Analysis of SWIR Imagers Application in Electro-Optical Systems

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***Abstract*— In this paper we explain properties of imaging in different spectral regions that are used in multi-sensor imaging systems for long range surveillance and analyze scenarios in which additional short wave infrared SWIR imaging sensor could improve its performances. Analysis of state-of-the-art SWIR components and additional functionalities of modern SWIR detectors based on InGaAs technology are given. We have implemented multi-sensor imaging system with imagers in LWIR, MWIR, VIS and SWIR spectral region and generated simultaneously captured examples of images for two scenarios of medium and long range imaging and explained the results and advantages of SWIR camera that are obtained.**

***Index Terms*—multi-sensor imaging system, long range surveillance, SWIR imager.**

I. Introduction

IN order to fulfil challenging task of border and coastal surveillance, multi-sensor imaging systems comprise diverse imagers and sensors sensitive in different spectral ranges.

When selecting imagers in multi-sensor long range imaging system it should be considered that visibility is greatly reduced by atmospheric obscurants that effect differently the propagation of radiation in different spectral ranges. It is important to select operation in a spectral region in which atmospheric transmittance is high and this is provided in four spectral bands: Visible VIS (390 to 700 nm), Shortwave Infrared SWIR (0.9 to 1.7µm), Mid Wave Infrared MWIR (3 to 5µm) and Long Wave Infrared LWIR (8 to 12µm) that provide minimal attenuation. For most other wavelengths, the atmosphere is relatively opaque. The graph of atmospheric transmittance is given in Fig 1 [1], [2].

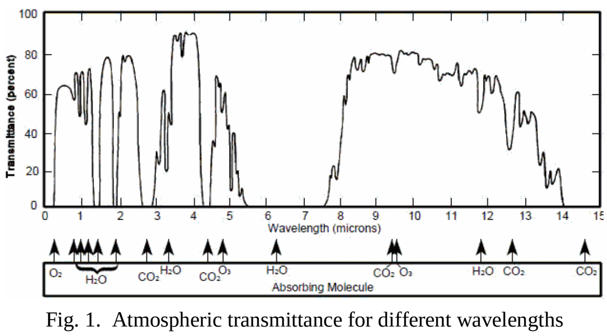

Fig. 1. Atmospheric transmittance for different wavelengths

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The task of border and coastal surveillance multi-sensor imaging systems is to provide 24/7 monitoring in all weather conditions. For night vision, a necessary component is the infrared imager in long wave infrared LWIR or mid wave infrared imager MWIR that are receptacle to emitted temperature difference between the object and a background, so they produce an image without any natural (sun, moon) or artificial illumination required. They are referred therefore as thermal imagers. Because they provide good contrast, their image can be used for detection at very long distances. Cryogenically cooled MWIR imagers are more used in demanding coastal scenarios as their sensitivity is higher than that in uncooled LWIR imagers. The price of installation and maintenance of cooled MWIR systems is therefore several times higher than that of uncooled LWIR systems.

For daylight imaging color visible camera provides more information than thermal imagers which is needed for identification, such as color and resolution which are intuitive to the human eye.

SWIR imagers are complimentary to MWIR and LWIR imagers when it comes to vision enhancement and low visibility in poor weather conditions. Imagery in the SWIR is similar to visible imagery, in that it senses reflected light, thus interpretation and scene analysis is improved over MWIR and LWIR systems which have good detection abilities, and are a good compliment to the short wave infrared. While emissive imaging can detect the presence of a warm object against a cool background, a SWIR camera can identify this object.

SWIR technology offers many benefits for a variety of electro-optical systems and applications: the image is reflective and thus more natural and intuitive compared with emissive. It penetrates fog and haze much better than detectors sensitive in the visible spectral range, especially for long range distances. For low light level conditions it can utilize the night glow phenomenon and it can provide wide dynamic imaging (from daylight to overcast night conditions). Another important advantage is the capability to perform active or gated imaging with "eye-safe" laser source [3].

