CompMon

Compliance monitoring pilot for MARPOL Annex VI

Best Practices Airborne MARPOL Annex VI Monitoring

Ward Van Roy - MUMM

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Abstract

Piloting of airborne platforms has been defined under Activity 3 of the CompMon Project. The main objective of this activity was to assess the use of airborne Fuel Sulphur Content (FSC) measurements for monitoring sulphur compliance of ships sailing in the open sea within the SECA area. During the recent years the development of sensor systems for airborne FSC monitoring has left the academic level and these sensor systems have been commercialised. Present systems are based on 1) standardized equipment for air quality monitoring that has been modified for flight operations 2) optical sensors or DOAS 3) light weighted low cost sensors with high response time for use on UAV or helicopter. Although these recent technical developments allowed the execution of airborne sulphur compliance monitoring, little progress has been made on the development of standardized operational procedures.

To tackle this issue, the development of a Best Practice report was defined under Activity 4 of the CompMon Project. As part of this activity two workshops addressing best practices on airborne MARPOL Annex VI monitoring were foreseen: an internal CompMon Operator Workshop for project partners, which took place in Helsinki on the 14th of April 2016 and a 2nd CompMon Operator Workshop addressing a broader audience which was held in Brussels on the 7th of December 2016.

During the first operator workshop, project partners were able to share and discuss their operational procedures when conducting airborne MARPOL Annex VI monitoring. During this first operator workshop a set of operational procedures was agreed upon and the findings were compiled into a draft 'Best Practice Airborne MARPOL Annex VI Monitoring' report. The operational procedures agreed upon during the workshop where used during the airborne MARPOL Annex VI monitoring campaigns in the further time frame of the CompMon project. The draft 'Best Practice Airborne MARPOL Annex VI Monitoring' report was submitted and presented at OTSOPA, the operational, technical and scientific working group of the Bonn Agreement to inform the BONN Contracting Parties about the Action and the operational procedures.

The operational procedures described in the draft 'Best Practice Airborne MARPOL Annex VI Monitoring' report have been thoroughly tested in the field for 6 months. The results, experiences and lessons learnt have been discussed during the 2nd CompMon Operator Workshop. The final outcome has been compiled in this final 'Best Practice Airborne MARPOL Annex VI Monitoring' report. This report provides an operational guidance on how to perform MARPOL Annex VI airborne monitoring. The monitoring of ship plumes poses an operational challenge and is not without risk. This report aims at enhancing the efficiency of and safety during MARPOL Annex VI monitoring operations as it gives indications on flight approach, altitude, distance to ships, speed, plume localization, sampling attempts, weather minima and safety recommendations.

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1 Introduction

1.1 CompMon Framework

On the 1'st of January 2015 the new sulphur content limits of the revised MARPOL Annex VI regulation, relating to a reduction in the Fuel Sulphur Content (FSC) entered into force in the European SECA area, which consists of the North Sea and the Baltic Sea. Within the European Union the new sulphur limits were ratified through the Council Directive 1999/32/EC of 26 April 1999, relating to a reduction in the sulphur content of certain liquid fuels and Directive 2012/33/EU of the European Parliament and the Council of 21 November 2012 amending Council Directive 1999/32/EC as regards the sulphur content of marine fuels.

In order to be able to address the issues concerning the use of new, innovative techniques in support of the enforcement of MARPOL Annex VI regulations, the CompMon (Compliance Monitoring) partnership was established in 2014. In 2015 the CompMon network applied for financing by the European Union funding program, Connecting Europe Facility (CEF). The project with projectname: "Compliance Monitoring pilot for MARPOL Annex VI (CompMon)" with proposal nr: "2014-EU-_TM-0546-S" was submitted by the CompMon partnership and accepted by the CEF. The goals and specifications of the CompMon project have been defined in the Grant Agreement (INEA/CEF/TRAN/M2014/1025268).

The CompMon project aimed to produce monitoring information which can be used by national PSC authorities to target on-board inspections in a cost-efficient manner. The CompMon consortium achieved this by using remote sensing and sampling methods to determine the compliance of individual vessels. While currently monitoring information needs to be complemented with other (on-board) evidence for legal proceedings (with fuel sampling and analysis currently forming the main evidence of a legal case), the CompMon actions:

- have demonstrated that targeting of vessels through airborne monitoring works effectively and significantly improves the enforcement chain as a whole;
- set the basis for further standardization and approval processes needed to use monitoring data as prima facie evidence.

Various CompMon activities have been ongoing in several EU Member States since 2014. In particular Sweden, The Netherlands, Finland and Denmark have installed several pilot fixed sniffing instruments and/or used remote sensing equipment for MARPOL Annex VI monitoring. Under Activity 3 of the CompMon project, Sweden and Belgium have equipped 2 fixed-wing aircraft with sensor systems and have executed monitoring flights. A third aircraft was equipped by FMI in Finland, but this aircraft has not been used for monitoring so far.

Chalmers University of Technology has installed and certified (conform EASA rules) a sensor system for airborne FSC measurements on a Navajo Piper. As part of CompMon, sulphur compliance monitoring of 74 vessels were carried out at the SECA border during 27 flight hours. As part of an associated project funded by the Danish Environmental protection agency additional 240 flight hours were carried out on the North and southern Baltic Sea. The results for the Chalmers measurements are given in a separate CompMon report.

MUMM (Management Unit of the North Sea Mathematical Models) has installed and certified (conform EASA rules) a sniffer system on board of the Belgian coast guard aircraft, a BN Islander. The aircraft conducted 152 on task flight hours during two years for MARPOL Annex VI compliance monitoring over Belgian waters and waters of neighbouring countries (Bonn Agreement Quadripartite Zone). The Netherlands (ILT) financed 25 flight hours of these 152 hours for monitoring over Dutch waters. In the total time frame of this project for 1347 ships FSC measurements were conducted using the Belgian aircraft and 107 incompliant ships (FSC >0.2%) have been observed and reported to PSC.

In addition the Netherlands Shipping Inspectorate have contracted a rotary wing aircraft (helicopter) for sniffer measurements, this action was not included in the CompMon project. Although some actions were not included in the CompMon project, compliance information for all mentioned actions was shared within the CompMon consortium.

1.2 First CompMon Operator Workshop

On the 14th of April 2016 the first CompMon Operator workshop was organised by Belgium (MUMM) in collaboration with Finland (TRAFI). There were participants from Belgium, Denmark, Finland, France and Sweden. Both academic, private as well as governmental organisations were represented. The main focus of the workshop was to assemble technical and operational experts, actively involved in airborne MARPOL Annex VI surveillance and enforcement to jointly discuss and agree upon standard operational procedures for the execution of MARPOL Annex VI aerial monitoring.

During the workshop the participants were able to exchange and discuss their respective views and opinions on MARPOL Annex VI airborne surveillance and jointly contributed to compose the draft operational procedures and standards for the execution of airborne MARPOL Annex VI monitoring. These draft procedures were to be tested during the following monitoring campaigns and if approved (during the final evaluation and fine-tuning workshop), they were to be adopted in a final 'best practice' document.

MUMM (Be), Chalmers University (Se) and the FMI (Fi) first presented their monitoring results obtained so far. Thereafter, the private companies CLS and Explicit presented the use of Remote Piloted Airborne Systems (RPAS) and helicopters in combination with low cost sensors. After this MUMM led the discussion about the operational procedures for airborne MARPOL Annex VI monitoring. Finally, ÄBO Akadem University presented the legal issues concerning the use of airborne data as evidence to court and possibilities for legal enforcement through the use of administrative penalties.

1.3 Second CompMon Operator Workshop

On the 7th of December 2016 the second CompMon Operator workshop was organised by Belgium (MUMM, in collaboration with FPS Mobility). There were participants from Belgium, Denmark, Finland, France and Sweden, also the European Commission was represented. Again, both academic, private as well as governmental organisations were represented during the workshop. This time however, participation was not limited to CompMon partners only, but was open to a broader audience of experts involved in aerial surveillance and monitoring.

In the morning session the needs of PSC were expressed. It was made clear by the PSC inspectors that airborne monitoring can provide vital targeting information to the PSC. Aircraft provide a wide scanning tool (both in time and space) to monitor compliance levels at sea. Furthermore the PSC inspectors made clear that reporting of possible non-compliant vessels needs to be done in the shortest time possible to enable the PSC inspectors to perform an on board inspection at the next port of call.

Next, Chalmers and Explicit presented the current situation on the development of airborne sensors for FSC monitoring. At the end of the morning, the results of the different airborne monitoring activities were presented by MUMM, ILT and Chalmers.

In the afternoon session the main focus was on the evaluation and finetuning of the draft operational procedures agreed upon during the first CompMon Operator Workshop, based on the experience gained and lessons learnt throughout the CompMon period. The workshop participants were able to intervene in the discussions and provide an expert view on the operational procedures.

2 FSC measurement sensors for airborne platforms

At present three types of sensor systems exist for the execution of airborne measurement of ship emissions and the calculation of the fuel sulfur content (FSC) of the monitored ships. The first is an optical sensor or DOAS, the second is an active high sensitive sniffer sensor, the third is a light weighted mini-sniffer system.

2.1 DOAS

The Differential Optical Absorption Spectroscopy (DOAS) sensor uses UV absorption characteristics of the ultraviolet portion of the sun or blue sky to determine path integrated concentrations of SO_2 and NO_2 across the stack gas plume of the ships. The SO_2 measurements can be combined with wind speed measurements and a calculation of the fuel usage to determine the sulphur fuel content of ships with a relative accuracy of about 50% at the 1 % FSC level. This is sufficient to discriminate between ship operating with 0.1% and 1 % FSC, respectively. A more straight forward variant, which has been applied in CompMon, is to utilize the measured ratio of SO_2 and NO_2 in the stack gas plume to discriminate between ships running on high (1%) and low FSC (0.1%). Test carried out as part of CompMon shows that it is possible to discriminate between high and low FSC ships with a probability of 80-90 %. See separate CompMon report and appendix on this topic. Since the DOAS measurements can only distinguish between high and low FSC ships the measurements are often confirmed by a more accurate and precise sniffer sensor. The advantage of the DOAS sensor is that it can be operated at higher altitude (800ft) than the sniffer systems, since it does not require contact with the emission plume, and that it is very easy to find the emission plume of the ships which makes the measurements faster. The disadvantage is the lower precision in determining the FSC and the fact that it can only be operated during daylight. However at the right meteorological conditions this system is can be efficient as an "early warning system" to distinguish between a high FSC (>1%) and a low FSC (<1%).

2.2 Sniffer

The standard sniffer sensor is based on a combination of an IR radiometer for the measurement of CO_2 concentrations and a UV fluorescence instruments for measurement of SO_2 concentrations in an airflow provided through a probe installed on the aircraft body. These rapid high sensitivity sensors measures very low gas concentrations (parts per billion and parts per million, respectively) with a resulting accuracy between 0.1-0.2% FSC which can be further increased if combined with an additional NO_x sensor (up to 0.05-0.1% FSC). The system can be used all year long and during most weather conditions but it requires an active sampling of ship exhaust plumes at low altitude. The sniffer monitoring is therefore not without risk for the aircraft and crew resulting in the use of safety precautions and more restrictions on the organisation of the monitoring flights (safety management, national authorization for low flight operations) and the type of aircraft (size, speed, multi-crew configuration, …).

