RINGO | Readiness of ICOS

Readiness of ICOS for Necessities of integrated Global Observations

D3.2

Report on implementation and technical realization of atmospheric measurements on the three SOOP platforms

RINGO (GA no 730944)

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Deliverable Review Checklist

A list of checkpoints has been created to be ticked off by the Task Leader before finalizing the deliverable. These checkpoints are incorporated into the deliverable template where the Task Leader must tick off the list.

√

- Appearance is generally appealing and according to the RINGO template. Cover page has been updated according to the Deliverable details. v
- The executive summary is provided giving a short and to the point description of the deliverable. v
- All abbreviations are explained in a separate list. v
- All references are listed in a concise list. v
- The deliverable clearly identifies all contributions from partners and justifies the resources used. v
- A full spell check has been executed and is completed. v

DISCLAIMER

EXECUTIVE SUMMARY

The ICOS Ocean observational program is running autonomous systems to measure the partial pressure of CO_2 (pCO_2) in surface waters on commercial carrier ships (Ships Of Opportunity, SOOP). Atmospheric dry air mole fractions are measured less frequent or not on SOOP lines, and are usually not acquired according to standards required for high-quality atmospheric measurements. Improving the atmospheric part of the measurements on SOOP lines according to the WMO and ICOS-ATC guidelines has been identified as a potential cost-efficient way to enhance the atmospheric data coverage. RINGO Task 3.2 develops and tests technological solutions for three different settings and approaches.

A system for the continuous recording of CO_2 CH_4, an CO mole fractions in air following ATC guidelines was designed and installed on SOOP TAVASTLAND, running between Oulu and Lübeck. The line is easily accessible, has a short round-trip repetition frequency, and bridges the land-based atmospheric ICOS network south and north of the Baltic Sea. At the stage of this report, all components have been installed, but final integration is still pending and first data flow is foreseen by mid-October. A second fully automatic ATC-conform system to monitor atmospheric mole fractions of CO_2, CH_4 and CO was installed on board the SOOP COLIBRI, which cruises from France (Le Havre or Marseille) to French Guiana (after stopover in Livorno -Italy-, and/or St Petersburg -Russia). This line has much longer transit periods, lower frequency, and covers a wide climatic range from Europe to the tropics. The system went into operation in March 2019 and proved to achieve ATC-conform data quality. Software amendments at ATC were implemented to allow the retrieval of data from moving platforms, an automated separation between harbor, coastal and open ocean parts of the ship track was realized, and the consistency of the open ocean data against results of the Copernicus CAMS forecast product was evaluated. On the SOOP ATLANTIC SAIL, commuting between Liverpool and Halifax with a round-trip time of ~5 weeks, an attempt is made to achieve non-continuous, but mostly ATC-conform atmospheric CO_2 data retrieval using the analytical instruments primary used for the measurement of seawater pCO_2 in a “switching mode”. The major aim of this set up is to develop a solution with existing equipment to generate high quality atmospheric air measurements at very low additional costs, though with a reduced spatial data coverage. On this line, a new sensor (Licor LI 7815) was also implemented and tested, as it will most likely be the standard analyzer for SOOP based measurements in the near future.

In this report, the technical description and first data examples are summarized for all three approaches, including a high level of detail for the different applications. As all three installations were delayed due to a variety of different problems with the platforms (i.e. the commercial vessels), recommendations are given which specifically address potential issues of “ship liaison”. This deliverable report will be complemented by the deliverable report 3.3, including a technical handbook and quality assessment of data from the three lines.

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1 INTRODUCTION

The ICOS Ocean observational program is running autonomous systems to measure the partial pressure of CO_2 (pCO_2)in surface waters on commercial carrier ships (Ships Of Opportunity, SOOP) which allows for high spatiotemporal data coverage, and is a major component of the OTC data stream. Atmospheric dry air mole fractions are measured less frequent or not on SOOP lines, and are usually not acquired according to standards required for high-quality atmospheric measurements. Improving the atmospheric part of the measurements on SOOP lines according to the WMO and ICOS-ATC guidelines has been identified as a potential cost-efficient way to enhance the atmospheric data coverage and to gather data from areas difficult to access, in some cases at critical regions in terms of air mass boundaries. RINGO Task 3.2 aims to develop and test technological solutions for three different settings and approaches, and assess the added value for the atmospheric observation network.

Construction and installation of a mobile stand-alone module (only requiring electricity and data connectivity) for continuous atmospheric CO_2 and CH_4 measurements was planned on the SOOP FINNMAID running between Helsinki and Lübeck (equipped by partner IOW). The developed module should be transferable with minimum amendments on most other SOOP lines providing enough space on the ship. The SOOP FINNMAID is easily accessible for partner IOW in Lübeck and for members of the ICOS HO in Helsinki, has a very short transit repetition frequency and bridges the land-based atmospheric ICOS network south and north of the Baltic Sea. A second fully automatic system was planned to be installed on board the SOOP COLIBRI (equipped by UVSQ), which cruises from France (Le Havre or Marseille) to French Guiana (after stopover in Livorno -Italy-, and/or St Petersburg -Russia) to monitor atmospheric mole fractions of CO_2, CH_4 and CO, to be maintained over the RINGO project time laps. The installation on SOOP COLIBRI is complementary to the one planned on SOOP FINNMAID, since it addresses a line with much longer transit periods, lower frequency and covering a wide climatic range from Europe to the tropics. On the SOOP ATLANTIC SAIL (equipped by GEOMAR, Canada to UK), an attempt was foreseen to achieve non-continuous, but mostly ATC conform atmospheric CO_2 data retrieval using the analytical instruments primary used for the measurement of seawater pCO_2 in a “switching mode”. The goal of this subtask is to find a solution with existing equipment to generate high quality atmospheric air measurements at very low additional costs, though with a reduced spatial data coverage.

System designs is accompanied and supported by expertise in atmospheric measurements from Université de Versailles Saint-Quentin-en-Yvelines (UVSQ) and Integrated Carbon Observation System Head Office (ICOS HO). SOOPs FINNMAID and ATLANTIC SAIL atmospheric measurements were planned to be verified against flask samples taken by a hand-controlled flask sampler provided by the Central Analytical Lab (CAL) during transit. The CAL was also responsible for the analysis of the flasks and provision of the calibration gases. Integration into the ATC framework and development of data products for mobile platforms was foreseen. In addition to quality assurance, the added value for the atmospheric station grid should be assessed through comparison to Copernicus CO_2/CH_4 forecasts and inverse modelling runs with and without the SOOP-borne atmospheric data.

In this report, we focus on the technical implementation on the SOOP lines. The implementation has been delayed for several reasons, which are briefly summarized, as it emphasizes the importance and the various problems of “ship liaison” between the scientific community using commercial ships of opportunity and the ship-owning companies.

2 ENHANCED INTERNATIONAL EFFORTS – INTERNATIONAL RECOGNITION OF THE IMPORTANCE AND CHALLENGE OF TRACE GASE MEASUREMENTS IN THE MARINE BOUNDARY LAYER

In the framework of this work, it is important to highlight a community position paper prepared for the Ocean Observation Meeting in Hawaii (Wanninkhof et al., 2019), with strong contribution of ICOS members, including several scientists involved in Task 3.2 of RINGO. The paper ”A Surface Ocean CO_2 Reference Network, SOCONET and Associated Marine Boundary Layer CO_2 Measurements” envisions a sustained, global Surface Ocean Network of pCO_2, in very many ways following the guidelines established within SOCAT and ICOS OTC. Moreover, it emphasizes the need for measurements CO_2 in the Marine Boundary Layer (MBL), to reduce the uncertainty of surface-data derived air-sea flux estimates, such as used e.g. in the Global Carbon Budget (Friedlingstein et al., 2019).

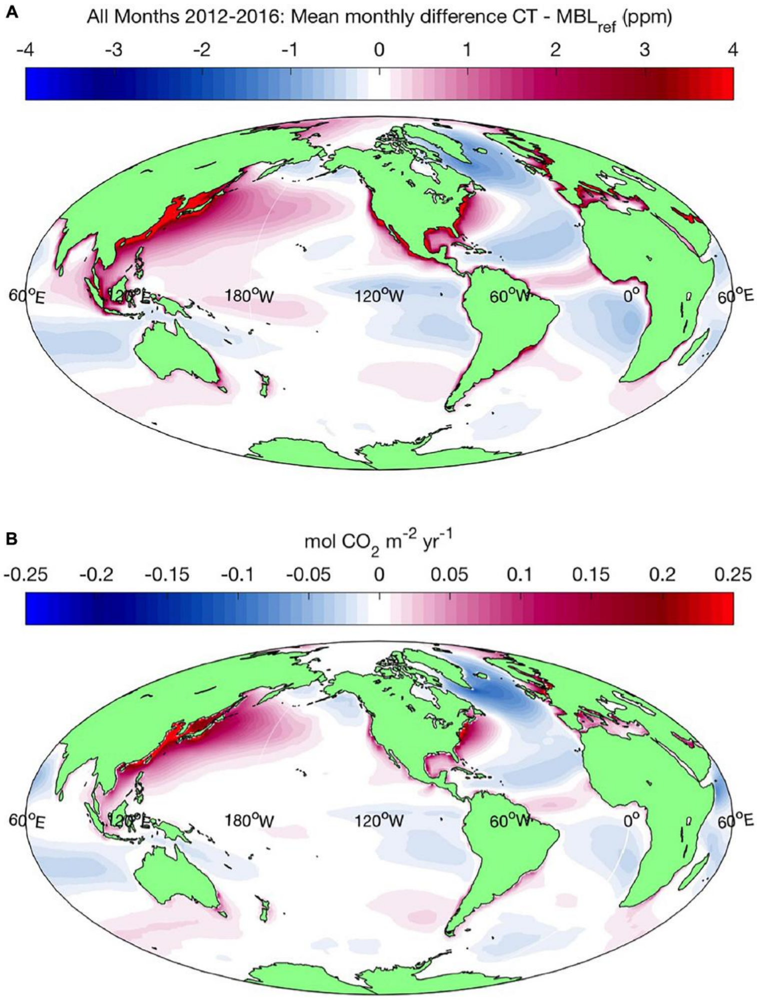


Figure 1: (**A**) Mean monthly difference in atmospheric CO_2 over the oceans between CT2017 and the NOAA MBL CO_2 reference product, for the period 2012–2016. Note the differences downwind of the northern hemisphere continental land masses; **(B)** annual mean difference in FCO_2 that arises from using atmospheric CO_2 from CT2017 compared to the NOAA MBL reference product (reprinted Figure 6 from Wanninkhof et al., 2019).

