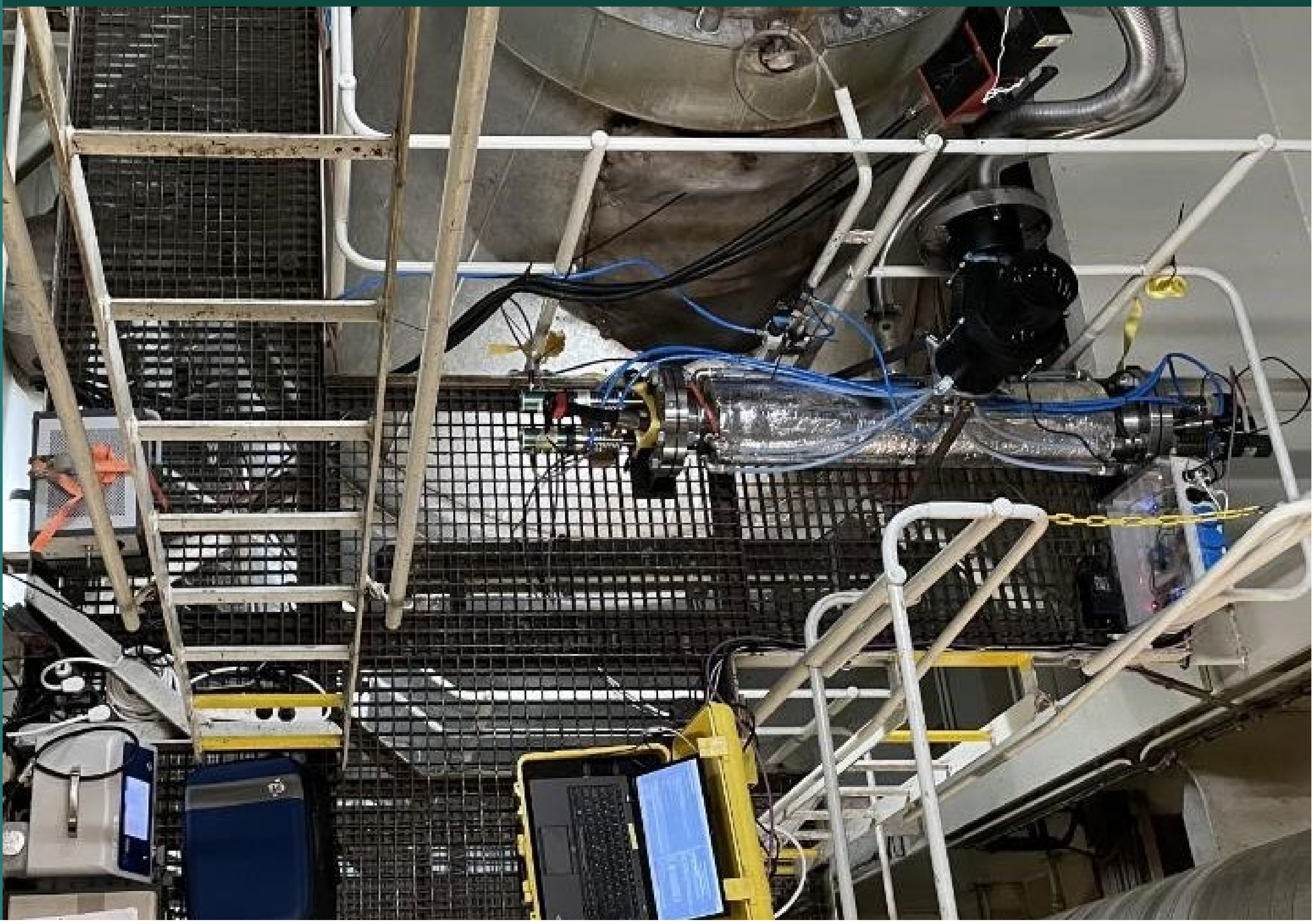
Ministry of Environment and Gender Equality
Environmental Protection Agency

Development of Maritime Black Carbon Sensor MUDP-project

MUDP Report

February 2025



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Miljøteknologisk Udviklings- og Demonstrationsprogram

Projektet, som er beskrevet i denne rapport, er støttet af Miljøteknologisk Udviklings- og Demonstrationsprogram (MUDP) under Miljøministeriet, der støtter udvikling, test og demonstration af miljøteknologi.

MUDP investerer i udvikling af fremtidens miljøteknologi til gavn for klima og miljø i Danmark og globalt, samtidig med at dansk vækst og beskæftigelse styrkes. Programmet understøtter dels den bredere miljødagsorden, herunder rent vand, ren luft og sikker kemi, men understøtter også regeringens målsætninger inden for klima, biodiversitet og cirkulær økonomi.

Det er MUDP's bestyrelse, som beslutter, hvilke projekter der skal modtage tilskud. Bestyrelsen betjenes af MUDP-sekretariatet i Miljøstyrelsen.

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1. Summary and conclusion

1.1 Summary and conclusion

Black Carbon (BC) is a climate and health problematic emission, caused by the combustion of fossil fuels in, e.g., the shipping industry. Efficient monitoring of the emissions is a first step towards reducing this harmful pollution.[1]

This report describes the development and testing of Green Instruments EMS BC sensor technology using the Extinction Minus Scattering (EMS) method to quantify the BC concentration in engine exhaust.

The EMS BC sensor is an online and in-situ measurement technique that has several advantages compared to the traditional extractive techniques as well as filter deposition methods, such as Filter Smoke Number (FSN) or Photoacoustic spectroscopy (PAS).[2]

The priorities in the development activities were to ensure that the measurement system has low maintenance, sufficient robustness, appropriate accuracy, and validity, and is relatively easy to install on various exhaust and ship types.

The system has been evaluated on test engine exhaust, followed by sea trial both as in-situ and extractive editions of the EMS BC.

The suitability of the EMS BC sensor for measuring BC from a diesel exhaust is addressed. The focus is on providing correlations i.e., the relative response of the BC concentrations – mainly because no reference method for measuring BC has been agreed upon.

The EMS BC method is tested to evaluate if it is in agreement with the FSN (Filter smoke number) method defined in ISO 8178:3 and ISO 10054, and by means of an aethalometer (AE33) on a diluted sample stream from different sources.

Measurements on a 4-stoke diesel engine exhaust show correlations as follows:

- EMS BC vs AE33 show a R^2 of 0.97
- EMS BC vs FSN show a R^2 of 0.83
- AE33 vs FSN show a R^2 of 0.80

Where R^2 is a measure of the quantitative correlation (likeliness) between two different measurement instruments or technologies – 1 is perfect correlation and 0 is no correlation.

The agreement of R^2 of 0.97 between EMS BC and the aethalometer proves the suitability of the method to measure BC.

In general, the EMS BC systems have performed better than expected in the first sea trial and installations.

- The EMS BC systems have responded to the low BC concentration in the exhaust.

[1] Bond, T. C. *et al.* (2013) 'Bounding the role of black carbon in the climate system: A scientific assessment', *Journal of Geophysical Research: Atmospheres*, 118(11), pp. 5380–5552. doi: 10.1002/JGRD.50171.
[2] Aakko-Saksa, P. *et al.* (2022) 'Suitability of different methods for measuring black carbon emissions from marine engines', *Atmosphere*, 13(1). doi: 10.3390/atmos13010031.

- No issues were found with dirty optical surfaces (fouling), which was one of the main engineering risks in the development of the EMS BC sensor.
- The scattering measurement showed good performance and stability.
- The presented data also showed good correlations between the EMS BC sensor and the two reference technologies.

Some challenges were also identified in the test campaign:
- The concentration of BC in the exhaust of the test ship was lower than expected especially at cruise load with less than 1 mg/m^3.
- Due to the low BC concentration, the known cross-interference with the NO_2 present in the exhaust became a considerable measurement error.
- Furthermore, due to the low BC, the accuracy and stability of the opacity (the most significant measured parameter in the EMS method) was a limiting factor in the in-situ system.

Based on the extended experience of the EMS method in this project, the following key points of the EMS BC sensor can be listed:
- Suitable real-time in-situ measurement in marine engine exhaust as an alternative to complex extractive techniques and filter deposition methods (FSN).
- Traceability, as the optical measurement of extinction and scattering can be calibrated using known and proven methods.
- Reduced cost of ownership, as it is easy to install and robust for maritime applications, with low maintenance and no need for specialist monitoring.

1.2 Sammenfatning og konklusion

Black Carbon (BC eller sod) er en klima- og sundhedsproblematisk udledning, forårsaget af forbrænding af fossile brændsler i fx skibsfarten. Effektiv overvågning af emissionerne er det første skridt mod en reduktion af denne skadelige forurening.[1]

Denne rapport beskriver udviklingen og testen af en Green Instruments EMS BC-sensor teknologi ved hjælp af EMS-metoden (Extinction Minus Scattering) til at kvantificere BC-koncentrationen i motorens udstødning.

EMS BC-sensoren er en online og in-situ måleteknik, som har flere fordele sammenlignet med de traditionelle ekstraktionsteknikker samt filteraflejringsmetoder, såsom Filter Smoke Number (FSN) eller Photoacoustic spectroscopy (PAS).[2]

Prioriteterne i udviklingsaktiviteterne var at sikre, at målesystemet har lav vedligeholdelse, tilstrækkelig robusthed, passende nøjagtighed og validitet og er relativt let at installere på forskellige udstødnings- og skibstyper.

Systemet er blevet evalueret på testmotorens udstødning, efterfulgt af test på skibe både som in-situ- og ekstraktionsudgaver af EMS BC.

EMS BC-sensorens egnethed til måling af BC fra en dieseludstødning behandles. Fokus er på at tilvejebringe korrelationer, dvs. den relative respons af BC-koncentrationerne - hovedsageligt fordi der ikke er videnskabelig enighed om en referencemetode til måling af BC.

EMS BC-metoden testes for at evaluere overensstemmelsen med FSN-metoden (Filter smoke number), der er defineret i ISO 8178:3 og ISO 10054, og ved hjælp af et aethalometer (AE33) på en fortyndet prøvestrøm fra forskellige kilder.

Målinger på en 4-stoke dieselmotor udstødning viser korrelationer som følger:
- EMS BC vs. AE33 viser en R^2 på 0,97
- EMS BC vs. FSN viser en R^2 på 0,83

- AE33 vs. FSN viser en R^2 på 0,80

Hvor R^2 er et mål for den kvantitative korrelation (sammenhæng) mellem to forskellige måleinstrumenter eller teknologier (1 er perfekt sammenhæng og 0 er ingen sammenhæng).

Korrelationen R^2 på 0,97 mellem EMS BC og aethalometeret beviser metodens egnethed til måling af BC.