Comparing the properties of imagers in different spectral regions we can note that:

TABLE I
PROPERTIES OF DIFFERENT SPECTRAL REGIONS FOR IMAGING

	Visible	SWIR	MWIR	LWIR
Image	Reflective	Reflective	Emissive	Emissive
Resolution	***	***	**	*
Sensitivity to turbulence	***	**	**	*
Atmospheric transmission	*	**	**	***

II. SWIR CAMERA

Current technology enables using of SWIR Focal Plane Array FPA detectors in InGaAs technology, which doesn't require cryogenic cooling and can work at room temperature. Modern technology enables commercially available FPA resolution to reach currently available 10μm pixel pitch, with 1280x1024 pixels. In order to serve a variety of security platforms, SWIR technology is rapidly advancing with better performance being achieved. Also development of broadband detectors is considered which can sense both SWIR and part of MWIR spectrum range.

For technology of III-V compounds, the most commonly used substrates are GaAs, InP, InAs, GaSb and InSb. The InGaAs alloy with a 1.7 μm cut-off wavelength is lattice matched to InP. Therefore it is generally fabricated on InP substrates. In order to extend its sensibility to longer wavelengths, the alloy has to be fabricated on a lattice-mismatched substrate. This can be done on an InP substrate or on a standard GaAs substrate [4].

In Table II typical characteristics of InGaAs commercial FPAs currently available on the market are presented.

TABLE II
TYPICAL CHARACTERISTICS OF INGAAS FOCAL PLANE ARRAYS

Pixel pitch μm	Resolution pixels	Frame rate FPS	Noise RMS
20	320 x 256	100 Hz	110 electrons (typical)
20	640 x 512	100 Hz	120 electrons
30	320 x 256	Up to 346Hz	<150 electrons
15	640 x 512	Up to 120Hz	40 electrons (typical)
12.5	1280x 1024	60Hz	25 electrons (typical)
10	1280 x 1024	60Hz	<35 electrons

SWIR cameras can be used as uncooled, but to achieve ultimate performances (detector response stability and low noise levels) Thermo-electric cooling TEC is applied in most the camera solutions.

Cameras that are used in multi-sensor imaging system usually have continuous zoom lenses which impose additional difficulties in system design. Cameras with detectors sensitive in SWIR wavelength can use standard glass lenses, but for maximum performance, lens design should be optimized for SWIR spectral region (0.9−1.7 μm).

III. RESULTS OF SWIR IMAGERY COMPARISON IN MULTI-SENSOR IMAGING SYSTEM

In order to present different performance of imaging in different spectral ranges, several image examples are presented. These examples are taken with two types of multi-sensor imaging systems that perform video acquisition in uncompressed raw video digital form in order to submit them to further real time high level video processing like image fusion and video tracking.

A. *Measurement setup*

Images are captured in Belgrade for two scenarios, medium range and long range object monitoring, like presented in the map in Figure 2. First scenario with medium range object monitoring has a building which is distant about 4 km and the second scenario with long range object monitoring has a road at distance of nearly 12 km shown in the map. The position of multi-sensor imaging systems are shown on the map in Fig. 2.

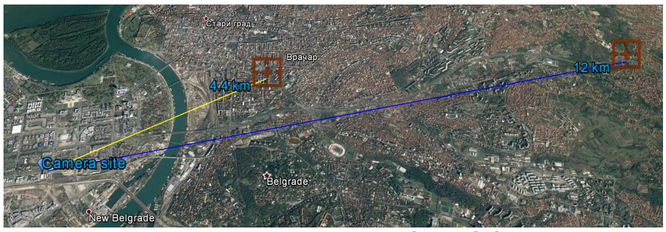

Fig. 2. Measurement setup – observed objects

Measurement setup for the first scenario with medium range multi-sensor imaging system with LWIR, VIS and SWIR cameras, which was developed in Vlatacom Institute and comprises:

- LWIR camera resolution 640 x 480 pixels, 8 x zoom lens
- VIS camera resolution 1028 x 596 pixels, 22 x zoom lens
- SWIR camera resolution 640 x 512 pixels, 12 x zoom lens

Measurement setup for the second scenario with long range multi-sensor imaging system with MWIR, VIS and SWIR cameras, which was developed in Vlatacom Institute and comprises:

- MWIR camera resolution 1280x1024 pixels, 22 x zoom lens
- VIS camera resolution 1028x596 pixels, 55 x zoom lens
- SWIR camera resolution 640x512 pixels, 35 x zoom lens

For the purpose of this experiment, all cameras are focused at the selected scenery and their fields of views are adjusted to match.

