Nondestructive Testing Labsessions

Radiographic Testing

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Contents

Synopsis :
The aim of these labsessions is to become familiar with the X-ray radiology technique. You will have at your disposal imaging simulation platforms (based on the Monte Carlo Geant4 / Gate toolbox) and an irradiation facility with an X-ray generator and a flat-panel type matrix detector. Your report is to be sent within one week after the end of the labsession[1].

[1] via email to J Adrien, M Mouchet, or JM Létang

1 User guides

1.1 Radioprotection

The use of X-ray generators or sealed radioactive sources does not release any radioactive material. This does not present any risk of internal exposure. On the other hand, the operators risk external exposure if they do not take the necessary measures to protect themselves from the ionizing radiations. According to the *Journal Officiel* of April 2, 2003, the effective dose limit for in-depth exposure for exposed Category A workers is 20 mSv per year. This corresponds to an accepted risk level of 10^{-4} of cancer. The corresponding hourly dose rate, based on an activity of 2000 hours per year, is 10 μGy·h^{-1} for X-rays. During these labsessions, you are considered non-exposed public workers, likely to receive a maximum effective dose of 1 mSv per year. In the remote control room, the dose rate is less than 1 μGy·h^{-1}. In the direct beam of a generator X the dose rate can easily reach 10 Gy·h^{-1} at 1 meter!

It is therefore necessary to have tools to detect the possible presence of radiation and to control the dose received in case of accidental exposure. Electronic dosimeters will be used to integrate the dose received during the labsession. Each student must sign early in the session the register to certify (i) the knowledge of the risks involved in handling radiology equipment and (ii) the observance of the safety instructions. The dosimeters used during the session can be reset at start-up if required. Electronic dosimeters are fragile and expensive, take care of them. The dose measured by the dosimeter is to be recorded on the register at the end of the session with the signature of each student. Ask the teacher if necessary for the use and operation of the different measuring devices.

1.2 Safety instructions

1. Before entering the blockhaus, take the key of the console and a dosimeter.
2. Leave the door of the blockhaus open to indicate the presence of someone in the blockhaus.
3. Place the dosimeter and the key on the table.
4. As long as there is a person inside the blockhaus, the key and the dosimeter must remain there.
5. The last person to leave the blockhaus brings them back in the control room.

1.3 Acquisition system

In order to take x-ray images, it is necessary to put in service the console of the x-ray tube. The acquisition is managed from the computer. The teacher will show you how to use the console and the software.

The acquisition PC is not connected to the network, you must only use the USB-key provided by the teacher to transfer the acquired images from the acquisition PC (under *Windows*) to the simulation PC (under *Linux*), and do not use this USB-key with your laptop. You can however use your own USB-key with the simulation PC.

X-ray generator: The X-ray generator is controlled by the Cegelec MP1 console. The key must be removed from this console after it is put in the upright position (ie without putting it back on 0 to remove it) when accessing the blockhaus. The operating range for the X-ray generator is:

- between 0 and 5 mA (be careful not to change the focus selector),
- between 20 and 120 kV.

Digital detector: The digital detector `PaxScan` of *Varian* (600 micron thick CsI fluorescent screen coupled to a matrix of photodiodes) which is used has a scanning dynamics of 14 bits, where the absence of irradiation corresponds to a zero intensity and saturation at an intensity of $2^{14} - 1 = 16383$. The pixel size in 194 μm and the imaging plane is located at the level of the black line on the side on the detector.

The computer that controls the acquisition is GMCCND04 (use the default login `TP`). The software that allows image acquisition is **Viva**, available as an icon on the desktop. Select the *4030CB - 1x1 4pf g2 full-res* acquisition mode if it is not. Click on the *Acquire Image* button, a dialogue window appears, where by default no recursive filtering in time is done (you can move the cursor to average on a few tens of images to reduce the noise). Stop the acquisition. To download the image, click *Retrieve Image*. Save the image as `Raw (*.raw)`. Be careful not to save in the format `tif`, `jpg` or any other that loses the dynamics of the image. NB: the acquired image is mirrored horizontally.

The software used to process the images is **ImageJ** (available in the "Start" menu). In **ImageJ**, select `File` ⇒ `Import` ⇒ `Raw` to read an image at format `.raw` (*16bit unsigned*, 2048×1536, *Little-endian*). The use of this software is quite intuitive, but do not hesitate to ask the teacher if you have difficulties.

