# Compensation of Scintillator Sensitivity Loss due to Irradiation Damage

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**Abstract.** Irradiation damage can decrease sensitivity of imaging devices during measurement, a phenomenon which has to be corrected prior to CT reconstructions. Two correction methods that can be used for this purpose are presented and discussed. It appears that even with the most simple method based on linear corrections of flat fields good results can be obtained.

## Introduction

Computed tomography reconstruction methods consider a normalized input signal. Images must be corrected using both a flat field record and a dark field record. Whereas there is no physical reason why the dark field would evolve during the experiment, the flat field may vary with time. One possible cause for flat field variation is irradiation damage which indeed occurs on the camera considered in this study. This paper considers different methods for taking into account the evolution of flat field due to irradiation damage. The aim is to keep the error resulting from bias on flat field at the same level than signal to noise ratio on fully illuminated areas of images, that is to say an error of 1%. Though this is still a work in progress, the methods proposed will be discussed and compared.

## Experimental setup

The experimental setup consists of a Nikon 225kV microfocus tube and a Photonic Science dual Imagestar X-ray camera. So as to provide 35µm over a field of view of 200mm, the camera makes use of two CCDs, each one viewing the scintillator through a 45° mirror (figure 1).

Although CCDs are shielded from direct beam using 5mm thick lead panes, it appeared that above 100kV X-rays scattered by mirrors and/or camera case would impact CCDs. As a consequence, inner camera setup was shielded from X-rays by placing a 10mm thick 70% PbO lead glass pane 20mm behind the scintillator. This solution proved to be effective as the camera can be used up to 225kV, even if some bright spots appear on images as energy increases.

An important drawback, however, is the darkening effect which affects lead glass as it is exposed to X-rays. As a consequence, flat field may vary by as much as 20% depending on irradiation conditions. Moreover, if an absorbing piece (such as a metal part) protects the scintillator from irradiation during measurement, the camera scintillating system will display luminous “ghosts” at the end of the experiment. This phenomenon is illustrated on figure 2: pieces with different x-rays absorption have been placed in front of the camera (figure 2, top). After an 15 hours irradiation at 160kV/350µA, the flat field shows ghosts of the pieces depending on the protection from x-rays they provided (figure 2, bottom). Since the lead glass is located 20mm behind the scintillator, there is an offset between the pieces images and the ghosts (figure 3).

