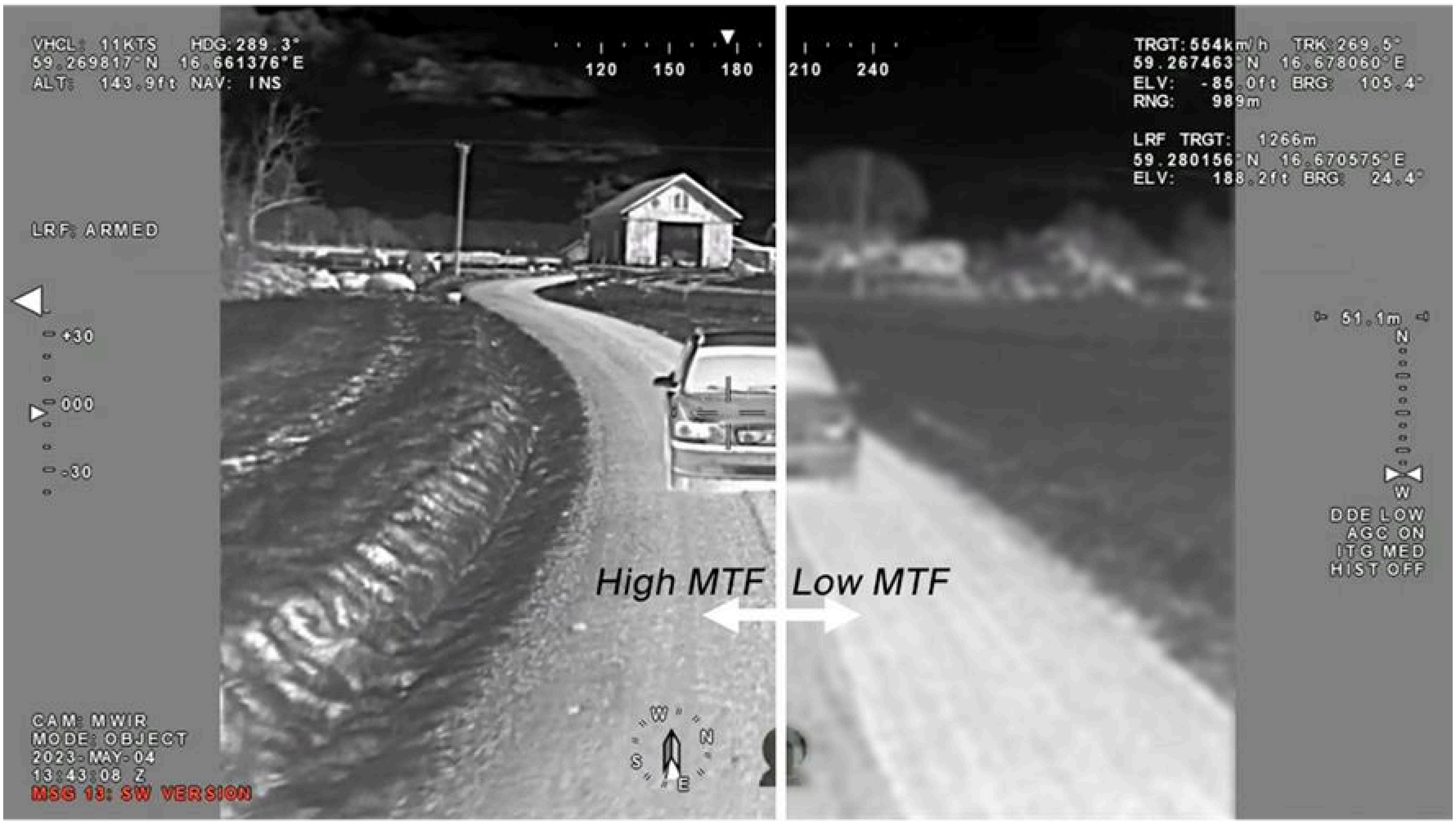
Modulation transfer function - MTF

T2SL detectors for ultimate infrared resolution

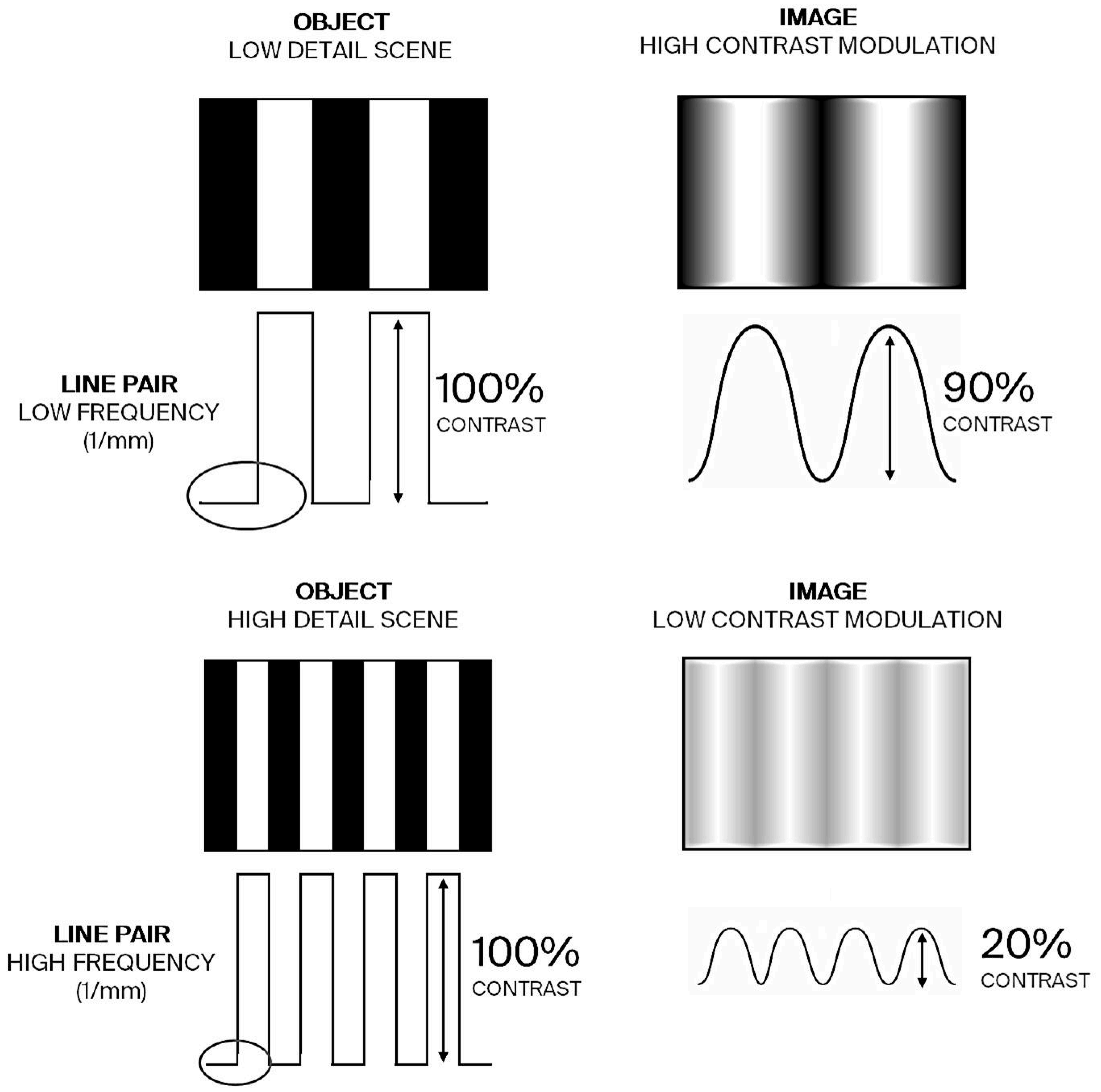


What is the MTF of a detector?

An imaging system should reproduce a scene preserving both the detail and contrast.

The system's ability to distinguish fine details is the resolution. It is usually expressed as spatial frequency in line pairs per millimeter, where one line pair consists of one bright line