EVALUATION OF MODIS DATA FOR MAPPING OIL SLICKS - THE DEEPWATER HORIZON OIL SPILL CASE (2010)

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ABSTRACT

In this paper Moderate Resolution Imaging Spectroradiometer (MODIS) multispectral imagery are used for oil spills mapping as an alternative to radar data. MODIS images of the northern Gulf of Mexico (USA) are analyzed to study the sea anomalies among the visible and infrared wavelengths in order to detect a reported oil slick. A simple spectral index and RGB false color bands combination are applied to detect fluorescence and emissivity anomalies due to oil spills in particular sun glint conditions. A monitoring system of sea surface may be built using high temporal resolution imagery as MODIS data. Applying the proposed index and RGB bands combination, also suitable on night-time overpasses, it's possible to further increase the availability of clouds free images using optical sensors.

Index Terms — Deepwater Horizon, oil spill, Remote Sensing, MODIS, thermal infrared.

1. INTRODUCTION

Petroleum products play a fundamental role in modern society, particularly in the transportation, plastics, and fertilizer industries and there are typically ten to fifteen transfers involved in moving oil from the oil field to the final consumer. Oil spills can occur during oil transportation or storage and spillage can occur in water, ice or on land. Marine oil spills can be highly dangerous since wind, waves and currents can scatter a large oil spill over a wide area within a few hours in the open sea [8]. The detection of oil slicks is an important Remote Sensing objective for both exploration and environmental applications. For exploration, persistent or recurrent oil slicks can point to the presence of undersea oil seeps. For environmental applications, early detection of anthropogenic oil slicks can make possible timely protection of critical habitats and helps identify polluters [17].

The environmental impacts of oil spills can be considerable. Oil spills in water may severely affect the marine environment causing a decline in phytoplankton and other aquatic organisms. Phytoplankton is at the bottom of the food chain and can pass absorbed oil on to higher levels in the food chain. Oiled birds suffer from behavioral changes and this may result in the loss of eggs or even death. The livelihood of many coastal people can be impacted by oil spills, particularly those whose livelihood is based on fishing and tourism [14].

On April 20, 2010, an explosion occurred to the Deepwater Horizon offshore oil platform, based about 80 km off the coast of the Louisiana, USA. After a two days fire (Figure 1), the drilling rig sank on April 22, 2010, causing a massive oil spill in the northern Gulf of Mexico that we estimated on April 29th, 2010 of at least 5,840 km^2. The spill was originated by the oil rig placed about 1.5 km under the sea surface, and could reach an estimated total amount of millions of barrels until the flow will be stopped. The oil spill rapidly expanded during the initial 8-day period and covered a very large area along the coast of Louisiana, extending approximately north to south for 120 km. Sediments in the region are generally thick, with the greatest sediment load provided by the Mississippi River [19]. Moreover, on April 30, 2010 the oil slick reached the Mississippi river delta, approaching the Delta National Wildlife Refuge and the Breton National Wildlife Refuge. Since the Mississippi river delta systems support a variety of coastal habitats [13], the spilled oil will adversely affect these fragile ecosystems, including endangered and threatened species.

Previous studies showed the potentialities of the Moderate Resolution Imaging Spectroradiometer (MODIS) for environmental monitoring (e.g. rapid response flood mapping [18]). The study area is shown in Figure 1, in which it's possible to notice a smoke plume coming out from the platform fire. In this paper we assess the capability of MODIS for oil spills detection and mapping. This work aims to demonstrate the great potential of coastal and marine environment monitoring using high temporal resolution MODIS datasets, in particular to identify anomalies over the sea surface and to evaluate their evolution in narrow time ranges.

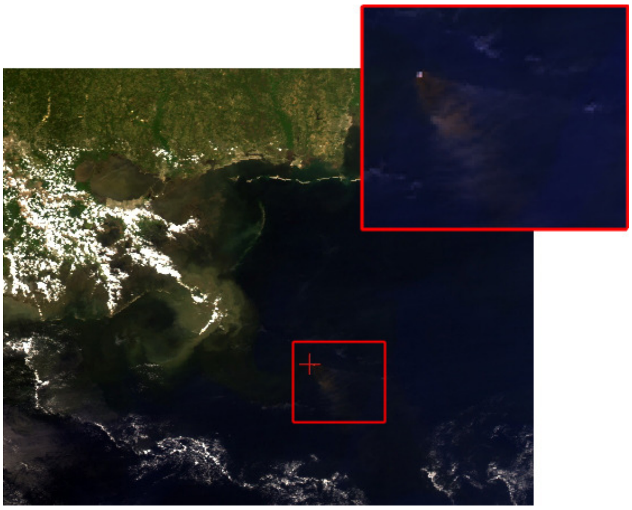

Figure 1: April 21, 2010 - MODIS true color composition image of the study area. The red cross indicates the oil platform coordinates; the red box indicates the zoom area on the platform fire and smoke plume.

