Operational quantitative mapping of oil pollutions at sea by joint use of an Hyperspectral Imager and a Fluorescence Lidar System on-board a fixed-wing aircraft

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Abstract— **Efficient observation means are required for supporting operational fight against oil pollutions at sea and recovering operations, including reliable choice and guidance of maritime and airborne fighting means. Among the suite of sensors available, the potential of airborne passive hyperspectral imagery and active fluorescence laser systems have been studied in the past. The potential of combining these two kinds of sensors for quantitative mapping of oil slicks at sea and for supporting the recovering operations is proposed for evaluation in that pilot project. Location, extents, volume of the oil spilled and its spatial distribution are the main useful parameters to be estimated. Ways towards the design of an operational system including both passive and active airborne optical sensors are presented.**

I. INTRODUCTION

In May 2004, three real oil spills at sea have been performed during a three days campaign off the coasts of Britanny, France. The campaign, named DEPOL04, was carried out under the responsibility of the French Navy represented by the CEPPOL ("Commission d'Etudes Pratiques sur les Pollutions") and of the French Customs, and managed by the CEDRE ("Centre de documentation de recherche et d'expérimentations sur les pollutions accidentelles des eaux"). The potential of airborne passive hyperspectral imagery [3] [8] and active fluorescence laser systems [10] [9] [1] [2] for remote sensing of oil spills at sea have been studied in the past. This controlled oil pollution offered the opportunity to test and develop an operational system using jointly an hyperspectral imager (CASI-2) and a Fluorescence Lidar System (FLS-AU) for oil slicks detection and quantitative mapping. That pilot project is conducted by ActiMar[1], a French SME specialized in operational oceanography and high resolution remote sensing, in collaboration with GET/ENST-Bretagne (TIME team, CNRS UMR 2872 TAMCIC), and is funded by the RITMER program of the French Ministry of Research under the name "DETECSUIV". Radar satellites as well as airborne reconnaissance missions are used to obtain oil slicks localization. Flight lines are prepared and integrated into a flight assistance system. CASI-2 and FLS-AU are installed onboard a fixed-wing aircraft (Cessna 404). Using an optimal flight configuration, 10 to 40 km^2 per hour can be recorded.

In order to extract the useful parameters from CASI-2 and FLS-AU data, a specific processing chain is developed. CASI data allow very high spatial resolution (1 and 2 meters) slicks maps to be produced, and the polluted surface to be estimated, after illumination corrections and definition of specific color spaces taking advantage of observed spectral phenomena. The impact of the illumination / acquisition geometry and of the sensor configuration on the quality of results is highlighted. Two CASI-2 configurations have been tested, including 18 and 32 spectral bands. The data acquisition campaign has been completed with spectroscopic measurements on the slicks at sea, onboard a small infloatable boat. A simple radiative transfer model in the water is quickly presented and is shown to be relevant for understanding the intra-slick spectral variability.

In-lab calibration of fluorescence spectra acquired by FLS allows thickness to be locally estimated. Those measurements are used to "calibrate" the CASI data and to extend the estimation of thickness over all the CASI pixels. That data fusion procedure is shown to be consistant with the radiative transfer model over a polluted water area including a thin layer of oil, and allows very high spatial resolution (1 meter) thickness distribution maps to be computed. Those maps show the spatial distribution of the oil thickness and allow the volume of oil spilled to be estimated. In order to show all the data processing steps, a demonstrator has been developed, starting from raw CASI-2 and FLS-AU data integration and fusion up to the visualization of high spatial resolution oil thickness maps and oil pollution quantitative results.

The potential and the limits of the whole approach are discussed, regarding the parameters estimation quality. Dispersants efficiency is quantified thanks to the study of oil slicks surface and volume variations. The relationships between the results obtained with the current system and the European visual interpretation process of oil spills at sea defined by the Bonn Agreement[2] is highlighted. Recommandations are made for the use of those combined sensors as a reliable observation mean for supporting operational recovering operations at sea.

