Remote and optical monitoring techniques applied to the maritime sector

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Abstract. A rising global attention to the environmental impact of anthropogenic activities pushes towards a continuous reduction of such impact and a control, through monitoring techniques, of the main sources of pollution. The transport sector is involved, as all other field of anthropogenic activities in the efforts towards a drastic abatement of emissions. Shipping activities generate greenhouse effect gases (GHGs), affecting the environment on a global scale, and other pollutants harmful for human health and the ecosystem on a local scale. These latter aspects are particularly relevant in ports where berths are close to densely inhabited areas. Many efforts have been and will be spent to predict and quantify these emissions with the aim of controlling them but direct measurements aimed at the identification and quantification of particularly polluting substances are to be considered a key point to achieve an effective control of emissions. In the context of ports, as in any transportation infrastructure, an identification of polluting vehicles and a quantification in an objective way of their emissions is crucial to implement any control activity of the polluting emissions. The development of optical remote sensing techniques appears to be particularly promising. This work provides a state of the art of the main techniques based on optical sensors (LIDAR, LIDAR DIAL, DOAS, camera UV) possibly applied in the maritime sector, highlighting advantages and potentialities. Results of a preliminary measurement campaign are reported to show the first encouraging feedback for the feasibility of the application.

1. Introduction
Anthropogenic activities are the main responsible for the climate change and global warming the earth is experiencing in recent years [1].

Transports, within the industrial sector, are stressed by global policies aimed at reducing the generation of greenhouse gases and of other pollutants harmful for people and the environment. The emissions related to the transport sector are chemical and they come from internal combustion engines. Sea transport covers about 90% of the global trade, but despite the enormous amount of goods transported by sea, ships remain one of the most efficient means of transport in terms of quantities of GHG produced per units of transported quantity and distance, with much less generation in comparison with road or air transports. As known, GHG emissions may be quantified in terms of the so-called CO\textsubscript{2}eq quantities, including, in addition to the main contribution due to carbon dioxide (CO\textsubscript{2}), also the effects
of other substances: like Methane (CH$_4$), Nitrous oxide (N$_2$O), Hydrofluorocarbons (HFCs), Perfluorocarbons (PFCs), Sulphur Hexafluoride (SF$_6$) and Nitrogen Trifluoride (NF$_3$) [2],[3].

The exhaust gases from naval engines, however, contain (more than the analogous emissions from internal combustion engines used in other fields) also local-scale (non-GHG) harmful pollutants such as Sulphur dioxide (SO$_2$), Nitrogen oxides, (NOx), particulate matter (PM), volatile organic compounds (VOC), black carbon (BC) and organic carbon (OC) [1], [2]. The generation of these harmful compounds depends on type, performances and operation conditions of the engines as well as on the quality and type of fuels.

The actual possibility for the local Authorities (Coast Guard, Port Authority, Municipality etc.) of monitoring the emissions generated by single ship units at port, is the first step to encourage the implementation of appropriate actions aimed at mitigate emissions and preserve the environment. For these reasons, a systematic monitoring of the emissions of ships in the port area, in transient as well as in stationary conditions, is of extreme interest for implementing control policies.

2. Emission from ships

2.1. A subsection Regulatory framework

The shipping sector, in proportion to its share in global emissions, has been activated at various levels for the drastic reduction of the quantities of CO$_2$ produced on a world-wide scale. According to 3rd IMO-GHG Report [3] referred to 2012, the emissions of CO$_2$ by shipping are 0.938 GtCO$_2$. NOx derive mainly from atmospheric nitrogen (thermal NOx and prompt NOx) and nitrogen in the fuel (fuel NOx). The rate of NOx produced during the combustion processes depends on the temperature of combustion, the quantity of oxygen free in the flame and the time duration for which gases are kept at this temperature. NO$_2$ is the product of the NO’s oxidation in combustion processes; this oxidation is inversely proportional to the temperature and directly proportional to the O$_2$ concentrations.

For NOx emissions, the reference requirement is the rule 13 of MARPOL (Annex VI). In order to obtain the EIAPP (Engine International Air Pollution Prevention) Certificate, the emissions need to fulfil the reference TIER based on ship construction date and engine rated speed. The current reference is TIER III for ships built after the 1/1/16 and operating in ECA (Emission Control Areas) zones; TIER II and I refer to ships respectively built during and after 2011 and 2000 [3].

The concentrations of SO$_2$ and SO$_3$ in the exhausts directly depend on the percentage of the mass of Sulphur in the fuel, since this element does not participate to the combustion processes. The reaction generating SO$_3$ is slower than the one generating SO$_2$, so in the exhaust gases the larger part of Sulphur oxides is represented by SO$_2$.