While most, though not all, SOOP lines make in situ MBL CO_2 measurements, FCO_2 is not usually calculated using these data. Instead, values for the atmospheric partial pressure are often derived from the MBL reference data product provided by the Global Monitoring Division (GMD) of NOAA/ESRL. This data product is generated from a subset of NOAA atmospheric CO_2 measurement sites near the coast that predominantly experience MBL air. These data are filtered, interpolated, and smoothed prior to being fitted at latitudinal intervals of 0.05 sine of latitude from 90°S to 90°N. Another global product which is used for global flux calculations is the Carbon Tracker pCO_2 product, which assimilates the global atmospheric CO_2 measurements. In Wanninkhof et al., (2019) an example is given of differences in flux calculation in a coastal area using the same surface water pCO_2 data sets, but using in situ measurements, the NOAA marine Boundary Layer Product and the Carbon Tracker product respectively for the atmospheric partial pressure of CO_2. The different atmospheric "products" used to derive the flux estimate for the area lead to differences of ~15 %. All of these approaches are used in the literature. Moreover, Wannninkhof et al. (2019) calculates the resulting differences in ΔpCO_2 and sea-air CO_2 fluxes for the integrated period 2012-2016 by using the two atmospheric air products, demonstrating large differences in particular downwind of land masses (Figure 1).

In the Wanninkhof et al. (2019) community paper we argue that reaching an accuracy of shipborne MBL CO_2 measurements of 0.2 µatm would be possible, which would still not reach WMO /GAW (Crotwell and Steinbacher, 2018) or ICOS ATC (Laurent et al., 2017) standards, but most likely already be of considerable value for inverse modelling approaches.

Given the additional cost involved in improved MBL CO_2 data from ships and moorings, interaction with the inverse modeling and observing system design communities will be used to identify regions where the added data have highest impact on uncertainty reduction.

Wanninkhof et al. (2019) suggests to improve oceanic community MBL CO_2 measurements following two pathways: by upgrading existing measurement systems that are not currently optimized for atmospheric CO_2 measurements; and to invest in new, purpose-designed measurement systems that employ more modern technologies such as laser-based techniques. In the paper, we acknowledge that "Within the European ICOS Network, pilot studies for the acquisition of MBL CO_2 data matching the standards of the atmospheric community are currently underway. SOCONET can make use of these investigations for the design of a network of high-accuracy MBL CO_2 measurement platforms with the aim to maximize the scientific return of investment."

This publication within the framework of the OceanObs 2019 Conference thus highlights the importance of the Task 3.2 of RINGO, and its potential to be seminal for the international community effort.

3 TECHNICAL DESCRIPTION AND STATUS

3.1 OVERVIEW

Figure 2: Approximate ship tracks of three SOOP lines used within Ringo Task. 3.2. SOOP TAVASTLAND in the Baltic Sea, SOOP ATLANTIC SAIL from Liverpool to Halifax, SOOP COLBRI from Europe towards French Guaiana. For SOOP Colibri, the ship track around Europe is not indicated; see Figure 14 for details.

In the following, we give technical descriptions of the installation on the SOOPs TAVASTLAND, COLIBRI and ATLANTIC SAIL to realize or enhance quality of atmospheric air measurements in the MBL along the cruise track of the vessels. The carrier SOOP TAVASTLAND running between Lübeck and Oulu with a round trip time of one week had to be chosen instead of the originally planned SOOP FINNMAID due to reasons given in Section 4, but without any caveats for the general approach, in particular as the ship is now component of the Swedish ICOS contribution and thus will have high quality seawater pCO_2 measurements along the same transect. On SOOP ATLANTIC SAIL, a new sensor (Licor LI 7815) is additionally tested, as it is likely to be the new standard instrument on ICOS pCO_2 installations. An overview of some key parameters of the installations on the 3 vessels is given in Table 1, an overview of the ship routes is shown in Figure 2.

Ship	SOOP TAVASTLAND	SOOP ATLANTIC SAIL	SOOP COLIBRI
Route	Baltic Sea; Lübeck - Oulu	North Altantic; Liverpool - Halifax	Around Europe with several ports; across the Atlantic from Europe to French Guiana
Round Trip Time	One week	5 weeks	N/A in European coastal waters due to varying schedule; ~1 month for the round trip across the Atlantic
Instrumentation	Continuous ATC conform station based on Picarro G2401 analyser	Continuous ATC conform station based on Picarro G2401 analyser	Atm. measurements with optimized SetUp for oceanic pCO_2, using LI 7000 and LI7815 sensor
Frequency of atmospheric measurements	Quasi continuous	Quasi continuous	On timeslots approximately every 4 hours
Rationale/Question	Transect surrounded by atm. network, continental to Arctic air masses, large temperature gradient	Determination of the quality of atm. CO2 measurements that can be reached using OTC-typical pCO_2 setup	Transect covering highly undersampled air masses with a large range of meteorological conditions (temperature, humidity …)

Table 1: Characteristics of the SOOP lines and instrumentation addressed within RINGO Task 3.2.

3.2 SOOP TAVASTLAND (IOW)

<u>Background information and rationale:</u>

In the beginning of the RINGO project, it became evident that there isn't any off-the-shelf solution for an atmospheric station to be built and used in SOOP operations, including a complete construction manual and parts list. However, our own experience with self-built automatic measurement systems of trace-gases in sea surface on SOOPs, the involvement of several groups with experience on the realization of ATC-conform atmospheric stations (Laurent 2017) as well as the ATC itself, provided a unique group of expertise to realize this line across the entire north-south gradient of the Baltic Sea. Instrumentation designs from different atmospheric ICOS stations (Pallas, Sodankyla, Utö (Finland), Hohenpeißenberg and Gartow (Germany)) were considered. The expected problem of ice formation at the ari inlet and in the air tubing was addressed by adopting solutions developed in Finland (Kilkki et al., 2015). Details addressing operation on ship in general as well as specifically for SOOP TAVASTLAND were discussed with the crew, chief engineer and captain of SOOP TAVASTLAND regarding the different aspects of onboard installation, concerning e.g. available space, infrastructure, ships operations and ship-specific safety regulations.

<u>Overview of the installation:</u>

The system for ATC-conform atmospheric measurements on SOOP TAVASTLAND is built entirely into a 19" steel rack. SOOP TAVASTLAND will facilitate power supply and internet connection (LAN, e.g. for data access and remote operations). A stand-alone solution for the remote access to the system is foreseen, as the ship's internet connection may sometimes be too slow for remote access via the ship. System remote access for checks, necessary adjustments and data download are planned to be at port calls of TAVASTLAND in Travemünde (Germany) and Oulu (Finland).

A description of technical realization used in SOOP Tavastland is shown in Figure 3. The required standard gas cylinders (up to 5 Luxfer, 20 L aluminium bottles), and the measurement system, are set up in the crew fire-fighting preparation room. The gas cylinders and regarding pressure reducers required for the system are mounted in a stand-alone gas cylinder rack, specially manufactured for this purpose by the IOW workshop.

During a three weeks test run the whole system was tested under different ambient conditions. As one result, the system was equipped with additional fans and ventilation openings for heat dissipation. Safety shutdowns were installed to prevent hazards in the event of excessive heat. Some additional options for remote control of some vital switching states was also installed, such as e.g. the emergency switching state of the water-guard-triggered solenoid valves, the uninterruptable power supply (UPS) and its states / shutdown, the proper shutdown of the Picarro analyzer, the switching of the air-pump circuit and the regulation of all flow-controller, and the regarding software was adapted accordingly.

In collaboration with chief engineers of SOOP TAVASTLAND, the setup of the system cabinet and gas bottle rack in the room was optimized for best access of all vital parts, including the UPS, the Picarro analyzer, the GPS and time-server, the data acquisition unit and all pumps and other sensors and switchboxes in the periphery. This had to be realized assuring also minimal spatial restrictions for the crew, as the room has to be used by several people at the same time in case of a fire-fighting exercise. A detailed plan of the construction in the crew's fire-fighting preparation room is shown in Figure 4. The construction of the entire set up would allow for a quick swap of vessel at a later stage.

The system hosts two air tubings of ~30 m each to allow for quick troubleshooting and as well as for comparison / reference measurements with ATCs mobile reference system. All tubing outside the system, in particular those that are attached to the ships superstructure, are going to be isolated and heated in order to avoid water condensation / ice formation. The air tubing has to be installed without kinks and with a constant gradient towards the measurement system, in order to avoid areas of condensed water collection inside the tubing/hosing, as such may enhance the risk of water entering the measurement system and delay of the CO_2 signal. The intake will be placed at the very same spot of the weather stations sensor holding frame. The location of the air inlet is a compromise between distance from the ship's exhaust and requirement to stay out of the area of severe sea spray in heavy winds. Weather shield to protect the inlet were designed and manufactured as in kind by the ATC.

Systems to be installed on ships have to be designed not only with maximum safety for the built-in hardware (e.g. the Picarro G 2401) but also for the crew of the ship, and the electrical and data circuits of the vessel. Safety and emergency cut-off facilities must be built-in and checked frequently. Final functional and safety tests were performed on the spot after installation on the SOOP TAVASTLAND.

Weather data will be measured and recorded, using an AANDERA AWS 2700 – automatic weather station, with the corresponding required sensors (humidity, temperature, wind speed and -direction), installed on the outer deck above the ship's bridge. On the same location, an autonomous GPS antenna for the position and time server is installed.