1.4 Softwares

List: The teacher will help you with the use of the software. You have at your disposal:

- **Gate software:** for all X-ray imaging simulations;
- **site XCOM:** to get access to the attenuation coefficient and its components for all materials; the mass attenuation coefficient μ/ρ is given in the penultimate column of the table which is the one marked `Total Attenuation With Coherent Scattering`;
- **ImageJ: software** for visualizing and processing the x-ray image;
- **root software:** for visualizing the simulated energy spectrum of the photons received by the detector.

Gate To start **Gate**, you have to be at the same level as the macro directory named `mac`, for example for the first job we will be in the `Gate_Filter` directory, and to start **Gate** open a terminal in this directory (or change directory with the command `cd`) and then start **Gate** with the command

```
Gate --qt -a [alias1,value1][alias2,value2] mac/main.mac
```

by replacing the aliases and their value as will be specified.

To validate or understand the geometry, the simulated **visualization of your scene** is done by launching only a few photons. The number of photons is set at the end of the file `main.mac` by modifying the last

```
/gate/application/setTotalNumberOfPrimaries 16
```

In addition, you need to have the visualization activate the corresponding macros in the file `main.mac` (comment lines start with a pound sign `#`)

```
/control/execute mac/visu.mac
#/vis/disable
```

Photons are represented by green lines in the viewing window. You can zoom in the GUI with the shortcut `CTRL+` (and zoom out with `CTRL-`). The mouse can change the viewing angle by clicking with the mouse or moving the viewing area by pressing `SHIFT` before clicking.

Conversely, to start the simulation with a large number of photons and thus have results with more statistics, you must disable the visualization by inverting the lines in comment

```
#/control/execute mac/visu.mac
/vis/ disable
```

the simulation will be complete when you see "GATE" appear and you can simply exit the window and use the results of the simulation.

To **save simulation time**, you can run multiple simulations in parallel in different terminals and with different parameter values, the names of the output files will be differentiated.

The database of available materials is in the file `GateMaterials.db` in the `data/` directory. This file is loaded at the beginning in the macro file `main.mac`. When the output is an image, it is saved under 2 files: the header `.hdr` and the data `.img`. You can find more information in the *Wikibook* of **Gate**.

ImageJ: Intuitive, here are some commands that will help you.

- Setting the display: `Image` ⇒ `Adjust` ⇒ `Brightness / Contrast ...`
- Profile in the image: line selection tool then `Analyze` ⇒ `Plot Profile`
- Stats in a region: rectangle selection tool then `Analyze` ⇒ `Measure`
- Management of Regions of Interest: `Analyze` ⇒ `Tools` ⇒ `ROI Manager`

root: To read the file `myFile.root` with extension **root** located in a subdirectory `output`, it will be enough to launch

```
AnalyseRootFile output/myFile.root
```

there is no need to change directories after starting **Gate** to exploit the output by **root**.

Screen capture: Under *Linux* it is possible to make a window capture in an image file (`png` or `jpg` for example) by the command

```
import name_of_your_image.png
```

Then click in the window whose contents you want to save.

Archive backup of your session: At the end of the session to save your working directory, open the file explorer and select the compression by right clicking on this directory. You will have the choice of the type of compression and the name of your archive. You can then transfer this archive file via `fex`, USB key...

2 Labsessions

Discuss systematically the studies done in simulation and manipulation. You can refer to the jupyter book *Xray Imaging* to deepen the concepts related to the physics of X-ray imaging. The **Gate** and **root** softwares start from the command line from a terminal window on the simulation PC. Before the simulations, copy in a new directory the content of `SGM` directory on the desktop of the simulation PC.

2.1 Imaging system calibration (Experiments)

The diagram of the acquisition system is given in the figure 1. Propose a precise methodology to determine the distance F from the x-ray source to the imaging plane (see Figure 1), and implement it experimentally after having validated it with the teacher. Check whether the distance is compatible with the x-ray acquisition system.