According to Regulation 14 of MARPOL (Annex VI) the Sulphur content of any fuel oil used on board ships should not exceed the 3.5% (m/m) after 1/1/2012 and 0.5% (m/m) on and after 1/1/2020. To these limitations, other, more stringent ones, are added in the ECA zones where, to preserve particularly fragile environments and ecosystems, the maximum Sulphur content in the fuel has been set to 0.1% (m/m) since 2015.

For ships in port, limits are also reduced in respect to the general rule applied in navigation: since 2015 all ships mooring in European ports must burn fuels with maximum 0.1% in mass of Sulphur or, as an alternative, they must use a certified SO$_2$ abatement system.

2.2. Emissions of a ship in port: characteristics and possible monitoring methods

Ships emit in harbor both during the phase of approach/maneuvering and when moored at quay (busy in hoteling, loading or unloading operations) [4].

In the former case, the propulsion system and the engine are particularly stressed by the transient operating conditions, with possible emission of a particularly high concentration of noxious compounds; in the latter one, the electricity generation system is running for comparatively long times to ensure power production for use on board. An estimate of the emissions in the maneuver and mooring phases
in port is difficult to achieve due to numerous and variable parameters describing the combustion process in transient conditions [6], [7], [10].

The piers in a port can be divided into moorings, for ships carrying goods (tankers, cargo ships, containerships, etc.), and piers for passenger ships (cruise ships, hydrofoils, ferries and yachts). The main parameters identifying the emissions from ship traffic are number and size of vessels entering the port, the time spent at pier and the power used when moored.

For example, in the passenger section of the port of Naples (one of the main in the Mediterranean Sea by number of passengers) it is not difficult to count up to four large cruise ships simultaneously present at pier, with an average mooring time of 8 hours. On each of these large units, an average electric power of 8 to 12 MW is generated all the time to cope with the various on-board needs during the ship stop, thus emitting exhaust gases in proportion [8].

A first level of accuracy in evaluating emissions can be achieved by estimations of the average emitted power and so-called “emission factors”. These coefficients relate statistically the rate of polluting compound to the power generated onboard. A slightly better prediction can be achieved on the basis of records of type and amount of fuel burned at port.

Several studies use the results of these estimates as input to effective dispersion models, which take into account weather conditions, orography and barriers pre-sent, to predict the dispersion of the main pollutants in the atmosphere and their concentrations and relapse on the ground [5], [8], [9], [10].

A more accurate assessment of the same phenomena can be achieved by direct measurements; these can be carried out by in-situ sensors contact analyzers placed on the ship and/or spread around the port area. Local samplers need to be placed in the immediate vicinity of funnels to identify the emissions by single ships. Further, when characterizing the situation in the whole port area, a large number of sensors is needed, making the survey complicated, time-consuming, expensive and subjected to uncertainties as far as the identification of spurious sources is concerned (think of the NOx produced by both cars and ships).

Therefore, a characterization of types and rates of the flow of exhaust gases from ships using remote sensors based on optical techniques seems to be an effective solution for ship emissions monitoring in real time. The possibility of investigating from a distance directly in the proximity of the funnel of the single ship eliminates the uncertainties associated with the source-emission correlation as well as with the apportionment of emissions to various sources and by-passes, too, the problem of access on board for measurements.

3. Remote sensing

Optical remote sensing allows measurement of the concentration of main pollutants emitted by ships [11]. The principal techniques of remote surveys are spectroscopic and electromagnetic radiation detection. Within spectroscopy-based techniques, active and passive methods can be mentioned: the former use artificial light sources while passive ones use sunlight, moon or starlight as energy source. Active systems normally use laser sources that, for applications aimed at detecting polluting emissions of exhausted gases, are capable of emitting high-power and narrow-band pulses of light.

The Light Detection And Ranging (LIDAR), is an active remote sensing technique that uses light pulses toward a target to obtain real time measurements of the target properties. A short pulse of light is emitted and the light reflected by the target is received with a telescope, spectrally selected, analyzed and detected. The target distance can be obtained by measuring the time lapse between sending and receiving the light pulse. The spectral analysis and the intensity of the scattered light give information about the optical and microphysical properties of the target.

Nowadays, the LIDAR technology can be applied to a wide range of measurements concerning atmospheric and climatological studies and to several other applications [12].

LIDAR with elastic/Raman capabilities give a better characterization of the aerosols, being able to measure their optical properties referred to the aerosol backscattering and extinction coefficients.

One of the most promising survey methods for the atmospheric gas concentration measure and for monitoring of ships in port is the LIDAR technique based on the molecular absorption processes, the
Differential Absorption Lidar (DIAL) technique. At the basis of DIAL is the detection of the differential characteristics of the return waves characterized by two close wavelengths, only one of which is absorbed by the pollutant. The return signals analysis gives information about the concentrations of the investigated species [13].

