THE SCIPPER PROJECT

Technical possibilities to monitor vessel emissions explored in the SCIPPER project

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TRA TRANSPORT RESEARCH ARENA
LISBON 2022
14 - 17 NOVEMBER

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement Nr.814893

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Background and Objectives

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Project Fiche

Call: 2018-2020 on Mobility for Growth

Section: 1 - Building a low-carbon, climate resilient future: Low-carbon and sustainable transport

Topic: LC-MG-1-1-2018: InCo flagship on reduction of transport impact on air quality

Duration: 36 + 9 months (Start date: May 1, 2019)

Budget: M€5,0

Coordinator: Aristotle University of Thessaloniki (AUTh)

Total Beneficiaries: 17 + 1 International partners

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Overarching Objectives

Need for:

- Compliance check of vessels with regard to environmental regulations
- More evidence on monitoring possibilities for low sulphur levels, new pollutants, as well as implications of non-compliant ships to air pollution.

Main objectives:

- To provide evidence on the performance and capacity of different techniques for shipping emissions monitoring and,
- To assess the impacts of shipping emissions on air quality, under different regulatory enforcement scenarios.

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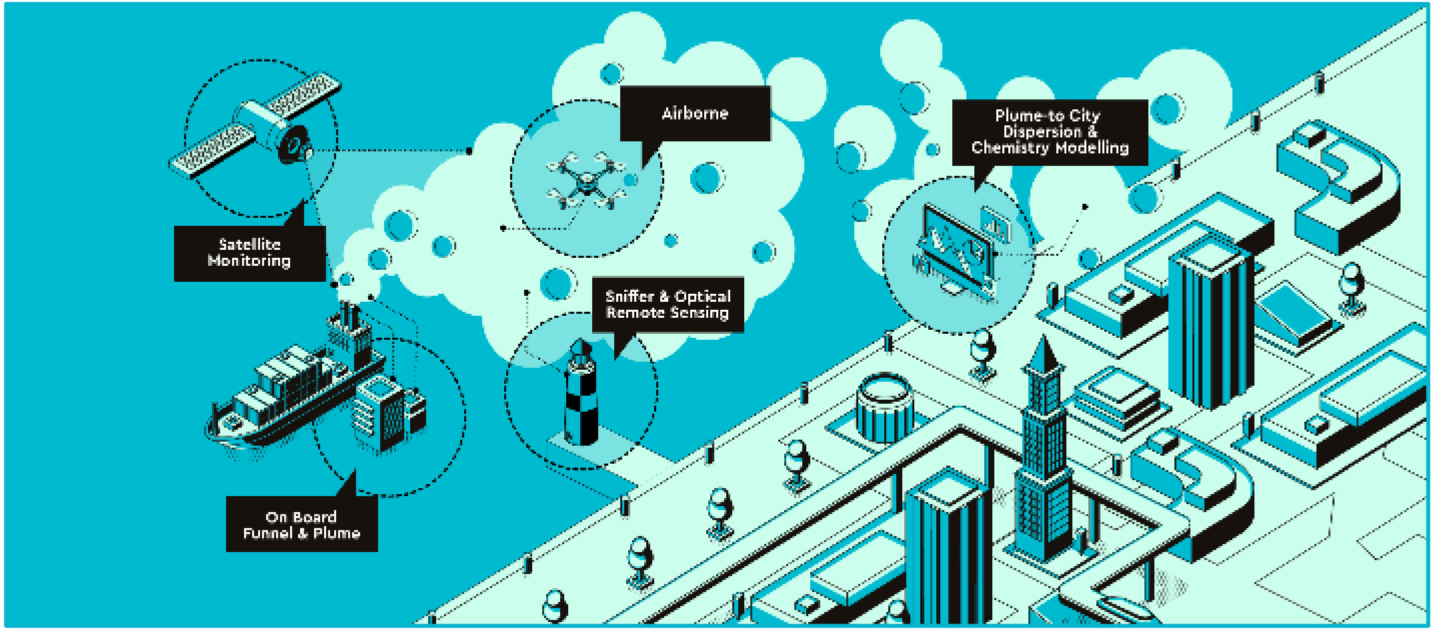
Concept

Real-world deployment of various monitoring techniques

Implementation of 5 experimental campaigns at different locations

Runs from 5.2019-1.2023



- ❑ Application / validation / comparison of various emission measurement and monitoring techniques for emission standards compliance checking purposes
- ❑ Determination of the impact of shipping on air quality at coastal and harbor level

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Shipping Emissions

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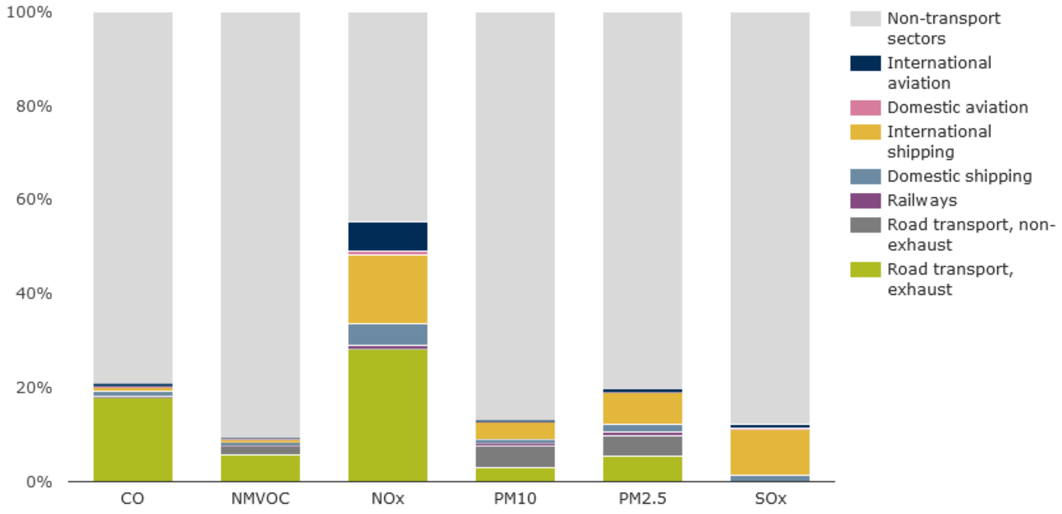
Air pollution from shipping

