VRI Final Technical Report on Phase I SBIR

Technology Development for a Multi-Mission Passive EO/IR Turret Applied to Maritime Search and Rescue

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14. ABSTRACT
The objective of this project is to develop polarization and sea foam mitigation techniques and camera components to improve the performance and reduce the form factor of turreted passive multi-spectral imaging systems, with specific application to an existing sensor system known as EPAS, for electro-optic passive ASW system. The work under this contract was focused on the application of this sensor system to Maritime Search and Rescue. The relative merits of the various sensors in the turret for this application were assessed, including the potential for mitigation of sea foam and the potential use of polarization, and a concept of operations that was developed that provides a day-night capability by means of the use of thermal imaging sensors in an optimal geometry coupled with algorithms suitable for real time processing. A plan was developed and proposed to collect data to evaluate target and clutter characteristics and to demonstrate detection performance. Subsequently the existence of data collected in another program was discovered that can be obtained and analyzed under the option tasks. This would obviate the special data collection.

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Abstract

The objective of this project is to develop polarization and sea foam mitigation techniques and camera components to improve the performance and reduce the form factor of turreted passive multi-spectral imaging systems, with specific application to an existing sensor system known as EPAS, for electro-optic passive ASW system. The work under this contract was focused on the application of this sensor system to Maritime Search and Rescue. The relative merits of the various sensors in the turret for this application were assessed, including the potential for mitigation of sea foam and the potential use of polarization, and a concept of operations that was developed that provides a day-night capability by means of the use of thermal imaging sensors in an optimal geometry coupled with algorithms suitable for real time processing. A plan was developed and proposed to collect data to evaluate target and clutter characteristics and to demonstrate detection performance. Subsequently the existence of data collected in another program was discovered that can be obtained and analyzed under the option tasks. This would obviate the special data collection.

Table of Contents

List of Figures

1. Introduction

This is the Final Report covering work under a Phase 1 SBIR intended to develop polarization and sea foam mitigation techniques and eventually, under possible later phases, camera components to improve the performance and reduce the form factor of turreted passive multi-spectral imaging systems, with specific application to an existing sensor system known as EPAS, for electro-optic passive ASW system.

Work commenced on the contract following a Kickoff meeting with the contract technical Point of Contact, Dr. Mike Contarino, on June 12, 2006, at the offices of Vista Research in Arlington, Virginia. On the advice of Dr. Contarino, the effort was focused on a specific application of the EPAS sensor, for Maritime Search and Rescue. Such a sensor must have day/night capability; for this and other reasons the effort focused on the thermal infared image sensors in EPAS. Dr. Contarino also indicated an interest in the best band to use, so both mid-wave IR (MWIR) in the 3-5μm band, and long-wave IR (LWIR) in the 8-12 μm bands were considered.

The result is a proposed concept of operations that will provide a significant advance in capability in Maritime Search and Rescue. An IR imaging capability such as that found in the EPAS sensor system, preferably enhanced with newly available cooled LWIR cameras, can provide a robust day/night Search and Rescue capability when coupled with real time processing to assist in detection and provide geo-location. A polarimetric capability in the sensor is not required in the concept of operations proposed herein. A high probability of detection should be achievable with a low false alarm rate. Data is required to validate such expectations, and plans to collect such data were developed and proposed in previous status reports as an effort to be undertaken under the option tasks, which have not been approved to date. In the meantime existing data has been identified that is suitable for this purpose. This data could be acquired and analyzed under the option tasks.

2. Problem Statement

The EPAS sensor is an airborne suite of image sensors, including multispectral visible and thermal IR, in a high performance azimuth-elevation turret or ball gimbal with an inertial sensor on the gimbal with the payload to provide pointing and positioning information so that the data can be mapped to the ocean surface. In the Maritime Search and Rescue operation this sensor is employed to detect a live person in the water, with or without a life jacket (Personal Flotation Device). In the daytime, the Personal Flotation Device will show up as a bright red or yellow/orange object in a blue/green water background, and objects in the water are highly reflective compared to the water in the near-IR band, which looks dark, so the multi-spectral sensor suite should have no problem in detecting such a distinctive object. Vista Research, Inc. has extensive experience and proven algorithms for use in this circumstance, and the surface object is relatively easy to detect compared to objects beneath the surface (see References 1-4).

The balance of the processing is the same as for the nighttime problem, the more difficult problem we have focused on in this investigation. Day or night, the exposed head of a person in the water will have very substantial thermal contrast with the water, and contrasting emissivity. Thus the problem comes down to the detection of a relatively small (< 1 pixel, - unresolved) object ("head in the water"), with or without the life jacket, in a field of clutter from surface waves with foam and whitecaps and wave breaking. Larger features, such as a person or persons in a life raft, would be much easier to detect, so the discussion is focused on the more difficult problem.

Strawman requirements for the detection problem and a concept of operations (CONOPS) for Maritime Search and Rescue (MSR) were defined in order to make the problem concrete. The straw-man requirements are shown in Table 1. These include operation day and night, operation in realistic sea states (3 to 5, say), high probability of detection (say 0.9), with low false alarm rate (say 1 per 10km by 10km box). A maximal search rate is desired, but in reality this is determined by existing sensors (e.g., EPAS) and platforms. Real time detection processing is obviously required, with geo-location, and a man in the loop for visual inspection of candidate detected objects in the water.

Strawman Requirements for Maritime Search and Rescue	
Probability of Detection (PD)	>0.9
False Alarm Rate	<1 per 100 km^2
Sea state	3-5
Processing	Real time, with geolocation
Platform	Low flying aircraft (below clouds)

Table 1.1 Strawman Requirements for Maritime Search and Rescue

The low false alarm rate is required to avoid degradation of the search rate by continually turning around to revisit false detections.

3. Prior Work

Our initial guidance was to address Maritime Search and Rescue, as this subject had received relatively little attention. In the course of the work, we performed a literature search and turned up two papers treating significant recent prior work (see references 5-6). These papers report the results of data collected for Search and Rescue with an airborne sensor suite consisting of a combination of a hyperspectral image sensor with an LWIR image sensor. Objects in the water were readily detected in the daytime with the HIS and the LWIR was found to be useful in rejecting false alarms due to foam and whitecaps, which have low thermal contrast with the water. However, the probability of detection with the LWIR was only 50% at a false alarm rate of 1 per square kilometer, a performance we would not judge acceptable. We would expect to do far better. One of the authors (Michael DeWeert) was contacted by telephone in an attempt to understand the nature of the problem with false alarms, to ask if we might collaborate with them, or gain access to the data. We did not receive a positive response to this offer. For this reason we proceeded to plan to acquire data by other means.

