Detection and mapping of the November 2002 *PRESTIGE* Tanker oil spill in Galicia, Spain, with the airborne multispectral CASI sensor

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ABSTRACT

After the Bahamas registered oil tanker *PRESTIGE* shipwreck off the Spanish coast on November 13th, 2002, an aerial remote sensing campaign was mobilized at short notice thanks to a collaboration between AvelMor and Borstad Ltd. (respectively French and Canadian research and development companies specialized in oceanography and high resolution remote sensing). CASI multispectral imagery was acquired to assess and demonstrate the capability of this aerial sensor to map the ext ent of a spill. Mission planning, instrument bandset configuration, flight line planning, data collection, processing, results, and analysis of the data obtained are presented here. Further conclusions will be drawn after the experimental oil spill planned for June 2003, which will be carried out off Brittany, France, and under the control of the French Navy. We intend to build an operational multispectral airborne remote sensing based system for an efficient and fast detection, characterization, mapping, and monitoring of possible future oil spills. As a presentation of the further studies, the paper presents the main scientific challenges and objectives of this project.

Keywords: Oil Spill, *PRESTIGE*, CASI, Aerial, Multispectral.

1 INTRODUCTION

Wednesday, November 13th, 2002 at 14h50 TU, the Bahamas registered oil tanker *PRESTIGE*, sends a MayDay out at sea nearby Cap Finisterre, Galicia, Spain (Fig. 1, left). The ship is damaged and requests an evacuation. The crew is taken off, except for the Captain, the second and the head mechanic. The ship drifts with the weather-oceanic conditions. *PRESTIGE* loaded 77 000 tons of heavy fuel at the terminal of Ventspills, Lettonia. It probably went to Singapore with a stopover in Gibraltar. At 17h00 local, an aerial survey undertaken by the Spanish authorities highlights an oil leakage at sea. Tuesday, November 19th, 2002, the tanker splits in two and sinks off the northwest coast of Spain. Much of the oil is spilled into the sea, and will continue to spill for several months (Fig. 1, right).

Tuesday, December 3rd, 2002, the POLMAR plan (MARitime POLlution fight plan) is set up in France to face the pollution that arrives on the French coasts. In the following days and in order to help the POLMAR aircraft equipped with different kind of sensors, the French Navy Hydrographic and Oceanographic Service (SHOM) decides to test the feasibility of an airborne multispectral survey to detect and map the spill. An aerial remote sensing campaign was mobilized at short notice thanks to a collaboration between AvelMor and Borstad Ltd. The aerial survey was carried out using the Borstad Associates' CASI to obtain multispectral imagery over the spill off the coasts of Portugal and Spain. The sensor was configured with the optimal spatial and spectral configurations for mapping oil spills, based on the previous experience from Borstad Associates Ltd..

Despite the adverse weather (clouds, mist, strong winds and currents, heavy seas and breaking waves), imagery was acquired on December 16th, 18th, 19th and 20th. Some of the data were radiometrically calibrated, geometrically and geographically corrected (at a ground station installed in Portugal) in the evening of the flights to quickly obtain maps of the spill extent. All of the images obtained were further processed in the following days and accurate maps of the spill -including large surface oil slicks, small tarry dispersed oil slicks (> 5 m²), sheens of oil yellow slicks, and probably subsurface oil slicks- were produced. The images obtained and cartographic products of pollution mapping derived from the images are presented. The processing flow chart including the calibration of the data, pre-filtering, detection and mapping techniques based on the study of the spectral signatures is developed.

Figure 1. *PRESTIGE* shipwreck. (Left) Position of the disater off Spain (© ESA); (Right) *PRESTIGE* tanker breaking and oil leakage (©Photos douanes Françaises / avion Polmar II).

2 DATA ACQUISITION AND PREPROCESSING

2.1 Instrumentation

The Compact Airborne Spectrographic Imager (CASI[1]) is a small, push-broom imager built by Itres Instruments Ltd. of Calgary, Canada [1]. The Borstad CASI[2] was flown for this project. CASI image data are recorded to Exabyte tape housed in the Instrument Control Unit. Data acquisition and camera configuration are controlled using Itres proprietary software. The CASI sensor was mounted in a bi-motor PIPER Navajo Chieftain aircraft equipped with a standard 500mm × 500mm photogrammetric hole in the floor.

