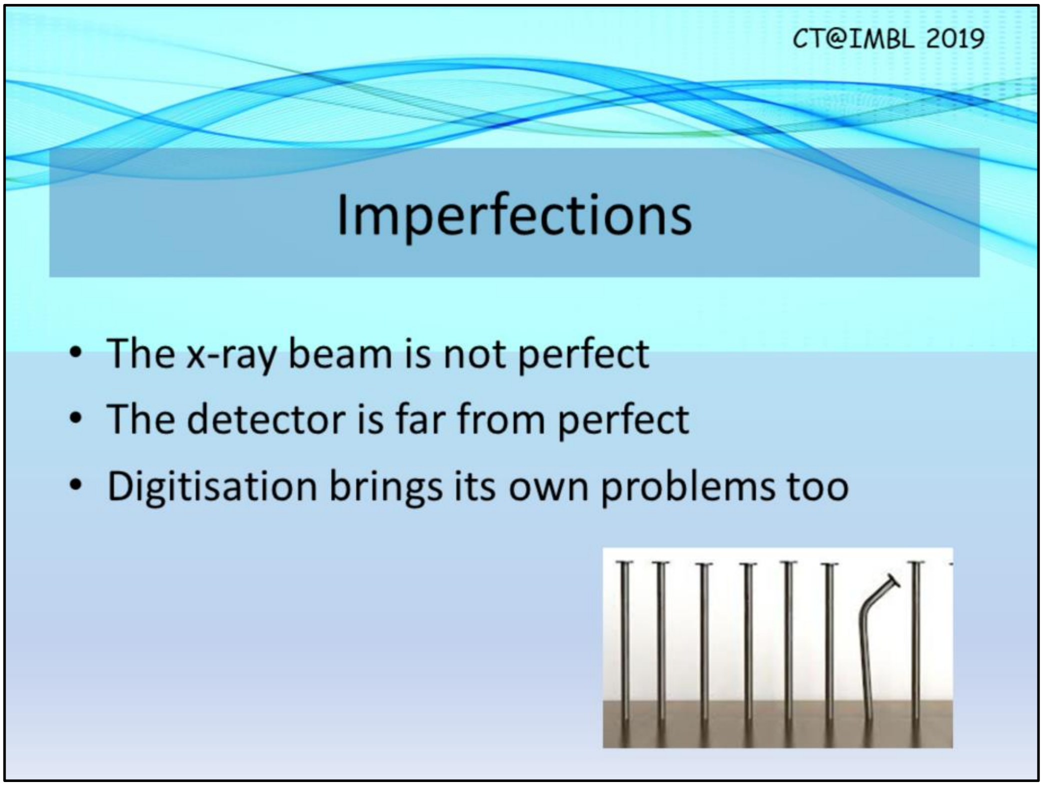
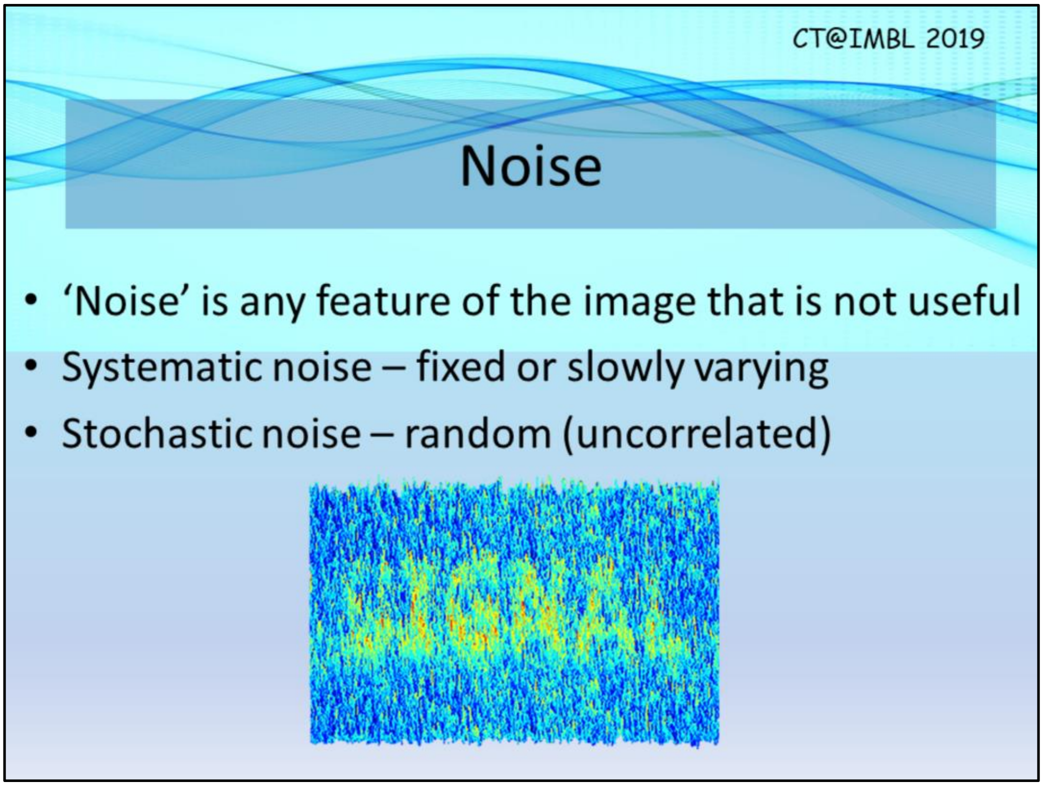
- Like cooking, if you start with great ingredients you will get great results.
- The ingredients for CT reconstruction are the set of 2D x-ray projection images.
- So it’s important to understand how to get the best quality projection set, to then get the best CT reconstruction.
- In this presentation we will explore some of the things that degrade an otherwise ideal 2-D projection image.