Vista Research, Inc. (VRI) personnel have extensive experience in ocean imaging over the past 30 years, using multispectral sensors and employing very sophisticated signal processing, including space-time processing in the spectral domain to deal with surface wave clutter, and multispectral imaging with various algorithmic techniques to deal with foam and whitecaps and sun glint (References 1-4). Our initial expectation and inclination was to employ such sophisticated processing techniques in the problem, looking out toward the horizon to maximize the search rate. Performing such processing in real time would be a very difficult task; the first step is to map the image sequence into a fixed and regular coordinate frame on the surface. However, upon further consideration, we find that there is an optimal geometry, discussed below, that does not necessitate the use of such complex processing steps.

4. Concept of Operations

The LWIR sensor will be carried on a low flying aircraft looking below and out to the side to a nadir angle out to about 45 degrees. The reasons for looking down are enumerated below:

1.) Given a fixed number of pixels there is no advantage in search rate in looking out near grazing. To the contrary, given the effect of perspective distortion in degrading the resolution at the far edge of the patch relative to the near edge, and the high resolution required to detect a head in the water, the search rate is somewhat larger looking more nearly straight down.

2.) In a humid atmosphere, which is common in the maritime environment, the contrast can be severely degraded by atmospheric path radiance and attenuation. Minimizing the path length, by looking more nearly straight down rather than out towards the horizon minimizes this effect.

3.) The sensitivity to wave slope goes to zero at nadir, and is small out to about 45-50 degrees incidence, so the dominant source of clutter, ocean surface waves, virtually disappears at those angles. (See Figure 1.)

4.) Wave shadowing is eliminated.

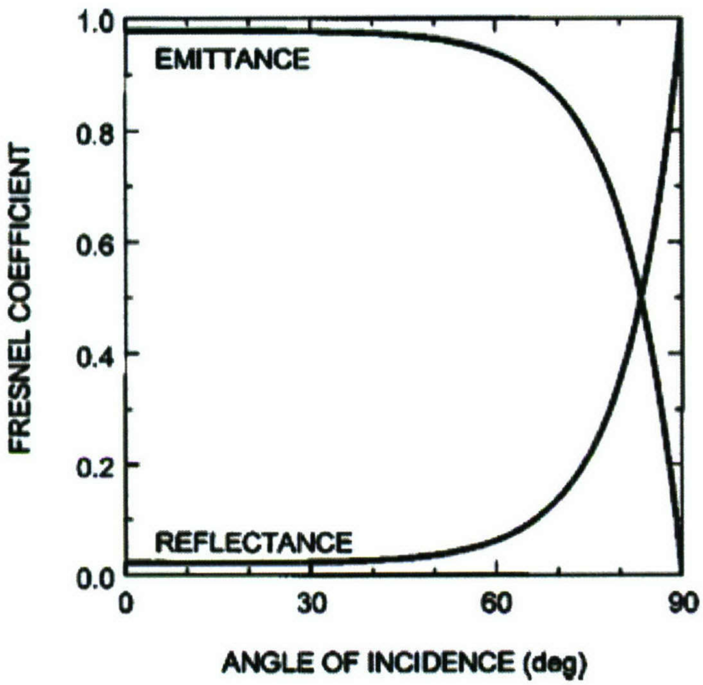

Figure 1. Emissivity and reflectivity in the IR as a function of incidence angle, showing small sensitivity for angles less than 45°, from Zeisse (Reference 9).

5. Processing

In this scenario, by looking nearly straight down, we have a relatively simple detection problem. Water reflectivity is very low, wave clutter is nil, the surface is seen in emission, so glitter is absent and foam and whitecaps have relatively low contrast (compared to the visible, where they act as Lambertian scatterers of direct sunlight, and can be extremely bright). The target is warm compared to the water and should be easily seen with a modern thermal IR image sensor with a NEdT (noise equivalent delta temperature) of 20 to 30 mK. Thus the target is expected to be readily detectable in the raw imagery by simply thresholding the data after non-uniformity correction. At this point a chip of the image containing the detection will be excised and mapped into ground coordinates for geo-location. To enhance the detection statistics when necessary, a tracker may be employed to enforce the persistence of the object over the period of the dwell. The image chips of the detected objects will then be presented to the operator for detailed inspection.

There is a tradeoff between search rate and detection performance in that the system can be operated at a a higher altitude with a larger patch and pixel footprint on the surface, degrading the resolution so that a man's head is much smaller than a pixel, diluting the contrast. While inspection or discrimination may not be very productive under these conditions, detections can be performed, and under these circumstances some temporal integration may be advantageous, and clutter may become a bit more of an issue. Clutter is discussed in the next section.

6. Foam, Wave Breaking, and Other Clutter

Foam and whitecaps are very bright and a big problem in the visible part of the spectrum, because they scatter direct sunlight in all directions, including into the sensor, whereas the ocean is specular and relatively dark unless one is looking into glitter. In the IR, looking near nadir where the reflectance is very low, and imaging is by emission, foam and whitecaps have low contrast, as is confirmed by the experience of DeWeert et al. in References 5-6 and other data to be discussed below. Wave clutter is hardly seen at angles less than about 50°, as is seen in Figure 2. However, there is an additional source of clutter to be discussed, as seen in Figure 2.

