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Thermal imaging: From Planck's law to ADAS performance improvement

Autosens USA 2024
Tutorial session

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Application Lab
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Tutorial educational goals:

- Identifying the use cases where system performance is improved by Thermal Imaging
- Pre-design a system fitted to the use cases: resolution, FOV
- Understand the key FOM of Thermal Imaging
- Settle and use a Thermal Camera

Have you other goals or expectation?

Abstract

Thermal imaging is a proven technology used since decades in many markets as defense, industry or security. For ADAS it is gaining interest at a fast rate due to complementarity in advanced conditions with established sensor technologies. However, thermal imaging remains perceived as an expensive and niche technology. In this tutorial, Lynred a global leader in the thermal imaging sensor market will demystify it and will give you the keys to design your own system.

After a landscape of thermal imaging applications and position with current sensing technologies, you will learn the building blocks of a thermal camera, the physical laws to consider and metrics related. Fields will be radiometry, optics, microelectronic, Image Signal Processing, AI & fusion.

Those learnings will then be applied to estimate range detection on real use-cases like the future NHTSA PAEB rulemaking proposition or on your owns.

As a recreational ending, you will be able to manipulate a thermal camera!

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Contents

Coffee break 11.15-11.45 am!

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Beware! I might use the metric system

$$°F = (°C \times 1.8) + 32$$

$$1m = 3.281\ ft$$

$$1\ km/h = 0.62\ mph$$

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Why automotive industry need other modalities?

Global Status Report On Road Safety 2018

World Health Organization

1.35 MILLIONS PEOPLE
die each year on the world's roads
8the leading cause of death for people of all ages

54%
are **V**ulnarable **R**oad **U**sers

88%
of pedestrian travel is on 1- or 2 - star roads

No sidewalk
No safe crossing,
No street light
60 km/h traffic

Source: WHO

Pedestrians fatalities happens in low visibility conditions…

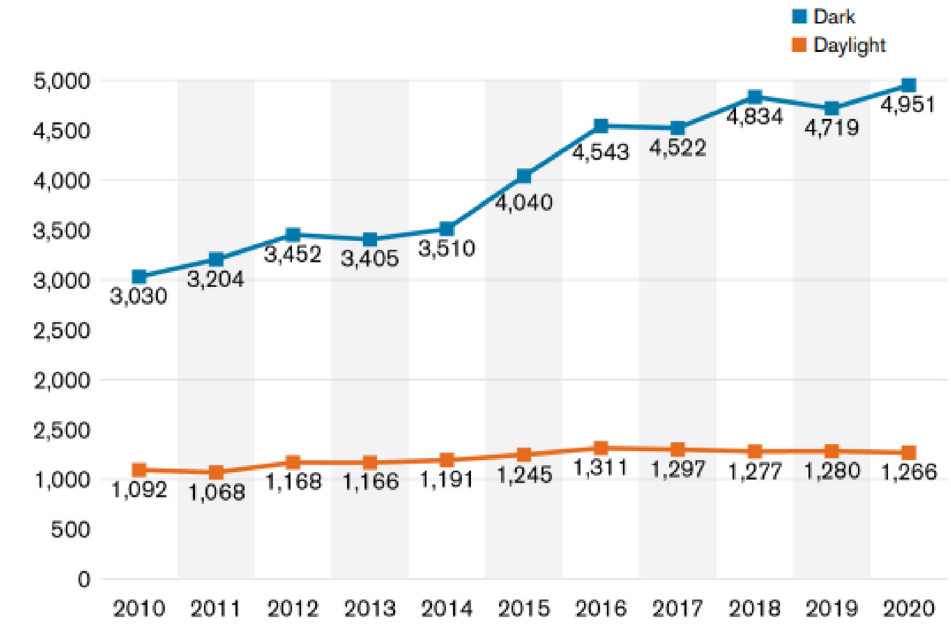
…when current AEB systems are ineffective

Pedestrian fatalities on Advanced light and/or Advanced weather conditions:

80% *in the US*
70% *in Europe*

NHTSA
European Road Safety Observatory

Source: NHTSA 2015-2019, ERSO 2017



Source: FARS

Pedestrian safety features
Fails in deadliest situations

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EU objectives and US rulemaking proposition

NHTSA rulemaking proposal to integrate Automatic Emergency Braking and Pedestrian AEB working at night and higher speed **adopted in May 2024**

EU Vision Zero ambitions to reduce by half the number of fatalities by 2030 and approach Zero by 2050

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Example: Driving at night

Country side road without streetlight, Night without moon,
Clear wheather, 7.2°C, 93.4%RH

Xenon low-beam according to ECE-R98

Night vision with thermal imaging !

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What’s infrared ?

LYNRED *is*

LYNRED | LYNRED USA | LYNRED Asia Pacific

85%
EXPORT

***> 2 MILLION** DETECTORS*
SHIPPED SINCE 1986

***15%** OF SALES*
*INVESTED IN **R&D***

FULL INFRARED
***SPECTRUM** COVERAGE*

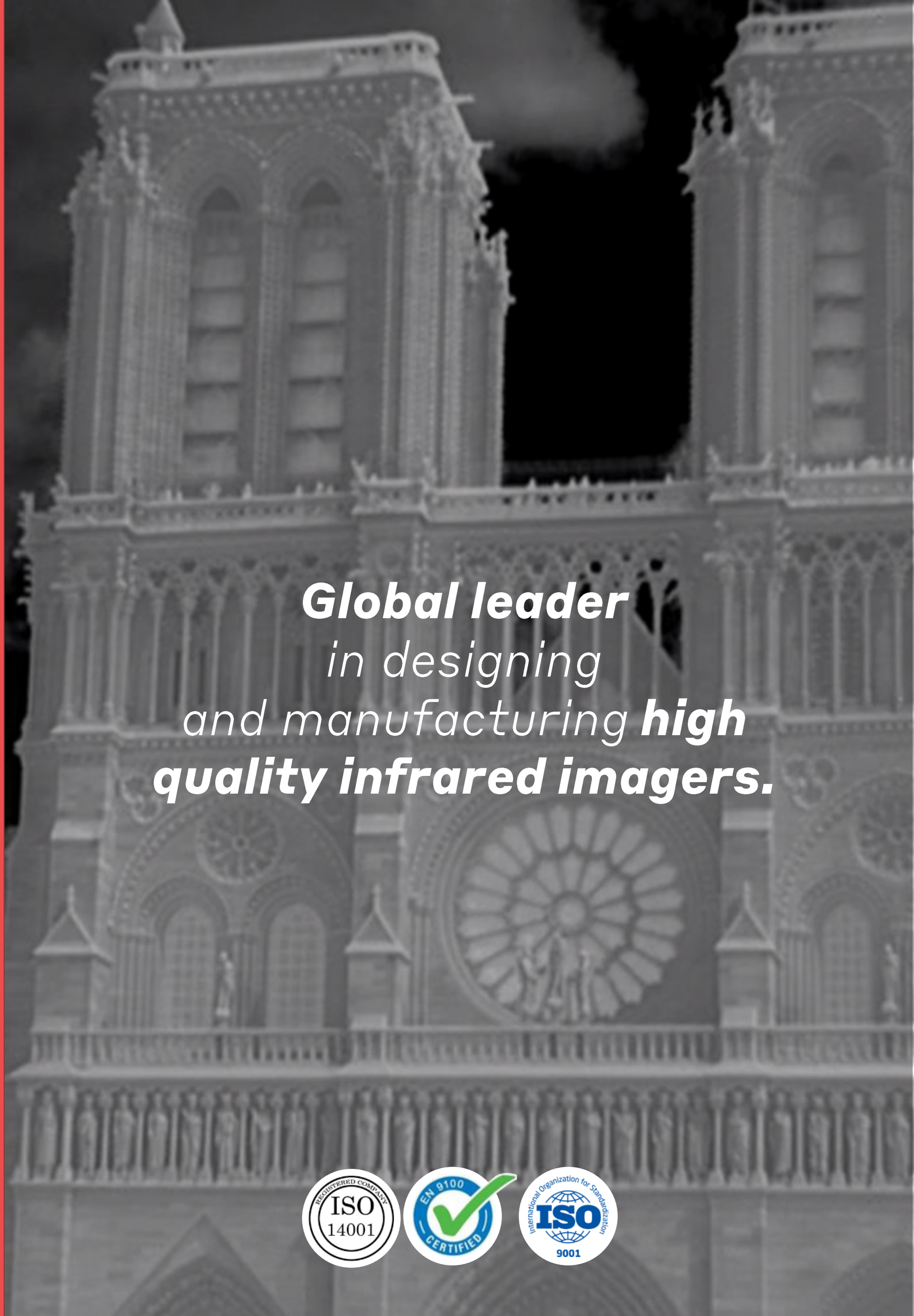
***> 133 PATENT** FAMILIES*
> 680** PATENT **FILED

STRONG PARTNERSHIPS
CEA LETI – ONERA – III-V LAB



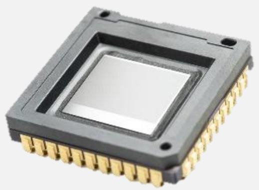




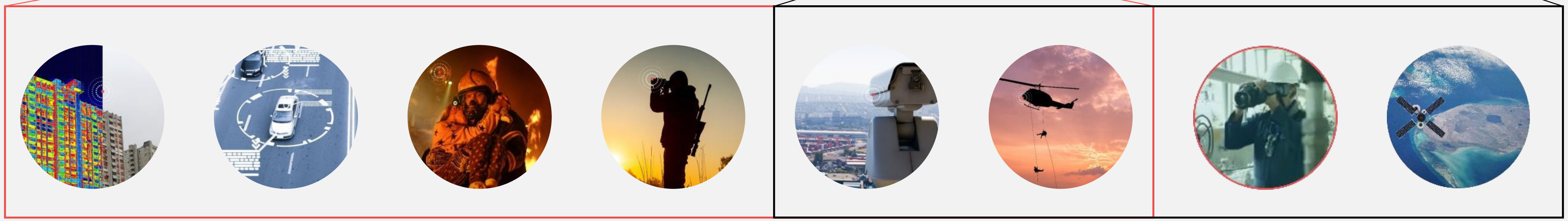
A DUAL OFFER **ENSURING SOVEREIGNTY**

Cooled – Uncooled duality
LYNRED supplies only the image sensors



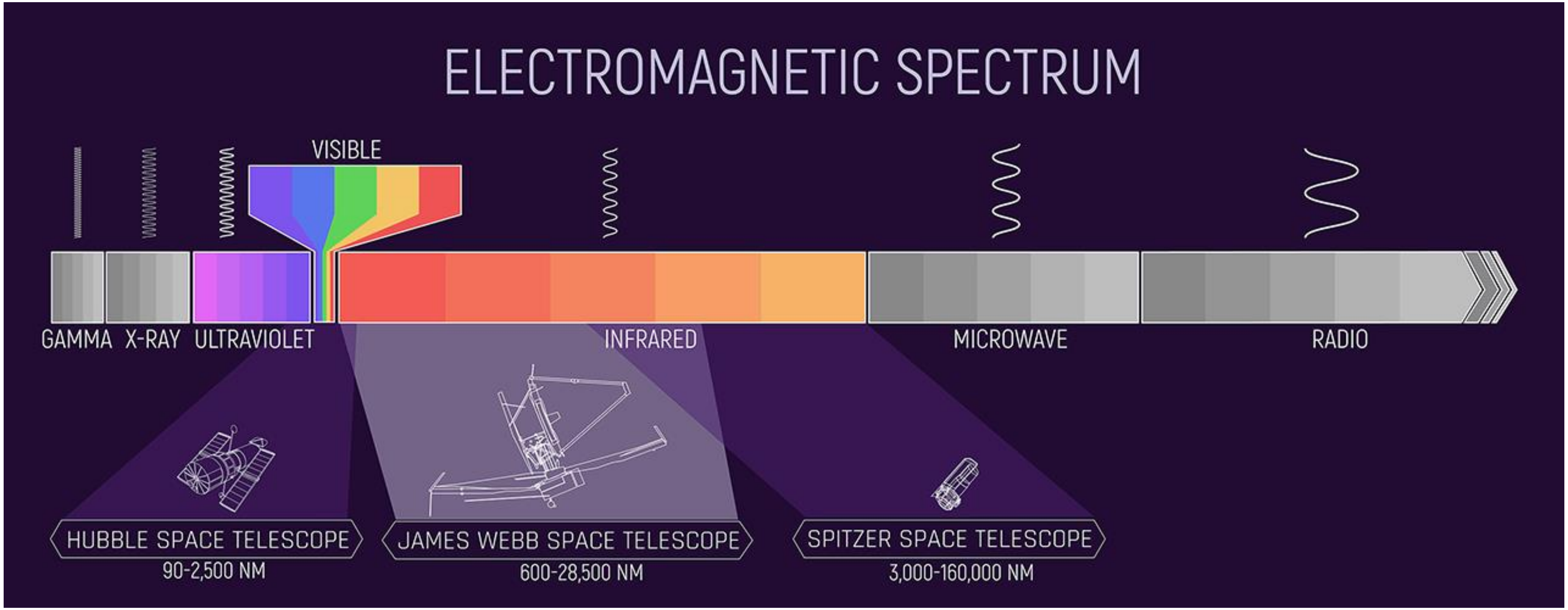
Uncooled

Cooled



Electromagnetic spectrum

Infrared : Wavelengths between 0.7µm and 100µm



@NASA

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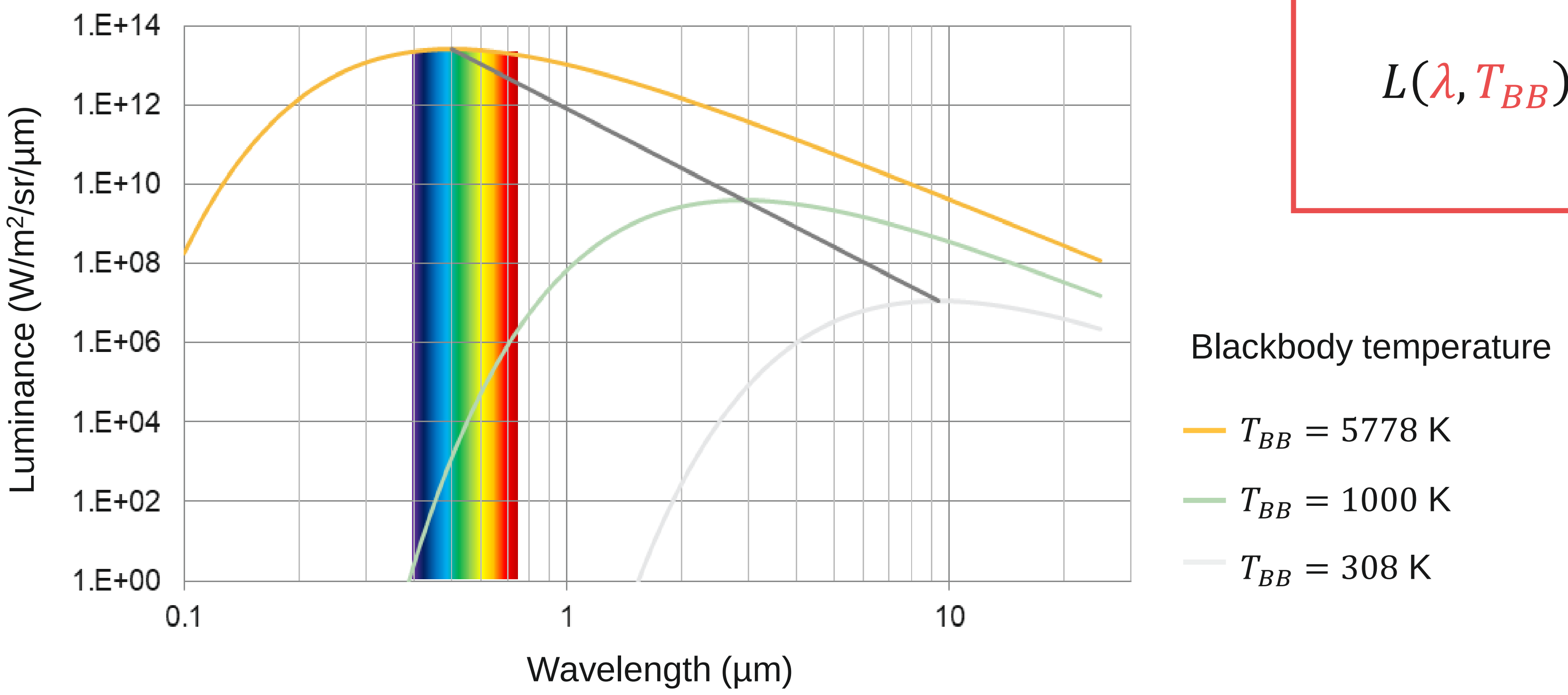
Blackbody radiation : Planck's law

Luminance spectrum depends on the temperature



Planck's Law :

$$L(\lambda, T_{BB}) = \frac{2hc^2}{\lambda^5} * \frac{1}{e^{\frac{hc}{\lambda k_B T_{BB}}} - 1}$$

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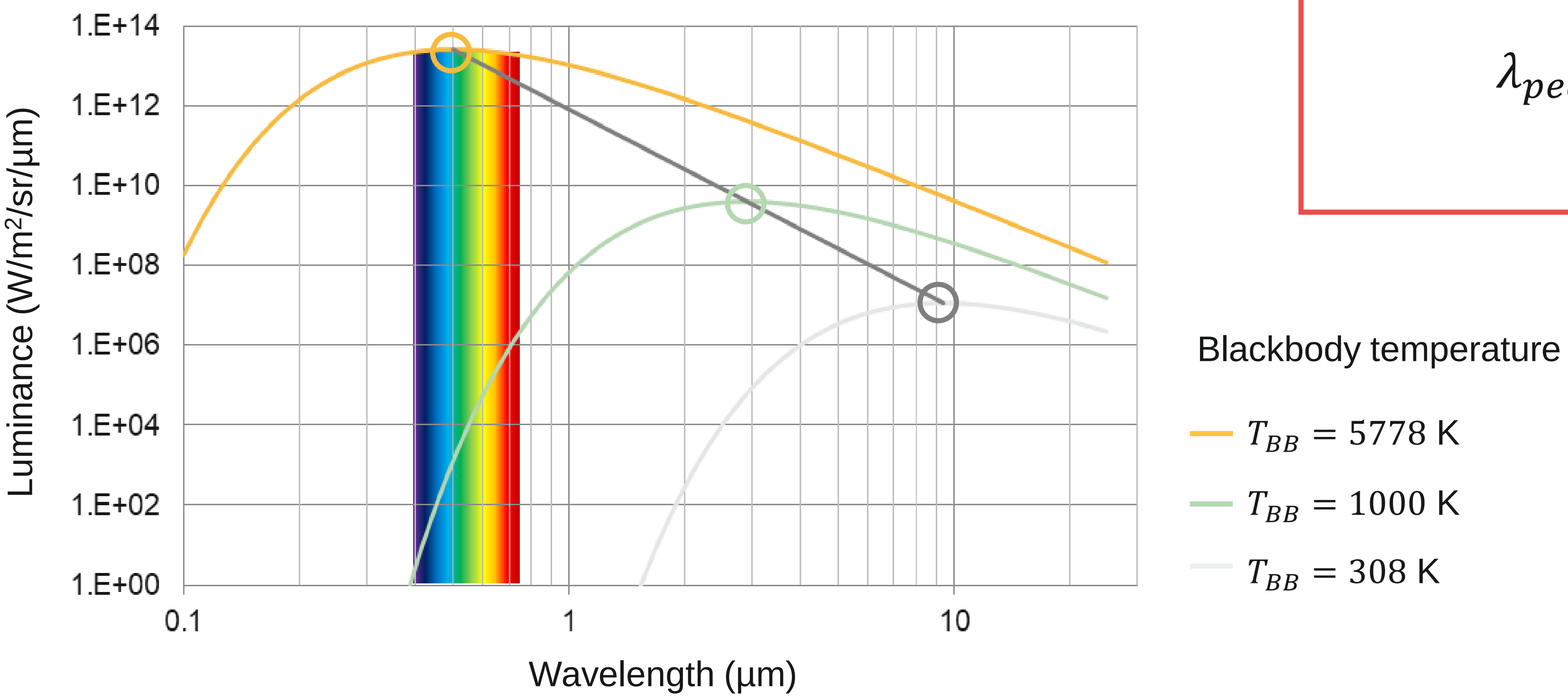
Blackbody radiation : Wien's law

Peak wavelength vs. temperature

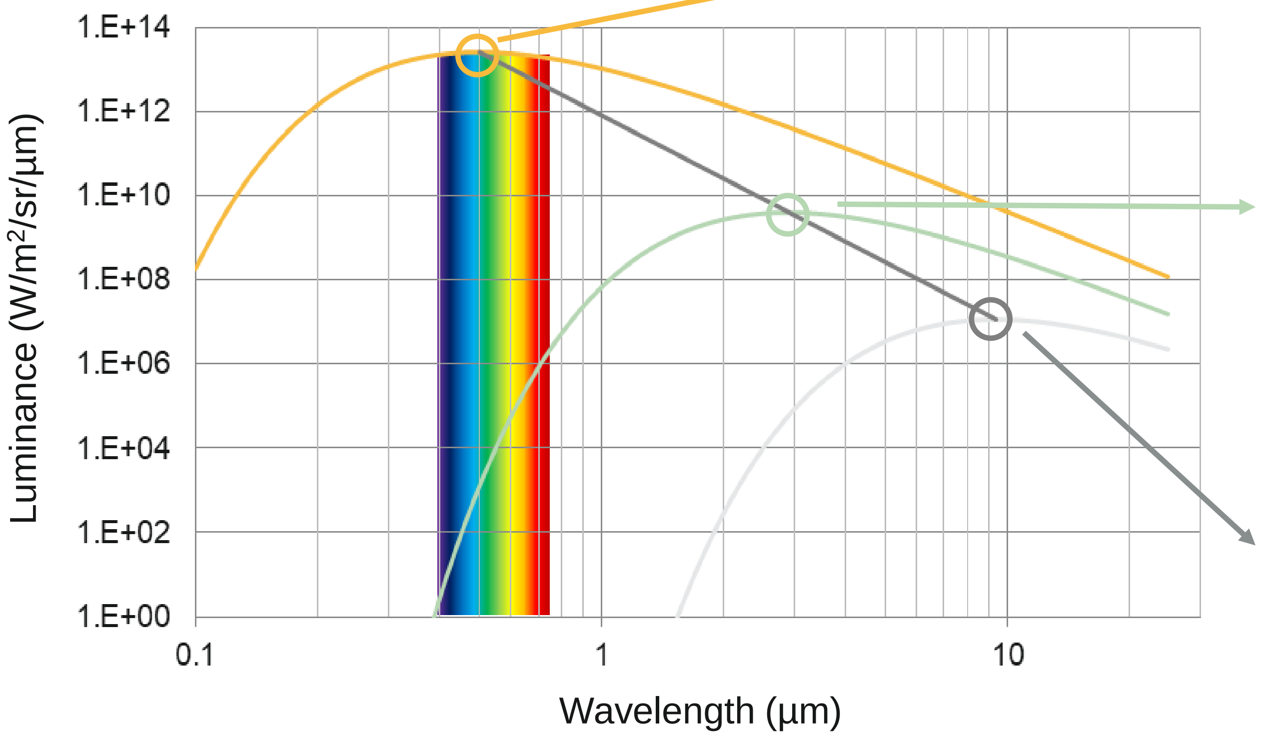


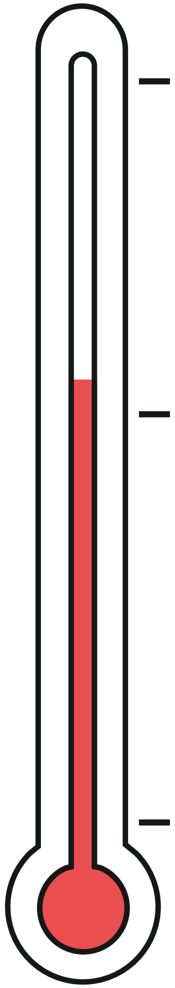
Wien's Law :

$$\lambda_{peak} \sim \frac{2898}{T[K]}\ [\mu m]$$

Blackbody radiation : Wien's law

Peak wavelength vs. temperature





$\lambda_{peak} = 0.5\ \mu m$

Visible

$\lambda_{peak} = 3\ \mu m$

Infrared

$\lambda_{peak} = 9.7\ \mu m$

A human is an infrared light bulb !

