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Izvorni znanstveni članak

Airborne Hyperspectral Surveillance of the Ship-based Oil Pollution in Croatian Part of the Adriatic Sea

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ABSTRACT. The airborne hyperspectral and multisensor surveillance of the ship sourced oil pollution of the sea was researched by the airborne system developed in the frame of the project "System for the multisensor airborne reconnaissance and surveillance in crisis situations and the protection of the environment" (MZOS 2007). While different methodologies, methods, technologies and techniques were used, the multilevel fusion was applied for linking the data, the processes and the outcomes. Fusion includes the aerial hyperspectral and the colour imagery, the visually detected oil spills, the formalised knowledge for the estimation of the oil spill area and oil's quantity based on Bonn Agreement Oil Appearance Code – BAOAC, the data about the spectral response of the clean sea and polluted sea, the results of hyperspectral classification. Besides the information acquired by the airborne multisensor system, the information provided by space based system CleanSeaNet of the European Maritime Safety Agency – EMSA was included in the fusion process (in the frame of the large trial – operational exercise in 2008). The advantages of the airborne remote sensing of the oil spills are reliable detection of the oil spills, accurate mapping of its position and the shape in geographic coordinates, classification of the contents of the spill, measurements of the oil spill's features, estimation of the oil quantity.

Keywords: oil spill, pollution, Adriatic Sea, hyperspectral, SAM, airborne remote sensing.

1. Introduction

The airborne hyperspectral and multisensor surveillance of the ship sourced oil pollution of the sea was researched by the airborne system developed in the frame of the project "System for the multisensor airborne reconnaissance and surveillance in crisis situations and the protection of the environment", supported by

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Croatian ministry of sea, transportation and infrastructure, Croatian Air Forces of Croatian Ministry of defence, Faculty of Geodesy University of Zagreb (MZOS 2007). While different methodologies, methods, technologies and techniques were used, the multilevel fusion was applied for linking the data, the processes and the outcomes. The multilevel fusion of the aerial multisensor images, data and knowledge of ship sourced pollution of the sea by illegal discharges of oil, was researched, solutions were developed, tested and evaluated and achievements are presented. The goal of the fusion is to produce the reliable and confident near real time[2] (NRT) evidences of the pollution, while the data and information provided by particular sources can not provide satisfying level of the detection probability, the confidence and the spatial mapping accuracy. This research was motivated by the needs to protect the sea of the anthropogenic pollution. Our research was focused on the Adriatic Sea, which has all characteristics of the Particularly Sensitive Sea Area (Vidas 2007, p. 121–127, 136–139) although the formalization of its status was not accomplished yet. Protection of the sea requires harmonized efforts of all coastal countries. The scale of the ship-based oil pollution of the Adriatic Sea can be seen in (Ferraro et al. 2007), (REMPEC 2007), (Vidas 2007, 2008). The recent data, based on interpretation of the satellite images acquired by synthetic aperture radar (SAR), are available due to the service of the *CleanSeaNet* (CSN) of the *European Maritime Safety Agency* (EMSA), (URL 2), and have been used in our research.

The state of art of the available and the operational remote sensing technologies is presented in (URL 2), (Trieschmann 2008), (Tarchi et al. 2006), (Bajić and Tomažić 2008), (Bonn Agreement 2007a), (Bonn Agreement 2007b), (Salem and Kafatos 2004), (Lennon et al. 2006), (URL 3), although other references exist. There are two complementary direction of the application of the remote sensing technology for the surveillance of the sea oil pollution: a) satellite based synthetic aperture radar (SAR) images of sea surface, while data about sea currents, wind could be available too, b) the images and data collected by the airborne electro-optical and by side looking antenna radar (SLAR) multisensor systems. The main advantages of the space based technology used by EMSA CSN are the wide coverage (300 x 300 km, spatial resolution 25 m, or 400 x 400 km, spatial resolution 50 m), day or night missions, short time of the interpretation of the imagery, delivery of alert reports at least in 30 minutes after the flight above the considered area. The main disadvantages are a low repetition frequency of the flights (e.g. over the Adriatic Sea – three to seven times per month), a very short duration of the imagery acquisition, a low confidence of the detection of the oil spills at the sea, possible false alarms due to many factors, lack of the estimation of the oil quantity, (Ferraro et al. 2010).

The airborne remote sensing of the ship based oil pollution can provide the data and information of the detected oil spill, by reconnaissance and surveillance missions in accordance to national needs and plans (Bajić and Tomažić 2008; URL 1; Bajić et al. 2008; MZOS 2007). In the same time the airborne data can serve to verify the information obtained from CleanSeaNet. The advantages of the air-

[2] In the considered case the term near real time pertains to the delay introduced, by whole activity between the time of the detection of the possible oil slick and the verification of this real oil slick by airborne multisensor mission and sending report to the decision makers.

borne remote sensing of the oil spills are reliable detection of the oil spills, accurate mapping of their position and the shape in geographic coordinates, classification of the contents of the spill, measurements of the oil spill's features, estimation of the oil quantity; all depends on the used sensors and the fusion. If only electro-optical sensors are used, the main disadvantages are the narrow coverage (typical width of the imaged strip-like area is from 30% to 80% of the height above the sea) and the optical visibility is needed. The oil spills can be visually monitored up to 3 km, in a good visibility conditions[3].

Our efforts were focused on the research of the fusion, aimed to fuse the temporally sensitive spatial data, provided by satellite based EMSA CSN service with images, data and knowledge provided by aerial electro-optical multisensor surveillance. The frame for this purpose was the operational research project (MMPI RH 2008), a large trial aimed to the fusion of the information acquired by the airborne electro-optical multisensor system and the information provided by space based system EMSA CSN. The rationale for this approach was the need to collect a basic experience about the real potentials and limitations of the space borne and the airborne technologies, about the processes, procedures and the conditions of the providing the evidence of the illegal oil discharges from the ships.

Our objective was to derive and approve the efficient and sustainable solution of the oil spill assessment based on the data acquired by the a) alone airborne multisensor system (MZOS 2007) and b) combined airborne service with the service of the EMSA CleanSeaNet (URL 2). The solution should provide needed evidences, that are valuable and strong enough at the court. Our case study was spatially constrained on the Croatian part of the Adriatic Sea. In the considered multisensor airborne system are in use the digital electro-optical sensors (URL 1), among them is the most important the hyperspectral imaging sensor. The data were provided by the hyperspectral imagery, by the measurements of the reflection coefficients of the oil spill and the clean sea, the experts' knowledge of Bonn Agreement Oil Appearance Code – BAOAC (Bonn Agreement 2007b; p. 55–64), (Lewis 2007), the colour photography and results of the visual observations. The fusion of the mentioned data was done at various combinations, from the pixel level, the features level and the decisions level. The development and implementation of the fusion in the considered environment is based on (Hall and Llinas 1997), (Hall and Llinas 2001), (Wald 2002), the basic and classic references which provide the wide methodological frame and enable to consider very different inputs to fusion.

A number of possible oil spills[4] in the Croatian part of the Adriatic Sea in year 2008 was 42, in accordance to EMSA CSN data. Table 1 contain the basic statistical parameters of the considered possible oil spills. Note that 35.71% of possible oil spills appear as a single in 15 days, while 64.28% appears as multiple in 11 days.