Generelt har EMS BC-systemerne klaret sig bedre end forventet i første skibstest og installationer.

- EMS BC-systemerne har reageret på den lave BC-koncentration i udstødningen.
- Der ses ingen problemer med snavsede optiske overflader (tilsmudsning), som var en af de største tekniske risici i udviklingen af EMS BC-sensoren.
- Spredningsmålingen viste god ydeevne og stabilitet.
- De fremlagte data viste også gode sammenhænge mellem EMS BC-sensoren og de to referenceteknologier.

Der blev også identificeret nogle udfordringer i testkampagnerne:

- Koncentrationen af BC i testskibets udstødning var lavere end forventet, især ved lav last med lavere end 1 mg/m^3.
- På grund af den lave BC-koncentration blev den kendte krydsinterferens med NO_2 i udstødningen en markant målefejl.
- På grund af den lave BC var nøjagtigheden og stabiliteten af opaciteten (den mest signifikante målte parameter i EMS-metoden) desuden en begrænsende faktor i in-situ-systemet.

Baseret på erfaringerne med EMS-metoden i dette projekt kan følgende nøglepunkter for EMS BC-sensoren opsummeres:

- Gangbar in-situ-måling i realtid i udstødning fra skibsmotorer som et alternativ til komplekse ekstraktionsteknikker og filteraflejringsmetoder (FSN).
- Sporbarhed, da den optiske måling af udryddelse og spredning kan kalibreres ved hjælp af kendte og gennemprøvede metoder.
- Reduceret ejeromkostninger, da den er nem at installere og robust i det maritime miljø med lav vedligeholdelse og intet behov for specialistovervågning.

2. Introduction

This project was supported by MUDP (grant 2020-15629) under the Ministry of the Environment. The project period lasted from January 2021 to August 2023.

The project consortium consists of:
- Green Instruments A/S
- Danish Technological Institute
- Danish Maritime
- Danish Shipping
- DFDS A/S
- MOL Chemical Tankers

2.1 Black Carbon and emissions from ship engines

Black carbon (BC) is a major component of fine particulates in the air and is formed by incomplete combustion of carbon-based material in, for example, engines.

The International Maritime Organization (IMO) has adopted the definition from Bond et al. [3] that BC has:

1. Strong visible light absorption (it is very black).
2. High vaporization temperature of 4000K.
3. It is insoluble in water and organic solvents.
4. It consists of aggregates of nanoscale-sized carbon spherules.

In relation to ship emissions, BC is considered the second most important parameter that affects global warming, after CO_2. The warming effect is especially existent in the Arctic regions where BC significantly influences the acceleration of the climate change. BC, sedimented on snow and ice, reduces the reflection of the sun's rays, and in that way contributes to the global warming and melting of the poles. At the same time, BC has significant adverse health effects for humans in the form of exposure to fine particulates.

Therefore, BC is a climate and health problematic emission from the shipping industry, and efficient monitoring of emissions is a first step towards reducing BC. In terms of climate, and if no actions are taken, the maritime sector is expected to account for up to 10% of total global greenhouse gas emissions in 2050[4], with a particular challenge in the Arctic regions in the form of BC emissions.

Research has shown that the greenhouse effect of BC is app. 3,000 times as powerful as CO_2, and therefore the BC contribution to the greenhouse effect is significant.[3]
The following example concretizes the effect: 1 kg diesel or HFO (heavy fuel oil) is burned to approx. 3.1 kg CO_2 and 0.01-1 g BC. As also used in other studies, we could assume a BC emission of 0.25 g BC/kg fuel and a BC to CO_2 equivalent factor of 3,000. Then a BC CO_2 equivalent of 0.75 kg CO_2/kg fuel is obtained, corresponding to approx. 25% of the CO_2 emission itself. Therefore, there is great potential for improvement in relation to the climate footprint of shipping by reducing BC emissions alone.

[3] Bond, T. C. et al. (2013) 'Bounding the role of black carbon in the climate system: A scientific assessment', Journal of Geophysical Research: Atmospheres, 118(11), pp. 5380–5552. doi: 10.1002/JGRD.50171.

[4] https://www.transportenvironment.org/challenges/ships/greenhouse-gases/

The international maritime organization (IMO) is aware of these effects. Through the past decade, IMO has worked to define BC and is looking into strategies that can reduce emissions. However, the focus of IMO has been on direct CO_2 emissions with new regulations within energy savings and efficiency measures. These will also lead to a reduction in BC; however, it is not possible to simply calculate the reductions 1:1 due to the complexity of the generation of BC.

Today, many technologies are being developed to reduce BC emissions from the maritime sector, but documentation of their effects is necessary, and there will most likely be requirements for documentation of BC emissions. Several of the actual measures currently being evaluated under the IMO could result in significant reductions of BC emissions. For example, particulate filters are extremely efficient under certain conditions and can reduce BC by more than 90%, whereas the effect is more uncertain when, e.g., SOx scrubbers are used. The use of alternative fuels also has a varied reduction potential with several different options (LNG, methanol, biofuels, distillates, etc.). There is also potential in engine optimization to improve combustion as a more cost-effective measure.

The stricter IMO requirements to sulphur emissions from ships, which have been rolled out over the past decade, including requirements to the use of either low-sulphur oil or scrubbers, have already led to less particle emissions in the form of fewer sulphates and organic particles. However, it should be emphasized that this does not necessarily also imply a lower BC emission. From a particle point of view, it is only BC that has a warming effect on the climate in the form of its strong light-absorbing nature.

Some of the new fuels on the market, especially those with higher aromatics concentration, even turn out to be able to cause significantly higher BC emissions than traditional low-sulphur fuels.[5] Today, there is no way to assess whether a purchased fuel type leads to higher BC emissions on a specific ship at a specific load; here it will be necessary to use BC measurement technology.

In addition to the climate impact of BC, there is a considerable health impact. WHO has identified air pollution as the greatest environmental risk to human health in the EU. It is well-documented that particulate pollution causes several hundred thousand premature deaths annually in the EU[6] of which the particulate matter, in the form of PM2.5 including BC, is a significant component. At European level, maritime traffic particulate emissions in the form of PM2.5 account for approx. 10% of the total PM2.5 pollution (2019). With associated socio-economic costs of several hundred billion DKK in the EU, even a small reduction in BC/PM2.5 emissions could have a major economic impact – solely from a health point of view.

Since the adoption of the stricter sulphur requirements, there has been a 50% reduction in SO_2 concentration in Denmark alone, which testifies to the importance of regulation, enforcement, and measurements in relation to reducing maritime emissions and improving air quality. Therefore, it is expected that the work in the IMO on BC regulation also will have a significant effect on emissions from the maritime sector.

In this context, the presence of a practical BC sensor that continuously carried out measurements could be an important part of the regulatory acceleration in the area and, not least, could be an important item for documenting and implementing BC reducing measures.

[5] IMO PPR8-11 INF

[6] https://www.eea.europa.eu/publications/air-quality-in-europe-2022/health-impacts-of-air-pollution

2.2 Technologies for measuring BC

As mentioned, IMO's focus is on BC emissions and how to limit them. Many, if not all, of the BC reducing measures under consideration, such as particulate filters, flue gas cleaning with scrubbers, engine optimization or alternative fuels, will benefit significantly from control and feed-back using a sensor that continuously measures BC.

After careful consideration, the IMO has identified three BC measurement principles that are considered appropriate for use in maritime applications:[7]

1. **FSN** (filter smoke number): blackening on filter material (paper) and subsequent measurement of light absorption.
2. **PAS** (photoacoustic absorption spectroscopy): measurement of the light absorption of BC using an acoustic signal generated by laser-heating of BC.
3. **LII** (laser-induced incandescence): measurement of the thermal light emission from heated BC using a laser.

Common to the three techniques is that they use the distinctive optical properties of BC, as the BC particles appear very black. In practice, the challenges when measuring BC in hot engine exhaust are that the smoke is very hot (up to 500°C), dirty (BC, SO_2, ash, other particles, etc.) and has high humidity (especially in connection with scrubber installations). These conditions place heavy demands on the design of the measuring equipment and on maintenance to achieve stable and reliable measurements.

Today, BC measuring equipment on the market has primarily been developed for either stationary test set-ups in the automotive industry (e.g., from AVL) or as a portable instrument based on measuring FSN (from Testo). Common to the instruments on the market is that they are not designed for continuous measurements without maintenance or monitoring by measurement specialists. In addition, the maritime environment places heavy demands on temperature tolerances, vibrations, and minimal maintenance, which the equipment today does not live up to.

It should also be mentioned that the PAS and LII instruments require a sample dilution system that requires a high degree of maintenance (e.g., cleaning operation every 24 hours).

2.3 Other content of engine exhaust

The content of engine exhaust is shown in FIGURE 1, adapted from ISO8178:3. It can be seen that filter PM (particle mass) covers more than BC (EC), opacity measures fewer components, whereas FSN measures the fewest types of matter. The "*!ª*" indicates that the methods have risks of cross interference from other components than intended. Especially, opacity is quite weak in this regard. Therefore, IMO has not accepted this method in the BC measurement list.

It is important that the chosen measurement technology of the BC sensor is not cross-sensitive to other components in the exhaust than BC.