- Shipping contributes to 3% of global GHG emissions (eqvl. 6th largest country)
- Majority of emissions take place near the coastline – affects air quality in cities
- Maritime transport work expected to increase in the future



Contribution of the transport sector to total emissions of the main air pollutants (EEA, 2019)

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SCIPPER Measurement Campaign on RO-PAX ferry (4-stroke diesel engine with SCR)

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- **On-board exhaust sampling to obtain physicochemical data**
  - **Assessment of NOx abatement and MeOH fuel**
- Testing of onboard compliance monitoring,
  - Selection and testing of equipment & sensors
  - Performance assessment , including uncertainty characterization for SO_2, NOx and PM/PN
- Intercomparison of different onboard and remote monitoring techniques
- Verification of monitoring techniques with high-end instruments

12 combinations of fuel – aftertreatment – engine load point investigated

3 mobile laboratories, 15 high-end instruments, 7 in-stack sensors, 5 remote monitoring systems

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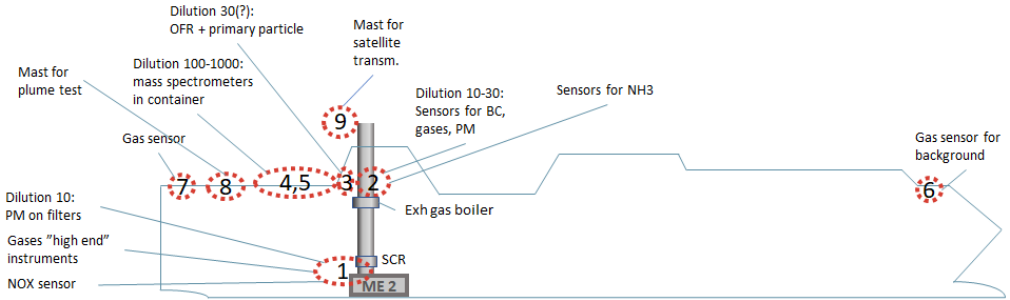
C2 Sensor Systems on-board

Partner	Instrumentation/sensor List	Placement	Measurement period
AUTH	BC Optoacoustic sensor	eDiluter, deck 7	2 weeks
TNO	Automotive sensors: NO_x/O_2, NH_3, temperature sensor (thermocouple)	2 raw (deck 2, deck 7)	4 months
AEROMON	CO_2 (NDIR), SO_2 (EC), NO_2 (EC), NO (EC), NH_3 (EC), CO (EC) and PM (OPC)	eDiluter, deck 7	1 week
TAU	Dilution system for particle measurement	deck 7	2 weeks
TAU	PN sensors, BC sensors (from FMI) and reference CPC	deck 7	2 weeks
TAU	Reference aethalometer	Deck 7 after WP3 sampling	1 week
CML	$PM_{2.5}$, PM_{10}, NO, NO_2, CO_2, SO_2	deck 7 / 10: (one box aft and one box stern)	1 week

C2 Gothenburg (SE) to Kiel (DE), September 2021

+ high-end reference measurements by IVL



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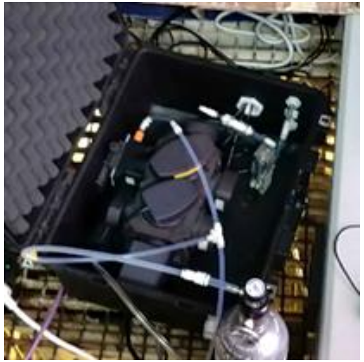
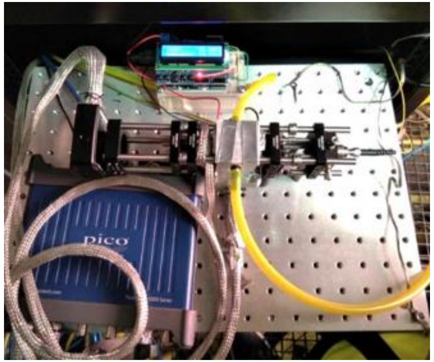
C2 Sensor Systems Setup



