SEICOR - SHIP EMISSION INSPECTION WITH CALIBRATION-FREE OPTICAL REMOTE SENSING

International maritime shipping forms the backbone of our globalized world. Since 1970, the amount of transported goods by ship has more than quadrupled, according to a 2021 World Ocean Review.[1] Today, roughly 80% to 90% of global trade is transported by ships, amounting to approximately 12 billion tons of cargo or 885 million Twenty-foot Equivalent Units (TEU) exchanged within 2022, reports a 2023 UNCTAD Review of Maritime Transport.[2]

Despite the crises of recent years, which led to a slump in freight volumes in 2020 (-3.6% due to the COVID-19 pandemic and -0.4% in 2022 due to the conflict in Ukraine and associated price shocks), UNCTAD is forecasting growth of 2.4% for 2023. A growth of just over 2% p.a. is also expected in the next 5 years.

As of January 2023, international maritime trade was handled by around 105,000 vessels (gross tonnage of 100 and above), with oil tankers, bulk carriers and container ships accounting for 85% of the total capacity. Regarding the volumes of freight handled, the capacity of the global commercial fleet is expanding at a rate of approximately 3% annually.

At present, almost all cargo ships are propelled by conventional engines and fuels. In 2022, the international shipping sector emitted around 1.1 billion tons of CO_2 equivalents, accounting for roughly 3% of the world's greenhouse gas (GHG) emissions. This amount is nearly on par with the overall GHG emissions of Japan, which has the world's third largest economy. Besides GHG, shipping is responsible for a variety of pollutant emissions that can impact air quality and the ecosystem. These include sulfur dioxide (SO_2), which is primarily produced through the combustion of sulfur-containing ship fuels (heavy fuel oil, HFO), and nitrogen oxides (NO_x), which are generated during the combustion process of fuels at high temperatures, contributing to air pollution and ground-level ozone formation, especially nitrogen dioxide (NO_2). Furthermore, particulate matter (PM), primarily in the form of soot, is emitted and affects air quality while posing health risks.

To mitigate the environmental footprint of the maritime industry, the International Maritime Organization (IMO) has developed the International Convention for the Prevention of Pollution from Ships or MARPOL – short for marine pollution. MARPOL came into force in 1983 with an initial focus on the discharge of oil into the ocean environment. Since then, the convention has continuously expanded its scope to include additional types of pollutants, such as noxious liquid substances, sewage, and ship-generated garbage. MARPOL Annex VI, which came into force in 2005, also introduced requirements for the regulation of air pollutants emitted by ships. Regulation 14 aims to reduce SO_2 emissions from ship exhaust gases by limiting the sulfur content in marine fuels. The global sulfur limit was lowered to 0.50% m/m (mass by mass) from 3.50% m/m on Jan. 1, 2020. Inside designated Sulfur Emission Control areas (SECA), the FSC limit was set to 1.50% m/m and was further reduced to 1.00% m/m in 2010 and 0.10% m/m in 2015. Alternatively, ships can continue using high-Sulfur fuels, but must then carry out exhaust gas aftertreatment (scrubber), to achieve the same reduction in SO_2 emissions as when using low-Sulfur fuels. The NO_x emissions from ship diesel engines with a power output of more than 130 kW are regulated in Regulation 13 of MARPOL Annex VI and the 2008 NO_x Technical Code Tiers. Tier I applies to ships constructed (i.e. keel laid) after 2000 and Tier II, to those constructed from 2011. The more stringent Tier III limits apply only for ships which are operated in a designated