Determine the errors associated with estimating this distance. For the record, the formula for the propagation of uncertainty of a function y of N variables $x_1, x_2, ..., x_N$ is the following rule for independent variables:

$$\text{uncertainty}\,(y) = \sqrt{\sum_{i=1}^{N}\left(\frac{\partial y}{\partial x_i}\right)^2 (\text{uncertainty}\,(x_i))^2} \qquad (1)$$

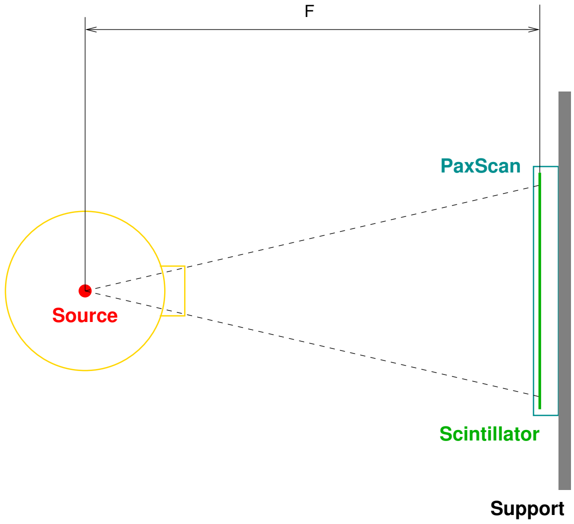

Figure 1: Sketch of the acquisition system.

2.2 Energy fluence (Experiments)

Make full flux acquisitions (ie without object) at different voltages and intensities.

- for an intensity of 3 mA, make acquisitions at 40, 60, 80, and 100 kV,
- for a high voltage of 60 kV, make acquisitions at 1, 2, 3, and 4 mA.

Study the influence of the voltage (in kV) and the current (in mA) on the image grey-value measure $I(p)$ in a region around the same pixel $p = (x, y)$. Propose a two-parameter (a, b) power function

$$I(p) \propto (\mathrm{kV})^a (\mathrm{mA})^b \tag{2}$$

to model the grey-value given by the detector.

2.3 Flat field (Experiments)

Experiments The radiological image is not uniform even when no object is present in the irradiation field: dark current of the detector, variable gain between detector areas, conical and non-uniform X-ray incident flux... To homogenize the image (that is to say a flat field) acquire three images:

- a radiation-free image called black image or $I_B(p)$
- an image with radiation but no object, called white image or $I_W(p)$
- an image with radiation and object, called $I_O(p)$

with $p = (x, y)$ the pixel. The conditions of the white image $I_W(p)$ – i.e. voltage, current, and geometry – must obviously be the same as those of the object $I_O(p)$. The flattening then consists in doing the following matrix operation

$$I_M(p) = \frac{I_O(p) - I_B(p)}{I_W(p) - I_B(p)} \tag{3}$$

You can do this with **ImageJ**. Arithmetic operations on images under accessible in the menu `Process` ⇒ `Image Calculator...` Make sure to select the output in `32 bits (float)` during operations. Note that if the black image is essentially null, you can omit the subtraction with I_B.

Do this flattening on a test object of your choice and show through profiles or statistics on intensity improvement of the flattening. Explain the probable causes of the overall form of intensity variation in I_W.

What is the relationship between I_W and the exponential attenuation law? For the rest, work preferably on flattened images, making sure to use the kV and mA conditions of I_O each time for the white I_W images.

2.4 Beam hardening (Simulations/Experiments)

The signal measured $I(p)$ by the flat panel detector is proportional to the deposited energy in the active area of the pixel $p = (x, y)$. Assuming there are M different materials crossed by the x-rays from the source to pixel p, the image $I(p)$ can be modeled as follows:

$$I(p) = \int_{E \in \text{spectrum}} D(E,p) N_0(E,p) \exp\left(-\sum_{m=1}^{M} \mu_m(E) X_m(p)\right) \mathrm{d}E \tag{4}$$

where E is the photon energy, $D(E,p)$ is the detector response, $N_0(E,p)$ the number of photons emitted by the source, $\mu_m(E)$ the linear attenuation coefficient of material m and $X_m(p)$ the corresponding material thickness. We can see that since the primary spectrum is not monochromatic the measurement is the sum of several attenuation laws. We could however compute the effective monochromatic attenuation that would give the same measurement:

$$I(p) = I_0(p) \exp\left(-\sum_{m=1}^{M} \mu_m\left(E_{eff}\right) X_m(p)\right) \text{ with } I_0(p) = \int_{E \in \text{spectrum}} D(E,p) N_0(E,p) \mathrm{d}E \tag{5}$$

where E_{eff} corresponds to the monochromatic energy that would give the same attenuation than the one measured.

