White Paper

Long Wave Imaging with Cooled and Uncooled Sensors

LYNRED®

See Beyond Horizons

Long Wave Imaging with Cooled and Uncooled Sensors

LYNRED's application lab

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Table of Contents

Glossary

BoM	Bill of Materials
CNR	Contrast-to-Noise Ratio
DRI	Detection Recognition Identification
EFL	Effective Focal Length (expressed in mm)
FoV	Field of View
FPA	Focal Plane Array
IDCA	Integrated Dewar Cooled Assembly
IFoV	Instantaneous FoV
ITR	Integration Then Reading
LWIR	Long-Wave IR (8 – 14 µm)
MCT	Mercury Cadmium Telluride, HgCdTe
NETD	Noise Equivalent Temperature Difference (expressed in mK)
RH	Relative Humidity
SWaP	Size Weight and Power
SXGA	Super eXtended Graphics Array (1280 × 1024)
TCO	Total Cost of Ownership
VGA	Video Graphics Array (640 × 480 or 640 × 512)

Abstract

Cooled or uncooled - What image sensor should I choose for thermal imaging in the long wave infrared (LWIR)? The answer to this question usually come naturally after properly defining the main operational constraints and tradeoffs for your usecase. This white paper discusses the key differences between the two types of sensors such as resolution, field of view, sensitivity, speed, SWaP, reliability etc... All those characteristics are discussed together with field examples in a various set of weather conditions, target distances and objective lenses. Understanding these characteristics at the system level is crucial to have the best-suited sensor for your application needs.

Chapter 1. Introduction

The LWIR (Long Wave InfraRed) is the waveband typically defined by the 8 – 14 µm wavelength range. It corresponds to a transparency band of the atmosphere where one can detect the most amount of emitted thermal radiation by scene at typical temperatures. Because of strong atmospheric attenuation above 12 µm, LWIR tele-objective lenses are commonly designed in the 8 – 12 µm range, hence the modified LWIR range definition

From the graph plotted in Figure 1.1, we see that the maximal contrast (red area) in the ambient to skin temperature ranges (20 – 35 °C) is found in the LWIR band.

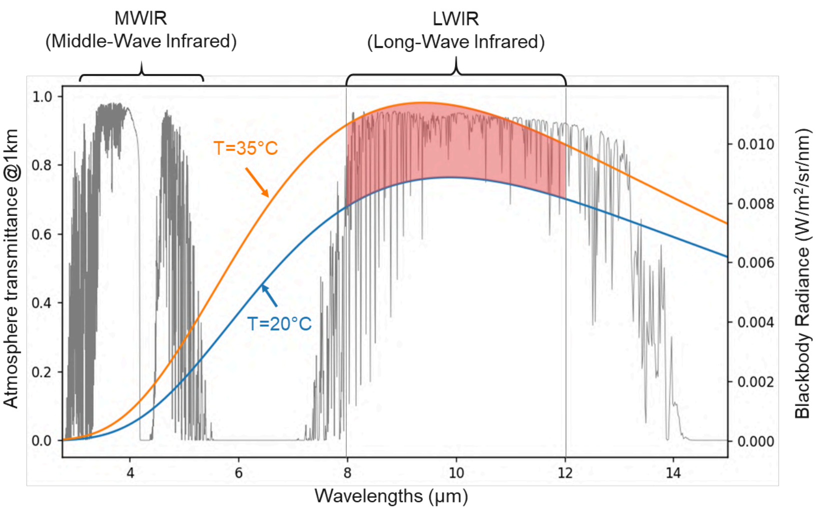

Figure 1.1. Blackbody radiance plotted alongside the atmosphere transmittance spectrum

The LWIR band is especially relevant in cold weather conditions, where the peak wavelength of emission is shifted toward longer wavelength. Compared with MWIR (Middle Wave Infrared: 3 – 5 µm), the LWIR band is also more resilient to blooming by hot objects and solar reflections; and has a better aerosol penetration (e.g. smoke, dust). This band is thus optimal for battlefield conditions or firefighting operations.

LYNRED offers two technologies for LWIR imaging, with cooled (SCORPIO LW) and uncooled (ATTO1280, PICO640S etc.) thermal image sensors, which rely on two different physical principles. In this white paper, we will describe the key characteristics of both sensor types and discuss the best-suited sensor based on the target application and operational conditions.