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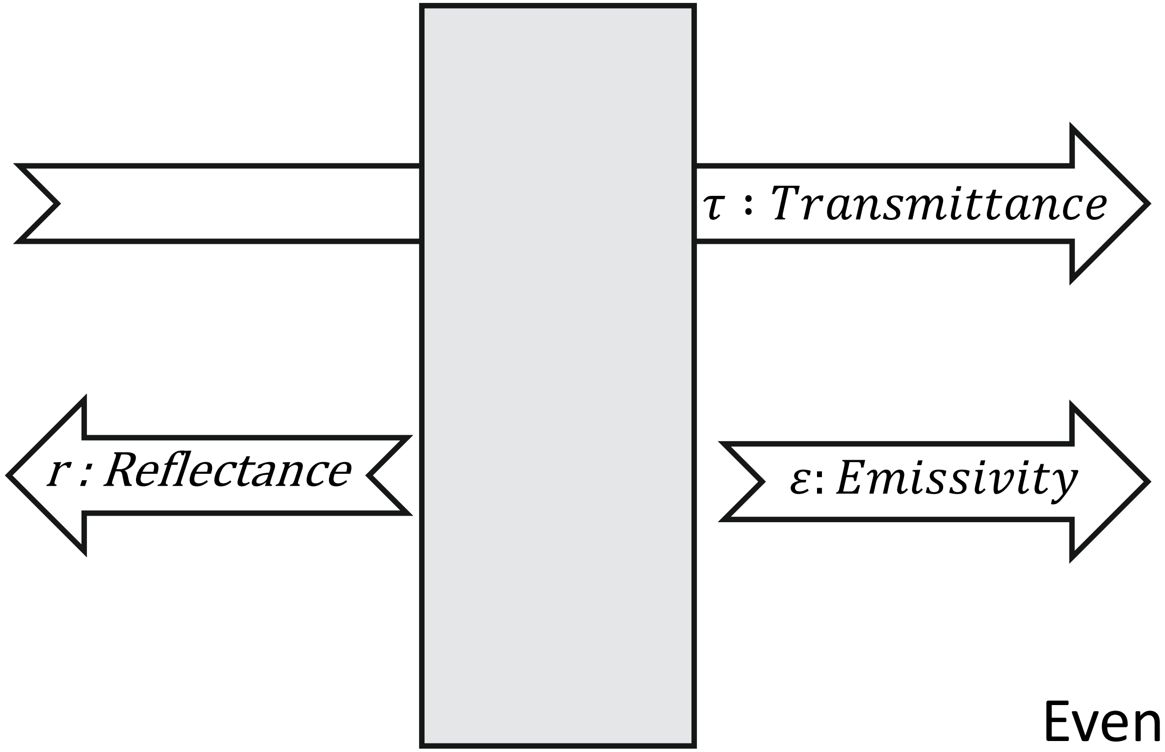
Emissivity, transmission & reflexion



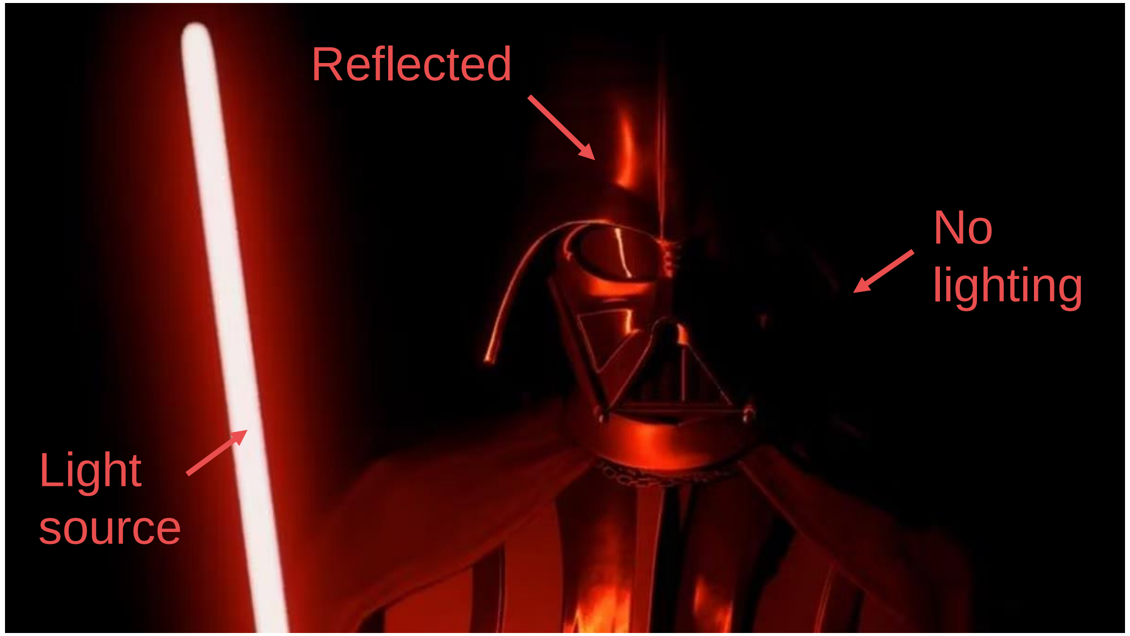
$$\varepsilon + r + \tau = 1$$

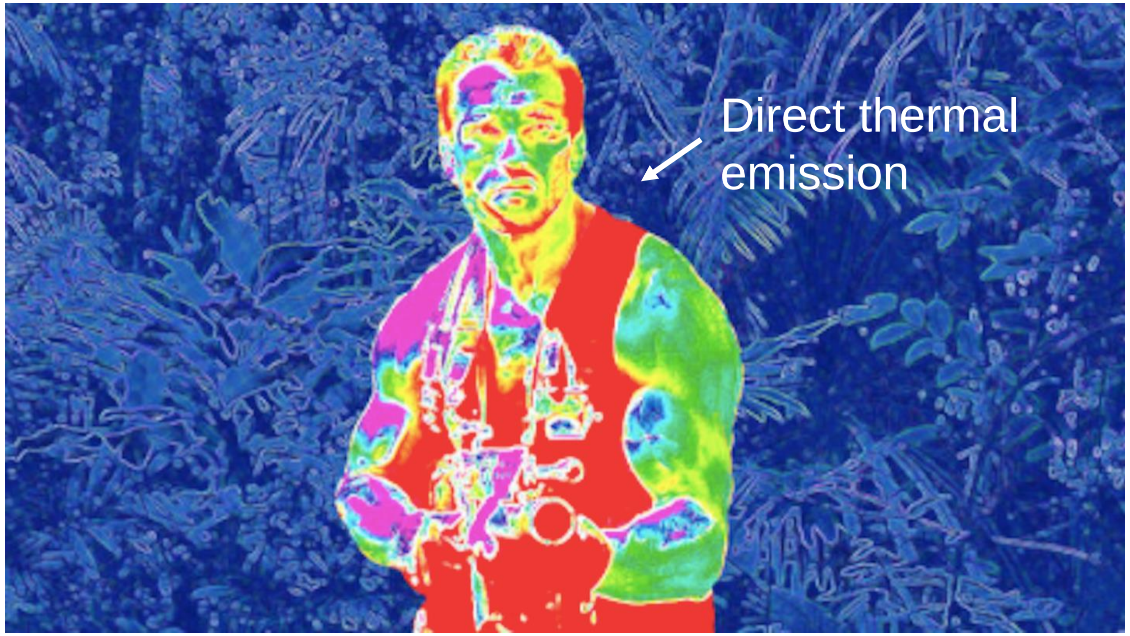
(Kirchoff law)

	R	τ	ε
Black body (perfect source)	0	0	1
Metal (perfect mirror)	1	0	0
Germanium (good for optics)	0	1	0

Even if everything is at the same temperature, we still have an emissivity contrast !

Reflection or thermal emission?

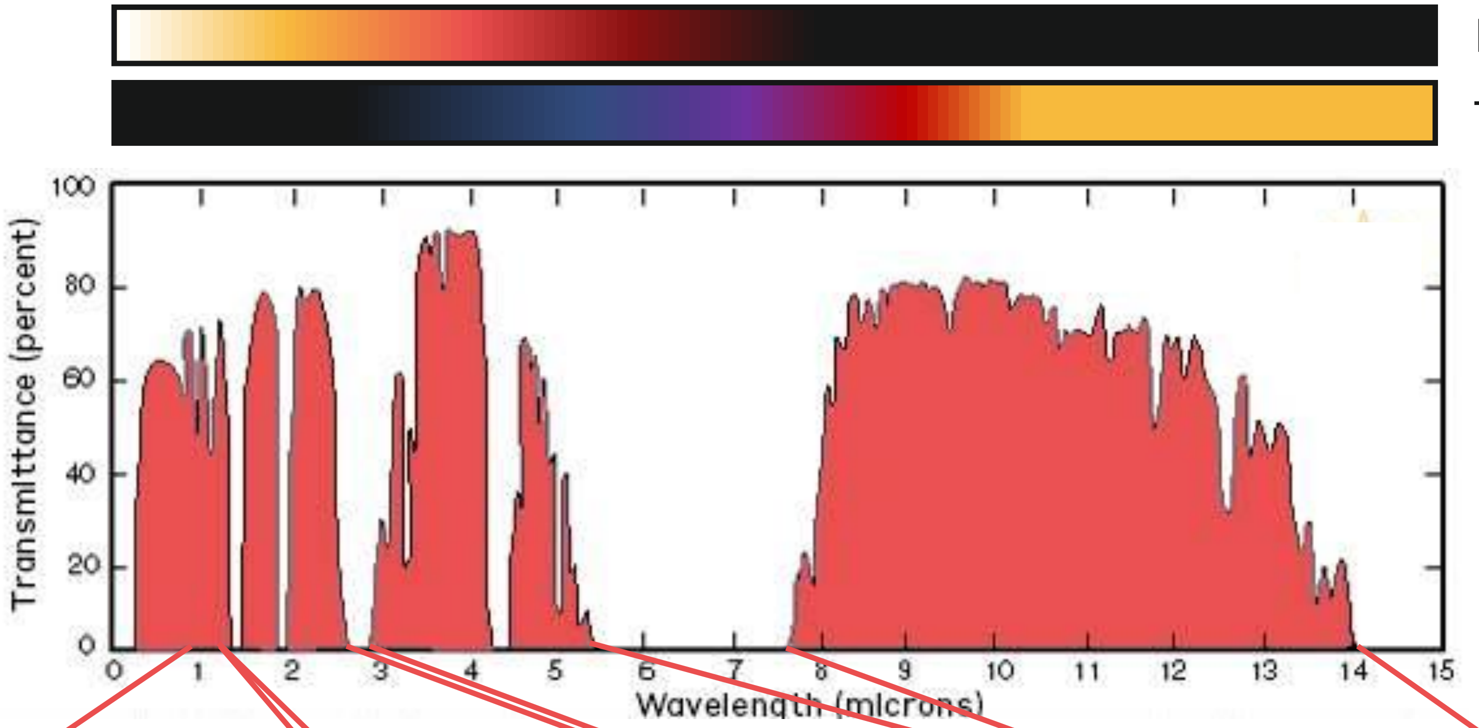




Reflection from external light source
→ Active imaging

Direct thermal emission
→ No light source needed
→ Passive imaging

InfraRed bands



Reflection

Thermal emission

Atmosphere transmittance

NIR
0.7 – 0.9 µm
Near InfraRed

SWIR
0.9 – 2.5 µm
Short Wave IR

MWIR
3 - 5µm
Middle-Wave IR

LWIR
7.5 – 14 µm
Long-Wave IR

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InfraRed bands : image examples

NIR

NIR lighting

SWIR

Natural lighting

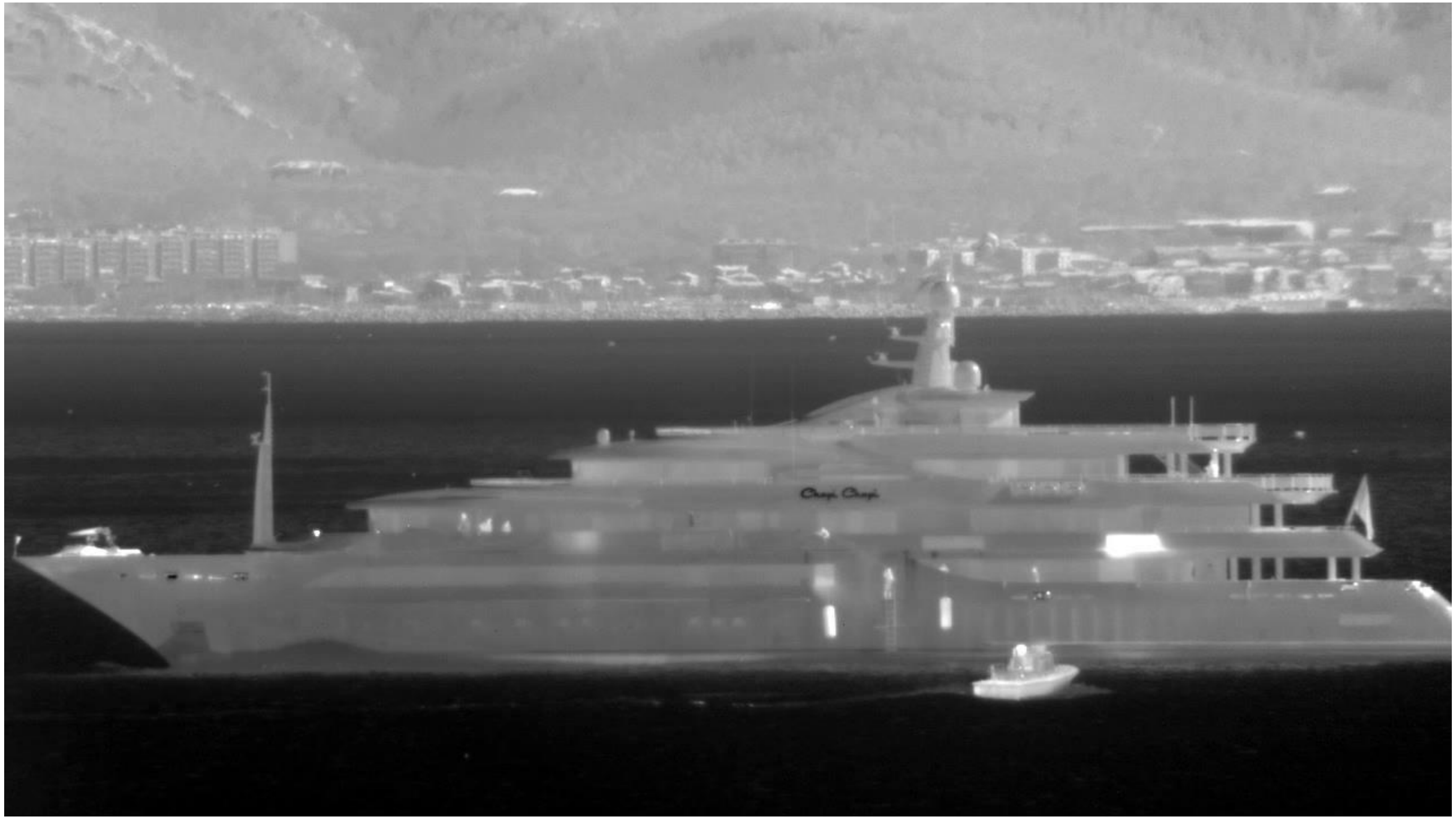
MWIR

Natural lighting & Thermal emission

LWIR

Thermal emission

QUIZZ : SWIR? MWIR ? LWIR ?



Answer:
MWIR !

Sensor :
Daphnis HD

QUIZZ : SWIR? MWIR ? LWIR ?

Answer:
LWIR !

Sensor :
ATTO1280

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QUIZZ : SWIR? MWIR ? LWIR ?

Answer:
SWIR !

Sensor :
SNAKE

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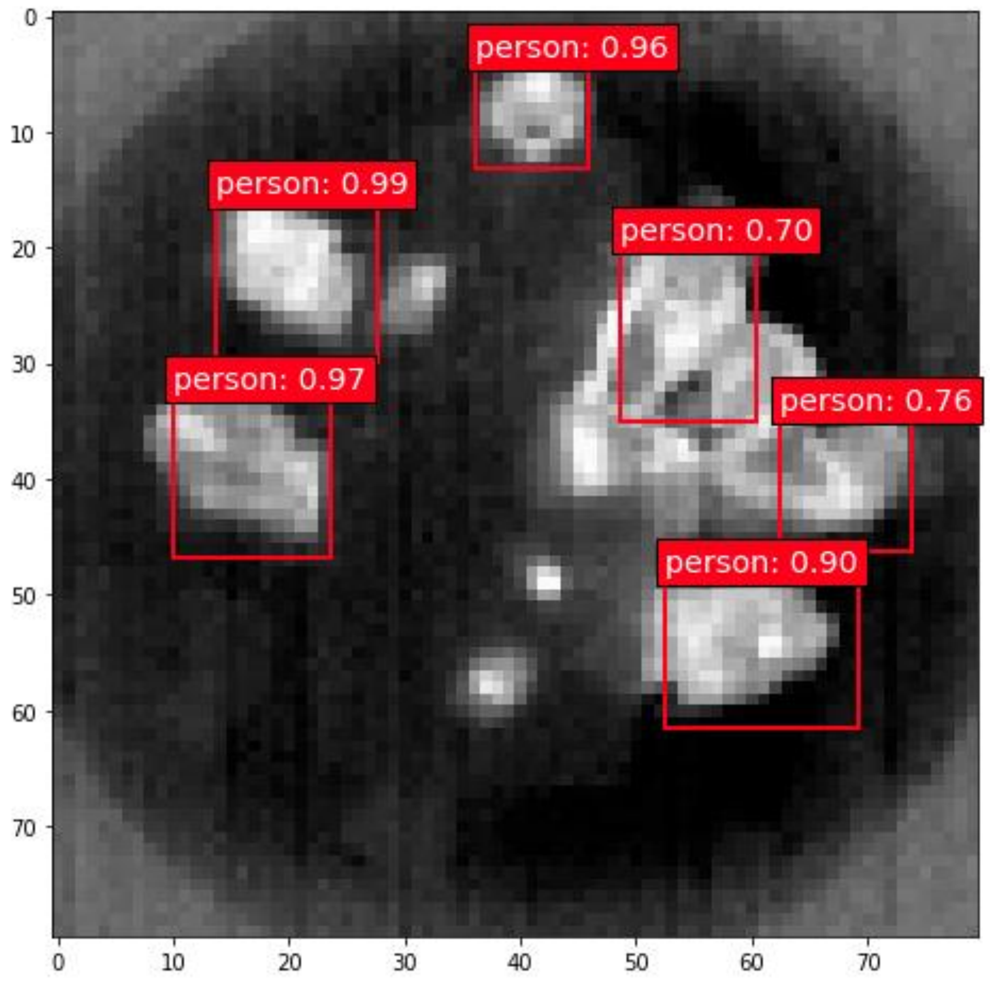
QUIZZ: SWIR? MWIR? LWIR ?



Answer:
LWIR !

Sensor :
MICRO80

Inexpensive, low resolution thermal imaging could be used for Child Presence Detection

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Light scattering

Smoke bomb

Light scattering is ineffective in LWIR compared to visible, due to the longer wavelength

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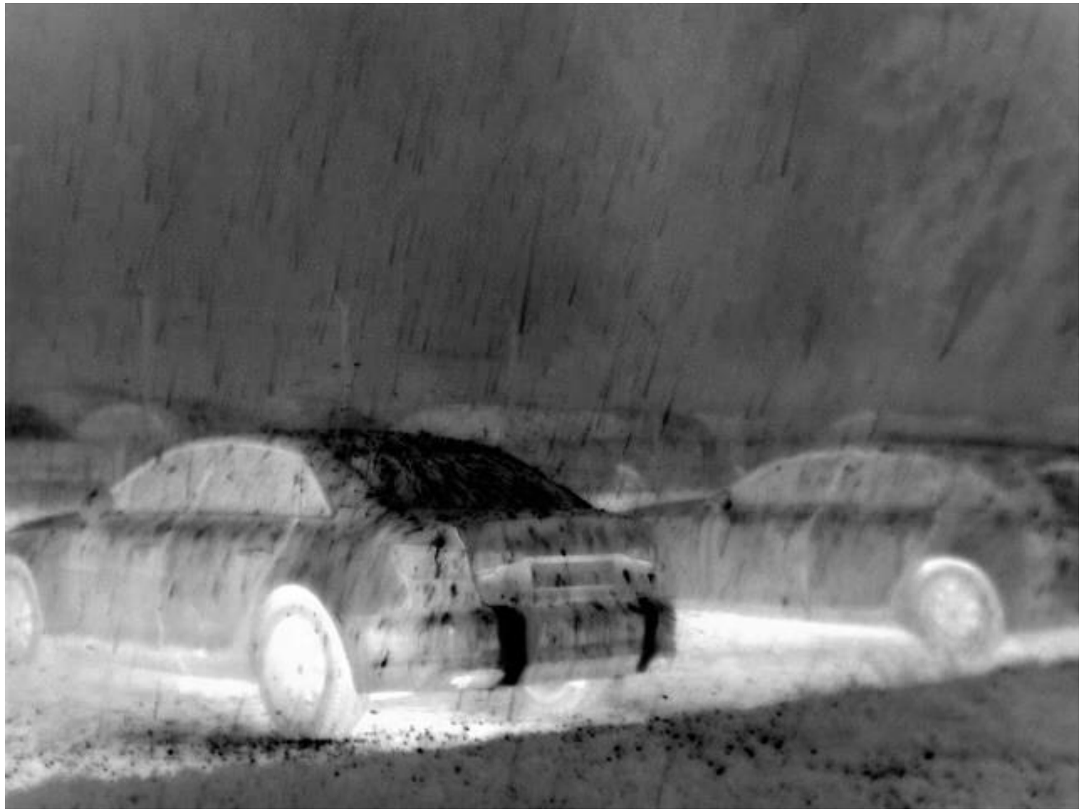
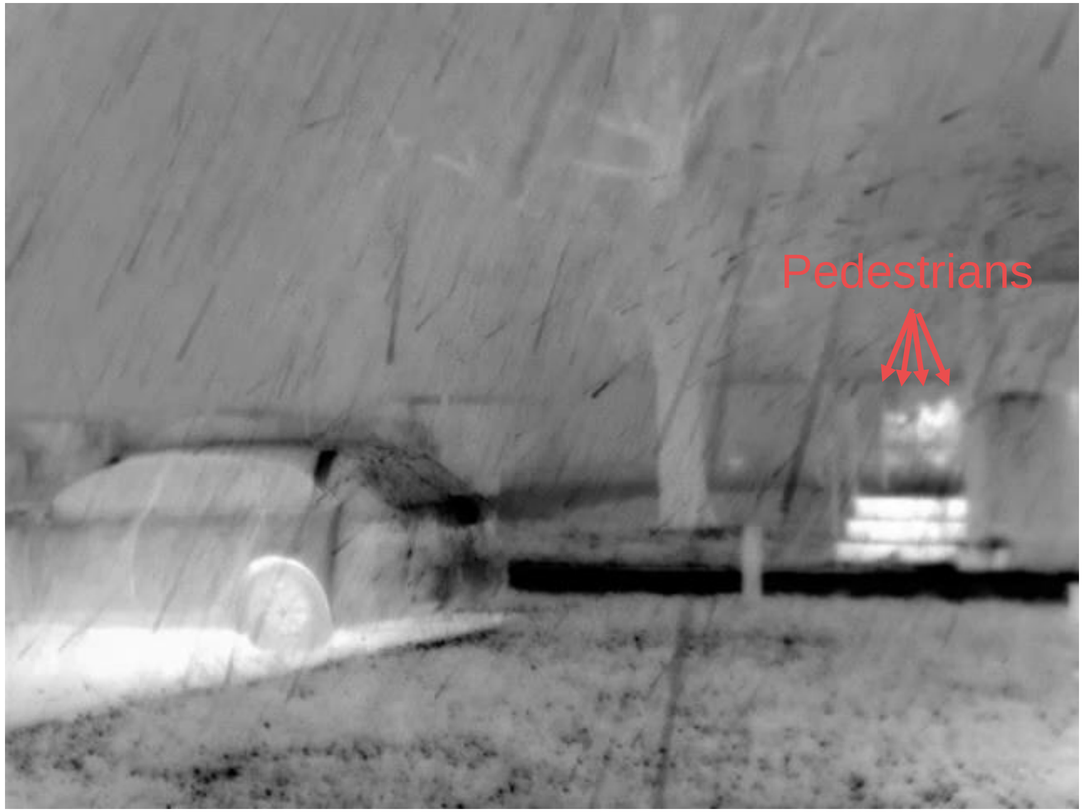
Heavy rain & hailstrom

The worst conditions to experience…





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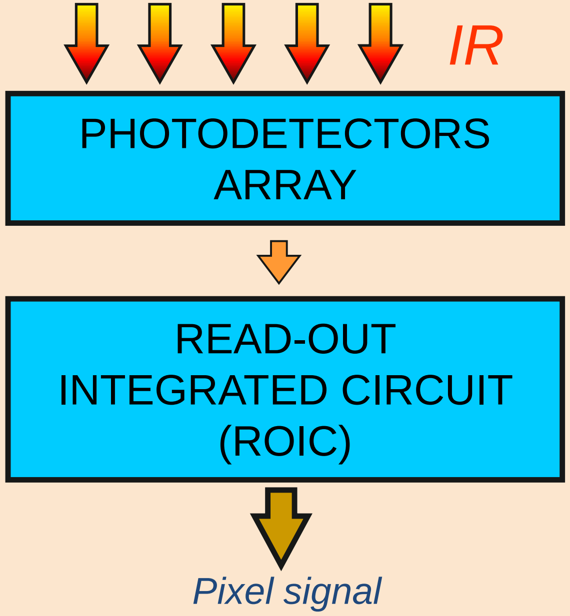
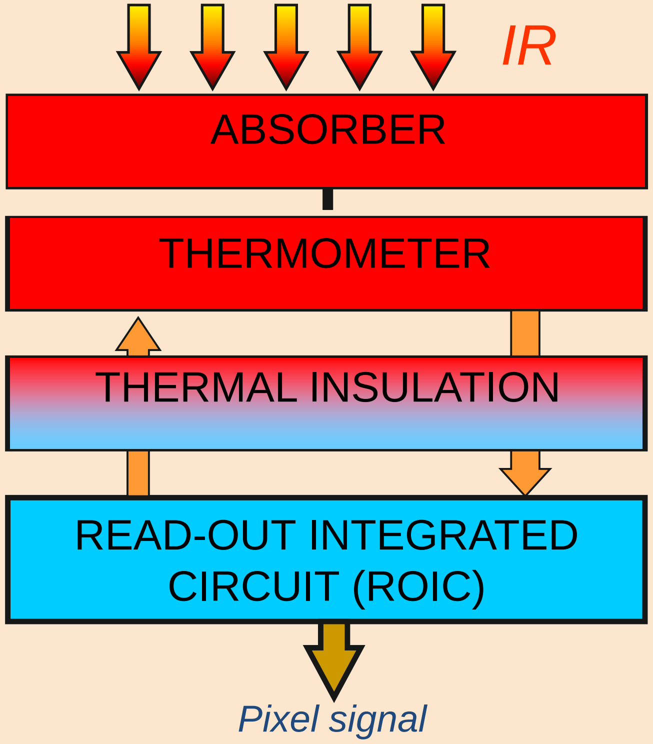
Key principles of thermal imaging

