Comparison of passive millimeter-wave and IR imagery in a nautical environment

Appleby, R., & Coward, P. (2009). *Comparison of passive millimeter-wave and IR imagery in a nautical environment*. 1-8. Paper presented at SPIE, Orlando, United States.

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ABSTRACT

Results are presented from a trial in which a real-time passive millimetre-wave camera was mounted on a landing craft. The vessel was operated on rivers in the UK, and imagery of surrounding terrain, structures, obstacles and other vessels was obtained. An IR camera was also used, and the differences in signatures of various features are discussed. Opportunities for image fusion are highlighted.

Keywords: passive, millimeter-wave, littoral, imagery, covert, infra-red, signature, phenomenology

1. INTRODUCTION

The design of a real-time passive millimetre-wave (PMMW) imager has been previously reported[1]. This imager has previously been used to collect flight trials data, as well as imagery of ground-based features in conditions of fog and airborne dust.

In order to investigate its capability in a littoral environment, this PMMW imager has now been operated from a UK MoD landing craft on waterways in the UK. An Infra-Red (IR) camera, GPS sensor, and data recording equipment were also used. This paper summarises the performance of the PMMW sensor in this environment and compares the PMMW phenomenology with that of the IR.

In the course of this work, the PMMW sensor was found to produce complementary imagery to the IR sensor, and there is potential for useful data fusion. Many ambient temperature objects, such as inactive boats and riverside buildings, appear with significantly higher contrast in the PMMW imagery than the IR imagery. Recognition and identification ranges are however short due to the low spatial resolution of a practical PMMW sensor.

The PMMW sensor is also shown to provide useful situational awareness information, such as surrounding terrain, obstacles such as piers and bridges, and the motion of the water such as waves and wakes. The weather conditions were good during the trial, however previous work[2] has confirmed the performance of this PMMW sensor in fog, illustrating the potential for this type of sensor to assist with covert, poor weather, maritime navigation.

This paper firstly describes the trial, outlining the sensors used and the weather conditions experienced. A section on phenomenology follows, where the influences of sensor capability on scene contrast are considered, both for the PMMW and IR sensors. Trials results are then presented, and conclusions drawn.

2. TRIALS INFORMATION

This section outlines the characteristics of the imagers used on the trial, and explains how the trial was conducted.

2.1 Imagers used

The design of the PMMW imager used on these trials has been previously reported[1]. The imager has a 150-element, 94-GHz receiver array, which is scanned over the scene 25 times per second by a spinning mirror. The aperture of the imager is 50cm, which results in a nominal beamwidth of 0.47°, resulting in a “spot size” of 80cm diameter at a range of 100m. The thermal sensitivity of the imager is of the order of 1K, and its field of view is approximately 50° (horizontal) x 30° (vertical). The PMMW imager is mounted in azimuth/elevation gimbals and housed within a polythene radome.

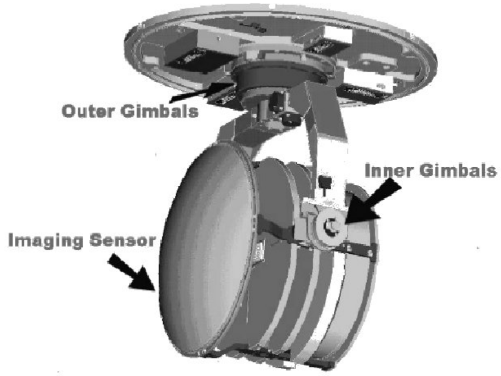


Figure 1: Schematic of PMMW imager

2.2 Ground Trials Vehicle

The PMMW imager and the IR camera (Indigo Systems Merlin™ uncooled 7-14 micron microbolometer camera[3]) had been previously used for helicopter flight trials. The equipment fit for those trials also included a GPS receiver, a Low Light TV camera and data recording equipment capable of recording the outputs from all four sensors simultaneously.

This equipment was subsequently fitted to a Land Rover Defender for ground trials. The data produced demonstrated ability of the PMMW sensor to operate in fog, and to penetrate airborne dust clouds of the type experienced in brown-out conditions.