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[1] http://www.actimar.fr

[2] http://www.bonnagreement.org

II. FLIGHT PREPARATION

A. Instrumentation

1) Aircraft: At least four persons have to be in the aircraft during the data acquisition phase (pilot, navigation assistant, CASI operator, FLS operator). The whole equipment is about 260kg weight. The power supply needed to run the instruments is around 1.6KVA@28VDC. A Cessna 404, fitted with a large trap-door, is very convenient to meet all of those requirements and is used in that experiment (Fig. 1 and Fig. 2).

2) CASI-2: The hyperspectral sensor installed in the aircraft is a CASI-2, designed and built by Itres[3], Canada, embedded with an Applanix POS/AV Inertial System and a GPS receiver. Post-processed DGPS correction is performed thanks to the measurements achieved by a ground GPS total station. The CASI-2 is a spectroscopic imager fitted with a diffraction grating, allowing images to be acquired over tenth (spatial mode) to hundreds (spectral mode) of spectral bands inside a 545 nm spectral range, ranging from 400 to 1000 nm. The spectral resolution can be up to 2.2 nm. 512 spatial pixels are simultaneously acquired across-track. Full flight lines are acquired along-track in a pushbroom mode. Images are registred in the UTM/WGS84 system with an accuracy around 2 meters after geometrical corrections and geo-referencing. CASI-2 schematics is shown on Fig. 3.

3) FLS-AU: The fluorescence lidar installed in the aircraft is a FLS-AU, designed and build by LDI3[4], Estonia. The FLS-AU is fitted with a 20Hz laser excimer operating at 308nm, and a CCD sensor allowing 500 channels to be recorded from 300 to 500 nm. The FLS-AU is optimized for operation onboard aircraft or helicopter to provide rapid analytical screening of wide areas of land and water. This data is displayed in real-time and archived for post-survey analysis. FLS-AU detects and maps organic pollution including oil and petroleum products in water and on soil at altitudes from 50 to 500 metres. Using the online expert system, contaminants are classified and their concentrations calculated down to the parts-per-million level at about 10 metres spatial resolution along-track. The FLS-AU has been used for pollution detection and quantification in lakes, rivers and coastal waters as well as on land. The FLS-AU is also capable of monitoring oil spills and detecting naturally occuring oil on land and on water. FLS-AU schematics is shown on Fig. 4.

4) Navigation system: A navigation system, called SAMM© and developped at ActiMar, is installed and used by the pilot to follow the flight lines on site. The SAMM© systems consists of a GPS receiver, a small computer, and a vizualisation screen installed in front of the pilot. The screen displays all informations for the pilot in an "aeronautical mode" (Fig. 5), including altitude, position, azimuth, deviation from the flight line, etc... The co-pilot is usually in charge of controlling the SAMM© system, especially for swithching to the next flight line at the end of each one.