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[7] 5th ICCT Workshop on Marine Black Carbon Emissions, 2018 and IMO PPR 7/8 and PPR 5/24

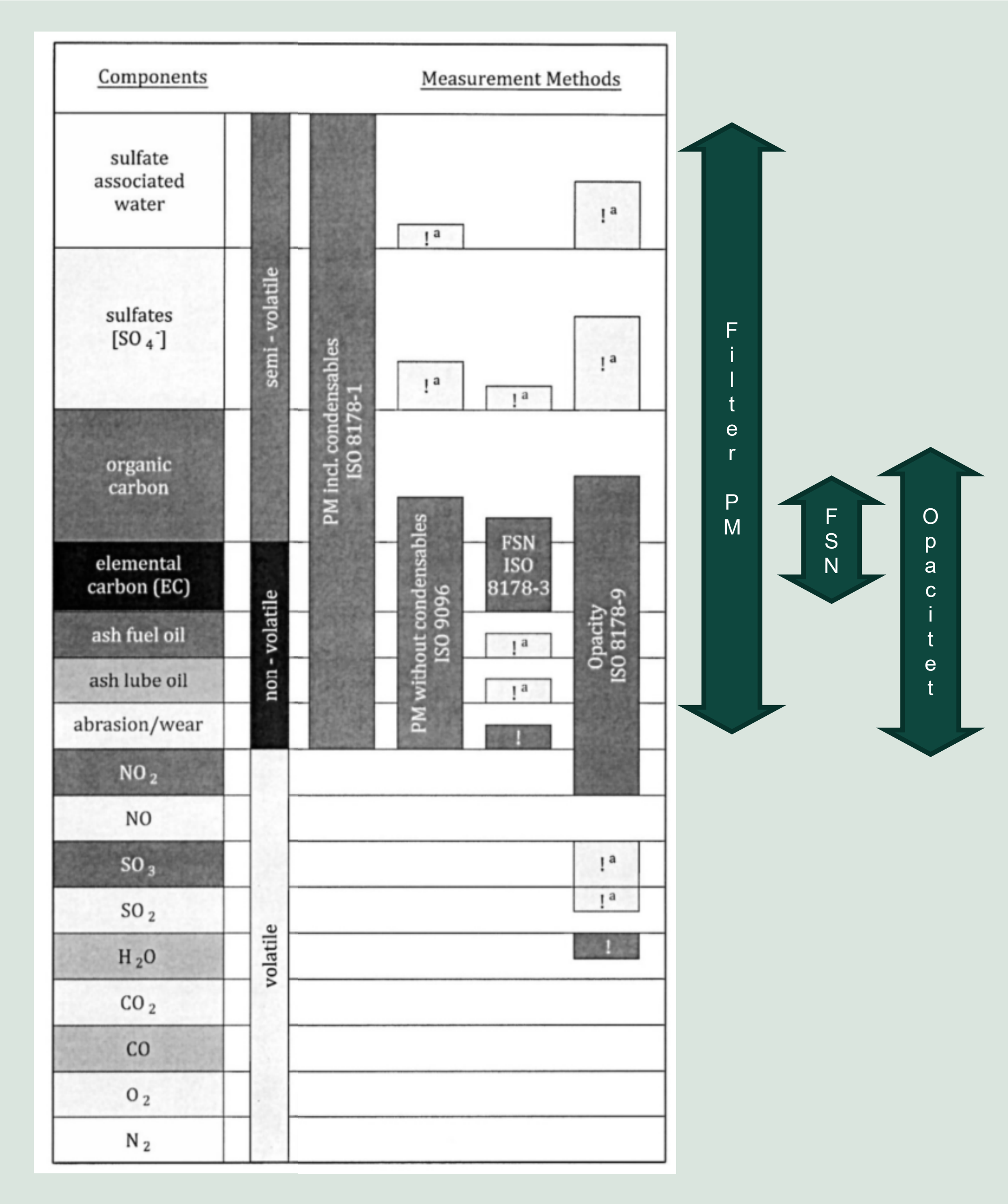

FIGURE 1. The solid fraction of engine exhaust, and different techniques used to measure the content. The elemental carbon (soot) fraction is mainly BC. Organic carbon is condensed or non-condensed hydrocarbons (unburned fuel and lube oils), and ash can be metallic oxides. *!ª* indicates potential cross-interference when the methods are used. From ISO 8178:3.

3. Sensor development

This section describes the development of the BC sensor in the project. The objective was an online and in-situ measurement with several advantages compared to the traditional extractive techniques and filter deposition methods.[8]

Several measuring concepts to quantify the BC concentration in engine exhaust have been evaluated early in the project. A final selection was based on a thorough technical evaluation as well as an external questionnaire, and the EMS (Extinction minus scattering) technology BC sensor was chosen for further testing. The main drivers were simple concept, robustness, and in-situ measurement.

3.1 Principle of operation of EMS

The purpose of the EMS BC sensor is to quantify the BC concentration directly in exhaust gas. BC is very black because it has a very high optical absorption, and therefore a measurement of the optical absorption of the exhaust is a measurement of the BC concentration.

This technology relies on measuring the amount of light *extinct* by traversing a sample path. The extinction is due to absorption and scattering of the gasses and particles in the sample. By measuring the extinction, which is directly related to the opacity of the gas, and measuring the light scattering of the sample, the absorption can be calculated as (extinction minus scattering):

$$\text{absorption} = \text{extinction} - \text{scattering}$$

The physical entity measured is the optical extinction and scattering (cross section) and has the unit of reciprocal metres (m^{-1}). BC has a mass absorption cross section (MAC) of about 7.5 m^2/g[9]. The mass concentration (mg/Nm^3) is then calculated as:

$$\text{Mass\_BC} = \text{absorption}/\text{MAC} = (\text{extinction} - \text{scattering})/\text{MAC}$$

In the Green Instruments EMS BC sensor this is realized by using an **opacity meter** (this measures the light extinction) and an in-situ **nephelometer** to measure the optical scattering of the sample. The opacity meter is a single or dual path configuration and the nephelometer is configured with multiple lasers to measure representative angle sections of the scattering function of the exhaust sample.

[8] Aakko-Saksa, P. *et al.* (2022) 'Suitability of different methods for measuring black carbon emissions from marine engines', *Atmosphere*, 13(1). doi: 10.3390/atmos13010031.

[9] Bond, T. C. *et al.* (2013) 'Bounding the role of black carbon in the climate system: A scientific assessment', *Journal of Geophysical Research: Atmospheres*, 118(11), pp. 5380–5552. doi: 10.1002/JGRD.50171

3.2 Specifications

The aim of the development was set by preliminary specification. The specifications for the instruments are listed in TABLE 1.

TABLE 1. Specifications.

Entity	Note
Continuous	Yes, > 0.1Hz
Measurement unit	Not determined. Mg/Nm^3, mg/KWh, mg/nauticalmile, mg/kg fuel
Precision BC	Better than regulatory requirements
Calibration interval	Calibration should be simple, robust, and repeatable. The need for calibration is postponed by means of own diagnostics and fouling compensation
Cleaning interval	Min. 30 days (Probe must be easily extractable)
Factory calibration	Yes, according to a standard determined by the vendor
Exhaust temperature	10-500 °C
Flue gas humidity	Potentially gas with droplet content and with RH 100%
Temperature sensor	Yes. Reference exhaust temperature
Tamper-proof	Yes
Air-purge	Yes, for optics cleanliness
Compressed air	Yes, e.g. ISO 8573-1 Class 2-2-2
Price	As cost-effective Total Cost of Ownership – aim for lowest TCO
Approvals (general)	Yes, IACS E10
IP rating	IP44 or higher
Vibrations	ACS UR E10.7, Requirement 4 G, Design 5-6 G
Surround temperature	Requirement 60°C, Design 65°C
Electronic interface	RS232/485, Modbus TCP/IP Ethernet, 4-20mA, DO alarm
Display	Yes
Internal log	Yes
Electrical voltage	110/230 VAC or 24V
Flange on smoke duct	JIS and DIN compatible

3.3 Design

The optical and mechanical design is subject to a patenting process; therefore, the technical details of the product have not been submitted in detail in this report.

The overall concept for the initial design is illustrated in FIGURE 2.
Several laser modules and detector modules are mounted directly on the exhaust stack. The lasers are turned on and off in a specific pattern to measure the opacity and the scattered light at different angles. The processing unit converts the measured signals in the BC concentration.

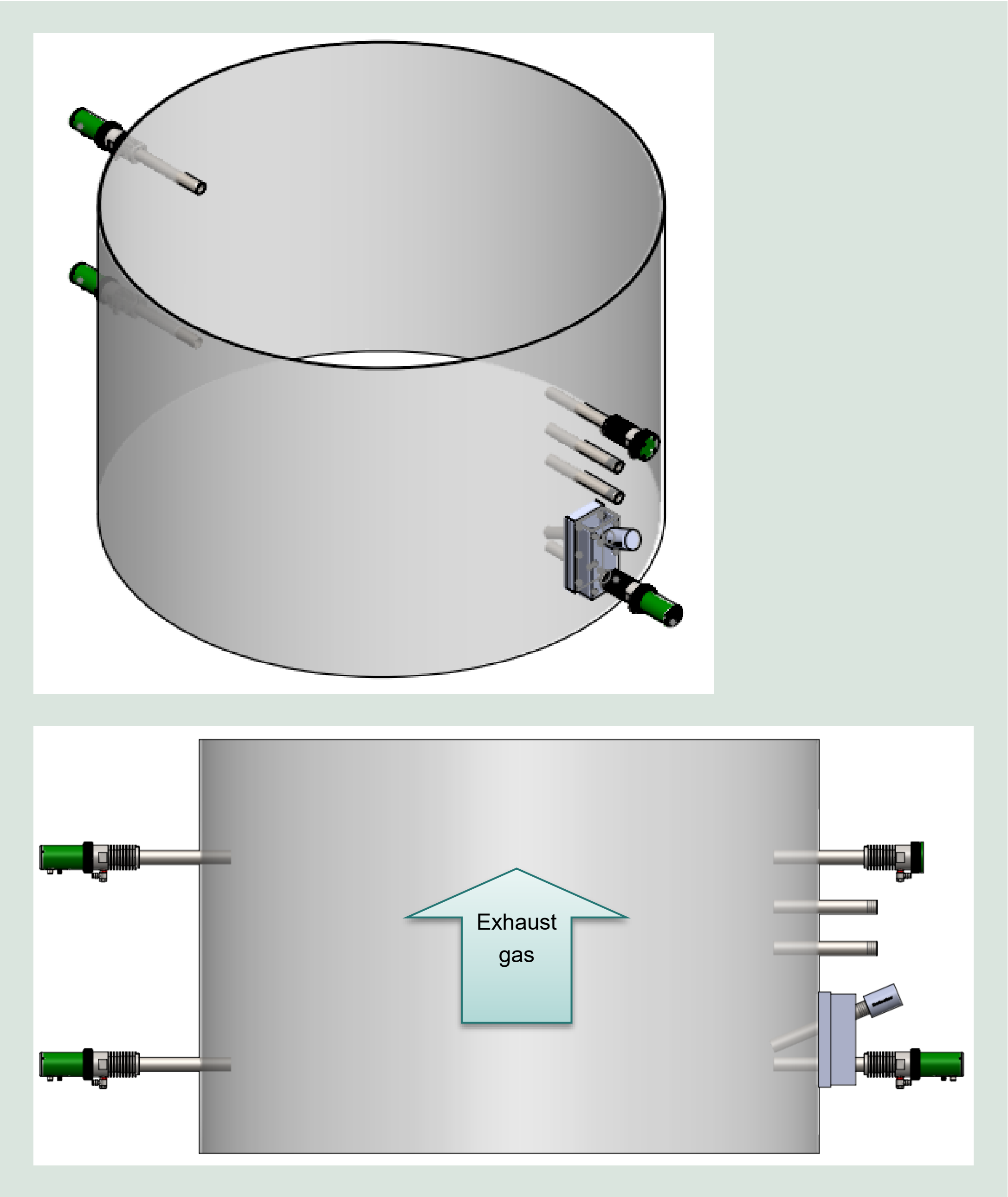

FIGURE 2. Drawing of the EMS BC sensor installed in an exhaust pipe. Additional tubes are installed in this set-up for reference measurement purposes.