2 main detection types

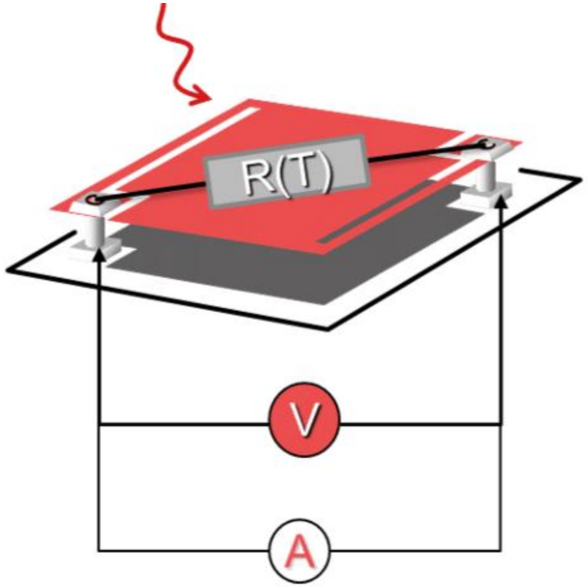
Detector type	Photodiodes	Bolometer = Photoresistance
Detection principle	**Convert photons to electrons** 	**Measure temperature variation** 

A microbolometer array provides an image with pixel values, like any camera

Microbolometer arrays : Uncooled thermal imaging

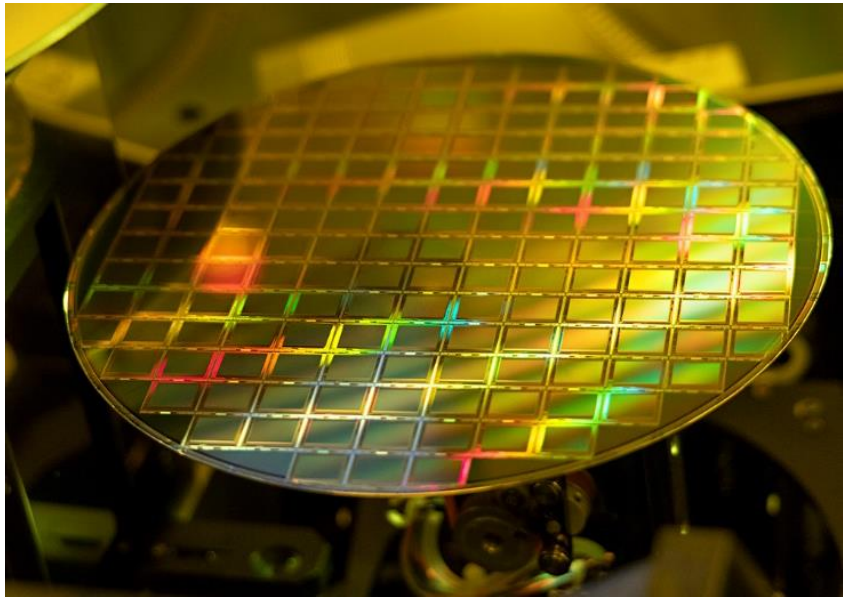
Cost effective thermal image sensors

IR radiation = f(T)



Thermo-resistance measurement
A bolometer is basically a thermometer

Bolometers arrays
chips in a 200mm wafer
CMOS & MEMS



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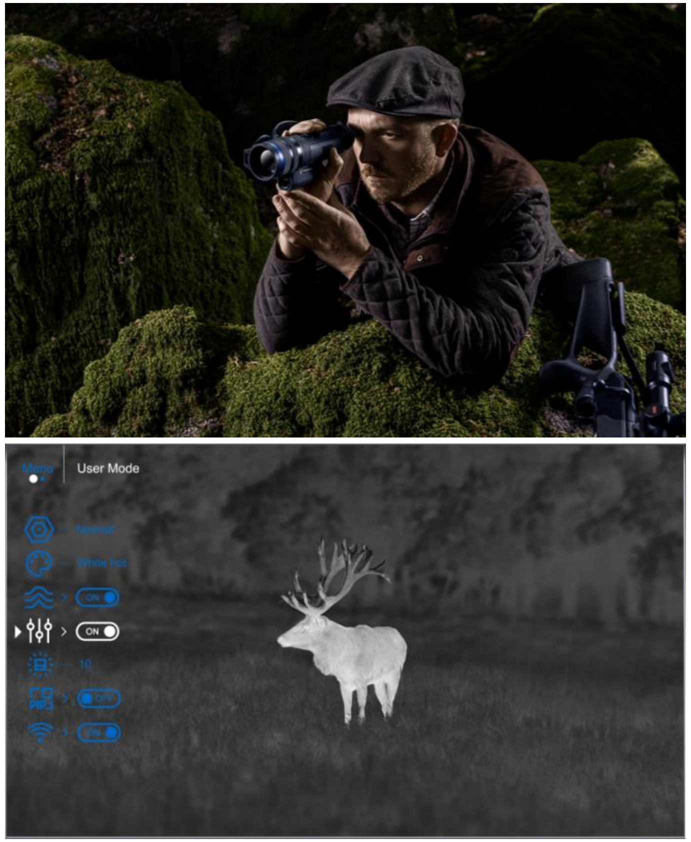
Thermal night-vision : from military to civilian applications

SWaP-C : Size, Weight, Power, Cost

Sophie Optima @Thales



TELOS @PulsarNV

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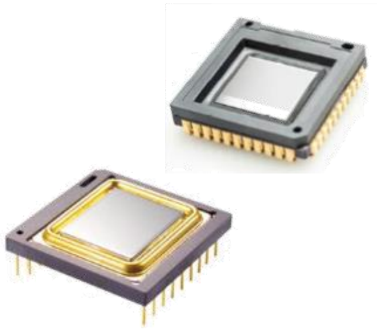
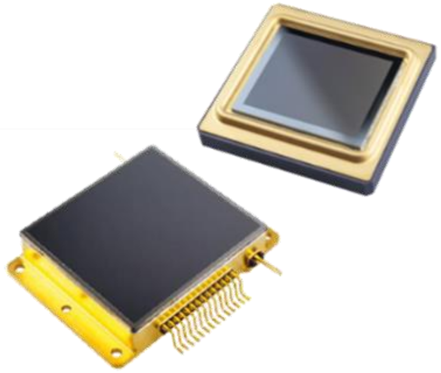
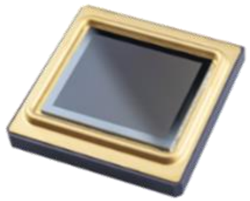
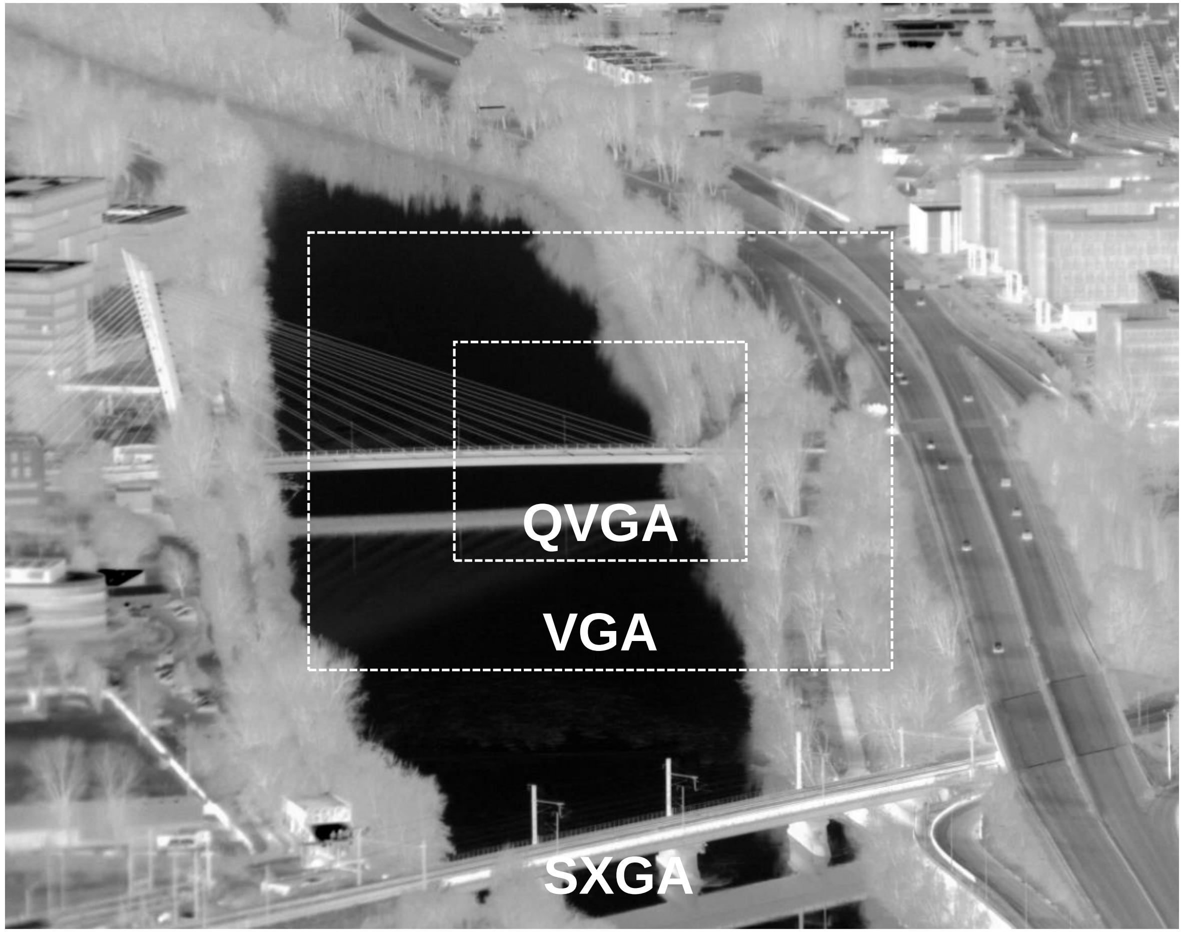
Lynred microbolometers product porfolio

80×80	QVGA	VGA	XGA	SXGA
				
M80-044 80 x 80 – 34µm	**ATTO320** 320x240 - 12µm **PICO384 GEN2** 384x288 - 17µm	**ATTO640** 640x480 - 12µm **PICO640 GEN2** 640x480 - 17µm	**ATTO1024** 1024x768 - 12µm **PICO1024-048** 1024x768 - 17µm	**ATTO1280** 1280x1024 - 12µm

Same lens, different image formats

Format	Array size	MPixels	Camera power [W]
SXGA	1280 x 1024	1.3	4
VGA	640 x 480	0.3	1
QVGA	320 x 240	0.08	0.4

Bigger format gives more context information



Field of view & resolution

Field of view formula

$$HFOV \sim 2\,\mathrm{atan}\left(\frac{w}{2f}\right)$$

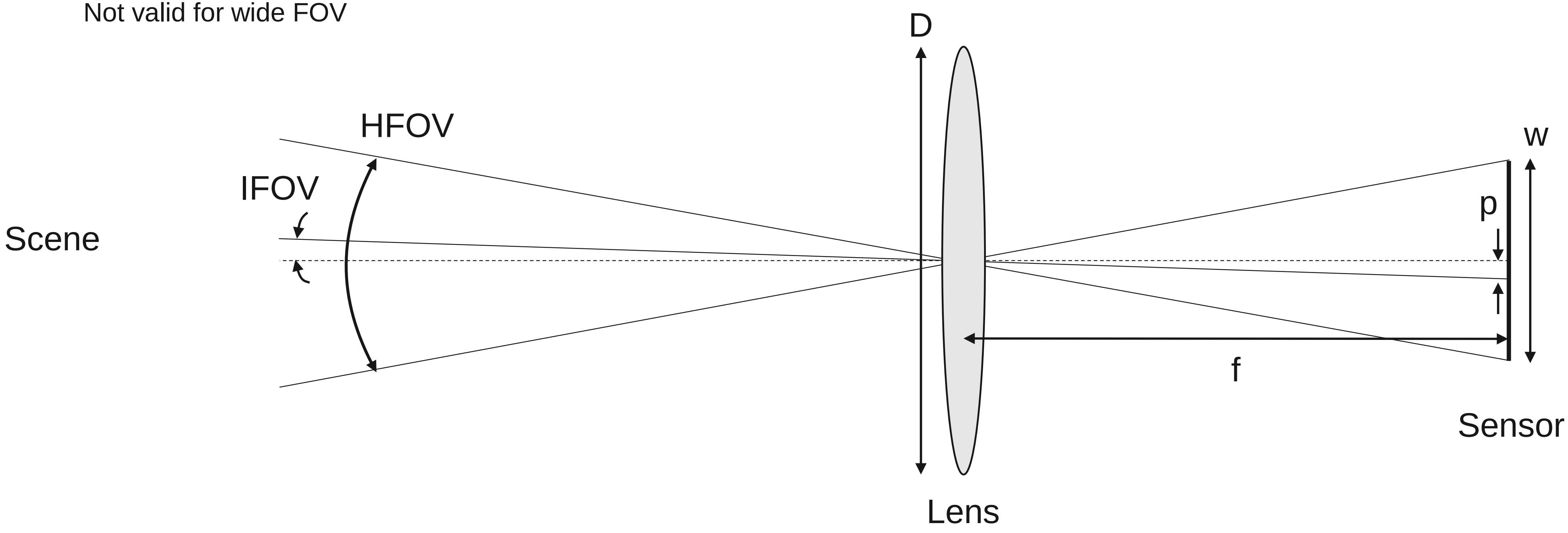
Not valid for wide FOV

Sensor width

$$w = n_{col}.p$$

Instanatenous field of view

$$IFOV = \mathrm{atan}\left(\frac{p}{f}\right)$$



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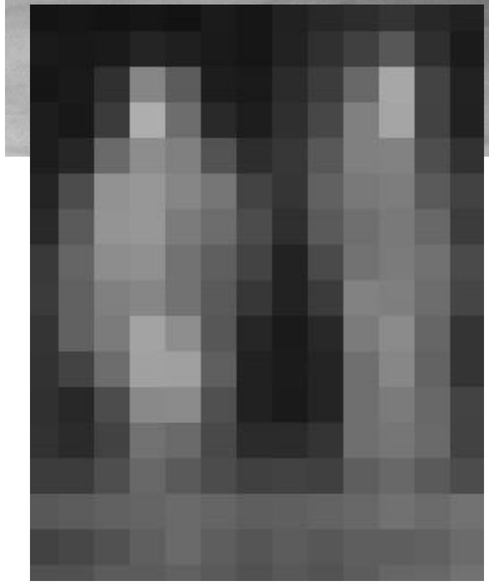
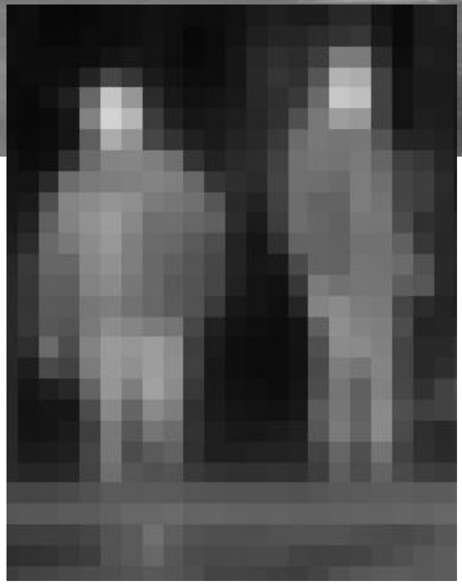
Focal length, on same sensor

(ATTO640, 640x480 @12µm pitch)

Pedestrians at 70m



→ Fitted for short range



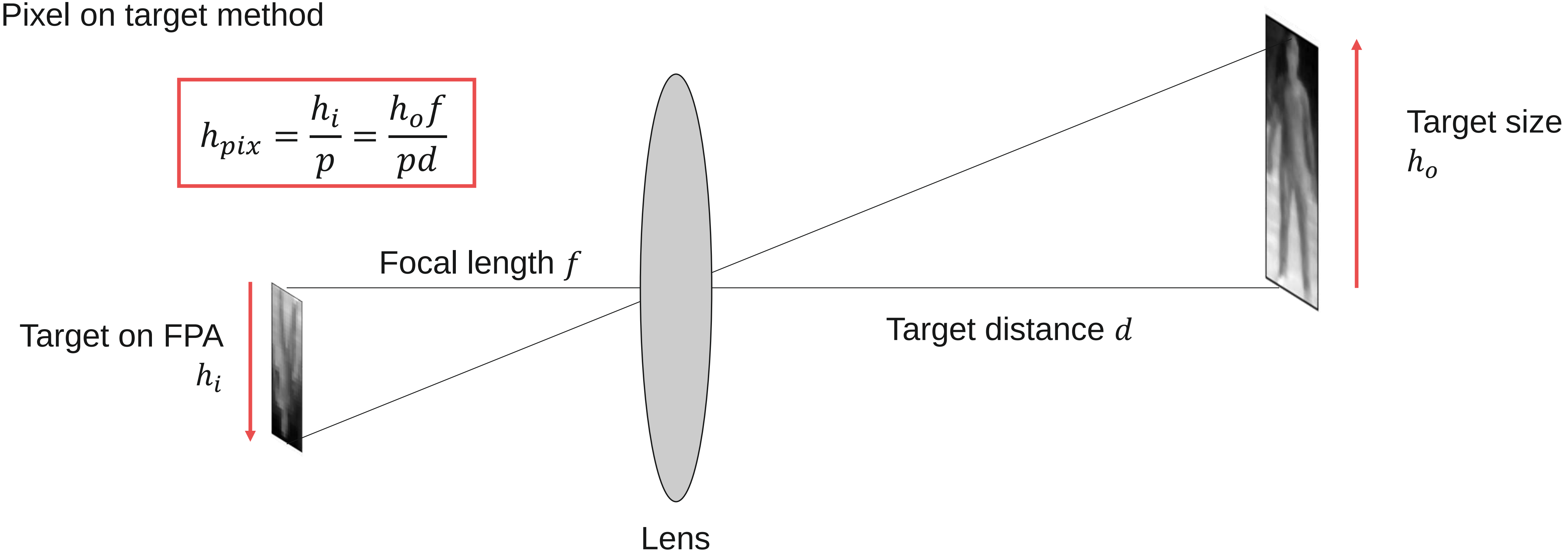
→ Fitted for mid range

→ Fitted for long range

Your use case

Pixel on target method

$$h_{pix} = \frac{h_i}{p} = \frac{h_o f}{pd}$$



~20 pixels is good

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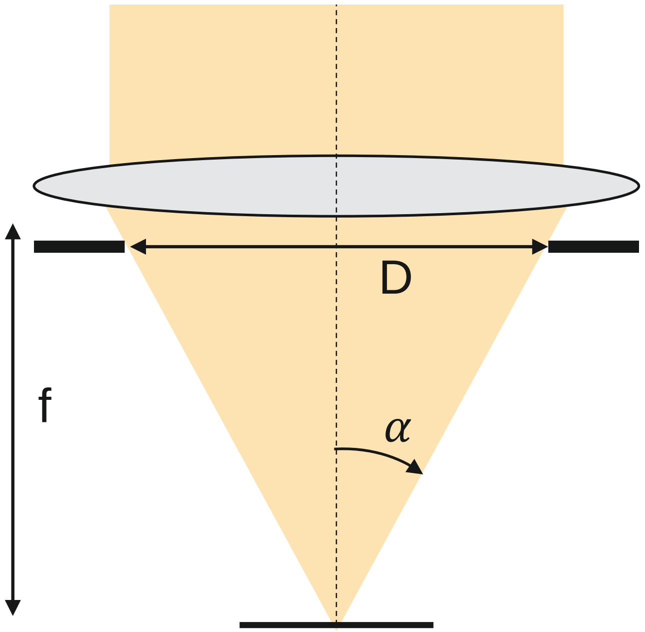
Lens aperture (f-number)



F-number

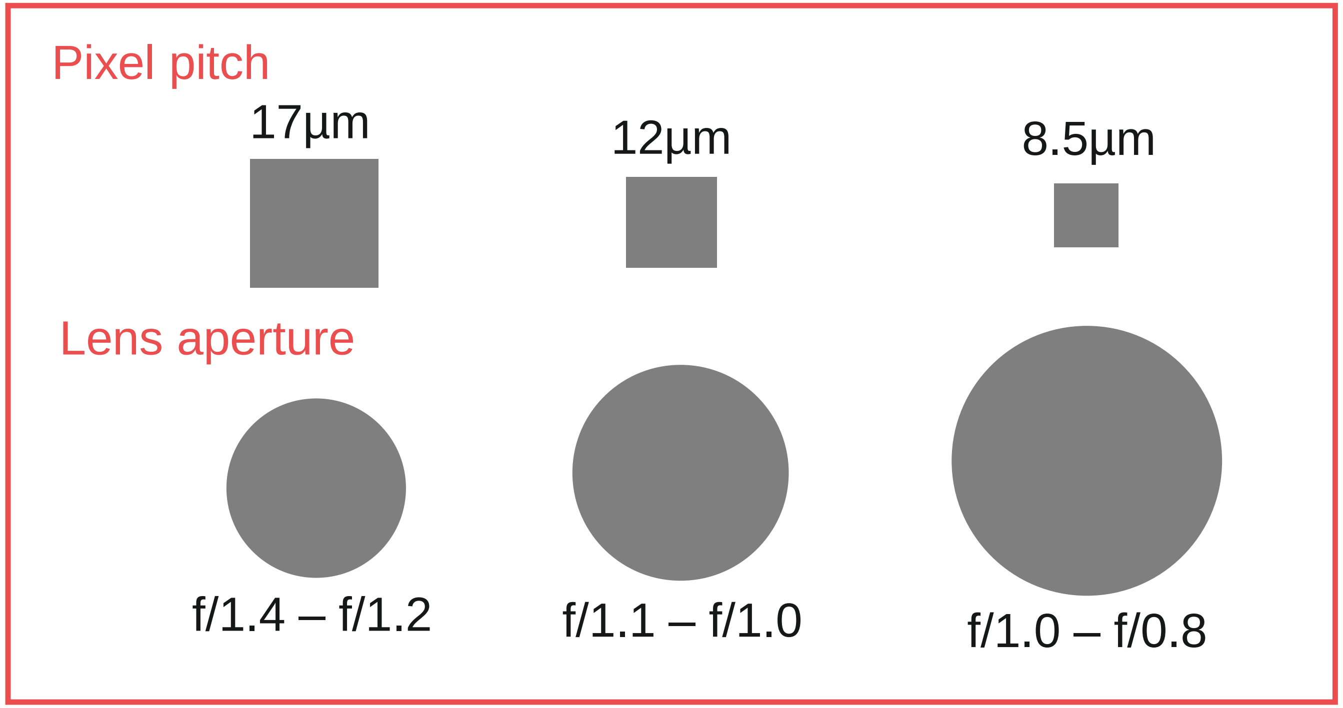
$$f/\# = \frac{f}{D}$$

Numerical aperture

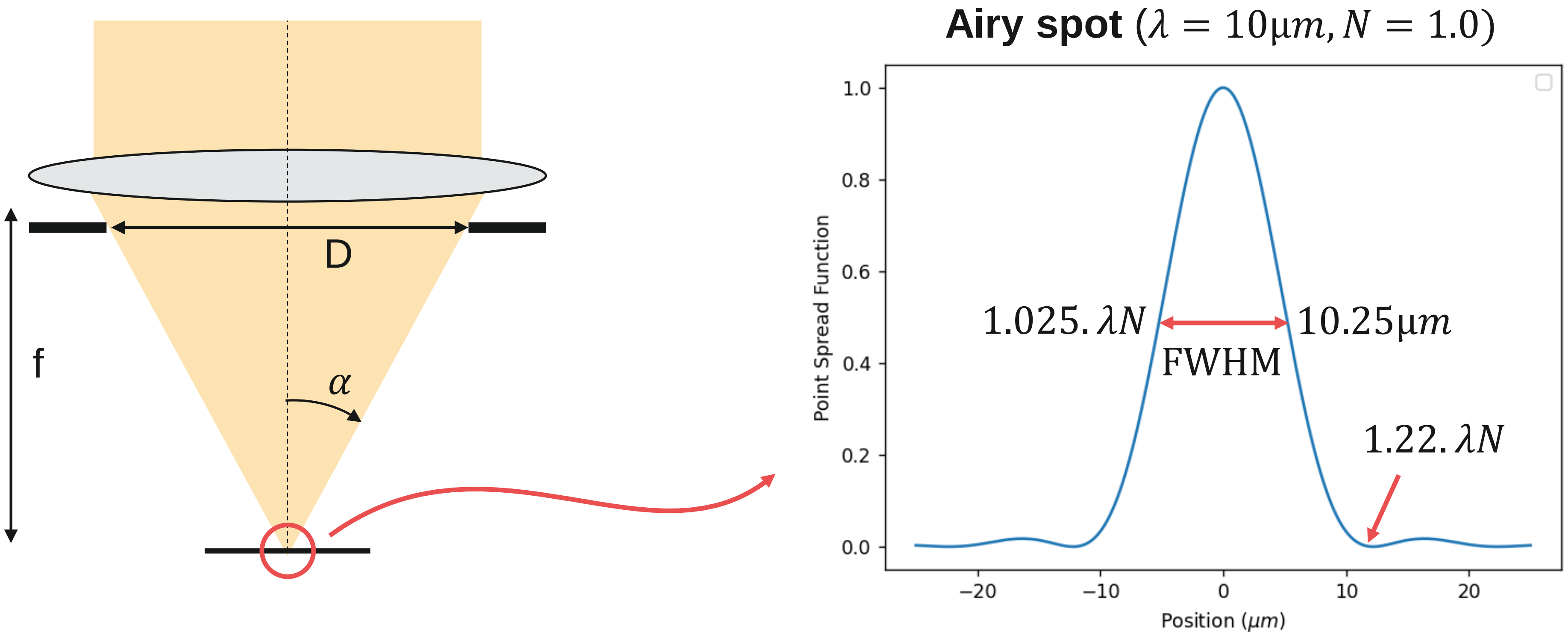
$$NA = \sin(\alpha)$$

Aperture is equivalent to the energy gathered by the optic:
« photon funnel »
The lower number, the higher energy collected

