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Chenault

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(54) **WIDE-AREA REAL-TIME METHOD FOR DETECTING FOREIGN FLUIDS ON WATER SURFACES**

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(51) **Int. Cl.**

***G01J 5/00*** (2006.01)
***G01N 21/21*** (2006.01)
*G01N 21/17* (2006.01)

(52) **U.S. Cl.**

CPC ....... ***G01N 21/21*** (2013.01); *G01N 2021/1793* (2013.01)

(58) **Field of Classification Search**

CPC ............ G01N 21/21; G01N 2021/1793; G01N 21/4738

(Continued)

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(57) **ABSTRACT**

A method using Infrared Imaging Polarimetry for detecting the presence of foreign fluids on water comprises estimating an expected polarization response for a foreign fluid desired to be detected. Oil from an oil spill is one such foreign fluid. An optimal position of a polarimeter to take images of the water's surface is determined from the expected polarization response. The polarimeter is positioned at the optimal position and records raw image data of the water's surface to obtain polarized images of the area. The polarized images are corrected, and IR and polarization data products are computed. The IR and polarization data products are converted to multi-dimensional data set to form multi-dimensional imagery. Contrast algorithms are applied to the multi-

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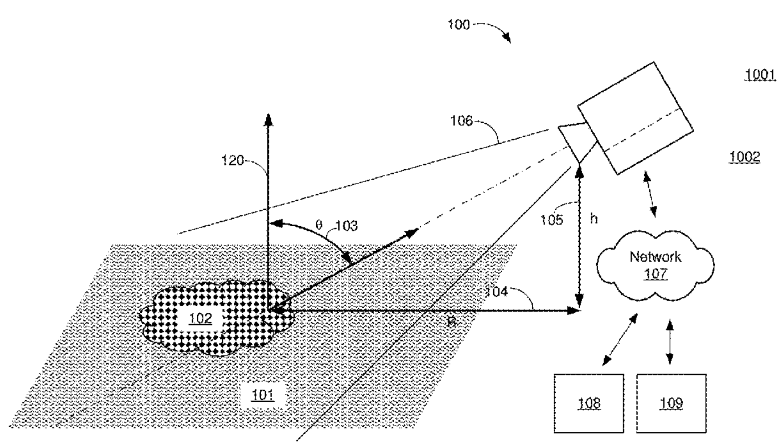

dimensional imagery to form enhanced contrast images, from which foreign fluids can be automatically detected.

**20 Claims, 11 Drawing Sheets**

(58) **Field of Classification Search**
USPC .................................................... 250/338.1
See application file for complete search history.

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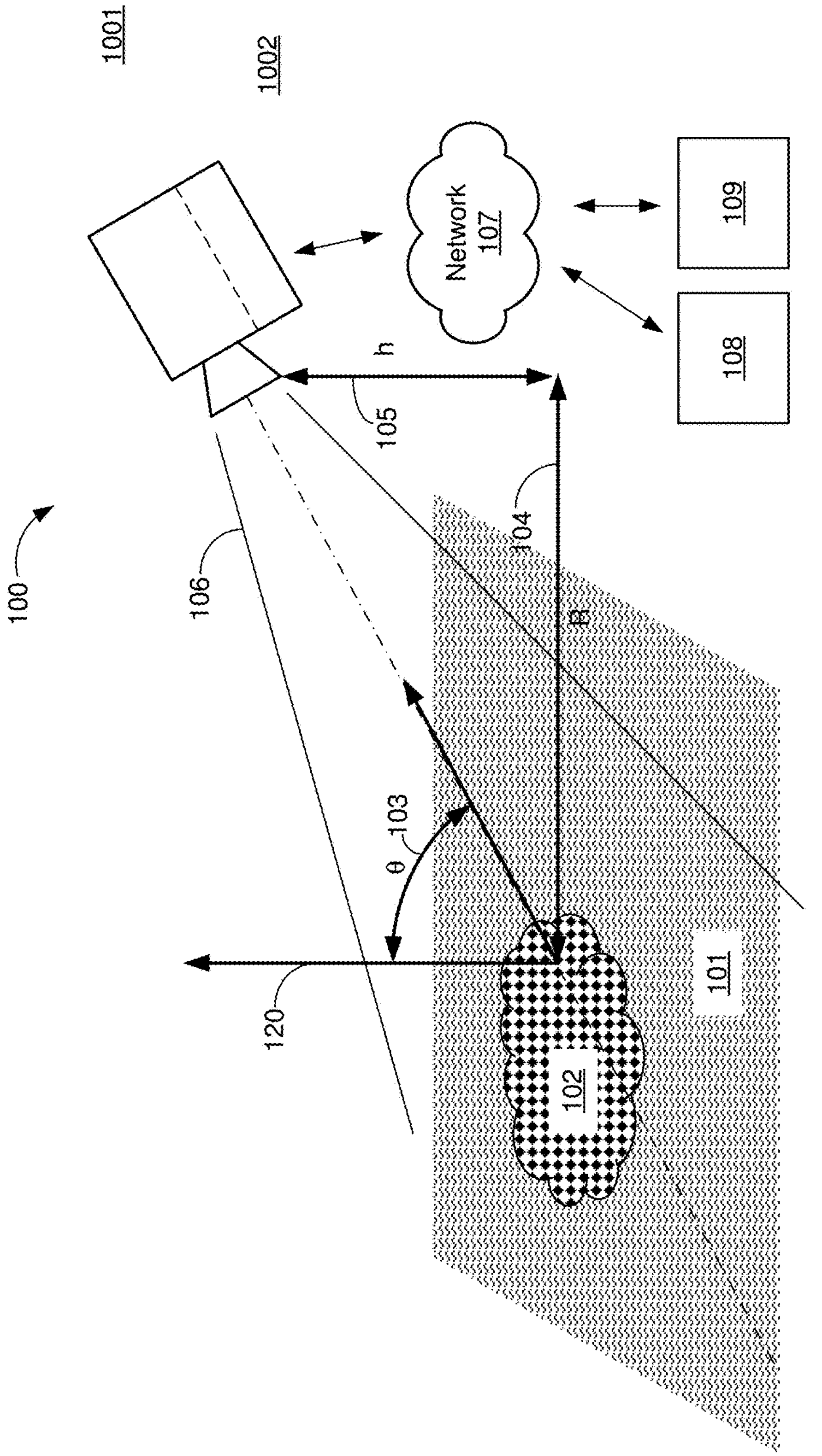
1001
1002
Network
107
109
108
h
105
104
R
100
106
103
θ
120
101
102

