Evaluation of X-ray Camera
As a Tool for Automated Beam Characterization

Otte Marthin
Abstract

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Several methods for analysing materials and proteins use highly concentrated beams of X-rays, e.g. SAXS and X-ray crystallography. To evaluate the outgoing beam, it is of high importance to know the light distribution of the incoming beam. Previously, a method for this has been to focus the X-ray beam onto a pinhole in front of a photodiode, a so called pinhole measurement. Although this method gives information about the radial distribution of the beam, it is very time-consuming. In this report a faster alternative has been developed and evaluated. In this new method an image is taken with an X-ray camera in the focus of the beam. Algorithms are then used to replicate a pinhole measurement by applying virtual pinholes.

Different pixels in an image act differently, referred to as spatial noise. This must be compensated for before information about the beam may be extracted. To do this, the camera noise was characterized and a calibration procedure developed for its minimization. It was shown that the spatial noise was greatly reduced, making the temporal shot noise the new largest noise source. Although the noise was successfully reduced, the calibration procedure failed to accurately remove all signal not originating from registered photons. Measurements done with low photon intensities, large exposure times or at high temperatures are therefore less accurate.

The measured camera signal was transformed into incident photon intensity using a responsivity proportionality constant. This constant was estimated by comparing the results from real and virtual pinhole measurements for several photon intensities and pinholes. The results gave a responsivity proportionality constant of 0.03 DN/X-ph. Further measurements were done concerning the temperature dependence of the camera responsivity and to investigate possible bleaching. The results indicated that the responsivity was held constant under changing temperatures and that the camera remained unbleached during the 114h long measurement.

Finally, real and virtual pinhole measurements were done for a series of pinholes and compared using the responsivity proportionality constant. A maximum relative deviation of 6% was measured between the two, indicating that virtual pinhole measurements give accurate results. The largest deviations of the measurement seem to occur when using small or large pinholes. These errors, however, have a high potential of being further minimized, resulting in higher accuracy.
Populärvetenskaplig sammanfattning


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1 Introduction

There are several techniques based on elastic X-ray scattering today. X-ray crystallography, for example, allows the analyzation of crystallized materials and small angle X-ray scattering allows the analyzation of macromolecules. In these techniques a beam of energetic electromagnetic radiation, later referred to as EM-radiation, is focused onto the target, creating a scattering pattern which is then measured and used to analyse the target. For any analyzation to be done, the intensity distribution of the incident beam has to be known. Furthermore, the beam width is an important factor in designing the input beam, since it affects both the resolution of the scattering pattern and the photon flux density. It is therefore vital to be able to characterize the intensity distribution of the focused beam. Different methods exist for finding this distribution, e.g. focusing the beam onto a calibrated photodiode with a pinhole in front of it. This method will be referred to as a pinhole measurement in this Thesis. By varying the diameter of the pinhole a radial distribution of the focused beam may be estimated. This method is however very time-consuming, requires user inputs on regular basis and gives little information of the actual distribution of the beam. In this Thesis an alternative method for the beam characterization is investigated, expecting to get equally good results without the mentioned downsides. This new method, referred to as a virtual pinhole measurement, utilizes an X-ray camera and image processing to mimic the procedures of a pinhole measurement. In this Thesis, algorithms for this virtual pinhole measurement are developed and the result of this measurement is compared to that of the pinhole measurement.

The X-ray camera to be used for this new method had previously been designed for the purpose of beam characterization, but its performance was unknown at the start of this Thesis. Before being used as a photosensor its own characteristics needed to be determined. The camera’s ability to resolve the focused beam depends on its noise, its ability to measure photons and its spatial resolution. The noise was divided into pixel non-uniformities, referred to as spatial noise, and temporal noise, which were then evaluated separately and methods for their minimizations developed in a process referred to as calibration procedure. The relation between the number of incident photons and the measured pixel values was evaluated and will be referred to as the responsivity of the camera. A theoretical estimation was made of the responsivity, indicating where improvements may be made. The spatial resolution of the camera was measured and temperature dependence and bleaching of the scintillator was investigated.

A server was written in C++ to manage the communication between the camera and the user. In addition, a system for saving and loading images, together with relevant parameters was developed, which allowed for easy handling of the images.

2 Background

To investigate the camera characteristics, some background information is needed to understand how to measure them and what they indicate about the system. First the different optical components of the camera will be discussed in section 2.1, consisting of short descriptions of the scintillator, lens and camera, together with how they affect the responsivity of the camera. Some theory of how spatial resolution of an optical system may be described will be presented in section 2.2. Finally the different noise sources of the camera will be discussed in section 2.3.

2.1 Optical Components

The X-ray camera used, consists essentially of three physical components that interact with incident EM-radiation and therefore constitute the optical system; a scintillator, lens and camera sensor. The function of the scintillator was to shift the wavelength of the EM-radiation to the visible regime, which the camera sensor preferred. A lens was used to optically couple these two components, see figure 1 for a simplified image of the internal optical system of the camera, where the scintillator is the object and the camera sensor is placed in the image plane. All three components affect both the overall responsivity and the spatial resolution of the camera, but their respective contributions may be described almost independently. This separated description will constitute the structure of this section.
As previously mentioned, scintillators convert high energy photons into photons in the visible regime. This conversion is done through several steps, beginning with the absorption of a photon and ending with the luminescence of several new photons of lower energies. This process takes some time, of the order of a few nano- or microsecond. In this Thesis however, much longer time periods are of interest and therefore the process will be approximated as instant and continuous. It is however worth noting that due to these delays, there exists some flow of irradiance where the conversion efficiency of the scintillator will decrease. The absorption of photons is due to different processes, like Compton scattering or photoelectric effect. For photon energies below 100keV, the absorption is mostly due to the latter process, releasing all the energy of a photon to some electron, exciting it from the valence band of the scintillator to the conduction band, creating a hole in the valence band. The energy of this electron is then dissipated to other electrons, exciting them. Some electrons then de-excite to the valence band, recombining with a hole, isotropically releasing energy as photons in the process. However, these emitted photons are energetic enough to excite new electron, i.e. the emitted photons may be reabsorbed. If the scintillator is doped, electrons may de-excite to so called activator states, before de-exciting to the valence band. Photons emitted this way are highly unlikely to be absorbed by the scintillator, making it transparent to them. In figure 2, a descriptive image of the process is seen.\[1\][2][3] These activator states are designed by the choice of dopant, however, in practise additional states exists between the valence band and the conduction band due to the crystal being non-perfect. In contrast to the activator states, these states might not allow de-excitation of electrons to the conduction band, or if so, might not emit light during the de-excitation. The states that do not allow de-excitation to the conduction band are called traps and may trap electrons. Heating the crystal may result in the trapped electrons getting enough thermal energy to excite back to the conduction band. This is exploited in a process called thermally stimulated luminescence, TSL, where the heating of a solid results in the emission of light from the de-excitation of previously trapped electrons. This process therefore requires the solid to have been previously irradiated, thus filling its traps. Constantly heating a solid and registering the intensity of the emitted light for each temperature, is a common technique for evaluating traps in crystals.\[4\]

Figure 1: Picture of the ideal case of the inner optics, where the scintillator is the object and the sensor is located in the image plane.
Figure 2: Descriptive picture of how an high energy photon excites an electron from the valence band of the scintillator to the conduction band, from where it de-excite, emitting photons in the visible regime.

Since the scintillator emits light isotropically, it may be treated as a volume of point sources.[2] However, it also means that all the emitted light will not reach the lens. The amount of light emitted from a point source reaching the camera sensor may be approximated using equation (1), where \( m \) is the linear magnification of the system, \( T \) is the lens transmittance, \( n \) is the refractive index in the medium of the point source and \( F\# \) is the lens f-number.[5] The formula takes into account that a lens will not transmit light for all angles of incidence, however assumes that no energy is lost due to reflection or absorption prior to the lens. The maximum angle of incidence which is transmitted by the lens defines what is called the acceptance cone of the lens. The half-angle of this cone can be related to the f-number of the lens as seen in equation (2), where \( \theta_{NA} \) is the half-angle, \( n \) is the index of reflection and \( \theta_{NA} \) is assumed to be small. This relation can be derived using the numerical aperture, \( NA \), defined in equation (3) and its relation to \( F\# \) seen in equation (4).[6]

\[
\eta_{coll} = \frac{Tm^2}{16(F\#)^2(1 + m)^2n^2} \tag{1}
\]

\[
\theta_{NA} = \frac{1}{2nF\#} \tag{2}
\]

\[
NA = n \sin \theta_{NA} \tag{3}
\]

\[
NA = \frac{1}{2F\#} \tag{4}
\]

The collection efficiency, \( \eta_{coll} \), assumes that no photons are reflected when moving from the point source inside the scintillator screen to the lens. This is however not correct due to reflectance when leaving the scintillator screen. Fresnel’s equations, see equations (5)-(6), gives the transmission coefficients for electromagnetic waves passing from medium 1 to medium 2 with an incident angle of \( \theta_1 \) and angle of transmission \( \theta_2 \), where \( t_{TE} \) and \( t_{TM} \) denotes the transmission coefficient for transverse electric field, \( TE \), and transverse magnetic field, \( TM \), respectively. In the case of a TE wave, the electric field only has a component parallel to the boundary, whilst TM waves has components both parallel and perpendicular to the boundary. The share of energy transmitted through the intersection, referred to as transmittance, is given by equation (7). The angle of incidence and angle of transmission is related to each other as described in equation (8).[7] The transmittance of a single lens may also be calculated using equation (7). However, since a camera lens consists of several lenses, a theoretical approach to approximate its transmittance is to treat it as a system of lenses. At each change of medium, some of the light is reflected due to the changes in the index of reflection. For glass, \( n = 1.5 \), and air, \( n = 1 \), the reflectance \( R \) of visible light is approximately 4%, calculated by insertion into equation (7). By treating the camera lens as a system of lenses, the transmittance of the camera lens may be approximated according to equation (9), where \( N \) is the number of lenses.[6]
\[ t_{TE} = 1 + \frac{n_1 \cos \theta_1 - n_2 \cos \theta_2}{n_1 \cos \theta_1 + n_2 \cos \theta_2} \]

\[ t_{TM} = \left( 1 + \frac{n_1 \sec \theta_1 - n_2 \sec \theta_2}{n_1 \sec \theta_1 + n_2 \sec \theta_2} \right) \frac{\cos \theta_1}{\cos \theta_2} \]

\[ T = \frac{\|t\|^2 n_2 \cos(\theta_2)}{n_1 \cos(\theta_1)} \]

\[ n_1 \sin(\theta_1) = n_2 \sin(\theta_2) \]

\[ T = (1 - R)^{2N} \]

The final component of the internal optical system of the camera is the camera sensor. At this step a matrix of pixels samples the ideally perfect representation of the emitted light of the scintillator, projected by the lens. The pixels only have some probability of detecting a photon, resulting in some loss of responsivity. The discretization of the image will also lead to some loss of information.

