Infrared polarimetric sensing of oil on water

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ABSTRACT

Infrared polarimetry is an emerging sensing modality that offers the potential for significantly enhanced contrast in situations where conventional thermal imaging falls short. Polarimetric imagery leverages the different polarization signatures that result from material differences, surface roughness quality, and geometry that are frequently different from those features that lead to thermal signatures. Imaging of the polarization in a scene can lead to enhanced understanding, particularly when materials in a scene are at thermal equilibrium. Polaris Sensor Technologies has measured the polarization signatures of oil on water in a number of different scenarios and has shown significant improvement in detection through the contrast improvement offered by polarimetry. The sensing improvement offers the promise of automated detection of oil spills and leaks for routine monitoring and accidents with the added benefit of being able to continue monitoring at night. In this paper, we describe the instrumentation, and the results of several measurement exercises in both controlled and uncontrolled conditions.

Keywords: Polarization, infrared polarimetry, remote sensing, oil spill, oil on water, environmental monitoring

1. INTRODUCTION

The Deepwater Horizon incident is a well-known example of a large volume oil release (210,000,000 gallons) that had considerable impact on the marine and coastal environment and significant costs for the response and economic fallout. For relatively small spills, the response is heavily dependent on being able to locate the spill based on sporadic, sometimes non-specific reports, and to determine its size. With larger spills, a coordinated response team may be continually on site, but recovery operations are usually limited to day light hours and require updates on the spill location in the morning before recovery operations can begin, often causing hours of delay in oil recovery or mitigation. While infrared imaging is used in some cases, the thermal contrast between the oil and the water background is typically small and is further confounded by wave action. In all cases, the ability for personnel to quickly and easily detect oil on water is clearly needed for an appropriate, consistent, and cost-effective response. The potential to automatically perform the same function could be a boon for oil responders and provide the opportunity for regular monitoring around drilling operations and facilities, transfer points, ports and harbors.

For many years, Polaris Sensor Technologies, Inc. has been developing imaging polarimetric sensors across the optical spectrum. With partial support from ExxonMobil Upstream Research Company (EMURC), we recently had opportunities to test infrared polarimeter Pyxis® at Ohmsett, the National Oil Spill Response Research & Renewable Energy Test Facility in northeast New Jersey in July of 2016 and October of 2017. This test facility (Figure 1), maintained and operated by the U.S. Department of Interior's Bureau of Safety and Environmental Enforcement (BSEE), provides independent, objective performance testing of oil spill response equipment on a large scale and in as realistic environment as possible. At these tests, a Polaris Pyxis LWIR 640 infrared imaging polarimeter recorded a number of controlled spills to test its detection performance as a function of time of day and angle, oil type and thickness, and of the evolution and motion of several oil types in both flat water and in waves. In all cases, the infrared (IR) polarimetric data showed superior detection over that of thermal IR alone and enabled detection of even small amounts of oil on water throughout the night and in situations when the thermal imagery showed no contrast. The 2016 test was reported on previously[1]; the 2017 test will be described here.

Pyxis is an infrared polarimetric sensor measuring not only the conventional thermal intensity of a scene but also the polarization magnitude and orientation of the plane of polarization. By measuring one or more parameters of the polarization ellipse, details can be extracted from a scene that are not readily apparent when using conventional thermal imagers alone. In the past, these measurements required large scientific instruments not readily applicable for hand-held

Figure 1. Ohmsett – The National Oil Spill Response Research & Renewable Energy Test Facility.
Aerial photo provided by Ohmsett. Wave action photo provided by Polaris Sensor Technologies, Inc.

use but the recent development of un-cooled, infrared sensor arrays has led to a significant reduction in size, weight, power and cost of high-performance polarimetric sensors. The Pyxis camera incorporates a micro filter array mounted in close contact to the microbolometer focal plane array (FPA). Pyxis is shown in Figure 2.

The strength and orientation of an infrared polarimetric signal relies on surface temperature, orientation, surface roughness, material properties, aspect angle to the sensor, down-welling sky radiance and terrestrial background radiance reflecting from the objects in the scene. Often times, the polarization signature of objects with different material properties is different than that of the surrounding background and most importantly, that difference is often present even when the intensity signature of the object of interest is in thermal equilibrium with the background[2,3]. In other words, the target can be completely invisible in the standard intensity image while at the same time exhibiting a strong polarimetric signature. Further, the fact that the polarization signal is based on emission, the polarization signal is available for day / night operations. It is this capability to provide polarization contrast resulting from material differences that we are exploiting here for oil on water detection.

