

# Fast MTF measurement of CMOS imagers using ISO 12233 slanted-edge methodology

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## ABSTRACT

The ISO 12233 standard provides a fast and efficient way of measuring Modulation Transfer Function (MTF) of digital input devices (such a digital still camera) using a normalized reflective target based on a slanted-edge method. A similar methodology has been applied for measuring MTF of CMOS image sensors, using 12233 slanted-edge technique associated with a prototype transmissive target. In order to validate the results, comparisons have been made between MTF measurements of image sensor implemented using a 0.25 $\mu$ m process, using this method and sine target direct measurements.

**Keywords :** CMOS Image Sensors, Modulation Transfer Function, Slanted-Edge method

## 1. INTRODUCTION

Image quality is one of the most important characteristics for all image sensing systems and the Modulation Transfer Function is a common metric used to quantify it. Traditional methods for MTF measurements were initially designed for devices forming continuous images. However, these techniques can give erroneous MTF results, due to the fact that the sampling of digital devices is not properly taken into consideration. Additionally, MTF results can depend on the chosen technique (sine target or bar target utilization, slit or knife-edge technique).

Sine target method consists in imaging onto the detector sinusoidal patterns at different spatial frequencies. Image contrast is calculated for each frequency and, after division by target contrast and finally by lens MTF, detector MTF is obtained. This method gives a direct result but requires one image per frequency of interest. For that reason, measurements require a long time. Knife-edge technique consists in imaging a sharp transition strictly aligned with the rows (or the columns) of the detector. By taking the response of the line perpendicular to the edge, the device Edge Spread Function (ESF) is calculated. The derivative of the ESF is the Line Spread Function (LSF) which yields to the device MTF by performing a one-dimensional Fourier transform. To avoid undersampling and phase shift dependence, it is necessary to move the knife-edge along the line perpendicular to it. The displacement must be small with respect to the pixel size so this technique needs a large number of images to compute MTF.

These measurement methods are now well-established but still present some disadvantages, the principal one being the long measurement time. The ISO 12233 methodology [1] has been established in order to provide a fast MTF measurement method based on only one image. In such a standardized way, the MTF data from various digital input devices may be easily and correctly compared. The purpose of this work is to apply such a methodology to get the MTF of CMOS Active Pixel Image sensors.

Section 2 gives some background related to the particularities of CMOS sensors in term of MTF. Section 3 describes ISO 12233 methodology and its advantages in comparison with others measurement methods. Section 4 presents measurements results, made with CMOS 0.25 $\mu$ m photodiode pixels at a wavelength of 500nm.

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## 2. THE MTF OF CMOS IMAGE SENSORS

The MTF is defined as the modulus of the Optical Transfer Function (OTF) which is the Fourier Transform of the impulse response of the system. It defines the ability of an optical system to resolve a contrast at a given resolution (or spatial frequency).

In the case of an image sensor, the MTF is a combination of different MTFs, each degrading the overall performance of the device. The main components are the geometric and the diffusion MTFs. The first one takes into account the influence of the pixel size (giving the spatial sampling frequency) but also the photosensitive area size and shape. As a first approximation, it can be considered that smaller is the pixel size, better is the MTF. The diffusion MTF describes the image degradation due to optical crosstalk between adjacent pixels. It can be deduced from the resolution of the diffusion equation in the detector substrate and it is depending, among others, on diffusion length of the minority carriers and on the photon absorption coefficient of the silicium (itself depending on wavelength). Considering a very simple pixel model, MTF can be expressed as the multiplication of the geometrical and the diffusion MTF [2]. Recent works on CMOS sensors [3] show a strong dependence of MTF on pixel shape and difficulties [4] to separate geometrical and diffusion MTF.