FIG. 1

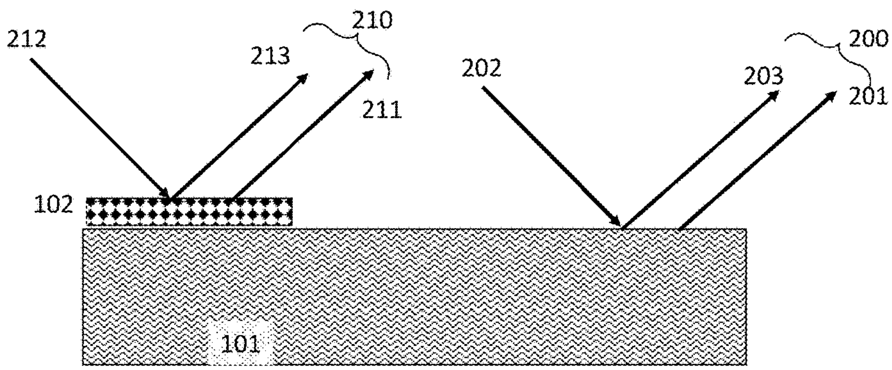


**FIG. 2**
**(Prior Art)**

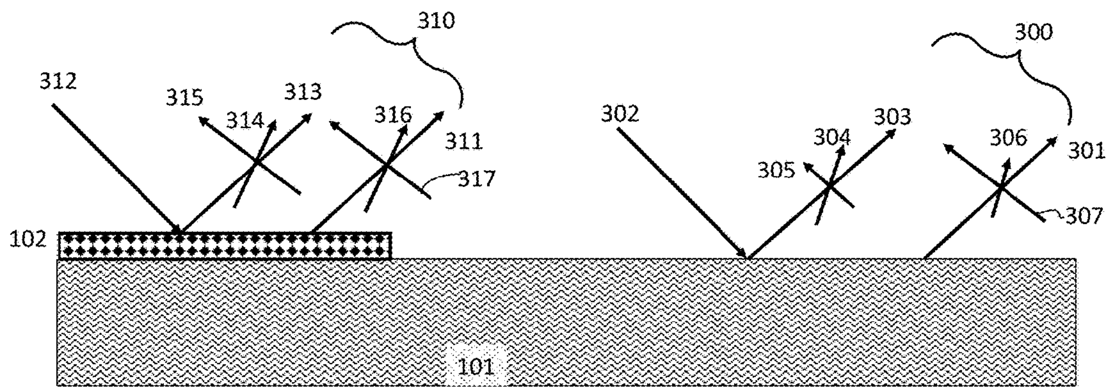


**FIG. 3**

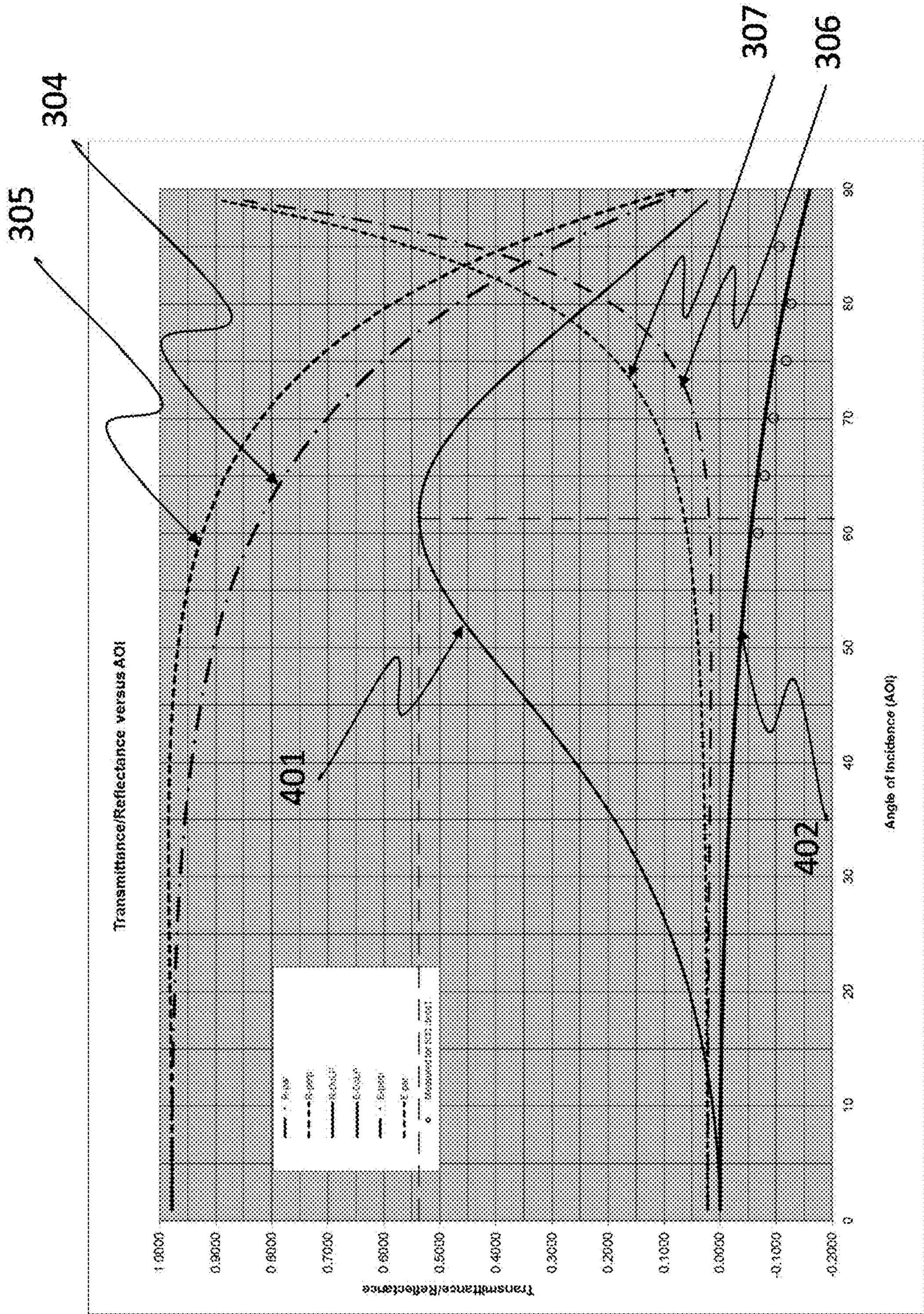
304
305
307
306
401
402
Transmittance/Reflectance versus AOI
Transmittance/Reflectance
Angle of Incidence (AOI)
1.0000
0.9000
0.8000
0.7000
0.6000
0.5000
0.4000
0.3000
0.2000
0.1000
0.0000
-0.1000
-0.2000
0
10
20
30
40
50
60
70
80
90

