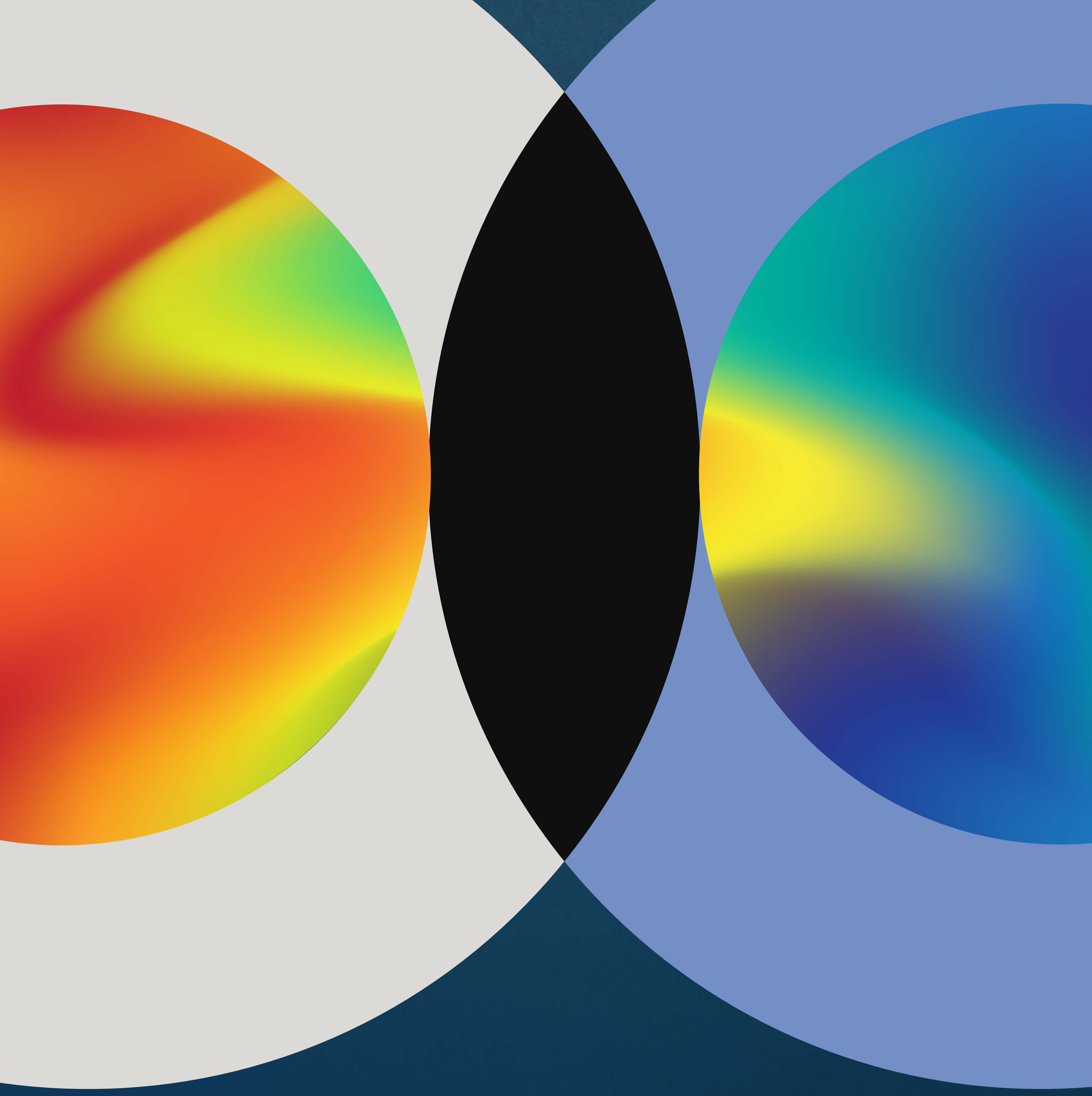

OWL AUTONOMOUS IMAGING • 2022

INFRARED
for ADAS and ROBOTIC MOBILITY APPLICATIONS

OWL

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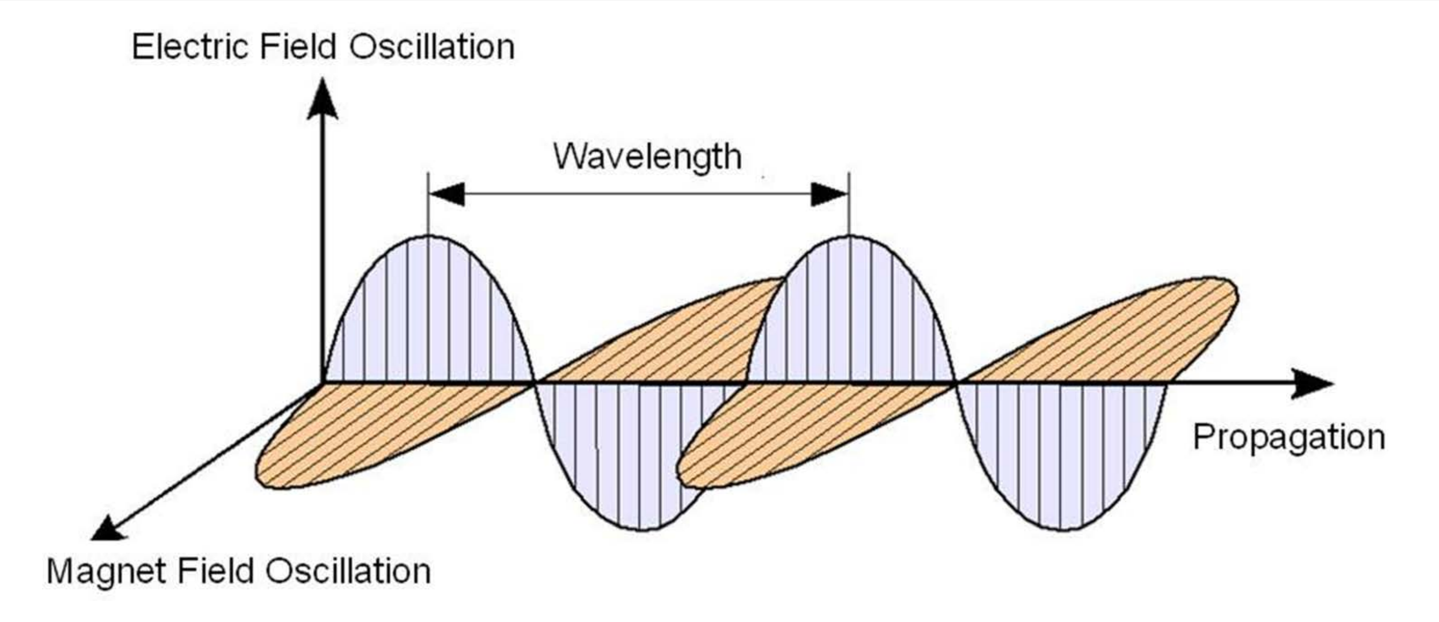
WHY LONG-WAVE INFRARED?

At Owl, our goal is reducing collisions between automobiles and pedestrians at night by providing actionable pedestrian location data to automatic emergency braking systems. We accomplish this by examining the patterns of infrared radiation emitted by warm bodies to provide both position and distance measures. Our videos show that this technique works. This white paper explains how infrared can provide appropriate information and why Owl selected long-wave infrared for its **Thermal Ranger**™ system.

Our goal is reducing collisions between automobiles and pedestrians at night.

THE ELECTROMAGNETIC SPECTRUM