2.3 Mini-sniffer

A new type of sniffer sensors has been recently developed based on light weighted, low cost sensors. These sensors have a much slower response time making them solely suitable for helicopter and RPAS installation and less suitable for fixed-wing aircraft installations. These sensors have shown promising results during initial test campaigns with a high precision in determining FSC at high flue gas concentration levels (RSD up to 0.03% FSC), validation measurements have been performed to compare FSC measurement data with on board fuel sampling data and standard sniffer FSC measurements and these results are looking promising, although more validation is required to determine the actual accuracy in the field.

As fixed-wing aircraft are still the most common airborne platforms for the execution of airborne maritime surveillance, the standard sniffer sensor is still considered to be the main sensor for airborne MARPOL Annex VI monitoring at sea, but dedicated rotary wing airborne maritime surveillance operations are frequently organised, therefore operational procedures for all sensor types were discussed during the workshop. More detailed information about the sensors is provided in Annex 1.

3 Flight procedures

3.1 Flight Approach

The monitoring of ship plumes with a sniffer sensor is not without risk and a well-considered flight approach is recommendable. For fixed-wing aircraft with sniffer sensors, 5 different scenarios for flight approaches can be defined according to the wind vector (Vw = direction and force) and the ship vector (Vs = course and speed).

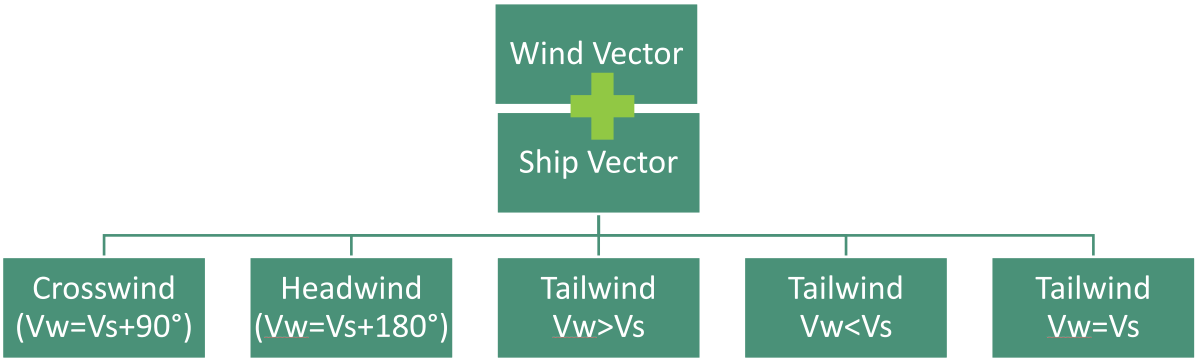

Figure 1 Flight pattern: 5 scenarios

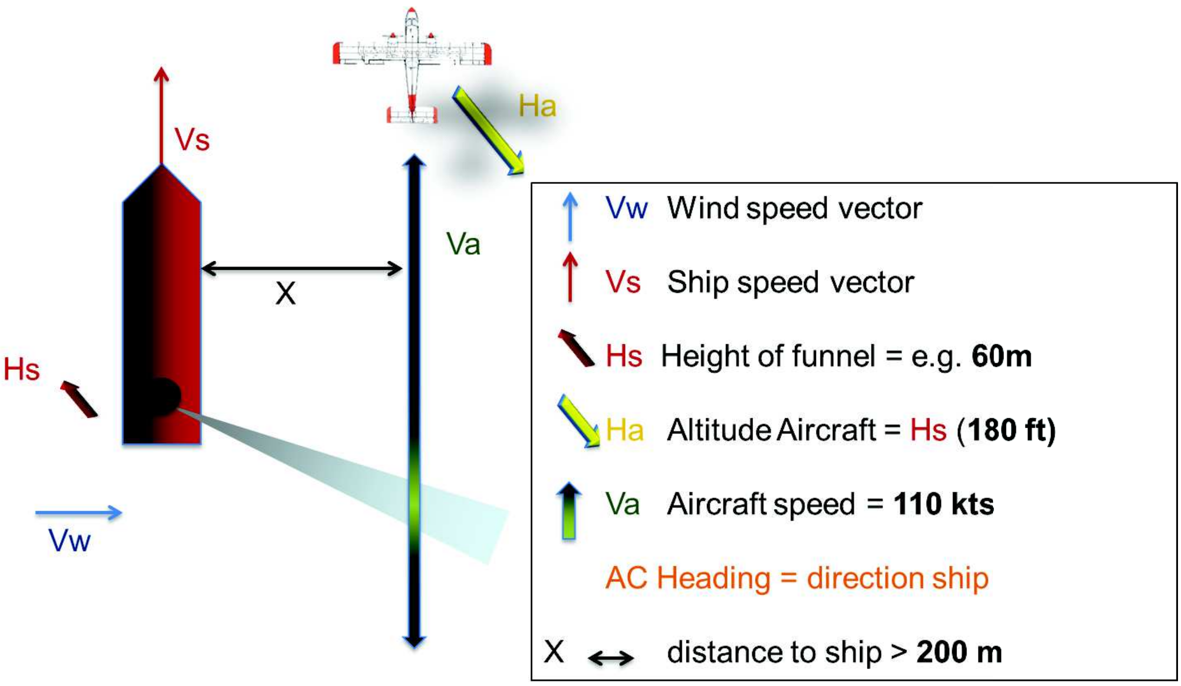

Figure 1 Crosswind Scenario (Vw = Vs +90°)

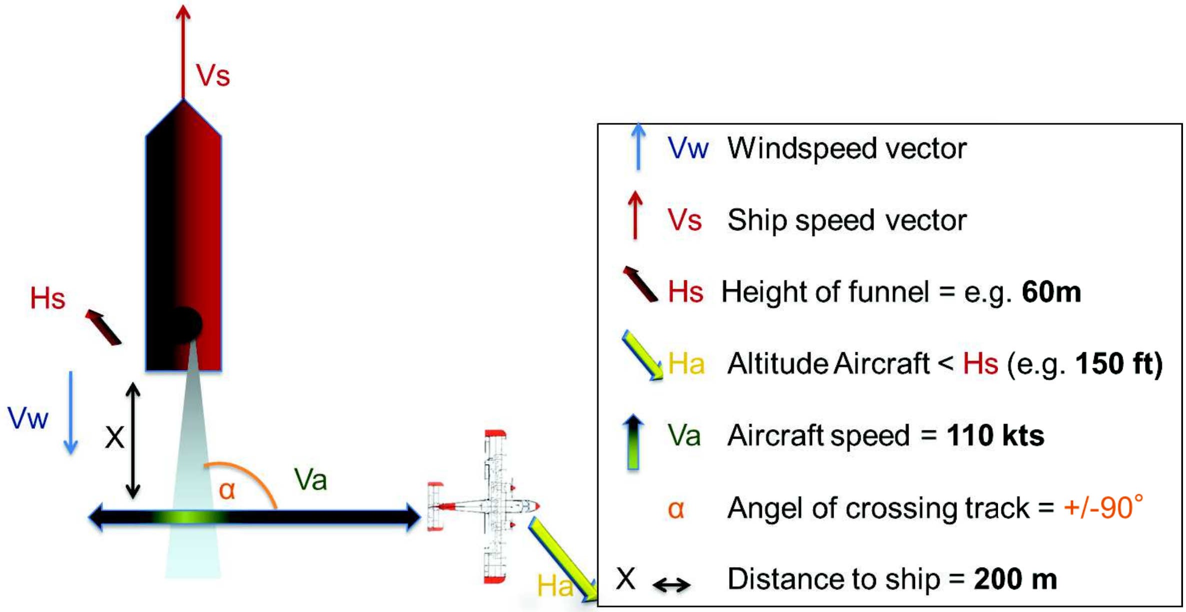

Figure 2 Headwind Scenario (Vw = Vs + 180°)

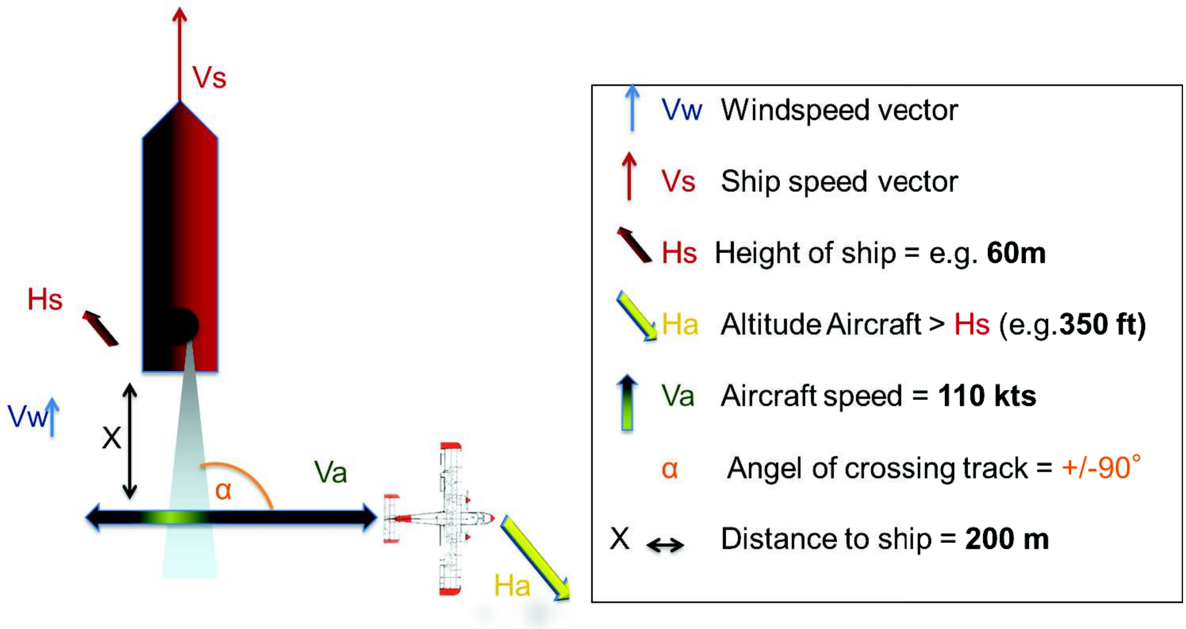

Figure 3 Limited tailwind Scenario (Vw<Vs)

