TEMPORAL DELTA COMPTON CAMERA: PRINCIPLES AND HOW TO USE IT

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CONTENTS

1. Temporal Compton camera: How does it work?

1.1. Compton camera principles

A Compton camera makes an image of gamma rays by using Compton scattering.

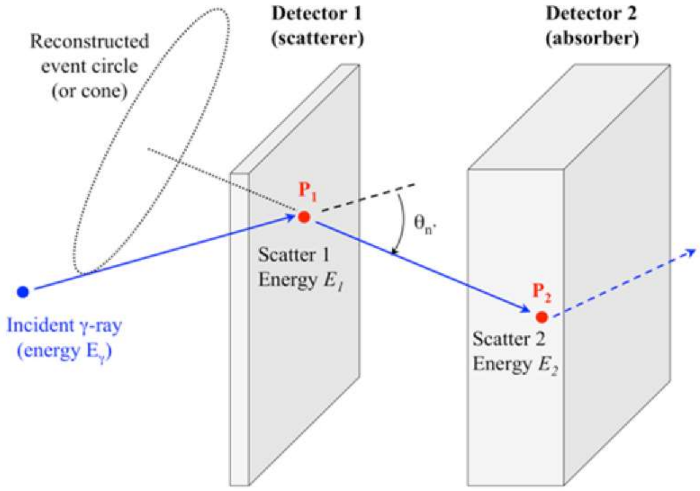
This type of imaging requires a high probability of Compton scattering, hence a gamma ray whose energy is of the order of the electron rest mass (511 keV). It works best above 300 keV. The performance of this type of imaging improves with higher energy in the range 300 keV-2000 keV.

A Compton event that is valid for imaging is characterized by the following sequence of events:

- The gamma photon enters the scattering plate (thin plate) with an energy E_γ. It is scattered in P1 by an angle $\theta = f(E_1/ E_\gamma)$ and deposits the energy E_1.
- The scattered photon is completely absorbed in the absorber plate in P2 and deposits the energy E2, thus : $E_\gamma = (E_1 + E_2)$
- In this case, the photon angle of incidence was on a cone whose axis is P1P2 and whose angle is θ.

Invalid events can be discarded in our temporal system if:

- ○ The relationship $\theta = f(E_{1/}\ E_\gamma)$ is incorrect (partial energy deposition)
- ○ The events P1 and P2 are not within tight time limits (<300 ps).



1.2. Temporal imaging specificities

Most of Compton cameras today are using semi-conductor detectors i.e CZT.

Those systems:

- Have a good energy resolution (1,1% on ^{137}Cs),
- But the detector is typically small (<10 cm^3), hence their efficiency is low.

- And are quite noisy:
  - The signal inside the detector is position dependent,
  - The time resolution is very poor (tens of nanoseconds), no time veto can be used to discard pile up events.

Our camera is the only one to use monolithic fast scintillating crystals (CeBr3), read-out by digital Si-PM and to use timing information for photon location.

The table below shows the differences in technology between our camera and CZT ones:

	Polaris 400	Temporal V2
Detection principle	Direct conversion CZT	Scintillation(CeBr3)/D-SiPM
Detector shape	Pixel	Monolithic crystal
Volume	10 cm^3 CZT	17cm^3 CeBr3
Type of image reconstruction	Compton Camera + coded mask (low énergy)	Compton Camera coded mask planned in 2021

This brings the following advantages:

- High detection efficiency (17cm^3 of $CeBr_3$),
- Very low natural radioactive background, ($CeBr_3$)
- Narrow time veto window (<300ps).
- High stability photon counts

Besides, we are using new position algorithms in monolithic crystals that use time distribution, not just photon distribution. This brings:

- Access to DOI (Z) inside the crystals
- Very precise positions (<1,5mm in X, Y, <3mm in Z/DOI)
- High homogeneity in detector response across detector.
- While keeping a good energy resolution for a scintillator (<7% @ 662 keV)

Our Camera is thus completely different from anything existing in the market and has the following advantages:

- Good spatial resolution (6-8° depending on energy),
- Capacity to make reliable images of extended or complex sources,
- 30% to 50% faster acquisition for high activity sources above 400 keV,

- Capacity to make images of very weak activity down to natural background (for example ^{40}K in flat glass), although this requires long acquisitions: We don’t create photons!
- High stability in photon counts allowing quantitative studies.

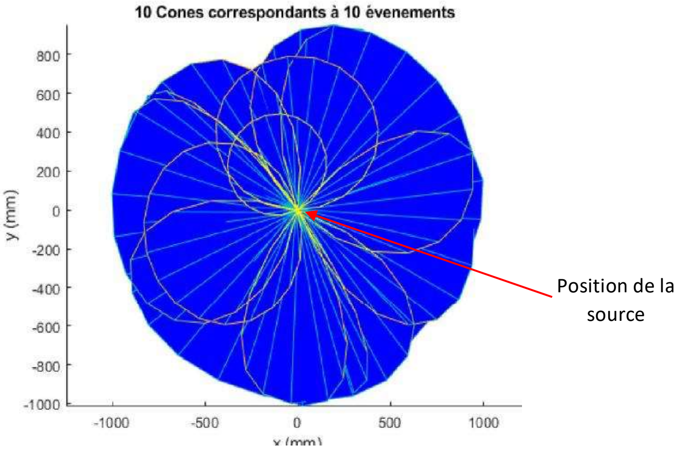
1.3. Compton image reconstruction

As we have seen earlier, for each valid photon detected, Compton imaging provides a cone which includes the direction of the incidence of the photon.

Various error sources (in energy, position…) can be modeled as a finite thickness for the walls of the cone.

If two photons are detected from the same source, there are two valid solutions regions, which are organized around the line of intersection of the two cones.

If more photons are detected the position of the source is the most probable intersection region.



Hence, **Compton image reconstruction is a statistical process.**

As a rule of thumb, you need 50 photons to be sure of the position of a single source with a single view. You need less in Multiview mode.

Our camera is using LM/MLEM algorithms to narrow down the position of the source using statistical treatments.

But it remains: The higher the statistics the better the image.