[3] If in addition a side looking radar (SLAR) is used, the oil spills can be detected up to 30 km from the aircraft and the probability of the finding the oil spills will increase.

[4] Data provided c.o. I. Tomažić, cover the first time period (from 2008-02-21 to 2008-12-09) when the EMSA CSN data were available in Croatia.

Table 1. *Basic statistical parameters of the possible oil spills in Croatian part of the Adriatic Sea, from 2008-02-21 to 2008-12-09.*

Oil spill	**Length**	**Width**	**Area**
Value	**km**	**km**	**km^2**
Median	5.385	0.475	1.640
Average	6.548	1.816	3.232
Standard deviation	5.437	3.400	3.642
Minimum	0.780	0.100	0.140
Maximum	23.810	20.550	13

The use of the multisensor aerial system for surveillance of the sea pollution by ship sourced oil is presented in section two. There are defined used methods and tools. In section three is presented classification of the hyperspectral images, in section four are considered particular aspects of the fusion, the new contributions, achievements, limitations of their application and future research. Follow conclusions, acknowledgments and references.

2. Use of the multisensor airborne system for the surveillance of the ship based oil pollution of the Adriatic Sea

In this section we consider the aerial electro-optical multisensor system used for the surveillance of the ship sourced oil pollution of the Adriatic Sea, its operational parameters, types of the aerial missions (surveillance if the a priori information is available about possible oil spill, reconnaissance if no a priori information exist), measurements of the coefficient of reflection of a spill and the clean sea water. In this section are introduced and applied the methods and tools of the fusion.

2.1. Airborne hyperspectral multisensor system for the surveillance of the ship based pollution of the Adriatic Sea by oil

The considered airborne electro-optical multisensor system was developed, tested in 2007. and 2008. in the project supported by Croatian Ministry of Science, Education and Sports (MZOS 2007), onboard of helicopter Mi-8. It contains the following digital sensors:

- *The hyperspectral imaging scanner (based on Imspector V9 line scanner).* Wavelengths range from 430 nm to 900 nm, 95 channels. Ground resolving distance in analysed examples was 1 m. Width of the mapped strip is 33% of the height above the sea surface. Optimum height ranges from 400 m to 1000 m.
- *Multispectral frame camera (MS-4100, Geospatial Systems).* Used in configuration of three bands. Central wavelength/channel width: green 550/~40 nm; red 670/40 nm; near infrared 800/160 nm. Each channel has own chip (charge coupled device – CCD).

- *Digital photo camera (Nikon D90)*. Channels blue, green and red. Used for imaging at the nadir.
- *Longwave infra red thermovision camera* (Photon 320, FLIR). Wavelengths' range from 8 to 14 μm.
- *Digital video colour camera (Sony FCB IX1)*. Channels blue, green and red.
- *Inertial Measuring Unit* (iVRU-RSSC, iMAR GmbH).

Note that one additional colour photo camera (Sony H2) was used for manual acquisition of the oblique photographys by visual observer.

More about the considered airborne multisensor system and the particular technical solution see (Bajic et al. 2004), (Bajić and Tomažić 2008), (URL 1), (Bajić et al. 2008), (Šemanjski and Gajski 2008). In October 2008. was realized the operational exercise of the integration of a data provided by satellite SAR service of CSN EMSA and the information and data obtained with the considered airborne multisensor system (MMPI RH 2008).

2.2. Basic operational parameters of the used airborne hyperspectral multisensor system

Main operational parameters of the considered airborne multisensor system onboard of the helicopter Mi-8, for the surveillance of the ship sourced sea pollution by oil were:

- The imagery acquisition speed 120 km/h, visual observation speed 100 km/h.
- Altitudes for the airborne visual surveillance from 150 m to 750 m, (Bonn Agreement 2007a; p. 59).
- Electro-optical surveillance at altitudes from 300 m to 1000 m, (MMPI RH 2008).
- The minimum coverage of the imaged area in one flight hour is shown in Table 2. It is limited by the field of view of hyperspectral imaging scanner, although other sensors have larger coverage.
- Endurance of the helicopter Mi-8 flight with additional fuel tank is 4:15 h.
- Pre-flight calibration on the ground of the sensors and the inertial measuring unit lasts up to 30 min.
- Post-flight calibration on the ground lasts up to 15 min.
- Electric power is autonomous or provided from helicopter.
- Crew: pilot, co-pilot and technician. If educated and trained, can be visual observer, who manually sketches and/or collects oblique photography of the perceived oil spill.
- Surveillance team: mission leader – interpreter, operator of sensors, visual observer (technician can do this).
- Navigation system for surveillance and reconnaissance mission, independent although compatible with the navigation system of the helicopter.
- Wide band communication system from air to land via Internet with *Maritime Rescue Coordination Centre Rijeka* (MRCC).
- Delivered evidences on the oil slicks: a) first report to MRCC, b) second report to MRCC, c) full report to MRCC, d) reporting to the court (if required).

Table 2. *Coverage of the imaged area (km^2/h, width of the imaged strip, the spatial resolution in the direction of flight, in the direction perpendicular to the direction of flight in dependence of altitude H above sea surface.*

H	Strip width	Coverage	Resolution in flight direction	Resolution perpendicular to flight direction
m	m	km^2/h	m	m
300	99.9	11.99	0.171	0.208
400	133.2	15.98	0.228	0.277
500	166.5	19.98	0.285	0.346
600	199.8	23.98	0.342	0.416
700	233.1	27.97	0.398	0.485
800	266.4	31.97	0.455	0.554
900	299.7	35.96	0.512	0.623
1000	333	39.96	0.569	0.693

2.3. Types of the airborne missions

The airborne surveillance shall be functionally integrated with the service of EMSA CleanSeaNet (if their warnings are available), with Maritime Rescue Coordination Centre (MRCC), (MMPI RH 2008), (URL 1). While the date and time of the expected EMSA messages is determined and known in advance, it is possible to optimize the whole response and achieve minimum response time of the airborne missions. The airborne surveillance of the ship based oil pollution of the Adriatic Sea shall collect and provide the objective, reliable evidences having high confidence, which are acceptable and efficient in the legal prosecution of the polluters. For this purpose the surveillance system shall provide: a) near real time airborne evidences and reporting to MRCC, b) evidences obtained by later analysis and reporting to MRCC, c) evidences upon court requirements, with qualified explanation and interpretation of the applied methods, procedures and data (testimony of witnesses). The airborne surveillance of the oil pollution can be realized as:

A. Airborne *surveillance/search* mission initiated by the information about one possible oil spill, obtained from EMSA via MRCC.

B. Airborne *surveillance/search* mission initiated by the information about multiple (two or more) possible oil spills, obtained from EMSA via MRCC.

C. Airborne *reconnaissance* missions that cover the perceived high risk areas of the Adriatic Sea in a random manner (in space and in time) and produce effect of the quasi permanent surveillance, when are not available the information of EMSA CSN.

D. Combined mission of a type A. or B. with C., whereas mission starts at the day of planed information of EMSA CSN but before its arrival time.