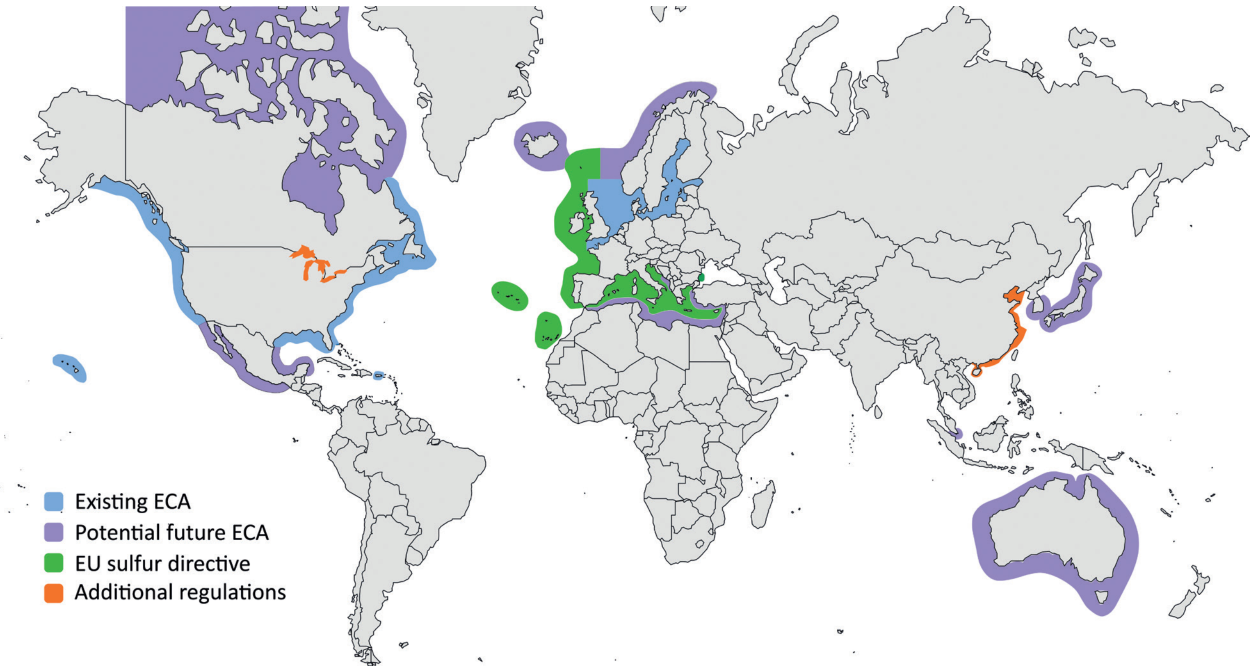

Figure 1: Map with existing and planned emission monitoring zones for sulfur and nitrogen oxide emissions.

Nitrogen Emission Control Areas (NECA) and are constructed from 2016 (North American NECA) and 2021 (European NECA), respectively. Furthermore, MARPOL Annex IV prohibits the deliberate emissions of ozone-depleting substances, such as chlorofluorocarbons (CFCs) and other halogenated (hydro-) carbons, and indirectly regulates the emission of particulate matter.

SECAs and NECAs can be summarized to emission control areas (ECAs). The following ECAs are currently established: the Baltic Sea, the North Sea, including the English Channel, 24 nautical miles off the Californian coast, 200 nautical miles off the North American coasts of Canada and the USA, including the Great Lakes and Hawaii, and the coastal waters around Puerto Rico and the US Virgin Islands. There are plans to expand these zones in the future, as shown in Figure 1.

EU Directive 1999/32/EC and its revisions 2012/33/EC and 2016/802/EC transpose the MARPOL regulations into European law. Implementing Decision 2015/253/EC stipulates that at least 10% of all ships arriving in a Member State each year must have a document and logbook inspection on board and at least 40% of the ships inspected must also have their fuel analyzed (Article 3, paragraphs 1-2). The fulfilment of this quota represents a considerable additional burden for the inspecting bodies – waterway police and port state control. However, it is permitted to reduce the fuel sampling and analysis frequency on board ships by a maximum of half of the member states "by deducting the number of individual ships whose possible non-compliance is checked using remote sensing technologies or quick scan analysis methods," states the Implementing Decision 2015/253/EC in Article 3.