In this paper, we describe the technology, the hardware and software, the tests, and finally the results of our 2017 testing at Ohmsett.

1.1 Technology Overview

The technology underlying the Pyxis sensor exploits the polarization of light in our environment, a fact that we use every day with our polarized sun glasses to reduce glare off the car in front of us in traffic. When ambient illumination is reflected off of an object, the reflected light becomes polarized. Likewise in the thermal infrared, light is polarized in both emission and reflection. Polarization is one of the fundamental quantities of light along with intensity and wavelength. However, these three quantities are independent of each other so that two beams of light with the same intensity and wavelength (or spectral distribution) can have very different polarization states. An imaging polarimeter measures these polarization states and provides additional information that exploits the polarization differences in the scene that are frequently different from the broadband intensity.

Figure 2. A Pyxis camera incorporates a micro filter array mounted in close contact to the COTS FPA.

Figure 3 depicts some of the phenomenology that gives rise to polarization signatures in passive polarization imaging. The polarization in the scene depends on the angles of the surface normals relative to the sensor look angle and the surface

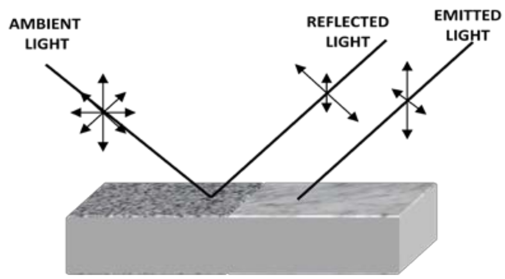

Figure 3. Phenomenology of polarization sensing. Emission and reflection of light from surfaces of different materials at different angles leads to a rich phenomenology for polarized light.

optical characteristics. The larger the angle between the surface normal and the sensor look angle (the angle of incidence or AOI), the higher the polarization signal from that surface. The surface optical characteristics depend on the materials of the surface and other surface characteristics, such as roughness and presence of dirt and water. As the surface roughness increases, the polarization signal reflected or emitted from the surface decreases.

It is well known that at certain times of day, the apparent temperature of the object of interest can match the apparent temperature of the surrounding background, and the object can be very difficult to see in the thermal image. These events are referred to as thermal cross-over periods and typically occur twice a day, once after sunrise and again after sunset, but can occur at other times depending on ambient conditions. Polarization excels in this situation. Though polarization measurement does not require intensity or thermal contrast, any thermal signature that is present is also detected. LWIR thermal and polarization are combined in a single camera so that together the camera provides advantages over conventional thermal imagers in detection applications.

1.2 Polarimeter architectures

The specific configuration of an imaging polarimeter depends on a number of design requirements which, in turn, is dependent on the application and the state-of-the-art technologies available to meet those requirements. The physical configuration can be broken into categories[2] according to the optical path and layout of the electro optical components. There are five primary configurations for imaging polarimeters: rotating element of division of time, division of amplitude, division of aperture, micro-optic or division of focal plane, and channeled instruments. For this scenario in which the scene is dynamic with wave action and the sensor and / or the sensor platform may be moving, the division of focal plane approach is the one implemented in the Pyxis handheld polarimeter.

Recent advances in micro-optics manufacturing have allowed the integration of micro-optical polarization elements directly onto a focal-plane-array (FPA), thus creating a **"Division of Focal Plane"** (DoFP) polarimeter. In this configuration, pixelated linear polarization elements are attached intimately to the FPA. Several systems operating in the visible, SWIR, and LWIR waveband have been built using this technology. Most DoFP systems use interlaced polarization super-pixels as shown in Figure 4. A typical system must compute the Stokes vector at interpolation points on the FPA, thus DoFP systems must trade-off spatial resolution for polarimetric information. It should be noted that the intensity information is still collected at the full resolution of the FPA. DoFP systems have some significant advantages. All polarization measurements are made simultaneously for every pixel in the scene and it uses a single FPA with no added complications to the optical train. The architecture is very similar to commercial color cameras that use a Bayer color filter overlay on the FPA.