In CMOS sensors, the pixel contains several distinct areas: the photosensitive element (photodiode or photogate), the readout circuitry (MOS transistors) and some opaque mandatory patterns (metal line, contact, vias...) as symbolized in figure 1. The fill-factor is much less than 100 percent (for full frame or frame transfer with vertical anti-blooming CCD it is nearly 100%). Optical transmission is not homogenous on the entire pixel area and the readout circuitry area affects slightly the signal of the pixel. Moreover, photosensitive and readout elements can have various shapes in the pixel, which induces different MTF in the two principal directions (horizontal and vertical).

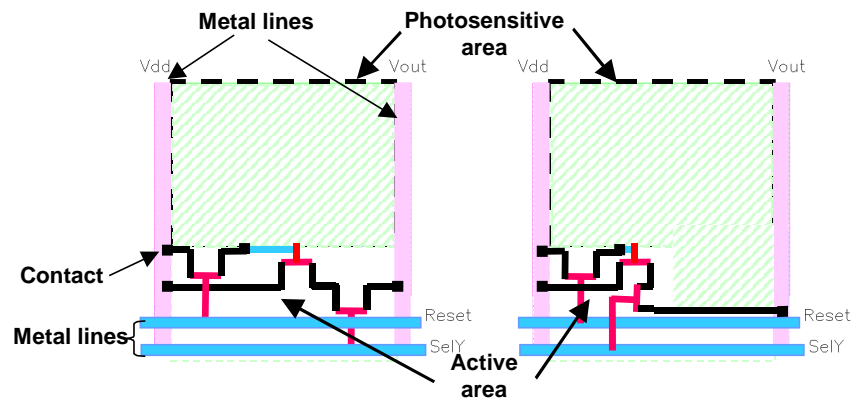


Figure 1 : Topological view of two shapes of pixel

The figure 2 shows as an example a view of  $0.5\mu\text{m}$  pixels,  $20\mu\text{m}\times 20\mu\text{m}$  size where the active elements are located in the nearby of and under the horizontal metal line.

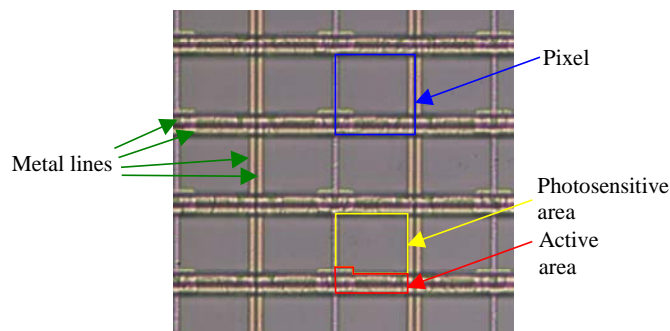


Figure 2 : Photograph of  $20\mu\text{m}\times 20\mu\text{m}$  pixels

Furthermore, CMOS sensors are generally built on thinner EPI layers than CCD. Combined with the lower drive level used for CMOS (5V, 3.3V), the space charge extension is limited giving the diffusion mechanism an important role in charge collection. Fortunately, the EPI to lightly doped substrate doping gradient provide a built-in field that enhances the collection of photocharges.

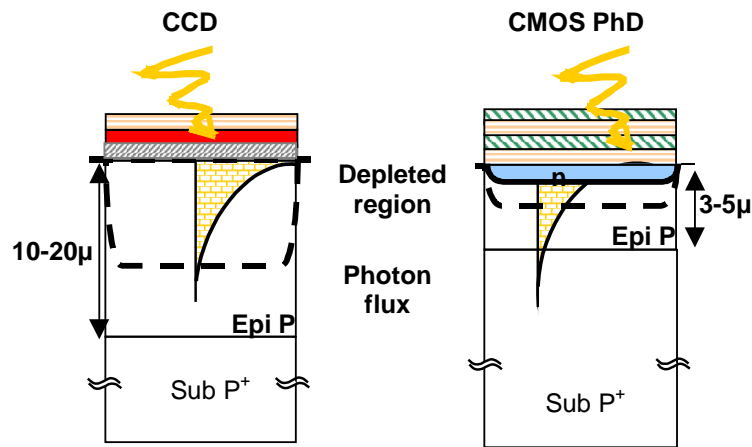


Figure 3 : Technological comparison of CCD and CMOS

MTF depends not only on the shapes of the photosensitive element, the layout of the metal patterns, but also on the transmission of the superficial layers, and the contribution of the active area and its topology. Due to various parameters in the case of CMOS image sensors, modeling MTF is very difficult and measurements at different wavelengths are required in order to get a better knowledge of pixel organization influence.