FIG. 4

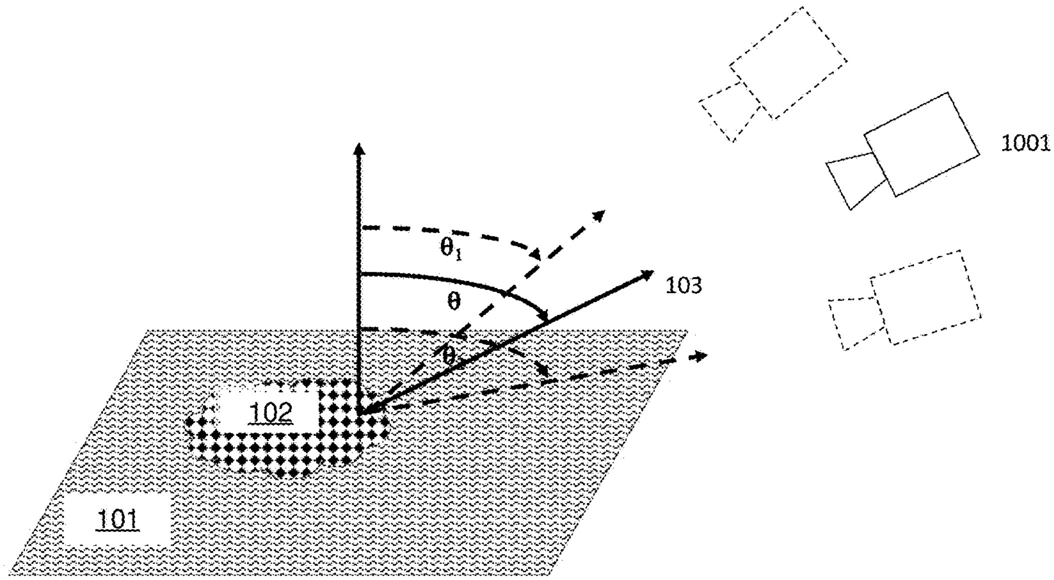


FIG. 5

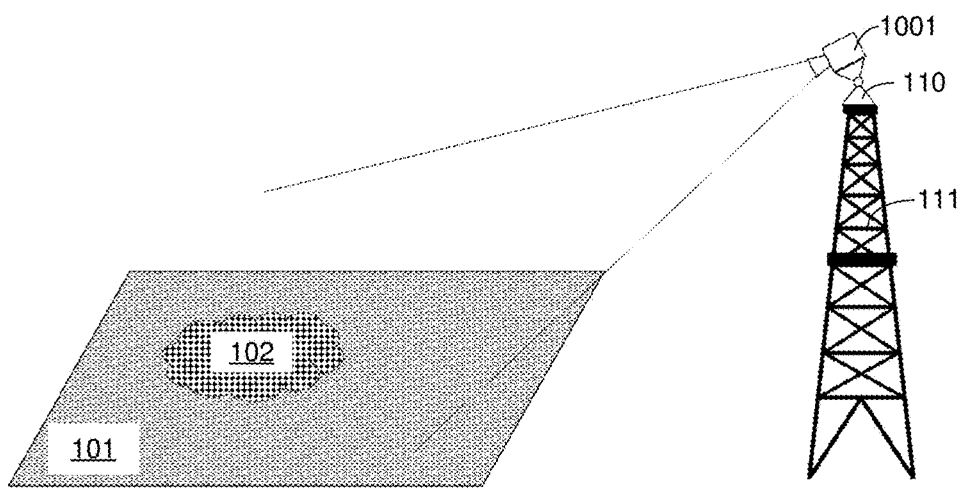


FIG. 6

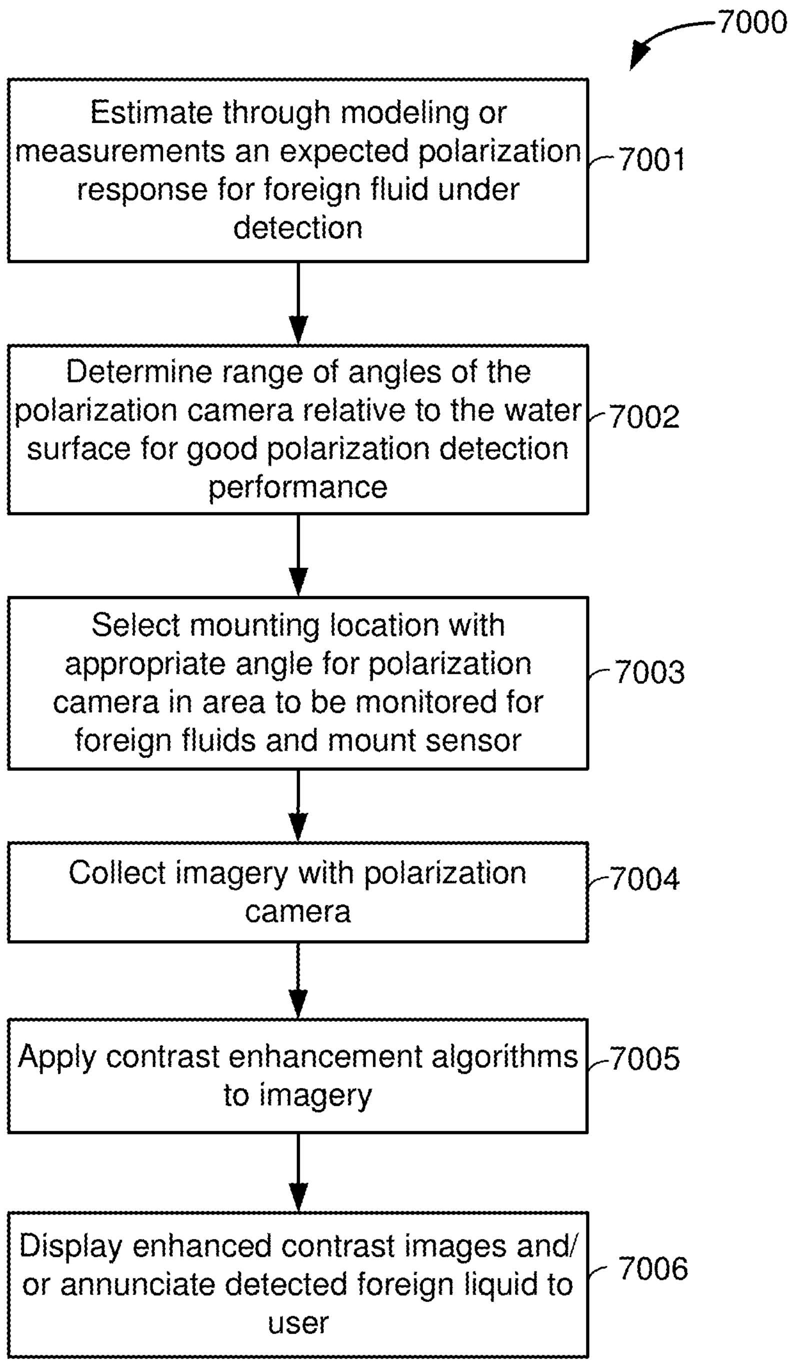
7000
Estimate through modeling or measurements an expected polarization response for foreign fluid under detection
7001
Determine range of angles of the polarization camera relative to the water surface for good polarization detection performance
7002
Select mounting location with appropriate angle for polarization camera in area to be monitored for foreign fluids and mount sensor
7003
Collect imagery with polarization camera
7004
Apply contrast enhancement algorithms to imagery
7005
Display enhanced contrast images and/or annunciate detected foreign liquid to user
7006

FIG. 7

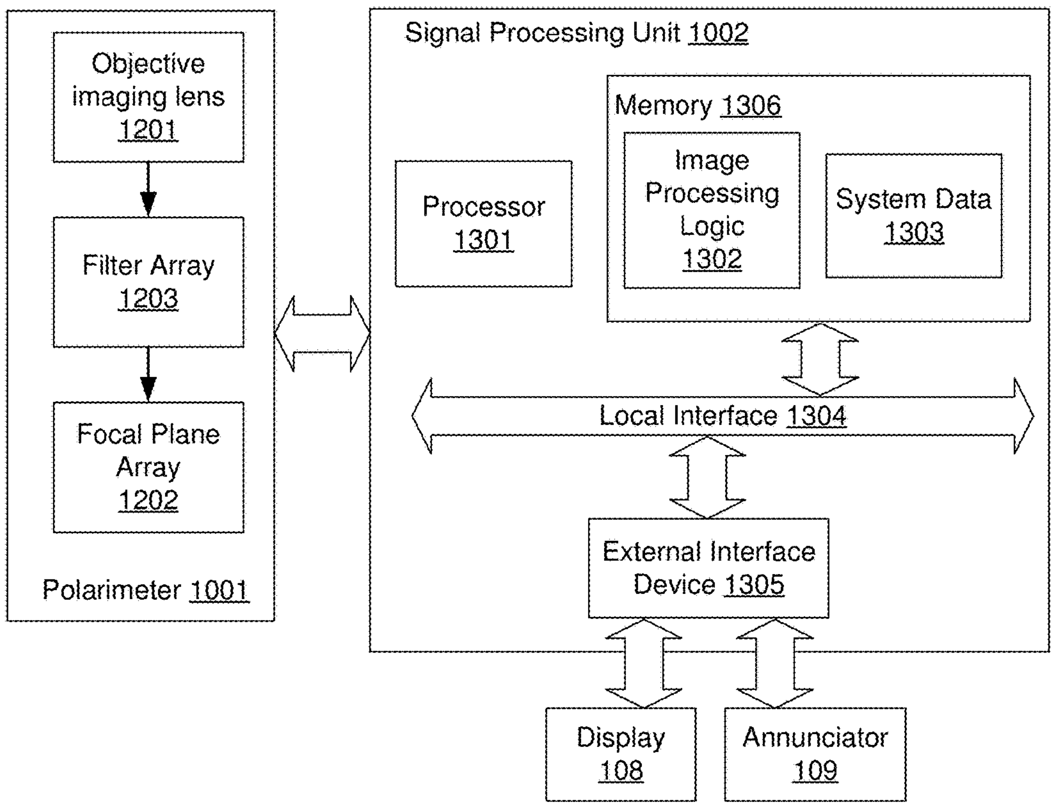
Objective imaging lens 1201
Filter Array 1203
Focal Plane Array 1202
Polarimeter 1001
Signal Processing Unit 1002
Memory 1306
Processor 1301
Image Processing Logic 1302
System Data 1303
Local Interface 1304
External Interface Device 1305
Display 108
Annunciator 109

FIG. 8

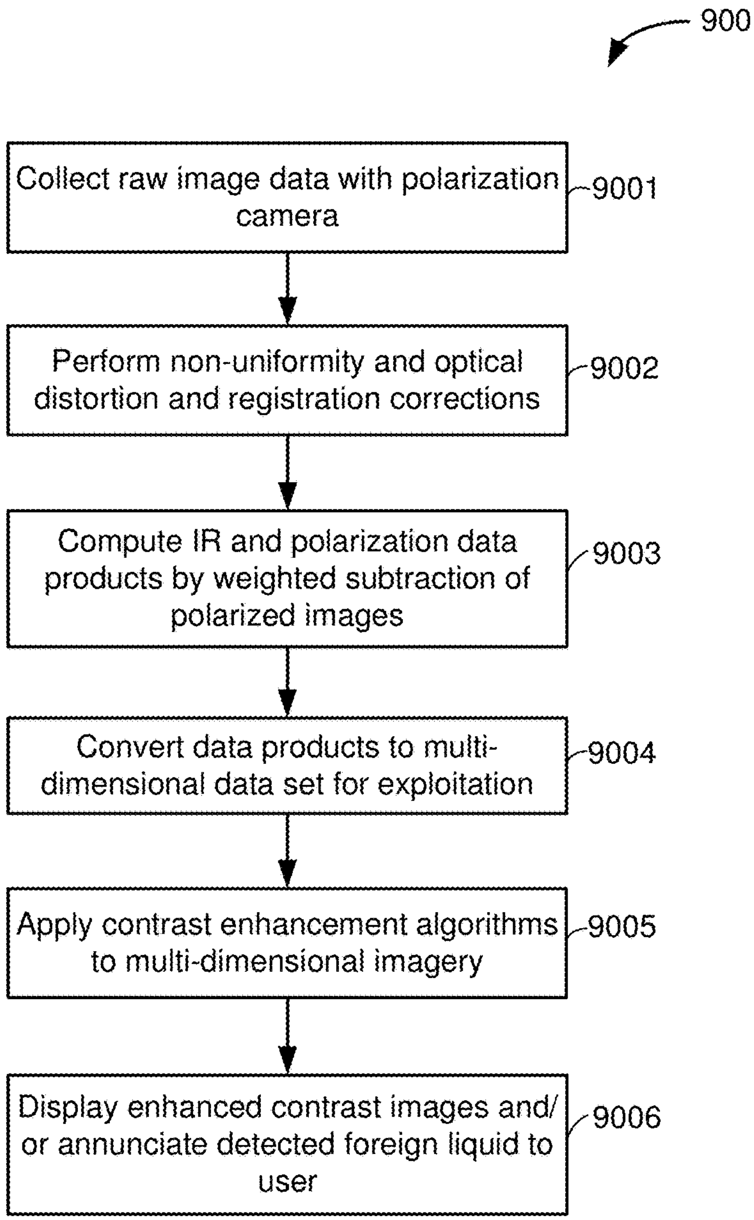
900
Collect raw image data with polarization camera
9001
Perform non-uniformity and optical distortion and registration corrections
9002
Compute IR and polarization data products by weighted subtraction of polarized images
9003
Convert data products to multi-dimensional data set for exploitation
9004
Apply contrast enhancement algorithms to multi-dimensional imagery
9005
Display enhanced contrast images and/or annunciate detected foreign liquid to user
9006