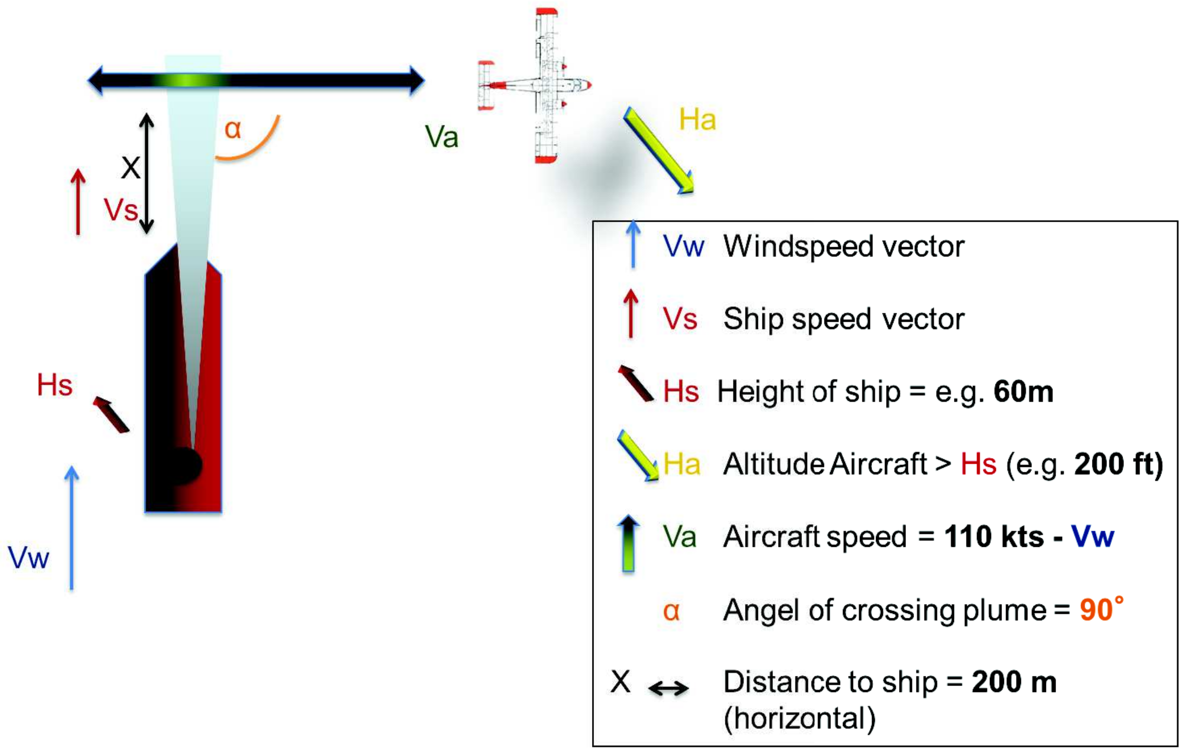

Figure 4 Strong tailwind Scenario (VS<VW)

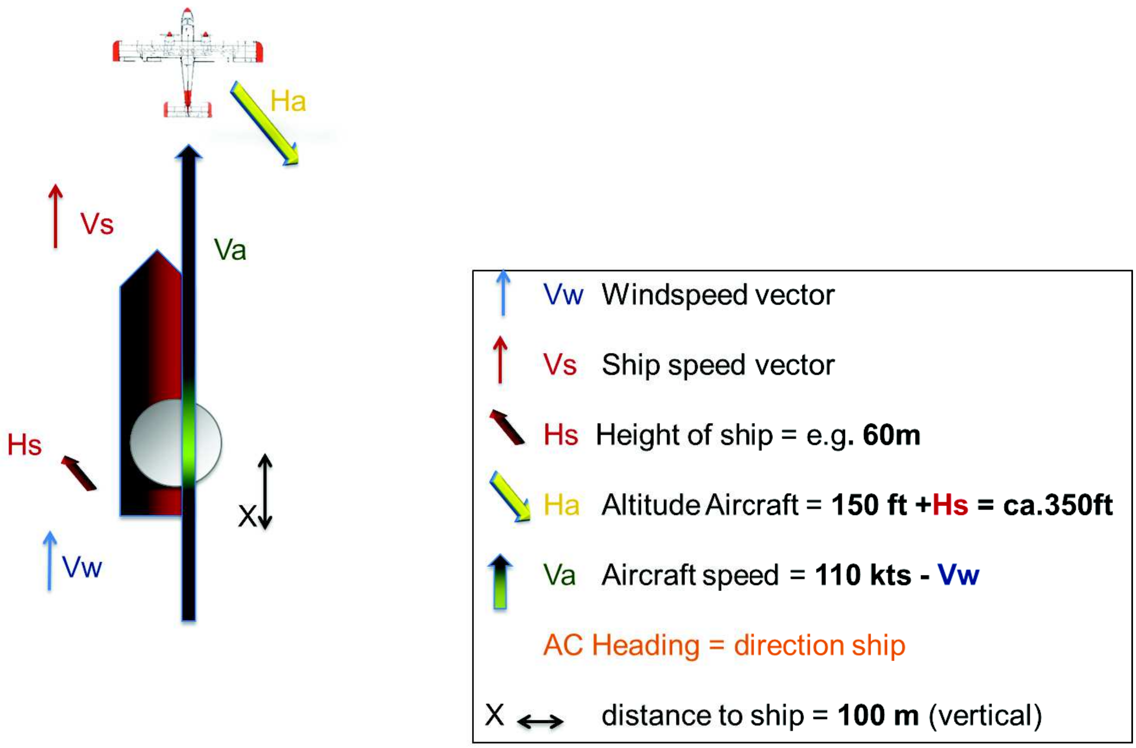

Figure 5 Vertical plume scenario (Vw=Vs)

The main principle is that the **exhaust plume is sampled in a straight line with a heading never directly towards the ship, against the apparent wind direction with an angle of ca. 90° relative to the direction of the exhaust plume**. Depending on the angle of the wind, the plume may be found higher or lower than the funnel height. In 4 out 5 scenarios the plume is sampled downward wind (wind will move the aircraft away from the ship), only in case of a soft tailwind, the wind may be blowing the aircraft towards the ship but at negligible force (<10 kts). To optimally plan the approach, it is important that the pilots have a good understanding on the location of the plume, therefore the use of well-developed navigation software and communication with the pilots is vital (see 3.5).

In 4 out of 5 scenarios, the aircraft never has to fly directly over the ship. Only in the (rare) scenario with tailwind where Vw = Vs giving a vertical smoke plume, the aircraft has to fly over the ship. In all other cases, a minimum distance of 200m from the ships is recommended.

For fixed-wing aircraft with DOAS sensor, the flight pattern is very simple, sunlight is reflected on the water surface and when passing through the smoke plume, some wavelengths of the light spectra are absorbed, the DOAS sensor just needs to be aimed on the smoke plume to detect this absorption. For clear readouts of the absorption in the smoke plume compared to the background value, it is advised to fly perpendicular to the direction of the smoke plume, but this is not strictly necessary.

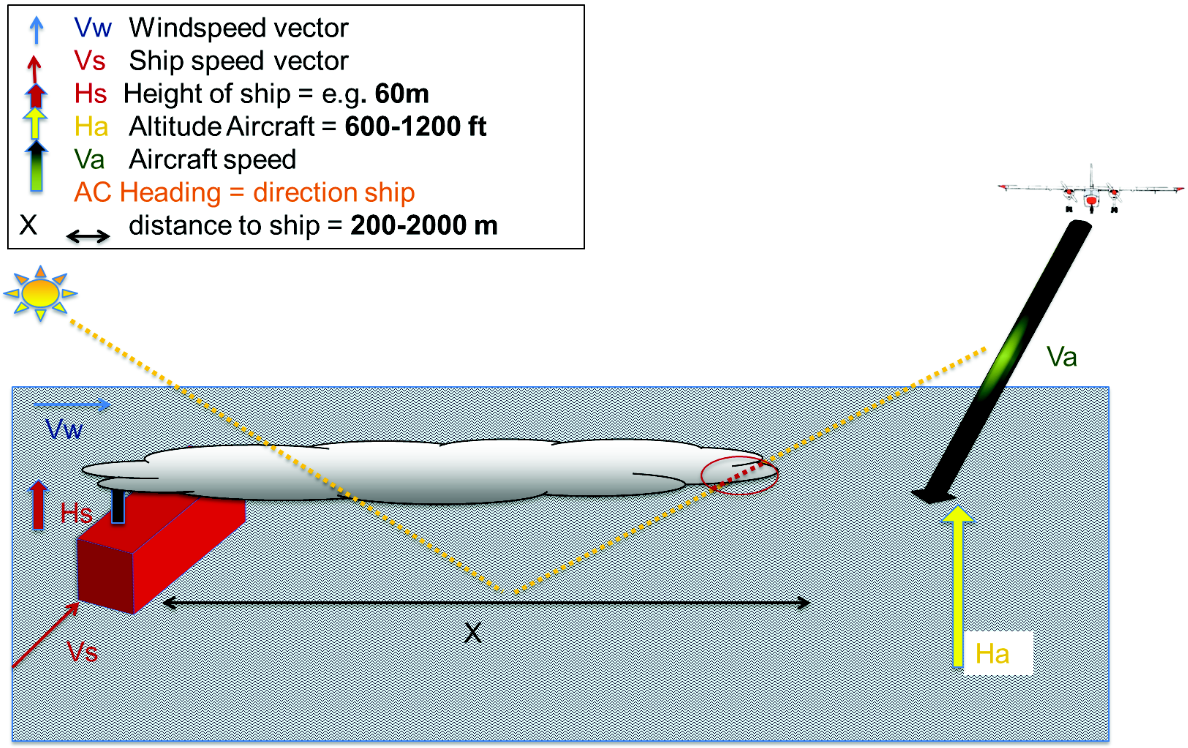

Figure 6 Flight pattern for fixed-wing aircraft with DOAS system

For rotary wing aircraft the optimal procedure is to fly against the wind, at a certain distance from the ship and descend until the aircraft arrives in the plume. This can easily be observed by looking at the NO_x concentration, as the NO_x sensor has the shortest response time. As soon as it is observed that the aircraft entered in the plume, the rotary wing aircraft should follow the plume towards the ship, and should then stay in the optimal measuring spot of the plume for 15-30 seconds for a good measurement. As this measurement technique requires to stay in the plume for some time, the aircraft has to fly against the wind in a radius from 30-330° in respect to the ship, therefore no measurements can be made in front of a ship, this would only be required in the scenario with a strong tailwind (Vw>VS).

