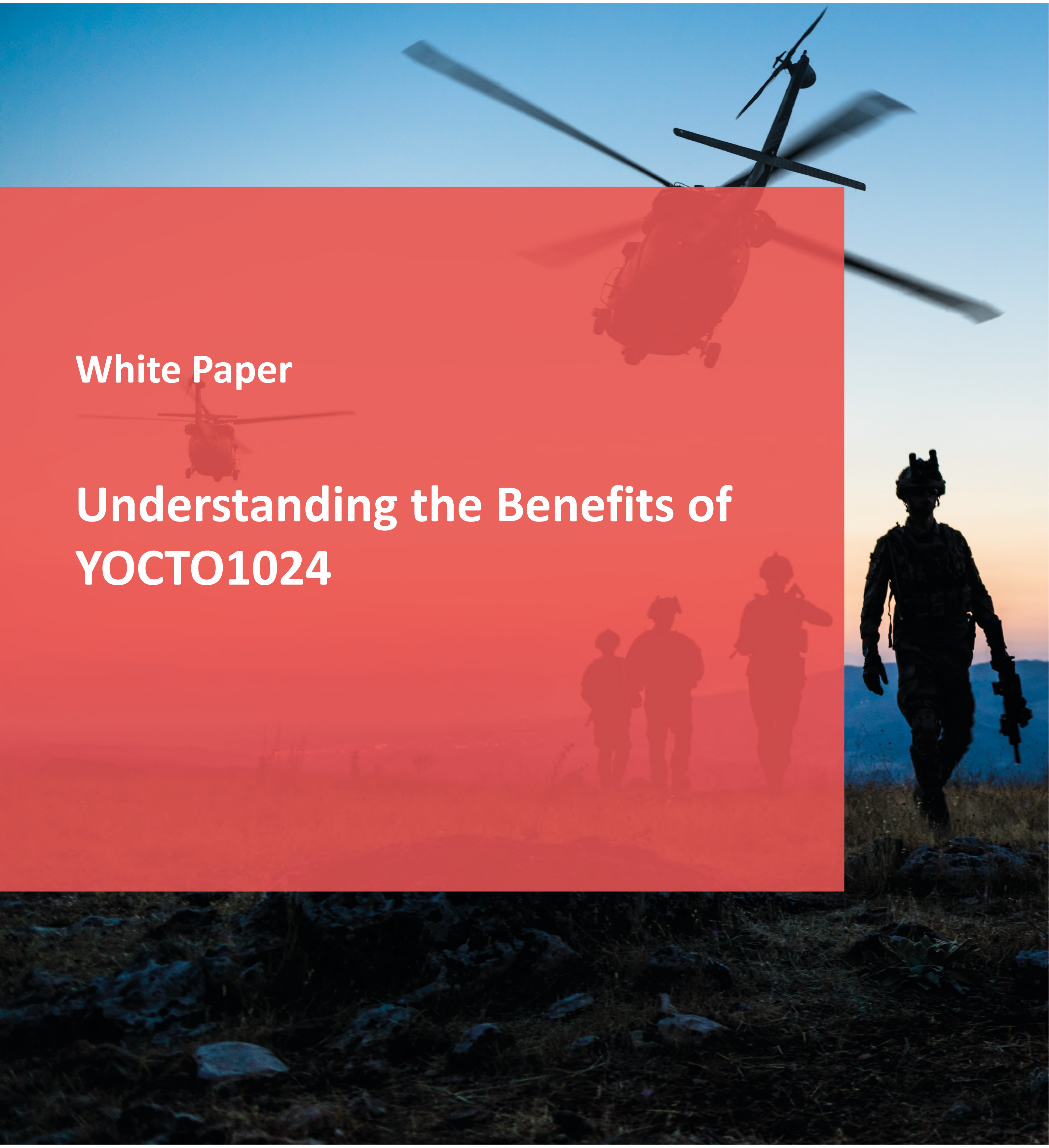

White Paper

Understanding the Benefits of YOCTO1024

LYNRED®

See Beyond Horizons

Understanding the Benefits of YOCTO1024

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June 17, 2026

This document describes preliminary concepts, architectures, and technical elements related to an ongoing research and development initiative. All content—including models, graphics, and simulations—is provided for illustrative purposes only and does not constitute a finalized design, validated performance data, or a confirmed implementation plan.

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Glossary

AI	Artificial Intelligence
EFL	Effective Focal Length (expressed in mm)
FoV	Field of View
FPA	Focal Plane Array
FWHM	Full Width Half Maximum
HFoV	Horizontal FoV
IFoV	Instantaneous FoV
IR	InfraRed
LWIR	Long-Wave IR (8 – 14 µm)
MTF	Modulation Transfer Function
NETD	Noise Equivalent Temperature Difference (expressed in mK)
PSF	Point Spread Function
SWaP	Size Weight and Power
VGA	Video Graphics Array (640 × 480 or 640 × 512)
XGA	eXtended Graphics Array (1024 × 768)

Introduction

LYNRED has launched YOCTO1024, the new generation of uncooled IR Focal Plane Array (FPA) with a XGA resolution (1024 × 768 px) and the small pixel pitch of 8.5 µm. The pixel pitch reduction allows us to fit ×2.56 more pixels within the same footprint, compared with ATTO640 (640 × 480 – 12 µm). Upgrading your optronic system from ATTO640 to YOCTO1024 enables a sharper and clearer image while ensuring forward compatibility.

This white paper aims to help understand the benefits of YOCTO1024 when implemented into an optronic system (such as a digital thermal sight), in terms of image quality, magnification and range performances.

Reduction of pixel pitch brings the question of lens compatibility, notably in terms of diffraction limit. When the lens blur becomes as large as the pixel, then why does it still make sense to reduce the pixel pitch from 12 µm to 8.5 µm? We will answer this question based on straightforward, illustrated theoretical arguments, as well as comparative examples of real-world images.

We may go further with discussion about appropriate lens f/# for the YOCTO small pixel pitch, and trade-off between image quality and range performances.

> ⓘ Note that, this white paper will become gradually more technical, which leaves the reader the liberty to jump directly to the conclusion when appropriate.

Chapter 1. Comparing FPAs

YOCTO1024 is an upgrade of our SWaP sensor ATTO640. It increases the image format from VGA to XGA, which allows for a better compromise between field-of-view (FoV) and resolution (IFoV). We do so without significantly increase the sensor size, thanks to pixel pitch reduction. Indeed, the two sensors share a similar package (see Figure 1.1), making forward compatibility easier.

Figure 1.1. ATTO640D-04W (Left) versus YOCTO1024 (Right) Packages

Side-by-side sensors characteristics are listed in the table below:

	ATTO640	YOCTO1024
Image format	640 × 480	1024 × 768
Pixel pitch	12 µm	8.5 µm
Image size	7.68 × 5.76 mm^2	8.70 × 6.53 mm^2
Package size	<17.3 × 17.3 × 4.9 mm^3	<18 × 18 × 4.85 mm^3

YOCTO1024 has a slightly larger image size than ATTO640, as illustrated in Figure 1.2.

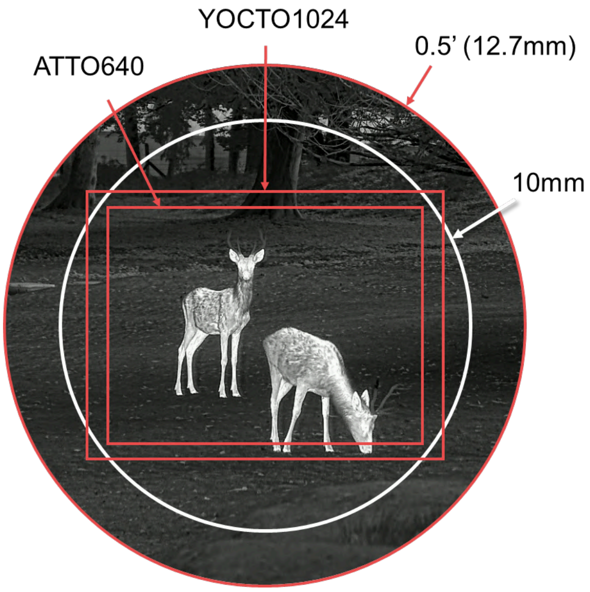


Figure 1.2. Sensor size comparison, together with typical image circle diameters

Lenses with a 0.5’ (12.7 mm) image circle are commonly used with VGA – 12 µm sensors, and will be compatible with YOCTO1024 because both sensors diagonal are smaller than the lens image circle diameter. SWaP lenses with a smaller 10 mm image circle are also compatibles with YOCTO1024, with acceptable image degradations in the corners.