The polarization imagery is represented as Stokes images

$$s_0 = \frac{1}{2}(I_H + I_V)$$

$$s_1 = I_H - I_V$$

$$s_2 = I_{45} - I_{135}$$

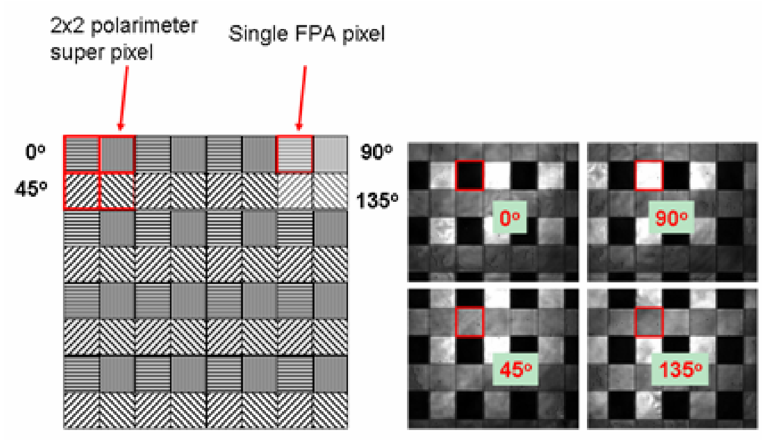

Figure 4. Polarization Elements of a Pixelated Imaging Polarimeter

where I_H,I_V,I_{45},I_{135} are images linearly polarized in the Horizontal, Vertical, 45° and 135° orientations. Note that the s_o image is simply the standard thermal image. The s_1 and s_2 images are often useful data products in and of themselves to view. However, additional data products derived from these three are often selected. For example, the degree of linear polarization (DOLP) image is often used to suppress background to detect an object. DOLP is given by,

$$DOLP = \sqrt{{s_1}^2 + {s_2}^2}.$$

Finally, data fusion is possible exploiting both the thermal and polarization data products. The imagery can be viewed independently or fused images can be formed from combinations. Data fusion captures all of the information and displays it in a single imager, giving the operator a more intuitive view of the scene. One of the preferred methods for displaying thermal and polarization together is called color fusion. Figure 5 shows a color-fused image taken with the Polaris Pyxis LWIR imaging polarimeter. In the color fused image, the un-polarized thermal image is displayed as normal grey scale. The polarization is displayed in color from a user defined threshold. A typical threshold is 1% DOLP. When a pixel exceeds 1% DOLP, the pixel is colored based on the orientation of linear polarization. The saturation of the color increases with increasing DOLP. For oil on water detection, this fusing capability tends to highlight the oil with color while still providing context through the gray scale IR image information.

Figure 5. LWIR color fused image of a vehicle. For thermal imagery, the color fuse enhances thermal information and is therefore dubbed eTherm®.

2. SENSOR HARDWARE

2.1 Pyxis description

Measurement of this polarimetric phenomenology requires capturing images with polarization filters. The approach chosen here is based on the Division of Focal Plane (DoFP) polarimetric architecture for imaging polarimeters. In this architecture, a pixelated polarizer array is attached to the FPA just above the sensing plane of the FPA (within a few microns). For infrared applications, the pixelated polarizer array uses an IR substrate such as silicon, germanium, or zinc selenide. A metal layer is deposited on the substrate and then the wire grid pattern is etched in to the metal layer using standard semi-conductor processing techniques creating the wire grid pattern. For the Pyxis, the substrate is silicon and the metal wires are aluminum. The polarizers are oriented at 0º and 90º, 45º and 135º, (left to right, top to bottom). Figure 4 (left) shows a schematic of the pixelated polarizer array. The pixels in different polarization states in a DoFP imaging polarimeter are combined to determine the polarization state of each pixel. A super-pixel is comprised of a 2x2 array of pixels. Figure 4 (right) shows the response of a larger segment of the pixelated polarizer array to vertically linearly polarized light. With vertically polarized light (90º orientation) incident, the horizontally polarized pixel is dark, the vertically polarized pixel is light and the 45º and 135º polarized pixels are gray. The measured incident polarization state is determined based on a weighted sum of interpolated pixels. It is important to note that both thermal and polarization images are captured at the full resolution of the array – spatial resolution is not lost. DoFP systems have the significant advantage that all polarization measurements are made simultaneously for every pixel in the scene. In addition, since the polarization sensitivity is integrated on the FPA, no additional optics are added to the optical train and the system is no larger and is equally rugged as a conventional camera.