In addition to the image data, CASI records data from auxiliary equipment which monitors aircraft pitch, roll and GPS position, to files on a separate computer. Latitude and longitude were logged by CASI from a Leica 9400N GPS receiver, to provide data for subsequent geocorrection of the imagery.

2.2 Aerial data acquisition

Location and meteorological conditions

Following the instructions from the SHOM authorities, the aircraft, the material and the team were placed at the disposal of the Portuguese POLMAR plan, and based in Ovar, Portugal. Flights of CASI data acquisition were carried out during the 5 days ranging from the 16th to the 20th of December included. The flight plans were established each morning according to the weather conditions and of the position of the slicks located by a Portuguese reconnaissance aircraft. The strong winds prevented acquisitions for the only day of December the 17th. CASI Images were acquired under relative bad meteorological conditions (presence of clouds below and above the airborne platform; presence of mist and fog; strong winds and currents, heavy seas and breaking waves; acquisition in the morning with low angles of solar incidence) during the 4 other days: December 16th, 18th, 19th, and 20th. Fig. 2 shows the geographical site of the missions for each day including data acquisition.

Flight parameters

The optimal configuration of flight (altitude 10800 feet, swath 4 km) could not be implemented because of the cloudy ceilings too low and the too small amount of energy supplied to the sensor (low solar illumination, moreover attenuated by the atmospheric conditions). The aircraft was in major part flown at 6,000 feet altitude over the ground. The across-track pixel size was 2.5 m and the image swath was 1.3 km. At an integration time of 45 msec and a ground speed of 100 knots, the along-track pixel size was also 2.5 m. The imagery was captured with the instrument fore-optics at f4 and a narrow angle (35° FOV) lens. Slight variations in speed or altitude may expand or contract pixels; however, during processing all pixels are re-mapped to obtain the desired pixel spacing. Depending on the local conditions, some of the images were acquired down to 1000 feet, 31 ms integration time, 1 m spatial resolution on ground.

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[1] http://www.borstad.com/casi.html

[2] [s/n 101 manufactured in 1990 by Itres Instruments Inc. and modified in 1995 to improve the blue sensitivity]

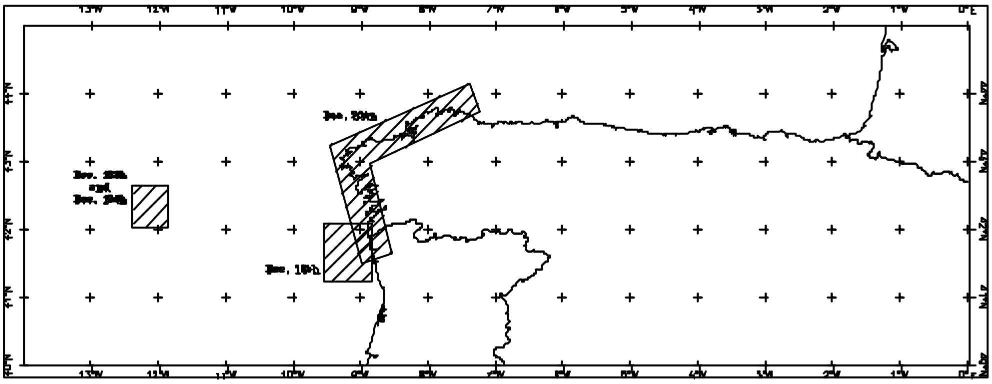

Figure 2. Geographical position of CASI data acquisition for each flying day.

Spectral configuration

The CASI was flown for this project in spatial mode and was configured to acquire 5 or 3 spectral channels, depending on altitude and illumination conditions (Table 1). The band configurations were chosen specifically for oil slicks mapping, using spectral channels previously selected for similar reclamation projects by Borstad Ltd. [2].

Table 1. CASI bandsets used for the 2002 *PRESTIGE* survey (**LL** : Low Light, **LA** : Low Altitude, **VLL** : Very Low Light).

LL	Wavelength (nm)			
Band	Start	End	Mid	Width
1	419,5	545,6	482,6	126.1
2	554,4	618,3	586,4	63.9
3	623,6	687,8	655,7	64.2
4	709,3	773,8	741,6	64.5
5	777,4	911,9	844,7	134.5

LA	Wavelength (nm)			
Band	Start	End	Mid	Width
1	428,2	461,3	444,8	33.1
2	533,2	549,1	541,2	15.9
3	630,7	639,6	635,2	8.9
4	739,7	746,9	743,3	7.2
5	854,5	874,2	864,4	19.7

VLL	Wavelength (nm)			
Band	Start	End	Mid	Width
1	470,6	514,9	492,8	44.3
2	640,3	653,2	646,8	12.9
3	855,2	900,4	877,8	45.2

Target locations and flight lines

Flight maps were established every morning using the information provided by the Portuguese reconnaissance aircraft, which flew daily carrying out visual detection of the oil slicks. A precise on-board graphical navigation software developed at AvelMor allowed the planned flight paths, as well as the real path of the aircraft during the flight along with the exact local time of survey to be recorded (Fig. 3).

