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# An Image Quality Evaluation Tool Simulating Image Sensors Including Quantum Efficiency Off-Axis Effect

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## ABSTRACT

The image quality evaluation of CMOS sensors is a big challenge for camera module manufacturers. In this paper, we present an update of the Image Quality Evaluation Tool, a graphical user interface simulating image sensors to assess the performance of a pixel. The simulated images are computed from operating conditions and sensor's characteristics like Quantum Efficiency including off-axis effect. Simulation of QE off-axis impact has been based on characterization data. The method does not require optics, making it suitable for early design phases as for optimizations and investigations. Both measurement and implementation in the tool will be explained. The QE degradation with angle effect will be highlighted on simulated images. A uniform gray scene or coloured image simulation from QE off-axis measurement will help engineers to calculate post-processing digital correction like colour shading correction or colour correction matrix versus pixel position.

**Keywords:** CMOS image sensor, Quantum Efficiency Off-Axis, image quality, image processing, colour shading

## INTRODUCTION

In most CMOS image sensors applications like mobile phones or digital still cameras, strong pressure is pushed on camera size along optical axis (i.e. the reduction of overall thickness) or on the footprint of the image module (i.e. the sensor, the objective lens, the lens barrel and holder mounted on the package). This trend implies the reduction of both pixel size and back focal lens whereas users expect at least the same image quality. Size reduction decreases the amount of light reaching the pixel, leading to an increase of noise,<sup>1</sup> while the back focal length reduction impacts the angle of incidence of light at the edge of the image, leading to a degradation of Quantum Efficiency (QE) at the edge i.e. artifacts on image like colour shading. This increase of the Chief Ray Angle (CRA) is an important issue as it will become very high (more than 30°) for new sensor generations. Higher CRA will be more easily addressed with Back Side Illumination (BSI) technology.<sup>2</sup>

In this paper, we present an improvement of the Image Quality Evaluation Tool (IQE Tool), a Graphical User Interface (GUI) developed with Matlab at STMicroelectronics which simulates CMOS image sensors.<sup>3</sup> Digital camera imaging simulation tools already exist for the evaluation of image quality<sup>4,5</sup> The purpose of this study was to develop our own tool focused on sensor simulation and image processing for the development of our new pixel generations. The main new functionality of this tool is the simulation of images computed from Quantum Efficiency (QE) of either on-axis pixels (pixels located at the center of the image) or off-axis pixels. This technique allows the characterization of the pixel itself without the objective lens and the distinction of the lens effect from pixel effects. The simulated images will help camera phone manufacturers to calculate the post-processing digital correction like colour shading correction or the colour correction matrix (CCM) versus pixel position.

This paper is organized as follows: in section 2 we will present the characterization method for pixel off-axis measurement based on a specific design of colour filters and microlens masks. Section 3 will present the Image Quality Evaluation Tool and the implementation of off-axis simulations. Finally, the results on a 1.4 $\mu$ m pixel will be detailed in section 4 in terms QE off-axis, Relative Illumination (RI), Colour Shading (CS) and Signal-to-Noise Ratio (SNR) map versus CRA. Simulated images of a uniform gray with a Macbeth ColorChecker will be generated, which will help engineers to calculate the post-processing digital correction at an early step of the pixel development.

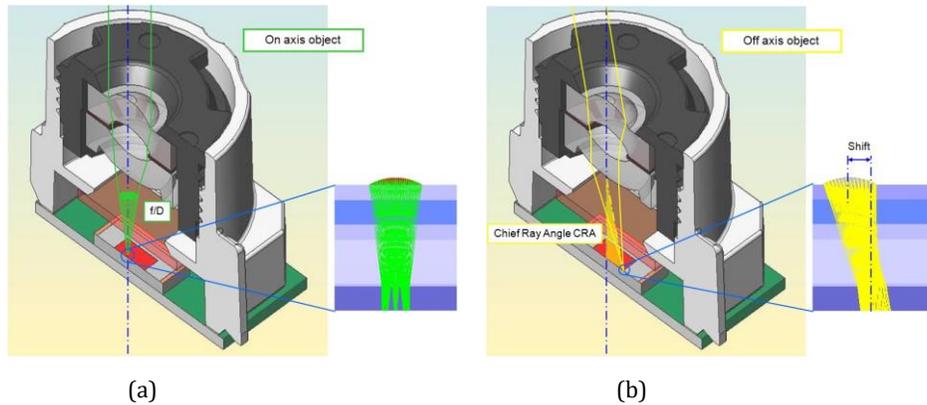


Figure 1: Illumination of pixels inside module: (a) for an on-axis pixel, (b) for an off-axis pixel. Insets present vertical cut view of pixel showing the microlens, the optical stack above the silicon and the light path.

## PIXEL CHARACTERIZATION

The Chief Ray Angle (CRA) is defined as the light ray passing by the center of the exit pupil of the objective lens and by the center of the microlens of the pixel of interest. Two kind of pixels are defined: on-axis pixel with nil (or very small) CRA and off-axis pixels with non-nil CRA. The illumination of on-axis pixel is only defined by the f-number (Fig. 1-a) whereas the illumination of off-axis pixels is defined by the f-number and the CRA (Fig. 1-b).

The QE off-axis characterization method has been developed from a previous off-axis pixel optical performance characterization method described by Vaillant,<sup>6</sup> which was primary used for relative illumination. This method allows characterizing the pixel itself according to the CRA without needing the objective lens. This methodology has several advantages: first of all the measurement is not impacted by the lens effect and we can explore more critical illumination conditions than the ones defined in the camera module, like higher angle of incidence. Furthermore, the measurement is independent from the lens positioning accuracy (lens tilt and offset) and the lens vignetting. Finally, the measurement is more accurate as we decorrelate the results from the lens performance dispersion. In this section, we will first describe the characterization bench, then the microlens and colour filter layout designed for pixel off-axis characterization and finally the acquisition of data.

### 1.1 QE off-axis characterization bench

For characterization, a test bench (Fig. 2) has been developed allowing to tune the illumination parameters: spectrum, f-number and CRA with a controlled intensity.