Recommendations:

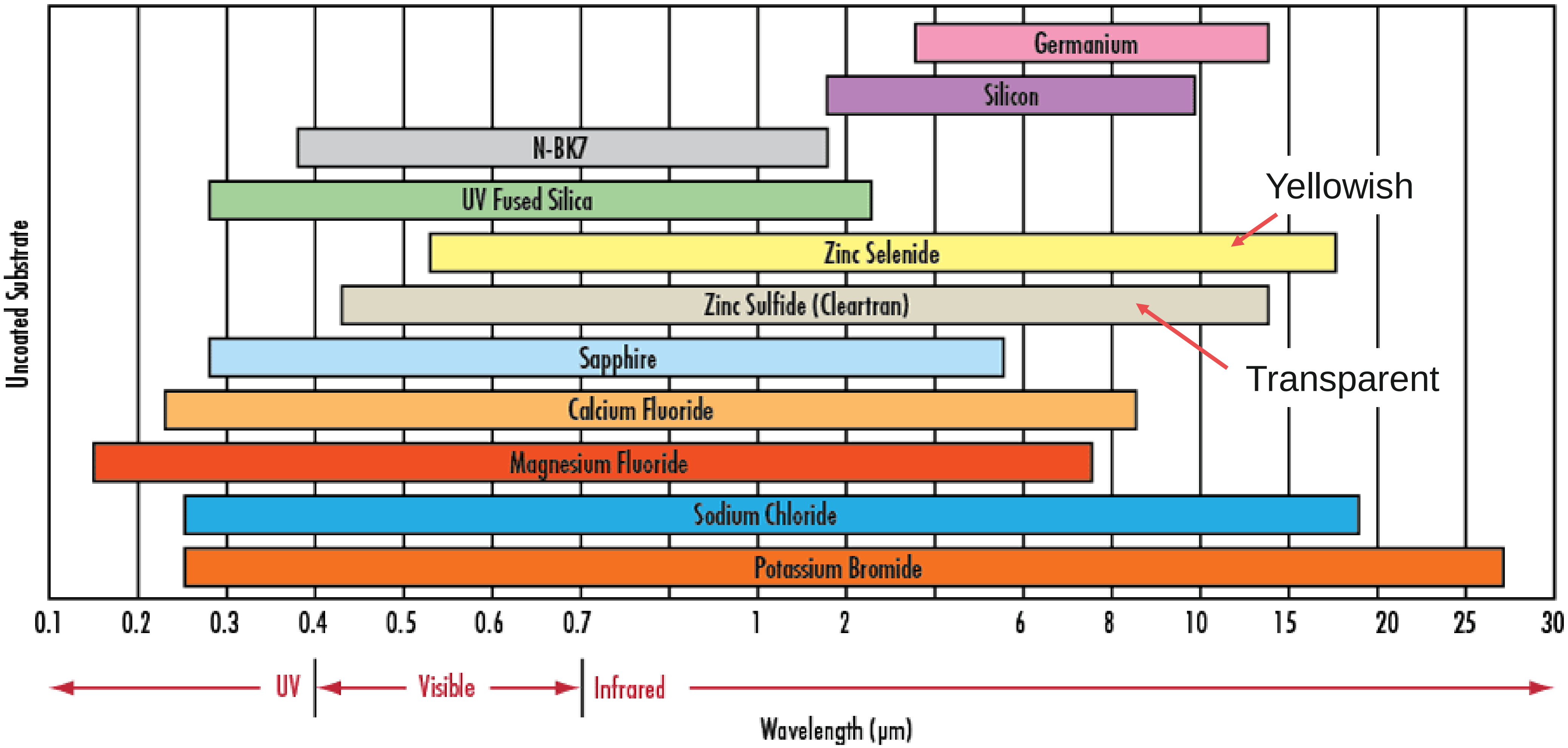


Point Spread Function : diffraction limit



→The diffraction spot (blur) is comparable with the pixel's pitch

Infrared materials



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Infrared materials: Germanium vs. Chalcogenide glasses

Germanium has is the best know material for LWIR optics thanks to its long history, high refractive index and low optical dispersion. The production process is more expensive though.

Chalcogenide glass, such as Umicore GASIR®, is the material of choice for high volume thermal sensing applications thanks to lower production cost and moldability.

Name	Composition	λ Range (µm)	Refr. index @10µm
Germanium (crystalline)	Ge	1.8-14	4.004
GASIR-2 / IRG25 / IG5 / BD-2	$Ge_{28}Sb_{12}Se_{60}$	1.0-12	2.602
GASIR-5 / IRG26 / IG6 / BD-6	$As_{40}Se_{60}$	1.0-14	2.770
NRL4 / BDNL4	Not available	1.0-15.5	2.636

(A few among many)

Negative thermal expansion coefficient
Good for athermal lenses

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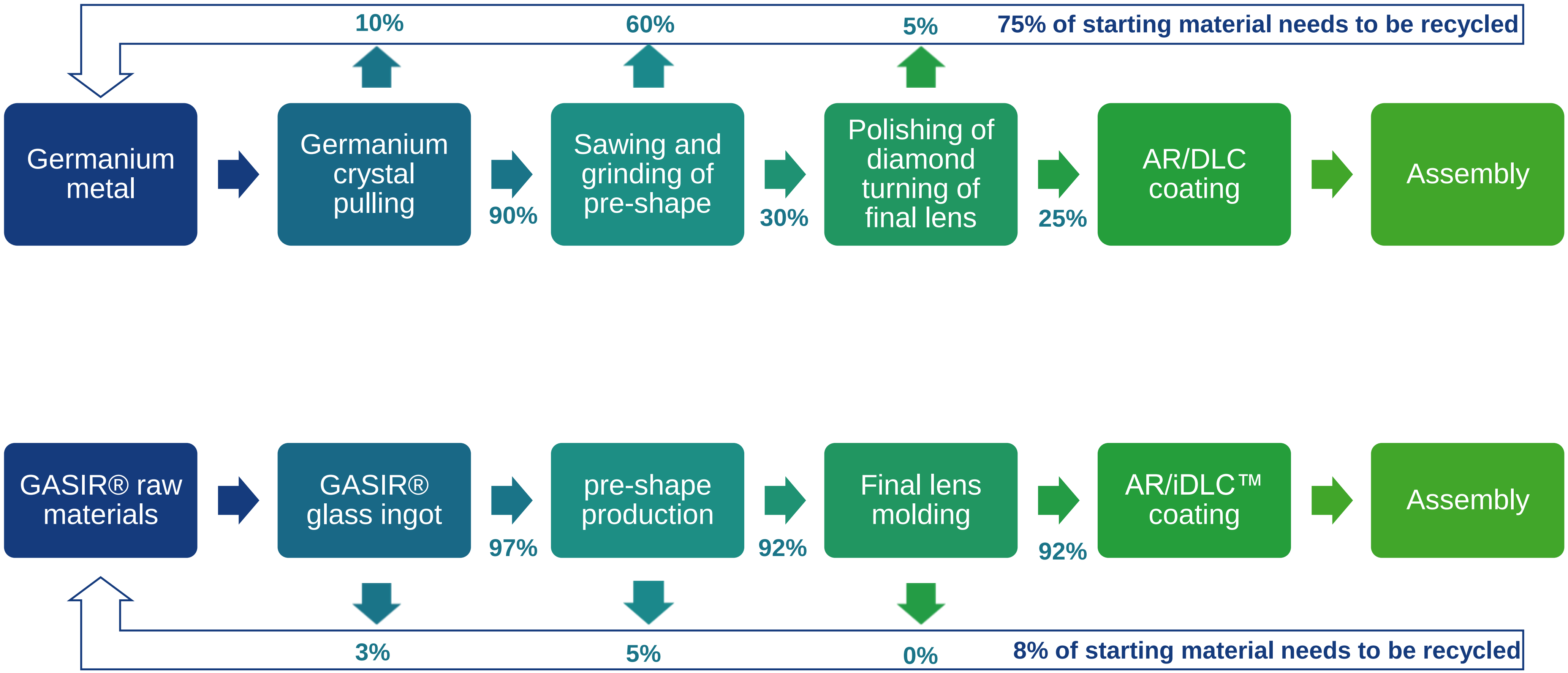
Germanium vs. Chalcogenide manufacturing



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umicore

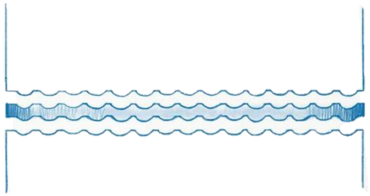
Cost Reductions driven by Technology Roadmap

2m – 10m units per year enables different technology routes

Glass

Material

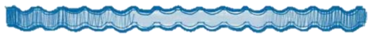
- Technology improvements to glass manufacture
- Technology improvements to pre-shape process



Molding

Molding

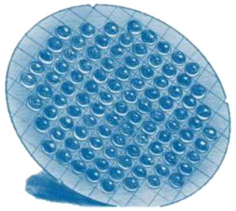
- Improved tooling
- Automation of load/unload



Coated wafer

Coating

- Larger coating chambers with improved tooling



Diced lens wafer

Coated Lenses

Lens assembly

Assembly & Test

- “Pick and place” assembly automation
- Dedicated fast test station with automated load/unload

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Umicore Tessella™

Wafer molding technology

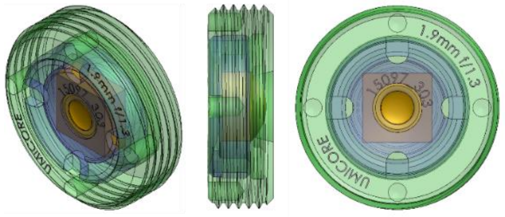
An enabling technology for high-volume, cost-effective thermal optics

Advantages

- ✓ Optimum number of lenses per molding shot
- ✓ Highest number of lenses in the coating chamber
- ✓ Reduced handling costs

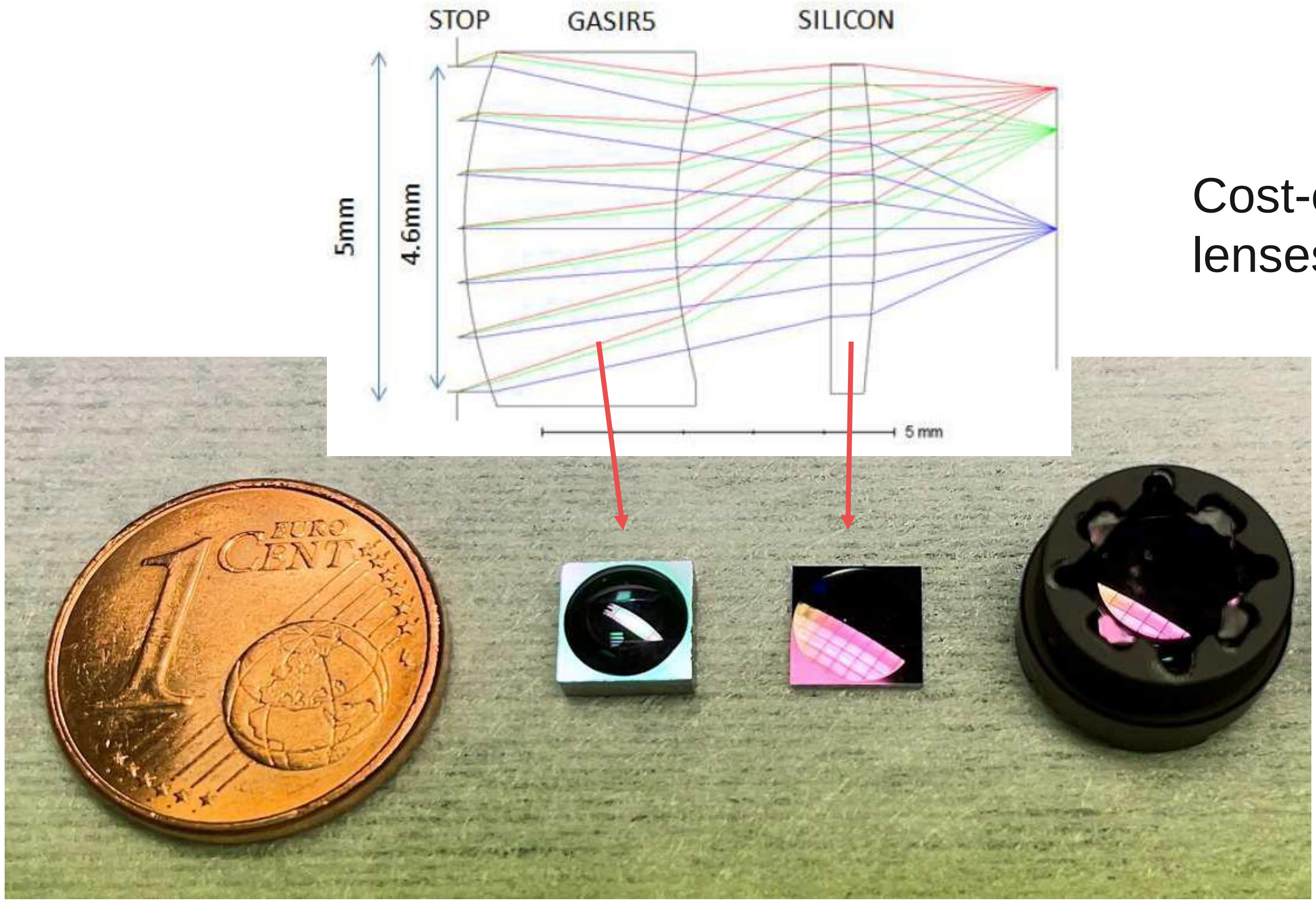
Important to note

- ❖ Limited to small size optics < 4mm
- ❖ Tooling investment cost



Wafer level optics (WLO)

Umicore Tessella™



Cost-effective infrared lenses for small sensors

Source:
G. Druart et al., Study of infrared hybrid Chalcogenide Silicon lenses compatible with wafer-level manufactuing process for automotive application, SPIR Optical Design and Engineering VIII, 2021

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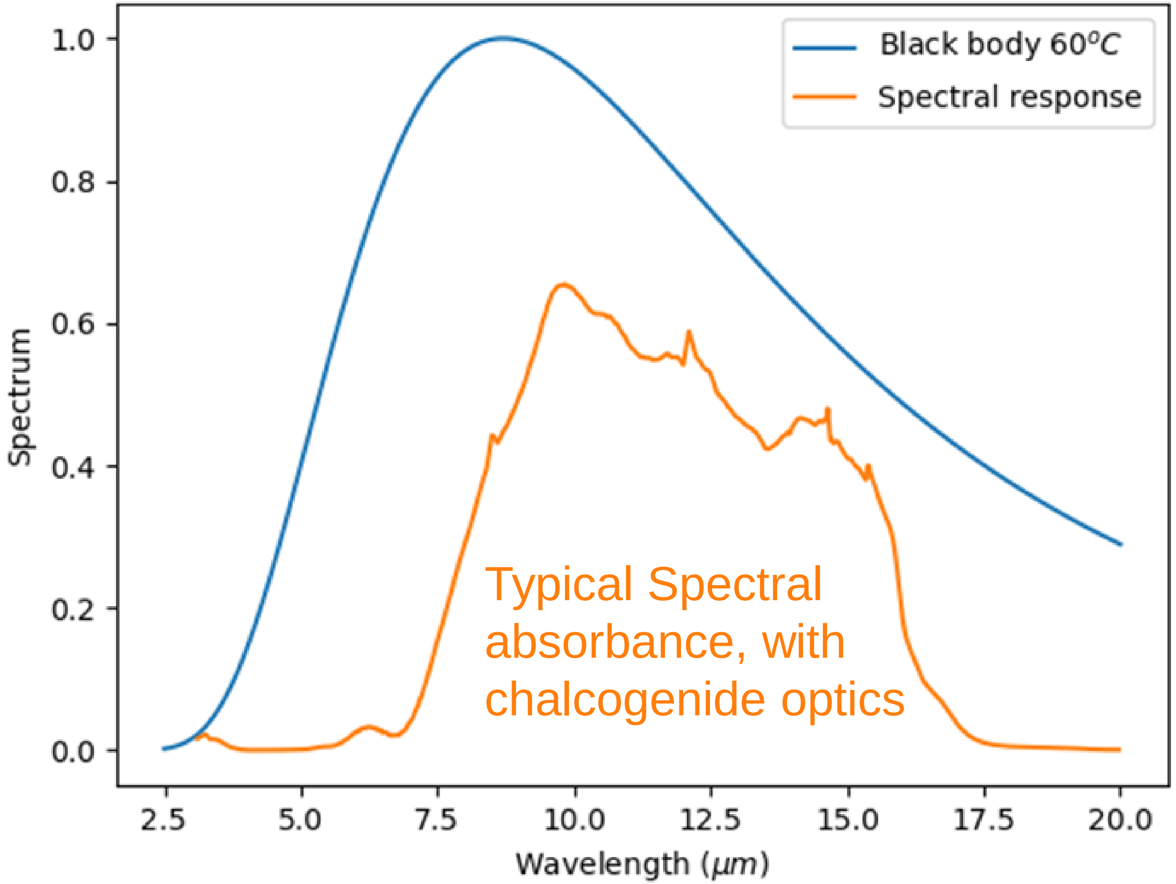
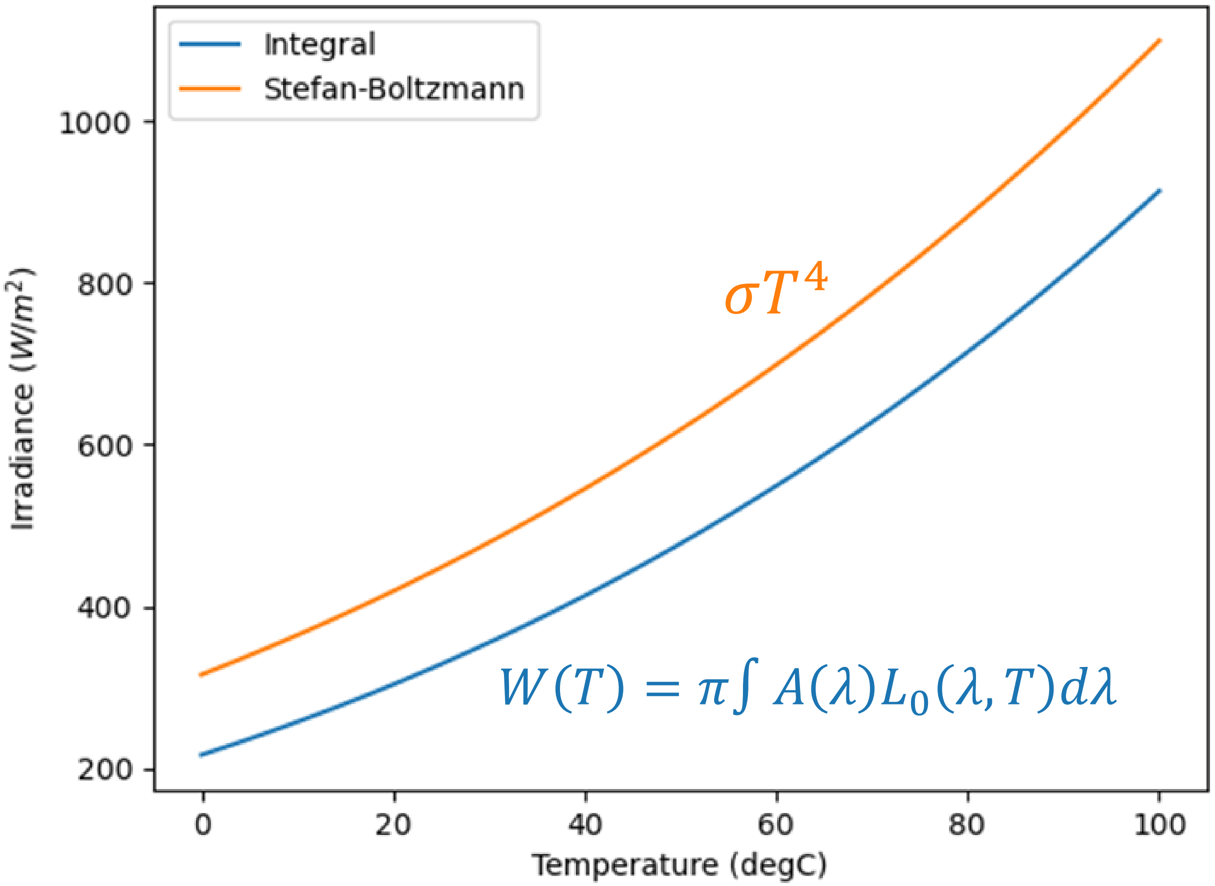
LWIR radiance





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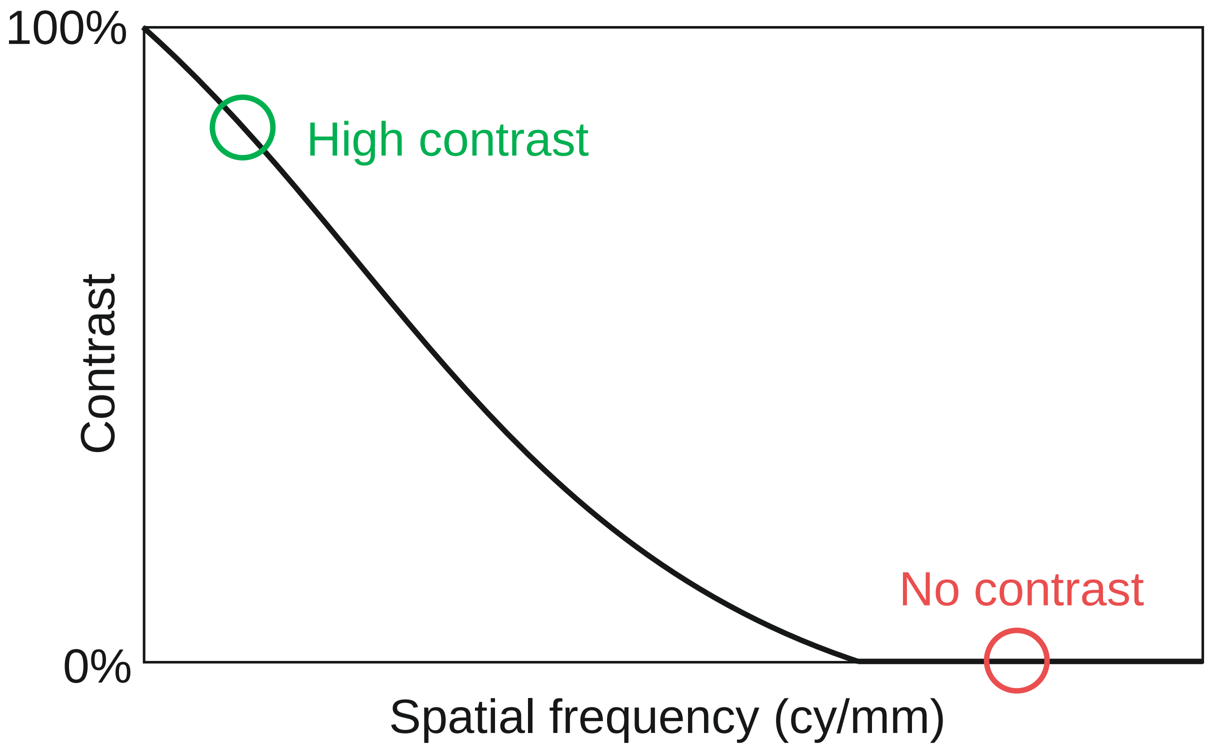
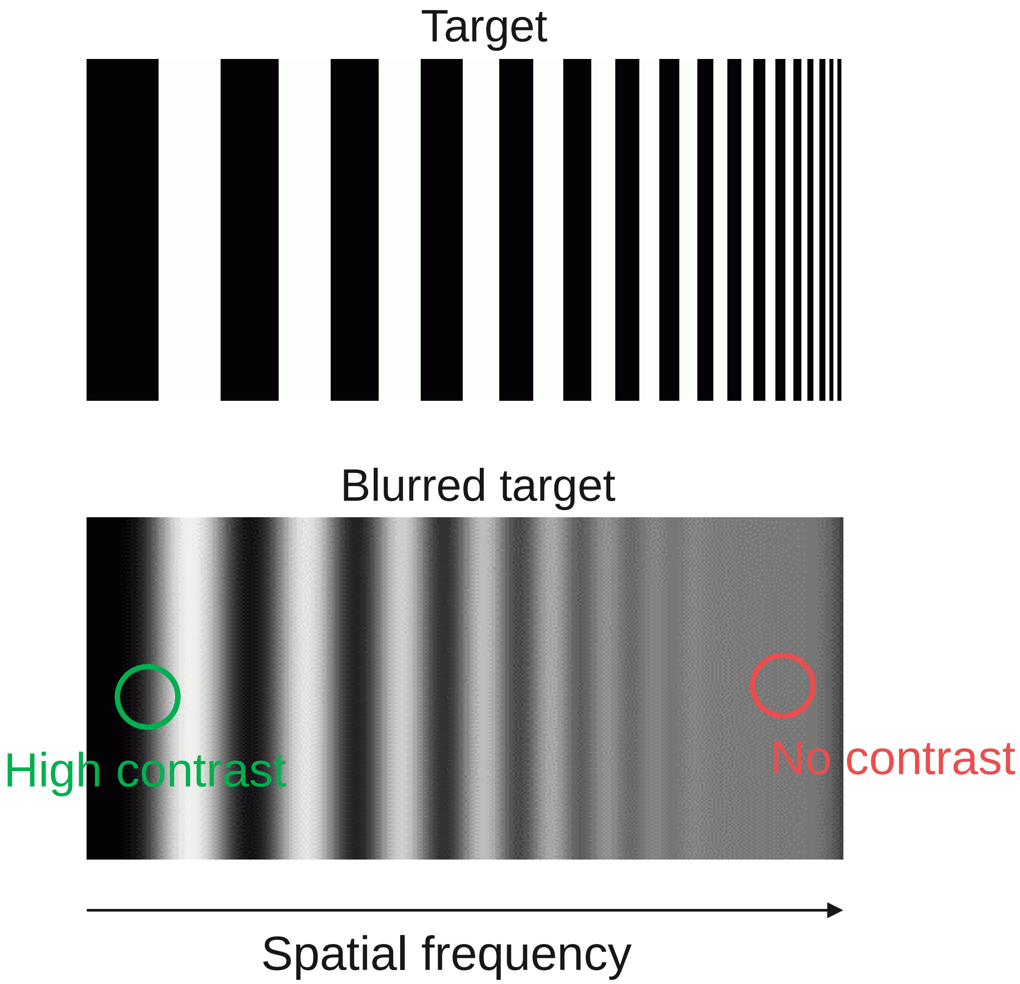
Camera performance metrics