Figure 1.2. Uncooled (ATTO1280 & PICO640S) and cooled (SCORPIO LW) image sensors

We summarize some of the key characteristics of such sensors in the following table:

	ATTO1280–02	PICO640S	SCORPIO LW
Technology	Microbolometer	Microbolometer	MCT LWIR
Wavelength range	8 – 14 µm	8 – 14 µm	7.7 – 9.3 µm
Image format - pitch	1280 × 1024 – 12 µm	640 × 480 – 17 µm	640 × 512 – 15 µm
FPA operating temperature	-40 °C ; +85 °C	-40 °C ; +85 °C	80 K to 90 K
Cold stop aperture	N/A	N/A	f/2 ; f/2.24 ; f/2.7
NETD (spec / typical)	< 50 mK / 35 mK (f/1, 300 K, 30 Hz)	< 30 mK / 20 mK (f/1, 300 K, 30 Hz)	< 25 mK / 22 mK (f/2, 300 K, 210 Hz)
Framerate (full frame)	Up to 60 Hz	Up to 120 Hz	Up to 210 Hz

SCORPIO LW is a cooled VGA 640 × 512 – 15 µm pitch LWIR Focal Plane Array (FPA). It is a quantum (or photonic) sensor as it relies on the conversion of a photon to an electron by a photodiode. SCORPIO LW's photodiode is made from the HgCdTe (MCT, mercury cadmium telluride) semiconductor alloy, with its composition specifically tuned for sensitivity in the LWIR band (spectral cut-off at 9.3 µm with 50 % sensitivity).

The FPA operates at cryogenic temperatures (80 K to 90 K) in order to suppress the sensor's response to its own temperature (notably the dark current). Thus it is integrated into an IDCA (Integrated Dewar Cooled Assembly) which integrates a cooler (a rotary Stirling machine: RM3 or K508N) and a cold shield with a given aperture ranging from f/2 to f/2.7 (more on this later).

SCORPIO LW is by far the most sensitive thermal image sensor, and is the go-to solution to detect small thermal contrasts even through harsh weather conditions (such as winter fog, rain), cold objects or when ultra-short exposure time is required.

Micro-bolometer arrays technology was developed to provide a low-SWaP–C (Size Weight and Power – Cost) alternative for thermal imaging, by removing the need for a cooler or temperature stabilization device and by reducing manufacturing cost. Micro-bolometers detect temperature variations of pixels with a lower thermal sensitivity than cooled detectors, but is sufficient for many use cases. We will discuss ATTO1280, a high definition SXGA (1280 × 1024) uncooled sensor at the 12 µm pixel pitch well suited for high resolution and wide field of view (FoV); as well as PICO640S, a VGA (640 × 480) array with the most sensitive 17 µm pixel technology among uncooled sensors.

Choosing the correct sensor type might appear obvious, as it depends whether or not the main operational constraint is a need for high sensitivity/speed, or a need for low-SWaP–C. We will discuss this assumption and its limit by using practical examples from our field experience while taking a system's point of view by including considerations on the objective lens.

Chapter 2. General Principles

In this section, we will illustrate the general principles cited previously, comparing sensor types with practical examples in various conditions. For the moment, we will ignore the lens' considerations (notably its focal length and aperture), as it will be the topic for the next section.

2.1. Good Atmospheric Conditions

In clear weather conditions and at relatively short distances (typically 5 km or below), constraints on sensitivity are not critical and uncooled sensors usually do the job. In these conditions, one can benefit from ATTO1280's high definition to provide maximum details in a wide FoV. This is especially suited for monitoring large areas at reasonable distances.

In Figure 2.1, we show two image examples in good conditions captured with ATTO1280 and a 50 mm f/1.0 lens. The left figure is a view of Jourdan Plaza, Brussels (Belgium) by night with a zoomed view of a person at about 100 m, probably ordering French fries at this most famous place. Right figure is a view from the heights of Nazaré city (Portugal) with a zoomed view of three beach soccer players at about 710 m. Both examples show a sharp image with high level of identification and recognition confidence, respectively. These examples demonstrate the benefits of using a sensor with high definition such as ATTO1280 when monitoring large areas while ensuring a good number of pixels-on-target.

