Synchrotron X-ray computed microtomography: procedures for image reconstruction and analysis

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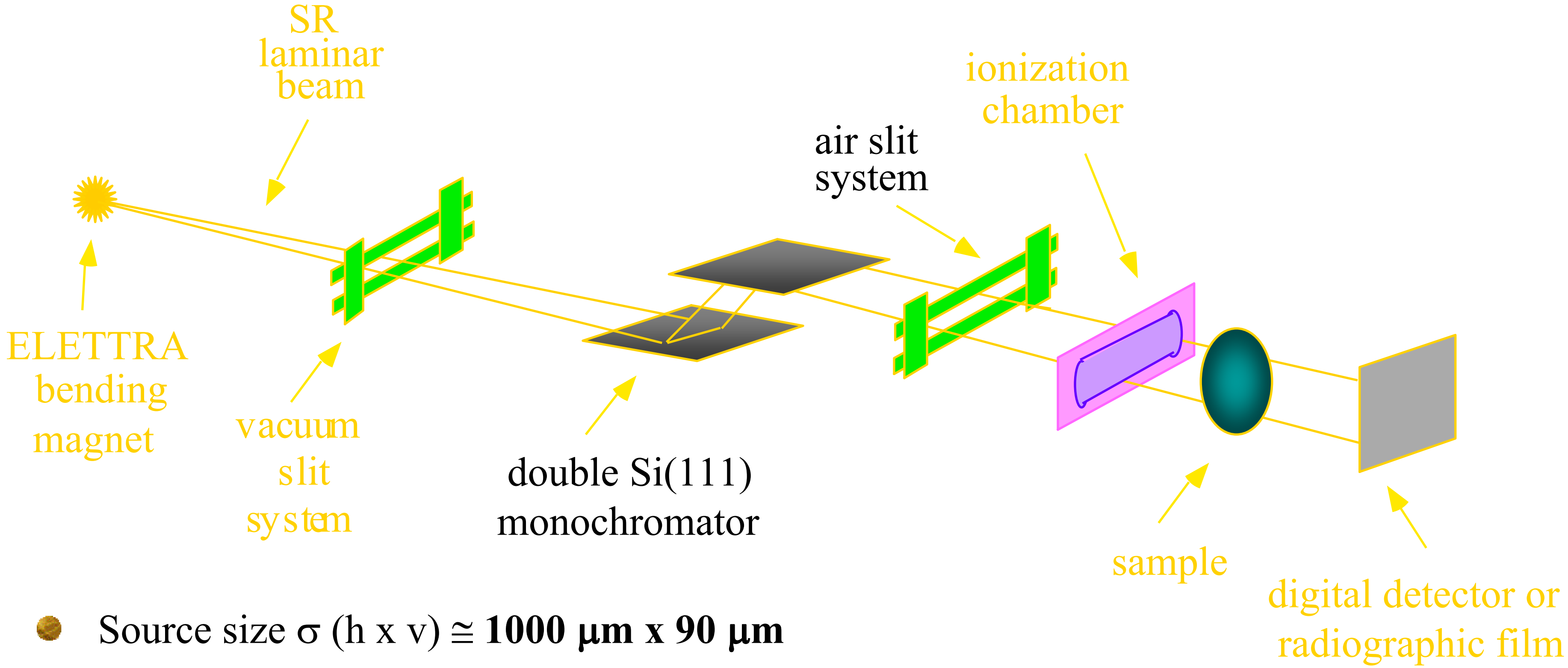
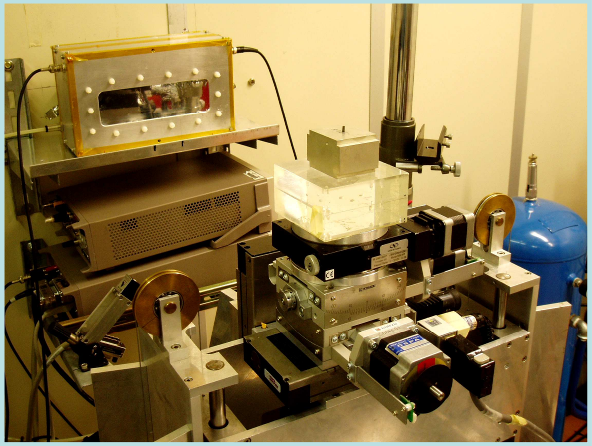
The SYRMEP beamline



- Source size σ (h x v) ≅ **1000 µm x 90 µm**
- Source-to-sample distance: **D ≅ 24 m**
- Beam size at sample (h x v) ≅ **150 mm x 6 mm**
- Energy range: **8.3 ÷ 35 keV**, Bandwidth **$\Delta\lambda/\lambda \cong 2\mathrm{x}10^{-3}$**
- Typical fluxes at 15 keV ≅ 2 * 10^8 phot./mm^2 s (@ 2 GeV, 300 mA)
  7 * 10^8 phot./mm^2 s (@ 2.4 GeV, 180 mA)

The experimantal hutch at SYRMEP



X-ray imaging at a 3rd generation SR facility

- high energy photons and high flux
  → **heavy** and/or **bulky samples** in transmission geometry
  → **tunability** in a large energy range
  → **short** exposure times

- small angular source size and big source-to-sample distance
  → **high spatial resolution** (<≈ 1 μm at SYRMEP)
  → possibility of **big sample-to-detector distances** (<≈ 1 m at SYRMEP)
  → **high** spatial **coherence** of the X-ray beam ($L_c \cong$ **10 μm @ 15 keV**)

Phase-sensitive techniques

SR X-ray imaging studies

Medical imaging:

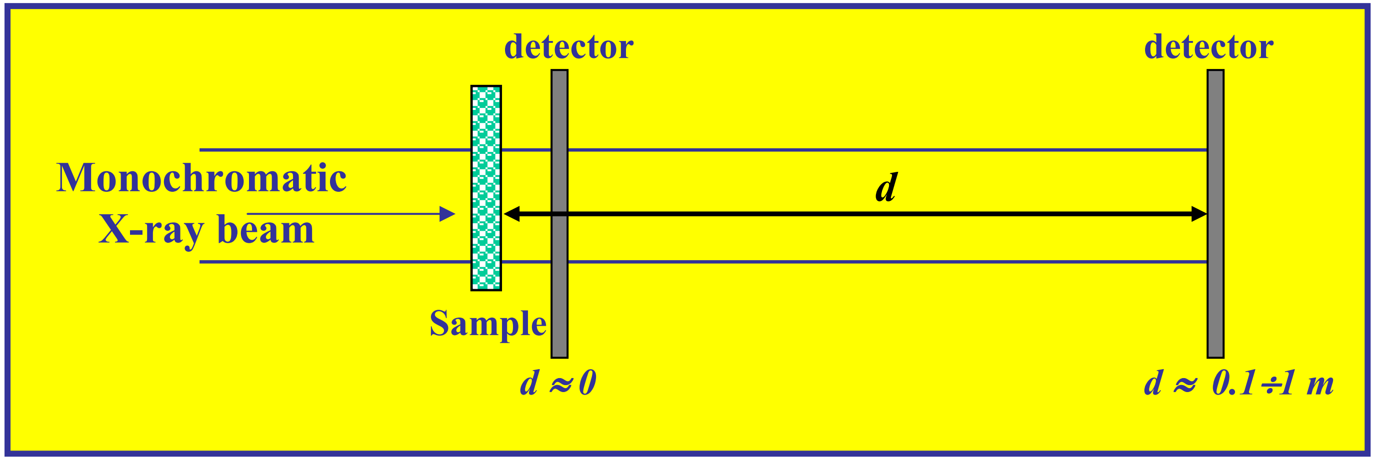
- → bones, dental implants
- → mammography
- → tissues ….

Material science imaging:

- → crystals
- → rocks and minerals
- → food science
- → archeological samples
- → engineering science ….

The X-ray imaging techniques

Absorption and Phase Contrast (PC) Radiography



$(\Delta I/I)_{abs} = e^{c\,\Delta\mu} - 1$

$\Delta\phi = 2\pi\, c\, \Delta\delta / \lambda$

$\mathbf{n} = 1 - \delta - i\beta$: refraction index

$\mu = 4\pi\, \beta / \lambda$: linear absorption coeff.

c : object size // to beam direction

$r \ll a \Rightarrow$ *edge detection regime*

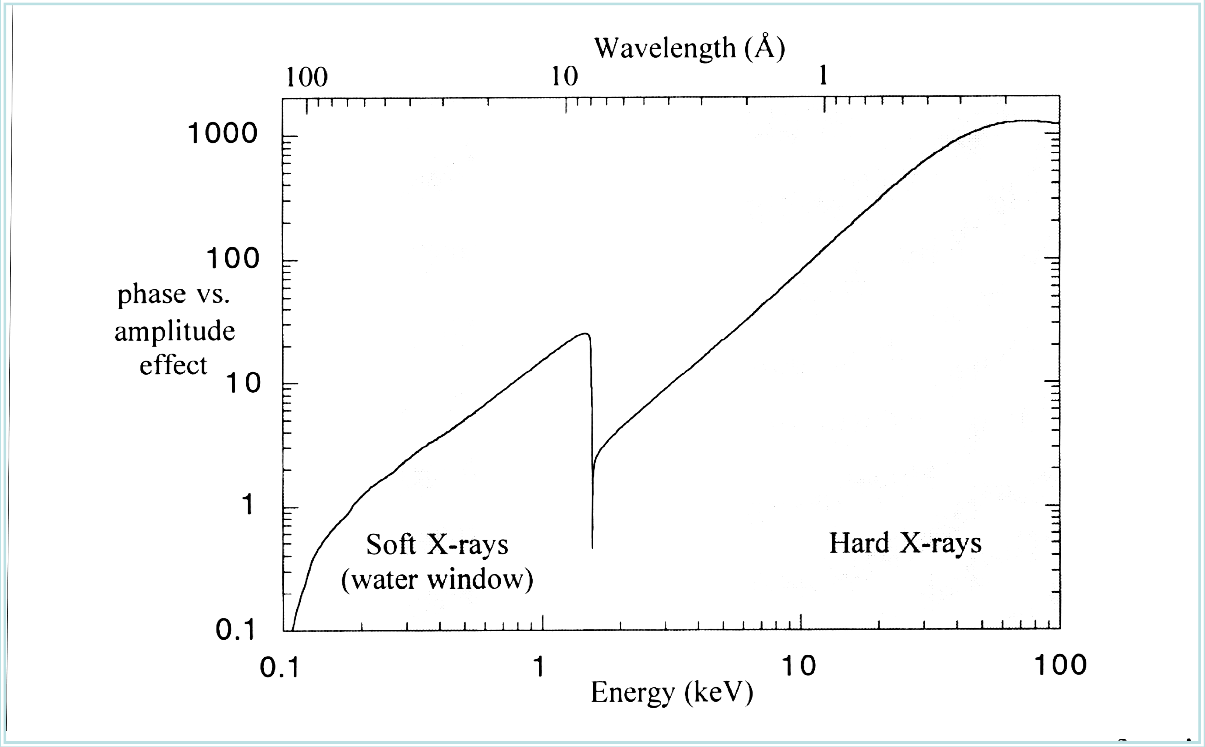
$r \cong a \Rightarrow$ *holographic regime*

$r \gg a \Rightarrow$ *Fraunhofer diffraction*

a : object size ⊥ to beam direction

$r = (\lambda\, d)^{1/2}$: first Fresnel zone radius

Absorption vs. Phase Contrast



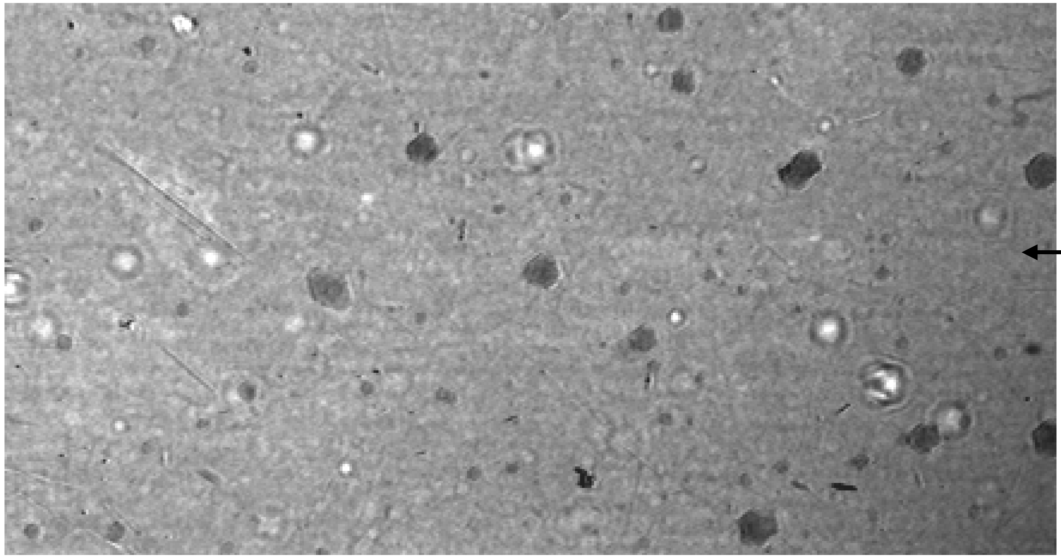
- Analysis of **materials**

  → with **weak absorption** with respect to **hard X-rays**

  → producing **significant variations** of X-rays **optical path**

Radiographs of an AlPdMn grain recorded at the ESRF (France)

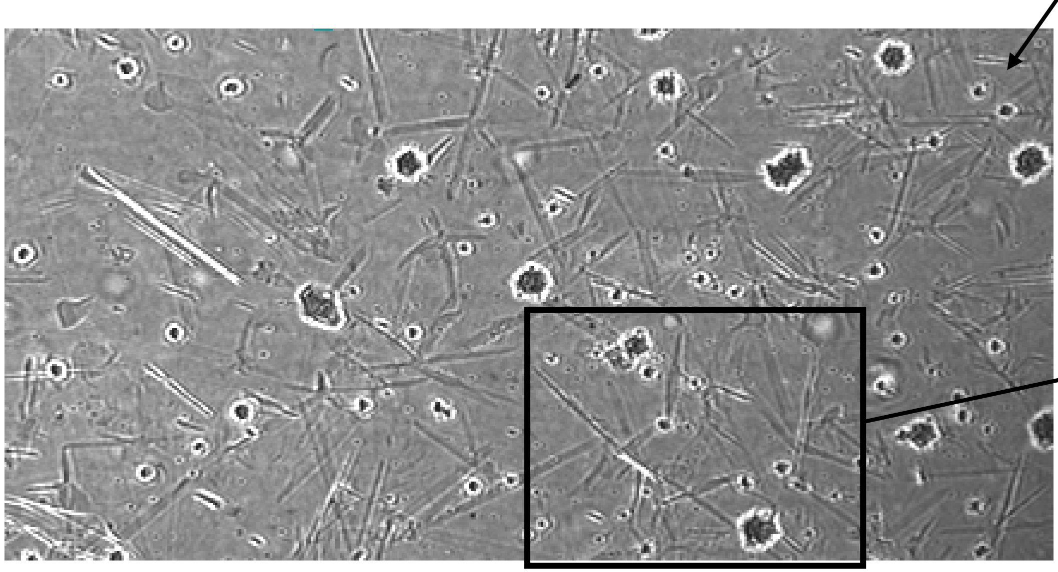
L. Mancini, PhD Thesis, 1998



d = 2 cm

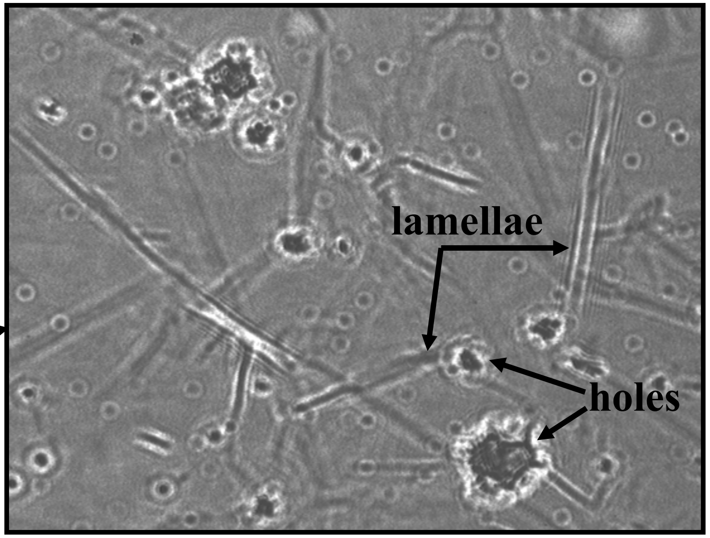
Absorption radiograph

Phase radiograph



400 µm

d = 50 cm



200 µm

Vertical source size σ estimation from PCR of a nylon wire

Sample: Nylon wire (120 μm Ø)