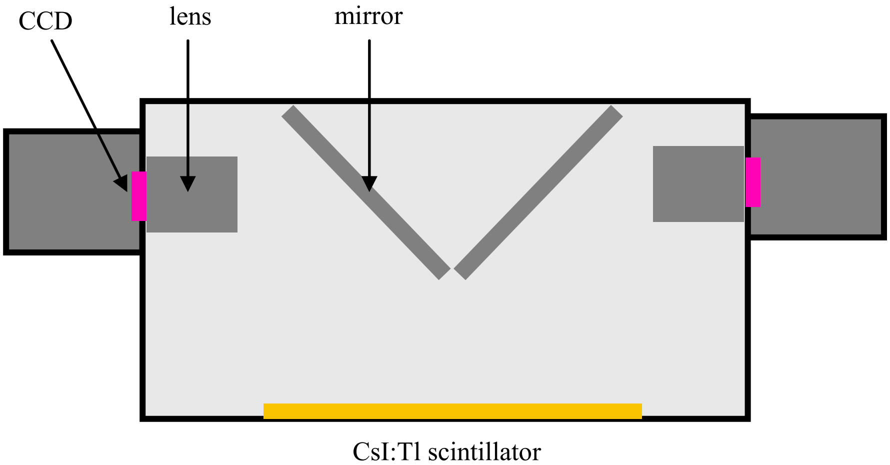


**Figure 1.** schematic view of the camera

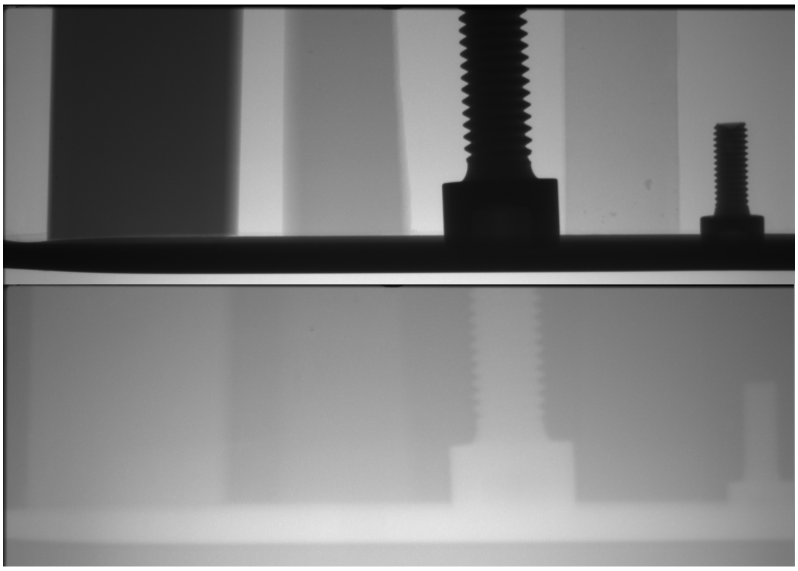

**Figure 2.** luminous ghosts resulting form protection from irradiation (top: static image 15s at 160kV/350µA, bottom: flat field after 15hrs at 160kV/350µA).

## Flat field correction methods

It is of course possible to record a flat field prior to each image capture. However, flat fields obtained considering means of several images so as to avoid excessive noise after image normalisation (we typically consider 60 images to compute a flat field). Such a method would increase measurement duration by at least a factor 10 whereas recording about 3,000 images already takes 15 hours. This method is thus not practical: the flat field must be interpolated in some way between flat field measurements.

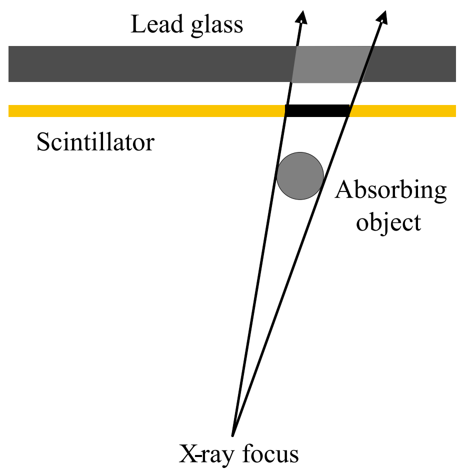


**Figure 3.** offset between object image ghost images due to gap between scintillator and lead glass panel

*3.1 Linear correction*

The most simple correction that can be performed is to record the flat field before and after experiment and interpolate flat fields considering a linear interpolation. Figure 4 shows the intensity decrease of a pixel with no protection form direct beam. Camera sensitivity has decreased by 12% throughout the measurement. The straight line (figure 4.a) shows that maximum error on flat field intensity at image #1500 is 2%

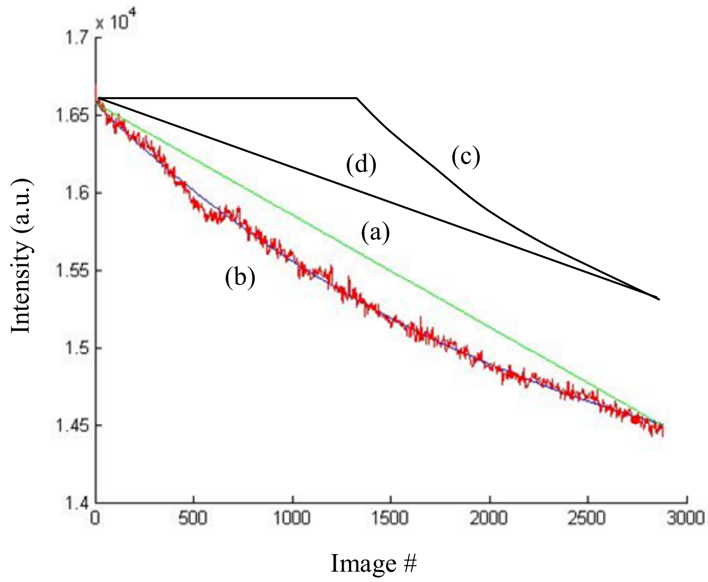


**Figure 4.** Intensity decrease of a pixel exposed to direct beam. (a) linear correction, (b) arithmetic series correction, (c) worst case scenario, (d) linear correction for worst case scenario.

