Multifrequency radar imagery and characterization of hazardous and noxious substances at sea

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The increase in maritime traffic, particularly the transport of hazardous and noxious substances (HNS), requires advanced methods of identification and characterization in environmental chemical spills.

Knowledge about HNS monitoring using radar remote sensing is not as extensive as for oil spills, however any progress on this issue would likely advance both the monitoring of chemical and oil-related incident.

To address this knowledge gap, an experiment was conducted in May 2015 over the Mediterranean Sea during where controlled releases of HNS were imaged by remote sensing system.

HNS is defined by the International Maritime Organization (IMO) as any substance other than oil which, if introduced into the marine environment, is likely to create hazards to human health, to harm living resources and marine life to damage amenities or to interfere with other legitimate uses of the sea.
POLLUPROOF: the partners
POLLUPROOF: experimentation at sea

Six chemical substances have been chosen to evaluate the capability of remote sensing sensors.

These chemicals are among the most transported substances by maritime freight in Europe. Some are classified as the most noxious substances in the IBC Code.

1 m³ of each of these six products was released at sea and images by airborne remote sensing payloads.

- **Category I: vegetal oil and fatty acid esters**
  - Rapeseed/colza oil - Floater
  - Fatty Acid Methyl Esters (FAME) - Floater

- **Category II: petrochemical products**
  - Toluene - Floater & Evaporator
  - Heptane - Evaporator
  - Xylene - Floater & Evaporator

- **Category III: alcohols and derivatives**
  - Methanol - Dissolver & Evaporator
**POLLUPROOF: airborne radar remote sensing**

<table>
<thead>
<tr>
<th>Frequency</th>
<th>Bandwidth</th>
<th>Polarization</th>
<th>Incidence angle</th>
<th>Swath</th>
</tr>
</thead>
<tbody>
<tr>
<td>X</td>
<td>300 MHz (9.6-9.9 GHz)</td>
<td>Quad-pol (HH, HV, VH, VV)</td>
<td>45° (34-52°)</td>
<td>1500m (slant range)</td>
</tr>
<tr>
<td>L</td>
<td>150 MHz (1.25-1.4 GHz)</td>
<td>Quad-pol (HH, HV, VH, VV)</td>
<td>45° (34-52°)</td>
<td>1500m (slant range)</td>
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</tbody>
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Optical imagery (LWIR, SWIR, UV) were also acquired during this campaign, but this is beyond the scope of this presentation.
HNS monitoring by airborne SAR remote sensing

• **Issue 1:** observability
  
  Are HNS detectable with SAR imagery? If yes, which of them

• **Issue 2:** quantification
  
  Does SAR imagery allows us to quantify pollutant discharged at sea?

• **Issue 3:** characterization
  
  Does SAR imagery allows us to characterize pollutant discharged at sea?
Observation of HNS at sea by airborne radar imagery (X- and L-band)

Methanol, heptane and toluene were never detected in SAR imagery at either X-band or L-band. The lack of detection is likely due to the extreme volatility of those HNS.

Xylene is observable as an area of reduced amplitude on SAR images. The approximate area extent of the spill was 0.26 km² (1 m³ has been discharged).
Observation of HNS at sea by airborne radar imagery (X- and L-band)

Rapeseed oil and FAME are both observable on SAR images acquired at X- and L-band. The two releases forms a single spill. Rapeseed oil, having been discharged first, corresponds to the right part of the spill; FAME is on the left. The overall surface of the spill is 1.745 km$^2$ (1 m$^3$ of each HNS has been discharged).
Polarization Difference : PD ⇔ « small scale »

\[ \sigma_{XY}^{0} = \sigma_{XY}^{0B} + \sigma_{wb} \]

\[ PD = \sigma_{0}^{VV} - \sigma_{0}^{HH} = \sigma_{0}^{VV} - \sigma_{0B}^{HH} \]

\( XY = HH \text{ ou } VV \)

\( \sigma_{0B}^{XY} : 2\text{-scale Bragg mechanism (~ small scale)} \)