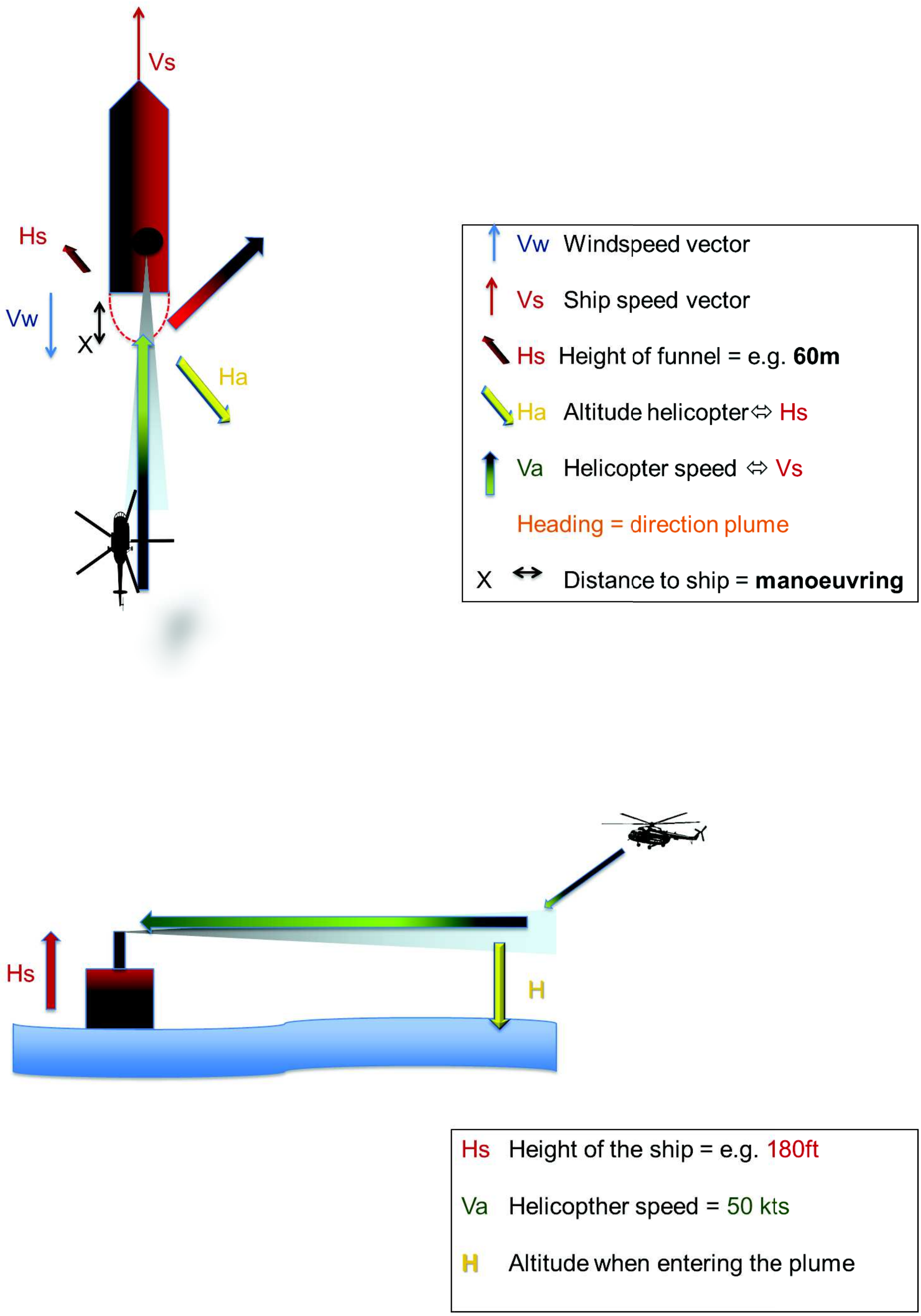

Figure 7 Flight pattern for rotary wing aircraft with mini-sniffer system

3.2 Altitude

For safety reasons a minimum altitude of 150ft is recommended for MARPOL Annex VI monitoring with fixed-wing aircraft with a sniffer sensor, this is of course if the aircraft has the authorisation to fly at this altitude. The maximum altitude where efficient measurements can still be taken is 350 ft (on the condition of course that the smoke plume reaches that height which will depend on the prevailing weather conditions).

For the time between sniffer measurements it is advised to fly at 500ft (or more, depending on the time between 2 measurements) for safety reasons and communication with air traffic control authorities.

For operations with the DOAS sensor, the optimum altitude depends on the light conditions and the position of the sun, but the ideal altitude can be found in the range 600-1200 ft.

Rotary wing aircraft are much less limited as they can fly at low speed close to the ships. Depending on the Standard Operational Procedures (SOP), rotary wing aircraft may operate at altitudes going as low as sea level.

3.3 Distance to ships

For safety reasons, the ship plumes should not be monitored closer than 200m from the ship with fixed-wing aircraft with sniffer sensor, the maximum distance that an efficient measurement can be executed is ca. 2000m but this is strongly depending on the prevailing wind conditions, the ship characteristics and the exhaust plume.

For fixed-wing aircraft with DOAS the optimum distance varies depending on the light conditions but is comparable as for sniffer measurements (200-2000m).

For rotary wing aircraft, measurements can be taken very close to the ship (25-50m), but there should always be a safe distance for emergency manoeuvring. It is not recommended to fly over the ships with rotary wing aircraft unless this is part of the SOP.

3.4 Speed

A well-known aviation quote goes as follows: "speed is life, altitude is life insurance". This means that flying at a safe altitude may provide extra time (time that can be turned into speed) in case of emmergency, but when flying at low altitude the speed or energy state of the aircraft is vital in case of emergency, loosing speed at low altitude may result in an emergency landing on water or ditching.

The recommended indicated air speed (IAS) to execute sniffer measurements for fixed-wing aircrafts is 100–120 kts. The maximum IAS for sniffer measurement with fixed-wing aircraft is 160 kts. This speed is based on the sensor response time of 1-2 seconds, a decrease of the sensor response time, by further development of the sniffer sensor may technically increase the maximum IAS, but for safety reasons it is not recommended to fly at low altitude at higher speeds. For the DOAS a maximum IAS of 200 kts is advised for technical and operational reasons.

A minimum IAS is not considered for fixed-wing aircraft because it is linked to the safety aspects for each type of aircraft but it is advised to fly at a safe speed well above stall speed to avoid unstable flying conditions. For instance the stall speed of the Belgian coast guard aircraft is 35 kts, but during operations the aircraft flew at cruising speed of 110 kts with engine power settings of 59%.

For helicopters the IAS is ideally the same speed as the ship but should not be lower than 5-10 kts.

3.5 Plume localisation

The localisation of a ship's exhaust plume can sometimes be challenging, even with (2D) software models and an experienced aircrew. The current software is providing the estimated direction of the exhaust plume and is able to visualize the plume location on a nautical chart together with the AIS information, which is of great help when approaching a ship. Unfortunately the software is not yet able to estimate the height of the centre of the plume. As a result several measurement attempts might be required before a successful measurement can be made.

To reduce the number of measurement attempts, which would also reduce the risk and flight time, a forward looking UV sensor or DOAS could possibly be used to localise the height of the centre of the plume. This would however mean a significant additional investment, but considering the flight cost, this is an investment that can have a potential high return rate.

Another solution would be the development of a 3D plume model, but current plume models have only been developed for fixed land sources and the development of a 3D plume model for moving sources in a marine environment can be costly and time-consuming and maybe even not possible as this requires significant knowledge on the ambient conditions and ship parameters (e.g. funnel height and shape).

If there is no visual indication of the height of the plume, it is recommended for fixed-wing aircraft with a sniffer sensor to do the first measurement at funnel height in case the exhaust plume is not visually detected, if needed followed by a second and/or third measurement attempt which can be done 25-50 ft higher or lower than the funnel height. Depending on the wind conditions it might be necessary to make a full 360° turn (in case of strong wind) or only a 180° turn (in case of moderate wind) for a consecutive measurement attempt. The information of the relative plume height (compared to the funnel) can be used for following measurements for ships with same heading and speed.

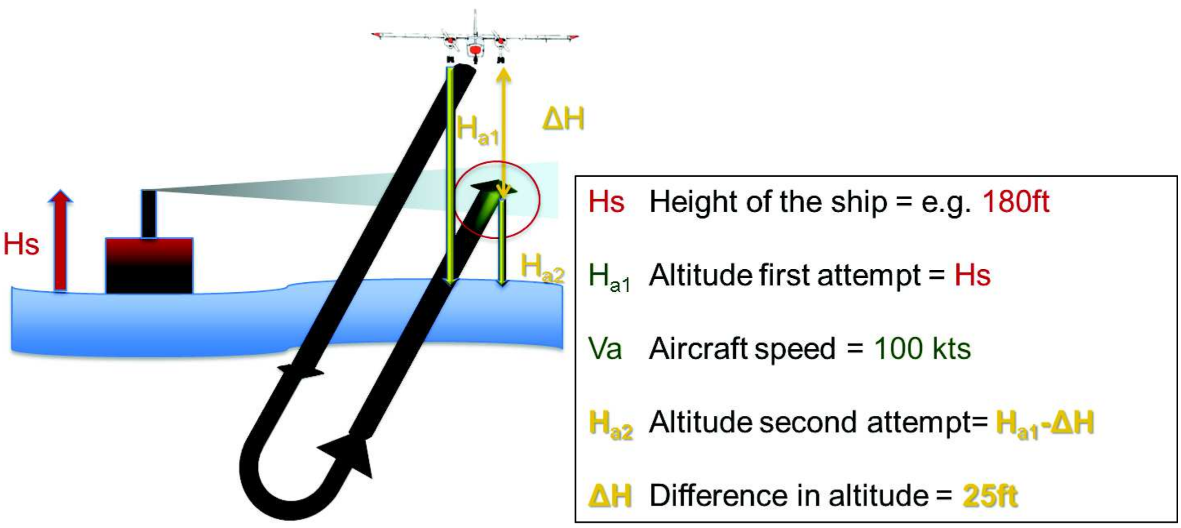

Figure 8 Sampling procedure in case the first attempt was not successful (low to moderate wind conditions).

3.6 Sampling attempts

Monitoring campaigns have shown that most vessels are compliant (estimate of 90-95% based on BE and SE monitoring results), and therefore in many cases 1 FSC measurement (= 1 low pass for fixed-wing aircraft with sniffer sensor) per vessel will be sufficient to verify compliancy, in most cases (80%) the first measurement attempt is successful. As mentioned above however, it may sometimes be required to perform several additional measurement attempts before a successful FSC measurement can be made. To limit the flight safety risks and optimise the aerial monitoring efficiency it is recommended to limit the number of measurement attempts. In case a first measurement attempt is unsuccessful it is recommended to perform not more than 2 additional attempts, after which the ship should be abandoned. In case a too high FSC is observed during (one of the) first attempt(s) (10% of the cases), up to maximum 2 measurement confirmation attempts can be performed before abandoning the vessel. For fixed-wing aircraft with DOAS, no maximum number of measurement attempts is defined.

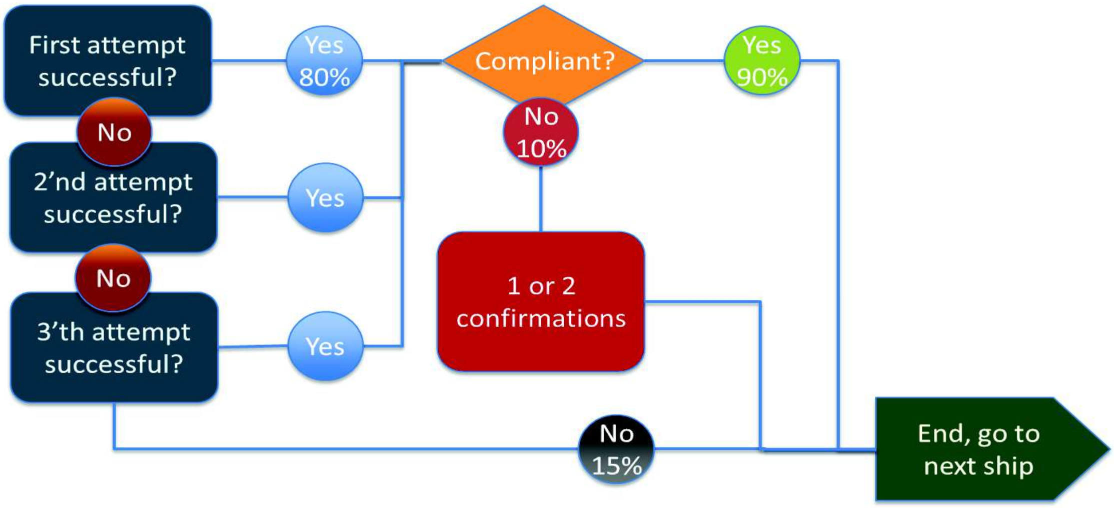

Figure 9 Schematic overview sampling attempts for fixed-wing aircraft with sniffer sensor.

