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Multi-gas detection and quantification over HNS release at sea using LWIR multispectral system SIMAGAZ

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ABSTRACT:

SIMAGAZ is a cryogenic camera working in the thermal infrared range and producing four images of different spectral content with a high signal-to-noise ratio and a high frame rate. This camera dedicated to gas monitoring has been used during the IPOMAC campaign in 2021. This measurement campaign was carried out several miles off the west coast of France as part of the preparedness for the response to pollution at sea. During this campaign, various chemicals, legally classified as HNS for Hazardous Noxious Substances (HNS), were released on the sea surface. The data processing is based on a physical radiometric model, a spectroscopic database containing the products of interest and includes morphological image processing tools. SIMAGAZ data analysis allowed the detection, identification and quantification of three gases evaporating from the spills (acetone, butyl acetate and heptane), sometimes for more than half an hour. For the other products whose absorption lines are outside the SIMAGAZ spectral range, no gas was seen as expected. Based on this success, the partners have planned a new campaign in 2022 to evaluate the potential of SIMAGAZ from an airborne platform for this application.

1. INTRODUCTION

Observation means for remote sensing of marine pollution exist but they need to be improved to adapt to environmental issues but also to better assess the safety of first responders and populations in case of gas or toxic cloud formation [1]. Within the framework of the IPOMAC campaign carried out by the CEPPOL (French Navy Centre of Practical Expertise in Pollution Response) with the support of the Centre of Documentation,Research and Experimentation on Accidental Water Pollution (CEDRE), ONERA carry out a measurement campaign with the SIMAGAZ instrument. The specific objective of this campaign for ONERA was to see to what extent it was possible to visualize volatile chemicals at sea following accidental liquid and gaseous spills during maritime transport with the SIMAGAZ multispectral infrared instrument. This paper presents the results of observation, detection, identification and quantitative visualization of evaporating plumes from spilled slicks at the surface obtained during the May 2021 sea trials.

2. Material

2.1. SIMAGAZ instrument

SIMAGAZ is a pre-industrial multispectral camera developed in collaboration between ONERA, LYNRED and NOXANT within the framework of the FUI IMAGAZ project with a Technology Readiness Level (TRL) of 5. SIMAGAZ is a cryogenic camera working in the thermal infrared range and producing four images of different spectral content on the same MCT sensor with a high signal-to-noise ratio and a high frame rate. SIMAGAZ is based on a previous laboratory demonstrator studied in a project between ONERA and TOTAL called NAOMI (New Advanced Observation Method Integration). For this application, the camera and the processing software have shown remarkable results on industrial sites from ground and UAV measurements [2, 3].

SIMAGAZ uses the LYNRED's state of the art architecture based on his cooled LW VGA format with a pixel pitch of 15µm and a RM3 cooler. So the outside view of the camera looks like a standard DDCA. The camera produces four images of the scene with different spectral properties on a single Focal Plane Array (FPA). The MCT technology of the infrared detector array offers high-speed operation with a high sensitivity. Indeed, a Noise Equivalent Temperature Difference (NETD) has a mean value of 40mK for

all the spectral bandwidths and with an integration time of 5ms and for a scene at around 20°C. Therefore, the camera combines the advantages of being simple (only two major optical components are used), cost effective (a single detection block is used), compact (the camera has the size of the detection block), sensitive (a cryogenic infrared detector is used), as well of having a high radiometric stability (the optics are cooled at cryogenic temperature, thus limiting the background signal). The specifications of SIMAGAZ are summarized in Table 1.

Table 1: Specifications of SIMAGAZ

Detector type	Multispectral MCT
Spectral Range	7.2-8.5µm
Image Size for a sub-image	320x256 pixels with a pixel pitch of 15µm
Measurement Rate (with image processing)	Up to 20Hz
Volume of the core camera	1L
Weight of the core camera	1.3kg
Focal length	7mm
F-number	4
Horizontal Field Of View (HFOV)	40°
Measurement rate	Up to 20Hz
Sensitivity of methane leak flowrates	<0.5g/s

A picture of the camera is given in Figure 1.

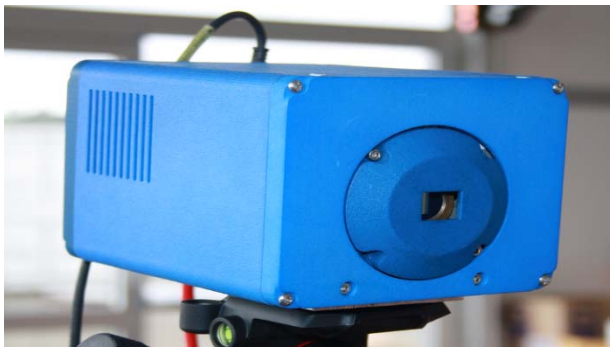


Figure 1: SIMAGAZ infrared multispectral camera.