3.4 Traceability

No international traceable standard or reference method is defined for measuring of PM in general or BC in particular.

The concept of the EMS sensor is adopted by the desire to employ a sensor concept that (in principle) has traceability to international metrology references:

- The opacity meter can be calibrated using a reference optical filter.
- The gas sample length is measured using a calibrated metal measuring tape.
- The nephelometer can be calibrated using the opacity meter with non-absorbing and scattering particles (fog).

Important state parameters of the instrument such as cleanliness of optics, laser powers, detector responses, and alignment of lasers will be tracked by implemented functions of the EMS BC sensor.

To know the BC concentration at reference conditions, the temperature and the pressure of the exhaust must be measured. These quantities are also traceable to international standards.

The EMS BC sensor outputs the mass concentration (mg/Nm^3), but IMO focuses on the FSN. However, FSN can be calculated from the mass concentration using empirical formulas described in ISO8178-3. This is standardized but not traceable.

4. Laboratory engine results

This section describes the results of the laboratory engine test carried out in the project.

4.1 Laboratory engine set-up

In the early development, the EMS BC sensor was installed in an extractive tube to enable portability and flexibility of the exhaust source. The physical realization can be seen in FIGURE 3.

To keep the optics clean, pressurized air is flushed over the optical surfaces. A fan is installed on the tube to suck the exhaust air through the tube. The position of the exit hoses of the tube ensures that minimal dilution of the sample takes place in the tube.

The engine test set-up is depicted schematically in FIGURE 4 and in pictures in FIGURE 5 and FIGURE 6.

The main equipment used was:

- Green Instruments EMS BC sensor installed in extractive tube
- Extractive tube 1000 mm, heated with wires to 180°C
- Extractive fan at the exhaust
- Diesel Engine, Peugeot 1.6L on test bed, 4 cylinders
- Road diesel as fuel
- Testo FSN meter 338
- Testo Rotating Disc Diluter at 900x dilution
- Magee Scientific AE33 Aethalometer (diluted exhaust gas)

State-of-the-art within measurement of BC in ambient conditions are aethalometers, which in essence is a very refined and accurate FSN type method. A dilution system is mandatory when exhaust gas is measured with an aethalometer. That takes place with similar equipment used for standardized exhaust gas measurements.

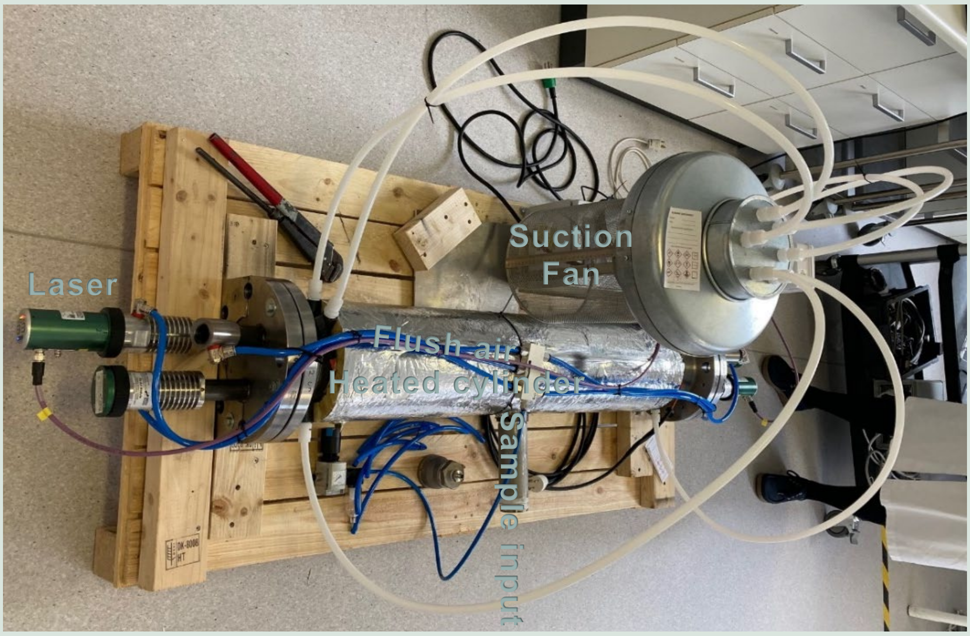

FIGURE 3. Physical realization of the EMS BC sensor installed in the extractive tube.

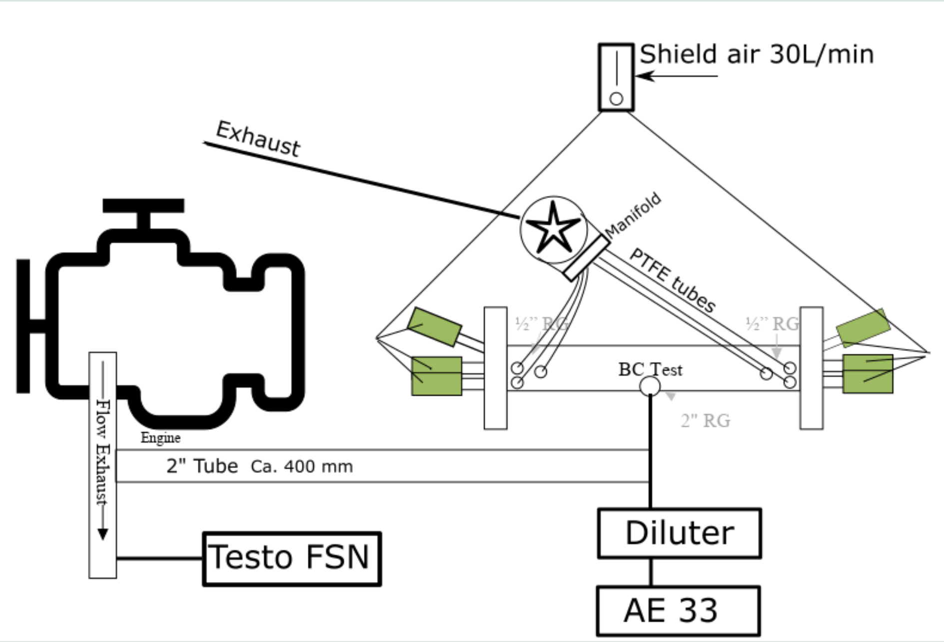

FIGURE 4. Schematics of the engine test.

FIGURE 5. Diesel engine set-up with EMS BC sensor installed in the extractive tube.

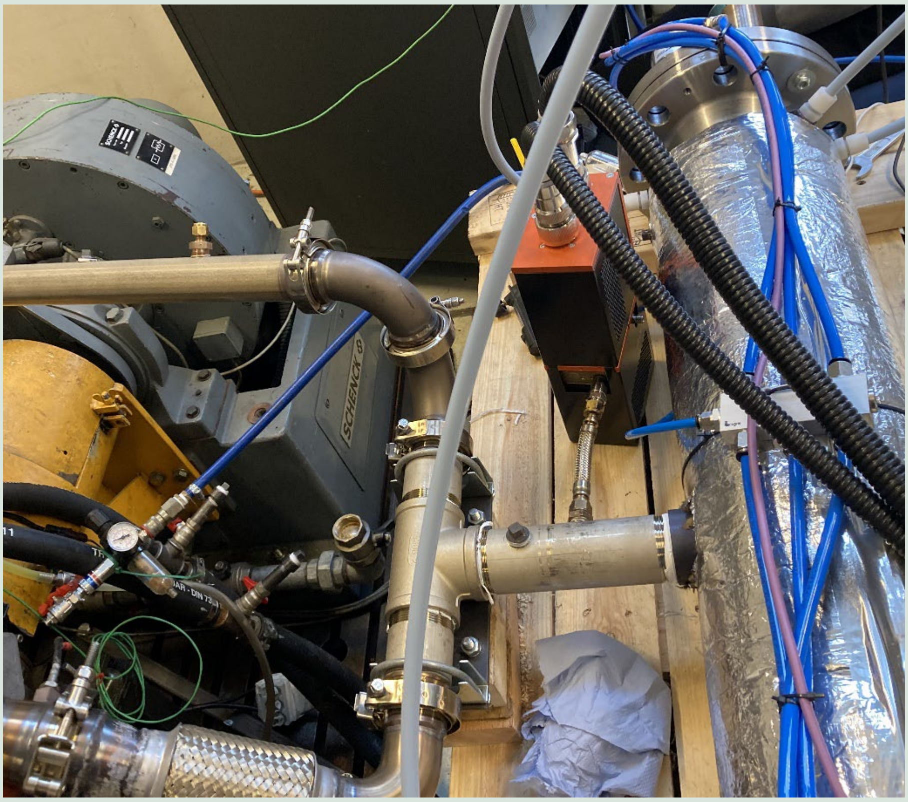

FIGURE 6. T-connection from the engine exhaust manifold to the tube and to the external exhaust.

4.1.1 Test protocol for the engine test

1. The components are installed, and airtightness is tested.
2. Pre-heat engine, tube, and diluter.
3. Pressurize the shield air for the EMS BC (app. 30 L/min in total).
4. Define engine parameters; the engine is fixed at 1800 rpm with a varying load of 30-80%. Due to oil heating issues, the ramp and hold times are limited to app. 3 minutes.
5. Start exhaust fan to fill the tube continuously.
6. Start all measurements.
7. At stable conditions carry out FSN sampling using the Testo 338.
8. Stop the engine motor to measure a period of clean air to check the zero point of the nephelometer and opacity meter (no contamination of the windows was observed).

4.2 Results

The results of the performance testing of the EMS BC sensor are presented in this section.

Two periods of testing were performed.

The main **period 1** consists of simultaneous measurements of all methods EMS BC, AE33 and a large number of samples with the manual Testo FSN. The measurement data over time in the main period 1 can be seen in FIGURE 7.

The directly measured optical cross sections can be seen in FIGURE 8. This shows that the extinction cross sections are 2-3 times higher than the scattering cross sections, which is expected in a sample containing a high fraction of BC.

Focus is on the correlations between the applied methods, which can be seen in FIGURE 9 and FIGURE 10. The R^2 correlation factors of 0.83 and 0.97 for the Testo FSN and AE33, respectively, are found.

The correlation between the reference methods (Testo FSN and AE33) can be seen in FIGURE 11. The degree of correlation (R^2) is about 0.80, which is similar to the EMS BC to Testo FSN correlation.