Fig. 1. Cessna 404 operated by ActiMar

Fig. 2. Equipment of the Cessna 404

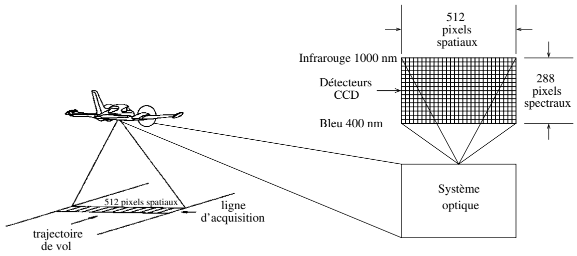

Fig. 3. CASI schematics

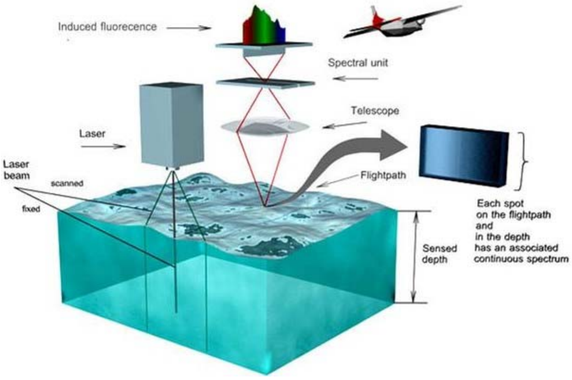

Fig. 4. FLS-AU schematics

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[3] www.itres.com

[4] www.ldi3.com

Fig. 5. SAMM© screen on-board

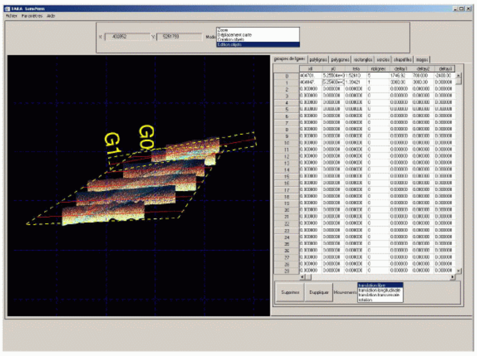

Fig. 6. TARA© display

B. Localization of the spills

Flight planning for CASI+FLS data acquisition requires the knowledge of approximate slicks localization. The first part of the "DETECSUIV" project is devoted to satellite SAR images segmentation for detection of oil slicks at sea [5] [7]. The use of this technique in an operational mode allows the oil slicks to be detected and localized over large regional areas. If satellite data are not available in a crisis scenario, localization from visual observers on-board reconnaissance aircrafts, possibly completed with SLAR sensors and slick drift forecast systems, can be used to get the approximate localization of the area to be surveyed. CASI-2 and FLS-AU sensors are able to produce very high resolution quantitative maps of the pollution but are not convenient for systematic search over large areas because of their limited swath.

C. Flight planning

1) Constraints:

a) Meteorological conditions: The CASI-2 is a passive sensor, the quality of the data are thus very sensitive to incident solar illumination. Meteorological conditions should hence be carefully accounted for while planning the survey. Sunny shining and dry atmosphere are ideal for limiting incident light attenuation by clouds and scattering by the atmosphere. Night data acquisition is not possible with CASI, acquisition above clouds is not possible neither with CASI nor with FLS-AU. Data acquisition over slicks from the Prestige however shown that the detection of slicks remained possible with CASI even with quite bad meteorological conditions [8].

b) Acquisition geometry: The geometry of the water surface is complex, including swell, gravity and capillar waves, etc... The chaotic nature of that surface makes quite difficult in some cases the post correction of images, and the extraction of the surface reflectance induced by the water column or the oil slicks on the surface, independently from the sea state. Flight planning as a function of azimut and height of the sun is thus very important, in order to minimize the contribution of specular reflexions, across-track illumination variations, and sun glint effects on the surface. An empirical rule is usually used, allowing flights for zenital angles ranging from 30° to 60°, and setting the flight azimut at 0° or 180° from solar azimut ("to" or "from" the sun). Using that configuration, about 8 hours flying a day are available at mid-latitudes during the spring. Going to the summer and/or to the low latitudes, the zenital period should be avoided for flying, in order to limit the important specular reflexions. Flight windows should then be splitted into two periods, one in the morning and one in the evening. Flight line azimut constraints due to solar illumination are unfortunately usually in conflict with the geometrical configuration of the slicks and potentially also with their drift direction. Solar illumination constraints are however the most important ones in order to get useful data even if the flight duration to survey the whole area is not optimal.

c) Flight duration: Once flight azimut is fixed by having taken into account the sun configuration, flight duration should be minimized in order to avoid for important slicks drifts during the data acquisition. If drift and flight duration are both important, slick areas could be missed or flown several times.

d) GPS constellation: If possible, a GPS total ground station should be installed on the nearest coast during the flight in order to perform a DGPS post-correction of the data. In that case, the GPS constellation configuration should be taken into account for flying while a sufficient number of satellites are available and the PDOP is acceptable. Even if less important than meteorological conditions and acquisition geometry, those GPS constraints have direct incidence on geo-localization accuracy and surface extents estimation quality.

e) Tidal regime: If possible, data should be acquired during a low currents regime in order to minimize once again the effects of the geometry of the water surface.

2) Planning the lines:

A flight planner, called TARA© has been developped at ActiMar, in order to take into account all of the constraints for planning the optimal flight lines for a particular survey. Depending on the constraints and configuration of the pollution, only one flight line can be sufficient to cover a whole slick, or several parallel flight lines should be required. Fig. 6 shows one possible display of TARA©. The system is very flexible and allows the operator to optimize all the parameters of the flight plan in a few minutes. Once the flight plan is fixed, it is exported from TARA© and imported into SAMM© for a direct use by the pilot.