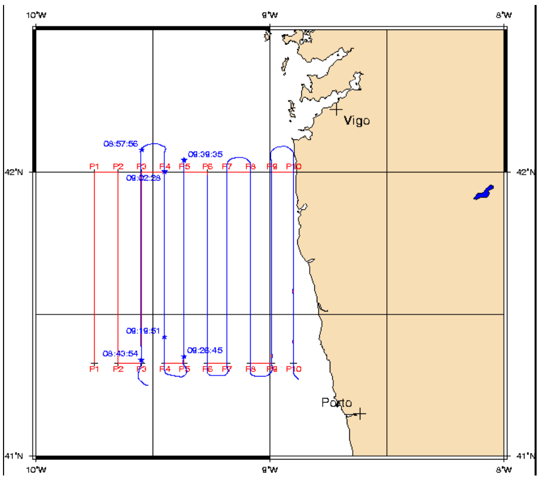

Figure 3. Example of flight map established for the day of Dec. 16th off the Portuguese coast and real flight path superimposed.

2.3 CASI data pre-processing

Radiometric calibration process

The raw image data are read from tape and processed through a Borstad Associates program that converts the raw values into upwelling radiance units (nW/cm^2/sr/nm). The dark and electrical offset signals for each pixel of each scan line of the data are removed. No atmospheric correction was carried out on the images. Also, no across-track illumination geometry correction was performed, although this would have greatly improved the imagery. Such radiometric corrections are very difficult to carry out in a near real-time during missions when the pollution maps need to be quickly produced the same day that the data are acquired. Time was of the essence, and we opted to process the radiance data keeping in mind that no radiometric correction had been performed.

First stage rectification

During acquisition, the roll and pitch of the aircraft were recorded by a two-axis mechanical gyro, and GPS position by a GPS receiver, for each scan line of image data. As part of the first order geocorrection process, Borstad software ("CMAP") used this roll, pitch and GPS data for each scan line to re-map the imagery and remove aircraft motion, using a nearest neighbour approach. Aircraft yaw is not recorded by the gyro but instead a single adjustment is made for each flight line during processing. Data processed to this first order mapping stage are in 16-bit signed format, in units of radiance (nW/cm^2/sr/nm) at the sensor, each file representing an individual flight line, mapped north up to NAD83 coordinates and corrected for aircraft motion.

3 OIL SLICKS SPECTRAL BEHAVIOUR AND PROCESSING FLOW CHART

The hydrocarbons absorb incident energy in the ultraviolet portion of the electromagnetic spectrum (< 400 nm) and re-emit a part of it in the visible portion of the spectrum (400-650nm) by a fluorescence phenomenon. The reflected energy becomes more significant in the blue portion of spectrum. Fig. 4 illustrates the spectral differences observed on the CASI images between seawater (blue spectrum in plot) and oil on the surface (red spectrum) corresponding to the blue patches in the image (false RGB color composition using bands 5, 3, 1, spectral configuration **LL**).

The seawater attenuates incidental energy in the high wavelengths (for the wavelengths higher than 700 nm, reflected energy is negligible). The energy reflected by a sub-surface target is attenuated in all the range of the electromagnetic spectrum according to the depth of the target. The maximum of the reflected energy is in the blue part of the spectrum, around 420 nm. Observation of CASI images showed that the sub-surface oil slicks or light oil traces are characterized by a relative decrease in radiance in the blue part of the spectrum as well as by a relative increase in radiance in the near infrared. Fig. 5 illustrates the difference between seawater and a -probably sub-surface- oil slick corresponding to the dark patches in the image (false RGB color composition using bands 5, 3, 1, spectral configuration **LL**). A certain "spectral rotation" is observed between the green and the red wavelengths, (precisely between 550 and 650 nm). In addition to this rotation, there is a general decrease in the radiance at all wavelengths caused by the absorption of the layer of water mixed or present between the slick and the surface layer.