E. Training missions, exercises, trials for the operational testing and development of the system.

F. Cooperation missions with other coastal countries of the Adriatic Sea, the first one should be with Italian Coast Guard regarding their Side Looking Antenna Radar[5].

The processes and the fusion that we consider depend in several aspects on the type of the airborne mission. Two types of missions were used to carry out the analysis of the fusion, and two examples are considered:

- Surveillance/search mission of the B type. EMSA CSN produced alarm for two possible oil spills, one was detected, and is named Oil spill 2008-10-14, Fig. 1.
- Reconnaissance mission of C type, without a priori information about the possible oil spill, although one was detected from air, and named Oil spill 2008-10-15, Fig. 2.

a) b)

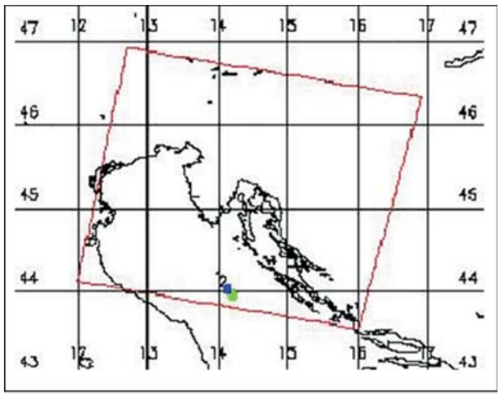
Fig. 1. *The Oil spill 2008-10-14. The geographic coordinates of the approximate centre of the spill detected from air were 44° 01' 41" N, 14° 07' 27" E. The data of this oil spill in space borne image reported 3:15 h before by EMSA CSN are shown in Table 3. The observer estimated the area 10550 m^2 of the oil spill from this raw, unprocessed image.*

Fig. 2. *Oil spill 2008-10-15 detected without earlier EMSA CSN information. It is shown on the raw oblique colour photography that the observer made by handheld Sony H2 photo camera, through the open door of the helicopter. On the right hand side is visible a part of the helicopter's winch. The geographic coordinates of the approximate centre of the spill were 44° 54' 16" N, 13° 28' 14" E.*

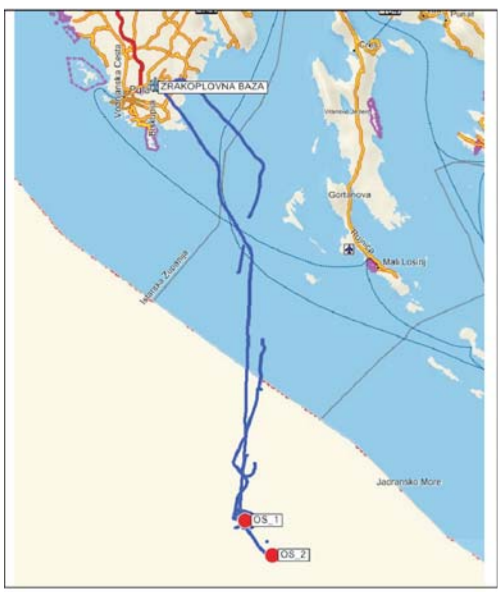
[5] Aulicino, D., Cau, D. (2010): Operational use of spaceborne SAR by the Italian Coast Guard, SeaSAR Symposium. Presentation at SEASAR 2010, the 3rd International Workshop on Advances in SAR Oceanography from Envisat, ERS and third party missions, 25–29 January 2010, ESA ESRIN, Frascati (Rome), Italy.

2.4. Airborne surveillance/search of the possible oil spill based on a priori alarm

The data about two possible oil spills No1 and No2 were received from EMSA CSN service via the MRCC Rijeka and the airborne mission was activated, Fig. 3. Only the oil spill No1 was detected (Oil spill 2008-10-14), Fig. 1, and despite an intensive search the possible spill No2 could not be detected. In EMSA report the confidence of the possible oil spill No1 was declared as medium in accordance to following criteria: medium contrast, sharp edges, smooth linear shaped slick, ho-



a)



b)

Fig. 3. *a) The EMSA CSN reports about two possible oil spills, initiated b) the airborne surveillance mission 2008-10-14. Legend: blue line – flight route, red dot – oil spills.*

mogenous surrounding. Its orientation was claimed SE – NW. The locations and dimensions of the spill No1 measured by EMSA CSN at 5:16 UTC and 3:14 h later by the airborne hyperspectral system differ, Table 3. The displacement could be a consequence of the sea currents and a wind. Airborne hyperspectral system used spatial resolution of 1 m, the spatial resolution of the SAR data was ~50 m, this could partially explain mentioned differences too. One more reason is also possible, the physical and chemical processes decrease area and oil quantity of the oil slick in time (evaporation and other).

The lack of the operational model of the spill shift due to wind and current speed and direction is critical for backward reconstruction of the oil spill positions and linking it to the positions of suspected polluter. The EMSA expectation of the availability of the mentioned models (shift, linking to the polluter) is rather sceptical (URL 4).

The airborne multisensor surveillance proved by several means, that *possible oil* spill No1 from EMSA CSN report is indeed a *real oil spill*. The processing, fusion and interpretation gave its size, shape, provided its map, measure of reflection coefficient, thematic map obtained by the classification of the hyperspectral images. Comparison of the EMSA CSN and the airborne assessment of this oil spill is given in Table 3.

By visual detection of the oil spill and by the application of *Bonn Agreement Oil Appearance Code* BAOAC (Bonn Agreement 2007b; p. 55–64), (Lewis 2007), to the geocoded photography Fig. 4, the oil spill assessment was approved. The main source of the data, information, were the hyperspectral images, of the oil spill and its surroundings, Fig. 5. The hyperspectral images are acquired at nadir and they are parametrically geocoded[6]. The observer's estimation was used in the fusion too.

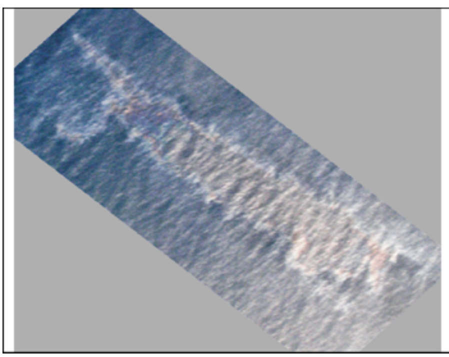


Fig. 4. *The best photography that visual observer made by hand held photo camera (Sony H2). Aimed for interpretation in accordance to BAOAC, thus it was registered to the hyperspectral images (and geocoded).*

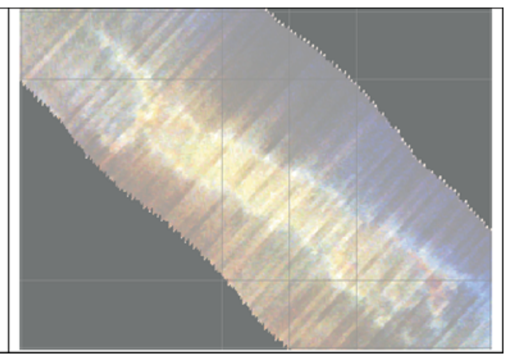


Fig. 5. *Three channels (0.755, 0.645 and 0.465 μm) of the hyperspectral images are visualised as red, green, blue image. Note that hyperspectral images are indeed a geographic map, showing the oil spill and the surrounding sea surface in the geographic coordinate system.*

[6] The parametric geocoding was done by PARGE software, Version 2.3, ReSe Applications Schlaepfer.