III. DATA ACQUISITION

A. Flight parameters

The joint use of two sensors implies to consider the limitations of both. For a single CASI data acquisition, the flight altitude should be maximized in order to reach the maximum swath if the meteorological conditions are adequate. In the present case, the flight altitude is limited by the maximum flight altitude of the FLS-AU, which is equal to 500m (about 1500ft). The speed of the acquisition should be minimized in order to acquire the maximum amount of data. The minimum speed is however limited by the capabilities of the platform. Using the Cessna 404, this minimum speed is fixed at 100kt. Below that treshold, the platform is subject to turbulences. The flight parameters are hence the following:

Altitude: 500m / Speed: 100 kts

B. CASI-2 configuration

Considering the flight parameters previously mentioned, the following parameters are used for the CASI sensor:

- Spectral range: 400-1000nm
- Number of spectral bands: 18 (equally distributed over the range)
- Spectral resolution: 30nm
- Spatial resolution: 1m
- Swath: 380m (FOV: +/- 21°)
- Overlap : 30%

A second CASI-2 configuration including 32 spectral bands (1500m altitude, 2m spatial resolution, 820m swath) has been used for acquisition without the FLS-AU sensor. The use of that single CASI-2 dataset is not discussed in this paper.

C. FLS-AU configuration

Considering the flight parameters previously mentioned, the following parameters are used for the FLS-AU sensor:

- Laser excimer: 308nm
- PRF: 20 Hz
- Spectral range: 300-500nm
- Number of spectral bands: 500
- Along-track sampling: 2.5m

In order to increase the SNR of the FLS-AU data, the data are filtered and resampled to a 25m along-track resolution.

D. In-flight assistance

Once the approximate localization of the slick is known, the flight can be set up. The two sensors have their own real time displays on-board. The presence or absence of a slick can be estimated with a good confidence by the two sensor operators. A first assesment of the data quality is also possible. The SAMM© system is controlled by the co-pilot and used by the pilot to follow the flight lines. Those flight lines can be adjusted in-flight thanks to TARA©, in order to best fit the real configuration of the slick and/or its potential drift. In an extreme emergency scenario, the whole flight plan can even be realized in the aircraft by the co-pilot in charge of the navigation assistance, during the transit to the polluted site. All the navigation softwares are available in the aircraft.

IV. DATA PROCESSING

The data processing steps are briefly explained below. The full development of the processing chain can be found in [6].

A. CASI-2 data processing

Radiometrically calibrated CASI-2 data are geometrically corrected and georeferenced thanks to INS/dGPS data. Across-track illumination corrections are performed, and a mosaic of flight lines is built. A standard three layers optical model including air, a thin layer of oil, and water is used to relate the reflectance above the water surface to the thickness of the oil layer. The model is used for the simulation of the signal reaching the sensor as a function of the thickness of the oil layer, in the whole spectral range of CASI-2 data. A procedure for the inversion of the model is built in order to compute, from the CASI-2 data, a parameter called “A” which is proportional to the oil thickness. The linear coefficient relating “A” to the thickness is a function of the diffractive index of water and oil and remains hence unknown. In order to take also into account the specular reflexion on the slick surface, as well as the “saturation variability” induced by the thickness varibility over the slick, two other parameters, called “L” and “S”, are computed as n-dimensional extensions of the “Lightness” and “Saturation” parameters used in the standard RGB to HLS color transform. Those parameters allow the main information regarding oil and water to be reduced to three dimensions, which is very convenient to visually highlight the useful information into a “ALS” color enhanced vizualization map. That ALS image is then segmented in order to provide the localization and geographical configuration map of the slick.

B. FLS-AU data processing

After georeferencing with handheld GPS data, and low-pass filtering of the data in order to increase the signal to noise ratio, along-track sampling is around 25m. Raman scattering beeing possibly influenced by external factors, only the fluorescence information is used for detection of oil on the sea surface. Thickness is then computed from each of the raw spectra where oil has been detected, thanks to the Raman scattering information. Standard or in-lab measurements of attenuation coefficients of water and oil are used to calibrate an empirical model relating the thickness of oil to the intensity of Raman scattering. Raman scattering is saturated after a certain threshold which depends on the type of the oil.