ⓘ A lens image circle characterizes the area on its focal plane where the image is formed with optimal optical quality, notably in terms of sharpness and relative illumination. Outside such image circle, defects may appears such as blur or vignette effects. The sensor image size has to fit within the lens' image circle for optimal image quality.

This part concludes that a lens originally designed for ATTO640 (or other VGA – 12 µm) most likely remain compatible with YOCTO1024 in terms of image circle diameter. YOCTO1024 offers a slightly larger image size than ATTO640, meaning that it will cover a wider FoV when using the same focal length, thus improving contextual awareness.

Higher pixel densities plays a role in image sharpness, and how far we can see.

Chapter 2. Better Digital Magnification

More pixels to zoom-in further! In this section, we will explain how digital magnification works for thermal sights.

This chapter consideres an assembly of a thermal optronic sight with an IR camera, a micro-display and an eyepiece.

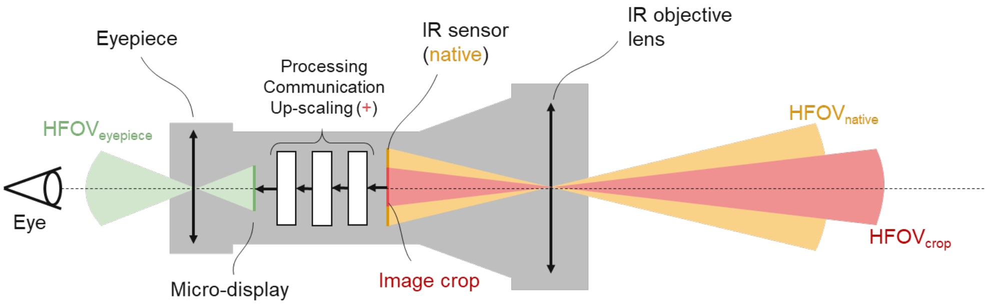


Figure 2.1. Schematic of a Thermal Optronic Sight

2.1. Native Magnification

For an optronic sight, we define magnification M as:

$$M = \frac{\partial\theta_{eyepiece}}{\partial\theta_{object}} \approx \frac{HFoV_{eyepiece}}{HFoV_{IRcam}}$$

Where θ_{object} and $\theta_{eyepiece}$ are the ray angles from the object/target (captured by the IR camera module), and the eyepiece module (including the micro-display) respectively. Magnification is approximated as the ratio of horizontal FoVs (HFoV) between the eyepiece and the IR camera module. By default, we take HFoV$_{eyepiece}$= 31°, a 'natural' field of view with perspective close to the human vision.

> Magnification (also known to as angular magnification) is an intuitive concept widely used for consumer optics. Magnification ×1 it is equivalent to looking at the scene with the naked eye through a porthole. Looking at a target using a ×2 magnification sight, it will appear twice as big, or twice as close.

We recall the formula of HFoV in the paraxial approximation (valid for small angles), where n_{col} is the number of pixels in the horizontal direction, p is the sensor pitch and EFL is the objective lens' effective focal length (expressed in the same unit of length as p, usually in mm):

$$HFoV = 2\arctan\left(\frac{n_{col} \cdot p}{2EFL}\right)$$

With the same objective lens EFL, the native HFoV of the YOCTO1024 is wider than that of the ATTO640, due the larger sensor width. For instance, with the same EFL 50 mm f/1.0 lens, the native magnification is ×3.5 and ×3.1 for ATTO640 and YOCTO1024 respectively. When viewed on the same micro-display, the YOCTO1024 will appear slightly zoomed-out compared with ATTO640 because of its lower magnification (see Figure 2.2 below).

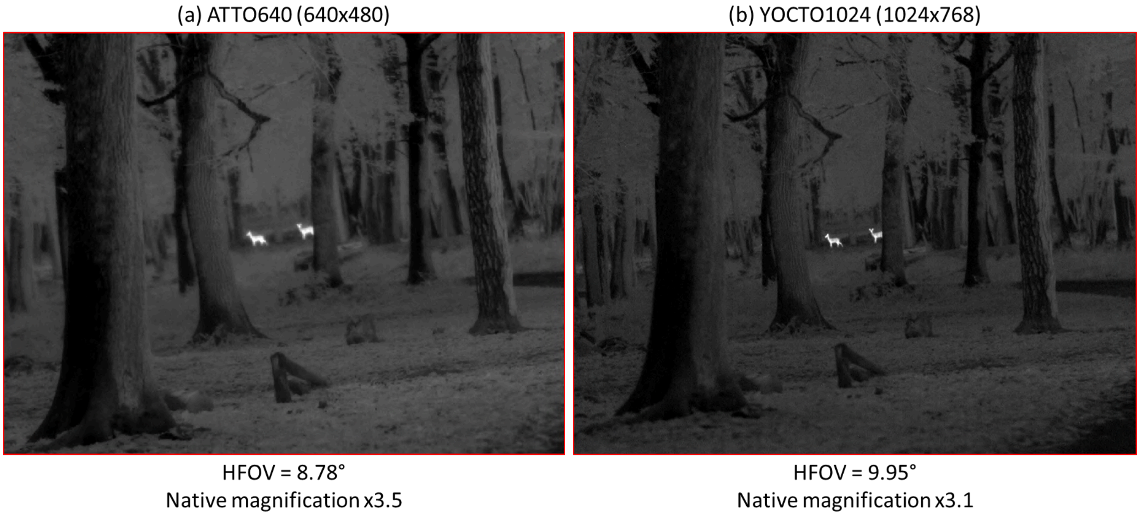


Figure 2.2. Same scene taking with both sensors and a 50 mm f/1.0 lens

If the micro-display pixel definition is higher than the sensor definition, the image is up-scaled with a bi-linear interpolation or nearest neighbor, for instance. Note that a native XGA sensor image displayed on a XGA screen, without up-sampling greatly reduces the perception of noise.

2.2. Digital Magnification

> ⓘ Digital magnification (or digital ‘zoom’) consists in cropping the image to reduce the camera FoV, and up-scaling the cropped image to the same micro-display.

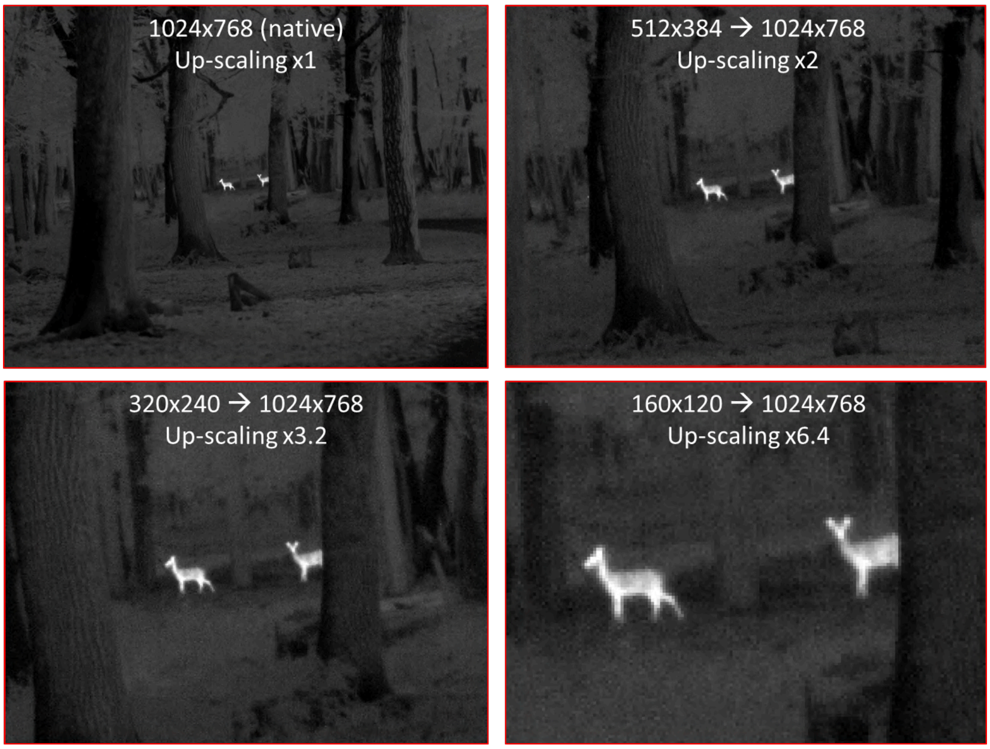


Figure 2.3. Digital zoom examples: cropped YOCTO1024 displayed on a 1024 × 768 micro-display

Figure 2.4 shows up-sampling imagery taken with YOCTO1024 displayed on a 1024 × 768 micro-display, from native down to a 160 × 120 crop. Display parameters (e.g. tone-mapping, histogram equalization) are applied on the cropped image statistics (histogram).