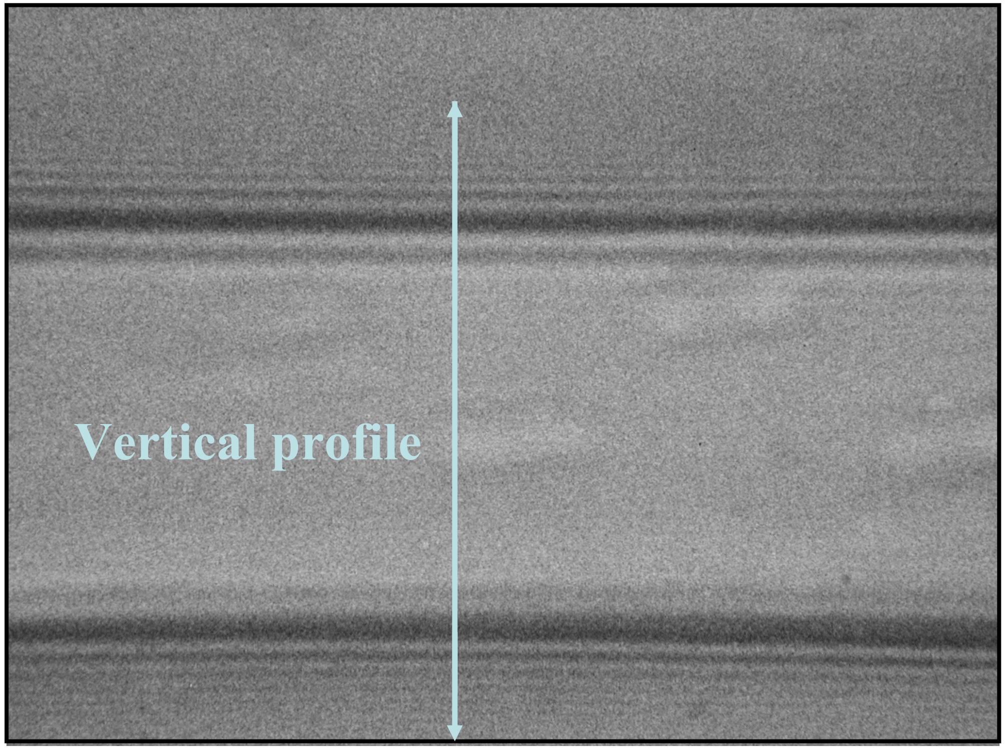
E = 10 keV

Refraction index: $\delta = 2.55\text{x}10^{-6}$, $\beta = 2.72\text{x}10^{-9}$

d = 1 m

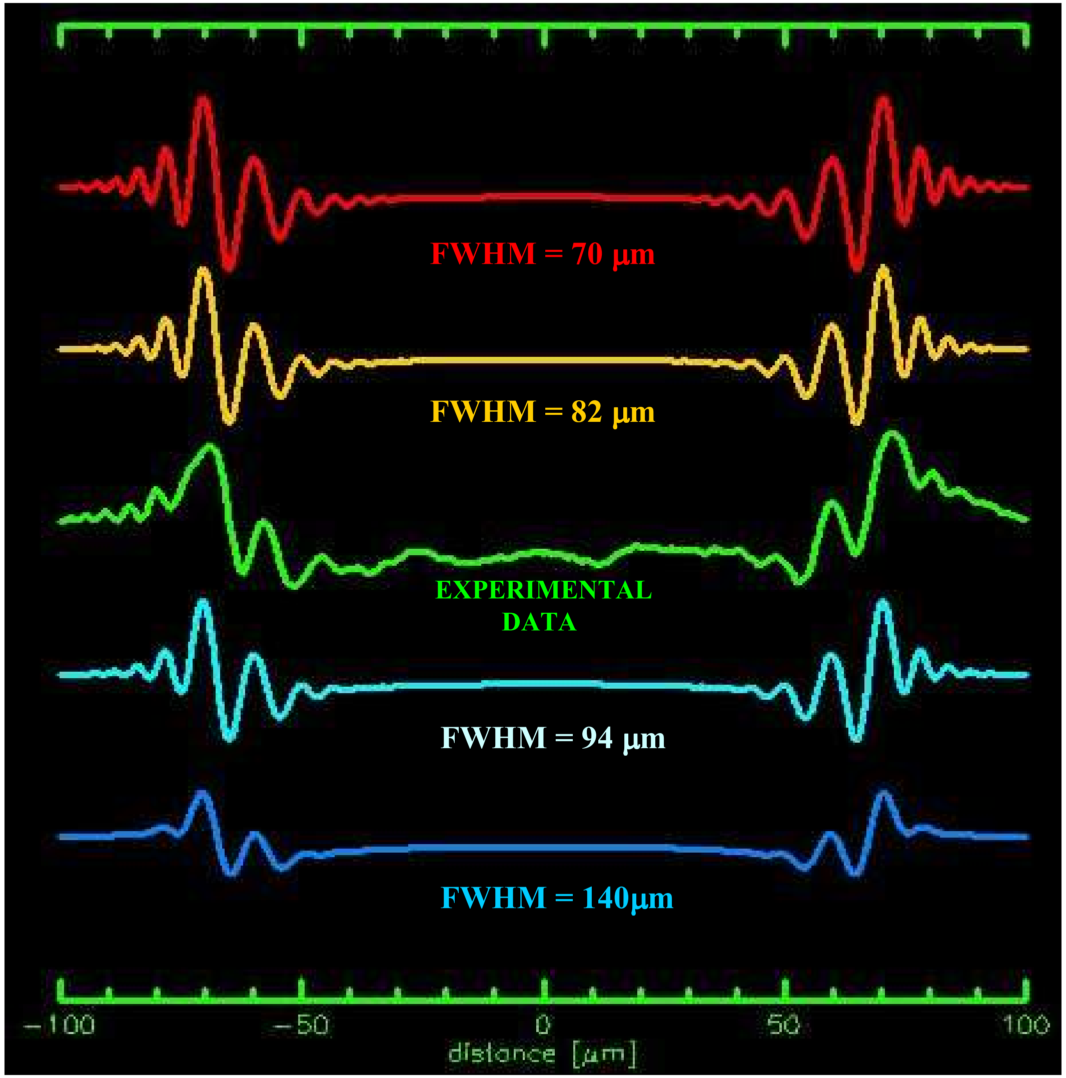
D = 24 m

Detector: 1 μm resolution film



L. Mancini, F. Montanari, G. Tromba

Experimental and simulated profiles for different σ values



Nylon wire (120 µm Ø)
E = 10 keV
d = 1 m

↓

σ < ≅ 90-100 µm

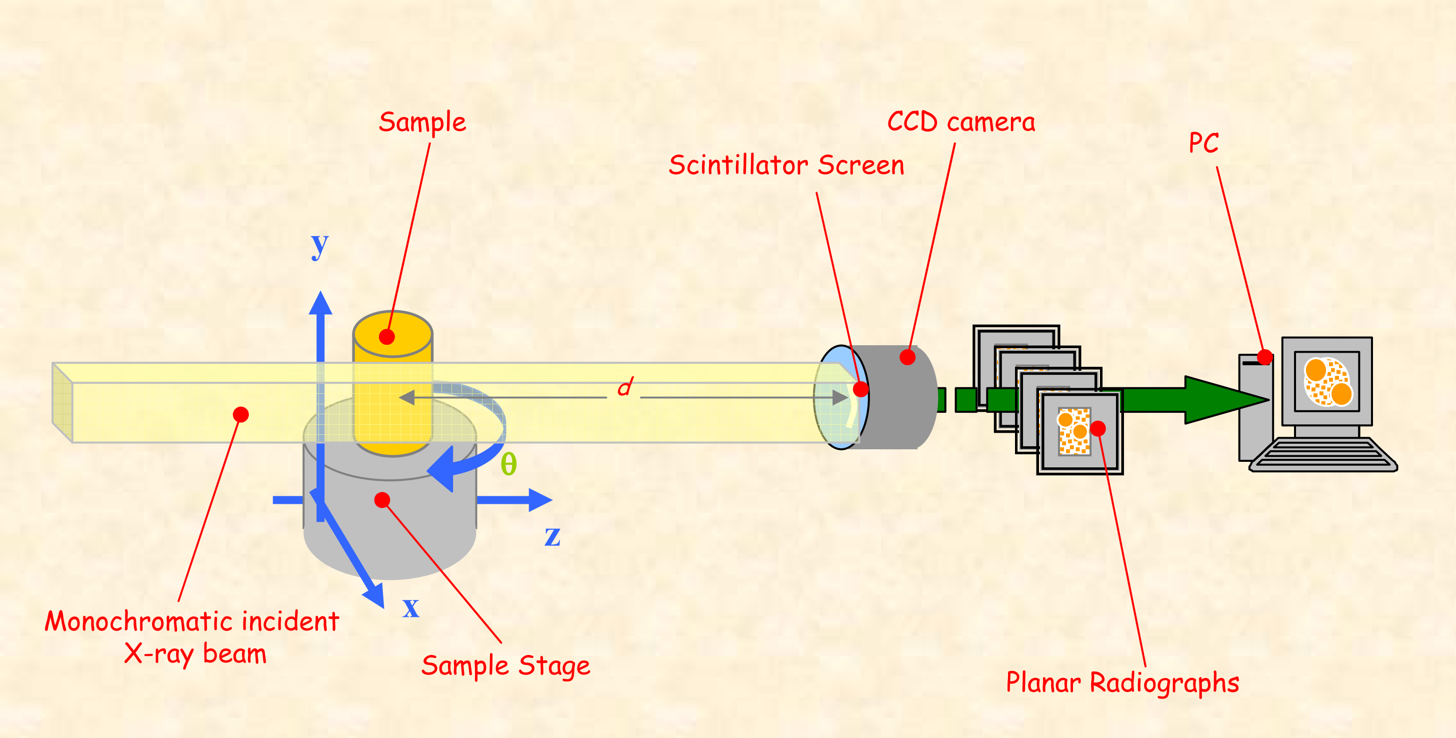
Results

- **Spatial resolution** $\rho = \sigma d / D < \cong 1\ \mu\text{m}$ **up to** $d = 0.3$ **m**
  $\cong 4\ \mu\text{m}$ **at** $d = 1$ **m**

- Possibility to work at **big sample-to-detector distances:** $D > \approx 1$ **m**

- **High transverse coherence of the beam:** $L_c = \lambda D / (2\ \sigma) \cong 10\ \mu\text{m}$

The principle of computed microtomography



CCD camera: 2048x2048 pixels^2, pixel size: 14 µm, FOV: 28x28 mm^2

- **Precious** for investigation of **internal features without** sample **sectioning**:
  - → in many cases the **sectioning procedure** modifies the structures under analysis
  - → the sample can be after **studied by other** experimental **techniques**,
  - → or submitted to several **treatments** (mechanical, thermal, etc...)

SR X-ray imaging

***In-situ* and *ex-situ* experiments in a large range of materials:**

→ growth processes
→ mechanical and thermal treatments
→ phase transitions ….

The aim

to investigate the relationship between microstructural

and physical properties

CCD Detector & Optics

- Photonic science
  - 2048 x 2048 pixel
  - each pixel 14 x 14 μm^2

- 1:1 Optics
  - 20 (40) μm thick IS
  - effective pixel size: 14 μm
  - PSF ~ 30 (50) μm

- 11:40 (Magnifying) Optics
  - ~ 5 μm thick IS
  - effective pixel size: 3.85 μm
  - PSF ~ 13 μm

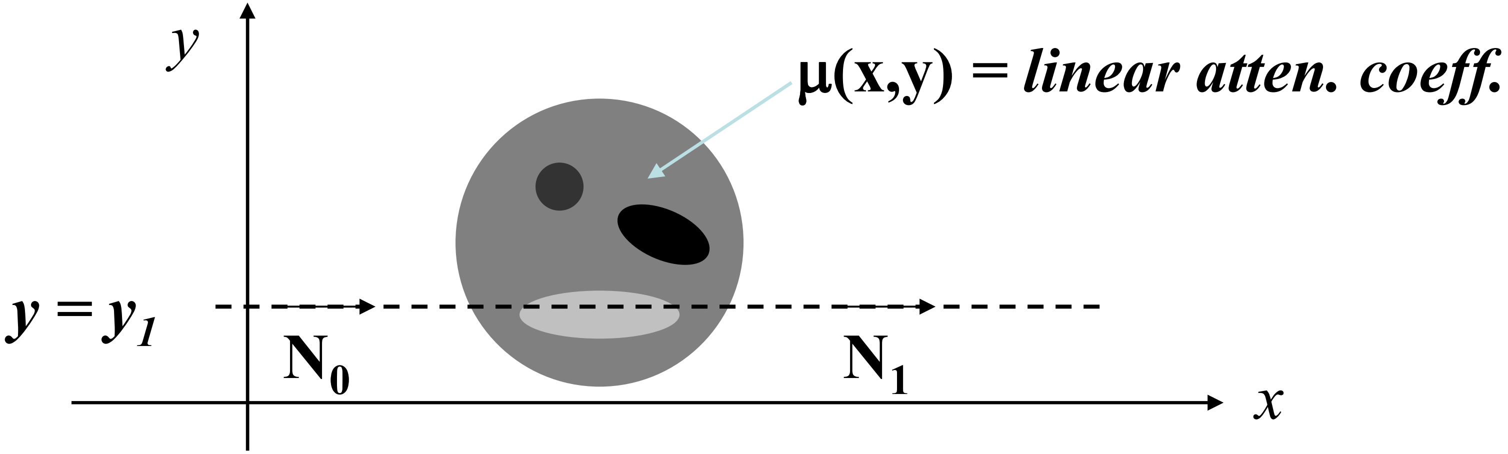
New VHR detector

- Water cooled **12/16 bit** camera
  - **4008 x 2672** pixels^2
  - each pixel 9 x 9 μm^2

- 1:2 (Magnifying) **optics**
  - ~ 9 μm thick GdOS scintillator
  - effective pixel size: 4.5 μm
  - PSF ~ 13 μm
  - 1.8 full frames/sec at bin = 1x1

Principles of transmission X-ray μ-CT

Kak A.C., Slaney M., IEEE Press, 1987



μ(x,y) = *linear atten. coeff.*

$N_1 = N_0 \exp[- \int_{path} \mu(x,y_1)\, dx]$ (***Beer-Lambert law***)

$\ln (N_0 / N_1) = \int_{path} \mu(x,y_1)\, dx = P_\theta(t)$ ((**θ,t**) polar coordin.)

Repeating such a measurement along a sufficient number of straight lines within the same slice delivers the **Radon transform** of the object. The inverse of the Radon transform **allows to reconstruct** the μ(x,y) map of the slice.