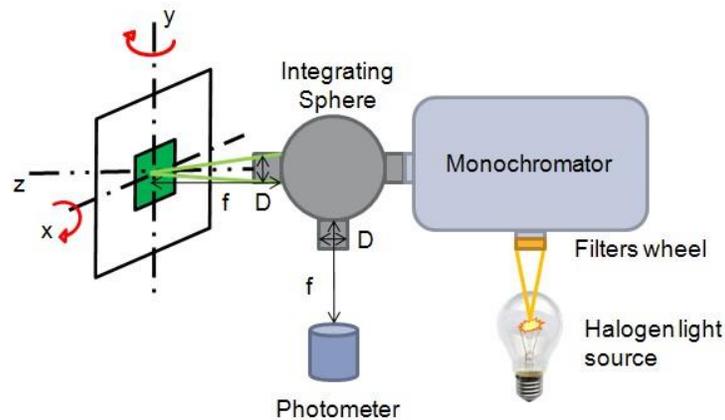


Figure 2: Bench used for QE off-axis characterization

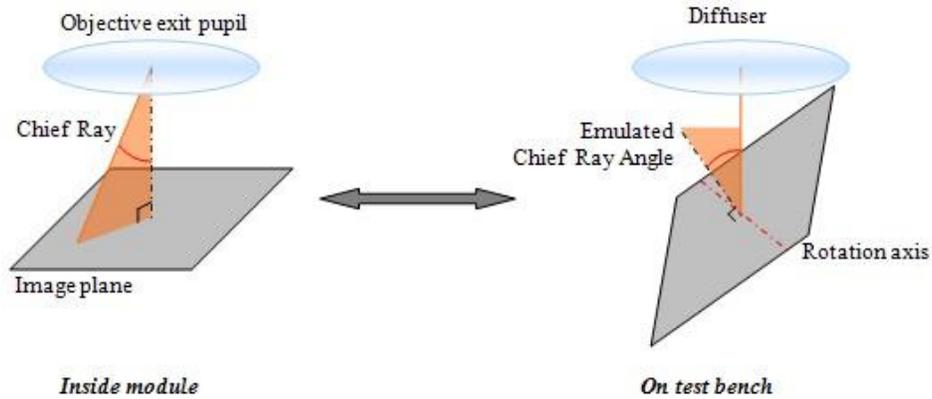


Figure 3: Emulation of Chief Ray Angle on test bench by tilting the sensor

The rotation of the sensor in front of the light emulates the Chief Ray Angle (CRA) thanks to the motorized rotation stages of the characterization board in the horizontal and vertical axis (Fig. 3). Any CRA can be emulated by tilting the sensor by paying attention to the rotation axis which must be located inside the sensor plane.

Illumination light is monochromatic (using a monochromator with blazed gratings) from 380nm to 700nm every 10nm with a spectral width of 5nm, which allows the knowledge of full spectral information for each CRA denoted  $\theta$ . A diffused light with a controlled f-number is performed by an integrating sphere after the monochromator and the control of the sphere output to sensor distance

A calibrated photo-diode is used for real-time light level control. If the sphere output diameter is large enough, we can consider that all pixels inside the sensor see the same illumination shape, defined by the f-number. On the test bench, the illuminance is measured on the optical axis while the sensor is tilted. The measured QE curves have to be corrected by the geometrical factor  $\cos(\theta)$  due to the tilt (see section 2.3).

This setup must be combined with a specific microlens and colour filter layout, described in section 2.2.

## 1.2 Microlens and colour filter layout

This pixel off-axis measurement method is based on a specific design of colour filters and microlens masks, which consists in several blocks. Each block is related to a given chief ray and then defines a point in the chief ray angle space. Fig. 4 illustrates the sampling of image plane along 8 directions and the position of each block on the test chip for characterization, corresponding to each sampled point in the module image.

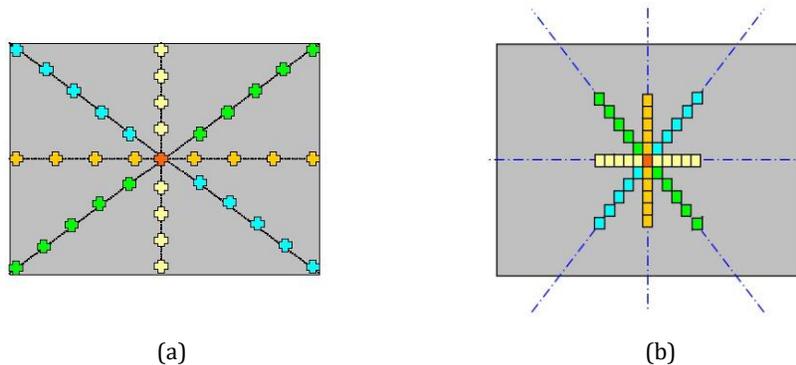


Figure 4: (a) Image and sample points. (b) Test chip with blockshifting.

All blocks must be carefully arranged on the mask: for a given CRA, the block is placed on the test chip along the rotation axis used to emulate the CRA. This rotation axis is orthogonal to the direction of chief ray as seen on Fig. 3.

Each block is composed by an arrangement of pixels with colour filters and microlens globally shifted. The shift of these components denoted  $\delta$  (in  $mm/^\circ$ ) can be calculated in first approximation with Finite Difference Time Domain (FDTD) simulations.<sup>7</sup>

### 1.3 Data acquisition

The standard flow for data acquisition is:

- Grab several “light” images (typically 10),
- Grab several “dark” images in darkness (typically 10),
- Average light and dark images to reduce the effect of temporal noise,
- Subtract average dark image to average light image,
- Extract ROI (Region Of Interest) for each block designed in 2.2 and colour planes,
- For each block, average the pixels of each colour plane to reduce the effect of spatial noise.

The integration times are chosen to reach half of the saturation for the colour with maximum signal at CRA=0 .

The spectral response denoted  $SR$  (in  $V/(J \cdot m^{-2})$ ) for each wavelength and each CRA is obtained by dividing the average level of signal for each colour plane denoted  $Signal$  (in  $V$ ) by the integration time  $T_{int}$  (in  $s$ ) and the sensor irradiance  $E$  (in  $W \cdot m^{-2}$ ) which is  $E_0$  measured by the photometer on axis corrected by the  $\cos(\theta)$  (see section 2.1). For each colour plane of a Bayer pattern Red, Green-Red, Green-Blue and Blue denoted  $i = \{R, GR, GB, B\}$ :

$$SR_i(\lambda, \theta) = \frac{Signal_i(\lambda, \theta)}{T_{int}(\lambda, \theta) \cdot E_0(\lambda) \cdot \cos(\theta)} \quad (1)$$

The QE (in %) is computed by multiplying the spectral response  $SR$  (in  $V/(J \cdot m^{-1})$ ) by the photons energy (in  $J$ ) and divided by the pixel area denoted  $A_{pix}$  (in  $m^2$ ) and the conversion factor denoted  $CVF$  (in  $V \cdot e^{-1}$ ).

$$QE_i(\lambda, \theta) = 100 \cdot \frac{SR_i(\lambda, \theta) \cdot hc}{A_{pix} \cdot \lambda \cdot CVF} \quad (2)$$

## IMAGE QUALITY EVALUATION TOOL

The Image Quality Evaluation Tool (IQE Tool) generates simulated images from operating conditions (integration time, aperture and lens transmission), scene parameters (illuminant spectrum, scene illuminance) and sensor’s characteristic data such as readout noise, dark current, PRNU, IR filter spectra and Quantum Efficiency. The validation of the results on simulated images has already been performed.<sup>3</sup> The main new functionality of this tool is the off-axis simulation performance of the sensor, based on the Quantum Efficiency off-axis measurement described in section 2.