The specificities of the CMOS sensors make the MTF measurements delicate :. Knife-edge technique implies to choose a correct sampling frequency to resolve the entire pixel pattern, particularly at long wavelengths where the diffusion phenomenon is important. So it is possible that the techniques previously presented do not give the same results if the measurement parameters have not been correctly chosen and these measurement methods, now well-established, still present some disadvantages that the slanted-edge method can avoid. Moreover, a long measurement time can be problematic in terms of temperature and stability of setup instruments.

### 3. SLANTED-EDGE METHODOLOGY IMPLEMENTED IN ISO 12233 STANDARD

The International Standard 12233 specifies methods for measuring resolution of electronic still-picture cameras and defines a test chart for performing these measurements. It allows the evaluation of visual resolution, limiting resolution, aliasing ratio, spatial frequency response, compression artifacts...In this section, we describe the measurement method employed in the ISO 12233 and the software which computes the MTF.

#### 3.1 Slanted-edge method

Slanted-edge method consists in imaging an edge onto the detector, slightly tilted with regard to the rows (or the columns) [5]. So, a vertically oriented edge allows to obtain the horizontal Spatial Frequency Response (SFR) of the detector. In that case, the response of each line gives a different ESF, due to different phases. These ESF are undersampled but it is possible to increase mathematically the sampling rate by projecting data along the edge. The figure 4 represents the target used to apply slanted-edge method. It is a transmissive prototype target made on Kodak 35mm film.

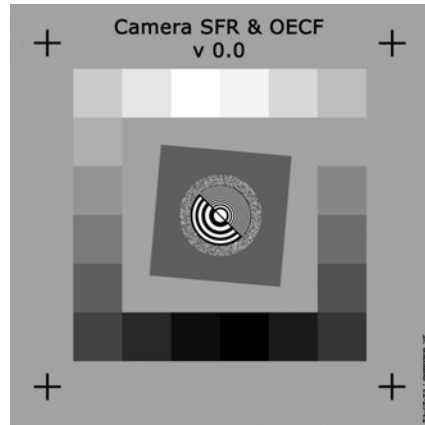


Figure 4 : Slanted-edge prototype target

From slanted-edge image given by the detector, the associated software (Matlab) computes the SFR. By selecting a rectangular region-of-interest (ROI), the region over which the calculations are done is defined, as shown in the figure 5.

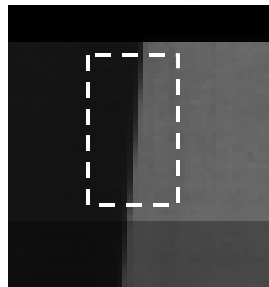


Figure 5 : Selected ROI

Edge is located for each scan line, and so the slope can be calculated. Data of each line are projected along the edge direction and accumulated in 'bins' that have a width inferior to the pixel width.