Radio waves and light are two examples of electromagnetic radiation, a physical phenomenon generated by a moving electric charge. The charge can be in a wire or on the surface of any object. It can also be made to move by almost any external power source, from an electric voltage difference to the motion of molecules caused by heat. The moving charge generates a field with two transverse components that are perpendicular to each other. These two components are in phase (which can be shown using math and physics far beyond the scope of this post) producing this result – an electromagnetic field propagating away from the generator, as seen below.



Credit: www.cleanenergywiki.org

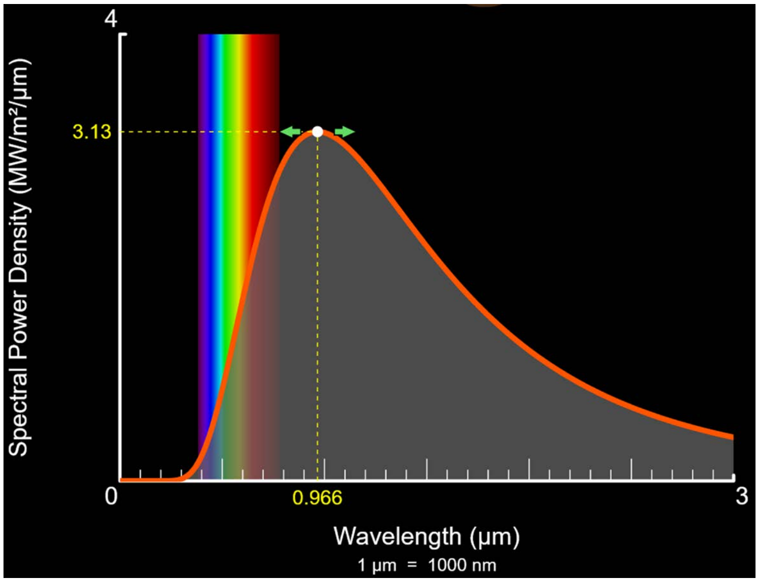
The EM waves (as they are called) have two properties that can vary – the amplitude and the wavelength. The amplitude represents the intensity of the wave, perceived for instance, as the brightness of a light source, while the wavelength indicates the "color" of the wave – colors like red, green, and blue in the case of visible light but colors with other sorts of names (like UHF and VHF) in different ranges of wavelengths.