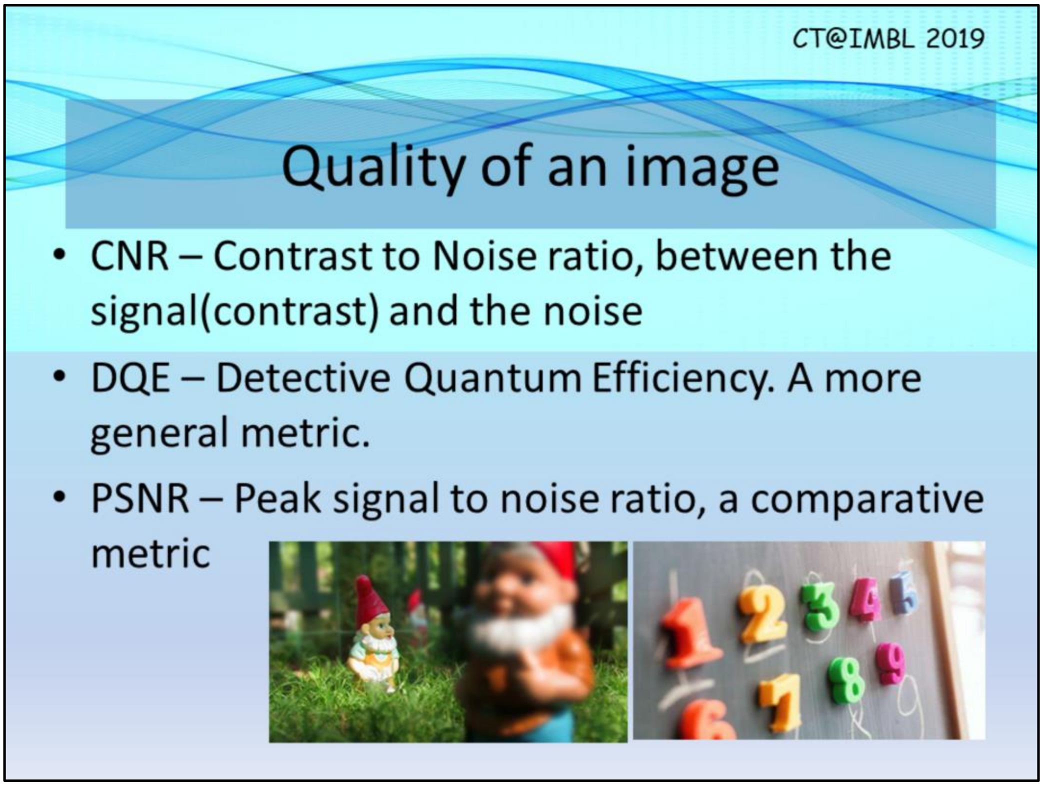


- The synchrotron x-ray beam is fairly parallel when it emerges from the source magnet.
- It does have a divergence, and the source is not infinitely small. (Remember Andrew's talk)
- A quick reminder: The divergence in the vertical direction is small (~0.1 mrad) and larger in the horizontal (~3.8 mrad)
- The source size is about 0.04 mm by 0.5 mm, and in our enclosure 2B it is ~35 metres from the sample.
- One way to think of the beam is a set of infinitesimally thin x-rays. Called the Ray Approximation.
- Rays are straight (don't worry about relativity ☺) as long as they propagate in a vacuum.
- As soon as a ray hits any material they <u>may</u> change direction slightly, or a lot.
- They may also stop dead and propagate no further.
- The consequences are: The rays potentially change a lot when they go through the monochromator.

- The beam never has perfectly smooth boundaries.



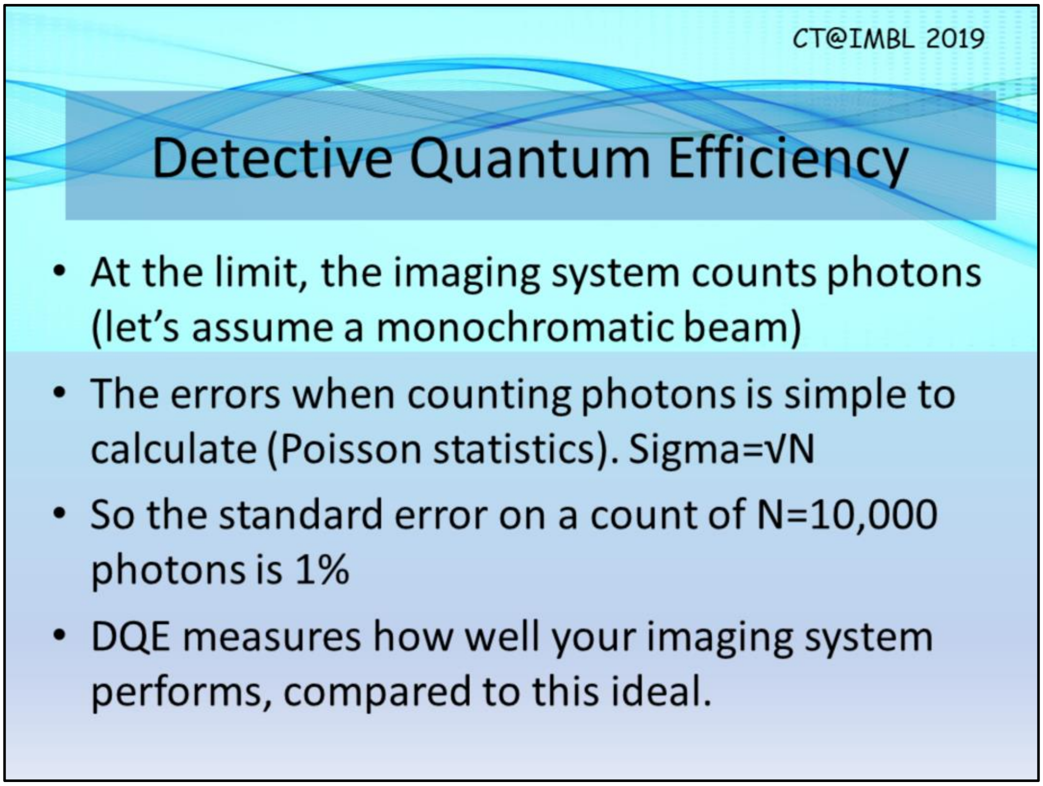
- Noise is a technical term. It describes the component of the measurement that is not useful.
- It arises from both imaging physics and readout electronics.
- It can come from beam scattering. It can come from the way we turn the beam intensity into digital images.
- Some imperfections in the beam and detector cause noise. These don't change much with time.
- Some noise is unavoidably - random.
- To a large extent we can calibrate out the first type of noise called Systematic Noise.
- At this stage we cannot do much about the second, but be aware of it.