Air quality sensor



Proto BC sensor

Automotive sensors

Plume air quality sensors

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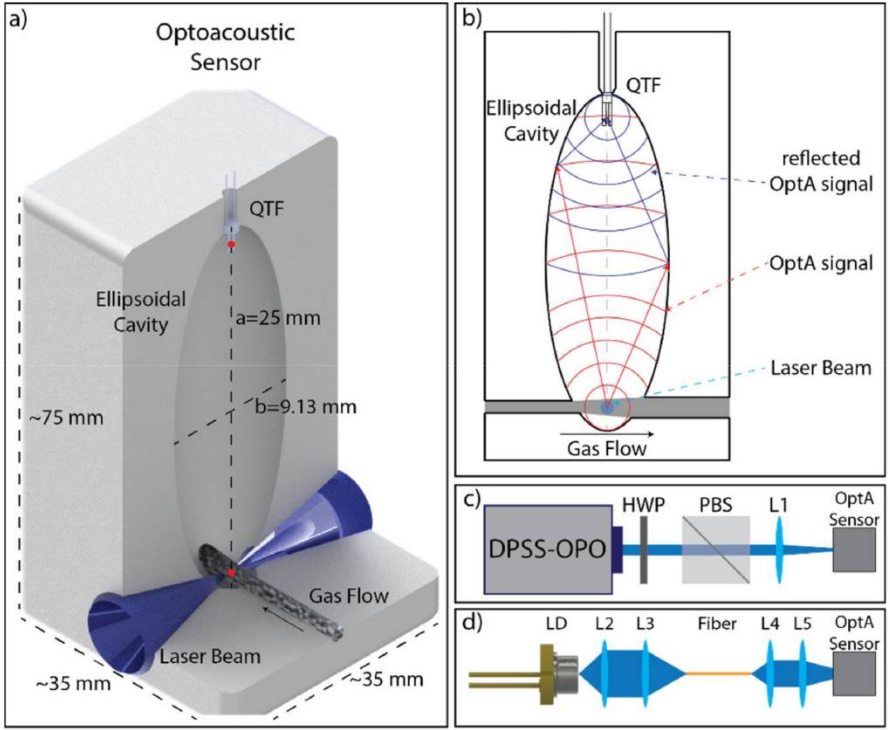
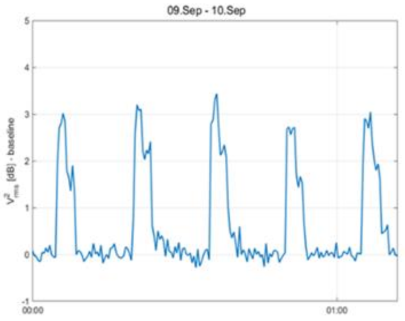
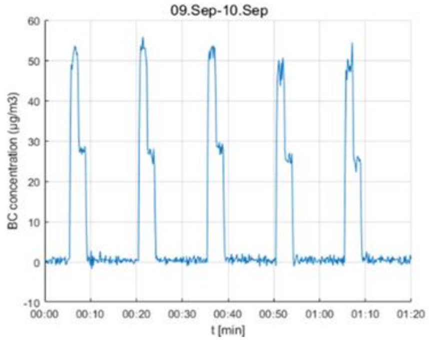
Our prototype BC sensor



RSENSE sensor



Reference - Aethalometer



Stylogiannis et al., Sensors 2021, doi: 10.3390/s21041379

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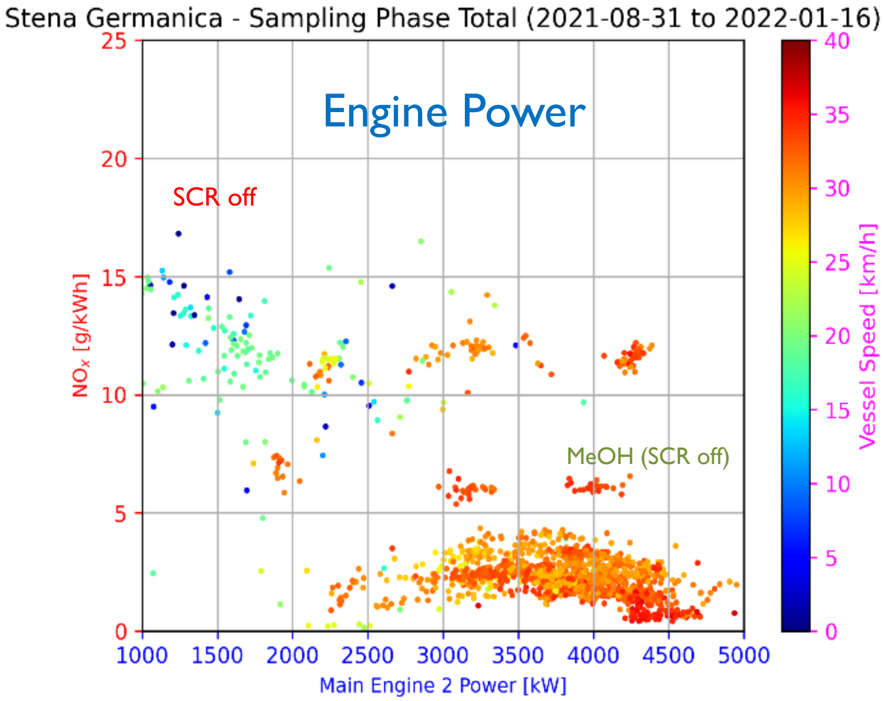
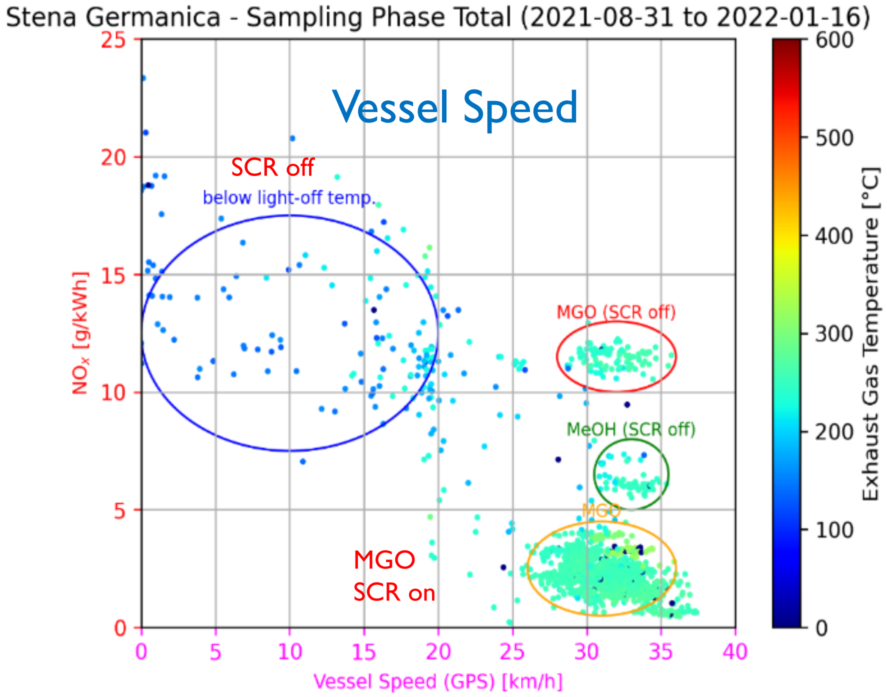
NOx (g/kWh): different levels such as with SCR on/off can be clearly identified