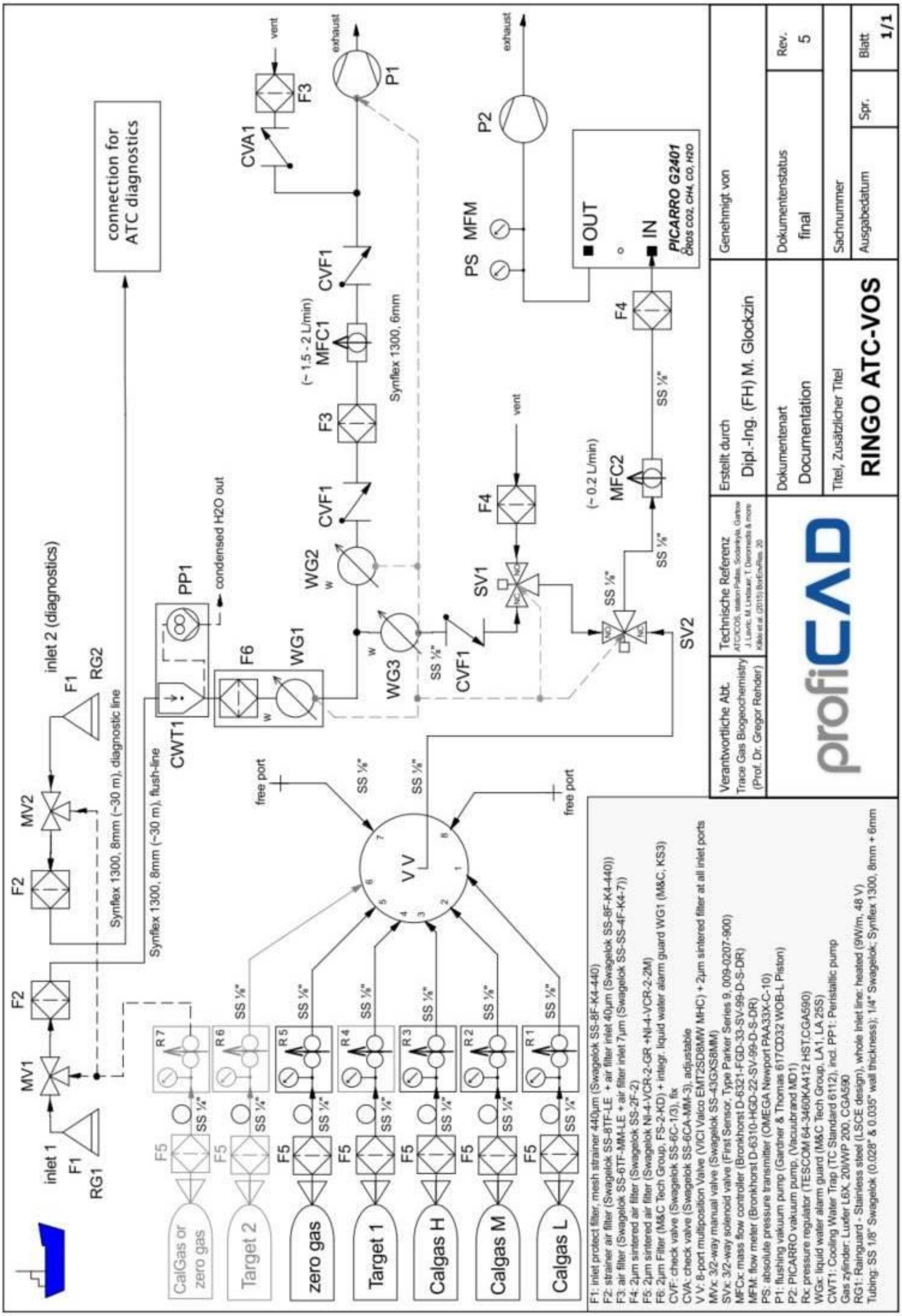
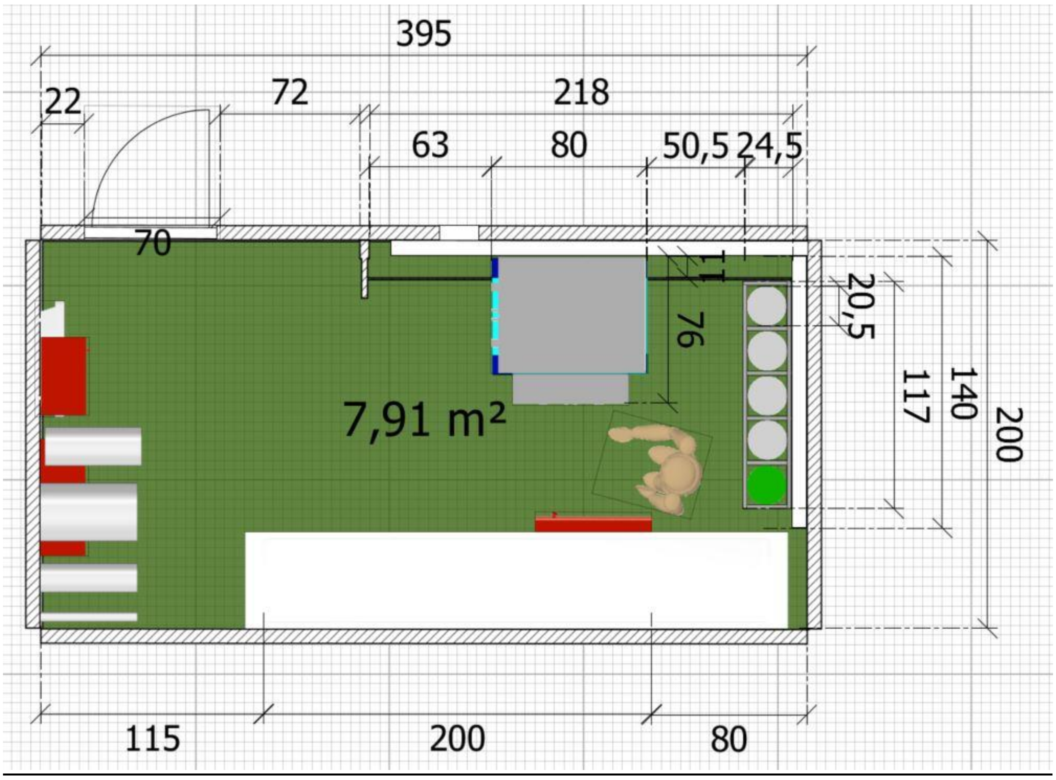


Figure 3: Schematic drawing of IOW RINGO-ATC-SOOP system with list of parts.



- RINGO – System is mounted in a 19" metal server rack (2mm wall thickness), 60x80x180cm, front facing entrance
- Gas bottles are mounted on the wall in a rack manufactured by IOW workshop,
- max. pressure: 200 bar, compressed air.
- 1/8" Swagelok linings (0.035 wall thickness, can hold up to ~710 bar max pressure) run into the rack, pressure reducer are inside the rack.
- The green-colored gas bottle is a future option, up to date only four bottles are needed

This setup allows for

- minimum interference with usage of the room
- easy changing of gas bottles
- easy access to all components
- easy access to electricity plugs
- easy access to LAN - plugs

Except soldering gas bottle holder + rack to the room bottom & walls, drilling a hole for the air-lines/GPS antenna above the 19" rack, only very minor reconstruction measures are needed. All other installations can stay in place where they are now!

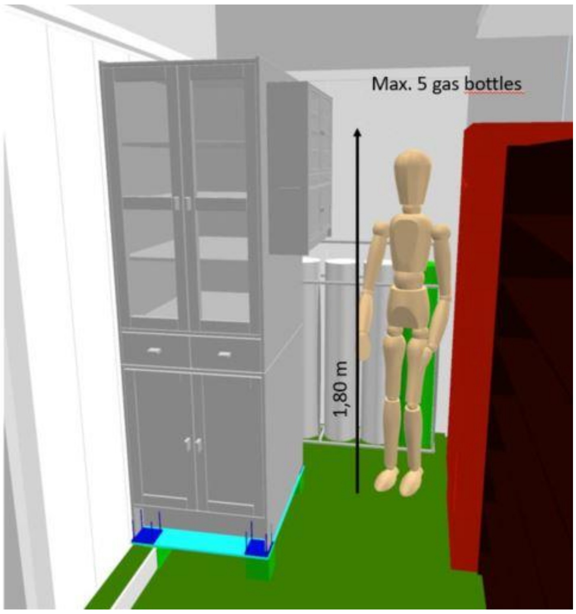


Figure 4: Setup of RINGO-ATC-SOOP System in the crews firefighting preparation room as approved by Chief of SOOP TAVASTLAND.

Installation details:

Ambient air is continuously sucked in through a ~30m-long (Synflex 1300, 8mm) hosing that is isolated (armaflex), heated (~5-15W/m, DC power supply <=48 V for safety reasons) hosing and dried (Peltier cooler). An aliquot of it is branched off to the gas distribution system (Swagelok 1/8" stainless steel line), and then led into the Picarro G2401 sensor for determination of CO_2, CH_4, and CO mole fractions. The drying unit reduces the water content down to approximately 0.8%. Both the continuous ambient air flow as well as the measuring gas flow are regulated and monitored using mass flow controller (Bronkhorst). Behind the Picarro analyzer and in front of the Picarro vacuum pump, a pressure transmitter (Omega) monitors the ambient underpressure. Between the Picarro and its vacuum pump, a mass flow meter (Bronkhorst) monitors the exhaust flow, and an additional pressure transmitter (Omega Newport) monitors the pressure on that line.

Air filters and check valves (Swagelok) are implemented at neuralgic points to protect pumps, magnetic valves and sensors against damage from minute particles, too high differential pressures, and backlashes. Water guard sensors protect the regarding hardware from water damage by switching magnetic valves and motors accordingly. Calibration gases and target gas are distributed via a VICI multiport valve (dead-end), controlled by the Picarro analyzer software. Data is recorded internally within the Picarro sensor. Moreover, the data flows from this and all other sensory units are recorded by a portable computer and an appropriate software solution.