2. BACKGROUND

2.1. Spectral properties overview

Remote Sensing data have been employed by a large number of researchers to investigate oil spills, focusing mainly on the mapping of the areal extent [1, 2, 4, 11], the evaluation of slick thickness [7, 9] and the classification of the oil type, in order to estimate environmental damages and take appropriate response activities [12].

In the visible region of the electromagnetic spectrum (VIS, approximately from 400 nm to 700 nm), oil has a higher surface reflectance than water [6], but also shows limited nonspecific absorption tendencies. Sheen shows up silvery and reflects light over a wide spectral region down to the blue. Overall, however, oil has no specific characteristics that distinguish it from the background [12]. Therefore, techniques that separate specific spectral regions in the VIS do not increase detection capability.

Oil, which is optically thick, absorbs solar radiation and re-emits a portion of this radiation as thermal energy, primarily in the 8-14 μm region. In thermal infrared (TIR) images, thick oil appears hot, intermediate thicknesses of oil appear cool, and thin oil or sheens are not detectable [12]. Specific studies in the TIR show that there is no spectral structure in this region [17]. Tests on a number of IR systems show that emulsions are not always visible in the IR, and cameras operating in the 3 to 5 μm range seem to be only marginally useful [10].

2.2. Limitations of optical satellite sensors for oil slicks detection

Optical satellite sensors provide a synoptic view of the affected area, but several problems are associated with relying on those for oil spill Remote Sensing. Besides a lower spatial resolution than airborne images (an extremely important matter when the oil is distributed in sparse windows and patches over large areas), atmospheric transmission in the ultraviolet (UV) region in which oil fluoresces [17] is poor, making satellite observations unprofitable in that range [3]. Another limitation is due to the timing and frequency of overpasses and the absolute need for clear skies to perform optical image collection. The chances of the overpass and the clear skies occurring at the same time give a low probability of seeing a spill on a satellite image. Moreover, the difficulty in developing algorithms to highlight the oil slicks and the long time required to do so may disrupt oil spill contingency planning [12]. For example, in the case of the EXXON VALDEZ disaster, although the spill covered vast amounts of Gulf of Alaska for over a month, there was only one clear day that coincided with a satellite overpass. As a consequence, it took over two months before the first group managed to detect the oil slick in the satellite imagery, although its location was precisely known [15].

In addition, other limitations are due to properties of oil surface on water in the TIR region [17]:

- the spectral reflectance properties of different crude oils vary, and TIR oil properties vary from day-time to night-time;
- water roughness changes the reflectance of surface, due to the backscatter of sun glint from wave sides oriented at the specular angle, as does the presence of sea foam;
- although in the TIR oil has a lower emissivity than water [17], resulting in a brightness temperature contrast that may be used for oil slick detection, variations in real kinetic temperature of water can produce false targets, and oil slicks and seawater may not be at the same temperature.

Consequently, we assume that reflectance contrasts between water and oil at any given wavelength in the VIS and IR may vary with sea status, illumination conditions and oil properties [16].

In conclusion, currently no single processing algorithm is able to identify all oil slicks in the optical region of the E.M. spectrum and the potential detection of false targets is consistent. Thus, although oil slicks (especially known slicks) have been repeatedly detected using different spectral bands, no single technique has been developed that unambiguously and reliably detects all oil slicks, and current best practice is to use a costly combination of techniques, including airborne radar and IR/UV line scanner [12].

3. METHODOLOGY

3.1. MODIS data

MODIS is a key instrument aboard the Terra (EOS AM) and Aqua (EOS PM) satellites. Terra's orbit around the Earth is timed so that it passes from north to south across the equator in the morning, while Aqua passes south to north over the equator in the afternoon. Terra MODIS and Aqua MODIS are viewing the entire Earth's surface every 1 to 2 days, acquiring data in 36 spectral bands, from the visible to the thermal infrared as shown in Table 1.