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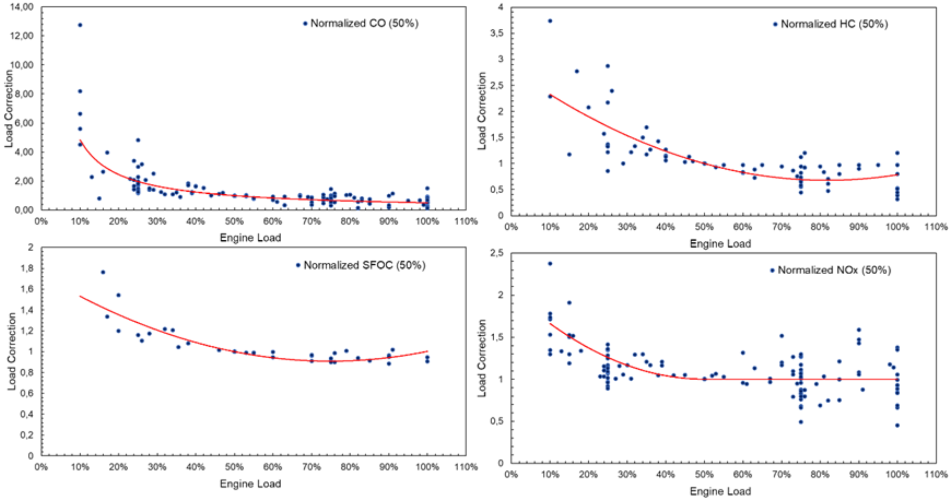
Emission factors from campaigns and literature

Base EF (Average values of measurements)

Pollutant	Engine type		
	Slow speed	Medium speed	High speed
NO_X (g/kWh)	14,4	12,4	11,7
CO (g/kWh)	0,714	0,974	1,10
HC (g/kWh)	0,358	0,405	0,662
SFOC (MJ/kWh)	8,48	8,42	9,74

×

Load Correction (Normalized emission rates' load dependency)



EFs development at each engine load for:

- **pollutants (NOx, CO, PM, HC, etc..) and SFOC**
- **engine types (slow, medium, high speed)**
- **fuels (BFO, MDO/MGO, LNG)**

Emission factors already part of the EMEP/EEA Guidebook and the STEAM model

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Cross-Instrumentation Campaigns

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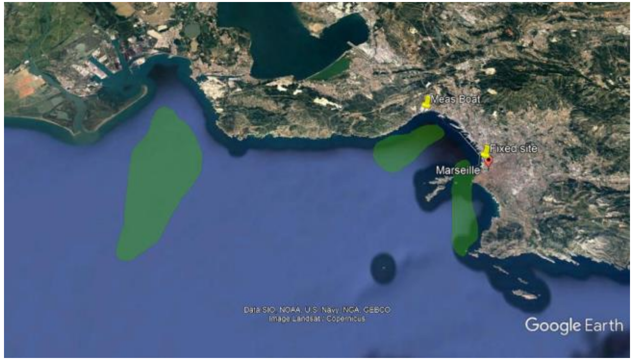
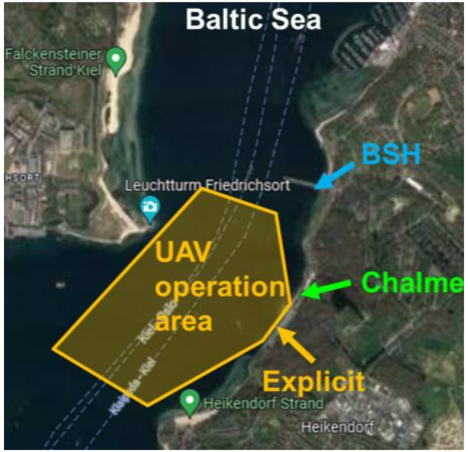
Relevant campaigns

C1 and **C4** Marseille, side-by-side observations from measurement vessel and fixed 2019 and 2022



C3 Wedel, side by side measurements Sep 2020

C2, on board Stena Germanica and on shore Kiel, side by side measurements, September 2021



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Overview of CI

CI Marseille, September 2019

- Remote compliance monitoring of FSC in ships in and outside the port before global FSC regulations
- First assessment of state-of-art remote and UAS comparability
- Assessment of state-of-art remote techniques including uncertainty characterization
- Input to AQ emissions before global FSC regulation

