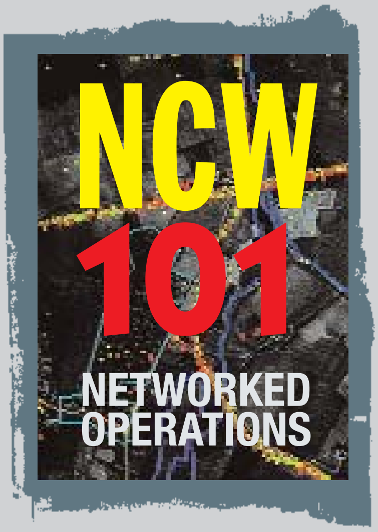


Thermal Imaging Sensors

NCW 101 part 6

Dr Carlo Kopp

Thermal imaging sensors are now ubiquitous, carried by most categories of combat aircraft, UAVs, many satellites, warships and ground vehicles. The capability to observe targets or terrain in the absence of sunlight has realised around-the-clock combat operations, a gain most prominent in aerial warfare. In the context of networked combat, thermal imaging sensors are and will remain a mainstay of Intelligence Surveillance Reconnaissance capabilities.

Intelligence, Surveillance, Reconnaissance and Targeting Applications

At present, thermal imaging sensors are truly ubiquitous, and over coming decades will improve in capabilities and decline in costs as the technology further matures.

Most thermal imaging devices in contemporary and legacy military equipment are used for navigation and targeting, with some proportion of systems used for specialised ISR applications.

Perhaps the most widely used podded infrared system is the US Air Force LANTIRN suite, comprising an AN/AAQ-13 navigation pod with a wide field of view FLIR, and AN/AAQ-14 targeting pod, with a longwave MCT FLIR boresighted with a laser designator/rangefinder. The AN/AAQ-14 is now being replaced by the new LM AN/AAQ-33 Sniper XR/PANTERA ATP (Advanced Targeting Pod). The Sniper XR is a dual band system, with an InSb FLIR and TV CCD sensors, laser designator/rangefinder, all using a sapphire glass window system, compatible with midwave FLIR. The Sniper XR is the baseline for the internal Electro Optical Targeting System (EOTS) in the JSF, although it is likely to be deployed earlier on the B-2A Spirit.

The US Navy relied primarily on the AN/AAS-38 NiteHawk FLIR/laser pod, and AN/AAS-50 navigation FLIR pod, on the F/A-18, supplemented by the AAQ-14 LANTIRN on the F-14D. With the withdrawal of the F-14D and increasing numbers of F/A-18E/F deployed, the USN is now deploying the new Raytheon AN/AAS-46 ATFLIR, technologically similar to the USAF Sniper XR.

Imagery produced by L-3 Cincinnati Electronics 2048 x 2048 pixel midwave band imaging array (L-3).

A major success story in the market is the Israeli designed Northrop Grumman AN/AAQ-28 Litening II pod, also a dual band system with FLIR and CCD channels. The Litening II was adopted not only by the Israeli AF, but also the US Marine Corps and Air National Guard in the US, the latter for use on F-16s. It was also selected for the B-52H to support persistent close air support and maritime strike roles. The subsequent AN/AAQ-28(V)4 Litening AT variant, with a 640 x 512 FLIR, a higher resolution CCD cited at 1024 x 1024, and embedded C-band datalink terminal. This variant was ordered by the USMC and RAAF for use on F/A-18As.

Russia is now actively marketing the Sapsan-E FLIR/laser targeting pod, designed for the Sukhoi Su-30, Su-27SMK and Su-35M. It is a design that is comparable to second generation Western pods. The Sapsan-E is likely to be exported to a range of Asian Sukhoi operators, especially those who cannot acquire Western pods.

Contemporary targeting FLIRs are frequently presented as ISR equipment, but this is in many respects an overstatement when they are compared to dedicated ISR sensors, exemplified by many current reconnaissance pods.