PHOTONS

Electromagnetic radiation can also be thought of as little packets of energy emitted by the source that travel along the direction of propagation. In that interpretation, the amplitude represents the number of photons and the wavelength tells how much energy each photon has. Note the distinction introduced by the photon interpretation. While the wave could allow any amplitude to exist, the photons are packets carrying energy in discrete amounts. Whether EM radiation behaves as a wave or as photons depends on the situation. Conveniently, the wave properties show up in situations where the energy packets cannot be detected and the photons materialize where wave behavior is unimportant. In situations where both wave and particle behavior provide explanations for observed behavior, both representations can appear simultaneously. Several demonstrations on YouTube (see the list at the end of this document) show this duality.

BLACKBODIES

Heat makes the atoms and molecules in materials move. The outer layer of these atoms and molecules are electrons – charged particles – so it is not much of a surprise that when they move, they emit electromagnetic radiation. Since the motion is random in both amplitude and direction, the radiation given off goes in all directions and with a variety of wavelengths. Due to constraints imposed by the quantization of energy, the distribution of photon energies takes on a particular shape called the blackbody curve. This curve shows the radiation given off by a material that does not retain any of the emission from the surface (100% emissivity) across its entire band of emitted wavelengths. The curve for a temperature of 3000K (a typical incandescent light bulb filament) can be seen in the image at right.

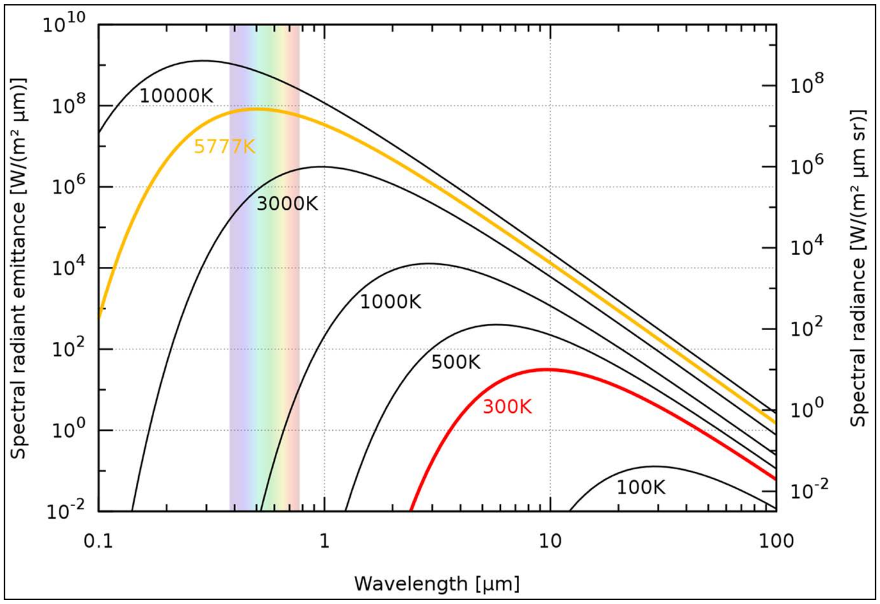


Credit: PhET Interactive Simulations *

A few characteristics of this blackbody curve have practical importance. First, note that the peak moves with the temperature of the radiating object. The path of this peak, the Wein displacement curve, is a straight line in log space because the position of the peak relative to wavelength is inversely proportional to the temperature.

BLACKBODY CURVE CHARACTERISTICS

Next, see that each curve is entirely above those at lower temperatures. When the peak moves towards shorter wavelengths, the radiation at longer wavelengths still increases. Similarly, the total power radiated (the area under the curve) increases rapidly (by T to the fourth power) as the temperature rises.



Credit: Wikimedia Commons †

Finally, observe that a blackbody at 300k – roughly room temperature – produces essentially no radiation visible to the human eye. A soldering iron tip at 600K might produce enough red light to be seen in a darkened room. Yet, there are materials that can detect radiation beyond the red – the infrared – to produce images in the neighborhood of the 300K peak at a wavelength of 10 μm, right in a window where the atmosphere does not absorb all the radiation. It is this combination of behaviors that make the thermal imaging used in the Owl AI Thermal Ranger system possible.