During test runs, the data structure and any necessary adjustments to comply with the ATC formats have been clarified and taken into account to ensure future data delivery to ATC. To minimize unnecessary ship control visits, and to have at least a minimum amount of control over system status by remote access, a National Instruments USB-6221 multi I/O unit is built in to function as interface between e.g. switching relays to control parts of hard- and according control software or to monitor safety relays (e.g. water guards). This allows not only for simple system monitoring but as well the possibility for a rudimentary remote system control of e.g. the switching of lines that are vital for a safe shutdown of the Picarro analyzer, Picarro VICI valve control, flow controller adjustments as well as UPS monitoring and shut down. The Picarro can be shut down safely and the whole system then be shut-off remotely. Finally, hard-wired automatic emergency shut-offs secure either partial or the entire system shut-downs, depending on the severity of the fault.

<u>Calibration gas supply:</u>

The calibration gases have been delivered by the CAL according to ATC protocols (see Table 2). All gas regulating and carrying components strictly follow ATC requirements(for components see Figure 3). Due to the test site character of the instrumentation, no long-term target has been integrated, but the peripherals for the long-term target is already foreseen in the construction (see Figure 4).

BOTTLE	CO2 (ppm)	CH4(ppb)
LOW	*380.825*	*1797.2*
MEDIUM	*405.76*	*1949.1*
HIGH	*448.96*	*2079.5*
TARGET	*420.3*	*1970.8*

Table2: set of four calibration gas bottles, already provided by CAL (MPI Jena) for operation on SOOP TAVASTLAND.

<u>Current Status:</u>

The whole system has already been built and was successfully tested in a long-term laboratory test-run (see Figure 5).

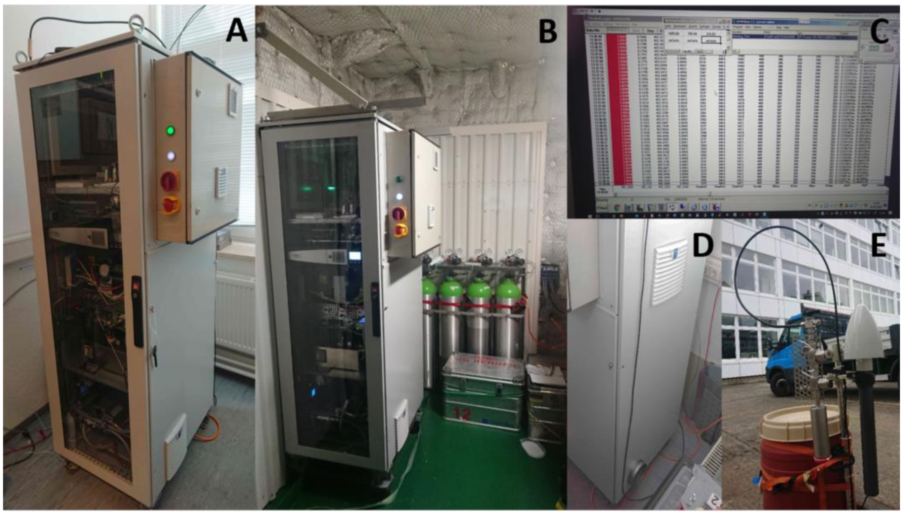


Figure 5: Final test run in IOW laboratory and placement on board SOOP TAVASTLAND - **A**: whole system, running and 19" cabinet closed; **B**: Placement of components on SOOP TAVASTLAND, mid-September 2020; **C**: software running on control laptop for data acquisition and system monitoring (not all shown here), **D**: backside of 19" rack with motor and housing vents, **E**: GPS antenna for position / time server and ATC France air inlet with the rain cap to cover the opening of the hosing.

The whole electrical interface, wiring and programming were completed , tested and approved, and a long-term test was carried out at IOW under natural conditions for three weeks in June 2020. All main components are onboard since September 2020, and the rack and cabinet were welded onto the floor for maximum security. Re-assembly of the hosing and electrical connections are doable only at time when the ship is at the harbor (approx.. 6 hours on Fridays), as the – preferred – two way journey onboard the vessel is currently not possible due to COVID-19 restrictions. Once the system is running, the heating of the hosing will be assembled to be installed before temperatures below freezing point are encountered.

3.3 SOOP ATLANTIC SAIL (GEOMAR)

Background information and rationale:

The M/V ATLANTIC SAIL (Atlantic Container Lines, ACL) is a combined car and container vessel operating on a service between North America and Europe. The first port calls on both sides of the Atlantic are Liverpool, UK, and Halifax, Canada. It also covers part of the European shelf as the ship also serves the port of Hamburg, Germany.

Figure 6: North Atlantic SOOP line M/V Atlantic Sail (photo is courtesy of Atlantic Container Lines).

The SOOP line between Europe and North America is operated since 2002 by GEOMAR with different ships. Since 2005 the pCO_2 instrumentation was installed on board of vessels of the Atlantic Container Line (ACL) shiping company. In 2018 the installation was moved from the old ship (ATLANTIC CARTIER) to the ATLANTIC SAIL. The main instrumentation (General Oceanics pCO_2 system 8050, GO system) is installed in the engine room, where fresh seawater is drawn from the lower sea chest at approximately 10 m water depth. Atmospheric air is drawn from outside through an 80 m long Dekabon tubing. The Air inlet is located on the top of the housing for the exhaust at approximately 35 m height. This was the only position that could be reached from the engine room. Even if the position is not optimal, clean air can reach the inlet. A weather station with wind speed and wind direction is installed next to the inlet so that unfavorable wind directions can be filtered.

The CO_2 measurements for sea surface pCO_2 are done using a LI-COR infra-red CO_2 sensor (LI7000). To improve the measurement uncertainty of the xCO_2 measurements it was planned to exchange the LI7000 with a Picarro sensor (G2131-i), which is available at GEOMAR. Since the sensor was also used for xCO_2 measurements in air that was in equilibrium with seawater we faced massive problems with the vacuum pump of the Picarro instrument and the exchange of the pump membranes was not a task that could be easily done on board. Therefore, we decided to seek for an alternative to better suit the demands of the ocean community. In 2019 first laboratory tests with a new CO_2 sensor (LI-COR LI7815) were performed. The integration of the LI7815 into the existing GO system is straight forward and the first tests showed promising results that need to be further evaluated in the field. There are groups at NOAA (Miami, USA) and CSIRO (Hobart, Australia) that also work on the integration of the LI7815 and new design of the whole GO system to better work with the LI7815. Thus, it is very likely that the LI7815 becomes the new standard for oceanic pCO_2 measurements. Other benefits are the price (it is the same as for the older Licor IR sensors) and the maintenance. The new LI7815 can be easily swopped between installations which is a huge advantage as the time for servicing the installation on board the vessels is often limited due to short port calls. Together with its high precision (see Figure 8) it makes this sensor a suitable candidate for the combined approach onboard vessels like the Atlantic Sail.

<u>Description of the instrumentation:</u>

Figure 7 shows the GO pCO_2 system on board the M/V ATLANTIC SAIL. The system is commercially available and is used by many groups around the world involved in surface pCO_2 measurements. The system was designed for the use of a classical infra-red detector from LI-COR (LI6262 or LI7000). As mentioned above, in order to improve the precision of the atmospheric measurements a different detector should be installed. The approach onboard the M/V ATLANTIC SAIL was to use the same instrumentation that is used for seawater pCO_2 measurements also for accurate atmospheric xCO_2 measurements (see Introduction). During a cruise in 2017 it was found out that using filter wool (like it is used in regular kitchen hoods) in the air inlet improved the stability of the measurements, likely due to prevention of sea spray entering the system and reducing the risk of the formation of salt crystals in the air tubing. Salt crystals might have an effect on the water vapor in the air tubing depending on its temperature. However, air is constantly pumped through the long hosing to ensure that the hosing is kept always well flushed. The whole system is set up in a way that it runs several standard gases followed by 10 minutes of atmospheric air before it measures seawater pCO_2 for three hours. Then the cycle starts again and repeats itself throughout the voyage meaning that the atmospheric air is measured approximately every 4 hours during the Atlantic crossing.