One important measure of performance for a polarimeter is the Noise Equivalent Degree of Linear Polarization or NeDOLP. The NeDOLP is the rms noise of the reported degree of linear polarization for an un-polarized scene averaged across all operating pixels of an imaging polarimeter. It gives an indication as to what level of polarization signature is detectable by a polarimeter. Cooled LWIR polarimetric sensors can achieve below 0.1%. The Pyxis typical NeDOLP is around 0.3%.

The ruggedized version, the Pyxis 640 LWIR–GR shown in Figure 6, outputs unprocessed digital data through a Gigabit Ethernet cable for processing on a laptop or tablet. The specifications are given in Table 1. Note that the noise equivalent noise parameters assume an f/0.85 lens, a faster lens than is usually used for microbolometer performance. Since the polarizer has lower throughput for unpolarized light, the loss of light is made up for through the use of a faster lens. However, with the faster lens, the sensor performance for the S_0 or radiometric imagery is similar to that of a (non-polarimetric) microbolometer.

Figure 6. The Pyxis 640-GR Ruggedized GigabitEthernet model.

Table 1. Pyxis Specifications

Detector	Uncooled VOx Microbolometer Array
Waveband (microns)	7.5-13.5
Pixel Pitch (microns)	17
Resolution (H x V pixels)	640 x 512
Camera Frame Rate (Hz)	7.5 or 30 Hz
Full Frame Pixel Operability	99.9%
Image products (from analog output, -A model only)	Radiance, S1, S2, DoLP, Orientation, ColorFuse, 14-bit raw
NEDT @ f/0.85	< 50 mK
NEDoLP @ f/0.85	< 0.5%
Size w/o lens (LxWxH in inches)	1.79 x 1.75 x 1.79
Weight w/o lens (g)	83
Input voltage (DC)	5
Steady state power @ 23° C (watts)	4
Peak power @ 23° C (watts)	5.3
Data interface	NTSC and 14-bit Camera Link standard GigE or LVDS optional
Lens Options (focal length, f/#)	20 mm, f/0.85 25 mm, f/0.86 50 mm, f/0.86

2.2 Sensor configurations and software

The Pyxis "core" is the sensor focal plane with an LVDS output and serial communications for setting sensor parameters. Several options exist for output configurations. These have been detailed elsewhere but in short, there are three different models. The Pyxis 640-A provides Camera Link and NTSC analog video out, the Pyxis 640-G replaces the -A back panel with one that only has an RJ-45 connector, and the -GR is a ruggedized version of the -G both of which give camera output and control over a Gigabit Ethernet connection. No analog polarization data products are available as output directly from the camera. The Pyxis 640-GR is the ruggedized version of the Pyxis 640-G and is shown in Figure 6 on the right. The case and cord are configured for IP67 environmental ruggedization but is otherwise operationally identical to the –G version. Multiple mounting points ease the use of the elongated case. In particular, mounting points on the bottom can be used to mount the sensor to a tripod or to a Picatinny rail which enables multiple mounting points include a hand grip.

All versions of the camera interface to a computer (or tablet) and use the Pyxis Vision Science (PVS) software framework developed by Polaris for commercial applications. PVS provides the ability to control the sensor, view the raw and processed sensor data, and record data for future processing. Note that the user interface provides a suite of standard color palettes, as well as toolbar buttons for selecting standard output imagery products. PVS gives the operator easy access to intensity data (temperature and radiance) as well as Stokes Vector polarimetry and degree of linear polarization (DoLP). The user has the ability to measure the value of a specific pixel, or to create a histogram or strip chart which displays the values for regions of interest within the image.