21 plumes measured by drones

30 plumes measured by a sniffer boat & 17 for intercomparison on SO_2 and NO_x

Air quality measurements at harbor sites

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Sniffer intercomparison campaign (C3)

C3 Measurement Campaign in Wedel/Hamburg (9.2020)

Various remote techniques on shore

Drone mini sniffer

966 plumes measured by sniffers from 436 vessels

65 plumes detected by drones

55 fuel samples

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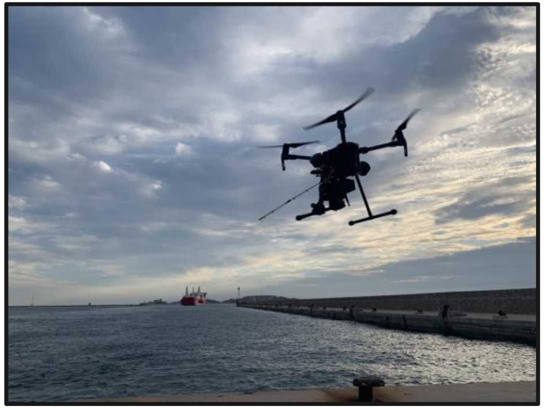
Post global FSC campaign (C4)

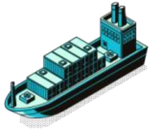
C4 Measurement Campaign in Marseille (7.2021)

Drone mini sniffer



Equipped Boat (Sniffer & ageing instrumentation)

Harbor AQ stations



38 different vessels measured

126 plumes

Equipped vessel - Drones - Harbor based stations - Network of AQ microsensors in the city

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Instrumentation on Sniffer Systems

Partner/Group	Instrument
BSH	3 sniffers (CO_2, SO_2, NO, NO_2, O_3) 2 particle size classifiers (5.6 nm – 10µm) 1 LP-DOAS (SO_2, NO_2) *
Chalmers	1 sniffer (CO_2, SO_2, NO_x) 1 laser spectrometer (CO_2, SO_2) 1 particle size classifier (5.6 nm – 10 µm) 1 aethalometer (BC) 1 zenith-sky DOAS (SO_2, NO_2) 1 mini-Sniffer on UAV (CO_2, SO_2, NO, NO_2, PM)
Explicit	1 mini-Sniffer on UAV (CO_2, SO_2, NO, NO_2)
TNO	1 sniffer (CO_2, SO_2, NO, NO_2) 1 CPC 1 particle size classifier (90 nm – 7.5 µm) 1 aethalometer (BC)

gaseous emission (in plume)
gaseous emission, (optical, remote)
particle emission (in plume)

* operated by University of Bremen

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Sensor systems

Sensors	Typical sensitivity	Platforms	Dist. ships	FSC principle	Meas priple	Accuracy
Ultra sensitive sniffer	SO_2: 0.06 ppb CO_2: 200 ppb	Fixed shipborne Airborne,	>1 km	ΔSO2/ΔCO2	Laser absorption	TBD
Standard sniffer	SO_2: 2 ppb CO_2: 200 ppb NO_x: 0.5 ppb	Fixed shipborne Airborne,	1 km	ΔSO2/ΔCO2	UV fluore NDIR	TBD
Mini-sniffer	SO_2: 10 ppb CO_2: 10000 ppb	Drone	50- m	ΔSO2/ΔCO2	Electro chemical NDIR	TBD
Optical remote sensing (UV/VIS)	SO_2: 1 ppmm NO_2: 1 ppmm	Fixed, shipborne Airborne, satellite	1 km	ΔSO2/ΔNO2	DOAS 300 -450 nm	TBD
Optical remote sensing (IR)	TBD	Fixed	50-200 m	SO2/CO2	Passive FTIR	Demo only