and one dark line. Contrast describes how well the intensity difference between bright and dark regions is preserved.

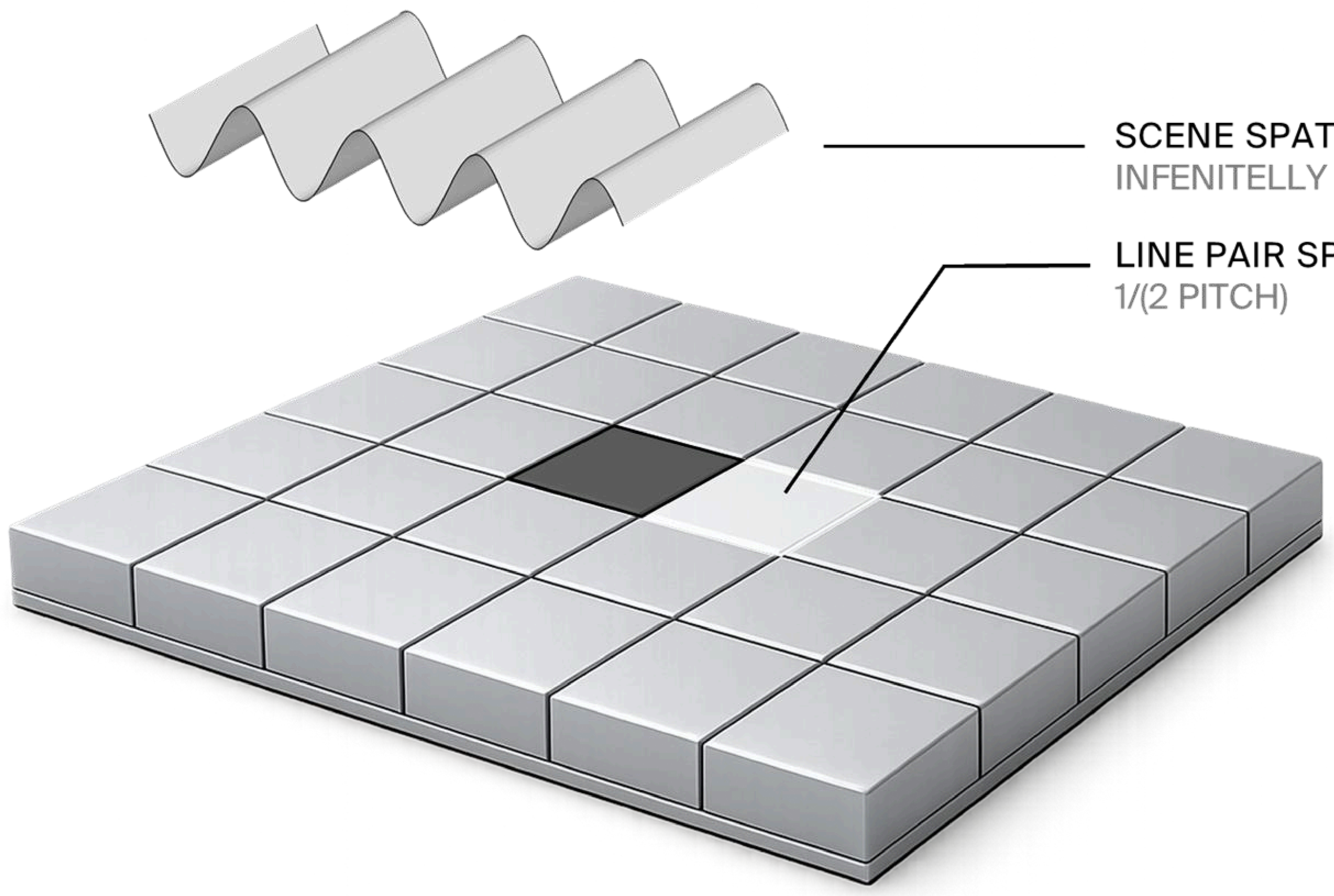
In thermal imaging systems, sensitivity is described by the NETD and sets the minimum contrast that can be detected in the scene. This value sets the ultimate thermal contrast at zero spatial frequencies. However, in practice even in systems with minimal blurring finer details are reproduced with reduced contrasts.

