QWIP Sensors in Military Applications

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ABSTRACT

During acquisition of new thermal imaging systems, the performance requirements from the international military community are increasing. At the same time the number of applications for TI systems are increasing and ranges from high quantity applications like rifle sights to IRSTs for airborne applications. Simultaneously, with shrinking military budgets, the cost must remain fixed or preferably be lowered. This means that, maybe except for the most expensive platforms, the price of the imager is one of the most dominating parameters.

In the last few years it is becoming more and more obvious that, for medium and high performance thermal imagers, the customer demands staring focal plane arrays, here referred to as third generation detectors.

Simultaneously, LWIR (8-12μm) operation is the preferred choice, at least for customers in the Northern Hemisphere, ruling out most of the hereto-available FPA systems.

Since the Gulf war, the range requirements have shifted from recognition at maximum weapons range, to identification at, or beyond, maximum weapons range in order to avoid fratricidal incidents. This excludes bolometric systems for the next five to ten years.

This paper discusses the different detector and systems technologies available today and in the near future, and how they measure up to these requirements. It is concluded that the only affordable alternative today and within the next ten years is QWIP technology.

A system based on a Swedish developed and manufactured 320x240 QWIP has been demonstrated in the field. This and examples of other systems under development are presented.

Keywords: QWIP, Infrared, Focal plane array, IR detectors, Military systems

1. INTRODUCTION

Thermal imagers are finding an increasingly extensive use among the international military community. Their use have changed from a pure night-vision tool to being the prime means of detection, recognition and identification for many systems, during both day- and night-time. The advantages concerning detection of objects hidden behind natural covers such as bushes and trees as well as behind purposely-devised man-made camouflage are obvious. Thermal imagers are also used as gun or missile sights and for missile seekers, applications that are well suited for third generation imagers.

With the spreading use, new requirements are being placed on performance and cost of these systems. The scope of this work is to exemplify some of these requirements and to review the current and near future alternatives in designing such systems.

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2. CUSTOMER REQUIREMENTS

2.1 Need for identification means a major step in performance.

Since the Gulf War with a large number of fratricidal incidents, the performance requirement has shifted. Target recognition (is the target a tank or a truck) at the maximum engagement range used to be sufficient. Today, identification (is the target a T-80 or an M1 tank) is required, at least as long as secure Identification Friend or Foe (IFF) systems are missing. Thus, identification at maximum weapons range is the desired performance limit when acquiring new thermal imaging (sighting) systems.

2.2 LWIR spectral band is preferred in army applications.

The first staring arrays appeared in the 3-5 um (MWIR) spectral band with detector materials as PtSi and InSb giving an excellent image quality. For army systems, the 8-12 μm (LWIR) spectral band is the preferred choice, at least for systems operating in the sub-arctic region and designed for moderate ranges[1]. It offers better transmission through the dust and smoke filled atmosphere of the typical army battlefield, and better sensitivity for targets at temperatures close to ambient, as the typical vehicle, soldier or building. In tropical atmospheres and against hotter targets (>400K) the 3-5 μm band has an advantage however.

2.3 3rd gen. detectors (i.e. Staring FPAs) – an investment in the future

Staring Focal Plane Detectors (FPA) have a number of technical advantages over scanning systems. The increased integration time and the potential for good image quality may be the two most important. While there are disadvantages as well, a clear trend with the military customer, be it wise or unwise, is to request staring FPAs for new systems. The reason for this may be purely emotional, a fear of being stuck with "old-fashioned" technology, but still the requirement is there. The most important aspect is however that all future development will be made on 3rd generation detectors resulting in major improvements in performance.

Regarding nomenclature, a dispute is raging whether to call these detectors 3rd generation or generation 2.5. The leading US authorities have decided that performance of the current large FPAs do not constitute a full generation step from the scanned 2nd generation systems. The term 3rd generation is however, well established on the market and we feel that the technical evolution in removing the scanning mechanism validates the use of that name.

2.4 Lower cost

With decreasing military budgets and increasing numbers of thermal imagers, the obvious requirement is lowered costs. This applies to initial price but especially to life cycle costs. In this respect FPA based systems have an advantage over scanned systems in that they make away with the need for the moving parts in the scanner. The cooled systems still have the need for expensive cooling engines but, as will be shown, the uncooled alternatives do not have the performance to compete for medium to high performance systems.