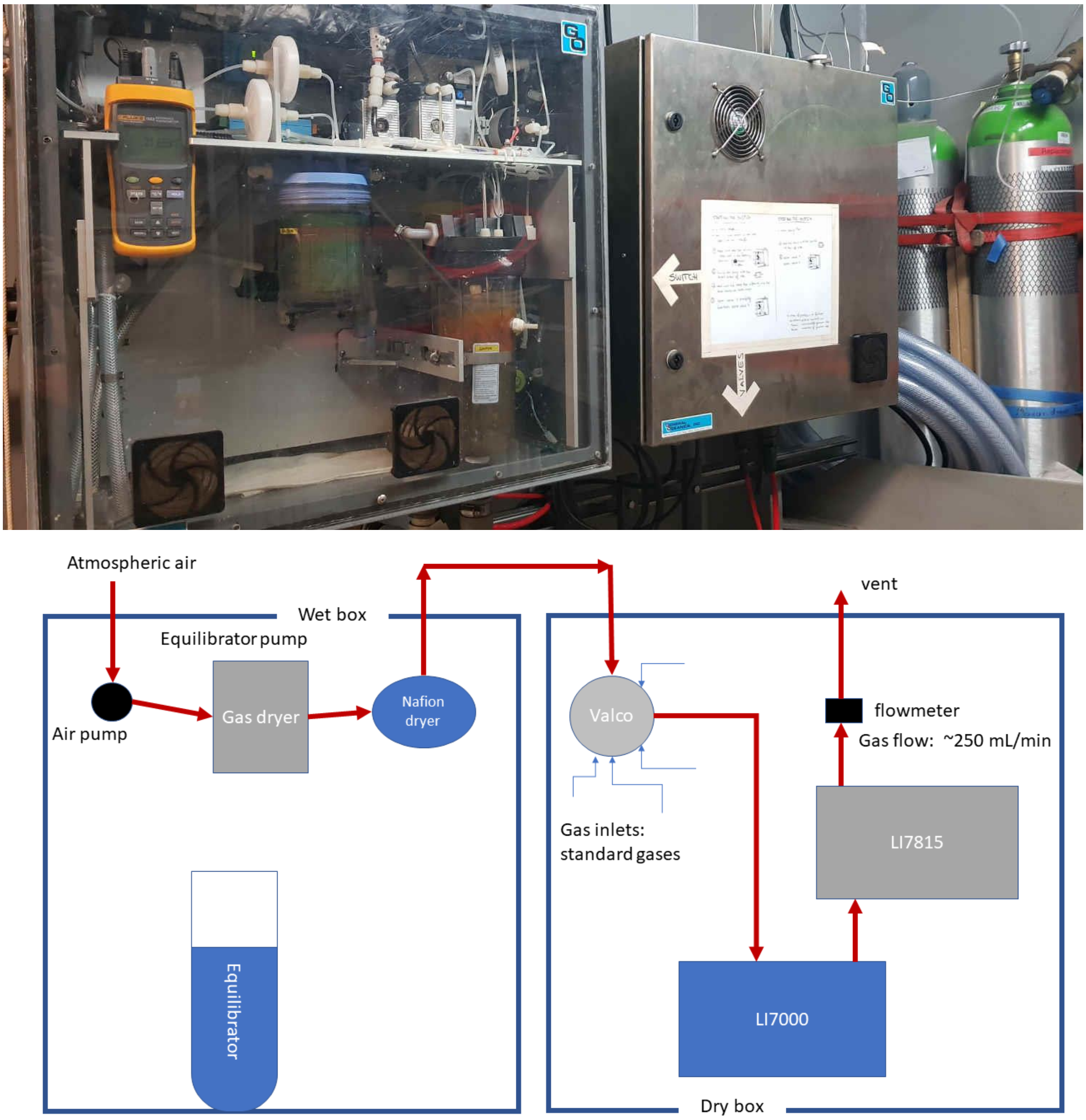


Figure 7: Photo and schematic of the GO system used onboard M/V Atlantic Sail. The upper photo shows the so-called ”wet box on the left where the seawater equilibration takes place. Also the pumps and drying units are located in the wet box. The ”dry box” to the right contains a Valco multi-position valve and the CO_2 sensors. In the background one can see the gas bottles with standard gases. The lower schematic shows the gas flow of atmospheric air. The tubing is directly connected to the dry box where constantly air is pumped from the inlet. The air is dried with a Peltier cooler and Nafion tubes. The dried air goes via the Valco valve to the CO_2 sensors.

When the system switches to atmospheric air, the air is dried using a Peltier cooler that operates between 2°C and 5°C and using a Nafion drier afterwards. Then the air is directed to the CO_2 sensor. The current setup onboard the M/V Atlantic Sail is illustrated in the lower part of Figure 7

As stated above, in the past the CO_2 detector used onboard the M/V ATLANTIC SAIL was a Licor LI7000, which uses infra-red detection. These sensors have proven to measure the xCO2 in seawater application to ±0.2 ppm, which basically determined the target accuracy for the MBL measurements by the SOCONET initiative (see Chapter 2 – Enhanced International Efforts). In 2019 a new sensor from Licor entered the market (LI7815) which is based on optical feedback cavity enhanced absorption spectroscopy (OF-CEAS). One of the first available sensors was used for laboratory experiments in summer 2019. Since the LI7815 has its own internal pump several changes to the GO system had to be made (take out equilibrator pump, change of idle states). While connected to the GO system a standard gas with known CO_2 content was run through the system to find the optimum averaging interval as the sensor measures at 1Hz (Figure 8).

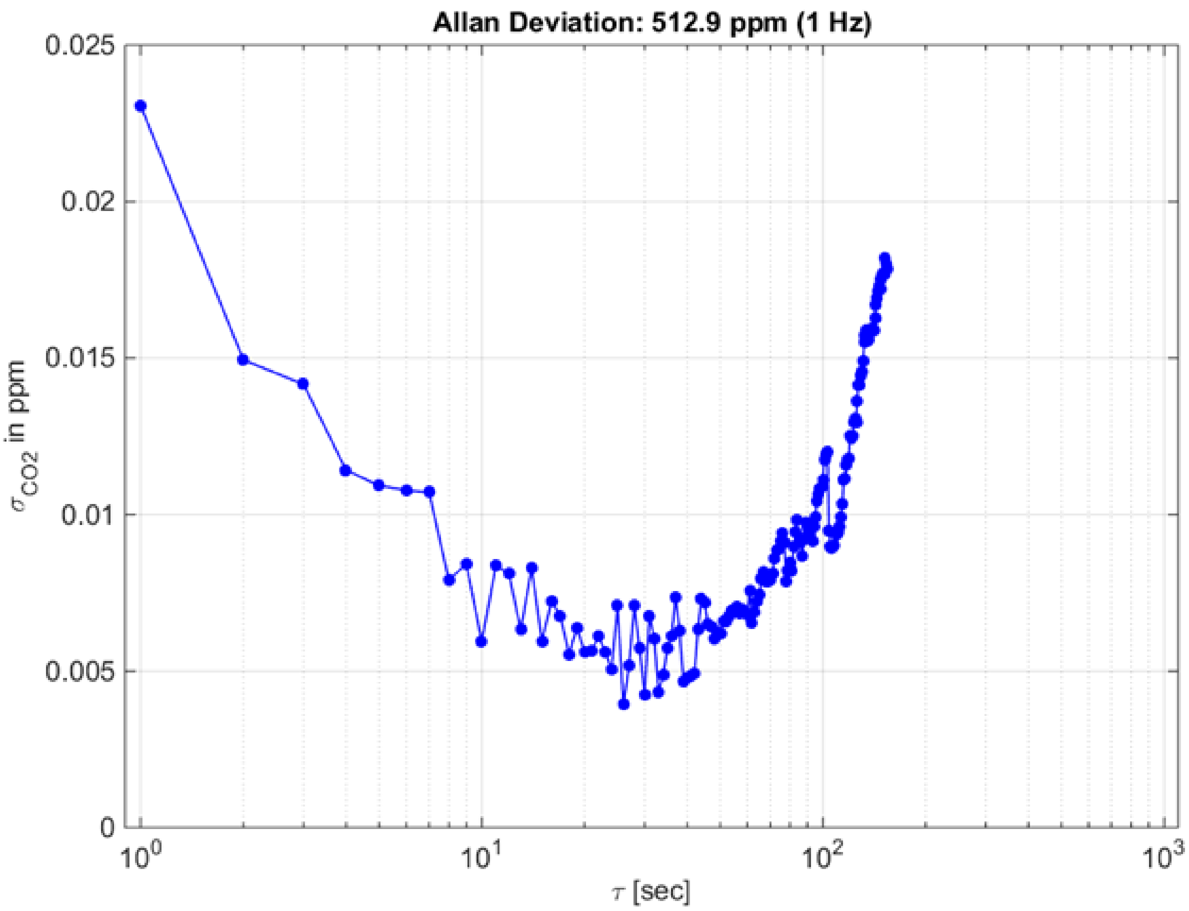


Figure 8: Allan deviation analysis of standard gas (512.9 ppm CO2) measurement with the LI7815. Measurements were recorded at 1Hz.

The Allan plot in Figure 8 shows that, for an averaging time of 10 seconds, the repeatability is better than 0.01 ppm CO_2. Towards long averaging times, the repeatability gets worse due to the increasing impact of long-term drift. Thus, we decided to average the measurements for 20 seconds. The GO system reports a data point approximately every minute and the last 20 seconds before reporting are used for averaging. However, the 1Hz raw data are always available, too, so that a reprocessing of the data is always possible.

Sequence	Repetition	Gas	Remarks
1	1	Zero	Natural air with 0 ppm CO_2 is run to set the LI7000's zero value
2	1	Span	The gas standard with the highest CO_2 value is run to set the LI7000's span value
3	3	STD1	Standard gas 1 is measured 3 times (CO_2 = 372.77 ppm)
4	3	STD2	Standard gas 2 is measured 3 times (CO_2 = 387.29 ppm)
5	3	STD3	Standard gas 3 is measured 3 times (CO_2 = 406.98 ppm)
6	3	STD4	Standard gas 4 is measured 3 times (CO_2 = 448.55 ppm)
7	10	ATM	Atmospheric air is measured 10 times
8	3	UNK1	The target gas is measured 3 times (CO_2 = 405.92 ppm)
9	180	EQU	Air that is equilibrated with the seawater is measured for approximately 3 hours

Table 3: Run sequence onboard M/V ATLANTIC SAIL.

The runtime sequences for measurements on board the M/V Atlantic Sail are set as shown in Table 3. After switching from one gas to the other (i.e. moving down one row in Table 3) the gas lines are flushed for five minutes without taking any measurement. This value needs to get determined for each installation. The repetitive measurements are done approximately every minute. Since the LI7000 is still installed onboard it needs to get adjusted for the zero and span value once per day what is done in lines 1 and 2. This is followed by measuring four standard gases bracketing the expected CO_2 range (lines 3 – 6). Then atmospheric air is measured for 10 minutes (line 7) followed by three consecutive measurements of the target gas (line 8). After that three hours of measuring air that is in equilibrium with seawater (9) follows. After the three hours of seawater air measurements, the cycle starts again in line 3. Once per day the seawater air measurements are followed by standard gas measurements and the sequence starts in line 1 again to adjust the LI7000's zero and span values.

Further Work:

With the two sensors in line and the calibration gases provided by the CAL, characterized by high accuracy and a relatively small range of concentrations centered around the atmospheric value, it will be soon possible to assess the repeatability and accuracy of the atmospheric MBL measurements which can be obtained by the sensors in a swopping mode with surface water measurements following a sequence used on most currently operated SOOP lines within the ICOS OTC network.

3.4 SOOP COLIBRI (LSCE)

Instrumentation overview:

The SOOP COLIBRI is a 115 meters long and 20 meters wide vesssel (Figure 9) that is dedicated to the transfer of the European Ariane rocket parts between Europe and the launching base of Kourou in French Guyana. Therefore, the ship which is primarily attached to Marseille harbour in the Mediterranean Sea also frequently moves to Le Havre in the North Sea (France), Livorno in Italy, Germany and St Petersburg in Russia to collect parts and/or equipment before crossing the Atlantic Ocean. The ship is already equipped since 2006 with a setup dedicated to measure the partial pressure of CO_2 in surface waters (Lefèvre and Diverrès, 2017).