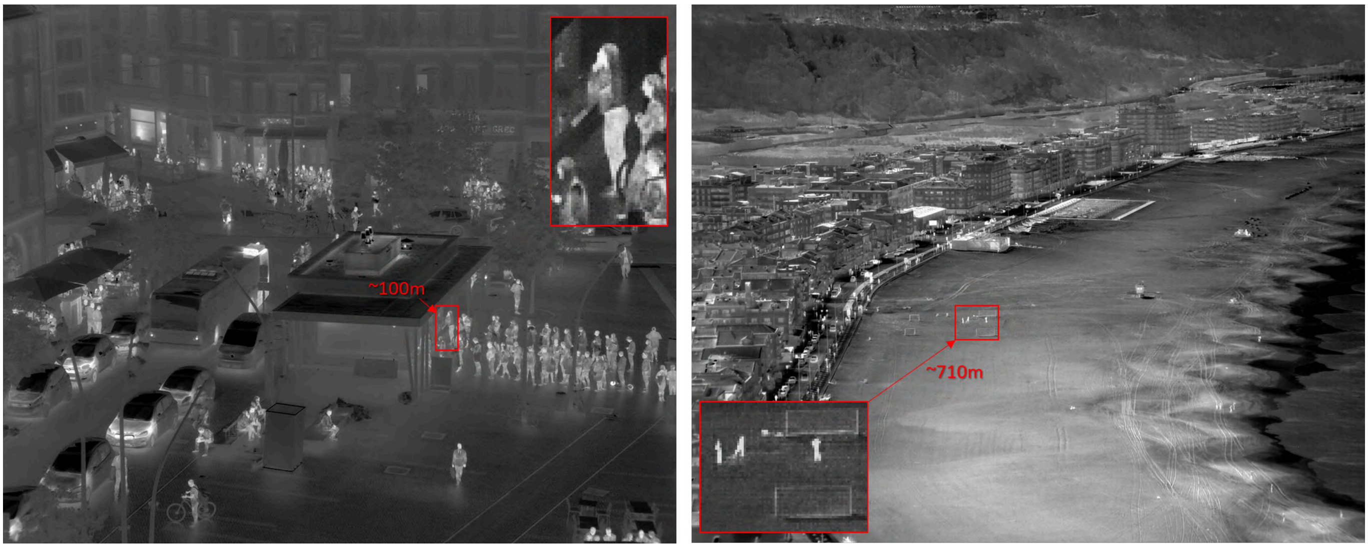

Figure 2.1. Image examples with ATTO1280 and a 50mm f/1 lens

With tele-objective lenses, uncooled cameras are also suited for distances above 1 km. In Figure 2.2, we provide two examples with ATTO1280 paired with a long 225 mm EFL lens. The left image is a night view of a cruise ship ("Norwegian Escape") docked at Marseille's port (France), at about 4 km. The right image of a heliport in a daylight snowy environment (Alpes d'Huez, France) at 2.5 km distance, with a zoomed view on the helicopter and probably its pilot. Both examples demonstrate that an uncooled camera can provide a very detailed view of targets above 1 km distance, with appropriate lens.

Conditions: Night
Distance: 4 km
18°C, 50%RH

Conditions: Day
Distance: 2.5 km
0°C, 67%RH

Figure 2.2. Images examples with ATTO1280 and a 225mm f/1.5 tele-objective lens

ⓘ Effective focal length (EFL) is an objective lens' characteristic that controls the optical magnification of the imaging system. For a given FPA, having a long EFL makes for both a narrow FoV, and a narrow IFoV (instantaneous FoV: object angle between the center of two adjacent pixels), which is required for long-range imaging.

Let us now compare ATTO1280 and SCORPIO LW with an identical EFL of 225 mm. ATTO1280's FPA is bigger than SCORPIO LW's by a factor ×1.6 (19.7 mm vs. 12.3 mm diagonal), which makes for a wider FoV by roughly the same factor. Moreover, the IFoV is smaller by 25 % due to the smaller pixel pitch (12 µm vs. 15 µm). Comparison with the same optical magnification is illustrated in Figure 2.3.

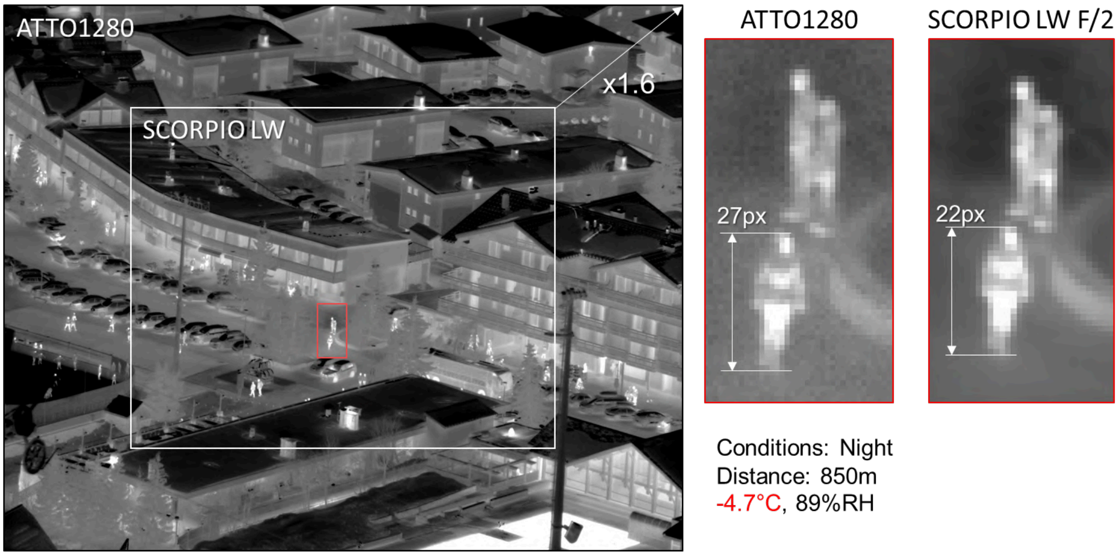

Figure 2.3. Comparative view of ATTO1280 and SCORPIO LW F/2 with the same 225 mm f/1.5 objective lens

The scene is a view of the Alpes d'Huez (France) ski resort at about 850 m distance at night during winter (-4.7 °C ambient temperature). The reduced FoV of the SCORPIO LW image is represented as a white rectangle on the ATTO1280 image. The zoomed view compares the same three pedestrians with both sensors. The SCORPIO LW image was captured with short 40 µs exposure time, and still provides a noise-free image even in such cold weather. The ATTO1280 (30 Hz) image still captures a good image with 25 % more pixels on target and acceptable noise level.