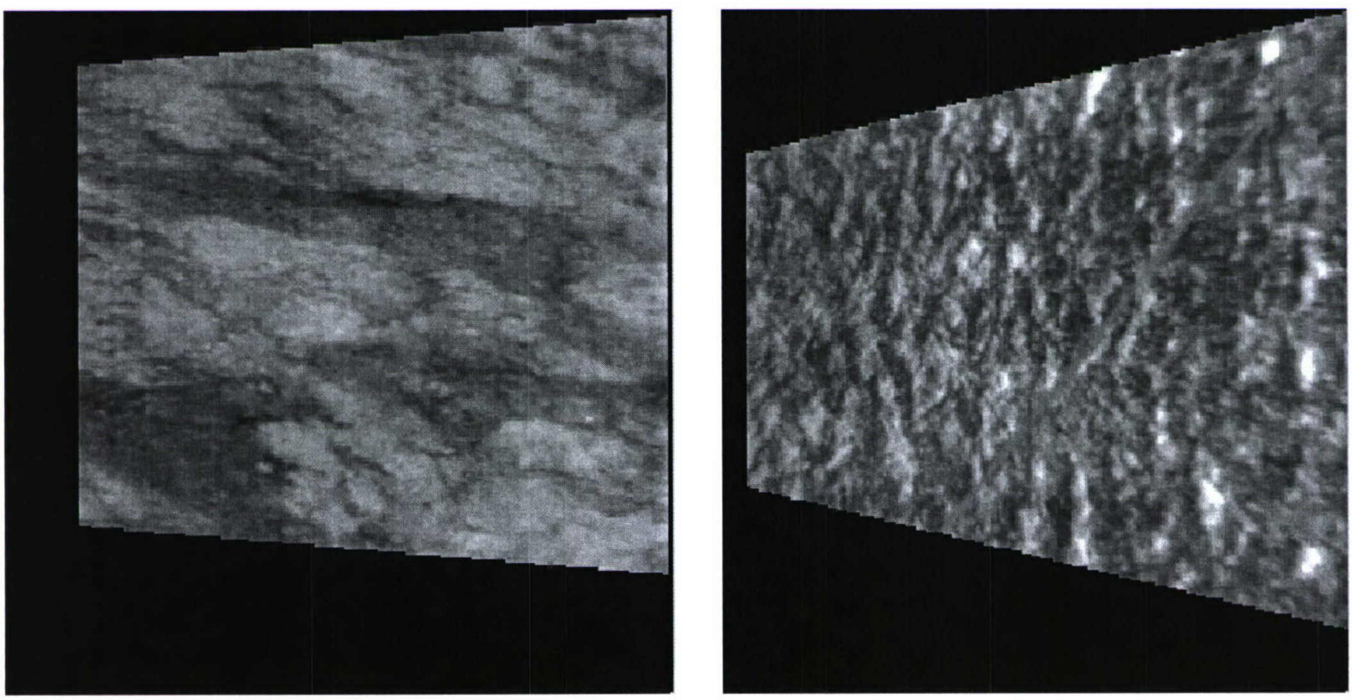

Figure 2. MWIR images of the ocean surface at small and large incidence angles. The grazing angle at the center of the patch for the left image is 45°, and for the right image 25°.

If played as movies, these image sequences show very clearly the surface wave nature of the clutter in the right image (propagation at the phase speed of the surface waves). This is confirmed by a wavenumber-frequency Fourier analysis, which shows the wave clutter localized on the surface defined by the dispersion relation. The lower-contrast clutter seen in the left image is anchored in the water and is due to surface renewal processes. The images were taken at a wind speed of 3 m/s, with a surface wave height of 0.4 m. The spatial extent of the images is only about 4m.

Surface renewal processes have become a subject of intensive study because they are an important factor in the energy balance at the ocean surface and in the exchange of energy between the ocean and the atmosphere, driven by the increased concern over global warming. They are driven by evaporative processes at the surface, which cool a very thin layer, less than a millimeter thick, which is called the “skin of the ocean”. These processes are shown in Figure 3. Since the surface skin is cooler, warmer water from below the surface rises and then moves laterally while cooling before sinking, creating small-scale circulation patterns that are seen at low thermal contrast with the excellent IR image sensors available today.

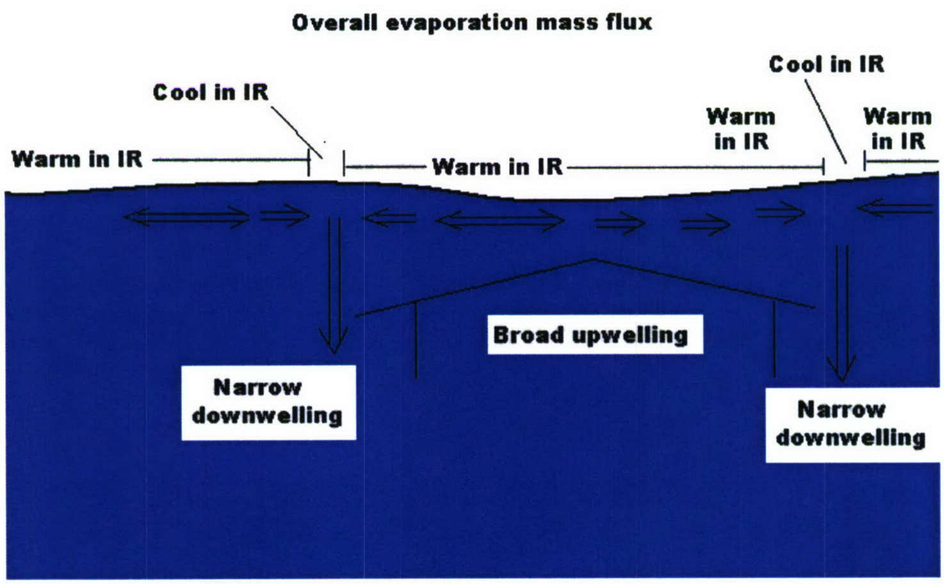

Figure 3. Illustration of surface renewal processes.

The SRP features are driven by evaporation, so they are always present. They are small in scale; at low wind speeds the scale is comparable to our “head in the water”. The temperature contrast typically on the order of 0.1 to 0.5 degrees at cm-level resolution; the contrast is reduced when seen by a sensor with lower resolution since many warm/cool granules are averaged. The SRP features become smaller and of lower contrast as the wind speed increases, as shown in Figure 4. They move with the surface water -- that is to say with any currents, including the orbital currents of surface waves, and any mean drift. They have coherence times of 1 to >10 seconds -- longer at low wind speeds, so that temporal integration may be effective, and persistence can be used for discrimination. Data is required to demonstrate the performance of Vista algorithms against such clutter.

In sequences of such imagery, another source of warm spots is seen, due to wave breaking on a wide range of scales. The breaking may not cause white water, but it stresses the skin of the ocean, allowing the warm water beneath the skin to cause a transient increase in the temperature observed by the IR image sensor. The transient breaking events are a significant source of clutter but are transient and have relatively high velocity, so signal processing based on temporal persistence and motion is effective for Search and Rescue. Again, data with swimmers is needed to substantiate this assertion.