Table 3. *Data about the airborne verification of the information for the spill No1 provided by EMSA CSN service.*

	EMSA CSN, space borne SAR	**Airborne, hyperspectral and visual (BAOAC)**
Date	2008-10-14, 07:16 h	2008-10-14, 10:30 h
Coordinates	44° 01’ 41” N, 14° 08’ 28” E	44° 01’ 41” N, 14° 07’ 27” E
Area	0.15 km^2	0.015003 km^2
Width	0.20 km	0.075 km
Length	0.78 km	0.341 km

2.5. Application of Bonn Agreement Oil Appearance Code

The important step of the airborne detection, measurement and the mapping of the oil spill is the application of the *Bonn agreement oil appearance code* (BAOAC), Table 4, Fig. 6. The BAOAC can be applied on the oil spill a) which was perceived visually and sketched by the observer, b) or/and on the oblique aerial colour photography made by the observer.

Table 4. *Estimation of the oil quantity by the The Bonn Agreement Oil Appearance Code, (Lewis 2007).*

Code	**Description of appearance**	**Layer thickness Interval (μm)**	**Litres per km^2**
1	Sheen (silvery/grey)	0.04 to 0.30	40 – 300
2	Rainbow	0.30 to 5.0	300 – 5000
3	Metallic	5.0 to 50	5000 – 50,000
4	Discontinuous True Oil Colour	50 to 200	50,000 – 200,000
5	Continuous True Oil Colour	200 to More than 200	200,000 – More than 200,000

The reason is following: international maritime law and international and national courts accept the information provided by visual application of BAOAC, being the very valuable and strong evidence at the court. Note that BAOAC enables classification in up to five classes, Table 4. After the application of BAOAC, the observer concludes (or not) that the unknown object is the oil spill and thus provides (or not) the first evidence about the sea pollution by oil. When this has happen, the mission can continue by airborne hyperspectral and multisensor imaging at nadir. The acquisition of the hyperspectral and multisensor images should be done in optimum manner, regarding the Sun position, the location of the oil spill,

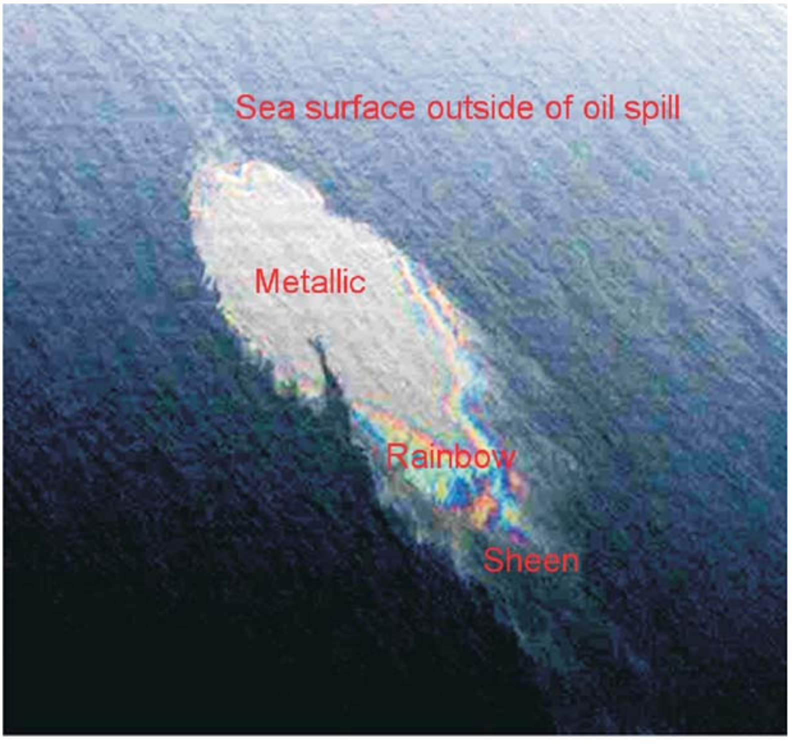


Fig. 6. *Example of the oil spill: metallic, rainbow and sheen appearance*[7].

flight direction, altitude and flight speed. The most important are the hyperspectral images, although images are acquired with other sensors too. The processing of the acquired hyperspectral data and the production of the hyperspectral images is quite complex (Šemanjski et al. 2008) and will not be considered here. The hyperspectral images are geocoded by means of the parametric geocoding and therefore they introduce high geographical and spatial accuracy (Schlaepfer et al. 1998), (Šemanjski and Gajski 2008).

As the next step, the observer acquires the best photography which will serve in further processing. This (the best) photography ought to be registered onto the hyperspectral images, after this processing it becames spatially and geographically accurate source of data for the application of spatially very accurate BAOAC estimation of the oil spill. Once the hyperspectral images and geocoded photography are available, it is possible to apply the knowledge of BAOAC on geocoded photography Fig. 4, Fig. 9 and achieve the very accurate spatial estimation of the oil spill features, Fig. 7, Table 5.

[7] Bjorn Vadt Christensen (2004): Appearance Code Sea surface Phenomena User Guide, Royal Danish Air Force, SQN 721 Air Base Aalborg, Thisted Landevej 53, DK-9430 Vadum, Denmark, June 2004. Access: June 2005.

Table 5. *Estimated quantities of oil by application of BAOAC on the best geocoded photographies Fig. 4, Fig. 9 of the oil spills from Fig. 1.a and Fig. 2.*

Oil spill date, area	**Minimum/maximum litres**			
	Sheen	**Rainbow**	**Metallic**	**Sum**
14.10.2008., 15003 m^2	0/0	2.40/40.07	34.94/349.45	37.35/389.52
15.10.2008., 220517 m^2	3.444/25.83	28.57/476.11	195.97/1959.65	227.98/2461.59