The working directory for **Gate** is `Gate_Filter`. To start **Gate**, you have to set the `Mat` material and its `X` thickness in mm as a command line parameter:

```
Gate --qt -a [Mat,Copper][X,2] mac/main.mac
```

for a copper plate 2 mm thick. The list of available materials is in the `GateMaterials.db` file in the `data` subdirectory. The visualization of the spectrum transmitted and the calculation of the average energy of a spectrum **root** at the output of the simulation is made by `AnalyseRootFile` :

```
AnalyseRootFile output/detector{Mat}{X}mm.root
```

Attention, if the filter is too attenuating, that is to say if the thickness considered for the filter is too strong, it is possible that no photon passes through it and reaches the detector.

Simulations with polychromatic beam The beam in the simulation reproduces the typical spectrum of a 100 kV x-ray generator. Use the `Mat` and `X` aliases on the `Gate` command line to vary the material and its thickness in mm.

1. Plot the average energy of the photons transmitted behind the filter (use `AnalyseRootFile` to get it) in terms of the filter thickness for `Copper` and then `Lead` filters.
2. Explain the difference between the two transmitted spectra (lead vs copper) by looking at the corresponding attenuation coefficients, which are available in a terminal with the command `mus.py` (available on simulation machines):

   ```
   mus.py Cu 8.96 Pb 11.34
   ```

3. Explain the difference in asymptote values.
4. For these two materials, find the corresponding filter thickness that suppresses energies below 40 keV. Check that this filter also works for other voltages (in the file `main.mac` change `spectrum/source_100kV.mac` to `spectrum/source_140kV.mac` for example).

Experiments Using several copper plates, those of a few centimeters of side and 0.15 mm thick, that you shift to make a step wedge of a few steps of different thickness (you can use the small clamp to hold them together). Make two acquisitions:

1. for 100 kV without beam filtration and
2. for 100 kV with the lead filtration that suppresses energies below 40 keV (there are small lead sheets on cardboard that you can insert in the filter holder close to the source).

Calculate by the Beer-Lambert attenuation law the values of the linear attenuation coefficient of copper for each step of your step and highlight the beam hardening. Discuss and give the asympote values of the linear attenuation coefficient in both experiments.

2.5 Beam quality (Experiments)

Experiments Ask the teacher to give you two small cylinders, one in magnesium (Mg density 1.74) and one in teflon (C_2F_4 density 2.25). Compare both linear attenuation coefficients:

```
mus.py C2F4 2.25 Mg 1.74
```

From (i) the comparison of the linear attenuation coefficients between 20 keV and 200 keV for the materials of your two cylinders and (ii) the beam hardening study, choose the acquisition conditions (appropriate high voltage and lead filtration in the filter holder) that allow to differentiate them at best and those that would not differentiate them. Make the corresponding acquisitions. Check the experimental values of the attenuation coefficients.

2.6 Scattered radiations: SPR (Simulations/Experiments)

The working directory for **Gate** is now `Gate_Scatter`.

Simulations The macros in this directory are set by default to simulate a monochromatic (60 keV) and parallel radiation source (as if the source was infinitely distant) and a 10 cm square detector (1 mm pixel). In the file `object.mac` a step wedge of PE has been defined (no need to edit it). To demonstrate the presence of secondary radiation (ie from the object) in the radiographic image, compare the x-ray images obtained with the step wedge against the detector to that obtained with at a great distance from the detector. Estimate the image of the secondary-to-primary radiation ratio (SPR) when the step wedge is pressed against the detector.

```
Gate --qt -a [Gap,XXX] mac/main.mac
```

with `XXX` the distance in centimeter between the step and the detector. This distance may be zero but must be strictly less than 500 cm.

Experiments Estimate the SPR for a step that you assemble with PE plates. Check the SPR in a few points with respect to the simulation. Confront your results with the **XCOM** database.