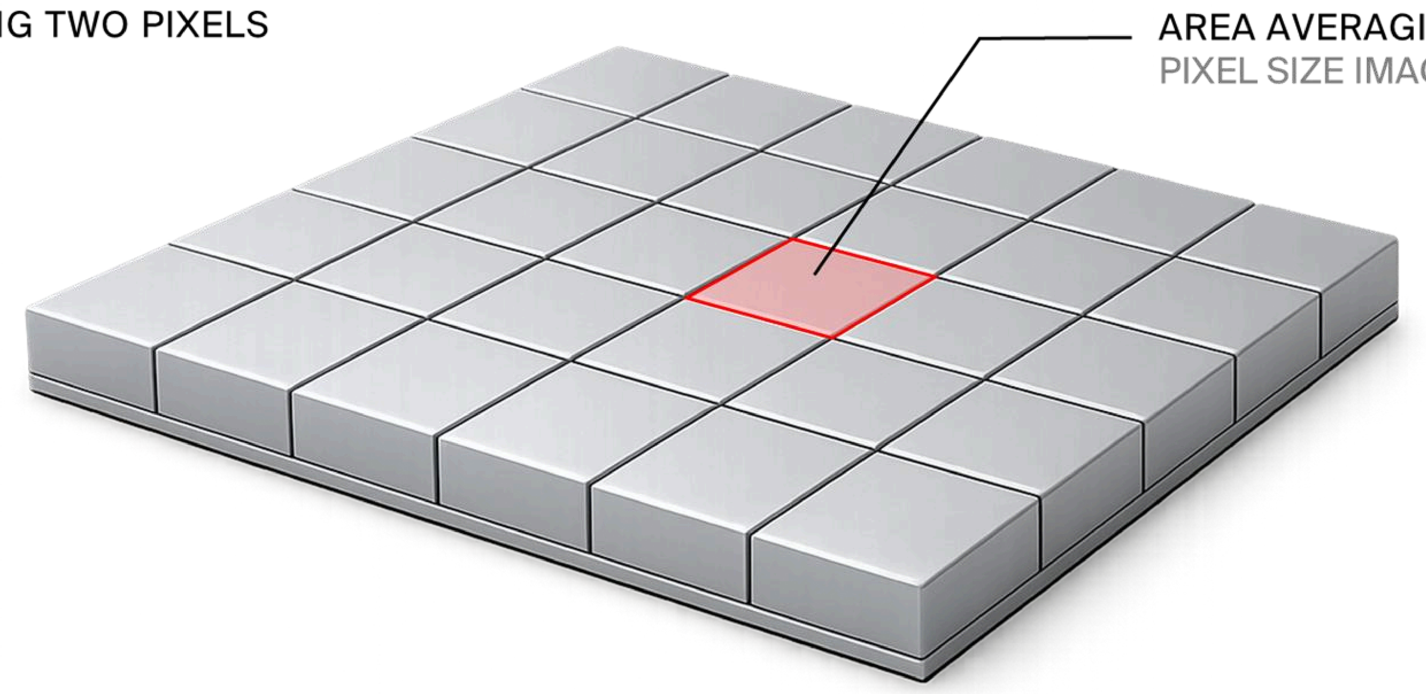


The ability of a system to preserve contrast as detail becomes finer is described by the modulation transfer function (MTF). This function gives contrast at each spatial frequency.

The MTF of a system is determined by the full imaging chain, including the optics, detector, motion, and electronics. Within this chain, the detector is especially important because it is the last stage before light is converted into an electrical signal. Signal spreading at this stage (interpixel crosstalk) can therefore limit the resolution of the full system.

The image on a detector is not recorded continuously. The scene is sampled to the pixel-to-pixel distance (pitch) and each pixel measures the signal over its area. This introduces two fundamental limitations.



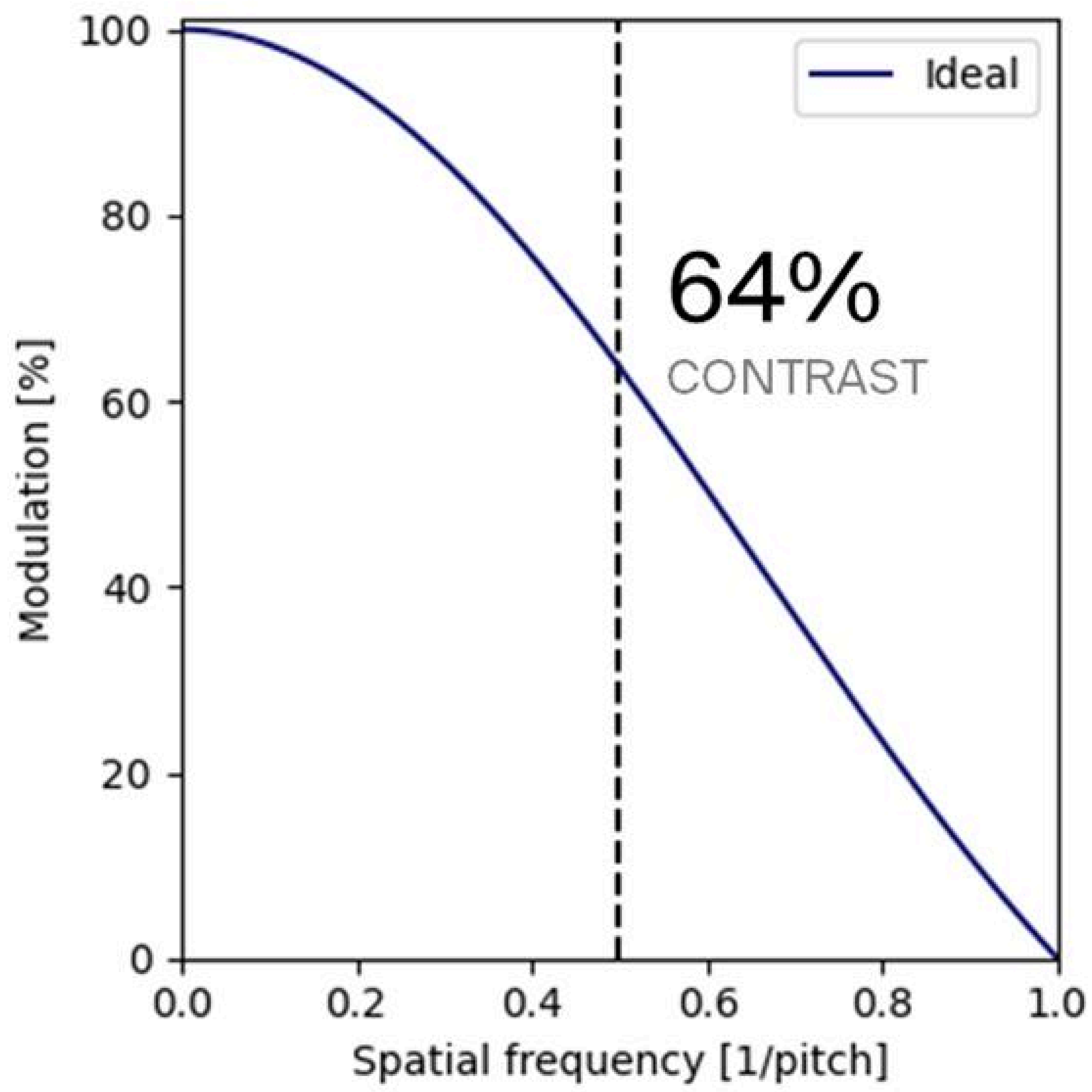


1. The pixel pitch sets the highest spatial frequency that can be sampled. This is the Nyquist frequency, It corresponds to one line pair over two pixels and defines the finest pattern that can be resolved without ambiguity.