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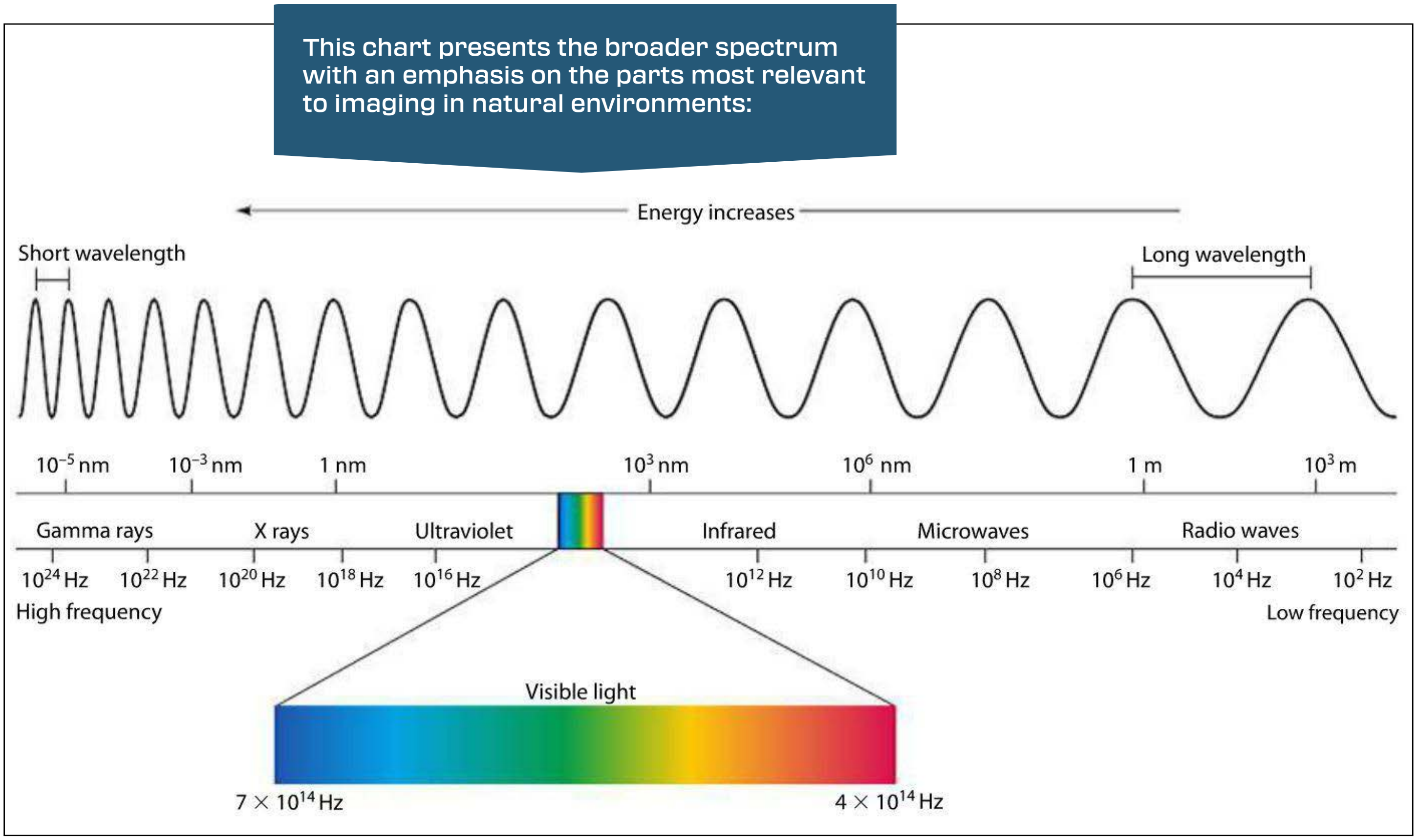
* Credit: Simulation by PhET Interactive Simulations, University of Colorado Boulder, licensed under CC-BY-4.0 (https://phet.colorado.edu).

† Credit: PROG, CC BY-SA 4.0, via Wikimedia Commons

INFRARED IN CONTEXT

On the curves in the image on the previous page, wavelengths corresponding to visible light are indicated to show their position relative to the blackbody emission spectra. Visible light spans the band of roughly 380 to 780 nm – violet through deep red. This is just about a ratio of 2:1, a very small part of the entire electromagnetic spectrum.



This chart presents the broader spectrum with an emphasis on the parts most relevant to imaging in natural environments:

Credit: Mini-Physics

Shorter wavelengths are to the left, in the domain of ultraviolet through gamma rays, longer wavelengths are on the right extending first through infrared and then on to microwaves and radio. The ratio of wavelengths from the left end to the right end of this chart is more than 1,000,000,000,000,000:1. For comparison, if we approximate the visible range at 2:1 (one octave), the whole range of wavelengths covers 50 octaves. On the same scale, infrared useful for imaging covers about four octaves.