The Fourier Slice Theorem

Kak A.C., Slaney M., IEEE Press, 1987

A **line integral $P_\theta(t)$** represents the integral of the $\mu(x,y)$ of the object along a line. $P_\theta(t)$ is known as the **Radon transform** of the function $\mu(x,y)$.

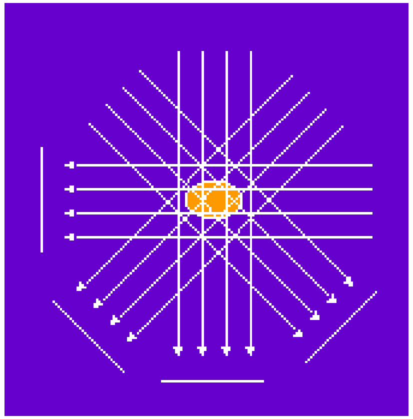
A **projection** is formed by combining a set of line integrals. The simplest projection is a collection of parallel ray integrals **at a given angle** (θ).

The **Fourier Slice Theorem** demonstrates that the 1D Fourier transform of a parallel projection of an image $\mu(x,y)$, taken at an angle θ, gives a slice of the 2D transform of the object function.

Then, **given the projection data**, it should be possible **to estimate the object by** simply **performing a 2D inverse Fourier transform**.

Elaboration of tomographic images

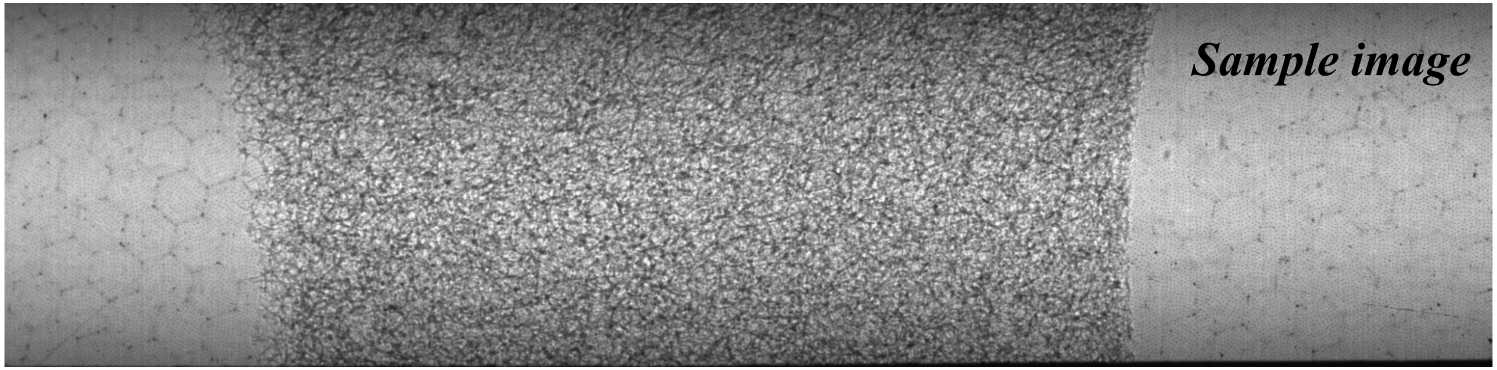
- Planar radiographs are elaborated by a **reconstruction procedure:**
  → **filtered backprojection** algorithm *[Herman, 1980]*
  → for each projection an **intensity map** is recorded in the xy detector plane
  → projections are submitted to **filtering procedures**
  → each intensity map is **back projected** along the normal to the projection itself
  → finally, the intensities are added for all the projections

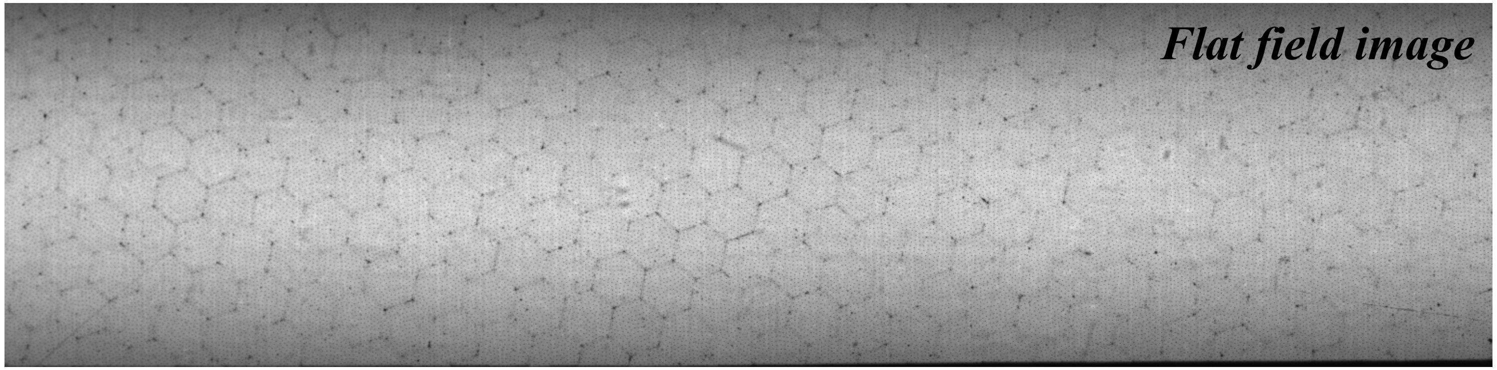


- Reconstructed slices are then treated by a **rendering procedure:**
  → 2D slices visualized as **Stack**
  → 3D views of the sample can be obtained (**Volume rendering**)

- Rendered images can be elaborated applying filters, false colors, **segmentation tools** to extract quantitative information.

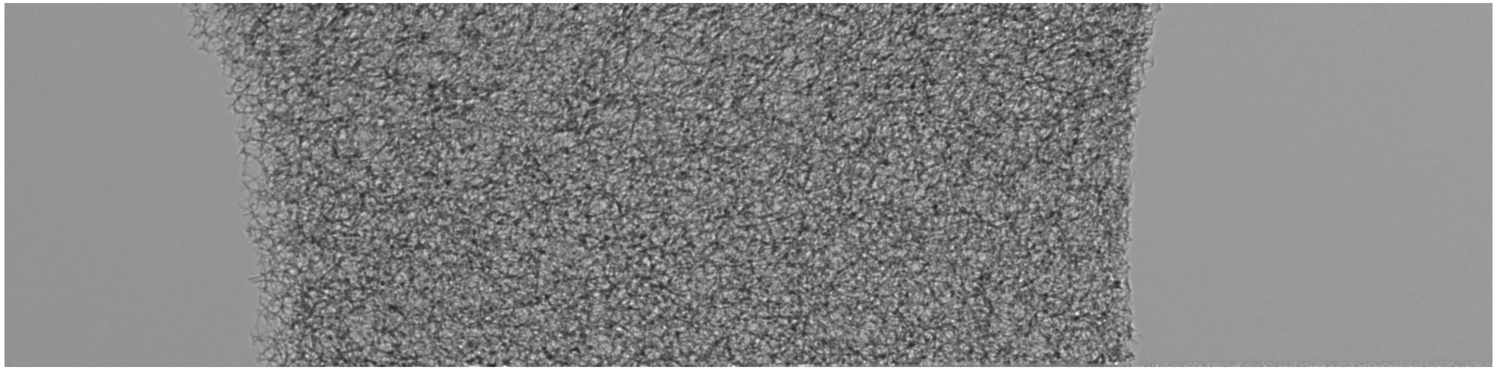
Recording of tomographic images


Sample image


Flat field image

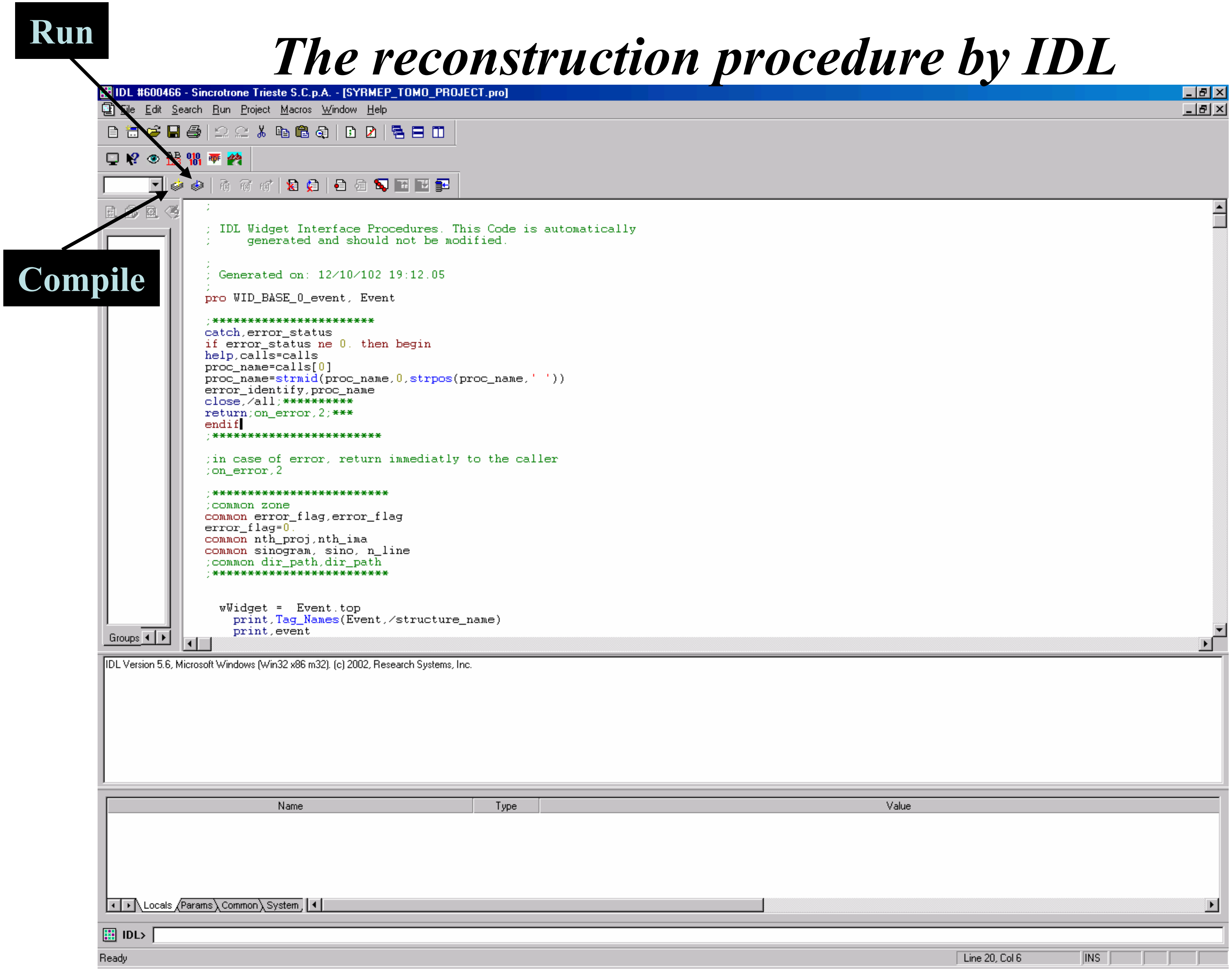

Dark field image

Flat procedure for the tomographic images



$$I_{flatted} = (I_{sample} - I_{dark})/(I_{flat} - I_{dark})$$

The reconstruction procedure by IDL



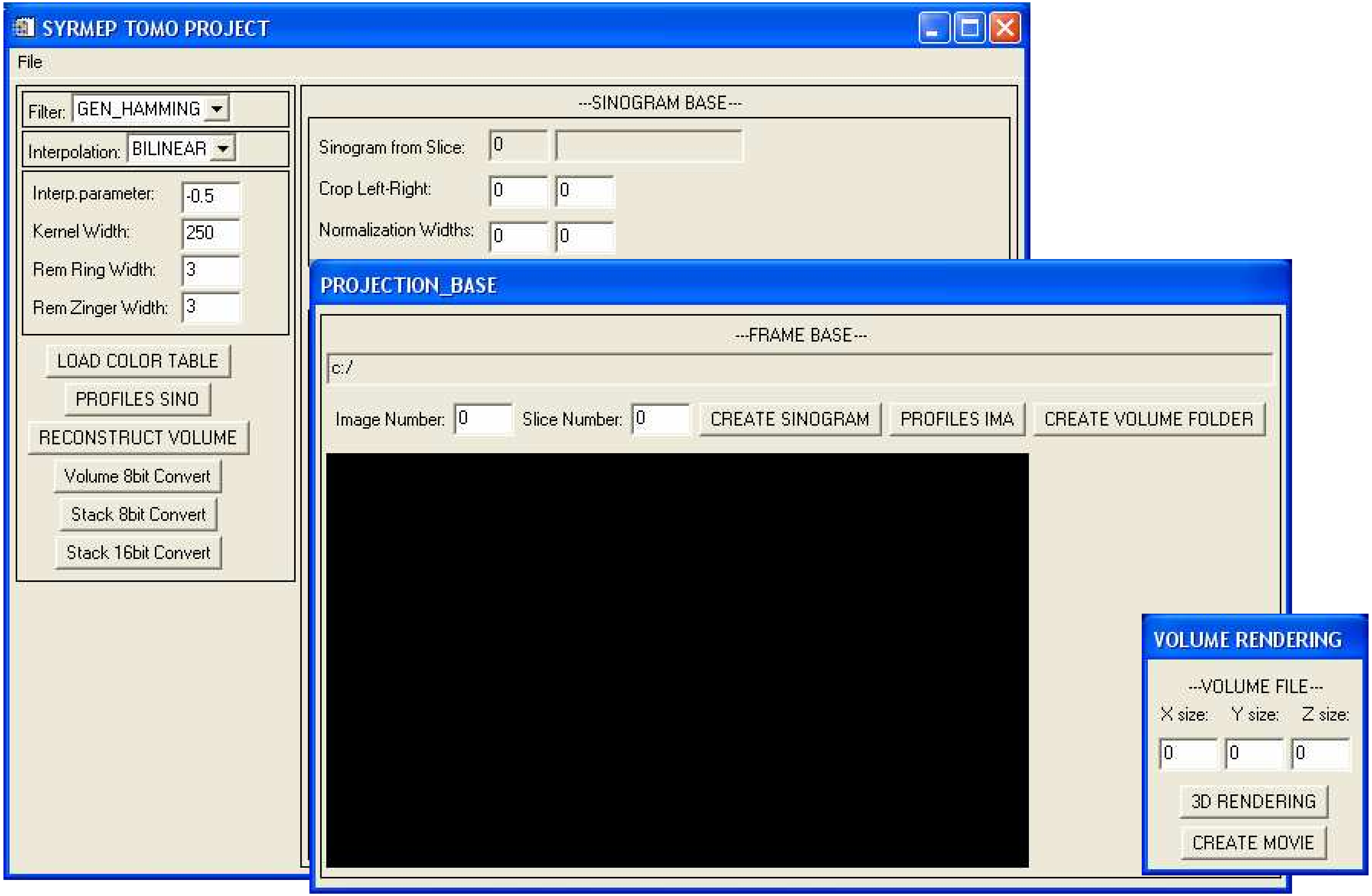
Run

Compile

```
;
; IDL Widget Interface Procedures. This Code is automatically
;     generated and should not be modified.

;
; Generated on: 12/10/102 19:12.05
;
pro WID_BASE_0_event, Event

;************************
catch,error_status
if error_status ne 0. then begin
help,calls=calls
proc_name=calls[0]
proc_name=strmid(proc_name,0,strpos(proc_name,' '))
error_identify,proc_name
close,/all;**********
return;on_error,2;***
endif
;*************************

;in case of error, return immediatly to the caller
;on_error,2

;**************************
;common zone
common error_flag,error_flag
error_flag=0.
common nth_proj,nth_ima
common sinogram, sino, n_line
;common dir_path,dir_path
;**************************


  wWidget =  Event.top
    print,Tag_Names(Event,/structure_name)
    print,event
```

```
IDL Version 5.6, Microsoft Windows (Win32 x86 m32). (c) 2002, Research Systems, Inc.
```