3.7 Flight plan and location

It is highly recommended to use the official Bonn Agreement and HELCOM waypoints for drafting a flight planning before every flight. There should be a focus on shipping lanes and other zones of interest (e.g. SECA border, port entry zones, anchorage areas…) when drafting the flight planning, but flight routing for the MARPOL Annex VI monitoring is very susceptible for changes in flight as in practice the flight route depends on the presence of ships. Therefore it is recommended to use dynamic flight routes (see example in Figure 10) based on predefined waypoints, but where the routing is adapted in flight to maximize the number of monitored ships.

Depending on the aircraft type and sensor system a spatial diversification can be applied to optimize measurement efficiency, for instance rotary wing aircraft operate most efficiently close to harbours, nearshore and in anchorage areas. Fixed-wing aircraft with sniffer operate ideally above offshore shipping lanes, outside anchorage areas. Fixed-wing aircraft with DOAS are more equipped for selecting the significant non-compliant ships (more than 1% FSC) and are therefore probably best applied at the SECA border or in busy shipping lanes.

It should be noted that flight routing for sniffer measurements can be influenced not only by the presence of ships but also by the prevailing weather and atmospheric conditions. In some cases contamination from land-based activities for example from harbours or industrial areas, or inversion layers (see 4.6), may significantly influence the quality of measurements which may lead to an adaption of the flight route. Also fog or bad visibility or severe precipitation may result in a flight route adaptation.

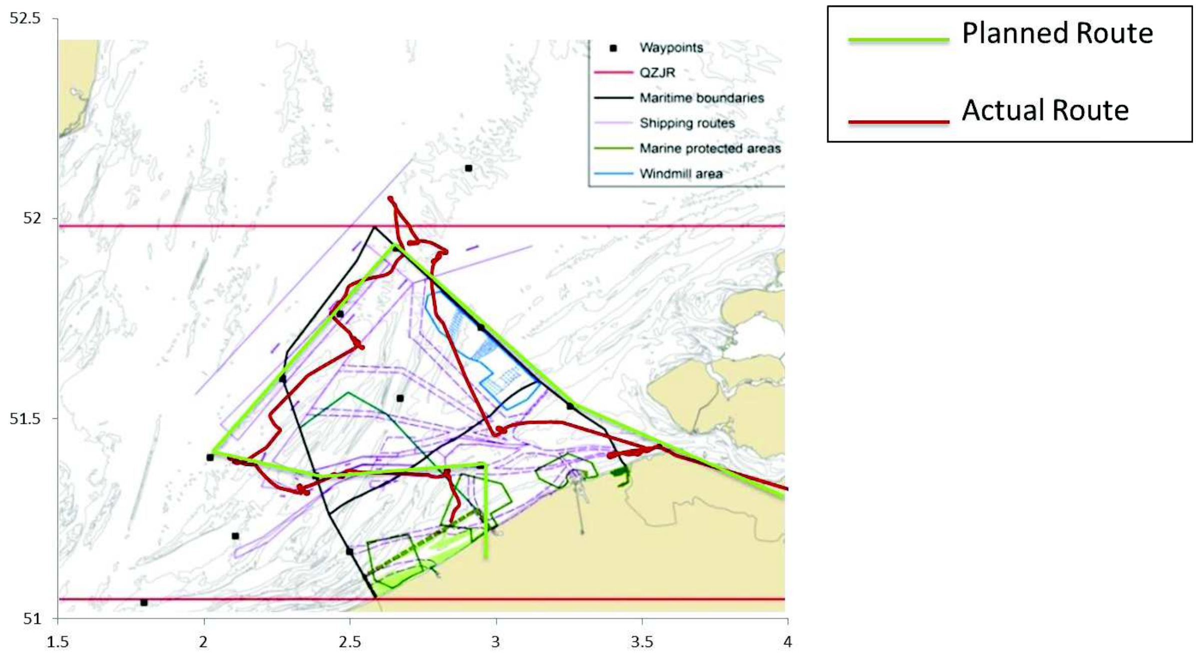

Figure 10 Example of planned and actual route of a MARPOL Annex VI monitoring flight in BE waters

3.8 Spreading

MARPOL Annex VI monitoring flights should preferably be spread equally over the year. The planning of flights should be unpredictable and therefore as randomly as possible. During winter time DOAS sensors can only be used during the middle of the day, when there is enough daylight, therefore during winter time Airborne MARPOL Annex VI monitoring is limited to fixed-wing or rotary wing aircraft with sniffer sensors.

3.9 Ship selection

The main purpose of airborne MARPOL Annex VI monitoring is currently still on the effective targeting of ships for port state inspection, and therefore as many different ships as possible have to be monitored at sea at various locations, without focusing on suspect vessels based on certain criteria.

The use of IMDatE could be a valuable asset in the sensor validation process as suspected non-compliant vessels, for instance based on previous measurements with fixed or mobile sniffers, can be visualised in a GIS application. This would be a possible way to select ships with highest priority for airborne monitoring. This would allow creating a database of comparable recurring FSC measurements where ships have been monitored using different techniques within a short time frame.

3.10 Calibration

The gas sensors used in sniffer sensor systems are not stable in time and measurement results may vary according to environmental conditions (temperature, humidity, …), therefore these sensors need to be calibrated on regular basis. Optimally this is done before every flight or mission, but this may vary according to the sensor specifications and the acquired sensor experience in the field. Calibration gasses for SO_2, CO_2, NO with specific gas-concentration can be purchased from special providers, but as the gas concentrations for calibration gasses are very low, the concentration mixture is not always stable and should be measured and/or certified on regular basis.

4 Weather minima

4.1 Wind speed

It is recommended to perform airborne MARPOL Annex VI monitoring flights with a maximum wind force of 30 kts for fixed-wing aircraft with a sniffer and 25 kts for rotary wing aircraft with a mini-sniffer. For fixed-wing aircraft with DOAS no other operational limit is defined than the weather limits of the standard flight operations. Obviously wind conditions should be followed up by pilots in-flight to avoid taking unnecessary risks.

A small amount of turbulence is often felt when passing through a smoke plume, which in a way gives a good indication for the crew to recognize the moment when the aircraft flew through the plume to sample the exhaust gases. Certain ships however, for instance roll-on/roll-off (RORO) ships may provide severe turbulence downwinds of the ship. When flying too close with strong winds this may result in turbulent ship approaches. This turbulence effect depends on the physical characteristics of certain ships: the impact of the structure of the ship on the wind may cause a strong "mechanical" turbulence, such as with RORO ships. For such types of vessels, this mechanical turbulence can already be severe during wind conditions of 25 kts (especially with crosswind). This aspect should be kept in mind when selecting vessels for compliance monitoring under strong wind conditions.

4.2 Visibility

It is recommended to fly only during VMC conditions, which means that a minimum visibility of 5 km is required. 5 km is a comfortable and safe visibility limit at an IAS of 110 kts for airborne MARPOL Annex VI monitoring flights. It should be noted however that with higher aircraft speeds a higher visibility may be required.

4.3 Cloud coverage

It is recommended to fly only during VMC conditions which require to fly clear of clouds, furthermore it is advised to have a cloud base at least 200 ft higher than the cruising altitude.

4.4 Precipitation

Light precipitation should not pose any problems for the monitoring, but heavy rain, snow or hail can result in low visibility or clogging of the sensor filters and should therefore be avoided.

4.5 Temperature

If the sampling probe is not heated, no measurements can be made during icing conditions, so during humid and freezing conditions.

4.6 Inversion layers

In normal conditions air temperature decreases with altitude. But when air temperature increases at a certain altitude an inversion layers may occur. This typically happens with wind-still cloud-free conditions. At an inversion layer typically air pollutants concentrate and form smog. If these inversion layer occurs at low altitude (<500 ft) they may interfere with FSC measurements as the background values for CO_2 and SO_2 may not be stable. It is noted that a change in the flight route or planning might be necessary (spatial and temporal modification of flight route). For instance the monitoring could be shifted to another area or the afternoon (more stable atmosphere).

5 Health aspects

Several coastguard officials, operators and pilots have expressed their concerns concerning the health impact from flying through ship exhaust plumes, especially because one can smell often the exhaust plume in the cabin. MUMM has therefore performed air quality measurements during the Belgian Sniffer Campaign 2015 by measuring the black carbon exposure for the aircrew during the monitoring flights. Also during the Belgian Sniffer Campaign 2016, air quality measurements were executed inside the cabin and cockpit of the surveillance aircraft. The results of these measurements have shown that the health impact for the crew is in fact negligible during the MARPOL Annex VI monitoring with fixed-wing aircraft (see Figure 11 below). Although the average black carbon exposure is slightly higher during sniffer flights than during normal surveillance flights, the difference is not significant. The measurements furthermore showed that average exposure values to black carbon are significantly lower during MARPOL Annex VI inspection flights than during commuting on land. In other words, the black carbon exposure at home (in Brussels) and on the road is much higher than during sniffer flights. A last, much higher black carbon peak which can be found in Fig.11 on the tarmac, was due to the refuelling of the aircraft.

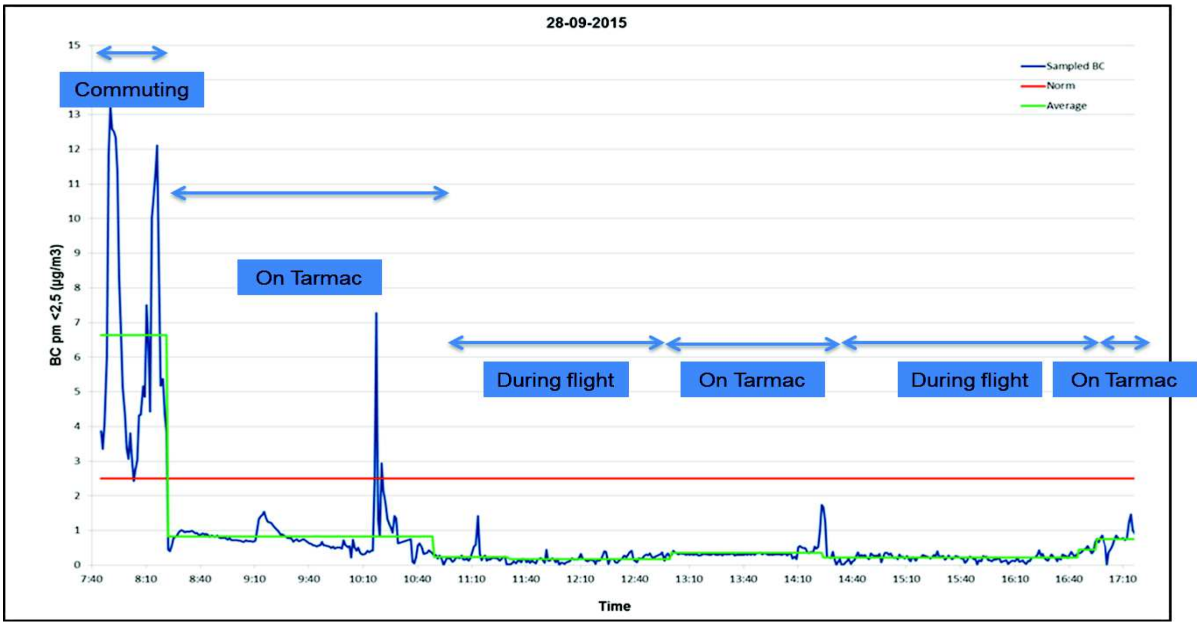

Figure 11 Break-down of Black carbon exposure during a typical working day of a MARPOL Annex airborne monitoring operator (2015)