Current methods for capturing emission parameters from bypassing vessels rely on in-situ procedures, utilizing shoreline-placed measurement containers equipped with established environmental measurement devices for NO_x, SO_2, and CO_2. Drawbacks include dependence on wind direction; in certain cases, the wind may not carry the exhaust plume to the measurement station, resulting in the measurement of only a small fraction of passing ships. Accurate allocation of measured plumes to individual ships is feasible only when passing vessels are distinctly separated and false signals can arise due to other emission sources. Another drawback is that in-situ devices need periodic calibration, requiring the availability of certified calibration gas at regular intervals.

In another approach, drones or manned aircraft fly directly through the exhaust plumes of the ships to record the concentrations of the relevant exhaust gas components. However, these methods for airborne measurement of exhaust gas components are very costly and labor-intensive. Due to the

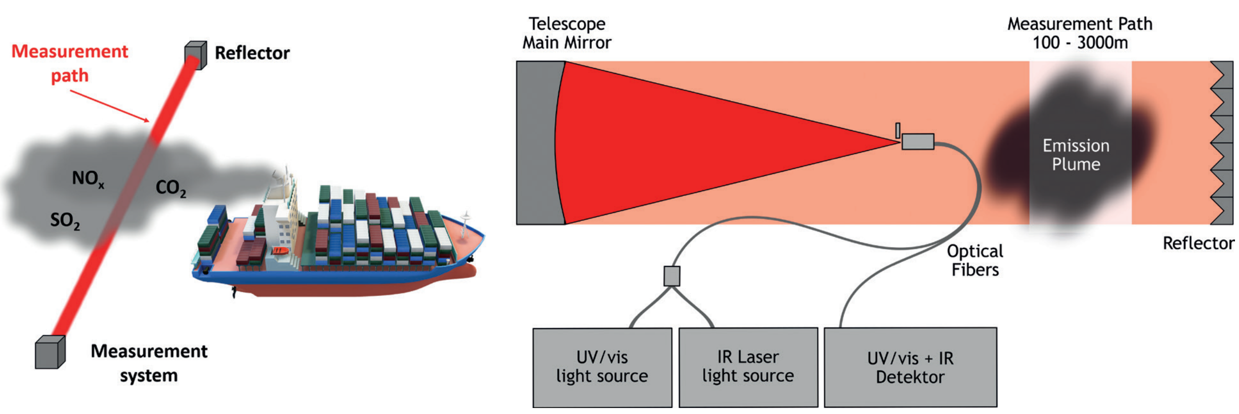

Figure 2: Concept for the development of the measuring instrument. IR and UV/VIS systems are combined into a remote measuring system to determine all necessary gases in exhaust plumes of sea and inland waterway vessels.