### 1.4 Graphical User Interface overview

The Graphical User Interface developed under Matlab is composed of several units: a sensor and noise model unit (Fig. 5-a) where it is possible to load QE on-axis or off-axis data. Operating conditions, scene parameters and noise model data can be specified in the GUI or in an input dialog box (Fig 5-b). Once all these parameters are specified for the sensor, it is possible to run the Colour Correction Matrix (CCM) optimization unit to compute sensitivities, White Balance (WB), CCM and quality metrics for a given Chief Ray Angle.

After having specified the sensor data, the image simulation tool can be run in order to generate a raw image by selecting a multi-spectral image from a database. Synthetic Macbeth chart is a particular case of multi-spectral images: the reflectance of every patch is known. Finally by choosing the pipe (WB, CCM, Demosaicking method), the corrected simulated image is displayed. The image processing pipe is detailed in section 3.2 and in Fig. 6.

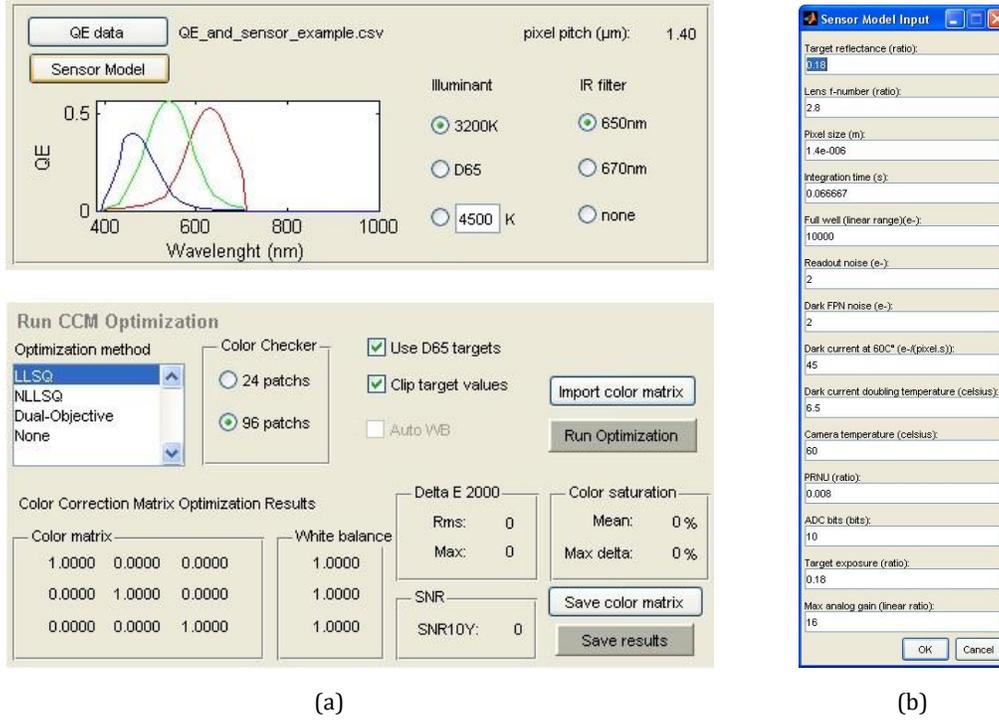


Figure 5: (a) Sensor-Noise Model Unit and CCM Optimization Unit. (b) Model Input Dialogbox.

## 1.5 Image Processing Pipe

The QE on-axis and off-axis measurement (or prediction) is an input of the tool. It means that the user has to load a cube of QE data for each colour along wavelength, x and y coordinates of the image. Then the tool will interpolate data using a *cubic* interpolation under Matlab in order to generate an image with the appropriate level of signal and noise depending on the CRA without discontinuities. For the image simulation, which is the objective of this study, we have to work in the image space whereas QE off-axis data are measured in angular space. The function of CRA *versus* the image height in focal plane, defined for a module lens, has to be chosen in the lens model unit. Apart from this model which is necessary to transform the angular space into the image space, the simulated images highlight the sensor performances without taking into account the lens quality. The objective is to evaluate the sensor performance on image without the lens and to quote the sensor quality by itself.

A map of signal (in  $e^-$ ) can be generated with the QE off-axis data, the sensor and noise model and the multi-spectral data of the image to be simulated. For each colour plane  $i = \{R, GR, GB, B\}$  and a pixel of coordinates  $(x, y)$  in the image space:

$$signal_i(x, y) = scene_{lux} \cdot \frac{a^2}{hc} \cdot \frac{1}{4f\#^2} \cdot \frac{\int_{\lambda} R(x, y, \lambda) \cdot I(\lambda) \cdot QE_i(x, y, \lambda) \cdot T(\lambda) \cdot \lambda d\lambda}{\int_{\lambda} I(\lambda) \cdot V_{Obs}(\lambda) d\lambda} \quad (3)$$

where  $scene_{lux}$  is the scene illuminance (in  $lux$ ),  $a$  the pixel pitch (in  $m$ ),  $h$  the Planck's constant (in  $J \cdot s$ ),  $c$  the speed of light (in  $m/s$ ),  $R$  the reflectance of each pixel  $(x, y)$  of the scene according to the wavelength,  $I$  the scene illuminant spectrum (in  $W/m^3$ ),  $QE$  the sensor Quantum Efficiency,  $T$  the lens transmission,  $\lambda$  the wavelength (in  $m$ ) and  $V_{Obs}$  the photopic luminous efficiency.

Then, a map of noise is computed from the map of signal and the noise model parameters. The distribution of noise is assumed to be Gaussian on the image; this is a limitation of the tool as other types of noise could appear on the image especially at low-light conditions. At this point, a RAW image can be generated for a Bayer pattern. Other patterns could be added for the next generations of the tool. Then, an image processing pipe is applied to generate the simulated image by choosing the WB (either manual, or computed for a "gray world" image), the CCM and the demosaicking method. Examples of simulated images will be given in section 4.

