment with the exposure setting to get the average to 0.50.
- Perform the FFC by going to `Options>Acquisition Modes` and selecting the third radio button. `X-Ray Off` should be deselected, and `Central Camera Position Only` should be selected unless a wide scan will be used. **Make sure the beam energy in the box under the active column matches the energy selected. Change if necessary.**
- Re-enable the FFC by going to `Options>Preferences` and enabling FFC. Set the beam energy back to the desired setting (it probably changed). Check the average intensity again. It should be $\in (0.8, 1.0)$, ideally at 0.88. If it isn't, redo the FFC after setting the FFC-off average intensity up or down to adjust.
- Now you can reinsert the specimen or move it back up. At this point, you will notice that you forgot to write down its former position, despite being reminded many times, and the regret will kick in. Act calm to hide your shame. Also, reset the beam energy. It will have returned to a default value.

The worst is over (for now). Hang in there.

2.7 Scan Settings

Finally, it's time to start the scan! Make sure all the settings in the bottom of the window are right (nothing was reset during FFC or anything like that). Then open the scan window. The important settings are (all of them, essentially):

File Name: Keep the name short, and don't use spaces or dashes. It's good practice to end the name with an underscore. *Make sure to save the scans on the* `D:\` *drive. If the target doesn't have enough room, the scan will crash. If you use an external drive, the bandwidth is too small and the scan will take much longer or crash.*

Rotation Step: The amount to turn the specimen between images. Keep this under 0.9° always. Smaller steps lead to better reconstructed slices. 0.05° is the smallest practical setting, while 0.2-0.5° is typical. Try to keep in the range of 0.05-0.10° for very high aspect ratio specimens. This setting has the largest impact on scan time and the dataset size.

Averaging: The number of images to capture at each rotation step to average out noise. At lower voltages, 6-10 is sufficient. Pick 10-20 for high voltages or if noise is a problem in previous scans at similar settings. Noise can only be reduced later by smoothing, so it's best to get rid of it by keeping

this as high as possible while keeping the scan time reasonable.

Random Movement: The maximum **number of pixels** to randomly move the specimen up and down to avoid dead pixels in the camera (there will *always* be dead pixels, more as the camera ages). For delicate specimens, keep this at 0. For small pixel sizes, 20 is good. For large pixels, stick near 10. This has almost no impact on scan time.

360°: For *very* inhomogeneous samples, where there is almost no radial symmetry, or for specimens with a dispersion of nearly opaque inclusions, enable this. It goes all the way around instead of 180°. **Don't use this unnecessarily**, as it doubles scan time and causes artifacts in the reconstructed slices.

Start Delay: Energizes the beam for the specified time before starting the scan. This helps the aperture get to a stable temperature, and prevents movement of the spot during the scan. Good to use for long scans. 15 minutes to 1 hour are reasonable numbers. Set this in `Actions > Preferences`.

X-Ray Off: Sets whether X-Ray source should be shut off after the scan. There doesn't seem to be much reason to leave the beam on after the scan.

Open Door: Sets whether the door will open after the scan. Again, not really useful.

Reduced Area: For objects that don't use the whole width of the FOV, clipping the image will reduce the file size. Preview lines will show up in the scan window to help pick a good value. Don't clip any of the specimen.

Once the settings are set, go ahead and start 'er up. Grab yourself a nice long novel, and make yourself comfy. It's going to be a while. Make yourself some hot cocoa (but don't drink it in the MakerSpace).

Typical scan times are 2 hours for low-resolution scans up to 24 hours for very high resolution. The datasets will range from a few GB up to 100 GB for crazy settings.

3 Reconstruction

Now that the scan is over, you will find yourself significantly older and in possession of a whole bunch of projection images. To get the internal structure from these images, we use *reconstruction*, which relies on the fascinating Feldkamp algorithm. The brightness of each pixel on a horizontal line of the scan corresponds to the inverse of the total absorption of the material along the path from the source to that pixel. This data is thus the Radon transform of the density field in the plane corresponding to that horizontal line. The Feldkamp algorithm is a rapid method of approximating the inverse Radon transform of the line scans captured by the camera. The output of this process is a series of *slices*, or images that show the density field inside the specimen at discrete heights (as opposed to for discrete rotations and all heights, as in the projection images).

To perform reconstruction, open the data

[3]It may be necessary to start `InstaRecon` first.

[4]The central slice is the fastest because a number of terms related to the spread of the conical beam go to zero. If the center is not very revealing of the structure you care about, you can pick another slice to base the adjustments off of. The speed difference is minor for most datasets.

set in NRecon[3]. Click Fastest in the upper right hand, then Preview. This will reconstruct the central slice of the dataset[4]. If the specimen was wider than the FOV, select the appropriate option in the right hand menu.

First, we correct for thermal drift of the beam. Go to Actions>XY Align with Reference Scan. Use the least squares method, and use all of the reference images. Line up the box with the widest projection of the sample (to reduce computation time) and click Match then Accept. If the thermal drift was small, the corrections will be only a few pixels (or less than 1 pixel for very good data).