B. *Multi-sensor imaging system with LWIR, VIS and SWIR cameras*

The images of the object distant about 4 km are captured using three different sensors LWIR, VIS, SWIR, and are presented in Fig.3, Fig.4, Fig.5. respectively.

The short wave infrared can aid in thermal crossover scenarios which can happen with LWIR imager. Thermal crossover is a point where the temperature of the object aiming to image is equivalent to the temperature of the background. In the images presented, the details of the building are lost when imaged with a LWIR camera whereas a SWIR camera detects the reflected light, not the temperature, therefore capturing more detail then LWIR and a visible camera.

Fig. 3. Image from LWIR camera (distance ~ 4km)

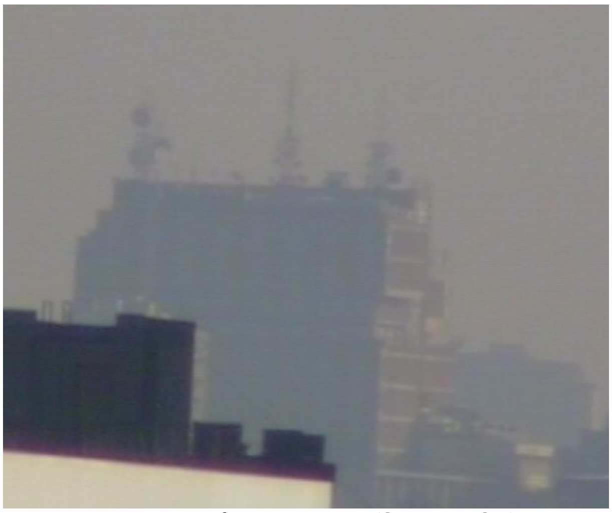

Fig. 4. Image from VIS camera (distance ~ 4km)

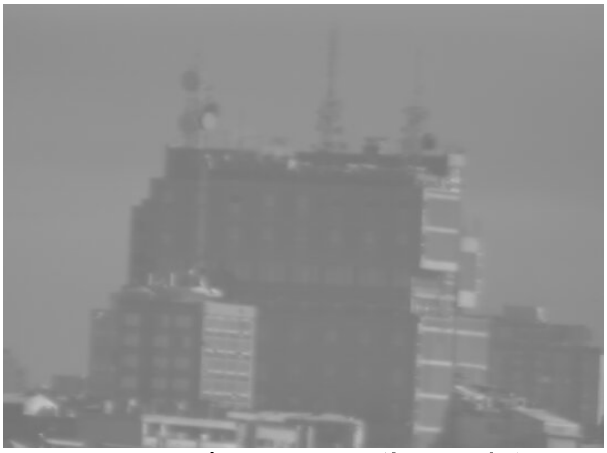

Fig. 5. Image from SWIR camera (distance ~ 4km)

C. Multi-sensor imaging system with MWIR, VIS and SWIR cameras

The images of the road distant about 12 km are captured using three different sensors MWIR, VIS, SWIR, and are presented in Fig.6, Fig.7, Fig.8. respectively.

It can be seen from the shown results that the multi-sensor imaging system that has both SWIR and MWIR imagers has more information and better detection, recognition, identification capabilities. SWIR images are produced by photons reflected from the scene, similar to visible-band images; therefore, the interpretation by the observer is more intuitive than the emission image in the MWIR band. Performance analysis and field tests show significant advantage of the SWIR imaging in the scenario of obscured atmospheric conditions which is frequently happening in long range imaging.