We plot the up-scaled images with a simplest 'nearest neighbor' interpolation, which may give a 'pixelated' look to the 160 × 120 image. Advanced super-resolutions methods could be applied instead, but not discussed in this document.

We consider the 160 × 120 crop as the smallest acceptable for consumer optics. The figure below shows a comparison of cropped views taken with ATTO640 and YOCTO1024. The higher pixel density of YOCTO1024 provides a sharper rendering at long distance.

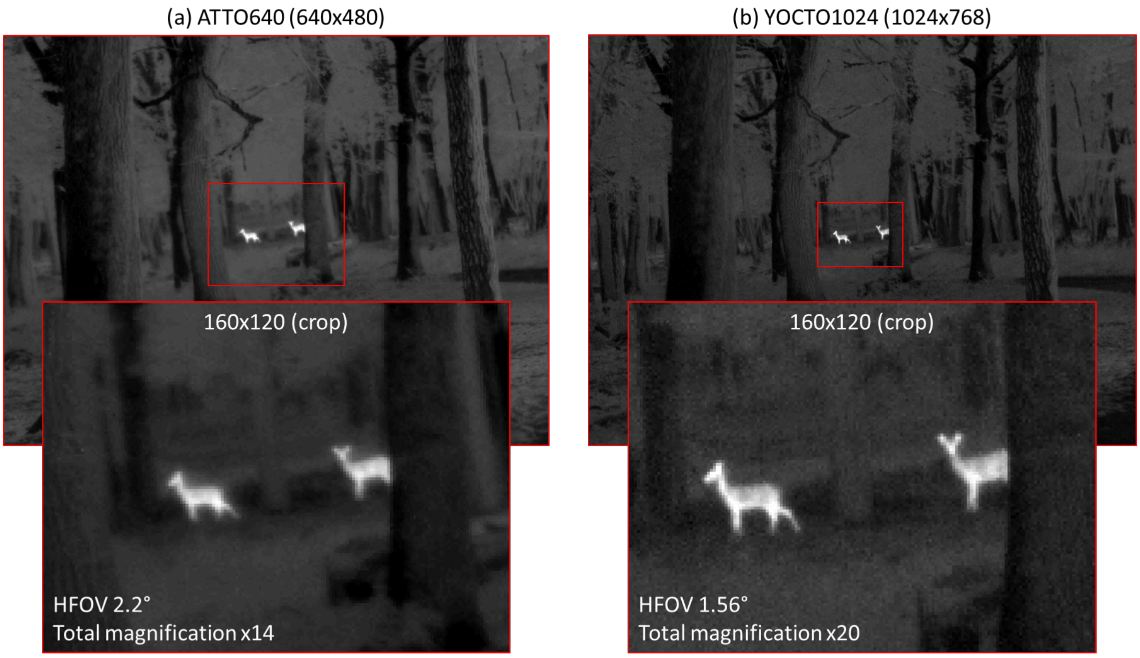


Figure 2.4. Same Lens, Same 160 × 120 Crop

Cropping the ATTO640 image from 640 × 480 to 160 × 120 corresponds to a digital magnification of ×4, the YOCTO1024 can achieve a better ×6.4 crop factor with the same output image format. YOCTO1024 enables further digital magnification, reaching total magnification ×20, which is 40 % better than ATTO640 with the same output crop.

Chapter 3. Sharpness and Spatial Resolution

3.1. Diffraction Limit

Specialists may already know the physical limit in terms of spatial resolution of an optical system, known to as the diffraction limit. Diffraction of light generates a blur, that is not negligible in the LWIR (λ= 10 µm). Point Spread Function (PSF) is the blurry spot which results of a point source object at infinity formed by an the optical system. The PSF of a diffraction-limited lens is modelled as the Airy spot, and is dependent of the lens $f/\#$ (‘f-number’).

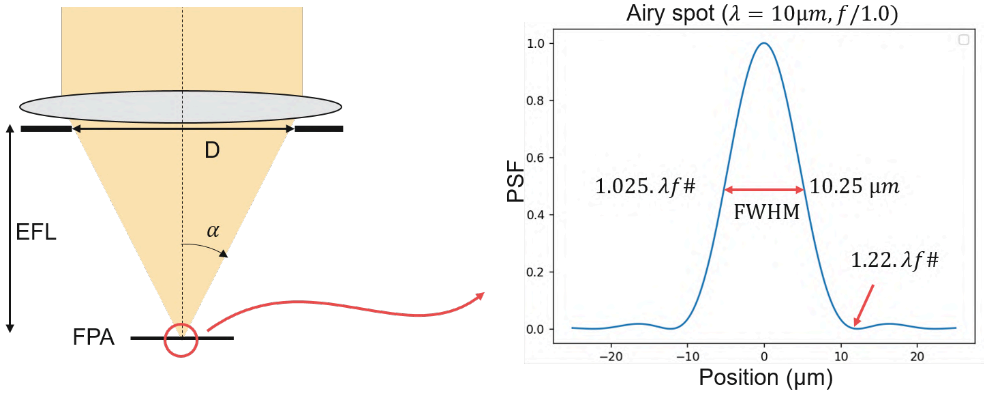


*Figure 3.1. Illustration of a Diffraction-Limited Point Spread Function (*PSF*)*

The f/# is derived from the image’s cone half-angle α :

$$f/\# = \frac{1}{2\sin\alpha}$$

ⓘ Note that, one should not use the approximation $f/\# \simeq EFL/D$, which is only valid only for small apertures (typically f/1.4 and above).

High aperture lenses (‘fast lenses’, f/# is small) have a wide image cone half-angle. For a given EFL, it usually means that the entrance pupil diameter D is large (may depend on the lens design). Thus, low f/# are associated with ‘bulky’, heavy and costly lenses.

The current state-the-art for reasonable high aperture fixed focal LWIR lenses is f/1.0, and is often paired with 12 µm pitch sensors. Such f/1.0 lenses have performances close to the diffraction limit (especially at the center of the image), thanks notably to aspheric lens elements.

It is often believed that sub-10 µm pitch sensors requires higher aperture lenses (‘ultra-fast lenses’), down to f/0.75 for the 8.5 µm pitch. Such lenses introduce new challenges, including increased optical aberrations, higher complexity with additional lens elements, shorter hyperfocal length, stricter alignment and manufacturing tolerances etc. [1]. This makes the system design with ultra-fast lens less desirable, with a suboptimal trade-off between performances, complexity, weight and cost.

Then why should we further reduce the pixel pitch down to 8.5 µm?