F-22A-EO-Fairing-AEDC-1

Testing of the infrared sensor fairing design mounted under the chin of the F-22A. Stealth denies the use of external podded sensors, forcing internal carriage and stealthy fairings. (US Air Force AEDC)

What targeting FLIRs provide is a niche reconnaissance and surveillance capability, or what the US DoD calls 'unconventional ISR'. This is typified by operations where a fighter aircraft orbits at 30,000 ft above ground troops performing counter insurgency operations, in rural or urban terrain, and provides the ground force with warning of hostile or suspicious activity, or aids the ground troops during an assault. Targeting FLIRs can also provide useful Bomb Damage Assessment (BDA) imagery. Where these systems are less than competitive is in trying to match specialised equipment in imaging at high resolution large swaths of terrain. This is inevitable, since the thermal imager used for targeting is designed to produce TV quality imagery in real time, and will have lower resolution, narrower fields of view, lower optics quality, and much shorter per frame integration times.
An eloquent Americanism is the description of the capability of a targeting FLIR being 'ISR through a soda straw', reflecting the fact that such systems are designed to image small areas, not large ones.
Specialised reconnaissance pods typically incorporate an InfraRed Line Scanner (IRLS), which is analogous to legacy strip mapping cameras. A contemporary IRLS such as the D-500A built by BAe Systems will image a 8,102 pixel wide swath of terrain in the longwave IR band, with a 70 degree field of view within a 140 degree field of regard, to permit oblique imaging runs. The CAI-8601 IRLS provides similar capabilities. For comparison, it would take 13 frames imaged side by side using a contemporary targeting FLIR to match the strip width mapped by an IRLS.
Framing cameras with thermal imaging capabilities are also available, often constructed as dual band designs using both an embedded CCD and thermal imager. The BAe Systems F-9120, used in the Advanced Airborne Reconnaissance System (AARS) pod is a good example, and uses a 13 inch stabilised aperture with a 120 inch focal length to support the two imaging sensors. Other notable products in this category are the Recon/Optical Inc CA-295 dual-band framing camera, and the CA-270 dual-band framing camera. These devices use the L-3 Cincinnati Electronics 2048 x 2048 pixel midwave band imaging array. For comparison, this device gathers almost 13 times as much data in a single frame, compared with that of a typical targeting FLIR imager.
With the advent of stealth, podded systems for targeting and imaging ISR are not viable due to the radar signature they incur. Accordingly, internal installations for such sensors are becoming the norm. Examples are the EOTS in the JSF and planned for early introduction in the B-2A, and the suspended (for funding reasons) infrared sensor on the F-22A. The latter progressed to the point of optical, stealth and aerodynamic testing of the chin fairing.

Raytheon AN/AAS-46 ATFLIR (Raytheon).

The Infrared Bands

Unlike visible band optical imaging sensors, there was limited usage of wet film media with thermal imaging systems, most of which were based on electro-optical hardware.
To appreciate how thermal imaging systems produce imagery without sunlight it is necessary to explore the underlying physics.
All thermal imaging systems are designed to use infrared radiation and illumination, which encompasses light wavelengths between 0.7 microns and 350 microns.
All natural light, visible and infrared, is a byproduct of an effect called blackbody thermal radiation, and is associated with heat. Any object at a given temperature radiates light, and the object's temperature determines how much radiation is emitted at what wavelength, following what is termed the blackbody radiation curve (refer diagram). Hotter objects emit shorter wavelengths more intensely, compared with that emitted by cooler objects.
The temperatures associated with visible light are typically greater than 1,000 degrees Centigrade, while objects at cooler temperatures emit in the infrared bands.
Physicists usually split infrared radiation into three bands. The near-infrared band is between 0.7 and 4 microns (down to 400 deg C), mid-infrared is between 5 and 25 microns (down to -150 deg C) and far-infrared between 25 and 350 microns. In military applications the near and mid-infrared are of most interest, and these are usually divided into the shortwave band between 0.7 and 4 microns, the midwave band between 4 and 6 microns, and the longwave band between 8 and 15 microns. Why the different labels? For military applications what is of interest is the radiation that can penetrate the atmosphere and be detected. It so turns out that the short, mid and longwave bands correspond to those wavelengths that easily penetrate air without being rapidly absorbed or scattered.
The shortwave band is associated with jet engine exhausts, gun barrel exhaust gasses, munition explosions and other hot objects. The midwave band is associated with running turbine and piston engines, and other objects at similar temperatures. The longwave band is associated with human body heat, structures or buildings, and other objects at similar temperatures.
Characteristically, due to the behaviour of the blackbody curve, an object that is bright in the shortwave band will also be bright in the midwave and longwave bands, but the opposite is not true.
Thermal imaging sensors have been traditionally built to operate in a specific band. This has been a byproduct of the detector technology used, and associated optical lensing. Only recently have detectors emerged capable of imaging in multiple discrete bands.
Infrared images produced by thermal imaging sensors will usually contain objects that are illuminated by background and atmospheric infrared radiation, and objects that are actively emitting due to their temperature.
A longwave sensor will produce images with a bigger proportion of emitting objects compared to a midwave sensor.
There has been considerable debate about the merits of longwave vs midwave thermal imagers. The reality is that both have advantages under specific operating conditions and the argument is largely meaningless, reflecting vendor competition more than operational utility.