ⓘ In practice, we use the same zoom lens model 25 – 225 mm f/1.5 for both sensors even though such model is designed for uncooled sensors. One must know that pairing a lens for uncooled sensor, with a cooled one can generate vignette effects due to optical design incompatibility of the cold stop geometry. Thus, one can only conclude on the system's performance at the center of the image, where the imaging system aperture is limited to the f/2 cold stop.

2.2. Harsh Atmospheric Conditions

Wet atmospheric conditions, such as rain or fog can cause significant signal attenuation, especially in LWIR band due to absorption by water molecules. Long range imaging in such conditions usually disqualifies uncooled solutions due to its limited contrast to noise ratio (CNR).

Examples captured with SCORPIO LW in cold and wet conditions are shown in Figure 2.4. The scenes are views of incoming vessels at Le Havre harbor (France) during foggy weather at winter. The lens has a 225 mm EFL (stopped at f/2 by the IDCA's cold shield).

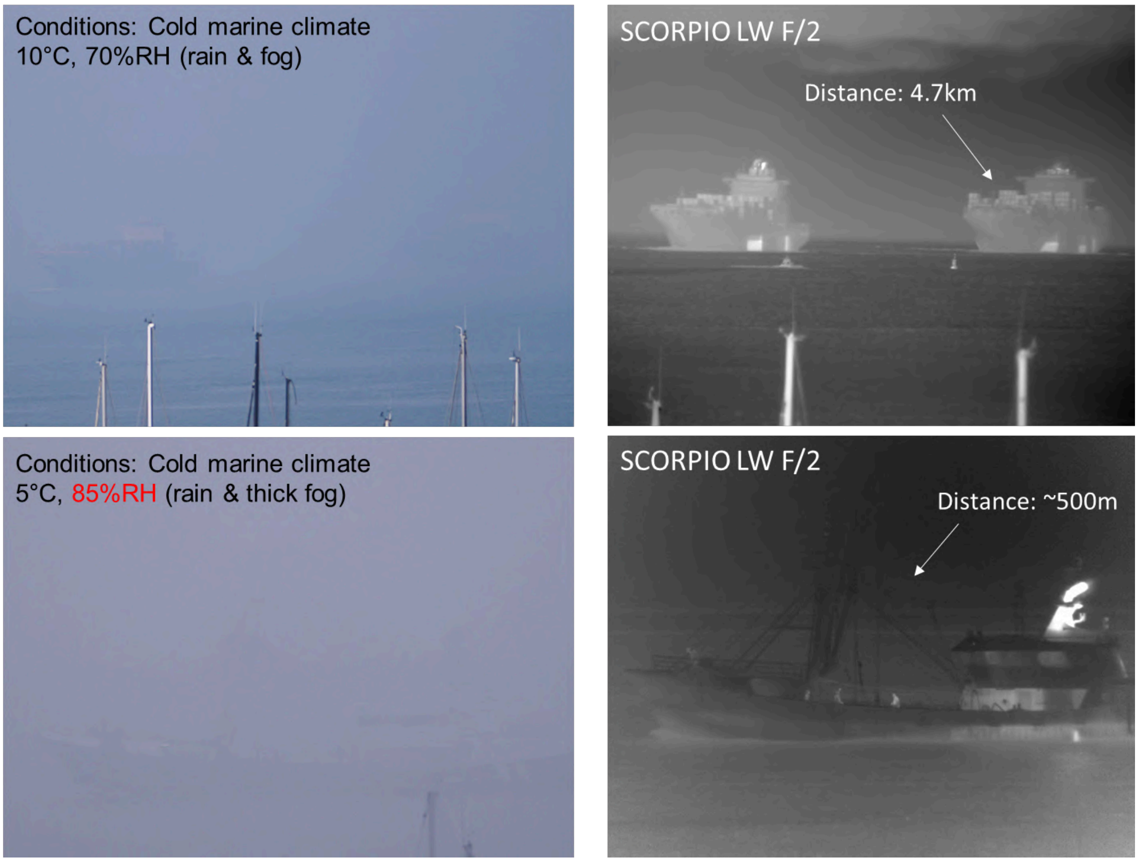

Figure 2.4. Visible and SCORPIO LW views in harsh weather marine conditions

The first scene shown in top compares the visible and LWIR images at the limit of the fog's visibility (< 5 km), and the second with a thicker fog (< 500 m visibility). In both cases, the SCORPIO LW images enable clear imaging through such a dense fog thanks to its great sensitivity, which compensates for the water attenuation, especially when looking at the hot engines. As we will see in the following, uncooled solutions are not suited for such conditions due to their reduced sensitivity.

> ⓘ To our experience, there is very few instances where SCORPIO LW lacked sensitivity, as one could always increase exposure time to more than acceptable levels, and/or take advantage or temporal noise reduction algorithms at higher framerates. From our own field experience, we recommend 800 µs exposure in ITR (Integrate Then Read) mode at 180 Hz framerate, with a 6–frames post-accumulation. This settings works in hot weather conditions without saturation.