Of course, medical and industrial imaging using x-rays is common and imaging in the ultraviolet and microwave bands support some special applications but none of these can be implemented easily with compact equipment on moving vehicles. Since automobiles in traffic are our primary platform, our examination of the electromagnetic bands will concentrate on the visible and infrared.

DETECTING VISIBLE AND INFRARED

Both the wave and particle properties of EM radiation affect detector design and performance. The wavelength relates primarily to the size of the detector elements while the photon energy relates to the materials used. In the simplest, most universal case, the detector is a material that responds in some way when its temperature changes. Thermocouples, for instance, generate a voltage that changes with temperature and many materials change resistance with temperature. To convert arriving radiation into a temperature change requires only the use of an absorber (usually something that looks black) that takes in radiated energy and converts it to heat. When you stand in the sun, you can feel your skin do this.

The absorber heats the detector material and then circuitry, with appropriate calibrations, reports the temperature change. An array of these elements fitted with a lens to make an image will take a picture of the emitted or reflected energy variations in a scene. If the absorber has a uniform spectral absorption, all of the energy that can pass through the lens contributes to the picture. Devices of this type are used for room occupancy monitoring, for instance. In this type of detector, the presence of photons has little significance; what is detected is simply absorbed energy.

> In a microbolometer, an absorber heats the detector material and then circuitry, with appropriate calibrations, reports the temperature change.

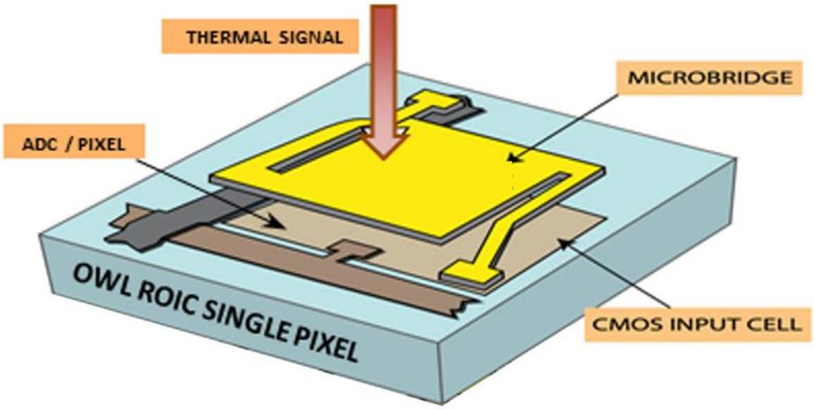
However, detectors that do recognize photons as individual packets have some advantages related to noise performance and are generally amenable to fabrication in smaller structures. As a result, these types are preferred in all but a few situations. To see why, consider the energy contained in the photon's corresponding wavelengths. Typically, photon energy is measured in electron volts (eV), the amount of energy an electron takes on when accelerated through a potential difference of one Volt. For reference, a photon with one eV of energy corresponds to a wave with a wavelength of 1.2 µm in the near infrared (NIR). A photon at the human vision peak (555 nm) has an energy of about 2.2 eV. In the long-wave infrared (LWIR) at, for example, 10 µm, the photon energy is only 0.12 eV.

The problem with photon detectors arises because they convert incoming photons into free charge that can be collected to form the output signal. In the visible, this can be done with a silicon detector which requires less than one eV to knock a charge free with low extraneous signals at room temperature. Materials that can generate free charge with only a tenth of an eV are much too noisy at room temperature to be useful as detectors and must be cooled, to a temperature of 77K (using liquid nitrogen) for reasonable performance or even to 4K (using liquid helium) for best results. This makes equipment using these detectors expensive and bulky. Other commonly used coolers present additional problems. Mechanical coolers such as Stirling engines are large and have moving parts with resultant lifetime limits. Thermoelectric coolers require a lot of power and substantial heat sinks and still generally do not deliver temperatures low enough to support operation of these photon detectors.

To sidestep the size and weight limitations of photon detectors, better and smaller thermal energy detectors have been developed. The technology chosen for this purpose is the microbolometer. The bolometer is a thermal detector made of a material that changes electrical resistance with changes in temperature. It has a long history, having been invented in 1878 by Dr. Samuel P. Langley, the namesake of one of the NASA research facilities. More recently, Honeywell developed an implementation of the bolometer small enough to be fabricated in arrays suitable for imaging. These "microbolometers" now use either vanadium oxides or amorphous silicon as the thermally-variable conductor. Cryogenic cooling is not necessary for these devices to produce usable images of room temperature objects. As a result, they have been widely applied to the manufacture of small lower-cost cameras with resolution, speed, and sensitivity suitable for real-time video imaging.

MICROBOLOMETER CHARACTERISTICS

A microbolometer image sensor consists of an array of detector elements each constructed from an absorber supported by a mechanical suspension platform on legs that conduct electricity.