3. MANPORTABLE SYSTEM (TYPICAL EXAMPLE)

In order to understand the considerations made in designing a thermal imager we choose, as an example, to look at an application which requires good performance but is produced in volumes that make the price very important.

A typical example of such an application is man-portable, medium range anti-tank missile systems. Basically all of these systems have, since a decade, a thermal imager as an option or as the primary sight. Most of these sights are, so far, based on first or second-generation detectors. These however cannot fulfil the requirement for full engagement range identification. In Table 1 are advertised data for some of today's competing medium range anti-tank missile systems.

System	Missile range/m	System weight/kg	NFOV	WFOV	Operation time
Javelin	2000	22.3	9x*	4x	4 h
Trigat MR	2400	43	3°	8°	5 h
Bill 2	2200	46	2.3°	4,6°	3 h
Gill	2500	26	N/A†	N/A	N/A

Table 1 Advertised data for some current missile systems

3.1 Size/weight constraints for thermal imager

To fit within the total weight budget of a system which comprises missile, day sight, stand and thermal imager, the thermal imager must weigh less than say 10 kg and should weigh about 5 kg. In some of the systems named in Table 1 a visual relay optic is used to inject the image into the day sight. To clarify the notions of this paper, the visual part will be excluded from the reasoning herein. Thus, stated weights and dimensions may differ substantially from the ones of the actual systems. In order to be easily carried by one man the imager external dimensions should not exceed 300 mm x 150 mm x 150 mm.

3.2 Field of view

The exemplified systems mostly provide two different fields of view. One wide field of view (WFOW) for surveillance, detection and possibly tracking and one narrow field of view (NFOV) for recognition and identification. We will limit ourselves to discuss the latter here since that is the one concerning the detection task used for the performance requirement above. A narrow field of view increases the range performance but if it is too narrow it may prove difficult to use. A reasonable NFOV seems to be about 3° horizontally. We will use 50 mrad (2,86°) to simplify the calculations.

3.3 Maximum range

A medium range anti-tank missile will have a range between 2000 and 2500 m. For reasons that will be obvious later, we choose to use the value of 2300 m for our calculations.

4. PERFORMANCE TRADE-OFFS

To reach a certain resolution a minimum number of pixels per mrad is needed. Thus the resolution requirement at a certain field of view drives the number of pixels needed towards a larger number of pixels.

The size of the imager is strongly dependent of the size of the optical system, the focal length and the lens diameter. The overall size requirement of the imager limits the focal length and F-number of the system. The focal length, in turn limits the pixel size for a defined number of pixels and a given field of view. In Figure 1 the darker ovals represent initial requirements. Arrows pointing rightwards indicate a trend towards smaller dimensions and higher resolution.

Since sensitivity is proportional to detector area, the sensitivity requirements will counteract some of these factors, driving for lower F-numbers, i.e. larger apertures and larger pixels. In Figure 1, the leftwards arrows indicate this conflict. As always, the end result is a compromise between conflicting requirements.

* Field of view figures have not been available, it is assumed that 9x magnification equates to roughly a 5° field of view and 4x magnification to a 12° field of view.

† Field of view data not available. The day sight has 10x magnification and a field of view of 5°. The thermal sight has wide and narrow fields of view.