Starting of the reconstruction procedure



Filter: GEN_HAMMING

Interpolation: BILINEAR

Interp.parameter: -0.5

Kernel Width: 250

Rem Ring Width: 3

Rem Zinger Width: 3

Sinogram from Slice: 0

Crop Left-Right: 0 0

Normalization Widths: 0 0

c:/

Image Number: 0 Slice Number: 0

X size: 0 Y size: 0 Z size: 0

Choice of the slice to reconstruct

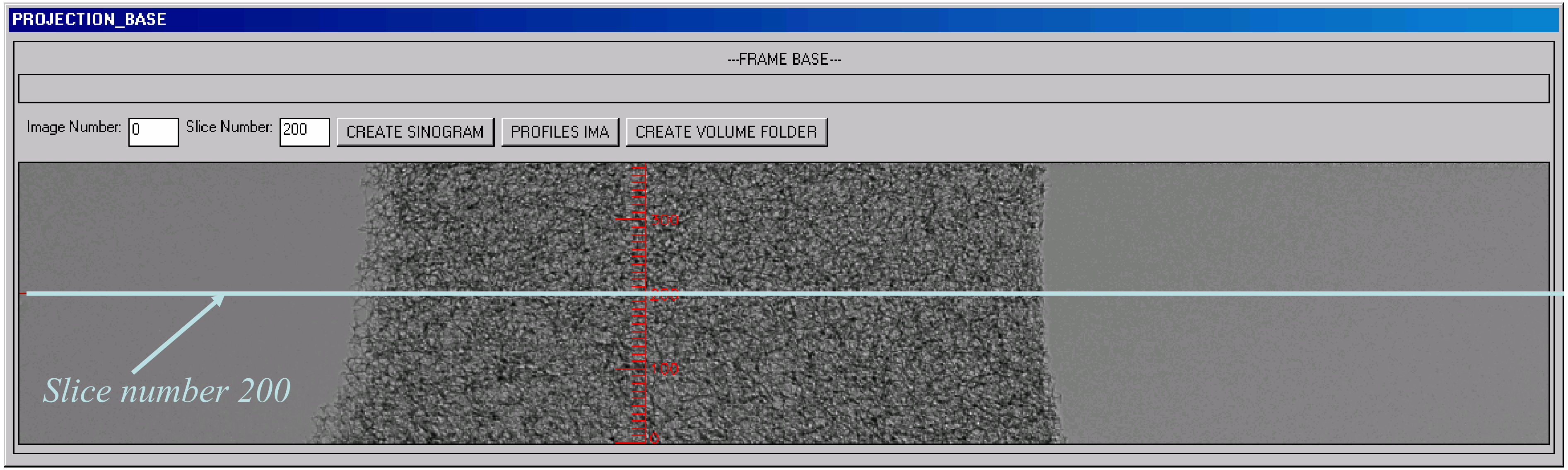
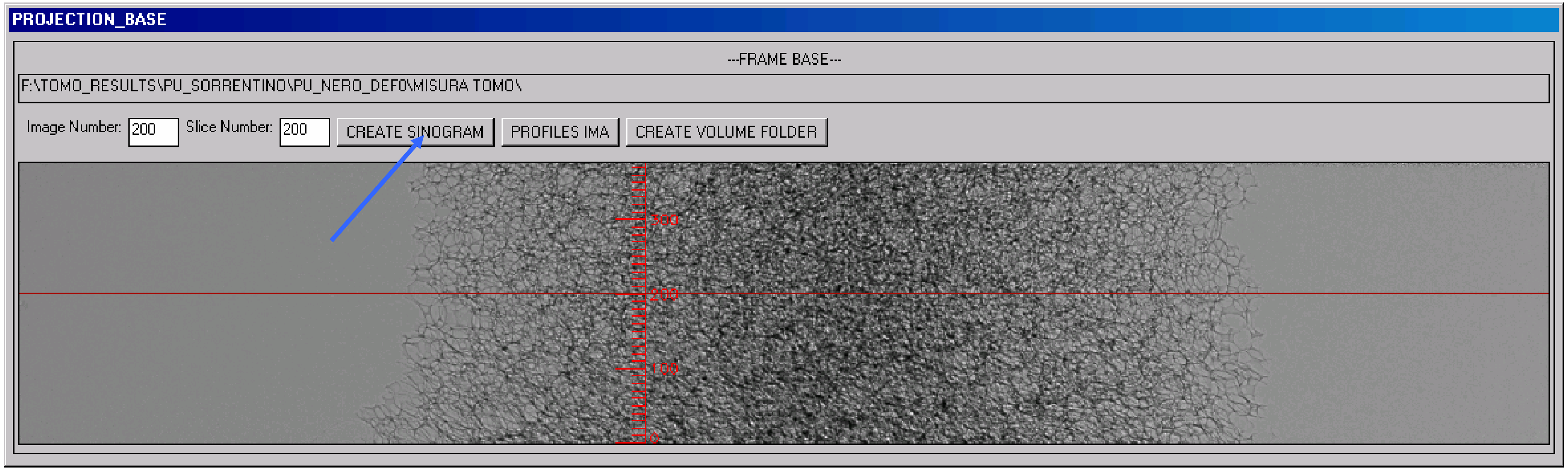


Image Number: 0
Slice Number: 200

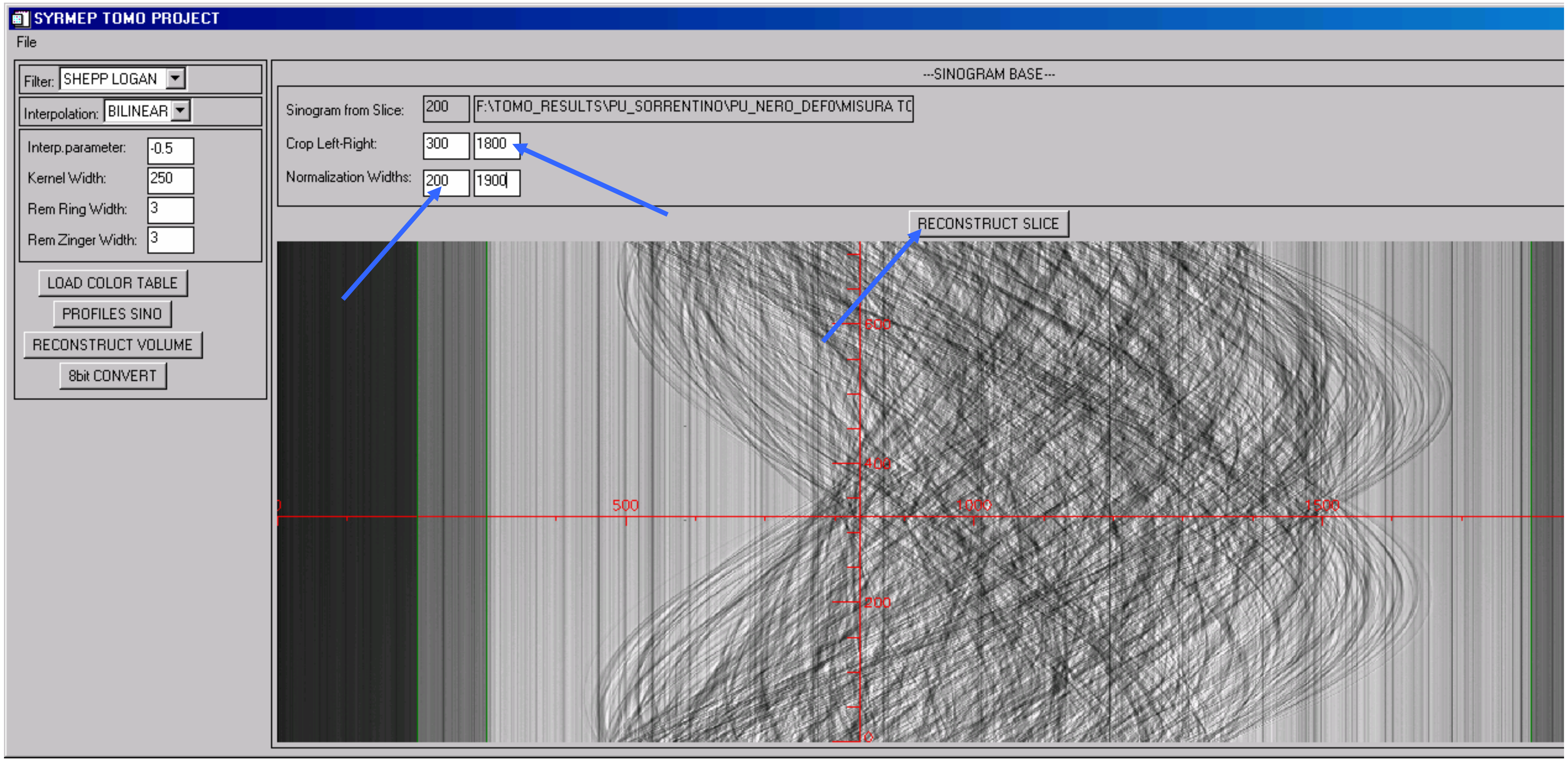
Slice number 200



F:\TOMO_RESULTS\PU_SORRENTINO\PU_NERO_DEFO\MISURA TOMO\

Image Number: 200
Slice Number: 200

Creation of the sinogram



SYRMEP TOMO PROJECT

Filter: SHEPP LOGAN

Interpolation: BILINEAR

Interp.parameter: -0.5

Kernel Width: 250

Rem Ring Width: 3

Rem Zinger Width: 3

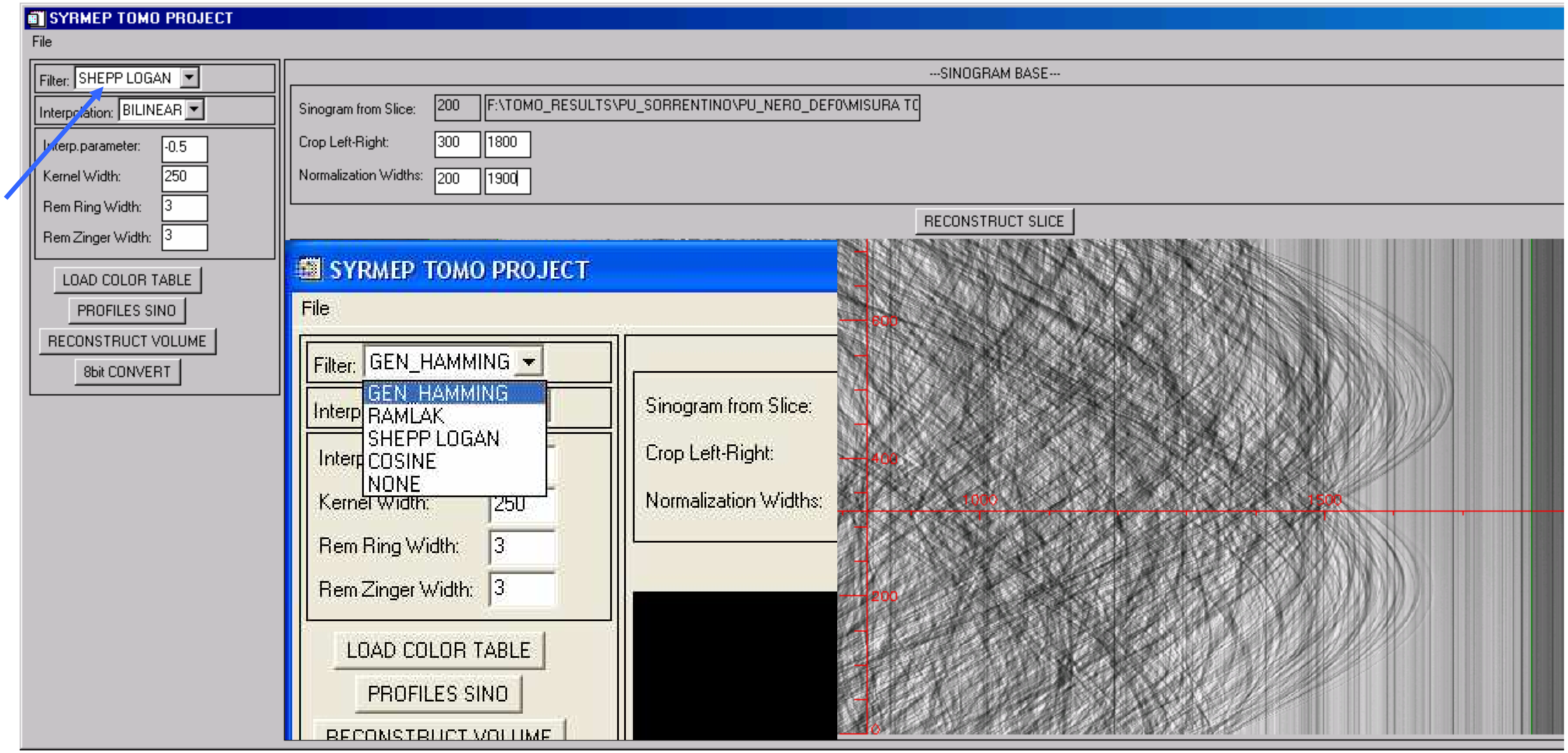
---SINOGRAM BASE---

Sinogram from Slice: 200 F:\TOMO_RESULTS\PU_SORRENTINO\PU_NERO_DEF0\MISURA TO

Crop Left-Right: 300 1800

Normalization Widths: 200 1900

Filtering procedure



SYRMEP TOMO PROJECT

File

Filter: SHEPP LOGAN

Interpolation: BILINEAR

Interp.parameter: -0.5

Kernel Width: 250

Rem Ring Width: 3

Rem Zinger Width: 3

---SINOGRAM BASE---

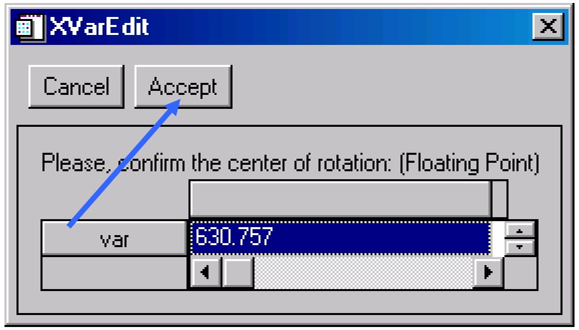
Sinogram from Slice: 200 F:\TOMO_RESULTS\PU_SORRENTINO\PU_NERO_DEFO\MISURA TO

Crop Left-Right: 300 1800

Normalization Widths: 200 1900

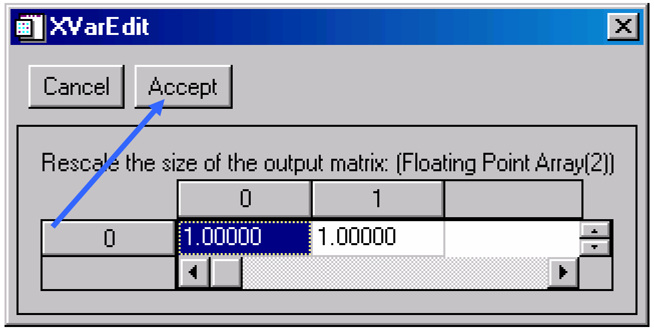
If in the reconstruction the backprojection is done without filtering the sinogram first, the resulting image is very blurry. In practice **one always filters the sinogram before the backprojection**. In this example the sinogram will be filtered using a **Shepp-Logan filter**, which is an edge-sharpening filter.