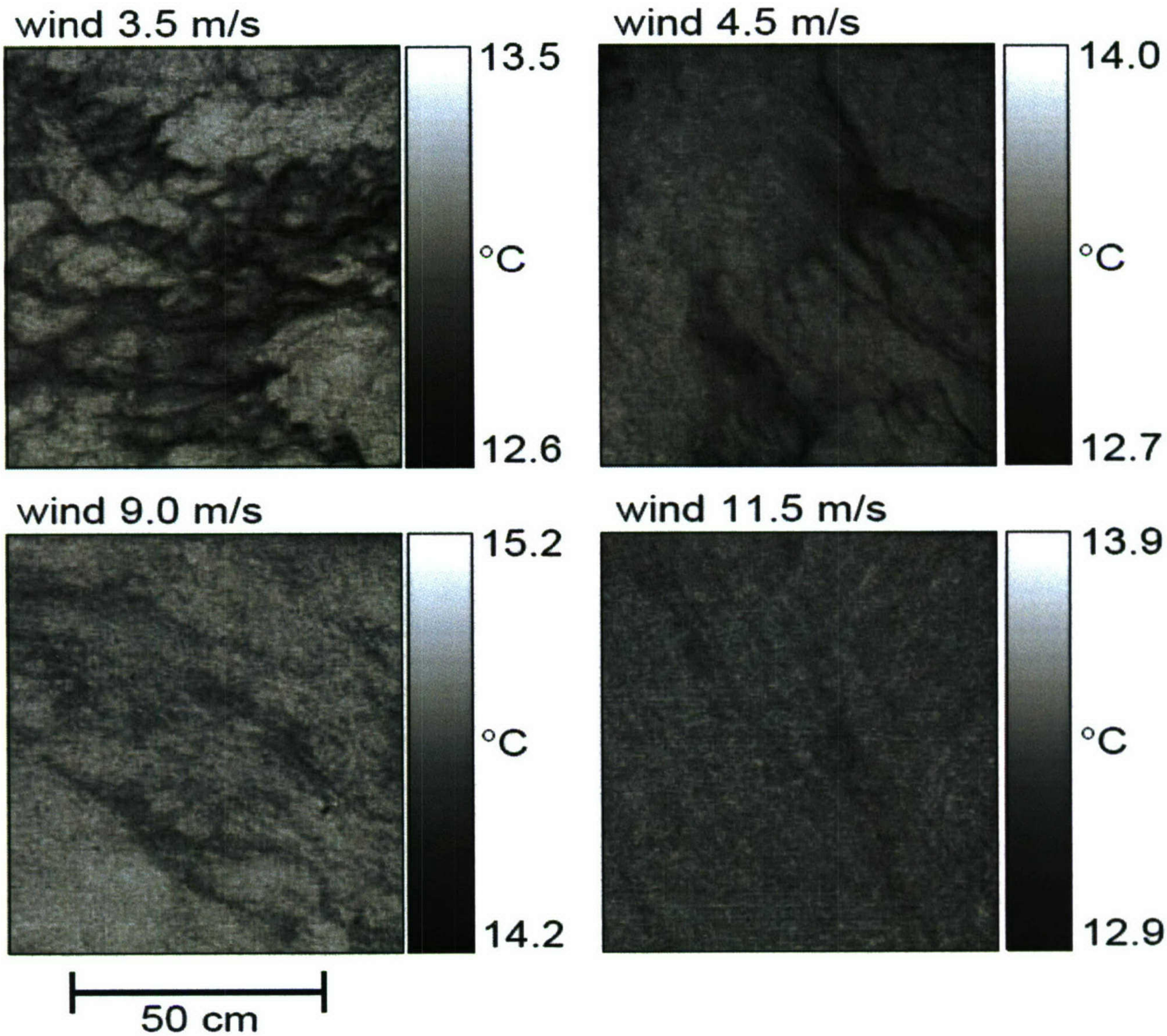

Figure 4. Surface renewal process contrast and scale changes with wind speed, from Jahne, et al., "Wind waves, turbulence, and exchange processes at the ocean surface", Image Sequence Processing to Study Dynamic Processes Workshop, 19 - 21 September 2000.

One final source of clutter is flotsam and jetsam – other materials floating in the water. These must be dealt with by human inspection.

7. Plan for Data to Demonstrate Detection Performance

Data is needed to demonstrate performance of the Search and Rescue operations and processing discussed above. To this end, Vista developed and proposed a plan to collect data with the Vista airborne IR camera system with swimmers in the water. The Vista camera system has 5 LWIR cameras, made by DRS, Inc., in a ball gimbal as shown in Figure 5. The cameras are pointed to cover adjacent areas, to increase the overall field of regard. The cameras are uncooled microbolometer arrays, a relatively new type of IR camera which is relatively inexpensive, and which has a very small form factor, partly due to the absence of a cooler. They are small enough that 5 cameras fit in the 10"-diameter turret.

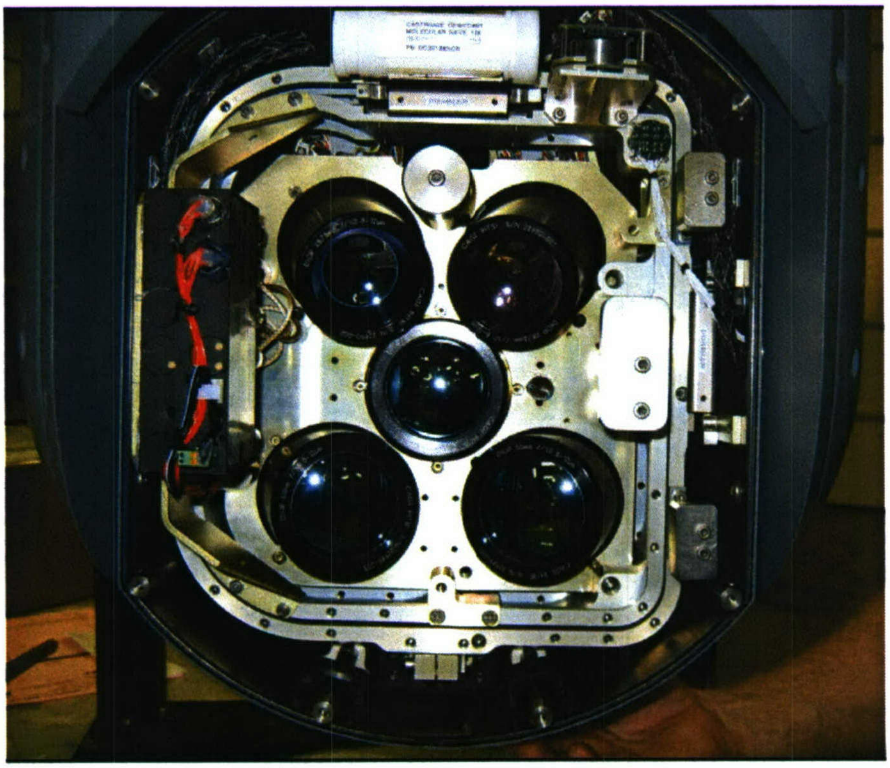

Figure 5. Five uncooled LWIR cameras in Vista ball gimbal.