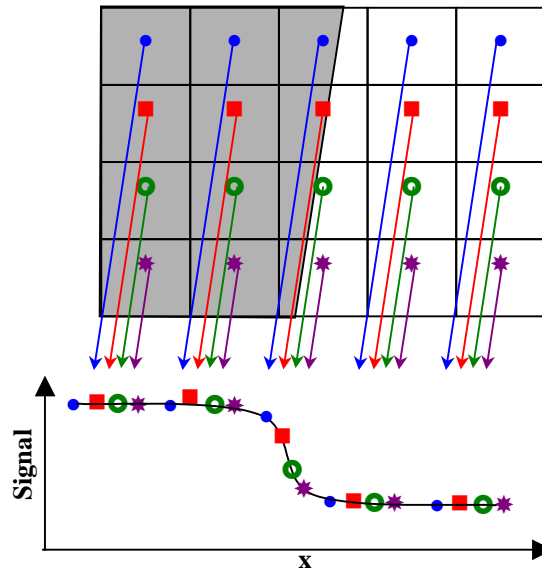


Figure 6 : Projection of data along the edge

The oversampling factor, determining the width of the bins, is equal to 4 by default but can be modified by the user. This process increases the sampling rate by forming a supersampled ESF and reduces the influence of signal aliasing of the measured SFR. The resulting ESF is then derived to get the LSF. The figures 7 and 8 show the ESF and LSF computed from a ROI of 15x25 pixels with an oversampling factor of 4.

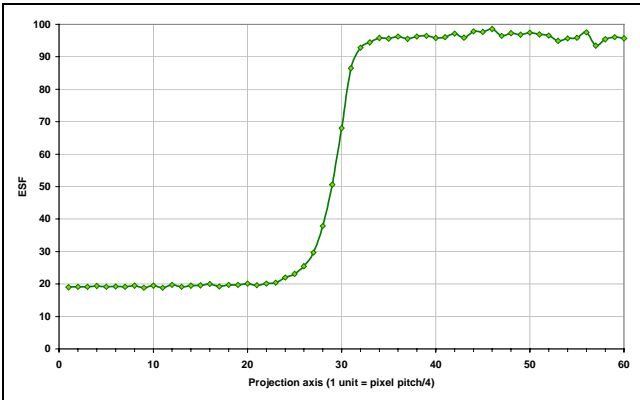


Figure 7 : Computed ESF by projecting data along the edge

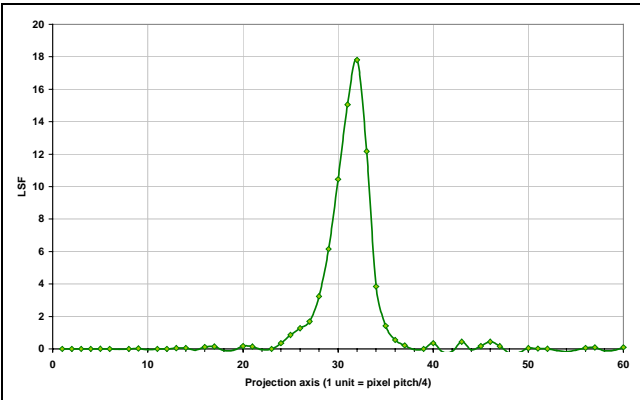


Figure 8 : LSF (derived from ESF)

To reduce the effects of the Gibbs phenomenon that results from truncation of an infinite series, a Hamming window is applied to the LSF. The system SFR can then be computed by a Fast Fourier Transform. The system MTF is deduced of the system SFR by the relation :

$$MTF_{system}(f, \lambda) = \frac{SFR_{system}(f, \lambda)}{FR_{target}(f) \times MTF_{deriv}(f)}$$

First, the frequency response of the target  $FR_{target}$  must be taken into account. It can be approximated by a polynomial so dividing frequency-by-frequency  $SFR_{system}$  by  $FR_{target}$  is easy. Furthermore, it is also necessary to correct errors due to the 3-point derivation process that has been applied by dividing by a corrective factor  $MTF_{deriv}$  (equivalent to an MTF).  $MTF_{deriv}$  is given by [6]:

$$MTF_{deriv}(f) = \frac{\sin(\pi \delta k f)}{(\pi \delta k f)} \quad \text{with} \quad \begin{cases} \delta = \frac{\text{pixel pitch}}{\text{oversampling factor}} \\ k = 2 \text{ (for the 3 - point derivative)} \end{cases}$$