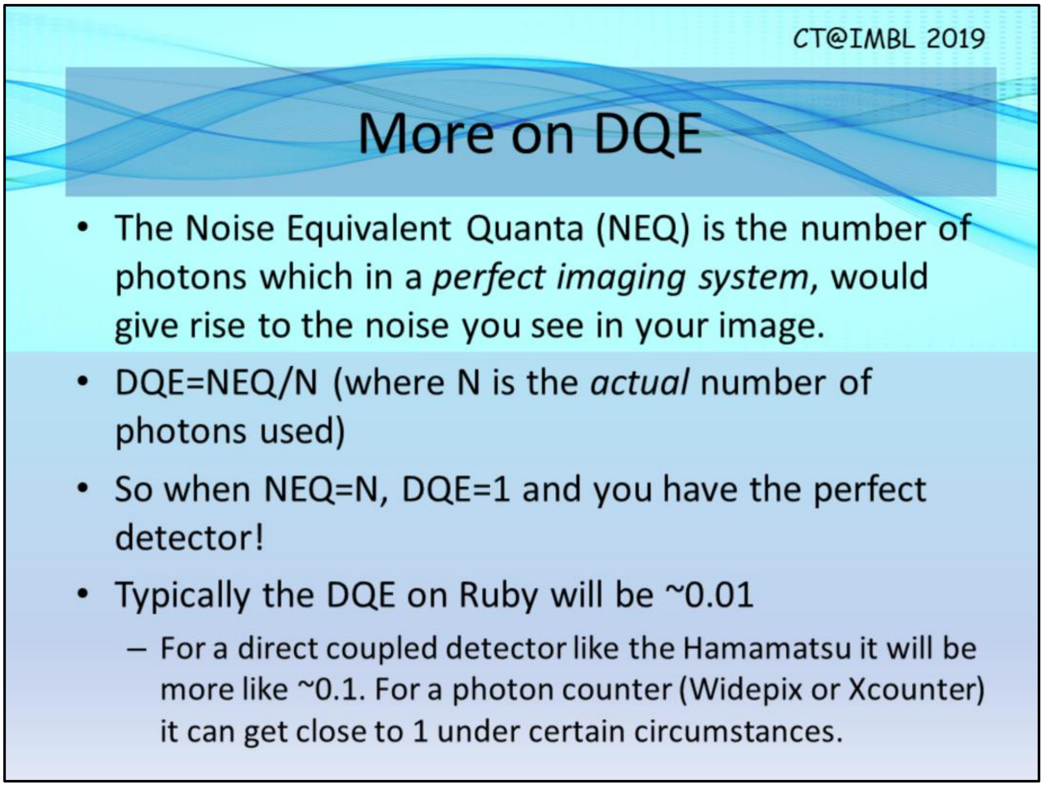
- We would like to quantify how good our images are.
- How to measure how well we are doing, when collecting a digital 2-D x-ray image?
- The basic measure is the ratio between the information (signal) and the noise in the image.
- Image contrast is the most important source of information. Hence we often calculate a contrast to noise ratio (CNR)
- The degradation of image quality due to detection is encapsulated in the detective quantum efficiency (DQE) – more about this later.
- A useful comparative measure between one image and another is the Peak Signal to Noise Ratio (PSNR).
- PSNR is a log quantity describing the ratio of the square of the digitisation accuracy to the mean square error (MSE) between the noisy and perfect images..
- To calculate the PSNR take 10 times the log of the ratio of the maximum value a pixel can have (255 in case of an 8 bit

image) to the MSE.

- PSNR is an *approximation* to human perception of reconstruction quality, but nonetheless useful.



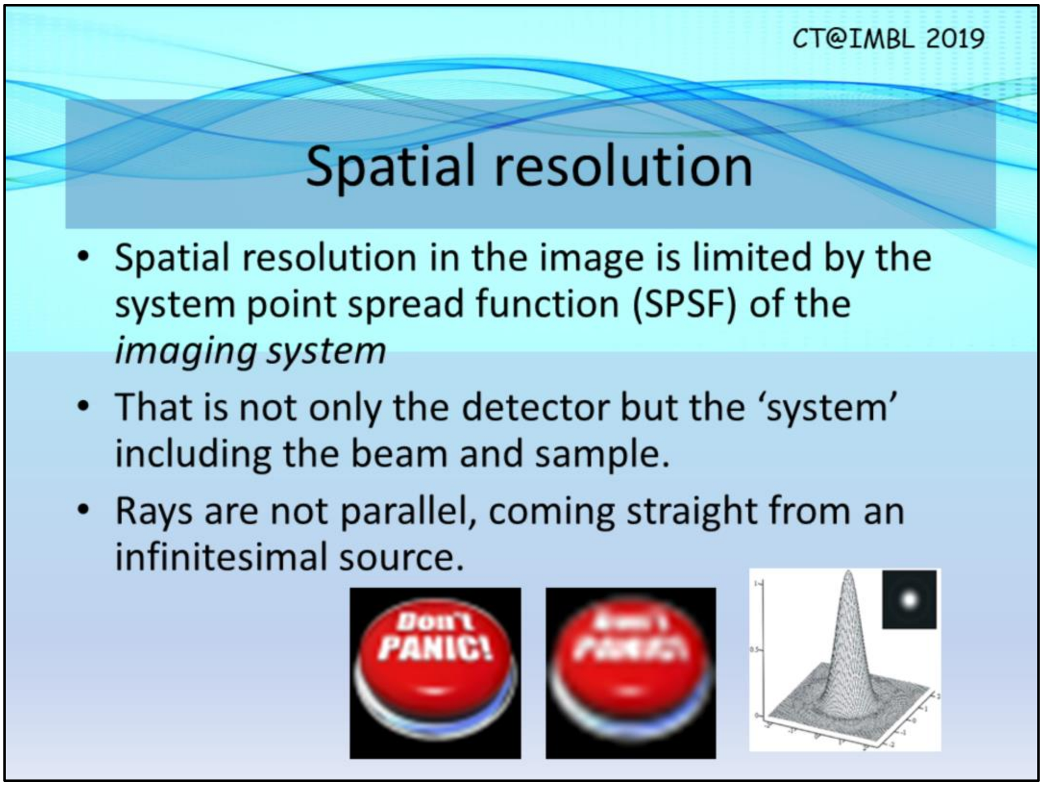
- If we assume that all the rays (let's call them photons) are the same energy (colour, wavelength, frequency). The detector measures how many photons hit a pixel during the exposure time.
- Counting (Poisson) statistics tells us the error on this count. It turns out to be the square root of the number.
- For instance if each pixel counts only 100 photons the error is +/- 1 photons (1%).
- Clearly the more photons we collect the smaller the error in the measurement.
- The very useful measure of additional error due to the detector is called the detective quantum efficiency, or DQE.