Another remote sensing technique for determining the concentrations and total amounts of atmospheric trace gases is the Differential Optical Absorption Spectroscopy (DOAS); the basic principle used in DOAS is the absorption spectroscopy. An interesting application of DOAS using sea scattered solar light as light source has been made by Berg et al (2011) [14]. The results of this measurement from airborne platforms show that the sensitivity is sufficient to detect SO$_2$ (wavelength 294 nm and 324 nm and spectral resolution of 0.71 nm) and NO$_2$ (wavelength 420 nm and 459 nm and spectral resolution of 0.97 nm) in the ship plume for a 1s observation time [14]. Emissions from ships funnels were measured in the port of Brindisi using an UV-VIS remote sensing DOAS system [15]. Uncertainties of estimated emissions were about 30% for SO$_2$ and 20% for NO$_2$. A good agreement between DOAS remote sensing measured emissions with inventory data is reported [15]. This confirms the suitability of this remote sensing technique to assess the mass flow rate of pollutants at ship funnels. Seyler et al(2017) [16] showed the feasibility of long-term measurements of NO$_2$ and SO$_2$ using MAX-DOAS (Multi Axis Differential Optical Absorption Spectroscopy) instruments. Masieri et al (2009) [17] measured the mass per second of NO$_2$ and SO$_2$ (12.4 g s$^{-1}$ and 4 g s$^{-1}$ respectively) for single ship through the MAX-DOAS measurement in the Venice Lagoon.

4. Application of remote sensing to cruise ships

4.1. Organization of the measurement campaign

The preparatory phase to the port emission monitoring campaign is crucial to its success. Below, a list of the main aspects to be taken into account:

- Choice of suitable equipment: the sensors must be designed for the specific survey of one or more pollutant compounds and need to be calibrated on various concentrations. Key characteristics are the possibility of a 24 hours/day operability and the use of eye safe light sources. A precise pointing system of the inspection light ray, with tracking capabilities of a moving source, is also important to follow a ship in navigation in the port area (speeds of 4 to 6 knots of a cruise ship for example) and in the manoeuvring phase, when engines are particularly stressed and are likely to emit more pollutants.
- Choice of the location for the equipment: the location should be in an upper position, suitable for monitoring a high number of vessels simultaneously present in port, with direct view on ships and funnels. Practical issues are also: gaining authorization for the access to the area, which is often under the jurisdiction of Coast Guard, Port Authority or Customs; checking number and position of the sockets necessary to supply electric power to the instrumentation.
- Previous analysis of port traffic, in order to identify from the port calendar: name and type of ships arriving; arrival and departure hours; position foreseen at pier.

Further valuable information about the incoming ships would also be length, width, height of the funnels on the sea level, etc.

4.2. Pilot experiences of LIDAR surveys

In order to complete the discussion, a brief summary of the results obtained during an explorative measurement campaign in the port area of Naples (Italy) is reported (24th - 27th of September 2018).

The sensor adopted was able of detecting only particulate matter emissions but the target of the campaign was to check the feasibility of the adoption of LIDAR systems in a port environment to survey ships funnels.

Intensive measurements of the particulate matter emitted by single ships have been carried out during the phase of the approach, maneuver, and mooring at quay.
4.3. Equipment adopted
The measurements were carried out using a portable scanning LIDAR named μ-POLIS (Microjoule POrtable LiDar System), developed by ALA s.r.l. (Advanced Lidar Applications srl) in the framework of the I-AMICA (Infrastruttura ad Alta tecnologia per il Monito-raggio Integrato Climatico-Ambientale) project. This LIDAR combines good accuracy, portability autonomy and safety, since it works in the eye-safe UV region.

The system swivels from vertical to horizontal plane to point the laser beam in the vertical plane from slightly below the horizon to the zenith. The receiver unit is designed to detect both the elastically diffused light with parallel and perpendicular polarization. The fundamental characteristics of LIDAR system are: laser source with a repetition rate 1 KHz and an average optical power at 355 nm of 0.04 W; the receiver unit is a 20 cm Ritchey-Chrétien telescope; the sounding range is from 100 m to 15000 m; the spatial resolution is of 15 m and the temporal resolution of 30 seconds.

Moreover, the system is equipped with a software for automatic continuous measurements and LIDAR data analysis.

In addition, a Doppler LIDAR (WindCube WLS7 v2 by Leosphere) was used for wind profiles measurements. This instrument emits 200 ns pulses of 10 μJ energy at a wavelength of 1.54 μm and is able to measure wind speed and direction profiles.