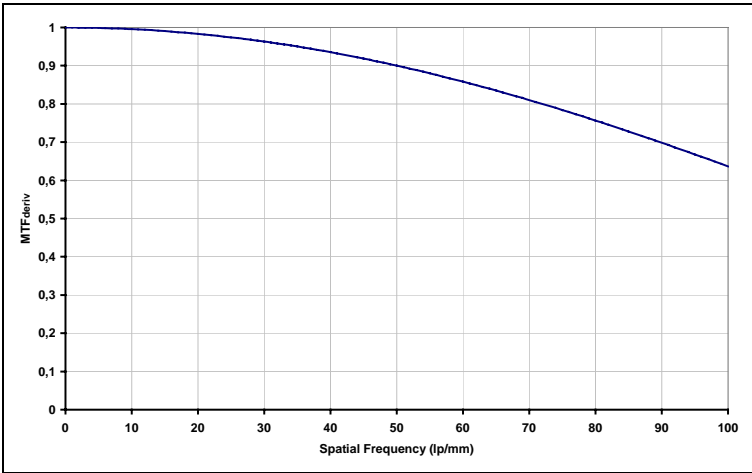


Figure 9 : Derivative error MTF (corrective factor)

It is represented in a particular case (10x10 $\mu$ m pixel, oversampling factor of 4) on the figure 9 for spatial frequencies varying between 0 and 100lp/mm. As can be seen, this derivation can have an important effect on the measured SFR, that must be removed.

### 3.2 Simulations

In order to verify the results obtained at different target to sensor tilt angles, Matlab simulations have been performed. First, the slanted-edge method is simulated : a program computes the theoretical response of a 100x100 pixels array reproducing a slanted-edge with a selected tilting angle. The generated synthetic image is used as an input for the slanted-edge software. MTF is obtained by correcting the computed SFR by the 3-point derivative error. The figures 10 and 11 give MTF results for two types of pixel (10x10 $\mu$ m square). The first one is a 100% fill-factor pixel, the second one being a L-shaped pixel.

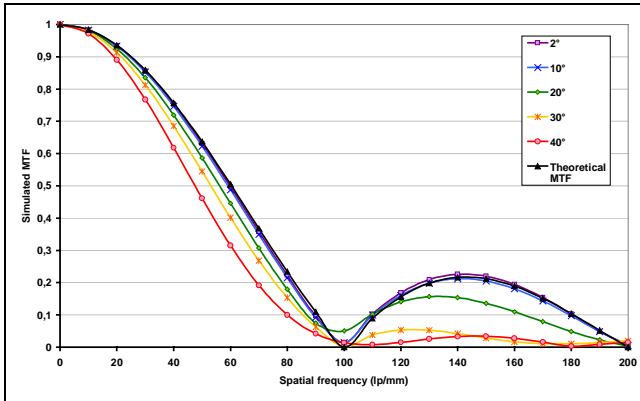


Figure 10 : Simulated MTF for 100% fill-factor pixel

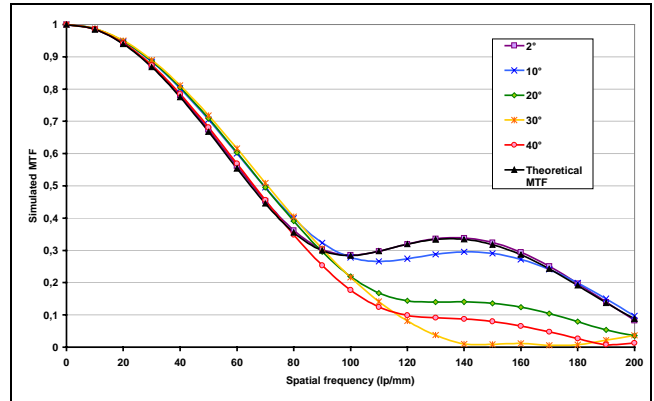


Figure 11 : Simulated MTF for L-shaped pixel

These results show that the obtained MTF is angle dependent for tilt angle above 10°. However, the simulated MTF obtained with small angles (up to 10°) is very close to the theoretical MTF. So, the slanted-edge methodology, if used with a small angle, provides a very good approximation of the detector MTF and tolerance for horizontal and vertical positioning.