In **period 2,** the EMS BC and AE33 are compared in FIGURE 12 and FIGURE 13. No valid Testo 338 FSN measurements were made due to lack of correct timestamping of the manual measurements.

4.2.1 Engine cycle test results

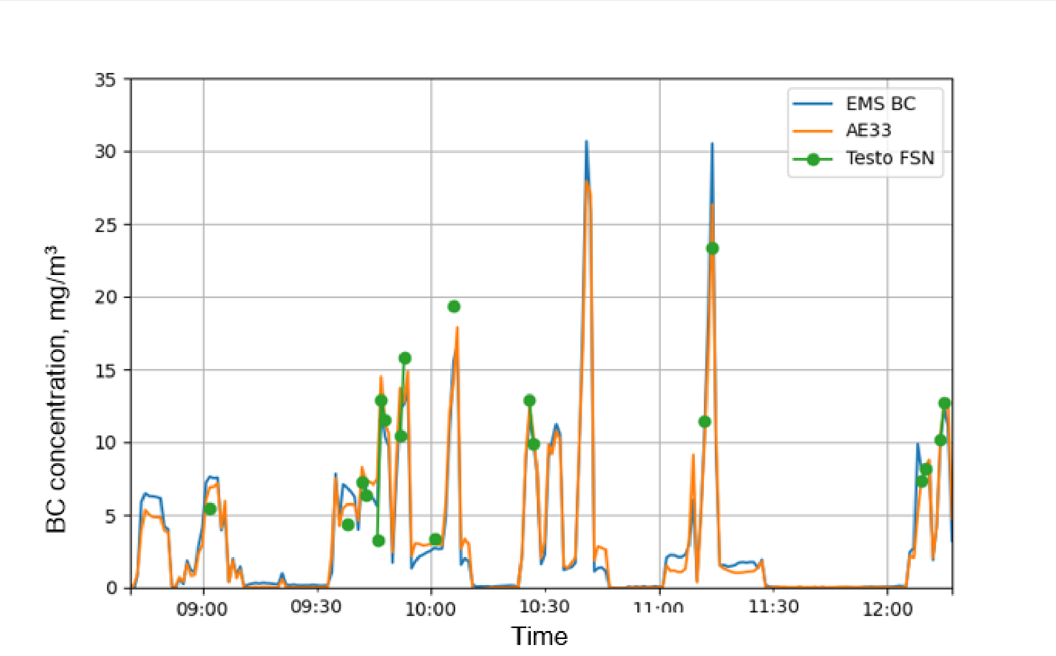

FIGURE 7. BC concentration measured by the 3 methods as function of time.

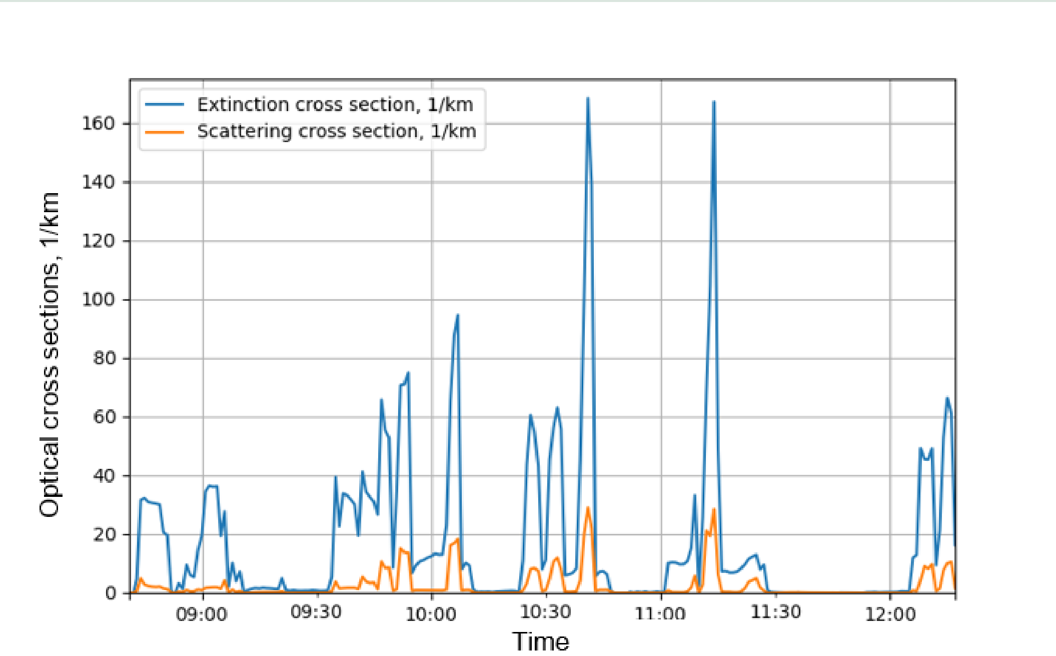

FIGURE 8. Extinction and Scattering Cross sections as function of time. Extracted from the EMS BC sensor.

4.2.2 Correlation EMS BC to reference methods

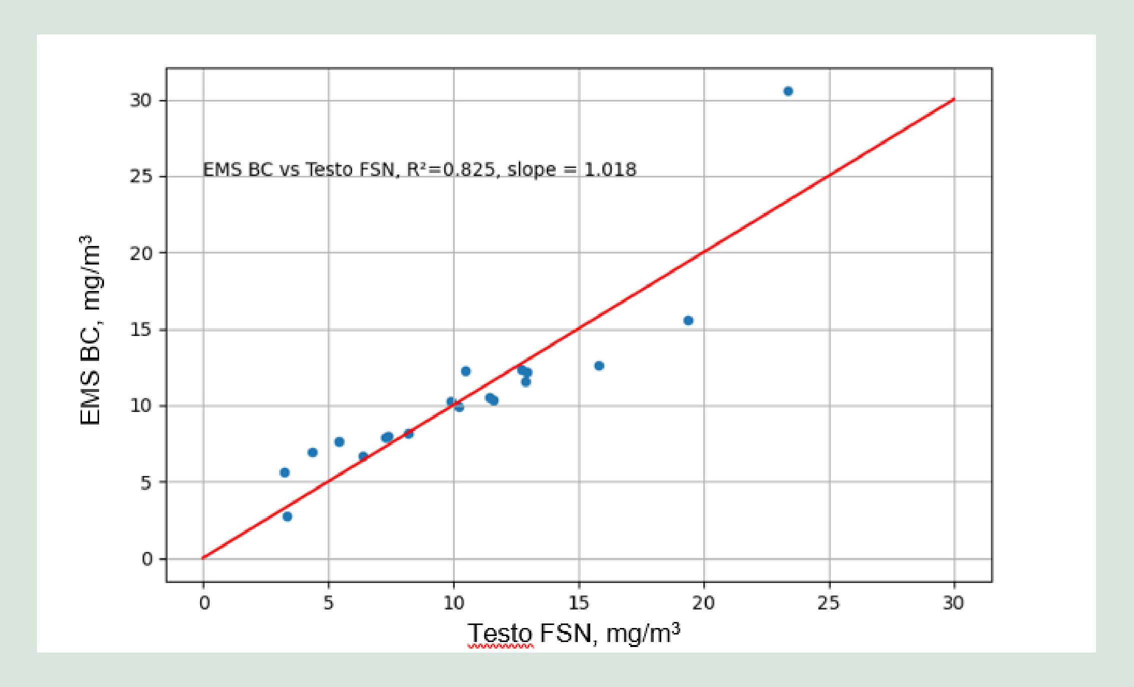

FIGURE 9. EMS BC sensor concentration compared to Testo FSN.

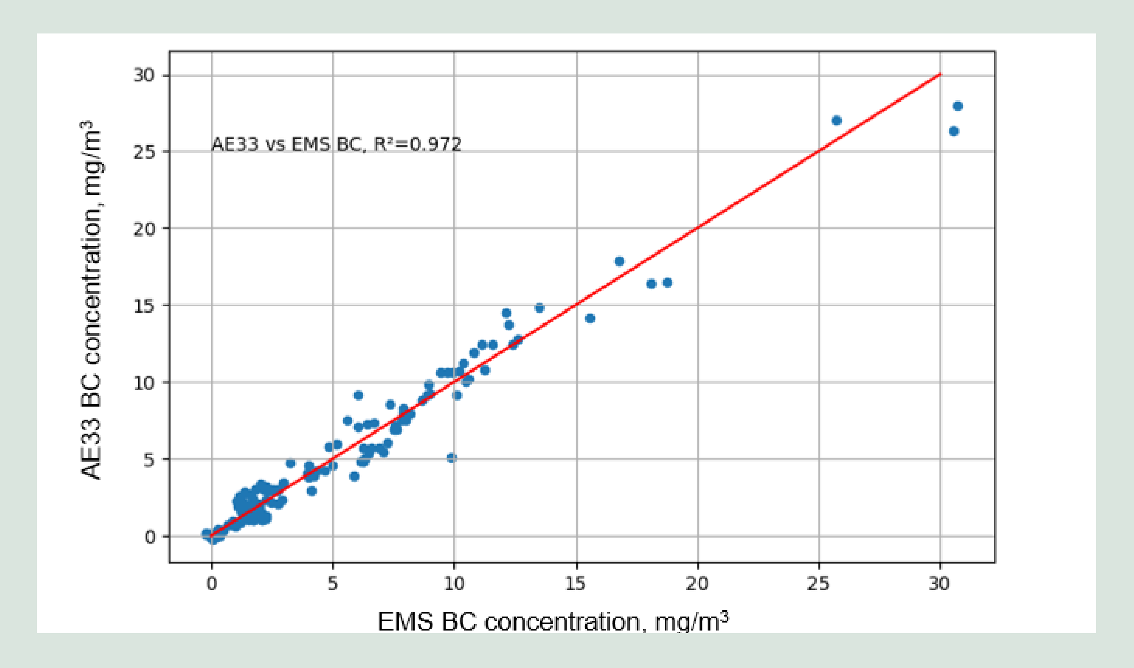

FIGURE 10. AE33 compared to EMS BC sensor.

