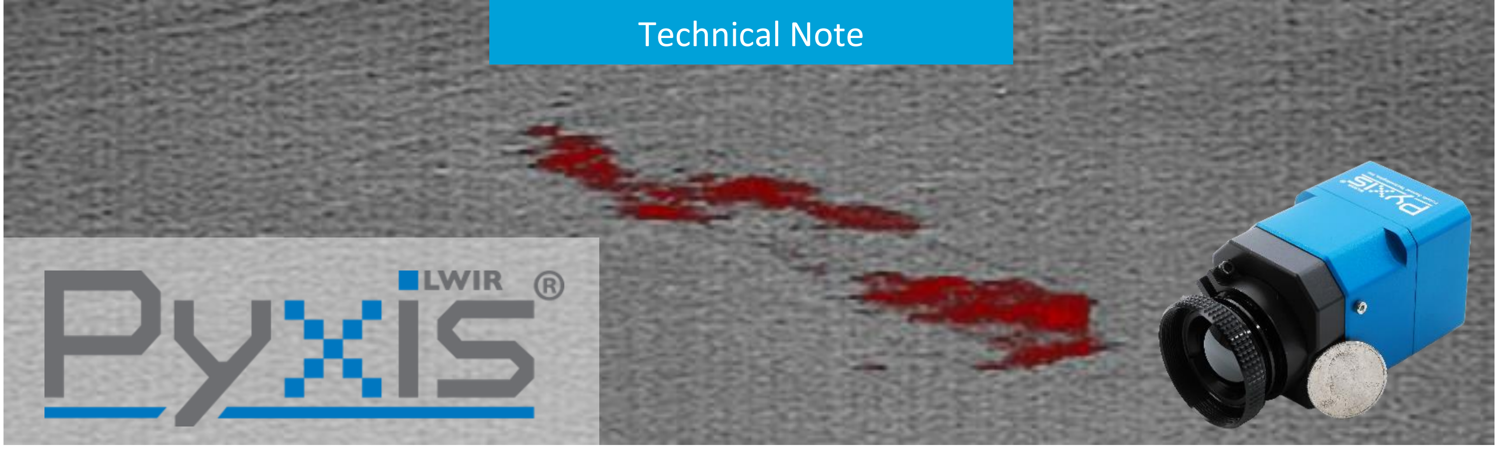

Why is Pyxis® Better than Thermal Alone for Oil Spill Detection and Monitoring?

When evaluating your options for sensors and comparing the Pyxis® to thermal cameras, you may wonder why you would choose the Pyxis. After all, thermal cameras have been around for a long time and are marketed as an oil spill detection sensor. The short answer is that the polarization sensing capability in Pyxis detects oil significantly better in a wider range of situations for a larger variety of spill conditions. Importantly, Pyxis adds this capability to thermal sensing and doesn't take away that capability. In this *Technical Note*, we'll describe how the Pyxis gives better contrast of oil on water, how this impacts detection, and show the improvement over thermal alone.

Overview of Pyxis, How it Works, and What it Measures

The proprietary technology of the Pyxis sensor exploits the polarization of light in our environment, this is well established in sports like racing, skiing and fishing, conditions where visibility plays a key role in performance. When ambient illumination is reflected off an object, the reflected light becomes polarized. Likewise, in the thermal infrared, light becomes polarized as it is emitted from the water and oil in an amount that depends on the material properties of the emitting substance. The key factor here is that the amount of polarized light *does not depend on temperature,* and thus, the water and the oil can be the same temperature and have different polarization signatures. Pyxis measures the polarization in addition to the thermal and hence performs detection more effectively in a greater variety of conditions. These conditions will be described in greater detail below.

The Pyxis camera itself uses a modified uncooled microbolometer camera core with the addition of a pixelated or checkboard pattern polarization filter. This approach enables real-time, simultaneous acquisition and calculation of the polarized *and* thermal video in a package that is compact, energy efficient, and light enough to be integrated onto small unmanned aerial systems (UAS) or drones. A range of standard lenses enables a selection of magnifications and fields of view.