It also hosts a full weather station run and processed by Météo-France and fulfilling all the WMO (World Meteorological Organization) measurements standards. The setup of our experimental device has benefited from our long and diverse field campaign experiences across the French greenhouse gases monitoring network.

Figure 9: Photo of the SOOP COLIBRI.

The experimental setup for ATC-conform measurements of atmospheric air on board SOOP Colibri consists of the following elements:

- Air inlet and air tubing;
- A greenhouse gases analyser (CO_2, CH_4, CO, H_2O cavity ring down spectroscopy analyser, Picarro G2401);
- A set of calibration and quality control compressed air cylinders (4) provided by the central calibration centre from ICOS-RI (Integrated Carbon Observation System Research Infrastructure) connected to a multi-position valve enabling the sequential measurement of the different cylinders and atmospheric air;
- A GPS set up to recover real time positioning of the vessel and absolute time stamp;
- A back-up system to ensure the data safeguard;
- An uninterruptible power supply to preserve the equipment in case of power fluctuations or shut-down;
- A 4G router used for data transfer during the time the vessel stays in a harbour.

Most of these elements are integrated in a single compact rack (except the four cylinders) that can be easily installed onboard the vessel (see Figure 10) and has been placed on the lower third deck of the vessel. The rack has been welded onto the deck, as well as the cylinders supports. The cylinders are retained by adjustable strips to the supports in order to prevent any movement in case of heavy sea conditions. All equipment inside the rack is fixed for the same reason and also to avoid too much vibration during the passage.

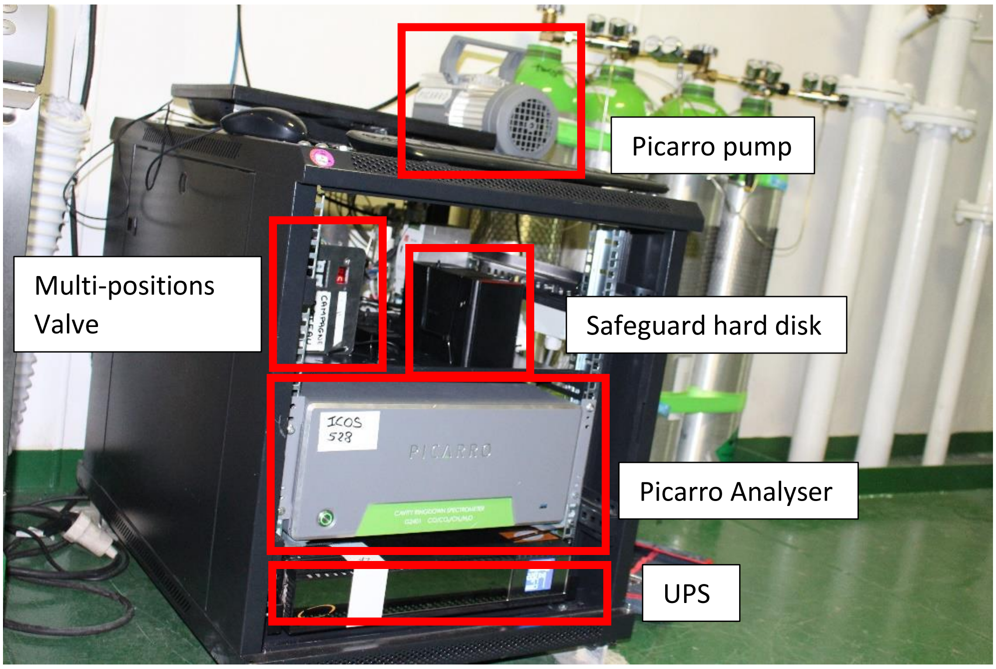


Figure 10: Photo of the instrumental set up on the SOOP COLIBRI.

A dedicated inlet has been placed on top of the mast on the upper floor of the boat, in front of the main exhaust of the vessel and connected to the multi position valve through Dekabon tubing (Synflex 1300, ¼ inch). The GPS system has also been installed on the main deck (Figure 11). The meteorological sensors providing information on temperature, pressure, relative humidity, wind speed and direction are placed opposite to the GPS system on the same platform.

Figure 11: View of air inlet (top left and right) and GPS sensor (bottom).

The inlet line and GPS cable are running from the upper deck to the instrumental rack through cable pathways over about 40 meters (Figure 12).

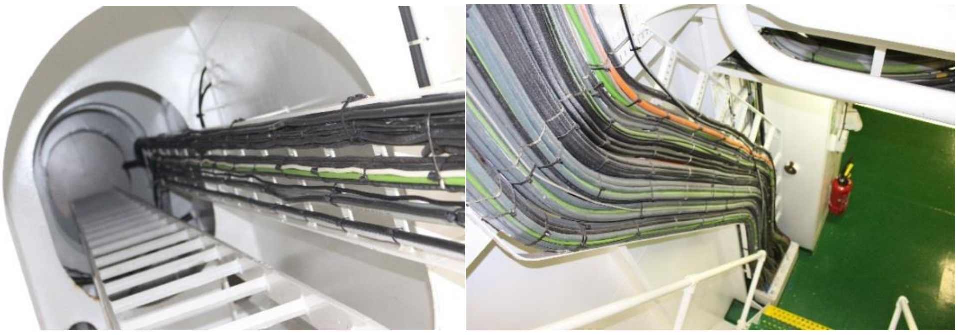


Figure 12: Air inlet line and GPS cable running through the cable pathway.

<u>System test and validation:</u>

All equipment has been first tested individually, then assembled and tested as a whole at LSCE. Tests have been done at the ATC, following protocols used for all ICOS atmospheric analysers in order to characterize the repeatability and the sensitivity to different parameters (water vapor, content, atmospheric temperature and pressure, etc.). We had then the opportunity to install and use the full system on board the British RV KOMMANDOR IONA during the intensive scientific campaign AQABA across Mediterranean and around the Arabian Peninsula (May - June 2018). This setup has shown to be reliable and adapted. It provided CO_2, CH_4 and CO data all along this campaign (Celik et al., 2020). This experience provided useful information about the set up (for example during this cruise the pumps were outside the container and showed to be quite rapidly corroded, so we decided to put all sensitive equipment inside the boat).

The setup of the monitoring system onboard the SOOP COLIBRI was realized in early March 2019 in Marseille, enabling first data acquisition starting from March 19th 2019. The first two months, the vessel was quayside in the harbour, which enabled us to test our instrumentation setting, resulting in a first upgrade of the GPS acquisition system interface that was done in May 2019. The GPS data acquisition occurring every second, initially piloted by the Picarro computer, was interfering with the Picarro G2401 (especially with the mouse and keyboard). In June 2019, the SOOP Colibri started its first trans-Atlantic cruise, followed by a second one in late August / early September. A first data recovery took place in mid-September when the vessel came back to France.

In November 2019, a second upgrade of the GPS acquisition system was implemented, as well as an automatic data transfer system activated every time the boat reaches a harbour and gets connected. A 4G router has been implemented into the instrumental rack and an automated routine (IcosStation developed at ICOS ATC and used currently used within the ICOS atmosphere network) has been implemented to enable automatic data transfer to the ICOS ATC database. With this new system we are also able to remotely connect and pilot the instrument while the vessel is at quay.

Since end of March 2019 the monitoring system has then been running continuously, and the data from the Colibri vessel are integrated and processed in the ICOS database.

<u>Measurement protocol:</u>

The GHG analyser onboard the SOOP Colibri is running continuously, wherever the boat is (at sea or at quay). The measurement protocol is similar to the one used for the ICOS atmospheric stations. A suite of three cylinders (Table 4) is used to calibrate the instrument every 30 days, then the rest of the time, the analysis sequence is altering 460 min of air and 20 min of target gas (TGT) for quality control. The calibration procedure consists of 30 minutes measurements of each of the calibration cylinders, reproduced four times. The evaluation of the calibration sequences is done automatically, based on the standard deviations of the raw measurements, the minute averages, and the injection averages (Hazan et al., 2016). The regular measurements of the target gas showed very good performances of the measurements with biases lower than 0.05 ppm for CO_2 and 0.5 ppb for CH_4 from March to September 2019, when work was done on the vessel near the analyser. Then we observed an increase of the biases up to 0.15 ppm and 0.3 ppb for CO_2 and CH_4 respectively. A small leakage on the pressure regulator used for the target gas cylinder was found during an inspection done in July 2020, indicating that the biases was not affecting the ambient air measurements but only the TGT measurements.

Cylinder ID	CO2 (µmol/mol)	CH4 (ppb)	CO (ppb)
CAL 1	386.34	1794.64	76.25
CAL 2	409.15	1947.13	153.7
CAL 3	448.38	2088.61	286.66
TGT	403.67	1962.7	135.97

Table 4: Calibration and target cylinders used onboard the Colibri Vessel while the vessel is at quay the data are automatically transferred to the ICOS data base and they are then automatically processed by the data base, following the standard ICOS data treatment procedure described in details in Hazan et al. 2016.

Picarro and GPS data files are generated and transferred separately to the ICOS data base. The files are formatted according to the ICOS standard provided by ATC. Specific developments have been implemented into the ICOS data base to take into account the mobile platform and ingest the GPS data together with the atmospheric measurements. The different types of data (Picarro, GPS) are processed separately and linked through campaign metadata. The campaign metadata include campaign description (name, bounding box, period, type of campaign, responsible institute and collaborators), vessel and instruments.

Example of data files, with their headers, are given below.