Another source for error which is not accounted for in figure 4 is that pixels are not uniformly irradiated during measurement. The scanned object rotates and may alternatively hide and reveal different areas of the scintillator/lead glass pane. For example, maximum error will occur in areas entirely shielded from x-rays for the first 180° of the measurement then will be fully exposed to x-rays for the rest of the experiment. (figure 4.c). The linear correction (figure 4.d) will then lead to an approximately 6% error, which is therefore the maximum error that can be committed in the case of an extremely anisotropic and absorbing object.

*3.2 Arithmetic series*

An alternative to the simple linear correction is to consider arithmetic series for computing the intensity of a given pixel:

$$I_{n+1} = a_n I_n + b_n \quad \text{(eq.1)}$$

Where $n$ is an image index and $a_n$,$b_n$ are two coefficients describing the intensity decrease at step $n$. For the moment, only the case of constant irradiation will be considered. In this case, a and b coefficient are constant throughout the measurement and thus, for a given pixel:

$$I_{n+1} = aI_n + b \quad \text{(eq.2)}$$

Equation 2 is ill-conditioned and a least-square regression yields poor result when computing $a$ and $b$. It can be however written as follows:

$$I_n = a^n (I_0 - r) + r \text{ with } r = \frac{b}{1-a} \quad \text{(eq.3)}$$

Least-square regression using equation 3 yields $a$ and $r$ parameters which properly describe intensity decrease at least for constant exposure to direct beam (figure 4.b).
However, correction of a series of images requires prior knowledge of parameters. They can be computed using calibration experiments and then chosen depending on $I_0$ (or, even better, $I_n$ in eq. 1 so as to compute $I_{n+1}$). Figure 5 shows the evolution of $a$ and $r$ as a function of $I_0$. Except for low intensities, $a$ is about constant and $r$ follows a linear trend.