That is why in **all our images, a photon count is showing how many photons have been used to produce the image.**

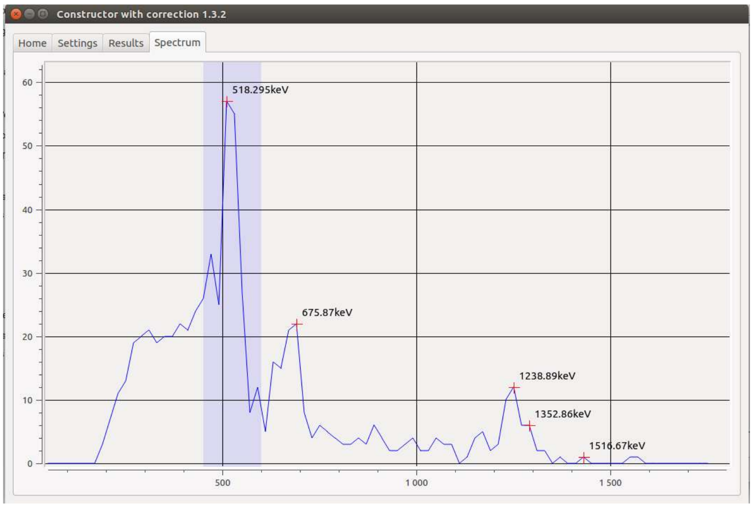
1.4. Summary of the pro & cons of a temporal Compton camera

Strengths	Weaknesses
No shielding	Ambiguity of image reconstruction • two intersection by pair of cones • Propagation direction (not for temporal)
High detection efficiency	Image reconstruction artefacts at low counts
Large angular acceptance	Requires heavy calculation real time
Wide energy dynamic range for imaging	Spatial resolution inferior to PET, but continuously improving.
Specific to Temporal imaging : • The best angular resolution possible… for gamma rays above 511 keV • Excellent ratio signal/noise • High stability photon counting • **Possibility to create 3D views from 2 images widely separated in angle.**	

2. Spectra obtained with the temporal δ camera

The spectrum obtained by our camera V2 is not a standard scintillation detector spectrum. It is a Compton sum spectrum. It only records photons that:

- Have been seen simultaneously by the 2 detector plates,
- Meet the Compton equations,
- Are above 200 keV or so.



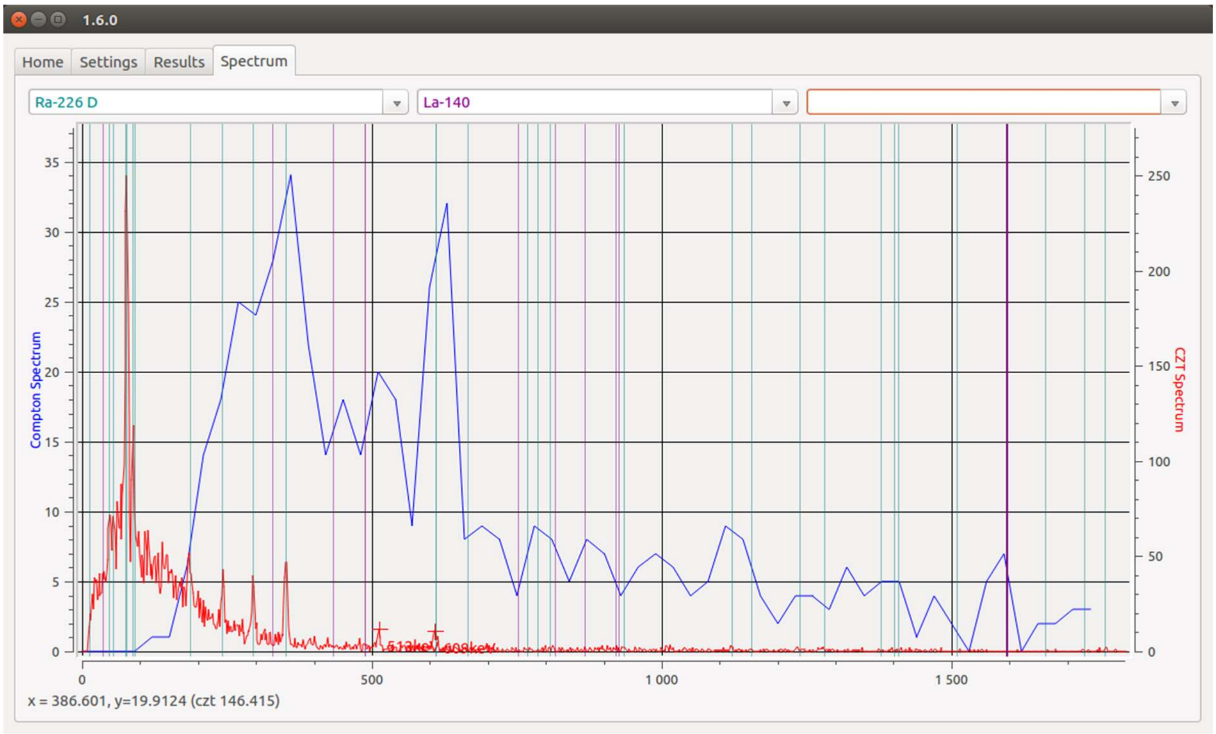
This has some interesting consequences:

- Time veto conditions are so strict that any valid event is a real gamma ray photon.
- Initially you don’t care about radioactive contamination outside the Field of View.
- Partial energy deposit (i.e. photons of 1,3 MeV deposing only 1 MeV in our detector) are mostly excluded from the image and the spectrum.
- Thus, isotopes energy peaks are visible even if statistics are poor.
- The photons in the Compton continuum are mostly photons scattered in the vicinity of the source (If you have a 1,3 MeV main peak and you see a 1 MeV photon, it’s probably a 1,3 MeV photon scattered by a piece of structure close to the source : hence you can image scattered photons.

The sum spectrum is corrected for various effects (acquisition temperature shift, detector saturation….).

If you use a V3 camera there is a second spectrum in red which is obtained with a small (0,5 cm3) spectrometric CZT detector. This spectrum complements the information obtained with the sum spectrum:

- With it’s higher energy resolution, the CZT spectrum allows easy Isotope identification
- This in turn allows you to identify the best available gamma line to image a given isotope
- Being mostly sensitive at low energy (<300 KeV) where our camera is blind, it allows us to have a complete sense of the radiative environment and basic radiometry.



Ra-226 D

La-140

x = 386.601, y=19.9124 (czt 146.415)

3. Launching an acquisition with Temporal δ

3.1. Cooling and performance

Our camera is using digital Si-PM’s. This type of detector is a time resolved (40ps) photon counter. It has very high timing performance and good quantum efficiency, but doesn’t work well at temperatures >0°C. Besides, acquisition heats-up the detector and degrades metrology. Thus, temporal Compton camera needs active cooling.

While starting the camera you must wait till the detector temperature is <0°C. This takes less than 2 minutes usually. Then a calibration of the Si-PM gains is done: it’s called VBias. This calibration is temperature dependent.

From that point onwards, all adjustments for temperature shifts are compensated automatically.

But the lower the acquisition temperature, the better the performance of the camera will be.

Once the camera is calibrated, you do not need to recalibrate (Vbias) to run a new acquisition if camera temperature is stable (+/-2° from Vbias).

The only case where a recalibration could be useful is if the temperature during your acquisition is more than 3° offset from Vbias temperature (ex: doing a Vbias at -5°C and having the camera operating at -10°C) and if you want precise photon counting. Manual Vbias is available on the software through a right click on “Camera”.