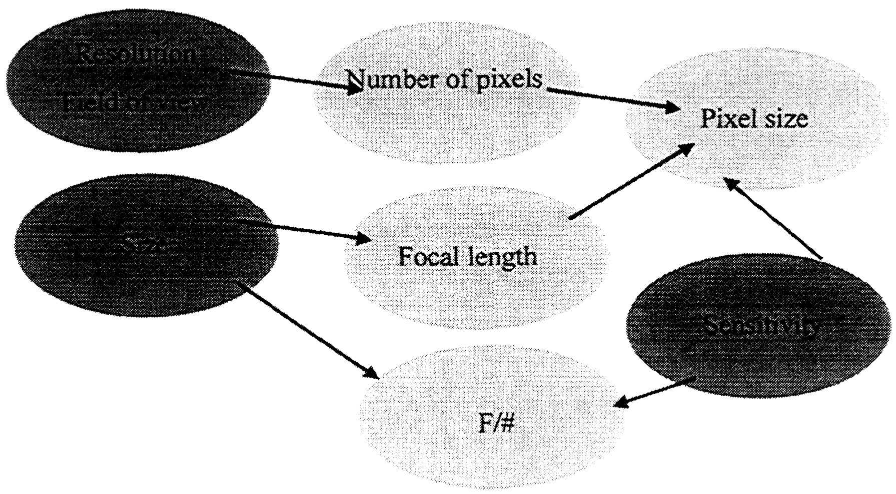

Figure 1 Performance trade-off interrelations

5. RANGE PERFORMANCE

If we assume the performance requirement as identification at maximum range, and that range is 2300 m, what is the resolution requirement of the imager? The standard NATO definition of a Main Battle Tank (MBT) target, is a 2.3 m x 2.3 m square with a temperature difference to the background of 2K. Thus, the target subtends 1 mrad (2.3 m/2300 m) of the field of view. The commonly used identification task criteria is 6 cycles over the target, thus the resolution required is 6 cycles/mrad. Note that if the target can be identified by means of other methods recognition can be sufficient, reducing the required resolution to 3 cycles/mrad. For a missile gunner it is however necessary to be able to identify the target. The conclusion is that to be able to identify, the thermal imager and its resolution has to be twice as good (four times more pixels are needed) than for an imager where recognition is sufficient.

The detected temperature difference at the imager from a 2 K target at 2300 m of course depends on the atmospheric transmission. The two attenuation coefficients normally used are $\sigma = 0.2\ km^{-1}$ for good transmission and $\sigma = 1.0\ km^{-1}$ for poor transmission.

Target ΔT	Attenuation	Detected ΔT
2 K	σ=0.2 km-1	1 K
2 K	σ=1 km-1	0.2 K

Table 2 Detected temperature differences as a function of atmospheric transmission

6. DETECTOR REQUIREMENTS

6.1 Resolution

How many pixels are needed to achieve 6 cy/mrad resolution in a 50 mrad field of view? There is currently no universally accepted performance model that accurately models staring FPA performance. Using the FLIR92[2] model the Nyquist frequency is considered the resolution limit. With this reasoning, 12 pixels would be needed to resolve 6 cycles. However, practical experience in the field has shown that this reasoning, at least when coupled with the old criteria, is too conservative. The German TRM3 model uses the minimum temperature difference perceived (MDTP) instead of MRTD at frequencies above Nyquist. Instead of stipulating that it shall be possible to resolve all four bars of the standard four-bar target at a certain temperature difference, it suggests that it shall be possible to detect a number of bars, which due to aliasing effects may be less than four and that these detected bars need not be of equal width. This method allows for performance beyond Nyquist, and since the actual field targets are aperiodic, aliasing is not the major problem. Using

TRM3 simulations, see figure 2, the actual frequency limit seems to lie between 1.5 and 1.75 times the Nyquist frequency, depending among other things on F-number and detector element size in relation to pitch.

To avoid too much optimism, we will use 1.5 times Nyquist as a reasonable performance limit in this case. Thus we need 8 pixels over the target to achieve identification. Together with the field of view requirement we find that we want to have more than 400 detector pixels horizontally over our FPA.