### 2.2 Spatial Resolution

The main purpose of the camera is to characterize the geometry of a focused beam. For this to be possible, the camera has to be able to resolve the beam. Even if the scintillator would give a perfect representation of the incident beam which would then be focused with an ideal lens, the light reaching the camera sensor would still be a blurry representation of the beam. This type of system is called a diffraction limited optical system and is the optimal optical system due to light being the limiting factor. The image of a point object in a diffraction limited system is called an airy disc and is seen in figure 3.

In a system consisting of real components, the spatial resolution is further decreased however. In this section, a theoretical description of an optical system will be discussed together with how to separate the overall performance into individual components.

Figure 3: A 3D representation of an airy disc, where its the magnitude is plotted as its height. The coordinates \(X\) and \(Y\) are the spatial coordinates relative to the disc center, multiplied with a factor \(k/(2F\#)\), where \(k\) is the light wave number and \(F\#\) the lens f-number.

As previously mentioned, the spatial resolution of an optical system is a description of its ability to depict details of objects. Optical systems are usually approximated to be linear systems, this is the case also in this Thesis. Linear systems satisfy the superposition principle, meaning that the image of the objects \(A\) and \(B\) equals the sum of images of the two objects taken separately. It is quite intuitive that every object may be expressed as a collection of points, making the image of a point object of high interest. The image of a point object is what is called a point spread function, PSF, which for an ideal diffraction limited optical system is the airy disc, figure 3.[6] When projecting \(A\), one first deconstructs it into several points. Each point is then separately projected onto the image plane, before being summed to
get the image of $A$. This can conveniently be expressed as the convolution of object $A$ and the PSF, which is equivalent to multiplication in fourier space. The fourier transform of the PSF is called \textit{optical transfer function}, OTF, and is a complex valued function which is often separated into amplitude and phase, see equation (10), where $\hat{x}$ is the spatial coordinate vector and $f$ is the spatial frequency coordinate vector. \textit{Phase transfer function}, PTF, is a real valued function describing the change of phase applied by the optical system. The function that will be evaluated in this Thesis is the real valued \textit{modulation transfer function}, MTF, describing any change of amplitude for waves traveling through the system. Likewise, for a linear system, consisting of several steps, the whole system may be described if each part of the system is understood. Therefore, in an optical system with several optical steps, the OTF of the full system may be described as the product of the OTF:s of each step, resulting in equations (11)-(12).[6] This also works in the opposite direction, allowing the OTF of a single optical component to be computed. If the spatial resolution is to be improved, the OTF gives information of what component to focus on.

\[ F\{\text{PSF}(\hat{x})\} = \text{OTF}(f) = \text{MTF}(f)e^{i\text{PTF}(f)} \]  

\[ \text{MTF}_{\text{system}} = \prod_{i=1}^{N} \text{MTF}_i \]  

\[ \text{PTF}_{\text{system}} = \sum_{i=1}^{N} \text{PTF}_i \]  

\subsection*{2.3 Noise Sources}

It was previously mentioned that the noise of the camera was divided into fluctuations in time, temporal noise, and fluctuations in space, spatial noise. Since the purpose of the camera is to measure the intensity distribution of the EM-radiation incident on the scintillator, it is important to know how to differentiate pixel intensity due to irradiation or other sources. What different sources of pixel intensity exists and their respective characteristics will be described in this section. First a single pixel camera sensor will be considered together with its temporal noise, followed by a camera sensor consisting of several pixels. Finally the effect of incident highly energetic photons will be discussed.

Assume the case of a camera sensor consisting of a single pixel which is under a constant radiation of photons. During the time $t_{exp}$, a total of $n_p$ photons hit the camera. However, only some actually interacts with the camera, referred to as \textit{registered} by the camera from now on, exciting electrons. The ratio of photons registered by the pixel and photons that actually hit the pixel, is called the sensor’s quantum efficiency, $QE$. The number of excited electrons per registered photons is called the sensor’s quantum yield. Both QE and quantum yield are dependent on the wavelength of the incoming photons but in the case of visible light, as in the case of this Thesis, the quantum yield is approximately constant and equal to 1.[8] The number of registered photons follow a Poisson distribution, see equation (13), where $S_e$ is the number of collected electrons by the pixel after $t_{exp}$ time and $\mu_e$ is the mean number of collected electrons. This temporal deviation of the collected electrons will be referred to as \textit{shot noise}.[8][9] For large mean values, Poisson distributions may be approximated as normal distributions, see equation (14), which will be the case most of the time in this Thesis. However, for small mean values, other deviations become more significant, making any error in the normal approximation insignificantly small. From now on, the shot noise will be denoted as normal distributed.

\[ S_e \sim \text{Poi}(\mu_e) \]  

\[ \text{Poi}(\mu) \approx N(\mu, \mu) \]  

However, even in a case where no photons hit the pixel, some electrons would still be collected. This is called \textit{dark signal} and may be approximated by equation (15), where $\mu_{d,e}$ is the dark signal, $\mu_{d,e}$ is called \textit{dark current} and $\mu_{d,0,e}$ is an offset added by the sensor during read out. The dark current in turn is a function of the temperature of the sensor, which may be approximated by equation (16), where $\mu_{d,e,ref}$ is the dark current at temperature $T_{ref}$, $\mu_{L,e}$ is the approximate dark current at temperature $T$ and $T_2$ is the change of temperature for which the dark current is doubled, referred to as the \textit{doubling temperature}.[9] Electrons collected by the pixel originating from the dark current are Poisson distributed, resulting in a temporal noise term called \textit{dark shot noise}.[9]
\[ \mu_{d,e} = \mu_{d,0,e} + \mu_{1,e} t_{exp} \]  

(15)

\[ \mu_{1,e} = \mu_{1,e,ref} 2^{(T - T_{ref})/T_2} \]  

(16)

The dark and normal shot noise cannot fully describe the temporal variations in collected electrons however. Therefore, a noise term referred to as read noise, \( \sigma_{r,e} \), is introduced and approximated to be normal distributed with zero mean. This results in the mean collected electrons \( \mu_{tot,e} \), see equation (17), and a variance \( \sigma_{tot,e}^2 \), see equation (18).

\[ \mu_{tot,e} = \mu_e + \mu_{d,0,e} + \mu_{1,e} t_{exp} \]  

(17)

\[ \sigma_{tot,e}^2 = \sigma_e^2 + \sigma_{r,e}^2 + \mu_{1,e}^2 t_{exp} \]  

(18)

The camera sensor converts the electrons into digital units, DN, which is then returned to the user. This conversion consists of several steps, but may be treated as a black box by multiplying the number of collected electrons with a factor \( k \), referred to as gain, with the unit \( DN/e^- \).\[8\][9][10] This results in a new mean \( \mu_{tot,DN} \), equation (19), with its corresponding variance, \( \sigma_{tot,DN}^2 \), seen in equation (20). The measured signal of the camera will be denoted \( S = k \mu_e \) and the dark signal as \( S_d = k \mu_{1,e} t_{exp} \). Remember that the discussed camera consists of a single pixel.

\[ \mu_{tot,DN} = k \mu_e + k \mu_{d,0,e} + k \mu_{1,e} t_{exp} \]  

(19)

\[ \sigma_{tot,DN}^2 = k^2 \sigma_e^2 + k^2 \sigma_{r,e}^2 + k^2 \mu_{1,e}^2 t_{exp} \]  

(20)

Different pixels have different values of the offset, gain, read noise and dark current, which means that different pixels will have different expectation values even though irradiated with the same photon intensity. The effect from this may be approximated by introducing spatial noise, also known as fixed point noise, or FPN. This FPN is due to non-uniformities of the different pixels, which may be divided into a signal dependent part photo response non-uniformity, PRNU, originating from variations in QE and gain, and dark signal non-uniformity, DSNU, arising from variations in dark current and pixel offset.\[9\] The FPN from PRNU increases linearly with the signal, \[8\], whilst the noise from DSNU increases linearly with the dark signal and hence time, see equation (15). An image of the pixel offsets will be referred to as bias frame.

This far, it has been assumed that a photon registered by a pixel is only registered by that one pixel. This is however not always the case. For high energy photons, the charge created in the pixel may diffuse into neighbouring pixels. For these energetic photons, > 10\(eV\), the quantum yield increases linearly with the photon energy.\[8\]

### 3 X-ray Camera

The X-ray camera in question have been briefly discussed, but not fully introduced this far. The different components of the camera will be presented together with their individual performances in section 3.1. By then combining the components in section 3.2, a theoretical performance of the camera as a whole will be derived. Finally the camera software written in this Thesis will be briefly discussed in section 3.3.

#### 3.1 Camera Hardware

As previously discussed, the camera consists of a scintillator which shifts the wavelength of the EM-radiation, which is then focused by a lens onto a camera sensor. In addition, a camera body was used to hold the components at place and block out any light incident outside of the camera aperture. Finally, a carbon disc was placed at the aperture to absorb incident low energy photons. The whole camera is seen in figures 4 and 5, with some of the parts of the camera denoted.
To quantify the efficiency by which the scintillator shifts the wavelengths of incoming photons, a ratio was used between the number of emitted and incident photons. This quota will be referred to as the scintillator efficiency, \( \eta_{\text{scin}} \), and was approximated to be \( 260.6 \text{ph}/\text{X-ph} \) for incident photon energies of \( 9.25 \text{keV} \). This was done by using tabulated values of the amount of emitted photons per absorbed energy unit and approximate values of the absorption efficiency of the scintillator.[11] The method of approximation was shown to give values 10% – 15% above tabulated values for other scintillator thicknesses and photon energies. This was however not compensated for. The temperature used when the scintillator was evaluated by the manufacturer is unknown. However, the efficiency of the scintillator may be approximated to be independent of temperature around room temperature. Thermoluminescence glow curves have been shown to have a peak around \( 300\text{K-350K} \), after the scintillator had been irradiated with X-ray. For visible light, the scintillator has an index of refraction of \( 1.96 \), which has been shown to be approximately constant around room temperature. The absorption of visible light may be approximated to be 0%.