2.3. Fast Moving Targets and Events

Micro-bolometers arrays technology enables thermal imaging by measuring the temperature of each pixel's micro-bolometer thermal plate. Response time is inherently limited by the thermal inertia of those elements (in other words, limited by the time it takes for the detector's pixels to heat up and cool down when looking at a fast moving hot object). Such response time is characterized as the time constant τ_{th}, which is about 12 ms for PICO640S. In the image, the uncooled sensor's inertia causes a motion-blur-like artefact.

As for the cooled sensor, the motion blur is reduced substantially thanks to ultra-short exposure times.

In **Figure 2.5**, we provide an example of cyclists in the Tour de France captured with both uncooled and cooled LWIR cameras. As expected, the PICO640S image is blurred as the result of the 12 ms thermal inertia of the micro-bolometer. The SCORPIO LW image is kept sharp, as the motion blur is kept within the pixel pitch thanks to the extremely short pixel exposure time.

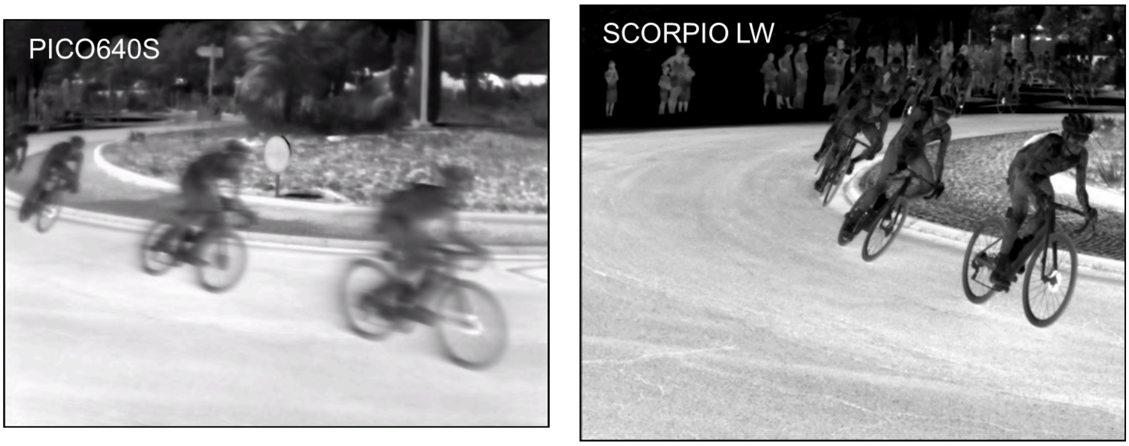

Figure 2.5. Motion blur comparison between PICO640S and SCORPIO LW

SCORPIO LW is far better suited for visualizing fast events or tracking moving targets as it can natively operate at a framerate of 210 Hz (full frame) in global shutter mode. This can notably unlock specific high-speed thermographic use cases.

Uncooled sensors such as PICO640S and ATTO1280 can operate at 120 Hz and 60 Hz respectively at full frame in rolling shutter mode. If a faster framerate is needed, one can take advantage of the windowing mode: for instance, ATTO1280 can run a framerate of 240 Hz when windowed at 320 × 240. Note that, faster framerate doesn't influence the micro-bolometer thermal response time but better temporal sampling can be relevant for tracking of de-blurring algorithms.

Chapter 3. Comparisons at System Level

The previous sections have compared both sensor types to state general principles on FoV, definition, sensitivity and speed. However, we did so without taking into consideration the objective lens paired with. This may lead to false conclusions, especially with low-SWaP constraints at a system level.

3.1. System Description and Methodology

The exceptionally high sensitivity of the SCORPIO LW enables the use of 'slower' optics compatibles with cold shield apertures of f/2, f/2.24 and f/2.7. In comparison, uncooled sensors require much faster optics to compensate for the higher NETD: 12 µm ATTO sensors are typically paired with lens apertures ranging from f/1.0 to f/1.5.

> ⓘ F-number (denoted f/#) characterizes the solid angle of the focused light beam at the image side. It is sometimes approximated as the ratio between the lens' EFL and its entrance pupil diameter. It characterizes notably the amount of light the optical system is able to collect within the solid angle. Thus 'fast optics' (with low f/#) increase system sensitivity, notably by increasing the overall size and complexity of the lens (for a given EFL). Large LWIR lenses made from Germanium elements may suffer from supply crisis, increased material cost, and extended delivery time. Note that, cooled sensors have an integrated cold stop to reduce stray light. One must ensure that the lens' aperture is compatible with the cold stop aperture. Lens aperture does have an effect on image sharpness, in accordance to the diffraction limit. This effect is not discussed here, but more details can be found in our other white paper.

At a system level, different balance between the objective lens and the sensor can be found, in terms of overall weight and complexity. For instance, Figure 3.1 shows a side-by-side photograph of two long-range setups that use ATTO1280 and SCORPIO LW with commercially available objective lenses at their respective upper f/# limits. Both systems are comparable in terms of TCO (total cost of ownership), as the larger lens becomes a significant part (if not the most) of the bill of materials (BoM).