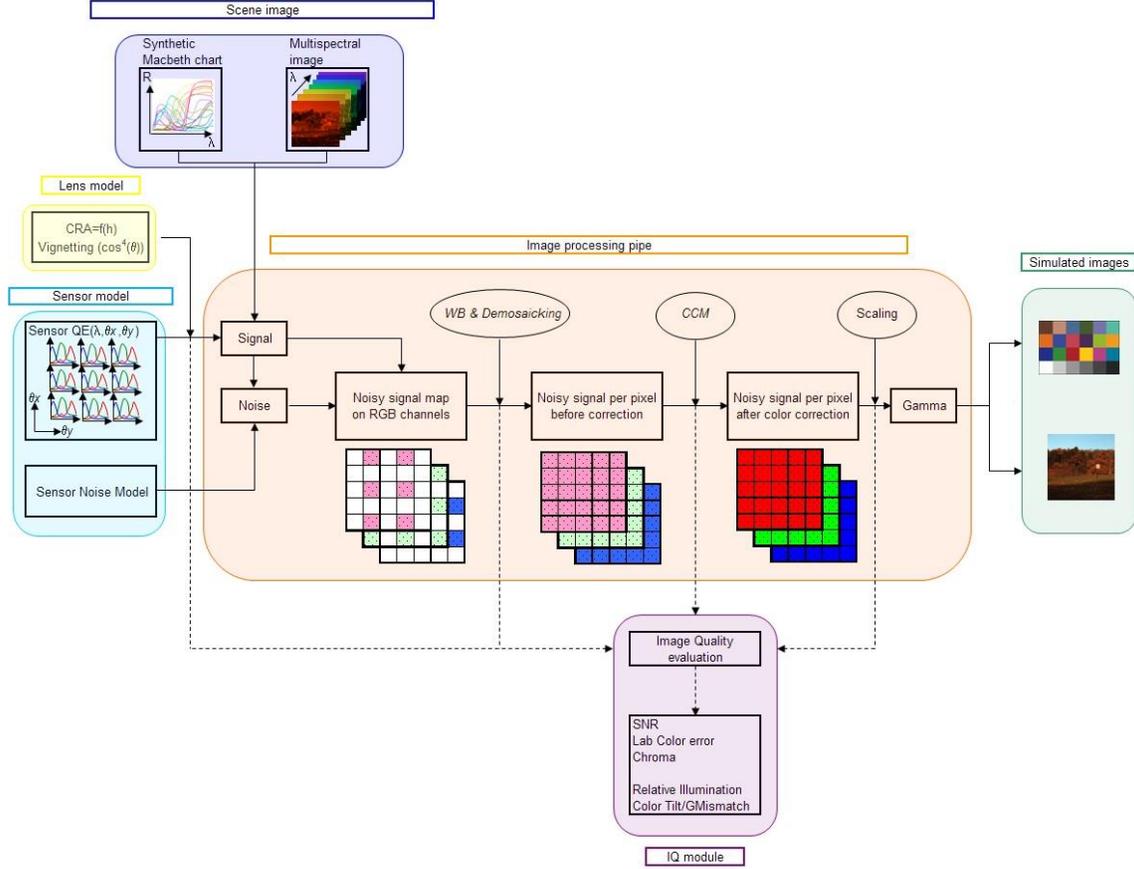


Figure 6: Illustration of IQE Tool's workflow

## 1.6 Off-Axis Metrics

With the Graphical User Interface described in previous section, all usual quality factors can be evaluated like colour accuracy or colour saturation but also the signal-to-noise ratio (SNR) according to the position on the image. For instance, a map of  $SNR_{10^8}$  versus CRA can be plotted in order to describe the SNR variation on the image (section 4). However, specific metrics will be defined to quantify the colour uniformity performance which can be computed by the IQE Tool.

Colour shading correction is based on two metrics measured under halogen light source: the relative illumination (RI) which evaluates the vignetting of the pixel and the colour tilt, deduced from the RI for each colour, to quantify the colour uniformity. The RI for each colour plane and for a given CRA called  $\theta$  is calculated as the ratio of the sensitivity of the pixel for this CRA over the sensitivity of the central pixel (normal incidence). These indicators can be computed in the IQE Tool: in fact, the sensitivity (in  $e^-/(lux.s)$ ) can be easily deduced from QE off-axis measurement by integrating under the chosen illuminant spectrum. For each colour  $i = \{R, GR, GB, B\}$ , and each CRA denoted  $\theta$ :

$$sensitivity_i(\theta) = \frac{a^2}{hc} \cdot \frac{\int_{\lambda} I(\lambda) \cdot QE_{Red}(\lambda, \theta) \cdot \lambda d\lambda}{\int_{\lambda} I(\lambda) \cdot V_{Obs}(\lambda) d\lambda} \quad (4)$$

$$RI_i(\theta) = \frac{sensitivity_i(\theta)}{sensitivity_i(0)} \quad (5)$$

where  $a$  is the pixel pitch (in  $m$ ),  $h$  the Planck's constant (in  $J.s$ ),  $c$  the speed of light (in  $m/s$ ),  $I$  the scene illuminant spectrum (in  $W/m^3$ ),  $QE$  the sensor Quantum Efficiency,  $\lambda$  the wavelength (in  $m$ ) and  $V_{Obs}$  the photopic luminous efficiency.

The colour tilts are computed from the relative illumination  $RI_R(\theta)$ ,  $RI_{GR}(\theta)$ ,  $RI_{GB}(\theta)$ ,  $RI_B(\theta)$ . They quantify the colour uniformity after white balance (computed at  $CRA = 0^\circ$ ). The relative illuminations corrected by the white balance are denoted  $R(\theta) = RI_R(\theta)W_R$ ,  $GR(\theta) = RI_{GR}(\theta)W_{GR}$ ,  $GB(\theta) = RI_{GB}(\theta)W_{GB}$ ,  $B(\theta) = RI_B(\theta)W_B$  and also  $G(\theta) = (W_{GR}RI_{GR}(\theta) - W_{GB}RI_{GB}(\theta))/2$ . Then the colour tilts are defined as follows:

$$\begin{aligned}
 R_{ColourTilt} &= \frac{R(\theta) - G(\theta)}{G(\theta)} \\
 GR_{ColourTilt} &= \frac{GR(\theta) - G(\theta)}{G(\theta)} \\
 GB_{ColourTilt} &= \frac{GB(\theta) - G(\theta)}{G(\theta)} \\
 B_{ColourTilt} &= \frac{B(\theta) - G(\theta)}{G(\theta)}
 \end{aligned} \tag{6}$$

These metrics can be map either in angular space or in image space. The first one is independent from the module lens design and gives sensor-only performances whereas the second one requires the knowledge of the CRA *versus* the image height in focal plane, which is defined by the module. For the image simulation, which is the objective of this study, we have to work in the image space so a function of  $CRA = f(\text{image height})$  has to be defined.