Figure 2: Ground Trials Vehicle, with PMMW imager in radome

2.3 Trials platform

The Land Rover, fitted with the PMMW and IR cameras and associated equipment, was loaded onto a Landing Craft Vehicle Personnel (LCVP) mk5, operated by the Amphibious Trials and Training Unit Royal Marines at Instow in Devon, in the UK.

The figure below shows the Land Rover embarked on the LCVP. The bow ramp would obstruct the sensors' forward view, so for this trial the cameras were pointed 45 degrees left of straight ahead. This provided a largely clear field of view, however a section of cabin fitted forward of the Land Rover was in the field of view of the IR camera.


Figure 3: PMMW sensor vehicle embarked on landing craft

2.4 Weather conditions

The trials took place over a two week period. The scheduling of the individual trials was dictated by the tides, and the two week duration assisted collection of data both during daylight and after dark.

An outline of the environmental conditions experienced is tabulated below. Due to the large influence that the millimetre-wave radiometric sky temperature has on passive millimetre-wave imagery, the radiometric sky temperature is noted.

Trial index	Time of day	94GHz sky temperature	Air temperature	Other
1	Morning	Up to 140K	7 - 10°C	Overcast, some heavy rain
2	Morning	Up to 70K	12°C	Overcast, dry
3	Evening (after dark)	Up to 150K	12°C	Some heavy rain
4	Evening (after dark)	Up to 90K	11°C	Dry

Table 1: Trials conditions

With the PMMW sensor used in these trials, sky temperatures of above 100K result in imagery of noticeably lower signal to noise ratio. Such conditions were found during periods of rain. This phenomenon is well understood, and achievable improvements in receiver performance will extend the availability of current PMMW sensors in conditions of heavy rain.

The PMMW imagery collected on the after dark trials was similar to that collected during the day (all other weather factors being equal). This is because the dominant source of contrast in the PMMW imagery is reflection of the sky, rather than the effect of solar heating.

The trials results presented in this paper were collected on an overcast, but dry, morning (Trial index 2 in Table 1). The IR and PMMW cameras perform well, and this data is the most useful from the point of view of phenomenology and signature analysis.

3. ANALYSIS OF SIGNATURES

This section explores the contrast and signature mechanisms that act in the PMMW and IR wavebands, in order to put the trials results, and image phenomenology, in context.

3.1 Contrast mechanisms

Passive millimetre-wave imagery is fundamentally a form of thermal imaging. As is the case with IR imagery, the PMMW signatures of objects (omitting resolution effects and atmospheric losses) are dependent on some or all of the following factors:

- surface emissivity, and (if that emissivity is non-zero) surface temperature
- surface shape, texture and orientation
- radiometric temperature of surroundings

It is the difference in signature between an object and its background that gives rise to its contrast. This is true of IR imagery as well as PMMW. However, there are two key differences between the contrast mechanisms seen in the IR and PMMW bands, discussed below.

3.1.1 Emissivity differences

Materials can have a substantially different emissivity in the millimetre-wave waveband to the IR. The most notable is the emissivity of painted metal, which is essentially zero in the millimetre-wave band, but is higher (of the order of 0.9) in the IR.

Hot, painted, metal surfaces can therefore appear with high contrast on an IR image. However, a hot metal object appears no different to a cool (but otherwise identical) metal object on a PMMW image.

The other aspect of this behaviour is that it is not possible to control the PMMW signature of a metal object by modifying its temperature. Whereas cooling a hot metal surface with water may reduce its IR signature, it does not affect its PMMW signature.

3.1.2 Illumination

The radiometric temperature of the sky in a PMMW scene is typically very low, capable of providing a source of contrast of the order of 200K. This phenomenon is referred to here as the PMMW “cold sky”.