4.2.3 Correlation between AE33 to Testo FSN

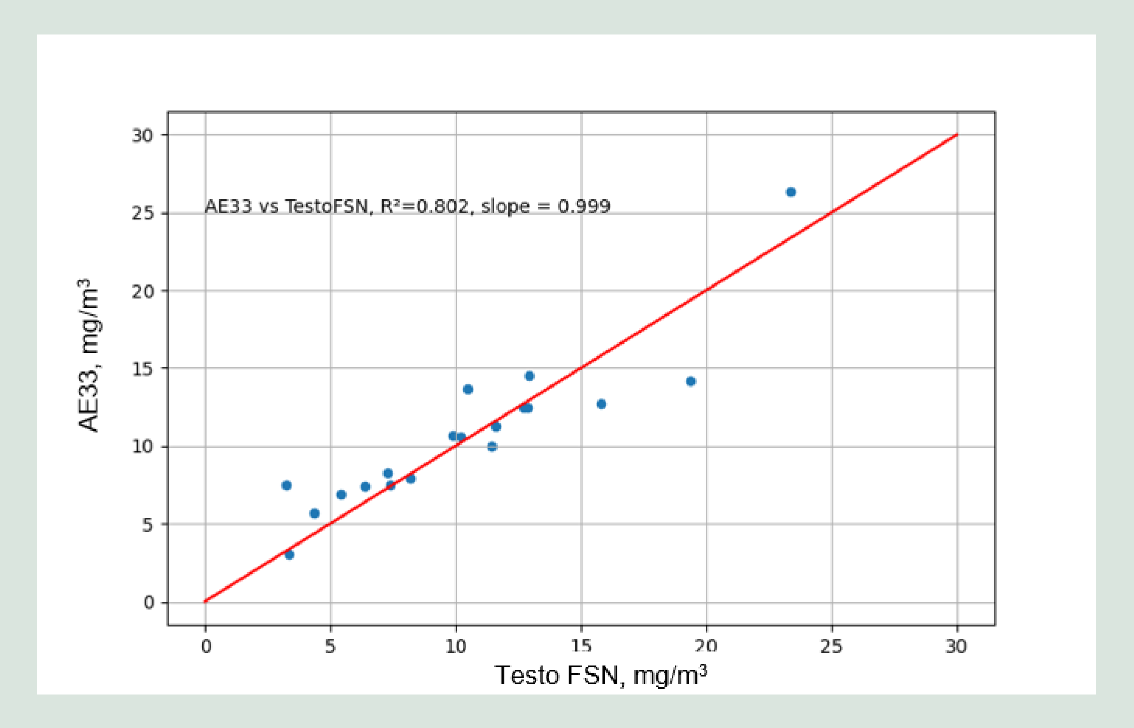

FIGURE 11. Correlation between AE33 and Testo FSN.

4.2.4 Period 2: Additional testing (with AE33)

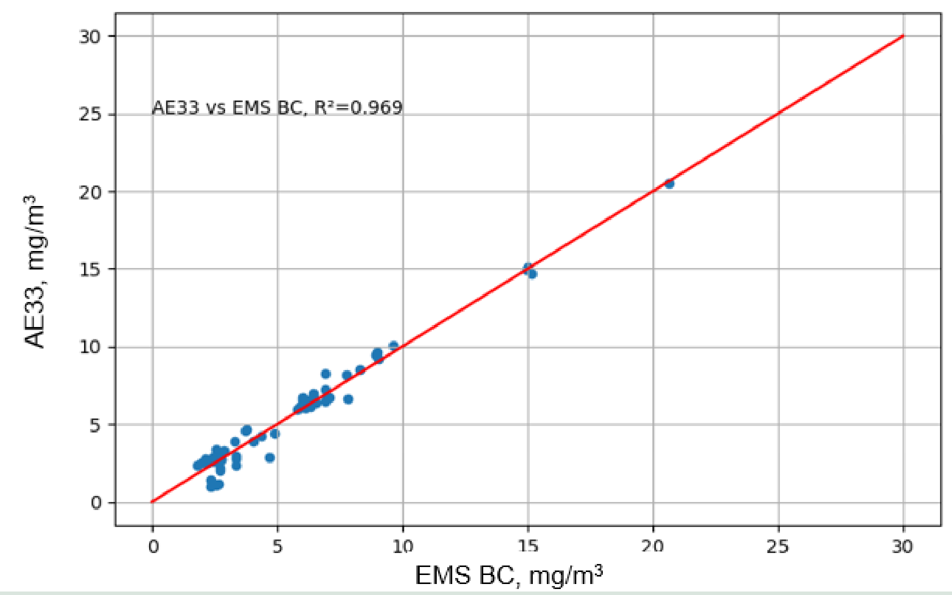

FIGURE 12. Correlation of EMS BC and AE33 in period 2.

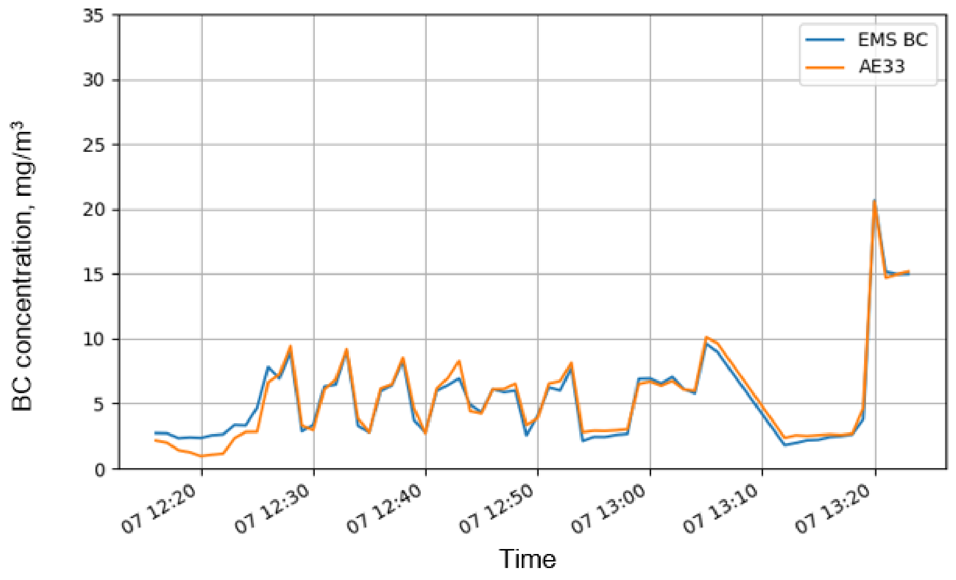

FIGURE 13. BC concentration measured by the EMS BC and AE33 as function of time in period 2.

4.3 Discussion

The suitability of the EMS BC sensor for measuring BC from a diesel exhaust was addressed. Focus was on providing correlations, i.e., the relative response of the BC concentrations – mainly as no reference method for measuring BC has been agreed upon. The main reference instruments in these tests were the AE33, which is known to be very precise in ambient BC measurements, and the Testo 388, which is designed for direct measurements of diesel exhaust.

Two periods of measurements on the diesel engine were analyzed, and the correlations were as follows:

- EMS BC vs. AE33 show a R^2 of: 0.97 (Period 1 and 2)
- EMS BC vs. Testo FSN show a R^2 of: 0.83 (Period 1)

The correlation between the two reference techniques were as follows:

- AE33 vs. Testo FSN show a R^2 of: 0.80 (Period 1)

It should be noted that the Testo FSN was carried out with handheld sampling for periods of 15-20 seconds. That is a rather long time compared to the periods of stable emissions from the engine, lasting less than 2 minutes. This has a negative influence on the temporal precision of the Testo FSN method and can likely explain the imperfect R^2 values of around 0.8.

The agreement of R^2 of 0.97 between EMS BC and the aethalometer proves the suitability of the method to measure BC.

Regarding the absolute values of the BC concentration, it has been chosen to use the Testo FSN as the absolute reference data and fit the slope of the EMS BC and the AE33 to these values. In further tests it is advisable to measure the exhaust temperature to enable qualitative results of the EMS BC sensor compared to the reference equipment at standard conditions.

5. Ship installations

The purpose of installing systems on-board ships was to evaluate the performance of the concept as well as the challenges in the harsh maritime environment.

5.1 Ship set-up extractive and in-situ

The system was installed on DFDS Belgia Seaways (IMO 9188233) in the autumn of 2022. Results were recorded on the trip from Frederica (Denmark) to Klaipeda (Lithuania) and back again.

The optical components of the developed in-situ system were mounted directly on each side of the smokestack, leading to direct cross-stack measurements without any exhaust gas extraction.

The extractive system was used on the way to Klaipeda, and the in-situ system was used on the return trip.

The main equipment used was:

- Green Instruments EMS BC sensor installed in extractive tube and in-situ
- Extractive tube 1000mm, heated with wires to 180°C
- Extractive fan
- Testo FSN meter 338
- Testo Diluter at 900x dilution
- Magee Scientific AE33 Aethalometer

Two fuel types were used during the field campaign trips: MGO (0.043% Sulphur) and ULSFO (0.078% Sulphur).

The extractive installation can be seen in FIGURE 14 and FIGURE 15.

The in-situ installation can be seen in FIGURE 16.

The results of the Belgia campaign are shown in the following sections.

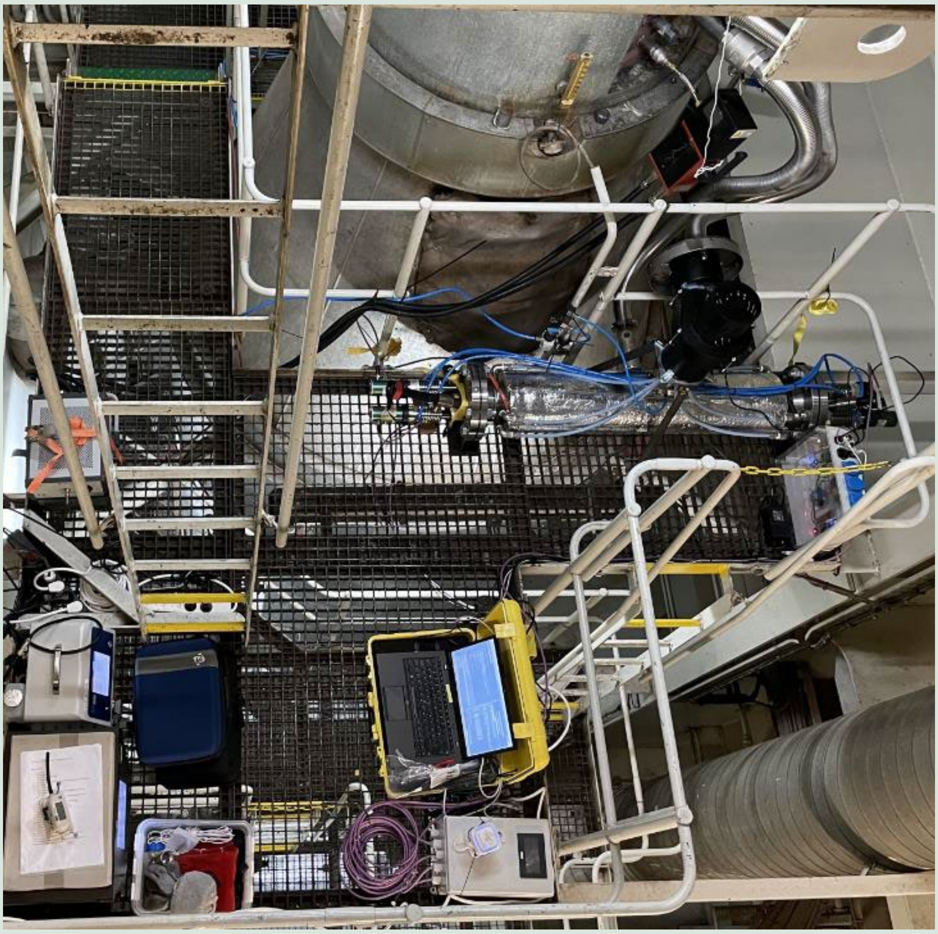

FIGURE 14. Extractive installation at Belgia. The extraction is in the upper right corner of the picture close to the extractive tube, and the reference equipment is in the lower left corner of the picture.