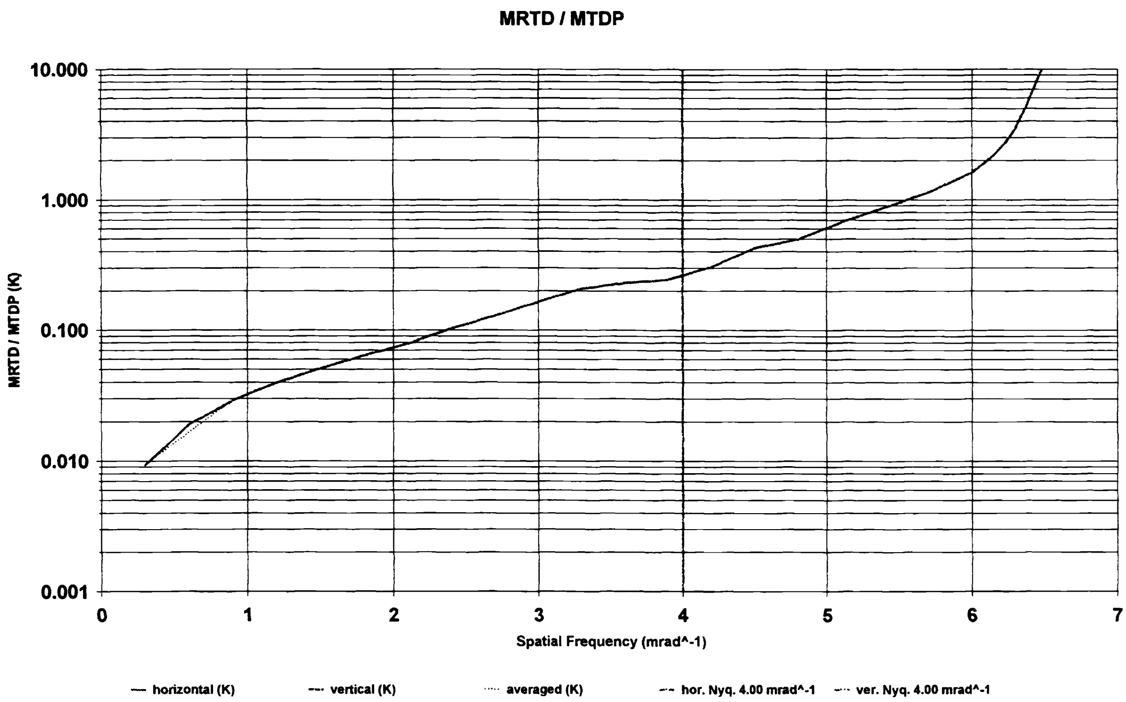

Figure 2 MRTD/MTDP plot of a simulated system with 4.0 cy/mrad Nyquist frequency and 30 mK NETD

In order to achieve a perceivable temperature difference, see Table 2, at frequencies nearing the limit, at 2300 m range, the NETD needs to be significantly better than 100 mK.

7. OPTICAL REQUIREMENTS

7.1 Focal length

The overall size of a man-portable imager limits the focal length of the system to about 250 mm. It is, of course possible to fold the optic, but this will reduce the aperture or otherwise increase the size of the imager. The pixel number and field of view requirements in 6.1 i.e. 8 pixels over 1 mrad gives an instantaneous field of view of 0.125 mrad. This is equivalent to a 250*0.125 µm=31.25 µm pixel pitch. Thus the drive is to have a pixel pitch lower than this to keep the size of the imager within limits.

7.2 Aperture

The aperture is likewise limited by overall size to approximately 100 mm. This gives us an F/# of 2.5 if we keep the focal length to 250 mm. The aperture is in a way a harder system driver than focal length, as the overall dimension and the weight tends to increase with the square of the aperture. Also the cost relies quite heavily on aperture size as large optical elements, especially Germanium lenses can be a significant contribution to the overall system cost.

8. AVAILABLE TECHNOLOGIES

Which detector technologies are available for a 8-12 µm, FPA imager? We identify three possible candidates: bolometers, MCT and QWIP.

8.1 Bolometers

Bolometers are a very attractive element in a solution. They don't need cooling, so the system cost is low, as is the power consumption. Large FPAs are feasible to manufacture today, even if most available bolometers still fall beneath the 320x240-pixel range.

The drawbacks of bolometers are low sensitivity and speed. Commercially available bolometers typically have a 100 mK NETD, with a 50 µm pixel pitch and at F/#=1. Development is decreasing both size and NETD even though they normally are conflicting requirements. Bolometers with 25 µm pitch have been demonstrated, as has NETDs down to 25 mK. But this is still at F/#=1.0 or larger apertures.

Performance is constantly improved and there is still room before the theoretical limits are reached. Judging from the laboratory results published today, there is still at least 10 years to go before bolometers can be a commercially available contender for medium performance thermal imaging.