As noted above, the emissivity of metal is zero, and the reflectivity is unity, in the mmw part of the spectrum. Therefore, the radiometric temperature of metal objects on a PMMW image depends entirely on the radiometric temperature of whatever is being reflected in that object. If a part of a metal object is reflecting the PMMW cold sky, then that part of the metal object will appear with very low radiometric temperature, irrespective of its physical temperature.

This process gives rise to the high contrast signatures of metal objects, such as vehicles and metal roofs, in a PMMW image.

3.2 Resolution

The maximum angular resolution of an imaging system is a function of its aperture and the wavelength of operation. The wavelength used by a 94GHz PMMW imager is approximately 300 times that used by a LWIR IR camera.

PMMW imagers have large apertures (compared to IR cameras) in order to recover some of the resolution loss that arises from the increased wavelength. However, the resolution of imagery produced by a practical PMMW imager will be less than that of a typical IR camera. The beamwidth of the PMMW imager used on this trial, at 0.47°, is wider than that of the IR camera, which had a beamwidth of 0.11°.

The consequence of this is that recognition and identification tasks, that classically require certain numbers of beam widths across the target, can only be accomplished by PMMW imagers at relatively short ranges when compared to the IR. However, the high contrast of metal objects on a PMMW imager means that the detection ranges of cool metal objects on a PMMW image can exceed IR detection range. This observation provides one means by which PMMW and IR imagery can be complementary. Examples of this behaviour are presented in section 4, below.

3.3 Thermal sensitivity

The thermal sensitivity of the IR camera, 0.08K, is approximately 10 times better than that of the PMMW camera. In heavily overcast conditions, where the benefit of the PMMW cold sky is substantially reduced, the signal to noise quality of the PMMW imagery is lower than that of the IR camera. However, in conditions where the PMMW cold sky illumination is strong, and the scene contains metallic objects, the signal to thermal noise quality of the two imagers can be comparable.

4. TRIALS RESULTS

The images presented in this section are still frames from video clips recorded during the trials. The left hand image of each pair is the 94GHz passive millimetre-wave image, with a “white cold” convention. The right hand image is the IR image, with a “white hot” convention.

Some key phenomenology which can be seen in the PMMW imagery is

- Warm, emissive terrestrial objects (such as trees) have a radiometric temperature close to ambient and show up dark on the PMMW image.
- Metal objects that happen to reflect the sky take on a cold radiometric temperature and show up white.
- The surface of the water appears grey, and (particularly in the video clips) wave action can be seen as a result of the changed surface angle of the water.
- The horizon sky appears as a warm (dark) band due to the long radiation path through the atmosphere. Higher sky elevations appear whiter; dense clouds appear as dark patches.
- The sun, if in the field of view, appears as a dark blob.

Figure 4 contains imagery of an industrial waterfront area. Large warehouse-type buildings are visible. The pilings on the side of the quay are metal, and are clearly angled back from the vertical, as they appear cold on the PMMW image. The horizontal white line at the right hand side of the PMMW image is the metal roof of a more distant structure; this also has much more contrast in the PMMW image than in the IR.