Table 1: MODIS band setting, wavelength ranges, resolution and primary uses.

Band	λ (μm)	Resol. (m)	Primary uses
1	0.620-0.672	250	Land, clouds, aerosols boundaries
2	0.841-0.890		
3	0.459-0.479	500	Land, clouds, aerosols properties
4	0.545-0.565		
5	1.230-1.250		
6	1.628-1.652		
7	2.105-2.155		
8	0.405-0.420	1000	Ocean color, phytoplankton, biogeochemistry
9	0.438-0.448		
10	0.483-0.493		
11	0.526-0.536		
12	0.546-0.556		
13	0.662-0.672		
14	0.673-0.683		
15	0.743-0.753		
16	0.862-0.877		
17	0.890-0.920		Atmospheric water vapor
18	0.931-0.941		
19	0.915-0.965		
20	3.660-3.840		Surface, cloud temperature
21	3.929-3.989		
22	3.929-3.989		
23	4.020-4.080		
24	4.433-4.498		Atmospheric temperature
25	4.482-4.549		
26	1.360-1.390		Cirrus clouds water vapor
27	6.535-6.895		
28	7.175-7.475		
29	8.400-8.700		Cloud properties
30	9.580-9.880		Ozone
31	10.780-11.280		Surface, cloud Temperature
32	11.770-12.270		
33	13.185-13.485		Cloud top altitude
34	13.485-13.785		
35	13.785-14.085		
36	14.085-14.385		

64 MODIS scenes from April 20, 2010 to May 05, 2010 by both Terra and Aqua satellites day-time and night-time overpasses were acquired. Among these, 16 images are cloud free over the slick and are potentially appropriated for the aim of this study. Table 2 shows a subset of data actually processed in this study.

Table 2: Date and time of acquisition and satellite of the processed images.

Date	Time (GMT)	Satellite
April 21, 2010	19:20	Aqua
April 29, 2010	07:30	Aqua
April 29, 2010	16:55	Terra
May 05, 2010	04:10	Terra

3.2. Approach

[17] demonstrated that although real differences in temperature between oil slicks and nearby seawater caused by differing absorption of sunlight may disguise the effects of emissivity differences, the spectral behavior of oil slicks and seawater in the 8-14 μm atmospheric window is distinctly different and surprisingly unaffected by variables that might be expected to alter them. Even then, real water temperature differences due to currents may introduce false targets. Thus, the only unambiguous difference between spectra of oil slicks and seawater lies in the different shapes of their spectral curves, usually referred to as their spectral signatures, making night-time measurements desirable because less dependent upon the observation conditions. Oil absorbs the solar radiation and emits a part of it as the thermal energy mainly in the TIR (8-14 μm). Oil has a lower emissivity than water in TIR and therefore, at these wavelengths, it has a distinctively different spectral signature compared to the background water [17].

In this study we aim to detect the slick at first during day-time exploiting reflectance properties of oil and seawater and subsequently during night-time analyzing the IR emissivity information.

4. IMAGE PROCESSING

4.1. Pre-processing

All MODIS images were resampled to a unique value of 1 km of spatial resolution. They provide directional hemispherical reflectance (ρ) from band 1 to 19 and directional emissivity (ε) from band 20 to 36. Every single scene was coarsely georeferenced to allow the overlay with ancillary vector data (i.e. coastline, localization of the platform).

4.2. Oil slick detection on MODIS day-time VIS and IR data

Spatiotemporal variations in the thermodynamic properties of oil and seawater have been mapped in order to identify oily surfaces. Although sun-glint and wind sheen may create a similar impression to an oil sheen, we assume that any observed anomaly is caused by the oil spill.