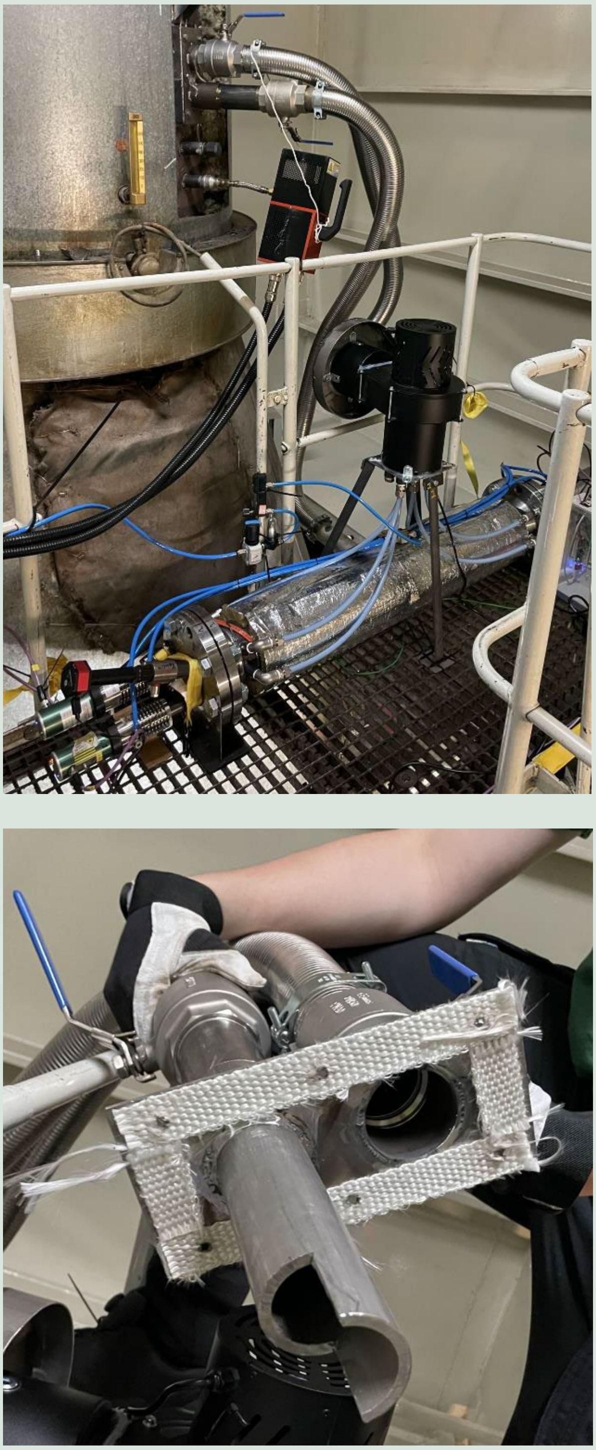

FIGURE 15. Extractive installation (top) and the probe head (bottom) used at Belgia.

FIGURE 16. In-situ installation with extractive probe installed from the reference sensors.

5.2 Results with the extractive system

It was apparent that the BC concentration was rather low during the campaign on Belgia Seaways. The measured BC concentration with AE33 and Testo FSN was below 1 mg/m^3 except for the periods during maneuvering in harbor. This had the unfortunate effect that the known interference of NO_2 on the BC results became a significant error. Consequently, in the presented results, the BC concentrations were compensated for the present NO_2 based on the best estimates of the NO_2 concentration and its influences.

In FIGURE 17, the results are shown from most of the test period of the extractive system. The EMS BC sensor data are shifted down by 8 km^{-1} (equivalent to BC concentration of 1.75 mg/m^3) to compensate for the NO_2 present in the exhaust gas. NO_2 is known to interfere with the EMS measurement at the laser wavelength used in the prototype system.

When approaching Klaipeda, this method did not yield plausible results. Therefore, an alternative method was suggested for this portion of the data. In FIGURE 18, the EMS BC sensor data was calculated with an overweight of the scattering contribution (hence lowering the absorption effect of the NO_2 in the BC concentration). This calculation method gave rather good agreement.

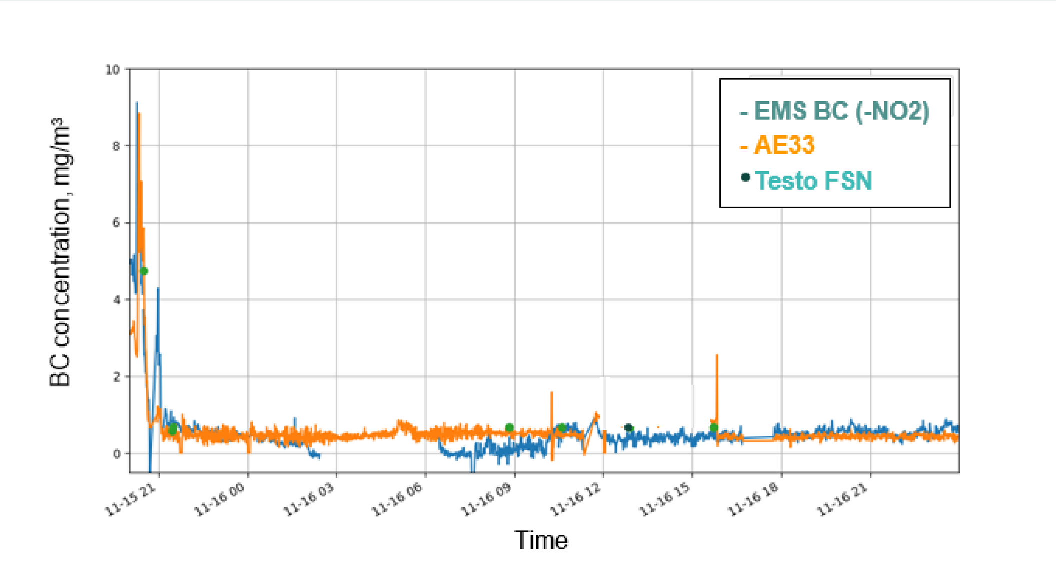

FIGURE 17. Results from the extractive system on Belgia. The EMS BC sensor data was shifted down by 8 km^{-1} to compensate for the NO_2 present in the exhaust gas, which is known to interfere with the EMS measurement in this specific setup.

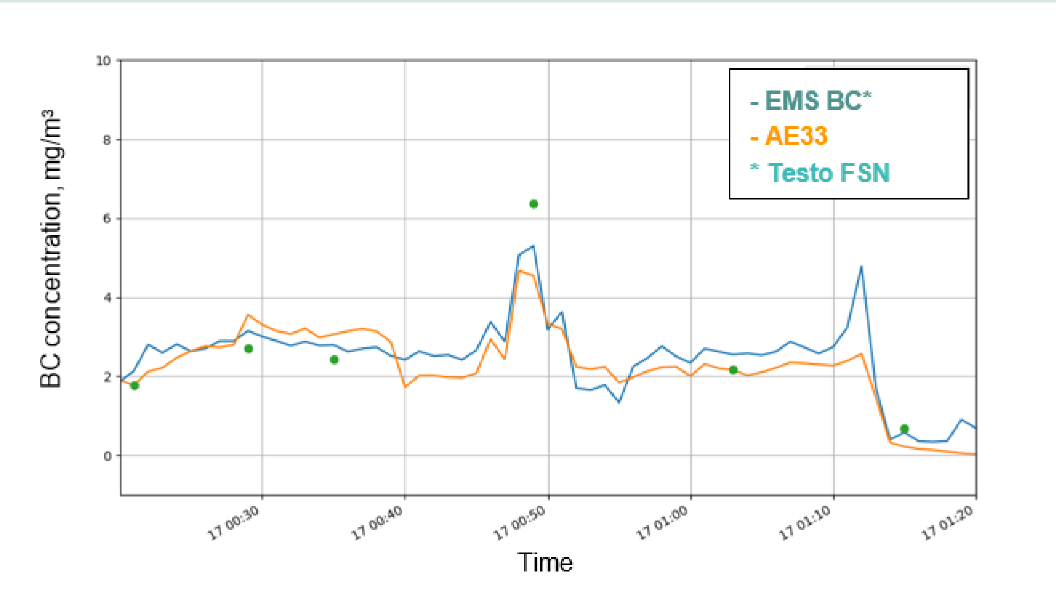

FIGURE 18. Results from the extractive system on Belgia when approaching Kleipeda. The EMS BC* sensor data in this plot was calculated with an overweight of the scattering contribution in the BC calculation to compensate for the NO_2 present in the exhaust gas, which is known to interfere with the EMS measurement in this specific setup.

5.3 In-situ system results

The in-situ system unfortunately suffered from an unexpected large temperature dependent variation in the zero point of the opacity meter (+/- 3% opacity or equivalent to BC concentration of app. 2 mg/m^3). So during periods with changing engine loads, the temperature of the stack changed the laser alignments to such a degree that most measurements became invalid. If the BC concentration was an order of magnitude higher, then this issue would be much less pronounced.

Furthermore, in the current development stage the calibration routes of the in-situ system are not fully developed. Therefore, the exact BC concentrations from the EMS BC sensor were fitted to the reference data of the Testo FSN.

Regarding the approach to Klaipeda, the in-situ system results are shown in FIGURE 19. The correlations are rather good given that the BC concentrations in the shown data are well above 1 mg/m^3, and the error from the opacity in this case has a minor effect.

When departing from Frederica, the results were not satisfactory using the method applied for the calculation in FIGURE 19. In order to achieve better correlations to the AE33 and FSN measurement it was necessary to only take the scattering into account (the opacity is not used), and the scale is fitted to the AE33 data. This analysis is shown in FIGURE 20.
The correlation between the AE33 and the EMS BC calculated by this method is shown in FIGURE 21.