8.2 MCT

MCT has for many years been the detector material "par preference", with very good sensitivity cooled to 77K. Typical NETD is 20 mK @ F/#=2.0 However, due to the crystalline nature of the material, the problems involved in producing large arrays, with good uniformity are huge, giving a very low yield and therefore a very high price. MCT FPAs are today basically only used for scientific applications or on expensive platforms.

8.3 QWIP

QWIP detectors are built from GaAs and GaAlAs using standard IC fabrication technology. Carried by the trends in the computer industry, the processes are well proven and fabrication of large FPAs is possible with excellent yield.

QWIP detectors have earned a bad reputation due to inherent low quantum efficiency. The Swedish company ACREO (formerly IMC) has developed and patented an optical coupler concept based on a two-dimensional reflection grating etched into the upper part of the detector mesa[3 4 5 6 7]. This improves the quantum efficiency by increasing the number of photons absorbed in the detector element. For practical purposes however, quantum efficiency is not a relevant figure of merit. Instead, FPAs must be judged on uniformity and NETD.

The QWIP detector developed in Sweden at ACREO is currently in production as a 320x240 element QWIP FPA with a pixel size of 38 µm and an NETD of 16 mK @ F/#=1.5 and a 5 ms integration time [8 9]. ACREO is a company created as a spin off from research at the Royal Institute of Technology in Stockholm. ACREO designs and manufactures the detector chip with its ROIC. The detector is bonded, mounted in a dewar and the cooling engine is attached by FLIR Systems AB in Sweden. A standard integrated cooling engine is used, operating at 70 K. This combination works nicely without major reduction of cooler life time or increase of power.

Together with the video electronics this forms a QWIP detector module which is common for several applications. This module is used by FLIR in their SC3000 QWIP camera that was introduced to the market at the SPIE Orlando meeting in 1999 and basically the same module is used in all application described below. A 640x480-element array with 25 µm pitch is under evaluation.

9. FURTHER QWIP ADVANTAGES

The GaAs structures of the QWIP are compatible with silicon structures enabling a close integration between detector chip and read-out circuitry. This makes advanced on-chip processing possible – intelligent detectors. Image processing such as edge detection, contrast enhancement or even automatic target recognition and tracking may be done directly on the chip, minimising the data that needs to be read out from the detector. The main problem is to decrease the power dissipation of the processors, in order not to increase the cooling need of the detector.

The narrow bandwidth of the QWIP is a disadvantage where sensitivity is concerned but offers advantages in a smaller Airy-disk and less need for colour-corrected optics. Also, for a LWIR QWIP it is possible to make the sensor insensitive to 10.6μm CO_2 laser radiation.

Through the fact that the spectral sensitivity is design related rather than material related, the spectral sensitivity of the QWIP can be tuned to the desired wavelength. Dual colour QWIPs can be made in any choice of spectral bands, NIR, MWIR, LWIR or VLWIR.

A NIR/LWIR dual colour QWIP can offer thermal imaging in the LWIR band while also being sensitive to 1.06 μm radiation, thereby making visible the radiation from laser range finders or target designators.

An MWIR and a dual colour (MWIR/LWIR) detector are under development at ACREO.

10. SYSTEM EXAMPLES

10.1 BIRC

The Bill Infrared Camera (BIRC) is a clip-on thermal imager for the Bill2 medium range anti-tank missile system. It is built on a unity magnification philosophy, where the thermal image is injected via visual relay optics into the day sight using the magnification of the day sight to achieve the required magnification in the image. The unity magnification principle has the advantage that excellent sightline stability can be achieved with no need for special alignment between thermal imager and day sight. BIRC is powered by Lithium batteries giving between two and three hours of continuous use. It is man-portable with a weight of about 9 kg and is designed against military environmental requirements including extreme temperatures, shock, vibration and electromagnetic compatibility.

BIRC is based on the ACREO 320x240 QWIP and was first demonstrated during winter trials in Rovaniemi, Finland during February 1999. The unit operated non-stop during 8-10 h days in –35°C (-31°F) with excellent performance. BIRC is currently developed under contract for the Swedish Defence Materiel Administration (FMV) with first delivery in November 2000.