Next, adjust the dynamic range. Double click the plot for log scale. Set the lower bound to zero[5], and play with the upper bound to get the best contrast.

Rotate the image by right-dragging a line in the Output tab and selecting the rotation option. Crop the images by selecting Use ROI in the Output tab.

Check for beam hardening by right dragging lines in the Settings tab that pass through major sections of constant density (but begin and end outside the sample). The constant density areas should have a flat profile. If it looks like a bowl, beam hardening correction is needed. If it looks like a dome, the beam hardening correction is too severe. Pick the best value by using the fine tuning feature. Start at 20% and work from there[6].

Correct for ring artifacts using Setup>Ring Artifact Reduction. The captions next to the slider are absolute nonsense and mean nothing. Use the fine tuning menu with a start point of 10 and 5 trials with a step size of 5. Then repeat around the best setting with a step size of 1 or 0.5. The fine tuning feature allows you to compute all the options then compare using the arrows at the top of the screen (Scroll through them by holding Ctrl+Shift+↑ / ↓). Stop on the best one and hit Preview again.

If the shifting of the specimen during the scan was due to actual motion rather than thermal drift, it may be necessary to use fine tuning on the thermal drift correction. Try five trials with the calculated value as center and 0.5 step size. The ideal setting is the one that keeps circles circular and straight lines straight. (Usually no fine tuning is needed.)

To remove noise, the Smoothing tool is used. Fine tune with start point at 3 and step size of 1.

When exporting, save as BMP for quantitative analysis, 16-bit TIFF for MIMICS, and JPEG for good compression when the images are only for visualization. At this stage, the empty top and bottom slices can be excluded. Check the ROI one last time to make sure nothing is cut off.

Click Start to begin reconstruction immediately, or Add to Batch to set up more datasets and process them later. Smaller (1K) datasets may take only a few minutes to process, while larger (4K) may take an hour or so.

4 2D Visualization

2D visualization is done using DataViewer. Open the reconstructed images, then load for 3D[7] visualization. Tilt and cropping are done using Ctrl+Dragging and Ctrl+Shift+V. Annotations are added using Options > Preferences:

[5]Zero is not the left of the log scale image. Click the button under the plot and type 0 in the box.

[6]The fine tuning menu isn't strictly necessary here, you can play around manually and get a good result.

[7]This is a misnomer. It just shows three orthogonal slices at chosen locations, not true 3D.

Annotation. For full resolution output, set the downscaling to 1. Otherwise the pixels will be averaged to downsample the image. Note that exporting the screen images (with the three slices) is done at screen resolution. Each slice has to be saved separately and then combined manually in an image editor to get full resolution.

When saving images from DataViewer, a dialog will appear with a convoluted diatribe and Yes, No, and Cancel buttons. **If you press Yes, every slice in the dataset is saved**. Press No to save only the current view.

5 3D Visualization

3D visualization is done in CTVox. Load the reconstructed slices to begin. The gamma transfer function is used to adjust transparency to get rid of the cloud of noise surrounding the specimen and inside its pores. An S-shape is a good starting point. Movies can be made using the Flight Recorder. Motions can be made manually, or more smoothly using Actions > Movement > Numeric. Export videos using Microsoft Video 1 at 100% compression quality.

6 Quantitative Analysis

To be added in future editions. In the meantime, consult the included manuals or someone trained already.

7 Advanced Options

7.1 Wide Area Scan

In the wide scan mode, the camera is moved left and right from its normal position to capture more of the projection of the beam. This mode is enabled by pressing Ctrl+W. Settings are available in Options > Preferences > Rescale Horizontal. FFC must be performed over the whole area by deselecting the Central camera position only option in the FFC menu. Camera offset is specified in the Scan menu.

7.2 Tall Item / Batch Scan

To scan at multiple heights, either for a very tall object or for separate specimens stacked in a transparent medium, go to Action>Set Oversize Scan. Do a scout scan to see the whole specimen height[8]. Name the first scan and select the top and bottom of the region (limited by the height of the camera). If the subsequent scans overlap, they will be stitched into one dataset. If they do not, give them separate names and they will be separate datasets. This is done after all other adjustments are done (just before starting the scan in the regular procedure).

7.3 Big & Tall Scan

It is possible to do a scan with multiple levels and camera offset (that is, to do a combined tall- and wide-scan). Unfortunately, it is not possible[9] to preview the entire scan. Using Ctrl+W will generate the wide pre-

[8] On occasion, the scout scan will simply do the bottom area and declare the job done. The solution appears to be to restart both the scanner and the computer. If you encounter this, you can save the FFC upon exiting SkyScan and reload it when you reboot to save some time.

[9] Confirmed with the service company

view at a given height, but there is no way to generate such preview in the Oversize Scan menu. To do this type of scan, first do the FFC as described in §7.1. Then do the scout scan as in §7.2. When the Scan menu appears after hitting Start from the Oversize Scan menu, enable Camera Offset. The stitching is automatic for both processes, and the full size scan will appear in NRecon.

7.4 Custom Filters

The September 2013 Tip of the Month provides suggestions and dimensions for custom filters. Custom filters are inserted in the holder and placed in front of the camera. They cannot be used with the automatic changer.