2. An infinitely small point is not recorded as an infinitely small point, it is imaged as one pixel instead. This averaging over an area reduces the contrast of fine details. This makes that even an ideal detector with no interpixel crosstalk will have decreasing MTF with increasing spatial frequency.

The figure below shows the MTF of an ideal detector, normalized to pixel pitch. Even in the ideal case (no crosstalk), the contrast at the Nyquist frequency is limited to 64%.

Extending performance to finer spatial frequencies requires pushing the Nyquist frequency higher with smaller pitch. But in practice this depends on the array structure as the detector can move away from the ideal behaviour as the pixels are reduced.



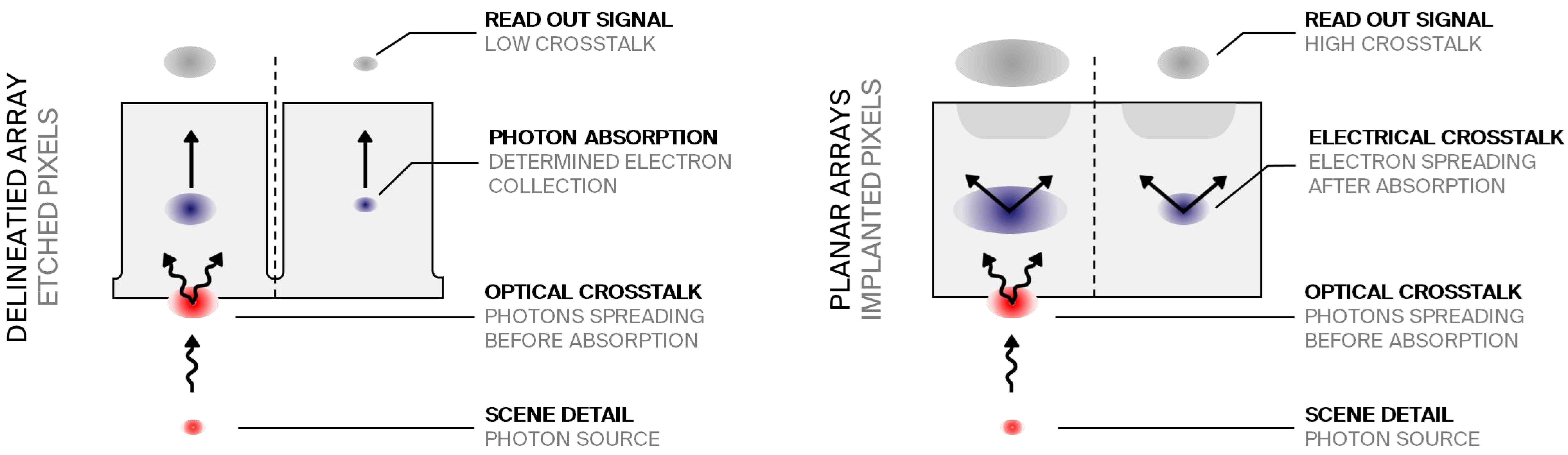
How does the detector structure impact the MTF?

The detector structure affects the MTF through two factors: pixel pitch and pixel architecture.

The pixel pitch directly sets the Nyquist frequency, 1/(2p), and therefore the highest spatial frequency that can be sampled. For example, reducing the pitch from 15 µm to 10 µm of a 640 × 512 sensor, would increase the detector bandwidth reproducing scenes with higher resolution with the same image format.

But a smaller pitch does not automatically mean better MTF. If the pitch is reduced and the interpixel crosstalk increases (which is typically the case), the benefit can be partly lost. The detector may sample finer detail, but it will not preserve its contrast as well. This is where the pixel architecture becomes important.

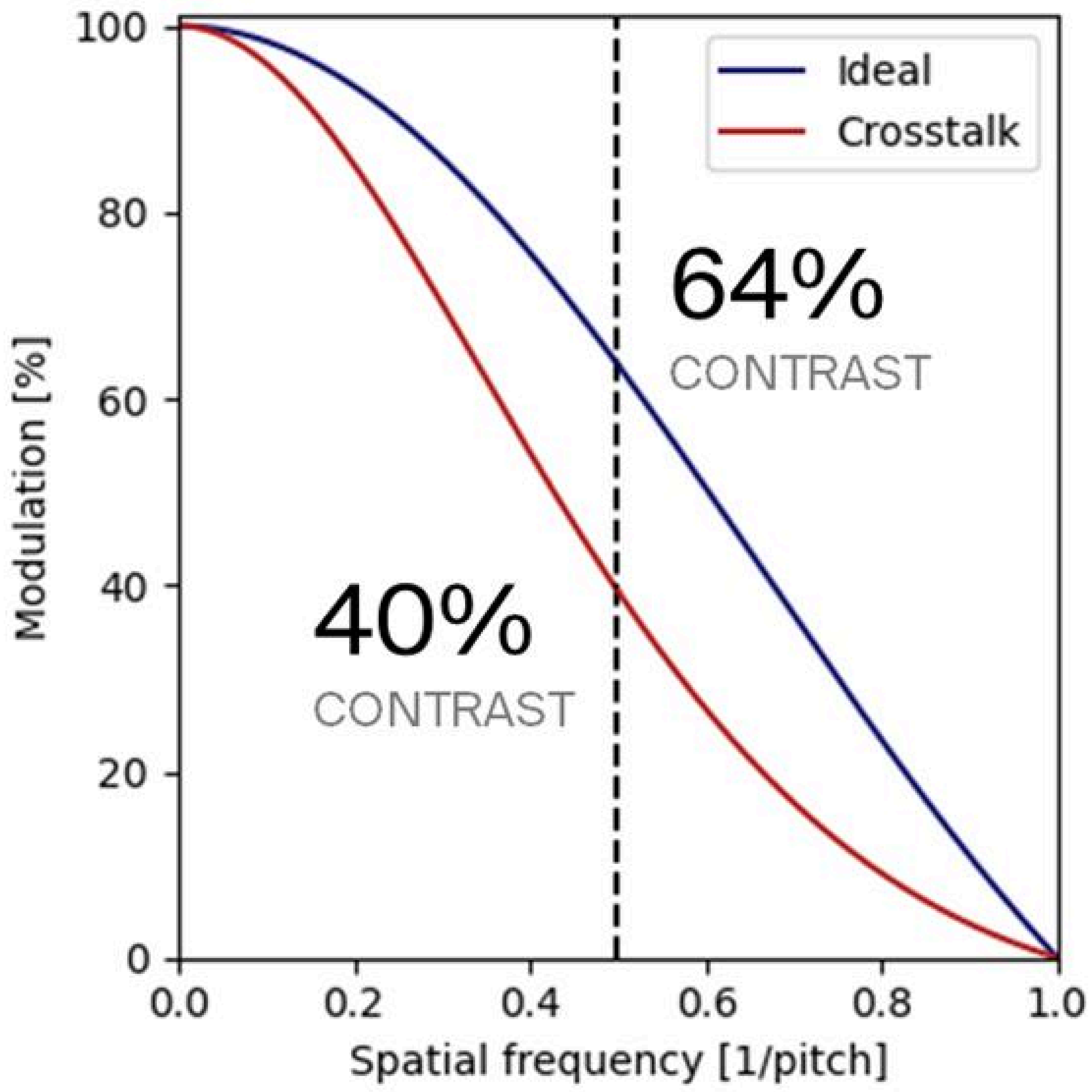
Fundamentally, detector structures can be divided into two groups: arrays in which pixels share part of the absorber, and arrays in which pixels are fully isolated from each other. In shared-absorber structures, the pixel that will carry the signal from the scene is assigned in the charge collection. While in isolated structures, the pixel is determined already at the absorption stage.