Imagery from this demonstrator unit can be seen in figures 4 and 6. The images were digitally captured during daytime at Lidingö, outside Stockholm, March 22nd 2000.

BIRC or derivatives thereof, can readily be adapted to other similar missile systems such as Milan, Tow or Eryx.

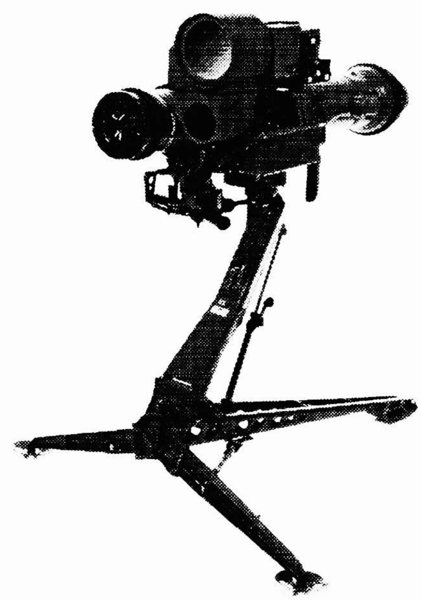

Figure 3 Bill system with BIRC thermal imager

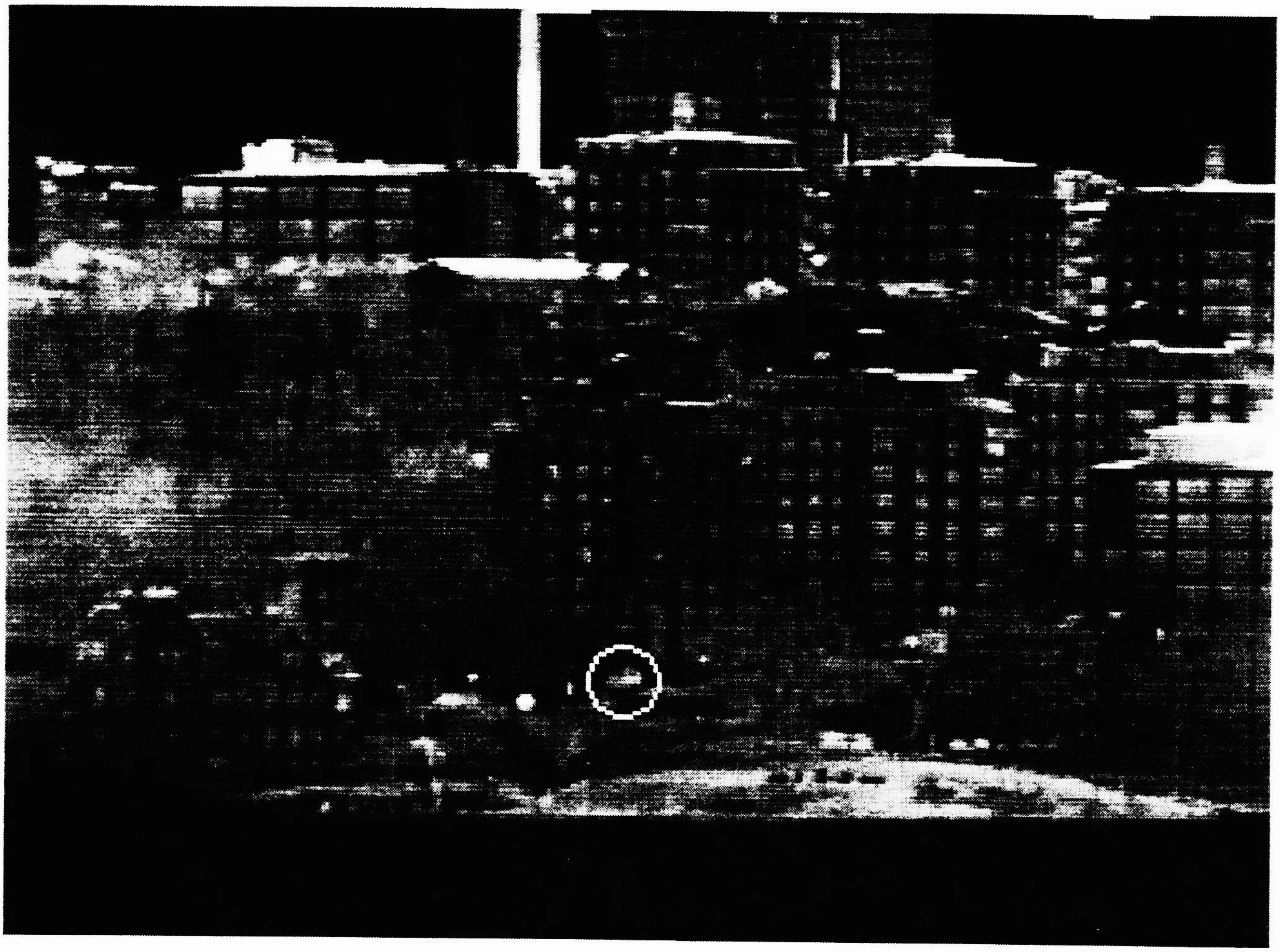

Figure 4 BIRC thermal image. Scene at 3000 m (over water). FoV=2.3°. Encircled is a medium sized car which is clearly recognisable.

10.2 EOI

The Swedish and Norwegian MoDs are co-operating in a purchase of an artillery forward observation instrument. For this application, CelsiusTech Electronics have teamed with Simrad Optronics in Norway, in developing a solution. The system is based on a Simrad LP10 handheld or tripod mounted laser range finder with integrated digital compass and GPS. A thermal imager based on the 640x480 QWIP can be mounted between the tripod and range finder or just beneath the range finder if used handheld. To minimise weight, the thermal image will be displayed in the LP10 display and the imager will be controlled from the LP10 controls. To enable autonomous operation as a pure observation imager, an optional display and control module will be developed.

Figure 5 Forward observer instrument with EOI thermal imager

10.3 Handheld imagers

Apart from the EOI, which can be configured as a handheld imager, several other design studies have been made to use the QWIP-module in handheld imagers. The field of view is an important driving factor in reaching the weight requirements for a handheld imager.