- DQE is the ratio between the number of photons in the image before being detected, to the number of photons which would need to be detected to account for the noise in the measurement.
- This second parameter is called the Noise Equivalent Quanta or NEQ.
- In a detector which can literally count photons arriving. The DQE is related to the fraction of the photons that are counted.
- Confusingly this is called the quantum efficiency (QE).
- In other detector types which can't count photons, the quantum efficiency is just part of a larger equation.
- On IMBL over the next months we will aim to measure the DQE of our detectors in typical imaging situations.

…Yet more on DQE

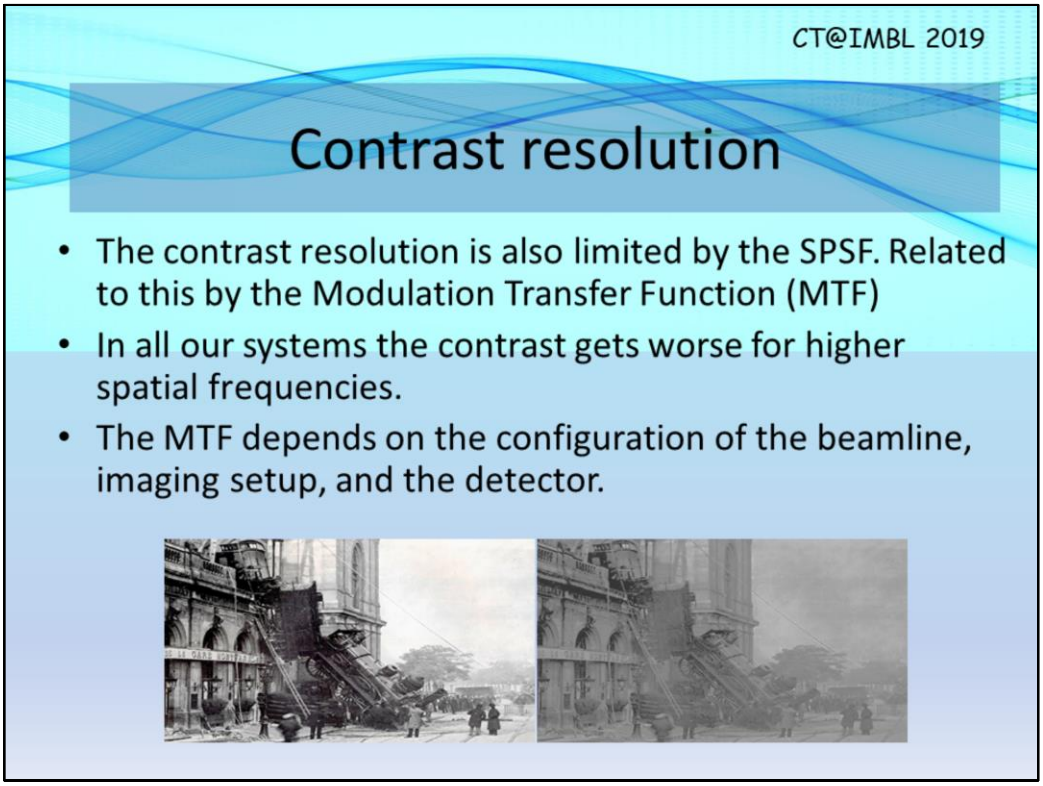
- The DQE is a function of the spatial frequency in the image.
- It is intimately connected to the spatial resolution



- Imagine an infinitely bright point in an otherwise black object. Assume the point is much smaller than the pixel size.
- An image of this point is called the system point spread function SPSF.
- The smallest features you can see are limited by the SPSF. Once again this is not just due to the detector but includes the beam quality, and x-ray optical effects.
- For instance rays emerging from different parts of the source disc will blur out small features within the sample. This is called Penumbral Blur.
- The detector further degrades the spatial resolution by collecting photons on a finite grid of pixels.
- There is further degradation because one photon does not necessarily drop all it's energy in just one of these pixels.
- There is a law in information theory that says you cannot measure features that are smaller than twice the pixel size (called the Nyquist limit, from the Shannon information

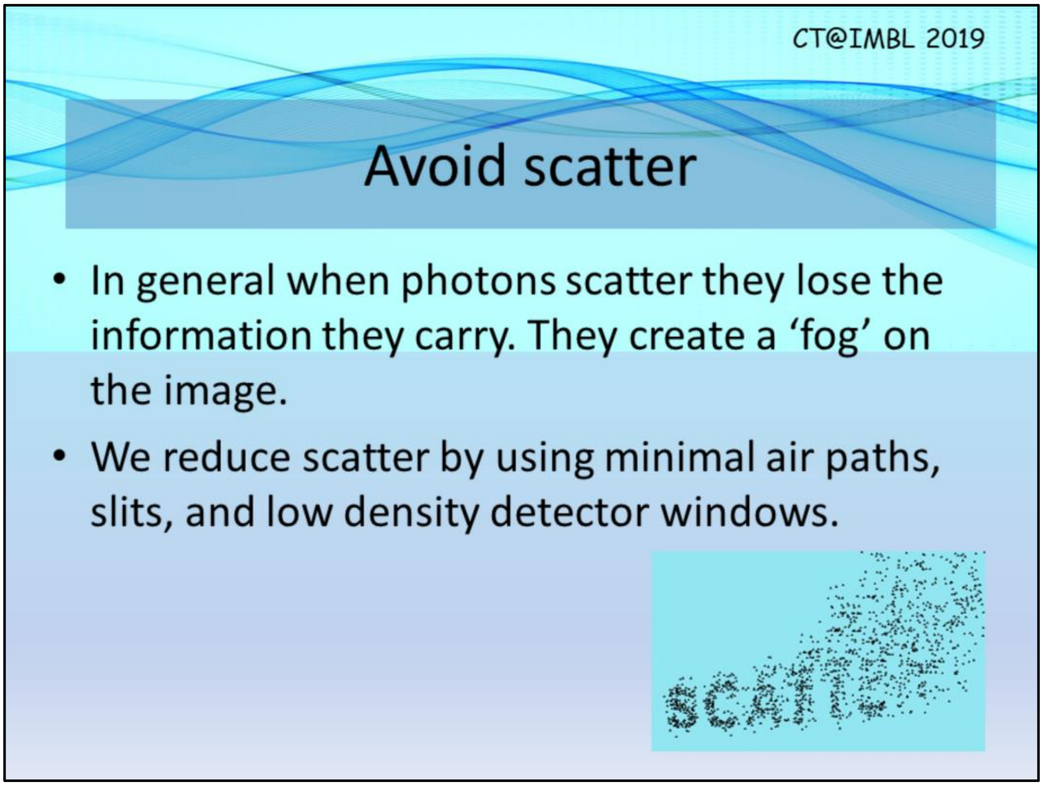
theory).