Picarro data file example: BBB_528_20200117.zip

DATE TIME FRAC_DAYS_SINCE_JAN1 FRAC_HRS_SINCE_JAN1 JULIAN_DAYS EPOCH_TIME ALARM_STATUS INST_STATUS Amb_P CavityPressure CavityTemp DasTemp EtalonTemp WarmBoxTemp species MPVPosition OutletValve CO CO2 CO2_dry CH4 CH4_dry H2O h2o_reported b_h2o_pct peak_14 peak84_raw

2020-01-17 00:00:00.256 16.00000296 384.000071 17.00000296 1579219200.256 0 963 0.0000000000E+00 1.4000204468E+02 4.4999900818E+01 3.2812500000E+01 4.4896415710E+01 4.4999595642E+01 2.0000000000E+00 1.0000000000E+00 2.6438039062E+04 1.4220984713E-01 4.1252628704E+02 4.1896513900E+02 1.9533135016E+00 1.9782370569E+00 9.9109457055E-01 1.2446830508E+00 1.2911871646E+00 5.8538924971E+02 3.5450719542E-01

2020-01-17 00:00:01.358 16.00001573 384.000377 17.00001573 1579219201.359 0 963 0.0000000000E+00 1.4000204468E+02 4.4999900818E+01 3.2812500000E+01 4.4896415710E+01 4.4999595642E+01 4.0000000000E+00 1.0000000000E+00 2.6438039062E+04 1.4095543880E-01 4.1252628704E+02 4.1896513900E+02 1.9533135016E+00 1.9782370569E+00 9.9109457055E-01 1.2446830508E+00 1.2934690874E+00 5.8538924971E+02 3.5168579899E-01

GPS data file example: BBB_660_20200117.zip

Contains 2 files, a file with the GPS data and a file with the journey information

<u>GPS data file: BBB_660_20200117.GPS</u>

Date;Time;LAT;LON;ALT-AMSL
16-01-2020;23:59:59;43.32904052734;5.34878683090;18.500000
17-01-2020;00:00:09;43.32904052734;5.34878015518;19.100000
...

<u>Journey file: BBB_660_20200117.journey</u>

journey_id=Colibri-2
operators=Marc Delmotte
start_datetime=2019-11-13 00:00:00
end_datetime=

After automated treatment the data can be visualized through the ATC quality control interface and then finally validated. Figure 13 illustrate a few months of CO_2 concentration data acquisition for the Colibri vessel with associated latitude variation.

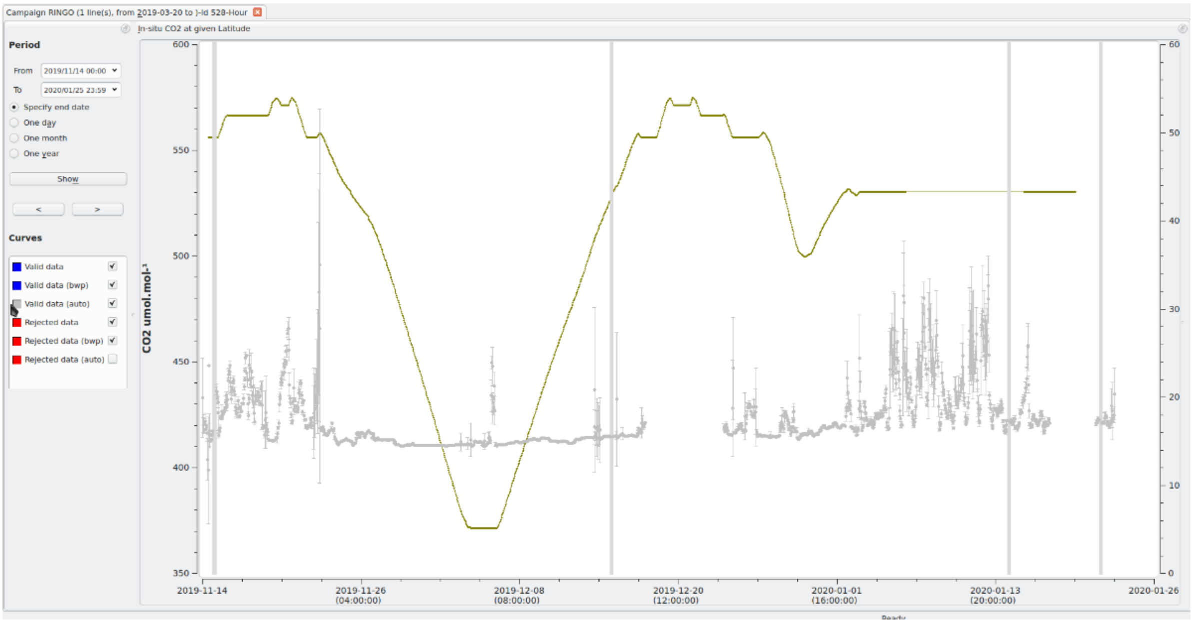


Figure 13: CO_2 concentrations measured from the Colibri vessel from mid-November 2019 to end of January 2020, with associated latitude variation (picture from the ATC-QC application used to validate the measurements).

<u>Data selection and analysis :</u>

As the instrument measures the ambient air constantly, we ended up with a dataset combining atmospheric observations made both in the ports and in the middle of the Atlantic Ocean, with very different variabilities. In order to facilitate the data analysis, we have evaluated an algorithm to select atmospheric measurements, depending on whether the ship is in or near a port; along the European coasts; or in an Atlantic transect (Figure 14). For this data selection we have entered in the database the coordinates of the harbours where the COLIBRI makes stop, and we separate the measurements along the European coasts, and the trans-Atlantic crossings by using coordinates also entered in the database.

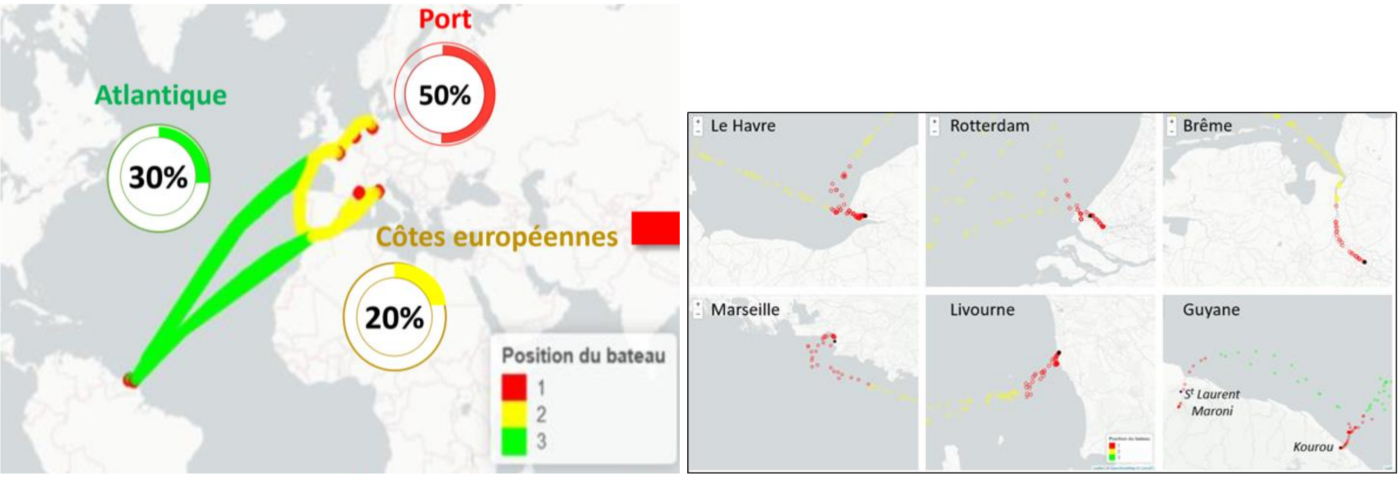


Figure 14: Left: Data selection in three categories depending on the vessel location. Right: zoom on the main harbours including ship locations within ±30km (red dots).

In addition to this selection of data according to the position of the ship, we have also validated the use of CO measurements as a tracer of local contamination from the ship's exhaust. For this step we use the spike detection algorithm set up in the ICOS data processing (El Yazidi et al., 2018). With this statistic tool we detect spikes in about 30% of the hours when the ship is located in a port, 9% when it is close from the European coasts, and 6% during the trans-Atlantic crossings.

Those developments have been tested and will be implemented in the ICOS/ATC database in the coming months, for systematic data selection process. In the longer term, it would be interesting to associate a calculation of retro-trajectories with the positions of the boat in order to help the interpretation of the observed variabilities. An example of these calculations, based on the use of the Hysplit model (Stein et al., 2015) applied to the COLIBRI transect in August-September 2019, is given in Figure 15, showing that a large part of the fast variabilities observed during the transects are related to the origin of the air masses.