3.2. Acquisition software

Once you have started your camera you need around 5 minutes to wait for the detector to cool and followed by calibration. This step is driven by the software ATLAS, so you don’t need to get involved. To get more details, please refer to the ATLAS user guide.

Here are the operations the camera will go through:

- Connection between the camera and the processing unit is using a fixed IP adress
- Acquisition folder creation. During this step:
    - The camera detectors are powered up,
    - Followed by calibration,
    - A file is selected to store the data (optical image and valid Compton events),
- Vbias: this is the detector calibration step. It takes about 1 minute. The temperature of the detectors should be <0°C for Vbias, otherwise the performance of the camera won’t be optimal. Thus the software waits till the camera cools to 0°C to start Vbias. The lower the temperature, the better the performance. If the temperature has shifted since Vbias, you may consider launching a Vbias manually.
- Acquisition duration: this is a key parameter. If the acquisition is too short you won’t get enough valid photons and the image will be poor. We thus advise you to **start with a 60 second acquisition of a scene.** Then you see in reconstruction results how many photons you have and a crude spectrum. A good quality image requires 200 photons for a single source, more if the source is extended or multiple. 50 photons/source is a minimum. So adjust the duration after this first test.
- Acquisition: once you start it takes 20 seconds to see the data coming in. During those 20 seconds the calibration is fine-tuned and an optical image is taken. When the measurement stops, the time should be around 80 seconds (the camera doesn’t take into account the 20 seconds dead-time)
- De-activation: When your observing run is finished, you should de-activate the camera and shut it down before switching off the power.

Except at very high-count rates, the image reconstruction runs in parallel to the acquisition. By default the gamma image is refreshed after each batch of 50 photons. Of course the first image can be noisy because of low statistics if there is more than one source. Just wait.

3.3. Image reconstruction software

3.3.1. The variables for the user

The camera “optical” variables are calibrated during manufacturing. Those variables are listed in a special tab (settings see 3.3.6). They will also be provided on paper with the camera testing report.

If those variables are changed, the images will be bad. This table appears because you may need to adjust those parameters following a camera recalibration each year.

Your camera must be recalibrated once a year.

The main variables you should play with while using the camera are the following

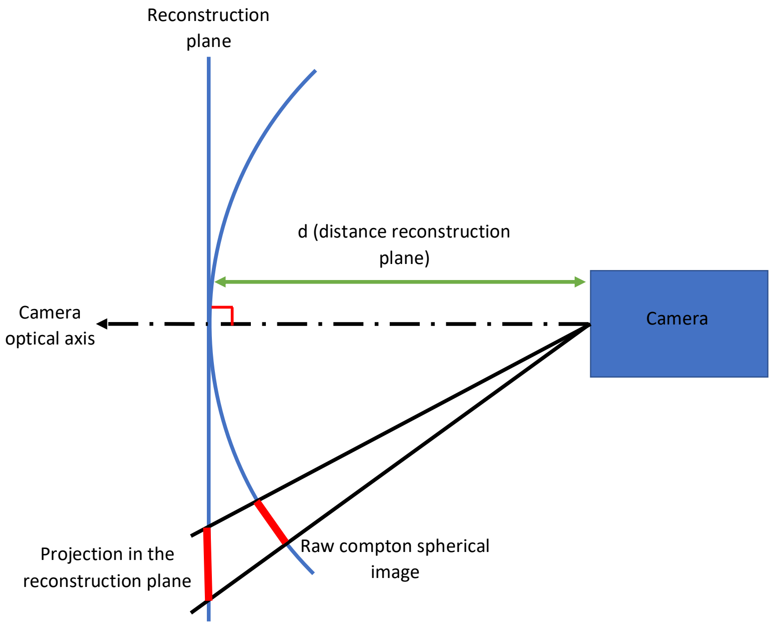
- Distance to the source (semi plane size), (see 3.3.2)
- Type of image Overlay Gamma on visible vs Gamma image only
- Sharpness parameter: number of iterations LM/MLEM, (see 4.3)
- Energy range for imaging (4.4).

3.3.2. What distance indication is used for

Our Compton image reconstruction software creates a spherical image. On this image, we position the source in angular deviation (θ, ϕ) from camera axis.

This image is then projected on a reconstruction plane, which is perpendicular to the camera gamma ray optical axis.

The semi plane size (d) you must enter in the image reconstruction is the distance between the Compton Head and the reconstruction plane.



The distance of the source (Z) is measured through a telemeter. But the telemeter is distant from the Compton camera axis. Thus the distance given by the telemeter may not be the source distance. You should thus check if the distance is correct before starting the acquisition.

On the spherical image, not knowing Z does not create errors on the position of the source.

But for visualization purposes, the spherical image is projected on a plane which is perpendicular to camera axis.

The optical image is also projected on the same plane.

Thus, if you give an incorrect value of distance, the source will appear displaced from its real position on the optical image.

You must give a distance to the reconstruction plane prior to launching reconstruction.

If you are seeing the source offline to the camera axis (say a source **45° offline at 1 meter**), the distance to consider is the distance between the plane of the source and the camera. **In this case the distance is 0,7 meter, not 1 meter.**

The number of photons detected from a given source at a distance r falls off as $1/r^2$.

If the source is off-axis, it is more distant that the reconstruction plane, thus it will appear fainter than a source along the axis. You should take that into account when estimating the source activity.

So try to aim your camera so that the main source is on camera axis: You'll have a better image.