- In certain circumstances, if there are features smaller than this artefacts can be created in the image (aliasing).
- We don’t usually worry about this because of the limits of the MTF, which we will meet next.

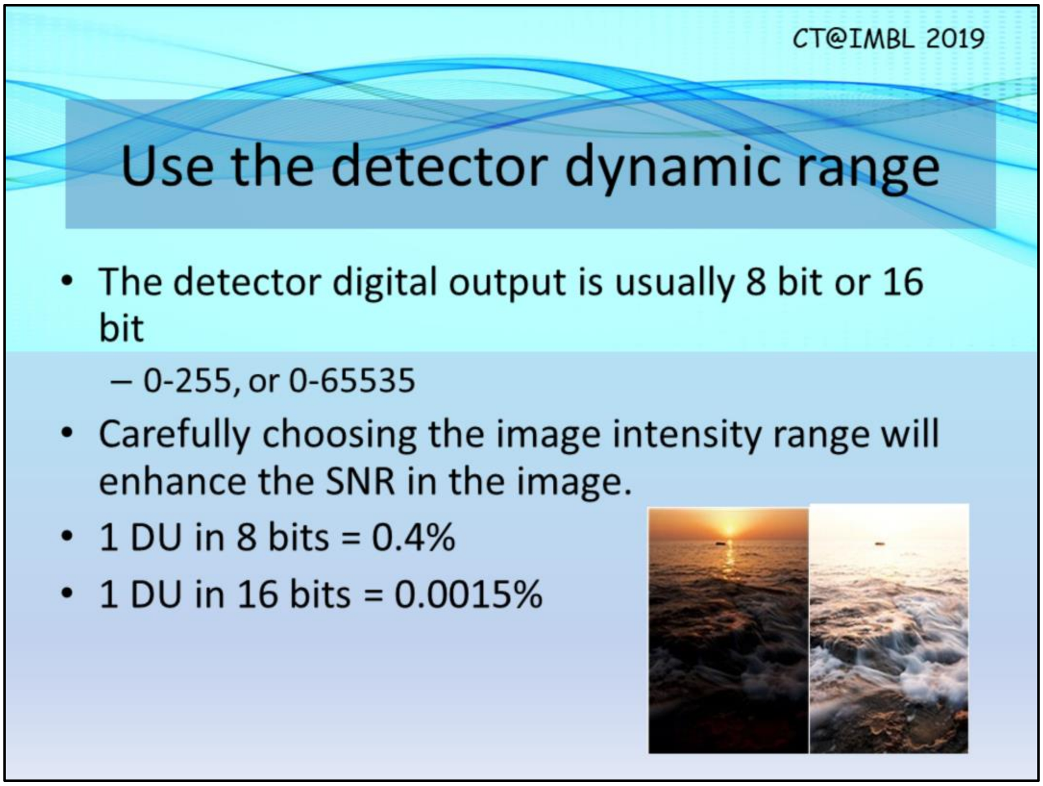


- When you are not close to the detector spatial resolution limit, the contrast is governed by the physics of the x-rays propagating through the sample.
- Contrast is usually defined as the ratio of the difference between signal and background, to the background.
- The DQE and the detector PSF are intimately related. Unfortunately the DQE is a function of spatial frequency.
- In most imaging systems, as the spatial frequencies in the image get higher, the contrast gets less.
- Contrast as a function of the spatial frequency is used a lot in imaging systems. It’s called the Modulation Transfer Function (MTF).
- MTF is used for assessment in medical imaging. Here a high DQE is critical to avoid using any more radiation than is necessary (ALARA principle).
- We won’t delve into how the MTF is measured but if it’s important the IMBL staff have ways and means to do this.

- An interesting derivation tells us that the DQE is the square of the ratio of the input SNR to the output SNR. (N=number of photons, G=system gain, M=MTF, and W = noise power spectrum).

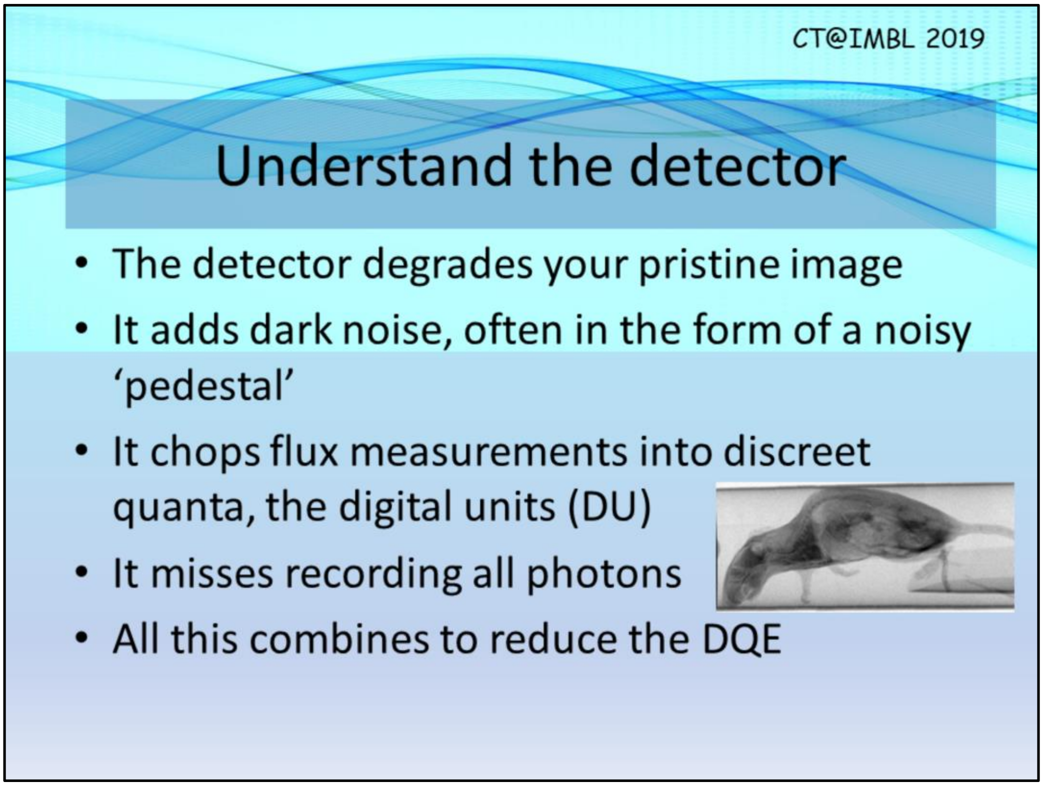


- Rays that are grossly deviated from their original path will lose a lot of the information they carry about the object.
- Some information can be recovered from scattered rays, but that topic is beyond our basic workshop.
- We want to avoid scatter or avoid scattered photons hitting the detector.
- There are a number of ways to reduce the scatter fog:
    - Avoid unnecessary material in the path of the beam. This includes air.
    - Scatter from slits is generally spread over a wide range of angles. So we use two (or more) slits the second one taking out the scatter from the first.
    - Keep the detector away from the slits, as far as practical.