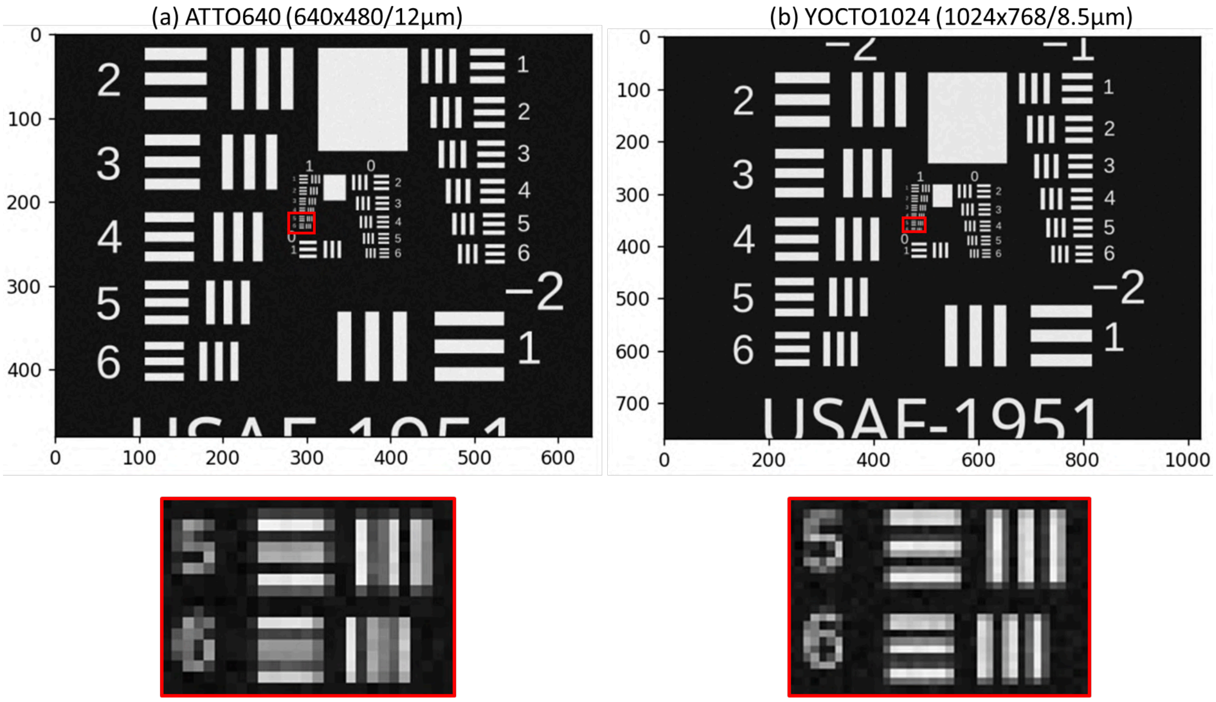
With f/1.0 and λ= 10 µm, the diffraction spot width (10.25 µm FWHM) is comparable with the 12 µm pixel’s pitch, the question is fair to be asked. The simplest answer will be presented, with practical examples first, and then we will provide theoretical elements.

3.2. Image Simulation

We make a simple image simulation of a USAF-1951 resolution target, which is projected onto the FPA with a ×1/10th magnification optics. It means that the target element 1 from group 1, which has a 250 µm line width in object space, is projected onto the image focal plane with a 25 µm width. This corresponds to 2.08 px for ATTO640 and 2.94 px for YOCTO1024.

The simulation consists of the following steps:

- A scaling of the high resolution source image (USAF-1951 target) to the appropriate magnification (1/10th)
- Convolution with the Airy spot (f/1.0, λ=10 µm) at source resolution
- Subsampling to the output resolution, with integration on the pixel's area
- Random noise injection (ΔT = 2 K Thermal contrast, NETD = 40 mK for ATTO640, and 50 mK for YOCTO1024)


(a) ATTO640 (640x480/12µm)

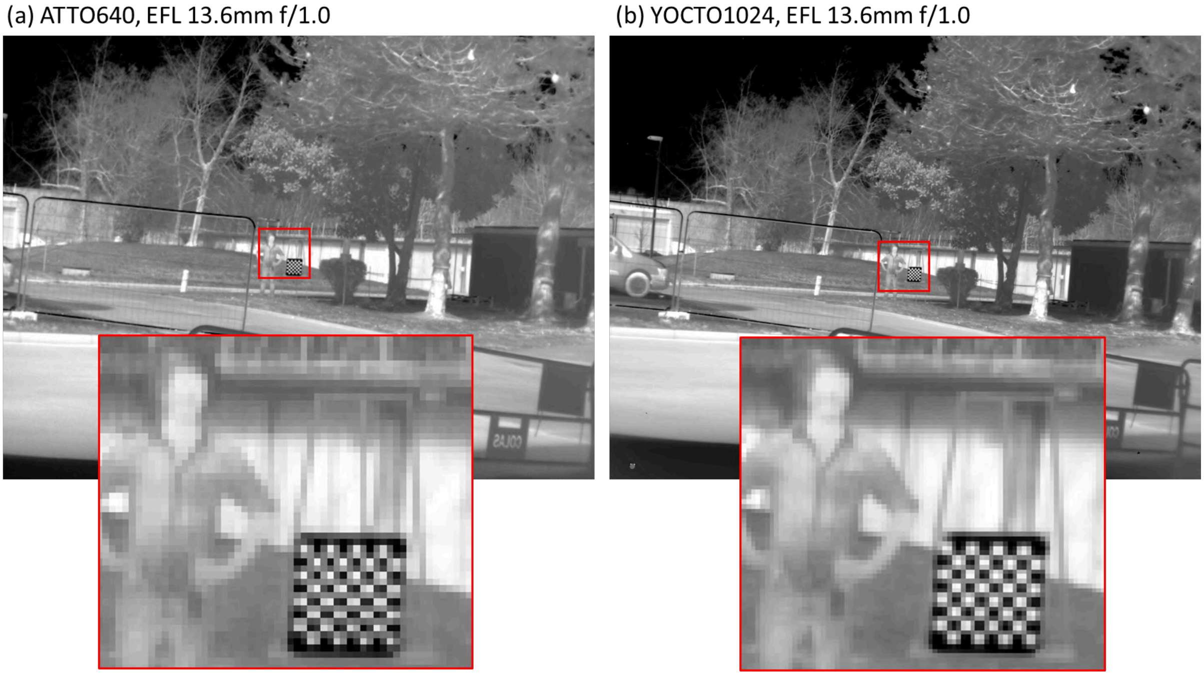
(b) YOCTO1024 (1024x768/8.5µm)

Figure 3.2. Image Simulation of a USAF-1951 Test Target

We display a zoomed view of elements 5 and 6 of group 1, where the benefits in terms of resolution of the YOCTO1024 over the ATTO640 are clear, even with an f/1.0 lens. This suggests that the f/1.0 lens is appropriate for the small 8.5 µm pitch.

3.3. Image Examples

We show a comparative example of the same scene taken with both sensor, and the same lens model: EFL 13.6 mm f/1.0, which has performances close to the diffraction limit. The lens model is a design for VGA – 12 µm, and not specifically for the sub–10 µm pixels.

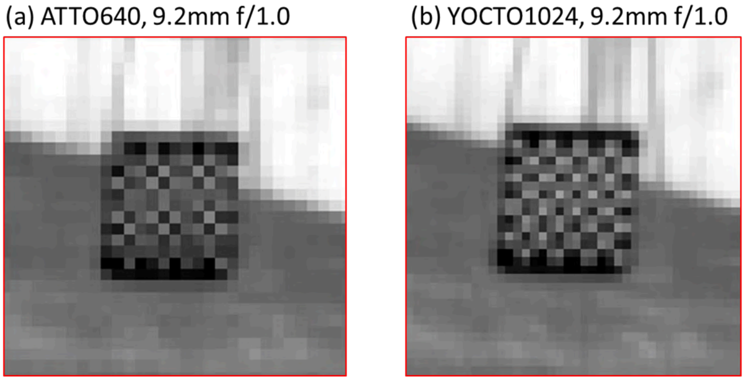

(a) ATTO640, EFL 13.6mm f/1.0

(b) YOCTO1024, EFL 13.6mm f/1.0

Figure 3.3. Comparative Image Example with the Same 13.6 mm f/1 Lens Model

The scene shows a person standing next to a chessboard at a 32 m distance. The comparison is indisputable: the ATTO640 image has aliasing artefacts due to under-sampling, and YOCTO1024 has a clear and sharp image, thanks to its increased number of 'pixels on target'.

We evaluate finer spatial frequency, using the same chessboard at the same distance, but with a 9.2 mm f/1.0 lens. **Figure 3.4** shows aggravated aliasing artefacts in the ATTO640 image.


(a) ATTO640, 9.2mm f/1.0

(b) YOCTO1024, 9.2mm f/1.0

Figure 3.4. Chessboard at 32m Distance with a 9.2 mm f/1.0 (Cropped)

Last, **Figure 3.5** shows an example with a slower lens. The view of the chessboard at 75 m distance, with a 35 mm f/1.14 lens, designed for a VGA – 12 µm sensor. Improvements with YOCTO1024 are still here!