These two groups have different crosstalk mechanisms. A clear illustration of such difference is in the comparison between planar pixels and fully delineated pixels. In planar structures, the pixels are defined by implantation, so the absorber remains continuous. In fully delineated structures, the pixels are physically etched and isolated from each other in three dimensions.

As a result, planar arrays are sensitive to both optical and electrical crosstalk, while fully delineated structures limit the signal spreading between neighbours to only optical.

Less crosstalk means higher MTF. The figure below shows an MTF comparison of an ideal detector and a detector with 25% crosstalk between pixels. The figure show that signal spreading between the pixel reduces the maximum modulation from 64% to 40%.



Why does high detector MTF matter at the system level?

The MTF is a system-level measure of image quality. A detector with higher MTF preserves more detail and contrast, improving the image seen by the operator or the processing software.

Despite not being an end-user metric, it has a clear quantitative impact on metrics that are. Below three examples illustrate its impact:

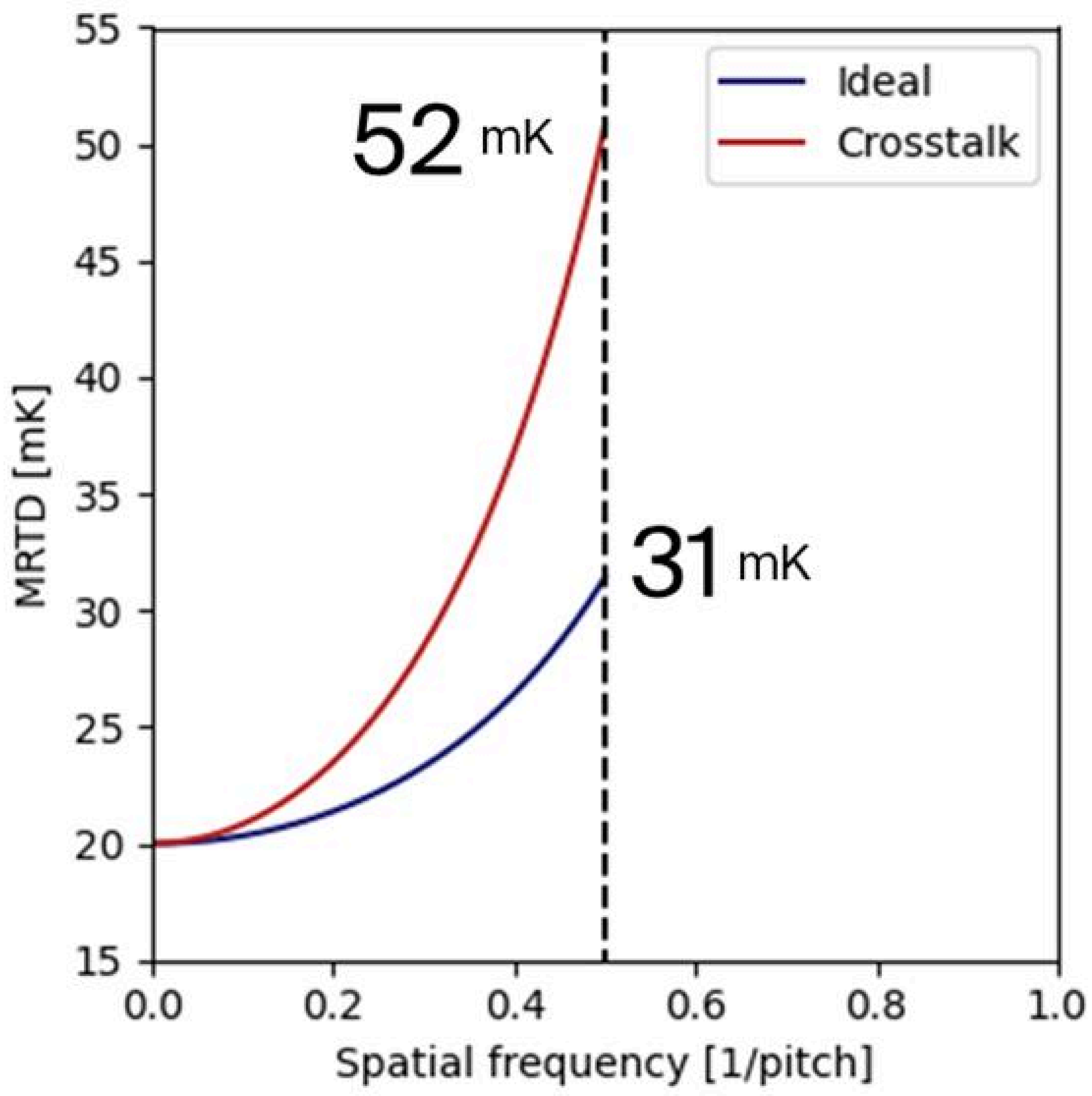
Lower MRTD

One important performance indicator for evaluating the end user perception of thermal detectors is the Minimum Resolvable Temperature Difference (MRTD). The lower the better.