The sensor package is carried on a small aircraft, the Navion shown in Figure 6. The aircraft is very inexpensive to operate. This sensor system was developed for other applications, and is definitely not optimal for search and rescue. The angular resolution is about 1 milliradian, resulting in larger pixels on the surface than desired for Search and Rescue, unless the aircraft is flown very low. In that case the temporal characteristics of the microbolometer sensors result in undesirable motion blur in the outer edges of the patch, but the sensor may be pointed at a point on the surface (where the swimmers are) and the motion blur is minimal in that portion of the image. The system is equipped with differential GPS accurate to about 10 cm in real time and has full digital recording.

Figure 6. Navion aircraft carrying Vista LWIR sensor payload.

A plan was developed to put swimmers in the water near a boat, with GPS and radio communications to coordinate operations and to geo-locate the target. Data adequate for a proof of concept was acquired by flying over the beach at Ocean City during an engineering checkout flight to verify that swimmers could be detected. We could see what we believe to be swimmers in the water near the shore, although they were unresolved. This plan was communicated to the sponsor in the second status report, with a statement that funding of the option tasks would be required to carry out the plan. No response has been received, and in the meantime we have developed an alternative approach that is actually better. We have found that very high quality data exists, collected in the context of Surface Renewal studies by the Naval Research Laboratory, with swimmers in the water in a controlled context much as we had planned. The spatial and thermal resolution are better than we could obtain with our sensor, just what we desire for the Search and Rescue study. Again, additional funding would be required to cover the processing of this data. The three optional tasks under this contract would be sufficient to cover this effort.

Figure 6 shows an image, a frame from a video sequence actually, acquired with a similar uncooled microbolometer camera, of two persons walking on a beach, with surf in the background. The human figures are easily seen against this background. The breaking waves and foam are also readily seen in the video sequence, which is acquired at 30 frames per second. Microbolometric LWIR cameras have improved significantly since this image sequence was acquired with an early prototype, and HgCdTe cooled cameras with much better performance and resolution, and nearly as small a form factor, are just now becoming available. These new cooled cameras have a much shorter exposure time, so that they would be better for the search and rescue application since motion blur can be eliminated. Dual band LWIR/MWIR and polarimetric versions of these cameras are also soon to be available. However, the current Vista cameras are adequate for the proposed data collection.

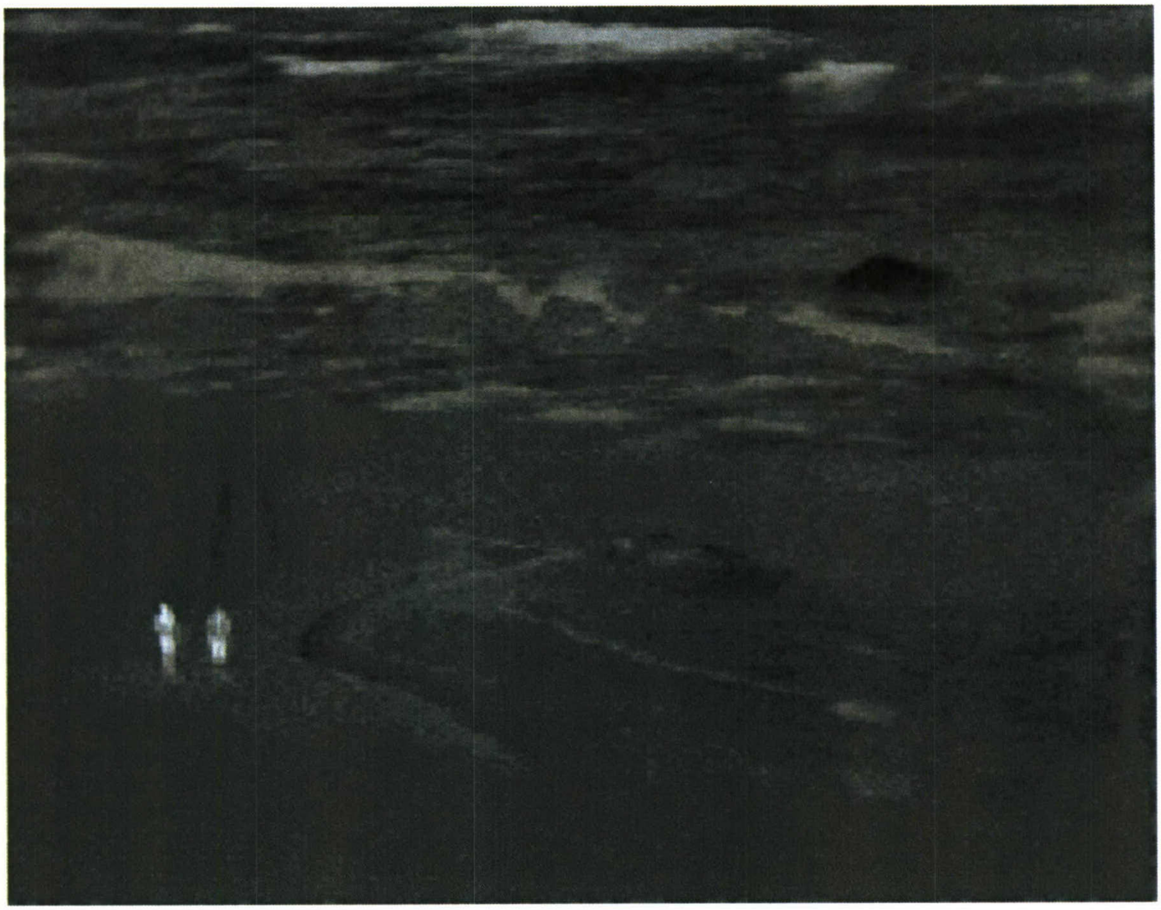

Figure 7. LWIR image of two human figures walking on a beach, seen via thermal emission with an uncooled microbolometer camera.

8. Polarization

The use of a polarimetric sensor has been shown to enhance the visibility of man-made objects in certain circumstances when substantial reflected light is involved. For example, painted or otherwise reflective objects may appear significantly polarized and visibility enhanced when observed against an unpolarized natural background of foliage and other land clutter. An example of this is shown in Figure 8, a frame of a movie provided by DRS showing imagery acquired with a prototype of a new polarimetric LWIR camera. The left frame is unpolarized, and the right frame is the polarimetric image with the polarization coded by color. Clearly the polarimetric capability is of great advantage in identifying certain man-made objects against the unpolarized ambient background.