2.7 Image unsharpness (Experiments)

NB: The total unsharpness observed on an X-ray image results from two contributions that quadratically combine:

$$\text{unsharpness}_{\text{total}} = \sqrt{\text{unsharpness}^2_{\text{detector}} + \text{unsharpness}^2_{\text{geometric}}} \tag{6}$$

where

- the detector unsharpness comes from the spatial spread of the electrons produced during their course in the scintillator,
- the geometric unsharpness is due to the fact that the source is not punctual and corresponds to the penumbra on the edges of the projection of the object.

To estimate the unsharpness, sample a profile perpendicular to an edge in the image: the unsharpness represents the width between levels 10% and 90% of the intensity drop (see figure 2).

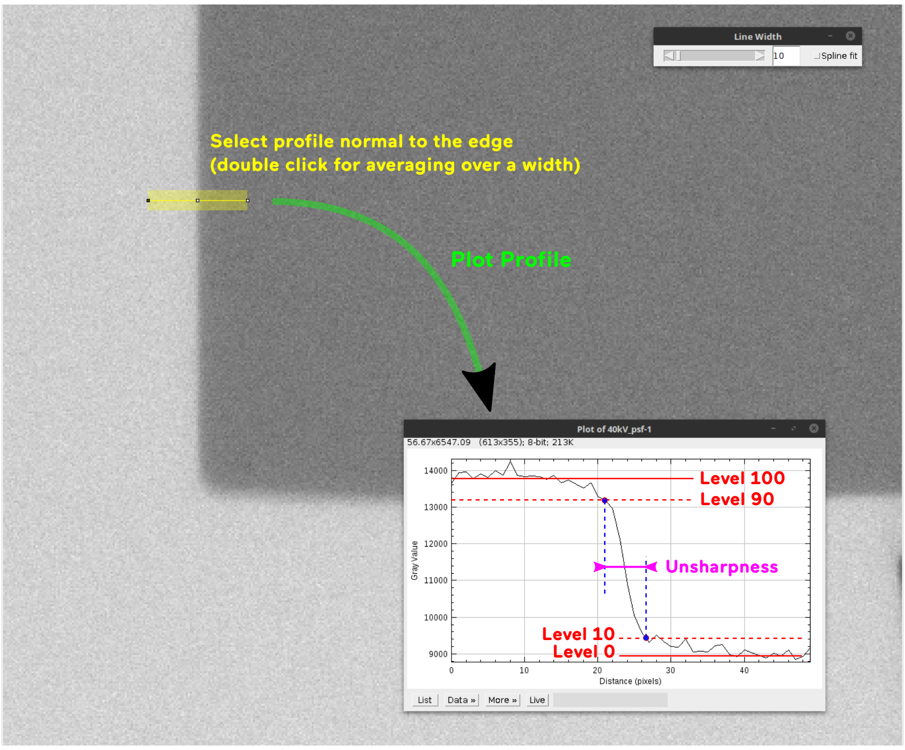

Figure 2: Unsharpness measurement method.

Experiments

1. Estimate the detector unsharpness (horizontal and vertical). Compare the measurement with the value of the maximum electron path in the scintillator material of the detector (Figure 3). Discuss the dependence of this detector unsharpness with respect to the energy of the photons.
2. Estimate the size of the emission source (for information the manufacturer announces a nominal size between 1 and 3 mm). Study the variability according to the direction of the considered edge (horizontal or vertical) and according to its position in the image.

2.8 Sensitivity to crack orientation (Simulations/Experiments)

The working directory for **Gate** is `Gate_Crack`.

Simulation of a crack with varying orientation In the macros, a 11 mm thick steel plate (in red in the OGL display) is placed at 1 cm from a 200 × 200 pixel detector (in yellow) with 50 micron square pixels. A crack of 6×9 mm^2 and 100 micron thick has been inserted. The **Gate** macros have been parameterized by the crack angle. Now you have to run the simulation as follows:

```
Gate --qt -a [angleLoF,XXX] mac/main.mac
```

replacing `XXX` with `0.5` if an angle of 0.5° is desired (a crack perpendicular to the plate is 0°).

Trace the evolution of the contrast of the crack according to its orientation. Determine the angular latitude so that the contrast remains at 10% of the maximum.

Experiments Make a sandwich of 2 black-PE plates to simulate a crack (use the small clamp to hold them together) and place them at the center of the motorized turning table, the x-ray beam tangent to the gap between the two plates. Validate experimentally the crack sensitivity with respect to the orientation (use the jog of the motor panel).