C. CASI-2 + FLS-AU data fusion

After CASI-2 and FLS-AU registration, the parameter “A”, is extracted from the CASI-2 spectral pixels for which an absolute value of the thickness as extracted from the FLS-AU data is available. The two datasets are then linearly correlated. The parameters of the linear correlation model are applied on the whole CASI-2 image pixels in order to provide a high resolution map of the spatial distribution of the thickness.

D. Quantification of the parameters

Surface and volume are estimated thanks to the integration of local estimated values over the whole pixels of the slick.

V. RESULTS

A. CASI enhanced vizualization map

An example of a CASI enhanced color vizualization map computed from the ALS decomposition is shown on Fig. 7. That map allows one to get a first qualitative assessment of the pollution. The distribution of the volume of the oil is highly revealed in the image (from blue to red). Fig. 7 shows that the maximum concentration of oil is located on the west side of the slick in a small area compared to its whole extent.

B. Localization and geographical configuration map

The segmentation of the CASI ALS map is shown on Fig. 8. From that map, the accurate localization and geographical configuration of the slick is derived. The exact extents of the slick can be computed.

C. Local oil thickness measurement map

Local geographical thickness measurements computed from the FLS-AU data is shown on Fig. 9.

D. High Resolution thickness distribution map

The CASI-2 and FLS-AU data fusion process leads to the computation of the high resolution thickness distribution map shown on Fig. 10. The colors associated to the estimated thicknesses are quantitatively reported in the legend. This map quantitatively confirms the qualitative assessment of the CASI enhanced vizualization map, and allows the whole volume of oil spilled to be estimated.

E. Quantitative results and critical study

Three 10 m^3 oil slicks, alpha, bravo, and charlie, have been spilled during the DEPOL04 experiment. The alpha slick was crude oil, while bravo and charlie included 65% HFO + 35% LCO. The quantitative results are listed in Tab. I. The results show that the volumes have been under-estimated for each slick, with an error factor ranging approximately from 5 (alpha) to 30 (bravo). Those errors are mainly due to the saturation of the optical measurements (and induced non validity of the radiative transfer model used) after a critical thickness which depends on the type of the oil observed. In the currrent experiment, the FLS-AU measurements were saturated at approximately 10μm for alpha, and 5μm for bravo and charlie. Those saturation threshold differences explain the best estimations over the alpha slick. The estimated thicknesses are quite accurate over thin layers, while saturated over thick layers. The most dispersed the volume is over a large surface, the most accurate the estimation of the volume is. In the current experiment, the slicks were not so much dispersed since data acquisition was performed a few hours after the spill. The system capabilites are hence limited to provide the minimal bound of the real volume of oil spilled, which should however be considered as reliable. It has to be noticed that the high resolution thickness distribution maps allow, despite the saturation areas, the limits of the slick and the spatial distribution of volumes to be reliably represented. Those informations are *a priori* the most important for the support of operational aerial and/or maritime recovering operations.