Figure 8. LWIR images of cars in a treed parking lot, unpolarized (left) and with polarization coded by color (right). Images courtesy DRS, Inc.

Similarly, there are circumstances, at relatively small grazing angles, when objects may be more observable against the ocean background. An example is shown in Figure 9, where a sailboat is (hardly) seen near the horizon in an unpolarized image on the left, but is very visible in an image on the right that DOLP). (These are small clips of much larger images, again from one frame of a movie, courtesy DRS.) Clearly there is quite a lot of reflected radiance from the sky, which must be warm and humid. The reflectivity of the water is high for small grazing angles, and very different for the two polarizations.

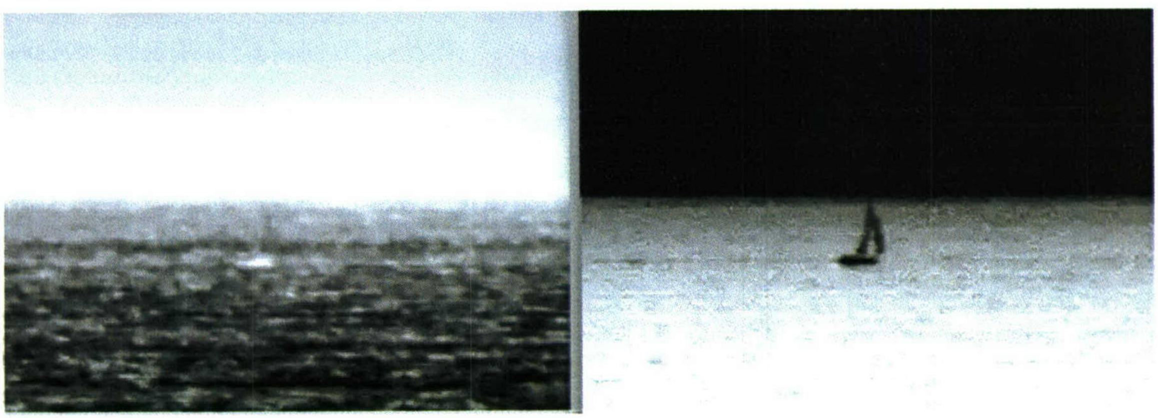

Figure 9. LWIR images of a sailboat against an ocean background, unpolarized (left) and with polarization to show Degree of Linear Polarization (right). Images courtesy DRS, Inc.

Obviously, the visibility of the sailboat is dramatically enhanced in this geometry by the polarimetric capability of the sensor. In this case, this is because the ocean is partially polarized and the sailboat and sky are not. Note that the surface wave and breaking wave clutter is severe when viewed in this geometry, near grazing incidence – the sailboat is hardly visible in the unpolarized image, while it appears almost as a shadow against the water in the DOLP image. This reinforces our point that the optimum geometry is looking down, near nadir, where the waves are essentially invisible. It does also show the value of a polarimetric capability in the sensor near grazing. Of course, this geometry is not good for search and rescue due to the enhanced wave clutter and because of the hiding of the object of interest due to wave shadowing. The increased atmospheric attenuation that would occur in the warm, humid atmosphere that generated the large reflected component is apparent in this image.

An example of the use of polarization in a situation such as might be encountered in search and rescue is shown in Figure 10, which shows two swimmers in the water with a plastic cooler and milk jug. Here the enhancement of the wave clutter is more apparent.

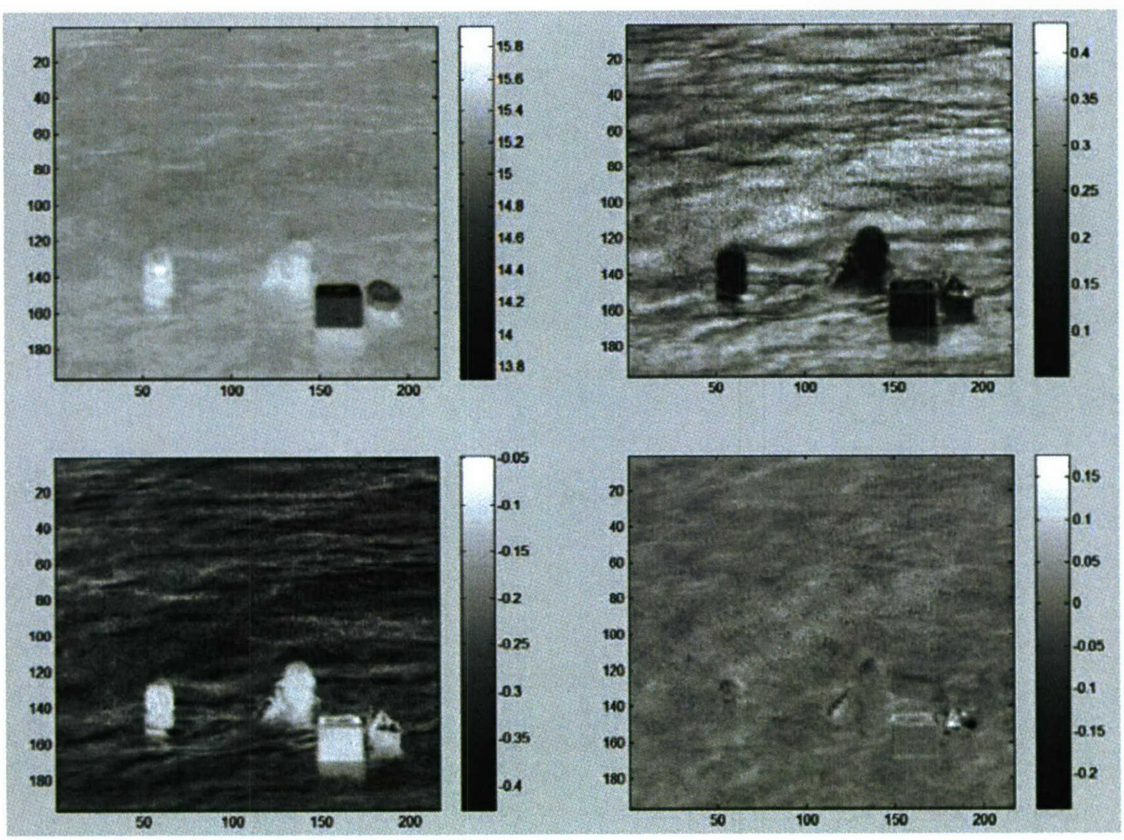

Figure 10. Upper left: LWIR image of two swimmers in ocean water with a picnic cooler and plastic jug (unpolarized). Upper right — Degree Of Linear Polarization (DOLP). Lower left – difference of vertical and horizontal polarizations. Lower right – difference of two diagonal polarizations.