Modulation Transfer Function (MTF)

Represents the ability the resolve fine details

MTF is the Fourier transform of the PSF





MTF of an optronic system

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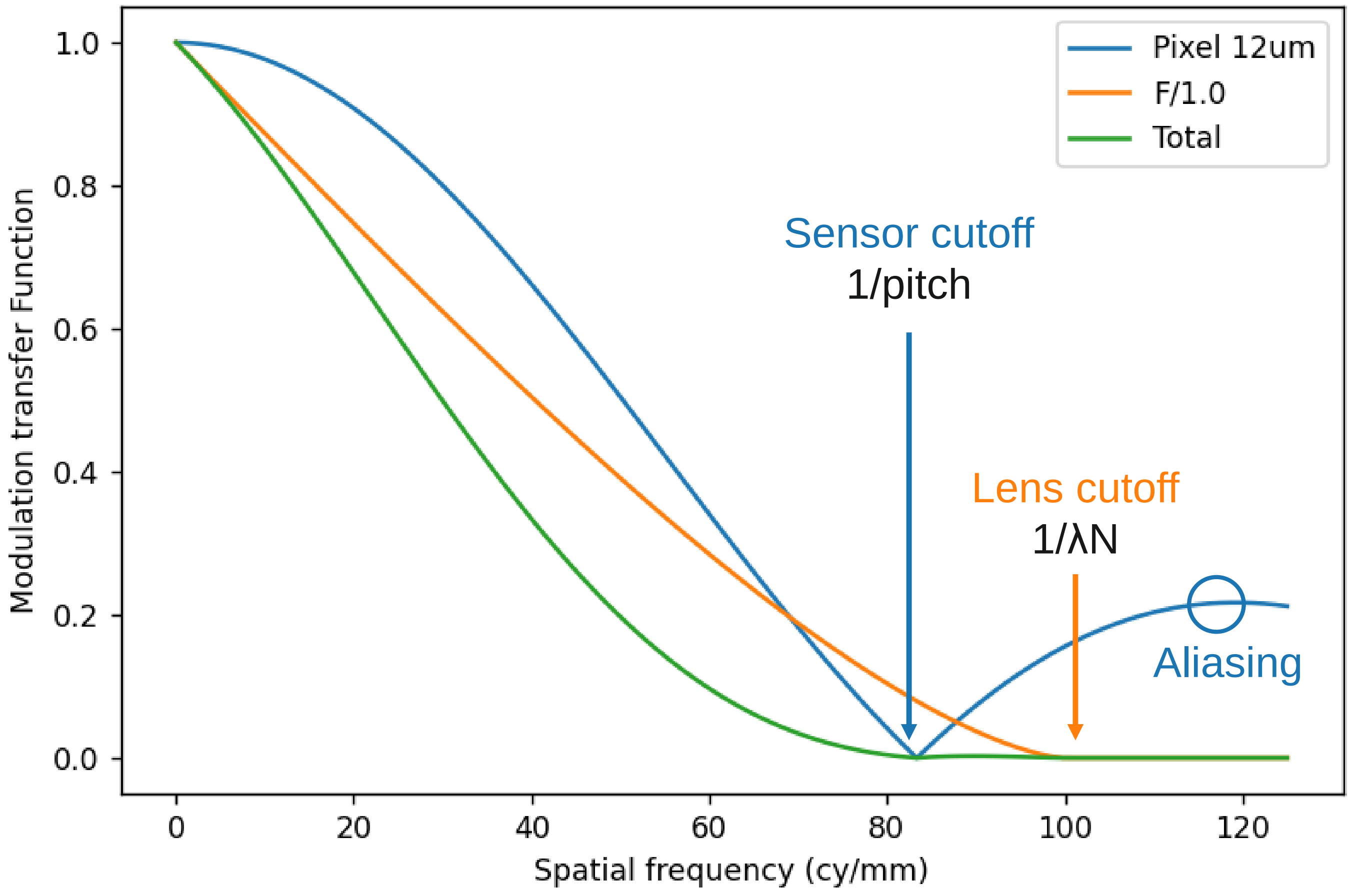


Lens cutoff frequency: $\nu_c = \frac{1}{\lambda N}$

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

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

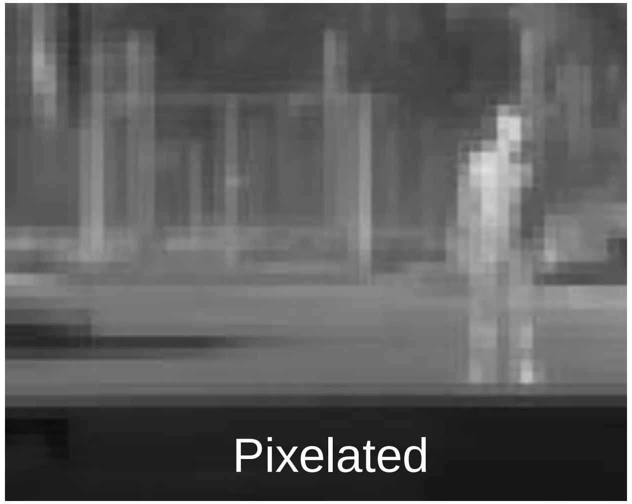
$$MTF_{total}(\nu) = MTF_{lens}(\nu).MTF_{pix}(\nu)$$

(ideal formulas)

Here : $\frac{1}{p} < \frac{1}{\lambda N}$

→ The resolution is limited by the sensor, not the lens

What’s limiting the resolution ? Lens or pixel ?



$$\frac{1}{p} < \frac{1}{\lambda N}$$

The resolution is limited by the sensor, the image is aliased
→ Undersampled

$$\frac{1}{p} \approx \frac{1}{\lambda N}$$

The lens is a perfect anti-aliasing filter
→ Well sampled

$$\frac{1}{p} > \frac{1}{\lambda N}$$

The resolution is limited by the lens’s diffraction
→ Oversampled

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Responsivity

Expresses the camera's sensitivity to temperature variation

We take two averaged uniform images in front of a blackbody : Hot & Cold

$$Resp[LSB/K] = \frac{\overline{Img}(T_2) - \overline{Img}(T_1)}{T_2 - T_1}$$

Blackbody
@HGH

Responsivity depends on :
- Sensor (e.g. pixel pitch)
- FPA temperature
- Lens aperture (f/#)
- Optics/window transmission
- Camera settings

Noise Equivalent Temperature Difference (NETD)

Expresses the camera's ability to distinguish small temperature differences

Equivalent to SNR=1

L Y N R E D

$$NETD[mK] = \frac{\sigma[LSB]}{Resp[LSB/K]}$$

Temporal standard deviation of a unform scene (blackbody)

Typical values:

- ATTO640D-02 sensor : <50mK
- ATTO640 camera with optics : ~60mK

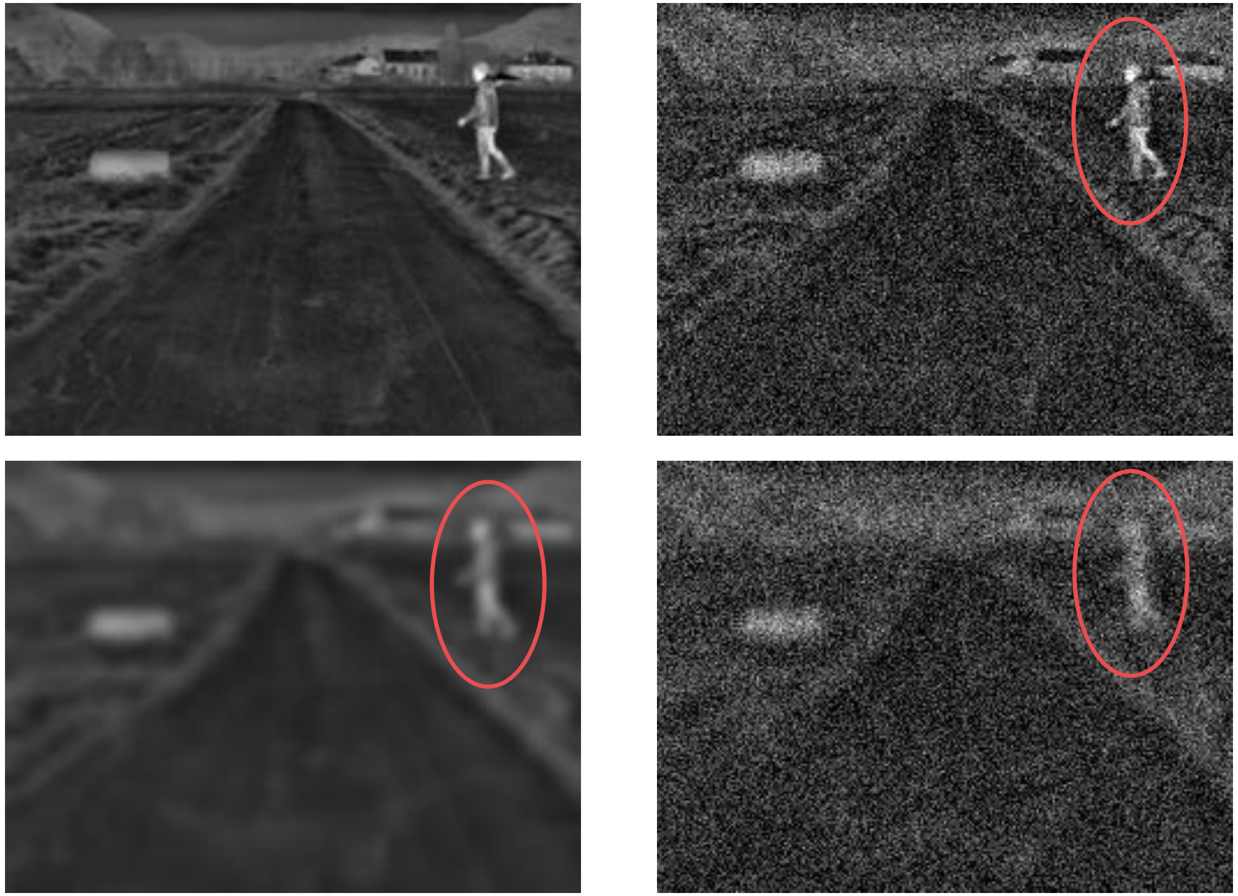
Minimal Resolvable Temperature Difference (MRTD)

Noise Equivalent Temperature Difference

Detector performance
Optic aperture

Modulation
Transfert
Function

Detector design
Optic design



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

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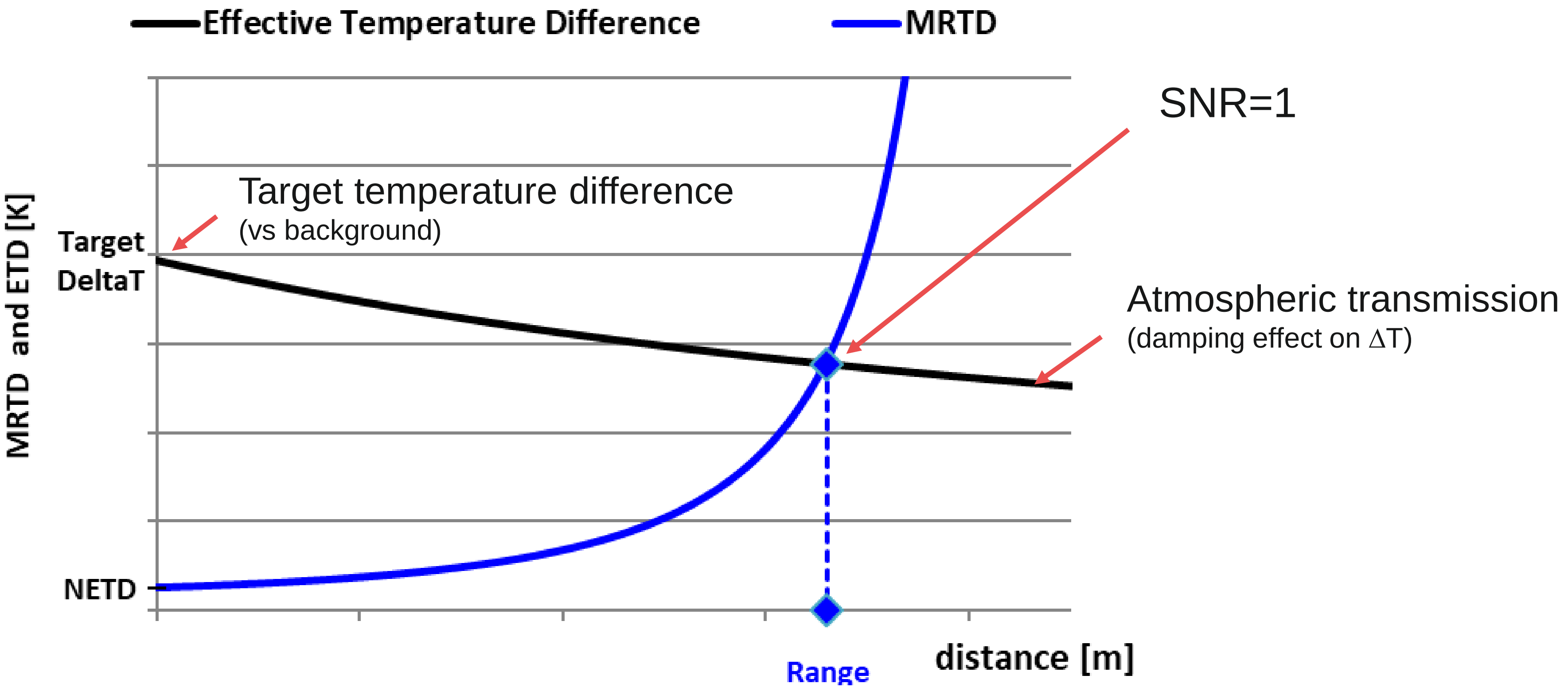
Range simulation

Range: distance where SNR=1

ETD : Effective Temperature Difference



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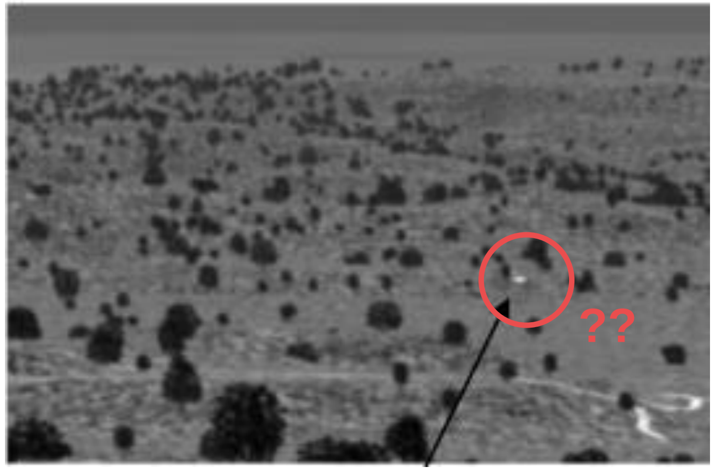
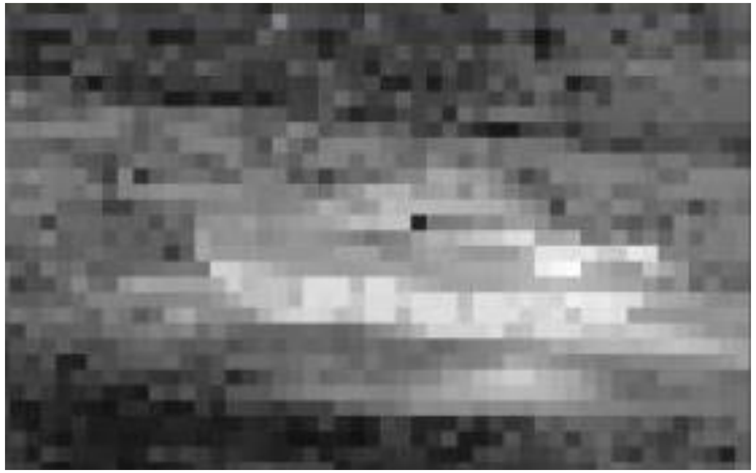
DRI : Johnson criteria

Let's borrow tools from the military !





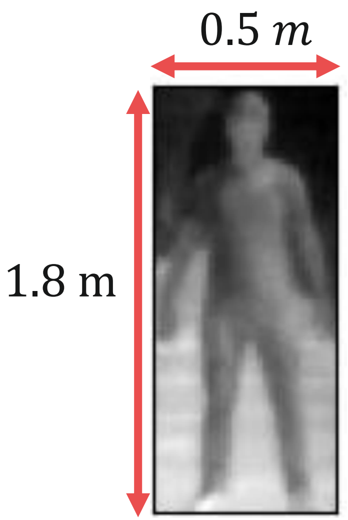
Detection:
I can see something

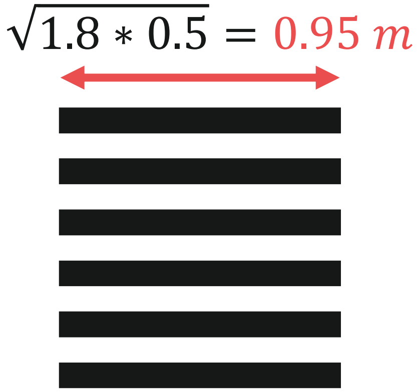
Recognition:
I know it's a tank

Identification:
I understand if he's an enemy or not

L Y N R E D

DRI range for a human





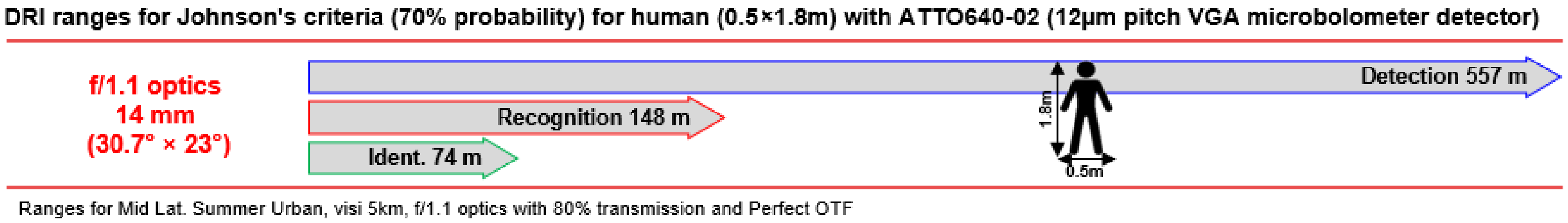
Equivalent target bar pattern

Criteria for 50% probability:
- Detection = 0.75 cycles
- Recognition = 3 cycles
- Identification = 6 cycles

DRI range estimation

Theory

f/1.1 optics
14 mm
(30.7° × 23°)



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Hot summer

ΔT=0.5°C temperature difference*

Identification Recognition

30m 70m 150m

*It really depends on both the target and background texture !

Image processing

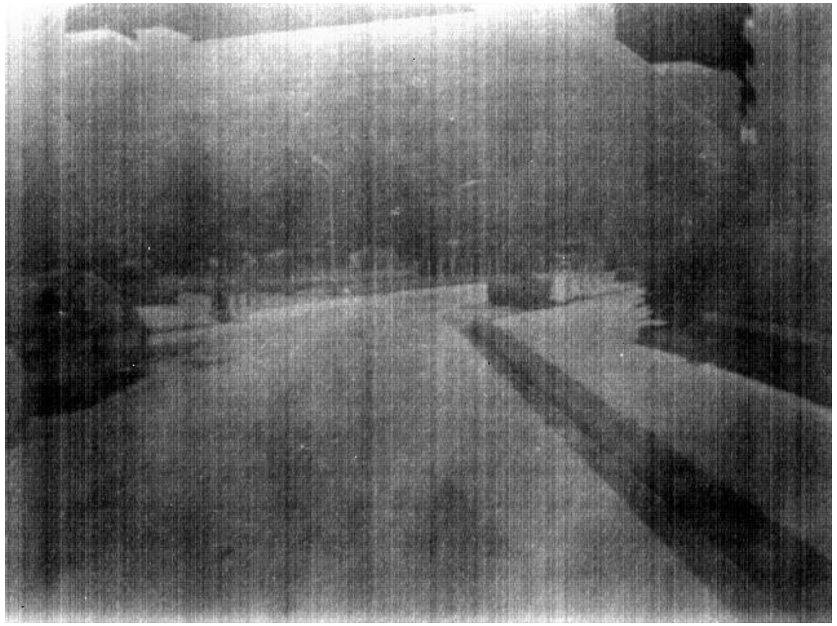
Non Uniformity Correction (NUC)

- Removes the fixed pattern noise (FPN) due to the pixels response dispersion

$$I_{corr} = G(Raw - O)$$

→ Gain and offset map are obtained during the **factory calibration**
Depends on sensor's temperature

Raw



NUC

Click!