PVS is a software framework which provides certain standard functionalities such as display and data recording, with customization for user control of sensor specific operational parameters such as sensor calibration parameters such as non-uniformity correction (NUC) data calibration, and custom processing of sensor raw data for display and analysis. Normal operation of the PVS software can be divided into two basic functionalities: sensor operation, and data reduction. The operator is able to display the current video imagery being returned by the sensor when operating either way, but the focus of the sensor operation mode is in configuring the sensor for the task at hand, calibrating the sensor, and collecting the raw data of the event of interest. Processing priority is given to receipt and recording of the raw data frames, and display update rate is given less priority in order to ensure that all raw data is safely stored on the host computer. PVS allows the user to determine the method of data recording. Raw data may be streamed to the disk by the user manually using the graphical data recorder interface. The user may also choose to use the scripted Periodic & Event Recorder which allows for a great deal of flexibility in how data is recorded. Using the Periodic & Event Recorder the user defines a sequence of Record Windows. These Record Windows define the frame rate and number of frames to record. The Periodic & Event Recorder will execute these windows periodically or at user specified times. The Periodic & Event Recorder allows the user to collect only that data that is of critical importance without having to store terabytes of data or having to be present with the sensor to manually record the event.

In data reduction mode the user loads a raw data file, and is able to play back the data for visual analysis, or to process the raw data into polarimetric or hybrid thermal/polarimetric data files. This processing can be performed on entire data sets, or, if the raw data files are large, can be performed on a subset of the raw data file which contains features or events of interest. These processed data files can be stored in numerical format for further analysis using external tools, or can be exported to standard video file format. Processing of the raw data can be performed as an offline activity after the data collection effort is complete. The algorithms which are used to compute the processed data files are coded in the C++ programming language as a library, and linked with the PVS software.

3. OHMSETT TESTING

In late Sepetember of 2017, Polaris was invited to participate in a week of oil spill detection tests at Ohmsett sponsored in part by the ExxonMobil Upstream Research Company, an ExxonMobil subsidiary that engages in research and development of technology for exploration, development, production and gas commercialization. The test matrix consisted of several days of testing to determine the limits of detection – how thin a film of oil could be detected; measurements of emulsified oil in waves; imaging oil on sand and rocks; and the effects of dispersant on detectability. Here we report only on the thickness and emulsified oil measurements.

The goal of the first experiment for Ohmsett testing was to watch different oil thicknesses over a period of time while the oil weathered. Pyxis LWIR 640-GR and a visible camera (both weatherproofed) were mounted to a stanchion on the main tank's bridge. A nine-unit array was constructed of PVC pipe to create eight sections of varying oil thicknesses and one section of clean water to serve as a control. HOOPS crude oil was used for this experiment. After the array was filled with the appropriate amount of oil, Pyxis and the visible camera were set up to take one second of data (30 frames) every ten minutes. Figure 7 shows the oil thickness array at 4:21pm. The top left image is from the visible that serves as a reference image. This image also shows the average thickness of the oil each PVC frame assuming uniform thickness. The top right image is a standard thermal image calculated from Pyxis. The bottom left shows the polarization image. The bottom right shows an eTherm image. The eTherm image is a combination of thermal and polarization images where polarization is