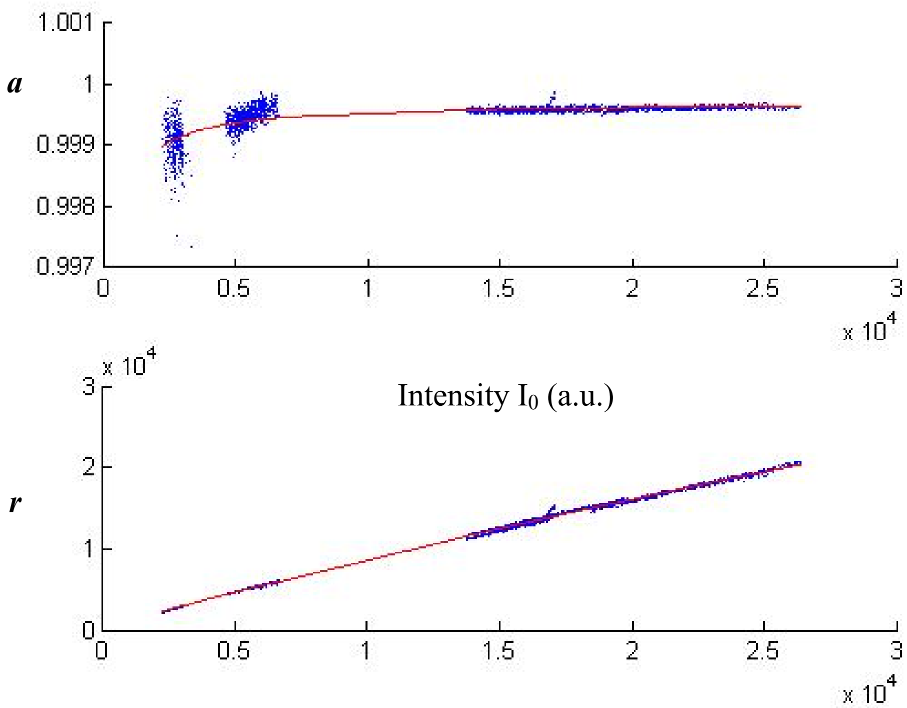


**Figure 5.** values obtained for $a$ and $r$ parameters as a function of initial intensity.

Given the data shown on figure 5, intensity decrease can be computed from the initial intensity. These are actually the sets of parameters that would be used to correct a real experiment. Figure 6 displays error resulting from linear correction, arithmetic series considering parameters computed from linear regression and arithmetic series computed from initial intensity considering curves shown on figure 5. Best results are obtained using parameters computed from least square regression. They are lower than 1% even for low intensities/high absorption and display a very limited dispersion. Results obtained using parameters inferred from initial intensity are similar at high intensity, however the error dramatically increase as the initial intensity decreases. Error due to linear correction is maximum at high intensities and remains below a few percents.

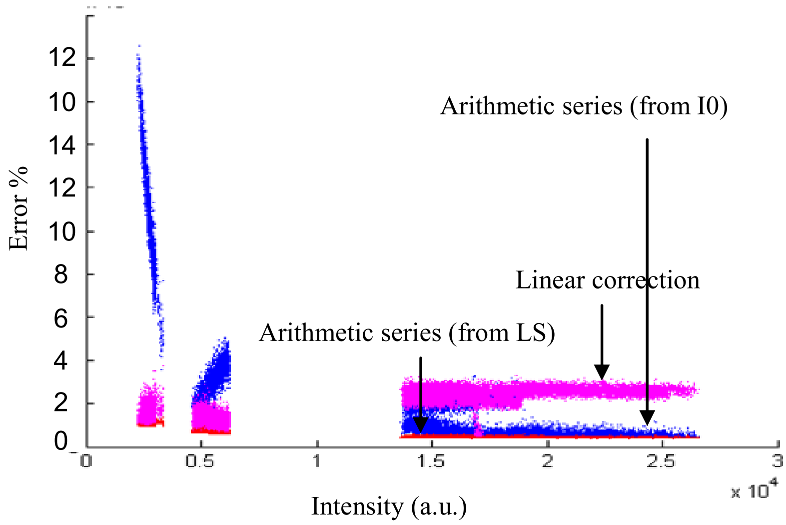


**Figure 6.** Errors resulting from linear correction compared to arithmetic series resulting from least square regression and $I_0$ values.

There are several reasons why intensities computed using parameters inferred from initial intensity yield poor results, such as a decreasing signal to noise ratio. However, it is likely that the biggest problem arises from the degeneracy of eq 3. If the intensity is null, then it means that the scintillator is entirely protected from radiation and sensitivity is kept constant. There are several sets of values for $a$ and $r$ that satisfy this property, including $a$=1, $r$=0 and $a$=0, $r$=$I_0$. However, it is logical to choose $a$=1, $r$=0 as the right solution. This means that analytical expressions for a and r have to be chosen so that the values $a$=1, $r$=0 are given for $I_0$=0. Besides finding appropriate analytical expressions for these parameters, there is another way for improving values obtained at low intensities. Given eq. 3, $r$ can be expressed in terms of $I_n$ :

$$r = \left( \frac{I_N - a^N I_0}{1 - a^N} \right) \qquad \text{(eq. 4)}$$

Parameter $a$ is then inferred from $I_0$ as usual whereas $r$ is now computed using initial and final values of the flat field. Figure 7 shows that this procedure leads to much better intensity values with an error below 1% even at low intensities. Thus, there is good hope that using this method the error on flat fields used for normalization can be kept below 1%.