The element is enclosed to provide a vacuum environment that insulates against heat loss and the legs are proportioned to provide a thermal time constant compatible with the sensor frame rate. Operation of the detector element is controlled by a readout integrated circuit (ROIC) situated below the element array. Thermal radiation is continually arriving so that the temperature of the element tracks the thermal emission of the object it is viewing. Periodically, a small current is sent through the legs to measure the resistance of the absorber. In the custom sensor device developed by Owl AI, each detector element has its own analog-to-digital converter (ADC) to assure that the thermal data received by the ROIC from the detector element is accurately preserved.

To maximize the detector efficiency, the surface of the detector element may be processed to make it appear black to incoming radiation in the wavelength band to be imaged, typically the range from 8 to 14 µm. The top surface also must include an IR transparent conductive coating, perhaps indium tin oxide (ITO) to provide a path through the detector material for the sampling current. Because the detector must be in a vacuum, the package needs an optical window to admit the thermal image. This is typically silicon, which, in thin sections, is transparent in the LWIR, or an appropriate infrared-transmitting glass. Either of these will generally include an anti-reflectance coating to minimize losses.

INFRARED OPTICS

With the midpoint of the LWIR band around 10 µm, the smallest resolvable dot is a little over 12 µm so that becomes a practical minimum spacing between microbolometers for general thermal imaging. The original microbolometer imagers had 50 µm, then 30 µm spacing, limited by the fabrication technology and the quality of the lenses available but improvements have brought the spacing down to the 12 µm range, the spacing used by OWL AI in its Thermal Ranger systems.

LWIR is absorbed by common glass so other materials are needed to fabricate lenses. Some special glasses can transmit LWIR but these are difficult to work and must generally be molded rather than ground and polished. The quality of molded optics is not sufficient to produce images at the diffraction limit so other materials are used. The most common is germanium, which is transparent beyond 1.5 µm. Germanium has two characteristics that must be accommodated. First, it has a very high index of refraction so about 40% of the arriving radiation will be reflected. To mitigate this, high-performance anti-reflection coatings must be applied to all surfaces. Second, the thermal conductivity of

INFRARED OPTICS continued

germanium drops substantially as its temperature increases leading to thermal runaway in the presence of high-power illumination sources. For passive thermal imaging, runaway is not a danger but germanium lenses (and germanium photodetectors) must be shielded from potential bright infrared sources including focused sunlight.

Diffraction Limit Formula

The finest detail that can be reproduced by conventional optics (called the diffraction limit) is defined by the formula:

$$\boxed{X = 1.22 * \lambda * f\#}$$

Where:
X is the diameter of the smallest dot that the lens can separate from another dot of size **X.**

λ (Greek letter lambda) is the wavelength of the EM radiation.

f# is the aperture (f-number) of the lens (where smaller numbers mean bigger apertures).

For efficient capture of the emitted radiation, LWIR lenses generally have an f/1 aperture.

WHY NOT MWIR?

To define the infrared bands as generally used in imaging:

NIR (near infrared) is that band between the end of visible and the absorption cutoff of silicon, roughly 800 to 1100 nm.