These physical properties allow the detection of hydrocarbons present on the ocean surface, and sub-surface up to a depth dependent on the supplied energy (related to the conditions of solar illumination) and on the state of the sea, typically a few meters. From the spatial point of view, the detection is possible at a scale dependent on the spatial resolution of the sensor (slicks of approximately 5m² for this present experiment), even slightly below (of the order of the meter) under good conditions of data acquisition.

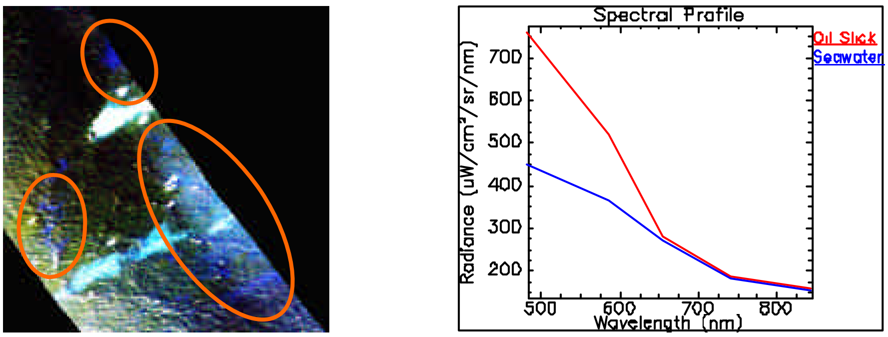

Figure 4. Response of a surface oil slick. (Left) CASI image; (Right) Spectral signature illustrating the fluorescence in the blue.

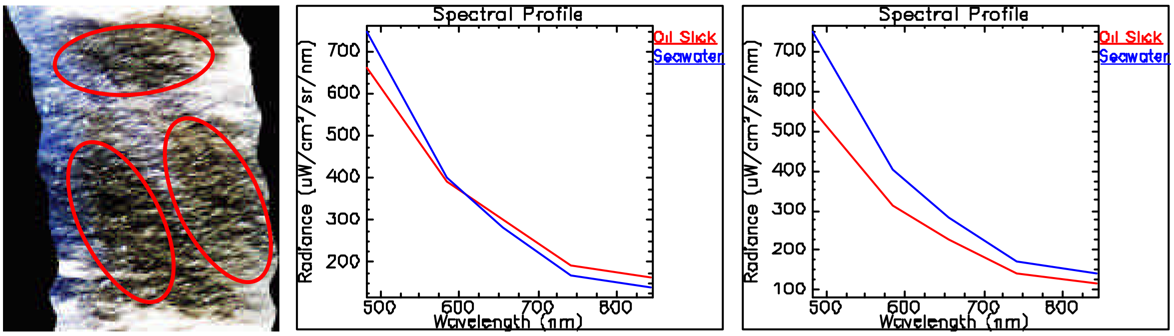

Figure 5. Response of sub-surface oil slicks or light oil surface traces. (Left) CASI image; (Middle) "Spectral rotation"; (Right) Spectral "rotation" + absorption.

The detection of the polluted zones was carried out initially in a visual way by photo-interpretation in the image space as well as in the spectral space. Oil slicks and oil sheens were distinguished on the sea surface. Moreover, sub-surface oil slicks or light oil traces on the surface can probably be identified in the imagery, although without validated ground truth data this can not be confirmed.

Due to the low solar illumination conditions and bad meteorological conditions, signal to noise ratio was very low for some of the data acquired. In that case, a spatial filtering was performed with a simple multidimensional median filter. More powerful spatial filtering techniques could be implemented at this stage of the data processing. Based on the spectral behaviour of the observed oil slicks , spectral indices were created to separate the slicks from the seawater. A "Fluorescence Index" (FI) is produced to measure the slope between the blue and red parts of the spectrum, and then to discriminate surface oil slicks from sea clutter (Fig. 4). In addition, the "spectral rotation" can be measured by the slope between the blue and near infrared parts of the spectrum, while the total absorption can be measured by the energy of the whole radiance vector. Combining both features allows us to produce a "Rotation-Absorption Index" (RAI) that discriminates sub-surface oil slicks or light oil traces from the sea clutter (Fig. 5). Detection maps are built by thresholding the spectral indices. FI and RAI indices are represented by:

$$FI = \frac{R_B - R_R}{R_B + R_R} \qquad\qquad RAI = \frac{R_B - R_{IR}}{R_B + R_{IR}} \|\boldsymbol{R}\|$$

with R_B,R_R,R_{IR} : radiance in blue, red, and infrared respectively; $\|\boldsymbol{R}\|$: norm of the radiance vector

Validation data are given by the daily reports of the visual observers from the Portuguese aircraft, which flew over the pollution every day. The reports include a description of the position and the type of pollution observed for each day and allows the results of the detection process to be confirmed. Fig. 6 shows the entire processing flow chart allowing the detection maps to be built from the original CASI data.