FIG. 9

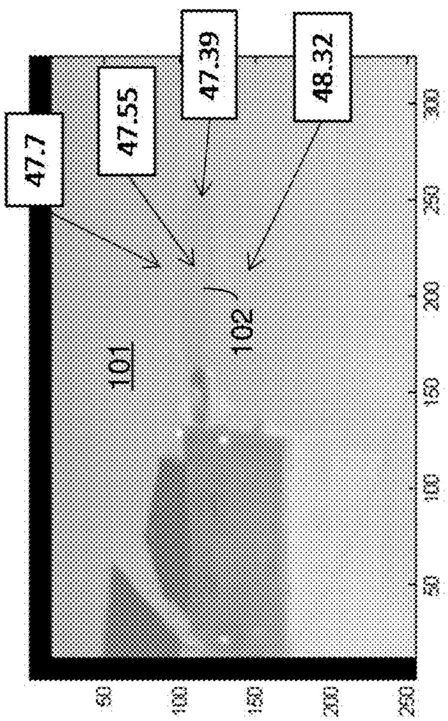


Fig. 10a

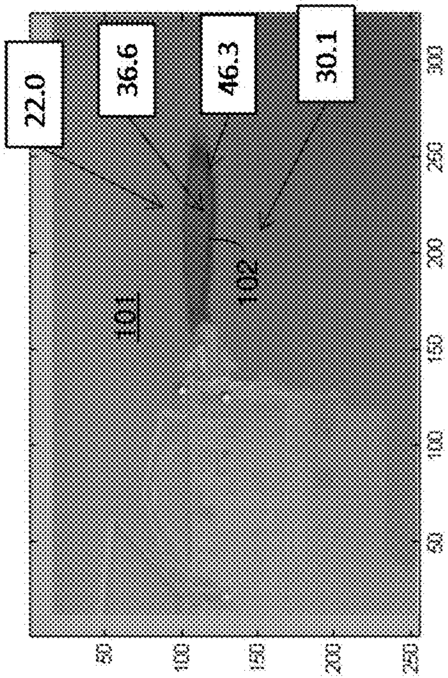


Fig. 10b

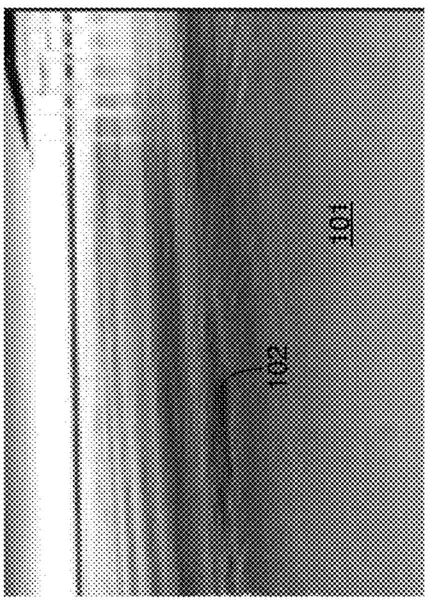


Fig. 11a

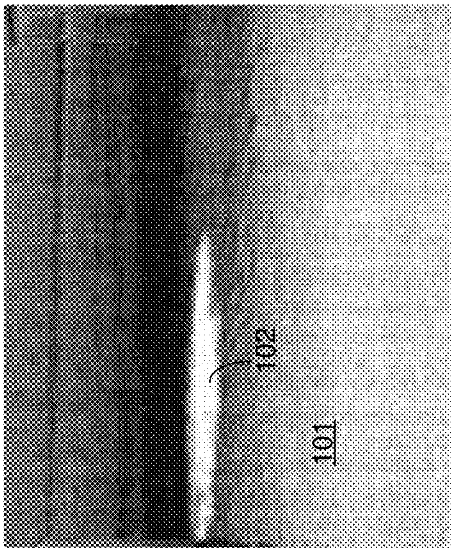


Fig. 11b

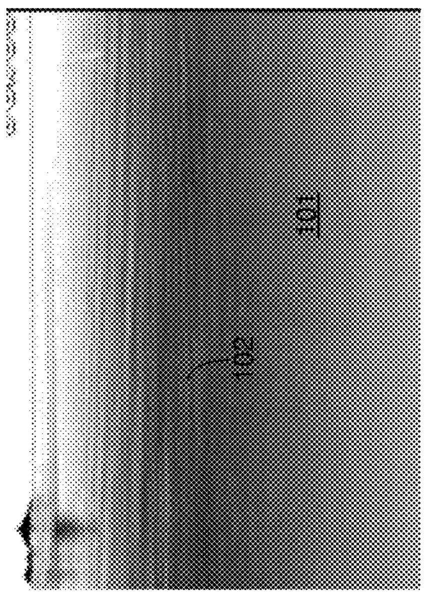


Fig. 11c

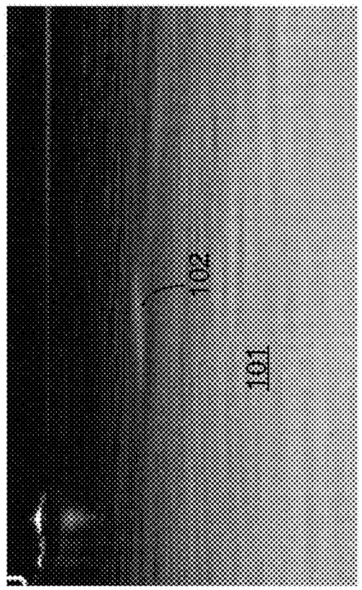


Fig. 11d

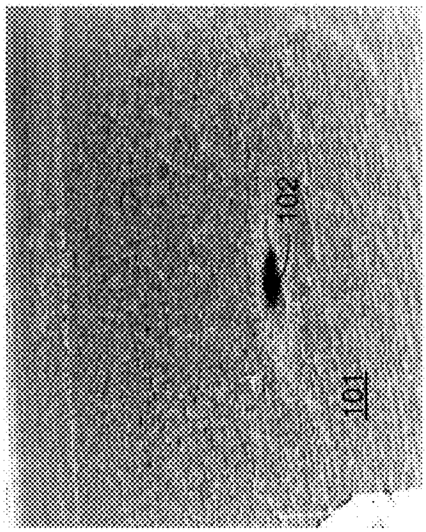


Fig. 12b

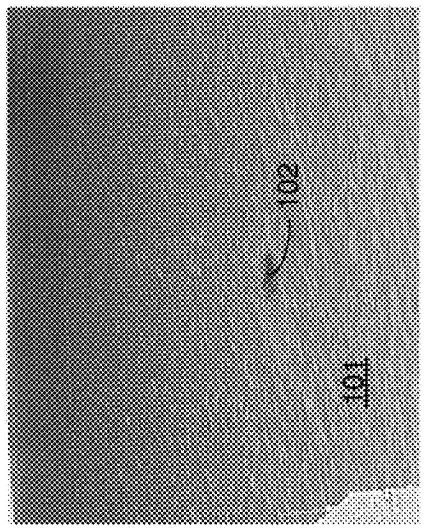


Fig. 12c

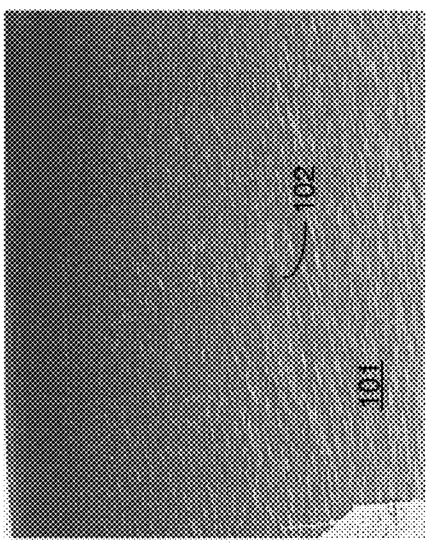


Fig. 12a

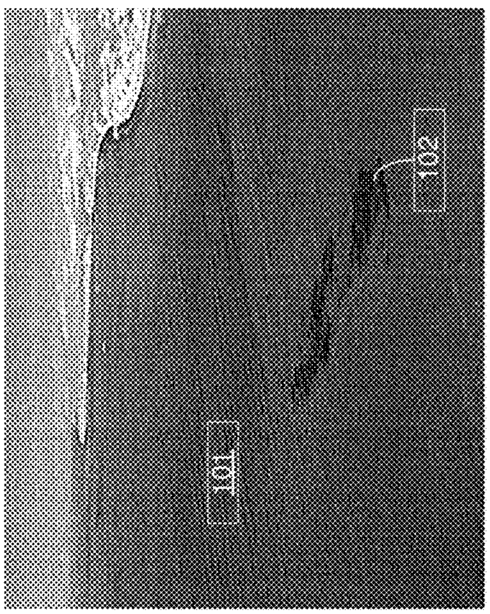


Fig. 13a

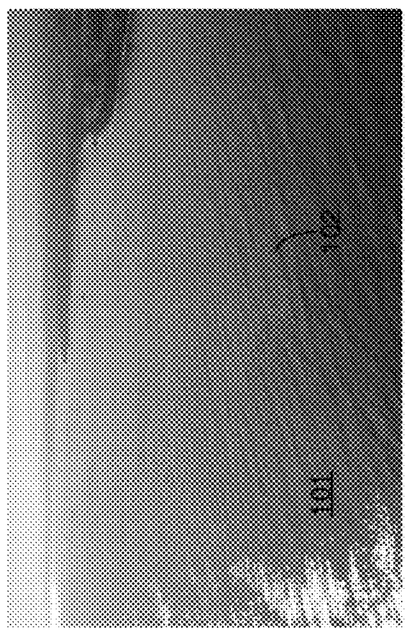


Fig. 13b

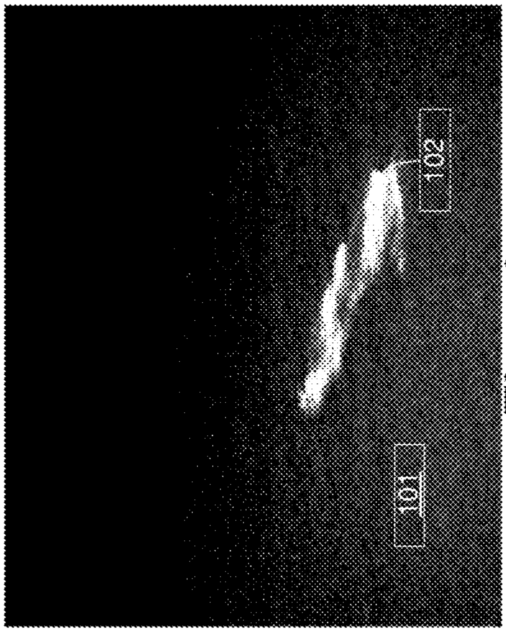


Fig. 13c

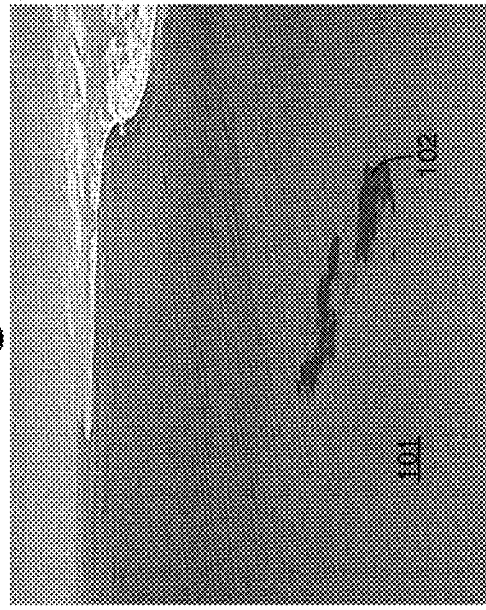


Fig. 13d

# WIDE-AREA REAL-TIME METHOD FOR DETECTING FOREIGN FLUIDS ON WATER SURFACES

## REFERENCE TO RELATED APPLICATIONS

This application claims priority to Provisional Patent Application U.S. Ser. No. 62/044,682, entitled "Polarimetry for the Detection of Oil on Water" and filed on Sep. 2, 2014, which is fully incorporated herein by reference.

## GOVERNMENT LICENSE RIGHTS

This invention was made with government support under Contract Number W31P4Q-09-C-0644 awarded by the U.S. Army. The government has certain rights in the invention.

## BACKGROUND AND SUMMARY

As used herein, Long Wave Infrared is referred to as "LWIR" or "thermal." As used herein, Mid Wave Infrared is referred to as "MWIR." As used herein, Short Wave Infrared is referred to as "SWIR." As used herein, Infrared is referred to as "IR." As used herein, Infrared refers to one, a combination, or all of these subsets of the Infrared spectrum.

A method using Infrared Imaging Polarimetry for the detection of foreign fluids on water surfaces is disclosed herein. The described method is not tied to any one specific polarimeter sensor architecture and thus the method described pertains to all Infrared sensors capable of detecting the critical polarimetric signature. The described method is not tied to any one specific portion or subset of the Infrared spectrum and thus the method described pertains to all sensors that operate in one or more of the LWIR, MWIR, or SWIR. The method comprises modeling of the foreign fluid on water or measurements of the foreign fluid on water under controlled conditions to understand the polarization response. This is done in order to select the best angles over which the detection will be most effective. The polarimeter is then mounted on a platform such that the sensor points towards the surface within the range of the acceptable angles. The polarimeter is then used to record raw image data of an area using a polarimeter to obtain polarized images of the area. The images are then corrected for non-uniformity, optical distortion, and registration in accordance with the procedure necessitated by the sensor's architecture. IR and polarization data products are computed, and the resultant data products are converted to a multi-dimensional data set for exploitation. Contrast enhancement algorithms are applied to the multi-dimensional imagery to form enhanced images. The enhanced images may then be displayed to a user, and/or an annunciator may announce the presence of the foreign fluid on the surface of the water.

## DESCRIPTION OF THE DRAWINGS

The patent or application file contains at least one drawing executed in color. Copies of this patent or patent application publication with color drawings will be provided by the Office upon request and payment of the necessary fee.