Choice of the reconstruction parameters



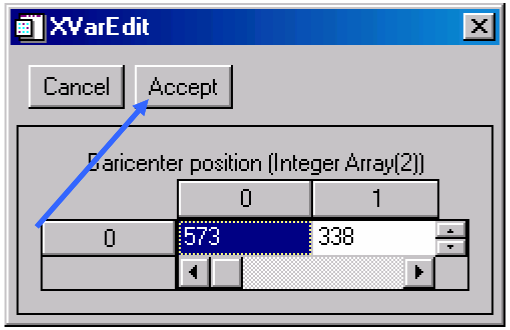
Please, confirm the center of rotation: (Floating Point)

var	630.757



Rescale the size of the output matrix: (Floating Point Array(2))

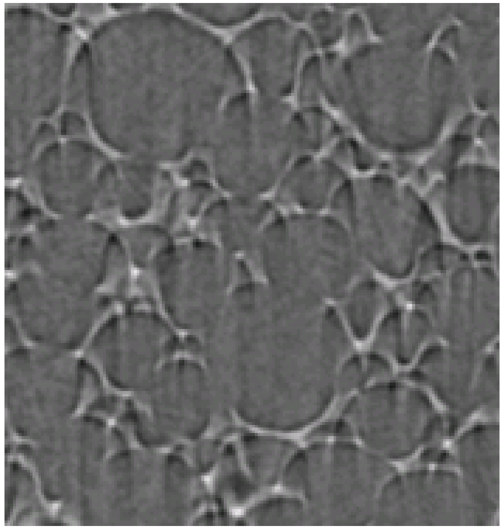
	0	1
0	1.00000	1.00000



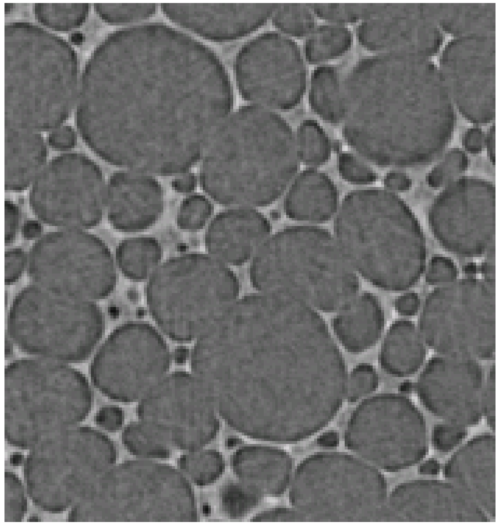
Baricenter position (Integer Array(2))

	0	1
0	573	338

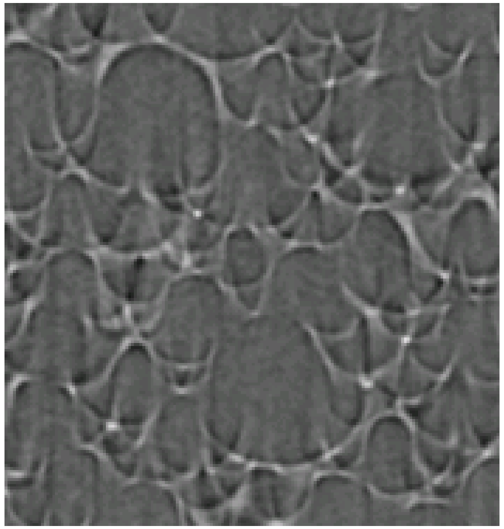
Slice reconstruction: optimization of the rotation center



C = 624.750



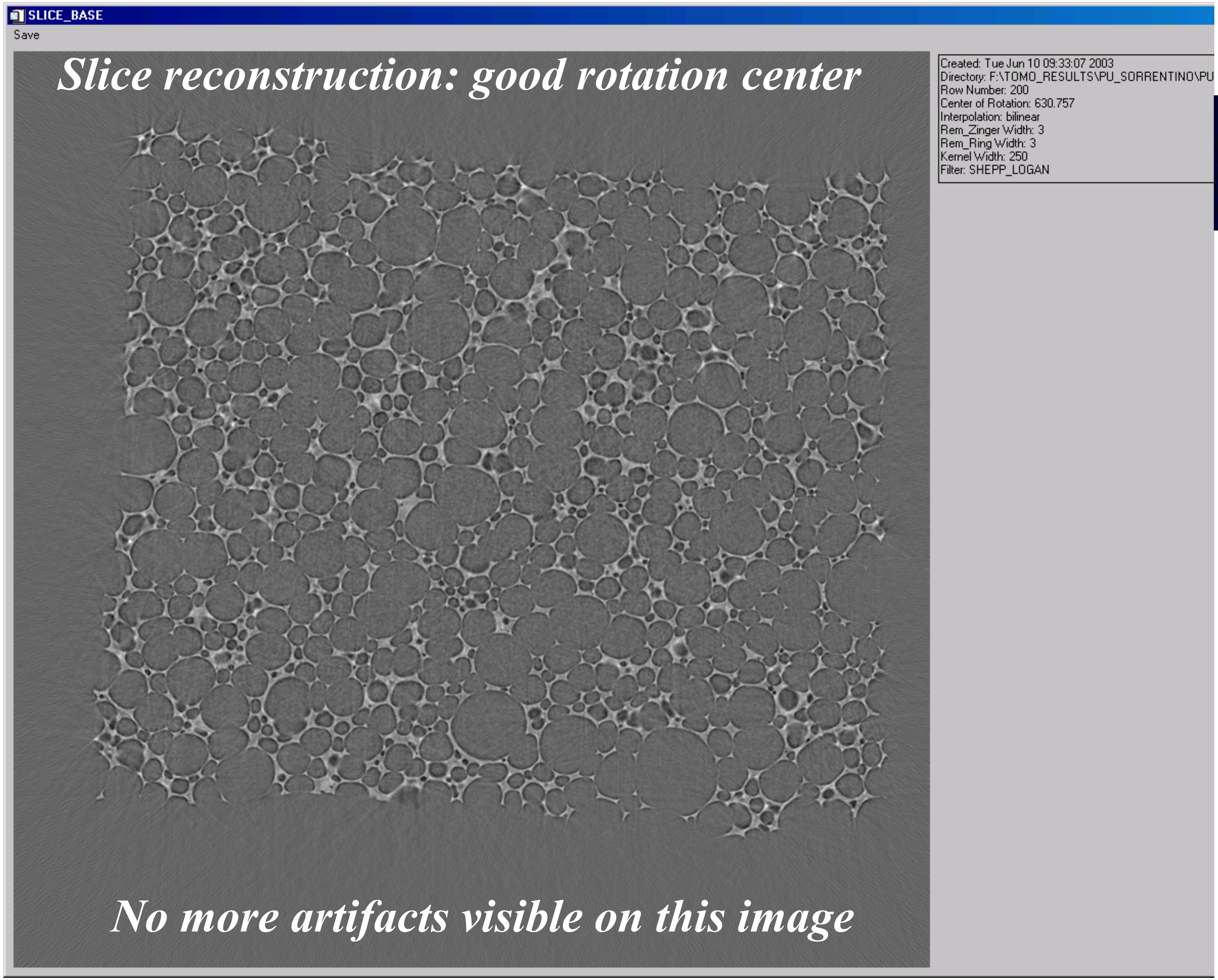
C = 630.750



C = 638.750

A poor centering causes **arc artifacts**. An automated centering procedure gives a sinogram which is better centered on the rotation axis by determining the center-of-gravity of each row in the sinogram, and fitting this center-of-gravity array to a sin wave. The symmetry axis of the fitted sin wave is the rotation axis. The sinogram is then shifted left or right so that the rotation axis is exactly on the center column of the sinogram array.

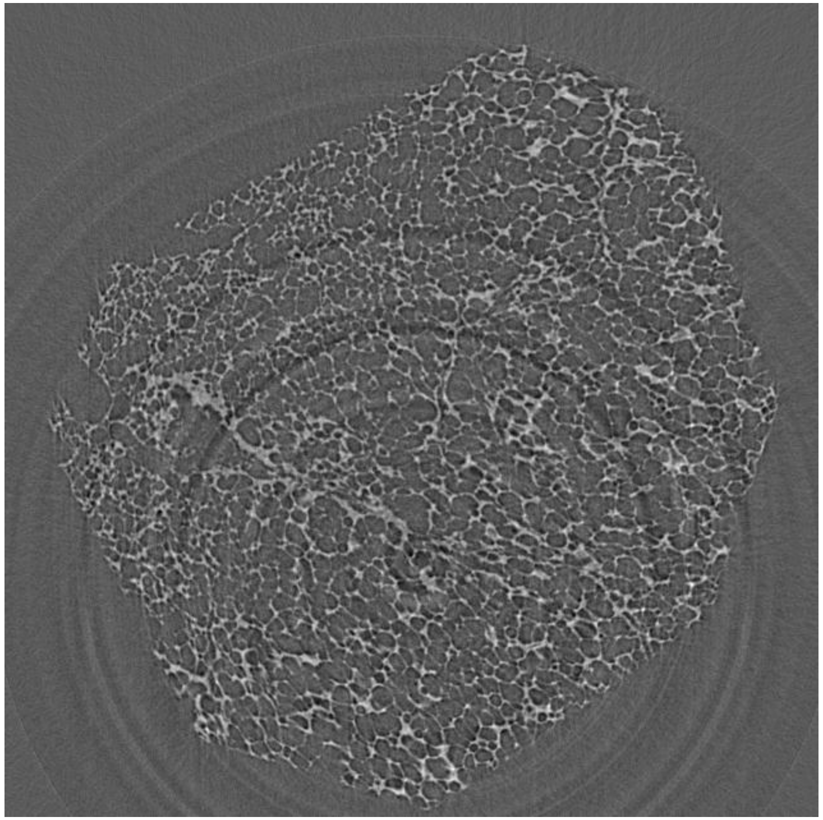
Slice reconstruction: good rotation center



```
Created: Tue Jun 10 09:33:07 2003
Directory: F:\TOMO_RESULTS\PU_SORRENTINO\PU
Row Number: 200
Center of Rotation: 630.757
Interpolation: bilinear
Rem_Zinger Width: 3
Rem_Ring Width: 3
Kernel Width: 250
Filter: SHEPP_LOGAN
```

No more artifacts visible on this image

Ring artifacts reduction



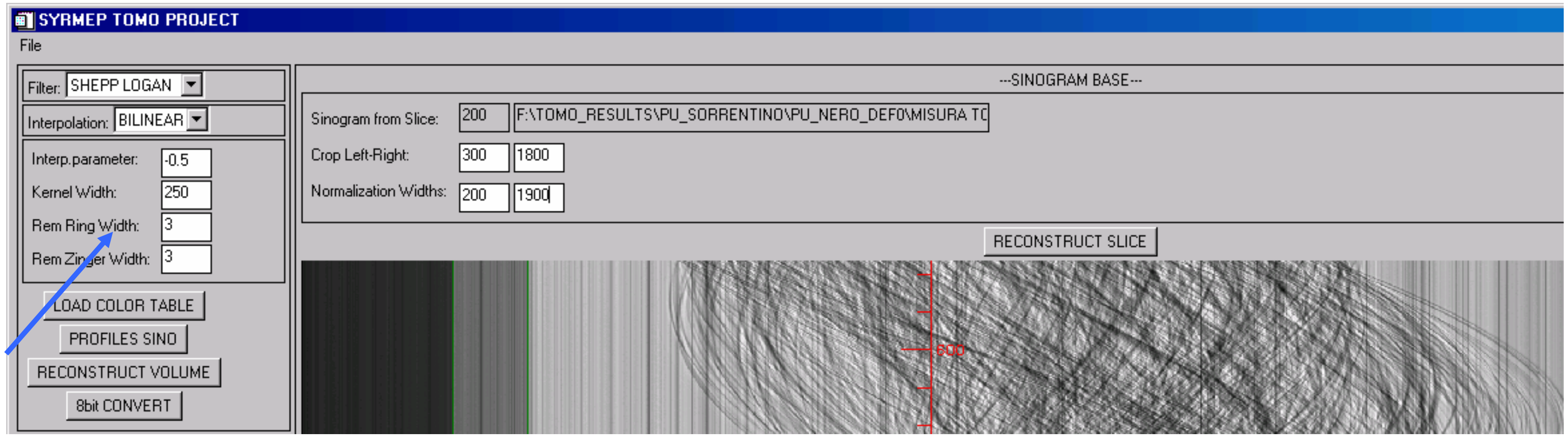
The ring artifacts are due to drifts or non-linearities in the detector response.

A bad detector element will show up as a vertical stripe in the sinogram.

Two vertical lines in the sinogram would appear as a a thin cylinder centered on the rotation axis in the real object.

The causes of these vertical stripes in the sinogram can include the following:
→ Drifts in the detector element sensitivity in between white-field calibrations
→ Non-linear detector element response
→ Higher energy harmonics in the incident beam

How to reduce the ring artifacts?



Filter: SHEPP LOGAN
Interpolation: BILINEAR
Interp.parameter: -0.5
Kernel Width: 250
Rem Ring Width: 3
Rem Zinger Width: 3

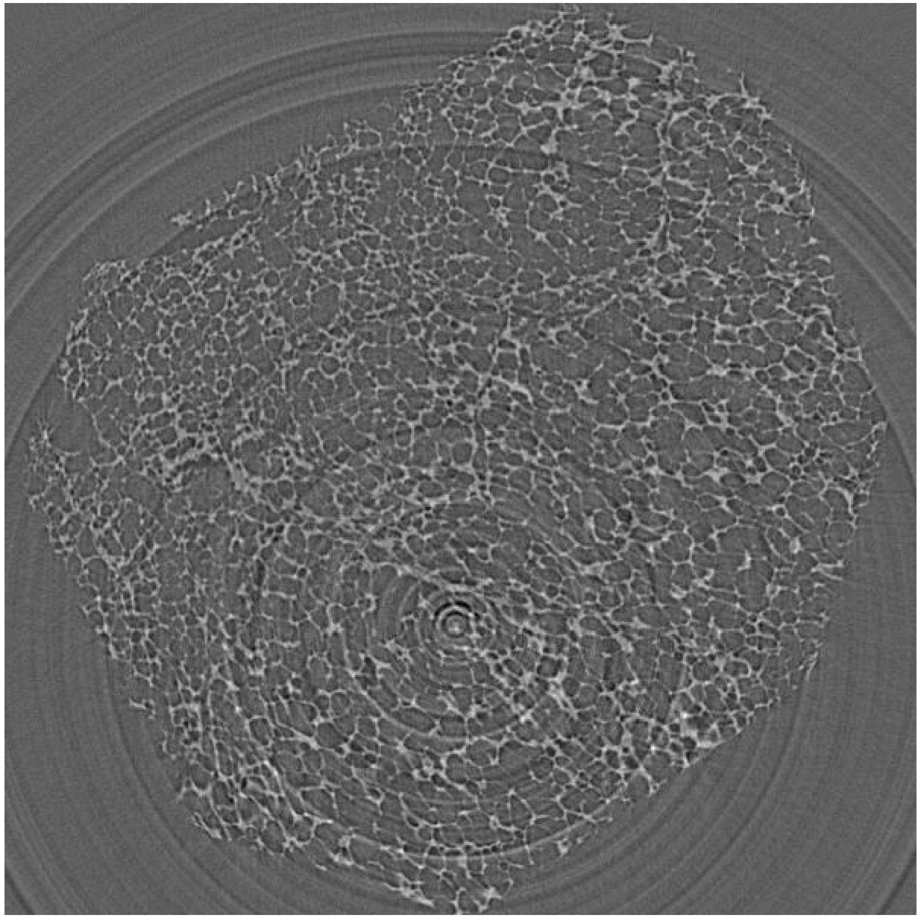
Sinogram from Slice: 200 F:\TOMO_RESULTS\PU_SORRENTINO\PU_NERO_DEF0\MISURA TO
Crop Left-Right: 300 1800
Normalization Widths: 200 1900

→ Compute the **average row of the sinogram** by summing down each column and dividing by the number of rows. This **average row** should have very little high-frequency content, since real objects will be moving in the sinogram, and will be blurred out when computing the average row.