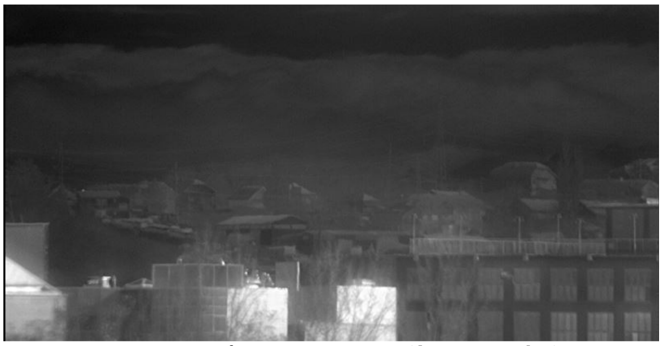

Fig. 6. Image from MWIR camera (distance ~ 12km)

Fig. 7. Image from VIS camera (distance ~ 12km)

Fig.8. Image from SWIR camera (distance ~ 12km)

Having in mind spectral band comparison from Table I., for a given aperture, the visible-band resolution and therefore image-quality should be better than image quality in longer wavelength-bands like the SWIR or MWIR bands. However, this is not true when real and frequent atmospheric conditions are taken into consideration. Both the SWIR and MWIR bands are more penetrative through particles than the visible band. It can be clearly seen from the presented set of images.

Furthermore, when considering the turbulence effects on the visible band image, the SWIR band may be much better solution.

IV. Asynchronous Laser Pulse Detection

Since the SWIR range covers also the spectral range of the eye safe laser emission - 1550nm, same of modern imaging detectors that are designed to have a special pixel readout structure which enables them to work in a particular mode of asynchronous laser pulse detection ALPD which is simultaneous with imaging. This can be used in various systems for military purpose as the functionality of laser irradiation detection, therefore can enable the development of small and compact systems that include additional functions of laser range finder and laser designator finder [5], [6].

ALPD capability of modern SWIR detectors can contribute to more compact, low power, and low cost modern multi-sensor imaging systems design in comparison to traditional systems. Integration of several components or functionalities, such as thermal imager, laser designator, laser range finder LRF, into one multi-function detector has been made enabled with this feature.

LRF is often needed component of high precision targeting units. The precise and accurate information about target distance is an essential variable in the fire control solution of currently developed military systems. Lasers are also used extensively as light detection and ranging LIDAR for 3D object recognition. With the recent advances of LIDAR technology, the accuracy potential of LIDAR data has significantly improved [5].

Another functionality that can be implemented using ALPD mode of modern SWIR detector is a laser designator spot detection. In earlier generations of systems this capability was achieved by accumulation of laser spot photons together with scene thermal photons on the same FPA pixels. The drawback of these systems is a fact that there is a relatively limited see-spot range in the scenes which have high-level background. The possibility enabled by modern SWIR detector with ALPD mode can discriminate in read-out circuitry between image photons that are emitted or reflected continuously from the object (to create the scene) and photons that originated from laser designators pulses.

Another important advanced capability of the modern SWIR detector is the two dimensional laser range finder TRLF mode which is used for small targets ranging. In order to implement a laser range finder with this mode, the system designer needs to add only a pulsed-laser source to its system without the need for another detector. This approach is simplifying the system design and reducing its cost. The key advantage over current existing solutions is that the user sees the exact object to which he is measuring the distance. This is made possible due to the fact that the same pixels that are being used for imaging are those that are measuring the time of flight. This feature enables the system to measure distances for as small targets as humans since there is no fear of boresight retention effects, which is inevitable in systems that use a separate LRF and thermal imager. The working principle of active SWIR imaging is illustrated in Fig. 9.