Clean seawater (rough surface: VV > HH): PD > 0

\( \sigma_{wb}^{XY} : \text{unpolarized contribution (~ large scale)} \)

Contaminated surface: PD ~ 0

Quantification: PD is varying from 0 (over slicks) to a maximum value (PD_{sea}) over clean sea

PD decreases as the impact of the substance increases

PD_{sea} can be estimated:

- Using a physical model for the polarimetric radar reflectivity over (clean) sea surface (GO-SSA*)
- Directly using clean sea area over airborne or spaceborne POLSAR acquisition

Quantification map: \( NPD = 1 - \frac{PD}{PD_{sea}} \quad 0 \leq NPD \leq 1 \)

NPD=1 : high impact of HNS

NPD=0 : clean sea


Quantification of HNS at sea by airborne radar imagery (X- and L-band)

Based on polarimetric SAR imagery, a method has been developed to detect and quantify the relative concentration of HNS on the ocean surface.
Quantification of HNS at sea by airborne radar imagery (X- and L-band)

X-band SAR imagery

Detection mask

Relative concentration map:
0 ⇔ low concentration
1 ⇔ high concentration

POLLUPROOF – S. Angelliaume
Characterization of HNS at sea by airborne radar imagery (X- and L-band)

SAR imagery can indicate whether the spilled product behaves like a viscoelastic film that is more or less homogenous and floating on the surface or if the spilled product is mixed with seawater within the upper few centimeters of the water column. This method yields the oil/water mixing index(*) .

Characterization of HNS at sea by airborne radar imagery (X- and L-band)

The normalized radar cross-section (NRCS) is defined as (Valenzuela 1978):

$$\sigma^0_{pp} = 4\pi k^4 EM_{\cos^4 \theta} \Gamma_{pp} W$$

\(\Gamma_{pp}\) : the reflectivity \(\Leftrightarrow\) Bragg scattering coefficients \(\alpha_{pp}\) \(\Leftrightarrow\) local incidence angle and the relative dielectric constant

\(W\) : the spectral density of the ocean surface roughness

Radar backscattered power is diminished by oil slicks through mechanical damping of Bragg-wavelength gravity-capillary waves and/or reductions in the relative dielectric constant.

By decoupling the relative contribution to signal attenuation of surface waves mechanical damping and changes in dielectric constant, we can define the characteristics of the slick along a spectrum ranging from thin surface films to thicker emulsions.
Characterization of HNS at sea by airborne radar imagery (X- and L-band)

- **Normalized damping factor:**
  \[ M_W = \frac{W_{\text{water}} - W_{\text{oil}}}{W_{\text{water}}} \quad 0 \leq M_W \leq 1 \]

- **Normalized power attenuation factor:**
  \[ M_\alpha = \frac{|\alpha_{\text{water}}^{VV}|^2 - |\alpha_{\text{oil}}^{VV}|^2}{|\alpha_{\text{water}}^{VV}|^2} \quad 0 \leq M_\alpha \leq 1 \]

- **Oil/water mixing index:**
  \[-1 \leq M = M_W - M_\alpha \leq 1\]

  \[ M < 0 : \downarrow \sigma^0 \Leftrightarrow \downarrow \varepsilon \]
  \[ M > 0 : \downarrow \sigma^0 \Leftrightarrow \downarrow W \]

Characterization of HNS at sea by airborne radar imagery (X- and L-band)

L-band SAR imagery

Oil/water mixing index (detection mask from X-band SAR imagery)

Film on the ocean surface

Mix with seawater
HNS monitoring by airborne SAR remote sensing

• **Issue 1:** observability
  
  Are HNS detectable with SAR imagery?
  
  Yes, volatility is a key issue

• **Issue 2:** quantification
  
  Does SAR imagery allows us to quantify pollutant discharged at sea?
  
  Yes, NPD allow to quantify the relative concentration

• **Issue 3:** characterization
  
  Does SAR imagery allows us to characterize pollutant discharged at sea?
  
  Yes, distinction between two HNS within the same spill is possible and SAR data allow to define the characteristics of a spill along a spectrum ranging from thin surface films to thicker emulsions (oil/water mixing index)