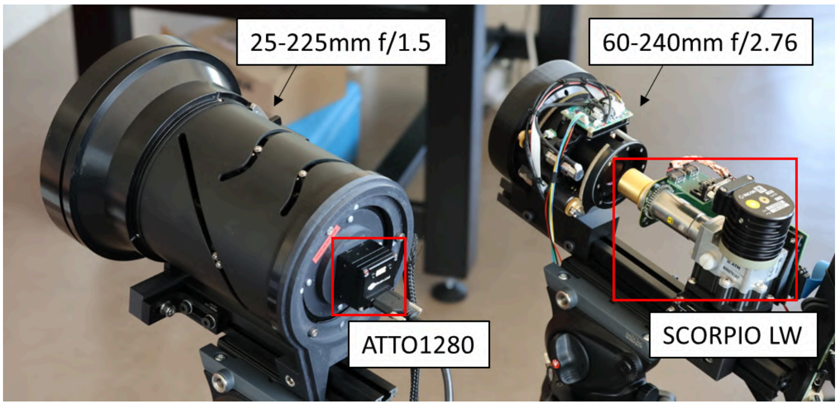

Figure 3.1. Side-by-side comparison of long-range setups using ATTO1280 and SCORPIO LW

The striking difference between the two systems is the balance in size between the objective lens and the sensor. The uncooled system pairs a bulky objective lens with a very compact camera core. Inversely, the cooled system has a relatively compact objective lens but the IDCA is much larger, both lengthwise and alongside the rotor's cooler.

In one hand, ATTO1280 is paired with the "SupIR" 25 – 225 mm f/1.5 continuous zoom lens from MKS/Ophir (referred to as system (a)). In the other hand, SCORPIO LW F/2.7 is paired with the "Jasper" 60 – 240 mm f/2.76 continuous zoom lens from RP optical lab (referred to as system (b)). In their narrow FoV position, both systems have a comparable IFoV of 53.3 µrad and 62.5 µrad for the ATTO1280 and SCORPIO LW systems respectively.

The NETD at system level (sensor and lens) was measured at 152 mK (60 Hz, 30.5 µs integration time) with the uncooled camera (system (a)), and 30 mK (60 Hz, 800 µs exposure) with the cooled camera (system (b)). We expect a native advantage of ×5 in terms of Contrast-to-Noise Ratio (CNR) in favor of the cooled system. Although SCORPIO LW could further increase exposure time or enable temporal denoising if needed.

System characteristics are summarized in the table below:

	(a) Uncooled	(b) Cooled
Sensor	ATTO1280-02	SCORPIO LW F2.7
Image format – pitch	1280 × 1024 – 12 µm	640 × 512 – 15 µm
Lens EFL; f/#	225 mm f/1.5	240 mm f/2.76
FoV (H × V)	3.9° × 3.1°	2.2° × 1.8°
IFoV	53.3 µrad	62.5 µrad
Camera NETD @ 60Hz	152 mK (30.5 µs integration)	30 mK (800 µs exposure)

In the next paragraph, we compare both systems by showing side-by-side views, in a selection of various scenes at different distances and conditions. For better comparison, images are presented from snapshots with minimal post-processing, and without de-noising process. Zoomed view may be presented tone-mapping-adapted to the region of interest.

3.2. System Comparison in Hot and Dry Weather

We first look at urban scenery from a bird's eye view. Weather conditions are dry, hot summer day (~30 °C ambient temperature, 40 % RH). In these conditions, thermal contrast to the scene is optimal, due to sun's heating; there is good atmospheric transmission thanks to the low humidity.

Figure 3.2 is a comparative short distance view of a supermarket parking lot at 1.5 km. We can recognize a human and identify a small vehicle is the region of interest (red box).