Pyxis Detection of Oil vs. IR

Pyxis discriminates oil from water due to the optical property material differences between oil and water. A thermal or infrared (IR) camera only senses temperature differences. For large, very thick oil slicks, sunlight heats up the oil, causing it to develop a strong heat signature. However, as the sun rises and sets, the oil-water temperature difference reverses and there is no contrast, and when the sun is not shining (such as at night and in overcast conditions) then thermal imagery just isn't as effective. One of the first tests on Pyxis was conducted overnight at the Ohmsett Oil Spill Response facility operated by the Bureau of Safety and Environmental Enforcement (BSEE) and examined thick and thin oil floating on water. **Figure 1** shows the experimental setup and the results. The red lines show the contrast of the thermal measurement of the oil relative to the water and the blue lines show the contrast of the polarization measurement relative to water. You can see that in the 15:27 thermal image, the thin bin thermal image is nearly indistinguishable from the surrounding water background. In the 17:17 image, the thermal contrast is better, due to heating by sun late in the day, but it is still not as good as the polarization image for both times. Polarization remains strong even at night, as visualized by the imagery for 21:27. Finally, in the morning hours, the thermal image of the thick oil bin gets quite bright, but this is the only time the thermal performs better. The time lapse video that shows all images and the complete plot over this time frame can be found in the video "Clean Gulf 2017" starting at the 1:10 mark on Polaris's YouTube channel at https://youtu.be/T_neM6jmj7c.

This same video shows several examples of crude oil and diesel in both very smooth water (a difficult scenario for oil detection radars) and in smooth and breaking waves. These video sequences, a snapshot of which is shown in

Figure 1. The plot shows a Contrast Metric computed on the thick oil and thin oil bins as compared to the water background for thermal (red) and polarization (blue) data products. Polarization performs better 92% of the time. The bottom imagery shows visible, thermal, and polarization imagery of the 5 mm thick (left bin, thick line in the plot) and 0.5 mm thick (right bin, thin line) oil samples at the times marked by yellow lines.

Figure 2, show the visible image in the upper left, the thermal image in the upper right, the polarization image in the lower left, and an "eTherm" or enhanced thermal image in the lower right. The eTherm® imagery combines both the thermal and the polarization into a fused image containing both data products that retains the thermal information in gray scale but highlights the detections through polarization using color.

Other tests were conducted at the BSEE Ohmsett facility with oil thicknesses ranging from $10\mu m$ (rainbow sheen) to $100\mu m$ (metallic) to $5mm$ thick. Further tests included measurements of emulsified oil and oil in the presence of dispersant. The emulsified oil was aged and subjected to ultraviolet and wave action to produce an emulsification with 80% water content. The oil being dispersed was visible right up to the moment when the oil left the surface