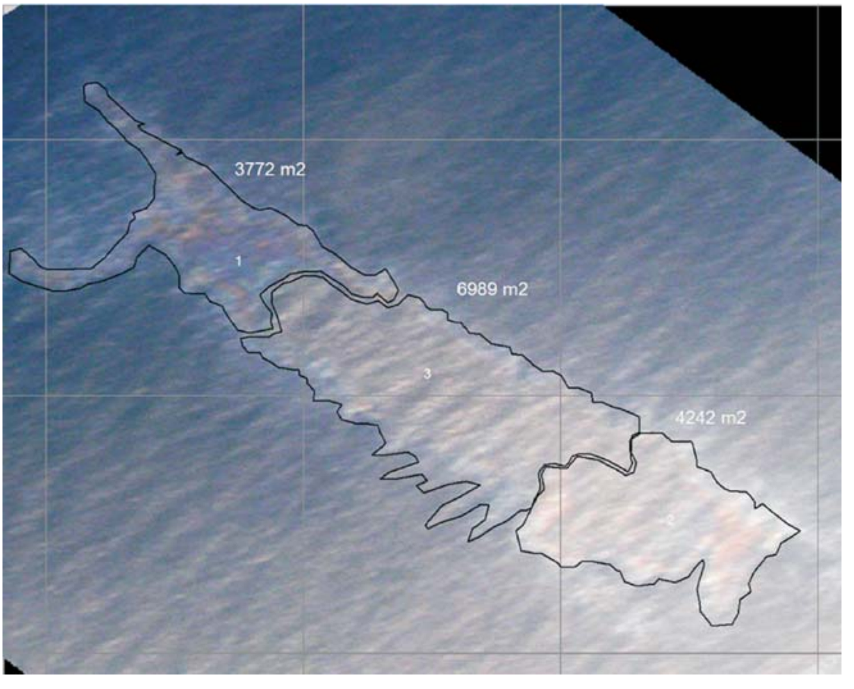
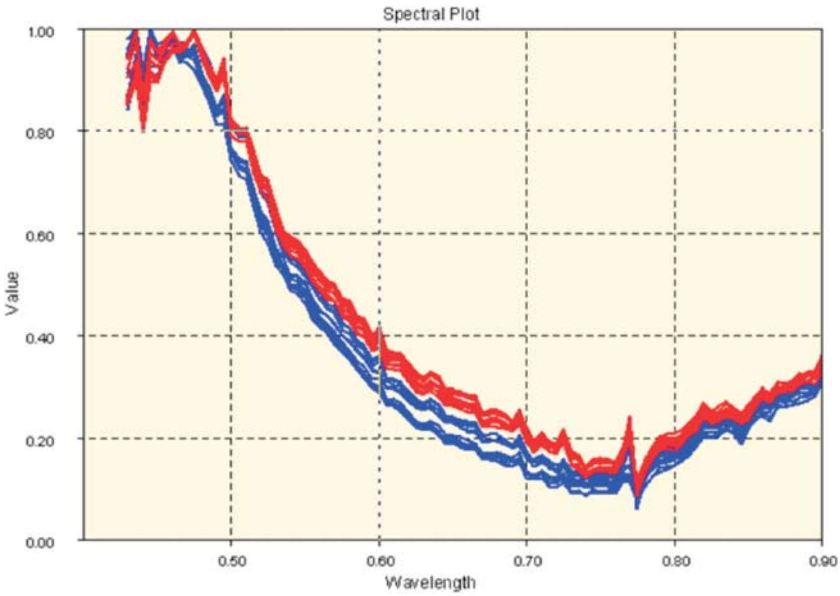


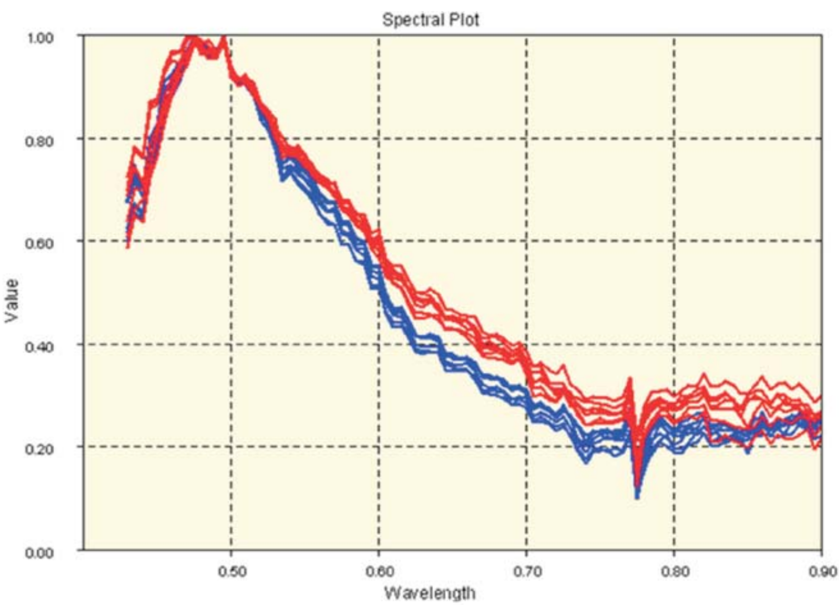
Fig. 7. *Estimation of oil spill features. Photography (acquired by Sony H2 photo camera) of the oil spill was registered and geocoded onto the hyperspectral images. By application of BAOAC on the geocoded photography the observer estimates area, shape, types and expected quantity of oil.*

2.6. Measurements of the oil spill reflectivity

Once, when the existence of the oil spill was positively confirmed by application of BAOAC, it is possible to add new evidences using the hyperspectral images. For this purpose the geocoded photography should be analysed, the polluted area, the clean water area outside of the spill should be identified and the coefficients of the reflection should be measured on the hyperspectral images. Measurement should be done at statistically significant number of points to provide reliable estimate of the measured reflectivity for both types of the surfaces, Fig. 8. The be-



a)



b)

Fig. 8. *Dependence of the coefficient of reflection on the wavelength in μ, measured for the samples inside of the oil spill area (red) and measured in the areas of clean sea water, outside of spill area (blue) on the hyperspectral images. a) Oil spill 2008-10-14, shown on Fig. 1, b) Oil spill 2008-10-15, shown on Fig. 2.*

haviour of the coefficient of reflection is new and very valuable feature of the oil spill, data obtained by the measurements of the reflectivity are new set of the evidences about the sea pollution by oil. The colour photography provides information in three wide wavelength bands (0.4 to 0.5 μm – blue, 0.5–0.6 μm green and 0.6 to 0.7 μm – red) and the visual estimation of the spectral features of the oil spill is coarse, while it is based on the radiometric resolution of colour of the spill. The hyperspectral images provide specific information about the oil spill in each of ninety five wavelength channels between 0.43 μm and 0.9 μm. Therefore the hyperspectral images provide thirty times finer spectral information then the colour photography.

2.7. Airborne reconnaissance of oil spill without a priori information

The airborne reconnaissance of the oil spill can be done if there is no a priori information about possible oil spill. Results of the example from Fig. 2 are shown in Fig. 9. Of course there are several important consequences in this case regarding the