3.3.3. Spectrum

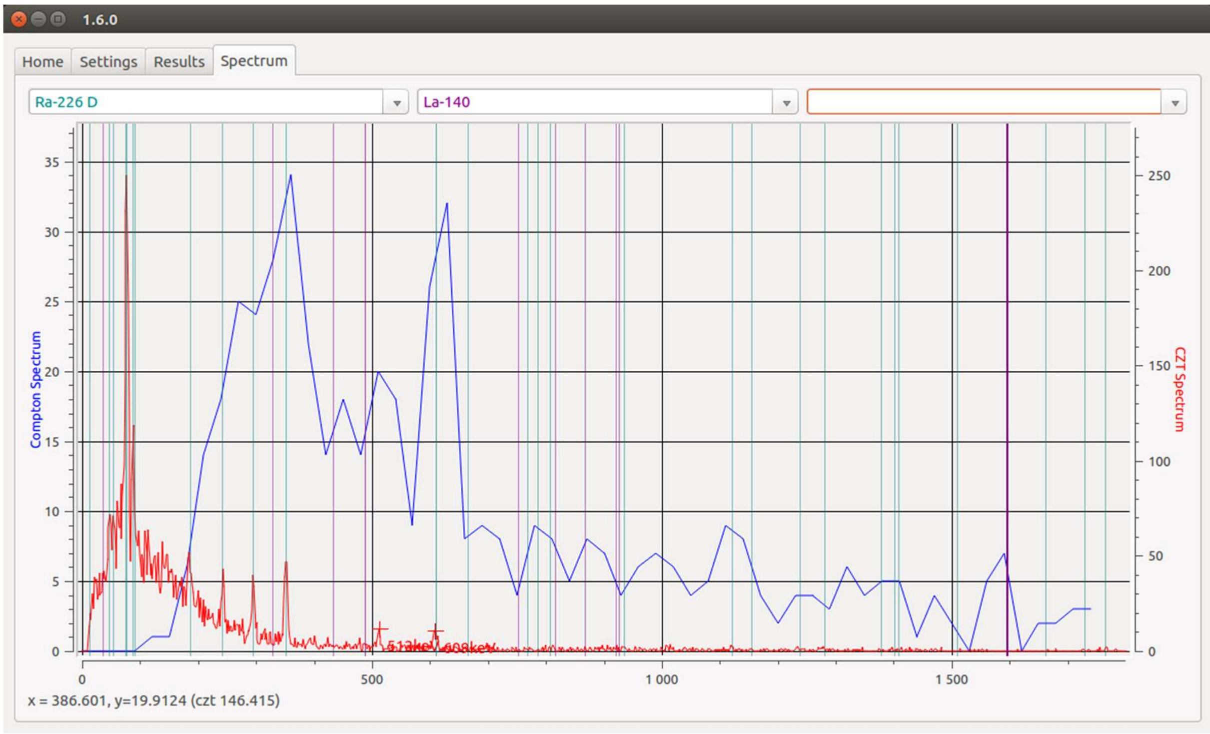
One of the outcomes of a measurement with our camera is a Compton sum spectrum. It's not a classical scintillation detector spectrum as we have seen earlier.

It records only the photons that are coincident in time and are used for imaging. Thus:

- It excludes all photons <200 keV.
- It excludes most photons that deposit only part of their energy in the scintillator: Hence the peak/background ratio is higher than in a classical spectrum.
- … But statistics are low: Only 1% of the photons crossing the detector go to this spectrum.

This spectrum enables to identify the main radio-elements present and to select an energy range for imaging. The camera has a database of the 200 most common radioisotopes and the gamma emitting isotopes from Uranium and Thorium decay chains. If you know which isotopes are present, you can select them from the database. If you don't know, you can scroll down the database till you find a match.

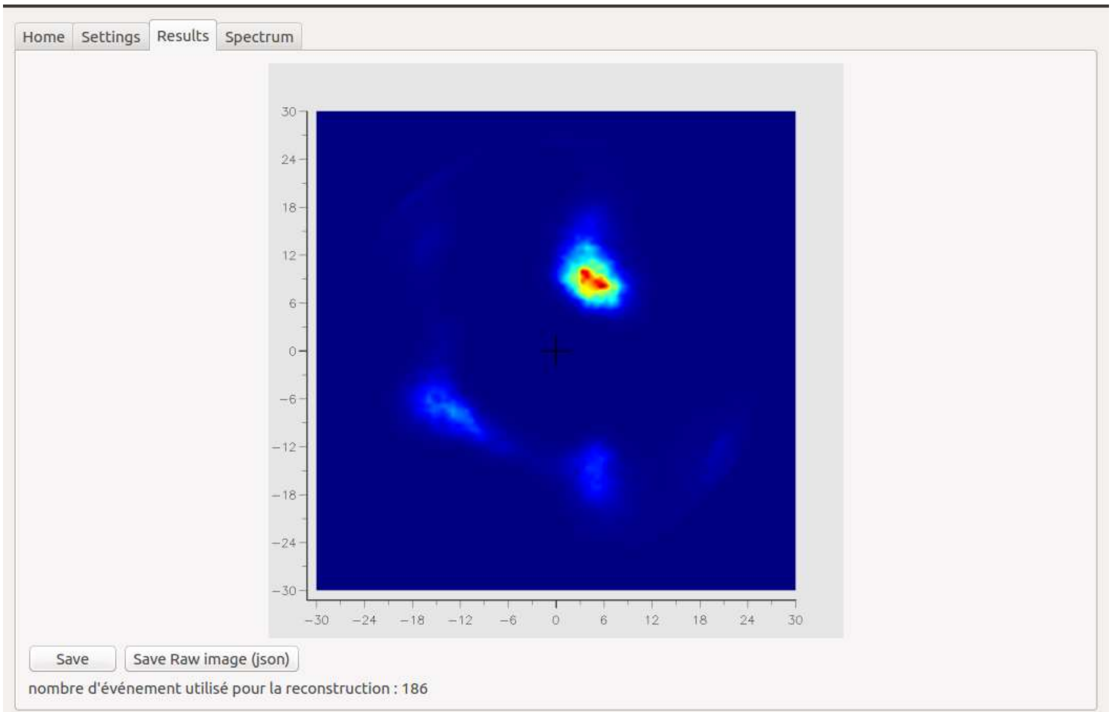
The spectrum below is from an old clock with Radium painted hands. You see the gamma lines from Ra226 Decay (Ra226D) and La140 as the phosphor is probably Lanthanum phosphate doped with Europium



x = 386.601, y=19.9124 (czt 146.415)

3.3.4. Results: Gamma -ray image (no overlay)

By default, you see the gamma image superimposed on the visible image. But the visible image has a slightly different field of view than the gamma image. Sometimes, it's useful to see the gamma image. Here is an example of a Gamma image.



nombre d'événement utilisé pour la reconstruction : 186

3.3.5. Results gamma ray image with Overlay

As a standard product you'll see the gamma image superimposed on the image taken by a visible camera located 65mm above the Compton camera axis.

The slight mismatch between the optical and gamma ray axis can create some inaccuracies in the overlay. Besides, when the object to observe is less than 30 cm distant from the camera, it may not be well visible in the visible image.

Hence if you want to make an image of a source closer than 30 cm try to put the object to image along the optical axis, not the gamma axis.

The camera records a good image even with the source being close. We have successfully imaged a mouse from 8 cm.

3.3.6. Camera settings

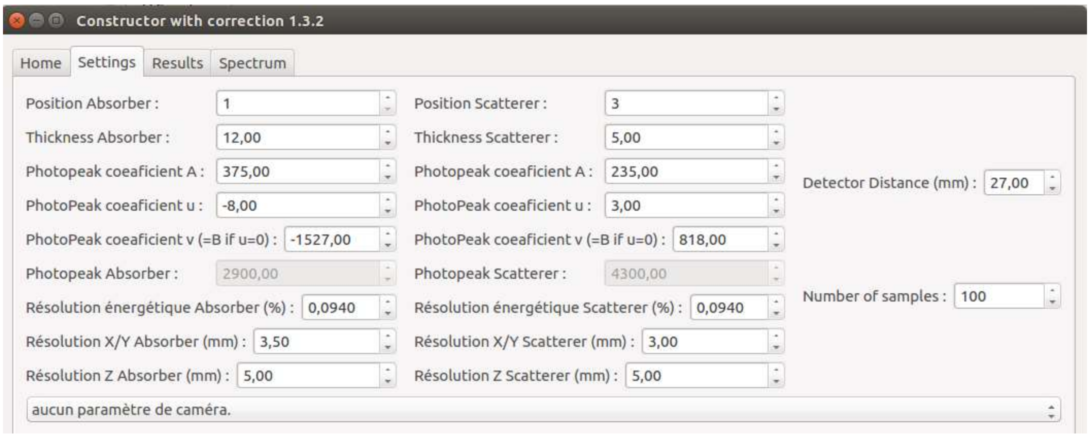
The tab setting is for experts only.