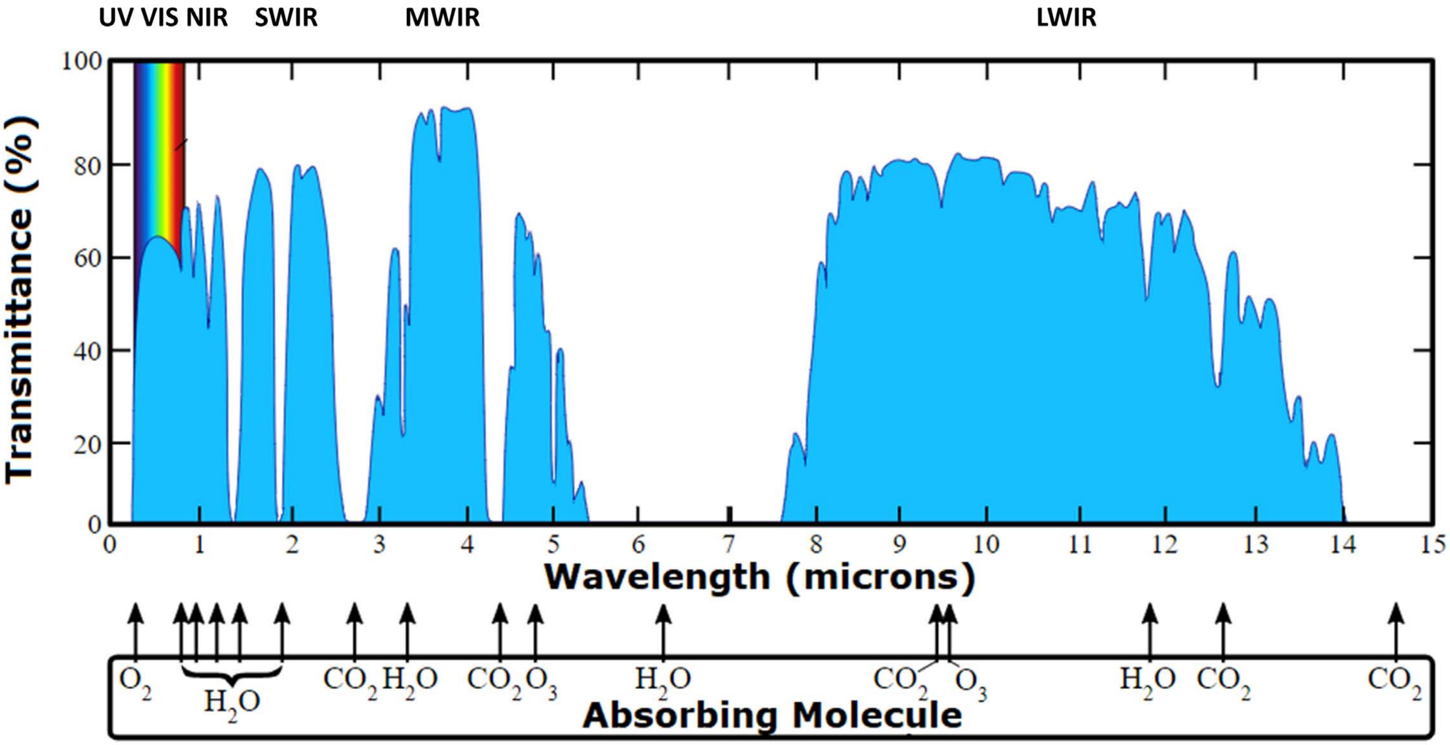
SWIR (shortwave infrared) includes wavelengths between the silicon cutoff and the atmospheric cutoff around 2500 nm. Often, this is split into two bands – below about 1600 nm, the cutoff of standard InGaAS sensor response, and above 1600 nm, called extended SWIR.

MWIR (mid-wave infrared) includes the two transmission windows in the 3 to 5 µm band. This band has an advantage over LWIR because it can use lenses made of silicon, which is cheaper than germanium and easier to fabricate.

LWIR (long-wave infrared) The 8 to 14 µm band used in the OWL AI Thermal Ranger system most often associated with room-temperature thermal imaging.

WHY NOT MWIR? continued

Atmospheric transmission permits infrared imaging in other parts of the spectrum as shown below.



Credit: D. Ilyin (original), U.S. Naval Academy (translation); CC license

So, if the optics are easier and cheaper to fabricate in the MWIR and the microbolometer elements can absorb MWIR radiation, why not use that band? The answer lies in the shape of the blackbody curves and atmospheric transmission. Note from the blackbody curve that the average radiation in the MWIR band is only about 10% of that in the LWIR band and note from the atmospheric transmission curve that the width of the MWIR window is only about one-third of the LWIR window width. This combined 30x difference in available radiation places an untenable burden on the noise performance of microbolometers and renders them unsuitable for MWIR imaging. While photon-detecting MWIR sensors are readily available, that technology is far too bulky and expensive for use in automobiles. A quick survey of the available MWIR cameras will reveal that all of them use cryogenically-cooled detectors.

Owl AI is constantly surveying the technologies in development suitable for MWIR imaging to determine when the development of a Thermal Ranger system operating in that band may be feasible.

OBSCURANTS

Outdoor imaging applications often include situations where viewing conditions are less than ideal. In these situations, referred to as DVEs (degraded visual environments) the viewing path may be obscured by water in the form of rain and fog or smoke from a variety of sources. The performance of imaging systems in the presence of obscurants varies substantially.