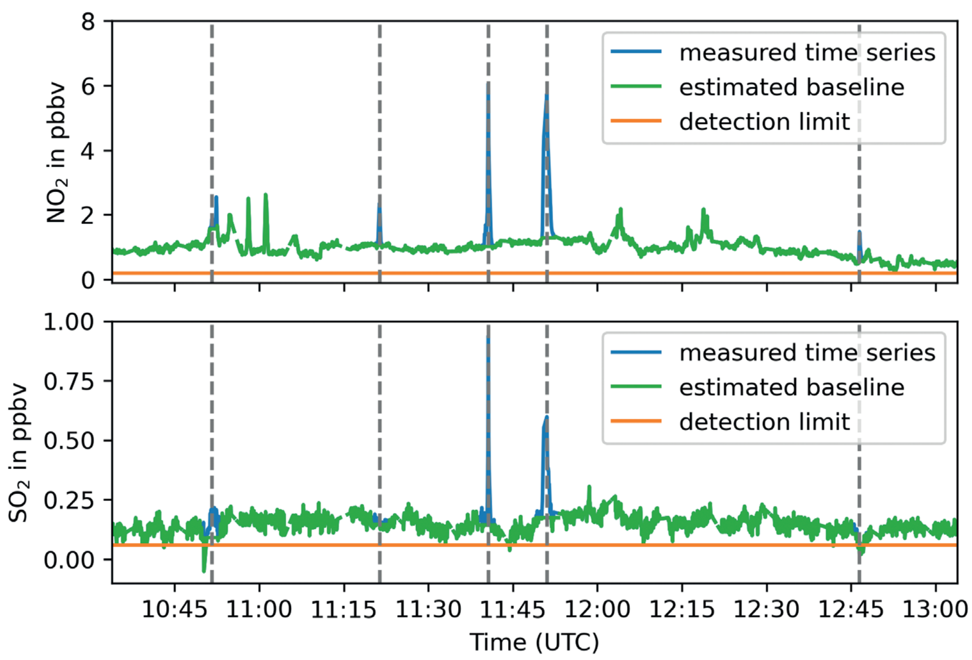

Figure 3: Example time series of measured SO_2 and NO_2 trace gas concentrations obtained during a preliminary study using LP-DOAS near Hamburg across the Elbe River. Emissions plumes with elevated levels of SO_2 and NO_2 stand out distinctly as peaks (blue lines) against measured background concentrations (green lines). The use of AIS allows for the assignment of corresponding ship passages to the peaks (grey dashed lines).

lack of operational readiness of such systems, only random sampling is possible. Achieving continuous, high-temporal-resolution monitoring of SO_2 and NO_x emission parameters at a cost-effective level is not feasible with drones or aircraft.

To address these challenges, the Ship Emission Inspection with Calibration-free Optical Remote sensing (SEICOR) project was initiated. This innovative approach relies on a calibration-free, optical remote sensing system for accurate 24/7 monitoring of SO_2, NO_x and CO_2 emissions. Developers aim to utilize the stationary system at ports or other ship traffic nodes autonomously with minimal maintenance and logistical costs. Furthermore, reporting will also be fully automated and made available to the relevant control bodies for easy integration into existing digital systems (e.g., port management), resulting in shorter throughput times (e.g., elimination of manual document and logbook checks on board in the case of remote measurement of the emission signature), increased flexibility and economic efficiency. The demonstration prototype developed through this project will monitor SO_2, NO_x (NO + NO_2), CO_2 and, in the future, particulates. Ensuring dependable, real-time monitoring of ship emissions from a distance requires a robust construction for operation under difficult conditions, such as wind, spray, and corrosive environments. The system concept is based on the open path spectroscopy methods UV/vis Long Path Differential Optical Absorption Spectroscopy (LP-DOAS) and IR Tunable Laser Diode Absorption Spectroscopy (TDLAS). The SEICOR demonstration prototype will combine UV/vis LP-DOAS with IR-TDLAS to enable remote sensing of ship emission plumes over long distances, covering harbor entrances, rivers or other marine traffic nodes. The main components of the instrument are light sources (high-power UV/vis LEDs and IR diode Lasers), which are coupled to a motorized telescope, a retro reflector and an analyzer unit (see Figure 2). A measurement path is formed between the telescope and the reflector. Within this measurement path, NO, NO_2, SO_2 and CO_2 abundances are measured by spectral analysis of the respective unique molecular absorbances in the UV/vis and IR spectral range. Combined with ship position and IDs taken from recorded AIS data, emission plumes can be detected, quantified and assigned to specific marine vessels.