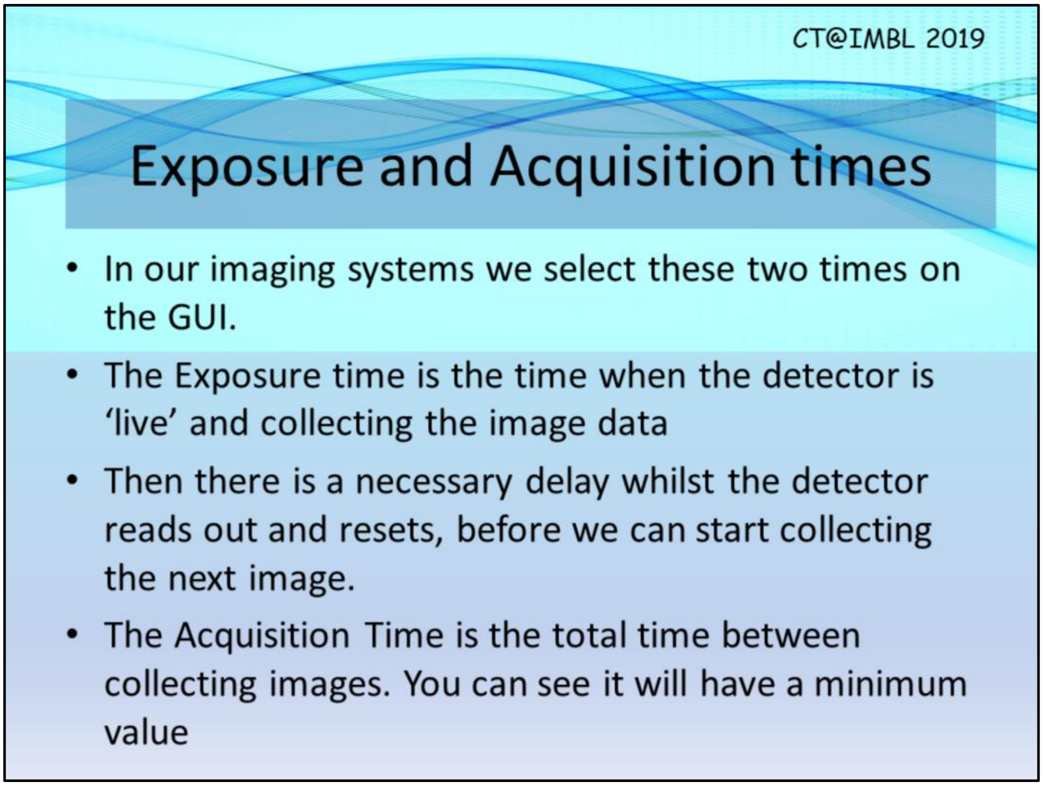
- Turning to the process of digitisation. In the detector we measure a current or charge that is proportional to the number of photons hitting a pixel.
- To keep imaging speeds high this number is usually a fixed size integer (12 or 16 binary digits).
- Each increment in this integer is referred to as a digital unit (DU).
- When we set up the exposure time we judge how high a number we can get, with nothing in the way of the beam.
- When it’s placed in the beam the x-ray transparency of the object might drop this to about half the ‘white field’ value.
- Sometimes it’s even worse and only a few percent of the photons hitting the object get detected.
- If the pixel values in the image get too low we run the risk of making the image noisy.
- Even though we collect many images in a CT set. The multiple image advantage will still struggle to get a good

signal from inherently noisy data.