It is filled in by the constructor during the camera calibration steps.

It contains all the parameters that characterize the optics of your camera and the various corrections done by our software.

This table is given to you with the camera. In case you suddenly get bad images verify if those parameters have not been changed.

This tab should only be modified after recalibration of your camera (one recalibration/year).



Position Absorber : 1
Thickness Absorber : 12,00
Photopeak coeaficient A : 375,00
PhotoPeak coeaficient u : -8,00
PhotoPeak coeaficient v (=B if u=0) : -1527,00
Photopeak Absorber : 2900,00
Résolution énergétique Absorber (%) : 0,0940
Résolution X/Y Absorber (mm) : 3,50
Résolution Z Absorber (mm) : 5,00

Position Scatterer : 3
Thickness Scatterer : 5,00
Photopeak coeaficient A : 235,00
PhotoPeak coeaficient u : 3,00
PhotoPeak coeaficient v (=B if u=0) : 818,00
Photopeak Scatterer : 4300,00
Résolution énergétique Scatterer (%) : 0,0940
Résolution X/Y Scatterer (mm) : 3,00
Résolution Z Scatterer (mm) : 5,00

Detector Distance (mm) : 27,00
Number of samples : 100

aucun paramètre de caméra.

4. Gamma Images: understanding what you see

4.1. Gamma images vs visible images

As Gamma radiation is highly penetrating, a gamma image always has a poor angular resolution. Our camera gives the best spatial resolution on the market above 511 keV.

As we have seen earlier, a Compton imager doesn't give per se the position of each photon. What you see is a map of the probability of a source being there.

This type of reconstruction is prone to artefacts (false positives) if statistics are low or if the radiative situation is complex.

Hence the more photons in the image, the better the statistics and the more accurate the image will be. As a rule of thumb you should see at least 50 photons from a potential single point source.

High energy photons can be scattered by dense material in the scene surrounding the source. In that case those photons appear at an energy lower than initial.

Hence to observe a radiative source position you must gate the image on the peaks emitted by the source if you want to discard diffused photons and have a precise position.

4.2. Overlay Gamma image on visible image

This is visible in the results tab of the reconstruction software

The Temporal δ Camera is equipped with a binocular optical camera in order to overlay the gamma image on the visible image. The Gamma image is a flat field image. Optical images have some deformations at the edges.

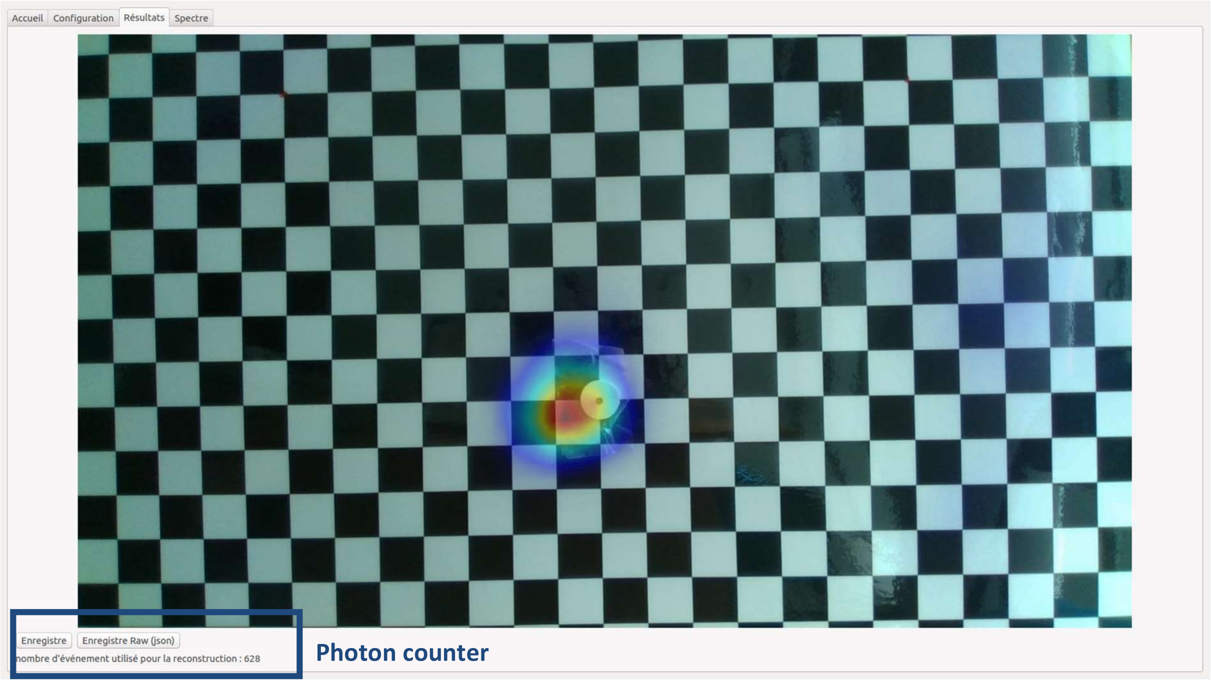
The gamma image is wider (90°x90°), the visible image is:

- (69°x42°) for Temporal V2
- 95 x95° for Temporal V3

There is a slight mismatch between the gamma axis and the visible axis. This is compensated for by the software, but not perfectly yet.

There is no size indication in the visible image, but there is one in the gamma image.

It is possible to only have a gamma image.



nombre d'événement utilisé pour la reconstruction : 628

Photon counter

4.3. Sharpness Factor: single source vs extended source

As we have seen earlier, gamma ray images are probability maps. Temporal δ Camera is using an advanced smoothing procedure called ML/MLEM to bring out small details from statistical noise. This appears in the tabs as “Sharpness factor”.

This is a very important tool to get the best performance from the temporal camera.