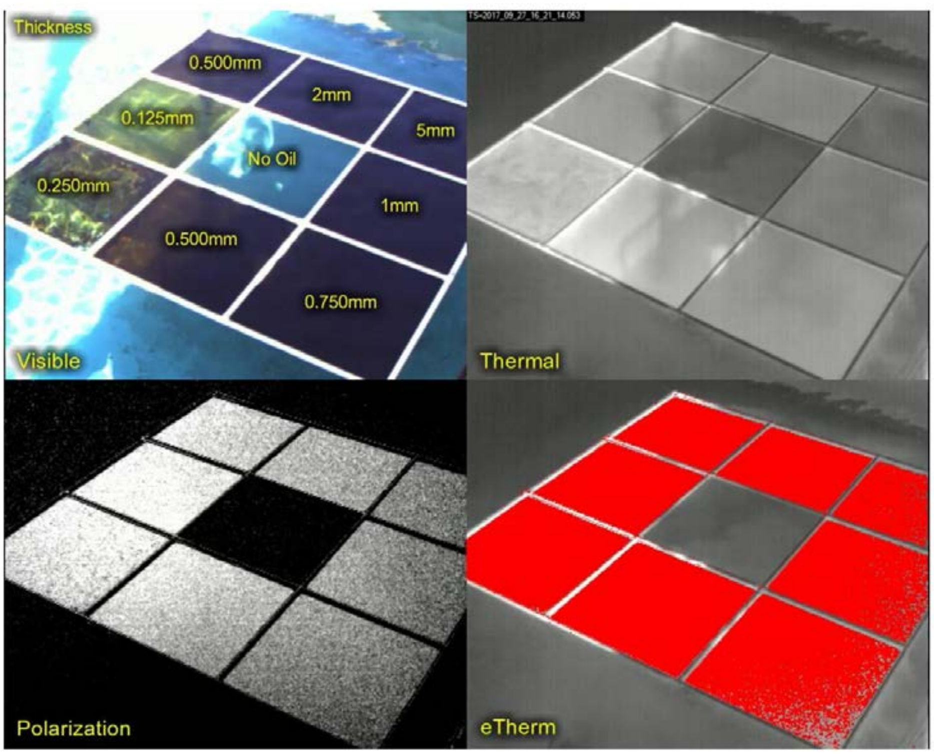

Figure 7. Thickness image at 4:21 pm.

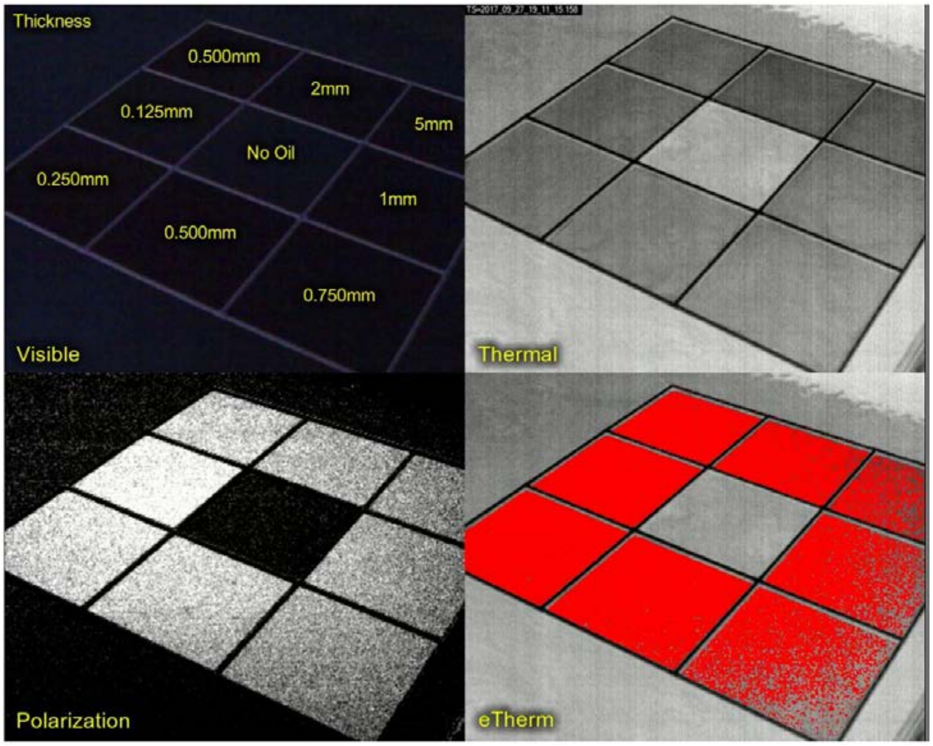

Figure 8. Thickness image at 7:11 pm.

colored red and overlaid on top of the standard thermal image. Figure 8 shows the array at 7:11pm. Note the thermal signatures in the oil range from hotter than the water to cooler than the water over the data set. The thermal signature of the oil is almost identical to that of the water at 5:31pm but the polarization maintains a high contrast. There is some variation in the polarization signature due to thickness. Films down to 125μm are consistently detected even when the thermal is not consistent.

A second experiment was conducted to examine thinner films. The setup is shown in Figure 9. It consists of 6 bins, shown in a visible image at the top. The thermal image is shown bottom left and the polarization image is shown bottom right.