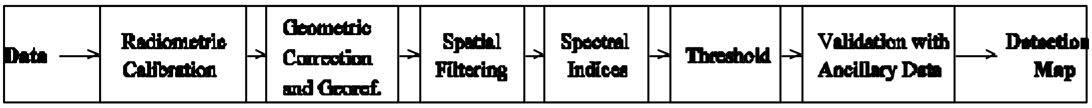

Figure 6. Processing flow chart.

The oil traces characterized by long narrow sheens could not be extracted by the semi-automatic processing flow chart described below because only the radiometric features are not sufficient to discriminate from the sea clutter. In that case, the detection was made by visual photo-interpretation of the images. A morphological criterion will have to be added in the process in the future to help in the semi-automatic detection process.

5 MAPPING RESULTS

Oil slicks detection maps were automatically built thanks to the processing flow chart presented in the last paragraph. Fig. 7 shows extractions of original CASI images and corresponding detection maps for the case of large surface oil slicks and scattered small oil slicks of about 20 m². Exhaustive maps of pollution extents were also built for each day data were acquired. Fig. 8 shows an example of the full cartographic product obtained for the day of December 16th for which a great number of scattered small oil slicks larger or equal to 5m² were detected.

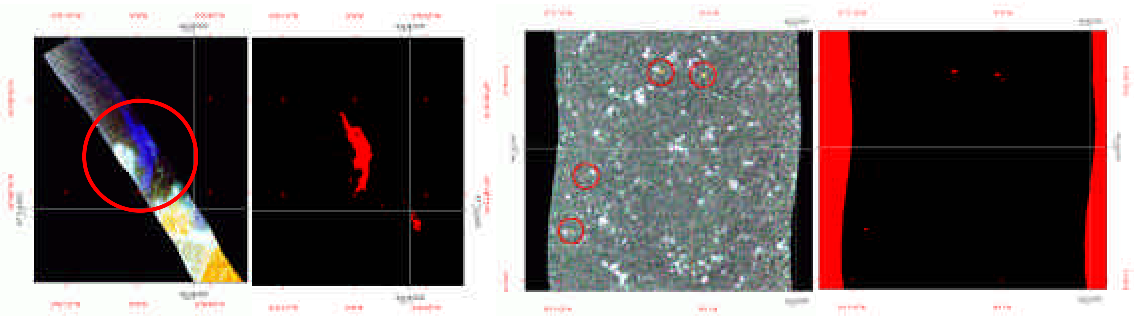

Figure 7. Mapping results: original images and detection maps. (Left) Large oil slicks; (Right) Scattered small oil slicks.