FIG. **1** is a diagram illustrating a system in accordance with an exemplary embodiment of the present disclosure.

FIG. **2** shows an exemplary cross-section of reflected and emitted radiation from a prior art system in which an IR camera measures IR contrast between oil and water.

FIG. **3** is a representation of reflected and emitted radiation from an exemplary cross-section of one embodiment of the current invention in which a polarimeter measures IR contrast and polarization contrast between oil and water.

FIG. **4** depicts a model of the dependence of the polarization signals of water as a function of the angle of incidence.

FIG. **5** depicts an exemplary positioning of the polarimeter to optimize the detection of a foreign fluid.

FIG. **6** depicts exemplary mounting of the polarimeter on a pan-tilt unit which is mounted on a tower on land.

FIG. **7** depicts a block diagram of a method for detecting a foreign fluid on a water surface.

FIG. **8** depicts an exemplary polarimeter system comprised of a polarimeter and signal processing unit according to an embodiment of the present disclosure.

FIG. **9** is a flowchart depicting exemplary architecture and functionality of the image processing logic in accordance with a method according to the present disclosure.

FIG. **10***a* is a thermal image of a foreign fluid on water at night.

FIG. **10***b* is a polarization image of the foreign fluid on water at night of FIG. **10***a*, depicting exemplary improvements of fluid detection of the polarization image

FIG. **11***a* is an exemplary thermal image of a foreign fluid on water at night.

FIG. **11***b* is an exemplary polarization image of the foreign fluid of FIG. **11***a*, also at night.

FIG. **11***c* is an exemplary thermal image of the foreign fluid FIG. **11***a* on water at night, with the polarimeter at a shallower angle than the image of FIG. **11***a*.

FIG. **11***d* is an exemplary polarization image of the foreign fluid of FIG. **11***c*, also at night and with the polarimeter at the same shallow angle as the thermal camera in the image of FIG. **11***c*.

FIG. **12***a* is a thermal image of a foreign fluid on water.

FIG. **12***b* is a polarization image of the foreign fluid on water of FIG. **12***a*.

FIG. **12***c* is a ColorFuse image of the foreign fluid on water of FIG. **12***a*.

FIG. **13***a* is a thermal image of the oil spill off the cost of Santa Barbara, Calif. in the summer of 2015, showing oil on the surface of the water.

FIG. **13***b* is a visible image of the spill of FIG. **13***a*.

FIG. **13***c* is a polarization image of the same spill showing the oil clearly visible.

FIG. **13***d* is a ColorFuse image of the same spill, showing the oil highlighted in red.

## DETAILED DESCRIPTION

FIG. **1** illustrates a polarimeter system **100** in accordance with an exemplary embodiment of the present disclosure. The system **100** comprises a polarimeter **1001** and a signal processing unit **1002**, which collect and analyze images of a water surface **101** for detection and annunciation of the presence of a foreign fluid **102** on the water surface. An exemplary foreign fluid **102** shown in FIG. **1** is petroleum from natural seepage, a leak from an oil drilling or processing facility, or a leak from a vessel, or from a vessel that was intentionally dumped overboard. As used in this disclosure, the terms "oil" or "foreign fluid" may refer to any liquid that is desired to be detected.