NB: A mechanical shutter can be used to update the Offset map when the sensor's temperature drifts,
The stream is interrupted during the aquisition of the new reference (shutter closed)

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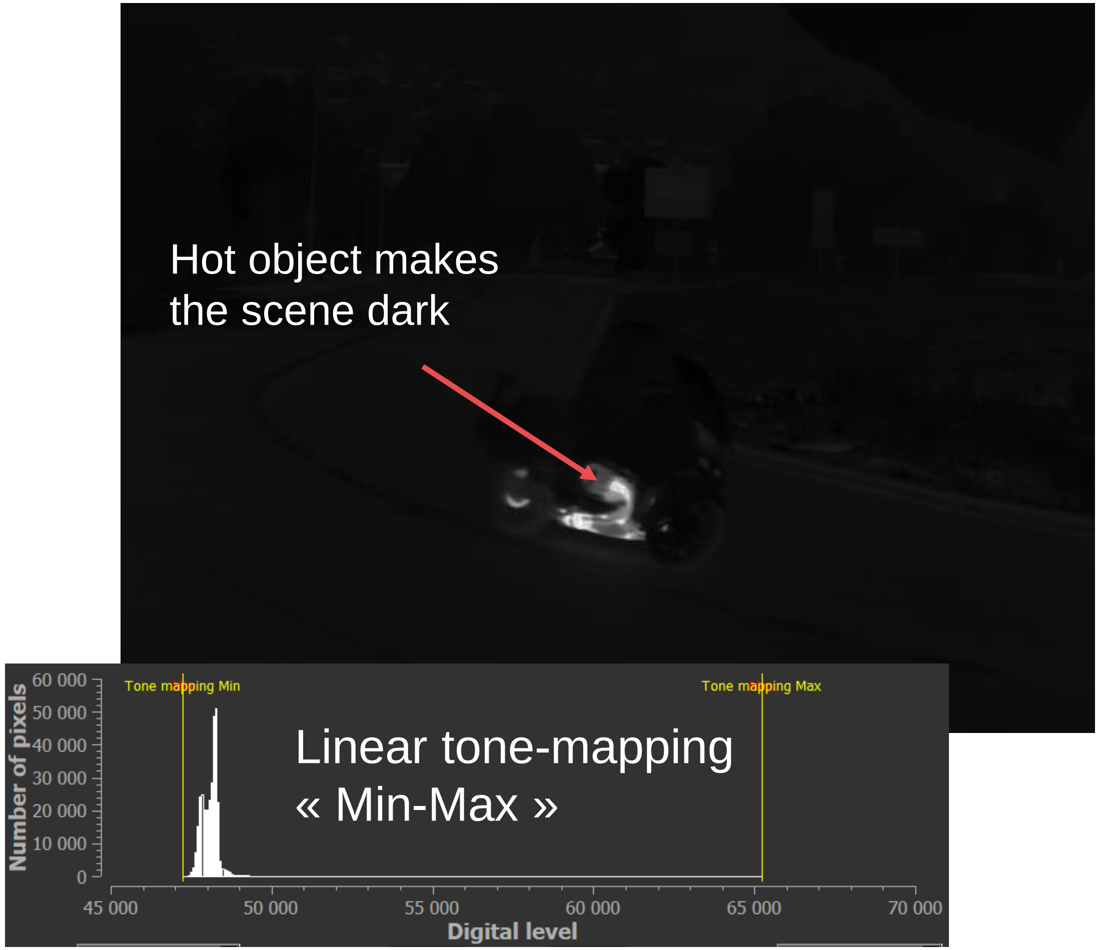
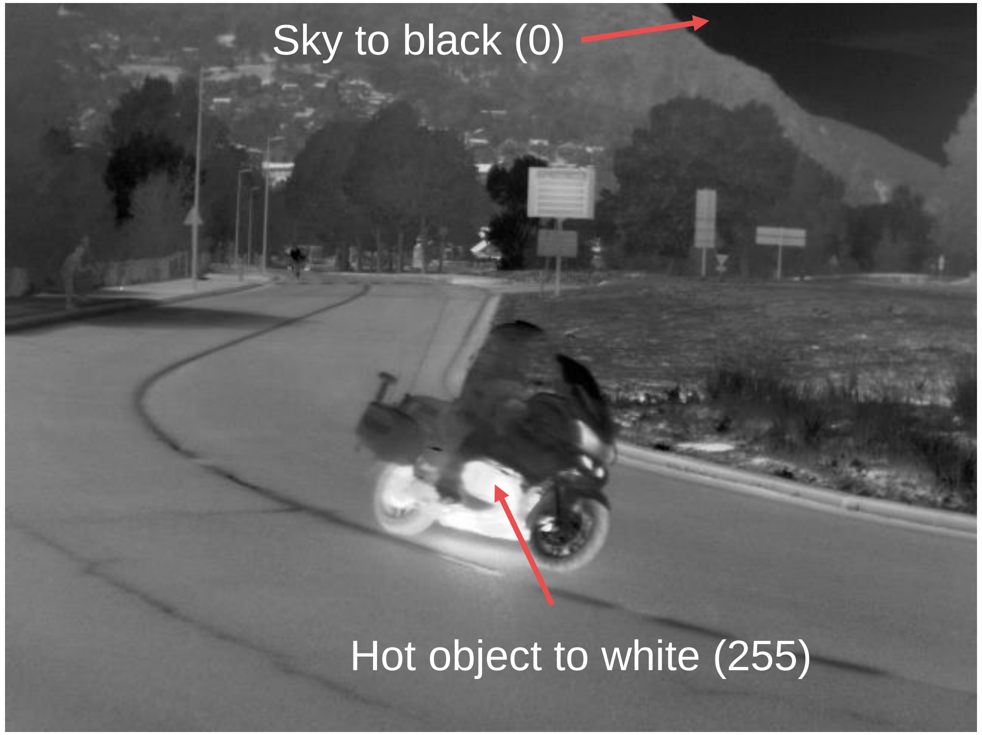
Tone-Mapping (or Automatic Gain Control, AGC)

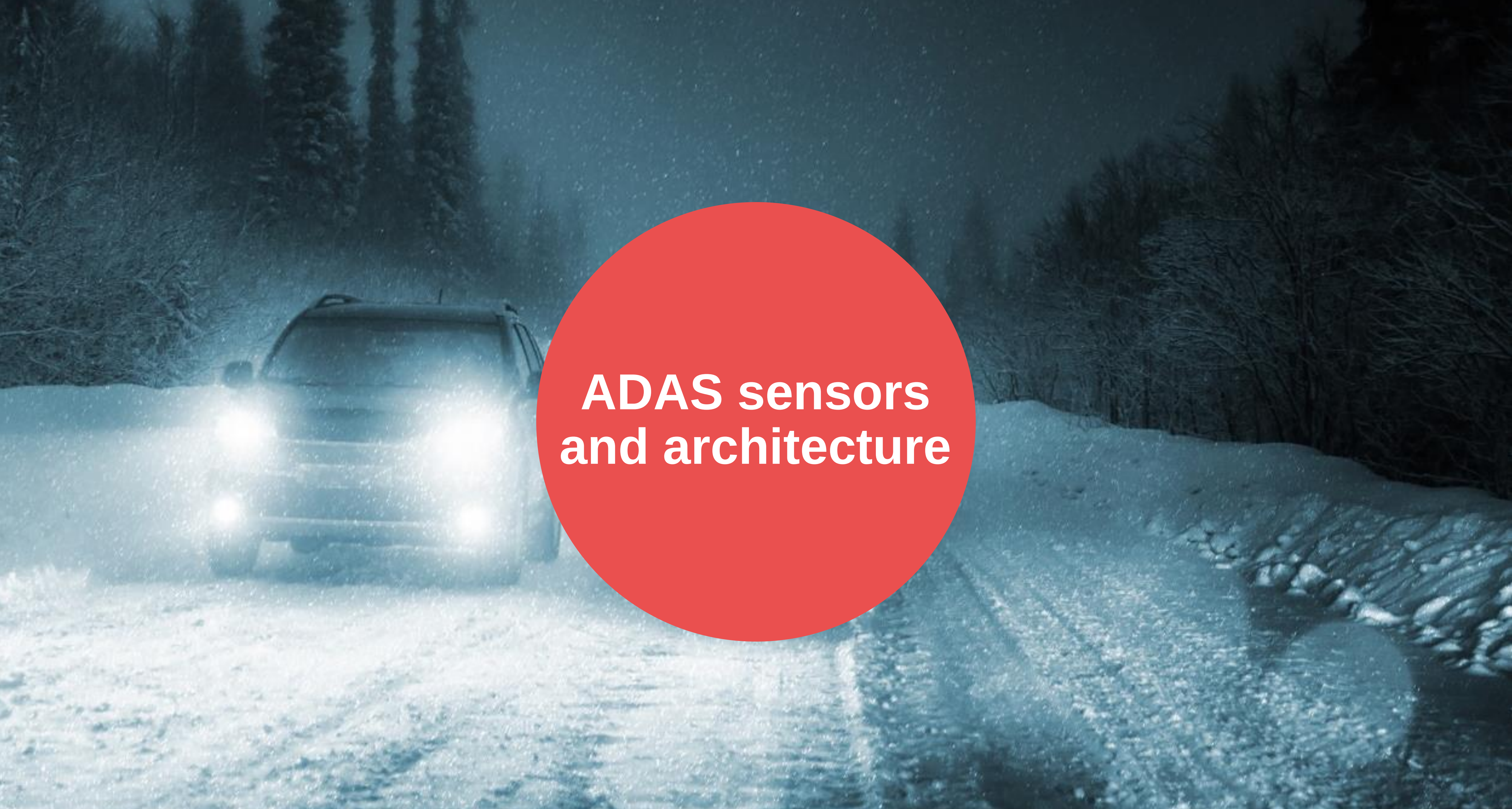
Display full thermal dynamics (+200°C) from 16bits to a displayable image in 8its grayscale

Like an HDR algorithm



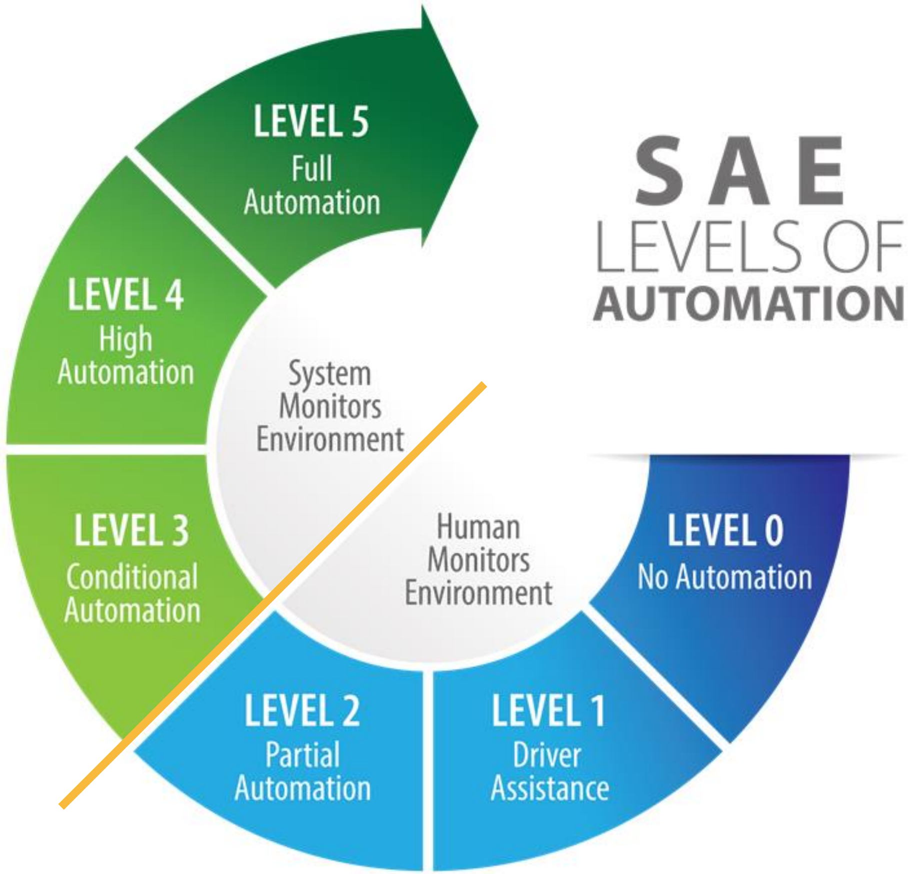


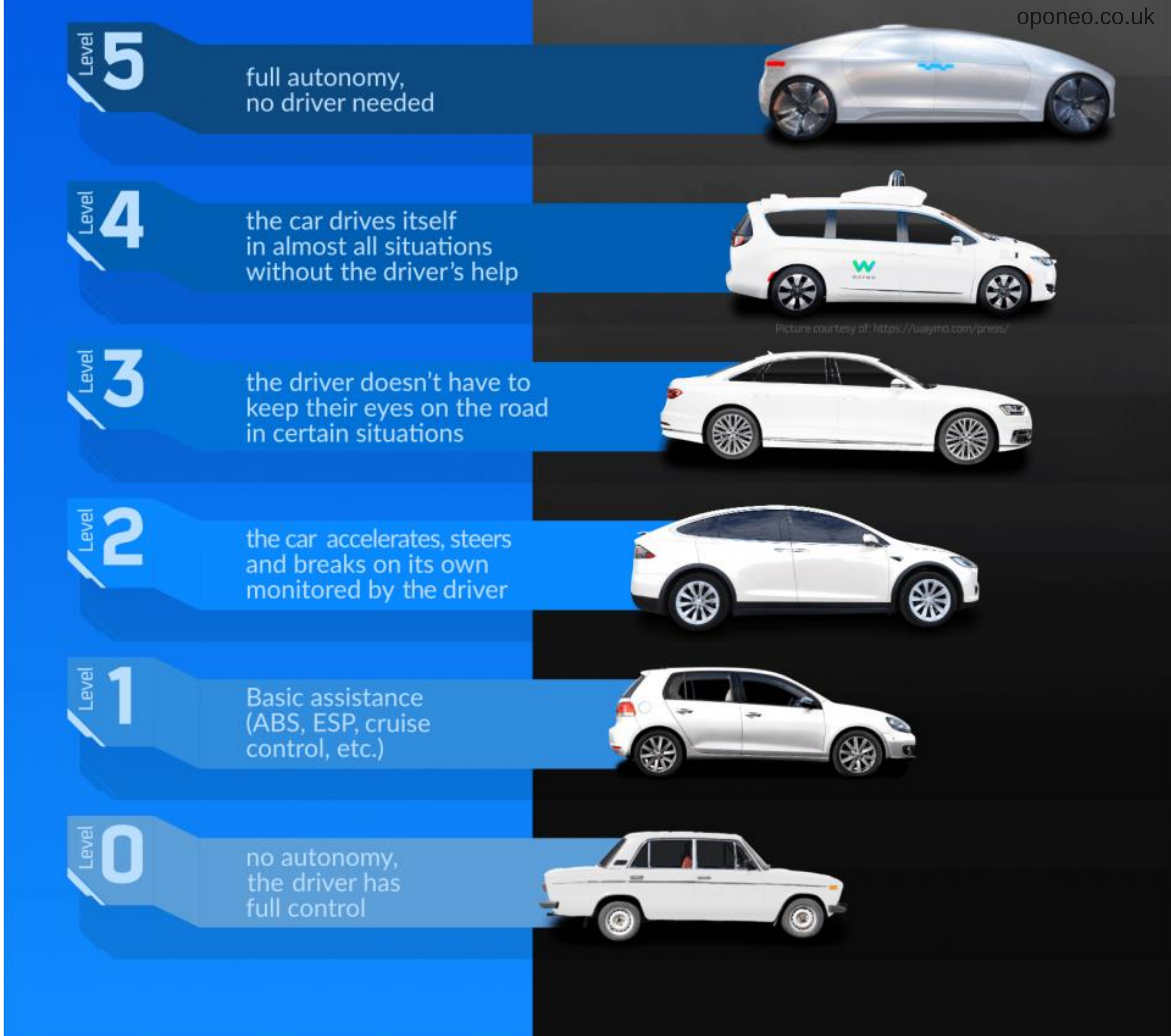
Histogram equalization
(plateau 1%)



ADAS sensors and architecture

Advanced
Driver
Assistance
System





Autonomous vehicle architecture

Sensor › Perception › Planning › Control

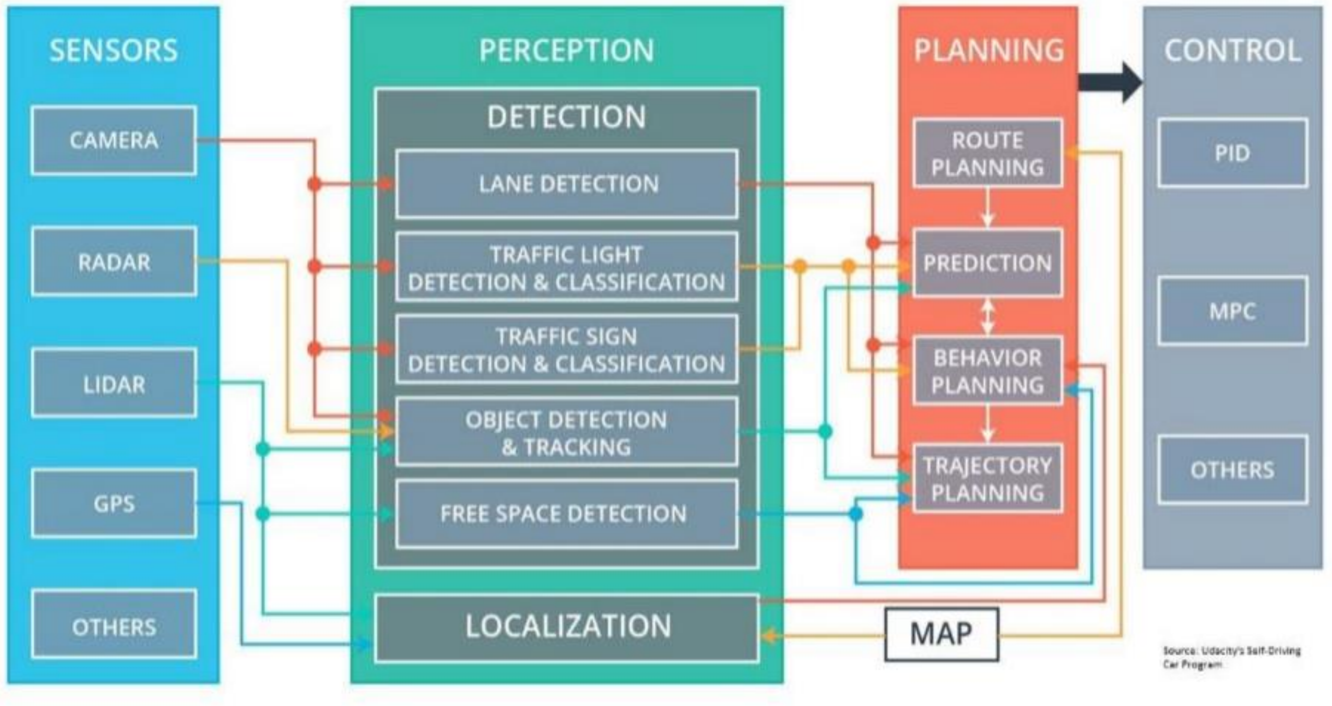


Figure 1: Autonomous vehicle functionality breakdown. Source: Udacity Self-driving Program.

Source: Udacity, Boeing

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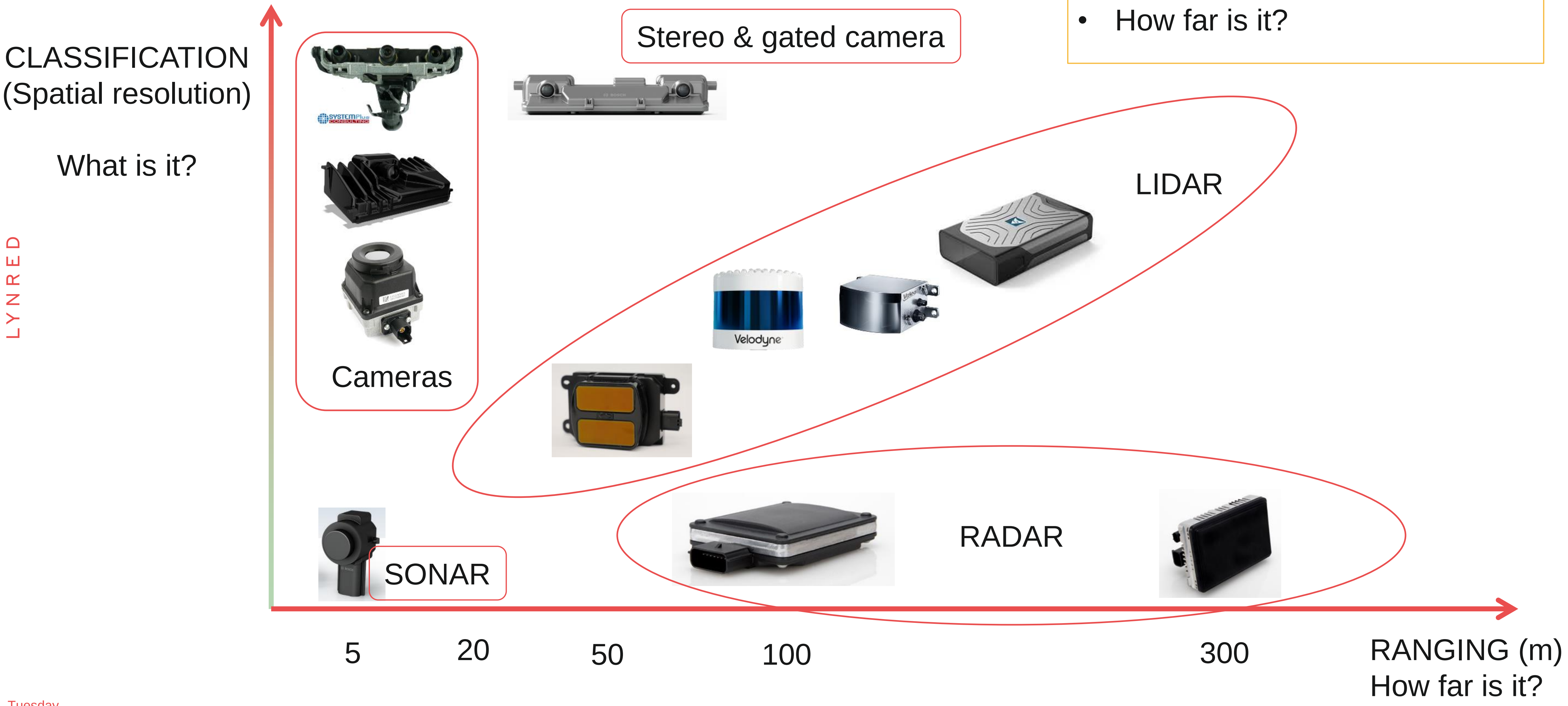
Sensors playground for ADAS

Wave type	Electro-magnetic					Acoustic
Band	VISIBLE	NIR 905 nm	SWIR 1550nm	LWIR	Micro wave 24 & 77 GHz	Ultrasound 58 KHz
Sensor	CMOS Image Sensor (CIS)		InGaAs or CQD	Bolometer	GaAs sensors	Ultrasonic sensor
Passive application	Camera, (Mono, Stereo, Triple)		Camera	Camera (Mono, Stereo)		
Active application	Gated camera, LIDAR				RADAR	SONAR

ADAS sensor portfolio

An ADAS vehicle needs to know:

- What is it?
- How far is it?