The above is for sulfur. Also NOx, particles (PM,PN,BC), and CH4 were measured

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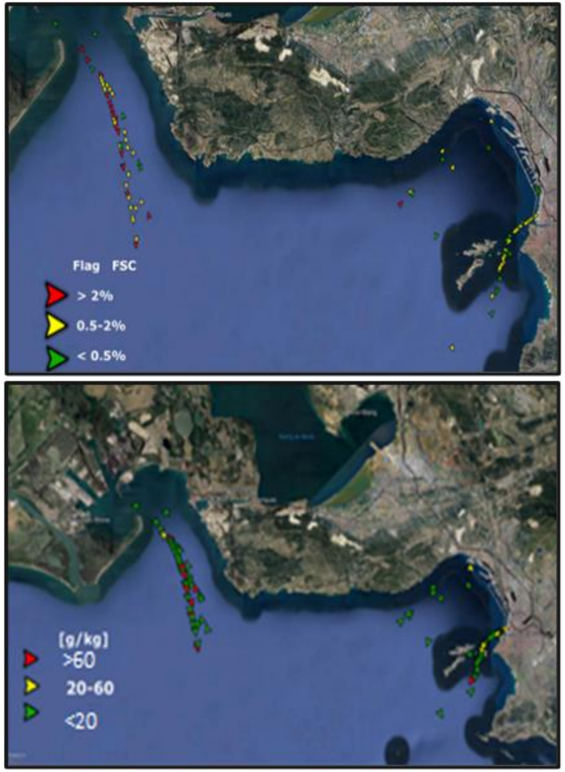
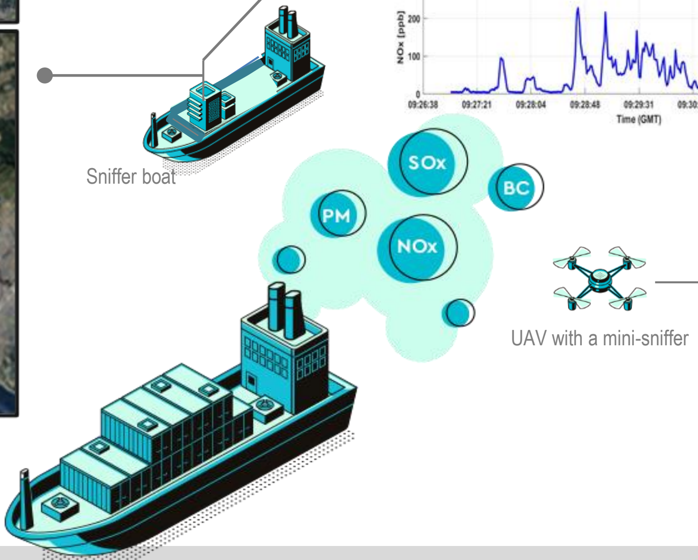
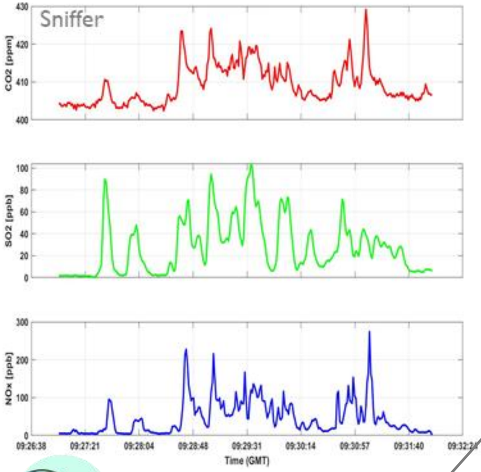
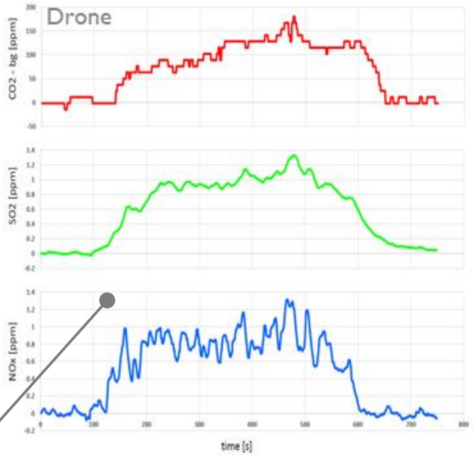
Key findings from C1



FSC and NOx levels before global sulfur cap with different techniques







Example: Sniffer on a vessel vs mini-sniffer carried by a drone detections comparison for a specific plume

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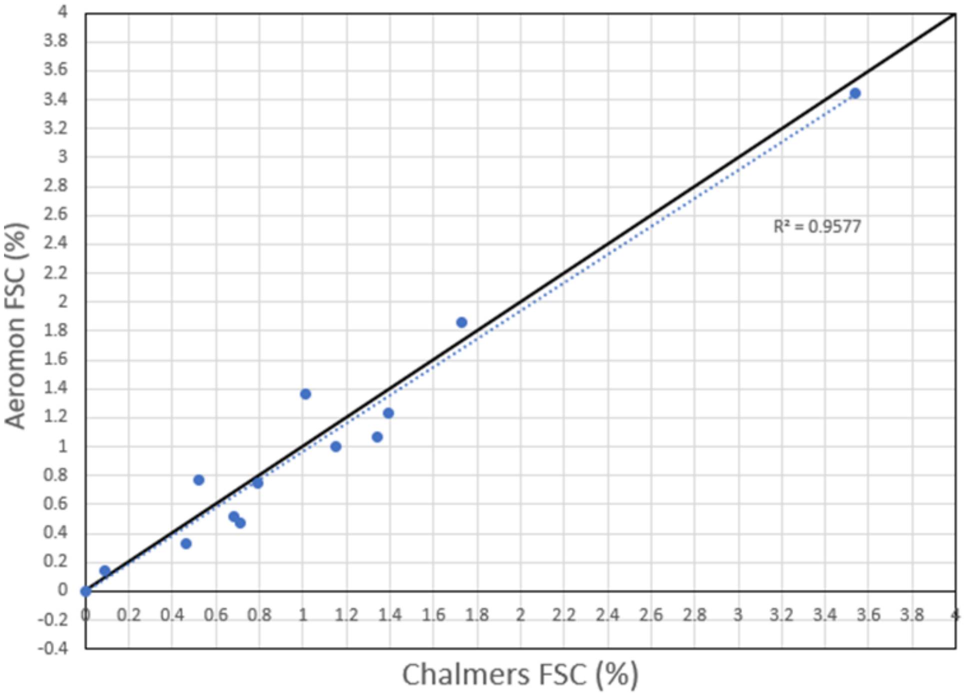
Highlight of CI



- Mini-sniffer (Aeromon BH-12) drone with SO_2, CO_2, NO, NO_2, PM_1, $PM_{2.5}$ and PM_{10} sensors.
  - Calibrated daily with certified calibration gases for traceability and quality control.
- In comparison with the Chalmers reference method, achieved a good linear fit between FSC% results from same plumes.
- Comparison between NOx and PM is ongoing and full comparison with all parameters will be published later this year.