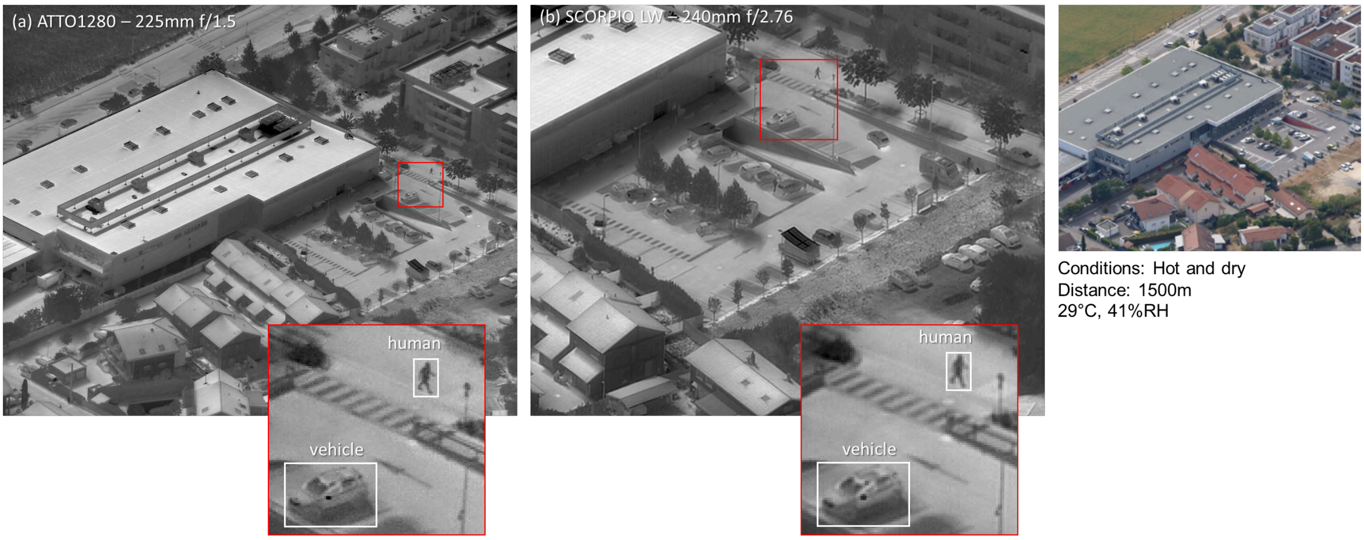

Figure 3.2. Supermarket parking at 1.5 km

Both systems have great contrast to noise ratio (CNR) due to these very favorable conditions. In a pure image assessment, there is little benefits for having SCORPIO LW's improved thermal sensitivity over ATTO1280. Moreover, ATTO1280's system (a) benefits from a slightly finer object space resolution, while having a wider FoV. Note that, in these hot summer conditions, the asphalt road is hotter than the pedestrian is, thus leading to contrast inversion (pedestrian appears darker than the road in the white-hot representation).

Figure 3.3 is a comparative view at a longer 5.9 km distance. The scene is a dam bridge, which crosses the Isère river. A large vehicle (a bus) is recognized equality with both systems without contrast limitations.

Figure 3.3. Large vehicle crossing a dam bridge at 5.9 km

Both systems have comparable spatial resolution in object space. In such favorable conditions, we argue that the uncooled system is able to match the range capabilities of the cooled system thanks to a large and expensive lens. However, the uncooled system has a higher NETD by a factor ×5, which can be limiting in harder weather conditions, such as rain (as we will see in the next section).

3.3. Systems Comparison in Wet Weather

The same systems are now compared in wet conditions (light rain, relative humidity (RH) from 57 % to 63 %), temperate (ambient temperature from 23.3 °C to 25.6 °C), rural settings.

Example presented in Figure 3.4 shows recognition of both a human and a small vehicle at 2.1 km distance. Again, we observe similar resolution on both systems. The contrast is reduced at this distance, notably due to the light rain. This effect becomes noticeable, especially with the uncooled system, which exhibits lower CNR.

Figure 3.4. Recognition of a human and vehicle at 2.1 km

The last example, presented in Figure 3.5 shows a scene with different depths and rain afar. In one hand, the ATTO1280 image (a) illustrates the loss of contrast with increasing distance, especially when comparing clear foreground objects (houses) with a washed out background. In the other hand, the SCORPIO LW image (b) is able to provide a clear view through the entire scene depth toward the background pine trees.