The camera lens have a magnification of 1:1, with an f-number, \( F\# \), of 4. The optical aberrations of the lens had earlier been measured not to limit the resolution[12], in the regions of interest in this report. The lens is actually a system consisting of 10 lenses placed two by two and has no anti reflecting coating according to the manufacturer. This reduces the light transmittance due to light being reflected. No data of the transmittance exists however, making it a big unknown factor in the camera efficiency.

A digital cmos sensor was used as camera sensor. Its characteristics given by the manufacturer is given in table 1. These values were measured at room temperature and their temperature dependence are unknown. Although the sensor has a bitdepth of 12 bits, pixel values are returned by the sensor as 16 bits, where the 4 least significant bits are left at zero. This effectively makes all pixel values multiples of 16. In this thesis, pixel arithmetic uses a floating-point format, but are stored as \textit{uint16}. Having pixel steps of 16 allows for the last 4 bits to be used as decimals. From now on, pixel values with steps of 16 will be referred to as \( DN_{16} \) or \( DN \), whilst when steps of 1 is used, the unit will be referred to as \( DN_{12} \). Please note the unit conversion \( DN_{16}/16 = DN_{12} \). It is worth noting that the pixels of the sensor are equipped with microlenses, i.e. small lenses in front of each pixel. Each lens is tilted towards the center of a hypothetical lens to increase the efficiency of the sensor. For the lens used, the tilting is too steep, possibly resulting in a loss of light intensity.
Table 1: Camera sensor characteristics measured by the manufacturer.[13]

<table>
<thead>
<tr>
<th>Measurement</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bitdepth</td>
<td>12</td>
</tr>
<tr>
<td>Quantum Efficiency (% at scintillator output)</td>
<td>62.5</td>
</tr>
<tr>
<td>Read Noise (e⁻)</td>
<td>6.58</td>
</tr>
<tr>
<td>Gain (DNb/e⁻)</td>
<td>10</td>
</tr>
</tbody>
</table>

To protect the sensor from unnecessary radiation, a 1 cm thick plate of Aluminum was used, with a hole, 3 mm in diameter, used as aperture. The scintillator was taped to the inner side of the Aluminum plate. However, since the scintillator is transparent to visible light, a 60 μm thick disc of Carbon was taped in front of the aperture to absorb incident light in the visible regime. In figures 6a and 6b, the transmission graphs of the Aluminium plate and Carbon disc, respectively, are seen.

![Al Density=2.6988 Thickness=10000. microns](image1)

(a) Aluminum plate.

![C Density=0.2 Thickness=60. microns](image2)

(b) Carbon disc

Figure 6: Transmission graphs of the aluminum plate, 6a, and carbon disc, 6b, for high energy photons, borrowed from [11].

### 3.2 Theoretical Performance

To estimate the theoretical performance of the camera, the relevant characteristics of each component needs to be well known. The camera noise will mostly be due to unevenly irradiation of the camera sensor or originating from the camera sensor itself. In table 1, the characteristics of the camera sensor given by the manufacturer is seen. In section 2.2, it was stated that if the OTF of all components are known, the OTF of the system may be calculated. The OTF of both the scintillator and lens are unknown however. In section 3.1, enough characteristics was however stated to estimate the responsivity of the camera. This section will derive a theoretical responsivity of the camera by describing the path a photon, incident on the camera, will take.

For the camera to register an X-ray photon, the photon must first travel through the carbon disc, probability \( p_C \). It is then absorbed by the scintillator previously discussed, and reemitted as visible light isotropically spread, see section 2.1. In section 2.1 the collection efficiency of a point source was shown in equation (1). The collection efficient is the probability that photons emitted from a point source will reach the sensor through a lens with transmittance \( T \). The camera lens in question consists of 10 lenses, which would result in a transmittance of 44%, according to equation (9). However, the lenses are placed in pairs of two with an unknown material in between. Due to reflectance being a function of the differences in indices of reflection, the camera lens may instead effectively act as a system of 5 lenses, resulting in a transmittance of 66.5%. It will be assumed that the lens transmittance is 60% in this calculation.

Furthermore, when leaving the scintillator, some of the photons will instead be reflected. Assuming that the scintillator is a perfect cuboid, the Fresnel’s equation of transmittance, equation (7), may be used. Snell’s equation, equation (8), allows for equation (7) to only depend on the angle of incidence \( \theta_i \), which however varies because of the photons being isotropically emitted. To account for this the
mean probability of transmission, $\eta_{\text{tran}}$, was calculated using equation (21), where $\theta_{NA}$ is the maximum half-angle of the cone accepted by the lens, calculated using equation (2), and $E_t$ is the proportion of photons transmitted for a fixed angle of incidence.

$$\eta_{\text{tran}} = \int_0^{2\pi} d\phi \int_0^{\theta_{NA}} d\theta_i E_t(\theta_i) \sin(\theta_i)$$

(21)

Finally, the photons hitting the sensor will only be registered with a probability $QE$. The number of photons registered by the sensor per incoming X-ray photon is given by equation (22). The theoretical estimate of this value, for photon energies of $9.25keV$, was calculated to be $1.92 \times 10^{-2}e^{-}/X-ph$, where the parameter values used are seen in table 2. This corresponds to a camera responsivity of $1.92 \times 10^{-1}DN/X-ph$ assuming a gain of $10DN/e^{-}$, as tabulated in table 1. The microlenses discussed in section 3.1 was however misaligned with regard to the lens used. This will lead to an intensity loss of unknown size.[12]

$$\eta_{\text{camera}} = \eta_C \eta_{\text{scin}} \eta_{\text{tran}} \eta_{\text{coll}} QE$$

(22)

### Table 2: Parameter values used in equation (22) and their respective source.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\eta_C$</td>
<td>0.9638</td>
<td>[11]</td>
</tr>
<tr>
<td>$\eta_{\text{scin}}$</td>
<td>260.6</td>
<td>section 3.1</td>
</tr>
<tr>
<td>$\eta_{\text{tran}}$</td>
<td>0.8940</td>
<td>equation (21)</td>
</tr>
<tr>
<td>$\eta_{\text{coll}}$</td>
<td>$1.526 \times 10^{-4}$</td>
<td>equation (1)</td>
</tr>
<tr>
<td>$QE$</td>
<td>0.6250</td>
<td>table 1</td>
</tr>
</tbody>
</table>

### 3.3 Camera Software

Communication with the camera was done using tcp/ip, between a client and a server. The server exchanged information with the camera using the software development kit, SDK, supplied by the manufacturer. Both the server and client was written in C++ using the winsock2 library for the tcp/IP-communication and pugixml library, [14], for writing and reading .xml-files. The purpose of this section is to give some basic understanding of how the user could exchange information with the camera. First a short explanation is done of the language the server and client uses for communicating. Then follow a description of the syntax the user must use to be understood by the server.

The server and client communicated synchronously, where each word started with a declaration of type, followed by the number of bytes forming the word. When all words had been sent, the sentence was ended with a good by-phrase. The other part then parsed the sentence, performed the required task, and sent an answer back. Below is an example of two words, Hello! and What’s up?, making up a sentence. Note that $s$ means string-type, $q$ means good by and the numbers, describing the string lengths, are actually sent as 32 bit integers and not as characters as in this example.

```
s 6 Hello! s10What ' s up?q
```

When starting the server, several parameters are needed to eg. find the camera or what files to use for calibration. To simplify this, most parameters were loaded from a .xml-file chosen by the user. While communicating with the camera, all other communication with the camera was blocked. However, while waiting for user input, the server allowed other sources to communicate with the camera.

The client is of the form of an executive file which communicates with the server by sending user inputs in the form of strings. The user gives the client inputs as string arguments, separated with spaces, when executing the client. The client builds a sentence, using each string as a word, and sends it to the server. This way any number of strings can be sent by the client in a single sentence. The first string must however be the IP-address of the server. An example of how to send two strings to the server, using the client executive, can be seen below.

```
\Client.exe 127.0.0.1 command1=param1@filename1--flag1 command2=param2@filename2--flag2
```

In the example above, two strings are sent to the server. These strings are parsed by the server into commands. Each command to the server consists of the command, command, and three optional parameters; param, filename and flag. The parameters must come in the order seen in the example. If a
parameter is in the wrong place or not understood by the server, it will simply be ignored. The different possible commands, and their parameters, can be found in the appendix, A.2. Numerical answers are converted to integers and sent in text form using string words, whilst files have their own word type. Images from the camera are stored as a picture class, having a header comprising the relevant information about the image and a bitmap, containing all pixel values of the image. During runtime, pixels are stored as 64 bit floating points, however, when saved to a file, each pixel are rounded off to the closest number describable by a positive 16 bit integer.

4 Method
4.1 Procedure of Virtual Pinhole Measurements

It has been previously stated that a pinhole will be used to estimate the radial distribution of a focused beam. In this section, the procedure for making such a pinhole measurement is first described, followed by the virtual replication used throughout this Thesis.

The basic principle of a pinhole measurement is that under the assumption that the focused beam is symmetric around its maximum, its radial distribution may be measured if a pinhole is centred at the beam maximum. This placement of the pinhole is however difficult. The photon flux passing through the pinhole was measured for different positions of the pinhole. The position of the maximum photon flux measured was assumed to be at the center of the beam. The maximum photon flux was then said to be the value of the cumulative radial distribution of the beam for the pinhole radius. The focussing of the beam was done using a multilayer mirror, which in addition made the otherwise broad spectra of photon energies quasi monochromatic around $9.25\text{keV}$. Photon fluxes was measured using a photodiode whose responsivity proportionality constant, $R_{\text{diode}}$, had previously been measured for photon energies of $E_\gamma = 9.25\text{keV}$, see equation (23). This energy flux could then be transformed into photons flux, $I_{\text{ph}}$, using equation 24, where $I_A$ is the diode’s output current. The pinholes used in this Thesis will be referred to by labels corresponding to a diameter as seen in table 3 and was assumed to block all incident photons outside of its aperture. An important note is that the largest pinhole, $O$, is actually the square photodiode surface with the side $1\text{mm}$, approximated to a circle with diameter $1.13\text{mm}$.