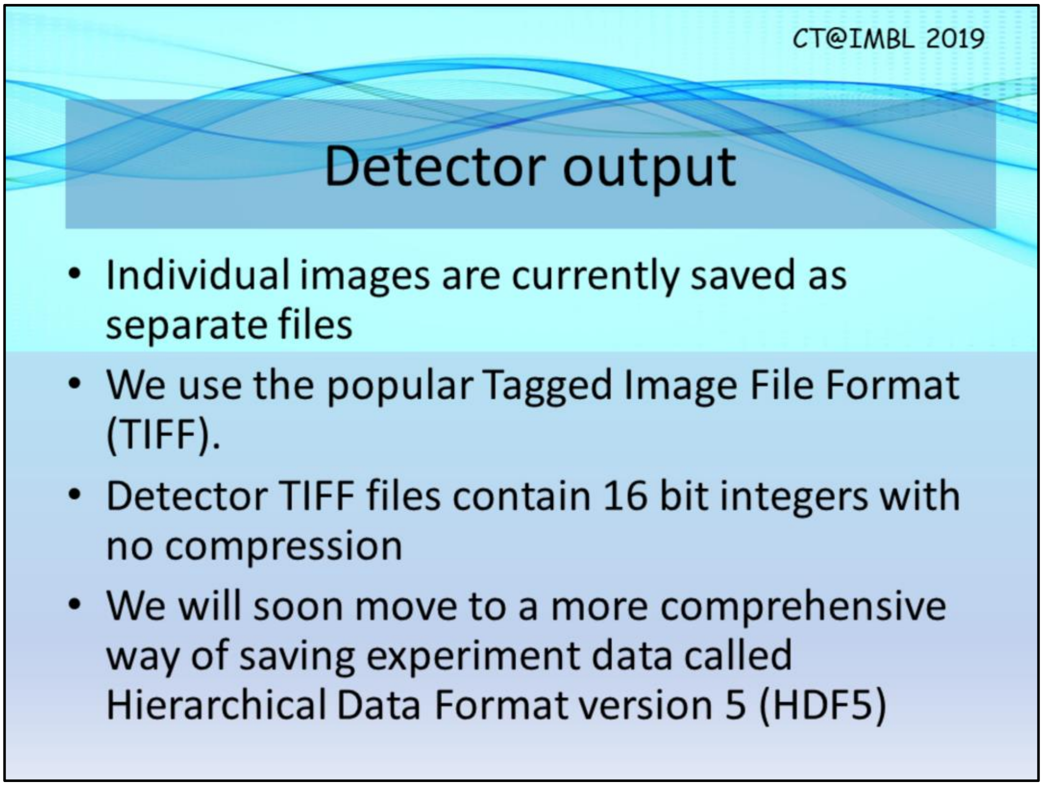


- If you understand the detector you are using. It's more likely you will be able to optimise the images.
- We only use one class of detector on IMBL at the moment – called an Integrating detector. (It's possible we may include Photon Counting detectors in the future.)
- Integrating detectors accumulate and measure charge throughout the exposure time.
- At the end of this time the total charge is measured and digitised.
- The charge is generated by the x-rays hitting the detector, but also through thermal effects, optical light, cosmic rays etc.
- The amplifiers used in boosting the small charge to a measureable level are noisy. They generate current/charge even when there are no x-ray photons arriving.
- These readout amplifiers are one of the primary noise sources.

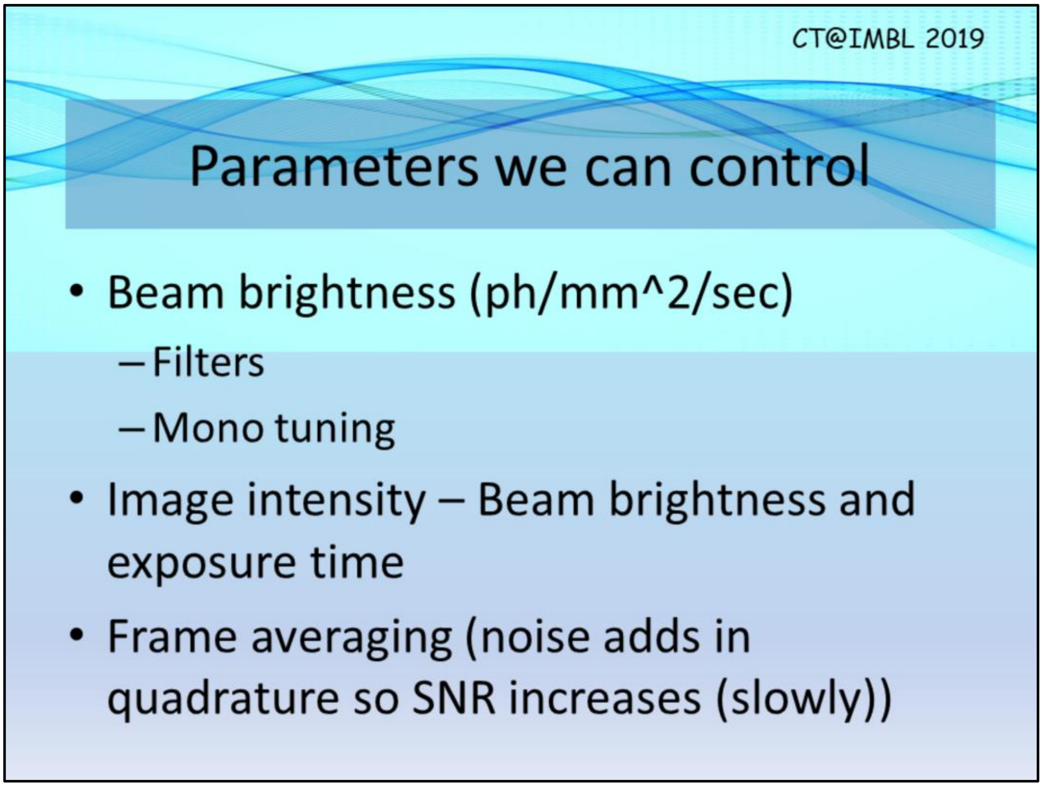
- Readout noise is manifest as a mean value which increases with readout time.
- Since this ‘dark current’ uses some of the range of the digitisation it reduces the DQE.



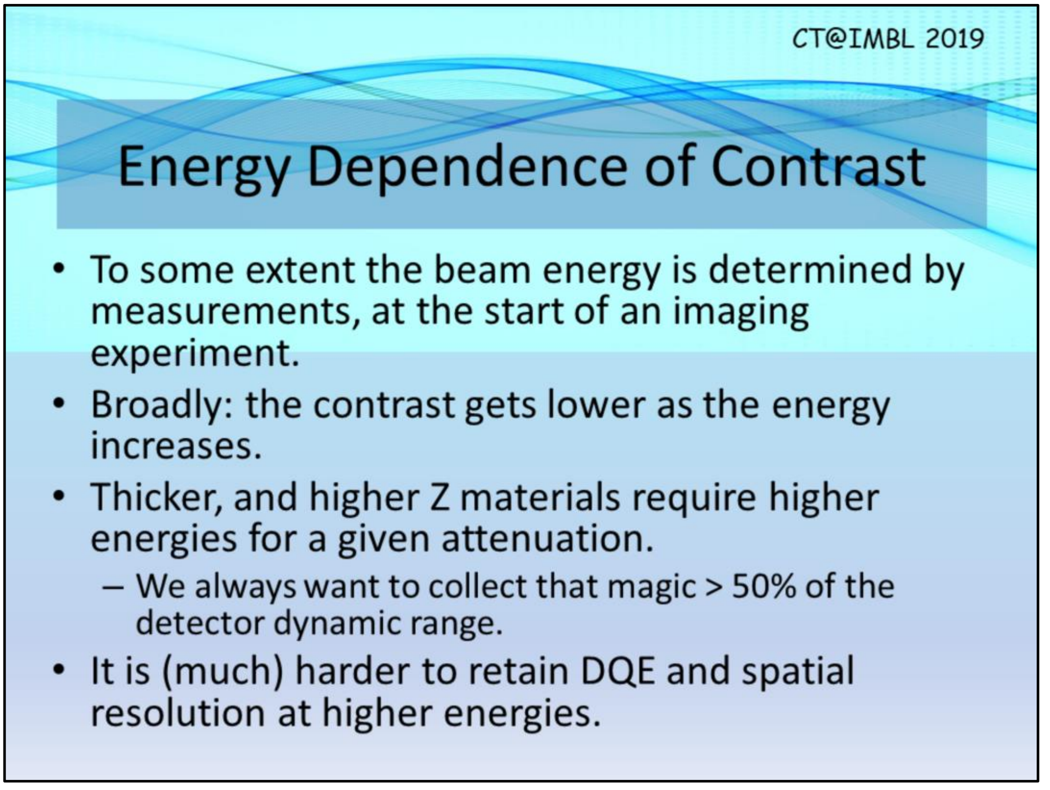
- As we push the technology to collect data faster we need to be aware of the limitations.
- The time taken to gather enough photons for our image is the Exposure Time. Similar to the concept in photography.
- With large arrays in the detector it can take a significant time to move this information from the sensor to the storage.
- Even with the fastest signal paths the PCO detector takes 0.5 milliseconds to shift the data before it is ready to collect the next image.
- Other bottlenecks downstream in the data flow may increase this time to several, if not 10s of milliseconds.
- The total time between collecting images is called the Acquisition Time.
- This clearly must be larger than the Exposure Time.