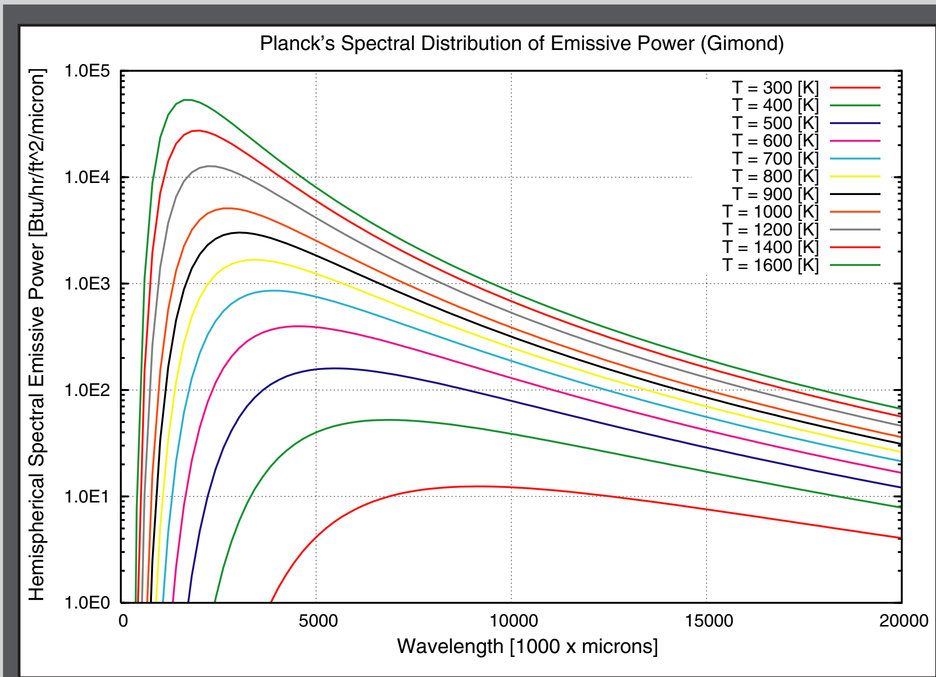


Image: blackbody-curve

Thermal Imaging Sensors

The earliest and simplest thermal imaging sensors were film cameras. These required unique lens materials, such as Germanium, Zinc Sulphide or Zinc Selenide, and infrared sensitive films, which had to be refrigerated during storage, use and developing. A large cost component in all infrared imaging devices is in the optics, since conventional glasses are unusable. A lens for such a system must use a material transmissive in the infrared band of interest, and the lens geometry must reflect the properties of the material and larger wavelengths involved.

Film cameras were cumbersome, especially due to the need to precisely control the temperature of the film medium and camera.

They were very soon supplanted by thermal imaging linescanners, devices that emulated conventional film cameras designed to produce strip imagery of terrain beneath an aircraft. Linescanners were the first widely used infrared imaging electro-optical sensors.

The success of IR linescanners led to the development of infrared or thermal imagers, essentially video cameras capable of imaging in the infrared bands. This technology appeared in operational use in the latter phase of the Vietnam conflict and has since become ubiquitous, evolving through several generations of technology.

Top: a nine pixel closeup of a QWIP imaging chip, the small dots are the actual quantum well structures.
Centre: QWIP imager operating in the longwave band.
Bottom: QWIP imager operating in the midwave band (Fraunhofer Institute).

Whatever the construction of a thermal imager or linescanner, the technology at its very core is that of the infrared detector. Infrared detectors produce an electrical output when illuminated by photons of infrared radiation.