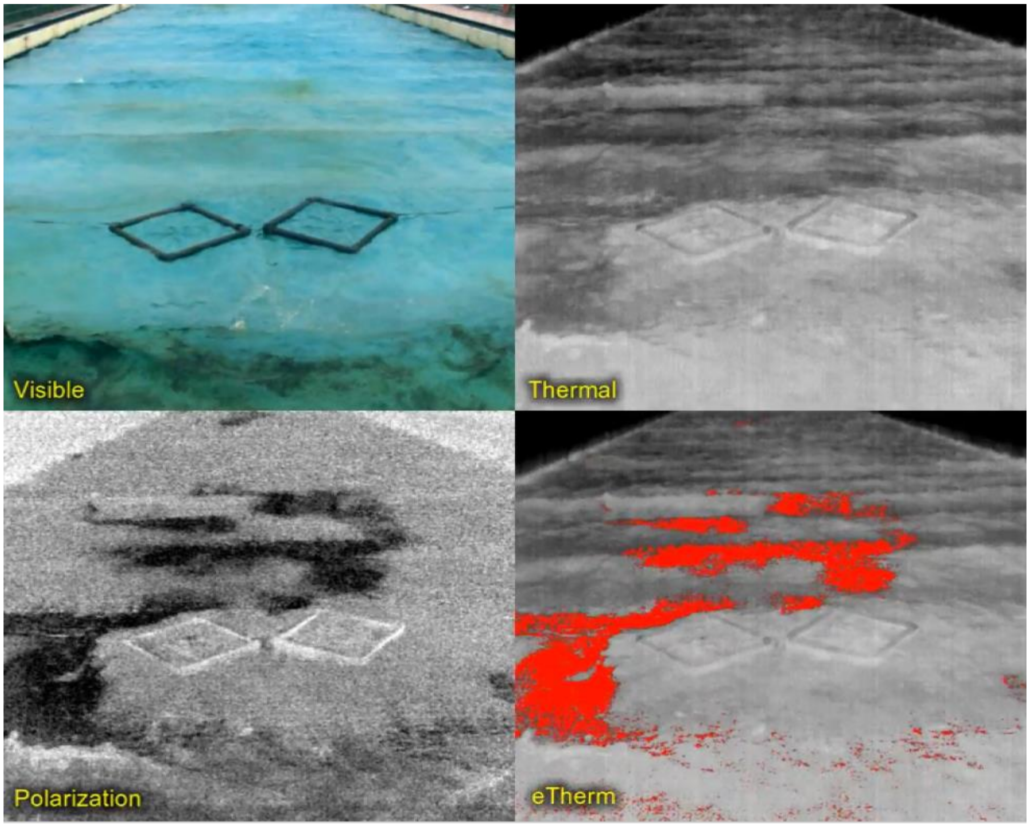

Figure 2. Visible, thermal, polarization, and eTherm imagery of crude oil on water in the presence of breaking waves. Oil is essentially undetectable in the thermal imagery. eTherm fuses polarimetric and thermal data into a single image.

and entered the water column. In every case, polarization showed better contrast and detectivity than thermal alone, either due to better contrast, or through the reduction of thermal clutter due to wave action. This is extremely helpful during cleanup efforts by determining areas that are clean and those are that are still affected.

Several opportunities to demonstrate the superior detection performance of Pyxis in the environment have also shown the benefit of polarization detection. Pyxis was deployed to Santa Barbara at the time of a pipeline spill where it was operated as a handheld camera from a manned helicopter. **Figure 3** shows visible imagery of the scene and the eTherm image. The eTherm image fuses the polarimetric and thermal data into a single image so that the benefits of both modes are available to improve probability of detection and reduce false alarms. In this scene there are several features that produce clutter in the scene in both the visible and the thermal imagery including a kelp forest, sun glint, and surface wellings. The oil sheen is observable in the visible image if you know where to look but is confounded by the other surface features. The eTherm image clearly highlights the thickest part of the sheen, and through the filtering provided by the polarization, the confounding clutter is suppressed.

Other deployments to the Gulf of Mexico and in a recovery operation for a marina fire have shown similar detection capabilities and superior performance over thermal cameras. Specifically, in the marina fire response, the Pyxis imagery was solely responsible for finding the location of a sunken vessel due to detection of leaking oil.

Finally, initial studies looking at oil pooling on sand or earth has shown significant capability of detection through polarization sensing over that of thermal. The thermal clutter resulting from the environment of a pipeline or beach is too great to reliably detect oil. In polarization, however, pooling oil is readily found even if it is diluted by water or waves.

Pyxis Detection of Oil vs. Radar

Detection of floating oil using radar relies on the effect that the oil has on the fine wave structure or capillary waves on the surface, and not on the material differences between water and oil like polarized IR. Oil-dampened waves have lower backscatter than waves without oil. Hence, radar does not work at winds speeds less than $2\ m/s$ ($4.5\ mph$). Other effects can cause false alarms such as natural surface films produced by plankton or fish, cold