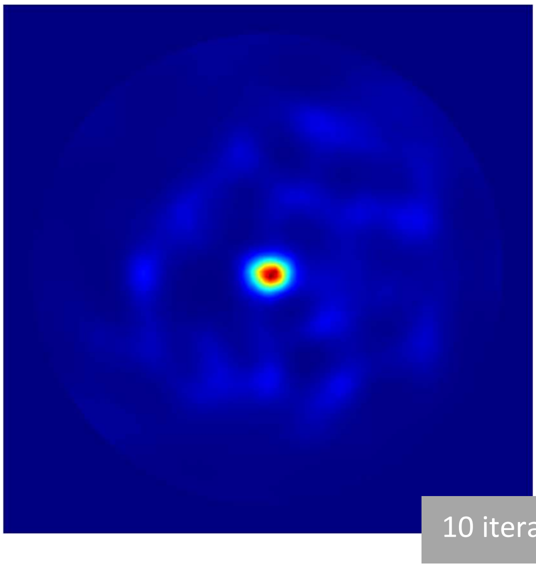
You can play on this sharpness factor by changing the number of LM-MLEM passes:

- N=1 : No smoothing here you see the retro-projection image. It is very fuzzy! **Not recommended except for severe under-sampling of an image** (<20 photons/voxel).
- N=5 low smoothing: This is of interest only if you have an extended source and a very low number of photons (<300)
- N= 10: this is recommended as a default first run: this brings out significant details. Fails only for extended sources when the number of photons is low.
- N = 30 recommended on gated imaging on single sources to get the best position possible.

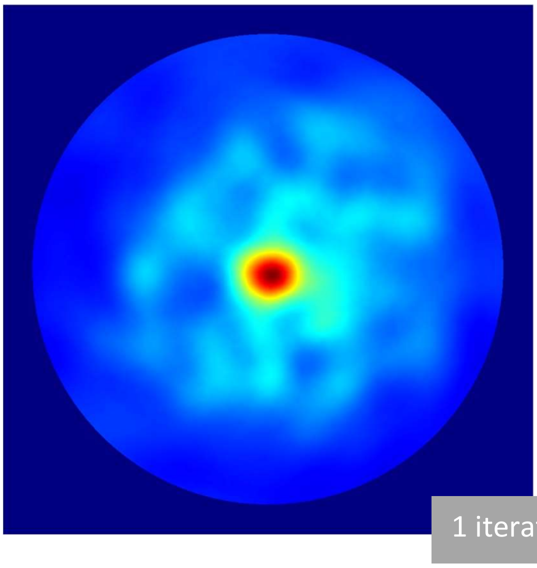
The camera is equipped with an automatic setting of the smoothing factor. It’s a good start but with some practice you’ll get better images by choosing manually.

We’ll show you the result of sharpness factor on the image of a point source and an extended one. This gives you an idea of the size of a point source. Any source wider than that is extended. All images here are at the same angular size

- The point source was ^{137}Cs.



10 iterations

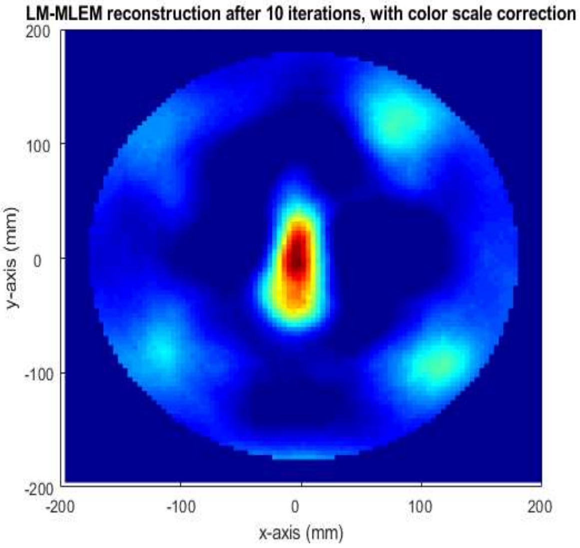


1 iteration

In an extended under-sampled image smoothing make it appear like a collection of point sources. But the problem disappears if sampling is correct.

Below we have an image obtained at Bruker of a Cylinder 180 x30 mm filed with 18FDG (Observed in 511 keV lines): 18.000 photons, Number of iterations = 10.

The overall shape and enhanced emission in the center of the cylinder is correctly captured.

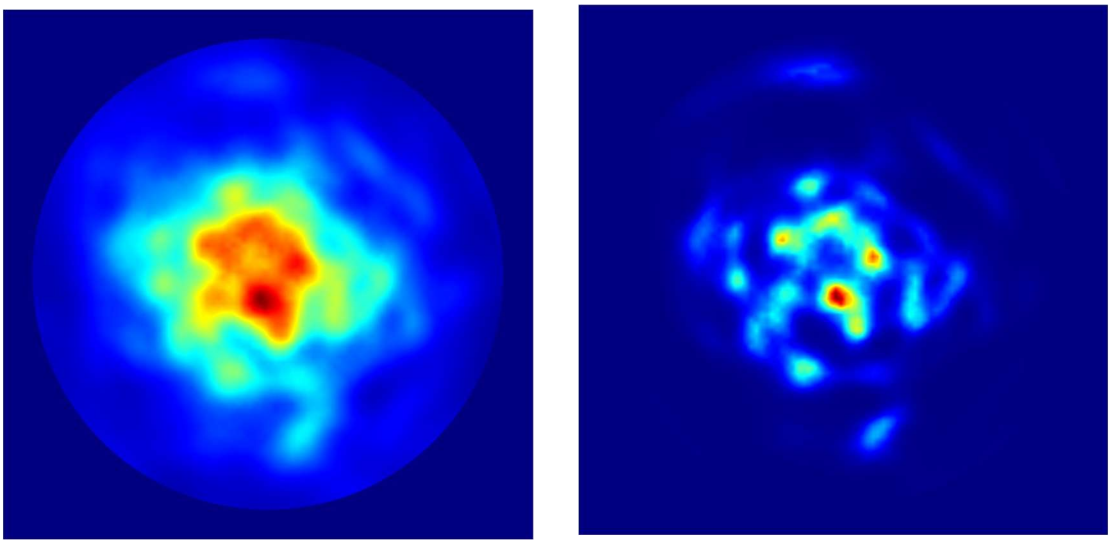


LM-MLEM reconstruction after 10 iterations, with color scale correction

Below is the image of an extended Uranium source obtained on the 1 MeV line of ^{234}Pa. There are only 350 photons in this image, thus it is massively under-sampled considering its size (25°x25°).

The image on the left is with a smoothing parameter of 1 and gives the correct size

The image on the right is with a smoothing parameter of 10 and breaks down in a collection of point sources.



4.4. All energy imaging mode

This is the default mode of Temporal δ camera.

If you face an unknown radiologic scene, you could use the "all energy" imaging mode. In this mode the camera will record every photon that satisfies the Compton conditions from 400 keV or so till 2 MeV. This type of image records all the valid photons. It is thus helpful to estimate the radiologic situation. It could also be helpful when statistics are low. It also allows to quickly detect the position of hot spots.