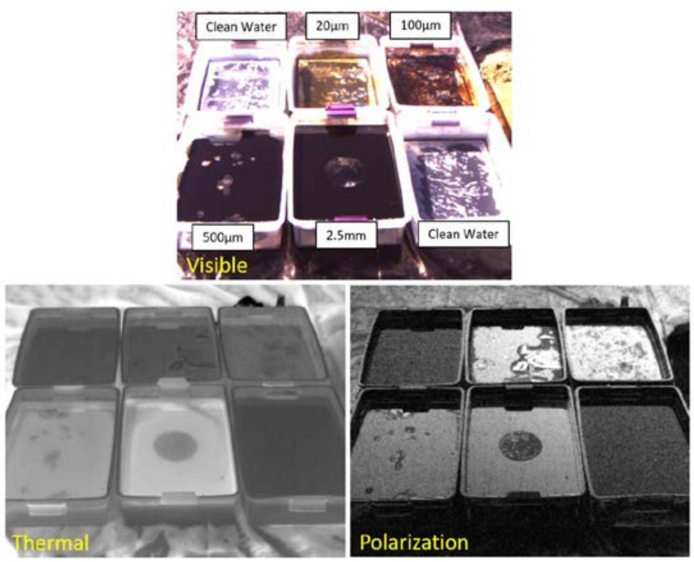

Figure 9. Second thickness measurement. The top middle bin shows detection at 20 μm.

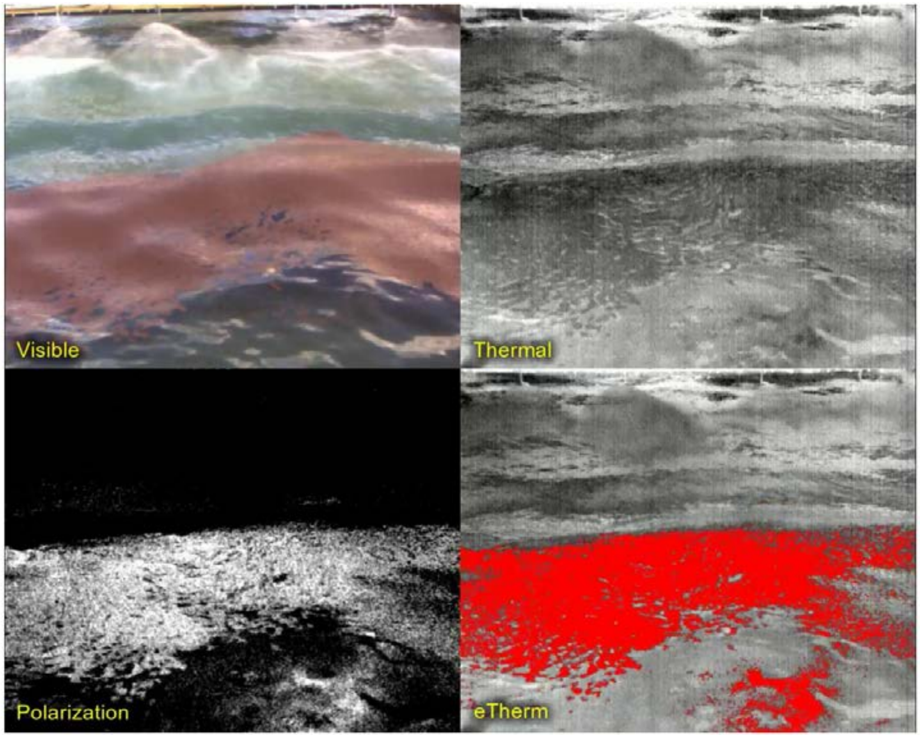

Figure 10. Still from video acquisition of emulsified oil. The thermal image (upper right) shows no ability for oil detection. The polarization (bottom left) and eTherm (bottom right) clearly show the detected oil when compared to the visible image (upper left).

Four of the bins were ramped from 10 um to 2.5 mm thicknesses with two no-oil controls. The bins were illuminated by the sun and the temperatures varied widely. Consistent detection for the polarization was demonstrated between 20 and 50 μm.

To study the performance for polarization for emulsified oil detection, 400 gallons of oil was placed in the tank and weathered for five days. The interaction of the oil with UV radiation changes the nature of the oil and more realistic for an oil spill response. After this period of weathering, the wave maker was turned on and within a few hours the oil became emulsified with an estimated 80% water content. Figures 10 and 11 show two snapshots of the acquired video. It is clear that the thermal imagery shows no detection at all while the polarization, and hence the eTherm, shows strong detection. The wave action tends to add clutter to the thermal imagery. It's important to note that at the Ohmsett facility, the visible contrast is significantly higher for the emulsified oil than it would be in the ocean due to the light color of the pool bottom and the shallowness of the pool.

