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Quantification of gas evaporating from HNS spills at sea by a multispectral infrared remote sensing system: SIMAGAZ

Pierre-Yves Foucher^a, Roland Domel^a, Stéphane Langlois^a, Philippe Déliot^a, William Giraud^b, Stéphane Le Floch^b, Raphaël Fachinetti^c

^aONERA, Chemin de la Hunière, 91761 Palaiseau Cedex, France;

^bCEDRE, 715 rue Alain Colas, 29218 Brest, France;

^cCEPPOL, Brest, France ;

Correspondence email : pierre-yves.foucher@onera.fr

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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 gas monitoring camera was deployed during the IPOMAC and MANIFEST campaigns in 2021 and 2022. These measurement campaigns were carried out several miles off the west coast of France as part of the response to pollution at sea. Various chemicals, legally classified as HNS (Hazardous Noxious Substances), were released on the sea surface and SIMAGAZ measurements were made from the ship and by air. The camera data processing is based on a physical radiometric model, a spectroscopic database containing the compounds of interest and includes a morphological analysis of the images. SIMAGAZ has thus enabled the detection, identification and quantification of several gases evaporating from spilled slicks (acetone, butyl acetate, propyl acetate, MTBE and heptane), sometimes for over half an hour. For other products with absorption lines outside the SIMAGAZ spectral range, no gas was seen as expected. On the basis of this success, the analysis of the concentration fields obtained and their dynamics can be compared with the results of evaporation and atmospheric dispersion modelling tools for HNS.

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 in 2021 and the MANIFEST campaign in 2022 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 carried out thermal multispectral acquisitions with two SIMAGAZ instruments. One of the specific objectives of these campaigns 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 and the June 2022 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 a cooled LW VGA format detector with a pixel pitch of 15µm and a RM3 cooler. Therefore, 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 given an integration time of 5ms and for a scene at around 20°C for a single image. The high acquisition frame rate (up to 75 images/s) makes the system suitable with mobile platform acquisition and help to enhance the signal to noise ratio. In turn, the camera combines the advantages of being simple (only two major optical components), cost effective (single detection block), compact (size of the detection block), sensitive (cryogenic infrared detector), with a high radiometric stability (cooling keeps background signal down) and a high speed acquisition. The specifications of SIMAGAZ are summarized in Table 1. A picture of the camera is given in Figure 1.

Table 1: Specifications of SIMAGAZ

Detector type	Multispectral MCT
Spectral Range	7.2-8.5 μ m
Image Size for a sub-image	320x256 pixels with a pixel pitch of 15 μ m
Measurement Rate	Up to 75Hz
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°
Sensitivity of methane leak flowrates	<0.5g/s @ 30m

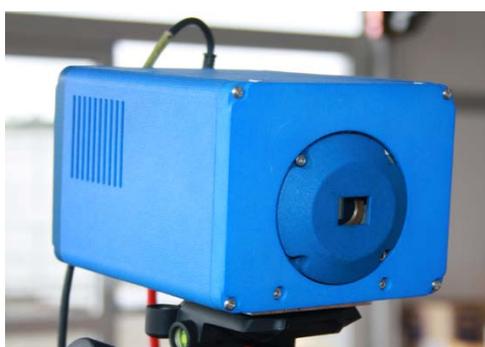


Figure 1: SIMAGAZ infrared multispectral camera.

2.2. Experimental set up

The measurement campaigns were 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 the campaigns, various chemicals, legally called HNS for Hazardous Noxious Substances (HNS), were released on the sea surface: acetone, butyl acetate, propyl acetate, methanol, heptane, MTBE, xylene and toluene.

One cubic meter of each product was released 100m from the bottom of the vessel using an appropriate pump and hose system. The spill time is about 5 minutes, and the ship speed is about 1 knot. Two SIMAGAZ instruments were used. The first one acquired images from the ship in a rear line of sight, the distance between the camera and the surface slick can range from 150 m to more than 1 km. Figure 2 shows the installation of the SIMAGAZ on the roof of the ship. One stabilization platform was used to correct the ship's motion at low frequency. The second was integrated into the PA03 aircraft of the IMAO company (Figure 3) during the MANIFEST campaign in 2022. Acquisitions were made at two different altitudes: 300 m (1000 ft) and 800 m (2500 ft). Several lines of sight for each product and for each altitude covering a distance of about 4 km were carried out.