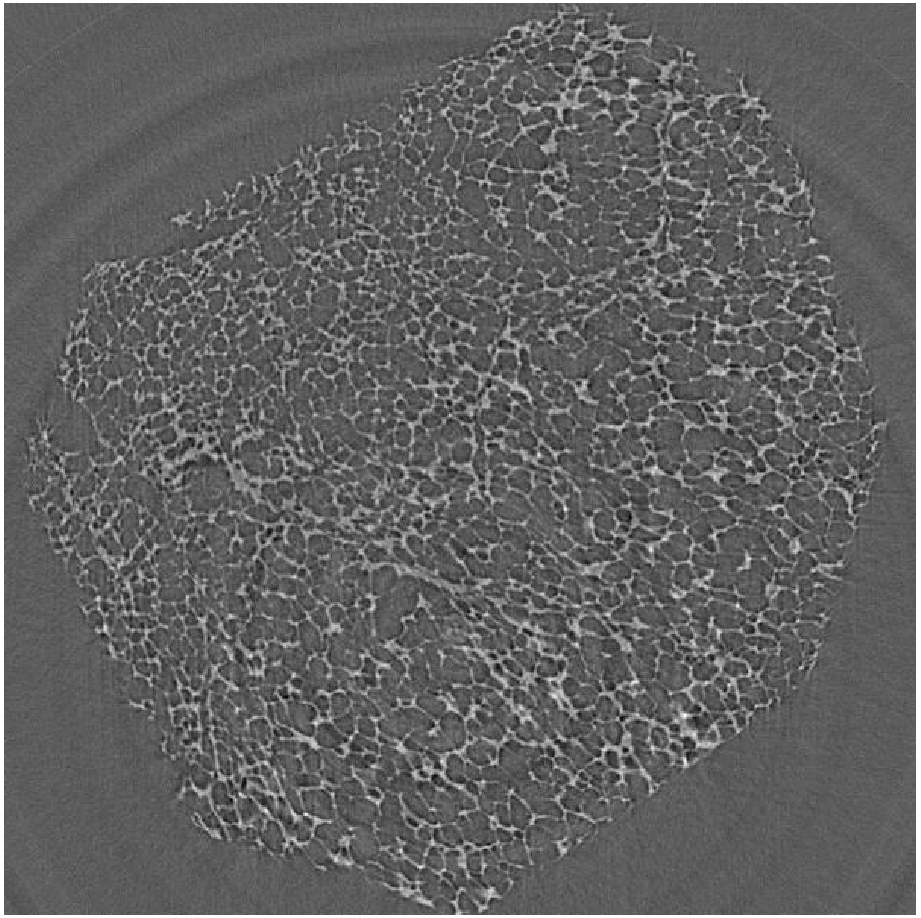
→ Compute the magnitude of these detector anomalies **by subtracting a smoothed version of the average row** from the average row.

→ **Subtract the result** of previous step, the detector anomalies, **from each row in the sinogram**. This results in a sinogram with much less vertical striping.

Result of the ring artifacts reduction



Before



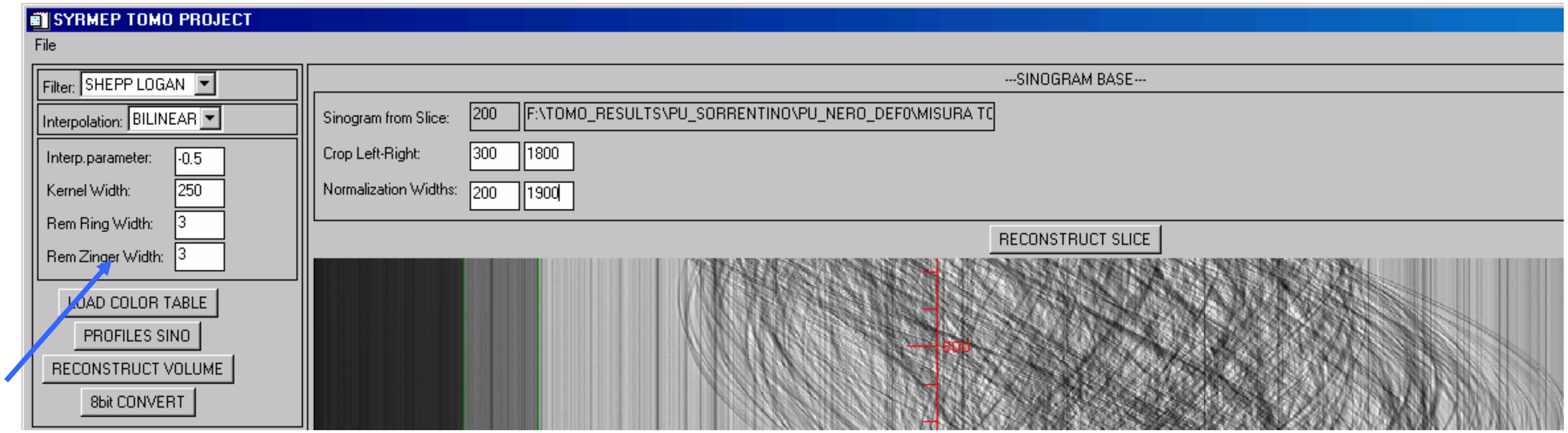
After (rem rimg = 7)

Zinger removal

A close look to the reconstructed slice can also reveal perfectly straight, bright lines at random orientations in the image. These bright lines, which look like scratches, are due to **zingers**, or anomalously bright pixels, in the raw images. These zingers are caused by cosmic rays or scattered X-rays hitting the CCD chip directly, causing large energy deposition relative to the visible light photons from the scintillator crystal.

Eliminating these zingers is best done when the raw data and white field images are first read in.

How to remove zingers?



Filter: SHEPP LOGAN

Interpolation: BILINEAR

Interp.parameter: -0.5

Kernel Width: 250

Rem Ring Width: 3

Rem Zinger Width: 3

Sinogram from Slice: 200 F:\TOMO_RESULTS\PU_SORRENTINO\PU_NERO_DEF0\MISURA TO

Crop Left-Right: 300 1800

Normalization Widths: 200 1900

→ Smooth the raw image with a low-pass filter

→ Subtract the raw image from the smoothed image

→ Divide the difference image from step 2 by the smoothed image to produce an image of anomalous pixels on a relative scale

→ Any pixels in the image from step 3 which are greater than a threshold value (typically 1.2) are defined to be zingers. The intensity of zinger pixel at location N is replaced by the average intensity of the pixels at location N-2 and N+2. Pixels N-1 and N+1 are not used because some zingers affect 2 adjacent pixels.

Volume reconstruction

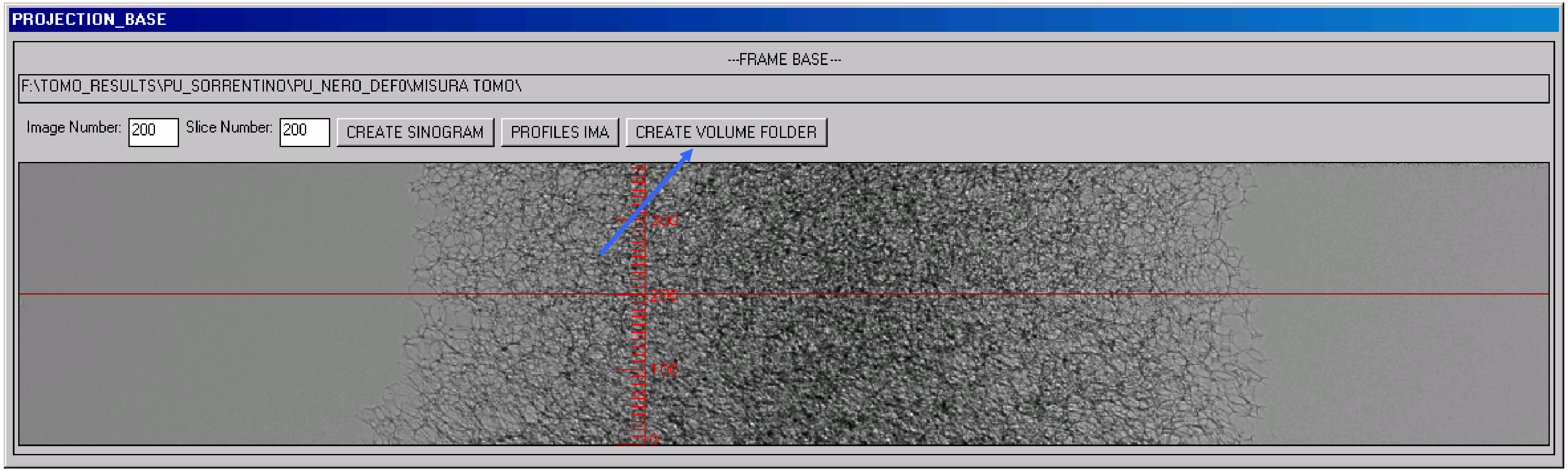


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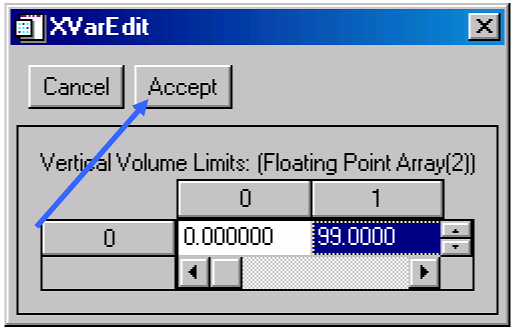
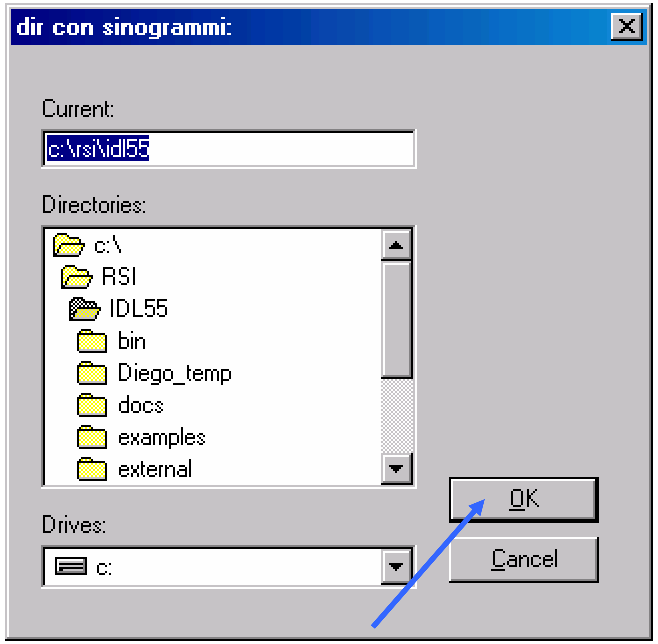
Image Number: 200

Slice Number: 200



Vertical Volume Limits: (Floating Point Array(2))

	0	1
0	0.000000	99.0000

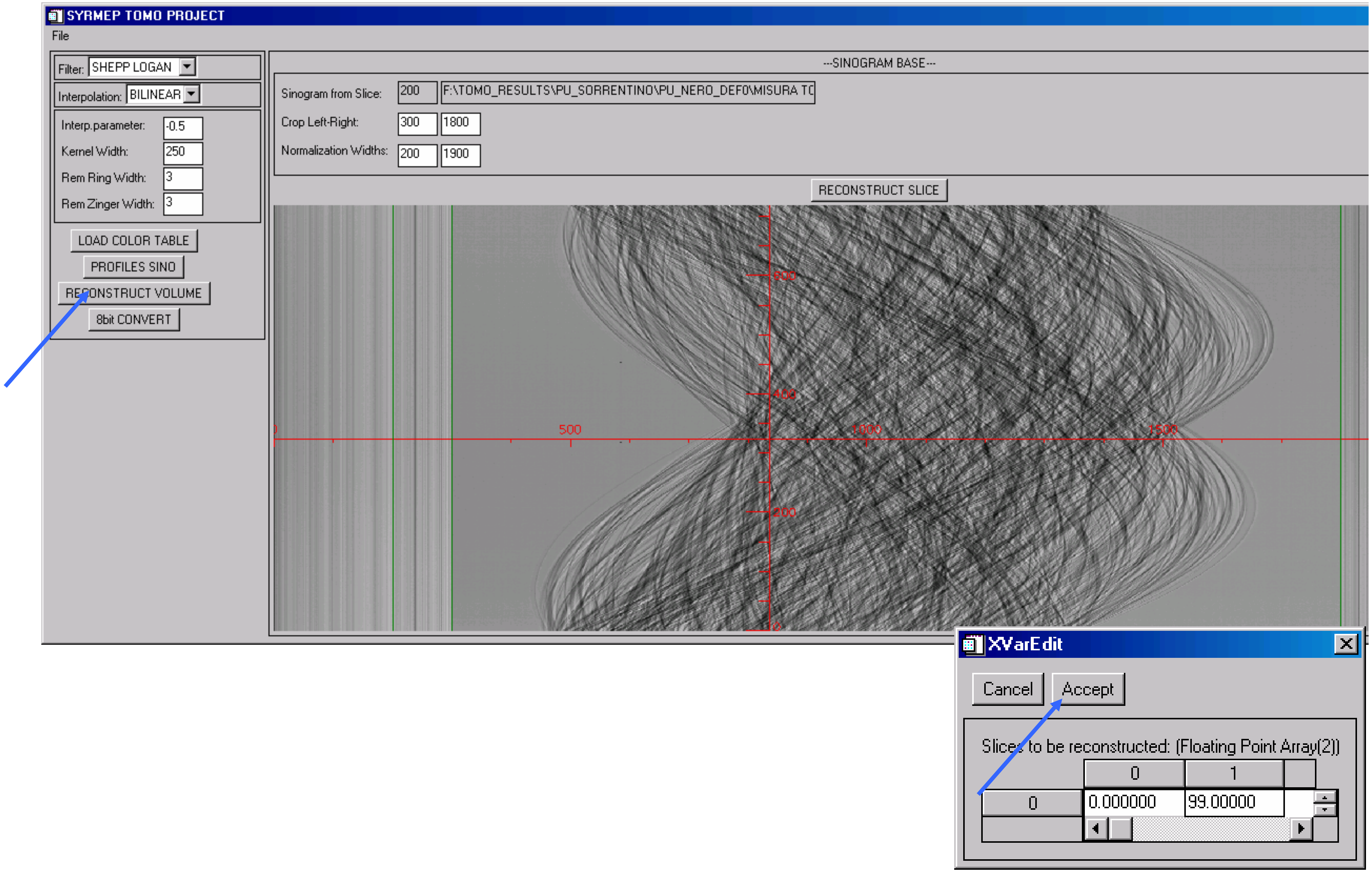


Current: c:\rsi\idl55

Directories:

- c:\
- RSI
- IDL55
- bin
- Diego_temp
- docs
- examples
- external

Drives: c:



Filter: SHEPP LOGAN

Interpolation: BILINEAR

Interp.parameter: -0.5

Kernel Width: 250

Rem Ring Width: 3

Rem Zinger Width: 3

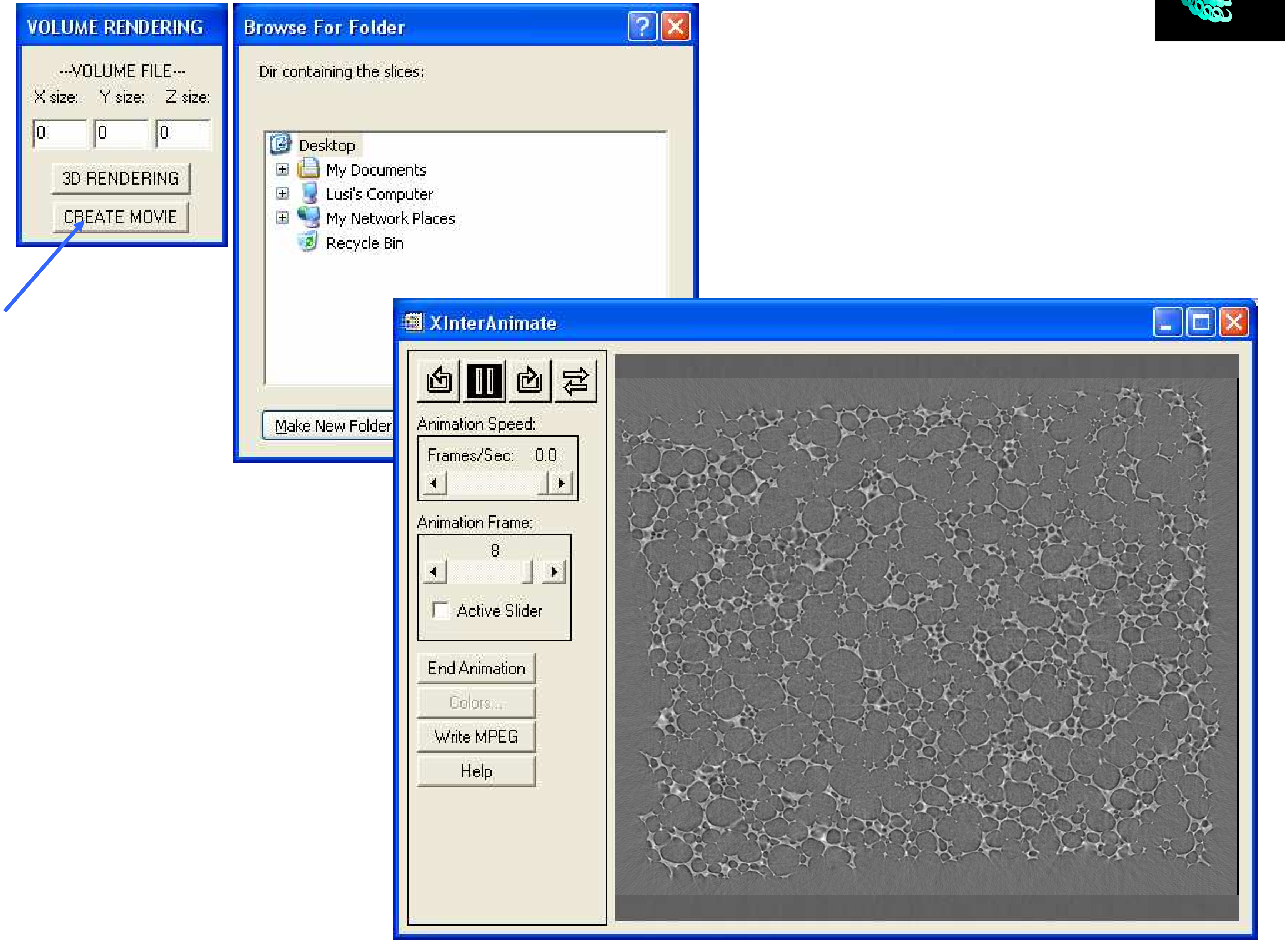
Sinogram from Slice: 200 F:\TOMO_RESULTS\PU_SORRENTINO\PU_NERO_DEFO\MISURA TO

Crop Left-Right: 300 1800

Normalization Widths: 200 1900

Slices to be reconstructed: (Floating Point Array(2))

	0	1
0	0.000000	99.00000



X size: 0

Y size: 0

Z size: 0

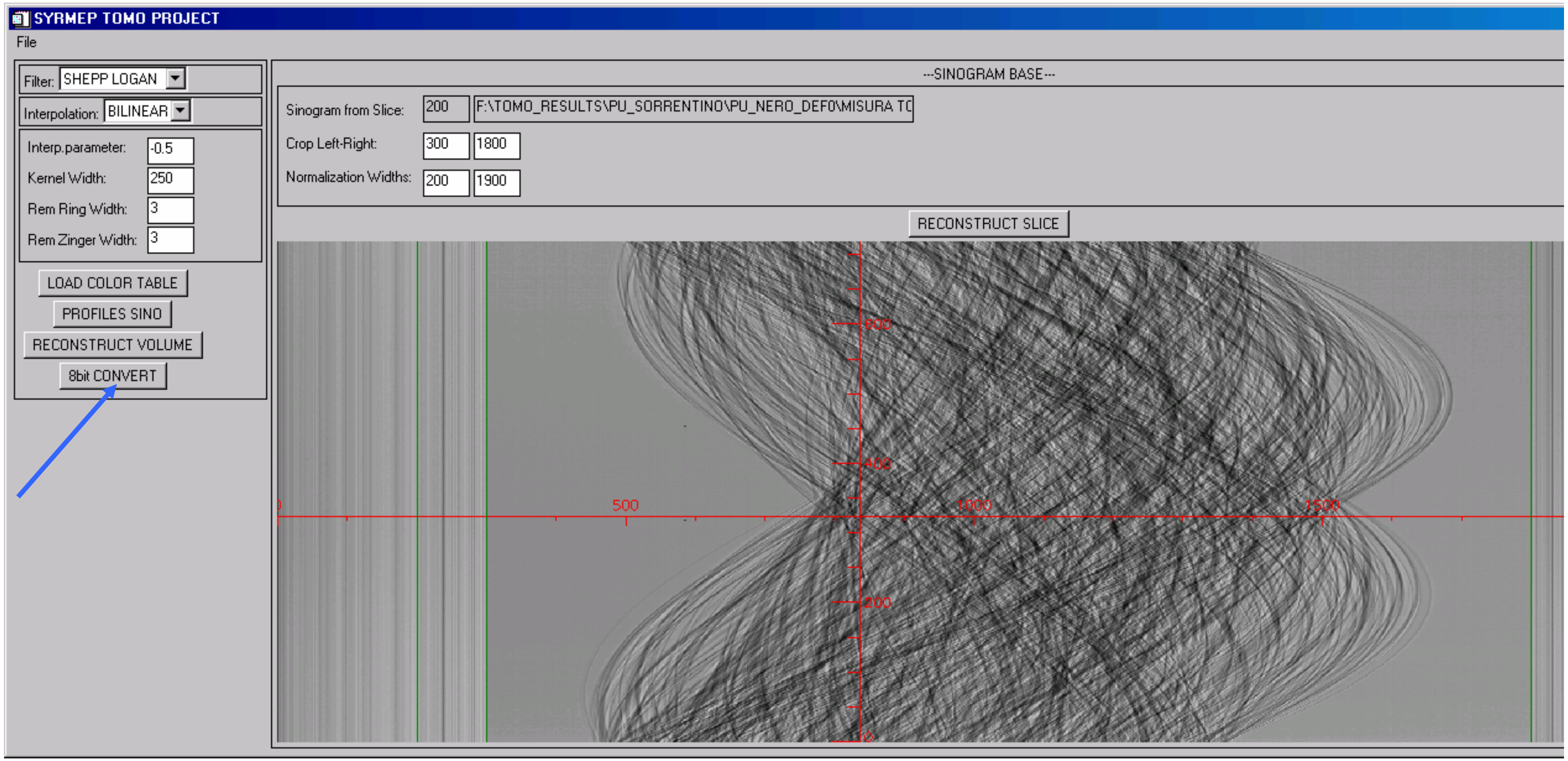
Dir containing the slices:

Frames/Sec: 0.0

Animation Frame: 8

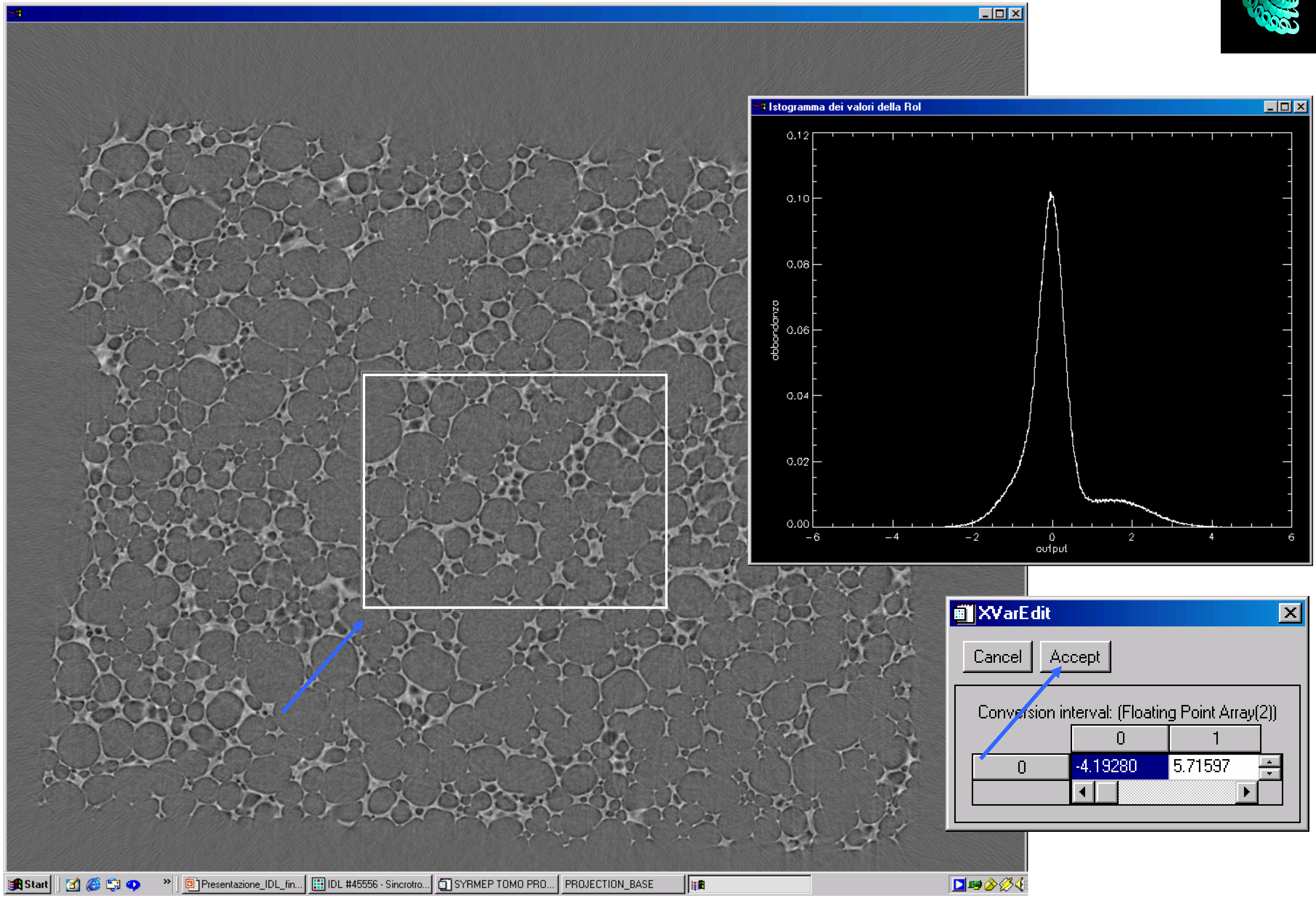
☐ Active Slider

8bit .raw volume creation



Filter: SHEPP LOGAN
Interpolation: BILINEAR
Interp.parameter: -0.5
Kernel Width: 250
Rem Ring Width: 3
Rem Zinger Width: 3

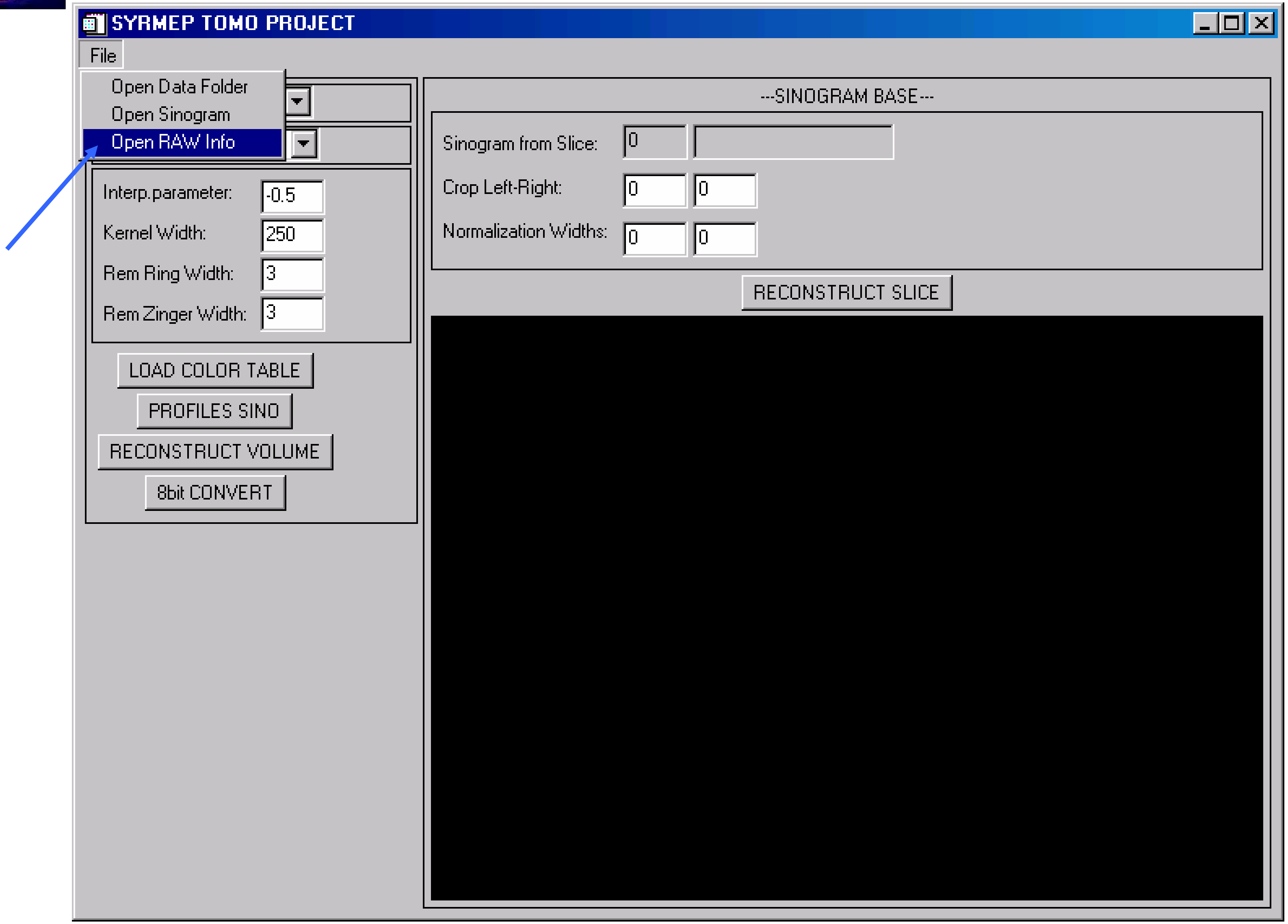
Sinogram from Slice: 200 F:\TOMO_RESULTS\PU_SORRENTINO\PU_NERO_DEFO\MISURA T
Crop Left-Right: 300 1800
Normalization Widths: 200 1900