2.2. Experimental set up

The measurement campaign was carried out several miles off the west coast of France as part of the preparedness for the response to pollution at sea. This campaign, under the command of the French Navy, involved CEDRE, CEPPOL and ONERA and aimed to test different LWIR systems on board ships or aircraft. During this campaign, various chemicals, legally called HNS for Hazardous Noxious Substances (HNS), were released on the sea surface: acetone, butyl acetate, methanol, heptane, xylene and toluene.

One cubic meter of each product has been released at 100m from the vessel back using an appropriate system of pump and pipes. The release time is around 5 minutes, and the vessel speed is around 1 knot. SIMAGAZ instrument acquired images with a backward line of sight, the distance between the camera and the spill is from 150 m to more than 1 km. The figure 2 shows the SIMAGAZ installation on the top of the vessel. A stabilisation platform has been used to monitor low frequency vessel movements.

Figure 2: SIMAGAZ instrument (blue one) integrated on a stabilised platform on-board CEPPOL vessel during the experiment.

3. Methodology & Results

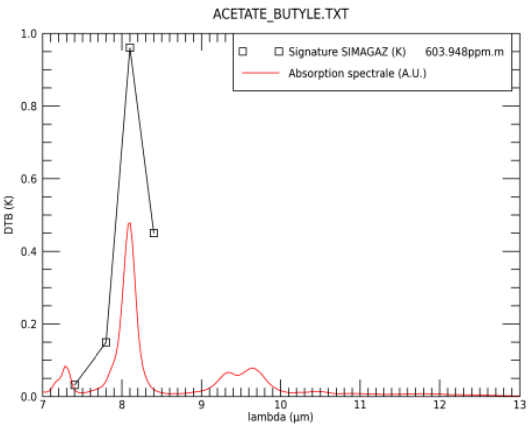
3.1. Multispectral physical model of gas absorption

Evaporating chemical spill is responsible for two changes in the environment of a scene observed in infrared remote sensing: the surface slick and the evaporating gas. The product in a liquid state can be identified by the creation of a "smooth" surface layer due to the attenuation of capillary waves with an apparent brightness temperature different from water (for miscible products as methanol this surface layer is not present). This thermal signature can be seen by any kind of high sensitive thermal imager.

However evaporating gas have very marked spectral features in relation to the position of its specific gas absorption lines. For most of gases, large band thermal imagers are not sensible to the evaporating plume. When narrow bands are used using a multispectral instrument as SIMAGAZ it becomes possible to detect, identify the gas plume

and quantify gas concentration inside the plume.

A multispectral radiometric model dedicated to SIMAGAZ instrumental features has been developed. This model aims to estimate SIMAGAZ camera spectral radiance and its sensitivity to evaporating gas, to surface and to environmental natural change. The radiometric equivalent radiometric noise of SIMAGAZ instrument in brightness temperature for a specific channel is around 0.05 K. The figure 3 shows in red database spectroscopic absorption features for butyl-acetate and acetone. SIMAGAZ differential signature in brightness temperature is shown in dark corresponding to the mean environmental conditions during the experiment: Atmosphere temperature at 16 °C and sea surface temperature at 13 °C and a water vapor volume concentration of about 15 000 ppm. In the case of butyl acetate it is shown that the third SIMAGAZ channel (8.1 µm) is the most sensitive to gas enhancement with a difference of 1 K for a total amount of gas of 600 ppm.m along the line of sight. In the case of acetone the fourth channel is the most sensitive to the gas with a difference of 1 K for a total amount of gas of 1200 ppm.m along the line of sight. Each gas is associated to a specific SIMAGAZ spectral response. This spectral response is used in a retrieval scheme to identify (among a list of potential target gas) the plume and to estimate integrated concentration pixel by pixel.



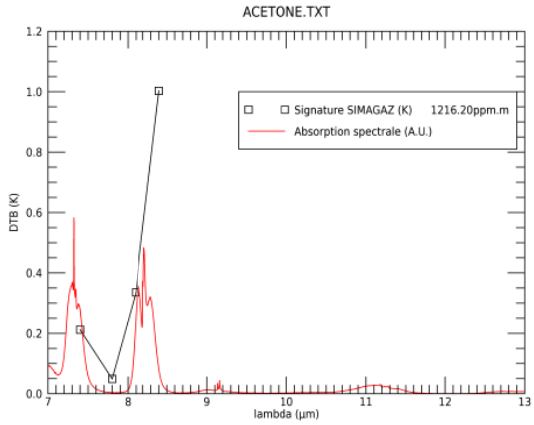


Figure 3 : Database spectroscopic absorption (arbitrary unit) features (in red) for butyl-acetate (top) and acetone (bottom). Model of SIMAGAZ response (in brightness temperature) of gas enhancement is in dark.