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



Figure 3 : Left : IMAO PA03 airplane, Right : SIMAGAZ instrument (blue inside the red circle) integrated in the airborne stabilised platform.

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 gases, large band thermal imagers are not sensitive to the evaporating plume. When narrow bands are used in a multispectral instrument like 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 environmental natural change. The radiometric equivalent radiometric noise of the SIMAGAZ instrument in brightness temperature for a specific channel is around 0.04 K. Figure 4 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 from the vessel point of view: 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 corresponding to the environmental condition and to the kind of point of view. 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.

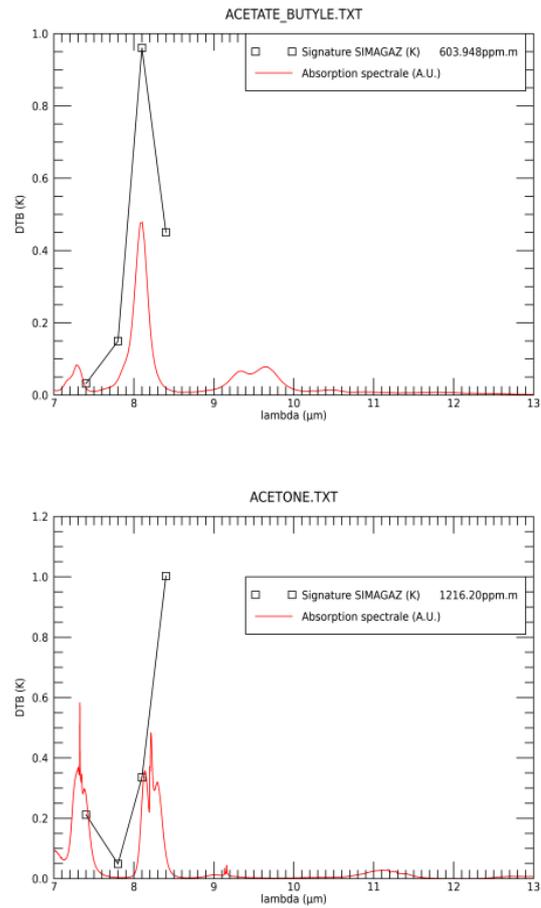


Figure 4 : Database spectroscopic absorption (arbitrary unit) features (in red) for butyl-acetate (top) and acetone (bottom). Model of SIMAGAZ response (in brightness temperature) of gas enhancement is in dark.

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 figure 5 shows example of false colour image using 3 of the 4 SIMAGAZ available bands in the vessel point of view case. The gas false colour is specific to each gas: heptane appears "yellow", butyl acetate "green" and acetone "blue". For the others products of this figure, 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.

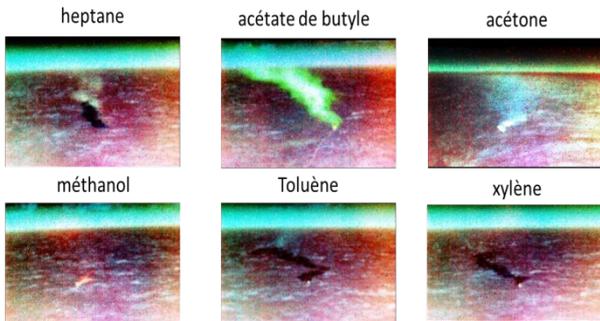


Figure 5 : Examples of false color instantaneous views of SIMAGAZ (RGB channels 7.8 μm , 8.1 μm and 8.4 μm) for each HNS releases from vessel point of view.

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 behavior 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 gas correlation map and to unmix surface and atmospheric components. Thresholding and a simple morphological approach are 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.

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

Figure 6 shows an example of results in the case of butyl acetate and acetone corresponding to two different releases. The first one corresponds to wind speeds around 10 m/s (left) whereas the picture on the right corresponds to wind speeds of about 2-3 m/s. Figure 7 and 8 show examples of results in the case of MTBE and butyl-acetate from airborne point of view. In the first case corresponding to quite high wind speed (10 m/s), the HNS spill and the evaporating gas are seen very well. In the second case (Figure 8), the wind speed is much more (1-2 m/s) lower and the flat sea surface makes ship wake visible in the thermal domain: the HNS spill is not so easy to detect, however the gas is still detected and quantified.