### 3.3 Comparison of the methods

The main advantage of the slanted-edge compared to others method is that it only requires a single image and so no displacement, thus giving a fast result. The sine target method needs at least one image (depending on the number of pixel) for each spatial frequency and knife-edge method needs one image for each target position (number depending on the desired sampling). As focusing is necessary after each displacement, measurement time is reduced by using slanted-edge method, reducing the temperature stability requirement.

Constraints on vertical and horizontal alignments are reduced as tilted angle has only to be small enough to provide a good approximation of the horizontal (and vertical) MTF.

The ISO slanted-edge target, as the sine target, is not a black-white transition but offers a moderate edge contrast. It allows simplest luminance adjustment to fit with linearity range of the sensor.

As a key point, this method doesn't require a large number of pixels. This number must be sufficient to compute a good ESF so smaller is the angle, bigger must be the ROI. The sine target method implies that at least one period of the sinus must be imaged onto the detector to compute the contrast. This can require a large number of pixels, specially for low spatial frequencies. So, slanted-edge method needs generally less pixels than sine target method. This property is really favorable when MTF measurements have to be made on test structures that are usually small structure arrays.

## 4. MEASUREMENTS

### 4.1 Measurement setup

The measurement setup is the same for the both techniques, sine target and slanted-edge. It consists in an uniform source associated with an integrating sphere to provide an uniform and monochromatical illumination. A MTF calibrated double-Gauss lens projects the image of the target onto the detector. Translation stages (manual and motorized), rotation stages and tilt tables allow optical alignments and focusing.

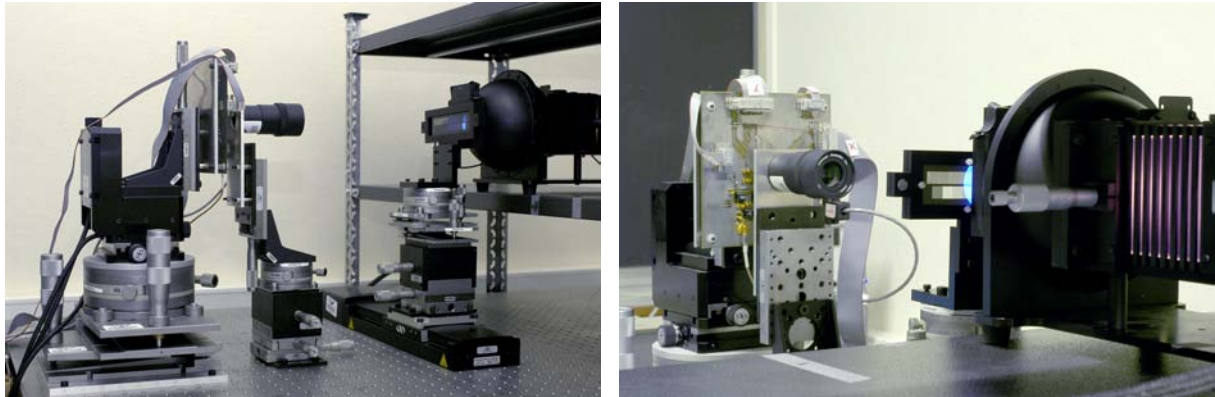


Figure 12 : Experimental setup for MTF measurements

The focusing procedure is the same for the both techniques. For each spatial frequency of the sine target (or a selected one in the case of the slanted-edge), a Matlab software computes the contrast (or SFR) as a function of the distance between the detector and the lens. The maximum of the resulting parabola gives the best focusing position.