For opaque bodies the transmittance is negligible and Kirchhoff's law can be written in the following simplified form [3]:

$$\varepsilon_{T,\lambda} = 1 - \rho_{T,\lambda} \tag{1}$$

The oil seeping from the sea bed passes from a colder to a hotter status during the ascension. We assume that its temperature gets to equilibrium once oil has reached the marine surface and remains constant regardless of its spatial distribution. Thus, we can further simplify Kirchhoff's law in the following:

$$\varepsilon_{\lambda} = 1 - \rho_{\lambda} \tag{2}$$

During the day oil has a lower emissivity and higher UV fluorescence than water. To enhance the contrast between the oil slick and the surrounding seawater a Fluorescence/Emissivity Index (FEI) has been developed on MODIS data and was defined as follows:

$$FEI = \frac{\rho_{Blue} + (1 - \rho_{Thermal})}{\rho_{Blue} - (1 - \rho_{Thermal})} = \frac{\rho_{Blue} - \varepsilon_{Thermal}}{\rho_{Blue} + \varepsilon_{Thermal}} \tag{3}$$

This normalized index is based on the relationship between blue and TIR ranges, respectively band 3 and band 31 in MODIS data, combining the theoretically higher blue range component of oil, due to fluorescence induced by $\lambda < 0.400$ μm sunlight rays [4], and the lower emissivity in the TIR. The higher is the value of the contribution of blue and the lower is the one of emissivity, the greater will be the FEI values.

4.3. Oil slick detection on MODIS IR data

Given that the information from IR should theoretically be useful to discriminate materials with different emissivity values, the intra-image emissivity variation on seawater surface was used on MODIS night-time data. The different spectral features of oil and seawater in this region can be enhanced with an appropriate IR bands visualization. For example, it is possible to combine emissivity values taken from mid-wavelength and thermal range limits, and on the edge between these two spectral regions. This visualization can also be performed on night-time images, potentially increasing the availability of clouds free images on the area of study.

5. RESULTS AND DISCUSSION

The considered dataset (acquired from April 20, 2010 to May 05, 2010 by both Terra and Aqua satellites day-time and night-time overpasses) is almost centered on the investigated sector and clearly shows anomalies close to the Louisiana coast: as sun-glint conditions emphasize the contrast against the surrounding marine water, applying the FEI index to the day-time MODIS data of April 29, 2010 it was possible to detect in the sea a curved plume brighter than the surrounding seawater and expanding from the platform coordinates (Figure 2). This anomaly seems corresponding for geographical position and shape to the oil slick reported in those days.

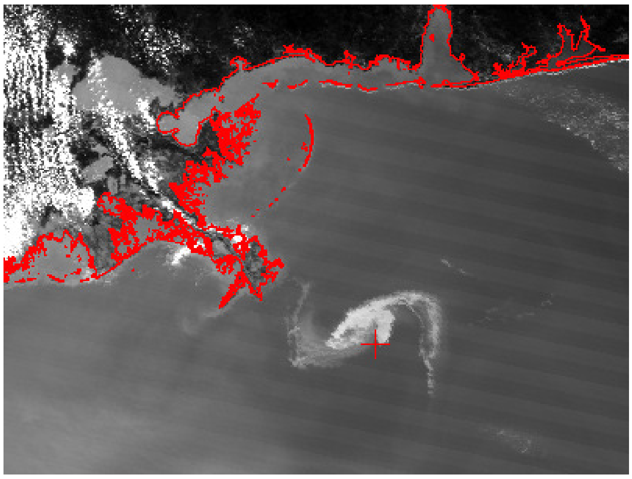

Figure 2: April 29, 2010 - MODIS day-time grayscale composition image of FEI. The red cross indicates the oil platform coordinates; the red line indicates the coastline.

On the same day-time MODIS image, a RGB false color visualization was performed combining bands 23, 31 and 29 respectively (Figure 3). This combination clearly highlights the slick from the background and the obtained result is consistent with Figure 2.

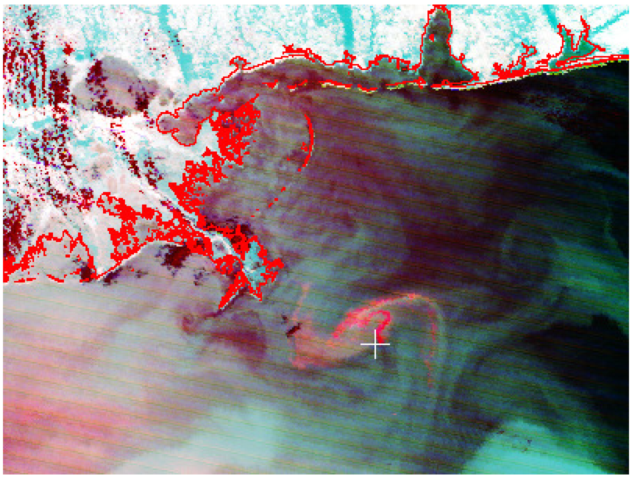

Figure 3: April 29, 2010 - MODIS day-time IR false color composition image. The white cross indicates the oil platform coordinates; the red line indicates the coastline.