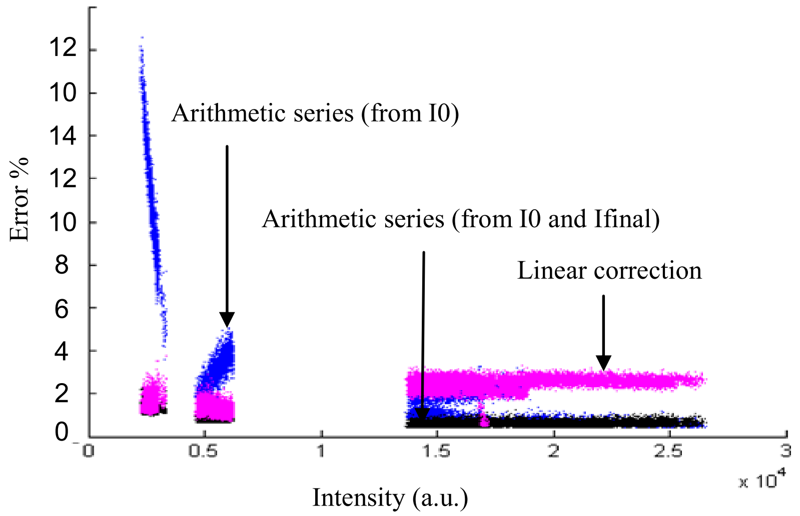


**Figure 7.** Errors resulting from linear correction compared to arithmetic series resulting from $I_0$ values only and resulting from initial and final intensity values.

## Discussion

Even if arithmetic series seem to be able to deliver a precision below 1% error on flat field variation with exposure to x-rays, complete correction procedure is complex. $(a,r)$ parameters against $I_0$ parameters set must be deduced from a calibration procedure which is yet to design. Moreover, it is likely that sensitivity variation with x-ray exposure depends on the spectral characteristics of the transmitted beam and therefore on the material the studied object is made of. The same consideration applies to any filtering that modifies spectral characteristics of the incident beam. It is thus likely that the calibration depends on experimental parameters in such a way that several calibrations are needed to properly cover the range of experiments. Finally, the offset between object image on the scintillator and the protection it provides on the lead glass makes computation even more complex (this point have been left aside in this paper for the sake of simplicity).

Linear correction, although less precise, does not need calibration. Computations are easy to perform and the ghost offset is implicitly taken care of. It is also possible to decrease error with intermediate flat field measurements. As can be seen on figure 2, an intermediate flat field measurement at image #1500 would quite minimize the error, with two straight lines almost within signal to noise ratio. Worst case scenario is estimated at 3% error, half the 6% value previously estimated. So, in the case of isotropic shapes such as is generally needed for best tomography measurement, precision considering an intermediate flat field measurement is likely to be within the 1% goal. For highly anisotropic samples (and supposing a high precision is still required despite the inappropriate shape), three intermediate flat field measurement will yield an error estimated to 1.5% at the cost of 180 image measurements (supposing a flat field derives from 60 images), that is to say 6% more image records to perform : a cost which is quite acceptable.

## Conclusion

Given the complexity of arithmetic series approach and the limitations it may be confronted to, it is clear that linear correction with intermediate flat field measurements is for now the best option to correct the sensitivity loss due to irradiation damage. Error on flat field used to normalize images can be kept below 1% for homogeneous, isotropic objects and below

2% for highly heterogeneous/anistropic objects at the cost of more intermediate flat field measurements (yet still compatible with reasonable durations).

Yet, the arithmetic series approach proved to be able to reproduce quite accurately the sensitivity loss due to irradiation damage. The complexity of the experimental setup (offset of ghosts due to gap between scintillator and lead glass panel, polychromaticity of incident beam…) makes it difficult to apply this method. However, it is a method to consider especially if the experimental parameters causing the variation are less complex than in this particular case.

Some readers may wonder if it’s possible to either change the lead glass for a grade less prone to blackening and/or modify internal camera shielding. As of now, we could not find a glass supplier which would provide ceria doped glass (less prone to x-ray damage) in the dimension/thickness/PbO concentration required. Lead glass protection could indeed be displaced in front of the lenses, outside direct beam path. This would however means heavy modifications and tests on a device that works and yields very good results provided corrections detailed in this paper are applied. Finally, lead glass panes can be rejuvenated at 150°C for a few days in an oven and can be swapped between measurements, thus minimizing the impact of glass darkening on overall camera sensitivity.