The polarimeter system **100** comprises a polarimeter **1001** for recording polarized images, such as a digital camera or IR imager that collects images. The polarimeter **1001** may be mounted on a tower or platform (not shown) such that it views the water surface **101** at an angle θ **103** from a normal direction **120** to the water surface **101** and at a horizontal range "R" **104** from a general center of the field of view to the polarimeter **1001**, and a height "h" **105** defined by the vertical distance from the water surface **101** to the polarimeter **1001**. The area imaged by the polarimeter is depicted by a field of view **106**.

The polarimeter **1001** transmits raw image data to the signal processing unit **1002**, which processes the data as further discussed herein. The processed data is then displayed to an operator (not shown) via a display **108**. Alternatively, detection is annunciated on an annunciator **109**, as further discussed herein. Although FIG. **1** shows the polarimeter **1001** and the signal processing unit **1002** as a combined unit, in certain embodiments the polarimeter **1001** and signal processing unit **1002** are separate units. For example, the polarimeter **1001** may be mounted remotely on a platform or tower (not shown) and the signal processing unit **1002** placed close to the operator. Similarly, the display **108** or annunciator **109** can be packaged with the system **100** or packaged with the signal processing unit **1002** or be separate from all other components and each other.

In the illustrated embodiment, the polarimeter **1001** sends raw image data (not shown) to the signal processing unit **1002** over a network or communication channel **107** and processed data sent to the display **108** and annunciator **109**. The signal processing unit **1002** may be any suitable computer known in the art or future-developed. The signal processing unit **1002** receives the raw image data, filters the data, and analyzes the data as discussed further herein to provide enhanced imagery and detections and annunciations. The network **107** may be of any type network or networks known in the art or future-developed, such as a simple communications cable, the internet backbone, Ethernet, Wifi, WiMax, wireless communications, broadband over power line, coaxial cable, and the like. The network **107** may be any combination of hardware, software, or both. Further, the network **107** could be resident in a sensor (not shown) housing both the polarimeter **101** and the signal processing unit **107**.

In the illustrated embodiment, the signal processing unit sends processed image data (not shown) to the display and annunciator over a network or communication channel **107** and processed data sent to the display **108** and annunciator **109**.

FIG. **2** shows an exemplary cross-section of reflected and emitted radiation from a prior art system in which an IR camera (not shown, with no polarization capability) measures IR contrast (i.e. radiance differences) between oil and water. In this embodiment, foreign fluid **102** is floating on a water surface **101**. The radiation from the water surface **101** incident on an infrared camera viewing this scene senses a "summed" radiance **200** that is the sum of emitted radiation **201** from the water surface **101** and the reflected radiation **203** from the background **202** reflected off the surface **101**. Likewise for the foreign fluid **102**, the "summed" radiance **210** is the sum of the emitted radiation **211** from the foreign fluid **102** and reflected radiation **213** from the background **212** reflected off the foreign fluid **102**.

The emitted radiation **201** depends on the temperature of the water **101** and the optical constant of the water, also known as the refractive index. The reflected radiation component **203** depends on the temperature of the background **202** and the optical constant of the water. Thus the summed radiance **200** depends on background temperature, water temperature, and water optical constants.

The emitted radiation **211** depends on the temperature of the foreign fluid **102** and the optical constant of the foreign fluid **102**. The reflected radiation component **213** depends on the temperature of the background **212** and the optical constant of the foreign fluid **102**. Thus the summed radiance **210** depends on the temperature of the foreign fluid **102**, the optical constant of the foreign fluid, and the temperature of the background **212**.

For detection of the foreign fluid using an IR camera, the summed radiances **200** and **210** must be different to result in radiance contrast. There are multiple possible combinations of the background and foreign fluid and water temperature values and variations in the foreign fluid optical constants such that there is very little difference in the summed radiances **200** and **210** resulting in low contrast and difficult detection of the foreign fluid.

FIG. **3** is a representation of reflected and emitted radiation from an exemplary cross-section of one embodiment of the current invention in which a polarimeter (not shown) measures radiance contrast and polarization contrast between oil and water. In this embodiment, foreign fluid **102** is floating on a water surface **101**. The summed radiation **300** from the water surface **101** is the sum of the emitted radiation **301** and the reflected radiation **303** from the background **302** reflected off the surface **101**. As known by persons with skill in the relevant art, the emitted radiation **301** consists of two polarization components, a "perpendicular" polarization component **306** and a "parallel" polarization component **307**. The difference in these polarization components **306** and **307** results in a net polarization for the thermal emitted radiation **301**.

Likewise, the reflected component **303** consists of two polarization components, a "perpendicular" polarization component **304** and a "parallel" polarization component **305**, resulting from the reflection of the background radiation **302**. The difference in these polarization components **304** and **305** results in a net polarization for the thermal emitted radiation **303**. The total polarization signal from the water is a combination of the polarization signals from the emitted radiation **301** and reflected radiation **303**. The net polarization signal is called the Degree of Linear Polarization or "DoLP".

Similarly, the summed radiation **310** from the foreign fluid surface **102** is the sum of the emitted radiation **311** and the radiation **313** from the background **312** reflected off the surface **102**. The emitted radiation **311** consists of two polarization components, the "perpendicular" polarization component **316** and the "parallel" polarization component **317**. The difference in these polarization components **316** and **317** results in a net polarization for the thermal emitted radiation **311**. Likewise, the reflected component **313** consists of two polarization components, the "perpendicular" polarization component **314** and the "parallel" polarization component **315**, resulting from the reflection of the background radiation **312**. The difference in these polarization components **313** and **314** results in a net polarization signal for the thermal emitted radiation **313**. The total polarization signal from the foreign fluid is a combination of the polarizations of **311** and **313**. The detection of the foreign fluid occurs when the polarization contrast of the foreign fluid is different from the polarization contrast of the water.

FIG. **4** depicts a model of the dependence of the polarization signals of water as a function of the angle of incidence **103** (FIG. **1**) and shows the perpendicular and parallel polarization components **304** and **305** for the reflected radiation and the perpendicular and parallel polarization components **306** and **307** of the emitted polarization. The DoLP results from the difference of perpendicular and parallel polarization components. The reflected DoLP **401** for the reflected radiation increases with increasing angle until it reaches a maximum of about 53% at an angle of about 62°. The emitted DoLP **402** for the emitted radiation monotonically decreases as a function of angle of incidence **103**.

It is important to note that the shape and nature of these curves depends on the optical constants of the material and thus these curves are significantly different for the foreign liquid being detected. The differences in DoLP between water and the foreign liquid are exploited by the current invention. A higher contrast difference for detecting oil on water is attained by examining these curves for the polarization performance as a function of angle. In one embodiment of the current invention, the optimal angles based upon experimental data obtained with oil are between 70° and 88° from normal (angle θ **103**) or between 2° and 20° elevation (measured from a horizontal). FIG. **7** is a block diagram of the process steps to achieve optimal detection that exploits these concepts.

FIG. **5** depicts an exemplary positioning of the polarimeter **1001** to optimize the detection where the polarimeter **1001** is positioned between angles $\theta_1$ and $\theta_2$. Using the optimal range from FIG. **4** as an example, $\theta_1$ may be 70° and $\theta_2$ may be 88°, and the polarimeter placed within this range. For one embodiment of the invention in which the sensor is mounted on a tower (not shown), these angles can be achieved by selecting the appropriate Range R **104** (FIG. **1**) and Height h **105** (FIG. **1**).

FIG. **6** depicts exemplary mounting of the polarimeter on a pan-tilt unit **110** which is mounted on a tower **111** on land. In another exemplary embodiment, the tower **111** is a mast or pole. In another exemplary embodiment, the tower **111** is a platform or other mounting point on a structure overlooking the water surface to be monitored. In other embodiments, the tower, mast, pole, platform or mounting point can be placed on a vessel, floating platform, fixed pier or platform, floating buoy, or the like. In another exemplary embodiment, the sensor system **100** and pan-tilt unit **110** is placed on a manned or unmanned aerial vehicle. The sensor system further in some embodiments is portable and can be hand-held.

FIG. **7** depicts a block diagram of a method **7000** to detect a foreign fluid **102** (FIG. **1**) on a water surface **101** (FIG. **1**) in the optimal conditions. In step **7001**, the polarized response of the foreign fluid is predicted through analysis of the emitted and reflected radiation of the fluid of interest, in the manner discussed with respect to FIGS. **3** and **4** herein. Alternatively, measurements of the fluid of interest can be performed experientially, or experimentally in a controlled environment such as a laboratory where the angles can be varied.

In step **7002** of the method **7000**, the results of step **7001** are used to determine the range of angles $\theta_1$ and $\theta_2$ (FIG. **5**) for good performance, as discussed with respect to FIGS. **4** and **5** herein. In step **7003**, the results of step **7002** are used to determine the best mounting location for the mounting options available, range R **104** (FIG. **1**) and height h **105** (FIG. **1**), and the polarimeter **1001** (FIG. **1**) is mounted.