Conversion interval: (Floating Point Array(2))

	0	1
0	-4.19280	5.71597

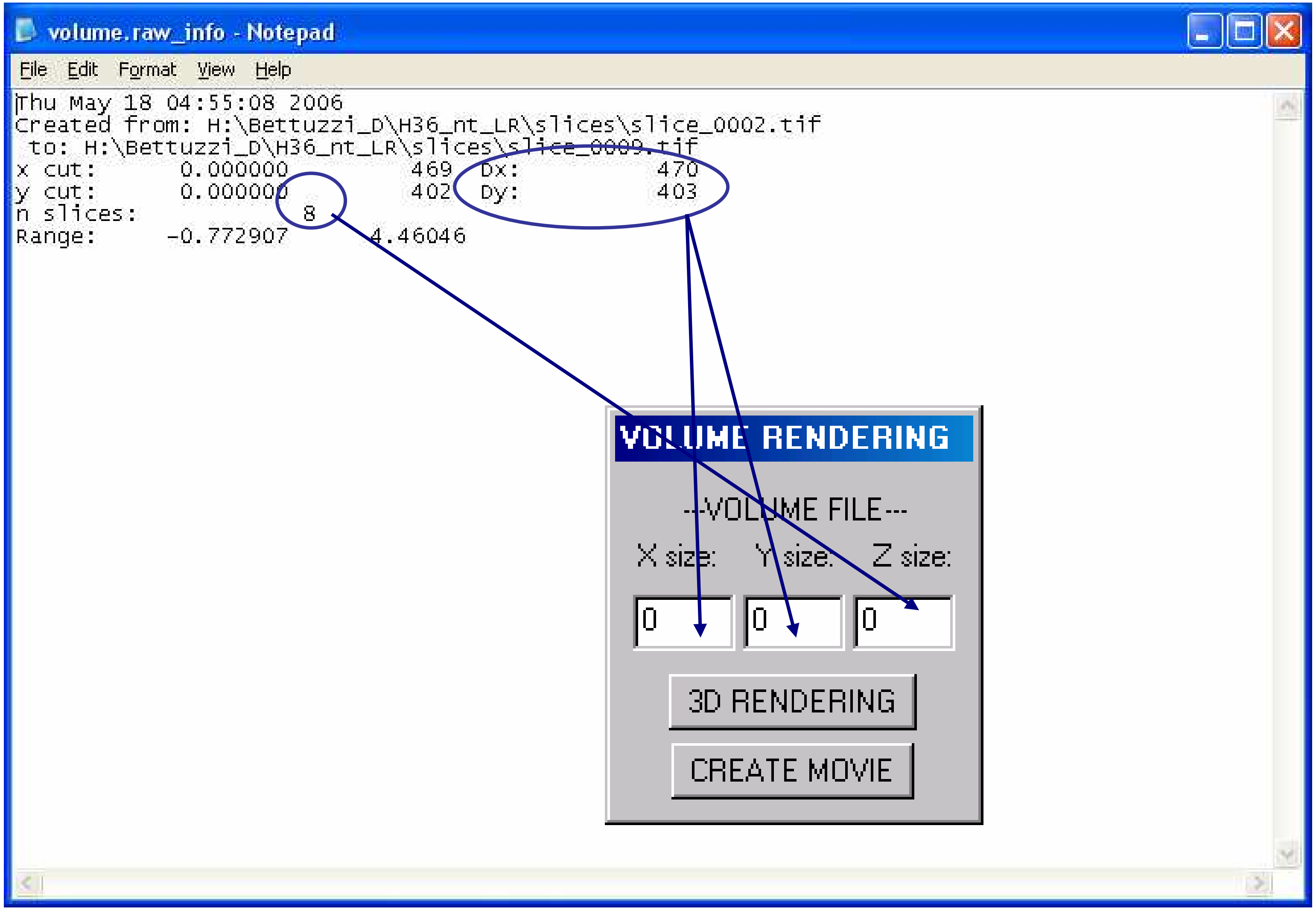
Data visualization: volume rendering



Interp.parameter: -0.5
Kernel Width: 250
Rem Ring Width: 3
Rem Zinger Width: 3

Sinogram from Slice: 0
Crop Left-Right: 0 0
Normalization Widths: 0 0

Volume rendering procedure



```
Thu May 18 04:55:08 2006
Created from: H:\Bettuzzi_D\H36_nt_LR\slices\slice_0002.tif
 to: H:\Bettuzzi_D\H36_nt_LR\slices\slice_0009.tif
x cut:        0.000000          469  Dx:            470
y cut:        0.000000          402  Dy:            403
n slices:                8
Range:      -0.772907      4.46046
```

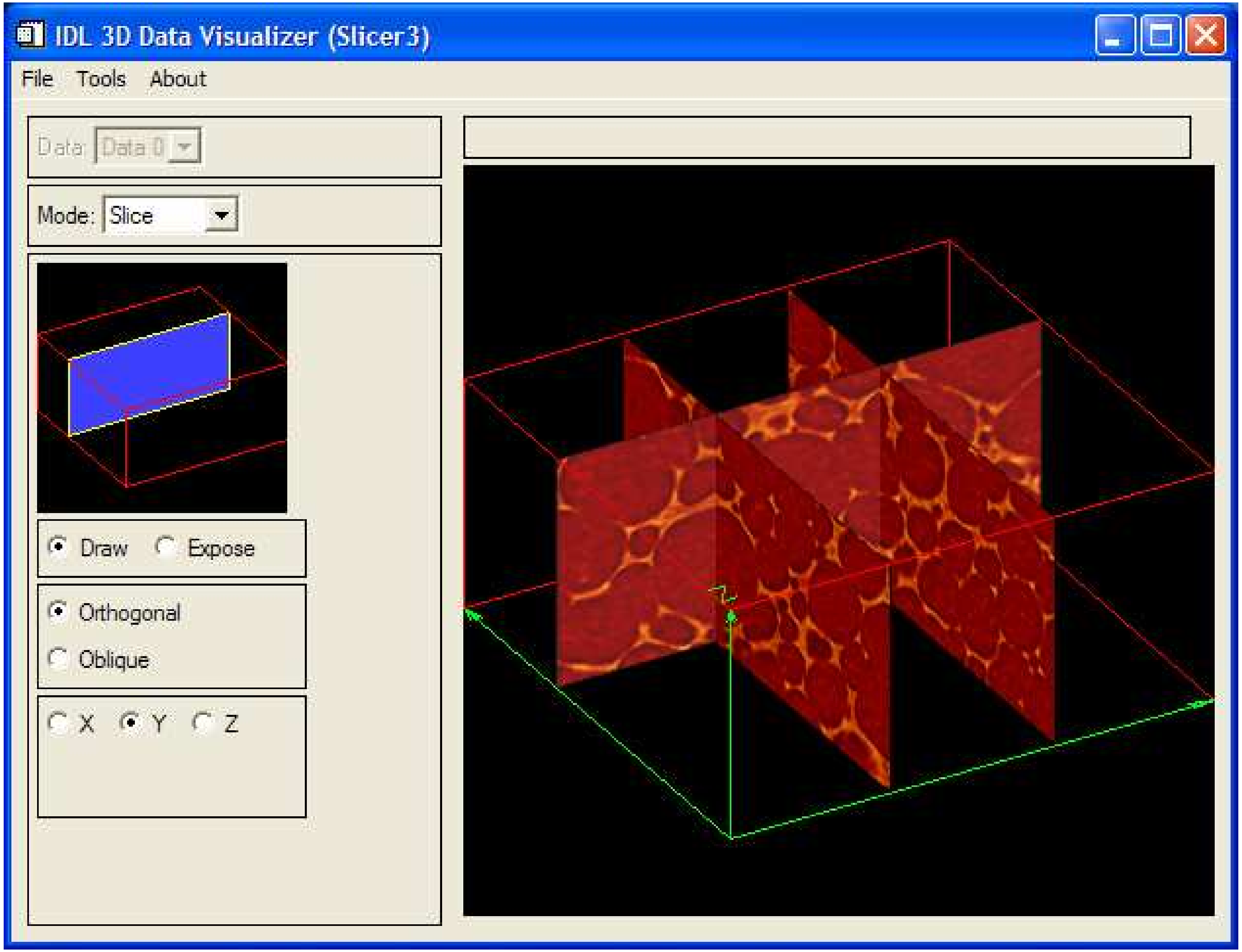
--VOLUME FILE--

X size: 0

Y size: 0

Z size: 0

Slice visualizer



Data: Data 0

Mode: Slice

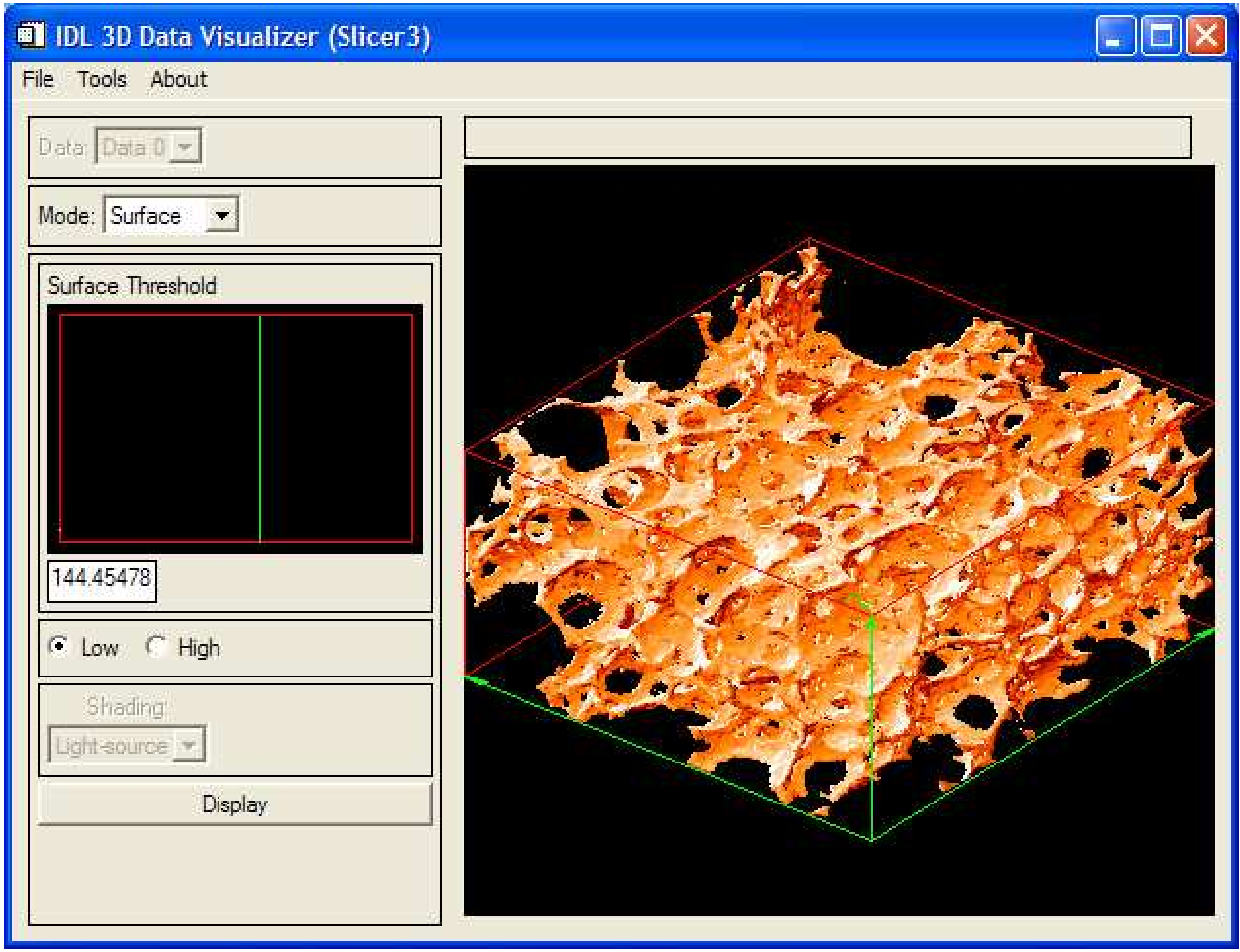
● Draw ○ Expose

● Orthogonal

○ Oblique

○ X ● Y ○ Z

Isosurface rendering



Data: Data 0

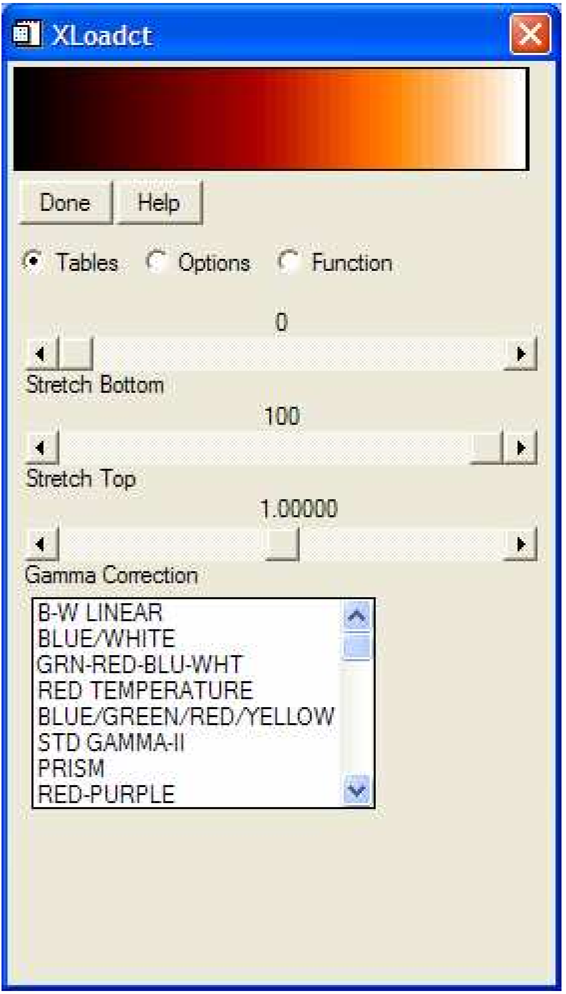
Mode: Surface

Surface Threshold

144.45478

● Low ○ High

Shading: Light-source



● Tables ○ Options ○ Function

Stretch Bottom: 0

Stretch Top: 100

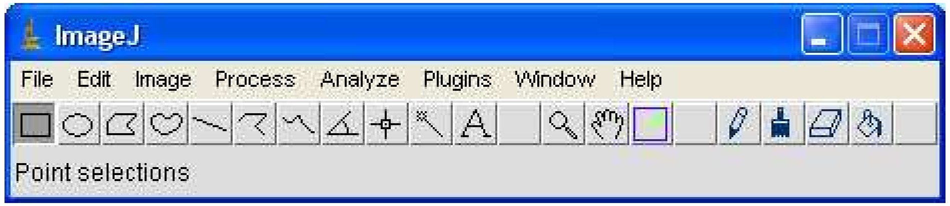
Gamma Correction: 1.00000

B-W LINEAR
BLUE/WHITE
GRN-RED-BLU-WHT
RED TEMPERATURE
BLUE/GREEN/RED/YELLOW
STD GAMMA-II
PRISM
RED-PURPLE

The ImageJ software

A public domain, Java-based image processing program developed at the National Institutes of Health.

http://rsb.info.nih.gov/ij/index.html



Rasband, W.S., ImageJ, U. S. National Institutes of Health, Bethesda, Maryland, USA, http://rsb.info.nih.gov/ij/, 1997-2007.
Abramoff, M.D., Magelhaes, P.J., Ram, S.J., *Image Processing with ImageJ. Biophotonics International, volume 11, issue 7, pp. 36-42, 2004.*