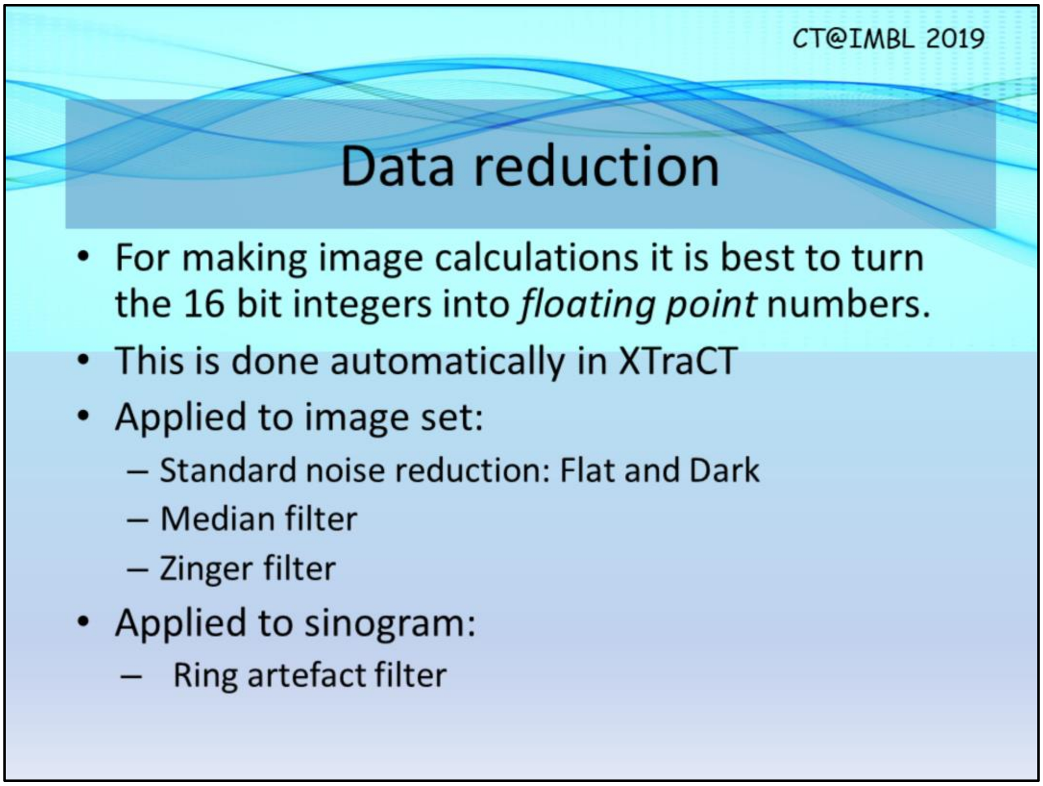
- Once the image has been digitised. It is safe(ish) from further degradation.
- It is very unlikely to be corrupted, but it may be lost!
- The image file standard IMBL uses right now is TIFF. It’s very versatile and can store many different types of digital image data.
- The versatility of TIFF can be a weakness though. Some image viewing programs don’t rigorously cope with all possible types of data.
- You may find the 16 bit integer image types just don’t view properly in some programs which say they accept TIFF.
- We highly recommend the program FIJI for viewing the data. (Session by Karen on Friday morning).
- FIJI copes with 16 bit and other TIFF image types very well.



- The beamline has a number of parameters we can control to optimise the quality of the 2-D images we collect.
- Some will be set by IMBL staff to suit your experiment.
- You will be able to vary many yourself.
- It is possible to increase SNR by taking several images and adding them. If this is done carefully the SNR will increase by approximately the square root of the number of images.
- For instance if we collect 100 images and add them. The signal is multiplied by 100. The noise adds in quadrature so it increases by 10. So the SNR improves by 10.
- Doing this slows down data collection, but can be used to get around the dynamic range limit.
- There is a ‘plugin’ in the imaging system which can be used for multi-image collections and averaging. It’s outside of the curriculum for this course but if you think you need it, talk to one of the IMBL staff.



- In all x-ray imaging experiments the signal (contrast) is dependent on the x-ray energy.
- On IMBL the energy can be chosen to suit the object and imaging situation.
- It is also possible to use a broad spectrum of energies.
- Currently this is treated as a special case used as a last resort.
- A rule of thumb is to tune the energy to allow no greater than 50% absorption in the thickest part of the object.
- At higher energies the detectors don’t work as well (both poorer efficiency and resolution).



- Raw data is great to be stored as 16 bit numbers.
- How do we ensure that we don't unnecessarily degrade the information as we start the processing?
- When we start processing we should convert values to floating point (real) numbers.
- The format we use for real numbers is double or quadruple the number of bits in the original (32 or 64 bit).
- This can put high demands on the memory, storage, and to some extent the CPU of the computer used for processing.
- The most fundamental signal improving (noise reducing) technique is called Flat and Dark processing. (Sherry will go into this)
- F&D processing dramatically reduces both the pedestal, and the systematic noise. It's done almost automatically in X-TRACT.
- Filtration is another standard way of improving the signal.
- There are some standard filtrations during X-TRACT pre-

processing which aid in SNR without degrading the contrast or spatial resolution.

- Sherry will go into more detail in her talk.

[redacted]

Yet more on DQE

- The DQE is a function of the spatial frequency in the image.
- It is intimately connected to the spatial resolution:
  - $SNR^2_{in}=N$, and $SNR^2_{out}=N^2G^2M^2(x)/W(x)$
  - $DQE(x)=NG^2M^2(x)/W(x)$
  - So $DQE(x)=SNR^2_{in}/SNR^2_{out}$