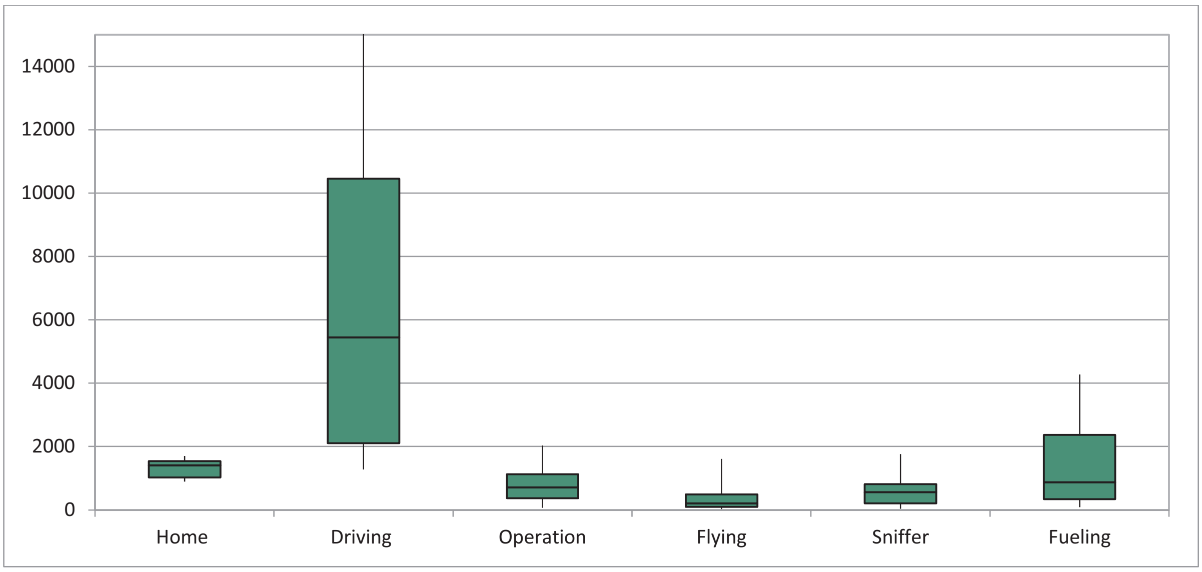

Figure 12 Box Plot of average black carbon exposure during different activities

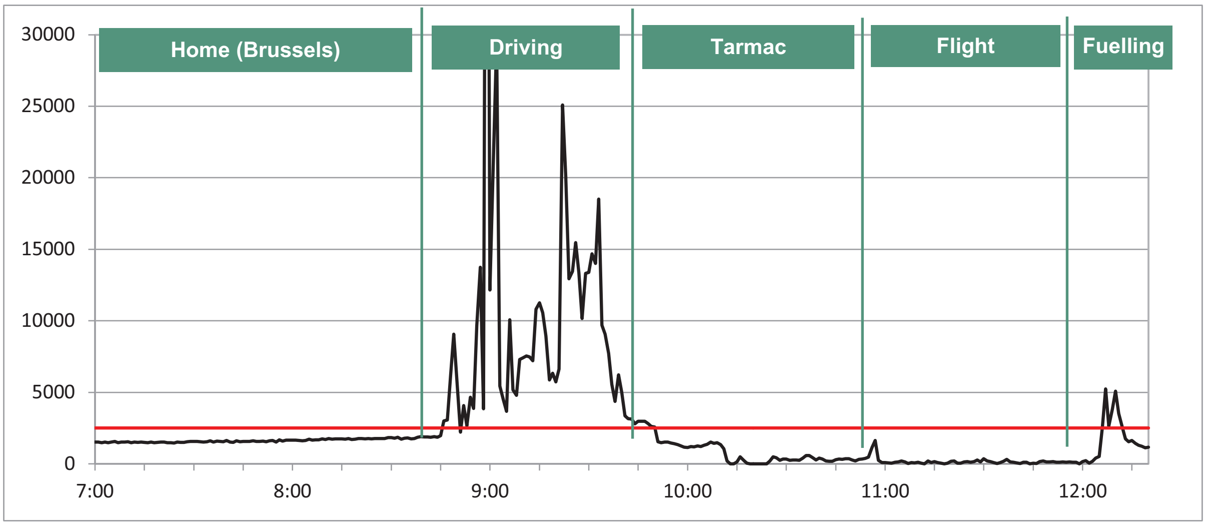

Figure 13 Breaking down of Black carbon exposure during a typical working day

Also air quality measurements inside the cabin of a rotary wing aircraft have been carried out during the Dutch MARPOL Annex VI monitoring operations organised by ILT in collaboration with Explicit. During these air quality measurements, a Particle Matter sensor has been used to measure $PM_{2,5}$ and PM_{10}. Furthermore a mini-sniffer system has been used to measure the gas concentration of SO_2, CO_2, NO_2 and NO. These air quality measurements have shown that there is no significant health impact, although some short-term peaks were observed during the approaches. When looking at the average concentrations, almost none of EU or occupational exposure limits were reached, only for PM2,5 the EU limit was barely reached for a 1 hour average, but as the EU limit is set for 24 hours, the actual 24 average would be much lower. Furthermore it should be noted that all measurements were done rather close to the ships (25-50 m) with the airvents open for an assessment of the "worst case" scenario, whereas during standard operating conditions with the rotary wing aircraft all airvents are normally closed during FSC measurements.

Table 1 Measurements on health aspects with a rotary wing aircraft flying close to the plume.

PM	Ambient air quality (24h average)	Moving average maximum in cabin	Moving average in cabin (1h average)
$PM_{2.5}$	25 µg/m³ (EU)	160 µg/m³	<30 µg/m³
PM_{10}	50 µg/m³ (EU)	200 µg/m³	<50 µg/m³
Gas	**Occupational exposure limits**	**Maximum concentrations inside the cabin**	**Five minutes averaging**
SO_2	0,5 ppm (average during an 8 hour working day)	0,15 ppm	0,05 ppm
NO_2	2 ppm (Limit value, should never be exceeded)	0,28 ppm	0,12 ppm
NO	25 ppm (average during an 8 hour working day)	5,2 ppm	2,2 ppm
CO_2	5.000 ppm (average during an 8 hour working day)	1.000 ppm	777 ppm

6 Safety Recommendations

The execution of MARPOL Annex VI monitoring flights poses a certain safety risk and safety precautions and considerations are therefore recommendable. The described flight procedures have been composed to enhance the safety of the monitoring flights. However, since flight safety management is mainly a national responsibility of each Member State, harmonized standards for safety equipment or training are not described in detail in this Best Practice report. As a minimum the flights should be carried out with a twin engine aircraft and dedicated SOPs with risk analysis should be composed for this type of missions. When developing a safety management system, the main safety aspects that should be minimally considered for sniffer flights are:

- Safety equipment (e.g. dry suits, life jackets, personal dinghies or life rafts, Mode-(E)S transponder, Traffic collision avoidance system,…)
- Safety training (e.g. Shallow Water Escape Training, Helicopter Underwater Escape Training, Sea Survival, Blind Static,…)
- Multi-engine platform (e.g. equipped with modern Avionics, IFR capability, well maintained, limited size and speed for optimal manoeuvrability,…)
- (Multi-pilot) platform and experienced crew.

7 PSC Communication

A crucial point in the use of airborne measurements for MARPOL Annex VI enforcement is the co-operation and communication with the Port State Control network, who is responsible for the inspection of a certain number of ships in port (in execution of EC Directive 2012/33/EU). At present the PSC inspections in port are time consuming and therefore costly, the selection of vessels is rather blind (although intelligent-blind) and only a limited number of ships entering a port can be inspected. The compliance rate found by PSC inspections without the 'targeting' through the use of sensors, is >95%. On top, ships leaving the EU ports and leaving or sailing through the SECA zone cannot be controlled through PSC alone which means that the very high compliance rate found in PSC inspections is distorted and does not reflect reality. By using a targeting system based on airborne monitoring, it becomes possible to do more directed inspections. The sniffer measurement results of non-compliant vessels have to be reported to PSC and the vessels will then be marked in the Thetis-EU database. In order to achieve an efficient targeting system a communication system has to be elaborated with agreements on reporting time and reporting thresholds between the airborne platforms and PSC.

7.1 Reporting time

MUMM underlined the importance of establishing a good communication flux to PSC as at this stage, the airborne monitoring is only serving as a 'targeting' system (i.e. targeting vessels with suspicious Sulphur emission values for a PSC inspection in port where the main evidence is still collected). Therefore the aerial monitoring results on non-compliant vessels should be reported in near real time to the PSC focal point. In Belgium, this took place via the national 24/7 coastguard station (MIK). Afterwards PSC, which should ideally also have a 24/7 contact point, is responsible for the timely submission of the monitoring results in Thetis-EU. For a non-compliant vessel, it is recommended to limit the reporting time to PSC to 1hr after landing, in order to provide sufficient time for the planning and prioritisation of port inspections. Also compliant vessels should be reported to PSC, this is less urgent however can be done by providing the data continuously on a web-database or by regular reports.

Table 2 PSC-Communication matrix

	Compliant	Non Compliance
Reporting Time	>24hr after flight	Near real time (<1hr after landing)
Reporting Means	Web-database	Mail

7.2 Threshold

It is generally accepted that thresholds are very useful for reporting FSC measurements and targeted vessels to PSC, since every measurement results will always have a certain level of uncertainty, independent of the sensor type. Therefore it is important that these thresholds should be based on the accuracy or uncertainty of the measurement. During the first workshop it was agreed to use three colour flags as an indication for the degree of compliance, the uncertainty and quality of the measurement. In this way a green, an orange and a red flag were defined. Unfortunately during the monitoring campaigns these flags have only been used by MUMM although they were approved by the PSC inspectors. During the second workshop this item was discussed again, and there was a clear consensus to use a threshold based system for reporting to PSC for vessel targeting. Furthermore it was agreed that the categories or colour flags should be based on the FSC value, the measurement-uncertainty and level of quality. But more validation and standardization of methods (EN 14211) and sensors (TC 264 WI 00264179) is needed to define and determine the measurement accuracy on a homogeneous way for the different sensors.