A range of technologies have been and continue to be used as infrared detectors. In terms of contemporary systems the two technologies of most interest are semiconductor bandgap detectors, and newer quantum well detectors.

Bandgap detectors are made of semiconductor materials, which require a photon to have a certain wavelength or energy before an electron can be dislodged from the crystalline lattice of the material, to produce a measurable electrical effect. The size of the bandgap of the semiconductor material determines which visible or infrared colours the detector can respond to. Materials with large bandgaps are blind to infrared, but can detect visible band illumination. Materials with narrow bandgaps can detect infrared.

The dominant detector material in early thermal imaging hardware was Mercury Cadmium Telluride (MCT or HgCdTe), which is capable of detecting longwave infrared. It continues to be used for longwave applications, especially InfraRed Search and Track (IRST) sensors. MCT is however difficult to fabricate and this has presented difficulties in transitioning to integrate focal plane arrays (refer CCDs last issue).

The dominant detector material in most contemporary products is Indium Antimonide (InSb), which is much easier to fabricate than MCT. Due to its bandgap, however, it is limited to midwave infrared applications. InSb has been widely used for focal plane array thermal imagers, and this has been critical to its adoption in affordable volume equipment.

Another material used sometimes is Platinum Silicide (PtSi), which is a shortwave infrared detector.

Legacy equipment and most current production equipment will use one of these three detector materials.

Quantum Well Imaging Photodetectors (QWIP) are quite different in how they operate, and offer some advantages over bandgap detectors. In a quantum well detector, a well-shaped microscopic hole is created in a semiconductor material, typically a Gallium Arsenide (GaAs) alloy. Within this well electrons are trapped, but can be dislodged if a photon of suitable energy falls into the well. The energy of that photon and thus its infrared wavelength depend on the depth of the well.

This is a significant development in technology since the colour sensitivity of a QWIP detector is dependent on the geometry of a structure etched into the detector material, rather than the fundamental properties of the material. Moreover, since QWIPs are typically fabricated in GaAs family materials, used for the mass production of radio-frequency chips used in mobile telephone, wireless networking and radar, mass production QWIPs are potentially much cheaper than established and legacy bandgap detectors.

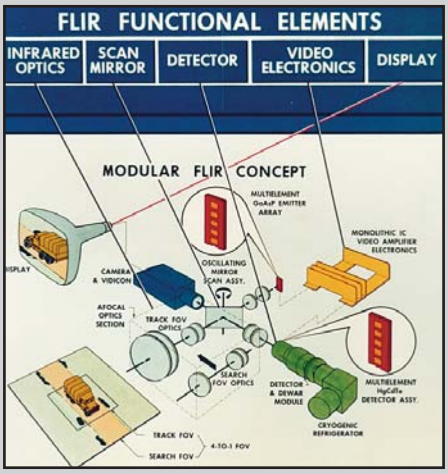
At this time we are seeing the first generation of QWIP detector based thermal imagers in the market.

Having a suitable detector technology, however, is not enough to make a thermal imaging camera or linescanner. A mechanism has to image the scene, and the detector must be cooled to cryogenic temperatures if viable sensitivity is to be achieved, especially in the midwave and longwave infrared bands. If not cooled, the thermal motion of the crystalline lattice would swamp the detector with electrical noise and bury the image in 'snow'.

A range of cooling systems has been used. For equipment that is not expendable these are either conventional closed cycle cryogenic refrigerators, or in some designs, Stirling closed cycle refrigerators. Much of the cost in any upper tier thermal imaging system is in the cryogenic refrigeration and thermal insulation package for the detector.

The earliest imager designs, be they linescanners or thermal imagers, used mechanical scanning with mirrors. Very simple mechanically scanned designs would use a single detector element and mirror that would be mechanically swept left-right and up-down, no differently than a television image is scanned, to create an image of a scene. This is cumbersome and produces a poor quality image.

The most widely used scanning systems, introduced during the 1970s and still used in some production equipment, use a linear detector array (effectively a row of side by side detectors) and a mirror, which either nods up and down or rotates. This line scan technique allows the imager to capture one line of a television image at a time, with the movement of the mirror determining which line in the image is being illuminated by the imaged scene.



A scanned thermal imaging module (Texas Instruments).