LIDAR data were analyzed in terms of particles backscatter coefficient ($\beta_p$) and calibrated particles linear depolarization ($\delta_p$) profiles. The former coefficient is related to the particles concentration while the latter one refers to particles shape, allowing to characterize the particulate size and to distinguish the contribution of solid and liquid particulate. The Klett-Fernald algorithm used to perform the recovery of the coefficient $\beta_p$, required a hypothesis on the LIDAR ratio (LR), which is a key parameter depending on the aerosol microphysical properties and typology [18] [19] [20]. Once $\beta_p$ was identified, the particle mass concentration at the emitting source can be obtained [21] [22]:

$$C = \sigma \text{LR} \beta_p \rho$$

Where
- $\beta_p$ and LR refer to the LIDAR signal measured in the plume;
- according to the literature, a constant value of 45 sr was assumed for the LR along the beam profile;
- $\rho$ is the mass density of particles generated by the combustion of diesel fuels;
- $\sigma$ is a conversion factor, function of the size distribution [23][24].

The instrument recorded the background of both the city and of the port area before the arrival of the ship. Then, the LIDAR was pointed in the direction of the plume, on the vertical of the funnel, following the ship in the maneuver and in the stationary phase.

4.4. Results of the pilot campaign
Figure 1 and 2 shows LIDAR profiles corresponding to measurement taken during the first day of campaign with 1-minute time integration. The figure 1 shows the plot of the $\beta_p$ profiles acquired with 7.5° elevation with respect to the horizontal plane (about 75 m above sea level on the vertical of the funnel) and pointing a specific ship approaching the port area (at a distance of about 550 m). During the maneuvering phase, the values of $\beta_p$ within the plume resulted about $4.0 \cdot 10^{-4}$. At shorter distances, the measured $\delta_p$ values resulted larger (20%) than the values measured at 570 m, this suggests a contribution of more spherical particles and the presence of water vapour in correspondence of the $\beta_p$ picks.

The figure 2 corresponds to intensive measurements performed by pointing the laser beam towards the plume emitted from two moored ships; the peak values of the backscattering coefficient are lower than those related to the maneuvering phase and correspond to the simultaneous emissions of two nearby moored ships.
An important observation is that the depolarization of the plume was about 10% in the maneuvering phase and 20% in the stationary phase. These results highlight and confirm that the ship's engines are operated at quite different regimes in the two phases as regards the emissions.

The color plot of the figure 3 and 4 show the temporal evolution of the Range Corrected Signal, i.e. the LIDAR signal corrected for the acceptance solid angle of the apparatus, and the particle depolarization, respectively, obtained from the elastic LIDAR return (355 nm as a function of the time). The two spots (at distances of about 0.5 km and 1 km), respectively, correspond to emission coming from two different ships in the port area. As reported in figure 4, asymmetrical and more depolarizing particles resulted from the more distant ship (stationary conditions), while water vapor could result from the nearer one (maneuvering phase).

Figure 1. Aerosol backscatter coefficient profiles measured during the maneuvering phase of a ship.

Figure 2. Aerosol backscatter coefficient profiles measured in the stationary phase of a ship.

Figure 3. Color map of the RCS Lidar signal at 355 nm.
The mass concentration at the emitting source was calculated by means of equation 1 with ρ of 2000 (kg m⁻³), a conversion factor (m) 3.3 x 10⁻⁷ and a mean βp value (m⁻¹sr⁻¹) of 1.2 ∙10⁻⁴. The estimated mass concentration is of 0.8 mg m⁻³. Assuming C as constant in the plume and measuring the horizontal wind speed (vₓ) with a Lidar Doppler, the flow rate of the particulate emissions was calculated. In particular, we assumed the vertical speed of the emitted plume equal to the horizontal wind speed (10 m s⁻¹). In these conditions, the flow rate of the particulate emissions can be calculated as the product between C and vₓ and is equal to 17 and 8 mg m⁻²s⁻¹ for maneuvering and stationary phase, respectively.

5. Conclusions
Real time experimental monitoring of the emissions of ships is considered a key issue for controlling the environmental impact of ports. In a pilot experience carried out in the port of Naples, new technologies based on LIDAR sensor for the remote analysis of exhaust gases emissions from internal combustion engines of ships proved applicable in the context of a port area.

The specific sensor adopted was able to detect particulate matter emissions, but similar optical techniques are available for the survey of other noxious compounds (NOx, SOx) in the exhaust. Further experiments are needed to calibrate and assess these other sensors, but the campaign carried out proves the possibility of developing an effective monitoring system of exhaust gases concentrations in a port. Surveys can be carried out in an intensive mode (as those actually carried out in the pilot campaign above described for particulate matter emitted by single ships funnels), but also in an extensive way, to characterize in real time the situation in the atmosphere above the port. A tool of this type would an asset for any Port Authority.

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