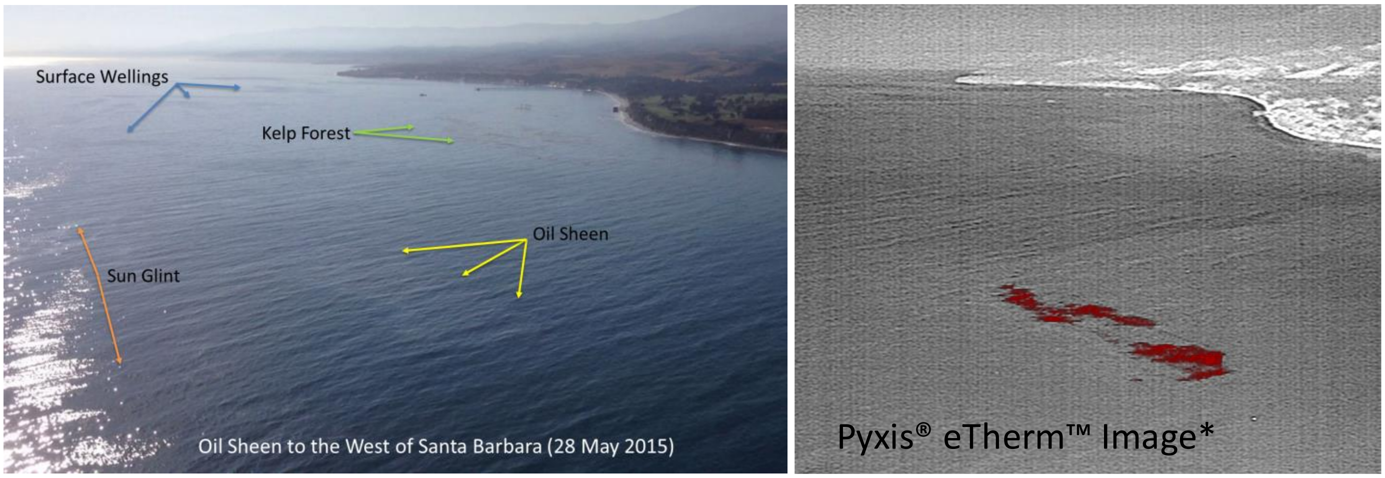

Figure 3. Oil spill detection off the coast of California. The Pyxis eTherm image shows the detection in red whereas the thermal and visible imagery show confusing clutter.

upwelling water which changes the stability of the air-sea interface, divergent flow regimes (e.g., with internal waves, tidal flow over underwater sand banks, and oceanic eddies), dry-fallen sand banks during ebb tide, or floating macro-algae including sargassum and kelp. In all these cases, Pyxis does not detect these as false alarms.

Video Case Studies

Day / Night Detection: https://youtu.be/U32ZQ7gmyGM
Pyxis performs well both day and night, and in many cases, it is more effective at night when visual observation is impossible. The thermal emission of the oil and water serves as the source of light for the Pyxis camera which requires no ambient illumination. To test this, an overnight data collection was performed in which a bin with a thick layer of oil ($\sim 5\ mm$) and a bin with a thin layer of oil ($\sim 0.5\ mm$) were placed in a larger basin of water and imaged with Pyxis and a visible camera from approximately 3:00 in the afternoon to 9:00 the next morning (**Figure 1**). A contrast metric quantifying the visibility of the oil relative to the water background was computed by comparing regions of interest in each oil bin to the water background. This video shows the superior performance of the Pyxis camera relative to thermal alone throughout the whole time period. In this video, the visible scene is shown on the left, the thermal image is shown in the middle, and the polarization data product from Pyxis is shown on the right. The visible goes dark between sunset and sunrise because there was no ambient illumination. The plot below the imagery shows the contrast metrics for thermal (red curve) and polarization (blue curve) at each time point. Visually, one can see how the visibility of the bin relative to the larger pool corresponds to the metric.

Another example in the larger Ohmsett pool is shown here: https://youtu.be/-4Vo4nkmfiY

Smooth Water: https://youtu.be/rLFDZWlGP_c
Pyxis was tested for detection performance of two crude oils and diesel fuel at Ohmsett in smooth and still water. The sensor was mounted to the moveable bridge and “flew over” the spills while collecting visible imagery, thermal imagery, the Pyxis polarization data, and the eTherm imagery fused from the thermal and polarization collected simultaneously with the Pyxis camera. This video shows the visible video in the upper left, the thermal imagery in the upper right, the polarization data product in the lower left, and the eTherm imagery in the bottom right. One of the oils was Alaska North Slope (ANS) crude oil, the second oil was a blend of crude oils, and the diesel was an off-road diesel blend. Note that the diesel is not detectable at all in visible imagery and only barely discernable in the thermal image. All three spills are easily detected with the Pyxis imagery. This scenario is representative of a situation in which radar would be ineffective, or an example of an oil slick in an inland waterway or marshy areas.

Waves: Swells: https://youtu.be/3qerdTF00CI; Breaking: https://youtu.be/WH2y5VWiWz8
Following the smooth water data collection above, the wave making machine was turned on at the Ohmsett pool to produce non-breaking waves of smooth swells. This video shows the same three spills (looking from the other direction, labeled in the video) with the same format in the presence of these waves. Note that Oil 1 and the diesel are difficult or impossible to see in the visible and thermal imagery, but they are very obvious in the polarization and eTherm images.