**Table 3: Pinhole series with respective diameters**

<table>
<thead>
<tr>
<th>Pinhole</th>
<th>O</th>
<th>C</th>
<th>A</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
</tr>
</thead>
<tbody>
<tr>
<td>diameter [mm]</td>
<td>1.13</td>
<td>0.7525</td>
<td>0.496</td>
<td>0.3009</td>
<td>0.1973</td>
<td>0.1465</td>
<td>0.1008</td>
<td>0.076</td>
<td>0.0492</td>
<td>0.0254</td>
</tr>
</tbody>
</table>

\[
R_{\text{diode}} = 0.05717A/W \tag{23}
\]

\[
I_{\text{ph}} = \frac{I_A}{R_{\text{diode}}E_\gamma} \tag{24}
\]

The first step in replicating this procedure was replacing the pinhole with a matrix representing the image of a hypothetical pinhole, referred to as *virtual pinhole* and further discussed in section 4.2. Under the assumption that a real pinhole blocks all photons incident outside the aperture, the virtual pinhole may be used as an estimate of where photons would end up. An estimation of the photon flux passing through a pinhole is the weighted sum of all the signal in an image, with the virtual pinhole matrix as weight. For this estimation to be good however, only the pixel signal corresponding to registered photons inside the camera aperture should be considered. This may be done by removing pixel signal from other sources, which will be further discussed in section 4.4. To mimic the movement of the real pinhole, the virtual pinhole matrix is convolved with the image of the focused beam. The virtual pinhole measurement is then defined as the maximum value of this convolved matrix. In equation (25) the virtual pinhole measurement is concisely described, where $P$ is the virtual pinhole matrix, $A$ is the image of the focused beam and $D$ is an image of pixel signal not originating from the beam intensity. Finally, the camera responsivity relation, $R(S_{\text{pin}})$, was used to transform the result into number of photons incident on the camera during the exposure time, $S_{\text{ph}}$, see equation (26).

\[
S_{\text{pin}} = \max(P \ast (A - D)) \tag{25}
\]
4.2 Virtual Pinhole Matrix

In this report a virtual pinhole will be used to approximate a real pinhole located right in front of the scintillator. To do this, a distribution function was needed to approximate the picture of a pinhole. In practice, the pinhole would be projected as a disc onto the scintillator, which would then be affected by the camera OTF before imaged by the camera sensor. This spreading of the disc will however be assumed to be small enough, such that the image will be the disc itself. What then remains is the pixel sampling of this perfect disc. In this section, the method used for sampling this hypothetical image of a pinhole will be discussed. First area weighted projector, AWP, used for projecting an image onto a line will be presented, developed by [15]. This method is then applied in a polar coordinate system to describe the disc projection.

To project an image onto a line, it is sufficient to describe the projection of a single pixel. In figure 7, a descriptive image is seen of how a pixel is projected onto a line, where \( r_{1st}, r_{2nd}, r_{3rd} \) and \( r_{4th} \) is the projections of the pixel’s corners. The pixel area is projected in the the shape of a trapezoid, as seen in figure 7, which is then used as a distribution function for projecting the pixel. This procedure is then done for each pixel in the image.[15]

The projection of the disc onto a grid of pixels was done by applying AWP backwards in polar coordinates. Note that a perfect disc may be described by a step function along the radial axis, i.e. 1 for radii less than the disc radius and 0 otherwise, as seen in equation (27). Pixels in a matrix are projected onto the radial axis and their projections are used to find out to what extent they are located inside the disc. To simplify calculations, the disc is assumed to always be centred at the center of a pixel. The projection of a disc, referred to as a virtual pinhole, with radius 4px is seen in figure 8.

\[
H(r) = \begin{cases} 
1 & r \leq R \\
0 & r > R 
\end{cases}
\] (27)

Figure 7: Descriptive picture of how a pixel is projected onto a general line. Image is borrowed from [15]

Figure 8: A continuous distribution function with a radius of 4px, red circle, together with its projection onto a grid of pixels.

4.3 Noise Characterization

The noise of the camera will in this Thesis be assumed to origin from the camera sensor. During its characterization, the noise was divided into a spatial and temporal part, allowing for different types of
noise sources to be evaluated. The method used for this will be discussed in this section, followed by how the temperature dependence of the dark current was investigated.

By assuming the noise is normal distributed and not pixel dependent, the total noise, $\sigma_{tot}$, and temporal noise, $\sigma$, may be approximated in an image $A$ using equations (28) and (29) respectively, for $L$ images of $M \times N$ pixels. Furthermore, assuming the temporal and spatial noise to be invariant, the total noise can be described with a temporal and a spatial term, as seen in equation (30). The spatial noise, $s$, may then be solved for by using equation (31).

$$\sigma_{tot} = \sqrt{\sum_{i=0}^{L-1} \sum_{j=0}^{M-1} \sum_{k=0}^{N-1} \left(A_{i,j,k} - \frac{1}{LMN} \sum_{i'=0}^{L-1} \sum_{j'=0}^{M-1} \sum_{k'=0}^{N-1} A_{i',j',k'}\right)^2 / (LMN - 1)}$$  \hspace{1cm} (28)

$$\sigma = \sqrt{\sum_{j=0}^{M-1} \sum_{k=0}^{N-1} \left(\sum_{i=0}^{L-1} \left(A_{i,j,k} - \frac{1}{L} \sum_{i'=0}^{L-1} A_{i',j,k}\right)\right)^2 / (L - 1) / (MN)}$$ \hspace{1cm} (29)

$$\sigma_{tot}^2 = \sigma^2 + s^2$$ \hspace{1cm} (30)

$$s = \sqrt{\sigma_{tot}^2 - \sigma^2}$$ \hspace{1cm} (31)

In section 2.3 the transformation between temporal noise in DN and registered photons was shown. This relation is utilized in photon transfer curves to give the values of the read noise and gain of the sensor. This is done by plotting the temporal variance against the mean pixel signal, resulting in a straight line, where the slope corresponds to the gain and the offset to the read noise of the sensor, see equation (32). Due to the characteristics of dark currents, non-irradiated images may be used. However, in this report only evenly irradiated images will be used, where the signal will be varied by changing the exposure time of the camera. This series of images will be referred to as the bright field series.

$$\sigma^2 = \sigma_r^2 + kS$$ \hspace{1cm} (32)

To characterize the dark current, two series of pictures were taken. The first was taken in darkness with varying exposure times, referred to as dark field series. This allowed for the exposure time dependence of the dark signal to be measured, where the dark current is the time derivative. The second series of pictures were taken in darkness with varying temperature at a constant exposure time of 1500ms. A total of 9 different temperatures were used with 12 pictures taken at each temperature. The temperature dependence of the dark current is described in equation (16), where the doubling temperature $T_2$ is the most important parameter. By taking the logarithm of the dark signal, the linear relation in equation (33), appear. The doubling temperature may then be approximated using equation (34). Please note that [9] uses the mean dark current, whilst in this Thesis the mean dark signal was used. They both give the same $T_2$ however, since they only differ with some constant factor, namely the exposure time. The dark signal was calculated according to equation (35), where $I_{cam}$ is the pixel intensity, $\mu_{d,0}$ is the bias frame, discussed in section 2.3 and approximated in section 4.4. Before calculating the dark signal, all full pixels from every point of measurement was found and removed from every measurement.

$$\log(S_d) = \log(S_d(T_0)) + \log(2) \frac{T_0 - T_0}{T_2}$$ \hspace{1cm} (33)

$$T_2 = \frac{\log(2)}{\frac{d}{dT} \left(\log(S_d)\right)}$$ \hspace{1cm} (34)

$$S_d = \sum_{pixels} (I_{cam} - \mu_{d,0})$$ \hspace{1cm} (35)
4.4 Calibration Procedure

In section 2.3, three sources of noise were discussed which alter the expectation values of pixels, namely the bias frame, the dark current and the PRNU. These are all somewhat measurable and hence possible to cancel out. Since the purpose of the calibration procedure is to reduce variations of different pixels’ expectation values for a given irradiation, the spatial deviation is a measure of the efficiency of the calibration. Another purpose is to have a constant relative intensity over the whole camera aperture. This means that if pixels at the sides always give less signal than pixels in the center, the calibration procedure should compensate for it. In this section a method for compensating for the bias frame and dark current will first be discussed, followed by a procedure of reducing the PRNU.

Since the bias frame has a constant expectation value, whilst the dark current is linear in time at constant temperature, their combined expectation value is a linear combination which will be referred to as background. In this report, to approximate the background for a given temperature, $T_{\text{new}}$, and exposure time, $t_{\text{exp,new}}$, two images were used, one approximating the bias frame, $D_0$, referred to as bias, and one as a measure of the dark current, $D_1$, referred to as dark. The dark image was taken at an exposure time, $t_{\text{exp,1}}$, of 1500 ms at a temperature, $T_1$, of 38°C, using the median of 1000 images. Since the dark current depends on temperature, it was approximated to the new temperature using equation (36) and (37).

$$D_1(T_{\text{new}}) = K_{DC}(D_1(T_1) - D_0) + D_0$$  \hspace{1cm} (36)

$$K_{DC} = 2^\frac{T_{\text{new}} - T_1}{T_1}$$  \hspace{1cm} (37)

Due to a hardware non-linearity, the bias picture $D_0$, could not be calculated by taking an image at a short exposure time, see section 5.1. Instead it was approximated by a linear fit between pixel signal and exposure time of a dark field series. The mean of 200 images were used for each exposure time given in $\text{ms}$ in equation (38). Picture $D_0$ was then approximated by the constant term in the fit. The background of an image could then be approximated using equation (39), where $t$ is the ratio of the exposure time of the image, $t_{\text{exp,new}}$, and the dark picture, $t_{\text{exp,1}}$.

$$t_{\text{exp}} = [35 : 15 : 80 100 : 20 : 180 200 : 100 : 500]$$  \hspace{1cm} (38)

$$D_{t_{\text{exp}}} = (1 - t)D_0 + tD_1(T_{\text{new}})$$  \hspace{1cm} (39)

As previously stated, the quantum efficiency and gain varies between pixels resulting in PRNU. Assuming they are linear, they may be compensated for however. This may be done by defining a signal where all pixels should give a uniform response. In this Thesis, this was done by first taking an evenly irradiated picture, referred to as bright, $B$. The background was then removed from this image, resulting in a picture referred to as flat, $F$. When the background has been removed, any remaining spatial variance in pixel signal is approximately due to variance in quantum efficiency and gain. Therefore, to compensate for the PRNU, this flat picture was used as a weighting function in a procedure referred to as flat field compensation, seen in equation (40), where $F_{i,j}$ is pixel $(i,j)$ of $F$ and $<\text{pic}>_F$ is the flat field compensated version of some picture $\text{pic}$. When evenly irradiating the camera, some high energy photons hit the camera sensor directly, causing the heavy temporal noise discussed in section 2.3. To get the bright image, the median picture out of 1000 was used, effectively removing this type of temporal noise, see section 5.1. The images were taken at exposure times of 1500 ms to get high amount of signal in the bright image. Even so, the mean pixel value of the bright picture had a value of 15% of the maximum value, whereof the bias frame constituted 7% of the maximum value. This may affect the flat field negatively at higher photon intensities.