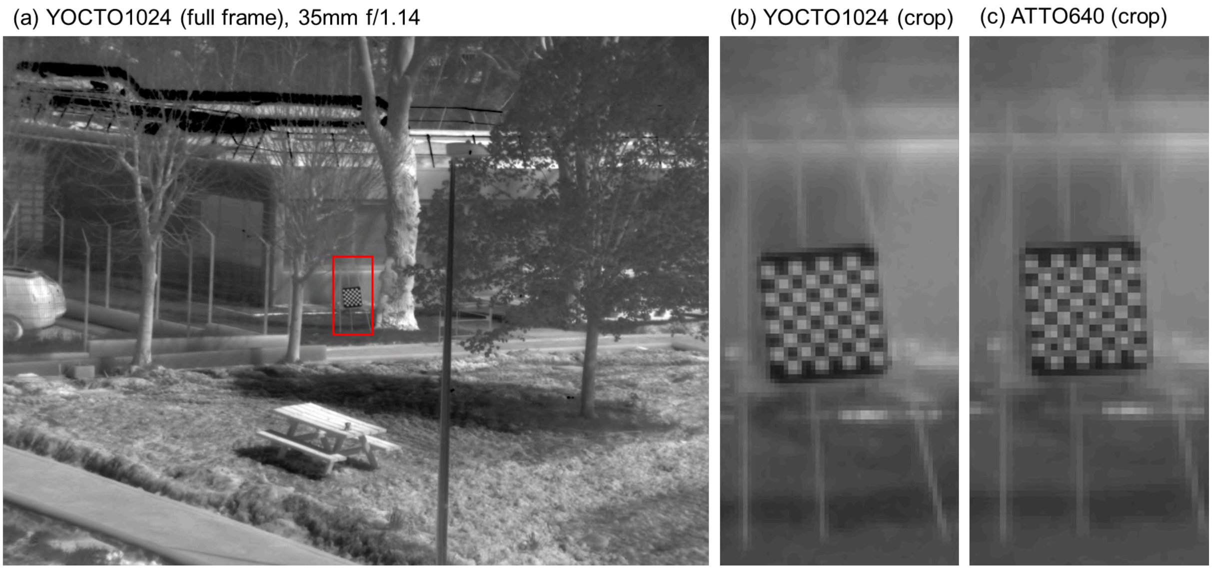


Figure 3.5. Chessboard at 75 m Distance with a 35 mm f/1.14 Lens

We validate the simulation with practical examples: YOCTO1024 brings a sharper image (and without aliasing) compared with ATTO640, even with f/1.0 lenses (and slower) that were originally designed for VGA – 12 µm sensors, and not specifically for sub-10 µm pixels.

3.4. Modulation Transfer Function

Modulation Transfer Function (MTF) is the standard metric for spatial resolution for optical and optronic systems. It represents the imaging system ability to resolve fine details with given contrast. This is a function of transferred contrast versus spatial frequency (given in cycles per mm: cy/mm). The MTF is typically a function that decreases with spatial frequency, meaning that finer details are carried out by the imaging system with reduced contrast. There is usually a cut-off frequency where contrast falls to 0 %, which is the hard resolution limit. MTF is calculated as the Fourier transform of the Point Spread Function PSF.

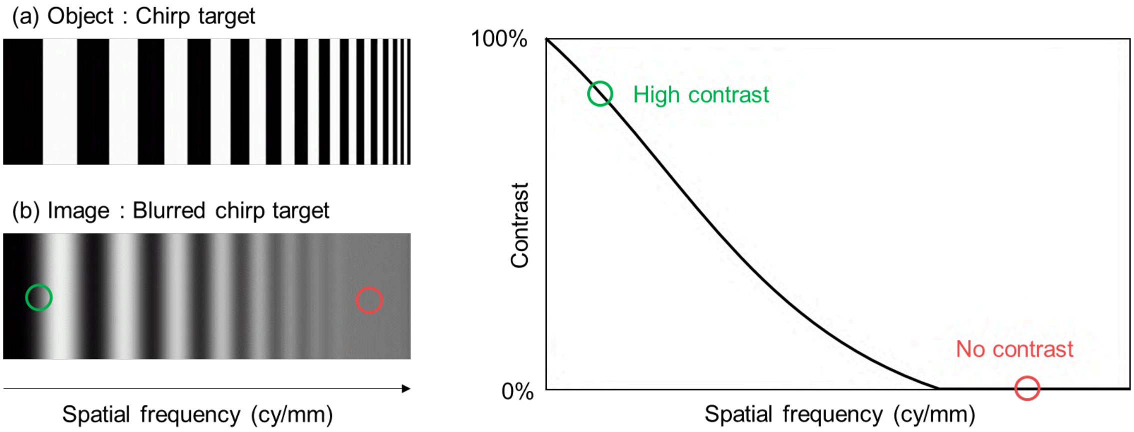


Figure 3.6. (a) Chirp Target Object. (b) Blurred Chirp Target Image through the Imaging System. (c) MTF Function Example

We will consider an optronic system with a diffraction limited lens and a pixel with ideal response. The diffraction-limited lens has a cut-off frequency $\nu_c = (\lambda f/\#)^{-1}$. We have a cut-off frequency of 100 cy/mm, with $\lambda = 10$ µm at f/1.0. The lens MTF is expressed as:

$$MTF_{lens}(\nu) = \frac{2}{\pi}\left(\operatorname{acos}\left(\frac{\nu}{\nu_c}\right) - \frac{\nu}{\nu_c}\sqrt{1-\nu_c^2}\right)$$

We consider a pixel with ideal response, i.e. with a ‘top-hat’ PSF response of width p (the pixel pitch). It has a cut-off frequency at $\nu_c = 1/p$. This corresponds to 83.3 cy/mm for the 12 µm pitch (ATTO640) and 117.7 cy/mm for the 8.5 µm pitch (YOCTO1024). We also define the Nyquist frequency $\nu_{Ny} = 1/2p$. The pixel MTF is expressed as:

$$MTF_{pixel}(\nu) = |sinc(\pi p \nu)|$$

Note that the pixel MTF does not fall to 0 after ν_c: the *sinc* function shows a first rebound after its first zero crossing. This non zero contrast above ν_c characterizes aliasing artefacts.

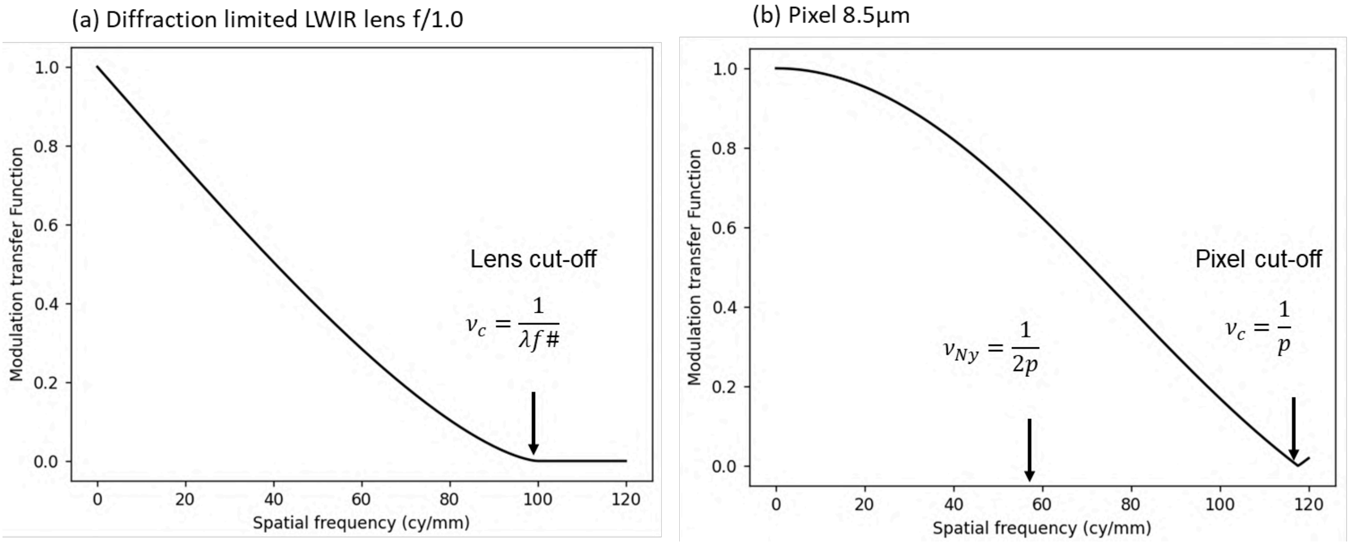

(a) Diffraction limited LWIR lens f/1.0
(b) Pixel 8.5µm

Figure 3.7. Ideal MTF of (a) LWIR Lens at f/1 and (b) 8.5 µm Pixel

The system's MTF is calculated by multiplying the lens' MTF by the sensor's MTF, or further multiplied by MTFs from other elements such as display, eyepiece etc., which are not considered here.