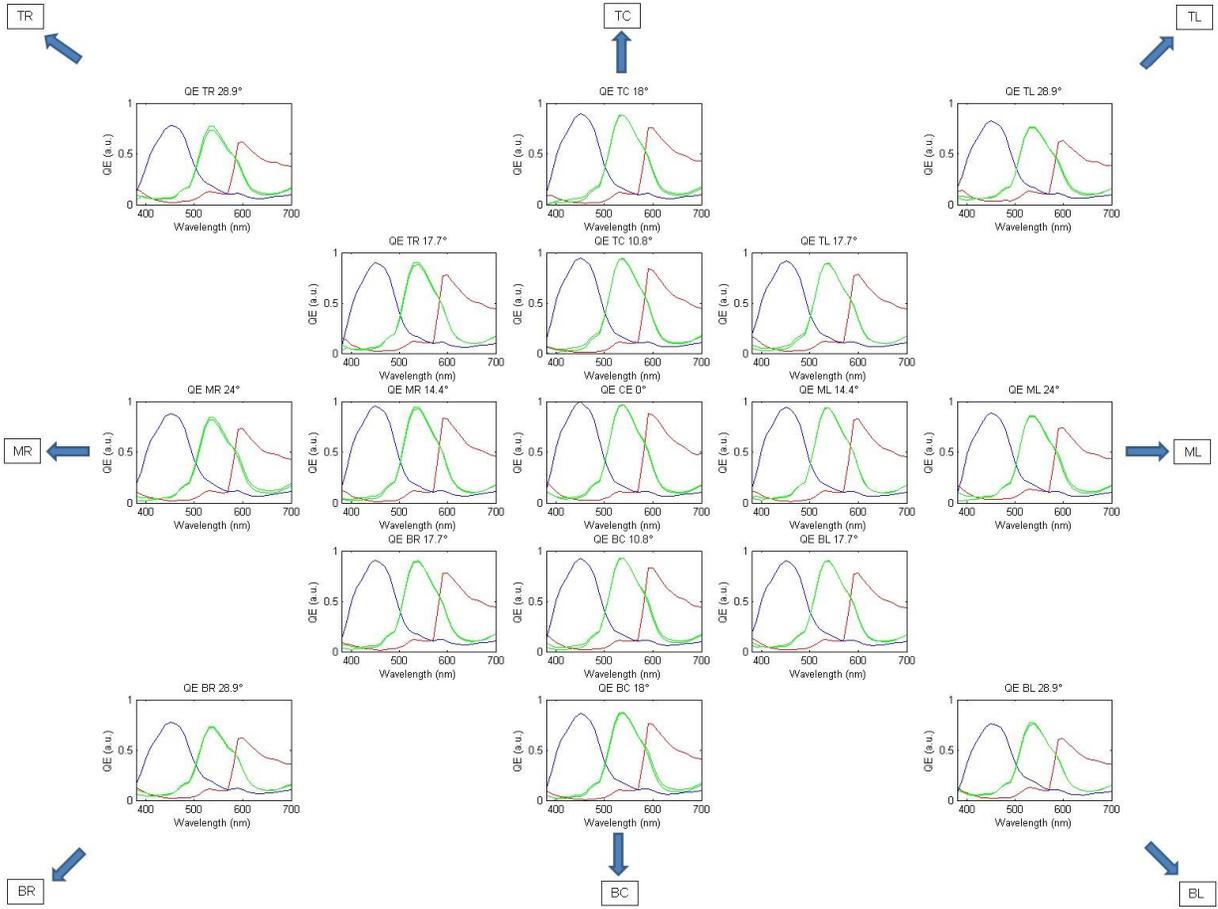
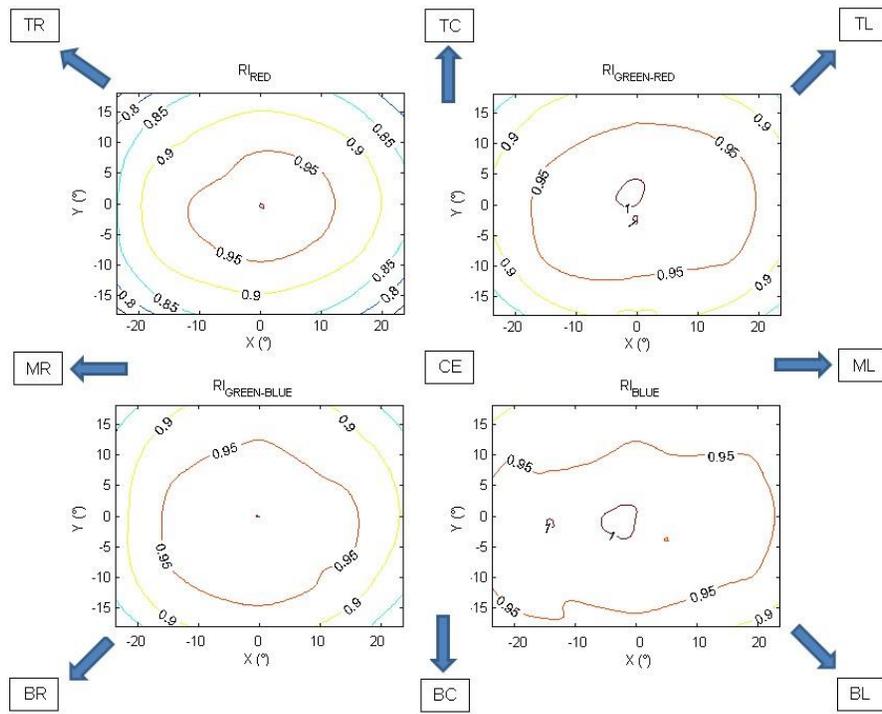
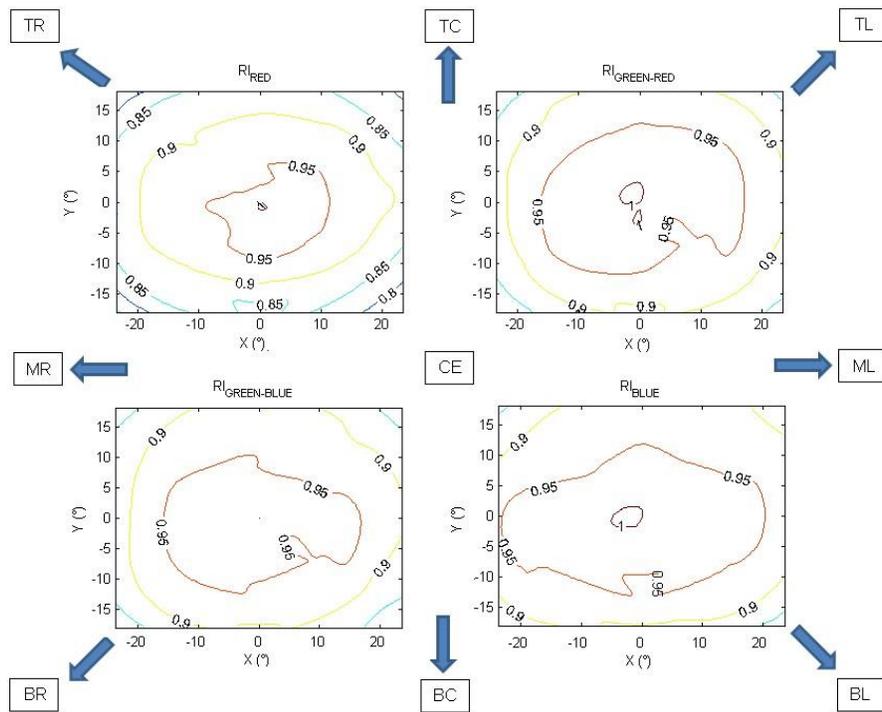