In a separate test, the ANS crude and crude oil blend were placed in square containment frames in the Ohmsett pool. The wave making machine was turned on to produce breaking waves which immediately spread the oil outside of the square frames. In this video, the Pyxis "flew" on the moveable bridge in the direction of the waves while viewing the two oil slicks in the same format as described above. Note that in the thermal image, the variation of the apparent temperature of the waves effectively hides the oil but remains obvious in the polarization image.

Emulsified Oil: https://youtu.be/LwwIu86qbzU
In a real oil spill, floating oil ages and changes properties significantly due the action of UV radiation and wave action. As the water content increases, the oil becomes emulsified, and detection can change significantly, particularly IR detection can suffer dramatically. In this video, emulsified oil was created at Ohmsett by exposing floating oil to several days of sunshine and using the wave machine to agitate the oil. In this video, we show detection of emulsified oil with the Pyxis camera. Note that background is so confusing in the thermal image that the oil is not detectable.

Oil in the Presence of Dispersants: https://youtu.be/LY7IyMiqsQE
One of the possible responses to an oil spill event is to apply dispersant. The objective of dispersants is to force the oil off the surface into the water column and to break it up into small droplets. Once it is submerged and in small droplet form, natural processes are effective in breaking the oil down. Ensuring the oil slicks effectively disperse after treatment is important and that just the right amount of dispersant is applied, no more and no less. Most effectiveness monitoring requires placing personnel in boats and sensors in the water. The Pyxis camera can be placed on the aircraft spraying the dispersant thereby eliminating safety concerns of boat-based monitoring and reducing the costs of labor and extra material. In this video, we show the progression over time of two oil spills at Ohmsett. One is without a dispersant, in which the oil slick on the surface grows continuously. In the second, the oil is treated with dispersant material and the oil is successfully dispersed off the surface. The video shows the thermal imagery of both as well as the Pyxis eTherm imagery. Pyxis shows very clearly the oil leaving the surface. In a response situation, the Pyxis camera could provide a more rapid, synoptic, and safer method of monitoring effectiveness of dispersants.

Detection of Oil from Sunken Vessel: https://youtu.be/gidXMRzCq9Q
In January 2020, a marina fire in Scottsboro, Alabama swept through a dock damaging and sinking a number of liveaboard boats and killing eight people. Polaris responded with a drone mounted Pyxis camera to survey the area for oil that had escaped containment. As part of this response, the Pyxis found a slick that indicated a sunken boat. The responders investigated and found that a previously unknown boat was indeed on the bottom below the slick detected by Pyxis. The vessel was subsequently recovered. This video shows some of the imagery that found the sunken vessel.

Monitoring Leak in Gulf of Mexico: https://youtu.be/pW2T4BcuuCc
In 2004, Hurricane Ivan damaged a well head that has been leaking into the Gulf of Mexico ever since. While attempts to stop the leak are ongoing, the situation provides an opportunity to test oil spill detection techniques. In this video, we show imagery of this leak collected by a handheld Pyxis and pointed out the open door of a helicopter overflying this leak nearly 100 miles southeast of New Orleans. The left image is the visible view of the scene, and the right image shows the Pyxis eTherm imagery. The first sequence shows the two image sequences in split screen mode, and the second sequence shows the imagery side by side. Note that the rainbow sheen is barely discernable in the visible imagery. The thickest parts of the slick are highlighted in red in eTherm.

Detection of Pooling Oil on Sand and Rocks: https://youtu.be/Lv3l7TEqQso
Pyxis detects material differences between oil and water when oil is floating on water. Similarly, Pyxis can detect oil when it is pooling on the surface of land or ice. This video shows the detection of oil on black rocks and oil-soaked sand when water causes the oil to rise to the surface and pool. This scenario represents detection of oil on beaches as part of Shoreline Cleanup and Assessment Technique (SCAT) operations or the pooling of leaks along pipelines.

Drone Deployment for Oil Spill Cleanup and Response (OSCAR): https://youtu.be/y15QdvkyVT0
The Pyxis camera is small enough to be flown on commercially available drones. This video shows the Pyxis mounted on a drone and several examples of data collections off the coast of Santa Barbara, CA, an oil processing facility, and in desert scenario. The OSCAR report is also shown.