$$<\text{pic}_{i,j}>_F = \frac{<F>_{i,j}}{F_{i,j}}$$  \hspace{1cm} (40)

It has now been discussed how to compensate for the background and PRNU. Some pixels are however simply unusable and will be referred to as bad pixels. A procedure was developed to find these bad pixels and replace them with the mean value of their nearest neighbours. To reduce the time requirements, the dark and bright pictures were used to find the bad pixels, which were then stored as a logical matrix. The definition of a bad pixel was based on the finite bit depth of the pixels and the error propagation during flat field compensation. If a pixel would have too large a background, the bit depth reserved for photons would be effectively decreased. Furthermore, a pixel responding weakly to photons will be of
little use in a photosensor. Finally, similar to the case of a large background, a pixel responding too quickly to photons will be filled quickly. These three cases are shown in equations (41)-(43), where the maximum value of a pixel is 65535. It is worth noting that the camera sensor replaced dead pixels with the mean value of its neighbour itself.

\[
BAD = \{(i,j) : D_{1,i,j} + 3\sigma(D_{1,i,j}) > 40000 \}
\]  

(41)

\[
BAD = \{(i,j) : B_{i,j} + 3\sigma(B_{i,j}) > 40000 \}
\]

(42)

\[
BAD = \{(i,j) : B_{i,j} - D_{iexp,i,j} < 0.3\text{Mean}(F) \}
\]

(43)

4.5 Spatial Resolution

The shape of the focused beam will look different in the plane of the scintillator and in the plane of the camera sensor. This is due to non-ideal optical components and the diffraction of light, discussed in section 2.2. It was seen that the amplitudes in Fourier space change when transmitted through an optical system. To estimate the MTF, and hence the resolution, it is sufficient to estimate the change of amplitudes in Fourier space. This was done by shadow imaging of line patterns. In figure 9, the concept of shadow imaging is seen. Two types of line patterns were used in this Thesis, both using square waves of 10\mu m thick gold onto 100\mu m silicon background.[16] In this section, first the procedure of measuring the MTF is discussed, followed by the differences between the two type of patterns used.

![Figure 9: A point light source is used to project a shadow of some object onto a screen. The shadow become magnified compared to the object.](image)

Due to the wavelength of the photons being much smaller than the line patterns, geometrical optics is applicable. The shadow of the line patterns is then approximately of the shape of square waves. Using fast Fourier transform, Matlab function \textit{fft}, over several periods, the aim was to get a good approximation of the Fourier components present in the pattern. The \textit{Hann} window was used to get a better precision in Fourier space. The script used, utilized a few points to find a coordinate system fitting the pattern. These points have a strong effect on the measured MTF however. Therefore, to decrease the effects of human error, the script tries a few points and choose the one with largest calculated amplitude. Amplitudes were calculated using equation (44), where \(S_i\) is the measured signal and \(w_i\) the Hann weighting factor at line segment \(i\). The amplitudes were then compared to the theoretical amplitude of the fundamental frequency of the square wave pattern, calculated as in equation (45). The maximum and minimum intensities, \(S_{\text{max}}\) and \(S_{\text{min}}\), was calculated using the mean of larger bright and dark areas to estimate the amplitude for patterns of 0Hz. Note that the amplitude for the fundamental frequency of a square wave of amplitude 1/2 is \(4/\pi\). To focus the camera the rectangular pattern with a period of 15\mu m was used, and resolution measured with the described method, exception being the optimization of point positioning. Hence the resolution presented here, might not be the most optimal. In figure 9, it is seen that the shadow of the object is magnified. This magnification was measured and compensated for
during measurements. Furthermore, it is clear that since the photons travel through the patterns, the finite width of the object will result in distortion of the imaged pattern. A similar result will come from the finite width of the source. The effects from these on the MTF were however estimated to be small enough.

\[
A = 2 \left\| \frac{\text{fft}(\{w_iS_i\})}{\sum w_i} \right\| 
\]

\[
A_{\text{teo}} = \frac{4}{\pi} \frac{S_{\text{max}} - S_{\text{min}}}{2}
\]

A rectangular pattern, seen in figure 10, was used to get accurate measurements of the MTF for a few frequencies. The AWP, discussed in section 4.2, was used to project the pattern onto a line. To define this line, two points were chosen along the pattern and a third perpendicular to it, as seen in figure 10. The fft of the line projection was then calculated and the largest Fourier component, within two steps of the estimated frequency, was saved as the amplitude of the pattern. The AWP allowed for line segments much smaller than the side of a pixel. The length of the line segments was chosen such that the total pixel area projected in mean per segment equaled the area of one pixel. Patterns with periods of 15\(\mu m\), 20\(\mu m\) and 25\(\mu m\) was used, each placed about 12\(mm\) from the scintillator and around 182\(mm\) from the source. For each pattern, a median picture was taken from 100 images taken at an exposure time of 1500\(ms\).

![Figure 10: Calibrated picture of the rectangular pattern with a period of 25\(\mu m\), together with the region of interest used for the projection and the three points that defined it.](image)

Siemens stars have the benefit of giving information about a broad spectrum of spatial frequencies. Therefore, the one seen in figure 11 was used to complement the rectangular pattern. In the case of the Siemens star, only one point was used to define the coordinate system, namely the center of the star. To translate the Cartesian grid of the camera sensor into polar coordinates, a script was created that stored values of pixels close enough to the user defined radii, with their respective angular coordinates, [17], see figure 12. The tolerance for being close enough to a radius was defined by the user. This gives a lot of points of measurements, however, no mean is taken of values, giving very noisy figures. In the fft, the noise is in some sense averaged out however. It is worth mentioning, that this method do not give points of measurements at equal distances, which might affect the result of Matlabs fft. When measuring the resolution using the Siemens

![Figure 11: Calibrated picture of the Siemens star used for the resolution measurements.](image)
star, a median of 200 pictures was used, taken at an exposure time of 1500ms. The pattern was placed about 12mm from the scintillator, which in turn was placed around 170mm from the source.

Figure 12: Procedure for choosing points of measurement in Siemens star, borrowed from [17].

4.6 Evaluation of Virtual Pinhole Measurements

The main goal of this Thesis is to evaluate the possibility of replicating pinhole measurements with virtual ones. For the two methods to be comparable, a unit transformation between output signal of the photodiode and the camera must be known. This is one goal for the responsivity characterization of the camera. However, the responsivity may vary with different temperatures, something that must be evaluated. Furthermore, the scintillator may bleach after long time exposure of high energy photons. These are the topics of this section.

To characterize the camera responsivity, real and virtual pinhole measurements were done and compared to find a linear relation between camera signal and number of incident photons. This was done using pinholes C and 2 for different beam intensities. A linear relation was then fitted between the camera signal and the number of incident photons. The constant term will be dependent on signal not varying with beam intensity and hence dependent on the pinhole area if the background is insufficiently compensated for. It was therefore added simply to get better accuracy of the linear term. Real and virtual pinhole measurements were then done using the whole pinhole series and compared to check if using the linear responsivity coefficient as a proportionality constant, was sufficient to get good agreement. In addition, this series of measurements may be used as a proof of concept of the virtual pinhole measurement.

For testing the temperature dependency of the responsivity, virtual pinhole measurements were done for different camera temperatures. The camera was first cooled down using a fan before placed in the focus of the beam. The camera sensor was then heated between measurements using a hair dryer. Temperature measurements were done using the internal sensor of the camera sensor.

Bleaching of the scintillator should depend on the time of exposure and the flux of photons. The camera was therefore placed in the focus of the beam with the scintillator irradiated for 114h to increase the potential of bleaching. To investigate any change of efficiency of the scintillator, measurements were done once an hour. Each measurement consisted of virtual pinhole measurements with the beam focused at first the bleached position, followed by a position used as reference. The two were then compared each measurement to investigate any change over time.

5 Results

5.1 Camera Characterization and Calibration

In this section the most important result concerning the camera characterization will be presented. First, the temporal noise of the camera will be investigated, followed by characterization of the dark current. The efficiency of the calibration procedure will then be evaluated. Finally the results concerning the spatial resolution of the camera will be presented.
Figure 13: Photon curves of the 200 small regions used to calculate the sensor gain, together with curves parametrized using the measured result, upper curve, and by the manufacturer given values, lower curve. In addition, figure 13a show the case where only median images were used to calculate temporal variance.

To evaluate the gain and read noise of the camera, photon curves of the evenly irradiated bright field series was used, see section 4.3 for a more detailed description. The data set was divided into 200 small regions, which were then fitted to equation 32 using least square. Histograms of the calculated values of the gain and read noise was then used to estimate the respective values of the camera sensor. In figure 13, the photon curve is seen together with curves parametrized using either the estimated gain and read noise, upper curve, or the respective tabulated values, lower curve, see table 1. Using the histograms, the gain was estimated to be approximately $17.5\text{DN/e}$ and the read noise around $82\text{DN}$. However, as suggested by figure 13, the tabulated values of $10\text{DN/e}$ and $65.8\text{DN}$ respectively, seem far better. A possible cause of the faulty values of the gain is the wide spread of measured temporal variance seen in figure 13 (red dots). To remove this spread, the same series of pictures were used, but this time the set of measurements were divided into two subsets. The median image of each subset was calculated and used to estimate the temporal variance. The resulting temporal variance is presented as the blue dots in figure 13, where a decrease in the spread is seen, although with an overall increase of variance. To physically explain the spread, two pictures was taken with the same parameters and with the light from the scintillator blocked using foam rubber, see figure (14). This was done because of foam rubber’s ability to block out visible light, whilst being transparent to high energy photons. In the figure, two clusters of high signal pixels are marked that appear in only one of the two images. When pictures were taken with the same camera settings but with the source turned off, clusters did not appear and disappear with time. The measurement of the read noise instead suffered from a hardware non-linearity, which is clearly seen as the discontinuity in figure 13b.
Figure 14: Two pictures taken, irradiated by the source but with the light from the scintillator blocked by foam rubber. Two clusters are marked where large amount of signal is measured in only one of the images. Please note that the difference in brightness is not due to pixel values but different settings in the image gray scale.

The dark current is characterized by its doubling temperature. A series of dark field images were taken with varying temperature, allowing for the doubling temperature $T_2$ to be estimated, see equation (16). The doubling temperature were estimated to be 7K, using equation (34), using a linear fit to the logarithmic relation between dark signal and temperature seen in figure 15a. The linear domain is seen in figure 15b. In both figures, a reference point is seen, corresponding to the background used during the calibration procedure, together with its interpolation to new temperatures used during calibration, see equation (36). Though not presented here, changing the region of interest resulted in a change of the calculated dark current in the reference picture. The temperature dependence presented is based on a total of 58000 pixels, however, when using all 1200000, the mean dark signal of the reference picture increased, whilst the pictures for the measurement remained constant.