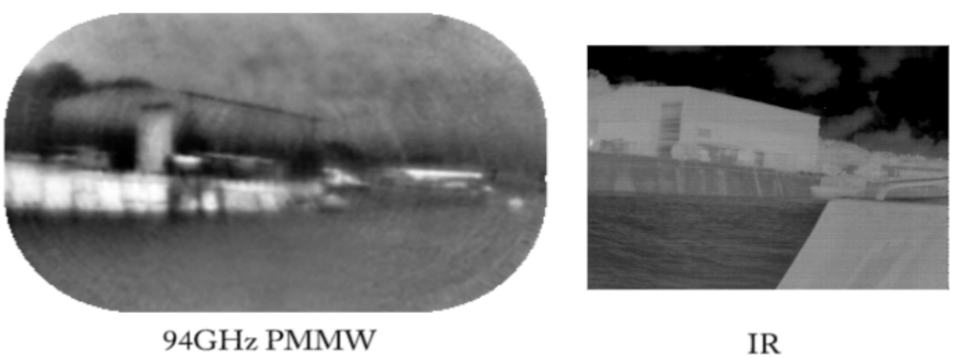
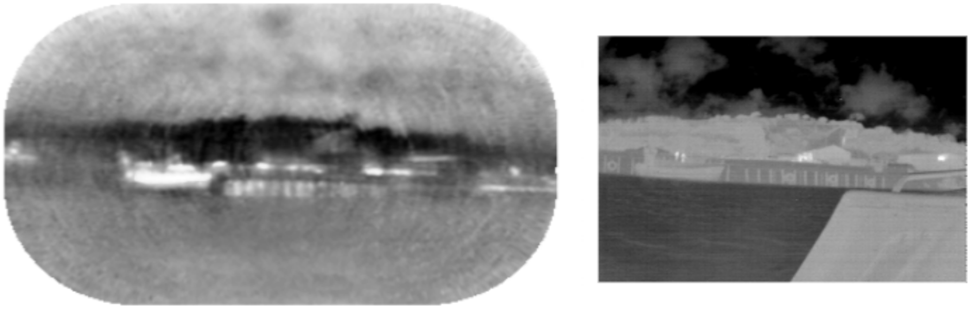


Figure 4: Industrial waterfront

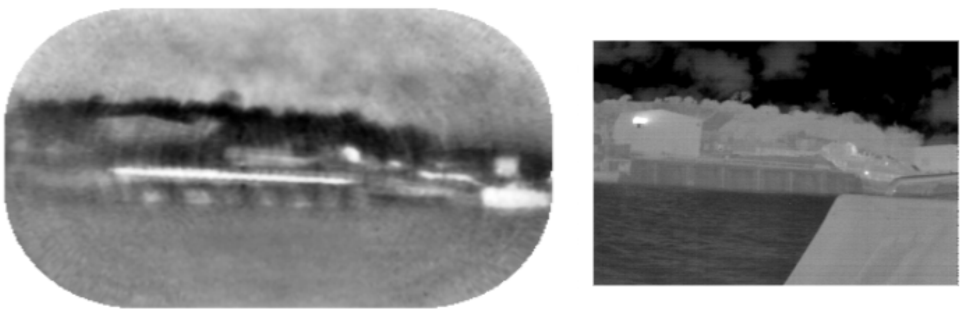
The key feature in the PMMW image in Figure 5, below, is a moored boat. This shows up cold on the PMMW, as some of its metal surfaces reflect the sky. In the IR, this boat, which is clearly inactive, has very little contrast with its background. This indicates that PMMW imagery may be of use when attempting to detect boats in a cluttered littoral environment.



94GHz PMMW IR

Figure 5: Detection of moored boat against its background

Figure 6 demonstrates that hot metal objects do not stand out on a PMMW image. The building on the left of the field of view has an area that is being heated (possibly by an air conditioning plant or similar). This shows up clearly on the IR image, but not on the PMMW, as the physical temperature of metal does not affect its PMMW signature. Between them, Figure 5 and Figure 6 demonstrate the benefits that might be had from fusion of PMMW and IR imagery.



94GHz PMMW IR

Figure 6: Visibility of hot metal

Figure 7 contains imagery of a small boat under way on the river. The main features of its PMMW signature are from particular areas of its structure, rather than from the whole vessel. The personnel standing on the boat are clearly visible in the IR, and are just visible, as a warm vertical blob, on the PMMW. The wake of the boat can be seen on the PMMW, illustrating its ability to detect disturbed water.

The dark blob at the top of the PMMW image is the sun. A distant metal-roofed building, and the skyline of the terrain beyond the river, can be seen on the PMMW imagery.