Summary

The Pyxis polarized thermal camera combines the advantages of thermal and polarization-based sensing. The polarization capability significantly enhances detection of floating oil over that of thermal in a variety of conditions including:

- Breaking waves and smooth waves
- Smooth water (wind speed $< 2\ m/s$)
- Crude and refined oil
- Oils interacting with dispersant
- Emulsified or aged oils
- Diesel, kerosene (or jet fuel), mineral oil
- Day and night
- Does not detect biologicals

It is important to note that Pyxis is a remote sensing technique that detects oil floating on water (and other petroleum products) and not subsurface oil, or oil entrained in the water column. It is a remote sensing surface measurement that covers a wide area in a single snapshot.

Polaris has developed the Pyxis Oil Detection System, or PODS™, for autonomously monitoring a site with minimal human intervention. The PODS system consists of the Pyxis camera, an environmental enclosure, and software. Environmental enclosure options include housings for fixed installations or low-cost pan-tilt units or certified intrinsically safe fixed and pan-tilt units for explosive environments. The pan-tilt unit provides large area coverage from a single position over a preprogrammed path, optimizing detection in high priority areas. The software leverages the robust detection while simultaneously testing each potential alarm against multiple checks in order to eliminate false alarms. Alarms are given on the display and optionally remoted to other locations. The PODS intrinsically safe version with pan-tilt is shown in **Figure 4**.

Figure 4. The PODS™ autonomous detection system

Comparison of LWIR Camera only and Polarization Enhanced LWIR

Description	LWIR camera only	Polarization enhanced LWIR
Well understood technology	Yes	Yes
General availability of camera	Multiple sources	One source
Strong signal with temperature difference	Yes	No effect on performance
Strong signal with no temperature difference	No	No effect on performance
Strong night time performance	No	Yes
Strong performance in waves	No	Yes
Strong performance in rain	No	No
Strong detection of emulsified oil	No	Yes
Strong performance in warm, low clouds	No	No

Export

The Pyxis thermal polarimetric camera comes in two versions, a 30 Hz frame rate and a 7.5 Hz frame rate. The fast version is governed by Department of Commerce EAR export regulations with an ECCN of 6A003 which requires a license for export to many countries. The slow version is covered under ECCN 6A993 and does not require a license for export to most countries. Please contact Polaris regarding export regulations requirements.

Pyxis Specifications

Pyxis® LWIR 640-G	
Resolution (H x V)	640 x 512 pixels
Field of View w/ Standard Lens	30.4° x 24.6°
Camera Frame Rate	30Hz or 7.5Hz
Input Voltage	5 VDC or POE
Steady State Power @ 70°F	4 – 6 Watts
Operating Temperature	0°C - 70°C
Size w/ standard lens	88 x 46.5 x 46.5 mm
Weight w/ standard lens	184 g

Pyxis Features and Benefits

Feature	Benefits
Real time operation	• User gets real-time feedback for spill response • Instantaneous video to command center or drone operator
Works day and night	• 24-hour monitoring of spills • Overnight spill response and spill tracking
Detection threshold around 50 μm	• Detects recoverable oil, saving time and money by identifying only oil thick enough for recovery
Senses temperature differences	• Retains benefit of standard IR camera and thermal contrast of oil on water
Senses polarization differences	• Adds benefit of polarization contrast for oil detection
Superior performance in waves	• Enables operation in rough weather
Superior detection of emulsified oil	• Detects weathered or aged oil when a response can take days to complete
Monitors effectiveness of dispersant	• Stop deploying dispersant when it is no longer effective saving time and money
Detects pooling oil	• Spill detection around pipelines and on beaches
Sensitive to petroleum products	• Detects crude and refined oil, diesel, and Jet-A / kerosene • Search and rescue operations by detecting spilled fuel • Insensitive to biologicals such as kelp and algae
Data and power by power-over-ethernet (POE) cable	• Low impact to infrastructure • Simple to install
Small and low power	• Easily deployed on drones • Low impact to infrastructure at fixed sites

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About Polaris Sensor Technologies, Inc.

Polaris Sensor Technologies, Inc. is a dynamic commercial and prime government supplier providing innovative designs, unique products, and state-of-the-art analyses of optical systems. We have a team of optical experts with extensive experience in designing high-performance systems. Our portfolio includes polarization-based imaging systems, sensors, seekers, light scattering modeling, and measurement services.

Located in Huntsville, Alabama, our engineering facility features an extensive laboratory. Holding many national and international patents, Polaris creates custom hardware and unique software solutions providing our customers with the ability to meet mission objectives. How can we serve you?

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