Figure 7: Quantum Efficiency (QE), in arbitrary unity, measured on QE off axis bench for middle height and extreme angle position in each direction.

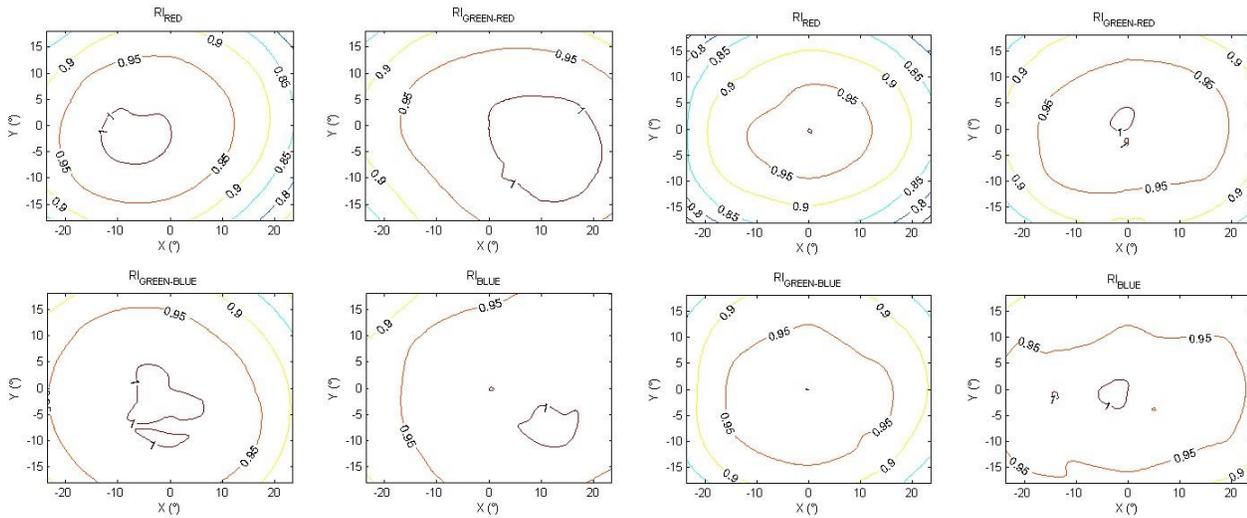


(a)



(b)

Figure 8: RI in angular space for the 4 colour planes (a) under 3200K. (b) under D65.



(a)

(b)

Figure 9: Relative Illumination in angular space under 3200K(a) Before process improvement. (b) After process improvement.

## RESULTS ON 1.4 $\mu$ m FSI PIXEL

The blockshifting (Fig. 4-b) design for the colour mask of a 1.4 $\mu$ m Front Side Illuminated (FSI) pixel has been layout for eight directions in the image plane (two horizontals, two verticals, and four diagonals) and six points per direction, *i.e.* leading to a total of 49 measurement points. The higher CRA which can be measured is around 30 (in a diagonal direction).

### 1.7 QE off-axis results

The studied 1.4 $\mu$ m Front Side Illuminated (FSI) pixel and associated blockshifting has been characterized on the QE off-axis bench described in section 2. Fig. 7 illustrates the QE on-axis and the QE off-axis for the height directions and for 2 positions on each direction: one at a middle height position and one another at a more extreme angle. The QE curves from center to middle height positions are pretty stable whereas higher degradation appears for extreme angles.

### 1.8 Relative Illumination results

The main off-axis metrics, the Relative Illumination (RI), has been computed from the QE off-axis measurement as described in section 3.3. The interest of the whole QE off-axis information is that the RI can be computed under any illuminant without another measurement. The results under halogen (3200K) and daylight (D65) illuminant in angular space for the 4 colour planes are illustrated in Fig. 8. The 8 measured directions of light highlighted in the figure are denoted to match the image space as Top-Right (TR), Top-Left (TL), Bottom-Right (BR), Bottom-Left (BL), Middle-Right (MR), Middle-Left (ML), Top-Center (TC), and Bottom-Center (BC).

The benefit of the QE off axis measurement can be highlighting by checking results for a preliminary 1.4 $\mu$ m pixel tested during process development. Indeed relative illumination results for this pixel showed an asymmetrical shape caused by a weakness in the isolation structure. This defect has been corrected for the new pixels generation, *i.e.* results presented in this section. The improvement on relative illumination results is illustrated on Fig. 9.