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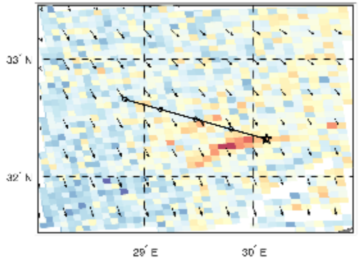
Single Ship Satellite Plume Detection

- Signatures of single ships are visible in TROPOMI NO_2 data, but observing conditions (satellite view geometry, meteorology) affect the detected signal strength together with actual ship NOx emissions (Sundström et al. 2022, in prep.):
  - Sun glint/no glint,
  - atmospheric stability,
  - wind speed & direction relative to ship heading

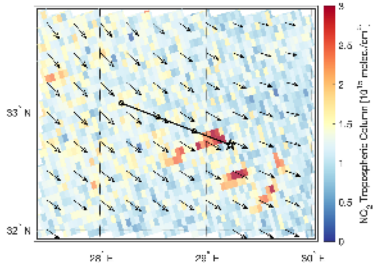
- Improved NO_2 retrieval algorithm for TROPOMI can give up to 15 % more signal over sea, and hence also the detection of single ships is enhanced (Riess et al. 2022)
- Improved automated segmentation of individual ship plumes using spatial correlation metrics and machine learning improve individual ship emission estimates (Kurchaba et al., 2021, 2022 (in prep.)
- More investigation is needed to be able to exploit satellite observations for compliance monitoring but these studies indicate that global monitoring is feasible for NO_2.

Examples of single container ship plumes in TROPOMI NO_2 data

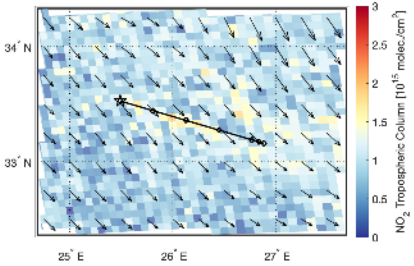
No glint: NO_2 enhancement often detectable



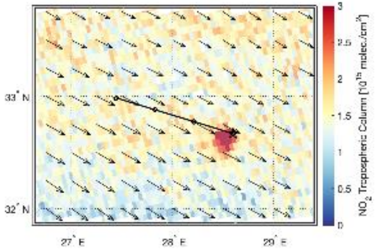
Sun glint: typically more clear NO_2 signal



Ship heading vs. wind direction: "Headwind"



Ship heading vs. wind direction: "tailwind"



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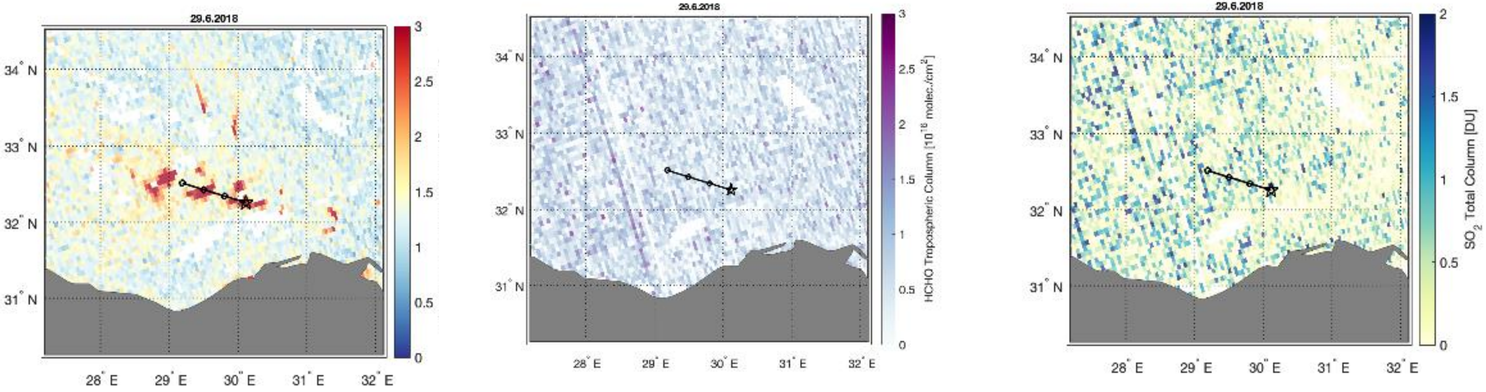
Simultaneous Satellite Observations

(black line indicates route of a large container ship 2h prior to satellite overpass)

NO_2 HCHO SO_2



- In optimal satellite viewing conditions (cloudfree, sun glint) NO_2 signal from single ships is clearly visible, while for other trace gases signal seems to be too weak and below satellite detection limit.
- With long temporal averaging and data filtering (e.g. account for winds) some elevated signal of SO_2 and HCHO could be detected over busiest shipping routes.

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Concluding Remarks

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General Observations

Project ends Jan. 2023 and final conclusions are yet to be discussed in the consortium. Our observations so far indicate:

- Airborne and stationary SO_x sniffers show acceptable comparability down to below 0.1% FSC. Physical and/or metrological reasons may be responsible for slight underestimation.
- NO_x is also shown to be reliably measured but conversion to g/kWh is an issue. g/kg fuel seems more appropriate if NO_x monitoring is to be considered.
- On-board sensors have the capacity to measure all relevant gases and a number of PM properties (PN, PSD, BC, etc). Long-term durability remains a challenge.
- Satellite monitoring of singular vessel NO_2 emissions appears possible but SO_2 signal is weak. Single-vessel satellite enforcement seems overall challenging.