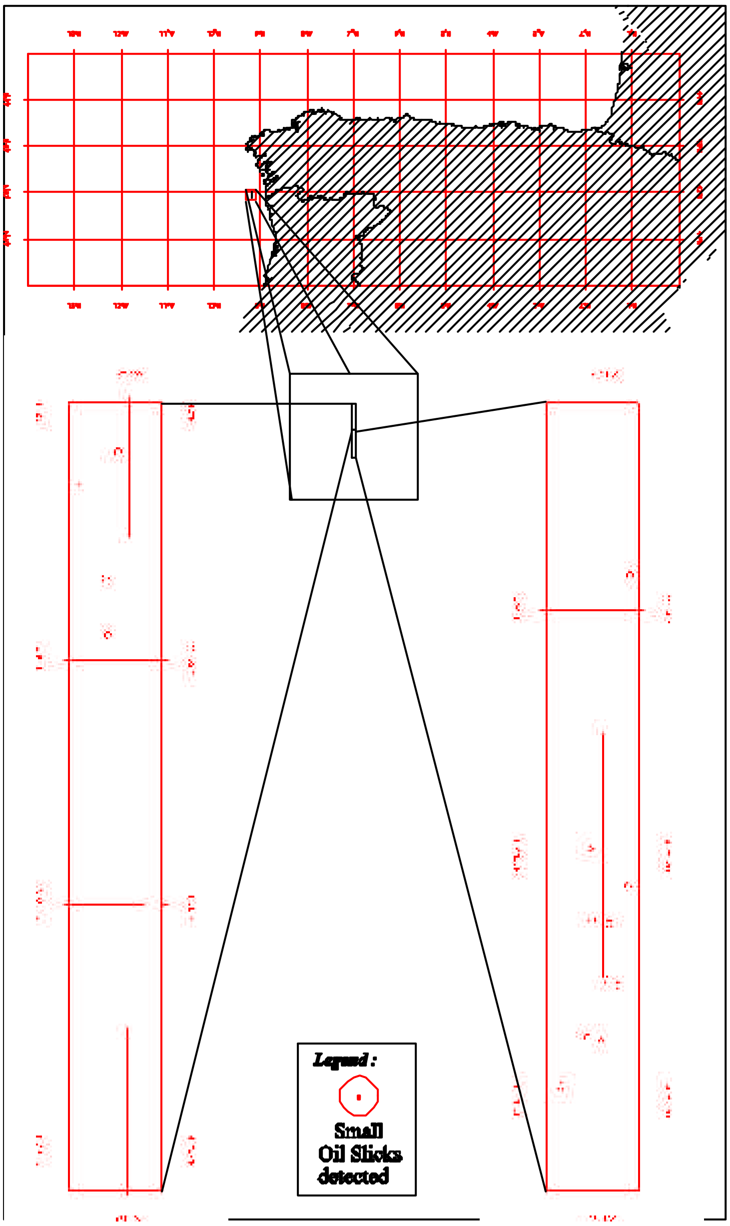

Figure 8. Full cartographic product of the pollution extents for the day of December 16th – Small oil slicks detected.

6 FURTHER WORKS: EXPRIMENTAL CONTROLLED OIL SPILL OFF BRITANNY

Following the *PRESTIGE* disaster, an experimental oil spill controlled by the French Navy ships will be performed in France at the beginning of June 2003. An multispectral airborne survey will be carried out, complete with in-situ measurements. The objective of the project is to build an operational airborne remote sensing based system for an efficient fast detection, mapping, and following of possible future oil spills. The main scientific challenges and objectives of the experience involve:

- to better understand the spectral signatures of the different kinds of slicks (sheens, tarry slicks, foams...),
- to identify the parameters that influence the spectral variability of oil (density, viscosity, in-depth penetration...),
- to determinate the smallest size boundary of slicks that can be detected,
- to build robust algorithms for the detection and mapping of the slicks on the multispectral images.

Spectroscopic measurements will be performed in the laboratory for an accurate characterization of the spectral signatures and parameters that influence the spectral variability. At sea, three 10 tons slicks will be spilled and will be controlled during two days. During the experiment at sea, visual observations from the ships and aircraft will enable the pollution type to be characterized and will help to validate the detection algorithms. These are based on the detection of a known class of spectral signatures in the sea clutter. Different spatial and spectral configurations of the CASI sensor will be tested in order to refine the optimal configurations. Software allowing fast mapping of pollution extents and best possible characterization of the pollution in the same day as the observations will be developed. This will lead to a fast and efficient mean of pollution control in case of future real oil spills.

7 CONCLUSIONS

This experience over the *PRESTIGE* showed that airborne multispectral imagery enables different kinds of surface oil slicks (large surface oil slicks, scattered small slicks larger than 5 m², light oil sheens) to be observed and detected, even with quite bad meteorological conditions.

Digital images of these different kinds of slicks are available. Simple detection algorithms have been developed, making it possible to validate the results. Cartography products of the pollution extents were derived from the images thanks to these algorithms.

The detection of subsurface slicks is possible in clear weather and quite calm sea, up to a depth remaining to be determined (about a few meters). It is probable that some subsurface slicks were detected during this present mission but it is not possible to confirm this with certainty because of a lack of validation data.

The weather conditions strongly influence the success of the observation and detection of the oil slicks. The quality of the observation, and thus of detection, is directly related to these weather conditions: the more significant the solar illumination, the better the detection of the slicks, in particular subsurface ones. Detection is much better when the weather is clear and the sea and wind are calm.

An experimental oil spill controlled by French Navy boats will enable the spectral behaviour of the different kinds of slicks to be better understood and software to be developed. This experience will allow us to build an operational hyperspectral-based airborne remote sensing system for an efficient fast detection, characterization, mapping, and following of possible future oil spills.

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