OBSCURANTS continued

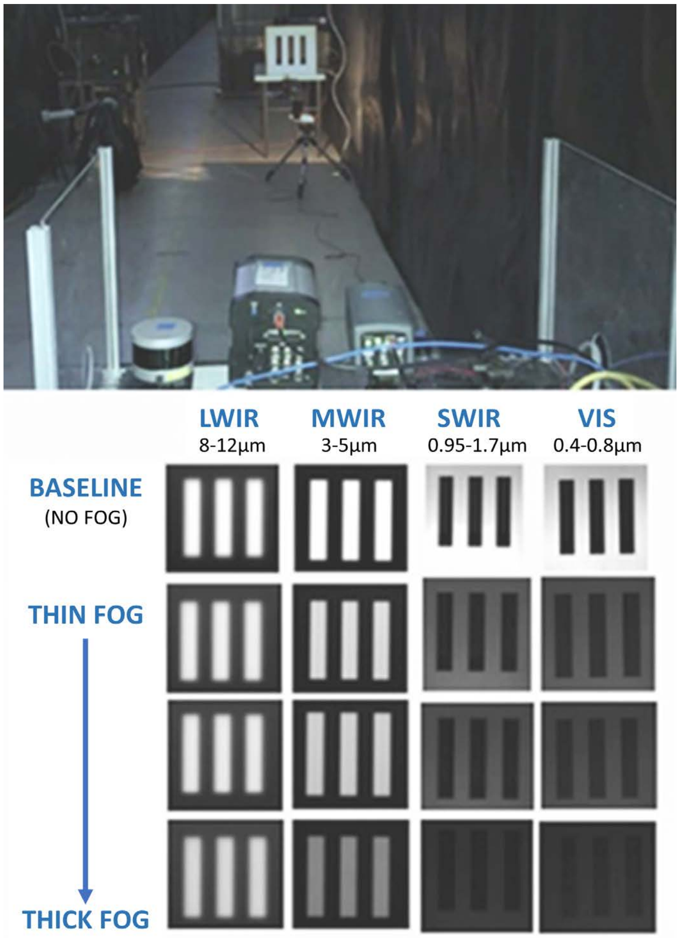
Both MWIR and LWIR can see through fog and smoke better than shorter wavelengths because the particles in these obscurants are smaller than the LWIR wavelengths. Smaller relative particles scatter less so the scene rather than the obscurant provides most of the signal. In addition, much of the radiation in the NIR and SWIR bands are absorbed by water, as the atmospheric transmission chart indicates, so rain and fog can block the scene image for these bands almost completely. In this image taken at 1064 nm, for example, a bottle of water appears black

Water appears black in this example.

Credit: AVC

The fog was introduced in various densities in the optical path without illumination. That causes the visible and SWIR images to go black. If headlights had been illuminating the scene from the camera location, these images would have gone white. The contrast in the MWIR and LWIR is reversed because the black bars are warmer than the background. The least degradation shows in the LWIR sequence because water absorption affects the contrast more in the MWIR band. Headlights would have had no effect on the infrared images but would have saturated the images in the visible and SWIR bands.

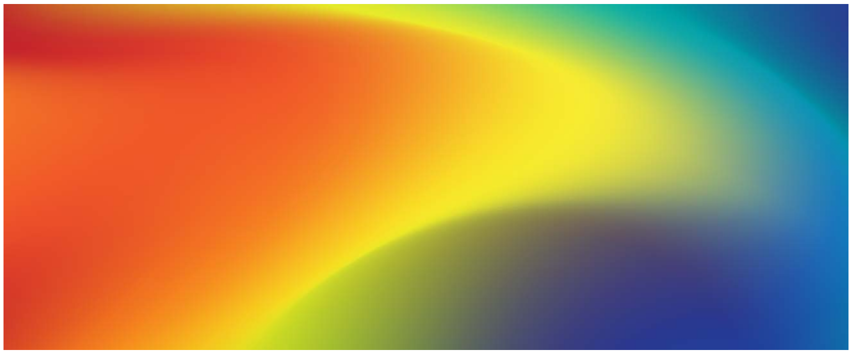
A comparison among cameras in the various bands shows the differences in performance in a DVE.



Credit: Teledyne FLIR Systems

INFRARED AT OWL AI

With the goal of locating and identifying pedestrians at night even in weather-degraded conditions, Owl AI studied the spectral band options, evaluated equipment operating in candidate bands, tested the resulting images in an AI recognition system and, based on the results, selected diffraction-limited, high-resolution imaging in the LWIR band as the best way to meet the goal. A new image sensor incorporating the Owl AI research results now becomes the latest embodiment of the OWL AI principle Safety Starts with Perception™.



Safety Starts with Perception

YouTube LINKS

THE PHYSICS OF EM RADIATION

EM Waves: https://youtu.be/bwreHReBH2A

Wave and Particle Properties: https://youtu.be/h1tflE-L2Dc

Double-Slit Experiment: https://youtu.be/O81CiIon1OM

Photoelectric Effect: https://youtu.be/MFPKwu5vugg

Understanding Thermal Radiation: https://youtu.be/FDmYCI_xYlA

Source of Thermal Radiation: https://youtu.be/-Es9u9wv1kO

The Ultraviolet Catastrophe: https://youtu.be/rCfPQLVzus4

DEMONSTRATIONS OF OWL AI TECHNOLOGIES

April 2022 Pedestrian Demonstration:
https://youtu.be/JaaTngahIms

January 2022 Pedestrian Comparison with Visible:
https://youtu.be/TmfzYcGRH_Y

November 2021 Pedestrian and Automobile Classification:
https://youtu.be/BMGLgnxNI6M

Example videos of our **THERMAL RANGER** in action can be found on our **YouTube Channel** at this link >>> YouTube

“OWL’s THERMAL RANGER system is unique as it delivers rich detail and 3D response day or night.”

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