The drawback of this type of image is that:

- You record all isotopes at once while you may only be interested in some of them.
- You record photons scattered by the surrounding of the source: this smears the image.
- **The spatial resolution is lower in this mode as unwanted photons interfere with images**.

4.5. Gated energy imaging mode

You access this mode by selecting an energy range in the image reconstruction software.

It's the mode that gives the best images.

You should watch the sum spectrum before making your selection.

The narrower the energy range around the peak:

- The sharper the image
- The lower is contribution from scattered photons
- But the lower also is the statistics

Thus after doing your selection you should check if the number of photons is correct.

If the number of photons recorded in a given energy range is below 100, your selection is too narrow.

Given the energy resolution of our camera an energy range +/- 30 keV to 50 keV is optimal.

- For Cs 137, depending on statistics you will choose 600-700 keV or 630 to 690 keV

The best imaging is always obtained on the highest energy peak that gives enough statistics. Doing that, the contribution of scattered photons is minimal.

- For example imaging ^{60}Co, the best images are obtained with the 1,3 MeV energy peak

4.6. Actual example imaging of a radioactive waste drum

Let's see how to use the camera when imaging a drum of radioactive waste (mostly ^{60}Co). The image was done at Andra (French waste agency) at a distance of 1,3m from the center of the drum with a 20 minutes acquisition. The ^{60}Co activity was 4,5 MBq

For this drum, we have:

- a radiography done by Andra which shows the content of the drum,
- a full energy image (400 keV-2000KeV) acquired with our camera,
- an image done with the 1,3 MeV 60Co line.

In this image we see 3 main components (starting from bottom):

- a pile of ashes,
- a dense filtration medium,
- a diffuse filtration medium in the upper third.

Radiography of the drum

The orientation of this image compared to gamma image is unknown, but seems reasonably similar.

Full energy image (400 keV- 2000 keV): 4 000 Photons

The main interest of the “all energy” image is to quickly acquire a complete sense of the radioactive situation (here 4000 photons).

In this image, we clearly see a halo around the drum. This halo comes from ^{60}Co photons scattered by dense elements in the background of the drum. This halo is denser where metal is present close to the radioactive source.

This halo makes the interpretation of images complex, but it is not an artefact: you can make an image using only scattered photons.

If you are only interested in a rough estimate of the total activity and rough location of the activity in the lower third of the drum, you can acquire an “all energy” image in 2 minutes. (400 photons)

Image done on the 1,3 MeV 60Co line: 400 photons

Here we see only the activity of ^{60}Co.

The image is much clearer, because most scattered photons are excluded.

Comparing this image with the radiography, we can see that the second component (dense filtration medium at the bottom of the drum) concentrates the activity of ^{60}Co.

There does not seem to be any ^{60}Co in the upper third of the drum.

The outline of the inner drum is visible. Could be from scattering. More probably it comes from ^{60}Co dust deposition inside the inner drum.

Any shorter acquisition would not show as many details.

Good image requires statistics hence some minutes of pause! Be patient!

Conclusion:

This example clearly shows that the information extracted from a gamma image is different from what you can learn from a radiography.

Like in medical imaging, radiography gives the anatomical situation. Gamma ray imaging gives the activity map.

Radiography and gamma ray imaging are thus highly complementary.

5. Imaging Uranium products

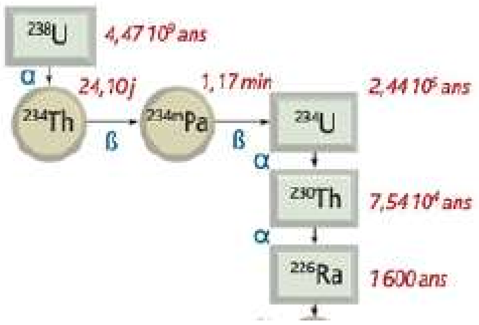
Uranium is the nuclear fuel, yet it is a special case for imaging with our camera:

- U 235 main line is at 185 KeV
- U 238 doesn't have any significant gamma emission.

So none of the uranium isotopes is seen with our camera! Doesn't't' work?

Yet we've been able to image 20g of uranium retention in steel tubes! How?

When an atom of ^{238}U disintegrates, it does so in ^{234}Th then in Protactinium 234.



Protactinium 234 has gamma lines between 650 keV and 1000 KeV and thus can be observed. The decay period of ^{234}Th and ^{234}Pa are brief enough that those isotopes are in secular equilibrium with ^{238}U in industrial situations. We can even use those lines for quantification of Uranium contamination.

Bismuth 214, from the same decay chain, is also seen in older plants. It can be used for uranium imaging, but not for quantification.

The table below compares a Compton camera with other options for observing Uranium in industrial context:

- α,β counters that allow mapping by contact measurements but not imaging
- Coded aperture imagers: they have found limited use so far.
- Compton camera: the new solution

For mapping of shielded contamination, a Compton camera, even if the efficiency is low, is the best solution because it sees well through shielding.

For mapping surface contamination, a Compton camera is slow but allows to analyse large surfaces while staying distant from the contaminated area. Scanning is also quite straightforward to automate.

Coded mask 185 keV	Imaging from distance, Strong line of U235	Narrow field of view (30°x30°), lot of gamma noise (diffused photons…), ambiguity of reconstruction	Imaging from distance, Strong line of U235	Absorption of 185 KeV line in steel, diffusion creates halo around the source
Compton camera 234Pa	Imaging from distance, Wide field of view (90x90°), unambiguous images possible, excellent signal/noise, quantification possible	Indirect Uranium detection, Low signal --> long pauses needed	Imaging from distance, Wide field of view (90x90°), unambiguous images possible, excellent signal/noise, quantification possible	Indirect Uranium detection, Low signal --> long pauses needed

Having practiced in an Uranium plant, Compton imaging works superbly for the patient operator (acquisition is fully automated).

6. The camera as a photon counter

The Compton camera acts as a precise and stable photon counter. **It thus allows relatively straightforward quantification of observation**. For a given temperature of the detector, the efficiency can be charted (translating observed photon counts in real photon flux). For a temperature of -8°C, the efficiency of our camera (imaging photons = counted photons) is 0,4%, which is 90% of theoretical value for a Compton camera with our optical design.

For a given energy line and a given V bias temperature, photon counting is very stable from one image to another.

This figure is given below each image in the result tab.

- Total photons are all photons that are usable for imaging
- Used photons are the photons in the energy range you have selected that are usable for imaging.

Both numbers counts the photons that:

- meet the Compton equation (partial energy deposit mostly excluded)
- are in the gamma field of view of the camera. Sources outside the FOV don’t significantly contaminate this figure
- are in the energy range you have selected for imaging
- the efficiency is typically 90% of the theoretical figure given by a Geant IV simulation. And it’s very stable from run to run.

This figure allows quantification of the activity or even the mass of radio-element present with suitable calibration.