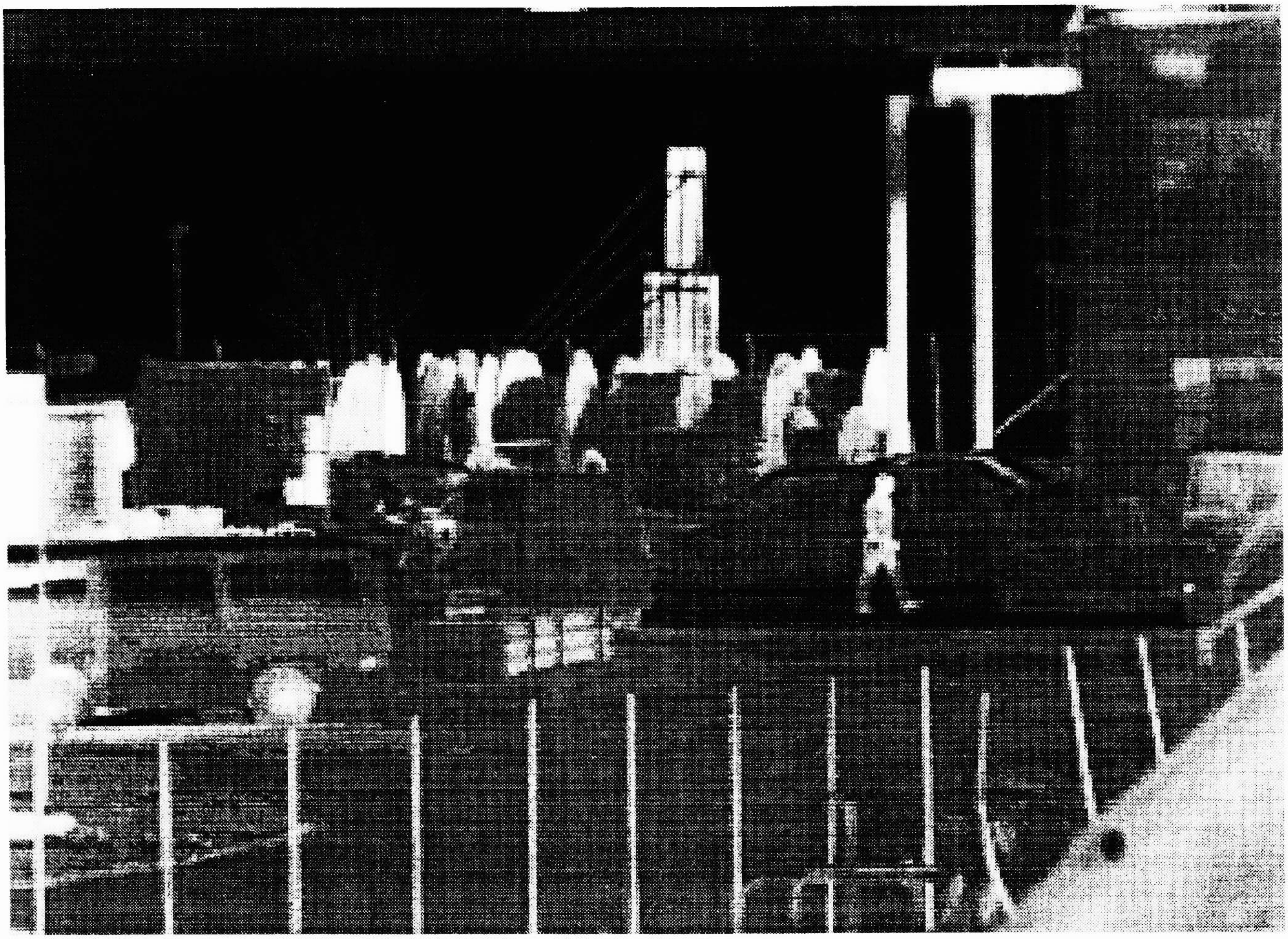

Figure 6 BIRC thermal image. Scene at approx. 300 m, FoV=4,6°

10.4 Vehicle mounted imagers

Development of thermal systems based on QWIP modules is taking place at CelsiusTech Electronics for implementation in different vehicle Fire Control Systems. The thermal systems will be based on either the 320x240 or the 640x480 detector depending on application and are intended for both new needs and for replacing older systems. The primary target is to introduce these vehicle-mounted imagers for the Swedish developed Combat Vehicle 90 family's commander's and gunner's sights using common units with the other QWIP developments and thereby creating systems suitable for integration in other vehicles.