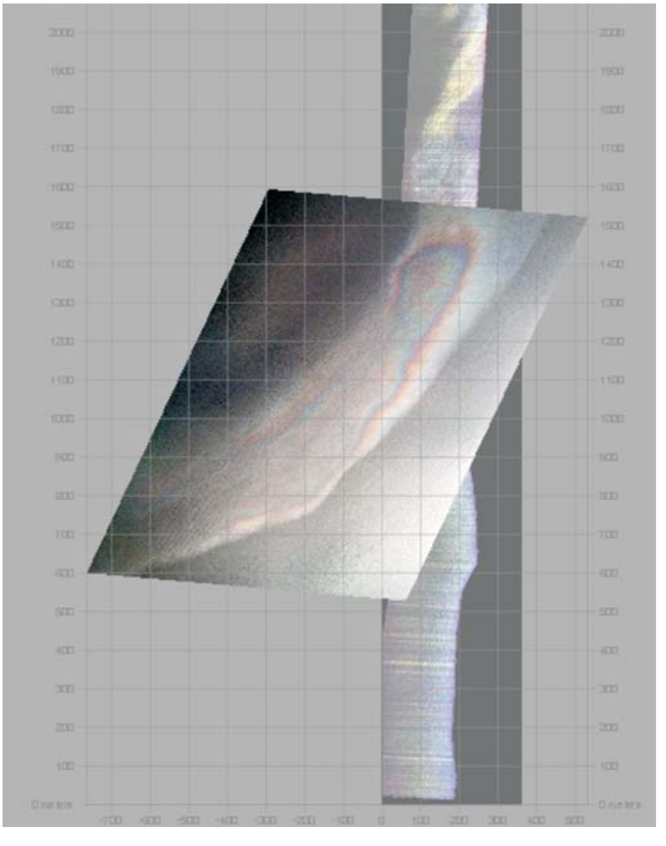
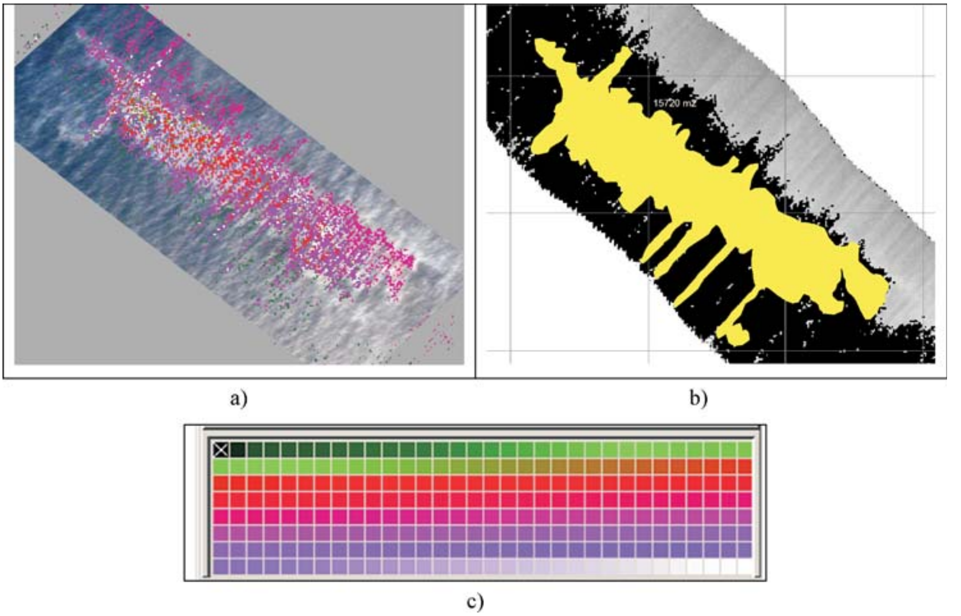


Fig. 9. *Oil spill 2008-10-15. The best photography that visual observer made by hand held (Sony H2) camera was geocoded on the hyperspectral images. Grid 100 x 100 m. The initial (raw and unprocessed) photography was shown on Fig. 2.*

whole process. The most important consequence is the increase of the time between the start of the airborne mission and the time when the oil spill will be perceived in comparison to the time needed when the initial information are given in EMSA CSN alarm. Once the oil spill was perceived and identified by visual observer or by pilots it is possible to detect it with all available means. After this event the procedure is similar to the procedure that was described above in sections 2.4., 2.5. and 2.6.

3. Detection of the oil spill by classification of hyperspectral images

The hyperspectral images enable very efficient classification and the detection of the oil spill and assessment of its area, its shape and estimation of the features of the spill, see example at Fig. 10. If combined with the subjective estimate in accordance with BAOAC of the oil quantity made by visual observer on the best geocoded photography, the thematic map obtained by the hyperspectral classification provides improvement of the oil's quantity estimate. This novel contribution overcomes the inability of the hyperspectral images to provide alone the measure of a thickness of the oil layer on the sea surface. Among several classification methods, the best results were obtained by SAM (Spectral Angle Mapping[8]) classifica-



a) b) c)

Fig. 10. *a) Classification map obtained by Spectral Angle Mapping method, for spectral angle threshold 2.3 degrees, b) spectral angle map, c) colour scale for the classification map. Made from hyperspectral image of the Oil spill 2008-10-14.*

[8] SAM is an automated method for directly comparing image spectra to a known spectra of end members as vectors and calculates the spectral angle between them. It is insensitive to illumination since the SAM algorithm uses only the vector direction and not the vector length. Date of access 2011-02-23, available from: http://www.csr.utexas.edu/projects/rs/hrs/analysis.html.

tion.[9] This classification method needs pure spectral samples – end members. The spectral samples should be taken on the hyperspectral images in the areas of the oil spill and in the areas of the clean sea water surface outside of oil spill. For the considered examples of the oil spills the best results were achieved with 2.3 degrees of the threshold spectral angle.

The dependence of the coefficient of reflection on the wavelength, Fig. 8, of the samples of the oil spill and the clean sea water provides additional information about their behaviour. Although the difference of the coefficients of reflection is visible, the ratio of the reflection coefficients is more informative Fig. 11, while it defines the region of wavelengths where discrimination could be expected. For the classification can be useful sub range from λ_a to λ_b, defined by ratio > 1. In example of the hyperspectral images Oil spill 2008-10-14, was λ_a = 0.475 μm and λ_b = 0.758 μm.

The hyperspectral classification by spectral angle mapping method (footnote 7), provides accurate assessment of the oil spill's area, its shape, distribution in different classes, its orientation in much more than five classes. In our analysis were

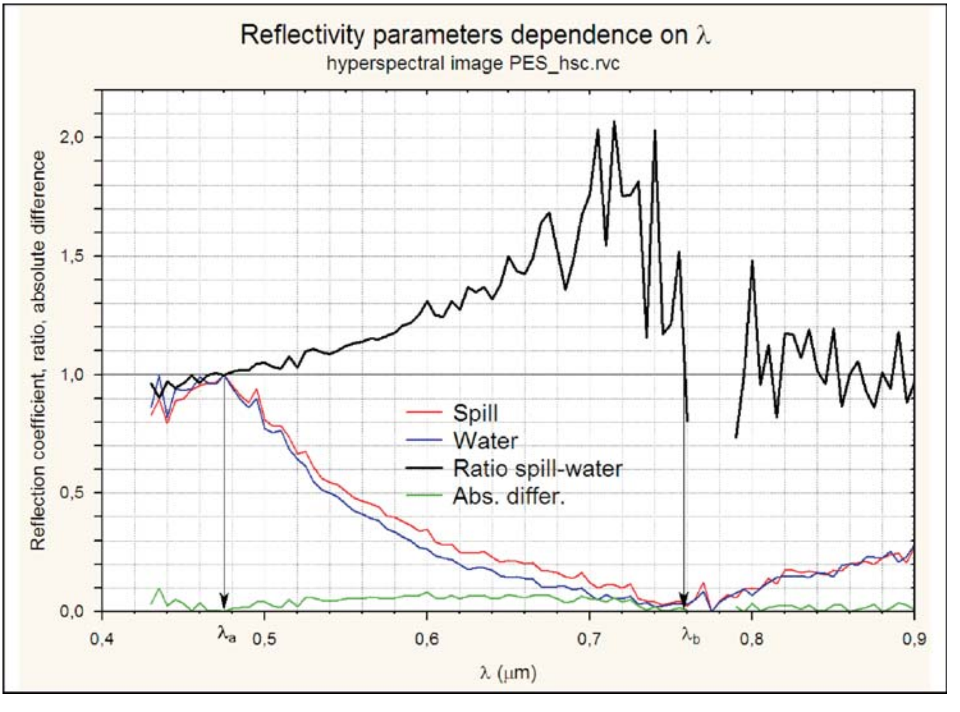


Fig. 11. *Ratio (black) and the absolute difference (green) of the reflection coefficients in the areas of the oil spill (red) and the clean sea water (blue), of the hyperspectral images of the Oil spill 2008-10-14. Absorption wavelengths are excluded from the calculations of ratio (black curve).*