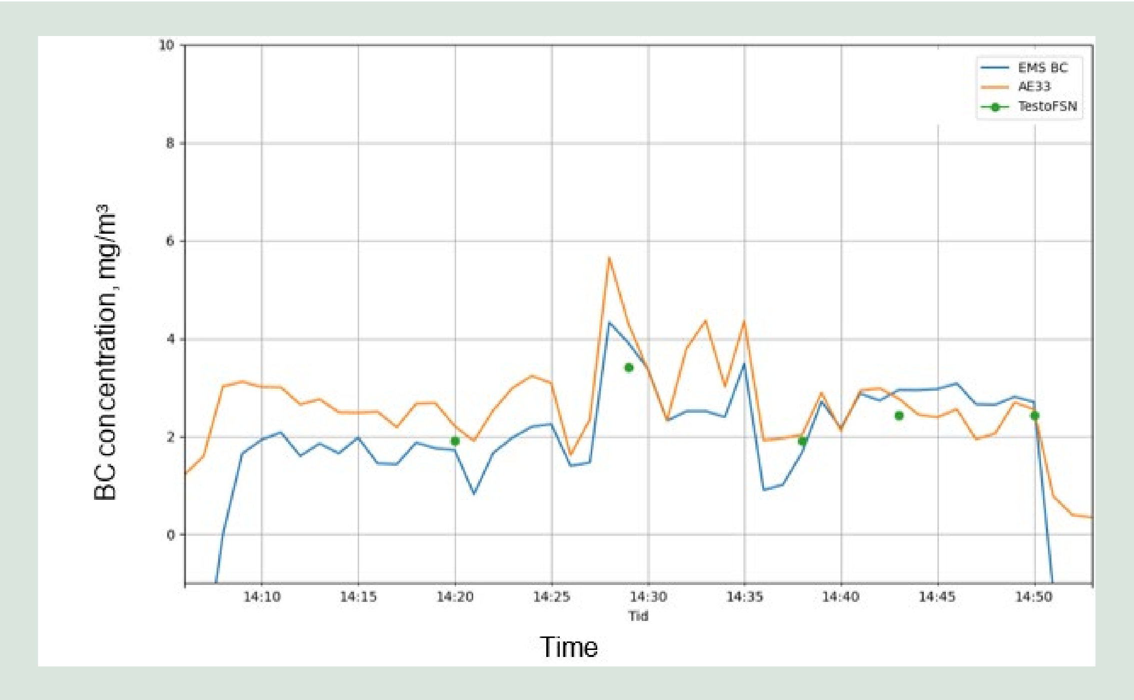

FIGURE 19. Belgia in-situ EMS BC and Testo FSN during a period with more than 1 mg/m^3 BC concentration. The EMS BC results were fitted to the FSN results to illustrate the correlation.

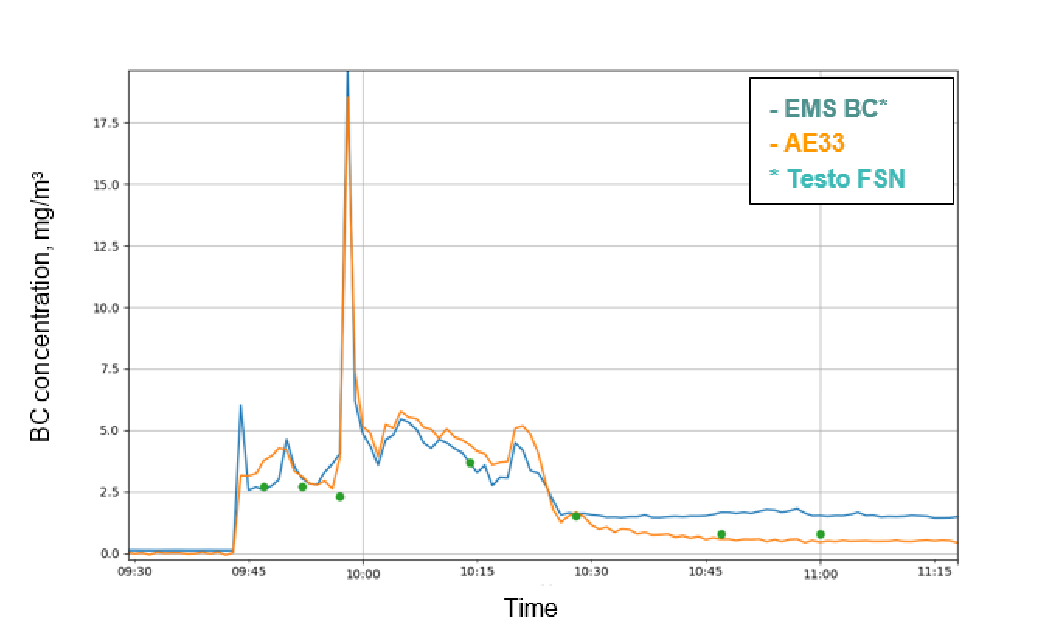

FIGURE 20. Belgia in-situ EMS BC and AE33 reference data. The EMS BC* was calculated by only taking the scattering into account (opacity was not used), and the scale was fitted to the AE33 data.

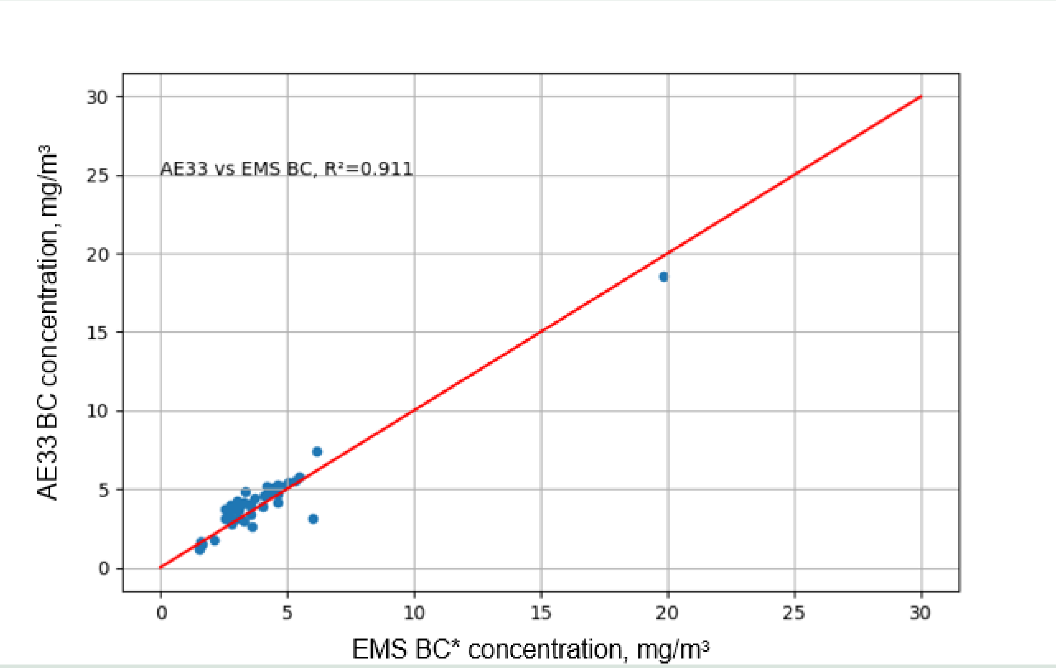

FIGURE 21. Correlation of the Belgia in-situ EMS BC vs. AE33 reference data. The EMS BC sensor concentration is calculated by only taking the scattering into account (the opacity is not used).

5.4 Discussion and conclusion

The results and a few of the challenges of the measurement campaign on Belgia have been presented in the sections above.

In general, the EMS BC systems have performed better than expected for a first sea trial and installations. The key points are:

- The EMS BC systems have responded to the low BC concentration in the exhaust.
- No issues were found with dirty optical surfaces (fouling), which was one of the main engineering risks in the development of the EMS BC sensor.
- The scattering measurement showed good performance and stability.
- The presented data also showed good correlations between the EMS BC sensor and the two reference technologies.

Some challenges with the protype system were also identified in the test campaign:

- The concentration of BC in the exhaust of the test ship was lower than expected especially at cruise load with less than 1 mg/m^3.
- Due to the low BC, the known cross-interference with the NO_2 present in the exhaust became a considerable measurement error.
- Furthermore, due to the low BC, the accuracy and stability of the opacity was a limiting factor in the in-situ system.

Based on the successful testing some additional and future tests were and will be carried out:

- The challenges with NO_2 can fully be resolved by increasing the laser wavelength from a green to a reddish color where the absorption cross-section of NO_2 is negligible.
- The stability of the opacity meter seems to stem from misalignment of the laser and inhomogeneity of the retroreflector. This issue is expected to be avoided by re-arranging the laser optics.
- So far, focus has been on the correlation to the reference techniques. However, it is also important to quantify the accuracy of EMS BC on a qualitative term so the overall system accuracy and precision can be determined for a range of different engine types and fuel mixtures. This also includes the measurement of temperature and pressure, so the results can be related to standard conditions.

Based on the extended experience of the EMS method in this project, the following key points of the EMS BC sensor can be listed:

- Suitable real-time in-situ measurement in marine engine exhaust as an alternative to complex extractive techniques and filter deposition methods (FSN).
- Traceability, as the optical measurement of extinction and scattering can be calibrated using known and proven methods.
- Reduced cost of ownership, as it is easy to install and robust for maritime applications, with low maintenance and no need for specialist monitoring.

Development of Maritime Black Carbon Sensor

Black Carbon (BC) is a climate and health problematic emission, caused by the combustion of fossil fuels in, e.g., the shipping industry. Efficient monitoring of the emissions is a first step towards reducing this harmful pollution.
This report describes the development and testing of Green Instruments EMS BC sensor technology using the Extinction Minus Scattering (EMS) method to quantify the BC concentration in engine exhaust.
The EMS BC sensor is an online and in-situ measurement technique that has several advantages compared to the traditional extractive techniques as well as filter deposition methods, such as Filter Smoke Number (FSN) or Photoacoustic spectroscopy (PAS).
The priorities in the development activities were to ensure that the measurement system has low maintenance, sufficient robustness, appropriate accuracy, and validity, and is relatively easy to install on various exhaust and ship types.
The system has been evaluated on test engine exhaust, followed by sea trial both as in-situ and extractive editions of the EMS BC.
The suitability of the EMS BC sensor for measuring BC from a diesel exhaust is addressed. The focus is on providing correlations i.e., the relative response of the BC concentrations – mainly because no reference method for measuring BC has been agreed upon.

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