4. SUMMARY AND FUTURE WORK

Thermal polarimetric imaging has been demonstrated to be very effective at detection oil and diesel spills at the Ohmsett test tank under a variety of conditions. The Pyxis LWIR 640 polarimetric camera was described as well as the phenomenology associated with thermal polarimetric signatures. Pyxis detected oil and diesel on the surface of the water with thicknesses of 20 micrometers, in waves, and at times of day in which the thermal signature underwent thermal cross-over. The signatures are strong enough and robust enough in various conditions that there is a strong possibility for automated detection for the oil and gas industry, for environmental monitoring, for ports and harbor surveillance, and other applications.

Work will continue to explore oil on water detection through infrared polarimetric imaging through measurement activities as well as through analysis and algorithm development. While one contrast metric was explored here, further approaches will be examined to ensure fair and accurate comparisons to conventional imaging techniques. This work will also be leveraged to establish and improve automated detection.

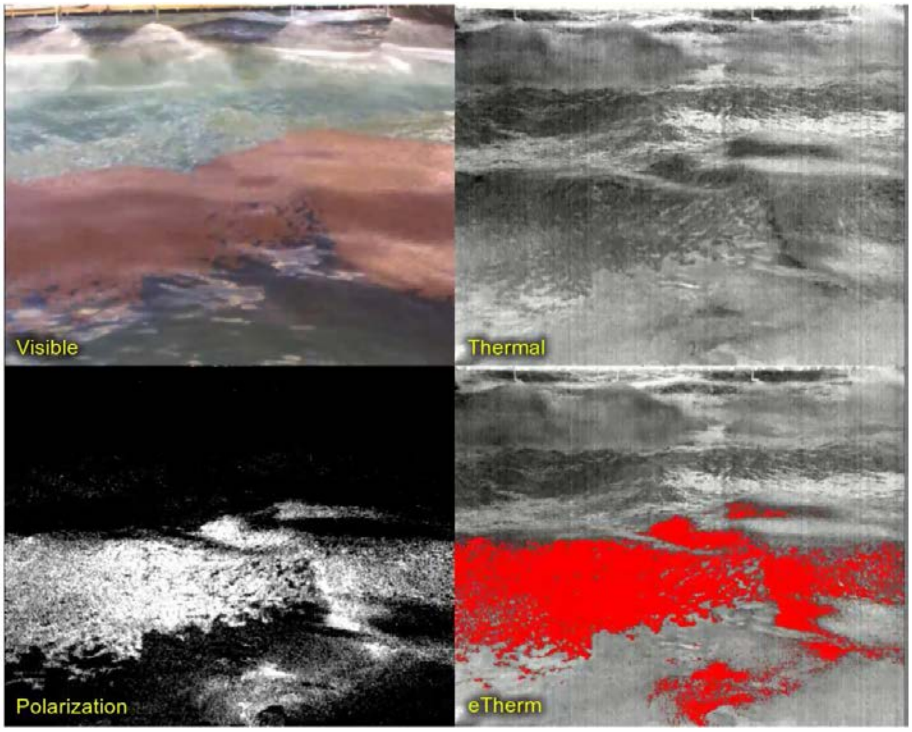

Figure 11. Still from video of emulsified oil. Video can be seen here. http://dx.doi.org/doi.number.goes.here

5. ACKNOWLEDGEMENTS

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REFERENCES

[1] David B. Chenault, Justin P. Vaden, Douglas A Mitchell, Erik D. DeMicco, "Infrared polarimetric sensing of oil on water," Proc. SPIE 9999, Remote Sensing of the Ocean, Sea Ice, Coastal Waters, and Large Water Regions 2016, 99990D (19 October 2016)

[2] Felton, M., Gurton, K. P., Pezzaniti, J. L., Chenault, D. B., and Roth, L. E., “Measured comparison of the crossover periods for mid- and long-wave IR (MWIR and LWIR) polarimetric and conventional thermal imagery,” Opt. Exp., Vol. 18. Issue 15, pp. 15704-15713 (2010).

[3] Felton, M., Gurton, K. P., Pezzaniti, J. L., Chenault, D. B., and Roth, L. E., “Comparison of the inversion periods for MidIR and LWIR polarimetric and conventional thermal imagery," Proc. SPIE 7672, (2010).