$$MTF_{system}(\nu) = MTF_{lens}(\nu).MTF_{pix}(\nu)$$

Here is a comparison of the sensors in the MTF systems, with respective sizes of 12 µm (ATTO640) and 8.5 µm (YOCTO1024), both paired with an f/1.0 lens:

- ATTO640: the 12 µm pixel cut-off frequency is lower than the lens cut-off frequency ($1/p < 1/\lambda f\#$), which means that the spatial resolution is limited by the sensor rather than the lens. In this case, we say that the system is ‘*under-sampled*’. One consequence is that aliasing artefacts from the sensor are carried out by the lens with non-zero contrast.
- YOCTO1024: the 8.5 µm pixel cut-off is slightly higher than the lens cut-off frequency ($1/p > 1/\lambda f\#$), which means that the spatial resolution is limited by the lens. In this case, the lens acts as an anti-aliasing filter.

Note that '*under-sampled*' systems are common among uncooled thermal cameras, and are adapted for applications that requires high thermal sensitivity. LYNRED's YOCTO technology allows for pixel pitch reduction while maintaining similar NETD performances than the ATTO technology [2]. This allows us to relieve lens requirements, notably on f/#. More details will be provided in the next section.

Figure 3.8 shows the result of plotting the MTF curve for both cases. The YOCTO1024 has an increase of +10 % MTF at Nyquist frequency (58.8 cy/mm) compared with the ATTO640 with that same f/1 lens at the same frequency.

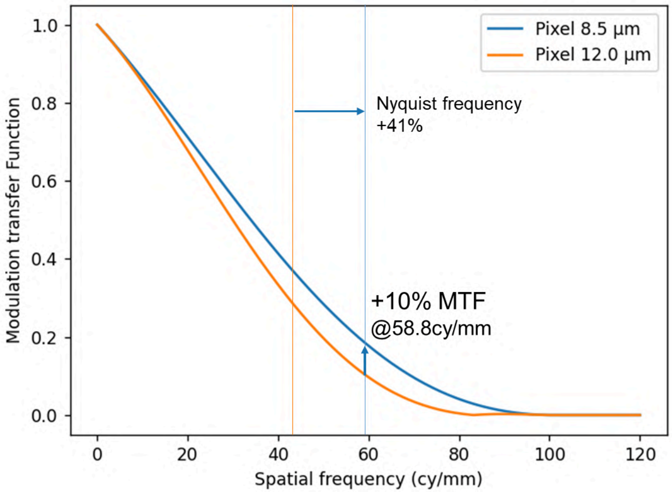


Figure 3.8. Systems MTF with 12µm and 8.5µm Pitches with the Same f/1.0 Lens

We determine that an f/1 lens (even one built for a 12 µm VGA sensor) is an appropriate size choice for a YOCTO1024 system and brings sharper images (+10 % MTF@Nyquist) compared with the same system equipped with an ATTO640.

Chapter 4. Choosing the Right f-Number

4.1. The Cost for Magnification

The lens entrance pupil diameter is representative of the size and cost of the objective lens. This is typically a limiting factor for a given application or mission profile. For simplicity, we assume that the entrance pupil diameter is equal to the lens' effective pupil diameter used in the f/# definition.

At a fixed lens pupil diameter D, one has to find appropriate lens characteristics (f/#, EFL) for a given FPA (e.g. YOCTO1024). Long EFL, makes high magnification (narrow IFoV) at the cost of a high f/# (slow lens, reduced image sharpness and contrast). Inversely, low f/# (fast lenses) makes high quality images, and wide FoV.

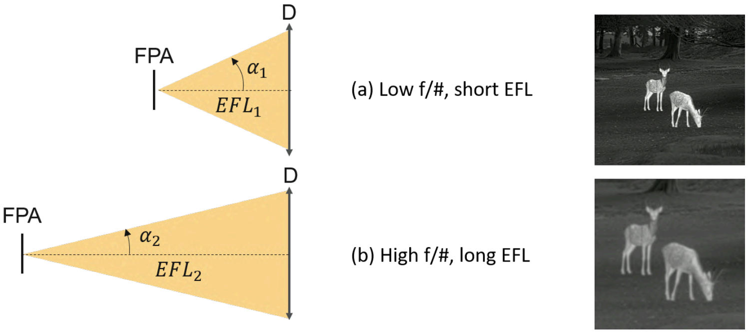


Figure 4.1. Illustration of Two Optronic Systems with the Same Pupil Diameter D

EFL is calculated as a function of f/#, at a fixed pupil D:

$$EFL = \frac{D}{2\ \tan\left(\arcsin\left(\frac{1}{2f/\#}\right)\right)} \neq D.f/\#$$

Figure 4.2 shows a practical example of YOCTO1024 and two lenses of similar size: 19 mm f/1.03 and 25 mm f/1.2. The scene is a chessboard at 35.5 m.

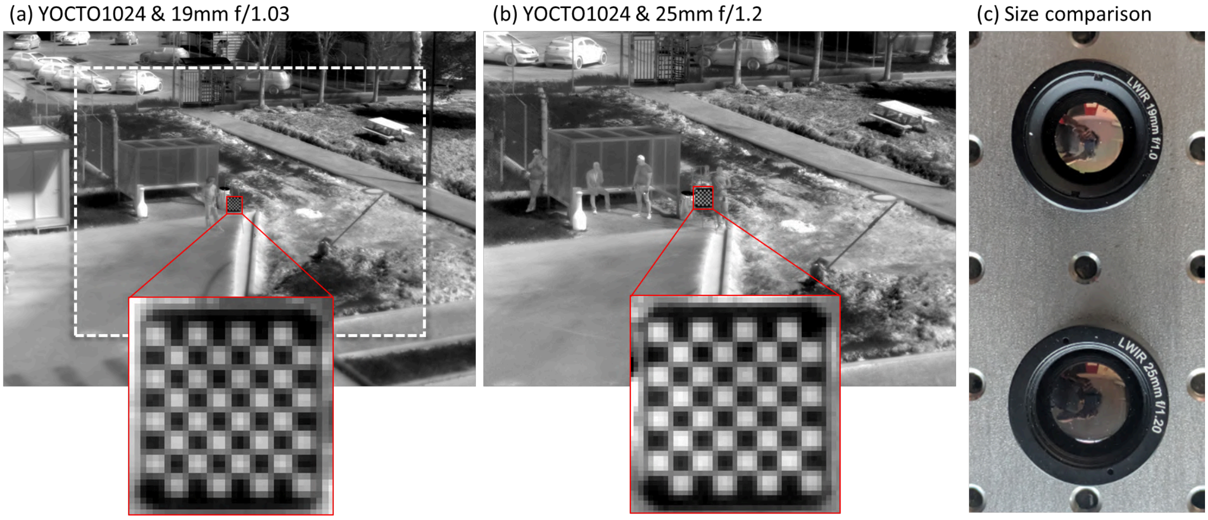

(a) YOCTO1024 & 19mm f/1.03
(b) YOCTO1024 & 25mm f/1.2
(c) Size comparison

Figure 4.2. YOCTO1024 with Two Lenses with Similar Pupil Diameter

The image obtained with the shorter EFL (19 mm in subfigure (a)) has wider FoV, and fair resolution when taking advantage of YOCTO1024's powerful digital zoom. The dotted rectangle outlines the reduced FoV of the longer 25 mm EFL system. Subfigure (b) shows that the spatial sampling of the target is improved, but improvements on spatial resolution in object space are mitigated by the diffraction limit from the f/1.2 lens. One might choose the former lens that has a wide FoV, with limited compromise on object spatial resolution.