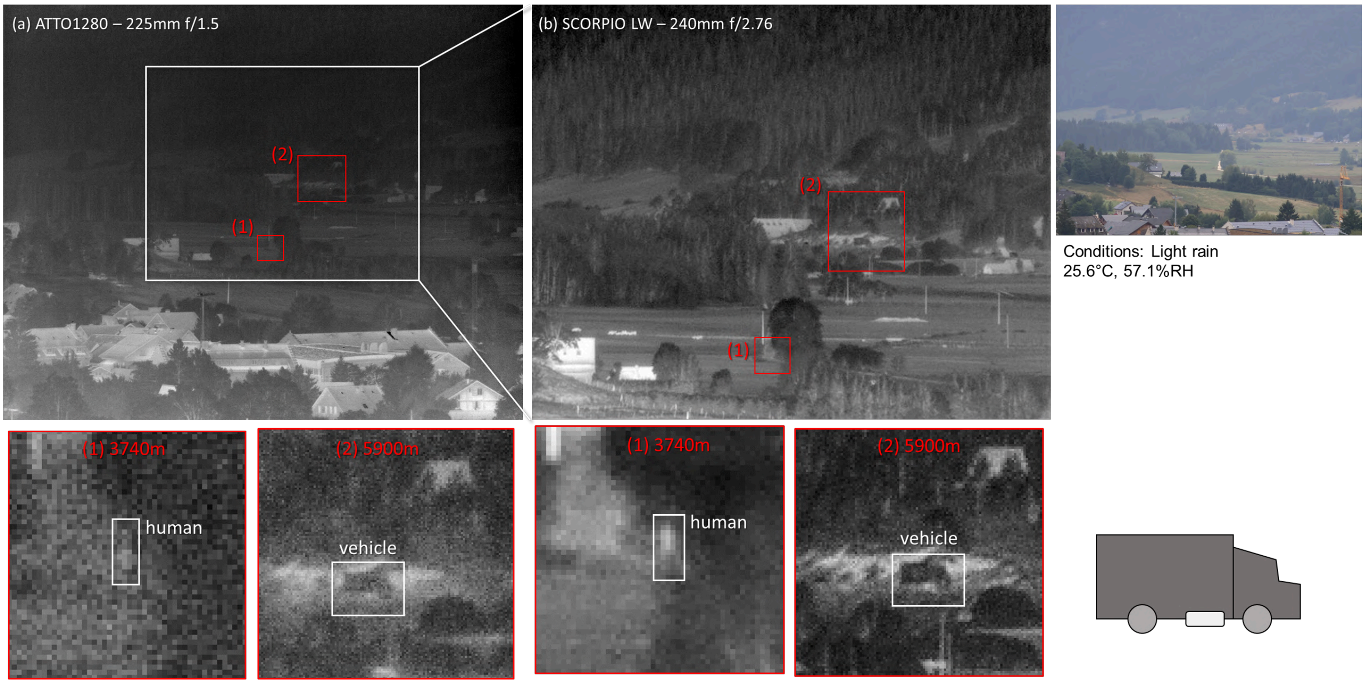

Figure 3.5. Detection of a human at 3.7 km and recognition of a vehicle at 5.9 km

We can evaluate contrast-limited situation: the detection of a human at 3.7 km and the recognition of a large vehicle at 5.9 km, at the same distance than in **Figure 3.3**. Perception is much easier on a video sequence (with target movement), than on a snapshot image, that is why we have redrawn the vehicle for indication. For both targets, the DRI performances of uncooled system are limited by sensitivity, which may greatly reduce the mission's probability of success. We recall that image are presented as snapshots without denoising. The ATTO1280 image can be further improved with advanced post-processing, but this is out of the scope of this paper.

These examples illustrate the benefits of the high sensitivity provided by SCORPIO LW over ATTO1280. This high sensitivity optimizes DRI range performances in wet conditions, even with a much more compact objective lens.

Conclusion

In this white paper, we have discussed the key differences between cooled (SCORPIO LW) and uncooled (ATTO1280, PICO640S) LWIR image sensors, together with field image examples in various conditions. Based on general principles and our own experience, we conclude on the benefits and limits of each sensors types.

Co-existence of both sensor types enables different trade-offs, which of course depends on the final use-case. Thus, one must carefully specify the required performances, and ask the following question: What does matter the most for the application: pure electro-optical performances (range of DRI: detection/recognition/identification, and under which climate), Field of view, SWaP, reliability, TCO (total cost of ownership)?

Thermal sensitivity: In one hand, cooled sensors such as SCORPIO LW benefit from exceptional thermal sensitivity, which allows capturing the smallest possible thermal contrasts from a scene. It is the only viable solution in harsh conditions such as wet weather, as tested through thick marine fog. In the other hand, uncooled sensors are still able to provide great images in good conditions (dry weather, short distances of typically > 1 km, good thermal contrast). When fitted with appropriate tele-objective lenses, we demonstrate that uncooled sensors remains relevant even at longer distances (up to 6 km), but with higher NETD (×5).

Resolution and FoV: High definition image sensors such as ATTO1280's SXGA image format provide both a good resolution and a wide FoV, which is ideal to monitor large areas at short range.

Speed: Looking at fast events or moving targets, SCORPIO LW is an obvious choice. Indeed, it can operate at high framerate (up to 210 Hz) in global shutter mode with ultra-short exposure time (< 100 µs). In opposition, uncooled micro-bolometers operate in rolling shutter mode, and the main limiting factor is the micro-bolometer's thermal response time (typically 10 – 12 ms), which generates a motion blur like artefact.

DRI with SWaP constraints: If one compares cooled and uncooled sensors alone, we may conclude that uncooled sensors are the best SWaP-C solution and this may be true for most setups. However, when considering narrow FoV setups designed for DRI range optimization, one must consider the system as a whole, including both the lens and the sensor. Indeed, SCORPIO LW benefits from having a slow aperture such as f/2.7 enabling much more compact objective lens, for a given focal length. As a corollary, the cooled solution improves DRI range for a fixed lens' entrance pupil diameter. This is why cooled solutions are preferred for DRI range optimization with SWaP constraints, such as those required in vehicle-mounted systems.

DRI without SWaPconstraints: Sometimes, the SWaP constraint is not critical, as it is the case for fixed, mast-mounted surveillance systems. In such cases, it can be relevant to consider a much simpler uncooled sensor paired with a bigger, faster but more expensive lens. However, such an uncooled system might be limited by poor contrast-to-noise ratio (CNR), especially in wet weather conditions.

Reliability: As the name indicates, the two sensor types differ by the presence (or lack thereof) of a cooling engine, that has moving parts. Superior reliability of uncooled systems are a bonus for 24/7 continuous operations, especially where maintenance operations are costly.

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LYNRED HEADQUARTERS
DEVELOPMENT & PRODUCTION CENTER
Actipole - CS 10021 - 364, route de Valence
38113 Veurey-Voroize - France

www.lynred.com