Main sensors for AEB

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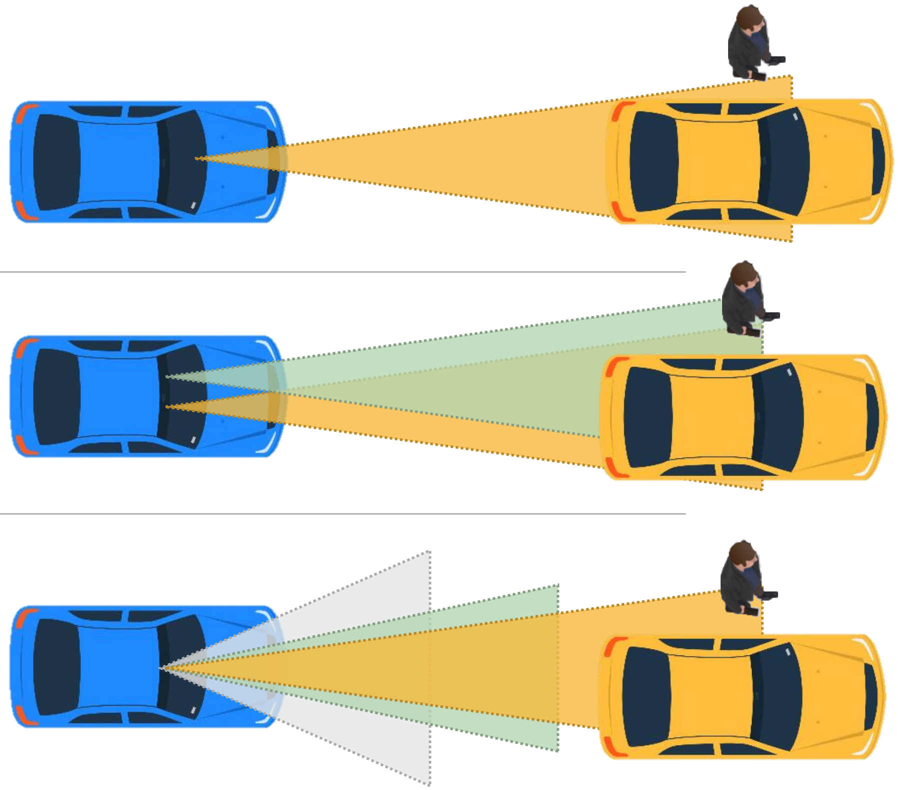
RGB cameras
for
CLASSIFICATION

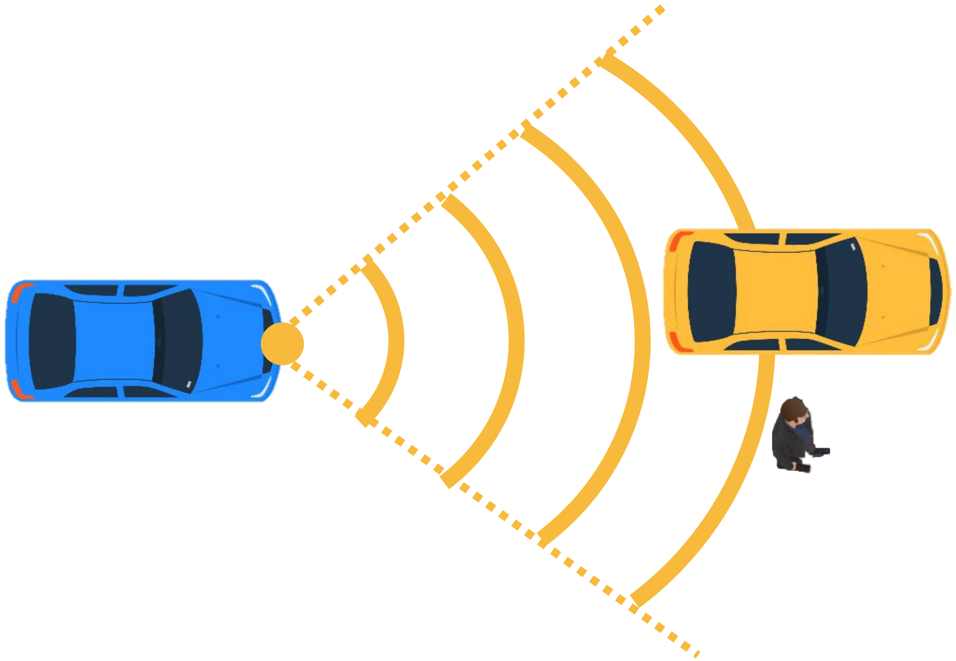
MONO

STEREO

TRI-
FOCAL



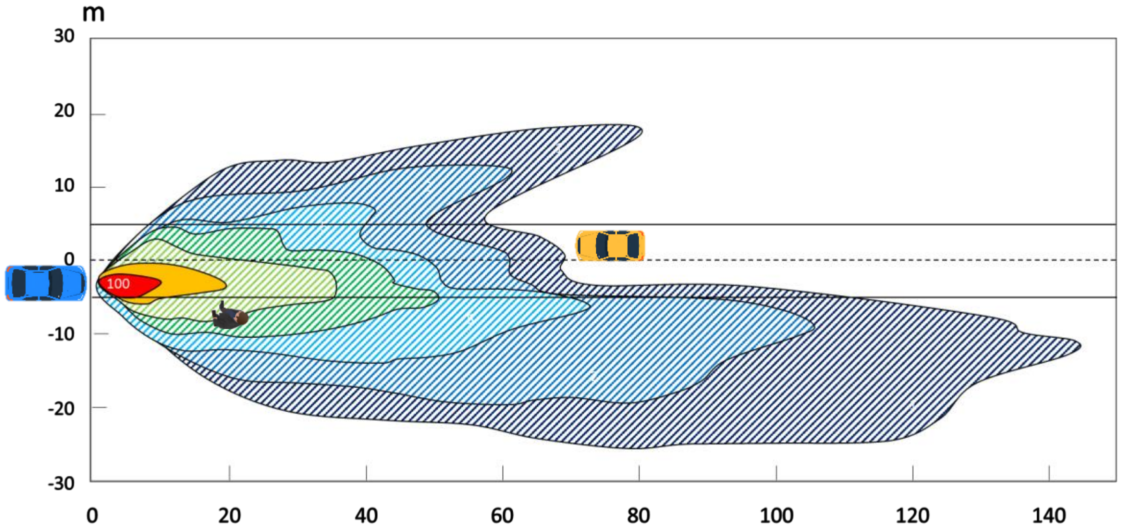
RADAR
for
RANGING



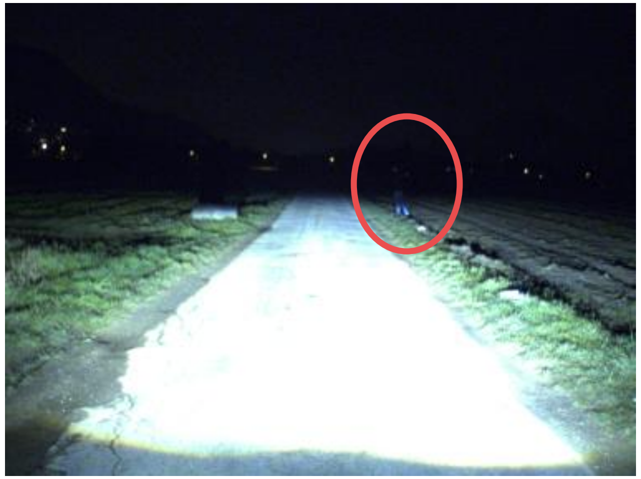
Current AEB sensors limitations

Sensor	Limitation	Examples
RGB camera	Low light	Night: rely on streetlight
	High Dynamic Range	Vehicle glaring, tunnel exit, sunrise/set
	Adverse conditions	Rain, snow, fog
RADAR	Spatial resolution	Pedestrian in front of a car

RGB camera is not reliable in reduced visibility where fatalities happens



Xenon low beam isolux



Pedestrian at 20m

Thermal is complementary to RGB

Grenoble city at dusk

VISIBLE THERMAL

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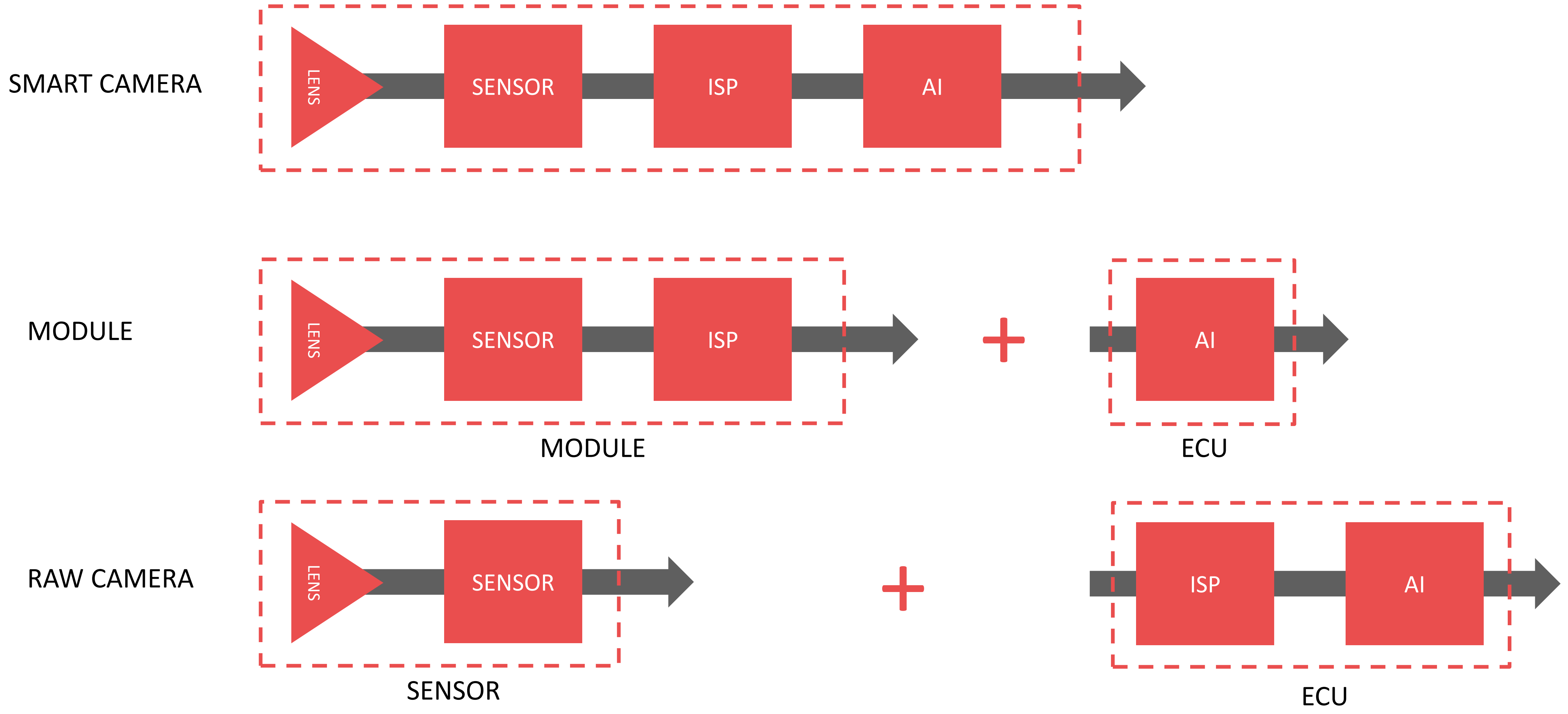
Architecture – 3 options

ISP : image quality
AI: Artificial intelligence
ECU: Electronic control unit



Camera integration in automotive

Lynred Automotive Development Kit (ADK)

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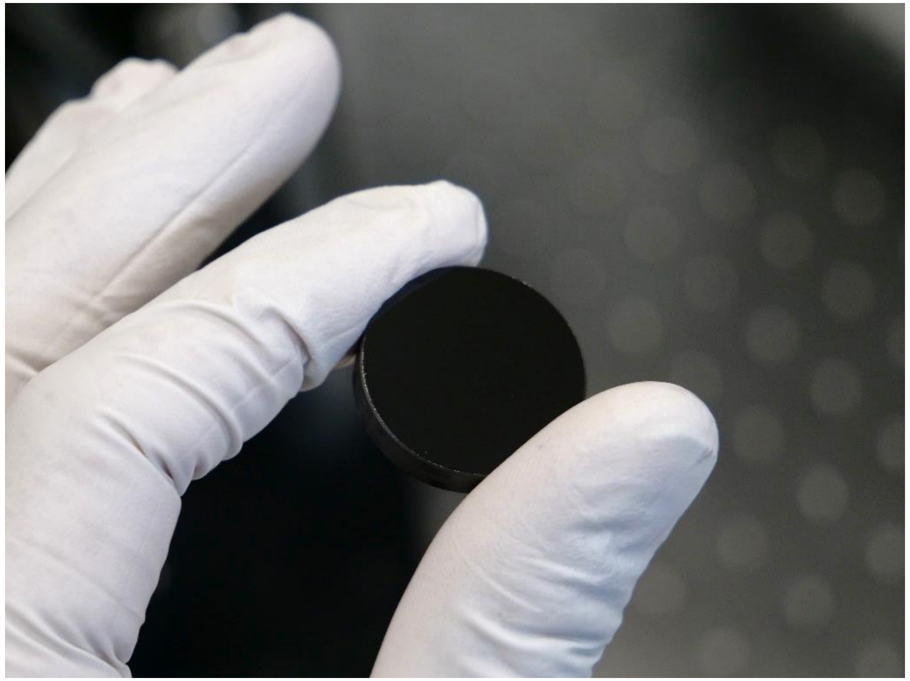
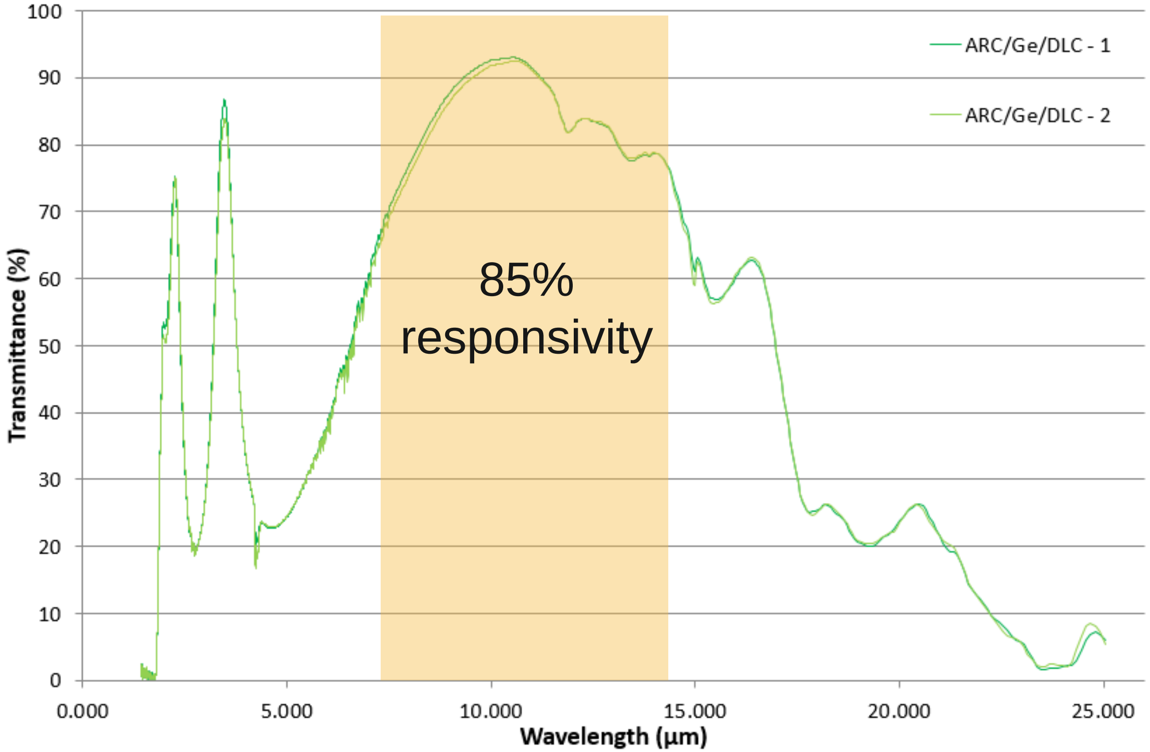
Not for sale. Only available under NDA and Loan Agreement with Lynred

Water proof casing
Infrared Window
Heating/Defrosting (12V compatible)

VGA 12µm, USB camera
Available lenses:
- 14mm f/1.0 → HFOV 31°
- 8.8mm f/1.0 → HFOV 50°
- 6.2mm f/1.0 → HFOV 75°

Infrared Window





DLC : Diamond-Like Carbon coating
Resistance to severe abrasion (MIL-C-675C military specifications)
Black aspect

Windshield integration

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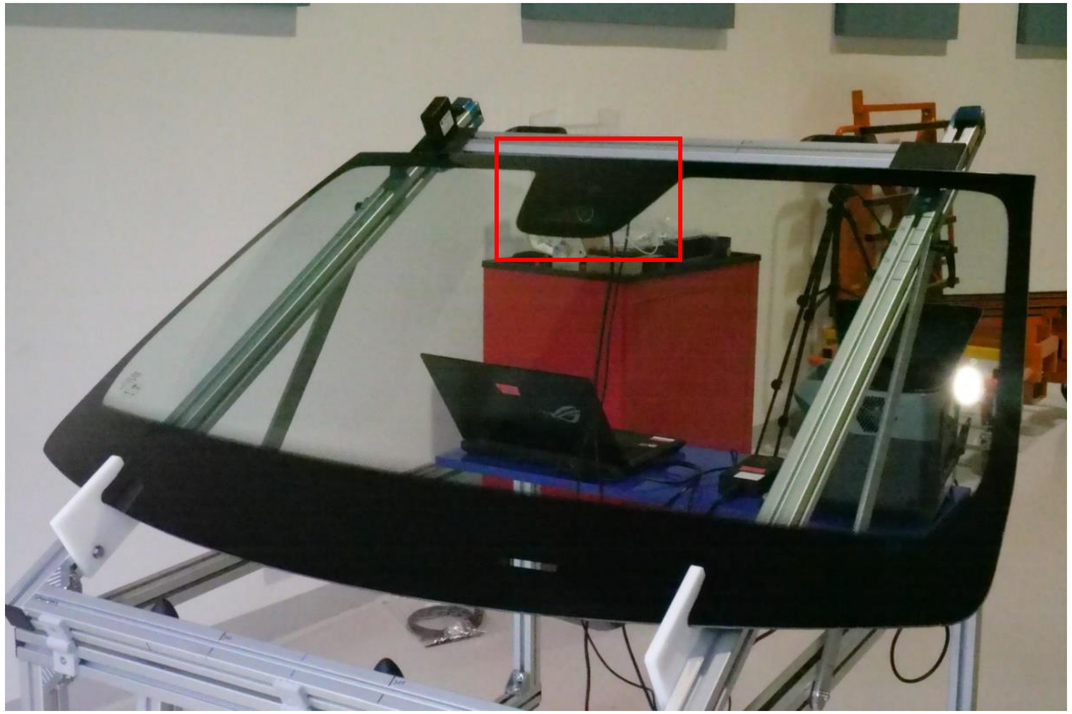
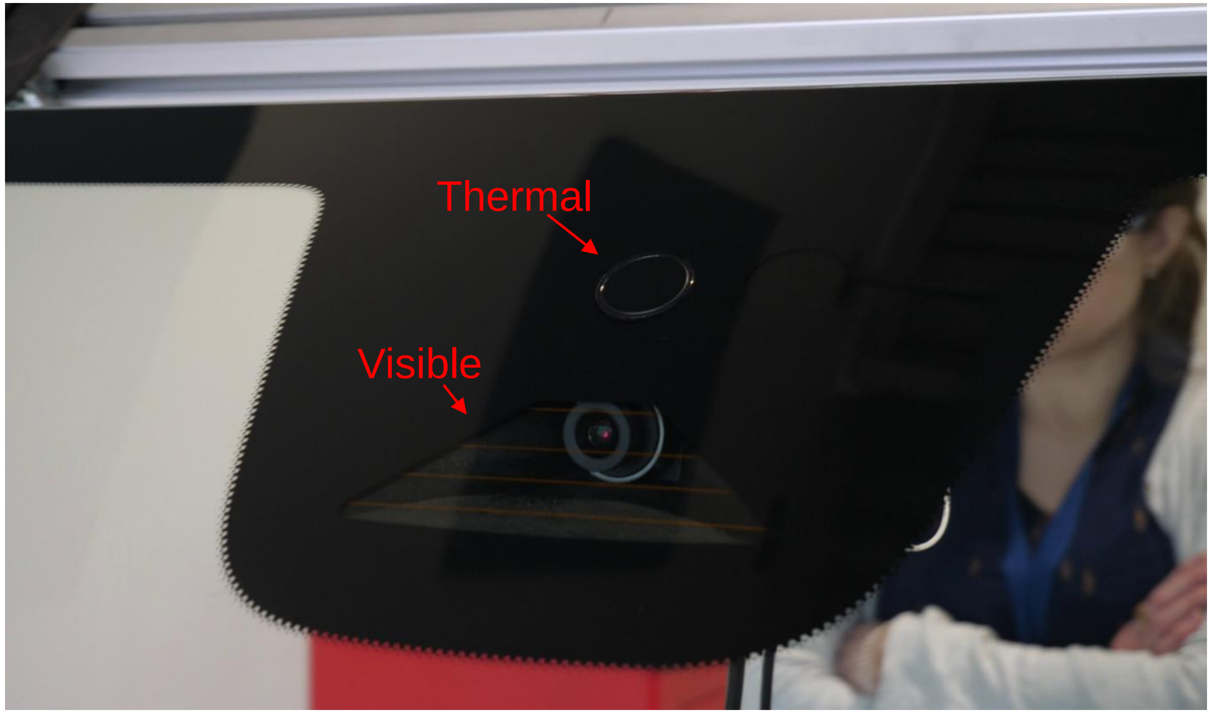




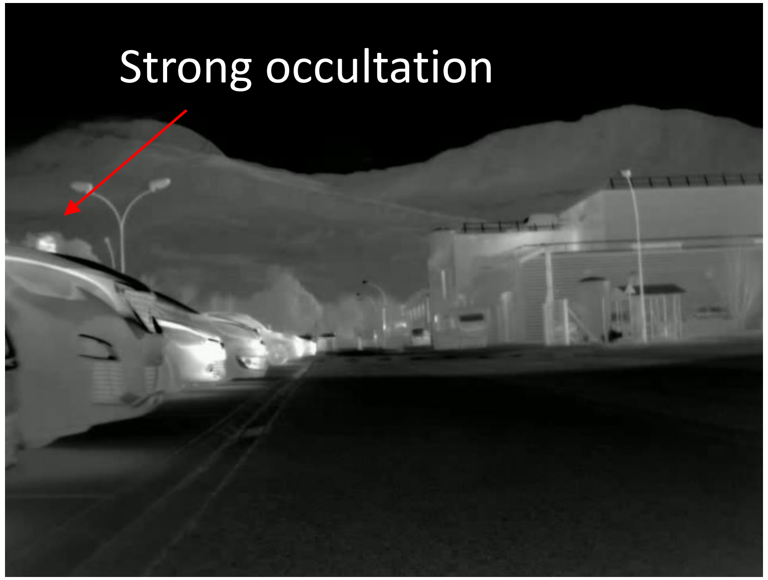
Come visit our booth !

Lynred x Sekurit

Bumper or windshield ? Point of View

Windshield PoV

Bumper PoV



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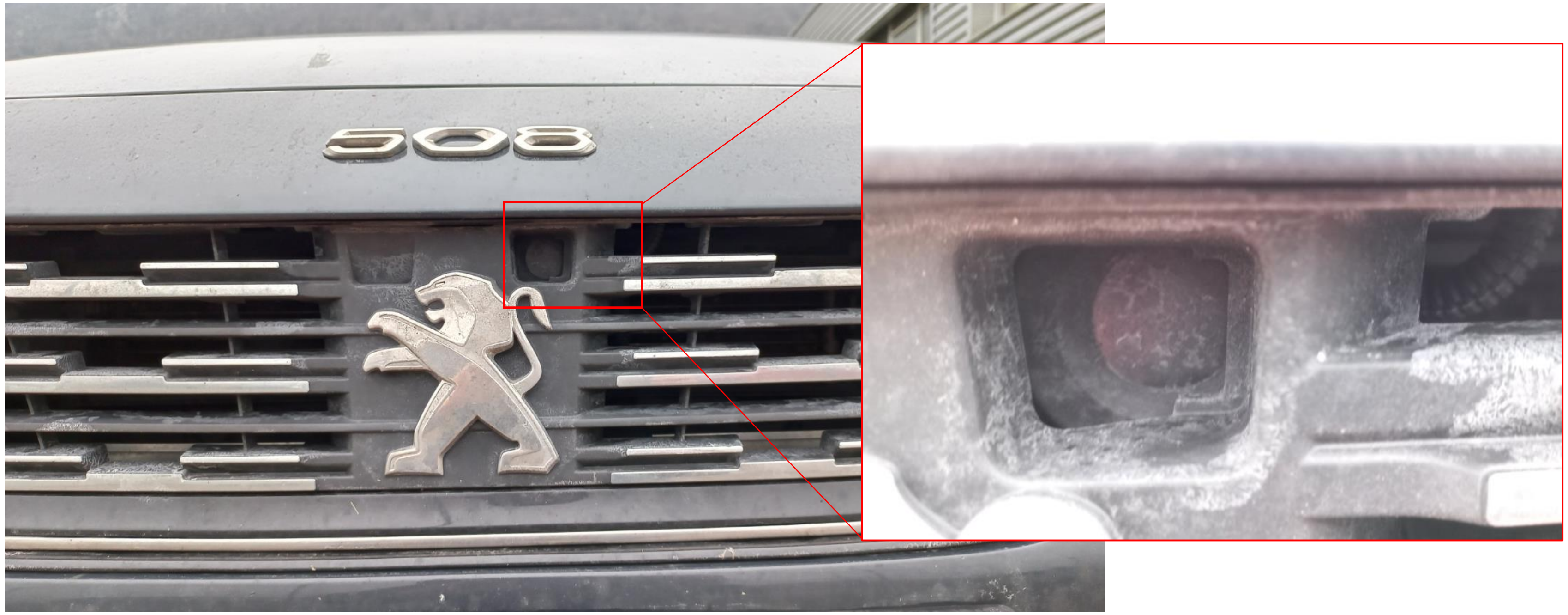
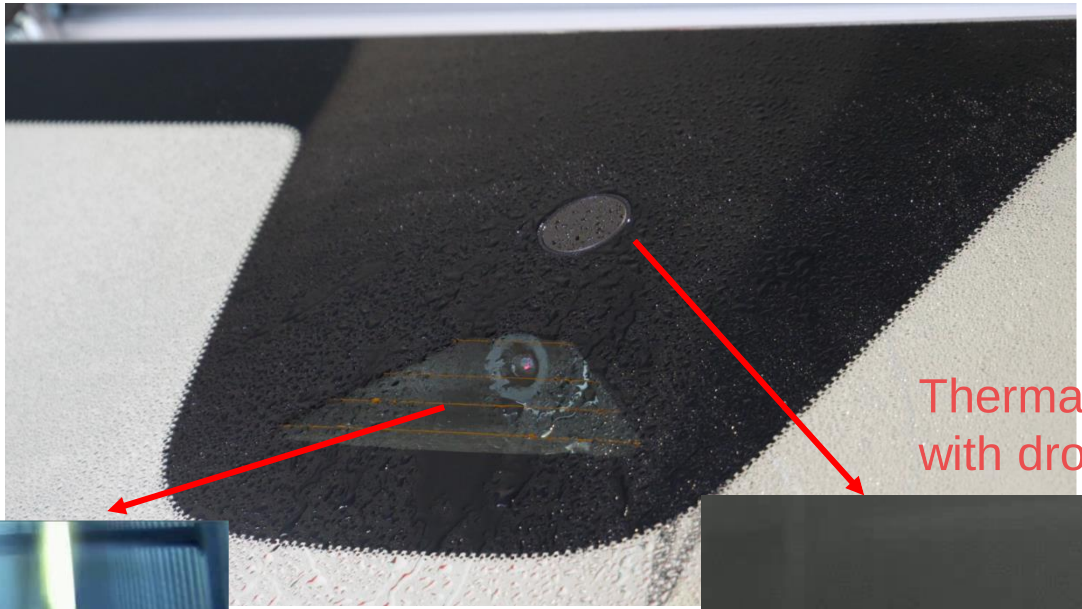
Bumper or windshield ? Soiling



The bumper is not quite the cleanest place to put a camera

L Y N R E D

Impact of droplets



Visible image is distorded by the droplets

Thermal still performs well even with droplets on the window

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Computer vision for automotive