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Methods Overview (On-going assessment)

Technique	On-Board	Small UAV	Patrol-Vessel	Aircraft/Large UAV	Fixed Station	Fixed station	Optical - Satellite
Method	**Sensors**	**Sniffers**				**Remote Optical**	
Most widespread detection techniques	SO_x (IR or DOAS) NO, NO_2 (Electrochem.) CO_2 (NDIR) BC/PN (various)	SO_2 (Electrochem., DOAS) NO, NO_2 (Electrochem.) CO_2 (NDIR) New concepts	SO_2 (UV Fluorescence) NO, NO_2 (CLD) PN (CPC) CO_2 (NDIR, CRDS)			SO_2 (DOAS, IR Iradiance) NO_2 (DOAS)	NO_2, SO_2 (DOAS)
Experience	Yes, Scrubber vessels	DK, FI, EMSA	DE, FR, SE	EMSA, BE, FI, (SE)	DE, NL, SE, DK, FI	DE	FI, GR, NL
Flexibility in terms of monitoring location	On-board	Yes (restrictions)	Yes (restrictions)	Yes (restrictions)	No	No	No (5.5×3.5 km^2, depends on pass)
Open Sea surveillance	Yes	No	Yes	Yes	No	No	Yes
Availability of results	Can be on-line	Immediately	Immediately	After landing	Immediately	Immediately	Post-processing
Suitable sites	vessels	line of sight (smaller harbour, canal, …)	ports, busy lanes	coast and open sea	<u>major</u> shipping lane (harbour, canal, pole, bridge,…)		Away from other major sources
Operation time	24/7 (automated)	daylight	24/7	daylight	24/7 (automated)	24/7 (automated)	daylight/weather
Resources (cost, personnel)/vessel	High	Low-Medium	Medium	High	Low	Low	Medium (currently processing-tedious)

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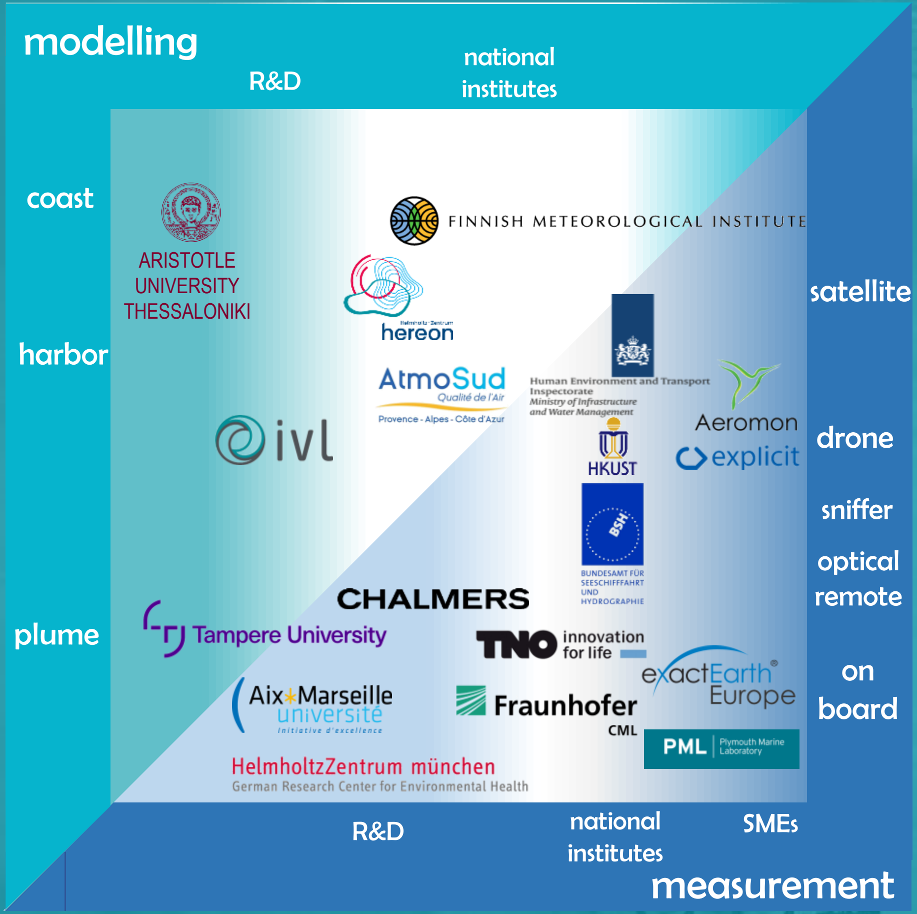
Acknowledgments

Armengaud, A.,, Au, C-N., Beecken, J., Buckers, J. Conde, V., Dal Maso, M., D'Anna, B., Deakin, A., Duyzer, J., Fink, F., Fridell, E., Griesel, S., Grigoriadis, A., Haedrich, L., Hallquist, Å., Irjala, M., Jalkanen, J.-P., Karl, M., Keskinen, J., Knudsen, B.,, Knudsen, J., Kousias, N., Kuosa, M., Lanzafame, G.-M., Majamäki, E.,, Mamarikas, S., Matthias, V., Mellqvist, J., Michailidou, A., Moldanova, J., Ntziachristos, V., Oeffner, J., Oppo, S., Proud, R., Schoppmann, H., Simonen, P., Smyth, T., Stylogiannis, A., Sundström, A.-M., Temine-Roussel, B., Timonen, H., van Dinther, D., van Vliet, J., Verbeek, R., Weigelt, A., Weisheit, J., Yang, M.,



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