In step **7004**, imagery is collected with the polarimeter **1001** as is described herein. In step **7005**, contrast enhancement algorithms are applied to the imagery to aid the detection of the foreign fluid by an operator or by autonomous detection algorithms. In step **7006**, the enhanced contrast images are displayed and/or the detection of the foreign liquid is annunciated.

FIG. **8** depicts an exemplary polarimeter system **100** comprised of a polarimeter **1001** and signal processing unit **1002** according to an embodiment of the present disclosure. The polarimeter **1001** comprises an objective imaging lens **1201**, a filter array **1203**, and a focal plane array **1202**. The objective imaging lens **1201** comprises a lens pointed at the water and foreign fluid surface **101** and **102** (FIG. **1**). The filter array **1203** filters the images received from the objective imaging lens system **1201**. The focal plane array **1202** comprises an array of light sensing pixels.

The signal processing unit **1002** comprises image processing logic **1302** and system data **1303**. In the exemplary signal processing unit **1002** image processing logic **1302** and system data **1303** are shown as stored in memory **1306**. The image processing logic **1302** and system data **1303** may be implemented in hardware, software, or a combination of hardware and software.

The signal processing unit **1002** also comprises a processor **1301**, which comprises a digital processor or other type of circuitry configured to run the image processing logic **1302** by processing the image processing logic **1302**, as applicable. The processor **1301** communicates to and drives the other elements within the signal processing unit **1002** via a local interface **1304**, which can include one or more buses. When stored in memory **1306**, the image processing logic **1302** and the system data **1303** can be stored and transported on any computer-readable medium for use by or in connection with logic circuitry, a processor, an instruction execution system, apparatus, or device, such as a computer-based system, processor-containing system, or other system that can fetch the instructions from the instruction execution system, apparatus, or device and execute the instructions. In the context of this document, a "computer-readable medium" can be any means that can contain, store, communicate, propagate, or transport the program for use by or in connection with the instruction execution system, apparatus, or device. The computer readable medium can be, for example but not limited to, an electronic, magnetic, optical, electromagnetic, infrared, or semiconductor system, apparatus, device, or propagation medium. Note that the computer-readable medium could even be paper or another suitable medium upon which the program is printed, as the program can be electronically captured, via for instance optical scanning of the paper or other medium, then compiled, interpreted or otherwise processed in a suitable manner if necessary, and then stored in a computer memory.

Exemplary system data **1303** is depicted comprises:

a. Raw image data (not pictured) from the polarimeter **1001** (FIG. **1**) obtained from step **9001** of the method **900** (FIG. **9**).

b. Corrected image data (not pictured), which is the data that has been corrected for non-uniformity, optical distortion, and registration per step **9002** of the method **900** (FIG. **8**).

c. IR and Polarization images obtained from step **9003** of the method **900** (FIG. **3**).

d. Conversion of polarization and radiance data to multi-dimensional image data applied in step **9004** of the method **900** (FIG. **9**).

e. Contrast enhancing algorithms applied to image data in step **9005** of the method **900** (FIG. **9**).

f. Image data applied to the display **108** and annunciator **109** in step **9006** of the method **900** (FIG. **9**).

g. Radiance image data as described herein.

h. Hybrid radiance/polarization images as described herein.

The image processing logic **1302** executes the processes described herein with respect to FIG. **9**.

Referring to FIG. **8**, an external interface device **1305** connects to and communicates with the display **108** and annunciator **109**. The external interface device **1305** may also communicate with or comprise an input device, for example, a keyboard, a switch, a mouse, a touchscreen, and/or other type of interface, which can be used to input data from a user of the system **100**. The external interface device **1305** may also or alternatively communicate with or comprise a personal digital assistant (PDA), computer tablet device, laptop, portable or non-portable computer, cellular or mobile phone, or the like. The external interface device **1305** may also or alternatively communicate with or comprise a non-personal computer, e.g., a server, embedded computer, field programmable gate array (FPGA), microprocessor, or the like.

The external interface device **1305** is shown as part of the signal processing unit **1002** in the exemplary embodiment of FIG. **8**. In other embodiments, the external interface device **1305** may be outside of the signal processing unit **1002**.

The display device **108** may consist of a tv, led screen, monitor or any electronic device that conveys image data resulting from the method **900** or is attached to a personal digital assistant (PDA), computer tablet device, laptop, portable or non-portable computer, cellular or mobile phone, or the like. The annunciator device **109** can consist of a warning buzzer, bell, flashing light, or any other auditory or visual or tactile means to warn the operator of the detection of foreign fluids.

In some embodiments, autonomous action may be taken based upon the foreign fluid **102** (FIG. **1**) detected. For example, a clean-up response may be automatically initiated. In some cases where automatic action is taken, the annunciator **109** may not be required.

In other embodiments, a Global Positioning System ("GPS") device (not shown) may interface with the external interface device **1305** to provide a position of the foreign fluids **102** detected.

In the illustrated embodiment, the display **108** and annunciator **109** are shown as separate, but the annunciator **109** may be combined with the display **108**, and in another embodiments, annunciation could take the form of highlighted boxes or regions, colored regions, or another means used to highlight the object as part of the image data display. See, for example, the darker colored region in FIG. **12***c*, which provides a visual indication of a foreign fluid **102** detected.

FIG. **9** is a flowchart depicting exemplary architecture and functionality of the image processing logic **1302** (FIG. **8**) in accordance with a method **900**. In step **9001** of the method **1000**, the polarimeter **1001** captures an image of water **101** and foreign fluid **102** (FIG. **1**) and sends raw image data to the signal processing unit **1002** (FIG. **1**).

In step **9002**, the signal processing unit **1002** (FIG. **1**) corrects imager non-uniformity of the images received from the polarimeter **1001**. Examples of imager non-uniformity include fixed pattern lines in the image, noisy pixels, bad pixels, bright spots, and the like. Algorithms that are known in the art may be used for correcting the imager non-uniformity. In some embodiments, step **9002** is not performed because the imager non-uniformity does not require correction.

Additionally in step **9002**, the signal processing unit **1002** removes image distortion from the image data. An example of image distortion is warping at the edges of the image caused by the objective imaging lens system. Algorithms that are known in the art may be used for correcting image distortion. Registration corrections may also be performed in step **9002**, using methods known in the art.

In step **9003**, IR and polarization data products are computed. In this step, Stokes parameters ($S_0$, $S_1$, $S_2$) are calculated by weighted subtraction of the polarized image obtained in step **9002**. The IR imaging polarimeter measures both a radiance image and a polarization image. A radiance image is a standard image whereby each pixel in the image is a measure of the radiance, typically expressed in Watts/cm2-sr, reflected or emitted from that corresponding pixel area of the scene. Standard photographs and IR images are radiance images, simply mappings of the radiance distribution emitted or reflected from the scene. A polarization image is a mapping of the polarization state distribution across the image. The polarization state distribution is typically expressed in terms of a Stokes image.

Of the Stokes parameters, $S_0$ represents the conventional IR image with no polarization information. $S_1$ and $S_2$ display orthogonal polarimetric information. Thus the Stokes vector, first introduced by G. G. Stokes in 1852, is useful for describing partially polarized light and is defined as

$$\vec{S} = \begin{bmatrix} S_O \\ S_1 \\ S_2 \\ S_3 \end{bmatrix} = \begin{bmatrix} I_0 + I_{90} \\ I_0 - I_{90} \\ I_{45} - I_{135} \\ I_R - I_L \end{bmatrix} \tag{1}$$

Where $I_0$ is the radiance that is linearly polarized in a direction making an angle of 0 degrees with the horizontal plane, $I_{90}$ is radiance linearly polarized in a direction making an angle of 90 degrees with the horizontal plane. Similarly $I_{45}$ and $I_{135}$ are radiance values of linearly polarized light making an angle of 45° and 135° with respect to the horizontal plane. Finally $I_R$ and $I_L$ are radiance values for right and left circularly polarized light. For this invention, right and left circularly polarized light is not necessary and the imaging polarimeter does not need to measure these states of polarization. For this reason, the Stokes vectors that we consider will be limited to the first 3 elements which express linearly polarized light only,

$$\vec{S} = \begin{bmatrix} S_O \\ S_1 \\ S_2 \end{bmatrix} = \begin{bmatrix} I_0 + I_{90} \\ I_0 - I_{90} \\ I_{45} - I_{135} \end{bmatrix} \tag{2}$$

Also in step **9003**, a degree of linear polarization (DoLP) image is computed from the Stokes images. A DoLP image is useful for providing contrast for foreign fluids on a water surface, and can be calculated as follows:

$$\text{DoLP}=\sqrt{(s_1/s_0)^2+(s_2/s_0)^2} \tag{3}$$

In step **9004**, the IR and polarization data products and DoLP computed in step **9003** are converted to a multi-dimensional data set for exploitation. Note that DoLP is linear polarization. As one with skill in the art would know, in some situations polarization that is not linear (e.g., circular) may be desired. Thus in other embodiments, step **9004** may use polarization images derived from any combination of $S_0$, $S_1$, $S_2$, or $S_3$ and is not limited to DoLP.