Trouver le lien public de la publi JRC

Inferrence of thermal images

Thermal Image

Inferred thermal image

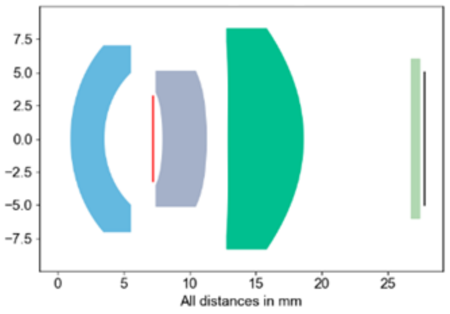
Inference with Resnet50 Neural Network

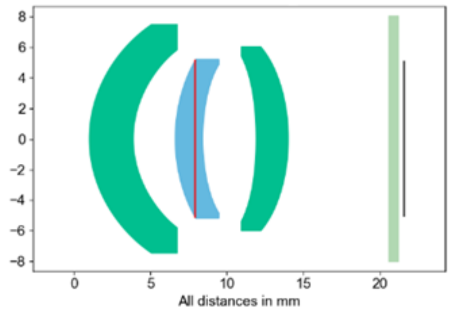
Fine tuned with 5000 thermal images

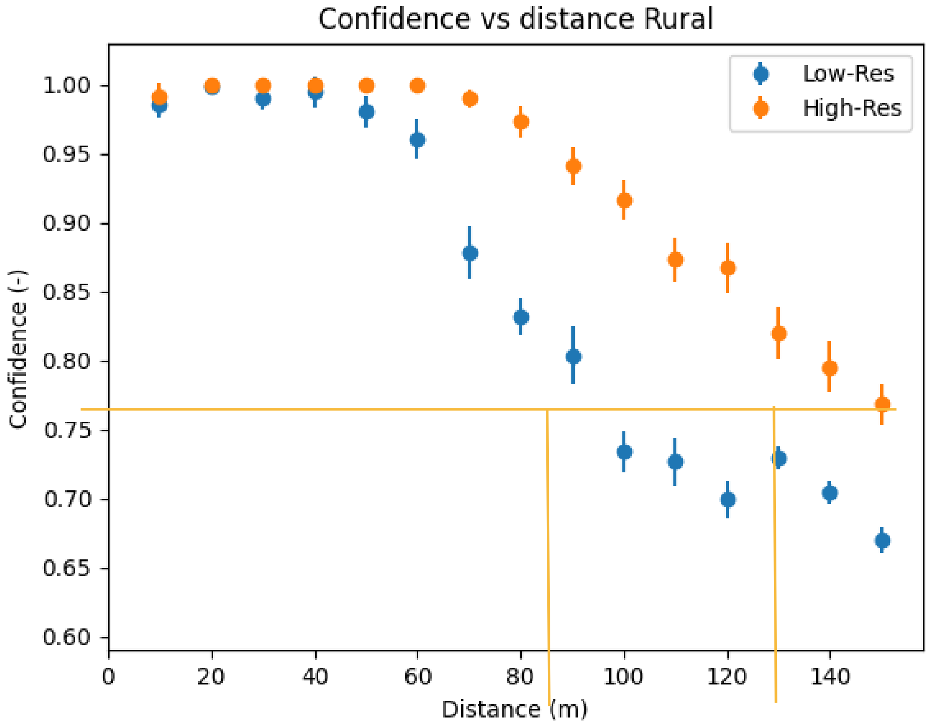
Confidence level > 60%

Source:
Dona R. et al., On the Assessment of Thermal Cameras and their Safety Implications for Pedestrian Protection: a mixed Empirical and Simulation-based characterization, Joint Research Center, Transportation Research Record, 2024

Pedestrial detection range, this time using AI







Low-res

36° FoV

320x240, 12µm pixels

High-Res

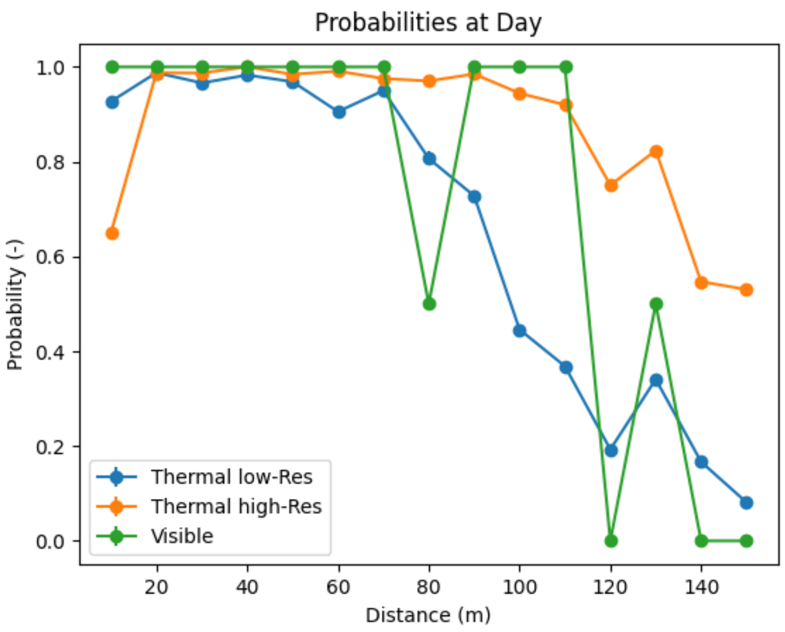
31° FoV

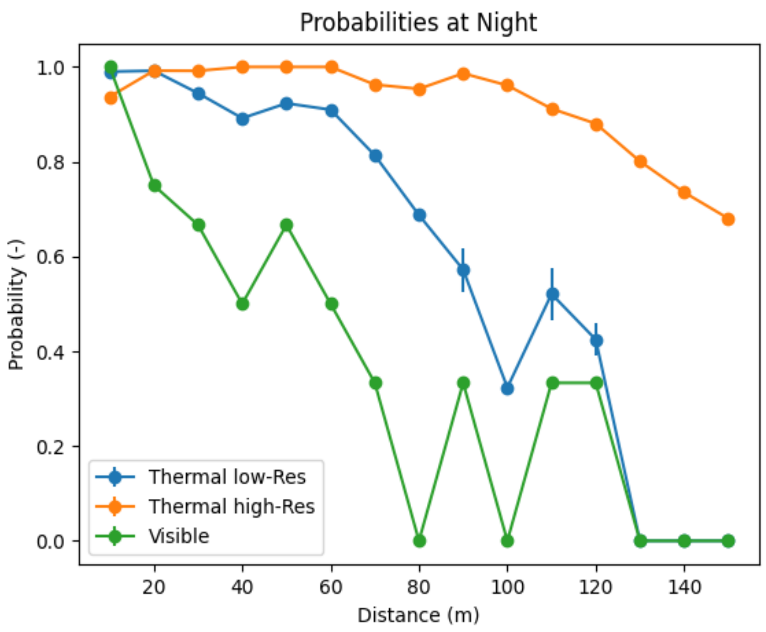
640x480, 12µm pixels

Pedestrian detection range with confidence > 80%:
> 90m for QVGA resolution sensor
> 120m for VGA resolution sensor

Source:
Dona R. et al., On the Assessment of Thermal Cameras and their Safety Implications for Pedestrian Protection: a mixed Empirical and Simulation-based characterization, Joint Research Center, Transportation Research Record, 2024

Pedestrian detection vs lighting conditions for thermal and visible cameras





Visible Camera Set-up

ADAS 3 camera setup

35, 50 and 120 FoV

1.2Mp – 3.7µm pixels

- ✓ Detection probability is **identical** whatever the **lighting conditions** for **thermal cameras**
- ✓ Detection probability **drops** dramatically when **lighting conditions** are **degraded** for **visible camera**

Combining Visible and Thermal camera would
extend AEB daytime performances to nightime conditions

Source:
Dona R. et al., On the Assessment of Thermal Cameras and their Safety Implications for Pedestrian Protection: a mixed Empirical and Simulation-based characterization, Joint Research Center, Transportation Research Record, 2024

Next generation of small pixel pitch : 8.5µm

Footage taken with :
- VGA 8.5µm sensor
- Lens 7.1mm, f/0.8

Prototype !

Come see the live demo on the booth !

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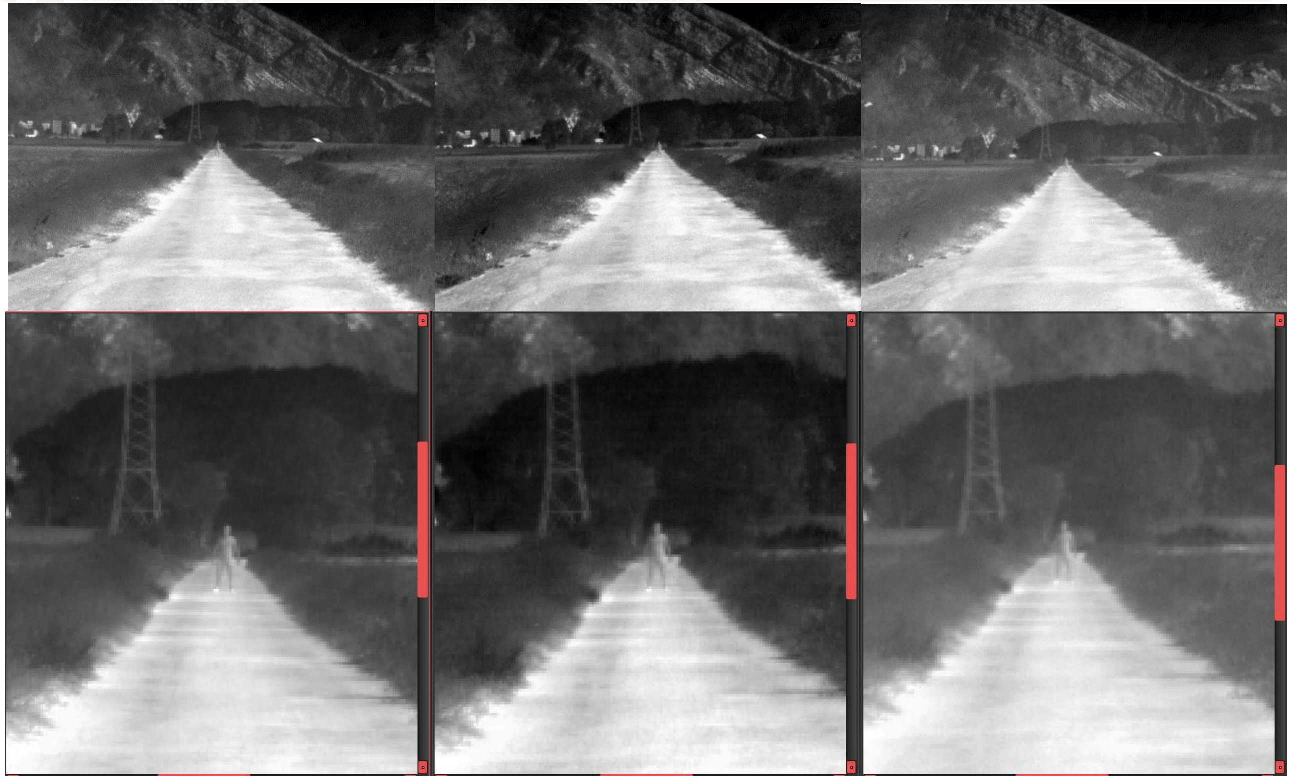
Effect of Pixel pitch on detection range : cameras configuration

Parameter	VGA17µm	VGA12µm	VGA8.5µm
Focal Length and aperture	19mm f/1.0	14mm f/1.0	8.8mm f/1.0
Lens coating and Mean Transmission (8-12µm)	High Efficiency AntiReflective Coating >94%	Diamond Like Carbon Coating >80%	Diamond Like Carbon Coating >80%
HFoV (°)	32	31	34
Camera NETD (mK)	33	67	91



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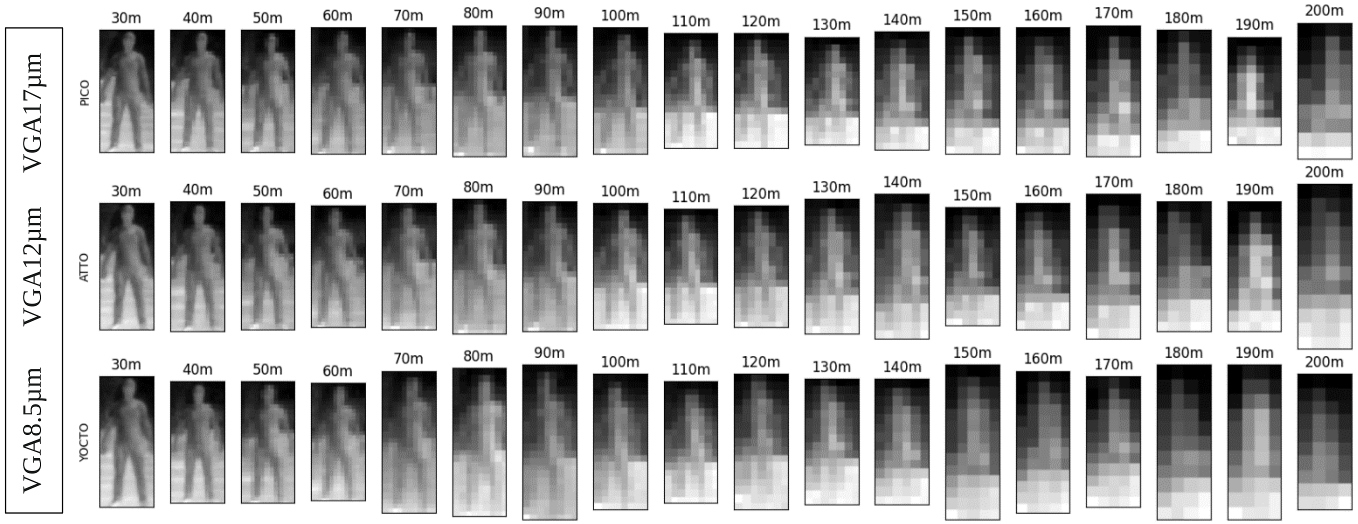
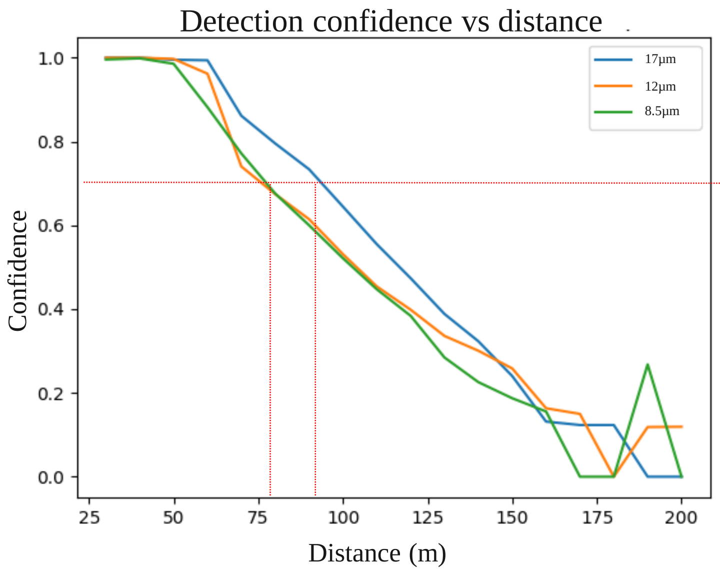
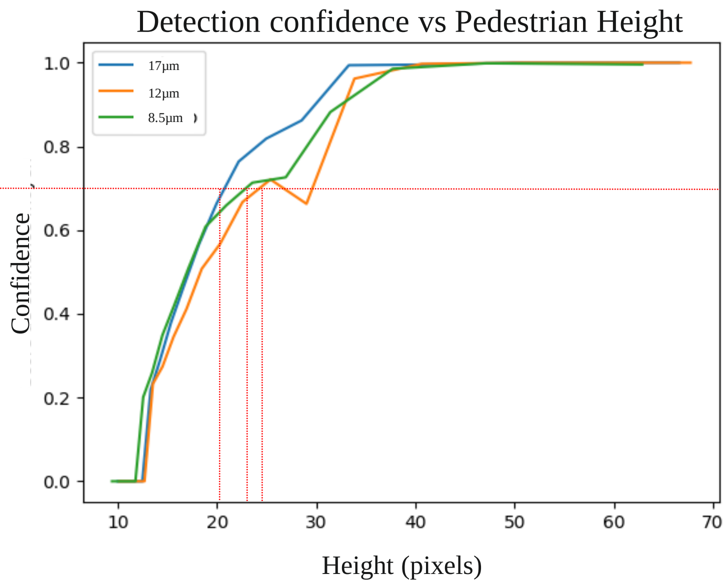
Tests parameters and conditions

- All camera are VGA
- All cameras use f/1.0 optics
- Ambiant temperature : 28°C
- Resnet50 NN trained with 5000 thermal images

Effect of Pixel pitch on detection range : Results







Tests Results

- 17µm presents about 20% more range
- No significant degradation between 8.5µm and 12µm
- 23 pixels on target (in height) are enough to detect a pedestrian

Source:
S. Tinnes et al., Automatic Emergency Braking: How can affordable thermal camera improve reliability and extend use cases to nighttime conditions, SPIE Defense Commercial and Security, 2024

Lynred fusion dataset

Labelled thermal   Labelled visible

Stereo recording setup

Other datasets:
- KAIST: 95K images, 3 classes
- FLIR: 9K images, 15 classes
- CVC-14: 7K images, 1 class

→ Still a need for more images

13k image pairs (visible/thermal) of labelled images & growing
9 classes (pedestrians, cars, buses, trucks, cyclists, motorbikes, traffic lights, traffic signs, scooter, train etc.)
Varietey of conditions (day, night, dusk, summer, winter, sunny, rain, fog)

Dataset is not publicly available

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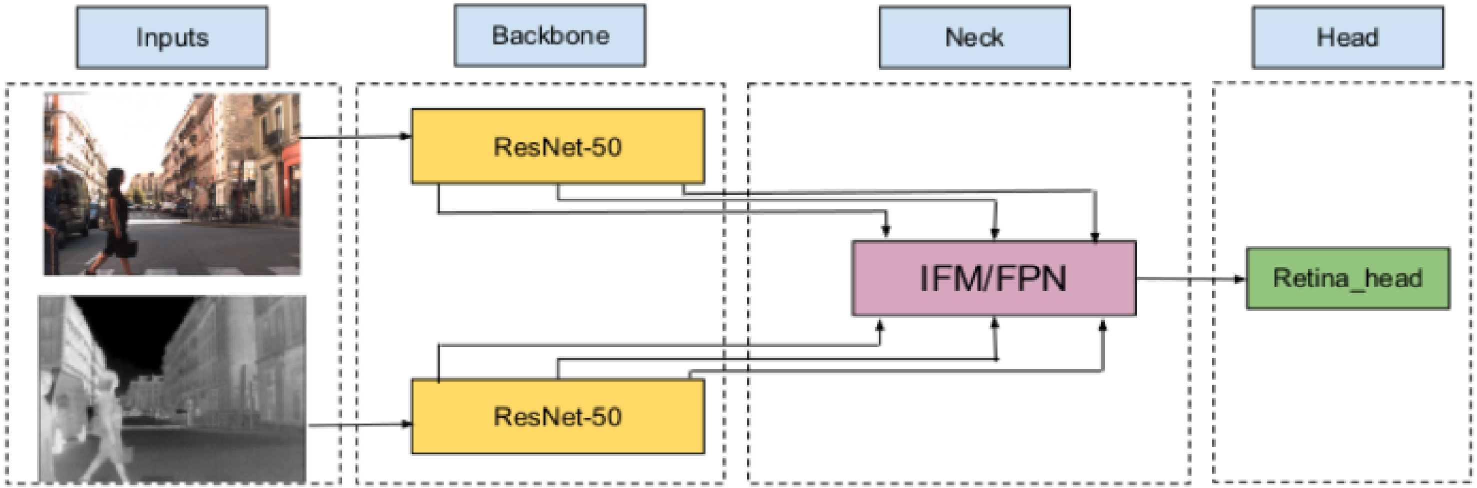
IR-RGB fusion

Typical IR-RGB multimodal detection network, featuring a fusion of features from IR & RGB
→ Improves the average precision in all conditions, day & night



Multispectral image pairs

Separate feature extraction

Multispectral features fusion

Detection network

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[Source : SIA Vision 2021, GMFNet: Gated Multimodal Fusion Network](#)

Hardest conditions, but differently hard

Deep fog, and ice on windows

Visibility impacted by scattering

Visibility impacted by absorption

Modalities are impacted by very differents effects
→ Fusion increase the robustness of detection

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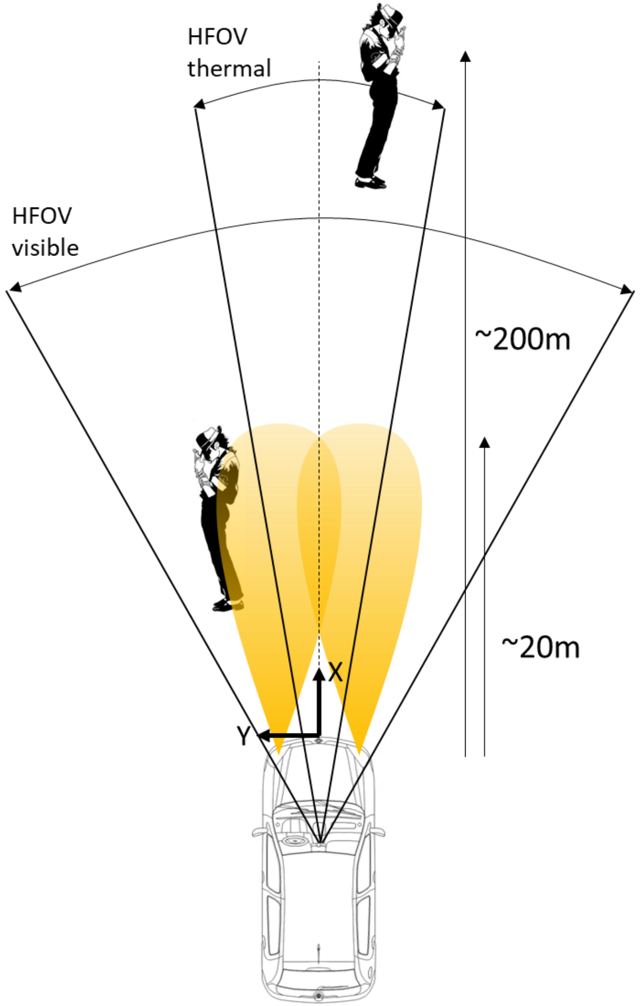
Less false positives using fusion

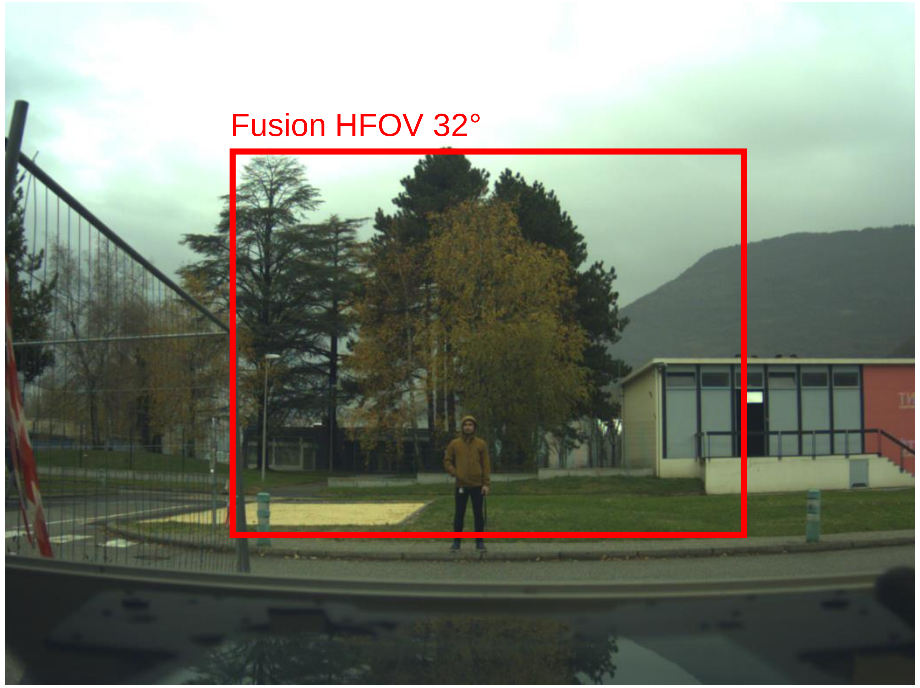
- Screens, advertisements etc.

Detection from screen

Visible-IR field of views



Narrow FOV thermal camera
→ Fitted for long range



Wide FOV visible camera
→ Fitted for short range

Affordable thermal camera concept to reduce pedestrian fatalities

- An **AEB system** working **day and night** would require a **large HFoV visible camera** combined with a **narrow HFoV thermal camera**

- To detect a 1.8m high pedestrian over 23 pixels at 46m,
  a thermal camera would require an IFoV of 0.1°

- To cover a >30° HFoV, a resolution close to a **QVGA** with an optimized aspect ratio would be enough

- The use of **8.5µm pixel pitch** reduces the size of the FPA

- The use of **f/1.0 optics** keeps the optics small and simple in design and integration

- With an optic diameter of less than 5mm, **Wafer Level Optics** can be used to lower optic costs

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Tier1s can build an AEB system based on a **<$100 thermal camera,**
that fullfils the **NHTSA requirements** for pedestrian detection in all lighting conditions