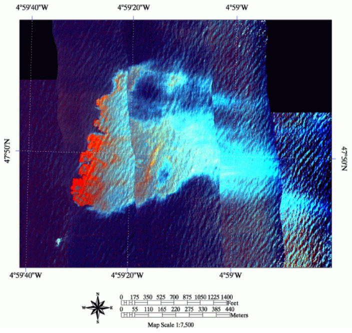

Fig. 7. "ALS" enhanced vizualization map

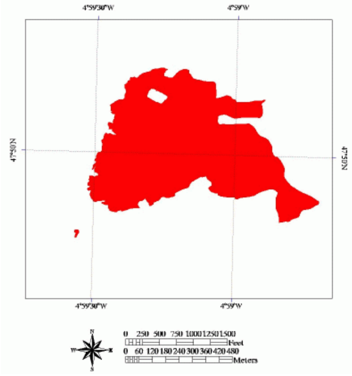

Fig. 8. Localization map

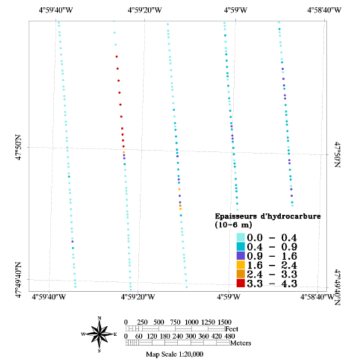

Fig. 9. Local oil thickness measurement map

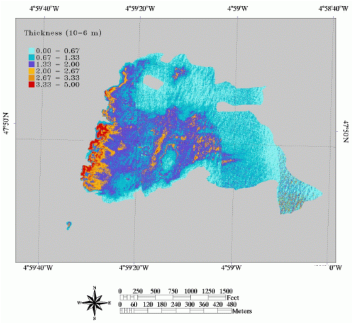

Fig. 10. High Resolution thickness map

TABLE I
QUANTITATIVE RESULTS

Slick	Estimated surface (km^2)	Estimated Volume (m^3)	Volume error factor
Alpha	0.97	2.08	4.8
Bravo	0.34	0.36	27.8
Charlie	0.39	0.49	20.4

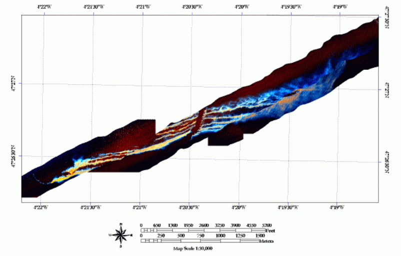

Fig. 11. Dispersants impact as observed by CASI-2

TABLE II

QUANTIFICATION OF DISPERSANTS EFFICIENCY

	Before	After	Variation
Surface (km^2)	1.85	1.72	-7.1%
Volume (m^3)	2.08	1.69	-18.7%

F. Quantification of dispersants efficiency

The three slicks have been dispersed from 5 to 8 hours after the spills, using OSR62 dispersive chemicals. Data acquisition after dispersing operations allowed the efficiency of dispersants to be quantified (Tab. II). Along-slick aerial dispersants tracks, as well as across-slick maritime dispersants tracks are clearly revealed on Fig. 11. Tab. I shows that 7% of the slick surface has been dispersed, corresponding to approximately 19% of ths slick volume. That reveals the importance of guiding the aerial and maritime fighting means over the highly concentrated areas during recovering operations.

VI. TOWARDS A SEMI-AUTOMATIZATION OF THE BONN AGREEMENT INTERPRETATION PROCESS

The Bonn Agreement aims at relating visual observations to physical quantities of oil spilled at sea in order to "inter-calibrate" the pollution reports from different observers in Europe. Recent studies lead to the adoption of a new color code brought into effect in January 2004. This code allows the thin oil layers to be affected into 5 different classes depending on their visual aspect. A thickness and a density range are defined for each class. The geographical configuration and size of the slick observed is also manually reported by visual inspection of the pollution. All of those visual observations allow extents and volume of the slick to be empirically quantified. The approximate scale of a pollution can hence be quickly quantified, but the uncertainties on real thicknesses can lead to a factor 10 on the whole volume estimation [4]. However, the minimimum estimation should be considered as reliable regarding the quantity of oil which was really spilled.

It has to be noticed that the DETECSUIV system allows the CASI-2 images of a spill to be digitally recorded. Following the data acquisition, CASI-2 images are segmented into classes for which a real thickness measured with the FLS-AU is available. The extent and volume of the spill are then automatically estimated thanks to the data fusion process. The quality of the estimated volume is dependent on the oil type and accumulation which saturate the optical sensors. The estimated values of the spilled oil volume over the current experiment lead to errors ranging roughly from 5 to 30. The DETECSUIV system then appears to be helpful in the semi-automatization of the Bonn Agreement interpretation process. The quality of the estimation is in the same range but has the advantage to be independent from the observer. It moreover allows digital images to be stored, which can be helpful for further support of operational recovering operations.

VII. CONCLUSION

This pilot project allowed us to make a step towards answering environmental concerns associated with accidents in oil storage and transportation. Passive and active hyperspectral sensors have been shown to be complementary. In particular, data fusion from both sensors allows high resolution spatial distribution of oil thickness to be geographically mapped. We think that the use of those combined sensors as a reliable observation mean for supporting operational recovering operations is a high potential value-added application. A demonstrator including the data processing chain has been developed as a basis for future operational software development.

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