[9] Used software: TNTmips 2008:74 (Windows 32-bit), Issue date: 4 Mar 2009; MultiSpec, URL: https://engineering.purdue.edu/~biehl/MultiSpec/download_win.html.

obtained eleven and twenty eight classes. Using the information of the coefficient of the reflection, of the spatial distribution of the oil spill obtained by BAOAC, of the interclass distance measure (e.g. Euclidean, Bhattacharrya) similar classess can be merged. The outcome of this process is new accurate and reliable map of the oil spill and the clean sea water, which uses information contained in all ninety five channels from visible and from near infrared wavelengths.

By means of the hyperspectral spectral angle mapping, the oil spill's area can be determined automatically (not manually, subjectively), using the spectral angle map. An example of the *Oil spill 2008-10-14* is shown on Fig. 10b. This is new potential for the assessment of the oil spill area, with advantages if compared with BAOAC assessment on the sketch of the oil spill, or on the raw unprocessed or even on the best geocoded photography, see comparison on Fig. 12.

a) 10550 m^2 b) 15003 m^2 c) 15720 m^2

Fig. 12. *Comparison of the methods for assessment of the oil spill area. Subjective manual estimation of the spill area by BAOAC methodology a) on the sketch or on the raw, unprocessed image from Fig. 1a, b) on the best geocoded photography. c) The automatic measurement of the oil spill area on the hyperspectral images.*

4. Fusion of aerial images, data and knowledge of the ship-based oil pollution of the sea

There are two main pillars of considered airborne system for the surveillance of the sea pollution by oil: use of the *hyperspectral airborne remote sensing* (imaging, mapping, measurement and interpretation) and the use of the *fusion*. Here we consider main aspects of the fusion, which can be compiled in simplified form from (Hall and Llinas 1997), (Hall and Llinas 2001), (Wald 2002):

"*Fusion is the use of techniques that combine data, information, knowledge from multiple sources and gather, process, interpret that data, information, knowledge in order to achieve inferences and/or decision which will be more efficient, more accurate, more reliable and confident, than if they were achieved by means of a single source*".

Fusion can be accomplished on data and information (lowest level), at the level of the features and signatures derived from data or from information (middle level) and on the level of inferences or decisions (highest level) provided by sources, with inclusion of the knowledge. All levels of fusion are applied in the considered airborne system for the surveillance of the oil slicks at the sea.

Processes and fusion levels

The processes of the considered oil spill detection start a) either with satellite SAR alarm (provided by EMSA CSN to MRCC) which contains information and data about the *possible oil spill*, its location, shape, features, b) or/and with the airborne multisensor detection. The EMSA CSN set of data and information is delivered at least 30 minutes after the detection of the possible oil spill and serves to initiate the aerial multisensor search and the reconnaissance. The location, dimensions and orientation of the possible oil spill are included into expected region of interest (ROI_0). The wider region is defined for search too (ROI_s). The airborne search starts at the position defined in EMSA CSN report, taking into account possible shift of the oil spill. In the case that the a priori information is not available, the mission starts with assumed wider region (ROI_{rs}) for reconnaissance and search, taking into account intensity of the vessel traffic in the Adriatic Sea, Fig. 13.

The visual search of the possible oil spill (made by pilots and visual observer) serves for decision whether to continue or to stop the mission. If the visual observer/or pilots perceive the *possible* oil spill and establish the truth by evidence and