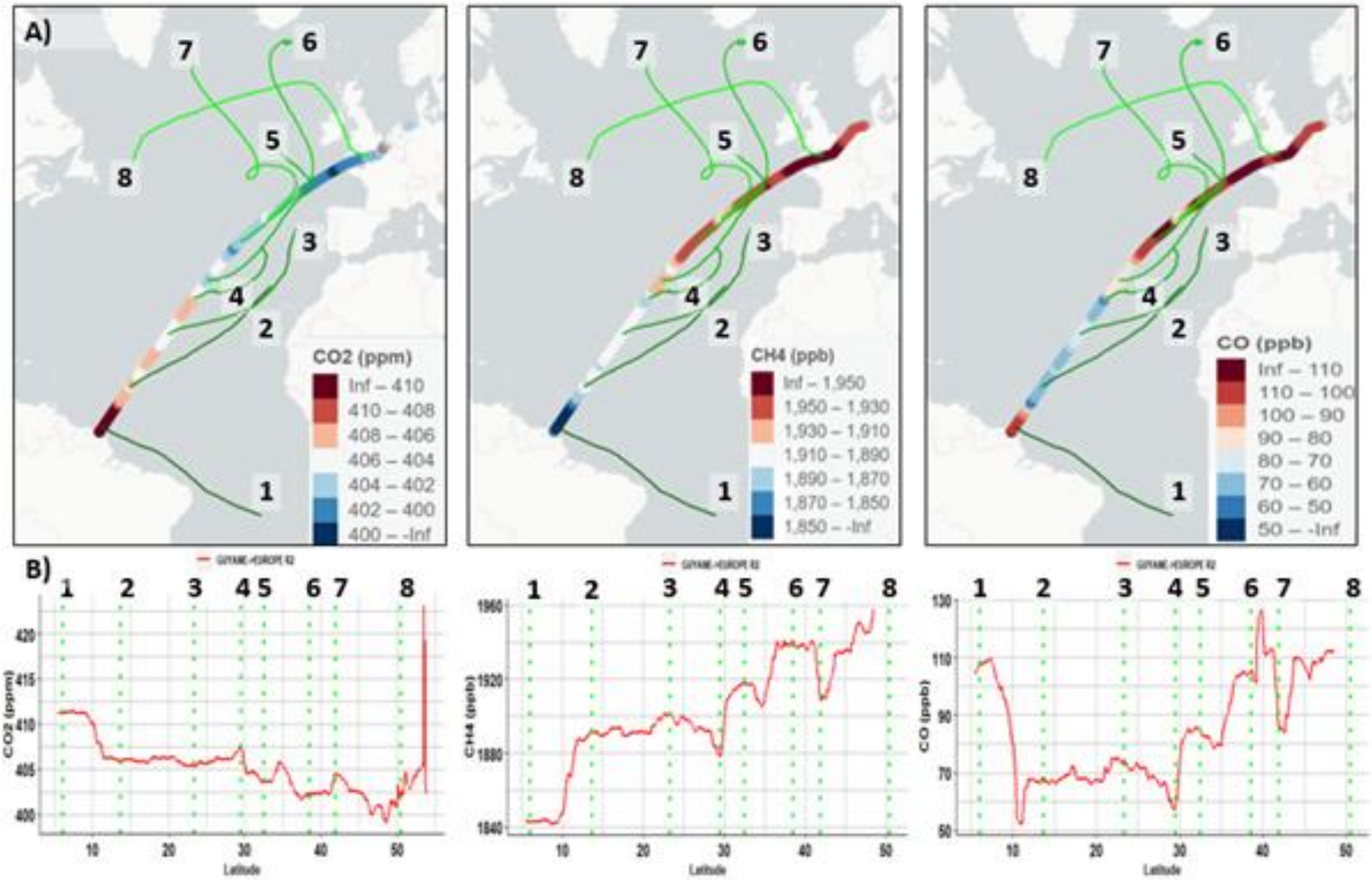


Figure 15: Atmospheric concentrations of CO_2 (left), CH_4 (middle) and CO (right) measured on board COLIBRI during the trans-Atlantic cruise in Aug-September 2019. Green curves indicate the 5-days back-trajectories calculated with Hysplit model.

4 CHALLENGES AND DELAY IN SHIPBOARD INSTATLLATION DUE TO TECHNICAL ISSUES AND PROBLEMS WITH CARRIER SHIPS

The installation of all three lines was severely hindered and delayed for several reasons, most importantly in connection to ship liaison.

SOOP TAVASTLAND

The sensor for the instrumentation to set up in the Baltic Sea was procured by the ICOS HO but not delivered before month 14 of the project. Moreover, despite negotiations and project description prior to the project, the ship carrier of SOOP Finnmaid did not give permission for installation of additional instrumentation on the ship. Thus, it was needed to find a new carrier which could fulfill the same objectives. We identified the vessel TAVASTLAND, equipped with pCO_2 instrumentation by the SMHI Sweden and on the list of future ICOS stations, as a very promising replacement, and approached the ship's owner with help of our Swedish colleagues. Permission for installation on SOOP TAVASTLAND was finally granted in February 2019 (month 26) and the construction of instrumentation started immediately afterwards. The SOOP TAVASTLAND leaves from Lübeck (same port than SOOP Finnmaid), but traverses the Baltic all the way up to Oulu (Finland) with a round trip time of one week. The ship thus covers the transition from continental to Arctic air masses, which might make the platform even better suited than the originally planned SOOP Finnmaid.

SOOP ATLANTIC CARTIER, now ATLANTIC SAIL

First tests with inlet filters and a buffer tank were made on SOOP ATLANTIC CARTIER in 2017 before the ship was taken out of service. In 2018 the whole underway pCO_2 measurement installation was moved to a new ship (M/V ATLANTIC SAIL) that is operating on the same route. Due to massive problems with the new ship itself the installation of the underway pCO_2 system took longer than expected. In 2018 the crew had no time to take care of this extra installation and the ship had several short stays in the shipyard. In the beginning of 2019 the installation was finally finished (including an air line from outside to the instrumentation in the ship's engine room for this task), but the ship then needed to go into shipyard again for an extended period of time. The ship started sailing again in November 2019, but due to the long unexpected stay in the shipyard some components of the pCO_2 system were broken and needed to be replaced. Swopping vessels and the diverse problems in the first years of the operation of the new carrier severely impacted the progress for the work proposed within RINGO. However, we plan to have a completed the installation in March 2020 and record data (atmosphere and ocean) during the trans-Atlantic crossings from then onwards.

SOOP COLIBRI

The commercial vessel named COLIBRI was chosen to set up our equipment as this vessel already hosted scientific equipment dedicated to pCO_2 measurement in the seawater since 2006, a complementary and interesting data to be used with our future measurements of atmospheric CO_2 as already illustrated in the introduction of this report. This boat is regularly crossing the Atlantic Ocean between France and French Guiana. A first visit of the ship took place in March 2017, confirming the possibility of installing our equipment in the vessel, and contacts have been taken to initiate a partnership between the ship owner company (Compagnie Maritime Nantaise) and LSCE/UVSQ. After this first contact, administrative processes were started to elaborate a partnership agreement between both parties. Difficulties relying on insurances policies and responsibilities (legal aspects) occurred, which resulted in several interactions between the parties and in consequent delays for the installation of the experimental system. In parallel to this work, a dedicated experimental set up was developed and tested to enable CO_2 atmospheric measurements on-board a commercial ship. A final agreement was signed with the "Compagnie Maritime Nantaise" beginning of March 2019. The installation of the analyzer with its calibration scale was done on the second half of March 2019, just after the signature of the agreement.

A note on ship liaison

Within Task 3.2 of RINGO, a variety of hurdles related to the platform (commercial vessels serving as ship of opportunity) have been encountered. Ships are decommissioned and replaced, and can change their routes due to economical reasons. In a time of reinforces safety regulations, granting access to the ship for personnel not belonging to the shipping community is getting more and more critical, and is often depending on individual decisions. Other than surface seawater pCO_2 measurement systems, which are usually situated below the water line, additional units for atmospheric measurements exclusively are ideally located on the upper decks, i.e. closer to the bridge and areas dedicated for passengers. Fire-, electricity-, and IT-regulations are often more stringent than on land for good reasons, and need to be considered in all aspects of the instrument design. While there are vast advantages for scientists to use commercial vessels for research, the added value for the shipping company is restricted to potential public relation products or is part of the company's environmental program, and it is difficult to establish a balanced give-and-take relation. Despite this situation, it has to be emphasized that the ship's crew, in particular in the engineering department, are usually incredible supportive and enabling in all aspects during installation and maintenance, once the decision for an installation has been made.

Based on these experiences, well known to the ocean community, but maybe less usual for the atmospheric branch of ICOS, and "encountered" in various form during the work related to Task 3.2 of RINGO,
we RECOMMEND:

- Seeking contact with the decision making bodies of the shipping company and the master and crew of the ship as early as possible;
- Try to get all information about the most likely fate of the ship in the years to come, special safety regulations both concerning placement and materials, and potential added value which could be produced for the shipping company;
- Install instrumentation in a way that would allow removal and re-installation on another ship as much as possible;
- Lastly, we encourage that the OTC strengthens products which documents added value for the ship, such as brochures, a web page of ICOS-supporting shipping companies, etc..

5 CONCLUSIONS AND OUTLOOK

Despite severe delays, we were able to install amendments / additional instrumentation on the three SOOPS TAVASTLAND, COLIBRI, and ATLANTIC CARRIER following three different approaches. The feasibility of meeting ATC conformity has already been shown for one system (SOOP COLIBRI), and will likely be demonstrated for SOOP TAVASTLAND before the end of the project. On SOOP ATLANTIC SAIL, it was possible to install the dedicated next generation of sensors for most ICOS pCO_2 lines, including needed amendments on the GO peripheral unit, allowing an assessment of the quality of atmospheric measurements that can be reached as a "by-product" of pCO_2 installations. The effort already had impact on national science implementation. The system installed on board SOOP COLIBRI will be duplicated in fall 2020 for installation on board the R/V Marion Dufresne as part of a French national research program. The Marion Dufresne Atmospheric Program in Indian Ocean (MAP-IO), will start atmospheric and oceanic observations in December 2020. The ship will be equipped for greenhouse gases measurements, using the concept developed for the COLIBRI, as well as for aerosols, reactive gases and meteorological measurements.

A technical handbook for the installation for such installations will follow as final deliverable of Task 3.2 of RINGO. Upon retrieval of several months of data from the stations, the added value for e.g. inverse modelling approaches will be shown, though unfortunately, this will not be possible within the duration of the project. Still, the data from SOOP COLIBRI have also been shown to be consistent, and suitable to further validation, of the Copernicus CAMS products.

6 DEFINITIONS, ACRONYMS AND ABBREVIATIONS

ACL	Atlantic Container Line (ship owner/operator)
ATC	Atmospheric Thematic Center
Copernicus	The European Union's Earth Observation Programme
CAMS	Copernicus Atmosphere Monitoring Service
ESRL	Earth System Research Laboratories
GAW	Global Atmosphere Watch
GEOMAR	Helmholtz Centre for Ocean Research Kiel
ICOS	Integrated Carbon Observation System
ICOS HO	Integrated Carbon Observation System Head Office
IOW	Leibniz Institute for Baltic Sea Research Warnemünde
MBL	Marine Boundary Layer
NOAA	National Oceanic and Atmospheric Administration
OTC	Ocean Thematic Center
pCO_2	Partial pressure of CO_2
SOCAT	Surface Ocean CO_2 Atlas (SOCAT)
SOOP	Ship of opportunity
UVSQ	Université de Versailles Saint-Quentin-en-Yvelines
WMO	World Meteorological Organization

7 APPENDIX A – References

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