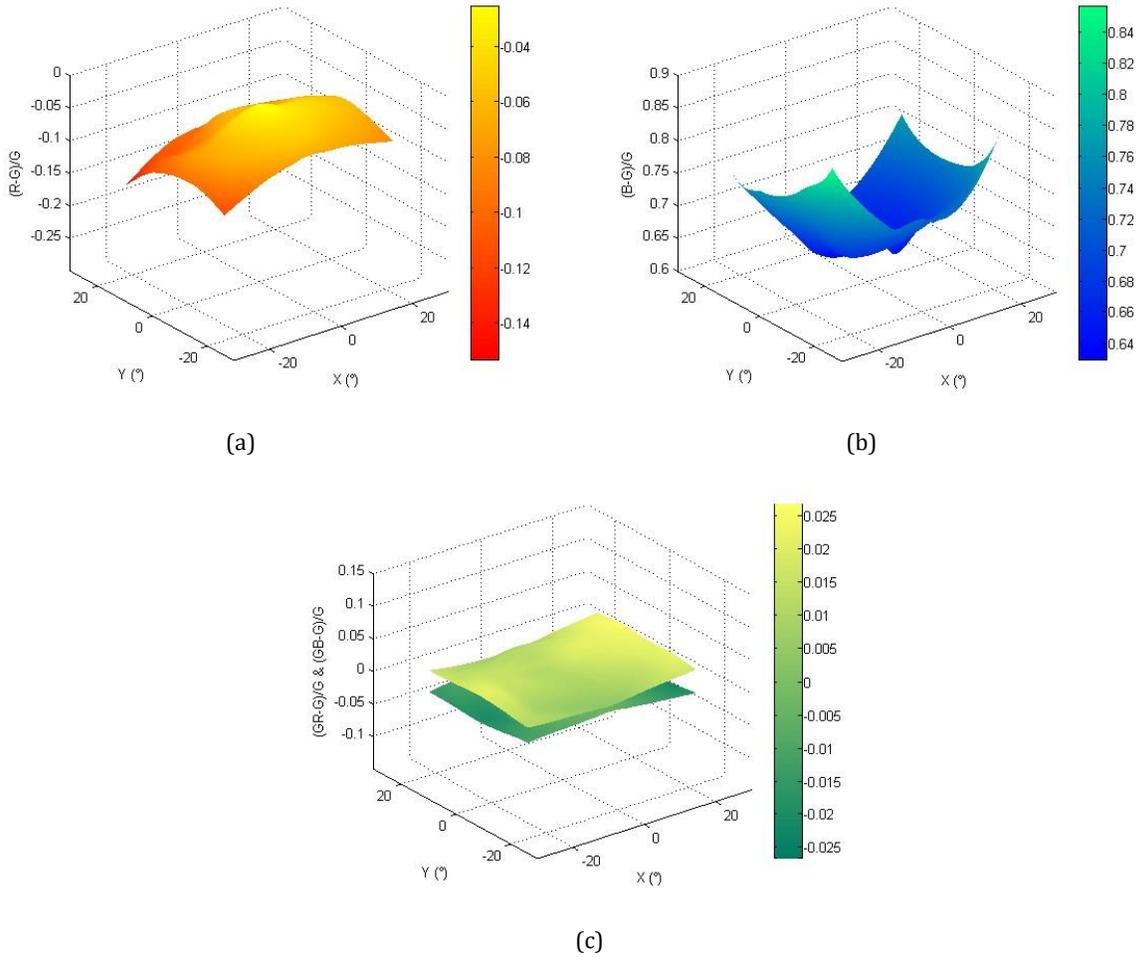


Figure 10: Colour tilt in angular space under 3200K (a) Red. (b) Blue. (c) Green-Red and Green-Blue.

## 1.9 Colour Shading results

From the RI results, it is also possible to extract the colour tilts which can be very useful for the colour shading correction. Colour Tilts under 3200K for the 4 colour planes are illustrated in Fig. 10. They are mapped in the angular space which has the advantage of being independent from the module lens and gives the pure sensor performances. The Green-Red and Green-Blue colour tilts under 3200K in angular space is shown in Fig. 10-c. A slight mismatch between the two green channels is visible and is due to the shared transistor architecture of the pixel. These results are helpful for the design phase of the pixel but also for the post processing pipe in order to compute the best colour shading correction for each colour plane.

## 1.10 Image Simulations

Finally, simulated images can be generated from a multi-spectral database<sup>9</sup> and the IQE Tool. The lens model apply in this section is a simple thin lens model with an Effective Focal Lens (EFL) of 4,23mm (Fig. 11):

$$\theta = \arctan \left( \frac{ImageHeight}{EFL} \right) \quad (7)$$

Fig. 12 shows the result of simulation for a synthetic Macbeth ColorChecker on a 18% gray background under 3200K and D65 illuminant at high light level, with a 1960x2608 pixels sensor and the simple thin lens model with a maximum CRA of 28 . Fig. 12-a,d have been generated with the QE at the center for all CRA whereas

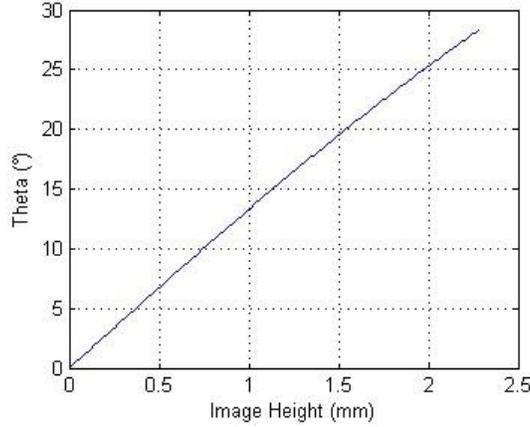


Figure 11: CRA ( $\theta$ ) versus Image Height(mm) in image plane

the QE off-axis effect is visible on Fig. 12-b,e. Finally, on Fig. 12-c,f we can see the effect of both sensor off-axis response and lens attenuation (following the  $\cos^4$  law). On all images, a simple processing pipe has been applied with a “gray world” White Balance, a Malhecut<sup>10</sup> interpolation, and a Colour Correction Matrix optimised for the QE at CRA =  $0^\circ$ . No colour shading correction has been applied to see the effect of the QE degradation for high CRA.

Fig. 13 shows the result of simulation for a multi-spectral image of a natural scene under the D65 illuminant at high light level with the same sensor and lens model. Fig. 13-a is the target image whereas Fig. 13-b,c are the simulated image with the same processing pipe as previous, without shading correction without and with the  $\cos^4$  attenuation law due to the model of image formation on a sensor.

Finally, the SNR<sub>10</sub> versus CRA can be computed. It is defined as the illuminance level (in *lux*) for a SNR of 10 on the luminance channel computed on a 18% gray patch, with a f-number of 2.8 and a frame rate of 15fps after colour correction (Eq. 8).

$$SNR_{10} = xlux \text{ as } SNR(xlux) = \frac{\beta_R R' + \beta_G G' + \beta_B B'}{\sqrt{(\beta_R \sigma_{R'})^2 + (\beta_B \sigma_{G'})^2 + (\beta_B \sigma_{B'})^2}} = 10 \quad (8)$$

With  $i = R', G', B'$  and  $\sigma_{i'}$  respectively the signal and the noise after colour correction on each colour plane.