In this figure, from Reference 7, we again see an apparent increase in contrast through the use of polarization in the LWIR. The upper right image shows the Degree Of Linear Polarization (DOLP). The swimmers and the plastic items are dark (unpolarized), and the water is relatively bright, showing that it is partially polarized.

However, in this case the improvement in contrast is nowhere near as dramatic as is the case with the sailboat, and we must be more careful in our assessment. These images were taken at incidence angles much larger than those optimal for detection in search and rescue, for multiple reasons, as discussed in Section 4. One of those reasons is the visibility of wave clutter, and Figure 11 illustrates that point – the wave clutter is very visible. While the contrast of the swimmers and objects appears to be increased in Figure 10, the contrast of the wave clutter is also greatly increased, so that it is not at all clear that detection performance is improved. (In fact, an effect very similar to that seen in Figure 10 is achieved by simply stretching the contrast of the unpolarized image digitally.) At the smaller incidence angles recommended for Search and Rescue, the waves would be hardly visible, the ocean radiance would be much less polarized, and the use of polarization would have little or no benefit.

The spectral degree of polarization of the ocean is shown in Figure 11, taken from Reference 8. The ocean surface is weakly polarized when observed at small grazing angles, and unpolarized near nadir.

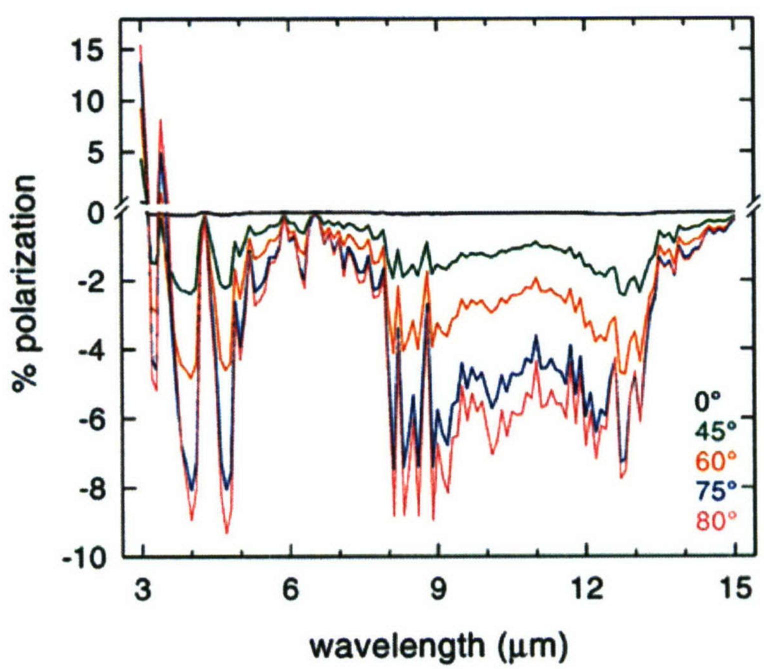

Figure 11. Spectral degree of polarization for the total radiance for a rough ocean surface (5 m/s wind speed) viewed at the indicated grazing angles.

This figure shows that the degree of polarization at incidence angles less than or equal to 45° from nadir (45° grazing) is less than 2%. The targets of interest for search and rescue, seen in emission in the IR are unpolarized, based on what we see in Figure 9.

For the recommended geometry, looking more nearly straight down, one is viewing the scene almost entirely in thermal emission, and both the water and the targets of interest are unpolarized. In this geometry there would seem to be little or no benefit to be had with a polarimetric sensor. Since the use of a polarimetric sensor entails significant compromises in terms of loss of spatial resolution and increased complexity in the sensor (although this is much less with the new sensors being developed by DRS), and in processing, and perhaps in sensitivity or SNR (depending on the sensor), and since the near-nadir geometry is advantageous for other reasons, as discussed in Section 4, we do not recommend a polarimetric sensor for the search and rescue mission with the recommended CONOPS. As shown above, such a sensor may have merits for other reasons.

9. Dependence on Wavelength in the IR (Which Band is Better?)

For the recommended near-nadir geometry, the ocean is seen in primarily in emission, and it would seem to make little difference which band, mid-wave or long-wave, is used, assuming equal sensitivity, as measured by NEdT. However, the long-wave band has two advantages that may be significant. The first is that the thermal emission spectrum for ambient scenes peaks at a wavelength near 10 microns, so that there are far more photons available in the long-wave IR and shorter exposure times can be used with an LWIR sensor. This allows shorter exposure times to be used in the LWIR, minimizing motion blur. This may allow higher platform velocities and search rates, or the use of simpler gimbals for the Search and Rescue mission. The second reason has to do with foam and whitecaps and sun glitter as a source of clutter. In the daytime, the sun provides a strong directional source that is seen by the mid-wave sensor and not by the long-wave sensor, as illustrated in Figure 12, which is a copy of Figure 19 from Zeisse, et al. (Reference 9), with it's caption. The ship is seen against sun glitter in the MWIR image, so it looks cold against the background, but the sun glitter is not seen in the LWIR image, so the ship looks hot against the background. Of course, in the daytime, a visible sensor would be employed, and it would also see the glitter in this geometry. The point is that the long wave camera does not. Ocean wave clutter, whitecaps and foam are sources of severe clutter in the visible and mid-wave IR, but are relatively invisible in long-wave images, especially with the recommended geometry. This permits the use of simple processing that will be much easier to implement in the required real time processor.