### 4.2 SFR measurements

Measurements have been made at a wavelength of 500nm on photodiode pixels implemented using a 0.25 $\mu\text{m}$  process, 10 $\mu\text{m}$ x10 $\mu\text{m}$  square, from a test chip including several sub-arrays (different detector types). The sampling frequency is then of 100 lp/mm.

Positive and negative edges have been imaged onto the detector and for each two different ROI have been considered. The figure 13 is an example of the target imaged onto the detector. The Nwell/P photodiodes sub-array is about 30x10 pixels and is positioned in the upper left of the whole array.

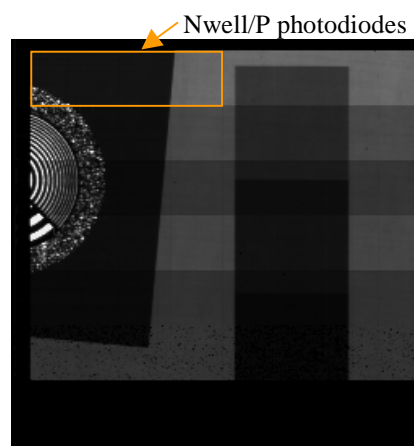


Figure 13 : Example of a positive edge imaged onto the detector

Different tests have been made with this detector. The figure 14 shows results obtained with the four horizontal positions of the edge, without correction of lens MTF.

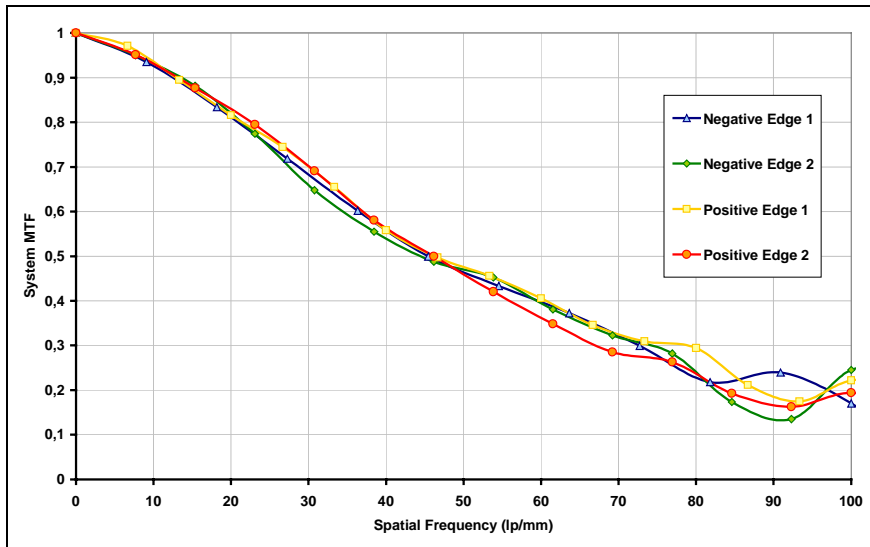


Figure 14 : Comparison of MTF calculated from four different images

As can be seen, the curves are very close and measurements appear to be non-dependant on edge position inside the pixels and on the selected ROI.

Measurements of tilt angle dependence have been made on the same structure array, for angles varying between 2° and 38°.