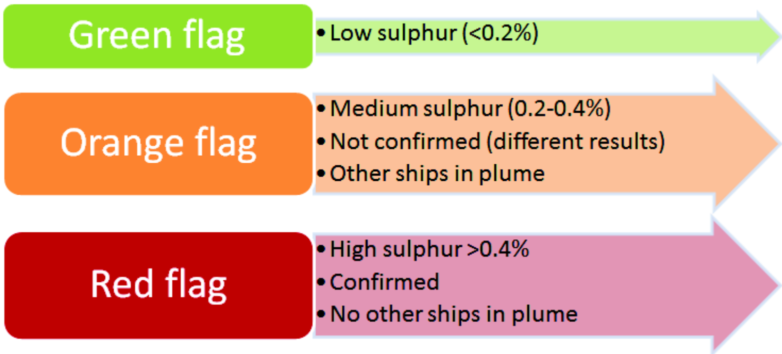

Figure 14 Threshold colour flags agreed upon during the first workshop (used by MUMM)

7.3 Data Sharing

It was recognised by all participants that a data sharing platform should be set up for the sharing of monitoring data between different users. This platform should be used for all different monitoring sources (fixed sniffer sensors, PSC results, airborne data, maritime data,...). The analysis and pairwise comparison of the data can allow a better targeting of ships for inspection and is crucial for the validation of the sensors. Thetis-EU (formerly Thetis-S) should ideally be used as this sharing platform, but to make this possible, Thetis-EU should be customized and linked to IMDatE.

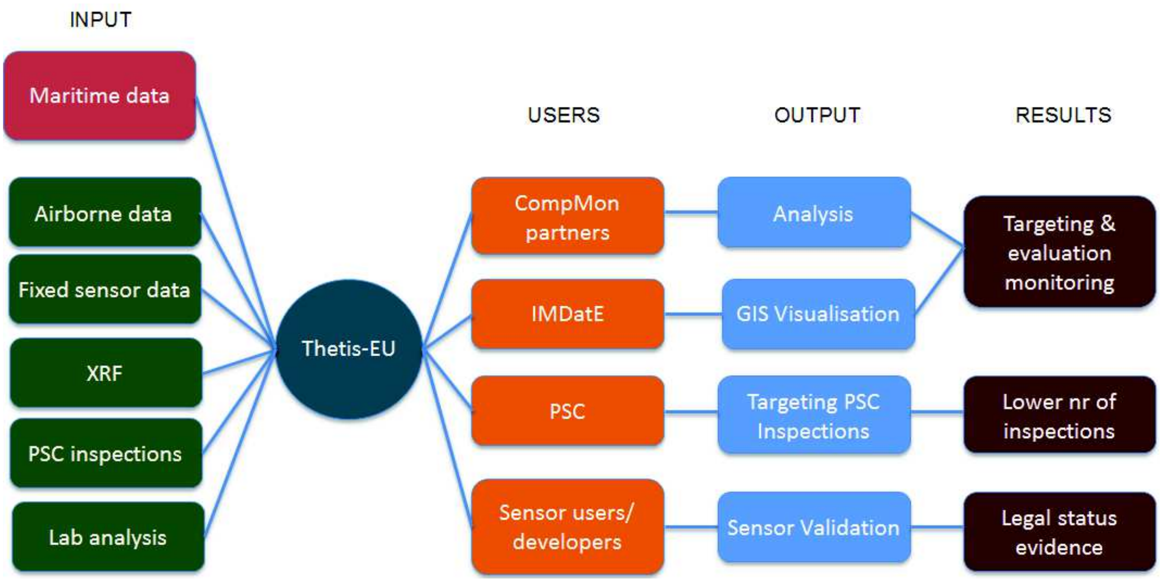

Figure 15 Data Sharing

8 Legal Aspects

As outlined and explained in the legal study performed by Åbo Akademi University in the framework of CompMon, MARPOL Annex VI monitoring flights are perfectly in accordance with maritime law. No (maritime) legislation was found to deny the authorisation to perform this type of surveillance flights at sea, although it is obvious that the airborne monitoring operations have to be in accordance with other national and international legislation such as, among others, aviation regulations.

CompMon has demonstrated that innovative sensor techniques can be used effectively for the targeting of vessels for inspection in port. But the ultimate long term objective for airborne MARPOL Annex VI monitoring is to achieve a legal status for airborne (sniffing) FSC measurements so that offenders can also be prosecuted based on airborne measurements. Various aspects have to be taken into account on the road to achieve this legal status for sniffer measurements. The validation of the technical robustness of a sniffer and its measurements is at this stage still a key issue. This can be done by:

- Performing frequent calibration/validation of sensors in the field to ensure traceability of the sensors performances.
- Validating the capability of sensor system to measure SO_2 and CO_2 ratios in the field by puffing premixed high concentration gas standards at the gas inlets to simulate plume measurements.
- Comparing the sniffer data with PSC results;
- Comparing the sniffer data from different sniffer platforms (fixed and airborne; inter-comparison of different sensor systems);
- Airborne monitoring validation (campaigns) in cooperation with the industry and maritime sector, for example:
    - with ships using scrubbers;
    - by taking fuel samples on board of vessels at the time of airborne measurements;
    - carrying out measurements at the SECA border.

Besides this FSC measurement validation, the different sensors and measurement results should be standardized in accordance with the European Standards approach. Such a standardization process is long, but indispensable for the future of airborne MARPOL Annex VI monitoring.

Annex 1 Technical description of Airborne FSC measurement sensors

Airborne system by Chalmers University of Technology

1. Overall description

The airborne surveillance scheme (Beecken et al., 2014a; Beecken, 2014b; Berg et al., 2012) is illustrated in Fig. 1 and consists of two parts. First optical measurements of reflected solar light from the water surface are carried out at 200 - 300 m altitude, from which the path integrated concentrations of SO_2 and NO_2 through a ship's plume can be retrieved (Berg et al., 2012). When this ratio is higher than a certain threshold (>1) this indicates that the ship is running on high sulfur fuel (1%). About 10 - 20 ships per hour can be checked from the air in this manner.

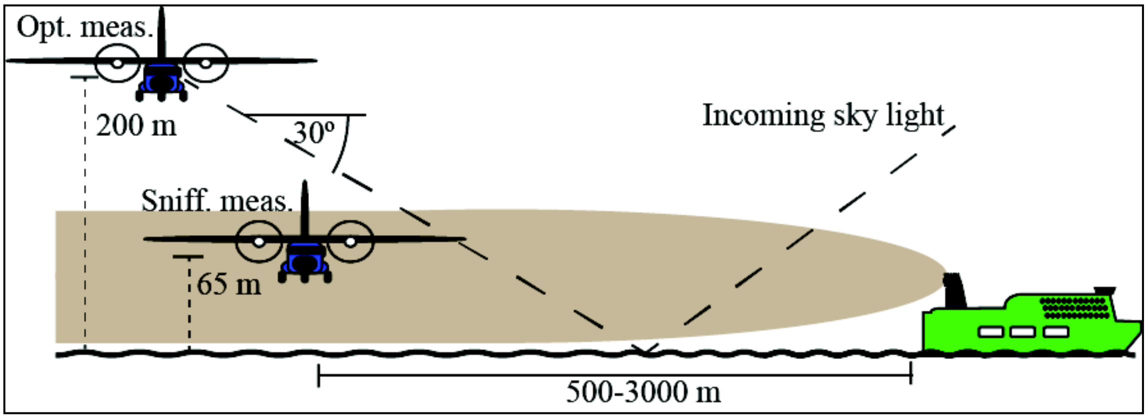

Figure 1. An illustration of the airborne surveillance methodology. Optical flux measurement are carried out at an altitude 300 – 600 m and then combined with modeling of the fuel consumption to get a rough indication of the FSC. For high emitters sniffer measurements at lower altitude (65-150 m) will be carried out to obtain emission factors.

The other part in the surveillance corresponds to sniffer measurements in which the exhaust gas plumes from the ship is extracted trough a gas inlet (sonde) on the airplane and then further analyzed by on-board instruments for SO_2, CO_2 and NO_x. This approach requires that the aircraft gets into physical contact with the ship plume and typically the flying is conducted at an altitude of 65-100 m at a distance of 0.5 to 3 km away from the ship. In this manner, about 4 - 10 ships per hour can be measured with an estimated relative uncertainty of 20 % for ships with 1 % fuel sulfur content and a relative uncertainty of 50-100% at 0.1 fuel sulfur content. The number of ships measured is limited by the ship traffic intensity. To make the surveillance more efficient, the sniffer measurements is usually triggered by results from the optical measurements.

The custom made analysis software IGPSreal, Figure 2, is used to calculate the FSC in the encountered ship plume in real time and to identify from which ship it originates. The program calculates the FSC for the ships from the ratios between the pollutants and CO_2 according to Eq. 1, which is consistent with the on board method described in the MEPC guidelines 184(59). In more detail the software detects the presence of the ship plume when the momentaneous value exceeds the long term background value, one minute running median value, by a certain threshold derived from the variability of the signal. It then assumes that both sides of the plume correspond to the background and it fits a line through these values which is subsequently used as the momentaneous background value.

$$FSC = 0.232 \frac{\int [SO_2 - SO_{2,bkg}]_{ppb} dt}{\int [CO_2 - CO_{2,bkg}]_{ppm} dt} \quad \text{[\% sulfur]} \qquad (1)$$

Here the CO_2 is given in the unit ppm (parts per million) while SO_2 in the unit ppb (parts per billion). The constant value of 0.232 in Eq. 1 corresponds to the ratio of the atomic weights of sulfur over carbon and a correction for that approximately 87 % of the fuel corresponds to carbon. Note that the elevated levels above the background value are being used when calculating the ratio. It is assumed that the ratio of the elevated SO_2 and CO_2 mixing ratios is directly proportional to the sulfur to carbon content in the fuel, assuming that all sulfur is converted to SO_2 in the combustion, see Eq. 1. This is only partly true since studies shows that around 5 % of the sulphur is present as sulfate in particles (Moldanova et al., 2009; Petzold et al., 2008) and therefore the FSC will be somewhat underestimated with the corresponding percentage.

The measurements are usually done in a zig-zag-shaped manner across the ship plume, and the software, which plots the ships, their plumes and location of the aircraft on a map, is essential for real time flight track planning.

The data are stored together with information from an Automatic Identification System (AIS) which provides the name and speed of the target ship. This can directly be transferred to a database for further usage by ship inspection authorities to target which ships to inspect once they are in harbors.