Figure 15: Temperature dependence of the dark signal, together with the analytical extension of the dark picture used during calibration. In figure 15a the logarithmic relation is seen, used during estimation of the doubling temperature. Figure 15b shows the corresponding relation with linear axis, with the difference of the two plotted as black stars. In addition, a linear regression of the difference is plotted (black curve).
In figure 15, the efficiency of the calibration procedure estimating the temperature dependence of the dark signal is seen. The result should be compared to the estimation of the exposure time dependence of the dark signal seen in figure 16, where instead the dark field series was used. To further investigate the efficiency of the calibration procedure, its effect on the spatial noise of the bright field series was estimated and is seen in figure 17. A large decrease of the spatial noise in the raw images are seen after the background compensation, see figure 17, but the spatial noise is increased during the flat field compensation. If the flat field image was not irradiated evenly enough or enough samples not taken, its resulting noise will spread during calibration. The latter is difficult to measure, but figure 18 shows that the flat field image was not evenly irradiated. However, in addition to reduction of PRNU, the flat field compensation is meant to reduce other pixel irregularities, such as uneven irradiation of the camera sensor. To test this, the horizontal and vertical intensity profiles of a picture was compared for both a background-compensated and a calibrated case. In figure 19, the vertical profile is seen, where the pixel intensity change consistently with position in the background-compensated case. This behaviour is then removed during the flat field compensation.

Figure 16: The dark signal for the dark field series after it has been subdued to background-compensation and calibration procedure respectively.

Figure 17: The temporal and spatial noise for the bright field series before and after it has been subdued to background-compensation and calibration procedure respectively, together with the temporal noise.

Figure 18: Flat field image used to reduce pixel non-uniformities, here image intensities are seen in the interval 3500$DN$ to 4500$DN$.

Figure 19: Vertical profile plot of the calibrated and the background-compensated cases of a homogeneously irradiated picture.
Finally, to estimate the spatial resolution of the camera both a rectangular line pattern and a Siemens star was used. In figure 20, the resulting MTF is seen and describes the camera resolution, see section 2.2. In addition to giving smaller values of the MTF, the Siemens star also gave more noise in the frequency domain. It is worth noting that the MTF is given relative to the amplitude at 0lp, which was estimated by approximating the amplitude of the square wave constituting the patterns. In the case of the rectangular line pattern, the amplitude of the square wave was estimated to have laid between $4DN_{12}$ and $4.5DN_{12}$. The rectangular line pattern for 62lp resulted in an MTF-value of 0.226, which is equivalent to an amplitude of the corresponding sine-function of around $1DN_{12}$. Note the conversion of units $1DN_{12} = 16DN$, where $DN$ is the unit used in general in this Thesis, see section 3.1 for a more detailed description.

5.2 Evaluation of Camera Responsivity and Virtual Pinhole Measurements

This section will contain the estimated camera responsivity needed for the virtual pinhole measurements. Furthermore, the performance and stability of the virtual pinhole measurements will be investigated by testing possible variation due to temperature or bleaching.

The camera responsivity was evaluated by comparing photon fluxes measured in a series of pinhole measurements with the intensity measured in the corresponding virtual pinhole measurements. In the latter case, 100 images were taken with an exposure time of 300ms and a temperature of 39°C, with the median image used during the measurement. The camera intensities was then linearly fitted against the photon fluxes measured by the diode, as seen in equation (46), where $I_{ph}$ is the photon flux, $R_{cam}$ the responsivity proportionality coefficient of the camera and $C$ some constant. The fitted parameters are seen in table 4. In figure 21, the measured camera intensities and photons fluxes are seen together with the corresponding fit. To test the result, pinhole measurements were done using the full series of pinholes, see table 3, and compared with the corresponding virtual result. In figure 22, the result of the two methods are seen together with their relative residual. Note that the results of the virtual pinhole measurement was converted to photon flux using equation (46), with $R_{cam}$ given by table 4 and $C = 0$. 
\[
\frac{S}{t_{\text{exp}}} = R_{\text{cam}} I_{\text{ph}} + C \tag{46}
\]

Table 4: Regression results of the linear responsivity fit.

<table>
<thead>
<tr>
<th></th>
<th>Calculated (95% confidence interval)</th>
</tr>
</thead>
<tbody>
<tr>
<td>( R_{\text{cam}} )</td>
<td>( 3.283 \times 10^{-2} ) ( ( 3.210 \times 10^{-2} ), ( 3.355 \times 10^{-2} ) ) \ DN/\text{X-ph}</td>
</tr>
<tr>
<td>( C )</td>
<td>( 1.528 \times 10^{6} ) ( ( -3.613 \times 10^{4} ), ( 3.093 \times 10^{6} ) ) \ DN/s</td>
</tr>
</tbody>
</table>

To evaluate the temperature dependence of the scintillator, virtual pinhole measurements were done at varying temperatures. In figure 23a a small pinhole with an area of 100px was used, whilst in figure 23b the whole camera aperture was used.

To evaluate the temperature dependence of the scintillator, virtual pinhole measurements were done at varying temperatures. In figures 23a the results from using a virtual pinhole with an area of 100px is seen, giving values varying within 2\%. When using the camera aperture as a virtual pinhole, the measured signal increases by almost a factor 2 when the temperature is increased, see figure 23b. The signal increasing with area may indicate an error in the background compensation. Therefore, the corresponding measurements were done with the temperature dependent dark field series, see figures 24a and 24b where the background compensation is seen to rather reduce the measured signal than to increase it. In the case of the dark field series, the virtual pinholes were placed in the center of the camera aperture.
Finally, the bleaching of the scintillator was investigated by irradiating a small area over 114h and comparing its responsivity with some reference area of the scintillator. In figure (25), the measured intensity at the bleached position relative to that of the reference position is seen as a function of time and rather show an increase over time than a bleaching. If the temperature is changed during the experiment, this may affect the result. Therefore, the measured intensities are instead shown as a function of temperature in figure 26 and show no clear temperature dependence of the signal.

Figure 25: The ratio of the measured camera intensity of bleached spot to the reference spot for two different virtual pinholes used, plotted against the time of measurement.

Figure 26: Measured camera intensity for the bleached spot and reference spot using a virtual pinhole diameter of 52.6px, plotted against the temperature at the time of measurement.

6 Discussion

6.1 Camera Characterization and Calibration

The camera noise was characterized using a series of evenly irradiated images of varying exposure times. The noise were then partitioned into several sources of temporal and spatial noise before evaluated. A calibration procedure was then developed to minimize the spatial noise and the camera resolution measured. The presented results of these topics will be discussed in this section.

The temporal noise consisted of the constant read noise, signal dependent shot noise and the random occurrences of high energy photons. In figures 13 and 14 it was shown that the latter type has a significant
effect on the temporal noise on small areas of the picture when using the full spectra of the X-ray source. By using the median picture out of several, the spreading of temporal noise was decreased, although increasing it overall.

By using the median picture out of several, the mean temporal noise increased, although more concise. This might be beneficial since the standard error decreases with number of images, but perhaps not fast enough to remove the errors from the high energy photons. It was further shown in figure 13 that the tabulated values of the camera gain, $10DN_{16}/e$, and read noise, $65.8DN$, seem to agree reasonably with the experiments presented.

The dark current of the camera was characterized by evaluating its doubling temperature. This was done by measuring the temperature dependence of the dark signal, which is seen in figure 15. The doubling temperature was measured to be $7K$, which should be compared to the minimum and maximum temperatures occurring naturally during the Thesis, namely $35°C$ and $40°C$. This means that the dark current may vary with almost a factor 2 in the experimental setup used. The series of pictures used during the estimation of the doubling temperature, however, showed distinctly less dark signal than the image used for background compensation. This may be due to the dark environment being created differently in the two cases. Since measuring the temperature dependence of the dark current relied on simply two points of measurements in time, whereas one was the approximated bias frame. This allows for large errors in the estimation of the doubling temperature.

To compensate for the dark current and bias frame, an interpolation between two images was made, one taken at high and one at low exposure time. Due to the discontinuity at low exposure time, a least square fit was done to approximate an image taken at zero exposure time. The temperature dependence of the dark current was compensated for using the measured double temperature. This interpolated image is used as a background compensation and have been shown to remove most of the dark signal, figures 15b-16, and reduce the spatial noise significantly, figure 17. The background compensation is however not optimal. In figure 16, the background compensation was seen to leave a dark signal of around $20DN \pm 20DN$ per pixel for an exposure time of $1500ms$, whilst the corresponding number in figure 15b is $-25DN \pm 25DN$ per pixel. These background miscalculations seem to increase with exposure time and temperature. If the dark picture used during the background compensation was not taken in total darkness, this might explain the negative leftovers in figure 15b since that series was taken using another method of creating darkness. If so, the background compensation overestimates the dark current. This will not, however, show up in figure 16 since that series used the same method of creating darkness as used in the dark picture. For high photon intensities, even the worst case of background miscalculations will give deviation much smaller than the temporal noise. For lower intensities, however, this uncertainty in the background might affect the result.

In addition to the background compensation, the calibration of a picture involved a flat field compensation. The first step greatly reduced the spatial noise, as previously discussed. The last step, however, increased it, see figure 17. One explanation for this may be that although the flat field compensation should reduce noise from PRNU, noise in the flat field image will spread during the procedure. That the spatial noise increases gives a hint that the contribution from PRNU is small compared to the noise spreading from the flat field image. In the ideal case, pixel signal in the flat field image would be proportional to the photon intensity, in a case where the camera had been evenly irradiated and the standard error due to temporal noise reduced to approximately zero. However, in the case of this Thesis, the camera had not been evenly irradiated, seen in figure 18. Furthermore, the approximated background deviated from the actual background, meaning that the flat field is not proportional to the incident photon intensity. These two facts are probable causes of the increase of spatial noise. The temporal noise is however still the main contributor of the total noise, for the investigated ranges, even after the increase of spatial noise. However, yet another reason for flat field compensation exists, variations between different parts of the image. The vertical profile of the intensity were used to evaluate this, see figure 19, where a small spatial dependence was seen and successfully removed during the flat field compensation. The horizontal profile did not show a spatial dependence however.