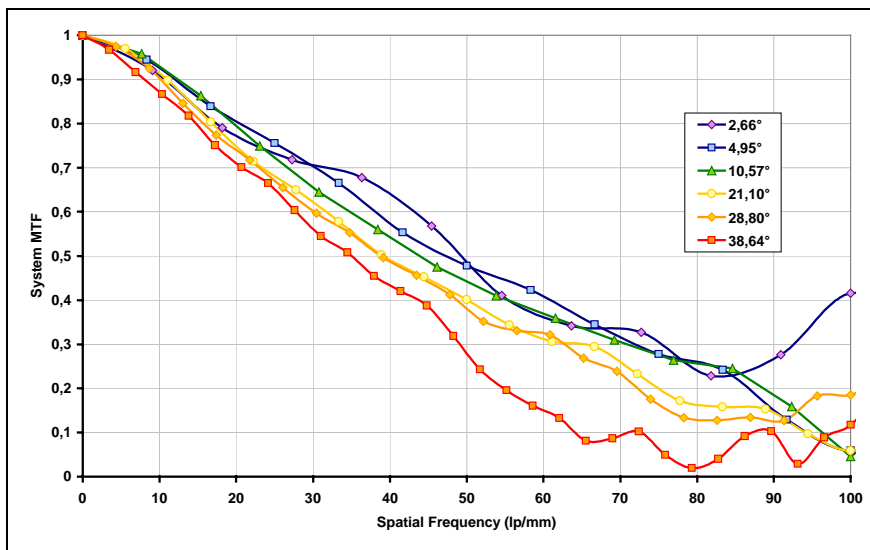


Figure 15 : Comparison of MTF calculated with different angles

From these graphs, the MTF measurements for 2°, 5° and 10° appear to be nearly the same. Only at higher angles, the differences between MTF is important. It appears that 5° is a good compromise between accuracy and slanted-edge utility.



### 4.3 Comparison with sine target MTF measurements

The MTF measurements using the sine target have been made with the same Nwell/P photodiodes, at a wavelength of 500 nm. The results are presented on the figure 16 for horizontal MTF.

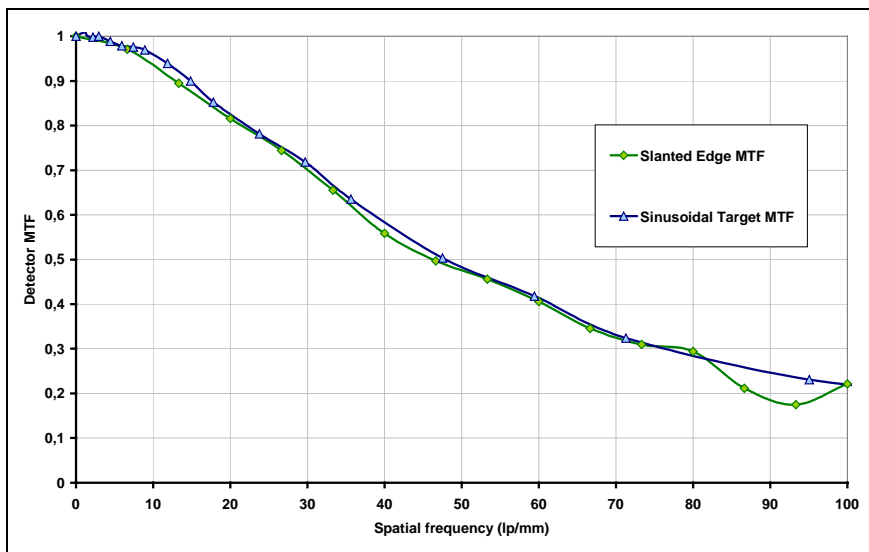


Figure 16 : Comparison of detector MTF obtained from sine target method and slanted-edge method.

Both MTF values, measured by sine target technique and slanted-edge method are very close. The last method was used with a tilt angle of approximately  $5^\circ$ . It can be verified that the MTF obtained with this angle is a good approximation of the horizontal MTF.

## 5. CONCLUSION

Although the ISO 12233 slanted edge methodology was originally designed mostly for digital still cameras MTF evaluation, it can successfully be applied at the image sensor level even in the case of CMOS image sensor whose pixel topology is complex when compared to CCD one.

The weak dependence on tilt angle for value less than  $10^\circ$  (the standard recommendation is  $5^\circ$ ) allows to relax the alignment constraints.

The use of a standardized target and associated software allows an easy comparison of MTF data that are quickly obtained from a single image.

ISO slanted-edge technique appears as a valuable alternative for fast and efficient MTF measurements allowing for the comparison of objective MTF data of various CMOS image sensors and a nice tool for supporting CMOS image sensors MTF modeling.

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