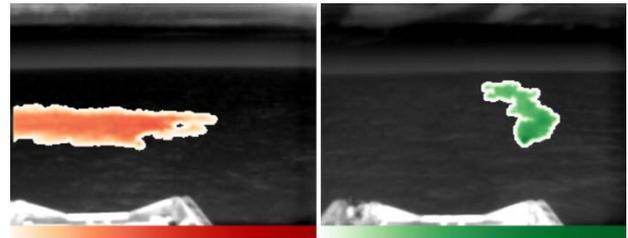


Figure 6: Butyl acetate (left) and acetone (right) quantitative map (0-1000 ppm.m colour scale) overlaid on the thermal image of the scene. Rear vessel point of view. Left: Strong wind conditions (from left to right in the image), right: Low wind condition.

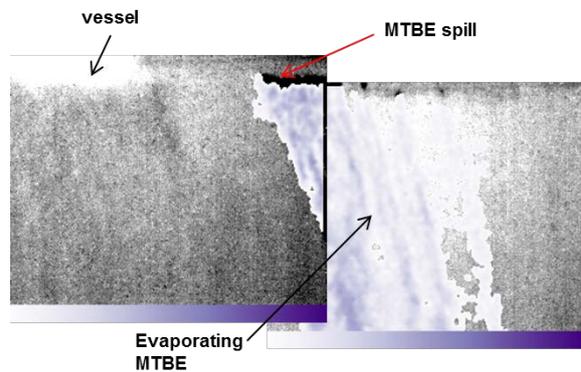


Figure 7: MTBE quantitative maps (0-1000 ppm.m colour scale) overlaid on the thermal image of the scene. Shown images have been extracted from the full video sequence seen from airborne point of view at 2500 ft (800m).

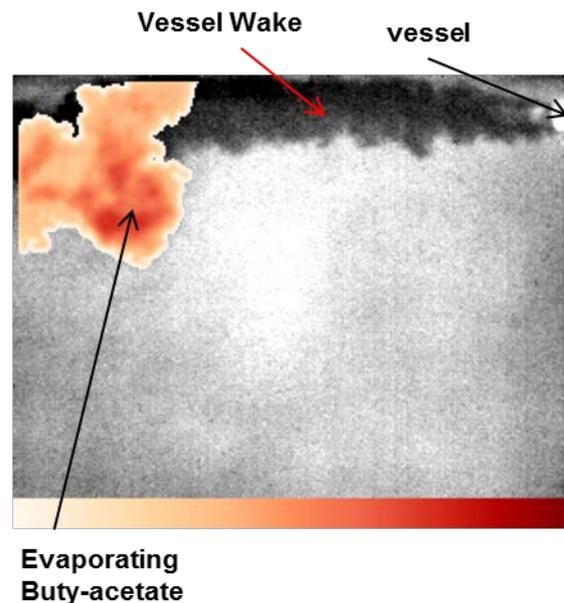


Figure 8: Butyl acetate quantitative maps (0-1000 ppm.m colour scale) overlaid on the thermal image of the scene. Shown images have been extracted from the full video sequence seen from airborne point of view at 2500 ft (800m).

4. Conclusion – Discussion

In this paper, we have presented an application of SIMAGAZ multispectral instrument developed at ONERA for chemical spill monitoring. Table 2 and 3 show a synthesis of the experimental conclusion of the IPOMAC vessel campaign and MANIFEST airborne campaign from SIMAGAZ results.

The main advantage of this instrument is to provide simultaneously information of the spill on the surface and a quantitative map of evaporating gas from the spill at a high frame rate (50 images by second for these campaigns). 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.

A future step will be conducted to make inter-comparisons and cross validations between quantitative amount of gas (or flow rates) estimated by SIMAGAZ and Chemistry and transport models of evaporating chemicals at sea.

Table 2 : Synthesis of SIMAGAZ results during IPOMAC campaign.

Product	Spill	Gas	Maximal horizontal 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

Table 3 : Synthesis of SIMAGAZ results during airborne MANIFEST campaign.

Product	Spill	Gas
Butyl acetate	“Cold spill”	Observation, Detection and Quantification @ 1000 ft and 2500 ft
Acetone	“Warm spill”	Observation – Detection @ 1000 ft and 2500 ft
Isopropyl Acetate	“Cold spill”	Observation – Detection Quantification @ 1000 ft and 2500 ft

MTBE	“Warm spill”	Observation – Detection Quantification @ 1000 ft and 2500 ft
Toluene	“Cold spill”	Only Spill
Xylene	“Cold spill”	Only Spill

5. REFERENCES

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