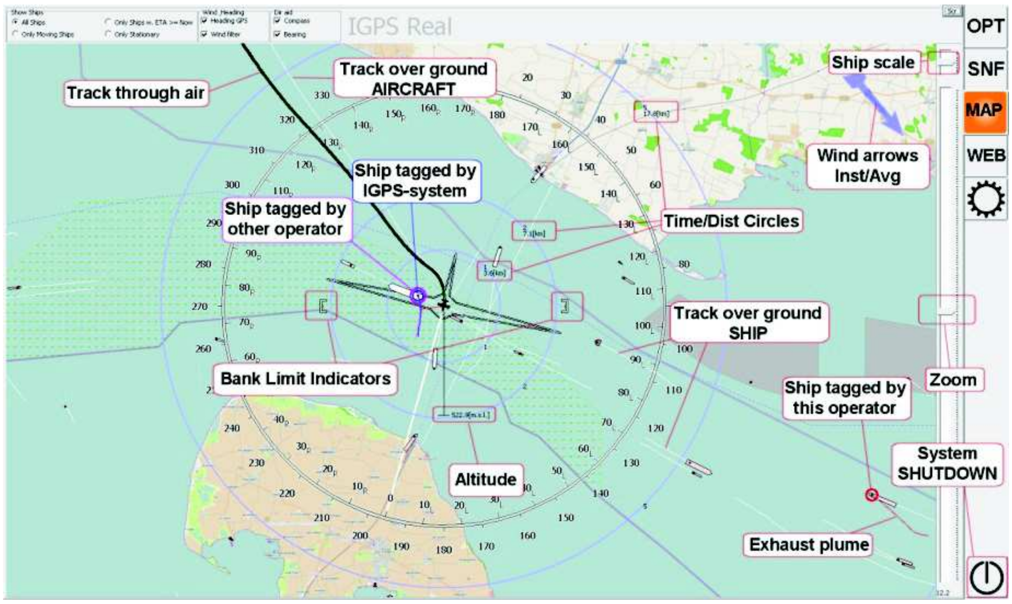

Figure 2. A screenshot from the program IGPS real when flying. The software utilizes information from AIS and GPS receivers and wind speed and direction to plot the location of the aircraft, ships and their exhaust gas plumes.

The airborne ship surveillance system has been tested on various airborne platforms, both fixed and rotary wing aircraft. An STC (Supplemental Type Certificate) approval to install the measurement equipment in a Navajo Piper aircraft, OY-MST has been obtained from the European Air Safety Agency (EASA STC 10051623) The preparatory work for the STC required combining several instruments into a new form factor, testing the equipment regarding electromagnetic interference and toxic material, and the design of special instrument racks, withstanding high gravitational forces. A window in the airplane was replaced by a probe plate, which carries windows for two telescopes and one video camera and probes to extract particles and gases from the air. The airplane was also equipped with a wind sensor.

2. System

The Chalmers aircraft system, Figure 3 and Figure 4, is divided into different instrument racks for optical remote sensing measurements and sniffer measurements of gases. The gas rack contains a battery box, custom FSC-module, NO_x instrument and a CRDS CO_2 sensor (Cavity ring down spectrometer). The custom made FSC module fits into a 19” rack with a weight of 47 kg and a power consumption of 15 A at 28 V-DC. This module includes all necessary hardware to carry out FSC compliance measurements from the air, i.e. logging computer, AIS receiver, GPS receiver, power converter, calibration gases, fluorescence SO_2-sensor, NDIR CO_2-sensor (non dispersive infra red) and pressure regulators. The module is also the central system in the airplane setup. The Belgian BN Islander aircraft is equipped only with an identical FSC module.

Figure 3. The ship surveillance system installed in a Danish Navajo Piper aircraft (OY-MST) (upper). To the left the gas rack is shown, in the middle the particle rack (Not applicable here) and on the right side the optical rack. In the upper right part of the picture a probe plate is shown containing telescopes and sondes.

The reason for using two CO_2 sensors is to combine high accuracy of the CDRS with high precision and short response time of the NDIR. The optics rack contains two UV spectrometers for simultaneous measurements of SO_2 and NO_2.. In the aircraft instrumentation, materials inside them that will produce toxic gases when burning, e.g. polyvinyl chloride (PVC), has been replaced for safety reasons. The instruments are also equipped with pressure regulators at the inlets to compensate for varying flight altitude and the CRDS has a special pressure compensation for the laser wavelength tuning. As part of flight certification, the instruments, built in to special racks, were tested and qualified regarding electromagnetic interference and magnetic properties (RTC DO 160/issue M/cat M/section 21 and section 15).

Figure 4. The ship surveillance system installed in a Danish Navajo Piper aircraft (OY-MST). To the left the custom made sniffer module is shown which includes all necessary hardware to carry out FSC compliance measurements from the air, i.e. logging computer, AIS receiver, GPS receiver, power converter, calibration gases, fluorescence SO2-sensor, NDIR CO2-sensor and pressure regulators (47 kg,15 A). On the right side the optical rack is shown, (5 A, 30 kg).

2.2 Gas analyzers/sensors

The surveillance system, see Table 1, consists of optical instruments for remote sensing measurements and extractive instruments for sniffer measurements of gases in the exhaust plume of the ships and more details can be found a separate Compmon reports and in several related papers (Berg, 2012, Beecken 2014a, Beecken 2014b). The gas instruments are based on the following physical principles: UV fluorescence for SO_2, chemiluminiscence for NO_x and two techniques, i.e. cavity ring down spectroscopy (CRDS) and non-dispersive infrared (NDIR) absorption for CO_2. The extractive techniques for gases are commercially available as state of the art instruments and they are being used worldwide as reference methods for air quality measurements. To fulfill flight requirements these instruments have been modified for fast response (1 -0.5 Hz), smaller weight, smaller form factor and field robustness. The detection limits of the extractive instruments are typically 1 ppb for SO_2 and NO_2, respectively and 200 ppb for CO_2. The optical method is based on a UV/visible spectrometer (f.c. 303 mm) equipped with a UV-sensitive CCD camera. A telescope with 150 mm focal length is connected to the spectrometer via a liquid guide fiber (Berg, 2010).

Foe the optical sensors the detection limit is 10 ppb over 100 m for SO_2 and somewhat better for NO_2.

2.1 Possible cross sensitivities and how to correct for this

The SO_2-sniffer instrument has a small sensitivity to NO (100 ppb NO corresponds to 1.5 ppb SO_2 reading), and if it is not compensated for by NO_x measurements, it will on the average produce an apparent absolute FSC of about 0.1 which will be relevant when measuring ships running on marine gas oil, i.e. FSC 0.1 %. NO_x is therefore measured as well, in most cases assuming that most of the gas is in the form of NO. Nevertheless, even without NO correction the accuracy is sufficient to differentiate ships running with a FSC of 0.4 % or higher against 0.1 %. The SO_2-instrument has an additional sensitivity to aromatic VOCs (100 ppb aromatic VOCs corresponds to 1 ppb SO_2 reading).

2.3 Calibration procedures for gas analyzers

The quality assurance of the sniffer measurements is based on calibration against gas standards before each flight on the ground. In addition, occasional in-flight calibrations are also carried out using small gas cylinders to test instrument stabilities. Typically the gas standards are diluted in nitrogen or air from Air Liquide with values for SO_2, $CO_{2,span}$, $CO_{2,ref}$, and NO of 401 ± (5 %) ppb, 370 ± (0.5 %) ppm, 370 ± (0.5 %) ppm and 191 ± (5 %) ppb, respectively, with dilution in nitrogen for latter gas and synthetic air for the former ones. To check the stability of the calibration gases, and to bridge the gap when changing gases a multigas calibrator and zero air generator (Thermo 146i and Thermo 1160) is also used together with, more stable, high concentration calibration gases from AGA Special gas AB corresponding to 101 ± (0.5 %) ppm for both SO2 and NO.

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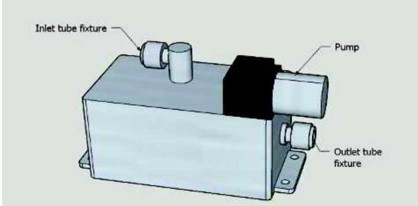
TECHNICAL AND OPERATIONAL SPECIFICATIONS

Payload - Technical specifications (sensor unit for UAV integration):



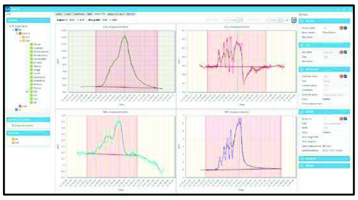
Sensor unit incl. pump

- *Payload weight:* Single sensor unit 500 g / Dual sensor unit 1.000 g
- *Sensors:* SO_2, CO_2, NO, NO_2, temperature, humidity
- *Components:* **Sensor unit:** L: 140 mm (incl. mounting wings), W: 65 mm, H: 78 mm (incl. inlet)
  Diaphragm pump: Vacuum; L: 34mm, W: 22mm, H: 56mm
  Inlet tube: Teflon, max 500 mm in total length with min. 50 mm in free air (outside)
  Outlet tube: Rubber tubing, max 1m
- *Power requirement:* 5v, 150 mA (sensor unit), 200 mA (pump)
- *On-board placement:* The sensor unit must be placed max. 200mm from the tube entry into the fuselage to mitigate the risk of loss in gas signal. Location of the pump is flexible, but may preferably be placed close to (or on) the sensor unit.
- *Inlet placement:* To avoid disturbance of the gas signal, the inlet tube must be placed free of any turbulence from rotors.
- *Data interface:* Digital, serial RS232 or Ethernet. Data can either be relayed via the Explicit ground station application, or directly to the Explicit cloud-platform for data analysis.
- *Mount:* The sensor unit is equipped with 4 mounting holes.
- *Maintenance:* All sensors are pre-calibrated. They do not require further calibration. Sensor units must be replaced min. every 2 years depending on usage.
- *Other considerations:* The final sensor data set must be correlated with the GPS track of the UAV and third-party AIS track of the ship to produce a complete compliance report per vessel.

Payload - Technical specifications (helicopter sniffer box) – same as above except for:

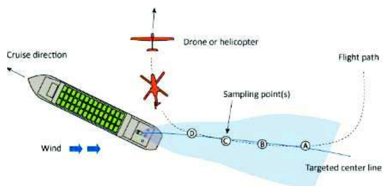
- *Payload weight:* 5.500 g (dual system)
- *Components*: Standalone instrument box including all necessary components (sensors, pumps, battery power, controllers etc.)
- *Mount:* Adaptable to different carrying arms
- *Data interface:* Communicates via radio link with the Explicit ground station application. Data is subsequently relayed to the cloud-platform for data analysis.
- Telemetry radio: Radio modem: 433 MHz (EU) and 915 MHz (US)

Data analysis:



- *Data processing:* The system includes a cloud-based application for analysing the sensor data and compiling final measurement reports per vessel. The analysis is performed automatically in real-time.
- *Other consideration:* In order to compile a complete emissions report, the sensor data stream has to be combined with the position tracks of the aircraft and the vessel AIS. Depending on the customer preferences, Explicit is capable of providing solutions for all data streams.

Operational specifications / conditions:



- *Target:* Vessel exhaust plume(s) of ships underway.
- *Distance to vessel:* UAV: Min. 50 m. Helicopter: Min. 25 m. Precise distance to the funnel is not necessary as long as the aircraft gets sufficiently into the plume. Aircraft must observe the safety of the crew and vessel.
- *Altitude:* Between 40-60m above sea level, depending on vessel.
- *Speed in plume:* **Up wind:** Down to 9-10 m/s air speed (equivalent to a ship travelling 10-15 knots at 5 m/s winds heading up wind). **Cross wind:** Down to 5m/s air speed.
- *Time in plume:* Min. 30 seconds. Between targets: Min. 2 minutes to clear out the sensor chamber.
- *Sample conditions:* Tested and verify in temperatures from -5 to +30 degrees Celsius. No flight in rainfall or snow (will wash out the sulphur from the air). Max. 10m/s average wind speed; more and the exhaust plume scatters.

For further see www.explicit.dk