The capabilities of LP-DOAS instruments in measuring ship emissions have already been demonstrated in previous studies. For example, in Krause et al., 2021, an LP-DOAS instrument has been set up at the Elbe River close to Hamburg.[3] The Elbe River serves as the entrance route to the port of Hamburg and is regularly frequented by a variety of ships. In this study, the instrument measured the abundance of NO_2 and SO_2 along a light path stretching across the river. When ships passed through, the NO_2 and SO_2 abundances increased for a short period of time and decreased shortly thereafter. Generally, the result was a peak-like structure in the time series that can be easily identified. In conjunction with simultaneously gathered AIS-Data, the respective source ship of each peak has been identified. An example of the measured time series of NO_2 and SO_2 is shown in Figure 3. Using this information, the emissions of the ships were quantified, but it became apparent that a simultaneous measurement of CO_2 would largely increase the capability to quantify and monitor the emissions of ships.

The new measurement system is intended to ensure a level playing field and sustainability of shipping by collecting reliable per-vessel emission data. Furthermore, the resulting emission data archive enables direct determination of the efficiency of future emission reduction measures and technologies in the maritime sector.

Thanks to its user-friendly operation, which includes autonomous data recording and reporting, minimal personnel costs, extended maintenance intervals, low material costs, and the absence of calibration with test gases, the demonstration prototype offers a straightforward solution. Furthermore, its independence from meteorological conditions, as opposed to passive, sunlight-dependent spectroscopy or shore-based point measurements relying on air mass transport, enables regulatory authorities to efficiently monitor ship emissions, ensuring both effectiveness and economic efficiency. The highly targeted sensitivity of the measuring system also creates compatibility to compliance monitoring of potential future directives, lowering emission limits for marine vessels.

In addition to optimizing operations by reducing the number of mandatory fuel analyses of incoming ships, the demonstration prototype enables port operators, for the first time, to validate the so-called "Environmental Shipping Index" (ESI) with actual measurement data. Depending on the level of the ship-specific ESI, which is based on emissions of SO_2, NO_x, CO_2, and the ability to be supplied with shore power, port operators grant particularly environmentally friendly ships discounts on berthing fees or other benefits. However, the ESI is based on voluntary information provided by the ship operators and has so far only been checked by port personnel on a random basis, if at all, in labor-intensive and time-consuming on-board inspections, such as document inspection and fuel analysis.

Another advantage for port operators is the autonomous, digital recording of total emissions (ships plus port infrastructure) from the port area and, based on this, the possibility of new environmentally and climate-friendly concepts such as an adaptive emissions management. SEICOR also offers the possibility of monitoring air quality in the port area and along waterways, and thus the potential to quantify the sustainability, efficiency, and climate compatibility of the shipping sector through publicly available measurement data.

The maritime industry, particularly shipowners, also benefit indirectly from the development and future use of the demonstration prototype. The main advantage is a more equitable environment within the shipping industry. The direct and large-scale monitoring of NO_x and sulfur emission factors by the SEICOR product exposes ships that gain a competitive advantage by not complying with guidelines, e.g., by using unauthorized, cheaper fuel (heavy fuel oil) in corresponding emission control areas (ECAs) or by manipulating or switching off NO_x SCR systems to save AdBlue and maintenance costs. This parallels the situation in the road transport sector, where comparable practices occur through devices called AdBlue emulators.

Continuously monitoring emissions allows for the detection of subtle changes in the emission signature, which may indicate a future defect. Comparing data from several passages of the same ship measured at different measurement locations makes it possible to counteract operational failures and increase the ability to plan maintenance work.

In general, the large-scale use of a measurement method, such as the SEICOR demonstration prototype, has the potential to drive the development and implementation of new environmentally and climate-friendly technologies in the maritime industry. The more efficient and large-scale official enforcement of emission guidelines made possible by SEICOR and the quantification of the impact of emission-reducing technology through SEICOR measurement data, provides incentives to invest in new, sustainable technologies and concepts, such as the use of filter systems (scrubbers), exhaust gas purification systems and the use and development of alternative fuels such as LNG, ammonia or hydrogen.

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Help shape future emission technology by taking our five-minute anonymous survey to evaluate the SEICOR technique and ensure it meets industry requirements: https://horiba.link/SEICOR

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