$$MRTD \propto \frac{NETD}{MTF}$$

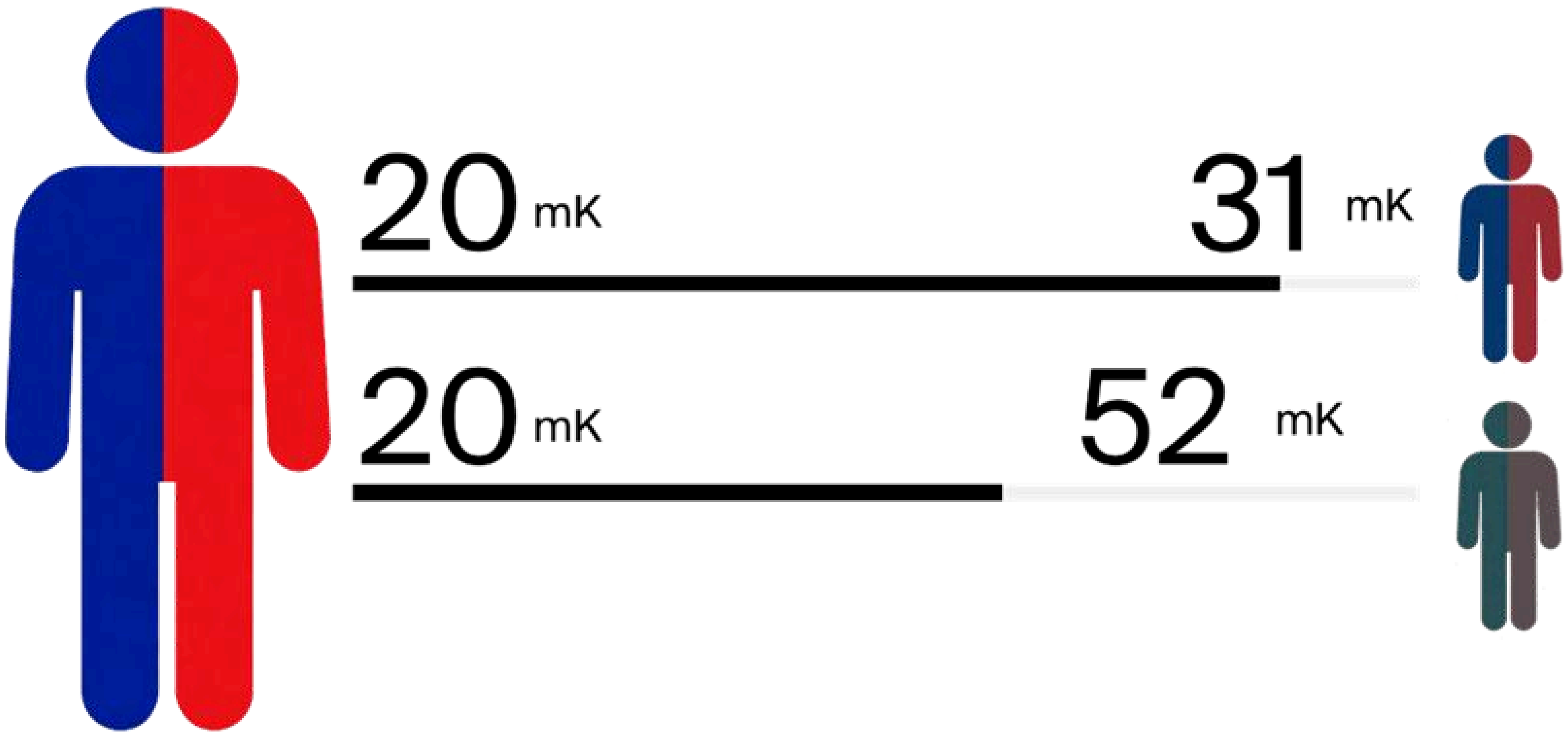
This metric combines the sensitivity and resolution, and it is proportional to the NETD divided by the MTF of the detector. This means that two identical systems, with the same NETD and pitch can result in different MRTD.

Assuming 20 mK maximum NETD and taking the ideal and crosstalk example:



The figure illustrates that at low spatial frequencies the end user would not see any difference. However for the finer details in the scene the higher crosstalk detector resolves the features with 52 mK and the ideal detector with 31 mK. This is a 67% degradation of the MRTD at Nyquist frequency.

These difference highlights that at system/operator level the performance is determined by NETD and MTF of the detector and not only the sensitivity towards big objects.



Longer DRI range

One of the main applications of thermal imaging in military systems is to detect, recognize and identify targets in complex environments. For this case, the longer range the better.

1. Detection (D) is defined as the ability to detect and object from the background
2. Recognition (R) is defined as the ability to classify the object class (animal, vehicle, human...)
3. Identification (I) is defined as the ability to describe the object in detail (a horse, a Jeep, a man with a coat...)

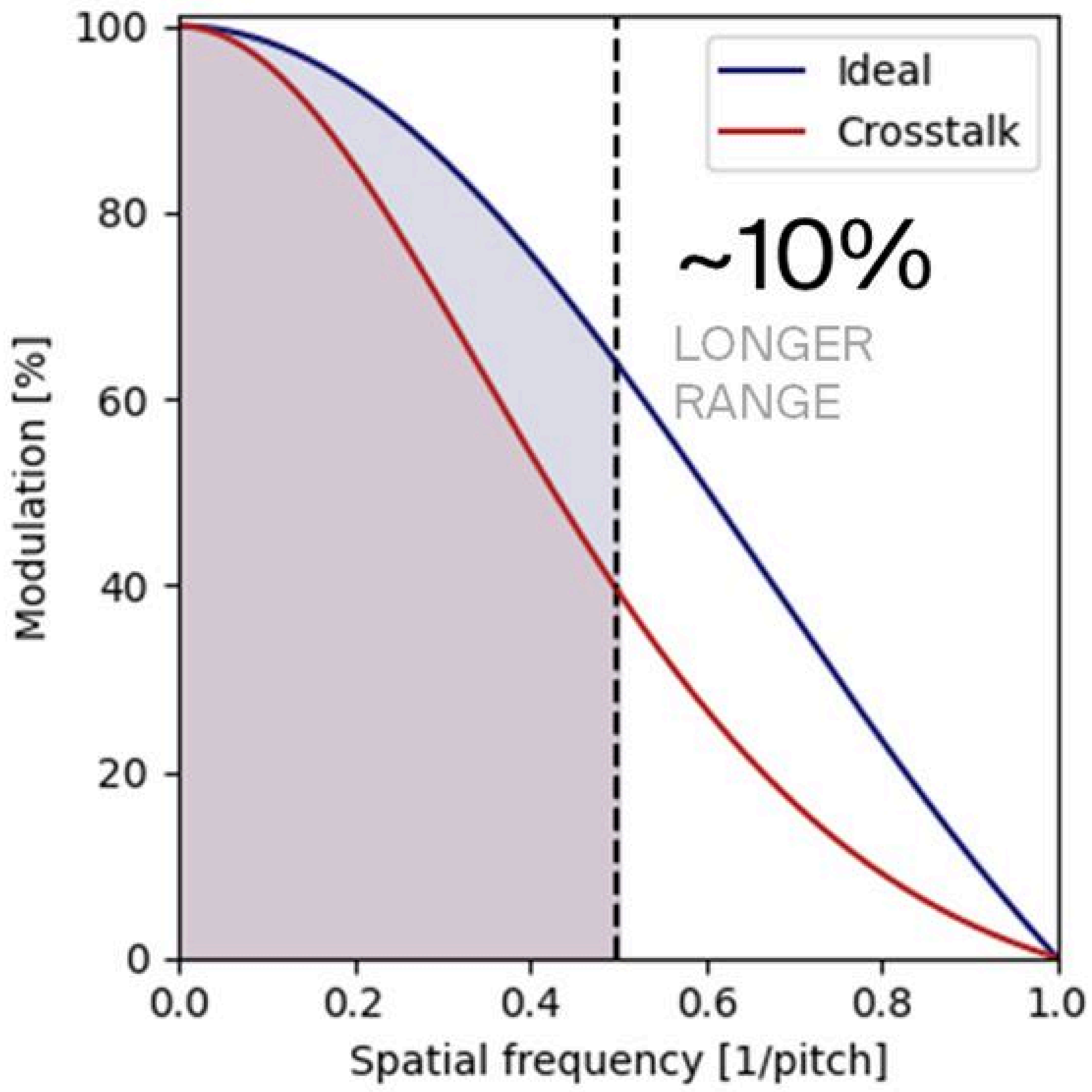
Maximization of such distance is very importance in military system design. Its calculation is complex since it must include all the different elements in the optical chain. Simulation of this parameter typically uses the Night vision integrated performance model from the US army night vision directorate.