If you want quantification, we suggest you to calibrate the counts with a known activity source and to avoid recording images with significant dead-time.

This figure is also very important for the confidence you should put in an image.

7. Dosimetry estimation

The camera also has a dosimetric indication. This indication is calculated using the small CZT detector, as it allows counting the full energy spectrum.

Unfortunately it is far less reliable that Compton camera photon counting.

This indication allows the operator to assess the radiologic risk he is facing.

8. 4 Pi Imaging

A Compton camera has the ability to image all sectors of space with a single head.

Sometimes using a wide field of view (180°) is a way to conceal the poor quality of the images.

Our choice is different. We want a camera that has a field of view slightly wider (90°) than the human vision to be easy to interpret. We also want weak optical images distortions in the FOV.

Our camera is designed to make good gamma images. We have selected an anisotropic design, thus sensitivity is angle dependant. This is corrected for inside the FOV.

With our camera it is never the less possible to identify the presence of a strong source outside the FOV of the camera. We are not making an image, just telling the operator in which sector of the sphere the source is probably located. This allows:

- To warn the operator of a potential risk
- To turn the camera in order to observe this strong source

The impact of a lateral source on camera performance is minimal. In case observation in noisy background is required, a special option of the software allows to electronically cancel sources outside the FOV.

9. Imaging tips

9.1. Estimating the minimal acquisition time

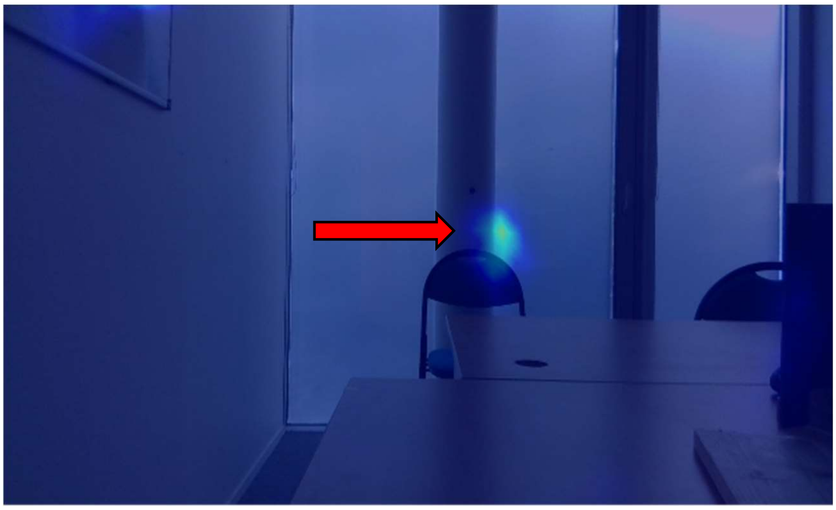
When facing an unknown radiological situation, we advise you to make a 60 second acquisition. Then you'll have a count of how many photons are recorded per unit of time and a very rough spectrum.

If all energy imaging suits your need just calculate the time you need to have around 300 photons for point sources. If you know the source to be extended, you must record more photons (1 000-3 000?)

If you are only interested in a restricted energy range, look on the spectrum to see how many requested photons you have recorded and base the time duration of the next acquisition on that.

9.2. Imaging very low activity sources

One key advantage of our camera is its capacity to image very weak contamination, down to the level of natural radioactivity. We have imaged a 30 KBq ^{137}Cs source at 3 meters!



This advantage comes from the very low level of noise in our camera:

- CeBr3 crystals have low levels of natural radioactivity
- We have a narrow coincidence test (<300 ps) between the 2 plates of our camera, efficiently rejecting most of the noise.
- Cosmic radiation is of no concern as its distribution is isotropic and thus doesn't show up in images

Getting reliable images of low activity sources remains challenging though:

- The number of photons detected per unit of time is low in those situations. Besides, only 1% of the photons going through the detector give a valid Compton event
- The natural background is always present, sometimes in surprising places:
  - ^{40}K in sheet glass or concrete
  - ^{214}Bi or ^{228} Ac in metallic structures: one tends to very clearly see Aluminum structures in a natural background!

There are practical solution for this tough imaging:

- Long pauses (hours) are the key: our camera is well suited for that. This allows to
  - Detect enough photons for an image.
  - Build signal above the noise from natural background
- If possible make a blank image first to understand the structure of the natural background in the surrounding
- Better know the isotope you are searching for: weak contamination doesn't pop up easily in the spectrum, but its spatial distribution is different from the background. If you gate on the energy line of the sought for isotope, you'll see its distribution.

- Make 2 images by slightly (20 cm or so) moving the camera. Background and artefacts won't appear at the same location: the source you're searching for will.

In the near future we'll build a binocular camera dedicated to this application and 3D imaging.

9.3. Lifting ambiguity in an image

Compton images are probabilistic: the higher the number of photons, the better the image.

If you see an image which is ambiguous here are the main tricks:

- Gate in energy (+/- 30 keV): narrowly energy gated images are the best.
- Count longer: longer acquisition lowers the probability of false positives and improves spatial resolution, all the more so if the object is extended (non-point source).
- Come closer: this will increase the number of photons collected and a given object will subtend a larger angle.
- Take a second image from a slightly different point of view in the same plane (moving the camera 20 cm or so perpendicular to optical axis). This is enough to change the distribution of artefacts.

10. Classical errors

10.1. Typical bugs in the image reconstruction system

10.1.1. The position of the photopeak of known sources (i.e. 137Cs) is shifted from the real value

- This happens when the statistics are low = count longer.
- Your camera temperature has shifted since Vbias: redo a Vbias

10.1.2. The position of the gamma source is shifted from its position on the visible image

- Did you give a correct distance for the reconstruction?
- Count longer: position is uncertain for low statistics.
- Our overlay process is not perfect, specially at short distances.

10.1.3. There are a lot of artefacts around the source

- Too low statistics: count longer.
- Are you using the “full energy” mode?
- Reduce the energy range around the main energy peak.
- Maybe there are sources you are unaware off. Move the camera slightly or make a blank.

10.1.4. I can’t see the emission peak I’m searching for in the spectrum

- Try an energy gated image on the emission peak of the isotope you’re searching for! This means that the radio-element emission you’re searching for is weak. If its spatial distribution is different from diffused photons and if statistics are sufficient, you may be able to see it even if you don’t see it’s peak in the spectrum .

11. Warranty exclusions:

- Forcing the power plug in the wrong position.
- Opening the upper half of the camera.

The upper half of the camera contains all the valuable equipment (Compton head, optical system, acquisition and processing electronic cards). Opening this part will probably require a camera recalibration! It is built to be watertight. It contains fragile equipment. You are not supposed to open this part of the camera. This is an exclusion of warranty case.

- Harsh mechanical damage breaking the upper half of the camera.
- Any repair trial not agreed on before by Damavan Imaging.