For ATTO640, the conclusion is different because diffraction from a f/1.2 lens is less of an issue becoause of the larger 12 µm pitch. One might choose the latter lens thanks to the better spatial resolution in object space (see, Figure 4.3).

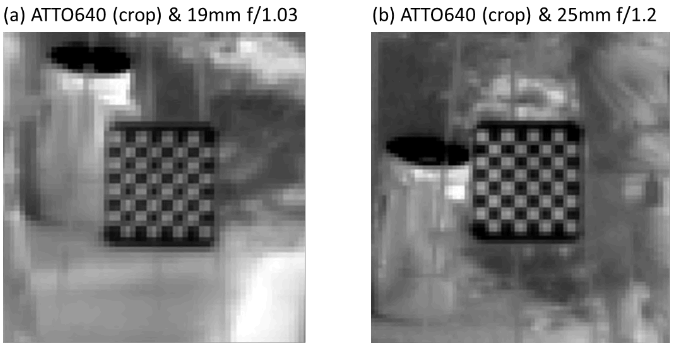

(a) ATTO640 (crop) & 19mm f/1.03
(b) ATTO640 (crop) & 25mm f/1.2

Figure 4.3. Same Scene with ATTO640 Cropped at the Same Swath) and Both Lenses

Tradeoffs setting f/# and EFL at a fixed pupil D and sensor pitch will be explained, together with design methodology, in order to better fit the applications needs.

> Higher optical magnification allows for better object spatial sampling (i.e. more pixels on target). However, it doesn't directly translates to an improved object resolution as one must take into consideration the lens' blur size in pixel units (notably the diffraction limit).

4.2. Holst Number

We introduce the Holst number h, in reference to Gerald Holst who democratized its use in optronic system design methodology [3].

$$h = \frac{\lambda f/\#}{p}$$

This number describes trade-offs between lens aperture and pixel detector size both in terms of resolution and contrast. This is the spatial frequency cut-off ratio between the diffraction-limited lens $(\lambda f/\#)^{-1}$ and the pixel $(1/p)$ (Figure 3.8). It also quantifies the compromise between the amount of light collected by the lens ($\propto f/\#^2$) and the pixel surface area ($\propto p^2$).

This number gives a line of identical performances between different optronic systems, notably in terms of image quality (NETD and sharpness) and range (at a fixed pupil diameter). For instance, the following uncooled LWIR systems have the same $h = 1$, thus the same performances in theory:

- 17 µm pitch with a f/1.7 lens
- 12 µm pitch and a f/1.2 lens
- 8.5 µm pitch with a f/0.85 lens

This assumes that we compare sensors with the same detectivity, and lenses with the same transmittance. We should warn that LYNRED implements technology improvements at each pixel size generation. For instance, technology improvements introduced with YOCTO aims to maintain similar NETD performances compared with the ATTO technology, even though we have reduced the pixel size from 12 µm to 8.5 µm [2].

> Detectivity D* is a performance metric for a given sensor technology, that normalizes signal-to-noise ratio by a number of parameters, including the detector surface area.

The choice for h is impacted by the sensor detectivity. For instance, cooled LWIR sensors shall have higher h, such as SCORPIO LW f/2.24 (h = 1.91). Uncooled LWIR sensor have smaller detectivities, which brings system designs with smaller h.

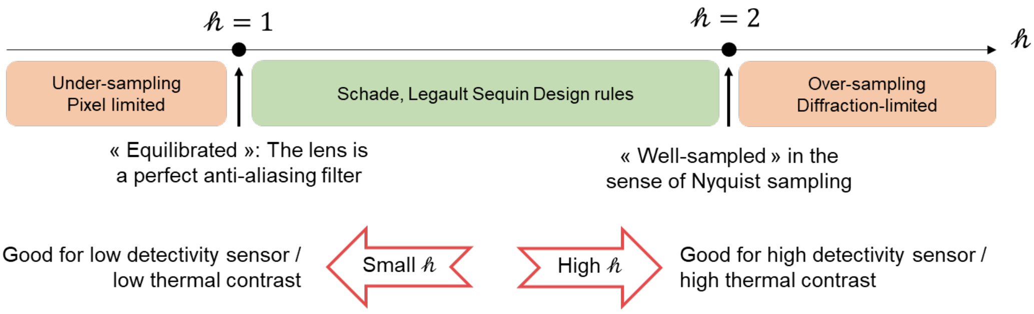


Figure 4.4. System Design Considerations Using the Holst Number: (Top) Resolution and (Bottom) Contrast Considerations

Influential studies from Ronald Driggers et al. [4] suggest that there is an optimal h that maximizes a function of merit based on range, for a given detector type and wavelength range.

In one hand, systems with a low f/# (Figure 4.1 (a)) have good image quality in terms of contrast and sharpness. Such systems are especially suitable for consumer devices where image should 'look good', even in harsh conditions. The short EFL provide low magnification, thus appropriate for contextual awareness, but not for range optimization.

In the other hand, systems with a high f/# (Figure 4.1 (b)) and long EFL trade image quality for magnification. It brings extended range in good conditions, but may suffer from poor contrast, especially in harsh weather. Range optimization at the expanse of image cosmetics should be reserved for specialized application such as military or automatic detection systems where the image is directly fed to an algorithm, and not shown to a human.

4.3. 'Best' and 'Good' f/#

Taking inspiration from reference [4], we write a simple range simulation as a figure of merit. We consider the following scenario:
- Recognition range at 75 % probability for a standard NATO vehicle
- Atmosphere model: US Standard Rural from MODTRAN [5]
- Background temperature T_{ref}=296 K
- Target to background thermal contrast ΔT=2 K (or ΔT=4 K for high contrast target)

Range calculation based on Johnson criteria is a standard methodology for IR system design, thus will not be discussed in great length in this document. One simply must know that range calculation combines multiple parameters such as:
- Noise (notably NETD)
- Target thermal contrast ΔT which decreases as a function of the distance due the atmospheric transmittance
- Object space resolution, derived from the system MTF

In Figure 4.5, we plot range simulation as a function of f/#, for a fixed pupil diameter of 50 mm, and an optics transmittance of 72 %. NETD (@f/1) values used in the simulation are 40 mK for the 12 µm pitch ATTO and 50 mK for the 8.5 µm pitch YOCTO, whitout denoising.

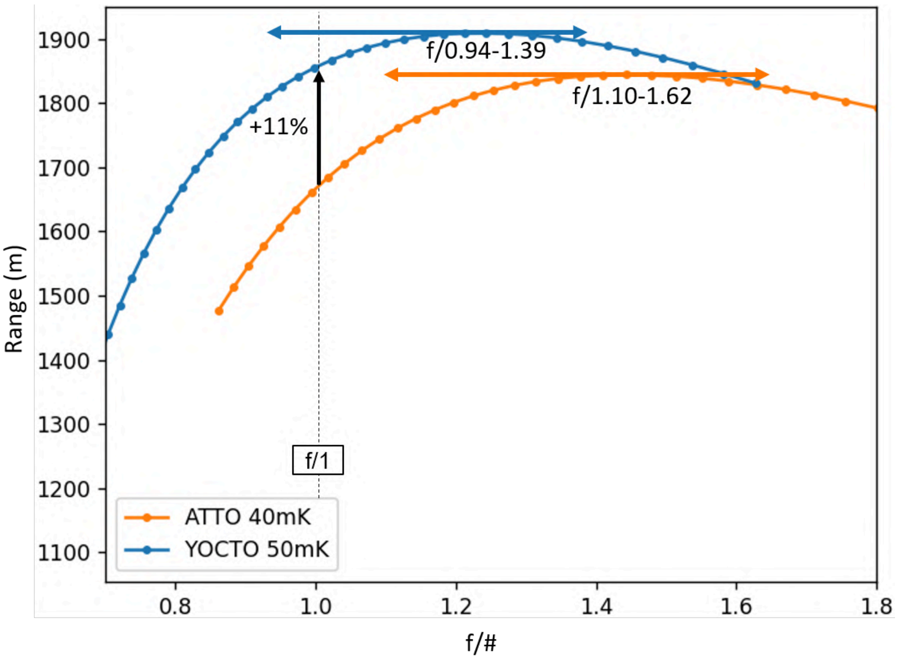


Figure 4.5. Range versus f/# for a 50 mm Pupil, ATTO versus YOCTO

We see that YOCTO outperforms ATTO in terms of range, for all apertures below f/1.62. With a typical f/1.0 lens (which is the current state-of-the-art for fixed focal LWIR lenses), we obtain a range improvement of +11 %. This confirms our prior statement that f/1.0 is appropriate for YOCTO.