Fig.14 shows the SNR<sub>10</sub> map of the measured sensor under halogen illuminant (3200K), with a lens transmission of 0.8 and the CCM computed from QE on-axis applied on the whole image. SNR data have been normalised at 100 at the center of the image.

## CONCLUSION

This paper presents an improvement of the Image Quality Evaluation Tool (IQE Tool) developed under Matlab, including QE off-axis effect based on measurement. It can be very helpful for the development of new pixels which is a very expensive and time-consuming process. It is also useful for the characterization of current pixel as the extraction of quality metrics (SNR, colour error...) and off-axis metric (RI, colour tilts, green mismatch) from QE data is very simple. This tool is in constant evolution: next steps could be to simulate the sensor resolution, *i.e.* the Modulation Transfer Function (MTF) of a pixel, and also the impact of the infrared filter according to Chief Ray Angle. For now, this tool is focused on sensor performances simulation but in the future, the camera lens could be simulated (OTF) in order to have a complete simulation of the camera module.<sup>11</sup>

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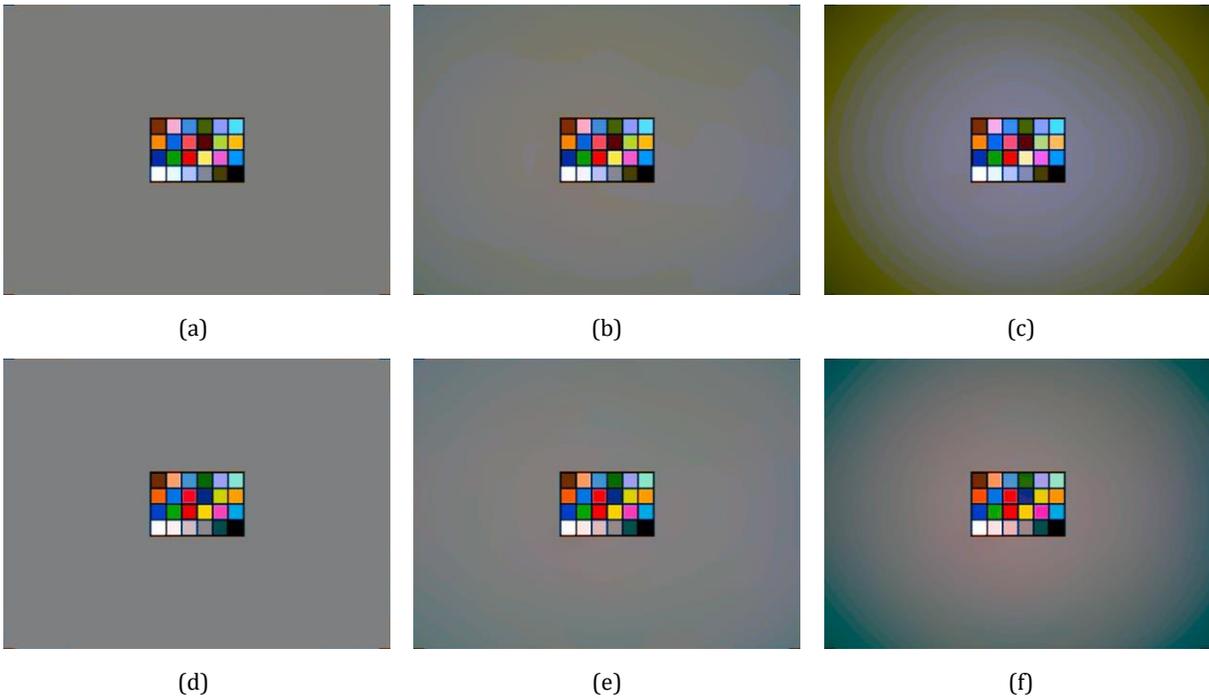


Figure 12: High-Light Simulated synthetic Macbeth ColorChecker for a 4/3 sensor with a maximum CRA of 28 after a simple processing pipe with a simple thin lens model (a) From QE on-axis under 3200K. (b) From QE off-axis under 3200K. (c) From QE off-axis under 3200K with  $\cos^4$  attenuation. (d) From QE on-axis under D65. (e) From QE off-axis under D65. (f) From QE off-axis under D65 with  $\cos^4$  attenuation.

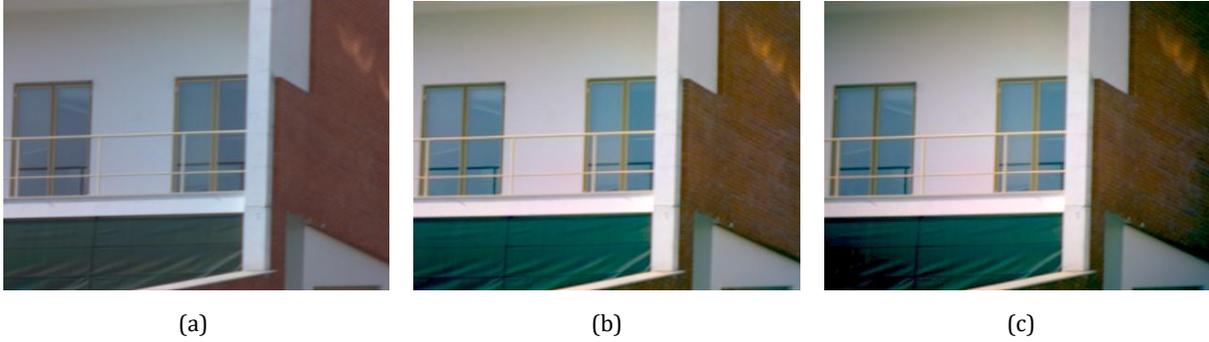


Figure 13: (a) Target Multispectral Image under D65. Highlight Simulated Image under D65 from QE off-axis for a 4/3 sensor with a maximum CRA of 28 after a simple processing pipe with a simple thin lens model (b) without  $\cos^4$  attenuation. (c) with  $\cos^4$  attenuation.

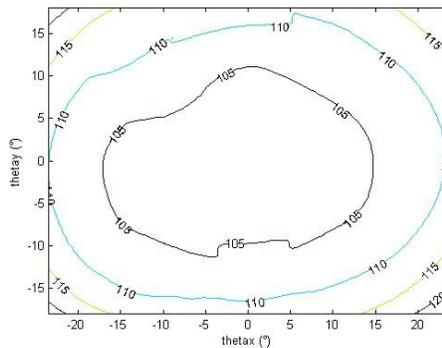


Figure 14: SNR map in angular space (normalised values scaled to 100 at the center of the image)

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