Finally, to measure the resolution of the camera system, the MTF was evaluated using a Siemens star for a continuous spectra of spatial frequencies and rectangular line patterns for precise data of three spatial frequencies. The resulting MTF-curve, seen in figure 20, show a worse resolution using the Siemens star than the rectangular patterns. When measuring the MTF, the result is dependent on the camera resolution, the number of periods of the pattern and the methods used for estimating the MTF-value. Since the camera resolution was the same during both types of patterns, this means that the results from Siemens star do not correspond to the camera resolution. If the MTF-value of more frequencies had been measured using the rectangular pattern, the PTF of the camera could have
been estimated. Parametrizing the PTF using only three frequencies seemed, however, to give too large uncertainties to be meaningful. Furthermore, if the MTF of the lens had been known, the MTF of the scintillator would have been possible to estimate, thereby allowing for the limiting factor of the resolution to be found. Finally, since the final method of measuring resolution had not been developed at the time of the focussing of the camera, the camera resolution during this Thesis may not have been the most optimal.

6.2 Evaluation of Camera Responsivity and Virtual Pinhole Measurements

To measure the responsivity of the camera, real and virtual pinhole measurements were done and compared for different photon intensities and pinholes. A linear fit was then made between the two, where the responsivity were assumed to correspond to the linear coefficient. The resulting responsivity were estimated to be $3.283 \times 10^{-2} DN/X-ph \pm 7.3 \times 10^{-4} DN/X-ph$, see table 4, for 9.25keV photons. This should be compared to the theoretical value $1.92 \times 10^{-1} DN/X-ph$, calculated in section 3.2. As seen, the theoretical and measured responsivities differ by a factor 6. The theoretical estimation has several unknowns with possibly large effects. It was mentioned that the lens transmittance was estimated to be 60%, whilst 40% was the theoretical worst case scenario. At the same time, the properties of the scintillator was unknown for its dimensions and the given photon energy, with a possible reduction of its efficiency of at least 10 – 15%. If both these two worst case scenarios were fulfilled, the measured responsivity would still differ by a factor 2.5 from the theoretical. However, it was assumed that the scintillator has the shape of a perfect cuboid to simplify fresnell’s law. If instead its surface is rough, the light travelling out of the scintillator may be severely scattered. This possibility was not investigated however.

If only the linear responsivity term is used to approximate the camera responsivity, the procedure would be greatly simplified. To test the validity of this, results of the real and virtual pinhole measurements for a series of pinholes was compared. It was shown in figure 22 that the two methods gave results with a relative residual of less than 10%. If the largest pinhole is removed from the measurement, due to it not being a pinhole with circular aperture, the maximum relative residual was reduced to 6%, located at pinholes C and 2. To begin the analysis of these errors, it is good to note that an error in the flat field image leads to a mean relative error per pixel, whilst an error in the background compensation leads to a mean absolute error per pixel. A small pinhole is therefore sensitive to errors in the flat field, since it is irradiated with a high intensity of photons, whilst having a small area. Large pinholes, instead have a large area, resulting in a sensitivity to errors in the background image.

In the case of a small pinhole, the error should be compared with the results from the bleeding of the scintillator, see figure 25. It was shown that two different locations of the spot may give a difference in signal of less than 2% for a small pinhole the first day. After the first day however, the difference in signal went up to 5%. If this had been due to variations of the shape of the beam, the difference would have been ±5%. Since this was not the case, it is probable that the difference is due to errors in the flat field image. It was, however, also seen that the relative deviation may have changed with almost 5% when measured one hour later. These changes should however be due to instability of the beam structure, since the camera calibration and the virtual pinhole measurements should be quite time independent. It is worth noting that the two locations used during the experiment was relatively close to each other.

For the larger pinholes, the 6% deviation of the virtual pinhole measurement, figure 22, should be compared with the largest error measured in the background. In figures 15 and 16, this largest mean error was measured to be ±50DN per pixel, for an exposure time of 1500ms. In the case of an mean error of 50DN per pixel, the deviation of the virtual pinhole measurement would be 5%, making it a possible explanation. However, since the virtual pinhole measurements used an exposure time of 300ms and the error increases linearly with exposure time, the corresponding worst case scenario should be 10DN per pixel, equivalent to 1% relative residual. It is therefore unlikely that an error in the background compensation is the main cause of the errors in the virtual pinhole measurements.

The temperature dependence of the responsivity was measured by virtual pinhole measurements with varying temperature and constant source intensities. The measurements did not show consistent results though. Hypothetically, the area of the pinhole should only affect the results in that a large pinhole decreases the noise whilst increasing the sensitivity to errors in the background compensation. If the responsivity was changed by temperature, this should lead to a relative increase of signal, independent on the pinhole. The measurements, however, showed a relative increase of signal of around 80% for the large pinhole, whilst the small pinhole did not show any change of signal other than a noise of around
2%, see figure 23. It has already been discussed that the temperature dependence of the background is not accurately known. In addition, big pinholes are sensitive to errors in the background compensation. To disprove the background compensation as the cause, virtual pinhole measurements were done on dark field pictures with varying temperature. In figure 24 it is seen that the small pinhole gives such a small net dark signal, that the irradiated picture should remain unaffected.

In the case of the larger pinhole, the largest error in background compensation show a net dark signal of $25 \times 10^6 \text{DN}$. This should be compared with $-29 \times 10^6 \text{DN}$ seen in figure 24 and the total increase of signal $30 \times 10^6 \text{DN}$. However, these dark signals were measured at 1500ms instead of 200ms. Since the net dark signal increases linearly with exposure time, as mentioned before, the resulting net dark signal would be around $4 \times 10^6 \text{DN}$. It therefore seem unlikely that the error from the background compensation is the cause of the increasing signal. What the measurements clearly state however, is that the temperature dependence of the responsivity, if any, is small.

Another note to be made about the temperature dependence of the responsivity is that the temperature was only measured in the internal sensor of camera sensor, i.e. the temperature of the scintillator is unknown. Since the heating was done using a hair dryer, the temperature of the scintillator might have changed too. If the temperature did change of the scintillator, a hypothesis is that the TSL might explain why the signal increases when using the larger pinhole but not the smaller, see figure 23. Normally when TSL is analysed, the crystal is first irradiated and then slowly heated, releasing trapped electrons or holes. In this Thesis, the temperature of the scintillator is approximately constant during each measurement. However, it is constantly irradiated. That is, the amount of trapped electrons are slowly reduced during normal TSL analysis, whilst in this case they are being constantly refilled. If the temperature increases, the rate of which the electrons escape traps increases, increasing the emitted light. Since there is a finite amount of traps, there is a maximum capacity of trapped electrons. Hence, if only a small amount of irradiation is sufficient to fill empty traps faster than they are emptied, the intensity of emitted light caused by the TSL is approximately the same in the whole area of the pinhole. Assuming that most of the camera is irradiated with a photon intensity high enough to refill some of the traps, this would show up almost as a dark current. For small pinholes, the traps get refilled faster than they are emptied, still increasing the emitted photons but barely leading to a relative increase. Far from the spot center, some photons will still be absorbed by the scintillator, filling traps. The relative increase of the number of emitted photons due to TSL, will then be larger than closer to the center. Likewise, the signal due to TSL will give a small relative increase for the small pinholes and a large relative increase for the larger ones. This hypothesis may also explain the residual of the real and virtual pinhole measurements when the whole pinhole series is used, seen in figure 22. In this case, the relative residuals show a behaviour of somewhat increasing with the pinhole area. Since the relative increase of signal due to TSL increases with the area, this may explain the area dependence of the relative residual.

An attempt was made to bleach the scintillator by focusing a beam onto a small area of the scintillator for 114h. The camera responsivity of that region was then continuously measured and compared with a reference spot using virtual pinholes. It was shown that the responsivity of the camera did not decrease during the measurement, but rather increase, see figure 25. Some possible causes of this already been discussed. The result, however, indicates that the scintillator does not bleach easily for the photon intensity of 9.25keV. Since the camera signal was measured instead of the responsivity, this opens up to uncertainties of the results.

6.3 Camera Software

After the Thesis the camera software was further developed and some key routines for taking photos and returning the image to the user were changed considerably. At this stage, the software was found to return the wrong photo to the user. The camera returned the last shot photo instead of the newly shot, resulting in always being one photo behind. This behaviour was not noticed during this Thesis, but it may be worth mentioning as a possible factor of error. However, if this occurred during the measurements presented here, it would probably not give large changes since most measurements were made using the mean or median out of several photos. For a point of measurement using 100 images, the camera being one image behind would result in 1 image being taken at the wrong time and 99 images at the correct time.
7 Conclusion

The camera suffers from heavy temporal noise from high energy photons when the full spectra of the source is used. This was however successfully compensated for using a median filter. When compensating for the background of an image the spatial noise is greatly reduced, making the temporal noise the main contributor to the total noise. The procedure however converge towards a slightly wrong value, giving a mean error of approximately $50\text{DN}$ per pixel in worst case scenarios. This is far less than the temporal noise for high intensities, however still making low intensity irradiation difficult to resolve. The most probable origins for the error is the unknown bias frame, the suspected light in the dark picture and the uncertainty in doubling temperature. It is therefore recommended to take a new dark picture in a pitch-black environment. Furthermore, the doubling temperature should be more deeply investigated. Estimating the doubling temperature by looking at the temperature dependence of the dark current, instead of the dark signal, should give more accurate results.

The flat field compensation, used to compensate for PRNU, was shown to increase the spatial noise of images instead of reducing it. Probable causes of this is the non-perfect background compensation and the camera not being evenly irradiated by the X-ray source. The flat field compensation did however remove non-uniformities on a macro-scale. By moving the camera while taking the bright picture the incident photon intensity may become more evenly distributed, reducing the effects from the uneven irradiation. Furthermore, one way to reduce the effect of the background compensation is to increase the photon intensity, resulting in a decrease of the relative error. The same result should come from taking the bright picture at a low temperature, effectively reducing the dark current. A different solution could be to actually measure the background with the same setup and parameters as for the bright field image, as opposed to estimating the background as was done in this Thesis. Finally, although the pixel-to-pixel non-uniformities was not successfully removed, the non-uniformities on a macro-scale were. If eg. a filter is applied to the flat field, it might still compensate for latter type whilst not increasing the spatial noise.

The measurements of the spatial resolution was done using two types of line patterns. The results from one of them gave inaccurate values. It was later concluded, however, that the second type were used with too few frequencies to allow for a accurate parametrization of the PTF of the camera.