The DoLP image is one available image used to view polarization contrast in an image. Another alternative image to view polarization content is a "ColorFuse" image that is generated by mapping the radiance, DoLP, and orientation images to a color map. "ColorFuse" is one embodiment of multidimensional representation that can be produced in step

**9004**. Those knowledgeable in the art can conceive similar mappings. For one example, the DoLP information may be emphasized when radiance values are low.

Persons with skill in the art makes the following mapping of polarization data to a hue-saturation-value representation for color:

$S_0$=value

DoLP=saturation

Orientation $\phi$=hue

This representation enables display of all optical information (radiance and polarization) in a single image and provides a means to show both radiometric and polarization contrast enhancing understanding of the scene. In many cases where polarization contrast is strong, this representation provides scene context for the surfaces or objects that are polarized. Those experienced in the art can imagine other ways of doing this.

Because the underlying optical radiation depends on emission, no additional light sources, illumination, or ambient light is required for polarization imaging. Further, the approach works equally well during the night time as it does during the day.

In step **9005**, contrast enhancing algorithms that are known in the art are applied to the multidimensional image from step **9004**. The multi-dimensional data exploits the polarization data to significantly enhance the information content in a scene. Non-restrictive examples include global mean, variance, and higher order moment analysis, Principal Component Analysis, or Linear Discriminate Analysis, computation of the statistics of the multidimensional data as a whole and then computation of local values based on a kernel convolved with the image as a whole and then normalized by global statistics of the scene.

In step **9006**, the contrast enhanced image of the detected oil is displayed to an operator. The detected oil is then annunciated to the user through visual or auditory means. Non-restrictive examples includes bells, buzzers or lights to draw the operator's attention to the display, or indications on the display such as distinctive colors or boxes in the region of the foreign fluid.

In other embodiments, steps **9003**, **9004**, **9005**, and **9006** are used in combinations that omit one or more of the steps. In other embodiments, the polarization image data, or the multi-dimensional (e.g. ColorFuse) data, may be viewed by humans for fluid detection, and no algorithms are applied.

Algorithms that exploit a combination of image features extracted from an IR imaging polarimeter can be used to detect foreign fluids. Once potential noteworthy features are detected, they can be automatically highlighted for the operator, and a warning can be given through some annunciation mechanism (buzzer or light).

FIGS. **10***a* and **10***b* are thermal and polarization images, respectively, of a foreign fluid (e.g., oil) on water at night depicting exemplary improvements of fluid detection of the polarization image. The values on the images show radiometric quantities for the thermal image and polarization quantities for the polarization image at various locations on the surface of the water **101** and in the area of the foreign fluid **102**. For the thermal image, the contrast between the fluid and water is very slight. For the polarization image, the contrast is significantly better.

FIG. **11***a* is an exemplary thermal image of a foreign fluid **102** on water **101** at night. As can be seen in FIG. **11***a*, the foreign fluid **102** is barely detectable in the thermal image.

FIG. **11***b* is an exemplary polarization image of the foreign fluid **102** of FIG. **11***a*, also at night. Importantly, no external light source is used with the method disclosed herein. The polarization image of FIG. **11***b* was produced using the method disclosed herein. The foreign fluid **102** is easily detectible in the polarization image. The polarization image of FIG. **11***b* shows a significant improvement over the thermal image of FIG. **11***a*. In FIGS. **11***a* and **11***b*, the thermal camera and polarimeter, respectively, were positioned at an oblique angle to the water's surface **101**.

FIG. **11***c* is an exemplary thermal image of the foreign fluid **102** of FIG. **11***a* on water **101** at night, with the polarimeter at a shallower angle than the image of FIG. **11***a*. The images of FIGS. **11***a* and **11** *b* were taken at roughly 15 degrees and the images of FIGS. **11***c* and **11***d* were taken at roughly 5 degrees. As can be seen in FIG. **11***c*, the foreign fluid **102** is really not detectable in the thermal image.

FIG. **11***d* is an exemplary polarization image of the foreign fluid **102** of FIG. **11***c*, also at night and with the polarimeter at the same shallow angle as the thermal camera was in the image of FIG. **11***c*. The foreign fluid **102** is easily detectible in the polarization image. The foreign fluid **102** is still easily detected in the polarization image of FIG. **11***d*. In FIGS. **11***a* and **11***b*, the thermal camera and polarimeter, respectively, were positioned at an oblique angle to the water's surface **101**.

FIGS. **12***a*, **12***b* and **12***c* are a thermal, polarization, and ColorFuse images, respectively, of a foreign fluid **102** on water **101**. The thermal image of FIG. **12***a* shows very little contrast, the polarization image of FIG. **12***b* shows strong contrast, and the ColorFuse image of FIG. **12***c* shows clear contrast in the detection of the foreign fluid.

FIG. **13***a* is a thermal image of the oil spill off the cost of Santa Barbara, Calif. in the summer of 2015, showing the oil **102** on the surface of the water **101**. FIG. **13***b* is a visible image of the spill of FIG. **13***a*. FIG. **13***c* is a polarization image of the same spill showing the oil **102** clearly visible. FIG. **13***d* is a ColorFuse image of the same spill, showing the oil **102**, which would be shown in red in a true ColorFuse image.

What is claimed is:

**1**. A method of detecting a foreign fluid on water, the method comprising:

estimating an expected polarization response for a foreign fluid desired to be detected;

determining, from the estimated expected polarization response, an optimal position of a polarimeter to take images of the water's surface;

positioning the polarimeter at the optimal position for taking images of the water's surface;

recording raw image data of the water's surface using the polarimeter to obtain polarized images of the area;

performing corrections on the polarized images to form corrected images;

computing IR and polarization data products from the corrected images;

converting the IR and polarization data products to a multi-dimensional data set to form multi-dimensional imagery;

applying contrast enhancement algorithms to multi-dimensional imagery to form enhanced contrast images;

automatically detecting foreign fluid on the water's surface from the enhanced contrast images.

**2**. The method of claim **1**, further comprising generating a map of foreign fluid detected.

**3**. The method of claim **1**, further comprising displaying the enhanced contrast images to a user.

**4**. The method of claim **1**, further comprising annunciating detected foreign fluid to a user.

5. The method of claim **1**, wherein the step of performing corrections on the polarized images to form corrected images comprises correcting the polarized images for non-uniformity.

6. The method of claim **5**, wherein the step of performing corrections on the polarized images further comprises performing optical distortion and registration corrections.

7. The method of claim **1**, wherein the step of computing IR and polarization data products from the corrected images comprises calculating Stokes parameters $S_0$, $S_1$, and $S_2$ from the polarized images to create Stokes images by weighted subtraction of the polarized images.

8. The method of claim **7**, further comprising computing polarization images derived from the Stokes images.

9. The method of claim **8**, wherein the step of computing polarization images derived from the Stokes images comprise computing a DoLP image from the Stokes images.

10. The method of claim **9**, wherein the step of determining an optimal position of a polarimeter to take images of the water's surface comprises determining an optimal range of angles for positioning the polarimeter based upon differences in a DoLP response of water and the foreign fluid.

11. The method of claim **9**, further comprising mapping the DoLP images and IR images to a color map, wherein the color map shows the detected fluid as a desired color.

12. The method of claim **1**, wherein the foreign fluid is oil.

13. The method of claim **12**, wherein the step of estimating an expected polarization response for a foreign fluid desired to be detected is performed experientially.

14. The method of claim **1**, wherein the step of recording raw image data is not dependent upon the brightness of available light.

15. The method of claim **1**, wherein no external light source is required.



16. The method of claim **1**, wherein the optimal position comprises an angle of the polarimeter with respect to the water's surface.

17. The method of claim **16**, wherein the optimal position further comprises a horizontal and vertical distance of the polarimeter from the water's surface.

18. A method of detecting a foreign fluid on water, the method comprising:

estimating an expected polarization response for a foreign fluid desired to be detected;

determining, from the estimated expected polarization response, an optimal position of a polarimeter to take images of the water's surface;

positioning the polarimeter at the optimal position for taking images of the water's surface;

without an external light source, recording images of the water's surface using the polarimeter to obtain polarized images of the area;

computing IR and polarization data products from the polarized images;

converting the IR and polarization data products to a multi-dimensional data set to form multi-dimensional imagery;

automatically detecting foreign fluid on the water's surface.

19. The method of claim **18**, further comprising applying contrast enhancement algorithms to multi-dimensional imagery to form enhanced contrast images.

20. The method of claim **19**, further comprising performing corrections on the polarized images to form corrected images.

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