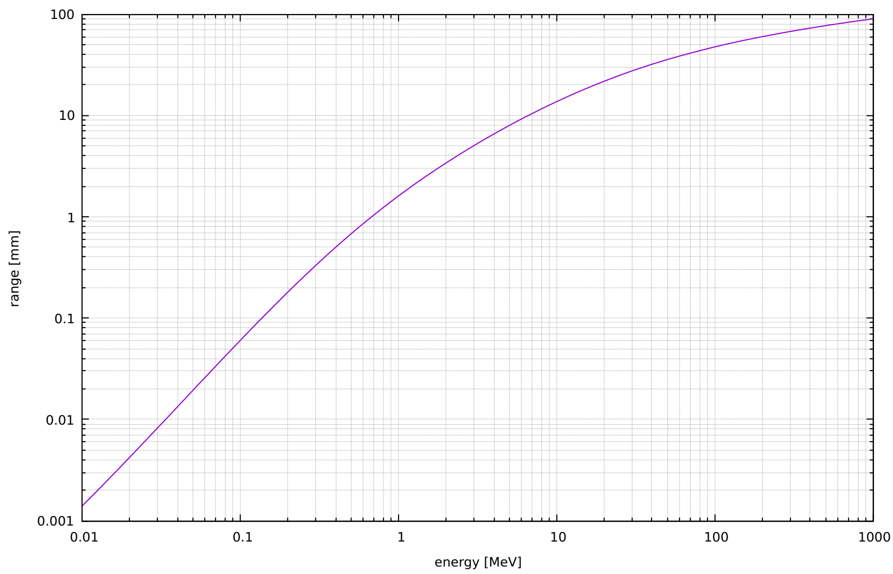

Figure 3: Electron range in CsI (detector scintillator material) as a function of the e^- kinetic energy.

2.9 Tomography (Simulations/Experiments)

The working directory is `Tomo`.

Sample 1. This part concerns the study of the sample 1 represented in the figure 4. Images can open in **ImageJ**. A visualization with orthogonal views for the tomography files is available in `Image` ⇒ `Stacks` ⇒ `Orthogonal Views`. Proceed as follows:

1. Study the sample from its tomography first. Note and size the most important defects. NB: to measure or zoom in the orthogonal-view mode, duplicate first the slice (right click in the window) before processing the slice.
2. Try to find these defects in the sinogram (set of projections) used to acquire the tomography
3. Make the radiographic testing to try to detect the defects seen in tomography.

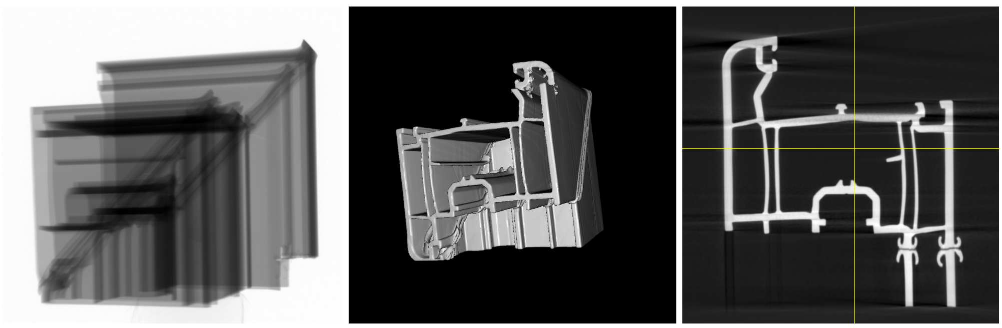

Figure 4: Sample 1: one acquisition (left) and one 3D slice of the reconstructed volume (right).

Sample 2. Repeat the same procedure as for sample 1: study of tomography, then that of the sinogram, and finally radiographic experiments. Conclude the detectability of defects in X-ray radiology according to the type of imaging (projection, tomography) and the geometry of defects.

2.10 Industrial radiography (Experiments)

Choose some aluminum casting parts. Perform the radiographic testing by choosing the voltage and intensity. The interpretation and identification of defects will be seen on-site through comparison with ASTM reference pictures (American Society for Testing and Materials). The ASTM reference digital snapshots are on the desktop in the **ASTM** directory. Make a *drag-&-drop* of these **tif** files in **ImageJ** to open them.