Furthermore, the camera responsivity was measured to be $3.283 \times 10^{-2} \text{DN/X-ph}$, which is around 17% of the theoretically estimated value. An attempt was made to bleach the scintillator. During the 114h long measurement no indication of a bleaching was seen. The temperature dependence of the responsivity was investigated by measuring the camera signal at different temperatures. The results indicated that any change of responsivity between 35°C and 42°C, was lower than the noise of the measurement. A signal was however measured, behaving as if a dark signal. It was estimated that the largest, reasonable, error in the background compensation, i.e. $50\text{DN}$ per pixel, could only explain around 12% of this unknown signal. To get a better understanding of the temperature dependence of the responsivity, it is suggested that several images are taken, with different photon intensities incident, for each temperature. The temperature dependence could then be estimated by looking at the responsivity directly, instead of the camera signal. The method could also be improved by using a more precise background estimation and flat field image, see previous suggestions.

Finally, real and virtual pinhole measurements were done and compared for a series of pinholes. It was shown that the virtual pinhole measurement successfully replicates the results of the real, with a maximum measured residual of 6%. Small pinholes should in theory be sensitive to errors in the flat field compensation and large pinholes to errors in the background compensation. Measurements made indicate that error in the flat field may introduce variations of 5%. For the larger pinholes, the worst reasonable error in the background compensation was estimated to only explain a relative error of 1%. To increase the accuracy of the virtual pinhole measurements, it is therefore suggested that the flat field compensation is either improved, see suggestions above, or removed. Furthermore, the form of the relative deviation of the virtual pinhole measurements indicated an increase with pinhole area. It is therefore suggested that this unknown signal should be investigated, hopefully leading to a parametrisation and removal.

References


A Appendix

A.1 Setting up the Server

The server is started using its executive file. Most parameters relevant for the server is stored in a .xml file. The server begins its life with asking for a settings file to load relevant parameters or create a new one. If a new file is created a tree with the needed parameters are created and the user is asked for values for one at a time.

At the time of creation, the server don’t check the validity of the inputs to the new settings file. However, most parameters will be found invalid at the time of usage, and the user will be asked for a new value. The server connects to the camera using its serial number, stored in the settings file, unique for each camera. That is, the server cannot run without a camera connected to it. It is also worth noting that the server assumes that the location of the calibration pictures, and their file extensions, are correct. The location is defined in the tree. If that is not the case, the server has to be restarted.

A.2 Calling the Server

Below the syntax for calling the server via the client executable is seen, here using the syntax of bash.

```bash
Client.exe 127.0.0.1 command=param@filename flag
```

The server parses the command into one of the groups in A.2.2. The meaning of the three other parameters are described in a table for each possible command, where a * is used when the parameter is mandatory. If a parameter is not shown for a command, no possible value exists for the command in question.

A.2.1 Parsing

If a parameter is given that is undefined for the command in question, the server will simply ignore it. A similar thing happens if one uses several occurrences of a parameter, or if a parameter is out of order. This time, however, the server parses them as a parameter value. The exception to this behaviour is if the server is expecting several values of the same parameter. Below is an example of a call to the server not following the syntax, and how the server parse it in table 5.

```bash
Client.exe 127.0.0.1 command1-flag1=param1=param2-flag2-flag3
```

Table 5: Parameters and their respective parsed values.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Parameter value</th>
</tr>
</thead>
<tbody>
<tr>
<td>command</td>
<td>'command1-flag1'</td>
</tr>
<tr>
<td>param</td>
<td>'param1=param2'</td>
</tr>
<tr>
<td>filename</td>
<td>'none'</td>
</tr>
<tr>
<td>flag</td>
<td>'flag2-flag3'</td>
</tr>
</tbody>
</table>

**Command** This call will certainly fail due to the parsing of the command includes the '-flag1' at the end. The parsing of command is done by comparing it, case insensitively, to the possible commands.

**Flag** In the example above, the form of 'flag2' and 'flag3' does not affect whether the call is runnable or not, this is due to flags never being mandatory and parameters making no sense simply being ignored. The flag-parameter is always a combination of independent single characters and are parsed simply by searching for their existence.

**Param** The parsing of param is done by first comparing it, case insensitively, to the possible string-values. If no match is found, param is converted to a float using the c++ function stof. The function returns the first part of the string that are of the form of a float, as a float. That is, if 'param1' was a text and 'param2' consisted of some text and an integer, the server would parse param as the integer in 'param2', since no possible string-value contains a '='.
Filename  Any empty parameter will be parsed as 'none', one could therefore trick the server for fun by giving a parameter the value 'none'. The solely purpose of filename is to be used as a filename when saving some file. Therefore it is not compared to anything but 'none', for checking if empty.

A.2.2  Allowed commands

Snap  This command is for taking pictures. The command always return only one raw picture, however this picture can be constructed using several others, defined by the parameters. All the flags can be used in any combination and order.

<table>
<thead>
<tr>
<th>param</th>
<th>number of pictures used to construct the return picture, default is 1</th>
</tr>
</thead>
<tbody>
<tr>
<td>filename</td>
<td>defining this causes the server to save the raw pic in the location of the calibration pictures of the server, with the name filename.pgm.</td>
</tr>
<tr>
<td>flag</td>
<td>three flags are allowed:</td>
</tr>
<tr>
<td></td>
<td>• m : the picture is constructed using the median filter, default is taking the mean</td>
</tr>
<tr>
<td></td>
<td>• s : calculates the temporal standard deviation of the taken pictures, pixel by pixel</td>
</tr>
<tr>
<td></td>
<td>• c : the constructed picture is calibrated</td>
</tr>
</tbody>
</table>

If the picture is to be calibrated and or returned with its temporal standard deviation, these are returned as separate pictures, for a total possibility of 3 pictures per Snap-command. The server returns the pictures in the order: calibrated, raw, temporal deviation. The first picture to be returned is saved by the client as picture1.pgm and for each returned picture, the client adds 1 to the number.

Roi  To set the region of interest of the camera, the roi-command is used. The command requires 4 values of param, which must be separated somehow. Any character is allowed, except for ',', '@', '-' or any number.

| param*    | defines the region of interest by (h0,v0,dh,dv)                     |
|           | • h0 : horizontal coordinate of upper left pixel                   |
|           | • v0 : vertical coordinate of upper left pixel                    |
|           | • dh : width of region [px]                                       |
|           | • dv : height of region [px]                                      |

Bin/Mode  This command sets tells the camera to bin or unbin the pixels. There exists two types of binning, both can however only bin pixels 2 × 2. When the camera change change binning mode, it resizes the region of interest to the new modes maximum region!

<table>
<thead>
<tr>
<th>param*</th>
<th>The new binning mode</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>• mode_0 / mode0 / 0 : no binning</td>
</tr>
<tr>
<td></td>
<td>• mode_1 / mode1 / 1 : 2 × 2 binning implemented in sensor, increasing the brightness. Only available for bitdepths of 12.</td>
</tr>
<tr>
<td></td>
<td>• mode_2 / mode2 / 2 : 2 × 2 FPGA sub sampling or decimation, doubling the frame rate.</td>
</tr>
</tbody>
</table>

Camera property  Any of the camera properties, as defined in the manual, can be sent as command and will be parsed as such by the server. The most properties available for the camera sensor used is seen in table 6.
Table 6: Camera properties that are reachable for this camera sensor using the server.

<table>
<thead>
<tr>
<th>command*</th>
<th>Description</th>
<th>Settable range</th>
</tr>
</thead>
<tbody>
<tr>
<td>Shutter</td>
<td>exposure time [ms] of pictures. Changing the property might result in a change of frame rate too.</td>
<td>0.029ms to 1905.736ms</td>
</tr>
<tr>
<td>Temperature</td>
<td>temperature given by the internal temperature sensor of the camera sensor.</td>
<td>not settable</td>
</tr>
<tr>
<td>Gain</td>
<td>internal gain factor, which is multiplied with the pixel intensities when sent from the camera sensor.</td>
<td>$-5.753dB$ to $13.034dB$</td>
</tr>
<tr>
<td>Brightness</td>
<td>controls the offset of raw pictures</td>
<td>0% and 25%</td>
</tr>
<tr>
<td>Exposure / Auto_exposure</td>
<td>sets the exposure of the camera using gain and shutter, can only change property values of properties on auto</td>
<td>$-7.585$ and $2.414EV$.</td>
</tr>
<tr>
<td>Sharpness</td>
<td>a filter that blurs the image if set below 1000 and sharpens it if larger.</td>
<td>0 and 4095.</td>
</tr>
<tr>
<td>Gamma</td>
<td>is used to make the camera resonsivity non-linear. It is applied after the AD-conversion.</td>
<td>0.5 and 4.</td>
</tr>
<tr>
<td>Frame_rate</td>
<td>sets the rate the camera sends taken images. The camera can’t send images faster than it takes them and therefore changing the frame rate may change the value of shutter too.</td>
<td>1fps and 33.898fps.</td>
</tr>
</tbody>
</table>

The possible parameters to send is seen in table 7. Not all parameter values can be set for every camera property, see the manual for more information about the properties and their possible settings. Impossible commands, like setting a value of property available for the camera software but not for the camera sensor itself, or turning off a property which cannot be off, will result in the server returning a string of the command not being successfully executed. If a property is set to a value below its minimum value or above its maximum value, the minimum or maximum value, respectively, will be set instead. The server will return the new value in the answer to the client. If the server is asked about the value of a property, it will return the value as the string "Read float num", where num is the value.

Table 7: Possible values to give the camera properties.

<table>
<thead>
<tr>
<th>param*</th>
<th>values parsed by the sensor</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>• ? : the server reads the current property value and returns it as an float</td>
</tr>
<tr>
<td></td>
<td>• off : turns off the property, if allowed</td>
</tr>
<tr>
<td></td>
<td>• any float : sets the property value to the parsed float, if possible. If property is off, it is turned on and set.</td>
</tr>
</tbody>
</table>

Reset The server is compiled with some values for the camera parameters, see table 8. Using the Reset-command, the server sets these values for the camera. No parameters exists for this command.

Table 8: Server default values of the camera settings.

<table>
<thead>
<tr>
<th>Roi</th>
<th>$(h0, v0, dh, dv) = (0, 0, 1280, 960)$</th>
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</thead>
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<tr>
<td>Mode</td>
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<tr>
<td>Shutter</td>
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<tr>
<td>Gain</td>
<td>0dB</td>
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<tr>
<td>Brightness</td>
<td>0%</td>
</tr>
<tr>
<td>Exposure / Auto_exposure</td>
<td>off</td>
</tr>
<tr>
<td>Sharpness</td>
<td>off</td>
</tr>
<tr>
<td>Gamma</td>
<td>off</td>
</tr>
<tr>
<td>Frame_rate</td>
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