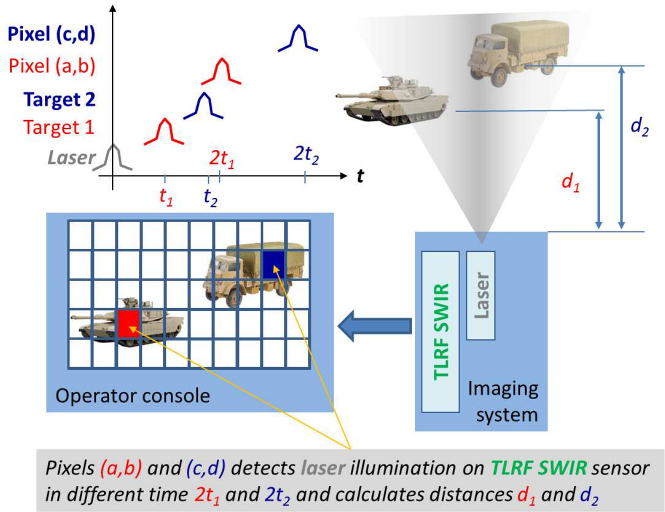

Fig. 9. Two dimensional LRF

V. Active SWIR imaging

The limitations of conventional passive infrared imaging for long range target identification using the MWIR and LWIR spectral band are well known [4]. At longer wavelengths the aperture size of the lens needs to be increased to maintain the sensitivity and very large aperture sizes are increasing the cost, weight and size of infrared optics. For smaller aperture sizes and lower F-number, less energy can reach the detector and long integration times are needed to keep detector sensitivity. In long range systems, images are more susceptible to distortion from atmospheric turbulence and platform vibration. Also, common problem with long range identification using passive thermal imaging is image clutter. Nearby objects can saturate the detector or general scene, originating from emissive objects around and behind the target area can affect identification outcome [6].

The resolution is improved in short wave sensor systems but the need for day/night and all weather operation cannot always be achieved with conventional visible and short wave infrared passive imaging. Active imaging using a pulsed laser can improve performance of systems that are facing these limitations. Usually a wavelength around 1550 nm is used as it is eye safe and corresponds to a window in the atmosphere which has a minimum attenuation.

In terms of the resolution of distant targets, active short-wave imaging has a significant advantage over passive infrared imaging. The wavelength is sufficiently short that conventional commercial optics for visible imaging can be used and even with custom antireflection coatings are an order of magnitude lower in cost than infrared optics of a similar aperture. The pulsed laser produces a highly collimated burst of photons so the perceived illumination level on a small distant object can far exceed the passive emission levels in the infrared region. The working principle of active SWIR imaging is illustrated in Fig. 10.

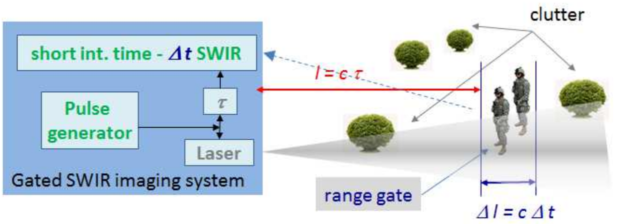

Fig. 10. Active SWIR imaging

Active imaging SWIR systems can be designed using a SWIR camera and a high power short pulse laser illuminator with wavelength 1550 nm and providing a gating for image acquisition in camera. Results reported in literature are promising as these systems are used for reading a ship's name 6 km away from shore, identifying its activities as well as classifying a ship located well beyond 10 km.

Usually in multi-sensor imaging systems, using high-level video processing and application of image fusion algorithm of most informative vision channels can be provided the most informative screen to the operator which then can quickly react and identify a threat even in high traffic areas and to properly distinguish between normal and suspicious activities.

Same concept of gated active SWIR imaging found a place in other applications, such as driver assistance instrumentation for vehicles and aircrafts as it can provide enhanced vision in all weather condition. SWIR is gaining advantage in this application over LWIR imager, as offer much more intuitive imagery to a human eye which is crucial in driver assistance equipment.

VI. Conclusion

SWIR imagers are becoming more present in modern multi-sensor imaging systems for commercial and military application. Properties of imaging in SWIR spectral range are explained. Experimental examples and performance comparison are given by imagery taken from two multi-sensor imaging systems which have LWIR, MWIR, VIS and SWIR cameras. Novel functionalities of modern SWIR detectors are presented as a possibility to optimize multi-sensor imaging system and to reduce its complexity and cost at the same time increasing its overall performance.

References

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