8 Micro-Positioning Stage

Using the MPS is fairly easy. It must be inserted carefully so as to not bend the pins. First remove the rotary nut. Carefully lower it straight down on the connector. The unit is properly aligned when the green light comes on. Tighten the captive screws *finger tight*. The control software is located on the desktop. Center the MPS using the homing button before trying to make any position adjustments so you do not reach the edges of its travel before the specimen is centered. Rotate to zero degrees and move left/right until the specimen appears centered. Then rotate to 90° and do the same. Spin around a little to check.

9 Material Testing Stage

Operating this thing is an ordeal. It takes at least two sets of hands and three brains[10]. You will need to call for help. First consult your doctor to be sure that you are mentally strong enough to survive this trial of your patience. Ask yourself one more time, do you really want to do this? Then consult someone familiar with the system, such as the benevolent and gracious author of this guide. *Do not use the MTS without proper guidance, as it is both fiddly and delicate.*

As a preliminary, make sure that your specimen is appropriate given the load and displacement limits of the system. The maximum load is 444 N (100 lb), and the maximum displacement is about 5.5 mm. Note that the displacement stage and load cell are located in the bottom of the device. Therefore the start point for compression is the bottom of travel, and for tension the top of travel.

- Install the desired clamp. The large outer ring clamps the bottom piece in, and can be manipulated with the large ring wrench. The top is fixed with the nut and integrated nut in the top cap.

- Install the MTS in the CT by removing the rotary nut, aligning the pins on the MTS with those on the CT, and lowering gently. The MTS should sit level and should not need to be forced to go down. The screws can be left loose for right now.

- Open the MTS software and jog the displacement stage to the desired start point for the experiment.

[10]The author of this manual counts as two and a half brains.

- Close the MTS software and remove the MTS from the CT.
- Install the specimen in the MTS. *Do not apply a pre-load to the sample*[11]. *The load cell has to be re-zeroed every time you remove the MTS from the CT. Do not install the sample with the MTS inside the CT, or you may damage it.*
- Reinstall the MTS. Very gently tighten the two hex screws located in the two holes around the plexiglass tube. *Do not touch the two regular screws.*
- Choose the position and energy settings for the scan as usual in SkyScan. To perform the FFC, the MTS must be removed. Close the MTS software before removing the device from the scanner, and open it again after it's reinstalled. Reinstall the MTS after FFC is complete.
- Set up the scan parameters in SkyScan using `Options > Acquisition` rather than the scan button. This sets the settings without starting the scan (only needed for batch scans — for a single scan, after the MTS loading is set a scan can be started as normal). **Set Random Movement to zero when using MTS.**
- Open the MTS software. Zero the load cell. Use the schedule menu to set a batch scan, or use the main window controls to set the loading for a single scan. Both methods will record the load-displacement data. For batch scans, the process is started within the MTS software.
- Be sure to save the load-displacement data from the software before closing. Save the data, not the plot.

10 Maintenance

When the misalignment correction values in `NRecon` get to be large, or every month, the system must be realigned.

- Insert the alignment pin.
- Set 2K mode, no filter, and FFC off.
- ∗Zoom out as far as possible.
- Go to `Options > Alignment` and perform an align scan.
- Go to 2μm pixel size.
- Go to `Options > Alignment` and perform an align scan.
- Return to the starred step until both alignments return `Align OK`. This may take many repetitions.

The chamber interior can be cleaned with a Swiffer or other lint-free cloth. Double-sided tape can also be used to remove debris.

The vibration damping feet should be kept inflated to 35–40 psi. If a foot sinks, reinflate with a bike pump to the correct pressure.

Keep enough free space on the hard drive or your scans will crash and you will be very unhappy (with your scan in particular and with your life in general). Once reconstruction is complete, the projection images can be deleted or transferred to a backup drive. Rotating the VOI in DataViewer also

[11] A very slight preload on compression samples can be used to hold it in place while handling the device. If doing this, make sure to raise the stage slightly above its bottom point so it can be lowered to get zero load while *in situ*.

creates a new image set, so the old ones can be safely discarded (as long as the rotated set wasn't downsampled).

11 Loose Ends

- The life of the source is 4-6 years, depending on use.
- If the scanner has to be moved, remove the cables first.
- The smallest pixel size possible is $0.5\mu m$.
- Don't use a vacuum or compressed air to clean inside.
- Updates are free from the Bruker website. Back up the software first.

12 Acronyms

FFC Flat Field Correction
FOV Field of View
MPS Micro-Positioning Stage
MTS Material Testing Stage
ROI Region of Interest
VOI Volume of Interest

Disclaimer

Version History

- Versions < 1: Draft versions. Not for use.
- Version 1.0: First full release. Incorporates mistakes found during training sessions.
- Version 1.1: Corrects minor (grammatical) mistakes. Adds draft MTS instructions.
- Version 1.2: Corrects grammatical mistakes and removes the "draft" notice from the MTS instructions.
- Version 1.3: Clarifies wide+tall scans procedure.