An illustration of SIMAGAZ potential to separate and identify gases is shown in the figure 4. This figure provides for each released products, false colours maps using 3 channels of SIMAGAZ. As expected, from gas absorption model (Figure 3), the evaporating gas are seen (and discriminated) in the case of heptane, butyl acetate and acetone. The gas false colour is specific to each gas: heptane appears "yellow", butyl acetate "green" and acetone "blue". For the others products, gas signatures are not seen by the SIMAGAZ channels, however as explained in section 2, the thermal behaviour of the spill is seen. Endothermic evaporating process leads to "cold" spills except for acetone and methanol corresponding to exothermic evaporating process.

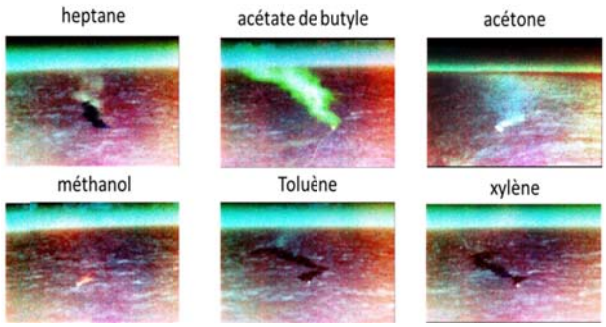


Figure 4 : Examples of false color instantaneous views of SIMAGAZ (RGB channels 7.8 µm, 8.1µm and 8.4 µm) for each HNS releases.

3.2. Gas plume segmentation and quantification

The SIMAGAZ spectral measurement $R(\lambda)$ is calibrated in brightness temperature for each channel . The relative homogenous background is used to estimate background "free gas" radiances $R_{bkg}(\lambda)$. A multispectral and multi-temporal analysis based on the direct model F dedicated to

SIMAGAZ is applied to fit the differential spectral behaviour of the plume with the gas model signature. The environment variable X_{env} corresponds to the atmospheric temperature, sea surface temperature and water vapor atmospheric concentration. First guess of this vector is provided from calibrated image data (temperatures) and from the vessel instrumentation (relative humidity).
A spectral correlation analysis is applied in order to provide a correlation map. Thresholding and simple morphological approach is used then to create a plume mask. For each pixel a quantitative retrieval process is then applied on the differential signal to minimize the difference between the differential measurement and the model.

$$R(\lambda) - R_{bkg}(\lambda) = F(\rho_{gas}, X_{env})$$

The figure 5 shows an example of results in the case of butyl acetate corresponding to two different releases. The first one corresponds to wind speed around 10 m/s (left) whereas the right figures corresponds to wind speed of about 2-3 m/s. A first global mass analysis provides evaporating flow rate higher than 10 g/s in this case of butyl acetate.

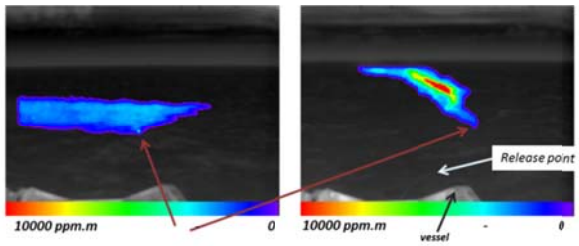


Figure 5: Butyl acetate quantitative map overlaid on the thermal image of the scene. Left: Strong wind conditions (from left to right in the image), right: Low wind condition.

4. Conclusion – Discussion

In this paper, we have presented application of SIMAGAZ multispectral instrument developed at ONERA for chemical spill monitoring. The table 2 shows a synthesis of the experiment conclusion of the IPOMAC campaign from SIMAGAZ results.

The main advantage of this instrument is to provide simultaneously information of the spill on the surface and quantitative map of evaporating gas from the spill. These information are very useful for early rescues during accidents and crisis management and would be an interesting tool for environmental and security monitoring of harbour or specific high traffic density area monitoring.
Based on this success, the partners have planned a new campaign in 2022 to evaluate the potential of SIMAGAZ from an airborne platform for this application. Then, the 2022 experiment will be conducted to establish a link and some cross validations between flow rates estimated by SIMAGAZ and dispersive model of evaporating chemicals at sea.

Table 2 : Synthesis of SIMAGAZ results during IPOMAC campaign.

Product	Spill	Gas	Maximal distance of gas or spill observation
Butyl acetate	“Cold spill”	Observation, Detection and Quantification	Gas > 1km Spill > 500m
Acetone	“Warm spill”	Observation – Detection Quantification	Gas > 300m Spill > 500m
Heptane	“Cold spill”	Observation, Detection	Gas > 500m Spill > 500m
Methanol	“Warm spill”	Only Spill detection	Spill > 500m
Toluene	“Cold spill”	Only Spill	Spill > 500m
Xylene	“Cold spill”	Only Spill	Spill > 500m

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