In this model the detector contribution is expressed analytically as below:

$$Range \propto \int_{0}^{Nyq.frec} \sqrt{MTF_{Detector}(\nu)}\, d\nu$$

Which shows that a lower crosstalk and higher detector MTF will translate into a longer DRI range.

Following the comparison of the ideal and crosstalk detector, the integral factor contribution translates into a 10% improvement in the range for the ideal detector.



This difference at a system level that can yield into kilometers of advantage in DRI range.

Below is an example of the theoretical DRI performance targeting a 2.5 m vehicle using the ideal and crosstalk detectors. The calculation uses the Johnson criteria, assumes a MW system with an f/4 aperture, a 200 mm lens, perfect transmission and a ΔT=2K of the vehicle respect to the background.

IDENTIFICATION

3 600 m 3 900 m

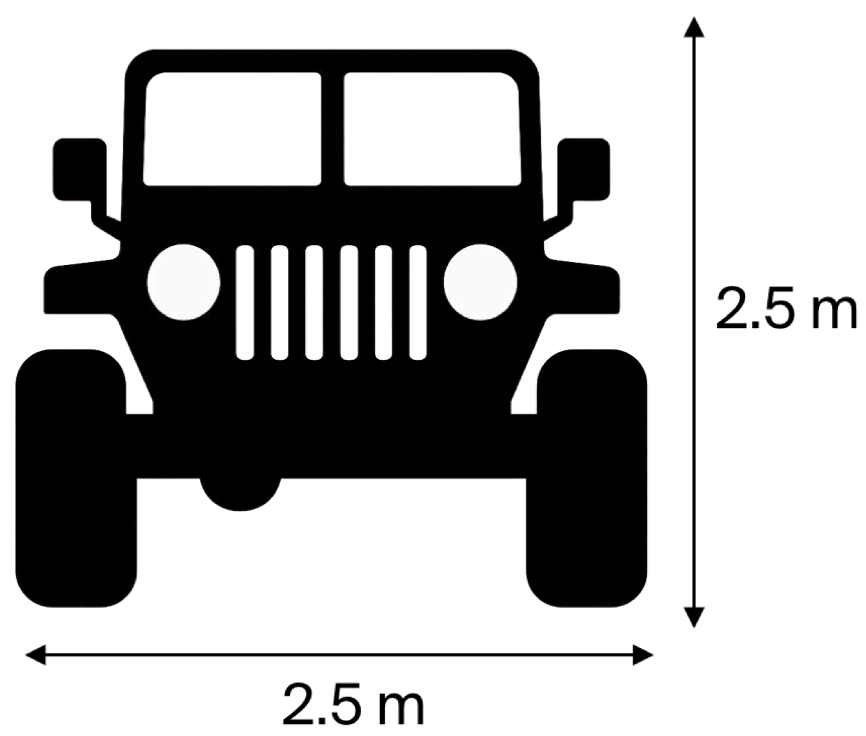
RECOGNITION

6 400 m 7 000 m

DETECTION

23 850 m 25 900 m

CROSSTALK IDEAL

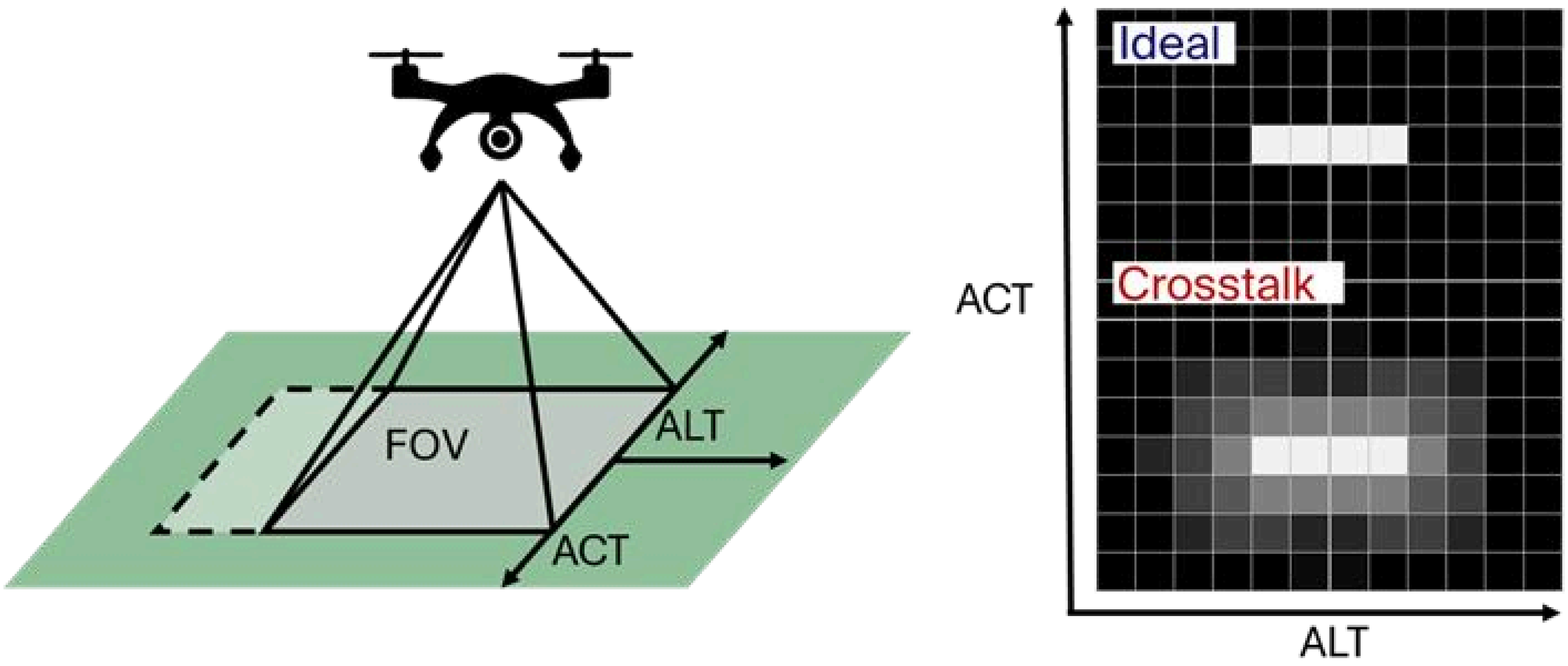


Reduced along-track blurring

In imaging systems on moving platforms such as satellites, drones, or helicopters, the motion along the flight direction causes along-track smearing, which reduces image sharpness.

This blurring is due to the movement of the field of view (FOV) during the integration time of the images. This effect requires balancing the platform speed, integration time, frame rate, and image resolution to optimize the system image quality.