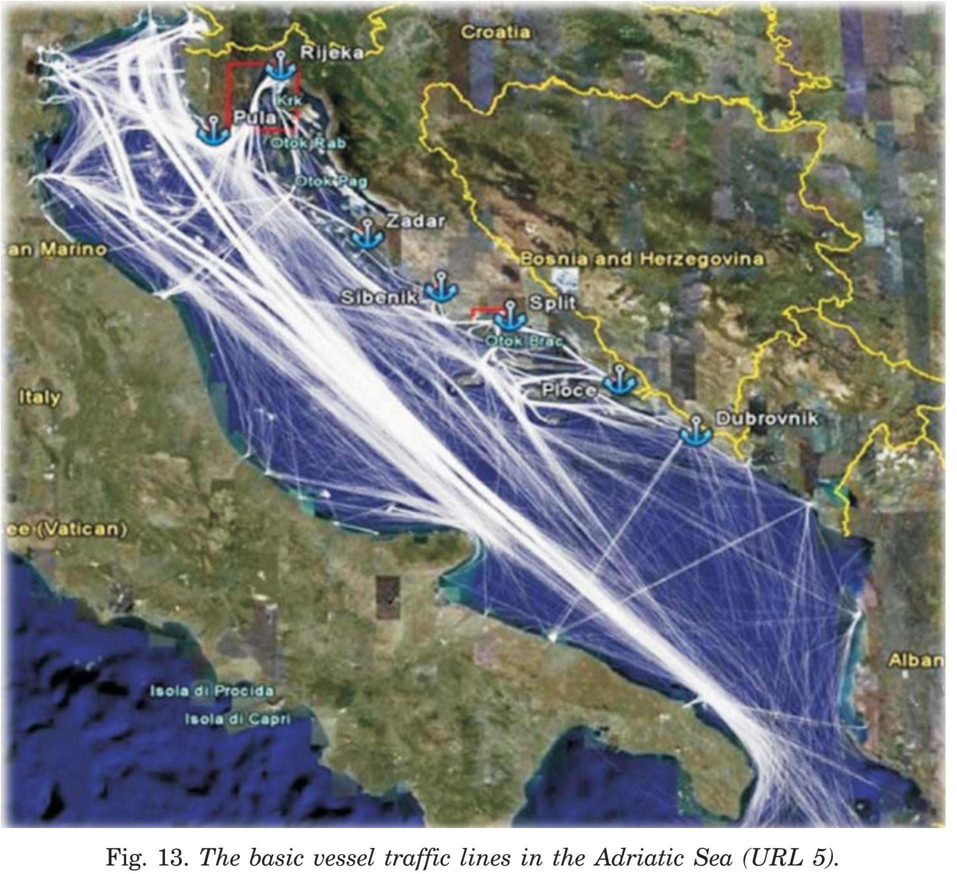


Fig. 13. *The basic vessel traffic lines in the Adriatic Sea (URL 5).*

arguments of BAOAC methodology (manual sketch, subjective estimation of the spill appearance, area and oil quantity) that this is a *real* oil spill, the mission can continue. The knowledge formalised in BAOAC and the data derived by the visual observer are the first inclusions into a fusion. Here the fusion was applied at the level of the inferences. The next process is the hyperspectral imaging of the oil spill at nadir and the production of the hyperspectral images, follow registering and geocoding of the manually acquired oblique photography onto hyperspectral images. The registering (and geocoding) of the best oblique photography onto the hyperspectral images is the second application of the fusion, which was done at the pixel level. Once the photography was registered and geocoded, starts higher level of the processing and the interpretation, which was described in the sections 2.4, 2.5, 2.6. The methodology of BAOAC can be applied once again but on the best geocoded photography. Due to high spatial accuracy and precision of the geocoded photography, obtained by the fusion, the area of the oil spill, although determined manually, has increased accuracy in comparison to the area determined in the first step. Besides the oil spill area, the clean sea surface is also defined by this step. Here the features (areas, borders) are fused. Due to the hyperspectral images, the oil spill area can be assessed automatically, with high spatial accuracy by means of the Spectral Angle Mapping classification and the spectral response can be measured. The measured coefficients of the reflection of the oil and the clean sea surface, the features of both kinds of surface, are the new evidences included in the fusion. Thematic map obtained by the classification provides much more than five classes (note that maximum limit of BAOAC is five classes). The similar classes can be merged gradually, checking their spatial distribution, the interclass distance measure (e.g. Euclidean, Bhattacharrya), coefficient of reflection. The outcome of this process is a map of the oil spill and the clean sea water, which contains information of all ninety five channels from visible and from near infrared wavelengths. At this level in fusion are included all derived features and the evidences about the oil spill provided by the aerial multisensor system.

5. Limitations and future research

The main limitations and disadvantages of the developed and considered aerial hyperspectral multisensor surveillance of the pollution of the sea by the ship sourced oil is its dependence on the optical visibility and the time duration of the whole process if the EMSA CSN message initiates the airborne surveillance. In this time between EMSA CSN message and the perceiving the oil spill from air, the polluter changes its position, the same happens with the spill, this decreases possibility and probability of the assessment of the right polluter, (Ferraro et al. 2010). Thus, the total time duration of the surveillance shall be minimized, particularly are critical several processes, marked in Table 6.

The applied hyperspectral mapping and interpretation, being strengthened by the fusion, is limited to the detection of the oil spill, without a priori available spectral library for oil spills. The statistically significant amount of the spectral samples was collected of the clean sea surface and of several oil spills during the first airborne mission (MMPI RH 2008). Collecting the spectral samples should continue. Moreover to the considered principal limitations, there are several technical

Table 6. *The list of the activities and corresponding execution times determined in the exercise (MMPI RH 2008). The most critical are the actions 4, 5, 6, less critical are 9, 10 and their times should be minimized.*

Nr.	Activity	Symbol	Feasibility of shortening
1	EMSA message arrival in MRCC Rijeka	T_{EMSA}	Nominally 30 min, often is shorter.
2	take-off at t_0, $t_0 – t_{emsa} < 5$ min	T_0	By training.
3	flight to expected region of interest	$T_{flight1}$	Depends on the distance from airport.
4	search of oil slick, perceiving, BAOAC	$T_{search1}$	Optimize search: pilots, two observers.
5	mapping oil slick, 1st reporting to MRCC	$T_{report1}$	Can be as short as 5–15 minutes, onboard.
6	pre-processing, 2nd reporting	$T_{report2}$	Optimise, make parallel, onboard.
7	landing; fuel tanking, repeating steps 4, 5, 6, 7, for next slicks flight to airport	$T_{tanking}$ T_{return}	
8	post-flight calibration	$T_{postcal}$	
9	processing, delivery imagery and data	$T_{processing}$	After landing.
10	post-flight interpretation, full reporting	$T_{fullreport}$	After landing and processing.

limitations in the existing system. The most important are a) the duration of the transforming of the acquired raw hyperspectral data into hyperspectral channels and b) the parametrical geocoding. In the time of the exercise (MMPI RH 2008) the processing of the raw data into channels lasted several hours for several kilometres of the mapped strip, later it was reduced to less than twenty minutes. The parametric geocoding lasted hours, now it can be done in the range of ten to thirty minutes. This proves that the lasting of the processes shown in Table 6 can be reduced, the research in this direction is under way. The future research could and should a) continue advancement of the aerial hyperspectral multisensor surveillance of the pollution of the sea by the ship sourced oil, b) start development and the implementation of the fusion at the level of evidences or decisions, between the aerial hyperspectral multisensor surveillance and Croatian vessel traffic monitoring and information system (CVTMIS), Automatic Identification System (AIS, 17 base stations) and the Adriatic sea radar network system (10 stations), (URL 6), c) start scientific cooperation with Coastal Guard of Italy regarding the common surveillance of the sea oil spills with their Side Looking Antenna Radar (SLAR) and our airborne hyperspectral multisensor surveillance.

6. Conclusion

The aerial hyperspectral and multisensor surveillance of the pollution of the sea by ship sourced oil spills was researched. The fusion decreased errors in area and oil spill quantity estimation from 4.5% to 32.8%, increased confidence of the oil spill detection from low (observers BAOAC estimation) to high (hyperspectral), and enables its implementation into operationally feasible system. Based on previous facts we uphold the further development of surveillance system of the ship sourced oil pollution of the Adriatic Sea, with key pillars already available: EMSA CSN and multisensor airborne surveillance system. The fusion of the aerial and the space borne remote sensing technologies with the Croatian vessel traffic monitoring and information system (CVTMIS), Automatic Identification System (AIS) and the Adriatic Sea radar network system should be a next goal.

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Zrakoplovni hiperspektralni nadzor uljnog onečišćenja s brodova u hrvatskom dijelu Jadranskog mora

SAŽETAK. Istražen je hiperspektralni i multisenzorski nadzor uljnog onečišćenja mora s brodova pomoću zrakoplovnog sustava razvijenog u okviru projekta "Sustav za multisenzorsko zrakoplovno izviđanje i nadzor u kriznim situacijama i zaštiti okoliša" (MZOS 2007). Budući da su korištene različite metodologije, metode, tehnologije i tehnike, primijenjena je višerazinska fuzija za povezivanje podataka, procesa i njihovih izlaza. Fuzija uključuje zrakoplovne hiperspektralne i kolor snimke, vizualno detektiranu uljnu mrlju, formalizirano znanje za procjenu površine uljne mrlje i količine ulja, na temelju koda iz sporazuma iz Bonna o pojavnosti ulja (BAOAC), podatke o spektralnom odzivu čiste i uljem onečišćene morske površine, rezultate hiperspektralne klasifikacije. Osim informacija prikupljenih zrakoplovnim multisenzorskim sustavom, u proces fuzije bile su uključene informacije dobivene od svemirskog sustava CleanSeaNet Europske agencije za pomorsku sigurnost – EMSA (u okviru velike pokusne aktivnosti – operativne vježbe u 2008.). Prednosti zrakoplovnih daljinskih istraživanja uljnih mrlja su pouzdana detekcija uljnih mrlja, precizno definiranje njezinog položaja i oblika u geografskim koordinatama, klasifikacija sadržaja uljne mrlje, mjerenje njezinih obilježja, procjenu količine ulja.

Ključne riječi: *uljna mrlja, onečišćenje, Jadransko more, hiperspektralno, SAM, zrakoplovna daljinska istraživanja.*

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