The same band combination was performed on a MODIS image acquired during the previous night (Figure 4). The oil slick seems to be well highlighted from the surrounding pixels. Moreover, the location, shape and extension of the slick have a good correspondence with both the previous results.

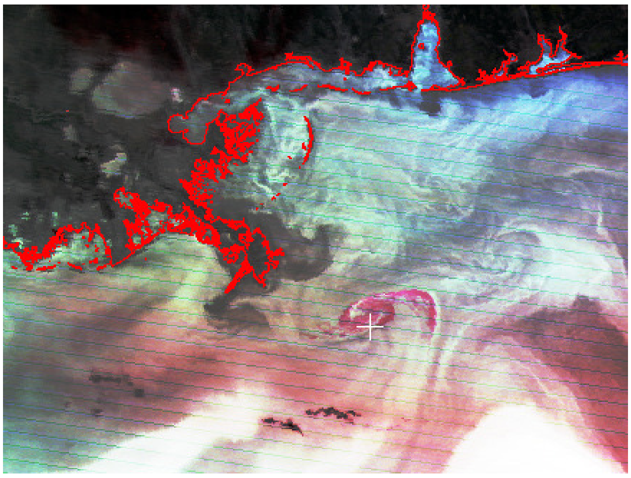

Figure 4: April 29, 2010 - MODIS night-time IR false color composition image. The white cross indicates the oil platform coordinates; the red line indicates the coastline.

Whereas on day-time images clouds were filtered out exploiting reflectance information, night-time data can be affected by potential clouds coverage. However, Figure 5 shows the proposed RGB bands combination on a cloudy image, in which the slick keeps the same hue as in Figure 3 and 4, while clouds are well distinguishable from oil.

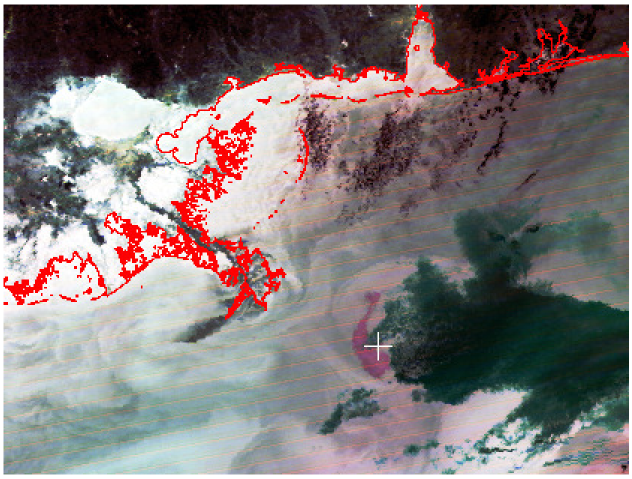

Figure 5: May 05, 2010 - MODIS night-time IR false color composition image. The white cross indicates the oil platform coordinates; the red line indicates the coastline.

6. CONCLUSIONS

The importance and complexity of the marine environment requires a continuous and multidisciplinary study. Multispectral thermal sensors like the MODIS seem appropriate to investigate processes occurring at sea [5], especially in particular sun glint conditions. In case of massive oil spills, MODIS sensor may highlight anomalies using a geometric resolution of 1 km.

The Fluorescence/Emissivity Index, calculated using MODIS bands 3 and 31, may represent an interesting mean to identify and discriminate oily substances floating on the sea surface, as enhancing the results obtainable using only visible data. Moreover, an appropriate RGB false colors bands composition of infrared emissivity data (bands 23, 31 and 29 respectively) highlights the oil slick in both day-time and night-time images. This also allows to detect the presence of a potential clouds coverage, that could represents false targets.

In conclusion, MODIS data may give a significant contribution for a marine and coastal monitoring system, also considering the availability of several daily acquisitions from Terra and Aqua satellites. A limitation of a MODIS data monitoring system remains the meteorological conditions, as cloud cover may prevent radiance penetration from sea surface, but using infrared data from night-time overpasses the frequency of acquisition of clear sky scenes may sensibly improve.

7. ACKNOWLEDGEMENTS

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8. REFERENCES

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