Early systems, such as the Texas Instruments Forward Looking InfraRed (FLIR) modules used a clever technique (see image) which used a double sided mirror, and an array of Light Emitting Diodes (LED). In this system, the signal from each MCT detector element was boosted by an amplifier and used to drive an LED. As the mirror mechanically rotates, its front side scans the imaged scene, reflecting infrared light into the row of MCT detectors, and concurrently reflecting via its rear side visible light from the row of driven LED emitters into a vidicon television camera tube. In this manner the system automatically synchronises its scan.

Scanned imagers of similar configuration are expected to remain in production for the forseeable future, as the difficulty in fabricating single chip MCT focal plane arrays of useful resolution for longwave applications makes this the only affordable technique.

Focal Plane Arrays, identical in concept to visible band CCDs, are the technology of choice for modern production thermal imagers. Such devices integrate up to millions of detectors, and combine the necessary on chip connections to read out the image. In effect, like CCDs, these focal plane arrays are single chip thermal imaging cameras.

The principal issue in such imagers is what the detector technology permits in terms of detector density on a slab of material. To produce a good quality television image, 640 x 480 up to 800 x 600 detector elements are required. To produce a viable framing camera image, even higher resolutions are required.

During the 1980s considerable effort was invested in trying to achieve such densities with MCT materials, but the results were disappointing. To date, MCT-based FPAs remain mostly in the 128 x 128 up to 640 x 512 category, with some midwave band MCT arrays achieving up to 2048 x 2048 pixels.

InSb has proven a more tractable material, accepting the limitation to midwave band operation. 640 x 512 category devices are widely available, and resolutions of 2048 x 2048 pixels are being marketed.

QWIPs represent the new frontier in thermal imaging arrays. As noted previously, the infrared colour sensitivity of QWIPs, unlike bandgap detectors, can be easily manipulated by controlling the depth to which the wells are etched. The GaAs material potentially permits much larger numbers of detectors per array, which affordable fabrication yields (ie reject rates resulting from dead pixels in production). Despite their immaturity, production QWIP imagers with 640 x 512 resolution have been commercially available since 2002. The latest research papers report demonstration prototypes with resolutions up to 2048 x 2048 pixels, suitable for framing camera applications. QWIPs fabricated as direct replacements for single colour legacy imagers will provide for midwave and longwave band single chip imagers, with higher resolution, lower unit costs and better quality than MCT and InSb devices, longer term as fabrication techniques mature.

What is no less important is that QWIPs permit multiple band imaging on a single array of detectors. In effect, a QWIP based imager can be fabricated to be capable of switching between shortwave, midwave and longwave imaging modes, or it can be fabricated to concurrently generate separate but perfectly geometrically registered images in multiple infrared colour bands. In effect, QWIP technology permits concurrent multiple infrared band imaging from a single device.

Germany's AIM were the first to produce a viable dual band QWIP, which images in both the midwave and longwave bands. US researchers recently reported (Choi et al) a four colour band QWIP, using corrugated QWIP fabrication technology.

In the long term we can expect QWIP-based imagers to displace bandgap imagers in most military applications, as new equipment is built around QWIPs and legacy equipment is upgraded with QWIPs. The potential for affordable higher resolution imagers will result in the gap between resolution performance of visible band CCDs and QWIPs to narrow over time. In turn, the capabilities of top end military infrared framing cameras and thermal imagers will expand.

The capability of suitably designed QWIPs to image in two or more infrared bands will prove especially valuable. In many applications it will allow an operator to instantly select whichever band is producing the best quality image for the local atmospheric conditions. In some ISR applications, the ability to image in two bands permits thermal profiling of a scene, by digital post-processing the two images and using the ratio of the brightness in the two bands, and the blackbody curve, to calculate the object's temperature. This can facilitate target identification and false target rejection.

The construction of a modern QWIP or MCT/InSb based imager will follow the pattern seen with CCD camera technology, with the addition of a cryogenic cooler for the detector chip. The big differences will lie in the types of materials used for lenses and mirrors and the geometry of these, as is the case with all thermal imaging hardware. Typically the video output is in analogue RS-170 or RS-343 format,

The Future

The long term trend for thermal imaging sensors will be progressive improvement in band coverage and resolution of infrared imaging devices, especially once QWIP technology matures. As with visible band CMOS and CCD sensors, optics quality and jitter stabilisation will set limits on achievable imagery quality.