In these cases, resolution is defined in two directions: along-track (ALT), along the flight direction, and across-track (ACT), perpendicular to it. ALT resolution is degraded by scene motion across the detector during the integration time, while ACT resolution is determined by the detector's spatial sampling, as in static imaging.

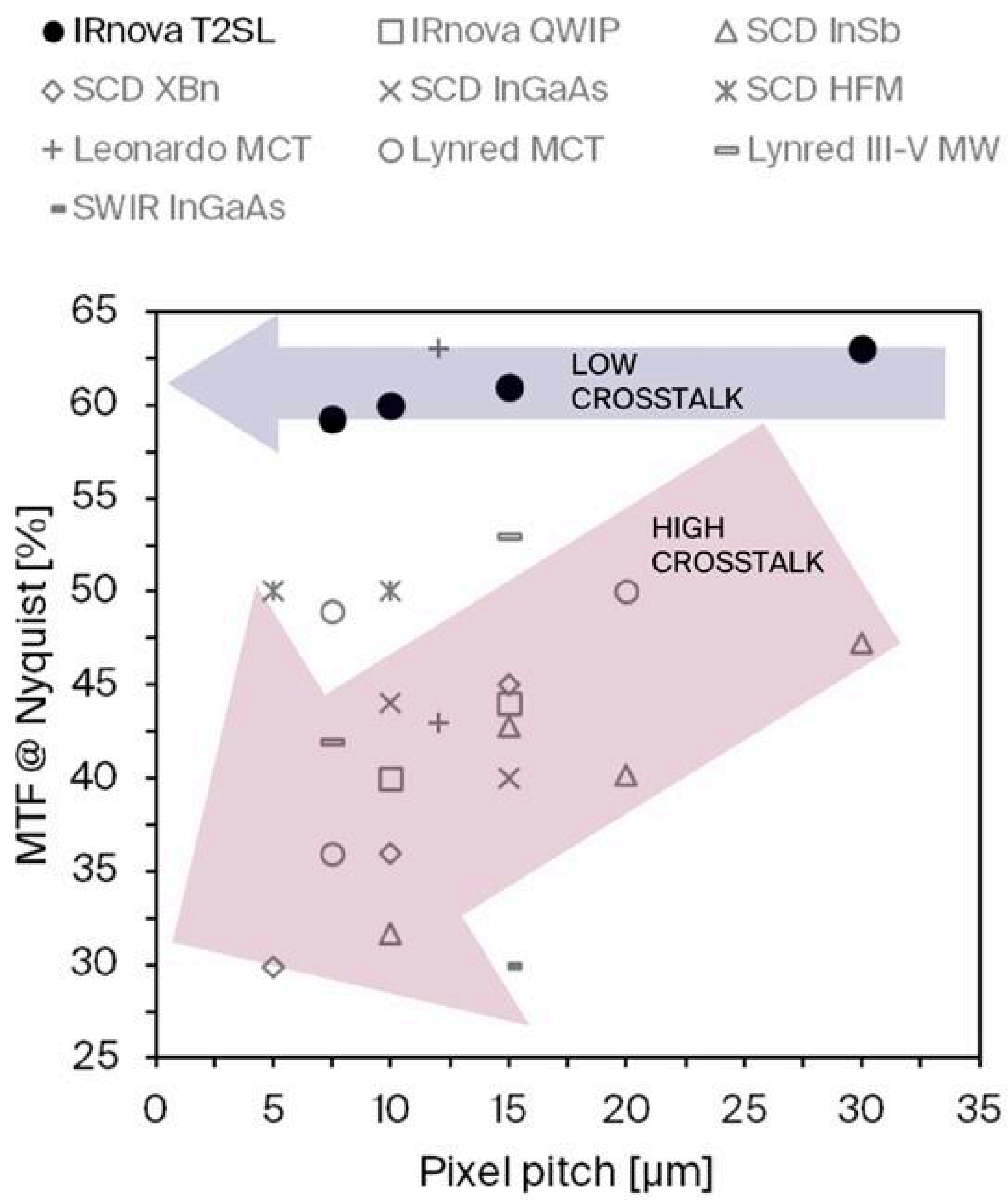


ALT smearing is inherent to the acquisition process. However, detector MTF remains important. Detectors with crosstalk suffer a double penalty: static blurring limiting the ACT resolution, with the motion further degrading the image through ALT smearing. A higher-MTF detector partially preserve image quality despite motion.

The example below compares a 4-pixel ALT smear for an ideal detector and a crosstalk-limited detector. The advantage at detector level translates directly into better imaging. Moreover, reduced smearing provides margin to increase integration time (improving sensitivity) and to operate at higher platform velocity.

IRnova T2SL state-of-the-art MTF

The figure below summarizes MTF at Nyquist frequency as a function of pixel pitch across current infrared technologies. As pixel pitch is reduced, most technologies exhibit increased crosstalk, leading to a systematic degradation of MTF at Nyquist.



IRnova's T2SL detectors, in contrast, consistently maintain high MTF at reduced pitch, indicating effective suppression of crosstalk in the array structure. This performance is achieved without compromising sensitivity, enabling smaller pixel designs that preserve both spatial resolution and detection capability. As a result, IRnova T2SL technology provides a clear advantage for next-generation IR systems targeting ultimate performance.