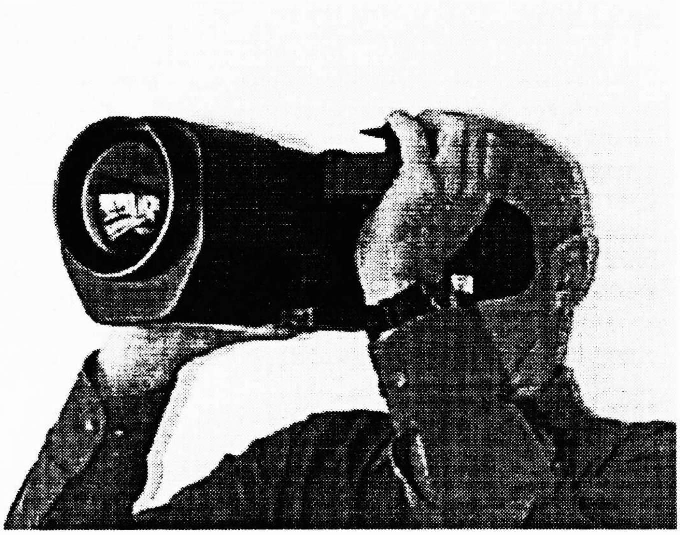

Figure 7 EOI thermal imager configured as a hand-held imager

11. CONCLUSIONS

Under the provisions presented, it is concluded that the only cost-effective solution available for 3rd generation, 8-12 µm band, medium-to-high performance thermal imaging systems for man-portable use today and in the nearest future is based on QWIP technology. CelsiusTech Electronics has demonstrated one system, BIRC, using this and has a serial delivery contract for this imager. Several other applications are studied under different contracts and prototypes for different applications will be delivered during 2000 and 2001.

12. ACKNOWLEDGEMENTS

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