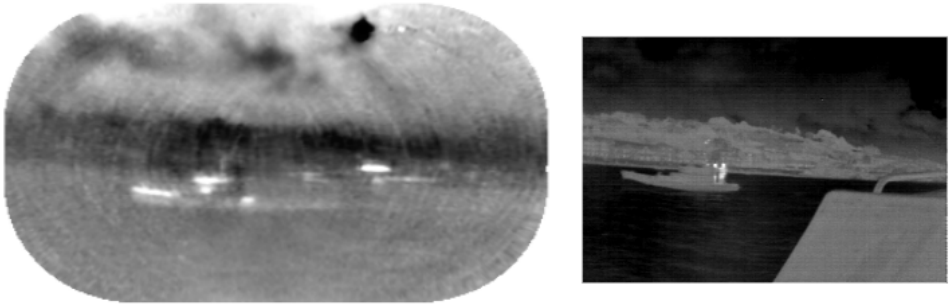


Figure 7: Boat under way

The imagery in Figure 8 is of another boat; this one is moored in more open water. It is cold and has low contrast to its background in the IR, yet shows up strongly in the PMMW.

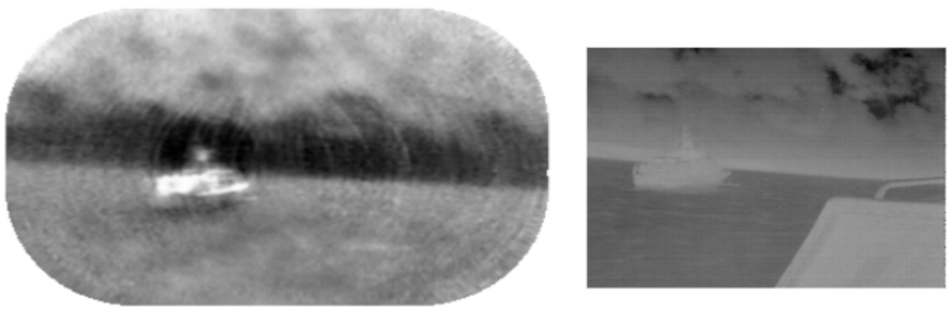


Figure 8: Moored boat

The imagery in Figure 9 is of a bridge; vehicles traveling across it are visible on the PMMW video. The ability of the PMMW camera to image structures and terrain features shows its potential utility if attempting to covertly navigate a waterway in conditions of obscured visibility, such as fog.

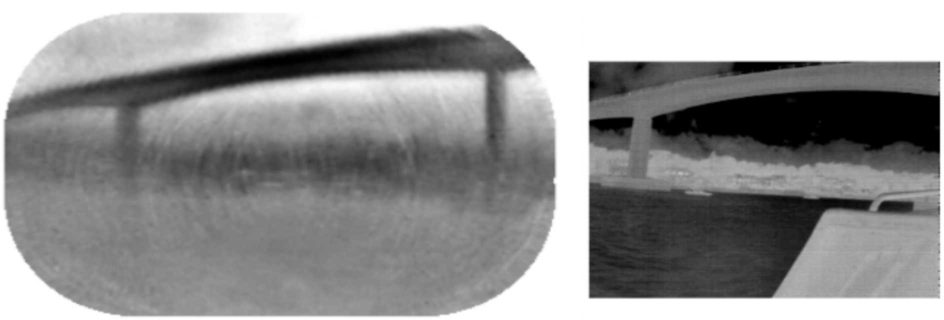


Figure 9: Road bridge

SUMMARY

Results from trials of a passive millimetre-wave imager, operated from a boat on a river, have been presented. The imagery has been compared to Infra-Red imagery, and complementary aspects of the two types of imagery have been discussed.

The results presented here show that, despite the lower spatial resolution of a PMMW sensor, a PMMW camera provides the following capabilities in a littoral scene:

- High contrast detection of boats, against land or water backgrounds, even when the boats are cold
- Imagery of surrounding terrain
- Detection of buildings and other structures
- Imagery of navigational hazards and features such as bridges, jetties, piers and buoys
- Imagery of the state of the water, wave action and wakes.

These capabilities of a PMMW imager are available in day and night, and in conditions of fog, without the need for active illumination. Therefore, PMMW imagery, fused with data from an IR camera, could assist with covertly navigating waterways in conditions of darkness and poor visibility.

ACKNOWLEDGEMENTS

The work described in this paper was funded by UK MoD.

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