Zeisse *et al.*

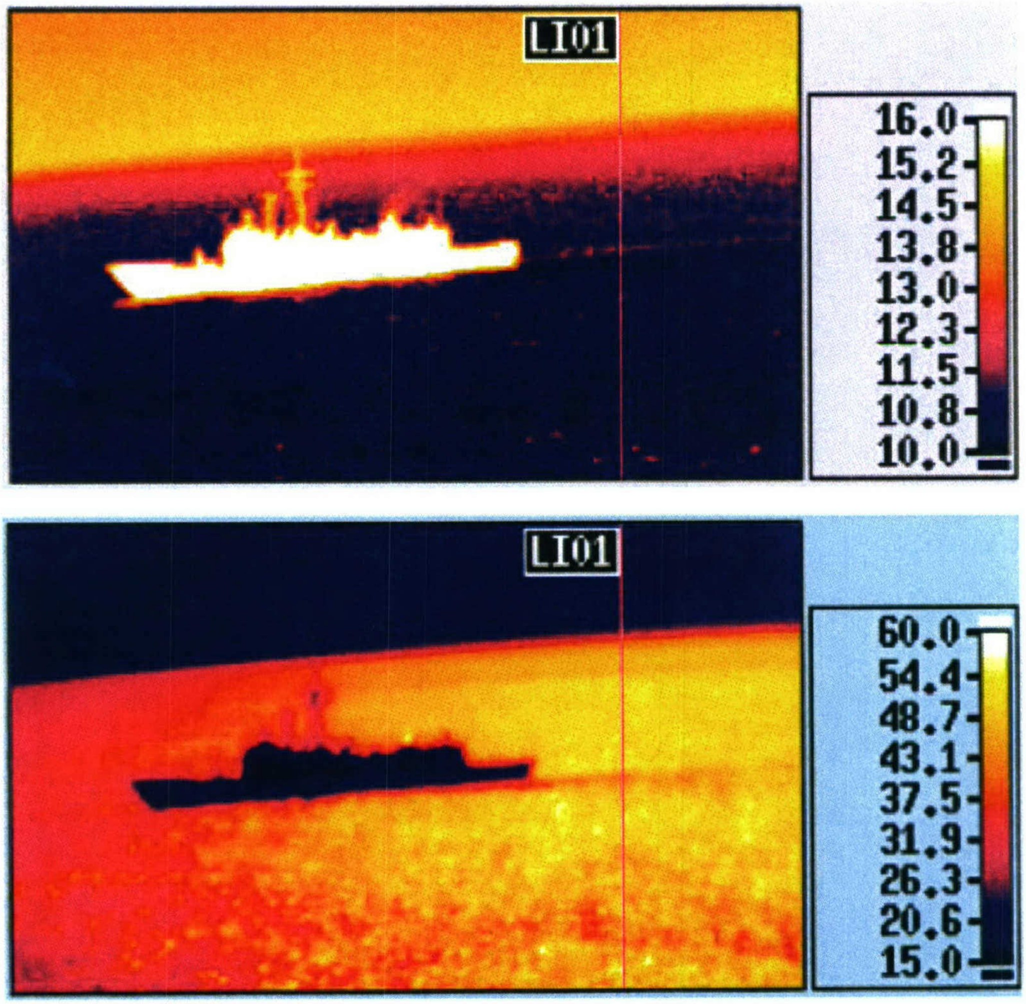

Fig. 19. Airborne view of ship near Point Loma, California, looking along the sun's azimuth from an altitude of 31 m on 8 February 1995. Upper, long-wave image; lower, mid- and short-wave image. The vertical lines labeled LI01 mark the location from which data have been taken. The color palette at the right, given in degrees Celsius, is different for each image. Note, for example, that although the ship is white in the upper image and dark blue in the lower image, it has the same temperature (~16 °C) in each.

Figure 12. Ship seen against sun glitter in LWIR (top) and MWIR (bottom), (Fig. 19 from Zeisse, et al., Reference 9.)

The advent of dual band LWIR/MWIR focal planes (see, for example, Reference 10.) creates some opportunities that remain to be explored, but are perhaps worth mentioning, in which some of the advantages of a polarimetric sensor may be obtained via the two bands, without loss of resolution. These bands could be selected such that the ocean-leaving radiance has opposite linear polarization at certain viewing angles, as shown in Figure 14, taken from Reference 8. Manmade objects may have different dependencies, possibly such that an improvement in contrast or discrimination is obtained.

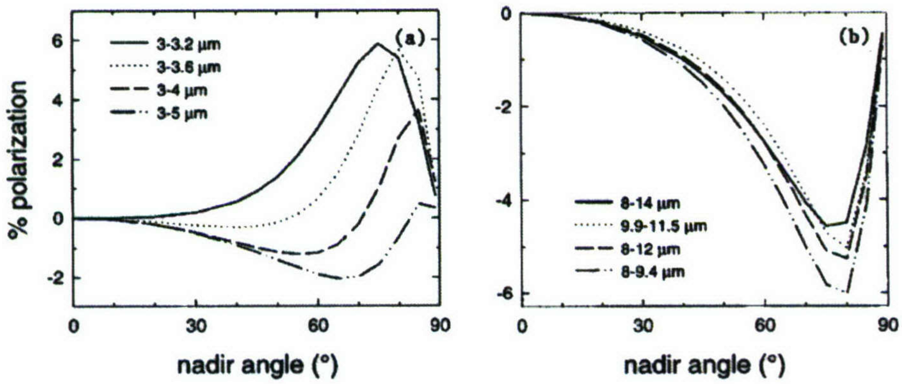

Fig. 8. Band-averaged degree of polarization for four (a) short-wave and (b) long-wave radiometer bands. The short-wave curves indicate dominant reflection polarization and the long-wave curves indicate dominant emission polarization. The magnitude of the long-wave polarization increases monotonically with angle up to approximately 75°, after which it decreases as the reflected atmospheric radiance begins to dominate the emitted surface radiance.

20 May 1999 / Vol. 38, No. 15 / APPLIED OPTICS 3161

Figure 14. Band-averaged degree of polarization of polarization as a function of incidence angle in viewing the ocean with mid-wave and long-wave sensors, from Shaw, Reference 8.

10. Summary and Recommendations

The development of technology for the application of the EPAS sensor to Maritime Search and Rescue has been evaluated. Imaging in the thermal emission bands (Mid-wave and Long-wave IR) provides a day-night capability and minimizes the visibility of foam and breaking waves. Strong reasons are found for using the sensor in a geometry in such that the angle of incidence is less than about 45 degrees from nadir. In this geometry, a polarimetric capability in the sensor appears to provide little benefit, and processing is simplified, so that real time implementation is straightforward. The long-wave band has advantages in minimizing clutter in the presence of sunlight, and in minimizing motion blur due to a shorter exposure time. Clutter in the form of patterns due to surface renewal processes is still present at these small incidence angles, but these patterns change rapidly with time and are thus susceptible to mitigation with algorithms that make use of a relatively short dwell time. Additional data is required to demonstrate evaluate this clutter and demonstrate performance with the proposed algorithms. Data collection plans were developed and proposed, but existing data has subsequently been identified, collected in another program, that can be analyzed under the option tasks to evaluate detection performance in the Search and Rescue context.

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