Both curves have a 'best' f/#, where the range calculation is maximal. This gives the following 'best' designs for both FPAs (ATTO640 and YOCTO1024) paired with an optimized 50 mm pupil lens:

FPA NETD	ATTO640 (40 mK)	YOCTO1024 (50 mK)
Best f/#	f/1.44	f/1.23
EFL (mm)	67.72 mm	56.46 mm
HFoV (°)	6.49 °	8.82 ° **(+36 %)**
Range (m)	1844 m	1909 m (+4 %)

We demonstrate the benefits for upgrading the FPA from ATTO640 to YOCTO1024: Increased range by +4 % and a wider HFoV by +36 % using the 'best' design.

Decreasing f/# below the 'optimum' brings several advantages such as better image quality (increased contrast and sharpness), better resilience to harder conditions, and a wider FoV for better contextual awareness (with the ability to have a digital zoom, thanks to YOCTO1024's high pixel count). We argue that there is a 'good' f/#, which benefit for such advantages while ensuring 95 % of maximum range.

Increasing f/# beyond this 'optimum' would not increase range in such conditions because of the lack of contrast to noise ratio. This may however be relevant when looking at high contrast targets. We set an upper limit for 'high' $f/\#$ recommendations, as the best f/# calculated with ΔT = 4 K.

We summarize the ’good’, ‘best’ and ‘high’ f/# simulation results in the table below, for a 50 mm lens' pupil:

	ATTO (12 µm pitch)	YOCTO (8.5 µm pitch)
NETD (f/1)	40.0 mK	50.0 mK
Good f/#	f/1.10	f/0.94
Best f/#	f/1.44	f/1.23
High f/#	f/1.62	f/1.39

Appropriate f/# range may fall between the ‘good’ and ‘best’ f/#, as a recommendation for range optimization in all conditions. Higher apertures designs (small f/#, short EFL) are preferred when having high quality images matter more than having a long range (e.g. consumer applications). In opposite, lower apertures (high f/#, long EFL) are preferred when the importance thing is to maximal range in good conditions, and image quality comes after (e.g. defense/security applications and AI systems).

4.4. Comparing f/# Recommendation and Pupil Diameter

The methodology described in the previous subsection is applied for pupil diameters ranging from 6.5 mm to 160 mm. Recommendations for f/# as a function of pupil diameter are plotted in Figure 4.6.

As stated earlier, recommended f/# for range in all conditions is found between ‘best’ and ‘good’ f/# (region displayed in darker color). We can extend the f/# recommendation range for specific applications (region displayed in light color):

- Applications that have extended range requirements, in good conditions (high target contrast, good weather) may have higher f/#.
- Applications that require a greater image quality (contrast and image sharpness, but not range) may have f/# down to f/1.0, with state-of-the-art for diffraction-limited LWIR fixed focal lenses.

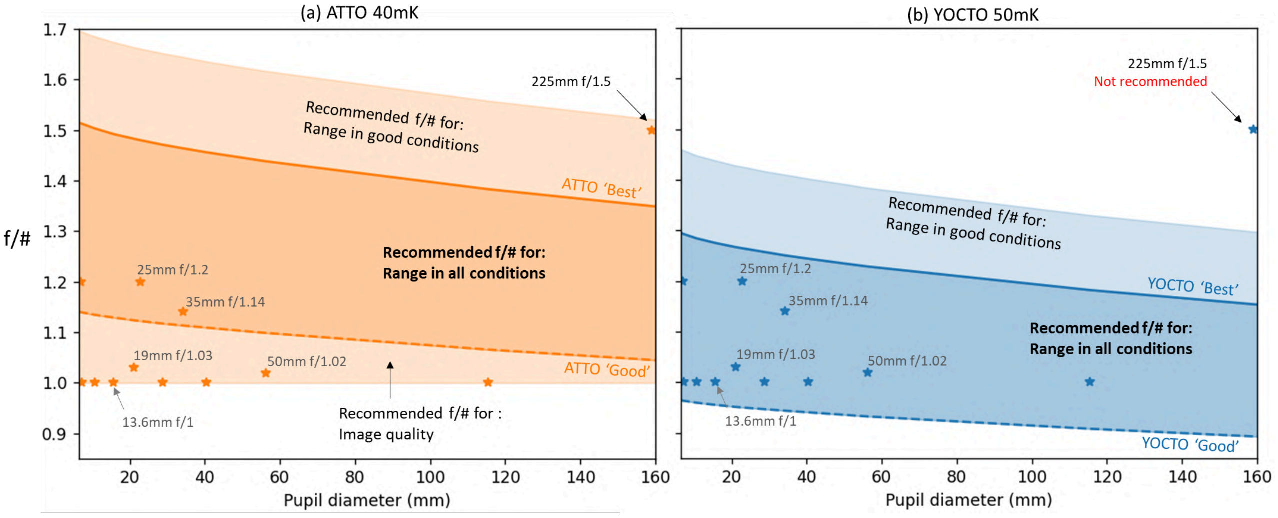


Figure 4.6. Recommendation Range for f/# as a Function of Pupil Diameter

In general, we recommand having faster lenses when paires with YOCTO1024, compared with ATTO640. As explained earlier, YOCTO1024 benefits from both wider FoV, powerful digital zoom and increased range.

Large pupils are fitted for longer-range applications: A long distances, we requires higher aperture lenses to compensate for the atmospheric contrast attenuation. This explains why the recommend values for f/# decrease as a function of pupil diameter.

We have tested several commercial lenses (marked as * on the graphs) that were originally designed for 12 µm pitch. Image examples obtained with some of these lenses were already provided in this white paper. We report that YOCTO1024 gave sharper and clearer images than ATTO640 with all tested lenses. The only exception was with the 225 mm f/1.5 lens, especially when used in harsh weather conditions (winter fog). With such a slow lens, the YOCTO image did not bring any advantage compared with ATTO image, because of the limited contrast to noise ratio.

Conclusion

This white paper outlines the benefits for upgrading the FPA from ATTO640 to YOCTO1024.

We increase image format from VGA (640 × 480) to XGA (1024 × 768), while reducing the pixel pitch from 12 µm to 8.5 µm. We have increased pixel count by ×2.56 within the same packaging footprint, providing better FoV to resolution trade-off, together with forward compatibly.

Using the same objective lens: The slightly larger sensor area makes YOCTO1024 readily compatible with existing lenses from ATTO640: we benefit from a wider FoV (+13 %), while improving digital zoom by ×1.4 thank to its higher pixel density (more pixels-on-target).

Field tests with commercially available lenses with apertures from f/1.0 to f/1.2 have showed than we can increase image sharpness when paired with YOCTO1024 over the ATTO640 they were originally intended for (and not specifically a sub-10 µm pixel pitch). This conclusion is backed by theory where is shown notably improvements in sharpness (+10 % MTF at the Nyquist frequency) and range (+11 %) with a diffraction limited f/1.0 LWIR lens.

Using the same lens' pupil diameter: We discuss the impact of f/#, at a fixed lens pupil diameter in terms of range performance. Compared with ATTO640, we show that YOCTO1024 improves the range with the apertures below f/1.62. Notably, theory shows that there is an optimal lens design (EFL, f/#) at a given pupil diameter that optimizes the range. The YOCTO1024 'best' design (f/1.23) outperforms that with ATTO640 (f/1.44), combining both a wider HFoV (+36 %) and extended range (+4 %).

Finally, we discuss the f/# recommendations for both ATTO and YOCTO, with considerations on the application, whether a 'good-looking' image is required (for consumer devices), or maximal range is needed for (defense/security or AI applications). These recommendations are based on both theory and field experience with commercially available lenses.

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